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High Energy Particle Physics at the University of Tennessee

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High Energy Particle Physics at the University of Tennessee

Stefan M. Spanier
• Cosmic Rays - Particle Physics: The Beginnings

• 1785 - **Coulomb** notices that a charged body left in air gradually loses its charge.

• 1905 - **Rutherford** concludes radioactivity in the earth is responsible.

• 1912 - **Victor Hess** reaches 5350 m altitude in a hydrogen filled balloon and shows conclusively that the rate of discharge increases significantly with height. He concludes that there is an extraterrestrial source of radiation.

(receives Nobel prize 1936)

*Electrometer:*
- Cloud Chamber as Particle Detectors

Chamber filled with supersaturated vapor (water)

Expand and illuminate to take photograph

in magnetic field

Charged particle  Free ions  Condensation droplets
The positive electron - First Discovery of Anti-Particles

1932  C.D. Anderson (Caltech)

Fits into theory: P.A.M Dirac
relativistic wave equation for electrons predicts the existence of particles
with charge opposite to electrons but same mass.

\[ C \, e^- = e^+ \]

Other important symmetry is parity P:
\[ P \, \vec{r} = -\vec{r} \]

How does it get produced?
Particle detection

Detection of elementary particles is based on their interaction with matter.

1937 Neddermeyer, Anderson find a heavy particle, but not as heavy as the proton in cosmic rays → the muon

→ check the energy loss of the particle in a metal plate and its momentum (curvature) in magnetic field

Another idea of resolving a particles mass:

Curvature ~ momentum $P$

Measure time of flight, $\Delta t$, through two stations in well defined distance $\Delta d$

velocity $= \frac{\Delta d}{\Delta t}$

$P = m \cdot v$  $\Rightarrow m = \frac{P}{v}$

But $v$ typically close to $c$, speed of light therefore $m = m_0 \gamma$, $m_0 =$ rest mass and for limited momentum range
• Cosmic ray laboratory

Cosmic Rays continually bombard the Earth. In fact, a large amount of cosmic rays will pass through a person every hour!

Cosmic rays are very energetic, but not sufficiently reliable and their rates are low!
Why reliable energy? Resolution of smaller Dimensions

Wavelength \approx \text{dimension to be resolved}

Wavelength \propto 1/\text{Energy}

\Rightarrow \text{The smaller dimension the higher the energy of the light (particle)}

Energy \approx 10 \text{ kilo electron Volt (eV)}

1\text{eV} = \text{kinetic energy an electron gains in a electric field of 1 Volt}

> 100 \text{ MeV}
• Accelerators

**Synchrocyclotron**: let particles run in a circle within a magnetic field and give them kicks with the electrical field at the same place in the right moment.

But: **Synchrotron Radiation** \(\rightarrow\) **Beam Energy Loss** \(\propto E^4\)**
• Linear Accelerators

Medical applications e.g. tumor treatment.
• Stanford Linear Accelerator Center

- 2 mile long accelerator (can be seen from moon)
- Final energy of 45 GeV for electrons/positrons
- Used to fill PeP II B-factory to measure CP violation
• What have we learned → Standard Model

Charge conjugation symmetry

\[ C: \text{Charge conjugation symmetry} \]

In accelerators (cosmic rays) particles and anti-particles are created and annihilate in pairs!
• What have we learned → Standard Model

4 fundamental forces:

- Electric
- Magnetic
- Weak
- Strong
- Gravity

4 fundamental forces: Maxwell

- Photons $m=0$
- $W^+, W^-, Z^0$ $m=80, 90 \text{ GeV}$
- Gluons $m=0$
- Gravitons $?$

$>100 \text{ GeV}$

Standard Model

today’s accelerators just about …

Planck energy

$\sim 10^{19} \text{ GeV}$

$\sim 10^{15} \text{ GeV}$ ?

GUT scale

coupling constants unify

The particle masses …
• Standard Model Symmetry Breaking?

Higgs particles acquire masses … The Higgs particle generation … symmetry breaking!

Fundamental to explain evolution of Universe …

Higgs Mass = 100 .. 300 GeV?

Higgs mass diagram showing exclusion and mass range.
- Evolution of the Universe?

- ~ 14 billion years
  - 1 meV Today (T=2.73K)
  - Solar system

- 400,000 yr
  - 1 eV Matter domination
    - onset of gravitational instability

- 1 s
  - 1 MeV Nucleosynthesis (D, He, Li)

- 10^{-8} s
  - 1 GeV Quark → Hadron
    - protons, neutrons form

- 10^{-11} s
  - 10^3 GeV Electroweak
    - Phase Transition

- 10^{-35} s
  - 10^{15} GeV Grand Unification

- 10^{-43} s
  - 10^{19} GeV Planck Epoch

- Particle Desert: Supersymmetric particles?
- Energy Budget of the Universe

**Composition of the Cosmos**

- Dark Matter: ~25%
- Antimatter: 0%
- Dark Energy: ~70%
- Heavy elements: 0.03%
- Neutrinos: 0.3%
- Stars: 0.5%
- Free hydrogen and helium: 4%
- Dark matter: ~25%
- Dark energy: ~70%
The Standard Model is not complete; there are still many unanswered questions, such as:

- Why can't the Standard Model predict a particle's mass?
- Are quarks and leptons actually fundamental?
- Why are there exactly three generations of quarks and leptons?
- Why do we observe matter and almost no anti-matter in the Universe?
- What is this "dark matter"?
- How does gravity fit into all of this?

LHC is the tool for a fundamental breakthrough.
• The LHC Project
• Proton-proton collider (14 TeV energy)
• 27 km in circumference, 50-175m deep
• between Jura mountains (France) and Lake Geneva (Switzerland)

Search for
- Origin of Mass
- New forces
- Universe origin
- Supersymmetry
- Other new particles
- Black Holes

First beams fall 2007!
• The LHC

> 2808 proton bunches/ring
> $\sim 10^{11}$ protons/bunch
> Beam current: 584 mA

> Collision every 25 ns
> Beam stays for 10 hours after fill (30min energy ramp)

Energy stored/beam: 360 MJ

Superconducting magnets:
1232 dipole magnets (bending)
$\sim 500$ quadrupole magnets (focus)

Energy stored in magnets: 700GJ

$\rightarrow$ Particle losses fatal!

Superconducting dipole magnet
• The Compact Muon Solenoid (CMS) Detector

CMS Detector assembled in SX5.
11 independent rings
The Compact Muon Solenoid (CMS) Detector

- 4 Tesla magnetic field
- Solenoid Magnet Assembly
- Higgs → 4 muons
• The CMS Pixel Detector
• 3-d tracking with about 66 million channels
• Barrel layers at radii = 4.3cm, 7.2cm and 11.0cm
• Pixel cell size = 100 µm x 150 µm
• ~15k front-end chips and ~1m² of silicon

Sensors are bump-bonded to the readout chips
- Charged particle creates free electrons and holes in silicon while passing (deposits small fraction of its energy) → For minimum-ionizing particle ~ 20,000 electrons

- Silicon pixel (strip) detector works like a semi-conductor diode in reverse bias with large depletion zone (no free charges) → very large electric field $E \sim 10^5$V/m pulls charges → very short collection time (few ns)
Irradiation modifies the electric field profile: varying Lorentz deflection. After irradiation, the charge width changes. Irradiation causes charge carrier trapping.

In the r-φ plane, the electric field \( \vec{E} \) is present with a B field, whereas in the r-z plane, the B field is absent. The charge is represented in pink.
• The LHC Computing

- 1 billion proton-proton collision events per second in detector
- 100 events of interest/second recorded permanently (trigger/filter)
  ➔ 1 GByte/second
    + Raw data, processed data, simulated events
  ➔ 15 PetaBytes/ year (= 15 M GBytes/year = 20 M CDs)
  ➔ computing power equivalent: ~ 100,000 standard PC processors.

• … needs **global** distribution of people & resources
• The LHC Global Data GRID (2007+)

...within the framework of the OpenScienceGrid (OSG)
• **Conclusion**

- High Energy Particle Physics (HEP) has answered many fundamental questions.
- In the energy regime below 100 GeV the picture appears complete
- but beyond this energy HEP opened many new questions

- LHC is the machine for a fundamental breakthroughs
- HEP is a challenging environment with many new technology developments to prepare for discoveries

*We are involved in*
- CP violation & Search for New Physics at BaBar, SLAC
- Readout and commissioning of pixel detector for CMS/LHC
- Beam radiation protection for the pixel detector at CMS
- Future radiation hard pixel detector development with PSI Switzerland
- GRID computing center at UT; R&D with UT’s Computer Science Dpt.
- Search for new particles and interactions *beyond the Standard Model*