Review from Last Class: Classification of particle detectors

- **Charged Particles**
  - Momentum: Determine trajectory in B field
  - Mass: More difficult; Measurement of velocity and momentum
  - Energy: Deposited as particle stops.
    - Energy loss from ionization, bremsstrahlung

- **Strongly Interacting Particles (charged or neutral)**
  - Energy: Deposited where particle stops
    - Energy loss from nuclear interactions

- **Photons**
  - Energy: Pair production followed by ionization

- **Muons**
  - Momentum: As for other charged particles
  - No nuclear interactions
    - Can pass through lots of matter before stopping
    - Additional tracking detectors after calorimeter

- **Neutrinos**
  - Often observed by their absence: missing momentum
  - Weak interactions, eg $\nu_\mu N^Z \rightarrow \mu^- N^{Z+1}$ or $\nu_\mu N^Z \rightarrow \nu_\mu X$
Silicon Strip Detectors

- Strips etched onto silicon wafer
  - Typical size of wafer: 3cm × 6 cm
  - Typical strip pitch: 50-100 µm
- One amplifier per strip
  - Only hit strips sent to data acquisition system
Pixel Detectors: Same idea, more channels

- Instead of long strips, 2D rectangles
- Electronics mounted on top of each pixel
- Example: ATLAS pixel detector
  - 1744 modules
  - 80 million pixels
  - Pixel size: 50µm x 400µm
  - Resolution 10µm in bending plane
Track Reconstruction

- Charged particles traverse many layers of detectors
- Detectors often placed in magnetic field
  - Lorenz force $F = qv \times B$
  - $p \cos \lambda = 0.3BR$
    - $p$: momentum,
    - $\lambda$: wrt transverse direction
    - $B$: Mag field in tesla
    - $R$: Radius of curvature in m
- Hits along trajectory are “fit” to form a track
  - Deviation from straight line proportional to momentum
  - Direction of curvature gives sign of charge

\[
\frac{\sigma_{pT}}{pT} = \sqrt{\frac{720}{N + 4 qB L^2}} \frac{\sigma_x}{pT}
\]
Vertex Reconstruction

- Extrapolate tracks to common vertex point
  - Good position resolution required
  - First measurement should be close to beam line
  - Minimize amount of material

- Impact Parameter: Distance of closest approach to primary vertex
  - Sign defined to distinguish particles that decay in front of or behind primary vertex
  - Mean value depends on mass and lifetime of decaying particle
Cherenkov Radiation: Separating particle species

- Charged particle moving faster than light in medium produces radiation
- Wave-front is a cone of light with angle that depends on the index of refraction $n$ of the medium
  \[ \cos \theta = \frac{1}{n\beta} \]
- Two types of Cherenkov detector:
  - **Threshold:** Separates species
    - Same $p$, different mass $\rightarrow$ different $v$
  - **Ring imaging:**
    - Measure $\theta$ to determine $v$
Examples of Cherenkov Detectors

AMS Detector (International Space Station)

Icecube Detector (South Pole)

Babar DIRC
Example of Tracker with Multiple Components
Calorimeters

- Calorimeters are blocks of matter that:
  - Degrade the energy of particles through their interactions with matter
  - Are instrumented to detect the ionization and de-excitation of excited states through conversion to electronic signals
  - Measure signal of a magnitude that depends on energy of incident particle
Radiation Length

• Definitions:
  ▶ Mean distance over which a high-energy electron loses all but $1/e$ of its energy due to bremsstrahlung
  ▶ $7/9$ of the mean free path for pair production from a high energy photon
  ▶ Units can be either cm or g/cm$^2$ (use density to convert)

• From Particle Data Group review:

$$
\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 [L_{rad} - f(Z)] + Z L'_{rad} \right\}
$$

where for $A = 1$ g/mol, $4\alpha r_e^2 \frac{N_A}{A} = 716.408$ g/cm$^2$; $L$ and $L'$ depend on the properties of the material

• A good approximation is

$$
\frac{1}{X_0} = Z(Z + 1) \frac{\rho \ln(287/Z^{0.3})}{A} \frac{1}{716 \text{ g/cm}^3}
$$
Longitudinal and Transverse Shower Development

- Cascade due to
  - Bremsstrahlung ($e \rightarrow e\gamma$)
  - Pair production ($\gamma \rightarrow e^+e^-$)

- This continues until electrons fall below critical energy $E_c$

- Transverse size set by Moliere radius

$$R_M = X_0 \left( 21 \text{ MeV} / E_C \right)$$

- For lead $X_0 = 0.56 \text{ cm}$ and $R_M = 1.53 \text{ cm}$

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

where $t$ is depth in radiation lengths
EM Calorimeters

- Total absorption calorimeter
  - Electrons and photons stop in calorimeter
  - Amount of scintillation light proportional incident energy
  - Blend of two materials: eg lead + crystal
  - Resolution typically $\propto 1/E^{1/4}$

- Sampling calorimeter
  - High $Z$ material to induce shower: “absorber”
  - Another material to detect particles: “active material”
  - Alternating layers of absorber and active material
  - Resolution typically $\propto 1/E^{1/2}$ (more later)
  - Can be segmented longitudinally and/or transversely

- Absorber most often Pb for EM calorimeters ($Z = 82$)
Example of Crystal (Total Absorption) Calorimeter: CMS

- **PbWO₄** (lead-tungstate)
  - 22mm x 22mm x 230mm crystals in barrel
  - 75,848 crystals in total
  - 1% resolution at \( E = 30 \text{ GeV} \)
  - Total depth: \( 25X_0 \)
Example of Sampling Calorimeter: ATLAS Barrel Calorimeter

- Accordion design
- Absorber: Pb
- Active material: liquid argon
  - Ionization electrons drift to sensors (Cu/kapton sheets)
  - Good transverse segmentation
- Resolution: 1.8% at 30 GeV
- 3 samples in depth
- Total depth: $22X_0$
Calorimeter energy resolution for sampling calorimeters

\[
\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c
\]

where

- a: “Stochastic term” (arises from fluctuations in shower)
- b: “noise term” (electronic noise, pileup)
- c: “constant term” (imperfections in calibration...)

Hadronic Showers

- Hadrons lose energy due to nuclear interactions in material
  - Characteristic length called “interaction length” $\lambda$
  - Depends on $A$ rather than $Z$ (as radiation length did)
- More complicated shower development than EM showers

Figure 12: Schematic of development of hadronic showers.
Example of Combined Calorimeter Package: CDF

- Sampling calorimeter with sandwich structure
- EM calorimeter in front; absorber is lead
- Hadronic calorimeter behind: absorber is steel
- Scintillator as active medium for both
- Projective “towers” that point to interaction region
Some comments on hadron calorimetry

- Nuclear interactions much messier than electromagnetic
  - Binding energies of nuclei in MeV range rather than the eV range of atomic processes
    - Energy of nuclear break-up not measured in calorimeter
    - Calorimeter response depends on material used for absorber
- Hadronic showers contain $\pi^0$ as well as $\pi^\pm$
  - $\pi^0 \rightarrow \gamma\gamma$ with $\tau = 8 \times 10^{-17}$s. (Decays before reaching detector)
  - $\pi^\pm$ has $\tau = 2 \times 10^{-8}$s (Exits detector before decaying)
    - Decay products of $\pi^0$ only interact electromagnetically but $\pi^\pm$ interact via strong force
    - Thus calorimeter responds differently to $\pi^0$ and $\pi^\pm$
    - Event-by-event fluctuations in charged-to-neutral ratio degrades response
- Hadron calorimeters typically have much worse energy resolution than EM calorimeters and do not have linear response at low energy deposition
  - $\sigma_E/E$ typically 50-100%$\sqrt{E}$
Muon Detection

- Muon properties:
  - Muon mass more than 200 times that of electrons → Don’t lose energy as quickly from bremsstrahlung
  - Are leptons → Don’t feel strong interactions
- Energy loss dominantly from ionization → travel long distances in matter
- Detect using tracking chambers placed after lots of material
- Sometimes additional $B$ field for a second momentum measurement
Neutrino Detection (I): via Missing Momentum

- Example of a $W^{-} \rightarrow e \bar{\nu}_e$ decay

Note: $m_W = 80$ GeV
Neutrino Detection (II): via weak interactions

- Charged current interactions
  \[ \nu_\mu + N^Z \rightarrow \mu^- + X^{Z+1} \]
- Neutral current interactions (\(X\) are hadrons produced in breakup nucleus)
  \[ \nu_\mu + N^Z \rightarrow \nu_\mu + X^Z \]
Accelerators: Introduction

• 1\textsuperscript{st} accelerators not man-made
  ▶ Radioactive sources: $\alpha$, $\beta$, $\gamma$
  ▶ Cosmic Rays

• Cosmics sources still used today
  ▶ $\nu$ from sun, or produced in atmosphere
  ▶ Dark matter??

• However:
  ▶ Can’t control energy or intensity
  ▶ Can’t turn them off
  ▶ Can’t select beam species

• Need for something more:
  Man-made accelerators
Components of an Accelerator

- **Beams**
  - Currents of charged particles that will be accelerated
  - Distributed in bunches (we’ll see why in a few slides)
  - Transported in ultr-high vacuum

- **Accelerating structures**
  - Use electric fields or RF waves to accelerate particles
  - New techniques (eg laser acceleration) under study

- **Magnets**
  - Guide beams into well defined path
  - Focus beams to small transverse area

- To optimize performance, components usually arranged in a series of separate accelerators, each feeding the next
The Most Basic Accelerator: Electron Gun

- Heated wire used to spit off electrons
- HV to generate $E$-field: $KE = e\Delta V$
- Same idea can be used to accelerate $p$ or $+$ ions
  - Attach electrons to atoms to make negative ions
  - Accelerate the ions
  - Strip ions of electrons by passing through foil
  - Mass spectrometer to separate
- Largest possible energy $\sim 20$ MeV
  - Typical energy $\sim 100$ KeV (Van der Graaff)
  - Can we do better?
    - Use AC rather than DC fields
The First AC Accelerator: The Cyclotron

Square wave electric field accelerates charge at each gap crossing.

Magnetic field bends path of charged particle.
Observations about the Cyclotron

- Constant bending field $B$
  - Radius of curvature changes as particle accelerates
  - $p = eRB$
  - $t = 2\pi R/v = 2\pi R/(eRB/m) = 2\pi m/e$ if particle non-relativistic

- Large $R$ needed to reach high energy if $B$ limited
- As particle becomes relativistic, simple relationship between $R$ and period no longer valid
- Solution
  - Change bending field as particle accelerates: Synchrotrons
A better alternative for accelerating structures

- Series of evacuated tubes with alternative tubes at opposite voltage
  - Inside tube, $E = 0$ so no acceleration
  - Between tubes $\sim$ constant field
  - Set frequency so sign of $E$ changes when particles in tube
  - Can get acceleration each time

- Must make tubes longer to compensate for increased velocity (until ultra-relativistic)

- Only particles with correct phase accelerated
  - Beam consists of bunches
A more realistic alternative: RF Structures

A voltage generator induces an electric field inside the rf cavity. Its voltage oscillates with a radio frequency of 1.3 Gigahertz or 1.3 billion times per second.

The electrons always feel a force in the forward direction.

An electron source injects particles into the cavity in phase with the variable voltage.

The electrons never feel a force in the backward direction.
Fitting the beam into RF buckets at the LHC

RF bucket

2.5 ns

<table>
<thead>
<tr>
<th>Energy</th>
<th>RMS bunch length</th>
<th>RMS energy spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV</td>
<td>11.2 cm</td>
<td>0.031%</td>
</tr>
<tr>
<td>7 TeV</td>
<td>7.6 cm</td>
<td>0.011%</td>
</tr>
</tbody>
</table>

R. Assmann
Bending the beam: Dipole magnets

• Pictures above show LHC dipole magnets
  ▶ Two bores since proton bunches travel in opposite directions
  ▶ 15 m long
  ▶ Superconducting magnets at temperature 1.9K
Focusing the beam: Quadrupoles

\[ B_x = B'y \quad B_y = B'x \]
\[ F_x = qv_z B'x \quad F_y = -qv_z B'y \]

- Force is restoring in one direction, anti-restoring in the other
- Acts like a converging lens in one direction and diverging one in the other
- Several quadrupoles in series with appropriate spacing leads to overall focusing of beam in both directions
How to get to high energy: the options

LINAC (planned for several hundred GeV - but not above 1 TeV, e.g ILC)

LHC circular machine with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV takes about 20 minutes

....requires deflecting magnets (dipoles)

Rüdiger Schmidt
Another accelerator complex: SLAC
Event rates: Colliders

- Event rate proportional to luminosity

$$\mathcal{L} = f n \frac{N_1 N_2}{4\pi \sigma_x \sigma_y}$$

- $f$: revolution frequency (LHC: 11 kHz)
- $n$: number of bunches (LHC: 2808 bunches)
- $N_i$: number of particles in bunch $i$ (LHC: $\sim 10^{11}$)
- $\sigma$: transverse size of the beam (LHC: $\sim 15 \, \mu m$)

- Luminosity measured in $\text{cm}^{-2}\text{s}^{-1}$ or $\text{pb}^{-1}\text{s}^{-1}$
  - Cross section per second
  - Specifies how many events per second would be observed for a process with unit cross section

$$N_{evt} = \sigma \mathcal{L} \Delta t$$
Event rates: Fixed Target

\[ R = \sigma N_b n_T L \]

- **\( R \)**: rate (interactions per section)
- **\( N_b \)**: Beam rate (particles per second)
- **\( n_T \)**: Target number density (\( \rho/m_0 \))
- **\( L \)**: Target length

- Much higher rates achievable even with modest beam current and size
  - eg 1 m hydrogen target and a beam of \( 10^{13} \) particles/sec is equivalent of \( \sim 10^{38} \, \text{cm}^{-2}\text{s}^{-1} \)
  - LHC is \( 10^{34} \, \text{cm}^{-2}\text{s}^{-1} \)
Fixed Target: Secondary and Tertiary Beams

- Primary proton beam hits target and makes secondaries
- Magnets used to select appropriate particle species and mass ($\pi, K$, etc)
- Masks and filters to removed unwanted particles
- Decay of selected particles used to create tertiary beam
  - Neutral beams (eg $\nu$) can be created
Colliders: The past 30 years

- $e^+e^-$
  - LEP (CERN) 1989-2000 $\sqrt{s} = 90-205$ GeV
  - SLC (SLAC) 1989-1998 $\sqrt{s} = 90$ GeV
  - Asymmetric B-factories $\sqrt{s} = 10$ GeV:
    - PEPII (SLAC) 1999-2009
    - KEKB (KEK) 1999-present

- $ep$
  - HERA (DESY) $\sqrt{s} = 920$ GeV

- Hadrons
  - Tevatron (FNAL) 1986-2010 $p\bar{p}$, $\sqrt{s} = 1.8-1.96$ TeV
  - LHC (CERN) 2010-present $pp$, $\sqrt{s} = 7, 8, 13$ TeV
    - Also lead-lead and lead-proton collisions $\sim 2.7$ TeV per nucleon
  - RHIC (BNL) 2000-present Heavy ions with $\sqrt{s} = 200$ GeV per nucleon
    - Also, polarized protons with $\sqrt{s} = 500$ GeV

$\sqrt{s} \equiv$ center of mass energy