Particle Physics Phenomenology

May 11, 2004
Detectors

- Interaction of Charged Particles and Radiation with Matter
  - Ionization loss of charged particles
  - Coulomb scattering
  - Radiation loss by electrons
  - Absorption of $\gamma$-rays in Matter
- Detectors of Single Charged Particles
  - Pictorial Detectors: Cloud Chambers, Emulsions, Streamer Chambers, Spark Chambers, Bubble chambers
  - Proportional counters, Spark and streamer chambers, Drift chambers, Scintillation counters, Cerenkov counters, Solid-state counters
- Shower Detectors and Calorimeters
  - Electromagnetic-shower detectors
  - Hadron-shower detectors

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Shower Detectors and Calorimeters

- Particle energies can be measured by absorbing the energy of an incident particle and measuring the signals generating in the absorber.
- The absorbed energy appears as ionization, excitation, radiation, or other signals proportional to the total absorbed energy.
- Examples:
  - ionization in liquid argon
  - Cerenkov radiation in lead glass
  - scintillation light in scintillating plastic
- Such devices are important method of detection of neutral particles, such as
  - gammas
  - $K^0_L$
  - neutrons
Shower Detectors and Calorimeters

- Typical tracking detectors have resolutions that deteriorate with increasing energy since the bending in a magnetic field is reduced.

- Absorption detectors, on the contrary, improve with increased energy, often improving as $E^{-1/2}$.

- Total absorption detectors also provide very fast signals, which are often employed as fast triggers for experiments.
Electromagnetic Cascades

- Electromagnetic cascades are the basis for electromagnetic shower detectors
- High-energy electrons and photons incident on an absorber initiate electromagnetic cascades as pair production and bremsstrahlung generate more electrons and photons with lower energy
- Longitudinal development is governed by the high-energy part of the cascade, and scales as the radiation length in the material
- Electron energies eventually fall below the critical energy, and then dissipate their energy by ionization and excitation rather than by the generation of more shower particles.
- In describing shower behavior, it is therefore convenient to introduce the scale variables
  \[ t = x/X_0 \]
  \[ \gamma = E/E_c \]
  so distance is measured in units of radiation length and energy in units of critical energy.
Electromagnetic Cascades

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

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>( E_c ), MeV</th>
<th>( X_0 ), g cm(^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen</td>
<td>1</td>
<td>340</td>
<td>63.1</td>
</tr>
<tr>
<td>helium</td>
<td>2</td>
<td>220</td>
<td>94.3</td>
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<tr>
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Electromagnetic Cascades

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

\[t_{\text{max}} = (a - 1)/b = 1.0 \times (\ln y + C_j)\]

\[C_e = -0.5\]
\[C_\gamma = +0.5\]
Electromagnetic Cascades

Transverse Profiles

- The transverse profiles of electromagnetic cascades are nicely represented by the Moliere radius ($R_M$)

$$R_M = \frac{X_0 E_s}{E_c} \quad (E_s = 21 \text{ MeV})$$

- Typical relations
  - $\sim 10\%$ of energy outside $R_M$
  - $\sim 99\%$ of energy within $3.5 R_M$
  - shower characterized by narrow core that broadens as the shower develops

$$f(r) = \frac{2r R^2}{(r^2 + R^2)^2}$$

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Electromagnetic Cascades

Lengths of showers

- The lengths of showers scale as $1/E_c$
  - this results from the fact that when the particles of the shower reach the critical energy, radiation ceases and the energy is deposited as ionization.
Electromagnetic Cascades

Review of Main Qualitative Features

- Maximum occurs at a depth that increases logarithmically with primary energy
- The number of shower particles at the maximum is proportional to the primary energy
- The total track-length integral is proportional to the primary energy
- Fluctuations in the total energy deposited about the average varies inversely with the square root of the number of particles in the shower, or inversely as the square root of the primary energy
Electromagnetic-shower Detectors

- Each calorimeter will detect a specific response which is proportional to the shower development, but may vary from technique to technique
  - energy deposition
  - track length
  - threshold energy

Table 24.5: Resolution of typical electromagnetic calorimeters. $E$ is in GeV.

<table>
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<th>Detector</th>
<th>Resolution</th>
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<tr>
<td>NaI(Tl) (Crystal Ball [72]; 20 $X_0$)</td>
<td>2.7%/\sqrt{E}</td>
</tr>
<tr>
<td>Lead glass (OPAL [73])</td>
<td>5%/\sqrt{E}</td>
</tr>
<tr>
<td>Lead-liquid argon (NA31 [74]; 80 cells: 27 $X_0$, 1.5 mm Pb + 0.6 mm Al + 0.8 mm G10 + 4 mm LA)</td>
<td>7.5%/\sqrt{E}</td>
</tr>
<tr>
<td>Lead-scintillator sandwich (ARGUS [75], LAPP-LAL [76])</td>
<td>9%/\sqrt{E}</td>
</tr>
<tr>
<td>Lead-scintillator spaghetti (CERN test module) [77]</td>
<td>13%/\sqrt{E}</td>
</tr>
<tr>
<td>Proportional wire chamber (MAC; 32 cells: 13 $X_0$, 2.5 mm tpe metal + 1.6 mm Al) [78]</td>
<td>23%/\sqrt{E}</td>
</tr>
</tbody>
</table>

Note: at very high energy these resolutions will be limited by the size of the constant term.
Electromagnetic-shower Detectors

Homogeneous Calorimeters

- Lead Glass
- NaI
- BGO
- BaF$_2$
- CeF$_3$
- CsI

- *e.g. BaBar, 5760 crystals the barrel
  - 820 in the endcap*
Electromagnetic-shower Detectors

Sampling Calorimeters

- Examples:
  - lead-scintillator
  - lead-liquid argon
  - silicon-tungsten
Electromagnetic-shower Detectors

Lead-scintillator

- Example: CDF barrel
  - 0.5 cm thick scintillator
  - 0.32 cm Pb absorber
  - 31 layers = 18 $X_0$
Electromagnetic-shower Detectors

Lead- liquid argon

- Example: SLD Calorimeter
  - 2 mm Pb
  - 2.75 mm Argon
  - 56 layers = 21 $X_0$
Electromagnetic-shower Detectors

Silicon- tungsten

- SLD Luminosity Monitor
  - 3.5 mm tungsten
  - 3.5 mm gaps for insertion of silicon diode detectors
  - 23 layers = 21 $X_0$
Electromagnetic-shower Detectors

Silicon- tungsten
Hadron-shower Development

- Hadron showers are more complicated
  - nuclear interactions absorb energy from the shower
  - this loss of energy typically removes 30% of the incident particle energy, but fluctuations in the number and nature of the nuclear interactions give this loss large fluctuation
  - therefore, the energy resolution is much worse than for electromagnetic calorimeters
    - the best is about 35% / \sqrt{E}
    - many of the best calorimeters achieve only 50-70% / \sqrt{E}
    - note: an additional constant term can be large (see compensation)

- Scale length:
  \[ \lambda_I \approx 35 \text{ g cm}^{-2} A^{1/3} \]

- Shower maximum:
  \[ x/\lambda_I \approx t_{\text{max}} \approx 0.2 \ln(E/1 \text{ GeV}) + 0.7 \]
Hadron-shower Development

- Average shower profiles
- Fluctuations about the average are very large
Hadron-shower Development

- Shower containment
Hadron-shower Development

- The response of a calorimeter to the electromagnetic component (primarily from $\pi^0$ s) is much different than the response to the charge hadrons. Fluctuations from shower to shower in the fraction of energy deposited electromagnetically translates into energy resolution fluctuations, unless the calorimeter is “compensating”

- Compensating refers to the restoring of a balance in the calorimeter response to EM and charged energy deposition
  - this can be achieved by boosting the signal when energy is lost through nuclear breakup - the original technique of Uranium calorimetry (Willis et al)
  - or by suppressing the response when energy is deposited by electromagnetic sub-showers
Hadron-shower Development

- The hadronic component showers have been shown to be well described by $(E/E_0)^{m-1}$
  - $0.80 < m < 0.85$
  - $E_0 \sim 1 \text{ GeV}$ for pions
  - $E > \text{ few tens of GeV}$

- Then the ratio of the response of the calorimeter to the two components is
  \[ \frac{\pi}{e} = 1 - (1 - h/e)(E/E_0)^{m-1} \]

- where $e/h$ is the intrinsic response

- **Calorimeters with $e/h$ close to one are then “compensating” and tend to have the best energy performance**
 Hadron-shower Detectors

- It was discovered in the 1980’s that the proper combination of scintillator and uranium achieved the best compensating calorimeter.

- This was implemented by ZEUS at HERA
  - 3.3 mm U, 2.6 mm scintillator

\[
\begin{align*}
&35\% / \sqrt{E} + 1\% \text{ for hadrons} \\
&17\% / \sqrt{E} + 1\% \text{ for electrons}
\end{align*}
\]
Hadron-shower Detectors

Figure 4: GEANT simulation of $e^+e^- \rightarrow Z^0\gamma(120\ GeV)$ event. The inner region of this figure corresponds to the tracker and the inner surface of the electromagnetic calorimeter is evident from the onset of photon conversions[9].
Hadron-shower Detectors

Energy flow calorimeters

- Since the tracker of a detector is more precise than the calorimeter in detecting charged particles, a measurement of jet energies based on the “energy flow” can give better jet energy measurements than a calorimeter alone measurement.

![Diagram showing comparison between E-Cal and Tracker in terms of energy resolution.](image)
Hadron-shower Detectors

Energy flow calorimeters

- To do this well requires a separation of the signals in the calorimeter from charged and neutral particles.

Fig. 3 Separation of charged and neutral particles in calorimeters
Hadron-shower Detectors

Energy flow calorimeters

- The linear collider projects are studying a silicon-tungsten calorimeter for this:
  - densest calorimeter
    - confines showers
  - most granular segmentation
    - allows readout of details
  - builds on experience with silicon calorimeters at SLD and LEP
Detectors

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