Measurement of Jet Constituent Yields in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV Using the ALICE Detector

Charles P. Hughes

University of Tennessee, Knoxville, chughe26@vols.utk.edu

Follow this and additional works at: https://trace.tennessee.edu/utk_graddiss

Part of the Nuclear Commons

Recommended Citation
Hughes, Charles P., "Measurement of Jet Constituent Yields in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV Using the ALICE Detector." PhD diss., University of Tennessee, 2022. https://trace.tennessee.edu/utk_graddiss/7244
To the Graduate Council:

I am submitting herewith a dissertation written by Charles P. Hughes entitled "Measurement of Jet Constituent Yields in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV Using the ALICE Detector." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Physics.

Christine E. Nattrass, Major Professor

We have read this dissertation and recommend its acceptance:

Christine Nattrass, Soren Sorensen, Kenneth Read, Guillermo I. Maldonado

Accepted for the Council:

Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)
Measurement of Jet Constituent Yields in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV Using the ALICE Detector

A Dissertation Presented for the

Doctorate of Philosophy

Degree

The University of Tennessee, Knoxville

Charles Philip Hughes

August 2022
Abstract

Hard partonic scatterings serve as an important probe of quark-gluon-plasma (QGP) properties. The properties of jets and their constituents can provide a tool for understanding the partonic energy loss mechanisms. Low momentum jets offer a unique window into partonic energy loss because they reconstruct the partons which have lost a significant amount of energy to the QGP medium. The main difficulty in studying low momentum jets in heavy ion collisions is the presence of a significant uncorrelated background of low momentum hadrons from soft processes. One way to deal with this background is to use jet-hadron correlations to fit and subtract the soft, flow-modulated background. This technique allows measurements of the near and away-side yields. I present constituent yields for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. These yields are a measurement of the raw fragmentation function. I also discuss prospects for unfolding the distributions of yields to get a corrected fragmentation function for low jet momenta.
Acknowledgments

I would like to thank my advisor Dr. Christine Nattrass for her never-ending patience and skillful editing pen. This thesis would not have been possible without her continued dedication to teaching and mentorship, her great attention to detail, and her programming skills. I would also like to thank Dr. Soren Sorensen for his invaluable contributions to my dissertation, my graduate career, and my overall understanding of the scientific enterprise. In particular, many great discussions were had on a wide range of topics - from issues including unfolding to The Structure of Scientific Revolutions by T.S. Kuhn and everything in between. Many of these discussions have directly and indirectly influenced the writing of this dissertation and it is assuredly better for it. I would like to thank Dr. Ken Read for his contributions, including very productive discussions about comparisons to models and other measurements. Thank you also to Dr. Ivan Maldonado for his contributions, including his thought-provoking questions about detectors and their inner workings.

Thank you very much to fellow grad student Joel Mazer whose patience with me in my early career helped bring me to this point. His wisdom and experience were critical to starting my graduate career in heavy ion physics. Thank you also to grad students Andrew Castro, Kyle Schmoll, and Rebecca Scott whose help included everything from how to cut copper pipes to the best programming practices. Thank you to Redmer Bertens, Adam Matyja, and Antonio da Silva whose post-doctoral guidance was crucial in many of my endeavors including simulations of fragmentation functions, TPC Pre-Commissioning, and ALICE analyses. Thanks to fellow grad student Will Witt whose skill as a craftsman made the biggest contribution to the number of copper pipes bent and front end electronics cards assembled and whose skill as an astronomer helped me understand the difference
between Mars and Jupiter in the night sky over Geneva. Thanks to fellow grad student Patrick Steffanic whose interest in machine learning and all things computing proved a crucial part of my learning process - and establishing just how much there is for me left to learn. Thanks to fellow grad student Austin Schmier whose questions allows proved useful for my understanding of just about everything and for allowing me to car-pool to ORNL. Thanks to grad student Tanner Mengel whose great ideas always proved a wonderful source of inspiration. Thanks also to Biswas Sharma for many helpful discussions about fitting functions. Thank you to Brennan Hackett, Becca Toomey, and Trevor Keen for all their great edits to this thesis. Thank you to Joshua Barrow for his insight into all things science. Thank you to Yuri Kamyskho and Yuri Efremenko for great discussions and guidance (if I have any presenting skills at all, both of them have certainly contributed to their development). Thanks also to Tony Mezzacappa for his support and guidance. Thank you to Anne Jennings for her dedication to teaching and all her help with grading exams. Thank you to the UTK physics administrative staff including Chrsianne Romeo, Maria Fawver, and Chloe Miller who all helped along the away during my Ph.D. I greatly appreciate your patience and advice on everything from travel to scheduling classes. Thank you very much to the physics machine shop staff at UTK including Ricky Hufstetter, Joshua Bell, and Alvin Peak for their never-ending patience with engineering drawing modifications. Thanks also for their great craftsmanship that made the assembly of the ALICE IROCs possible. Thank you to Jason Chan from the UTK physics electronics shop whose help setting up the oxygen sensor read out was instrumental in getting leak testing set up. Thank you very much to Richard Sexton in the UTK Agriculture Library whose 3D printing experience was critical for copper pipe assembly. Thank you to Raymond Ehlers, Hannah Bossi, Caitlin Beattie, and Michael Oliver at Yale University for all of their help with various aspects of this analysis including the RPF fit, running LEGO trains, and their patience with combined Quark Matter presentations. Thank you very much to Richard Majka and Nikolai Sminrnov at the Yale Wright Lab for their wonderful instruction in all of the IROC testing and assembly procedures. Thank you very much to the ALICE TPC crew including Chilo Garabatos, Robert Munzer,
Christian Lippmann, Renato Negrao, and Torsten Alt. Thank you to Robert Munzer in particular for his great mentorship and willingness to work with me over 6 time zones in the middle of a pandemic. Thanks very much to Renato Negrao whose great instruction helped me learn a lot about the ALICE TPC. Thank you also to Kristjan Gulbrandsen who taught me how to exercise patience after the LHC loses cryo for its magnets. Thank you to Cristina Terrevoli and Manuel Colocci for their valuable leadership as Run Managers during my shifts at the LHC.

Thank you to my parents whose love and support got me to this point. Finally, thank you very much to my loving partner Katie McGuire for her un-wavering support and encouragement. Without her and her incredible copy-editing skills, this dissertation would not have been possible.
# Table of Contents

1 Introduction and Background 1

1.1 Quantum Chromo-Dynamics .......................... 1

1.2 QCD Phase Transition .............................. 3

1.3 Quark Gluon Plasma ............................... 5

1.4 Heavy Ion Collisions ............................... 7

1.4.1 Initial Conditions and Impact Parameter ............ 7

1.4.2 QGP Formation .................................. 9

1.4.3 Hadronization and Kinetic Freezeout .............. 12

1.5 Final State Particles: Jets and Underlying Event .... 14

1.5.1 Flow .......................................... 15

1.5.2 Jets .......................................... 18

1.5.3 Jet Finding Algorithms .......................... 18

1.5.4 Jet-Hadron Correlations ........................ 21

1.6 Fragmentation Functions ............................ 22

1.6.1 Lund String Model of Fragmentation ............... 24

1.6.2 Fragmentation in Experiment .................... 27

1.7 Path length Dependence in Different Jet Energy Loss Mechanisms .... 29

2 Detector Equipment and Instrumentation 34

2.1 Large Hadron Collider ............................. 34

2.2 ALICE detector .................................... 37

2.2.1 TZERO ........................................ 37
3 Previous Measurements, Software, and Service Work

3.1 Previous Analyses ...................................................... 57
3.2 Software Framework .................................................. 61
3.3 Fragmentation Functions in Simulations ............................ 62
  3.3.1 Heavy Ion Background Simulation .............................. 63
  3.3.2 Jet-Hadron Correlations and Background Subtraction in Simulation . 70
  3.3.3 Two-Dimensional Unfolding in Simulation ...................... 70
  3.3.4 JEWEL Simulations .............................................. 73
3.4 Service Work ......................................................... 73
  3.4.1 IROC Assembly ................................................ 76
  3.4.2 Leak Test ...................................................... 80

4 Data Processing and Computing ....................................... 88

4.1 Vertex finding ....................................................... 91
4.2 Track Finding ....................................................... 92
  4.2.1 TPC cluster finding ........................................... 92
  4.2.2 TPC track finding ............................................ 95
  4.2.3 TPC+ITS Track Finding ..................................... 97
  4.2.4 ITS Standalone Track Finding ............................... 99
4.3 EMCAL Data Reconstruction ....................................... 99
  4.3.1 Raw Analyzer ................................................ 102
  4.3.2 Digit Maker .................................................. 102
  4.3.3 Clusterizer .................................................. 102
4.4 Centrality Determination ......................................... 103
4.5 Event Plane and Flow Coefficient Determination ................. 103
# 5 Analysis Method

- 5.1 Fragmentation Functions from Jet Hadron Correlations
  - 5.1.1 Acceptance Correction
  - 5.1.2 Reaction Plane Fit Subtraction Method
  - 5.1.3 Fragmentation Function from Correlation Yields
  - 5.1.4 Unfolding Fragmentation Functions
- 5.2 Methods for Feasibility Model Study
  - 5.2.1 Simulation Packages
  - 5.2.2 Acceptance Correction
  - 5.2.3 Background Subtraction
  - 5.2.4 Unfolding Fragmentation Functions
- 5.3 Methods for Data Analysis
  - 5.3.1 Data Selection
  - 5.3.2 Acceptance Correction
- 5.4 Jet Hadron Correlations
  - 5.4.1 Reaction Plane Fit Subtraction Method
  - 5.4.2 Yield Extraction and Yield Ratios
  - 5.4.3 Systematic Error Analysis

# 6 Results and Discussion

- 6.1 Fragmentation Function in Model Studies
  - 6.1.1 Proton-Proton Collisions
  - 6.1.2 Heavy Ion Collisions
- 6.2 Correlation Functions
  - 6.2.1 Reaction Plane Fits
  - 6.2.2 Background Subtracted Correlations
  - 6.2.3 Yields
  - 6.2.4 Yield Ratios and Comparisons to JEWEL
- 6.3 Connection to Previous Measurements
  - 6.3.1 Comparison to 2.76 TeV Yields
List of Tables

5.1 Table showing the axes and the index of of the 4 dimensional response object, R. ................................................................. 125

1 Acronymns/Abbreviations/Symbols ........................................ 225
2 In Plane Near Side Yields: $p_T^{jet} = 20$-40 GeV ...................... 250
3 Mid Plane Near Side Yields: $p_T^{jet} = 20$-40 GeV .................... 250
4 Out of Plane Near Side Yields: $p_T^{jet} = 20$-40 GeV ................. 251
5 Inclusive Near Side Yields: $p_T^{jet} = 20$-40 GeV .................... 251
6 In Plane Away Side Yields: $p_T^{jet} = 20$-40 GeV .................... 252
7 Mid Plane Away Side Yields: $p_T^{jet} = 20$-40 GeV .................... 252
8 Out of Plane Away Side Yields: $p_T^{jet} = 20$-40 GeV ............... 253
9 Inclusive Away Side Yields: $p_T^{jet} = 20$-40 GeV .................... 253
10 RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc.} = 0.5$-1 GeV .... 254
11 RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc.} = 1$-1.5 GeV ... 254
12 RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc.} = 1.5$ - 2.0 GeV ........ 255
13 RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc.} = 2.0$ - 3.0 GeV ... 255
14 RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc.} = 3.0$ - 4.0 GeV .... 256
15 RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc.} = 4.0$ - 5.0 GeV .... 256
16 RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc.} = 5.0$ - 6.0 GeV .... 257
17 RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc.} = 6.0$ - 10.0 GeV .... 257
18 Single Track Reconstruction $\epsilon(p_T)$ Fit Parameters, LHC2018q, 5.02 TeV 30 - 50 % ................................................................. 258
Single Track Reconstruction $\epsilon(\eta)$ Fit Parameters, LHC2018q, 5.02 TeV 30 -

50 \% ................................................................. 259
List of Figures

1.1 Static Quark Potential for a Quark, Anti-Quark Pair . . . . . . . . . . . . . 2
1.2 QCD phase diagram. Figure taken from Ref. [74]. . . . . . . . . . . . . . . 4
1.3 Energy density divided by temperature to the fourth power as function of
temperature caluclated by various Lattice QCD simulations. Figure taken
from Ref. [53]. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 6
1.4 Time evolution of a heavy ion collision. Figure taken from Ref. [67]. . . . . 8
1.5 Cartoon illustrating the relationship between the average impact parameter,
\(<b>\) and the charged particle multiplicity \(N_{ch}\). As the average impact
parameter, \(<b>\) increases, the cross section \(\frac{d\sigma}{N_{ch}}\) decreases monotonically.
Figure from [59]. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 10
1.6 Cartoon demonstrating the elliptic flow occuring during QGP formation and
expansion as due to initial state azimuthal anisotropy. Figure taken from
Boris Hippolyte. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 11
1.7 Measurements of elliptic flow parameter \(v_2\) made by the PHENIX (left) and
STAR (right) collaborations from \(\sqrt{s_{NN}} = 200\) GeV at the RHIC. These
measurements show a clear universal quark scaling; that is the curves of \(v_2\) all
lie on top of each other when scaled by the number of valence quarks. . . . . 13
1.8 Cartoon Showing the reaction plane of the colliding nuclei. \(\Psi_{RP}\) is the reaction
plane angle, \(\phi_\alpha\) and \(\phi_\beta\) are the angles of the final state hadrons produced in
the collision. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16
1.9 Azimuthal Distribution of final state particles from individual harmonic contributions (5 left pictures) and the sum (furthest right picture). Semi-Realistic values are chosen for each reaction plane and $v_n$ magnitude.

1.10 Cartoon of hadrons produced from a hard scattering of electrons and positrons which produces a virtual gamma ray.

1.11 Cartoon of a 3 jet event in $e^+$ and $e^-$ collisions.

1.12 Measured Jet-Hadron correlations in 0-20% centrality Au-Au collisions by the STAR collaboration. The jet momentum threshold was $p_T^{jet} > 20$ GeV/c and the associated particle momentum bin was $1.0$ GeV/c $\leq p_T^{assoc} \leq 2.5$ GeV/c. Closed symbols are Au-Au data, open symbols are from p-p collisions. Figure taken from [61].

1.13 Cartoon illustration of the different stages of a heavy ion collision. Figure taken from Ref. [57].

1.14 Lund String Model Space Time Pictures. The quark anti quark pair fragments, producing hadrons.

1.15 CMS measured fragmentation functions. Figure taken from [56].

1.16 Energy loss of partons in the QGP medium in the weakly-coupled, static approximation. Figure courtesy of Caitlin Beattie.

1.17 Path length dependence of jet energy loss due to collisions only (solid) and radiative effects only (dotted) in the QGP medium for somewhat realistic assumptions. All jets have an initial energy of 10 GeV. Figure taken from [37].

1.18 (Upper panel) Fragmentation function in $\gamma$ tagged jets in p-p, 0-30 % and 30-80 % Pb-Pb collisions along with accompanying models. (Lower panel) Ratios of 0-30 % Pb-Pb to p-p and 30-80 % Pb-Pb to p-p along with accompanying models [28].

2.1 CERN accelerator complex. Figure taken from Ref. [26].

2.2 LHC crossing points and detectors. Figure taken from Ref. [26].

2.3 ALICE Detector Overview.
2.4 From left to right (gold) TZERO, VZERO, and FMD detectors on the A side ($\eta > 0$). The Inner Tracking System layers are shown in grey. Figure taken from Ref. [31].

2.5 ALICE VZERO-A and VZERO-C front side. Figure taken from Ref. [11].

2.6 ALICE Inner Tracking System. Figure taken from Ref. [11].

2.7 ALICE TPC Stereographic View

2.8 TPC Working Principle taken from Ref. [52]

2.9 ALICE TPC Wire Geometry for Outer (left) and Inner (right) Read Out Chambers. Figure taken from Ref. [35].

2.10 ALICE TPC Electric Field Line configuration for gating grid closed (top) and gating grip open (bottom). Figure taken from Ref. [17].

2.11 ALICE TPC Front End Cards for Readout Electronics. Figure taken from Ref. [35].

2.12 Example of differing magnitude pre-amplified signals from the CERES NA45 experiment. Note the long tails. The top curve is before tail cancellation, the middle curve after the first filter, and the bottom after the final filter. Figure taken from Ref. [35].

2.13 ALICE TPC FEC Tail Cancellation. Output 1 is after 1st filter and Output 2 is after 2nd filter. Figure taken from Ref. [35].

2.14 ALICE EMCAL Tower, top view. Figure taken from Ref. [36].

2.15 ALICE EMCAL super module. Figure taken from Ref. [11].

3.1 Measured $\xi$ Distributions in Pb-Pb collisions. The Bottom Panel Contains the Ratio of the $\xi$ Distributions in Pb-Pb Collisions to the $\xi$ Distributions in p-p Collisions. Made by the CMS Collaboration [29].

3.2 Ratio of measured $z$ Distributions in various centrality bins in Pb-Pb collisions. Made by the ATLAS Collaboration [16].

3.3 Boltzmann Gibbs Blast Wave fit to measured $K^+$ $p_T$ spectra for various centralities.
3.4 $v_2$ vs $p_T$ polynomial fit to measurements for 10 - 20 % centrality ...................... 66
3.5 Flow chart depicting the inner workings of TennGen [47]. HF stands for Harmonics Flag which allows the user to select which (if any) harmonics to include in the $\phi$ distribution of each particle. ................................. 68
3.6 Jet candidates made from TennGen particles. The $v_n$ combinations have been varied and different backgrounds were produced. Then, the anti-$k_T$ clustering algorithm with jet resolution parameter $R = 0.2$ was ran on each set of backgrounds. For each $v_n$ combination, 10000 background events were produced. ............................................. 69
3.7 RPF method applied to 30 - 50 % central $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collision data. The blue bands represent the uncertainty in the RPF background fit. Figure taken from Ref. [55]. ................................. 71
3.8 Typical Results for 2-Dimensional Unfolding. Top Left: True $p_T^{\text{jet}}$ vs $p_T^{\text{assoc}}$. Top Right: Measured $p_T^{\text{jet}}$ vs $p_T^{\text{assoc}}$ (True distribution run through a $p_T$ dependent efficiency). Bottom Left: Unfolded $p_T^{\text{jet}}$ vs $p_T^{\text{assoc}}$ via the singular value decomposition method. Bottom Right: Unfolded $p_T^{\text{jet}}$ vs $p_T^{\text{assoc}}$ via the iterative Bayesian method. Figure produced by William Witt. ................. 72
3.9 Example of a single scattering event in JEWEL occurring in medium. On the left, a solid black line (quark) and squiggly black line (gluon) scatter off each other elastically (grey circle) and then further radiate. Figure taken from [77]. 74
3.10 Example of a multiple scattering event in JEWEL occurring in medium. On the left, a solid black line (quark) and squiggly black line (gluon) scatter off each other elastically (grey circle) and then further scatter within the medium (additional grey circles) on a comparable time scale. Figure taken from [77]. 75
3.11 Flow chart showing the different institutes who took part in the ALICE TPC Upgrade and their roles. The University of Tennessee and their role (IROC Body Assembly) is circled. .......................................................... 77


3.14 Panel showing the different assembly steps for the ALICE TPC IROCs. Top left: Shaping the copper pipe. Top middle: applying the epoxy/copper dust mixture. Top right: Using the clamp/jigs to bond the copper pipe into the groove. Bottom left: applying epoxy to the pad plane. Bottom middle: attaching strong back and pad plane. Bottom right: final assembly curing on the vacuum table.

3.15 Leak test setup for the IROCs. From left to right, nitrogen flows into the test vessel/IROC combination, out into the oxygen sensor, and out through a pigtail into paraffin oil.

3.16 Example of a leak test for IROC 38. The various features of the leak test are highlighted, including the final leak rates which are in the box on the upper right.

3.17 Distribution of leak rates for all IROC bodies produced at the University of Tennessee. The threshold leak rate is highlighted (0.25 mL/hr).

3.18 Electronics schematic for the DAQ/laptop connection. The oxygen sensor is connected in series with a 121 Ohm resistor and a power supply. The DAQ is connected across the resistor and to the laptop.

3.19 Labview front end, allowing the user to change the sensitivity of the measurement, see the oxygen trend over time, and view the moving average of the oxygen content in the sensor.

4.1 Table showing typical event sizes in a p-p minimum bias event and a Pb-Pb central event in ALICE for difference ALICE detectors. Figure taken from Ref. [41].
4.2 ALICE DAQ Architecture Overview. Data tend to flow from FERO (Front End Read Out) to the Event Building Network to the Storage Network. Data rates start at 25 GB/s and eventually reduce to 1.25 GB/s at storage. Figure taken from Ref. [41]. ................................................................. 90

4.3 Resolution of Vertex $z$ component as a function of $\frac{dN_{ch}}{d\eta}$. Solid line is from a parameterized fit. Figure taken from [34]. ................................................................. 93

4.4 Schematic example of ADC values in the pad row-time plane used for the STAR Experiment. Red circles illustrate clusters found by the clustering algorithm (those values which are greater than the zero suppression threshold). Figure taken from Ref. [27]. ................................................................. 94

4.5 Schematic showing seed finding in the TPC. The two red points on the right side of the picture are the pair and the red curve is the helix projected back to the collision vertex region. The circle around the left most red point represents the artificially large uncertainty given tho the collision vertex at this stage of the track finding. Figure taken from Ref. [18] ................................................................. 96

4.6 Schematic showing an example of a candidate tree in the ITS from a track starting in the TPC. The final chosen track is shown in solid green while all the possible tree branches are shown in dotted green. Figure taken from Ref. [19]. ................................................................. 98

4.7 Reconstruction Efficiency for low momentum ($p_T$ < 1.5 GeV) TPC and TPC+ITS tracks. Extension of track to the ITS decreases the reconstruction efficiency by as much as 20 %. Figure taken from Ref. [41]. ......................... 100

4.8 ITS event display after removing hits assigned to tracks found with help of the TPC. The xy plane is the transverse plane, the zy plane is one of the longitudinal planes. Figure taken from Ref. [34]. ......................... 101

4.9 ALICE event reconstruction. EMCAL online components shown in green. Figure taken from Ref. [64]. ......................... 101

4.10 Centrality Bins from VZERO amplitudes. Figure taken from Ref. [1]. ...... 104
4.11 Centrality resolution from multiple detectors. The V0A and V0C are shown as red and green triangles, respectively. The combination of the V0A and V0C is shown in blue circles and provides the best centrality resolution amongst all detectors across the entire centrality range. Figure taken from Ref. [3].

4.12 Second Order Event Plane Resolution as a function of centrality in Pb-Pb collisions. Measured from VZERO. Figure taken from Ref. [1].

5.1 Scheme for obtaining fragmentation functions from jet-hadron correlations. Correlations are calculated, background is subtracted from the correlations (using the RPF method), the background subtracted yields are extracted, and finally the yields are unfolded to correct for detector effects.

5.2 Schematic representation of a jet-hadron correlation in azimuthal space. The red dotted cone and line are the jet and jet axis respectively. The black arrows are the hadrons produced in the event. The black arrows which fall within the dotted red cone are the near-side jet constituent hadrons. The correlation variable, $\Delta \phi_{\text{jet-hadron}}$, is the difference in the jet axis $\phi_{\text{jet}}$ and the $\phi_{\text{hadron}}$.

5.3 Jet-Hadron Correlation in $\Delta \phi$ for simulated 13 TeV proton-proton collisions using PYTHIA for 10-30 GeV anti-$k_T$ jets and all associated hadrons. Two peaks at $\Delta \phi=0$ and $\Delta \phi=\pi$ are visible.

5.4 Jet-hadron correlation without acceptance correction for $R = 0.2$ anti-$k_T$ $p_T = 27.5-30$ GeV jets and 2-3 GeV hadrons using PYTHIA simulations of 2.76 TeV p-p collisions. Notice the trapezoidal shape the near-side jet peak sits on top of - this is due to the finite particle and jet acceptance.

5.5 Simple acceptance correction for the model studies ($R = 0.2$ anti-$k_T$ jets). The shape is trapezoidal along the $\Delta \eta$ axis and constant along the $\Delta \phi$ axis. This is an appropriate assumption for the model feasibility studies.

5.6 Acceptance corrected and normalized Jet-Hadron correlation for $R = 0.2$ anti-$k_T$ $p_T = 27.5-30$ GeV jets and 2-3 GeV hadrons using PYTHIA simulations of 2.76 TeV p-p collisions. After the acceptance correction, the baseline is flat.
5.7 Illustration of the different reaction plane orientations; red is in plane, white is midplane, and blue is out of plane. Figure taken from Ref. [66].

5.8 Fit of Jet-Hadron Correlations taken from Run 1 30-50 % central \( \sqrt{s_{NN}} = 2.76 \) TeV Pb-Pb ALICE data to RPF for in plane, mid plane, out of plane, and all jets. \( p_T^{assoc.} = 1.5 - 2.0 \) GeV/c and \( p_T^{jet} = 20 - 40 \) GeV/c jets. Figure taken from [55].

5.9 Result of subtraction of RPF fit from Jet-Hadron Correlations taken from Run 1 30-50 % central Pb-Pb collisions \( \sqrt{s_{NN}} = 2.76 \) TeV Pb-Pb ALICE data to RPF for in plane, mid plane, out of plane, and all jets for \( p_T^{assoc.} = 1.5 - 2.0 \) GeV/c and \( p_T^{jet} = 20 - 40 \) GeV/c. Figure taken from [55].

5.10 Figure showing a single track reconstruction efficiency calculated from HIJING simulations anchored to the ALICE 2018 5.02 TeV 0-10 % central Pb-Pb dataset. The solid line is a parameterized fit done between 1 and 25 GeV in \( p_T \).

5.11 Example of a projection of the response object along the jet \( p_T \) axes (measured and truth). The projection is across the entire \( p_T^{assoc.truth} \) and \( p_T^{assoc.meas.} \) range.

5.12 2D Kinematic Efficiency as a function of \( p_T^{assoc} \) and \( p_T^{assoc.} \). Most of the inefficiency (lowest values) is at low \( p_T^{assoc} \) and low \( p_T^{assoc.} \). This efficiency is calculated as in Equation 5.8.

5.13 Figure showing the schematic goal of the model feasibility study. A signal (PYTHIA simulations of proton-proton events) is embedded into a background (TennGen simulations of Pb-Pb events). Jet-hadron correlations are calculated from these combined events and the background subtraction method (RPF) is applied from which the correlation yields are then obtained. Next, the yields are unfolded using 2D unfolding. The result is compared to the signal, and if they agree “closure” is obtained and feasibility is demonstrated.
5.14 Pedestal subtraction in model study. Solid correlation function is before the pedestal subtraction, dotted correlation function is after pedestal subtraction. The red shaded region indicates the near-side peak which is integrated to obtain the near-side yield.

5.15 RPF subtraction in model study. Solid correlation function is before the RPF subtraction, dotted correlation function is after RPF subtraction. The red shaded region indicates the near-side peak which is integrated to obtain the near-side yield.

5.16 Top: Particle level in model studies. Bottom: Detector level in model studies. Holes represent single track reconstruction efficiency. Spikes represent momentum smearing. The $K^0_{long}$ and $n,\pi$ have been completely removed at detector level.

5.17 Event Selection from 0 - 10 % central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The black line (underneath the red line) shows the labeled cuts only. The red line shows the labeled cuts with the addition of the minimum bias trigger. The blue line shows the addition of the minimum bias trigger and the specified centrality selection. The x-axis shows the effect of each individual cut on the dataset statistics, except for the last bin which shows the effects of all the cuts.

5.18 Event Selection from 30 % - 50 % central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The black line (underneath the red line) shows the labeled cuts only. The red line shows the labeled cuts with the addition of the minimum bias trigger. The blue line shows the addition of the minimum bias trigger and the specified centrality selection. The x-axis shows the effect of each individual cut on the dataset statistics, except for the last bin which shows the effects of all the cuts.

5.19 2D single track reconstruction efficiency for 0 - 10 % central Pb-Pb events in the 2018q data set.

5.20 2D single track reconstruction efficiency for 30 - 50 % semi-central Pb-Pb events in the 2018q data set.
5.21 1D projection along the $p_T$ axis of the single track reconstruction efficiency for 0 - 10 % central events
5.22 1D projection of the $\eta$ axis of the single track reconstruction efficiency for 0 - 10 % semi-central events.
5.23 Fit to 1D projection of the $p_T$ axis of the single track reconstruction efficiency for 0 - 10 % semi-central events using Equation 5.12.
5.24 Fit to 1D projection of the $\eta$ axis of the single track reconstruction efficiency for 0 - 10 % semi-central events using Equation 5.13.
5.25 Residual of fit to the single track reconstruction efficiency for the 0-10 % centrality bin. Across the fit range, deviations of the efficiency simulation from the fit average at 0 and are no more than 6 %.
5.26 Residual of fit to the single track reconstruction efficiency for the 30-50 % centrality bin. Across the fit range, deviations of the efficiency simulation from the fit average at 0 and are no more than 10 %.
5.27 Figure showing the effect of the bad channel map correction on the spectrum of EMCAL clusters in events with jets > 15 GeV in 2018qpass3 dataset.
5.28 Jet spectra utilized in this analysis with the cluster/track and leading hadron biases listed on the plot. Jets found in 2018qpass3 dataset. The binning is reflective of the binning used in this analysis.
5.29 Example of mixed-event acceptance correction for $p_T^{jet} = 20-40$ GeV and $p_T^{assoc.} = 0.5 - 1$ GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.
5.30 Example of an un-corrected jet hadron correlation for $p_T^{jet} = 20-40$ GeV and $p_T^{assoc.} = 0.5 - 1$ GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.
5.31 Example of an acceptance corrected jet hadron correlation for $p_T^{jet} = 20-40$ GeV and $p_T^{assoc.} = 0.5 - 1$ GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.
5.32 Example of the RPF fit to the in-plane, mid-plane, and out of plane jet hadron correlations for \( p_T^{jet} = 20-40 \text{ GeV} \) and \( p_T^{assoc.} = 0.5 - 1 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV Pb-Pb dataset. Note that the fit only occurs on the near-side or \( |\Delta \phi| < \pi/2 \). Fit residuals to the entire \( \Delta \phi \) region are shown in the bottom panel.

5.33 Near-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for \( p_T^{jet} = 20-40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV Pb-Pb dataset. Uncertainties are statistical, and systematic including a 4 % scale uncertainty from the single track reconstruction efficiency.

5.34 Away-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for \( p_T^{jet} = 20-40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV Pb-Pb dataset. Uncertainties are statistical, and systematic including a 4 % scale uncertainty from the single track reconstruction efficiency.

5.35 Ratios of the near-side yield ratios of mid-plane to in-plane jet hadron correlations for \( p_T^{jet} = 20-40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.

5.36 Ratios of the near-side yield ratios of out-of-plane to in-plane jet hadron correlations for \( p_T^{jet} = 20-40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.

5.37 Ratios of the away-side yield ratios of mid-plane to in-plane jet hadron correlations for \( p_T^{jet} = 20-40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.

5.38 Ratios of the away-side yield ratios of out-of-plane to in-plane jet hadron correlations for \( p_T^{jet} = 20-40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.

6.1 Comparison of truth level jet constituent momentum to reconstructed and unfolded level jet constituent momentum in \( R = 0.2 \) anti-\( k_T \) 10-30 GeV jets in \( \sqrt{s} = 2.76 \text{ TeV} \) PYTHIA proton-proton simulations. The pink points are the truth level and the blue points are the reconstructed, pedestal-subtracted, unfolding level.
6.2 Comparison of reconstructed level jet constituent momentum in PYTHIA proton-proton (red) to reconstructed jet constituent momentum in PYTHIA + TennGen simulations for R = 0.2 anti-\( k_T \) 10-30 GeV jets (black).

6.3 Jet Hadron Correlations for \( 20 < p_T^{\text{jet}} < 40 \text{ GeV} \) and \( 1.5 < p_T^{\text{assoc}} < 2.0 \text{ GeV} \) in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only (\(|\Delta \phi| < \frac{\pi}{3}\)). The bottom panel shows the ratio of the residual of the fit and the data to the fit.

6.4 RPF subtracted jet-hadron correlations for \( 20 < p_T^{\text{jet}} < 40 \text{ GeV} \) and \( 1.5 < p_T^{\text{assoc}} < 2.0 \text{ GeV} \) in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region (\(|\Delta \eta| < 0.6\)).

6.5 near-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for \( 20 < p_T^{\text{jet}} < 40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV PbPb dataset. Uncertainties are statistical and systematic including a 4 % scale uncertainty from the single track reconstruction efficiency.

6.6 away-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for \( 20 < p_T^{\text{jet}} < 40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV PbPb dataset. Uncertainties are statistical and systematic including a 4 % scale uncertainty from the single track reconstruction efficiency.

6.7 Ratios of the near-side yield ratios of mid-plane to in-plane jet hadron correlations for \( 20 < p_T^{\text{jet}} < 40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.

6.8 Ratios of the near-side yield ratios of out-of-plane to in-plane jet hadron correlations for \( 20 < p_T^{\text{jet}} < 40 \text{ GeV} \) in the 30-50 % 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
6.9 Ratios of the away-side yield ratios of mid-plane to in-plane jet hadron correlations for $20 < p_T^{jet} < 40$ GeV in the 30-50% 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain. ................................................................. 179

6.10 Ratios of the away-side yield ratios of out-of-plane to in-plane jet hadron correlations for $20 < p_T^{jet} < 40$ GeV in the 30-50% 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain. ................................................................. 180

6.11 Ratios of the in-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................................. 182

6.12 Ratios of the in-plane away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................................. 183

6.13 Ratios of the mid-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................................. 184

6.14 Ratios of the mid-plane away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................................. 185

6.15 Ratios of the out-of-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................................. 186

6.16 Ratios of the out-of-plane away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................................. 187

6.17 Ratios of the inclusive near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................................. 188
6.18 Ratios of the inclusive away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................. 189
6.19 Ratios of the out-of-plane / in-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................. 191
6.20 Ratios of the out-of-plane / in-plane away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................. 192
6.21 Ratios of the mid-plane / in-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................. 193
6.22 Ratios of the mid-plane / in-plane away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................. 194
6.23 Ratios of the in-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................. 195
6.24 Ratios of the in-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................. 196
6.25 Ratios of the mid-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................. 197
6.26 Ratios of the mid-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c. ................................................. 198
6.27 Ratios of the out-of-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.

6.28 Ratios of the out-of-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.

6.29 Ratios of the inclusive near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.

6.30 Ratios of the inclusive away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.

6.31 Ratios of the out-of-plane / in-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.

6.32 Ratios of the out-of-plane / in-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.

6.33 Ratios of the mid-plane / in-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.

6.34 Ratios of the mid-plane / in-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.

35 Jet Hadron Correlations for 20 < \( p_T^{\text{jet}} \) < 40 GeV and 0.5 < \( p_T^{\text{assoc.}} \) < 1 GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only (\(|\Delta\phi| < \frac{\pi}{3}\)). The bottom panel shows the ratio of the residual of the fit and the data to the fit.

xxvi
Jet Hadron Correlations for $20 < p_{T}^{\text{jet}} < 40$ GeV and $1.0 < p_{T}^{\text{assoc.}} < 1.5$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.

Jet Hadron Correlations for $20 < p_{T}^{\text{jet}} < 40$ GeV and $1.5 < p_{T}^{\text{assoc.}} < 2.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.

Jet Hadron Correlations for $20 < p_{T}^{\text{jet}} < 40$ GeV and $2.0 < p_{T}^{\text{assoc.}} < 3.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.

Jet Hadron Correlations for $20 < p_{T}^{\text{jet}} < 40$ GeV and $3.0 < p_{T}^{\text{assoc.}} < 4.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.

Jet Hadron Correlations for $20 < p_{T}^{\text{jet}} < 40$ GeV and $4.0 < p_{T}^{\text{assoc.}} < 5.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.

Jet Hadron Correlations for $20 < p_{T}^{\text{jet}} < 40$ GeV and $5.0 < p_{T}^{\text{assoc.}} < 6.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.

Jet Hadron Correlations for $20 < p_{T}^{\text{jet}} < 40$ GeV and $6.0 < p_{T}^{\text{assoc.}} < 10.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
RPF subtracted Jet Hadron Correlations for $20 < p_{T}^{jet} < 40$ GeV and $0.5 < p_{T}^{assoc.} < 1.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).

RPF subtracted Jet Hadron Correlations for $20 < p_{T}^{jet} < 40$ GeV and $1.0 < p_{T}^{assoc.} < 1.5$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).

RPF subtracted Jet Hadron Correlations for $20 < p_{T}^{jet} < 40$ GeV and $1.5 < p_{T}^{assoc.} < 2.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).

RPF subtracted Jet Hadron Correlations for $20 < p_{T}^{jet} < 40$ GeV and $2.0 < p_{T}^{assoc.} < 3.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).

RPF subtracted Jet Hadron Correlations for $20 < p_{T}^{jet} < 40$ GeV and $3.0 < p_{T}^{assoc.} < 4.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).

RPF subtracted Jet Hadron Correlations for $20 < p_{T}^{jet} < 40$ GeV and $4.0 < p_{T}^{assoc.} < 5.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).

RPF subtracted Jet Hadron Correlations for $20 < p_{T}^{jet} < 40$ GeV and $5.0 < p_{T}^{assoc.} < 6.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).

RPF subtracted Jet Hadron Correlations for $20 < p_{T}^{jet} < 40$ GeV and $6.0 < p_{T}^{assoc.} < 10.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).

Near-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for $20 < p_{T}^{jet} < 40$ GeV in the 30-50 % 2018 5.02 TeV PbPb dataset. Uncertainties are statistical and systematic including a 4 % scale uncertainty from the single track reconstruction efficiency.
Away-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for $20 < p_T^{jet} < 40$ GeV in the 30-50 % 2018 5.02 TeV PbPb dataset. Uncertainties are statistical and systematic including a 4 % scale uncertainty from the single track reconstruction efficiency.

Ratios of the near-side yield ratios of mid-plane to in-plane jet hadron correlations for $20 < p_T^{jet} < 40$ GeV in the 30-50 % 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.

Ratios of the near-side yield ratios of out-of-plane to in-plane jet hadron correlations for $20 < p_T^{jet} < 40$ GeV in the 30-50 % 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.

Ratios of the away-side yield ratios of mid-plane to in-plane jet hadron correlations for $20 < p_T^{jet} < 40$ GeV in the 30-50 % 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.

Ratios of the away-side yield ratios of out-of-plane to in-plane jet hadron correlations for $20 < p_T^{jet} < 40$ GeV in the 30-50 % 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
Chapter 1

Introduction and Background

In heavy ion collisions, nuclear matter undergoes a phase transition where its degrees of freedom (ordinarily protons and neutrons) melt into basic partonic matter constituents - quarks and gluons. These quarks and gluons form a dynamic, strongly-interacting state of matter called a Quark Gluon Plasma (QGP). This Quark Gluon Plasma state of matter is short-lived and therefore difficult to study using external probes. One means of studying the Quark Gluon Plasma is to use internally-generated probes produced early on in the collision from high momentum partonic scatterings called jets. Jets pass through the Quark Gluon Plasma, are modified, and lose energy. This thesis studies the manner in which jets are modified as they pass through the Quark Gluon Plasma medium produced in heavy ion collisions.

1.1 Quantum Chromo-Dynamics

Quantum Chromodynamics (QCD) is the theory of the strong interaction. The fundamental degrees of freedom of QCD are quarks and gluons. The quarks are fermionic (carry spin \( \pm \frac{\hbar}{2} \)) particles, and the quarks are bosonic (carry spin \( \pm \hbar \)). Quarks interact with each other via the gluon field. For example, in the case of two static quarks, one a quark (\( q \)) and one an anti-quark (\( \overline{q} \)) are shown below in Figure 1.1.
Figure 1.1: Static Quark Potential for a Quark, Anti-Quark Pair
QCD is a quantum field theory with a running coupling strength parameter (similar to Quantum Electrodynamics). The running of the coupling strength parameter means that the interaction between a pair of quarks vanishes at high energies. The vanishing of the coupling constant at high energies means that perturbative expansions can be done to the coupling strength for quark interactions at high energies (or small distances). However, for low energies (or large distances), the coupling constant is too large to be perturbatively expanded about zero. In this energy regime, Lattice QCD techniques are often used to calculate the properties of QCD matter. Lattice QCD is the practice of calculating QCD properties in a discrete space-time environment. Lattice QCD can explain (to a limited extent) the properties of hadronic matter. One example of a successful explanation is a calculation of the mass spectrum of hadrons which agrees strongly with that measured in experiment [42].

1.2 QCD Phase Transition

The QCD phase diagram is shown in Figure 1.2. The x-axis of the diagram in Figure 1.2 is the baryon chemical potential. The y-axis is the temperature of the quarks and gluons. Ordinary nuclear matter exists around 900 MeV baryon chemical potential near 0 temperature. Ordinary nuclear matter consists of protons and neutrons which comprise the nuclei that make up the elements of the periodic table. As ordinary nuclear matter is heated up, it forms a hadron resonance gas which includes excited states of ordinary nuclear matter as well as hadronic states such as pions and kaons. However, if temperature is continually increased, there is a phase transition and the degrees of freedom become quarks and gluons instead of hadrons. This phase of matter is referred to as the Quark Gluon Plasma.
Figure 1.2: QCD phase diagram. Figure taken from Ref. [74].
1.3 Quark Gluon Plasma

Lattice QCD predicts a sharp increase in energy density around a critical temperature of \( T_c = 173 \text{ MeV} \). This critical temperature corresponds to a critical energy density of around \( \varepsilon = 0.7 \text{ GeV}/f m^3 \). This is shown below in Figure 1.3.

One can see a sharp increase in \( \varepsilon/T^4 \) around a critical temperature of \( T_c = 173 \text{ MeV} \). These calculations, along with many others from QCD, led to the understanding that a) a phase transition was occurring in nuclear matter at a critical energy density and b) nuclear matter was transitioning from hadronic degrees of freedom into partonic degrees of freedom (quarks and gluons). The nature of these degrees of freedom at the critical energy density was thought to be analogous to an ideal gas where the degrees of freedom are non-interacting [76].

In August 2000, physics Nobel laureate Frank Wilczek wrote “In this spirit we tentatively assume that we can describe high-temperature QCD starting with free quarks and gluons” in Physics Today [76]. It was hypothesized that the critical energy density needed to achieve this QGP matter could be realized in collisions of relativistic heavy ions. These relativistic heavy ion collisions have been achieved in the Relativistic Heavy Ion Collider, the Super Proton Synchrotron, and its successor the Large Hadron Collider (LHC). These colliders have also achieved the necessary temperature at the proper baryon chemical potential (near zero) to produce the Quark Gluon Plasma. In addition, detector collaborations associated with these colliders have observed a large variety of evidence produced that is consistent with the modification of experimental probes relative to proton-proton collisions (which do not achieve the critical energy density). This text will focus on a particular probe for studying the Quark Gluon Plasma, jets, the collimated spray of hadrons formed by a high energy scattering of a quark or gluon within the expanding medium.
Figure 1.3: Energy density divided by temperature to the fourth power as function of temperature calculated by various Lattice QCD simulations. Figure taken from Ref. [53].
1.4 Heavy Ion Collisions

Heavy Ion Collisions are used to create the conditions necessary to reach the predicted critical energy density ($\varepsilon \sim 0.7 \text{ GeV}/\text{fm}^3$ [53]) required to realize the phase transition of QCD matter. This analysis focuses on Pb-Pb collisions. The time evolution of a heavy ion collision can be broken down into several phases which are shown in Fig. 1.4.

The left side of Figure 1.4 (to the left of pre-equilibrium dynamics) depicts the colliding nuclei at the instant just before contact. The two nuclei are depicted as pancakes to illustrate the Lorentz contraction that each nuclei experiences. ¹ These nuclei, in general, are not perfectly aligned and thus their centers will be displaced from each other. This displacement, $b$, is called the impact parameter or centrality. In addition, the incoming nucleons fluctuate in position in their respective nuclei. The colliding nuclei create the QGP medium which consists of a liquid-like state of quarks and gluons. This QGP medium thermalizes and reaches chemical equilibrium. However, as the medium expands and cools, it breaks up and the quarks and gluons hadronize. Everything up to this point is labeled as the QGP phase in Figure 1.4. After this point, the QGP refreezes and the degrees of freedom become hadrons (bound states of quarks). The hadron fraction of the evolving medium eventually becomes fixed and the system equilibrates chemically. After this, the expanding medium of hadrons continues to cool, collisions between the hadrons cease, and kinetic freeze out occurs. At this stage, the hadron fractions and momentum distribution of the hadrons is fixed. Finally, the hadrons free-stream and go on to interact with particle detectors. The short-lived hadrons will decay into other particles; e.g. $\pi^0 \rightarrow \gamma\gamma$. The following sub-sections detail these phases in more detail.

1.4.1 Initial Conditions and Impact Parameter

The incoming nucleons fluctuate in their positions inside their nuclei. “The initial state of the incoming nuclei is not precisely known, but its properties impact the production of final state particles” [30]. The incoming nuclei can be modeled as independent nucleons which

¹This is despite the fact that, on average, most heavy nuclei are spheres and a Lorentz contracted sphere still looks like a sphere [73].
Figure 1.4: Time evolution of a heavy ion collision. Figure taken from Ref. [67].
is referred to as a Glauber initial state. The Glauber model is purely based on nuclear geometry. It assumes that nucleus-nucleus collisions can be viewed as a sequence of nucleon-nucleon collisions and that individual nucleons travel along straight-line trajectories [59]. A Glauber model is used to estimate the parameters of the collision. These parameters include \( N_{\text{part}} \) (number of participants, those nucleons which collide and interact) and \( N_{\text{coll}} \) (number of binary nucleon-nucleon collisions). However, \( N_{\text{part}} \) can be related to the amount of energy that forward (near the beam-line, see Chapter 2) or central detectors measure in heavy ion collisions. In practice, the per-event distribution of charged particles \( \left( \frac{1}{N_{\text{event}}} \frac{dN_{\text{event}}}{dN_{\text{ch}}} \right) \) produced in a large sample of collisions is measured and plotted. The multiplicity curve is then binned in quantiles and related to the centrality. In addition the average number of participants, \( N_{\text{part}} \), and the impact parameter, \( b \), are determined statistically. This is shown in Figure 1.5.

### 1.4.2 QGP Formation

The formation of the QGP medium and, thus the thermal and chemical equilibrium of its constituent partons, is thought to occur within a time frame of about 0 - 1 fm/c. While thermalization of the QGP medium itself can not be directly observed, it results in observable correlations in the final state particles that experimentalists measure in their detectors. “Thermalization generates thermodynamic pressure in the matter created in the collision, which acts against the surrounding vacuum and causes rapid collective expansions of the reaction zone” [44]. These collective expansions are often colloquially referred to as flow. The anisotropic angular distribution of the final state particles results from correlations caused by this flow. One such example of flow is the “elliptic flow”. This elliptic flow (to describe the non-spherically symmetric expansion) occurs during the thermalization phase and results from a non zero impact parameter (non-central collisions). This is shown in the cartoon in Figure 1.6. This elliptic flow is quantified through the \( v_2 \) parameter which is discussed in more detail in the “Underlying Event” subsection, 1.5.1. This flow must occur early during the QGP phase as it is a result of initial conditions.
Figure 1.5: Cartoon illustrating the relationship between the average impact parameter, \( <b> \) and the charged particle multiplicity \( N_{ch} \). As the average impact parameter, \( <b> \) increases, the cross section \( \frac{d\sigma}{N_{ch}} \) decreases monotonically. Figure from [59].
Figure 1.6: Cartoon demonstrating the elliptic flow occurring during QGP formation and expansion as due to initial state azimuthal anisotropy. Figure taken from Boris Hippolyte.
Measurements of the $v_2$ parameter from the observed azimuthal correlations in final state particles produced in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions in the Relativistic Heavy Ion Collider (RHIC) show a clear universality when they are scaled by $n_{\text{quark}}$ (the number of valence quarks present in the final state hadrons). Figure 1.7 shows this scaling. This universal scaling supports the hypothesis that the measured azimuthal anisotropy parameter distributions are the result of correlations produced from a thermalized state of matter whose fundamental degrees of freedom are partonic, rather than hadronic (e.g. a quark gluon plasma). However, in Pb-Pb collisions at LHC energies, a deviation of up to 20% from number of constituent quark scaling has been observed at intermediate particle $p_T$ (3-6 GeV) [68]. One proposed explanation for the breaking of the scaling is the high phase-space density of constituents quarks in Pb-Pb collisions [68].

1.4.3 Hadronization and Kinetic Freezeout

After $\tau \sim 5$ fm/c, the QGP medium starts to undergo a phase transition into a hadron resonance gas, where the degrees of freedom cease to be partonic and become hadronic. “As the medium expands and cools, it approaches a density and temperature where partonic interactions cease, a hadron gas is formed, and the hadron species ratios are fixed” [30]. This hadronization process takes place anywhere from 5 - 10 fm/c after the QGP thermalizes, depending on the collision energy, shortly after the phase transition between QGP and hadron resonance gas occurs. The system expands and cools. As it cools, inelastic collisions between the hadrons in the gas will cease, hadrons will stop changing identity as a consequence, and the hadron ratios become fixed. The chemical freezeout temperature has been determined to be around 160 MeV in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from measurements of hadron ratios whose values are sensitive to model predictions of the temperature [9].

Kinetic freezeout is achieved after chemical freezeout. During this stage, the average distance between the constituents of the hadron resonance gas grows larger than the interaction range of the strong force. At this point, elastic collisions cease and the momentum spectrum of the hadrons in the gas is fixed. This stage occurs at the end of the $\sim 5 - 10$ fm/c period between QGP thermalization and final state particle production. The kinetic
Figure 1.7: Measurements of elliptic flow parameter $v_2$ made by the PHENIX (left) and STAR (right) collaborations from $\sqrt{s_{NN}} = 200$ GeV at the RHIC. These measurements show a clear universal quark scaling; that is the curves of $v_2$ all lie on top of each other when scaled by the number of valence quarks.
freezeout temperature is found to be very dependent on the initial conditions in the colliding system of nuclei. In particular, a strong impact parameter dependence was found in [45].

The momentum spectrum of the particles which is fixed during kinetic freezeout can be modeled in several different ways. One way is to use the Boltzmann Gibbs Blast Wave model. This model will be utilized in simulations for the purpose of validating the proposed analysis method. This is discussed in further detail in Chapter 3.3.1.

1.5 Final State Particles: Jets and Underlying Event

The QGP phase is short lived (∼ 5 - 10 fm/c) and thus it can not be probed externally. Only probes produced internally in the QGP system can be used to understand its properties. This analysis uses one such class of probes: jets in Pb-Pb collisions. A jet is a collimated spray of relatively high energy final state particles produced as a result of a hard scattering. They are influenced by the properties of the QGP matter as they pass through it and are modified via its transport properties. Jet signals are difficult to measure in heavy ion collisions due to correlations from other sources not caused by hard scatterings. These correlations are a result of the soft processes in a heavy ion collision. A low momentum background of particles which result from the evolution of the QGP medium are present along with the higher momentum particles from hard scatterings. Jet finders (discussed in section 1.5.3) are used to cluster these particles but can not distinguish between the sources of particles. Jet finders group all particles into jet candidates, and therefore some of the candidates will be combinatorial, meaning that they are composed entirely of particles unrelated to hard scattering. However, these jets can be culled with the use of constituent thresholds and background subtraction. This analysis makes a clear distinction between jets, which come from clustered particles related to hard scatterings, and the background which consists of low momentum particles with broad spatial and momentum correlations.
1.5.1 Flow

The soft background is the vast majority of particles present in heavy ion collisions. The particles in the soft background contain spatial and momentum correlations. In particular, the azimuthal distribution of particles contains correlations due to flow. This is demonstrated below in Figure 1.8. The Reaction Plane $\Psi_{RP}$ is defined by the beam axis and the line joining the centers of the two nuclei.

The azimuthal distribution of the background particles can be expanded in a Fourier series:

$$
\frac{dN}{d(\phi - \Psi_{Rn})} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_{Rn}))
$$

(1.1)

where $\phi$ is the angle of the particle with respect to the horizontal, $\Psi_{Rn}$ is the $n^{th}$ order symmetry plane, and $v_n$ is the $n^{th}$ order anisotropy coefficient. The magnitude of the Fourier coefficients decreases for increasing $n$ \cite{8}. “The even $v_n$ mostly arise from anisotropies in the overlap region of the incoming nuclei if one considers the nuclei to be smoothly distributed in the nucleus with the density depending only on the radius” \cite{30}. “The odd $v_n$ for $n > 1$ are generally understood to arise from the fluctuations in the positions of the nucleons within the nucleus” \cite{30}. The symmetry planes, $\Psi_{Rn}$, are also distorted by fluctuations in nucleon position. In practice, the event planes are measured while the symmetry plane arises from the $\Psi_{Rn}$ in Eq 1.1. At low momenta ($p_T < 5$ GeV/c) the $v_n$ come from mostly soft processes and at higher momenta (5 - 10 GeV/c) jets can contribute to $v_n$. Fig. 1.9 shows the contribution of each $v_n$ to the shape of the azimuthal distribution individually and together from $v_1$ to $v_5$.

The probability distribution for finding low momentum particles ($p_T < 5$ GeV/c) with a given $p_T$ is often modeled using a Boltzmann-Gibbs Blast wave distribution parametrized as in \cite{51}. This will be discussed further in Chapter 3.3.1. The $v_n$ will also fluctuate event by event depending on the centrality class. Figure 1.6 exhibits an example of what $\frac{dN}{d(\phi - \Psi_{Rn})}$ (as in Eq. 3.1) may look like for a reasonable choice of event planes and $v_n$ magnitudes.
Figure 1.8: Cartoon Showing the reaction plane of the colliding nuclei. $\Psi_{RP}$ is the reaction plane angle, $\phi_\alpha$ and $\phi_\beta$ are the angles of the final state hadrons produced in the collision.
Figure 1.9: Azimuthal Distribution of final state particles from individual harmonic contributions (5 left pictures) and the sum (furthest right picture). Semi-Realistic values are chosen for each reaction plane and $v_n$ magnitude.
1.5.2 Jets

Jets are the final state hadrons which result from the hard scattering of partons early in a collision event. Jets have been measured in a multitude of collision systems, including simple ones like electron-positron. In Figure 1.10, an incoming electron and positron annihilate to produce a virtual gamma ray that becomes a quark-anti-quark pair, which results in a shower of hadrons.

In a typical experimental setup, the hadrons tend to travel in opposite directions in the plane transverse to the beam because the incoming beams have little transverse motion, so the net transverse momentum is 0. One would like to measure the properties of the final state hadrons and relate them back to the scattered partons. This is not possible due to the ambiguity in defining jets, even on the partonic level. This is shown below in Figure 1.11.

In 1.11, one can see that in this case the $e^+ e^- \rightarrow q \bar{q}$ becomes $e^+ e^- \rightarrow q \rightarrow q q g$. One quark emits a gluon. “Gluons emitted at small angles relative to the quark are usually considered part of the jet, whereas gluons emitted at large angles relative to the parent parton may be considered a 3rd jet” [30]. This ambiguity, which manifests even at the particle level, means that the way in which the final state particles are grouped together to determine jet properties is paramount. Theorists and experimentalists must use the same jet finding algorithms in order to compare results as was agreed upon in the 1990 Snowmass Accord [49].

1.5.3 Jet Finding Algorithms

There are many kinds of jet algorithms used to cluster final state particles. One popular class are the iterative algorithms. Prevalent iterative jet finding algorithms include SIScone, the $k_T$ algorithm, anti-$k_T$ algorithm, and the Cambridge-Aachen algorithm. This analysis extensively utilizes the anti-$k_T$ and makes some use of the $k_T$ algorithm. The definitions of these algorithms are below [30]:

1. Calculate:

$$d_{ij} = \min(p_{T_i}^{2p}, p_{T_j}^{2p}) \frac{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}{R^2}$$

(1.2)
Figure 1.10: Cartoon of hadrons produced from a hard scattering of electrons and positrons which produces a virtual gamma ray
Figure 1.11: Cartoon of a 3 jet event in $e^+$ and $e^-$ collisions
and
\[ d_i = p_{T_i}^{2p} \]  

(1.3)

for every pair of particles where \( p_{T_i} \) and \( p_{T_j} \) are the transverse momenta of the particles, \( \eta_i \) and \( \eta_j \) are the pseudorapidities of the particles and \( \phi_i \) and \( \phi_j \) are the azimuthal angles of the particles. \( p \) is a parameter set from the choice of algorithm, \( p = -1 \) for the anti-\( k_T \) algorithm, \( p = 1 \) for the \( k_T \) algorithm and \( p = 0 \) for the Cambridge/Aachen algorithm.

\( R \) is the resolution parameter, which in this case is

\[ R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]  

(1.4)

where \( \Delta \phi \) is the distance from the jet axis in azimuth and \( \Delta \eta \) is the distance from the jet axis in pseudo-rapidity, \( \eta \) A.1.

2. Find the minimum of the \( d_{ij} \) and \( d_i \). If the minimum is a \( d_{ij} \), combine these particles into one jet candidate, adding their energies and momenta, and return to the first step.

3. If the minimum is a \( d_i \), this is a final state jet candidate. Remove it from the list and return to the first step. Iterate until no particles remain.

The anti-\( k_T \) algorithm is particularly useful for reconstructing jets from hard scatterings in a heavy ion environment because it is less sensitive to the underlying event compared to other algorithms. This is because it starts clustering around high momentum particles (see the definition of the algorithm above). It is also computationally favored because computation time scales like \( N \ln N \) for \( N < 20000 \).

1.5.4 Jet-Hadron Correlations

Measurements of jet-hadron correlations are sensitive to the broadening and softening of the fragmentation function [30]. Raw jet-hadron correlations are \( \Delta \phi \) distributions, where \( \Delta \phi = \phi_{\text{jet}} - \phi_{\text{assoc}} \) [61]. \( \phi_{\text{jet}} \) is the location of the jet axis \( \phi \) coordinate and \( \phi_{\text{assoc}} \) is the location of the associated particle \( \phi \) coordinate. Jet-hadron correlations are of particular significance
for this analysis because they serve a crucial role in removing the heavy ion background (underlying event) present in the jet signal. An example of jet-hadron correlations measured in 0-20 % centrality Au-Au collisions by the STAR collaboration are taken from Ref. [61] and shown below in Figure 1.12. The peak around $\Delta \phi = 0$ is known as the “near-side” while the peak around $\Delta \phi = 0$ is known as the “away-side.”

1.6 Fragmentation Functions

The details of how a parton fragments into final state hadrons are described by the fragmentation function. The fragmentation function quantifies the number and momenta of jet constituents relative to their parent parton. In other words, does your parton fragment into many low momentum hadrons or does it fragment into a few high momentum hadrons? The fragmentation function is usually quantified in terms of the momentum fraction, defined as $z = \frac{p_h}{p}$ where $p_h$ is the momentum of the hadron and $p$ is the momentum of the parent parton. The fragmentation function, $D(z)$, is a function of $z$. This is understood broadly in the context of the factorization theorem:

$$\frac{d^3\sigma^h}{dyd^2p_T} = \frac{1}{\pi} \int dx_a \int dx_b f^A_a(x_a)f^B_b(x_b)\frac{d\sigma_{ab\rightarrow cX}}{dt} D^h_c(z)$$  \hspace{1cm} (1.5)

Here, two incoming nuclei, A and B, with nuclear parton distribution functions $f^A_a(x_a)$ and $f^B_b(x_b)$ collide. The parton distribution functions describe the probability of finding partons a and b with momentum fractions $x_a$ and $x_b$, respectively. This stage of the collision is shown below in Figure 1.13 with the two gray ellipses (representing nuclei A and B) and the green and red dots within (representing the partons a and b). These partons (a and b) interact to produce another parton c (and other things, X) with differential interaction cross section $\frac{d\sigma_{ab\rightarrow cX}}{dt}$. This cross section is calculated using pQCD. The parton, c, has momentum p. This is represented below in Figure 1.13 with the two converging gray arrows and the blue dot (representing the interaction of green parton a and red parton b). The two diverging gray arrows pointed at angles relative to the horizontal represent parton c and other particles produced, X. The QCD branching labeled portion of Figure 1.13 is also part of this process.
Figure 1.12: Measured Jet-Hadron correlations in 0-20 % centrality Au-Au collisions by the STAR collaboration. The jet momentum threshold was $p_T^{jet} > 20$ GeV/c and the associated particle momentum bin was $1.0$ GeV/c $\leq p_T^{assoc} \leq 2.5$ GeV/c. Closed symbols are Au-Au data, open symbols are from p-p collisions. Figure taken from [61].
Parton c fragments to produce hadrons, h, according to the fragmentation function \( D_c^h(z) \). \( \hat{t} \) is the 4 momentum of parton c. This process is illustrated by the last picture on the far right of Figure 1.13. In heavy ion collisions, the parton fragmentation function \( D_c^h(z) \) is expected to be modified due to the presence of the QGP medium, resulting in jet quenching (however, the other portions of 1.13 are not expected to differ from proton-proton collisions).

### 1.6.1 Lund String Model of Fragmentation

Calculating fragmentation functions, \( D_c^h(z) \), is difficult to do in QCD. Theoretical models of fragmentation use different approximations of QCD. That is to say, no one model is the complete, correct explanation of the physical fragmentation function, but different models accurately fit data in different ranges. The Monte-Carlo parton shower generator PYTHIA (see Chapter 3.2) models fragmentation using the Lund String model. “This model is based on the dynamics of relativistic strings, representing the color flux stretched between the initial q \( \bar{q} \) [75]”. The string produces a linear confinement potential and an area law for matrix elements:

\[
|M(q\bar{q} \to h_1...h_n)|^2 \propto e^{-bA}
\]  

(1.6)

where A is the space time area swept out ”(see Figure 1.14).

The string breaks up into hadrons via quark-anti-quark pair production in the intense color field. Gluons produced in the parton shower lead to “kinks” on the string. Figure 1.14 illustrates this process.

The fragmentation function, \( D(z) \), in the Lund model (for the light quarks) is given as [23]:

\[
D(z) \propto \frac{1}{z}(1-z)^a e^{-bm_{\perp}^2/z^2}
\]  

(1.7)

where \( z \) is the momentum fraction, \( m_{\perp} \) is the transverse mass, given as \( m_{\perp} = \sqrt{m_0^2 + p_{\perp}^2} \), and \( a \) and \( b \) are parameters fit to experimental measurements.
**Figure 1.13:** Cartoon illustration of the different stages of a heavy ion collision. Figure taken from Ref. [57]
**Figure 1.14:** Lund String Model Space Time Pictures. The quark anti quark pair fragments, producing hadrons.
1.6.2 Fragmentation in Experiment

Figure 1.15 shows the measurements of fragmentation functions for $\sqrt{s_{NN}} = 2.76$ TeV p-p collisions measured by the CMS collaboration.

Instead of the $z$ distribution, this figure displays the $\xi$ distribution which is related to $z$ in the following way: $\xi = \ln(\frac{1}{z})$. Measuring fragmentation functions in heavy ion collisions can constrain models which describe medium transport properties. This is because partons lose energy to the medium produced in heavy ion collisions [30]. In general, this can occur two ways. One way is through collisional energy loss, where partons from hard processes scatter off the constituent partons of the QGP medium and transfer their energy away. Another way partons lose energy to the medium occurs when partons radiate gluons in a process known as gluon bremsstrahlung (in reference to the analogous effect in quantum electrodynamics when high energy charged particles radiate photons). If the radiated gluons or the energy from collisional energy loss become equilibrated with the QGP medium, then the gluons’ daughter hadrons will be indistinguishable from the lower momentum heavy ion background particles and thus not grouped into jet candidates (of course, this somewhat depends on the parameters of the jet finding algorithm used to cluster final state hadrons). In addition, the medium’s partonic constituents may also become correlated with partons resulting from hard scatterings. The degree to which the processes occur will depend on the transport properties of the medium (e.g. $\eta/s$, $\zeta/s$, thermodynamic properties, etc...) which are not currently known. Theoretical models make predictions about these properties and the physics framework that governs how partons move through QGP matter with these properties. These should affect the final state hadrons which are generated from modified parton properties. In particular measurement of the fragmentation functions $D_{jet}(z)$ should be sensitive to models that predict medium transport properties which result in modification of high energy partons by the medium and softening of final state hadron distributions due to medium interactions.
Figure 1.15: CMS measured fragmentation functions. Figure taken from [56].
1.7 Path length Dependence in Different Jet Energy Loss Mechanisms

Partons which pass through the QGP may lose energy due to a combination of collisions and radiation (gluon bremsstrahlung). The path length dependence of partonic energy loss depends on the energy loss mechanism. In a simple case assuming a static and weakly-coupled medium, the path length dependence due to collisions is expected to be proportional to $L$ (or linearly dependent on the path length). The path length dependence due to radiative losses is expected to be proportional to $L^2$ [25]. This is illustrated as a simple cartoon in Fig. 1.16.

However, the QGP is neither static nor weakly-coupled. The QGP is dynamic and strongly-coupled as discussed in Sections 1.4.2 and 1.5.1. More realistic estimates of the path length dependence of the path length dependent energy loss for collisional and radiative effects are done in [38] and [37]. Fig. 1.17 shows that for all flavors of quark the collisional losses are approximately linear and the radiative losses approximately quadratic in their respective path length dependencies.

In reality, partons experience both collisional and radiative energy loss effects as they traverse the QGP. This results in an effective path length dependence of $L^b$ where $1 < b < 2$. In simulations performed in [39], the authors calculate that $b = 1.4$.

It is also important to note that the fragmentation function characterizes the change in constituents momentum rather than the overall jet energy loss described here. The fragmentation function or jet constituent yields (similar to the fragmentation function but not normalized for jet $p_T$) characterize the distribution of the jet constituent $z$ or $p_T$. Path length dependence is still expected to play a role in modification of the fragmentation function. An ATLAS analysis of the fragmentation function in $\gamma$ tagged jets found a difference in 0-30 % and 30-80 % data and simulations [28]. Figure 1.18 shows this difference can be seen by looking at the model curves in the lower panel when comparing the ratios between 0-30 % Pb-Pb to p-p and 30-80 % Pb-Pb to p-p.
Figure 1.16: Energy loss of partons in the QGP medium in the weakly-coupled, static approximation. Figure courtesy of Caitlin Beattie.
**Figure 1.17:** Path length dependence of jet energy loss due to collisions only (solid) and radiative effects only (dotted) in the QGP medium for somewhat realistic assumptions. All jets have an initial energy of 10 GeV. Figure taken from [37].
Figure 1.18: (Upper panel) Fragmentation function in γ tagged jets in p-p, 0-30 % and 30-80 % Pb-Pb collisions along with accompanying models. (Lower panel) Ratios of 0-30 % Pb-Pb to p-p and 30-80 % Pb-Pb to p-p along with accompanying models [28].
The authors state “the degree of the suppression and enhancement in the 30-80% peripheral Pb+Pb collisions is smaller than that in the central Pb+Pb collisions according to CoLBT-hydro simulations due to the shorter effective path length and in-medium effective temperature experienced by hard partons.” The authors also note that the model predictions do not match the data well - highlighting the need for better understanding of path length dependent energy loss.
Chapter 2

Detector Equipment and Instrumentation

2.1 Large Hadron Collider

The Large Hadron Collider (LHC) is a particle accelerator designed to accelerate and collide protons up to $\sqrt{s} = 13$ TeV and lead ions up to $\sqrt{s_{NN}} = 5.02$ TeV. The LHC straddles the borders of France and Switzerland and is part of the “Conséil Europeen pour la Recherche Nucléaire” or CERN. The CERN accelerator complex is shown in Figure 2.1.

Protons (indicated by gray arrows) are accelerated to 6.5 TeV (or 99.9999991 % the speed of light) when they enter the LHC. The LHC circulates the proton bunches in opposite directions, with half the bunches going clockwise and the other half going counter-clockwise, in separate beam lines which are designed to cross at specific points. Detectors are built around these crossing points. The 4 main detectors in the LHC beam line (CMS, ATLAS, ALICE, and LHCb) are built at these crossing points. This is shown below in Figure 2.2. The LHC also collides lead ions in addition to protons. The lead ions originate from a highly purified lead (Pb) sample heated to a temperature of around 800°Celsius [26]. When the Pb sample is heated up, it becomes lead vapor. The Pb vapor is ionized and then guided into the accelerator complex. When the Pb$^{82+}$ ions enter the LHC, they are accelerated and collide at crossing points in the LHC (see Figure 2.2). The maximum energy achieved
Figure 2.1: CERN accelerator complex. Figure taken from Ref. [26].
Figure 2.2: LHC crossing points and detectors. Figure taken from Ref. [26].
per nucleon of Pb$^{82+}$ is 2.56 TeV. The A Large Ion Collision (ALICE) detector is the main detector dedicated to studies of Pb-Pb collisions in the LHC.

2.2 ALICE detector

The ALICE detector is specifically designed to analyze the products of heavy ion collisions in the LHC. The total volume of the detector is $16 \times 16 \times 26 \text{ m}^3$. The total weight of the ALICE detector is approximately 9000 metric tons. ALICE has a central solenoid magnet which bends the track of the charged particles resulting from the collisions. The aluminum solenoid magnet produces a maximum field of 0.50 T.

ALICE consists of many sub-detectors which do the following: 1) trigger on collisions which produce interesting data, 2) reconstruct the tracks of particles produced in the collision, 3) identify the particles produced in the collision, and 4) measure the energies (momenta) of particles produced in the collision. The ALICE detector is shown below in Figure 2.3. Sub-detectors which are devoted to triggering include the V0 and T0. This set of sub-detectors provide data for the forward (A Side - $\eta > 0$) and backward (C Side - $\eta < 0$) regions. Detectors focused on track reconstruction include the ITS (Inner Tracking System) and the TPC (Time Projection Chamber). Detectors which perform particle identification include the Time of Flight (TOF), High Multiplicity Particle Identifier (HMPID), Transition Radiation Detector (TRD), Inner Tracking System (ITS), and Time Projection (TPC). Detectors which measure particle energies include the Electromagnetic Calorimeter (EMCAL), DCAL (not shown in Figure 2.3), and PHOS (Photon Spectrometer). The following sections will focus on the V0, ITS, TPC, and EMCAL/DCAL as these detectors are used in this proposed analysis.

2.2.1 TZERO

The TZERO consists of fused quartz Cherenkov radiators optically coupled to Photo Multiplier Tubes. When high energy particles enter the TZERO they induce Cherenkov radiation in the quartz which is guided into the Photo Multiplier tubes, converted to electrical charge, and then read out. The TZERO also delivers a “wake-up” trigger to the
Figure 2.3: ALICE Detector Overview
Transition Radiation Detector (TRD) and provides a time reference to the Time-of-Flight (TOF) particle identification system. The TZERO measures an approximate vertex position, roughly estimates event multiplicity, and confirms one side (A or C) of the TZERO receives a valid pulse. The TZERO’s measurement of the approximate vertex position discriminates against events where the heavy ion/proton beam interacts with residual gas in the beam pipe. The TZERO can identify the vertex with $\pm 1.5$ cm resolution [31]. If the TZERO identified vertex falls within acceptable limits, a trigger signal will be produced. The TZERO’s second mentioned function, estimating event multiplicity, backs up the VZERO functionality of measuring centrality (see Section 1.4.1). The TZERO measures multiplicity in an event and compares this to 2 preset values, generating the following possible signals: “$T0(\text{minimum-bias})$”, “$T0(\text{semi-central})$”, or “$T0(\text{central})$”. A comprehensive list of the TZERO trigger signals can be found in [31]. The TZERO covers the pseudo-rapidity range of $4.5 < \eta < 5.0$ on the A side and $-3.3 < \eta < -2.9$ on the C side. A 3-dimensional oblique view of the rough orientation and appearance of the T0 and V0 sub-detectors is shown in Fig. 2.4.

2.2.2 VZERO

The VZERO measures charged particle multiplicity (see Ch. 1) and indirectly measures the reaction plane for collisions. The VZERO is a scintillating detector which utilizes BC404 plastic for its material. BC404 is a scintillator plastic consisting of 32 % Polyvinyl toluene and 68 % Anthracene [32]. BC404 is used in the VZERO for fast counting of charged particles. The VZERO sub-detector has two main components: VZERO-A and VZERO-C. VZERO-A covers the pseudorapidity range $2.8 < \eta < 5.1$. VZERO-C covers the pseudorapidity range $-3.7 < \eta < -1.7$. The VZERO-A and C are circular detectors which are divided into 4 rings in the radial direction and 8 sections per ring in the angular direction. This is shown below in Figure 2.5.

2.2.3 ITS

The ITS detector is designed to localize the primary vertex to within $5 \mu m$ (in PbPb collisions - see Figure 4.3), to track and identify particles down to a momentum of less than
Figure 2.4: From left to right (gold) TZERO, VZERO, and FMD detectors on the A side ($\eta > 0$). The Inner Tracking System layers are shown in grey. Figure taken from Ref. [31].
Figure 2.5: ALICE VZERO-A and VZERO-C front side. Figure taken from Ref. [11].
200 MeV/c, to improve momentum and angle resolution for particles reconstructed by the TPC, and to reconstruct particles traversing dead regions of the TPC \cite{11}. The ITS consists of 6 different silicon layers which cover the rapidity range \( |\eta| < 0.9 \). The ITS surrounds the beam pipe and covers a radial range of 3.9 cm to 43.0 cm (measured from the center of the beam pipe). Silicon Pixel Detectors (SPD) make up the first two silicon layers, Silicon Drift Detectors (SDD) make up the middle two silicon layers, and Silicon Strip Detectors (SSD) make up the outer two silicon layers. Figure 2.6 shows a schematic view of the ITS with the SPD, SDD, and SSD layers highlighted in stereographic(left) and transverse (right) projections.

2.2.4 TPC

The ALICE Time Projection Chamber is a gas detector designed to image the tracks of charged particles. The active volume is cylindrically shaped with an inner radius of 84.8 cm and an outer radius of 246.6 cm. The length of the TPC’s active volume is about 500 cm, making the total volume of the detector approximately \( 98.125 \times 10^6 \, \text{cm}^3 \). Figure 2.7 shows a schematic view of the ALICE TPC. The TPC covers the full range in the azimuth (\( \phi = 2\pi \)) and \( |\eta| < 0.9 \) in pseudo-rapidity.

High energy particles ionize the gas in the TPC. Electrons from the ionization of gas molecules drift in an electric field of around 400 V/cm. The field is oriented parallel to the beam pipe pointing toward the central electrode shown in Figure 2.7. The drift velocity is the velocity at which ionization electrons drift in the TPC towards the end plates. The drift velocity is dependent on many factors including the composition of the gas, pressure of the gas, temperature of the gas, the electric field, and magnetic field. The design drift velocity is \( 2.7 \, \text{cm}/\mu\text{s} \) which gives electrons a maximum drift time of 92 \( \mu\text{s} \). The electrons travel opposite the direction of the electric field and are passed through a grid of electrically charged wires collectively called a Multi-Wire Proportional Chamber (MWPC) before they terminate at the TPC end caps. The MWPC consists of a 3-layer grid of wires. The first layer is called the gating grid, the second layer is the cathode grid, and the final layer is the anode grid. The electron is multiplied as it passes through the wire grid, becoming a shower (see Section
Figure 2.6: ALICE Inner Tracking System. Figure taken from Ref. [11].
Figure 2.7: ALICE TPC Stereographic View
2.2.4). After passing through the anode wire, the electron shower arrives on a “pad plane” consisting of segmented copper sensors. The copper sensors record the electron’s arrival in time and locate it in transverse space (x,y). The copper pad sensors measure the ionization electrons arrival as an analogue signal which is then digitized (along with the timing from the passage of the electron through the gating grid) to reconstruct the path of the particle responsible for the ionization. Figure 2.8 shows a representation of this process. There are 557568 pad pixels (and readout channels). The TPC has a position resolution of 1100 to 800 \( \mu \text{m} \) in the \( r\phi \) direction and 1250 to 1100 \( \mu \text{m} \) in the z (beam axis) direction.

Field Cage

The TPC field cage is a cylindrical volume which contains a highly uniform electrostatic field. This field is responsible for transporting the primary ionization electrons through the TPC drift volume towards the end plates. The TPC field cage consists of a central HV electrode with inner and outer vessels as shown in Figure 2.7. The central electrode is an annular aluminum disk maintained at a voltage of 100 kV.

Gating Grid & Wire Planes

Ionization electrons move towards the end plates of the TPC as they drift in the electric field. In order to record their time of arrival and location, they must be deposited on a conductor that transfers their charge to readout electronics. These electrons, alone, would not induce a large enough signal to be read out. They are multiplied by passing through a strong electric field. This field is achieved with the combination of cathode and anode wires made of Cu/Be and Au plated W. The wires have have a small (2-3 mm) gap in between them and are held at different voltages resulting in a large electric field. All wires run in the \( \phi \) direction. The gating grid geometry is shown below in Fig. 2.9. In this field, an avalanche occurs where the electron is accelerated into the gas and ionizes the gas molecules to produce more electrons. One electron is amplified by the gating grid into \( 2 \times 10^4 \) electrons [35].

As the incoming electron triggers an avalanche, it also produces positively-charged gas ions. These ions move in the opposite direction of the electrons, back towards the drift
Figure 2.8: TPC Working Principle taken from Ref. [52]
Figure 2.9: ALICE TPC Wire Geometry for Outer (left) and Inner (right) Read Out Chambers. Figure taken from Ref. [35].
volume. It is undesirable to have these ions enter the drift volume as they will accumulate and distort the drift field. An additional layer of wires, called the gating grid, is added above the cathode and anode wires. In the open gate configuration, the wires of the gating grid are held at the same potential, allowing electrons to pass through. In the closed gate configuration, the wires are held in a “dipolar” configuration with alternating effective charge, preventing electrons from passing through. The on/off field configurations of the gating grid is shown below in Figure 2.10. The ionic backflow suppression quantifies how many ions pass through the gating grid into the TPC active volume for each ion produced in the gating MWPC. The average ionic backflow suppression is approximately $1 \times 10^{-4}$.

**Pad Plane**

As the electrons are multiplied and accelerated through the wire planes, they generate a large flow of positive ions back towards the drift volume. While the electrons ultimately terminate on the anode wire plane, the ions they create induce a positive signal on the pad plane below them, which is read out. Figure 2.8 shows a schematic example of how this process works. The pad plane consists of rectangular copper segments of varying length and width. For the Inner Readout Chambers (IROCs), there are 5732 4 mm x 7.5 mm copper pads. For the “inner” radius of Outer Readout Chambers (OROCs), there are 6038 6 mm x 10 mm copper pads. For the “outer” radius of Outer Readout Chambers (OROCs), there are 4072 6 mm x 15 mm copper pads. The entire TPC has a grand total of 570312 copper pads.

The location of the deposited signal on the copper pads can be used to resolve the x,y position of tracks in the TPC. The timing between deposits of signal across pads (referred to as clusters) can be used to recover the z position of the tracks ($z = \text{drift velocity} \times \text{drift time}$).

**Front End Electronics**

The front end electronics consist of 570312 channels (1 channel for each read out pad in the chambers). These chambers deliver a current signal with a fast rise time their pads
Figure 2.10: ALICE TPC Electric Field Line configuration for gating grid closed (top) and gating grip open (bottom). Figure taken from Ref. [17].
(less than 1 ns) and a long tail due to the motion of the positive ions [35]. The Front End Cards (FEC) are the electronic components which amplify, shape, digitize, process and buffer the TPC signals. Figure 2.11 shows the basic components of the front end card. The PreAmplifier/ShAper (PASA) is a combination of charge-sensitive amplifier and a Gaussian pulse shaper. An example of what the signal looks like after passing through the PASA is shown below in Fig. 2.12. After the signal passes through the PreAmplifier/ShAper, it encounters a 10-bit Analogue to Digital Converter (ADC) which samples the signal at 5.66 MHz. Immediately after the ADC, the signal enters an Application Specific Integrate Circuit (labelled in Fig. 2.11 as “digital circuitry”) called an ALice Tpc ReadOut (ALTRO). The ALice Tpc ReadOut is a custom CMOS (complementary Metal Oxide Semiconductor) chip which performs the tail cancellation, pedestal subtraction, zero suppression, formatting, and buffering. The result of the tail cancellation is shown below in Fig. 2.13. The pedestal subtraction removes a baseline of noise from the signal. Zero suppression rejects all values below a certain threshold. This compresses the data stream by discarding data that do not contain useful information.

GEM Upgrade

The TPC’s current use of MWPC technology limits its ability to take in tracking data for high luminosity events. Up until 2018, ALICE’s event rate was \(\sim 1\) kHz and the TPC’s readout rate approaches 3 kHz in the best case scenario (which also means that it has a “refresh” rate which requires a dead time of around 400 \(\mu\)s). However, after the LHC’s upgrades from 2019-2021, event rates for Pb-Pb collisions are expected to be around 50 kHZ. This requires an upgrade to the TPC’s readout technology. The MWPC technology was replaced with Gas Electron Multiplication (GEM) which allows for a continuous readout [54]. My contributions to the TPC upgrades will be discussed in Chapter 3 in the service work section [4].
Figure 2.11: ALICE TPC Front End Cards for Readout Electronics. Figure taken from Ref. [35].
Figure 2.12: Example of differing magnitude pre-amplified signals from the CERES NA45 experiment. Note the long tails. The top curve is before tail cancellation, the middle curve after the first filter, and the bottom after the final filter. Figure taken from Ref. [35].
Figure 2.13: ALICE TPC FEC Tail Cancellation. Output 1 is after 1st filter and Output 2 is after 2nd filter. Figure taken from Ref. [35].
2.2.5 EMCAL

The ALICE Electromagnetic Calorimeter (EMCAL) is a lead scintillating detector designed to measure the energy of electromagnetic particles (e.g. $\gamma$ from $\pi^0$ decays) and thus improve the resolution of jets. The EMCAL covers an azimuthal range of $\phi$ of $107^\circ$ and a pseudo-rapidity range of $|\eta| \leq 0.7$. The EMCAL is segmented into 12288 6.0 cm x 6.0 cm x 24.6 cm rectangular towers of alternating layers of Polystyrene based scintillator and natural Pb absorbers. Each tower is composed of 76 layers of 1.44 mm Pb and 77 layers of 1.76 mm scintillator. Figure 2.14 shows an ALICE EMCAL tower from the top down. There are 10 full-size and 2 one-third size super modules in the EMCAL (full size: $\Delta \eta = 0.7$ and $\Delta \phi = 20^\circ$, one-third size: $\Delta \eta = 0.7$ and $\Delta \phi = 7^\circ$). Each full-size super module consists of 288 modules which in turn contain 4 towers. Figure 2.15 contains a drawing of one of the super modules.

The EMCAL measures high energy photons and electrons. When a particle deposits energy into the EMCAL, it results in scintillation light in the EMCAL towers. The scintillation light is guided into fiber optic cables. The fiber optic cables terminate in avalanche photo-diodes which emit electrons upon being struck with the scintillation light. These electrons are fed into a charge sensitive pre-amplifier and then the charge sensitive pre-amplifier signal is digitized using the EMCAL Front End Electronics (FEE) cards.
Figure 2.14: ALICE EMCAL Tower, top view. Figure taken from Ref. [36].
Figure 2.15: ALICE EMCAL super module. Figure taken from Ref. [11].
Chapter 3

Previous Measurements, Software, and Service Work

3.1 Previous Analyses

Previous measurements of fragmentation functions in Pb-Pb collisions have been made using different detectors in the LHC. The ATLAS and CMS collaborations have measured fragmentation functions in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In 2014, ATLAS [16] measured the fragmentation function for Pb-Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV using data from the ATLAS collaboration. Aad et. al used the anti-$k_T$ algorithm to reconstruct $R = 0.2, 0.3, 0.4$ jets for $85 < p_{jet}^T < 100$ GeV. In 2014, the CMS collaboration measured the fragmentation function for Pb-Pb and p-p collisions with $\sqrt{s_{NN}} = 2.76$ TeV [29]. This was done for inclusive jets with $p_{T}^{jet} > 100$ GeV using reconstructed particles with $p_{T}^{ch} > 1$ GeV in a cone of $R = 0.3$ around the jet axis using anti $k_T$ algorithm. These measurements were done for 5 centrality bins, 0% - 10%, 10% - 30%, 30%- 50%, 50% - 70%, 70% - 100%. The CMS measured ratio of the fragmentation function in Pb-Pb to p-p as a function of $\xi = \ln(\frac{1}{z})$ is shown below in Fig. 3.1.
Figure 3.1: Measured $\xi$ Distributions in Pb-Pb collisions. The Bottom Panel Contains the Ratio of the $\xi$ Distributions in Pb-Pb Collisions to the $\xi$ Distributions in p-p Collisions. Made by the CMS Collaboration [29].
In 2014, Add. et. al measured the fragmentation function for Pb-Pb collisions in the √s_{NN} = 2.76 TeV dataset with the ATLAS detector. This was done with the charged particles inside inclusive R = 0.4 jets with \( p_T^{jet} > 100 \) GeV. The ATLAS measured ratio of the fragmentation function in 0 - 10 %, 10 - 20 %, 20 - 30 %, 30 - 40 %, 40 - 50 %, 50 - 60 % Pb-Pb to 60-80 % Pb-Pb as a function of z is shown below in Fig. 3.2.

The fragmentation function in the CMS analysis differs from my analysis in three critical ways. The first way is the underlying event subtraction. The CMS analysis uses \( \eta \) reflected cone method to subtract out the underlying event. "In this method the background jet cone is obtained by reflecting the original jet cone around \( \eta = 0 \) while keeping the same \( \phi \) coordinate" [29]. Then these “background” cones are subtracted from the raw jet spectrum and corrected for jet biases from PYTHIA+HYDJet Monte Carlo simulations. The ATLAS analysis subtracts the contributions of the underlying event to the measured jets by identifying per-jet underlying event yields over the kinematic range 2 GeV < \( p_T^{ch} \) < 6 GeV for all jet radii (R = 0.2 , 0.3 , 0.4) with \( \Delta R = 0.4 \). This quantity (which is subtracted out) is defined as

\[
\frac{dN_{ch}^{UE}}{dp_T^{ch}} = \frac{1}{N_{cone}} \frac{\Delta N_{ch}^{cone}(p_T^{ch}, p_T^{jet}, \eta^{jet})}{\Delta p_T},
\]

where \( N_{cone} \) is the number of background cones having a jet of a given radius above the corresponding \( p_T^{jet} \) threshold, and \( \Delta N_{ch}^{cone} \) is the number of charged particles in a given \( p_T^{ch} \) bin in all such cones evaluated for jets with a given \( p_T^{jet} \) and \( \eta^{jet} \). My method uses jet-hadron correlations to subtract out the underlying events contribution to the measured jet candidates on both the near-side (\( \Delta \phi \sim 0 \)) and the away-side (\( \Delta \phi \sim \pi \)). This is a statistical approach and not a jet-by-jet method as in Ref. [16].

The second way is related to the first way. The background subtraction method utilizes the jet-hadron correlation. This allows the near-side and away-side background contribution to the jet to be removed. This makes the measurement of the away-side jet possible. This set of jets could contain crucial information about the fragmentation function modification as it has passed through more medium then the near-side jet. This also reduces the selection bias the previous measurements suffer from. The ATLAS and CMS measurements only reconstruct near-side jets. near-side jets will have not traveled through as much of the expanding medium as away-side jets. This is a type of “survivorship” bias because ATLAS
Figure 3.2: Ratio of measured $z$ Distributions in various centrality bins in Pb-Pb collisions. Made by the ATLAS Collaboration [16].
and CMS are only selecting for jets they can easily reconstruct and not sampling from those jets which been quenched heavily by the medium interactions.

The third way this analysis differs from the previous analyses is the momentum threshold of the jets studied. In my analysis, I reconstructed jets in a heavy ion environment down to 20 GeV. This differs from the lowest momentum measured in ATLAS which was a threshold of 85 GeV. This is critical in order to learn how lower momentum jets fragment in heavy ion collisions. These lower-to-middle range momentum jets hold the greatest possibility of revealing interesting information as their fragmentation should be much more sensitive to effects due to the medium [30].

While this analysis differs in the way that it measures fragmentation functions and the kind of jets it measures, it is similar to previous analyses in $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb by Mazer [55]. In fact, the method described in Section 5.3 is also used in [55]. This analysis aimed to extend work done by Mazer by unfolding (see Section 5.2.4) the yields obtained from the correlation functions described above. I encountered difficulties with this unfolding method in a model study and was not able to apply it fully to data. Chapter 6 contains the results and discussion of the model study of fragmentation functions obtained with the method described above (including the difficulties). In light of the challenges encountered, this analysis replicated measurements of the jet constituent yields relative to the even plane made by Mazer but in the $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb dataset (as this would have given the yields necessary to unfold and obtain the fragmentation function).

### 3.2 Software Framework

The software packages utilized in the analysis and simulation are ROOT, AliROOT, PYTHIA, and FastJet. ROOT is an object-oriented programming language made by CERN for the purpose of analyzing particle physics data. ROOT is written in C++ and uses a C++ script and command line interpreter. AliROOT is the framework the ALICE collaboration uses for offline analysis of the data it collects. It uses ROOT as its foundation with specific functionality for simulating the sub-detectors performance for high energy particles.
passing through them. PYTHIA is a Monte-Carlo parton shower generator which simulates the particles produced during proton-proton collisions at various center of mass energies. PYTHIA includes theory and models for various physics aspects, including hard interactions (e.g. high energy parton scattering), soft interactions (e.g. gluon bremsstrahlung), parton distributions (e.g. in colliding protons), multiparton interactions, fragmentation (e.g. from the Lund String Model), and decay. FastJet is a software package utilized for implementing sequential recombination clustering algorithms (such as the anti-\(k - T\) algorithm discussed in Section 1.5.3).

### 3.3 Fragmentation Functions in Simulations

Before the proposed analysis method can be used on data, it must be validated in simulation first. This involves using the software tools previously mentioned in Section 3.2 to calculate the fragmentation function. These fragmentation functions come from the known functional form described in Section 1.6.1. This functional form comes from the PYTHIA packages application of the Lund String Model which is fit to experimental data but is not a fully accurate representation of the actual processes going on in experiment. For the purposes of this simulation, the PYTHIA package works more than well enough to ignore the issues that occur when the model fails to describe data. It is, however, worth acknowledging that PYTHIA is only selected in this simulation as a way of producing particles according to a well-prescribed fragmentation process. It is not selected because this fragmentation process is actually what occurs in experiment. Calculating the fragmentation function in simulation involves embedding PYTHIA output in the output of the heavy ion background generator described below in 3.3.1. The anti-\(k_T\) jet finding algorithm is run on two sets of data: particles generated from PYTHIA only and particles generated from PYTHIA and the background generator. The algorithm clusters these two data sets into two sets of jet candidates. Each jet candidate’s fragmentation function will involve the \(p_T^{assoc}\) of the associated particle and the \(E_{jet}\) of the candidate. However, the jet candidates with constituents from PYTHIA and the background generator contains particles not related
to hard scattering processes (as jet candidates in data would). The information these jet
candidates contain would be used calculate the “raw” fragmentation function. It is necessary
to remove the effects of the background particles on the PYTHIA jet candidates. This
removal is accomplished via jet-hadron correlations. After removal, these jet candidates
will contain information used to calculate the “corrected” fragmentation function. Then
the “corrected” jets (from the background subtracted jet candidates comprised of PYTHIA
and background generator particles) along with the “true” jets (from the jet candidates
comprised solely of PYTHIA particles) are used to fill a response matrix. This response
matrix is used to unfold the two dimensional array of $p_{T}^{assoc}$ and $E_{jet}$ from the “corrected”
jets. The method is considered successful if the unfolded $p_{T}^{assoc}$ and $E_{jet}$ arrays match the
$p_{T}^{assoc}$ and $E_{jet}$ arrays from the set of jet candidates comprised solely of PYTHIA particles.
This method was mostly successful. However it suffered some setbacks related to the jet
$p_{T}^{constit.}$ thresholds. The method is described in more detail in Section 5.2. The model study
results are discussed in Section 6.1.

### 3.3.1 Heavy Ion Background Simulation

This simulation is a toy model based on data taken from LHC Run 1 $\sqrt{s_{NN}} = 2.76$ TeV Pb-
Pb collisions called TennGen [47]. TennGen simulates a realistic $p_{T}$ probability distribution,
realistic $\phi$ distribution, and realistic particle number for $\pi^{+}, \pi^{-}, \pi^{0}, K^{+}, K^{-}, p, \bar{p}$ in 0 – 5%,
5 – 10%, 10 – 20%, 20 – 30%, 30 – 40%, 40 – 50%, 50 – 60% centrality collisions. TennGen uses
fits to hadron momentum spectra in data, then fits to low momentum anisotropy coefficients
as a function of hadron momentum in data, then finally uses the Fourier decomposition of
hadron azimuth to construct a realistic $\phi$ distribution.

$$\frac{dN}{d(\phi - \Psi_{n})} = 2\pi(1 + \sum_{n=1}^{\infty} 2v_{n}(p_{T}) \cos (n(\phi - \Psi_{n}))) \quad (3.1)$$

Realistic $p_{T}$ distributions are achieved by fitting the Boltzmann-Gibbs Blast Wave model
to the $p_{T}$ distributions of the previously-mentioned hadrons measured in Ref. [2].
\[ \frac{d^2N}{dp_Tdy} = N_{p_T} \int_0^1 r'dr' \left( \sqrt{m^2 + p_T^2} \right) \cdot I_0 \left( \frac{p_T \sinh \left( \tanh^{-1} \left( \beta_s r'' \right) \right)}{T_{\text{kin.}}} \right) \cdot K_1 \left( \frac{\sqrt{m^2 + p_T^2} \cosh \left( \tanh^{-1} \left( \beta_s r'' \right) \right)}{T_{\text{kin.}}} \right). \]  

(3.2)

In Equation 3.2, \( p_T \) is the transverse momentum, \( y \) is the rapidity, \( N \) is the normalization, \( m \) is the mass of the particle, \( \beta_s \) is the surface velocity, \( n \) is an exponent describing the evolution of the velocity profile, and \( T_{\text{kin.}} \) is the kinetic freeze out temperature [48]. The \( I_0 \) and \( K_1 \) are modified Bessel functions. The reduced radius, \( r' \), is integrated over from 0 to 1. An example of the Boltzmann-Gibbs Blast Wave fit to the measured \( p_T \) spectra of \( K^+ \) is shown below in Fig. 3.3. It should be noted that these model fits to data are not perfect but they are realistic enough for the purposes of this simulation.

Realistic \( \phi \) distributions are achieved by fitting polynomials to the measured dependence of \( v_2, v_3, v_4, v_5 \) coefficients on \( p_T \) (measured in Ref. [8]). An example of a polynomial fit for \( v_2 \) vs \( p_T \) is shown below in Figure 3.4.

\( v_1 \) is taken to be \( v_1 = v_2 - 0.02 \) for all particles and centralities based on measurements of \( v_1 \) made in Ref. [14]. These \( v_1 - v_5 \) are then assembled (per particle) according to the \( \frac{dN}{d(\phi - \Psi_{R_n})} \) Fourier decomposition discussed in Section 1.5.1. The 2\textsuperscript{nd} and 4\textsuperscript{th} order reaction planes are both arbitrarily set to zero due to the strong measured correlation in corresponding event planes [15]. The 1\textsuperscript{st}, 3\textsuperscript{rd}, and 5\textsuperscript{th} order reaction planes are randomized on a per event basis to reflect their weak correlation [15]. Finally, a realistic number of particles are thrown per event based on charged particle multiplicity densities measured in [3].

TennGen makes the several assumptions. 1) The Boltzmann-Gibbs Blast wave fits can be extrapolated down to 0 \( p_T \) (below the lowest \( p_T \) bin in the measured spectra, \( \sim 200 \text{ MeV} \)) and up to 100 GeV \( p_T \) (above the highest \( p_T \) bin in the measured spectra \( \sim 2 \text{ GeV} \)). 2) The \( \pi^0 \) blast wave fit, \( v_n \) vs \( p_T \) dependence, and multiplicity can all be taken to be the same of that of the \( \pi^- \) distributions. 3) The \( v_n \) polynomial fits can be extrapolated below the
Figure 3.3: Boltzmann Gibbs Blast Wave fit to measured $K^+$ $p_T$ spectra for various centralities
Figure 3.4: $v_2$ vs $p_T$ polynomial fit to measurements for 10 - 20 % centrality
lowest measured $p_T$ values ($\sim 200$ MeV) unless they result in a zero value. 4) The $v_n$ fits are set to be zero whenever the fit results in a $v_n \leq 0$. 5) The $v_n$ fitting polynomials are set to be equal to their functional form evaluated at the highest measured $p_T$ values ($\sim 4$ GeV) beyond the highest measured $p_T$ value. 6) The variation in measured per-event charge particle multiplicity is ignored and is constant according to the mean values measured in ref [3]. 7) The pseudo-rapidity values are taken as a uniformly distributed random number $-1 < \eta < 1$ (this may be subject to change). TennGen is still advantageous to other background generators such as HIJING or HYDJET because the toy model contains no information related to hard scattering processes. It is solely a background generator. Additionally, TennGen, one can see the effect of different parameters (such as $v_n$) on the background. This is because it allows the user to change or exclude these parameters. Finally, it takes less computational resources and CPU time to run one event from my generator than it does to run a HIJING event.

The simulation framework is shown below in Figure 3.5.

Essentially, the user calls TennGen with the desired centrality bin and combinations of harmonics (different $v_n$ can be switched on and off). TennGen chooses a $p_T$ from the Boltzmann Gibbs Blast Wave fit. This $p_T$ is plugged into the polynomial fits for the $v_n$, and the $v_n$ are used to make the $\phi$ distribution according to the Fourier Decomposition discussed in Section 1.5.1. Then a $\phi$ is chosen from the $\frac{dN}{d(\phi - \Psi R_n)}$ distribution. The $\eta$ is chosen from a uniform random distribution. This is done for the seven particle species discussed above in a loop. The amount of times it is looped over is the multiplicity for each particle species. TennGen then takes these particles with their mass (flavor ID) and 4 vector ($E, p_x, p_y, p_z$) and gives them back to the user as the ROOT data type TClones Array. The user can specify how many $v_n$ to include in TennGen. Figure 3.6 shows an example of jet candidates produced from TennGen for various $v_n$ combinations using the anti-$k_T$ clustering algorithm.

Figure 3.6 shows a peak around 15 GeV due to $E_{jet} = \rho \pi R^2$. $\rho$ is the energy density, and $R$ is the jet resolution parameter which, in this case, is a radius because the anti-$k_T$ clustering algorithm produces conical jet candidates.
**Figure 3.5:** Flow chart depicting the inner workings of TennGen [47]. HF stands for Harmonics Flag which allows the user to select which (if any) harmonics to include in the $\phi$ distribution of each particle.
Figure 3.6: Jet candidates made from TennGen particles. The $v_n$ combinations have been varied and different backgrounds were produced. Then, the anti-$k_T$ clustering algorithm with jet resolution parameter $R = 0.2$ was ran on each set of backgrounds. For each $v_n$ combination, 10000 background events were produced.
3.3.2 Jet-Hadron Correlations and Background Subtraction in Simulation

As detailed above in Section 3.1, previous measurements of fragmentation functions have focused on removing the underlying event from jet candidates on a jet-by-jet basis. This analysis will use jet-hadron correlations to remove the underlying event on a statistical basis instead. This is realized via a Reaction Plane Fit (RPF) background subtraction technique detailed in Ref. [66]. Figure 3.7 contains an example of the RPF method applied to jet-hadron correlations measured in LHC $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collision data.

All jet candidates with a certain energy (any bin in $E_{jet}$) are chosen. The “raw” jet-hadron correlation will be calculated for each particle in each $p_{T}^{assoc}$ bin for that $E_{jet}$. The heavy ion background will be fit using the RPF technique and subtracted from the “raw” jet-hadron correlation. The RPF method will allow this to be done for jet candidates whose axis has any orientation (in-plane, mid-plane, and out-of-plane). The background subtracted jet-hadron correlation, or “corrected” j-h correlation will be for the full range, $-\pi/2 < |\Delta\phi| < 3\pi/2$. This is important because it allows the contribution of background to the near-side ($\sim 0$ radians) and the away-side ($\sim \pi$ radians) to be removed.

3.3.3 Two-Dimensional Unfolding in Simulation

The jet-hadron corrections are done for all $E_{jet}$ bins and $p_{T}^{assoc}$ bins. At this point, one will have two data sets, each set represented by a two-dimensional array. The total number of entries in these arrays will be determined by the binning in $E_{jet}$ and the binning in $p_{T}^{assoc}$. These two sets of arrays will be used fill a response matrix. The response matrix will be used to accomplish two-dimensional unfolding, where the “corrected” array will be unfolded to produce a “reconstructed” array. The process of unfolding is detailed in Ref. [10]. Typical results from 2-D unfolding for PYTHIA simulations (where the distortion comes from a $p_T$ dependent efficiency) are shown below in Fig. 3.8.

From the unfolded array, $z$ and $D(z)$ (the fragmentation function) can be calculated.
Figure 3.7: RPF method applied to 30 - 50 % central $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb collision data. The blue bands represent the uncertainty in the RPF background fit. Figure taken from Ref. [55].
Figure 3.8: Typical Results for 2-Dimensional Unfolding. Top Left: True $p_T^{jet}$ vs $p_T^{assoc}$. Top Right: Measured $p_T^{jet}$ vs $p_T^{assoc}$ (True distribution run through a $p_T$ dependent efficiency). Bottom Left: Unfolded $p_T^{jet}$ vs $p_T^{assoc}$ via the singular value decomposition method. Bottom Right: Unfolded $p_T^{jet}$ vs $p_T^{assoc}$ via the iterative Bayesian method. Figure produced by William Witt.
3.3.4 JEWEL Simulations

Jet Evolution With Energy Loss (JEWEL) is a Monte Carlo physics simulation which uses a perturbative approach to describe partonic energy loss in a QGP \cite{77}. JEWEL is, like PYTHIA, an effective model which captures the complex physics of the jet dynamics in the QGP medium as a sum of perturbative interactions. JEWEL assumes that the medium the jet traverses consists of entirely partons. The medium in JEWEL can be dynamic, incorporating hydrodynamic models to describe its expansion. In JEWEL incoming hard partons interact with soft medium constituent partons. These interactions can consist of single scatterings (e.g. $2 \rightarrow 2$ processes shown in Fig. 3.9) or multiple scatterings (e.g. $2 \rightarrow 2 \rightarrow N$ processes shown in Fig. 3.10) within the medium and this can be included or excluded within JEWEL as desired by the user. JEWEL is used in this analysis to compare to the jet-hadron correlation yield ratios in data.

3.4 Service Work

All graduate students that are part of the ALICE collaboration must perform at least six months work of service work. My service task was to work on the ALICE TPC upgrade project. This upgrade project’s goal is to replace the ALICE TPC’s Multi-Wire-Proportional-Chamber data technology with Gas Electron Multiplication (GEM) technology (see Section 2.2.4). This work was shared between many different institutes across the world. I helped build the Inner Read Out Chambers (IROCs). At the University of Tennessee, we assembled the IROC from its constituent parts, the Aluminum Body, Strong Back Support, and Pad Plane Sensor. We put copper cooling pipes in the Aluminum Body, used an epoxy mixture to attach the Strong Back Support and Pad Plane Sensor to the Aluminum Body, and leak tested the assembled IROC. The leak testing is to ensure that none of the TPC gas mixture will leak out and no Oxygen from outside will leak in. The leak-tested and assembled IROCs were then shipped to Yale University in New Haven, CT where the GEM foils are attached and further QA tests were performed. Then, the final assembled IROCs were

73
Figure 3.9: Example of a single scattering event in JEWEL occurring in medium. On the left, a solid black line (quark) and squiggly black line (gluon) scatter off each other elastically (grey circle) and then further radiate. Figure taken from [77].
Figure 3.10: Example of a multiple scattering event in JEWEL occurring in medium. On the left, a solid black line (quark) and squiggly black line (gluon) scatter off each other elastically (grey circle) and then further scatter within the medium (additional grey circles) on a comparable time scale. Figure taken from [77].
shipped to CERN. I traveled to CERN in October 2018 to perform the final acceptance tests on the IROCs. The following section details the work done at the University of Tennessee.

3.4.1 IROC Assembly

At the University of Tennessee, the ALICE TPC Inner Read Out Chambers (IROC) were assembled and leak tested. Fig. 3.11 shows the different institutes who participated in the ALICE TPC upgrade and their respective contributions.

The ALICE TPC (described in Section 2.2.4) consists of outer and inner read out chambers on either side. The IROCs consist of 4 basic components: An Aluminum Body (Alubody), plastic Strongback, copper/PCB pad plane, and a stack of 4 GEM foils. This is shown in Fig. 3.12.

The University of Tennessee was responsible for assembling all of these components except the GEM foil stack. This was done with the use of an epoxy consisting of a 1:1 mix of resin and hardener. In addition, a cooling system consisting of a copper pipe was inserted into the Alubody using the same epoxy mixture with an addition of ground copper dust. The addition of the copper dust ensured thermal contact with the rest of the Alubody. I used AutoDesk Inventor and 3D printing of solid ABS plastic to design and construct a chisel and clamp jig for the cooling system assembly. Fig. 3.13 shows these 3D-printed blocks.

The process of assembling the cooling system was as follows. Cut a 1/4” copper pipe. Using a chisel and mallet, bend the pipe to fit the groove. Bend the copper pipe down at both sides of the groove (shown in the upper right in Fig. 3.14) and cut again. Apply the epoxy/copper dust mixture into the groove. Re-insert the bent copper pipe into the groove. Use the clamps and jig (3D-printed blocks, shown in Fig. 3.13) to secure the copper pipe and allow the epoxy/dust mixture to cure over night. Remove the clamps and jig. The top panel of Fig. 3.14 shows these steps visually.

After the copper cooling pipe was successfully bent, inserted, and bonded into the Alubody, the next step was to attach the pad plane and Strongback. This was done by using paint rollers and the epoxy. The rollers were used to first cover the pad plane, then both sides of the Strongback. The Strongback was then attached to the pad plane. Another layer of
Figure 3.11: Flow chart showing the different institutes who took part in the ALICE TPC Upgrade and their roles. The University of Tennessee and their role (IROC Body Assembly) is circled.
Figure 3.12: Components of an ALICE TPC Inner Read Out Chamber. Upper left: fully assembled IROC including the 4 GEM stack). Upper right: pad plane. Bottom left: Aluminum body (Alubody). Bottom right: Strongback.
Figure 3.13: 3D-printed blocks used for cooling system assembly. Top: mallet with 3D-printed chisel. Bottom: 3D-printed clamp jig.
epoxy was applied to the top of the Alubody. The Alubody was then flipped and attached to the Strongback and pad plane. Finally, the whole assembly (top to bottom: pad plane, Strongback, and Alubody) was put flush with the vacuum table and with the use of an O-ring and vacuum pump sucked into it. Then the assembly was allowed to cure overnight. The bottom panel of Fig. 3.14 shows all of these assembly steps visually.

3.4.2 Leak Test

After the IROCs were assembled, they had to be leak tested. The idea is that oxygen, commonly encountered as \(O_2\) in the atmosphere is a very electronegative element (registering a 3.44 on the Pauling electronegativity scale - only fluorine is higher). This means the oxygen has a strong affinity for binding to electrons. If oxygen is allowed to enter the TPC, it may distort tracks by absorbing electrons from ionization events in the detector volume. To mitigate this, the IROCS (and OROCs) have to be leak tight against oxygen. After assembly, a leak test was performed on each chamber. The leak test setup is shown in Fig. 3.15. The IROC is put into an aluminum test vessel held together with nuts and bolts. Then this test/vessel IROC combination is connected to bottles of nitrogen on one side (input) and a GE Oxy-IQ oxygen sensor one the other side (output) with copper pipes. The oxygen sensor is coupled to a plastic pigtail (plastic pipe wrapped around several times) and terminates in a bubbler. The bubbler is a beaker filled with paraffin oil.

In the leak test, two bottles of nitrogen are used at different times. At the start of the test, a bottle consisting of lower purity nitrogen is used to flush the test vessel/IROC at a high rate, lowering the concentration of oxygen from atmospheric (200,000 ppm) to < 100 ppm or so. From there, the flow is lowered and switched to a higher purity nitrogen. Then the high purity nitrogen flows through the system at a very low flow, < 1 L/min. At this point, the oxygen levels will reach a plateau value (provided the leak is small) determined the leak rate and the nitrogen flow rate. A formula derived from simple assumptions (conservation of mass, conservation of flow, etc...) is used to calculate the leak rate from the plateau oxygen value.
Figure 3.14: Panel showing the different assembly steps for the ALICE TPC IROCs. Top left: Shaping the copper pipe. Top middle: applying the epoxy/copper dust mixture. Top right: Using the clamp/jigs to bond the copper pipe into the groove. Bottom left: applying epoxy to the pad plane. Bottom middle: attaching strong back and pad plane. Bottom right: final assembly curing on the vacuum table.
**Figure 3.15:** Leak test setup for the IROCs. From left to right, nitrogen flows into the test vessel/IROC combination, out into the oxygen sensor, and out through a pigtail into parrafin oil.
\[ f_l = \frac{\rho_O - \rho_N}{\rho_l - \rho_O} f_N \quad (3.3) \]

Where \( f_l \) is the leak rate, \( \rho_O \) is the oxygen concentration in the oxygen sensor (the plateau value), \( \rho_N \) is the oxygen contamination in the nitrogen bottle, \( \rho_l \) is the oxygen concentration leaking into the test vessel/IROC (atmospheric oxygen is 200,000 ppm), and \( f_N \) is the flow rate of the nitrogen into the test vessel/IROC. These variables are also visually described in Fig. 3.15.

The plateau values of the oxygen are determined at 2 different flow rates of the high purity nitrogen to get a more accurate measurement of the leak rate. A typical leak test looks like Fig. 3.16. The y axis is the parts per million oxygen in the oxygen sensor and the x axis is the time in hours. The oxygen concentration starts out at 200,000 ppm. Then, the low purity nitrogen enters the setup at 2.0 L/min, lowering the oxygen concentration rapidly. Then the concentration falls below 10 ppm and the flow rate is switched to 0.15 L/min and the bottle is switched over to the high purity nitrogen. The oxygen content in the sensor plateaus at 1.1 ppm and the leak rate is 0.047 mL/hr as determined by the formula in Equation 3.3. The flow rate is switched to 0.10 L/min and another plateau value is reached at 1.6 ppm and the calculated leak rate is 0.046 mL/hr.

The University of Tennessee assembled and leak tested 46 total IROCs. The results of the leak tests are shown in Fig. 3.17. All IROCs produced have measured leak rates below 0.25 mL/hr - the target leak rate. The average leak rate was 0.069 mL/hr and the median leak rate was 0.056 mL/hr.

I set up the oxygen sensor data link using a bread board, jumper wires, a resistor, and a LabJack DAQ. The schematic for this setup is shown in Fig. 3.18. As the oxygen content in the sensor changes, the current in the circuit changes. This will change the voltage across the resistor. This voltage can be related to the ppm oxygen in the sensor through calibration constants. I also wrote a computer program using Labview to do this calibration, display and record the oxygen content over time, and adjust the sensitivity of the measurement. This can be seen in Fig. 3.19 which shows the graphical user interface of the Labview program.
Figure 3.16: Example of a leak test for IROC 38. The various features of the leak test are highlighted, including the final leak rates which are in the box on the upper right.
Figure 3.17: Distribution of leak rates for all IROC bodies produced at the University of Tennessee. The threshold leak rate is highlighted (0.25 mL/hr).
Figure 3.18: Electronics schematic for the DAQ/laptop connection. The oxygen sensor is connected in series with a 121 Ohm resistor and a power supply. The DAQ is connected across the resistor and to the laptop.
Figure 3.19: Labview front end, allowing the user to change the sensitivity of the measurement, see the oxygen trend over time, and view the moving average of the oxygen content in the sensor.
Chapter 4

Data Processing and Computing

The ALICE detector is composed of many sub-detectors. Chapter 2 details those detectors used for this analysis. For a typical central Pb-Pb collision, the sum total of data per event is around 87 MB. Figure 4.1 shows a breakdown of the per-event data budget for each ALICE detector and the trigger in a minimum bias pp collision and a central Pb-Pb collision. The event rate in a central Pb-Pb collisions will depend on the type of physics analysis but will be up to a few hundred Hz, at maximum [41]. This gives an estimate of a maximum of tens of GB/s as a total bandwidth.

These tens of GB/s of data are not all stored. The raw data are reduced via online processing and triggering, causing a reduction in bandwidth by a factor of 10. An event building network also aggregates the data and reduces the bandwidth by a factor of 2 before storage. The system which accomplishes this is the ALICE Data Acquisition or DAQ. Figure 4.2 shows an overview of the ALICE DAQ architecture. The ALICE detectors receive trigger signals and information from the Central Trigger Processor (CTP) via a Local Trigger Unit (LTU) which is connected to a Timing, Trigger, and Control (TTC) system.

The data produced by the detectors at their Front End Read Out (FERO) get injected into the Detector Data Links (DDL). The data are received at the other end of the DDL by a DAQ Readout Reciever Card (D-RORC). These D-RORCs are hosted in personal computers called Local Data Concentrators (LDC). The LDCs are the first stage of event assembly where event fragments are assembled into sub-events. These sub-events are fed into Global Data
Table showing typical event sizes in a p-p minimum bias event and a Pb-Pb central event in ALICE for different ALICE detectors. Figure taken from Ref. [41].

<table>
<thead>
<tr>
<th>Detector</th>
<th>pp (kB)</th>
<th>Pb–Pb (MB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITS Pixel</td>
<td></td>
<td>0.140</td>
</tr>
<tr>
<td>ITS Drift</td>
<td>1.8</td>
<td>1.500</td>
</tr>
<tr>
<td>ITS Strips</td>
<td></td>
<td>0.160</td>
</tr>
<tr>
<td>TPC</td>
<td>2450.0</td>
<td>75.900</td>
</tr>
<tr>
<td>TRD</td>
<td>11.1</td>
<td>8.000</td>
</tr>
<tr>
<td>TOF</td>
<td></td>
<td>0.180</td>
</tr>
<tr>
<td>PHOS</td>
<td></td>
<td>0.020</td>
</tr>
<tr>
<td>HMPID</td>
<td></td>
<td>0.120</td>
</tr>
<tr>
<td>MUON</td>
<td></td>
<td>0.150</td>
</tr>
<tr>
<td>PMD</td>
<td></td>
<td>0.120</td>
</tr>
<tr>
<td>Trigger</td>
<td></td>
<td>0.120</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2500</td>
<td><strong>86.500</strong></td>
</tr>
</tbody>
</table>

**Figure 4.1:** Table showing typical event sizes in a p-p minimum bias event and a Pb-Pb central event in ALICE for different ALICE detectors. Figure taken from Ref. [41].
Figure 4.2: ALICE DAQ Architecture Overview. Data tend to flow from FERO (Front End Read Out) to the Event Building Network to the Storage Network. Data rates start at 25 GB/s and eventually reduce to 1.25 GB/s at storage. Figure taken from Ref. [41].
Collectors (GDCs) via an Event Building Network which provides information to the LDCs about which GDCs are busy and which are available. At this stage, the data throughput is reduced by about a factor of 10 to around 2.5 GB/s via a combination of event rejection and compression [41]. The GDCs collect the sub-events and assemble them into whole events. At this point the events enter a storage network and eventually end up in Permanent Data Storage (PDS) at a rate of around 1.25 GB/s (another reduction in bandwidth). In addition to building up events from individual detectors, there is also a High Level Trigger (HLT) system which receives a copy of all the raw data, processes it with Front End Processors (FEP), and generates data and decisions which are transferred to LDCs and then processed as described above.

There is also quite a lot of processing done at the FERO level for different detectors. The purpose of this processing is, in general, to take the raw data of detector hits, voltages, timing and extract physics information. There is also a lot of post-processing done in the reconstructed events. The collision vertex, charged particle tracks, and calorimeter energy deposits are examples of information obtained in online and offline processing. The following section will provide a detailed description of the processing done in the VZERO, Inner Tracking System, Time Projection Chamber, and Electromagnetic Calorimeter which are the 4 main detectors used in this analysis.

### 4.1 Vertex finding

The location of the colliding beams within the ALICE detector can vary from event to event. The transverse coordinates of the collision vertex (x and y) are fixed due to the relatively small rms widths of the colliding particle bunches ($\sigma_x = \sigma_y = 15 \, \mu m$). The longitudinal (beam direction - z) coordinate of the collision vertex varies within a relatively large distance range. This is due to the fact that the bunch Root Mean Squared width in the z direction is $\sigma_z = 5.3 \, cm$. Therefore, the ITS identifies the z coordinate of the collision vertex only. This is done by correlating hits in the two pixel layers of the SPD (mentioned in 2.2.3) which are within some threshold azimuthal ($\phi$) separation [34]. The value of the separation has to be
optimized to balance between background (e.g. too large a $\Delta \phi$ threshold and you select on multiple scatterings which would mis-identify the vertex) and statistics (too small a $\Delta \phi$ and there are not enough statistics to confidently identify the vertex). In addition, the charged particle multiplicity as a function of pseudo-rapidity ($\eta$) influences the resolution of the $z$ vertex as shown in Fig. 4.3. At low charged particle multiplicites, the $z$ vertex resolution is dominated by statistical error, multiple scatterings and systematic errors. At high charged particle multiplicities, the $z$ vertex resolution is dominated by residual ITS misalignment.

4.2 Track Finding

The tracks of charged particles are reconstructed in the ITS and TPC. The process of reconstructing the tracks uses hits from both detectors as inputs to an algorithm called the Kalman Filter [20]. The Kalman filter takes in discrete inaccurate measurements and reconstructs continuous accurate trajectories. Tracks can be found standalone in the ITS or together with the ITS and TPC. Prior to track finding in the TPC, a cluster finding procedure searches for groups of detector hits in space and time. The following sections describe these procedures in detail.

4.2.1 TPC cluster finding

Two-dimensional (1 space + 1 time) clusters in the TPC are found before undergoing track reconstruction. The TPC cluster finding searches for adjacent cells in the pad row-time plane with ADC values above the zero suppression level (see Section 2.2.4). These adjacent cells are known as pre-clusters [35]. An example of a few pre-clusters is shown in Fig. 4.4. In this figure, there are many ADC values but only those circled are greater than the zero suppression threshold. For each pre-cluster, all the local maxima ADC values are found. The local minima, or saddle-points, are also found. Each local maximum in a pre-cluster is reduced to the level of the nearest saddle point. Then, the centroid is calculated for each group of these cut maxima. These centroids are taken to be the reconstructed positions of the corresponding space points. These space points are used in the next stage of track
**Figure 4.3:** Resolution of Vertex z component as a function of $\frac{dN_{ch}}{d\eta}$. Solid line is from a parameterized fit. Figure taken from [34].
**Figure 4.4:** Schematic example of ADC values in the pad row-time plane used for the STAR Experiment. Red circles illustrate clusters found by the clustering algorithm (those values which are greater than the zero suppression threshold). Figure taken from Ref. [27].
finding as inputs to the Kalman filter. The errors associated with these points are assumed to be proportional to the dispersion of the cluster.

4.2.2 TPC track finding

TPC Track finding begins by seed finding. Seed finding consists of a search for all pairs of points in the outermost pad row and in pad row 20 rows closer to the interaction point which are projecting to the collision vertex \[35\]. When a “reasonable” pair of points is found, the parameters of a helix passing through these points and the collision vertex is found. An example of this is shown in Fig. 4.5. The covariance matrix of these parameters is found by taking the point errors from the cluster finding and an artificially large uncertainty associated with the collision vertex. The magnitude of the collision vertex uncertainty is taken to be the radius of the beam pipe in order to take into account multiple scatterings and particle decays close to the interaction point. The Kalman filter is initiated from the determined helix parameters and their associated covariance matrix from the outer most point to the inner one (20 pad rows closer to the interaction point). If a minimum of half the possible points between the initial two points were associated with the helix, then it is called a seed track and saved. A second seed-finding process is started with different TPC pad rows to avoid a bias from cluster distortions.

After the seed finding, the seeds are sorted according to increasing track curvature. The Kalman filter is applied, starting from the stiffest (largest radius of curvature) tracks. For each seed, the track parameters and covariance matrix are calculated at the next pad row. This extrapolation step takes into account multiple scattering and mean energy loss by assuming the particle associated with the track is a pion \[35\]. At this next pad row, a window is defined along the pad direction where associated clusters are sought. The window dimensions are calculated from the space point errors and the uncertainty in track position from the covariance matrix (multiplied by a constant determined by a parameter of the tracking program). Then, the window is searched for all clusters that appear within it. There are 3 possibilities:
Figure 4.5: Schematic showing seed finding in the TPC. The two red points on the right side of the picture are the pair and the red curve is the helix projected back to the collision vertex region. The circle around the left most red point represents the artificially large uncertainty given the collision vertex at this stage of the track finding. Figure taken from Ref. [18]
1. No clusters within the window. In this case, the Kalman filter algorithm will proceed to the next pad row. If there are several consecutive pad rows with empty windows, then the tracking is terminated and the seed track is removed from the list. However, all of the clusters associated with the seed track are kept.

2. One cluster within the window. If the $\chi^2$/NDF for the cluster is $< 12 / 2$ D.O.F., then the cluster is attached to the track and the track parameters are updated according to the Kalman filter algorithm. Then the cluster is removed from the event. If the $\chi^2$/NDF for the cluster is $> 12 / 2$ D.O.F., then the cluster is kept and the algorithm proceeds to the next row as in case 1.

3. Multiple clusters within the window. In this case, the cluster with the smallest $\chi^2$/NDF is chosen to be associated with the track. Then the Kalman filter algorithm proceeds to the next row.

When the algorithm reaches the inner boundary of the TPC, the track is checked to see if at least 40% of all possible clusters that can be associated with it. If they are, the track candidate is considered a “found track” and all of its associated clusters are removed from the event. If less than 40% of all possible clusters are associated with it, then the track candidate is removed from the list and its corresponding clusters are left in the event. The algorithm continues until all tracks are considered a “found track” or removed from the list.

4.2.3 TPC+ITS Track Finding

After tracks have been found in the TPC, they are matched to tracks in the ITS. This matching uses the Kalman filter algorithm, as in the TPC track finding, but with some differences. One difference is that as the Kalman filter algorithm iterates through the ITS layers (SSD, SDD, SPD), all the hits with a threshold $\chi^2$/NDF in the moving window are associated with the track. This is in contrast with the procedure in the TPC where only the cluster with the minimal $\chi^2$/NDF is chosen. In this way, a tree of ITS track candidates is made for each TPC track. An example of this is shown in Fig. 4.6. The final track is resolved from the branches of the tree.
**Figure 4.6:** Schematic showing an example of a candidate tree in the ITS from a track starting in the TPC. The final chosen track is shown in solid green while all the possible tree branches are shown in dotted green. Figure taken from Ref. [19].
This is done by choosing the path along the tree which has a minimal $\chi^2$ for a maximal number of the assigned ITS hits. Once the path is chosen, all the ITS hits associated with it are removed. The algorithm then continues and attempts to extend all TPC tracks into the ITS. Extending the tracks from the ITS to the TPC results in a decrease in reconstruction efficiency by as much as 20%. However, the probability of reconstructing a “fake” track remains under 5% for ITS+TPC tracks with $p_T > 200$ MeV. This is shown in Fig. 4.7.

4.2.4 ITS Standalone Track Finding

After removal of the hits assigned to ITS+TPC tracks, standalone track finding is performed in the ITS. The ITS standalone track finding is done using only the ITS hits left after the global ITS+TPC track finding. An example of an ITS event display after removing hits from the ITS+TPC track finding is shown in Fig. 4.8. The standalone track finding is useful for recovering low $p_T$ tracks ($< 150$ MeV/c pions and $< 400$ MeV/c protons) and high $p_T$ tracks lost in the dead zone between TPC sectors [19]. The standalone track finding is done using the Kalman filter. Seeds are defined using 2 clusters in the 2 ITS innermost layers and the SPD vertex (see Section 4.1). Matching ITS hits are found on all ITS layers within a “search road”. All combinations of these hits are fitted by the Kalman filter and the best track candidates are kept. This procedure is repeated for increasing “search road widths” in an attempt to get low $p_T$ particles and secondaries from particle decays in the ITS.

4.3 EMCAL Data Reconstruction

As discussed in Section 2.2.5, the EMCAL consists of scintillating plastic crystals coupled to Avalanche Photo-Diodes. These produce raw signals which, when processed, reveal energy and timing information for arriving electrons and gamma rays. However, the raw signals require several steps of processing in order to properly analyze them. Figure 4.9 shows the reconstruction done to the digital signals which leave the EMCAL front end cards in green. The steps consist of a Raw Analyzer (performs signal amplitude and timing data extraction), a Digit Maker (uses the Analyzer output to prepare input for the cluster algorithm), and a
Figure 4.7: Reconstruction Efficiency for low momentum ($p_T < 1.5$ GeV) TPC and TPC+ITS tracks. Extension of track to the ITS decreases the reconstruction efficiency by as much as 20%. Figure taken from Ref. [41].
**Figure 4.8:** ITS event display after removing hits assigned to tracks found with help of the TPC. The xy plane is the transverse plane, the zy plane is one of the longitudinal planes. Figure taken from Ref. [34].

**Figure 4.9:** ALICE event reconstruction. EMCAL online components shown in green. Figure taken from Ref. [64].
Clusterizer (which sums the digits from the Digit Maker to cluster cell information). The following sections provide more information on these three reconstruction components.

4.3.1 Raw Analyzer

The Raw Analyzer extracts the energy and timing for the EMCAL cells. The extraction method is an algorithm called kCrude. kCrude produces an amplitude (proportional to energy) using the difference between the maximum and minimum values of the digitized time samples from the EMCAL Front End Cards [64]. The time bin of the maximum is taken to be the arrival time. An alternative method kPeakFinder can also be used which constructs the amplitude from a weighted sum of the digitized samples. kCrude represents a faster, less-accurate method while kPeakFinder is more accurate but takes slightly longer [64].

4.3.2 Digit Maker

DigitMaker takes the raw cell signal amplitudes and transforms them into digit structures by processing the cell coordinates where those amplitudes occur. In addition the dead channel maps and gain factors are applied at this stage.

4.3.3 Clusterizer

The clusterizer takes the input from the DigitMaker and uses it to combine the amplitude information from adjacent EMCAL cells into clusters. There are two algorithms which are used to accomplish this. The first algorithm, called V1, sums up all the neighboring cells around a seed-cell threshold until no more cells are found [64]. The second algorithm, called NxN, sums up the amplitudes from all cells around the seed until the number of clustered cells reaches a pre-determined cut off value. The second method is preferred as it is less computationally intensive. The EMCAL online reconstruction uses a cutoff of 9 cells (3x3).
4.4 Centrality Determination

The centrality is estimated in the VZERO detector from the charged particle multiplicity. The charged particle multiplicity \( dN_{ch}/d\eta \) is proportional to the measured VZERO amplitude. The VZERO amplitude is measured in several pseudo-rapidity bins, which correspond to the different coverages of the rings in the VZERO detector. The measured distribution can be fit to a Glauber model (see 1.4.1) which reproduces the correct VZERO amplitude distribution as shown in Figure 4.10. Then measured VZERO amplitude distribution (or the Glauber model fit) is then binned in percentiles which define the centrality classes (also shown in Figure 4.10). Additionally, one can extract average values for impact parameter \(<b>\) and number of participating nucleons \(<N_{part}>\) from a mapping of the Glauber model fit to the measured distributions. The centrality resolution of various detectors is shown below in Fig. 4.11. The VZERO detectors (V0A and V0C), when taken together, provide the best centrality across the entire centrality range \(<2\%\).

4.5 Event Plane and Flow Coefficient Determination

The 2nd order event plane, mentioned in Section 1.5.1, is of essential importance for this analysis. The reaction plane fit background subtraction method [66] relies on measurements of jets relative to the 2nd order event plane. This requires a measurement of the 2nd order event plane, \(\Psi_2\).

The event planes are measured from the \(n^{th}\) order harmonic anisotropy of the event itself, \(v_n\). In practice, this is done with the \(q_n\) vector technique utilizing many detectors. However, the actual \(v_n^{\text{observed}}\) have a magnitude less than \(v_n\) and must be corrected by the event plane resolution in the following way, \(v_n = v_n^{\text{observed}}/R_{\Phi_n}\), using the sub-event correlation technique. The sub-event correlation technique involves measuring the event plane at different collision centralities (particularly around semi-central) where the flow effect is largest. The resolution is then constructed from the correlations. The resolution of the 2nd Order Event Plane is shown below in Figure 4.12.
Figure 4.10: Centrality Bins from VZERO amplitudes. Figure taken from Ref. [1].
Figure 4.11: Centrality resolution from multiple detectors. The V0A and V0C are shown as red and green triangles, respectively. The combination of the V0A and V0C is shown in blue circles and provides the best centrality resolution amongst all detectors across the entire centrality range. Figure taken from Ref. [3].
Figure 4.12: Second Order Event Plane Resolution as a function of centrality in Pb-Pb collisions. Measured from VZERO. Figure taken from Ref. [1].
Chapter 5

Analysis Method

The following sections describe the analysis method mentioned for measuring the fragmentation function and jet constituent yields in detail. There is a general description of the method which details the analysis methods in a feasibility study with simulated heavy ion collisions with PYTHIA [69] and TennGen [47] in Section 5.2. In Section 5.3 there is a description of the methods used on the analysis with LHC data which differs slightly in its implementation from the feasibility study. An outline of the general method is described directly below and then elaborated on in Section 5.1.

The fragmentation function itself is extracted from the near-side yield of the background-subtracted correlation functions which is done only in the model studies. The background subtraction method used is the Reaction Plane Fit (RPF) method [66]. This method fits the background in the correlation function for the near-side peak at large $|\Delta \eta|$ and then subtracts the background from the entire correlation function. Because the yields are determined from the near-side and away-side jet peaks they contain information about the constituents of the jet. The normalized yield measures the number of hadrons per jet at a fixed $p_T^{\text{assoc.}}$ in jets with a fixed $p_T^{\text{jet}}$. The fixed $p_T^{\text{assoc.}}$ and $p_T^{\text{jet}}$ are determined in bins so that they are ranges of values determined by their respective bin widths. The away-side yields are used to construct an observable closely related to the fragmentation function measured on the near-side. Since the away-side jet momentum cannot be constrained by any information available, the away-side yield is binned relative to the near-side jet momentum and normalized by the number.
of near-side jets in that momentum bin.

After the raw fragmentation function is constructed from the yields \( Y_{i,j}^{\text{Back,Sub.}} \), where \( i \) and \( j \) are the associated particle and jet \( p_T \) bins, respectively, it still needs to be corrected for detector effects: primarily the un-reconstructed jet momentum caused by single track reconstruction efficiencies. This is done using a technique called unfolding [10]. The response matrix used in the unfolding procedure is based on simulations where jets at the detector level are matched to jets at the particle level. After unfolding, the yield distribution can be used to to obtain the jet constituent momentum distribution, \( \frac{dN}{N_{\text{jet},j} dp_T^{\text{constit.}}} \) for a each \( p_T^{\text{jet}} \) bin. Then the \( p_T^{\text{constit.}} \) axis can be divided by the average \( p_T^{\text{jet}} \) value in bin to determine \( \frac{dN}{N_{\text{jet},j} dz^{\text{constit.}}} \). Figure 5.1 shows an overview of the general method.

In the model studies, the steps are as outlined above with some differences/exceptions. The jet-hadron correlations are corrected for acceptance (not shown in Fig. 5.1), background subtracted following the RPF Method [66], and yields are obtained via two dimensional integration over the near-side and away-side jet peaks. The yields are unfolded using the ROOUnfold [10] iterative Bayesian method [33] to correct for for \( p_T^{\text{assoc.}} \) smearing and jet \( p_T \) loss due to particle reconstruction inefficiencies. Unfolding is done based on an embedding technique using PYTHIA [69] and TennGen [47] simulations.

In the data analysis, the steps are also as outlined above except with the following differences/exceptions. The acceptance correction is obtained using a mixed-event technique. The yields are evaluated only in one dimension. The unfolding method is based on proton-proton simulations embedded into Pb-Pb data and a full detector simulation.

In both cases, the unfolded yields represent the \( p_T \) spectrum of constituent particles for a given \( p_T^{\text{jet}} \). This is the information contained in a traditional fragmentation function \( \frac{dN}{dz} \).
**Figure 5.1:** Scheme for obtaining fragmentation functions from jet-hadron correlations. Correlations are calculated, background is subtracted from the correlations (using the RPF method), the background subtracted yields are extracted, and finally the yields are unfolded to correct for detector effects.
5.1 Fragmentation Functions from Jet Hadron Correlations

A jet-hadron correlation measures the distribution of jet constituents in azimuth ($\phi$) and pseudorapidity ($\eta$, defined in Appendix A.1) relative to the jet axis. Fig. 5.2 shows a cartoon of the azimuthal distribution of hadrons in a low multiplicity collision where the jet and associated hardrons are highlighted. Fig. 5.3 shows a jet-hadron correlation in PYTHIA [69] simulations of proton-proton collisions. In Fig. 5.3, one can see a peak at $\Delta \phi = 0$ and $\Delta \phi = \pi$ representing the near-side and away-side peaks of particles associated with a jet.

5.1.1 Acceptance Correction

An acceptance correction accounts for finite volume effects including sharp thresholds on jet and associated particle pseudorapidity and detector geometry effects (e.g. sector boundaries, dead spaces, etc ... ). The acceptance correction for jet hadron correlations is calculated as a function of $\Delta \phi$ and $\Delta \eta$. The jet hadron correlation is corrected by dividing by the acceptance correction. Since this also corrects for sharp cut-offs in pseudorapididity, this must also be applied to simulations. Equation 5.1 shows how the acceptance correction is applied to the uncorrected jet-hadron correlation.

$$\frac{d^2 N^\text{corrected}}{d\Delta \phi d\Delta \eta} = \frac{d^2 N^\text{uncorrected}}{d\Delta \phi d\Delta \eta} \ast \frac{1}{a(\Delta \phi, \Delta \eta)} \quad (5.1)$$

In the feasibility study done with pure simulations, the detector has a uniform acceptance over a finite volume ($|\eta| < 0.9$). The acceptance correction is required because of the finite acceptance in $\eta$ which limits $\Delta \eta$ and therefore affects the correlation function even though detector effects (e.g. sector boundaries) are not present in the model study. The acceptance is 100 % efficient at small $\Delta \eta$ and 0 % efficient at large $\Delta \eta$. This leads to a trapezoidal shape for the acceptance corrections in the model studies because the acceptance is flat, falling linearly to 0 at large $|\Delta \eta|$ as in Fig. 5.5.
Figure 5.2: Schematic representation of a jet-hadron correlation in azimuthal space. The red dotted cone and line are the jet and jet axis respectively. The black arrows are the hadrons produced in the event. The black arrows which fall within the dotted red cone are the near-side jet constituent hadrons. The correlation variable, $\Delta \phi_{jet-hadron}$, is the difference in the jet axis $\phi_{jet}$ and the $\phi_{hadron}$. 
Figure 5.3: Jet-Hadron Correlation in $\Delta\phi$ for simulated 13 TeV proton-proton collisions using PYTHIA for 10-30 GeV anti-$k_T$ jets and all associated hadrons. Two peaks at $\Delta\phi=0$ and $\Delta\phi=\pi$ are visible.
In the data analysis, the detector has a more complex acceptance which also depends on the jet and associated particle $p_T$ with non-trivial corrections to uniformity. The acceptance correction in the data analysis is obtained by use of mixed-events. These mixed-events take jets from one event and randomly selected tracks from other events and combine them to obtain the acceptance correction. This ensures that the detector effects remain in the mixed-events while other correlations do not (e.g. from hydrodynamical flow).

Fig. 5.4 shows an uncorrected 2-dimensional Jet-Hadron Correlation (in $\Delta \phi$, $\Delta \eta$ space) calculated from PYTHIA simulations of p-p collisions. The simulations show the effect of the finite acceptance on the shape of the correlation function; the correlation peaks shown in Fig. 5.3 sit on top of of a trapezoid (note the trapezoidal shape is due to the differences in jet and particle acceptance in $\eta$). The trapezoid’s upper base has a length of twice the difference between the particle acceptance and the jet acceptance (in $\eta$) and its lower base extends the entire $\Delta \eta$ range. The acceptance correction for the model feasibility study itself is shown in Fig. 5.5. In this simple incarnation, the acceptance correction varies only in the $\Delta \eta$ direction. After dividing by the acceptance correction, the Jet-Hadron correlation for p-p collisions has a flat baseline. This is shown in Fig. 5.6.

In heavy ion collisions, the shape of the soft background is more complicated and depends on the orientation of the trigger jets relative to the reaction plane. However, the effect of the acceptance correction is still the same: to remove the effects of the finite acceptance, including anisotropies in detector efficiency.

### 5.1.2 Reaction Plane Fit Subtraction Method

The acceptance corrected, background subtracted correlation function can be expressed as (building on Equation 5.1)

$$\frac{d^2 N^{\text{signal}}(\Delta \phi, \Delta \eta)}{d \Delta \phi d \Delta \eta} = \frac{d^2 N^{\text{raw}}(\Delta \phi, \Delta \eta)}{d \Delta \phi d \Delta \eta} \ast \frac{1}{a(\Delta \phi, \Delta \eta) \epsilon(\phi, \eta)} - \frac{d^2 N^{\text{bkgd.}}(\Delta \phi, \Delta \eta)}{d \Delta \phi d \Delta \eta}$$ (5.2)
Figure 5.4: Jet-hadron correlation without acceptance correction for R = 0.2 anti-$k_T$ $p_T$ = 27.5-30 GeV jets and 2-3 GeV hadrons using PYTHIA [69] simulations of 2.76 TeV p-p collisions. Notice the trapezoidal shape the near-side jet peak sits on top of - this is due to the finite particle and jet acceptance.
Figure 5.5: Simple acceptance correction for the model studies (R = 0.2 anti-$k_T$ jets). The shape is trapezoidal along the $\Delta \eta$ axis and constant along the $\Delta \phi$ axis. This is an appropriate assumption for the model feasibility studies.
Figure 5.6: Acceptance corrected and normalized Jet-Hadron correlation for $R = 0.2$ anti-$k_T$ $p_T = 27.5-30$ GeV jets and 2-3 GeV hadrons using PYTHIA simulations of 2.76 TeV p-p collisions. After the acceptance correction, the baseline is flat.
The background term, \( \frac{d^2N^{bgd.}(\Delta \phi, \Delta \eta)}{d\Delta \phi d\Delta \eta} \), is obtained from the RPF method. In the RPF method, the near-side (|\(\Delta \phi\)| < \(\pi/2\)) background is fit at large \(\Delta \eta\), far away from the near-side jet peak at \(\Delta \eta\) (typically |\(\Delta \eta\)| > 1.0) for differing orientations of the trigger jets relative to the second order event plane [60, 22]. The RPF method assumes that the correlation function has a region where it is entirely background. This assumption holds true for PYTHIA and all known heavy ion collision models for sufficiently large \(\Delta \eta\). This background region can be fit to determine the background. The shape of the background depends on the angle between the trigger jet and the second order event plane. It should be noted that this method can also be applied to correlations relative to other event planes [60]. Only correlations relative the second order plane are considered in this thesis.

The form of the background fit function is given below in Eq. 5.4 [66, 22]. Eq. 5.3 defines the effective \(v_n\), \(\tilde{v}_n^{R,t}\) and effective background, \(\tilde{\beta}^R\).

\[
\tilde{v}_n^{R,t} = \frac{v_n^t + \cos n\phi_s}{n_c} R_n + \sum_{k=2,4,6,...} (v_{k+n} + v_{|k-n|}) \cos k\phi_s \frac{\sin k\xi}{k_c} R_n \\
\phantom{\tilde{v}_n^{R,t}} \left(1 + \sum_{k=2,4,6,...} 2v_k^t \cos k\phi_s \frac{\sin k\xi}{k_c} R_n\right) \\
\tilde{\beta}^R = B \left(1 + \sum_{k=2,4,6,...} 2v_k^t \cos k\phi_s \frac{\sin k\xi}{k_c} R_n\right) \\
\frac{d^2N^{bgd.}(\Delta \phi, \Delta \eta)}{d\Delta \phi d\Delta \eta} = \pi \tilde{\beta}^R \left(1 + \sum_{n=1}^{\infty} 2\tilde{v}_n^{R,t} v_n^a \cos n\Delta \phi\right)
\]

The free parameters in the RPF fit are the overall background level \((B)\), the \(v_n\) coefficients for the trigger jet \((v_n^t)\), and the \(v_n\) coefficients for the associated particles \((v_n^a)\). In principle, one can fit to arbitrary order in \(v_n\) but, in practice, fitting is only done up to \(v_4\) or \(v_5\) at most. This is because the magnitude of the \(v_n\) decrease for increasing \(n\) [5]. For odd \(n\), the \(v_n^a\) and \(v_n^t\) are not uniquely determined; instead the product \(v_n^t \cdot v_n^a\) is what is fit. This is because of \(v_n\) terms which are not a multiple of the event plane (in this analysis \(\Psi_2\)) would otherwise drop out of Eq. 5.4 due to destructive interference effects between them [15].

\(R_n\) are the reaction plane resolution terms (between 0 and 1) which are determined by
correlating event planes of different order. This term is fixed in the fit and therefore must be measured independently. The $\phi_s$ and $c$ terms in 5.3 are set based on the binning relative to the event plane which defines the relative orientation of the jet and the 2nd order event plane. In this analysis:

- In plane: $\phi_s = 0, c = \pi/6$
- Mid plane: $\phi_s = \pi/4, c = 3\pi/4, \pi/12$
- Out of plane: $\phi_s = \pi/2, c = \pi/6$

as shown in Figure 5.7.

This fit is performed simultaneously for the in plane, mid plane, and out of plane regions which are shown in Fig. 5.7. An example of this fit to jet hadron correlation data is show below in Fig. 5.8.

The blue band represents the RPF background to the black points which are the background dominated $\Delta \eta > 0.6$ region of the correlation function. Note that only the $\Delta \phi < \pi/2$ region is actually fit.

### 5.1.3 Fragmentation Function from Correlation Yields

An example of a background subtracted correlation calculated in 30-50 % central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is shown in Fig. 5.9.

Fig. 5.9 shows a distinctive near-side peak for $\Delta \phi = 0$, called the near-side, and a more spread out peak around $\Delta \phi = \pi$, called the away-side, for all reaction plane orientations. The correlations in figure 5.9 oscillate around a baseline of 0 for points in between the near-side and away-side peak - indicating the successful removal of the fluctuating background.

There are as many background subtracted correlations as the product of the number of $p_T^{jet}$ and $p_T^{assoc.}$ bins. Each $p_T^{jet}$ and $p_T^{assoc.}$ bin has two yields; $Y_{i,j}^{NS}$ (the near-side peak yield) and $Y_{i,j}^{AS}$ (the away-side peak yield). The $i^{th}$ index runs over all the $p_T^{assoc.}$ bins and the $j^{th}$ index runs over all the $p_T^{jet}$ bins. These yields are calculated with the following equations:
Figure 5.7: Illustration of the different reaction plane orientations; red is in plane, white is midplane, and blue is out of plane. Figure taken from Ref. [66].
Figure 5.8: Fit of Jet-Hadron Correlations taken from Run 1 30-50 % central $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb ALICE data to RPF for in plane, mid plane, out of plane, and all jets. $p_T^{assoc.} = 1.5 - 2.0$ GeV/c and $p_T^{jet} = 20 - 40$ GeV/c jets. Figure taken from [55].

Figure 5.9: Result of subtraction of RPF fit from Jet-Hadron Correlations taken from Run 1 30-50 % central Pb-Pb collisions $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb ALICE data to RPF for in plane, mid plane, out of plane, and all jets for $p_T^{assoc.} = 1.5 - 2.0$ GeV/c and $p_T^{jet} = 20 - 40$ GeV/c. Figure taken from [55].
\[ Y_{i,j}^{NS} = \iint_{NS} \frac{d^2 N^{bkgd,sub,i,j}(\Delta \phi, \Delta \eta)}{d \Delta \phi d \Delta \eta} d \Delta \phi d \Delta \eta \]  \hfill (5.5)

\[ Y_{i,j}^{AS} = \iint_{AS} \frac{d^2 N^{bkgd,sub,i,j}(\Delta \phi, \Delta \eta)}{d \Delta \phi d \Delta \eta} d \Delta \phi d \Delta \eta \]  \hfill (5.6)

where the \( Y_{i,j} \) are the yields for the \( i \)th \( p_T^{assoc} \) bin and the \( j \)th \( p_T^{jet} \) bin, the NS refers to the near-side peak area, the AS refers to the away-side peak, and the \( \frac{d^2 N^{signal}(\Delta \phi, \Delta \eta)}{d \Delta \phi d \Delta \eta} \) is the background subtracted, acceptance corrected correlation function. The details of this will be discussed in the following sections. The near-side area is defined by a cone centered at \( \Delta \phi = 0 \) and \( \Delta \eta = 0 \) with a radius equal to the jet resolution parameter input into the anti-\( k_T \) algorithm. This definition of the near-side area is motivated by a desire to directly compare to the anti-\( k_T \) jet finding algorithm which usually produces conical jets. The away-side area is defined by a rectangle with its shorter side in the range \( \pi/2 < \Delta \phi < \pi/2 \) and its longer side spanning the entire \( \Delta \eta \) range of the correlation function. The systematic errors arise from uncertainties in the fit parameters discussed in Section 5.1.2 as well as the overall background level uncertainty from the acceptance correction. The details of the calculation of this systematic error on the yields change in the data analysis and model feasibility study.

### 5.1.4 Unfolding Fragmentation Functions

The yields obtained after integrating the near-side and away-side peaks of the background subtracted correlation function are not corrected for the jet energy resolution, single track reconstruction efficiency or particle momentum smearing. The most prominent effect is the single track reconstruction efficiency. This is caused by detector effects in the tracking detectors that result in the inability to reconstruct every track that is present in the detector in a given collision. Figure 5.10 shows an example of a single track reconstruction efficiency for 0-10 % Pb-Pb collisions.

The primary effect of the loss of tracks/cluster inside the detector is on the jet energy/momentum. The net effect of the single track reconstruction efficiency will be to
Figure 5.10: Figure showing a single track reconstruction efficiency calculated from HIJING simulations anchored to the ALICE 2018 5.02 TeV 0-10 % central Pb-Pb dataset. The solid line is a parameterized fit done between 1 and 25 GeV in $p_T$. 
remove momentum from the jets clustered on the remaining tracks. In addition to the single track reconstruction efficiency, there is also particle momentum smearing which distorts the track/calorimeter cluster $p_T$. We assume a small effect on the order of 0.5 % in $p_x$ and $p_y$ and 0.1 % in $p_z$ - broadly consistent with known detector properties [35]. However, its presence does contribute to the overall smearing/distortion present in the final measurement.

These detector effects are corrected for by use of the unfolding [72]. Unfolding is a procedure used to correct smearing from instrumental precision in measurements. These detector effects result in migrations of jets or particles into the different bins (e.g. due to reconstructing a given particle at a lower energy) or outright reduction in the number of particles measured (e.g. due to not reconstructing a particle at all). This is written as:

$$\frac{d^2N_{\text{meas.}}}{dp_{T,i}^{\text{assoc.}}dp_{T,j}^{\text{jet}}} = \sum_{k,l} R_{ijkl} \ast \frac{d^2N_{\text{truth}}}{dp_{T,k}^{\text{assoc.}}dp_{T,l}^{\text{jet}}} \quad (5.7)$$

Where $\frac{d^2N_{\text{meas.}}}{dp_{T,i}^{\text{assoc.}}dp_{T,j}^{\text{jet}}}$ are the 2D matrices of measured yields (as in Eq. 5.5 or Eq. 5.6) in the $i^{\text{th}}$ $p_{T,i}^{\text{assoc.}}$ bin and the $j^{\text{th}}$ $p_{T,j}^{\text{jet}}$ bin, $\frac{d^2N_{\text{truth}}}{dp_{T,k}^{\text{assoc.}}dp_{T,l}^{\text{jet}}}$ is the true value in the $k^{\text{th}}$ $p_{T,k}^{\text{assoc.}}$ bin and the $l^{\text{th}}$ $p_{T,l}^{\text{jet}}$ bin, and $R_{ijkl}$ is the response matrix which quantifies the effect of the detector. The response matrix, $R$, is constructed using Monte Carlo models with detector simulations. The Monte Carlo realistically models the expected signal and the detector simulations model the expected detector performance in the the data run or sample. The Monte Carlo truth is matched to the Monte Carlo + detector measurement.

In principle, one could apply the inverse response matrix object, $R^{-1}$ to the measured yields, $\frac{d^2N_{\text{meas.}}}{dp_{T,i}^{\text{assoc.}}dp_{T,j}^{\text{jet}}}$, to obtain the true value. However, in practice this is not possible because the response matrix containing large non-diagonal terms and numerical fluctuations from the simulation. These effects result in large fluctuations when the matrix is inverted which introduce unacceptable artifacts into the truth spectrum. This is known as the inversion problem [71].

The well-known inversion problem is solved by using techniques such as Bayes’ Theorem.
and Single Value Decomposition. Bayes Theorem will be discussed in the context of our particular unfolding problem. The first step to the entire unfolding process is to fill the response matrix. In the feasibility model study, the Monte Carlo model chosen as the signal source is PYTHIA merged with TENNGEN for the soft, flow-correlated background. In the data analysis, the Monte Carlo model chosen for the signal is PYTHIA embedded into Pb-Pb collision data which are used for the background. Section 5.2 and Section 5.3 discuss the details of the response matrix filling in the model studies and data analysis respectively.

Within the Monte Carlo model, the application of the distortions creates two classes of yields; a “total truth”, \( \frac{d^2 N_{\text{tot.tru.}}}{dp_{T,k}^{\text{assoc.}} dp_{T,l}^{\text{jet.}}} \), which is untouched by detector effects and comes directly from signal (PYTHIA) and a “total measured”, \( \frac{d^2 N_{\text{tot.meas.}}}{dp_{T,i}^{\text{assoc.}} dp_{T,j}^{\text{jet.}}} \), which is signal + background after the application of detector effects. The \( p_{T}^{\text{jet}} \) is the transverse momentum of the jet (particles clustered together using the FASTJET anti-\( k_T \) algorithm) and \( p_{T}^{\text{assoc.}} \) is the transverse momentum of the constituent particles of the jet object. The filling of the response object is accomplished by matching the jet objects in the “total truth” set to the jet objects in the “total measured” set of the Monte Carlo. The jet matching procedure is slightly different for the model feasibility study and the data analysis. Once these matches have been found we now have two sub-sets of the Monte Carlo: “matched truth” and “matched measured”. The sub-sets are referred to as the matched truth, \( \frac{d^2 N_{\text{match.tru.}}}{dp_{T,i}^{\text{assoc.}} dp_{T,j}^{\text{jet.}}} \) and the matched measured, \( \frac{d^2 N_{\text{match.meas.}}}{dp_{T,k}^{\text{assoc.}} dp_{T,l}^{\text{jet.}}} \).

The response object, \( R_{ijkl} \), is filled from the matches. Note that this excludes true jets which were not matched to a reconstructed jet. Table 5.1 shows the axes of the response.

An example of a projection of the response matrix along the \( p_{T}^{\text{jet.truth}} \) and \( p_{T}^{\text{jet.meas.}} \) axes is shown in Fig. 5.11.

\(^1\)The response object is actually a multi-dimensional tensor, not a 2D matrix. Response matrix is the commonly used terminology regardless of the object’s dimensionality.
Table 5.1: Table showing the axes and the index of of the 4 dimensional response object, \( R \).

<table>
<thead>
<tr>
<th>Axis</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{T, \text{jet, truth}} )</td>
<td>( i^{th} )</td>
</tr>
<tr>
<td>( p_{T, \text{assoc., truth}} )</td>
<td>( j^{th} )</td>
</tr>
<tr>
<td>( p_{T, \text{jet, meas.}} )</td>
<td>( k^{th} )</td>
</tr>
<tr>
<td>( p_{T, \text{assoc., meas.}} )</td>
<td>( l^{th} )</td>
</tr>
</tbody>
</table>
Figure 5.11: Example of a projection of the response object along the jet $p_T$ axes (measured and truth). The projection is across the entire $p_T^{\text{assoc.truth}}$ and $p_T^{\text{assoc.meas.}}$ range.
The data can be unfolded after construction the response matrix using RooUnfold [10]. For both the model studies and data analysis, the iterative Bayesian unfolding method is used [33].

The unfolded spectrum \( \frac{d^2 N^{unfolded}}{dp_{T,i}^{jet}dp_{T,j}^{assoc.}} \) will only agree with the matched truth level \( \frac{d^2 N^{match.tru.}}{dp_{T,i}^{assoc.}dp_{T,j}^{jet}} \) because the information the response matrix uses is specified on the truth level and therefore affects the matches between the detector/measured level. The matched truth does not necessarily match the total truth because of matching inefficiencies. Not all signal+background jets will be matched to signal jets due jet-clustering effects (even in the absence of detector effects like single track reconstruction efficiencies). Thus, it is necessary to further correct the unfolded distribution of yields with a kinematic efficiency, defined as:

\[
\epsilon^{\text{kin.}}_{ij}(p_T^{jet},p_T^{assoc.}) = \frac{\frac{d^2 N^{match.tru.}}{dp_{T,i}^{jet}dp_{T,j}^{assoc.}}}{\frac{d^2 N^{tot.tru.}}{dp_{T,i}^{assoc.}dp_{T,j}^{jet}}} \] (5.8)

This kinematic efficiency, \( \epsilon^{\text{kin.}}_{ij}(p_T^{jet},p_T^{assoc.}) \), quantifies how many “misses” have occurred - that is, how many of the “total truth” jets failed to be matched to a ”measured” jet. Figure 5.12 shows values for this efficiency in a proton-proton toy model.

The efficiency is quite close to 1 (perfectly efficient) except at low \( p_T^{jet} \) and \( p_T^{assoc.} \) and high \( p_T^{jet} \). At low \( p_T^{jet} \) and low \( p_T^{assoc.} \) the single track reconstruction efficiency reduces the overall kinematic efficiency (with jet matching efficiencies also playing a role). At high \( p_T^{jet} \) low statistics are the main driver in the low kinematic efficiency. The application of the kinematic efficiency is as a divisor to the unfolded spectrum of yields

\[
\frac{d^2 N^{final}}{dp_{T,i}^{jet}dp_{T,j}^{assoc.}} = \frac{1}{\epsilon^{\text{kin.}}_{ij}(p_T^{jet},p_T^{assoc.})} \cdot \left[ R_{ijkl}^{-1} \frac{d^2 N^{tot.meas.}}{dp_{T,k}^{jet}dp_{T,l}^{assoc.}} \right] \] (5.9)

where \( \frac{d^2 N^{final}}{dp_{T,i}^{jet}dp_{T,j}^{assoc.}} \) is the final unfolded spectrum of yields (corrected for the “missing” fraction of truth jets not matched in the response matrix), \( \epsilon^{\text{kin.}}_{ij}(p_T^{jet},p_T^{assoc.}) \) is the kinematic efficiency, \( R_{ijkl}^{-1} \) represents the “inversion” of the response matrix (which is not strictly an...
Figure 5.12: 2D Kinematic Efficiency as a function of $p_T^{\text{jet}}$ and $p_T^{\text{assoc.}}$. Most of the inefficiency (lowest values) is at low $p_T^{\text{assoc.}}$ and low $p_T^{\text{jet}}$. This efficiency is calculated as in Equation 5.8.
inversion but accomplished by the previously mentioned Bayesian unfolding method), and 
\[ \frac{d^2 N^{\text{tot.meas.}}}{dp_{T,k}^{\text{jet}} dp_{T,l}^{\text{assoc.}}} \]
is the spectrum of yields from Section 5.1.3.

5.2 Methods for Feasibility Model Study

The goal of the feasibility study is to demonstrate that the method detailed in the previous sections will provide “closure” (successfully reconstruct a signal) in a quasi-realistic heavy ion environment. Fig. 5.13 shows schematically the goal of the model study: a recovery of a simulated proton-proton jet signal inside a realistic heavy ion background within a reasonable detector simulation.

The feasibility study methods follow the outline in Section 5.1. The following sections will discuss the details of the model study including the simulation packages used, the application of the acceptance correction, specific application of the RPF method, and the unfolding.

5.2.1 Simulation Packages

The simulation packages utilized in the analysis and simulation are PYTHIA [69] (to simulate proton-proton collisions) and TennGen [47] to simulate realistic distributions of heavy ion momentum, azimuth, and pseudorapidity at mid-rapidity.

PYTHIA

PYTHIA is a Monte-Carlo parton shower generator which can simulate the particles produced during proton-proton collisions at various center of mass energies. PYTHIA includes theory and models for various physics aspects including hard interactions (e.g. high energy parton scattering), soft interactions (e.g. gluon bremsstrahlung), parton distributions (e.g. in colliding protons), multiparton interactions, fragmentation (e.g. from the Lund String Model), and decay. PYTHIA has been tuned extensively to proton-proton collision data. Simulations of proton-proton events are therefore realistic for most observables. The Perugia 2011 tune is used for this analysis [70]. Section 3.3 discusses PYTHIA in more
Figure 5.13: Figure showing the schematic goal of the model feasibility study. A signal (PYTHIA simulations of proton-proton events) is embedded into a background (TennGen simulations of Pb-Pb events). Jet-hadron correlations are calculated from these combined events and the background subtraction method (RPF) is applied from which the correlation yields are then obtained. Next, the yields are unfolded using 2D unfolding. The result is compared to the signal, and if they agree “closure” is obtained and feasibility is demonstrated.
detail. In this simulation, PYTHIA is run at $\sqrt{s} = 2.76$ TeV with the Les Houches Accord Parton Density Function interface used as the parton distribution function input [43].

**TennGen**

TennGen [47] is a heavy-ion background generator. It uses fits to hadron momentum spectra in data, then fits to low momentum anisotropy coefficients as a function of hadron momentum in data, then finally uses the Fourier decomposition of hadron azimuth to construct a realistic $\phi$ distribution. Section 3.3.1 discusses the inner workings of TennGen in more detail. In this analysis, TennGen is run for 0 -5 % central collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the full $v_1 - v_5$ harmonics utilized. TennGen only throws $\pi^+/-/0, K^{+/-}, p, \bar{p}$.

**Embedding PYTHIA into TennGen**

In the model study a PYTHIA p-p event is generated with $\sqrt{s} = 2.76$ TeV. At detector level, final state reconstructed $\pi^{+/-/0}, K^{+/-}, K^0_s, p, \bar{p}$ are clustered into $R = 0.2$ jets with the anti-$k_T$ algorithm. If there are any reconstructed PYTHIA jets with $p_T > 10$ GeV, then the PYTHIA event is mixed into one TennGen event. The TennGen event is a pre-generated 0-5 % Pb-Pb event with all harmonics ($v_1 - v_5$). Then, the reconstructed TennGen particles and reconstructed PYTHIA particles are clustered with the anti-$k_T$ algorithm. This means that the set of PYTHIA + TennGen jets comes from a set of 1:1 PYTHIA + TennGen events.

**5.2.2 Acceptance Correction**

As described in Section 5.1.1, an acceptance correction is applied to the correlations calculated with PYTHIA only and PYTHIA + TennGen. In either case, the acceptance correction is the same. The mathematical form of the acceptance correction is:

$$a(\Delta \phi, \Delta \eta) = \begin{cases} 
(\frac{\Delta \eta}{1.6 - 0.2}) + \frac{1.6}{1.6 - 0.2}, & -1.6 < \Delta \eta \leq -0.2 \\
1.0, & -0.2 < \Delta \eta \leq 0.2 \\
(\frac{\Delta \eta}{0.2 - 1.6}) + \frac{-1.6}{0.2 - 1.6}, & 0.2 < \Delta \eta \leq 1.6 
\end{cases} \quad (5.10)$$
Fig. 5.5 displays this function. In Equation 5.10, the 0.2 comes from the jet resolution parameter used in the model study and the 1.6 comes from the limits of the correlation function (|\Delta \eta| < 1.6) as determined by the particle acceptance in the model studies (|\eta| < 0.9)).

### 5.2.3 Background Subtraction

Background subtraction for the p-p + Pb-Pb correlations is handled in the model study according to the description in Section 5.1.2. It is important to note that the correlation functions that are fit to determine the background are not normalized by the number of triggers. The normalization is done after the unfolding.

There are two stages in the model study. One stage is a simplified study with only p-p simulations. In this case, the background subtraction is a simple pedestal subtraction. This pedestal is assessed simply by averaging the background at large |\Delta \eta| < and subtracting the average value from the entire correlation function. Fig. 5.14 illustrates this process.

In the second stage, the PYTHIA p-p simulations are combined with TennGen Pb-Pb simulations according to the prescription in Section 5.2.1. In this case, the background subtraction algorithm for the correlations calculated in the p-p + Pb-Pb simulations is the RPF fit discussed earlier. Fig. 5.15 illustrates the process in the p-p + Pb-Pb model studies.

In the p-p + Pb-Pb model study, the RPF fit uses all 3 event plane orientations (In Plane: |
\phi_{jet} - \Psi_2| \leq \pi/6, Mid Plane: \pi/6 < |
\phi_{jet} - \Psi_2| \leq \pi/3, Out of Plane: \pi/3 < |
\phi_{jet} - \Psi_2| \leq \pi/2) to determine the correlation background in all 3 orientations + inclusive jets (jets with any orientation with respect to the second order event plane). The yields which are passed to the unfolding algorithm come only from the inclusive jets. The event plane orientation is necessary for the RPF algorithm.

### 5.2.4 Unfolding Fragmentation Functions

In both stages of the model study (p-p only, p-p + Pb-Pb), the un-normalized yields are unfolded using the Bayesian unfolding algorithm. While the near-side and away-side yields were considered for this study, only the near-side yields were unfolded.
Figure 5.14: Pedestal subtraction in model study. Solid correlation function is before the pedestal subtraction, dotted correlation function is after pedestal subtraction. The red shaded region indicates the near-side peak which is integrated to obtain the near-side yield.

Figure 5.15: RPF subtraction in model study. Solid correlation function is before the RPF subtraction, dotted correlation function is after RPF subtraction. The red shaded region indicates the near-side peak which is integrated to obtain the near-side yield.
The particle level and detector level prescriptions were briefly described in Section 5.2.1. Fig. 5.16 shows a visual depiction of the particle and detector level convention used in the model studies.

The response matrix in the model studies is filled by a unique method called the “area overlap”. After jet candidates are clustered and there exist a set of particle level jets (in both stages of the model study, this is PYTHIA only) and detector level jets (stage 1: reconstructed PYTHIA only jets, stage 2: reconstructed PYTHIA + TENNGEN jets) the jets must be matched to determine the response. A pair of particle and detector level jets is matched if their shared fraction of ghost particles are higher than any other pair. Ghost particles are very low momentum “fake” particles thrown into the anti-$k_T$ algorithm along with existing particles at detector and particle level. The ghost particles are so low-momentum they do not affect the jet momentum. They are distributed uniformly through the detector volume in each event which means that provided they are are dense enough, counting the ghost particles in a jet amounts to measuring it’s area. Thus the particle/detector level jet pair with the largest shared fraction of ghosts represents the largest area overlap. This matching technique is done to minimize kinematic biases.

After the response matrix is filled with one set of events and a separate set of events has been used to calculate the correlation function, the unfolding can take place. This unfolding is consistent with the general method described in Section 5.1.4. In the case of the p-p methods, the correlation yields were normalized after the unfolding. This was done by performing an additional unfolding on the $p_T^{jet}$ spectra to obtain the correct number of jets in each $p_T^{jet}$ bin. Many $p_T^{jet}$ bins were used in the model study but only 10-30 GeV/c is reported here.

5.3 Methods for Data Analysis

The data analysis utilizes the same method detailed in Section 5.1 but with some additional details. The acceptance correction is obtained is obtained using mixed-event techniques. The
Figure 5.16: Top: Particle level in model studies. Bottom: Detector level in model studies. Holes represent single track reconstruction efficiency. Spikes represent momentum smearing. The $K^0_{long}$ and $n,\pi$ have been completely removed at detector level.
RPF background subtraction technique is the same but with 1D integration used for the nearside and away-side peaks. Finally, the unfolding is done with a response matrix created using PYTHIA events embedded in Pb-Pb data rather than PYTHIA events embedded TennGen.

5.3.1 Data Selection

Event Selection

This analysis uses data from Pb-Pb collisions measured at the ALICE detector in the LHC in 2018. Specifically, this analysis uses LHC18pass3 (including LHC18q and LHC18r). The Appendix B.2 details the individual runs included in those LHC18q and LHC18r datasets. This analysis requires the use of high-quality tracks in order to confidently determine the correlation function. These high-quality tracks require a set of cuts to determine as well as a quantified efficiency and acceptance.

There are 3 sets of cuts applied to the data; 1) event/pileup cuts, 2) minimum bias cuts, 3) multiplicity/centrality cuts. These cuts are similar to those in [55, 40]

The following list of event cuts were applied:

- ≥ 1 contributing track to primary vertex
- |z_{\text{vertex}}| ≤ 10 cm of ALICE nominal interaction point
- primary vertex determined by the Silicon Pixel Detector and the primary vertex determined by the other detectors must agree within 0.2 mm
- primary vertex must be ≤ 10 \( \sigma \) of the SPD primary vertex and ≤ 20 \( \sigma \) of the overall tracking primary vertex. \( \sigma \) is the spatial resolution of each respective primary vertex reconstruction method
- The maximum SPD primary vertex resolution must be ≤ 2.5 mm if only the SPD can be used to reconstruct the primary vertex

The following is a list of the pileup cuts:
• Correlating the number of tracks found in all detectors with the number of tracks found only in the TPC

• Correlating the total number of tracks in the ITS + TPC with those ITS + TPC tracks that can be matched in the TOF

• Correlation between number of TPC clusters and sum of SDD+SSD clusters (2018 only)

The minimum bias trigger applies no trigger cuts (e.g. requiring a certain amount of energy deposited in a certain area in the EMAL) to the selected events. The multiplicity cuts select for the specified centrality (see Section 4.4). Figure 5.17 shows the effects of all the cuts on the data in the 0 - 10 % central data set. Figure 5.18 shows the effects of the cuts on the data in the 30 % - 50 % semi-central data set.

Track Selection

In addition to the event cuts, there are also cuts on the tracks used in this analysis. The following is a list of the track cuts:

• $|\eta| < 0.9$

• $p_T > 150$ MeV

• 70 space points used

• $\frac{\chi^2}{NDF} < 4.0$

• require SPD & ITS refit

There are also effects of a non-uniform track reconstruction efficiency in the TPC. This is due to a multitude of effects such as the presence of dead channels in the TPC, sector boundaries, mis-reconstruction of tracks, interactions with the detector material (e.g. TPC gas) that push tracks outside the TPC acceptance, and missing hits associated to a track. The net effect is that not all tracks that are present within a collision will be reconstructed. In
Figure 5.17: Event Selection from 0 - 10 % central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The black line (underneath the red line) shows the labeled cuts only. The red line shows the labeled cuts with the addition of the minimum bias trigger. The blue line shows the addition of the minimum bias trigger and the specified centrality selection. The x-axis shows the effect of each individual cut on the dataset statistics, except for the last bin which shows the effects of all the cuts.
Figure 5.18: Event Selection from 30% - 50% central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The black line (underneath the red line) shows the labeled cuts only. The red line shows the labeled cuts with the addition of the minimum bias trigger. The blue line shows the addition of the minimum bias trigger and the specified centrality selection. The x-axis shows the effect of each individual cut on the dataset statistics, except for the last bin which shows the effects of all the cuts.
general, tracks with low transverse momentum and large $|\eta|$ will have the smallest efficiencies. Figure 5.19 shows the single track reconstruction efficiency in 2 dimensions ($p_T$ and $\eta$) for the relevant range in this analysis.

The single track reconstruction efficiency is obtained using Monte Carlo physics simulations of HIJING anchored to LHC2018q. The production is LHC18l8b3 and ALICE detector simulations using GEANT4. The Monte Carlo is pre-generated and the output particles are propagated through the GEANT4 detector simulation. A match is made between the generated particles and the particles reconstructed is quantified after propagation through the detector simulation is made. Then, a ratio of $N_{\text{recon.matched/ogen.}} / N_{\text{gen.}}$ tracks is made as a function of pseudo-rapidity ($\eta$) and tranverse momentum ($p_T$) is made. Figures 5.19 and 5.20 show the single track reconstruction efficiencies obtained using the above method for the 0-10 % central and 30-50 % semi-central data set.

In order to smooth out the bin to bin variation in the single track reconstruction efficiency, a parameterized fit is used in this data analysis. This bin-to-bin variation is caused by fluctuations due to poor statistics at higher $p_T$ due to exponentially falling track spectrum. This fit makes the assumption that the efficiency is separable and therefore that the $p_T$ dependence and the $\eta$ dependence are independent of one another.

$$\epsilon(p_T, \eta) = \epsilon(p_T) \cdot \epsilon(\eta)$$

(5.11)

Then the parameterization for $p_T$ dependence is as follows:

$$\epsilon(p_T) = \begin{cases} p_0 + p_1 p_T + p_2 p_T^2 + p_3 p_T^3 + p_4 p_T^4 & p_T \leq 2.7 \\ p_5 + p_6 p_T + p_7 p_T^2 + p_8 p_T^3 + p_9 p_T^4 + p_{10} p_T^5 & 2.7 < p_T \leq 10 \\ p_5 + p_6 \cdot 10 + p_7 \cdot 10^2 + p_8 \cdot 10^3 + p_9 \cdot 10^4 p_T + p_{10} \cdot 10^5 & p_T > 10 \end{cases}$$

(5.12)

Where the low $p_T$ dependence ($p_T \leq 2.7$) and mid $p_T$ dependence ($2.7 < p_T \leq 10$) are $4^{th}$ and $5^{th}$ order polynomials in $p_T$ respectively. The high $p_T$ dependence is simply constant.
Figure 5.19: 2D single track reconstruction efficiency for 0 - 10 % central Pb-Pb events in the 2018q data set.
**Figure 5.20:** 2D single track reconstruction efficiency for 30 - 50 % semi-central Pb-Pb events in the 2018q data set.
defined by the mid $p_T$ dependence evaluated at $p_T = 10$ GeV.

The parameterization for the $\eta$ dependence is as follows:

$$
\epsilon(\eta) = \begin{cases} 
\frac{1}{p_{10}} \left( p_0 e^{-1.0 \cdot \left| \eta - 0.91 \right|} \right)^{p_2} + p_3 \eta & \eta \leq -0.1 \\
\frac{1}{p_{10}} \left( p_4 + p_5 p_T + p_6 p_T^2 \right) & -0.1 < \eta \leq 0.12 \\
\frac{1}{p_{10}} \left( p_7 e^{-1.0 \cdot \left| \eta + 0.91 \right|} \right)^{p_9} & \eta > 0.12
\end{cases}
$$

(5.13)

Where the low and high $\eta$ dependencies ($\eta \leq -0.1 \& \eta \geq 0.12$) are exponential parameterizations and the middle range is simply a 2$^{nd}$ order polynomial. The parameter, $p_{10}$ is a normalization parameter common to all $\eta$ ranges are discussed below.

Fits to these parameterizations are done using the ROOT fitting utility with MINOS error handling. A $\chi^2$ minimization technique is used. Before fitting, the 2D efficiency is projected along each axis as in Figure 5.21 and Figure 5.22.

Then, Eq. 5.12 is used to fit the $p_T$ projection and Eq. 5.13 without the normalization parameter, $p_{10}$ is fit to the $\eta$ projection. The normalization parameter $p_{10}$ is assessed with a simple scaling - it is the product of maximum efficiency of the $p_T$ projection and the maximum efficiency of the $\eta$ projection divided by the maximum efficiency of the 2D efficiency.

$$
p_{10} = \frac{\text{Max} (\epsilon (p_T)) \cdot \text{Max} (\epsilon (\eta))}{\text{Max} (\epsilon (p_T, \eta))}
$$

(5.14)

This accounts for the scaling which occurs when the 2D distribution is projected to either the $p_T$ or $\eta$ axes. Figures 5.23 and 5.24 show an example of the fits to the 1-D projections for the 0 - 10% centrality bin. Figures 5.25 and 5.26 show the residuals between the efficiency fits and simulations for the 0 - 10% and 30 - 50% centrality bins respectively. Differences between the simulation and fits average at 0 but are no more than 10% in the worst case. Appendix C.4 contains the results of the fit for the 30-50% central dataset.
Figure 5.21: 1D projection along the $p_T$ axis of the single track reconstruction efficiency for 0 - 10 % central events
Figure 5.22: 1D projection of the $\eta$ axis of the single track reconstruction efficiency for 0 - 10% semi-central events.
**Figure 5.23:** Fit to 1D projection of the $p_T$ axis of the single track reconstruction efficiency for 0 - 10% semi-central events using Equation 5.12.

**Figure 5.24:** Fit to 1D projection of the $\eta$ axis of the single track reconstruction efficiency for 0 - 10% semi-central events using Equation 5.13.
Figure 5.25: Residual of fit to the single track reconstruction efficiency for the 0-10 % centrality bin. Across the fit range, deviations of the efficiency simulation from the fit average at 0 and are no more than 6 %.

Figure 5.26: Residual of fit to the single track reconstruction efficiency for the 30-50 % centrality bin. Across the fit range, deviations of the efficiency simulation from the fit average at 0 and are no more than 10 %.
EMCAL cuts

The electromagnetic calorimeter (see Section 2.2.5) is also used for the data analysis. The EMCAL is used to obtain the neutral portion of the jet energy. This is done by obtaining EMCAL clusters using the v2 clusterizer (see Section 4.3) algorithm seeded with cells that have an energy > 300 MeV and requiring all cells contributing to a cluster to have at least 100 MeV of energy. The EMCAL analysis also requires a set of calibrations for the data that it collects. This is accomplished using the EMCAL Corrections Framework [12]. The inclusive list of cuts/calibrations used in this analysis are listed below.

- Cell Energy Calibration
- Temperature Calibration
- Bad Channel Correction
- Cell Time Calibration
- Cluster Exotics Correction
- Cluster Non Linearity Correction
- Cluster Hadronic Correction

Figure 5.27 shows an example of the effect of the bad channel map correction on the EMCAL spectra recorded in events with jets > 15 GeV. The EMCAL Bad Channel Map uses the Offline Analysis Database (OADB) files to determine the bad channels in the runs specified by the user. All of the bad channels are set to have an energy of 0 so they are not included in the cluster.

Jet Selection

This analysis uses full jets, or jets that include charged tracks from the ITS and TPC and neutral clusters from the EMCAL. Jets are reconstructed from these constituents (tracks and clusters) using the FastJet [24] 3.2.1 implementation of the anti-$k_T$ jet reconstruction.
Figure 5.27: Figure showing the effect of the bad channel map correction on the spectrum of EMCAL clusters in events with jets $> 15$ GeV in 2018qpass3 dataset.
algorithm with the $p_T$ recombination scheme. A jet resolution parameter of R = 0.2 is used. This analysis uses a constituent cut of $p_T^{ch.trk.}/E_{clus.} > 3$ GeV. This constituent cut is necessary to reduce the effect of the combinatorial background on the reconstruction of the jet axis [55] and was done in previous analyses using jet-hadron correlations. In addition, a leading track bias of $p_T^{lead.ch.trk.} > 5$ GeV is also applied to the jets to further insure the likelihood that jets reconstructed in this analysis originate from a hard parton scattering. Fig. 5.28 shows the spectrum of jets measured in 0-10 % and 30-50% central collisions for this analysis.

**Event Plane Determination**

The Event Plane is determined using the V0-A and V0-C detectors (see Section 2.2.2). The arbitrary ($n^{th}$) order event plane is calculated according to the following formula:

$$\Psi_n = \frac{1}{n} \arctan \left( \frac{\sum_i w_i \sin (n\phi_i)}{\sum_i w_i \cos (n\phi_i)} \right)$$

(5.15)

In this analysis, $n = 2$ (because correlations are calculated for the relative angle between the jet $\phi$ and 2$^{nd}$ order event plane. The weights, $w_i$, come from the V0-A and V0-C amplitudes after applying corrections/calibrations for gain equalization, detector alignment, and detector acceptance.

In addition to identifying the 2$^{nd}$ order event plane, it is also necessary to quantify how well that event plane is determine, i.e. the event plane resolution. This is important because the event plane resolution is directly input into the RPF Method (see Section 5.1.2). The 2$^{nd}$ order event plane resolution is determined by the 3 sub event technique [13].

**5.3.2 Acceptance Correction**

The acceptance correction is generally based on the method described earlier in Section 5.1.1 but with some key differences in its implementation in a data analysis. This data analysis uses the ALICE detector which in addition to having limited track acceptance in pseudo-rapidity, $\eta$, also has additional in-efficiencies due to sector boundaries, dead zones,
Figure 5.28: Jet spectra utilized in this analysis with the cluster/track and leading hadron biases listed on the plot. Jets found in 2018qpass3 dataset. The binning is reflective of the binning used in this analysis.
etc... (these affects are not present in the model study). So, to obtain the acceptance correction in the data analysis some additional considerations are require. This analysis uses a mixed-event technique in combination with normalization to obtain the acceptance correction. Mixed-events are composed of tracks chosen randomly from different events. These mixed-events are run with the following settings:

- All mixed-events with $p_T^{assoc.} > 2$ GeV are combined together
- Mixed-events for the three event plane orientations (in-plane, mid-plane, and out-of-plane) are combined together
- Number of tracks per mixed-event > 5000
- Number of tracks per mixed-event < 50000

The mixed-event correlations are binned with respect their $z_{vertex}$ orientation in bins of 2 cm: [-10, -8, -6, -4, -2, 0, 2, 4, 6, 8, 10]. The different $z_{vertex}$ bins are summed over and then normalized to unity at maximum efficiency such that the acceptance correction becomes

$$a(\Delta \phi, \Delta \eta) = a_0 \frac{d^2 N_{mixedpair}}{d\Delta \phi d\Delta \eta}$$  \hspace{1cm} (5.16)

where $a_0$ is the normalization factor. Because the same event correlations and mixed-event acceptance correction are summed over their $z_{vertex}$ orientations, a correlated scale systematic uncertainty is incurred. This will be discussed in a following section. Figure 5.29 shows an example of the mixed-event acceptance correction for the $p_T^{jet} = 20-40$ GeV and $p_T^{assoc.} = 0.5 - 1$ GeV bins in the 0-10 % 2018 5.02 TeV Pb-Pb dataset.

### 5.4 Jet Hadron Correlations

The un-corrected jet hadron correlation is obtained directly from the analysis code run on the ALICE Analysis train [78]. This is the correlation function divided by the single track reconstruction efficiency.
Figure 5.29: Example of mixed-event acceptance correction for $p_T^{jet} = 20-40$ GeV and $p_T^{assoc.} = 0.5 - 1$ GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.
\[
\frac{d^2 N^{\text{un-corrected}}}{d\Delta\phi d\Delta\eta} = \frac{d^2 N^{\text{raw}}}{d\Delta\phi d\Delta\eta} \ast \frac{1}{\epsilon(\Delta\phi, \Delta\eta)}
\]  

(5.17)

An example of the un-corrected correlation function for 20-40 GeV R = 0.2 in-plane jets and 0.5-1 GeV associated hadrons in the 2018 5.02 30-50 % central dataset is shown in Fig. 5.30. This un-corrected correlation function is divided by the acceptance correction as in Equation 5.1 to obtain the corrected correlation function which is shown for the 20-40 GeV R = 0.2 in-plane jets and 0.5-1 GeV associated hadrons in the 2018 5.02 30-50 % central dataset in Fig. 5.31.

5.4.1 Reaction Plane Fit Subtraction Method

After applying the acceptance correction to the correlation function, the background can be assessed and subtracted. As described in Section 5.1.2, the background is assessed using the RPF [66] method as in Equation 5.2. The background is assumed to be independent of \( \Delta\eta \). The free parameters in the RPF fit are the overall background level (B), the \( v_n \) coefficients for the trigger jet (\( v_n^t \)), and the \( v_n \) coefficients for the associated particles (\( v_n^a \)). In principle, one can fit to arbitrary order in \( v_n \) but in practice fitting is only done up to \( v_4 \) or \( v_5 \) at most. This is because the magnitude of the \( v_n \) decrease for increasing \( n \) [5]. For odd \( n \), the \( v_n^a \) and \( v_n^t \) are not uniquely determined; instead the product \( v_n^t \cdot v_n^a \) is what is fit. This is because terms \( v_n \) terms which are not a multiple of the event plane (in this analysis \( \Psi_2 \)) would otherwise drop out of Eq. 5.4 due to destructive interference effects between them [15].

\( R_n \) are the reaction plane resolution terms (between 0 and 1) which are determined by correlating the event planes with different. This correlation must be done before starting the fit process. The \( \phi_s \) and \( c \) terms in Equation 5.3 are set based on the binning which defines the relative orientation of the jet and the 2nd order event plane.

This fit is performed simultaneously for the in plane, mid plane, and out of plane regions which are shown in Fig. 5.32 shows an example of the fit to the background region for the \( p_T^{\text{jet}} = 20-40 \) GeV and \( p_T^{\text{assoc.}} = 0.5 - 1 \) GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.
Figure 5.30: Example of an un-corrected jet hadron correlation for $p_T^{jet} = 20-40$ GeV and $p_T^{assoc.} = 0.5 - 1$ GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.

Figure 5.31: Example of an acceptance corrected jet hadron correlation for $p_T^{jet} = 20-40$ GeV and $p_T^{assoc.} = 0.5 - 1$ GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.
Figure 5.32: Example of the RPF fit to the in-plane, mid-plane, and out of plane jet hadron correlations for $p_T^{jet} = 20-40$ GeV and $p_T^{assoc.} = 0.5 - 1$ GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset. Note that the fit only occurs on the near-side or $|\Delta \phi| < \pi/2$. Fit residuals to the entire $\Delta \phi$ region are shown in the bottom panel.
5.4.2 Yield Extraction and Yield Ratios

After using the RPF method to fit the background, the background is subtracted from the entire correlation function. The yields are assessed for the near-side and away-side peaks of the correlation function according to the following formula.

\[
Y_{i,j}^{N.S.,A.S.} = \sum_{N.S.,A.S} \frac{1}{N_{jet,j}} \frac{dN_{i,j}}{d\Delta\phi} - \int_{N.S.,A.S.} B^{i,j} d\Delta\phi
\]  

(5.18)

Where \(i\) and \(j\) are the \(i^{th}\) \(p_{T}^{assoc.}\) and \(j^{th}\) \(p_{T}^{jet}\) bin, N.S. and A.S. indicate the limits of the integration that define the near-side (\(\Delta\phi < \pi/2\)) and away-side (\(2\pi/3 < \Delta\phi < 4\pi/3\)) regions in \(\Delta\phi\). \(B^{i,j}\) is the RPF background assessed for the correlation in the \(i^{th}\) \(p_{T}^{assoc.}\) and \(j^{th}\) \(p_{T}^{jet}\) bin. This formula describes the assessed yield as the difference between the bin counting in the un-subtracted correlation function (the \(\sum_{N.S.,A.S.}\) term) and the integral of the of the RPF background. Figures 5.33 and 5.34 show the near-side and away-side yields obtained from the correlations calculated with 20-40 GeV jets in the 30-50 % central 5.02 TeV Pb-Pb dataset from 2018. The \(p_{T}^{assoc.}\) bins considered are [0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 10.0] (GeV/c). The yields are shown for all the different reaction plane orientations: inclusive jets, in-plane jets, mid-plane jets, and out-of-plane jets.

In addition to the yields, the yield ratios between the different RPF orientations are also considered. The yield ratios are considered relative to the in-plane orientation; mid-plane/in-plane and out-of-plane/in-plane. Figures 5.35, 5.36, 5.37, and 5.38 show the yield ratios for correlations calculated with \(p_{T}^{jet} = 20-40\) GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.

5.4.3 Systematic Error Analysis

There are 3 main sources of systematic uncertainty in this analysis; 1) an overall uncertainty in the correlation scale due to the single track reconstruction efficiency, 2) a correlated scale uncertainty due to the summation over the \(z_{vertex}\) bins in the acceptance correction, and 3) the background uncertainty due to the uncertainty in the determination of the background.
Figure 5.33: Near-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out-of-plane jet hadron correlations for $p_T^{\text{jet}} = 20-40$ GeV in the 30-50% 2018 5.02 TeV Pb-Pb dataset. Uncertainties are statistical, and systematic including a 4% scale uncertainty from the single track reconstruction efficiency.
Figure 5.34: Away-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for $p_T^{jet} = 20-40$ GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset. Uncertainties are statistical, and systematic including a 4 % scale uncertainty from the single track reconstruction efficiency.
Figure 5.35: Ratios of the near-side yield ratios of mid-plane to in-plane jet hadron correlations for $p_T^{jet} = 20-40$ GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.
Figure 5.36: Ratios of the near-side yield ratios of out-of-plane to in-plane jet hadron correlations for $p_T^{jet} = 20-40$ GeV in the 30-50% 2018 5.02 TeV Pb-Pb dataset.
Figure 5.37: Ratios of the away-side yield ratios of mid-plane to in-plane jet hadron correlations for $p_T^{jet} = 20$-40 GeV in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.
Figure 5.38: Ratios of the away-side yield ratios of out-of-plane to in-plane jet hadron correlations for $p_T^{\text{jet}} = 20-40$ GeV in the 30-50% 2018 5.02 TeV Pb-Pb dataset.
Uncertainty due to reconstruction efficiency

The uncertainty due to the determination of the single track reconstruction efficiency is 4 % as determined from the ITS-TPC matching efficiency [65].

Uncertainty due to mixed-event acceptance correction

The correlated scale uncertainty, as described in Section 5.3.2, results from the the mixed-event acceptance correction and its effect on the RPF. The overall background level is dependent on the $z_{\text{vertex}}$ measured in the event, particularly at large $\Delta \eta$ values. Since the RPF background is fit at large $\Delta \eta$ ($|\Delta \eta| > 0.6$), it will be affected. As mentioned in Section 5.3.2, the procedure for determining the mixed-event acceptance correction involves summing over all the $z_{\text{vertex}}$ orientations for the mixed and same events, then dividing by the acceptance correction:

$$
\frac{d^2 N_{\text{corrected,meth.1}}}{d\Delta \phi d\Delta \eta} = \frac{\sum_{z_{\text{vertex},i}} d^2 N_{\text{un-corrected},z_{\text{vertex},i}}}{\sum_{z_{\text{vertex},i}} a(\Delta \phi, \Delta \eta)^{z_{\text{vertex},i}}} \tag{5.19}
$$
Chapter 6

Results and Discussion

In this section, model studies for fragmentation functions are discussed and the correlation functions and jet constituent yields in $\sqrt{s_{NN}} = 5.02$ TeV are presented.

6.1 Fragmentation Function in Model Studies

The goal of the model studies is to demonstrate the feasibility of all steps of the analysis method (see Ch. 5). Feasibility is demonstrated when the simulated data at the “truth” or particle level fragmentation function agree with the reconstructed fragmentation function.

6.1.1 Proton-Proton Collisions

Fig. 6.1 shows the results of the model studies for the baseline case for proton-proton collisions at $\sqrt{s} = 2.76$ TeV. The Perugia 2011 tune was used for PYTHIA [70]. The pink points represent the “truth” level which is the fragmentation function calculated using the constituents of the truth-level jets. The blue points are calculated from the pedestal-subtracted jet-hadron correlations yields after unfolding to correct for momentum smearing and jet $p_T$ resolution due to neutral particles and single track reconstruction efficiency.

Figure 6.1 shows the unfolded jet-hadron correlation yields in pp collisions demonstrating closure (i.e. successfully reconstructs the signal). This can be seen by looking at the bottom panel with the ratio of the truth and unfolded points for each $p_T^{assoc.}$ bin. This ratio is
Figure 6.1: Comparison of truth level jet constituent momentum to reconstructed and unfolded level jet constituent momentum in $R = 0.2$ anti-$k_T$ 10-30 GeV jets in $\sqrt{s} = 2.76$ TeV PYTHIA proton-proton simulations. The pink points are the truth level and the blue points are the reconstructed, pedestal-subtracted, unfolding level.
in agreement with unity at all $p_T^{assoc.} > 4$ GeV. The discrepancy from unity for $p_T^{assoc.} < 4$ GeV is due to the fact that the blue points have the underlying event removed (from applying the pedestal subtraction to the jet-hadron correlation) while the truth level points do not. In proton-proton collisions there is still an underlying event consisting of soft particles uncorrelated in space. This would be largest at low $z$ or in the case or low $p_T^{assoc.}$. This difference would manifest itself in as an excess of particles inside the jet at low momentum as seen in Fig. 6.1.

### 6.1.2 Heavy Ion Collisions

Fig. 6.2 shows the results from simulations of Pb-Pb collisions, including heavy ion background from TennGen and proton proton signal from PYTHIA. The Perugia 2011 [70] tune was used for PYTHIA. The red points are calculated from the pedestal-subtracted jet-hadron correlation yields from jets clustered with reconstructed level pions, kaons, and protons after unfolding to correct for momentum smearing and jet $p_T$ resolution due to un-reconstructed neutral particles and single track reconstruction efficiency. The black points are calculated from the background subtracted jet-hadron correlation yields from jets clustered with reconstructed level pions, kaons, and protons after unfolding to correct for momentum smearing and jet $p_T$ resolution due to un-reconstructed neutral particles and single track reconstruction efficiency.

Fig. 6.2 shows that the jet constituent momentum for the proton-proton and heavy-ion agree well for higher momentum, roughly above 10 GeV. From 5 GeV to 10 GeV, the ratio of pp/pp + HI falls below unity systematically, maintaining a value from 0.9 to 1.0. Below 5 GeV, the ratio behaves erratically - decreasing to 0.8 in the 3-4 GeV bin and increasing to 1.35 in the 2-3 GeV. These deviations from unity by up to 40 % in the ratio represent a challenge to applying this method to data.

The “non-closure effect” in the heavy ion model study is most likely due to the fact that the correlation yields in proton-proton collisions and the correlation yields in the heavy ion collisions come from jets with differing $p_T^{constit.}$ thresholds. The proton-proton (red points)
Figure 6.2: Comparison of reconstructed level jet constituent momentum in PYTHIA proton-proton (red) to reconstructed jet constituent momentum in PYTHIA + TennGen simulations for $R = 0.2$ anti-$k_T$ 10-30 GeV jets (black).
results have a constituent cut of 150 MeV and the heavy ion results (black points) have a constituent cut of 3 GeV. The 3 GeV constituent cut is to suppress the contribution of combinatorial jets to the jet hadron correlations. In addition, a 3 GeV constituent cut also suppresses the fluctuations in the reconstructed jet axis position due to the presence of low momentum particles. Combinatorial jets and mis-reconstructed jet axes result in artifacts in the correlation function which would give unreliable results in the fitting process. However, this constituent cut is not necessary in the proton-proton studies as the background, while present (see Section 6.1.1) is not as significant.

The effect of the differing jet biases applied to jets in the proton-proton collisions and heavy-ion collisions is that the spectra of jet constituents is expected to be different. In principal, this could be addressed in several ways:

1. Apply the same $p_T^{constit.}$ threshold to the reconstructed jets in proton-proton and heavy ion model studies

2. Attempt to correct for the different thresholds with a different unfolding technique than the one used in this thesis

3. Apply an ad-hoc correction after the unfolding to bring the heavy ion collision results into agreement with the proton-proton results

The third way (applying an ad-hoc correction) might be the easiest but least reliable. A simple ad-hoc correction is not guaranteed to be robust in all situations - for example when this method is extended to higher jet momentum or tried on different centralities in TennGen. The first way (applying the same constituent threshold in both cases) is the second easiest and probably most honest “apples to apples” approach. The second way (changing the unfolding method in the heavy ion case) would be the most difficult. Considerable time and effort was spent on improving the unfolding method used in this analysis. The specific approach implemented used a “3 way unfolding” method which attempted to match a) PYTHIA truth level jets with no constituent threshold to b) PYTHIA reconstructed level jets with a 150 MeV threshold to c) PYTHIA + TennGen reconstructed level jets with
a 3 GeV threshold. The idea behind this approach was to fill a sparse multi-dimensional histogram with the matched $p_T^{\text{jet}}$ from constituents $> 3$ GeV in a) and c) and matched $p_T^{\text{constit.}}$ from a) and b). This is then used to create a response matrix for unfolding (see Section 5.2). This approach was thought to be the best way to alleviate the effects of the jet bias using the response matrix. However, upon analysis, some closure problems still persisted - indicating a need to understand this approach better. This approach, with some modifications, is the best way forward to refining the method for use in data.

### 6.2 Correlation Functions

This section discusses the correlation functions during the RPF fit, after background subtraction, extracted correlations yields and yield ratios and comparisons to JEWEL. For brevity only the correlations in the $1.5 < p_T^{\text{assoc.}} < 2.0$ GeV are displayed in this section. All of the RPF fits, background subtracted correlations, yields and yield ratios can be found in Appendix C.

#### 6.2.1 Reaction Plane Fits

The following figure shows the Reaction Plane Fits to the in, mid, and out of plane regions of the correlation functions measured with $R = 0.2$ anti-$k_T$ jets with a $p_T^{\text{constit.}}$ threshold of 3 GeV and a leading track bias of $p_T^{\text{lead.trk.}} > 5$ GeV. These correlations were calculated in Pb-Pb collisions measured in the ALICE detector in 2018. Figure 6.3 shows the RPF fit for $20 < p_T^{\text{jet}} < 40$ GeV and $1.5 < p_T^{\text{assoc.}} < 2.0$ GeV. The $\frac{\chi^2}{NDF}$ close to 1 and the small residual (bottom panel) across the entire $\Delta \phi$ domain show the success of the fit method for this $p_T^{\text{assoc.}}$ bin. Appendix C.3 contains the fit parameters for each $p_T^{\text{assoc.}}$ bin in the 30-50 % 2018 5.02 TeV Pb-Pb dataset.

#### 6.2.2 Background Subtracted Correlations

Figure 6.4 shows the RPF subtracted correlation functions for $20 < p_T^{\text{jet}} < 40$ GeV and $1.5 < p_T^{\text{assoc.}} < 2.0$ GeV.
Figure 6.3: Jet Hadron Correlations for 20 < \( p_T^{\text{jet}} \) < 40 GeV and 1.5 < \( p_T^{\text{assoc}} \) < 2.0 GeV in the 2018 ALICE 30-50 \% Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only (\( |\Delta \phi| < \frac{\pi}{3} \)). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
Figure 6.4: RPF subtracted jet-hadron correlations for $20 < p_T^{jet} < 40$ GeV and $1.5 < p_T^{assoc} < 2.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).
The subtracted correlation functions in this $p_T^{assoc.}$ qualitatively display what would be expected: a doubly peaked function ($\Delta \phi = 0, \pi$) with the near-side peak higher in magnitude. There are still some residual features in this subtraction which are particularly relevant in the mid-plane orientation. These features show the method does not perfectly remove all background - but this imperfection is reflected in the systematic uncertainties.

6.2.3 Yields

The yields are obtained from the background subtracted correlations like the one shown in 6.2.2. The yields, statistical errors, and systematic errors are listed in tables in Appendices C.2 (near-side) and C.2 (away-side).

The yields are evaluated on the near-side (\(|\Delta \phi| < \frac{\pi}{3}\)) and the away-side (\(\frac{2\pi}{3} < |\Delta \phi| < \frac{4\pi}{3}\)):

$$Y_{ij}^{NS} = \int_{-\pi/3}^{\pi/3} \frac{dN^{bgd.sub.,ij}}{d\Delta \phi} d\Delta \phi$$  \(6.1\)

$$Y_{ij}^{AS} = \int_{2\pi/3}^{4\pi/3} \frac{dN^{bgd.sub.,ij}}{d\Delta \phi} d\Delta \phi$$  \(6.2\)

where in Eq.’s 6.1 and 6.2 \(\frac{dN^{bgd.sub.,ij}}{d\Delta \phi}\) is the signal dominated region of the background subtracted correlation function in the $i^{th}$ $p_T^{assoc.}$ bin and the $j^{th}$ $p_T^{jet}$ bin. This is done for all the different event plane orientations (in, mid, and out, all) and the following $p_T^{assoc.}$ bins [0.5,1.5,2.0,3.0,4.0,5.0,6.0,10.0]. Figures 6.5 and 6.6 show the background subtracted correlation yield for every bin mentioned above.

The near-side and away-side yields decrease with increasing $p_T^{assoc.}$. Systematic uncertainties due to correlated uncertainty from determining background level is especially high for the mid-plane yields on the near-side and away-side. This is because the background is less well-constrained in the mid-plane bin due to the dominant $v_3$ term. In the in-plane and out-of-plane bins, the $v_2$ term dominates, which is well-constrained due to the dependence of the background itself on the 2nd order reaction plane.
Figure 6.5: near-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for $20 < p_{T,jet} < 40$ GeV/c in the 30-50 % 2018 5.02 TeV PbPb dataset. Uncertainties are statistical and systematic including a 4 % scale uncertainty from the single track reconstruction efficiency.
Figure 6.6: away-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for $20 < p_T^{\text{jet}} < 40 \text{ GeV}/c$ in the PbPb dataset. Uncertainties are statistical and systematic including a 4\% scale uncertainty from the single track reconstruction efficiency.
In addition to the relatively large uncertainty in the mid-plane points, there is also an interesting ordering of the event planes which changes from low to high $p_{T}^{\text{assoc.}}$. For the near-side yields the ordering for low $p_{T}^{\text{assoc.}}$ nominally goes as out-in-mid for points $< 2$ GeV. At low $p_{T}$ this ordering is not very significant with only around a 1σ different. Above 2 GeV the near-side yield ordering goes as in-mid-out tending toward smaller and smaller differences until all yields appear to be roughly equal in the highest $p_{T}^{\text{assoc.}}$ bin. At higher $p_{T}$, the ordering is more significant. The ordering is also similar for the away-side yields.

### 6.2.4 Yield Ratios and Comparisons to JEWEL

Figures 6.7 and 6.8 shows the near-side yield ratios for Mid/In and Out/In including comparisons to JEWEL. Figures 6.9 and 6.10 shows the away-side yield ratios for Mid/In and Out/In including comparisons to JEWEL. The statistical and systematic error ratios have all been separated to make their relative sizes more apparent.

The yield ratios obtained in this analysis were compared to calculations in JEWEL [77]. Two different scenarios were considered; simulations which excluded recoils and simulations which included recoils. JEWEL predicts very little event plane dependence - with the largest predictions on the order of 5 % depending on the $p_{T}^{\text{assoc.}}$. One reason for JEWEL’s lack of event plane dependence for this observable could be that within JEWEL, the jet-by-jet fluctuations are most likely the dominant effect washing out event plane dependence. For example, within JEWEL the di-jet asymmetry observable has been shown to be much more sensitive to these jet-by-jet fluctuations than event plane (or path length) dependence [58].

The results show that the near-side out/in and mid/in yield ratios are qualitatively comparable to the JEWEL simulations. The ratios on the away-side have less of an agreement with either of the JEWEL simulations.
Figure 6.7: Ratios of the near-side yield ratios of mid-plane to in-plane jet hadron correlations for $20 < p_T^{\text{jet}} < 40$ GeV in the 30-50% 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
Figure 6.8: Ratios of the near-side yield ratios of out-of-plane to in-plane jet hadron correlations for $20 < p_T^{\text{jet}} < 40$ GeV/$c$ in the 30-50% 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
Figure 6.9: Ratios of the away-side yield ratios of mid-plane to in-plane jet hadron correlations for $20 < p_T^{\text{jet}} < 40$ GeV in the 30-50 % 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
Figure 6.10: Ratios of the away-side yield ratios of out-of-plane to in-plane jet hadron correlations for $20 < p_T^{\text{jet}} < 40$ GeV in the 30-50 % 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
6.3 Connection to Previous Measurements

Previous measurements of the yields and yield ratios were made in the $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb data set [6, 55] and the $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb data set from the 2015 runs [40]. The measurements of the yields in the 2015 $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb data set were not published; however they are still considered as a comparison to this analysis.

6.3.1 Comparison to 2.76 TeV Yields

Figures 6.11 and 6.12 compare the In-Plane yields in this analysis to those in the 2.76 TeV [55]. Figures 6.13 and 6.14 compare the Mid-Plane yields in this analysis to those in the 2.76 TeV [55]. Figures 6.15 and 6.16 compare the Out-of-Plane yields in this analysis to those in the 2.76 TeV [55]. Figures 6.17 and 6.18 compare the Inclusive yields in this analysis to those in [55]. In all figures, the bottom panel is labeled Charles/Joel, where Charles is the author of this thesis (2018 5.02 TeV) and Joel is the author of [55] (2011 2.76 TeV).

The yields are compared in every $p_{T}^{\text{assoc.}}$ bin except for the $0.5 < p_{T}^{\text{assoc.}} < 1.0$ GeV which was not published in [6]. The in-plane yields show the same qualitative trend on the away-side but have some deviation from unity on the near-side (favoring the 5.02 TeV yields). This is the same trend for most of the $p_{T}^{\text{assoc.}}$ bins in the mid-plane, out-of-plane, and inclusive yields. The yields are systematically higher on the away-side for the 5.02 TeV dataset than the 2.76 TeV for most $p_{T}^{\text{assoc.}}$ bins. One reason for this could be a shift in the way the jet constituent momenta are distributed in jets in the 2.76 TeV and 5.02 TeV Pb-Pb collision energies. In particular, the details of the jet quenching for the away-side (which tends to select for jets with less surface bias) may differ depending on the collision energy. Another reason that the away side yields in the 2.76 TeV analysis might be lower is systematic error. The 2.76 TeV analysis allowed a non-zero $v_{1}^{f} \cdot v_{1}^{a}$ while this analysis fixed that parameter. The 2.76 TeV analysis also uses the same ALICE detector but with slightly different corrections/calibrations. A more careful comparison considering the systematic errors between the two analyses is warranted to further understand these differences.
Figure 6.11: Ratios of the in-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.12: Ratios of the in-plane away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.13: Ratios of the mid-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.14: Ratios of the mid-plane away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.15: Ratios of the out-of-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.16: Ratios of the out-of-plane away-side yields in 2.76 TeV \cite{55} and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.17: Ratios of the inclusive near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.18: Ratios of the inclusive away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
6.3.2 Comparison to 2.76 TeV Yield Ratios

Figures 6.19 and 6.20 compare the Out-of-Plane/In-Plane yield ratios in this analysis to those in the 2.76 TeV [55]. Figures 6.21 and 6.22 compare the Mid-Plane / In-Plane yield ratios in this analysis to those in the 2.76 TeV [55]. In all figures, the bottom panel is labeled Charles/Joel, where Charles is the author of this thesis (2018 5.02 TeV) and Joel is the author of [55] (2011 2.76 TeV).

The yield ratios are compared in every $p_{T\text{ass}}$ bin except for the $0.5 < p_{T\text{ass}} < 1.0$ GeV which was not published in [6]. The Out/In comparisons show that the overall trend in the data in this analysis and that in [55] agree. That is, an enhancement at low $p_{T\text{ass}}$, suppression at mid $p_{T\text{ass}}$ and unity at high $p_{T\text{ass}}$. The Mid/In comparisons show that the overall trend in the data in this analysis and that in [55] agree above 2-3 GeV/c. Below 2-3 GeV/c, [55] shows a diminished version of the same trend in the Out/In ratios: an enhancement at low $p_{T\text{ass}}$. This is not seen in the data in this analysis though a full consideration of systematic errors may show a more consistent picture.

6.3.3 Comparison to 2015 5.02 TeV Yields

Figures 6.23 and 6.24 compare the In-Plane yields in this analysis to those in the 2015 data [40]. Figures 6.25 and 6.26 compare the Mid-Plane yields in this analysis to those in the 2015 data [40]. Figures 6.27 and 6.28 compare the Out-of-Plane yields in this analysis to those in the 2015 data [40]. Figures 6.29 and 6.30 compare the Inclusive yields in this analysis to those in the 2015 data [40]. In all figures, the bottom panel is labeled Charles/Raymond, where Charles is the author of this thesis (2018 5.02 TeV) and Raymond is the author of [40] (2015 5.02 TeV).

The in-plane yields contain the same qualitative trend on the near-side and away-side. The mid-plane yields agree at high $p_{T\text{ass}}$ for the near-side and away-side but disagreement on the order of 30 - 60 % for low $p_{T\text{ass}}$, though the error bars are also large for these yields. The out-of-plane yields also follow this trend. The inclusive yields agree on the near-side to within 10-15 %. The inclusive yields on the away-side also show good agreement to within 20 %.
Figure 6.19: Ratios of the out-of-plane / in-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.20: Ratios of the out-of-plane / in-plane away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.21: Ratios of the mid-plane / in-plane near-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.22: Ratios of the mid-plane / in-plane away-side yields in 2.76 TeV [55] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.23: Ratios of the in-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.24: Ratios of the in-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.25: Ratios of the mid-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.26: Ratios of the mid-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.27: Ratios of the out-of-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.28: Ratios of the out-of-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.29: Ratios of the inclusive near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.30: Ratios of the inclusive away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
6.3.4 Comparison to 2015 5.02 TeV Yield Ratios

Figures 6.31 and 6.32 compare the Out-of-Plane/In-Plane yield ratios in this analysis to those in the 2015 5.02 TeV [40]. Figures 6.33 and 6.34 compare the Mid-Plane / In-Plane yield ratios in this analysis to those in the 5.02 TeV [40]. In all figures, the bottom panel is labeled Charles/Raymond, where Charles is the author of this thesis (2018 5.02 TeV) and Raymond is the author of [40] (2015 5.02 TeV).

The Out/In comparisons show a difference in the overall trend in the data in this analysis and that in [40], particularly at low \( p_{\text{assoc}} \). In this analysis an enhancement at low \( p_{\text{assoc}} \) was observed but the opposite was seen in [40]. The Mid/In ratio comparisons show the same disagreement at low \( p_{\text{assoc}} \) and the away-side Mid/In ratio is systematically lower in this analysis than in [40]. In general, the effects seen in [40] tend to be consistent with no event-plane dependence while those in this analysis strongly support an event plane dependence. A more careful consideration of systematic errors is needed when looking at the two analysis as both of them were performed at the same \( \sqrt{s_{NN}} \) with the same detector. The systematic errors between the two analyses may therefore be non-trivially correlated.

6.4 Conclusions

The methods applied in the model study show great promise toward application in data. The challenges encountered in the unfolding can be overcome with a relatively small amount of additional effort. This is important as a new method such as this would make it possible to reconstruct the fragmentation function in data down to 20 GeV (or possibly lower) jets. Developing this method for data will involve finishing the model studies (by following the guidance laid out in Section 6.1.2).

The yields analyzed in data show generally good agreement with past measurements at lower \( \sqrt{s_{NN}} \) and at the same energy (though systematic errors should be fully considered when making comparisons). One future improvement will be the correct use of Event Plane Calibration which used the 2015 calibration in this analysis. In addition, the yield ratios
Figure 6.31: Ratios of the out-of-plane / in-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.32: Ratios of the out-of-plane / in-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.33: Ratios of the mid-plane / in-plane near-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
Figure 6.34: Ratios of the mid-plane / in-plane away-side yields in 2015 5.02 TeV [40] and 2018 5.02 TeV Pb-Pb collisions. Only statistical errors are shown. The units of the x-axis are GeV/c.
presented in this analysis could be further improved by additionally correcting them for the event plane dependence as in [62]:

$$I_{RP}^{corrected} = \frac{(1 - R_{2,2}^{-1}) + (1 + R_{2,2}^{-1})I_{RP}^{meas.}}{(1 + R_{2,2}^{-1}) + (1 - R_{2,2}^{-1})I_{RP}^{meas.}}$$

(6.3)

where $I_{RP}$ is the ratio between the out/in yields and $R_{2,2}$ is the reaction plane resolution term.

One important physics conclusion from this analysis is that fluctuations in the background shape for a given centrality greatly impact the yield. This effect is averaged over in the data (which does not control for the background shape) but not in the JEWEL simulations. This could be one reason for the small event plane dependence predicted by JEWEL. However, despite these caveats one can infer something about the physics of the medium through the modification of the jet constituent yields. This is from looking at the ratios of out/in and mid/in which suggest an effect of larger amount of medium in the mid-plane to the out of plane. In addition, both of these ratios have larger modification for their away-side components also suggesting the effect of the surface bias. The results show a very clear and significant difference in the jet constituent yields for the different event plane orientations. The difference is most noticeable for the near and away-side jet constituent yields in the Out/In ratio (Figures 6.8 & 6.10). This conclusion is consistent with what was seen in previous constituent yield analyses [55] but allows for stronger conclusion because of the reduced statistical error bars. The difference in yields for the Out/In ratio suggests an event plane dependence. One interpretation for this event plane dependence would be path length dependence. Section 1.7 briefly discusses model predictions and experimental observations of path length dependence of the fragmentation function in $\gamma$ tagged jets. If the fragmentation function does indeed exhibit path length dependence it can be expected that the jet constituent yields would as well. It is tempting to conclude that the difference in event plane dependence of the jet constituent yields is indicative of a path length dependence. However, it is worth considering that other physical effects might also result in the same signature. Fluctuations in the event shape and jet-by-jet may also give rise to some kind of event plane dependence. Section 6.2.4 mentions that in JEWEL, fluctuations might wash
out path length dependence. In [58], the authors investigated the origins of di-jet asymmetry using JEWEL. They state, “...fluctuations, rather than systematic path-length differences, are most relevant in building up the asymmetry” and further describe path length dependence as a “sub-leading effect”. While the di-jet asymmetry is not the same observable as the jet constituent yields or the fragmentation function, this highlights the need to carefully consider the role of jet-by-jet fluctuations in jet observables. In JEWEL the jet-by-jet fluctuations clearly serve as a confounding physical effect that serves to wash out path length dependence. In the case of fragmentation function and jet constituent yields, more model studies should be undertaken in order to more carefully understand the role that jet-by-jet fluctuations play.

In addition to jet-by-jet fluctuations, fluctuations in the shape of the event may also play a role in the observed jet constituent yields in different event plane orientations. Within a given centrality class, the shape of the event may change from event to event. This is discussed in Chapter 1. Fluctuations in the event shape are caused by nucleon position fluctuations in the colliding nuclei as well as parton density profile fluctuations within the nucleons. There exist several observables which can quantify the shape of the event on an event-by-event basis [50]. In [50], the authors discuss the eccentricity vectors, $\varepsilon_n$, as being an interesting variable to study event shape fluctuations. This eccentricity is correlating with the reduced flow vector, $q_n$ which can be calculated from the measured $v_n$ and the transverse energy: $q_n = \frac{\sum E_T v_n^{meas}}{\sum E_T}$. There are several heavy ion analyses that have studied different observables in various $\varepsilon_2$ and $q_2$ bins [21, 7]. It would be interesting to repeat this analysis of jet constituent yields with additional measurements of $q_2$ or $\varepsilon_2$. One could then look at the event plane dependence of the jet constituent yields (or fragmentation functions) and see how it depends on $q_2$ or $\varepsilon_2$. This could better control for these event shape fluctuations and further help elucidate the role path length dependence plays. Even in the case the jet-by-jet and event shape fluctuations contribute to (or suppress) event plane dependencies in the jet constituent yields, path length dependence would still play some kind of role. The question is how do all of these effects combine to give rise to the observed difference in the yields for the different jet orientations relative to the second order event plane. All three effects can be expected to be present but the relative magnitude of each event is important. Detailed model
studies using simulations that capture multiple physics effects such as JETSCAPE [63] are necessary to determine the interplay between fluctuations and path length dependence. On the experimental side, this analysis makes a strong case that an event plane dependence is resolvable within systematic and statistical errors. This combined with the fact it shows roughly the same trends as a previous jet constituent yield analysis presents a strong case for the correlations and RPF method as a powerful tool to better understand jet structure.
Bibliography


213


[31] Cortese, P. et al. (2004). ALICE technical design report on forward detectors: FMD, T0 and V0. xiv, 39, 40


[34] Dellacasa, G. et al. (1999). ALICE technical design report of the inner tracking system (ITS). xvii, 91, 93, 101


215


[62] Oliver, M. (2022). $\pi^0$-hadron correlation in pb-pb collisions at $\sqrt{s_{NN}} = 5.02$ tev. unpublished analysis note. 208


217


Appendices
A Summary of Equations

A.1 Derivation of Rapidity and Pseudo-Rapidity

Writing a Lorentz Transformation applied to a four displacement, one obtains the following expression.

\[
\begin{pmatrix}
ct' \\
\rightarrow x'
\end{pmatrix} = \begin{pmatrix}
\gamma & -\gamma \beta \\
-\gamma \beta & \gamma
\end{pmatrix} \begin{pmatrix}
ct \\
\rightarrow x
\end{pmatrix} \quad (4)
\]

The Lorentz Transformation is the operator expressed by the matrix, the four displacement vector being transformed is to the right and the transformed four vector is on the left (denoted by the primed coordinates).

One can parameterize the elements in the matrix representing the Lorentz transform as hyperbolic trigonometric functions of the rapidity, y.

\[
\begin{pmatrix}
ct' \\
\rightarrow x'
\end{pmatrix} = \begin{pmatrix}
\cosh y & -\sinh y \\
-\sinh y & \cosh y
\end{pmatrix} \begin{pmatrix}
ct \\
\rightarrow x
\end{pmatrix} \quad (5)
\]

The rapidity is then related to \(\gamma\) and \(\beta\) through the following expression.

\[
cosh y = \gamma, \sinh y = \gamma \beta \quad (6)
\]

Using the fact that the \(\tanh x = \frac{\sinh x}{\cosh x}\), one can obtain an explicit relation between \(\beta\) \((v/c)\) and the rapidity, y.

\[
\tanh y = \frac{\sinh y}{\cosh y} = \beta, y = \tanh^{-1} \beta \quad (7)
\]

From special relativity, one can obtain the total energy, E (kinetic + rest-mass), and total momentum, p, of a particle. These expressions depend on the \(\gamma\) factor.

\[
E = \gamma m_0 c^2, p = \gamma m_0 v \quad (8)
\]
Taking the ratio of the total momentum to the total energy, one obtains the $\beta$ parameter as a function of the total energy and total momentum.

\[ \frac{p}{E} = \frac{\gamma m_0 v}{\gamma m_0 c^2} = \frac{v}{c} \cdot \frac{\beta}{c} \cdot \beta = \frac{p c}{E} \quad (9) \]

One can use this expression for the $\beta$ parameter to obtain the rapidity, $y$, as a function of the particles total momentum, $p$, and total energy, $E$.

\[ y = \tanh^{-1} \beta = \frac{1}{2} \ln \frac{1 + \beta}{1 - \beta} \]
\[ = \frac{1}{2} \ln \frac{1 + pc/E}{1 - pc/E} = \frac{1}{2} \ln \frac{E + pc}{E - pc} \quad (10) \]

A common convention is to consider a particle's rapidity relative to the beam line. This requires replacing the $p$ (total momentum) in the above expression with $p_L$ (longitudinal component of the particle’s momentum). $p_L$ is the projection of a particle’s 3 momentum onto the longitudinal axis. In experiment, the longitudinal axis is the axis of the beam line (considering a coordinate system centered in the middle of the detector) and is also designated as the $z$-axis.

\[ y = \frac{1}{2} \ln \frac{E + p_L c}{E - p_L c} \quad (11) \]

For the pseudo-rapidity, one considers the case of highly relativistic particles. In this case, the magnitude of the particle’s momentum is much greater than the particle’s mass.

\[ pc \gg m_0 c^2, E \sim |p| \quad (12) \]

In this case, the total Energy of the particle is approximately the magnitude of its 3 momentum. Replacing $E$ in Expression 8 with $-p-$ (to explicitly differentiate the total magnitude of the particles 3 momentum from the projection of its 3 momentum on the longitudinal axis), one obtains the expression below for the pseudo-rapidity $\eta$. 

222
\[ \eta = \frac{1}{2} \ln \left| \frac{p + p_L c}{p - p_L c} \right| \]  

(13)

Pseudo-rapidity, \( \eta \) is often preferable to the rapidity because one can define the pseudo-rapidity without measuring the particle’s mass.

One benefit of using rapidity and pseudo-rapidity coordinates is that rapidities in special relativity are additive while velocities are not. The special-relativistic velocity addition formula is in the expression below.

\[ v_{\text{tot.}} = \frac{v_1 + v_2}{1 + \frac{v_1 \cdot v_2}{c^2}} \]  

(14)

Expression 11 assumes that one can define an inertial reference frame (\( \alpha \)). Another inertial reference frame (1) is moving relative to the \( \alpha \) at a velocity defined by \( \vec{v}_1 \). A third inertial reference frame (2) is moving relative to (1) at a velocity defined by \( \vec{v}_2 \). An observer co-moving with the reference frame \( \alpha \) will measure the velocity of (2) as \( v_{\text{tot.}} \). \( v_{\text{tot.}} \) can be calculated from \( \vec{v}_1 \) and \( \vec{v}_2 \) using the expression above.

If frames (1) and (2) are moving co-linearly, the the above expression can be simplified to the following (applying the definition of the \( \beta \) parameter, \( \beta = \frac{v}{c} \)):

\[ |v_{\text{tot.}}| = |v_1| + |v_2| \cdot \frac{\beta_{\text{tot.}} \cdot c}{1 + \frac{|v_1| \cdot |v_2|}{c^2}} = \frac{\beta_1 \cdot c + \beta_2 \cdot c}{1 + \beta_1 \cdot \beta_2} \]  

(15)

Multiplying both sides of the equation by \( c \), one obtains:

\[ \beta_{\text{tot.}} = \frac{\beta_1 + \beta_2}{1 + \beta_1 \cdot \beta_2} \]  

(16)
Applying Equation 4 one obtains:

\[
\tanh y_{\text{tot.}} = \frac{\tanh y_1 + \tanh y_2}{1 + \tanh y_1 \cdot \tanh y_2}
\]  \hspace{1cm} (17)

The above expression can be simplified using the hyperbolic-trigonometric identity:

\[
\tanh x + y = \frac{\tanh x + \tanh y}{1 + \tanh x \tanh y}.
\]

\[
\tanh y_{\text{tot.}} = \tanh y_1 + y_2 = \frac{\tanh y_1 + \tanh y_2}{1 + \tanh y_1 \cdot \tanh y_2}
\]  \hspace{1cm} (18)

Requiring that the arguments of the tanh functions be equal we can obtain the additive property of rapidities. This property also holds for pseudo-rapidities.

\[
y_{\text{tot.}} = y_1 + y_2, \eta_{\text{tot.}} = \eta_1 + \eta_2
\]  \hspace{1cm} (19)
# B Acronym Legend and List of Runs

## B.1 Table of Acronyms/Abbreviations/Symbols

<table>
<thead>
<tr>
<th>Acronym/Abbreviation/Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>A Large Ion Collision Experiment</td>
</tr>
<tr>
<td>ATLAS</td>
<td>A Toroidal LHC Apparatus</td>
</tr>
<tr>
<td>Au-Au</td>
<td>Gold-Gold</td>
</tr>
<tr>
<td>BGBW</td>
<td>Boltzmann-Gibbs Blast Wave</td>
</tr>
<tr>
<td>CERN</td>
<td>Conseil Europeen pour la Recherche Nucleaire</td>
</tr>
<tr>
<td>CMS</td>
<td>Compact Muon Solenoid</td>
</tr>
<tr>
<td>EMCAL</td>
<td>Electromagnetic Calorimeter</td>
</tr>
<tr>
<td>eV</td>
<td>electron-Volt</td>
</tr>
<tr>
<td>FWD</td>
<td>Forward Detectors</td>
</tr>
<tr>
<td>GEM</td>
<td>Gaseous Electron Multiplication</td>
</tr>
<tr>
<td>HIJING</td>
<td>Heavy Ion Jet Interaction Generator</td>
</tr>
<tr>
<td>IROC</td>
<td>Inner Read Out Chamber</td>
</tr>
<tr>
<td>ITS</td>
<td>Inner Tracking System</td>
</tr>
<tr>
<td>LHC</td>
<td>Large Hadron Collider</td>
</tr>
<tr>
<td>LHCb</td>
<td>Large Hadron Collider beauty experiment</td>
</tr>
<tr>
<td>MWPC</td>
<td>Multi Wire Proportional Chamber</td>
</tr>
<tr>
<td>(N_{\text{coll.}})</td>
<td>Number of Binary Collisions</td>
</tr>
<tr>
<td>(N_{\text{part.}})</td>
<td>Number of Participants</td>
</tr>
<tr>
<td>OROC</td>
<td>Outer Read Out chamber</td>
</tr>
<tr>
<td>PDF</td>
<td>Parton Distribution Function</td>
</tr>
<tr>
<td>p-p</td>
<td>Proton-Proton</td>
</tr>
<tr>
<td>Pb-Pb</td>
<td>Lead-Lead</td>
</tr>
<tr>
<td>(p_T)</td>
<td>Transverse Momentum</td>
</tr>
<tr>
<td>QCD</td>
<td>Quantum Chromodynamics</td>
</tr>
</tbody>
</table>
### Table 1 Continued: Acronyms/Abbreviations/Symbols

<table>
<thead>
<tr>
<th>Acronym/Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGP</td>
<td>Quark-Gluon-Plasma</td>
</tr>
<tr>
<td>RPF</td>
<td>Reaction Plane Fit</td>
</tr>
<tr>
<td>SDD</td>
<td>Silicon Drift Detector</td>
</tr>
<tr>
<td>SPD</td>
<td>Silicon Pixel Detector</td>
</tr>
<tr>
<td>SSD</td>
<td>Silicon Strip Detector</td>
</tr>
<tr>
<td>TPC</td>
<td>Time Projection Chamber</td>
</tr>
<tr>
<td>UE</td>
<td>Underlying Event</td>
</tr>
<tr>
<td>$v_n$</td>
<td>$n^{th}$ order azimuthal anisotropy coefficient</td>
</tr>
<tr>
<td>$y$</td>
<td>Rapidity</td>
</tr>
<tr>
<td>$z$</td>
<td>Jet momentum fraction</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Polar Angle</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Pseudo-Rapidity</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Azimuthal Angle</td>
</tr>
<tr>
<td>$\Psi_{RP,n}$</td>
<td>$n^{th}$ order Reaction Plane</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Lorentz factor, $\gamma = \frac{1}{\sqrt{1 - (\frac{v}{c})^2}}$</td>
</tr>
</tbody>
</table>


B.2 List of Runs used for Data Analysis

LHC18qpass3: 296623, 296622, 296621, 296619, 296618, 296616, 296615, 296594, 296553, 296552, 296551, 296550, 296548, 296547, 296516, 296512, 296511, 296509, 296472, 296424, 296423, 296420, 296419, 296415, 296383, 296381, 296379, 296376, 296375, 296312, 296309, 296307, 296303, 296280, 296279, 296270, 296247, 296246, 296243, 296242, 296241, 296240, 296198, 296197, 296196, 296195, 296192, 296143, 296133, 296132, 296123, 296074, 296068, 296066, 296065, 296063, 296062, 296060, 296016, 295942, 295941, 295937, 295936, 295913, 295909, 295908, 295881, 295861, 295860, 295859, 295856, 295855, 295854, 295853, 295831, 295829, 295825, 295822, 295819, 295818, 295816, 295791, 295788, 295786, 295763, 295762, 295759, 295758, 295755, 295754, 295725, 295723, 295721, 295718, 295717, 295714, 295675, 295671, 295668, 295667, 295666, 295665, 295615, 295612, 295611, 295610, 295589, 295588, 295587, 295585
C Data

C.1 Data Plots

RPF Fits to Data

Figure 35: Jet Hadron Correlations for $20 < p_T^{\text{jet}} < 40$ GeV and $0.5 < p_T^{\text{assoc.}} < 1$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
Figure 36: Jet Hadron Correlations for $20 < p_T^{jet} < 40$ GeV and $1.0 < p_T^{assoc.} < 1.5$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta\phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
Figure 37: Jet Hadron Correlations for $20 < p_T^{jet} < 40 \text{ GeV}$ and $1.5 < p_T^{assoc} < 2.0 \text{ GeV}$ in the 2018 ALICE 30-50% Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
Figure 38: Jet Hadron Correlations for $20 < p_T^{jet} < 40$ GeV and $2.0 < p_T^{assoc} < 3.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
Figure 39: Jet Hadron Correlations for $20 < P_T^{jet} < 40$ GeV and $3.0 < P_T^{assoc} < 4.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
Figure 40: Jet Hadron Correlations for $20 < p_T^{\text{jet}} < 40$ GeV and $4.0 < p_T^{\text{assoc.}} < 5.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta\phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
Figure 41: Jet Hadron Correlations for $20 < p_{T}^{\text{jet}} < 40$ GeV and $5.0 < p_{T}^{\text{assoc.}} < 6.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
**Figure 42:** Jet Hadron Correlations for $20 < p_T^{\text{jet}} < 40$ GeV and $6.0 < p_T^{\text{assoc.}} < 10.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. The fit is performed in the background dominated region on the near-side only ($|\Delta \phi| < \frac{\pi}{3}$). The bottom panel shows the ratio of the residual of the fit and the data to the fit.
RPF Subtracted Correlations

**Figure 43:** RPF subtracted Jet Hadron Correlations for $20 < p_{T}^{jet} < 40$ GeV and $0.5 < p_{T}^{assoc} < 1.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ( $|\Delta \eta| < 0.6$ ).
Figure 44: RPF subtracted Jet Hadron Correlations for \( 20 < p_T^{\text{jet}} < 40 \) GeV and \( 1.0 < p_T^{\text{assoc}} < 1.5 \) GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region (\( |\Delta \eta| < 0.6 \)).
Figure 45: RPF subtracted Jet Hadron Correlations for $20 < p_T^{jet} < 40$ GeV and $1.5 < p_T^{assoc} < 2.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ( $|\Delta \eta| < 0.6$ ).
Figure 46: RPF subtracted Jet Hadron Correlations for $20 < p_T^{jet} < 40$ GeV and $2.0 < p_T^{assoc} < 3.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ( $|\Delta\eta| < 0.6$ ).
Figure 47: RPF subtracted Jet Hadron Correlations for $20 < p_T^{jet} < 40$ GeV and $3.0 < p_T^{assoc} < 4.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).

---

240
Figure 48: RPF subtracted Jet Hadron Correlations for $20 < p_T^{jet} < 40$ GeV and $4.0 < p_T^{assoc} < 5.0$ GeV in the 2018 ALICE 30-50% Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).
Figure 49: RPF subtracted Jet Hadron Correlations for $20 < p_T^{\text{jet}} < 40$ GeV and $5.0 < p_T^{\text{assoc}} < 6.0$ GeV in the 2018 ALICE 30-50 % Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta\eta| < 0.6$).
Figure 50: RPF subtracted Jet Hadron Correlations for $20 < p_T^{\text{jet}} < 40 \text{ GeV}$ and $6.0 < p_T^{\text{assoc}} < 10.0 \text{ GeV}$ in the 2018 ALICE 30-50% Pb-Pb collision data. Blue curve represents the signal dominated region ($|\Delta \eta| < 0.6$).
Yields

Figure 51: Near-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for $20 < p_{T}^{\text{jet}} < 40$ GeV in the 30-50 % 2018 5.02 TeV PbPb dataset. Uncertainties are statistical and systematic including a 4 % scale uncertainty from the single track reconstruction efficiency.
Figure 52: Away-side yields of the RPF subtracted correlations for inclusive in-plane, mid-plane, and out of plane jet hadron correlations for $20 < p_{T,\text{jet}} < 40$ GeV in the 30-50% 2018 5.02 TeV PbPb dataset. Uncertainties are statistical and systematic including a 4% scale uncertainty from the single track reconstruction efficiency.
Yield Ratios

Figure 53: Ratios of the near-side yield ratios of mid-plane to in-plane jet hadron correlations for $20 < p_T^{jet} < 40$ GeV in the 30-50% 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
Figure 54: Ratios of the near-side yield ratios of out-of-plane to in-plane jet hadron correlations for $20 < p_T^{\text{jet}} < 40$ GeV in the 30-50% 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
**Figure 55:** Ratios of the away-side yield ratios of mid-plane to in-plane jet hadron correlations for $20 < p_T^{\text{jet}} < 40$ GeV in the 30-50% 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
Figure 56: Ratios of the away-side yield ratios of out-of-plane to in-plane jet hadron correlations for $20 < p_T^{\text{jet}} < 40$ GeV/c in the 30-50% 2018 5.02 TeV PbPb dataset. Only the correlated scale uncertainty and statistical uncertainties remain.
C.2 Data Tables

Near-Side Yields and Errors

### Table 2: In Plane Near Side Yields: $p_T^{jet} = 20-40$ GeV

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 1</td>
<td>2.81</td>
<td>0.22</td>
<td>0.43</td>
<td>0.15</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>1.76</td>
<td>0.14</td>
<td>0.084</td>
<td>0.092</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>1.28</td>
<td>0.085</td>
<td>0.064</td>
<td>0.056</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.74</td>
<td>0.033</td>
<td>0.013</td>
<td>0.021</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.58</td>
<td>0.017</td>
<td>0.003</td>
<td>0.008</td>
</tr>
<tr>
<td>4 - 5</td>
<td>0.41</td>
<td>0.011</td>
<td>0.001</td>
<td>0.004</td>
</tr>
<tr>
<td>5 - 6</td>
<td>0.34</td>
<td>0.009</td>
<td>2.11e-05</td>
<td>0.003</td>
</tr>
<tr>
<td>6 - 10</td>
<td>0.19</td>
<td>0.003</td>
<td>3.34e-05</td>
<td>6.78e-04</td>
</tr>
</tbody>
</table>

### Table 3: Mid Plane Near Side Yields: $p_T^{jet} = 20-40$ GeV

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 1</td>
<td>1.96</td>
<td>0.22</td>
<td>0.54</td>
<td>0.15</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>1.45</td>
<td>0.14</td>
<td>0.29</td>
<td>0.092</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>1.12</td>
<td>0.085</td>
<td>0.11</td>
<td>0.057</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.66</td>
<td>0.033</td>
<td>0.036</td>
<td>0.021</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.51</td>
<td>0.017</td>
<td>0.007</td>
<td>0.008</td>
</tr>
<tr>
<td>4 - 5</td>
<td>0.38</td>
<td>0.011</td>
<td>0.0003</td>
<td>0.002</td>
</tr>
<tr>
<td>5 - 6</td>
<td>0.34</td>
<td>0.010</td>
<td>0.0002</td>
<td>0.002</td>
</tr>
<tr>
<td>6 - 10</td>
<td>0.19</td>
<td>0.003</td>
<td>1.55e-05</td>
<td>0.0005</td>
</tr>
<tr>
<td>------------</td>
<td>-------------------------------</td>
<td>------------</td>
<td>-----------------</td>
<td>----------</td>
</tr>
<tr>
<td>0.5 - 1</td>
<td>3.46</td>
<td>0.23</td>
<td>0.072</td>
<td>0.14</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>2.38</td>
<td>0.14</td>
<td>0.014</td>
<td>0.084</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>1.67</td>
<td>0.086</td>
<td>0.005</td>
<td>0.05</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.66</td>
<td>0.033</td>
<td>0.019</td>
<td>0.018</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.53</td>
<td>0.018</td>
<td>0.0005</td>
<td>0.008</td>
</tr>
<tr>
<td>4 - 5</td>
<td>0.36</td>
<td>0.012</td>
<td>0.001</td>
<td>0.004</td>
</tr>
<tr>
<td>5 - 6</td>
<td>0.33</td>
<td>0.010</td>
<td>2.61e-05</td>
<td>0.003</td>
</tr>
<tr>
<td>6 - 10</td>
<td>0.19</td>
<td>0.004</td>
<td>6.24e-05</td>
<td>0.001</td>
</tr>
</tbody>
</table>

**Table 5: Inclusive Near Side Yields: $p_T^{jet} = 20-40$ GeV**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 1</td>
<td>2.72</td>
<td>0.13</td>
<td>0.006</td>
<td>0.09</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>1.84</td>
<td>0.081</td>
<td>0.072</td>
<td>0.054</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>1.34</td>
<td>0.051</td>
<td>0.016</td>
<td>0.033</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.69</td>
<td>0.020</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.54</td>
<td>0.010</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>4 - 5</td>
<td>0.38</td>
<td>0.007</td>
<td>5.88e-05</td>
<td>0.002</td>
</tr>
<tr>
<td>5 - 6</td>
<td>0.34</td>
<td>0.006</td>
<td>5.85e-05</td>
<td>0.002</td>
</tr>
<tr>
<td>6 - 10</td>
<td>0.19</td>
<td>0.002</td>
<td>3.15e-06</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
Away-Side Yields and Errors

### Table 6: In Plane Away Side Yields: $p_T^{jet} = 20-40$ GeV

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 1</td>
<td>2.38</td>
<td>0.22</td>
<td>0.43</td>
<td>0.15</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>0.87</td>
<td>0.13</td>
<td>0.084</td>
<td>0.095</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>0.63</td>
<td>0.08</td>
<td>0.064</td>
<td>0.058</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.29</td>
<td>0.031</td>
<td>0.013</td>
<td>0.022</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.12</td>
<td>0.014</td>
<td>0.003</td>
<td>0.009</td>
</tr>
<tr>
<td>4 - 5</td>
<td>0.069</td>
<td>0.007</td>
<td>0.001</td>
<td>0.004</td>
</tr>
<tr>
<td>5 - 6</td>
<td>0.075</td>
<td>0.005</td>
<td>2.11e-05</td>
<td>0.003</td>
</tr>
<tr>
<td>6 - 10</td>
<td>0.024</td>
<td>0.001</td>
<td>3.33e-05</td>
<td>6.74e-04</td>
</tr>
</tbody>
</table>

### Table 7: Mid Plane Away Side Yields: $p_T^{jet} = 20-40$ GeV

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 1</td>
<td>1.31</td>
<td>0.22</td>
<td>0.54</td>
<td>0.15</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>0.61</td>
<td>0.13</td>
<td>0.29</td>
<td>0.092</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>0.51</td>
<td>0.083</td>
<td>0.11</td>
<td>0.057</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.13</td>
<td>0.031</td>
<td>0.036</td>
<td>0.022</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.10</td>
<td>0.014</td>
<td>0.007</td>
<td>0.008</td>
</tr>
<tr>
<td>4 - 5</td>
<td>0.05</td>
<td>0.007</td>
<td>0.0003</td>
<td>0.003</td>
</tr>
<tr>
<td>5 - 6</td>
<td>0.071</td>
<td>0.005</td>
<td>0.0002</td>
<td>0.002</td>
</tr>
<tr>
<td>6 - 10</td>
<td>0.024</td>
<td>0.001</td>
<td>1.55e-05</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
### Table 8: Out of Plane Away Side Yields: $p_T^{jet} = 20-40$ GeV

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 1</td>
<td>2.63</td>
<td>0.23</td>
<td>0.072</td>
<td>0.14</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>1.35</td>
<td>0.13</td>
<td>0.014</td>
<td>0.083</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>0.80</td>
<td>0.082</td>
<td>0.005</td>
<td>0.05</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.15</td>
<td>0.031</td>
<td>0.018</td>
<td>0.019</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.094</td>
<td>0.014</td>
<td>0.0005</td>
<td>0.008</td>
</tr>
<tr>
<td>4 - 5</td>
<td>0.052</td>
<td>0.007</td>
<td>0.001</td>
<td>0.004</td>
</tr>
<tr>
<td>5 - 6</td>
<td>0.070</td>
<td>0.005</td>
<td>2.61e-05</td>
<td>0.004</td>
</tr>
<tr>
<td>6 - 10</td>
<td>0.022</td>
<td>0.001</td>
<td>6.24e-05</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

### Table 9: Inclusive Away Side Yields: $p_T^{jet} = 20-40$ GeV

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 1</td>
<td>2.10</td>
<td>0.13</td>
<td>0.006</td>
<td>0.091</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>0.92</td>
<td>0.079</td>
<td>0.072</td>
<td>0.055</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>0.64</td>
<td>0.049</td>
<td>0.016</td>
<td>0.034</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.19</td>
<td>0.018</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.11</td>
<td>0.008</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>4 - 5</td>
<td>0.06</td>
<td>0.004</td>
<td>5.88e-05</td>
<td>0.003</td>
</tr>
<tr>
<td>5 - 6</td>
<td>0.07</td>
<td>0.003</td>
<td>5.85e-05</td>
<td>0.003</td>
</tr>
<tr>
<td>6 - 10</td>
<td>0.02</td>
<td>0.0007</td>
<td>3.15e-06</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
C.3 Background Fit Parameters

Table 10: RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc} = 0.5$ -1 GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
<th>Fit Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>4608.1</td>
<td>10.976</td>
</tr>
<tr>
<td>$v_t^1 \cdot v_t^a$</td>
<td>0.000</td>
<td>0.0001</td>
</tr>
<tr>
<td>$v_t^2$</td>
<td>0.0800</td>
<td>0.0022</td>
</tr>
<tr>
<td>$v_a^2$</td>
<td>0.1057</td>
<td>0.0031</td>
</tr>
<tr>
<td>$v_t^3 \cdot v_t^a$</td>
<td>-0.0022</td>
<td>0.0017</td>
</tr>
<tr>
<td>$v_t^4$</td>
<td>0.0131</td>
<td>0.0038</td>
</tr>
<tr>
<td>$v_a^4$</td>
<td>0.0146</td>
<td>0.0055</td>
</tr>
</tbody>
</table>

Table 11: RPF Fit Parameters, $p_T^{jet} = 20$-40 GeV, $p_T^{assoc} = 1$ -1.5 GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
<th>Fit Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>1722.2</td>
<td>6.6422</td>
</tr>
<tr>
<td>$v_t^1 \cdot v_t^a$</td>
<td>0.000</td>
<td>0.0001</td>
</tr>
<tr>
<td>$v_t^2$</td>
<td>0.0860</td>
<td>0.0035</td>
</tr>
<tr>
<td>$v_a^2$</td>
<td>0.1564</td>
<td>0.0050</td>
</tr>
<tr>
<td>$v_t^3 \cdot v_t^a$</td>
<td>0.0054</td>
<td>0.0028</td>
</tr>
<tr>
<td>$v_t^4$</td>
<td>0.0114</td>
<td>0.0062</td>
</tr>
<tr>
<td>$v_a^4$</td>
<td>0.0234</td>
<td>0.0089</td>
</tr>
</tbody>
</table>
Table 12: RPF Fit Parameters, $p_T^{jet} = 20-40$ GeV, $p_T^{assoc.} = 1.5 - 2.0$ GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
<th>Fit Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>652.66</td>
<td>4.0465</td>
</tr>
<tr>
<td>$v_1^t \cdot v_1^a$</td>
<td>0.000</td>
<td>0.0001</td>
</tr>
<tr>
<td>$v_2^t$</td>
<td>0.0794</td>
<td>0.0056</td>
</tr>
<tr>
<td>$v_2^a$</td>
<td>0.2092</td>
<td>0.0080</td>
</tr>
<tr>
<td>$v_3^t \cdot v_3^a$</td>
<td>-0.0053</td>
<td>0.0044</td>
</tr>
<tr>
<td>$v_4^t$</td>
<td>0.0036</td>
<td>0.0095</td>
</tr>
<tr>
<td>$v_4^a$</td>
<td>0.0459</td>
<td>0.0143</td>
</tr>
</tbody>
</table>

Table 13: RPF Fit Parameters, $p_T^{jet} = 20-40$ GeV, $p_T^{assoc.} = 2.0 - 3.0$ GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
<th>Fit Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>369.21</td>
<td>3.0630</td>
</tr>
<tr>
<td>$v_1^t \cdot v_1^a$</td>
<td>0.000</td>
<td>0.0001</td>
</tr>
<tr>
<td>$v_2^t$</td>
<td>0.0666</td>
<td>0.0075</td>
</tr>
<tr>
<td>$v_2^a$</td>
<td>0.2311</td>
<td>0.0106</td>
</tr>
<tr>
<td>$v_3^t \cdot v_3^a$</td>
<td>0.0082</td>
<td>0.0059</td>
</tr>
<tr>
<td>$v_4^t$</td>
<td>0.0076</td>
<td>0.1272</td>
</tr>
<tr>
<td>$v_4^a$</td>
<td>0.0624</td>
<td>0.0189</td>
</tr>
</tbody>
</table>
Table 14: RPF Fit Parameters, $p_T^{jet} = 20-40$ GeV, $p_T^{assoc.} = 3.0 - 4.0$ GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
<th>Fit Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>65.858</td>
<td>1.2859</td>
</tr>
<tr>
<td>$v_1^t \cdot v_1^a$</td>
<td>0.000</td>
<td>0.0001</td>
</tr>
<tr>
<td>$v_2^t$</td>
<td>0.0695</td>
<td>0.0176</td>
</tr>
<tr>
<td>$v_2^a$</td>
<td>0.2278</td>
<td>0.0247</td>
</tr>
<tr>
<td>$v_3^t \cdot v_3^a$</td>
<td>0.0093</td>
<td>0.0137</td>
</tr>
<tr>
<td>$v_4^t$</td>
<td>4.3703e-09</td>
<td>0.0652</td>
</tr>
<tr>
<td>$v_4^a$</td>
<td>0.0511</td>
<td>0.0436</td>
</tr>
</tbody>
</table>

Table 15: RPF Fit Parameters, $p_T^{jet} = 20-40$ GeV, $p_T^{assoc.} = 4.0 - 5.0$ GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
<th>Fit Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>15.554</td>
<td>0.6144</td>
</tr>
<tr>
<td>$v_1^t \cdot v_1^a$</td>
<td>0.000</td>
<td>0.0001</td>
</tr>
<tr>
<td>$v_2^t$</td>
<td>0.0263</td>
<td>0.0353</td>
</tr>
<tr>
<td>$v_2^a$</td>
<td>0.2032</td>
<td>0.0531</td>
</tr>
<tr>
<td>$v_3^t \cdot v_3^a$</td>
<td>0.0163</td>
<td>0.0279</td>
</tr>
<tr>
<td>$v_4^t$</td>
<td>0.0000</td>
<td>0.0005</td>
</tr>
<tr>
<td>$v_4^a$</td>
<td>0.0000</td>
<td>0.0010</td>
</tr>
</tbody>
</table>
### Table 16: RPF Fit Parameters, $p_T^{jet} = 20-40$ GeV, $p_T^{assoc.} = 5.0 - 6.0$ GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
<th>Fit Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>1.7391</td>
<td>0.5388</td>
</tr>
<tr>
<td>$v_1^t \cdot v_1^a$</td>
<td>0.000</td>
<td>0.0001</td>
</tr>
<tr>
<td>$v_2^t$</td>
<td>-0.0402</td>
<td>0.2441</td>
</tr>
<tr>
<td>$v_2^a$</td>
<td>0.5048</td>
<td>0.3700</td>
</tr>
<tr>
<td>$v_3^t \cdot v_3^a$</td>
<td>-0.0764</td>
<td>0.2435</td>
</tr>
<tr>
<td>$v_4^t$</td>
<td>0.0000</td>
<td>0.0005</td>
</tr>
<tr>
<td>$v_4^a$</td>
<td>0.0000</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

### Table 17: RPF Fit Parameters, $p_T^{jet} = 20-40$ GeV, $p_T^{assoc.} = 6.0 - 10.0$ GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
<th>Fit Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>1.3057</td>
<td>0.5136</td>
</tr>
<tr>
<td>$v_1^t \cdot v_1^a$</td>
<td>0.000</td>
<td>0.0001</td>
</tr>
<tr>
<td>$v_2^t$</td>
<td>-0.0224</td>
<td>0.3447</td>
</tr>
<tr>
<td>$v_2^a$</td>
<td>-0.0051</td>
<td>0.4565</td>
</tr>
<tr>
<td>$v_3^t \cdot v_3^a$</td>
<td>0.0385</td>
<td>0.2678</td>
</tr>
<tr>
<td>$v_4^t$</td>
<td>0.0000</td>
<td>0.0005</td>
</tr>
<tr>
<td>$v_4^a$</td>
<td>0.0000</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

257
### C.4 Single track Reconstruction Efficiency Fit Parameters

#### Table 18: Single Track Reconstruction $\epsilon (p_T)$ Fit Parameters, LHC2018q, 5.02 TeV 30 - 50 %

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_0$</td>
<td>0.7274</td>
</tr>
<tr>
<td>$p_1$</td>
<td>0.2232</td>
</tr>
<tr>
<td>$p_2$</td>
<td>-0.1586</td>
</tr>
<tr>
<td>$p_3$</td>
<td>0.0577</td>
</tr>
<tr>
<td>$p_4$</td>
<td>-0.0087</td>
</tr>
<tr>
<td>$p_5$</td>
<td>0.8686</td>
</tr>
<tr>
<td>$p_6$</td>
<td>-0.02144</td>
</tr>
<tr>
<td>$p_7$</td>
<td>0.0099</td>
</tr>
<tr>
<td>$p_8$</td>
<td>-0.0021</td>
</tr>
<tr>
<td>$p_9$</td>
<td>0.0002</td>
</tr>
<tr>
<td>$p_{10}$</td>
<td>-8.143e-06</td>
</tr>
</tbody>
</table>
Table 19: Single Track Reconstruction $\epsilon(\eta)$ Fit Parameters, LHC2018q, 5.02 TeV 30 - 50 %

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_0$</td>
<td>0.7880</td>
</tr>
<tr>
<td>$p_1$</td>
<td>0.0021</td>
</tr>
<tr>
<td>$p_2$</td>
<td>0.3760</td>
</tr>
<tr>
<td>$p_3$</td>
<td>-0.0178</td>
</tr>
<tr>
<td>$p_4$</td>
<td>0.6927</td>
</tr>
<tr>
<td>$p_5$</td>
<td>-0.0004</td>
</tr>
<tr>
<td>$p_6$</td>
<td>1.294</td>
</tr>
<tr>
<td>$p_7$</td>
<td>0.7321</td>
</tr>
<tr>
<td>$p_8$</td>
<td>0.0057</td>
</tr>
<tr>
<td>$p_9$</td>
<td>0.6988</td>
</tr>
<tr>
<td>$p_{10}$</td>
<td>0.6829</td>
</tr>
</tbody>
</table>
Vita

Charles Hughes grew up in Lynn Haven, Florida. After high school, he attended Gulf Coast State College and received an Associate of Arts degree in Pre-Mechanical Engineering. He then attended the Georgia Institute of Technology in Atlanta, Georgia. At Georgia Tech, he received a Bachelor of Science in Mechanical Engineering with a minor in Physics. After graduating he chose to attend the University of Tennessee in Knoxville to pursue a Doctor of Philosophy degree in Physics with a concentration in High Energy Nuclear Physics. Along the way, he was awarded a Master of Science in Physics as well. His research interest includes studying the path length dependence of jet energy loss in the Quark Gluon Plasma and assembling/testing particle detectors. His research took him to the European Organization for Nuclear Research (CERN) to work on the ALICE detector in the Large Hadron Collider. After graduation, he will continue his work at the University of Tennessee as a postdoctoral research assistant. He is incredibly grateful for all the help and support from his loving girlfriend, friends, professors, and family.