Lecture 4: Accelerators and Detectors
February 21st 2008

• Particle Beams and Accelerators
  • Particle Physics Labs
  • Accelerators
  • Synchrotron Radiation

• Particle Detectors:
  • A modern collider detector
  • Interactions of particles with matter
  • Particle reconstruction
Particle Acceleration

Long-lived charged particles can be accelerated to high momenta using electromagnetic fields.

- $e^+, e^-, p, \bar{p}, \mu^\pm(?)$ and Au, Pb & Cu nuclei have been accelerated so far...

Why accelerate particles?
- High beam energies $\Rightarrow$ high $E_{CM}$ $\Rightarrow$ more energy to create new particles
- Higher energies probe shorter physics at shorter distances
- De-Broglie wavelength: $\lambda = \frac{\hbar c}{p}\approx \frac{197 \text{ MeV fm}}{p \text{ [MeV/c]}}$

- e.g. 20 GeV/c probes a distance of 0.01 fm.

An accelerator complex uses a variety of particle acceleration techniques to reach the final energy.
# Particle Physics Colliders around the World

<table>
<thead>
<tr>
<th>Location</th>
<th>Collider</th>
<th>Years</th>
<th>Process</th>
<th>Energy 1</th>
<th>Energy 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC, California</td>
<td>SLC</td>
<td>1989-1998</td>
<td>$e^- e^+$</td>
<td>50 GeV</td>
<td>50 GeV</td>
</tr>
<tr>
<td></td>
<td>PEP II</td>
<td>1997-2008</td>
<td>$e^- e^+$</td>
<td>9.0 GeV</td>
<td>3.1 GeV</td>
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<tr>
<td>Fermilab, nr Chicago</td>
<td>Tevatron</td>
<td>1987-2009</td>
<td>$p \bar{p}$</td>
<td>980 GeV</td>
<td>980 GeV</td>
</tr>
<tr>
<td>CERN, Geneva</td>
<td>LEP</td>
<td>1989-2000</td>
<td>$e^- e^+$</td>
<td>$E_{CM}$: 89 to 206 GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LHC</td>
<td>2008-…</td>
<td>$p p$</td>
<td>$E_{CM}$: 14 TeV</td>
<td></td>
</tr>
<tr>
<td>DESY, Hamburg</td>
<td>HERA</td>
<td>1990-2007</td>
<td>$e^- p$</td>
<td>920 GeV</td>
<td>30 GeV</td>
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<tr>
<td>KEK, near Toyko</td>
<td>KEKB</td>
<td>1999-…</td>
<td>$e^- e^+$</td>
<td>8.0 GeV e$^-$</td>
<td>3.5 GeV e$^+$</td>
</tr>
<tr>
<td>Brookhaven National Lab, Long Island</td>
<td>RHIC</td>
<td>2000-…</td>
<td>AuAu, CuCu</td>
<td>200 GeV/nucleon</td>
<td></td>
</tr>
</tbody>
</table>
The Tevatron Complex

- As a example, we’ll follow the chain of the Tevatron accelerator.

Fermilab’s Accelerator Chain

Cockroft-Walton Accelerator
DC Voltage accelerates particles through steps to about 1MV

Proton source: 7 litre bottle of hydrogen. Cost US$200. 1 bottle lasts about a year
After Cockroft-Wolton comes the linac (linear accelerator)
Charged particles in vacuum tubes accelerated by an alternating current, with a very high frequency: “Radio Frequency” (RF)
RF frequencies typically a few 100 MHz
Field strengths - few MV/m requires specialised power sources: “klystrons”

The tubes act as Faraday cages: when the particles are in the tubes they feel no force
Outside of the tubes they feel the potential difference between successive tubes, they accelerate forward
Alternating current ensures that the difference always has the correct sign for acceleration.
Cyclotrons and Synchrotrons

• **The Cyclotron** - invented by Ernest Lawrence

• **Two D-shaped electrodes** - perpendicular magnetic field
  - Constant frequency AC current applied to each electrode
  - Can to accelerate particles to \(~10\, \text{MeV}\)
  - At higher energies relativistic effects take over, circular path cannot be maintained need...

• **Synchrotron accelerators** use variable $B$-field strength and radio frequency $E$-field, synchronised with particle speed to accelerate charged particles to relativistic energies.

  - Series of bending and focussing magnets

  - Beams have a constant radius in a synchrotron.
  - Synchrotrons used as storage rings and colliders.
Synchrotrons at the Tevatron

- Many synchrotrons used at the Tevatron:
  - **Booster**: proton energy from 400 MeV to 8 GeV
  - **Recycler**: stores antiprotons at 8 GeV
  - **Main Injector**: 8 GeV to 120 GeV
  - **Tevatron**: 120 GeV to 980 GeV

- **Storage ring**: once particles have desired energy, they can be stored. Typically 8-24h.

- The Tevatron stores both the proton and anti-proton beam travelling in opposite directions.

- **Collider**: two beams are steered to collide at two points in the (CDF and DØ experiments).
Antiproton Production

- Protons from the main injector are fired onto a nickel target.
- 1 million protons produces 20-30 8 GeV antiprotons.
- Magnetic field used to separate $p$ from $\bar{p}$.
- Stored in the accumulator synchrotron for several hours to several days - until required for collision in Tevatron.
- At the end of a ‘store’ in the Tevatron any remaining antiprotons are stored in the Recycler synchrotron.

Two collision points in the Tevatron: CDF and DØ
- We’ll see the CDF detector in a moment...
• In a synchrotron the accelerated charged particles emit photons: synchrotron radiation.

• The energy lost every turn depends of the energy and mass of the particle \((\gamma = E/m)\) and the radius of the orbit, \(\rho\):

\[
\Delta E = \frac{q^2 \beta^3 \gamma^4}{3\epsilon_0 \rho}
\]

• Synchrotrons are used as high-energy photon sources

• In a storage ring, the energy lost due to synchrotron radiation must be returned to the beam to keep the collision energy constant.
A Modern Collider Detector

- Use CDF at the Tevatron as an example.
- Most collider detectors are quite similar - same component pieces, different implementations

- From inside to out:
  1. Silicon tracker
  2. Gaseous tracker
  3. 1.4 T Solenoid Magnet
  4. Electromagnetic Calorimeter
  5. Hadronic Calorimeter
  6. Muon detectors
Interactions with Matter

- An experiment should detect all particles that live long enough to interact with the detector.
- Detector generally starts a few centimetres from the interaction point.
- Length travelled before decay is $L = \beta \gamma c \tau$, therefore particles with $\tau > \sim 10^{-10}$ s appear in detector
  - $e^\pm, \mu^\pm, \pi^\pm, K^\pm, K^0, p, n, \gamma, v$
- Use series of different detection techniques to identify these particles.
- Infer the existence of shorter-lived particles from the decay produces.
Charged Particle Energy Loss

- Energy loss of charged particle through matter is described by **Coulomb scattering**. Moving charged particles scatter off atomic electrons causing ionisation.

- Ionisation energy loss given by **Bethe-Bloch** formula:

\[
\frac{-dE}{dx} = \frac{4\pi}{m_0 c^2} \cdot \frac{N_A Z \rho}{A} \cdot \frac{Q^2}{\beta^2} \cdot \left( \frac{e^2}{4\pi \varepsilon_0} \right)^2 \cdot \left[ \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]
\]

- \( \frac{-dE}{dx} \) - particle energy lost per \( x \) [MeV g\(^{-1}\) cm\(^2\)]
- \( x \) - distance travelled by particle
- \( Q \) - particle charge (e)
- \( N_A \) - Avogadro’s number
- \( Z, A \) - atomic and mass number of medium
- \( I \) - excitation energy of medium
- \( \rho \) - density of medium

- Measure \( \frac{-dE}{dx} \) to identify the type of particle (as we know the medium we are using for our detector).
- Also measure total energy absorbed by detector.
Charged Particle Tracking

- Charged particle trajectories are curved in magnetic fields.
- Use the curvature, $\rho$, to measure the momentum transverse to the field, $p_T$.
  \[ p_T[\text{GeV/c}] = 0.3 \times B[\text{T}] \times \rho[\text{m}] \]
- **Old method**: use a homogenous substance to trace out the entire motion.
- **Modern method**: take several position measurements as charged particle passes. Reconstruct a ‘track’
- **CDF Silicon detector**: charged particle ionises silicon semiconductor. Six very accurate position measurements per track.
- **CDF Drift chamber**: large volume filled with argonne-ethane-CF$_4$ mixture. Gas is ionised and drifts towards cathode and anode wires. Up to 96 position measurements per track.
Electromagnetic and Hadronic Calorimeters

- **Calorimeters** measure the energy deposited when particles are absorbed.
- Electrons, positrons and photons are mainly absorbed in the **electromagnetic calorimeter**.
- Hadrons: \( \pi^\pm, K^\pm, K^0, p, n \) are mainly absorbed in the **hadronic calorimeter**.
- CDF uses a **sampling calorimeter**: sample parts of the shower. Extrapolate to obtain the full amount of energy.
  - CDF electromagnetic calorimeter: Lead + light sensitive scintillator.
  - CDF hadronic calorimeter: Iron + light sensitive scintillator.

- Better energy measurements may be made using a **homogeneous calorimeter** -
  - A **homogeneous calorimeter** measured *all* deposited energy
    - scintillating crystals (*e.g.* Caesium Iodide)
    - Cryogenic liquids (argon, krypton, xenon).
Neutrino Identification at Colliders

- Neutrinos are not charged and only interact via the weak force ⇒ they do not interact at all in the detector.
  \[ \sum \vec{p}_{\text{initial}} = \sum \vec{p}_{\text{final}} \]

- The initial momentum of the collision is along beam direction, no perpendicular component.
- Total reconstructed momentum perpendicular to the beam should sum to zero.
- We infer neutrinos from absence of momentum seen in a particular direction.

We’ll talk about the signal produced by quarks in a detector in lecture 6.
Summary

- We accelerate particles to obtain more $E_{CM}$ in order to produce new, as yet, undiscovered particles.
- Long-lived charged particles may be accelerated in a magnetic field.
- An accelerator complex uses a system of **Linacs** and **Synchrotrons** to accelerate particles to the desired energy.
- Synchrotrons can also be used to store energetic particles.
- **Synchrotron radiation**: energy loss due to photon emission
  - energy need to be added back to beam at a collider
  - can be exploited produce high frequency gamma rays
- **Particle detectors** strive to reconstruct all long-lived particles.
- System of complex subdetector systems used to reconstruct position, momentum, energy and particle type.
- Charged particles leave several position measurements in the tracking detector. Positions are joined up to trace out a ‘track’, used to reconstruct the momentum.
- Most particles (except muons and neutrinos) loose their energy in calorimeters, allowing the energies of these particles to be measured.