SLUO LECTURE SERIES

Calorimetry I

LECTURE # 13

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SLUO Detector Techniques Series
Introduction

- Calorimeters are used to measure energy of neutral and charged particles
  - neutral particles cannot be momentum analyzed
  - electrons can be measured with better precision, and identified with a calorimeter
  - as energy increases
    - momentum measurements are less precise \[\sigma_p / p \sim p\]
    - energy measurements become more precise \[\sigma_E / E \sim 1 / E^{1/2}\]
- jets are often best measured by total absorption rather than measurement of individual particles
Introduction (cont.)

- Fundamental underlying principle: conservation of energy
  - convert energy of incident particle to detector response
    - ionization
    - Cerenkov radiation from charged particles
    - scintillation of excited molecules
    - acoustic energy
    - .............

- Details of this conversion complicate measurement
  - this is especially true for strongly interacting particles (hadrons)
Outline

- Introduction
  - examples of important applications
- Electromagnetic showers
  - fundamental processes
  - characteristics of showers
- Electromagnetic Calorimeters
  - resolution
  - examples of calorimeters

- Next week: Hadron Calorimetry
Calorimeters are subdivided into electromagnetic and hadronic subdetectors

- Electromagnetic interactions develop over shorter distances than hadronic interactions
- Fundamental processes of signal generation differ, calling on different optimization
Evolution of Calorimeters

• Nuclear Physics
  • the advances of solid state detectors in the '50s broadened the technique of total absorption and energy measurement of nuclear radiation

• Cosmic Rays
  • 1958 - JETP 7, 348 (1958)
    Grigorov, Murzin and Rapoport report construction of first sampling calorimeter

• Particle Physics
  • First electromagnetic calorimeters, eventually hadronic calorimeters became essential components
Evolution of Calorimeters (cont.)

- **Uranium/Compensation**
  - in an effort to advance energy resolution, Willis et al introduced uranium calorimeters (1975) to "compensate" for the lost energy in nuclear collisions.
  - Zeus took the emerging understanding of the underlying mechanisms in hadronic showers to build the best hadronic calorimeter to date, uranium - scintillator

- **High Precision Electromagnetic Calorimetry**
  - Crystals have continued to advance
  - Other techniques, as well, are pushing the performance limits
    - e.g., accordion liquid argon
    - scintillating fiber calorimeters
Evolution of Calorimeters (cont.)

- Today, calorimeters are in widespread use in particle physics
  - $4\pi$ detectors at colliders
    - energy measurements
    - particle identification
    - triggers
  - neutrino detectors at accelerators
  - underground proton decay detectors
  - underground neutrino detectors
- and in astrophysics
  - space-based detectors (---GLAST)
  - air showers
Examples of Calorimetry in Discovery

• Discovery of the anti-proton
  • Total absorption lead glass detector used to identify anti-proton annihilations.

• Discovery of the τ
  • Detection of electron-muon + missing energy events identified.

• Charm Spectroscopy
  • The radiative lines were studied in charmonium. (see figure)

• Discovery of the W
  • High transverse energy electron was detected and measured, and the recoiling neutrino was deduced and shown to balance the electron. (see figure)
Examples of Calorimetry in Discovery (cont.)

- **Measurement of $A_{LR}$**
  - The SLD Calorimeter provides the primary instrument for triggering and event tagging.

- **$W$ mass measurement**
  - Di-jet events are reconstructed.

- **$e^+e^- \rightarrow \gamma + \text{missing energy**}**
  - Measurements of EM showers, combined with missing energy in the hadron calorimeter. (see figure)

- **Higgs $\rightarrow \gamma\gamma$ (future?)**
  - The preferred channel for discovery at LHC has an enormous background; high precision is demanded. (see figure)
Charm Spectroscopy

- The Crystal Ball
Discovery of the W

- High transverse energy electron was detected and measured, and the recoiling neutrino was deduced and shown to balance the electron
$e^+e^- \rightarrow \gamma + \text{missing energy}$

**Photonic events with missing $E_T$**

- Standard Model measurement $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$
- New physics: $\tilde{\chi}_0\tilde{\chi}_0^0$ (LSP), $\tilde{\chi}_0\tilde{\chi}_0^0$ (light $\tilde{G}$ LSP), $\nu^*\bar{\nu}$

**Single photon recoil mass**

![Graph showing single photon recoil mass distribution](image)

**Acoplanar photons recoil mass**

![Graph showing acoplanar photons recoil mass distribution](image)
Higgs $\rightarrow \gamma \gamma$ at the LHC

- Outstanding EM resolution is needed to discover the Higgs $\rightarrow \gamma \gamma$ at a hadron collider (LHC)
Ideal Calorimeter

- excellent energy resolution
- stable calibration
- excellent position resolution
- large dynamic range
- excellent shower containment with multi-shower separation
- compact
- fast (high rate capability)
- operates in a magnetic field
- inexpensive
- robust

Compromise is always required
Electromagnetic and Hadronic Showers

- **Electromagnetic**
  - multiplication through pair production and bremsstrahlung
  - mean free path $9X_0/7$ for $\gamma$
  - $X_0/\ln(E/k)$ for $e$
  - no invisible energy

- **Hadronic**
  - multiplication through multiparticle production in nuclear interactions
  - mean free path $\sim \lambda$
  - nuclear binding energy and neutrinos invisible
Electromagnetic Showers

- In matter high energy electrons and photons interact primarily through electromagnetic interactions with the nucleus (and at lower energies with the atomic electrons)
- Electrons
  - Bremsstrahlung (nuclear)
- Photons
  - Compton scattering (atomic electrons)
  - pair production (nuclear)
  - photoelectric effect (atomic electrons)
Electromagnetic Showers: Electrons

- Bremsstrahlung

\[
\frac{dE}{dx} \bigg|_{\text{brems}} \approx \frac{E}{X_0}
\]

\[
X_0 \sim \frac{716 \, \text{g cm}^{-2} \, \text{A}}{Z (Z+1) \ln (287/12)}
\]
Electromagnetic Showers: Electrons (cont.)

- Electron energy loss

![Graph showing electron energy loss as a function of energy (MeV). The graph includes curves for Ionization, Electrons, Positrons, Bremsstrahlung, Moller (e^-), Bhabha (e^+), and Positron annihilation. The y-axis is labeled as \(-\frac{dE}{dx}\) in units of L^{-1} rad, and the x-axis is labeled as E (MeV). The y-axis ranges from 0 to 0.2, and the x-axis ranges from 0 to 1000. The units cm^2/g are also indicated on the y-axis.}
Electromagnetic Showers: Electrons (cont.)

• Critical Energy ($E_c$)

At high energy, the energy loss of an electron from bremsstrahlung dominates over ionization loss.

At a low enough energy, the ionization loss becomes important.

The energy at which ionization loss equals bremsstrahlung loss, is the critical energy ($E_c$)

(eg. $E_c \sim 7$ MeV for Lead - see last and next transparencies)
Electromagnetic Showers: Electrons (cont.)

- Critical energies of materials

\[ E_c = \frac{610 \text{ MeV}}{Z + 1.24} \quad \text{and} \quad E_c = \frac{710 \text{ MeV}}{Z + 0.92} \]

\( E_c \) (MeV) vs. \( Z \)

- Solids
- Gases
Electromagnetic Showers: Photons

- Compton scattering

- pair production

- photoelectric effect
Electromagnetic Showers: Photons (cont.)

Photon cross sections

![Graphs showing photon cross sections for Carbon (Z=6) and Lead (Z=82).](image)
Many important properties of an EM shower can be understood by a simple model:

- after one radiation length a photon produces an $e^- e^+$ pair
- the electron and positron each emit one bremsstrahlung photon after another radiation length.

\[ N(t) = 2^t \quad \text{(for} \ t \ \text{steps)} \]

\[ E(t) = E_0 / 2^t \]
Electromagnetic Showers

Illustration of simple model of shower
Electromagnetic Showers

- Longitudinal development scales with the radiation length ($X_0$)
  $$X_0 \approx 180 \frac{A}{Z^2} \frac{g}{cm^2}$$
  (higher Z materials have shorter radiation lengths).

- Transverse dimension scales with the Moliere radius ($R_M$)
  $$R_M \approx 21 \text{ MeV} \frac{X_0}{E_c}$$
  where $E_c \approx 550 \text{ MeV} / Z$
## Typical Scales for EM Calorimeters

<table>
<thead>
<tr>
<th>Material</th>
<th>Atomic No.</th>
<th>Critical Energy ($E_c$) (MeV)</th>
<th>Radiation Length ($X_0$) (g/cm$^2$)</th>
<th>Moliere Radius ($R_M$) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beryllium</td>
<td>4</td>
<td>116._</td>
<td>65.19</td>
<td>35.28</td>
</tr>
<tr>
<td>Carbon</td>
<td>6</td>
<td>84._</td>
<td>42.70</td>
<td>18.8_</td>
</tr>
<tr>
<td>Aluminum</td>
<td>13</td>
<td>43._</td>
<td>24.01</td>
<td>8.9_</td>
</tr>
<tr>
<td>Iron</td>
<td>26</td>
<td>22._</td>
<td>13.84</td>
<td>1.76</td>
</tr>
<tr>
<td>Copper</td>
<td>29</td>
<td>20._</td>
<td>12.86</td>
<td>1.43</td>
</tr>
<tr>
<td>Tungsten</td>
<td>74</td>
<td>8.1</td>
<td>6.76</td>
<td>0.35</td>
</tr>
<tr>
<td>Lead</td>
<td>82</td>
<td>7.3</td>
<td>6.37</td>
<td>0.56</td>
</tr>
<tr>
<td>Uranium</td>
<td>92</td>
<td>6.5</td>
<td>6.00</td>
<td>0.32</td>
</tr>
</tbody>
</table>
EM Showers: Longitudinal Development

- Electrons generate photons through bremsstrahlung and photons produce electrons and positrons through pair production.
- The observed development depends on the minimum kinetic energy of an electron or a positron that can be detected (known as the cut-off energy).

This means the shower maximum will occur when the energy falls to $E_c$:

$$E_c = \frac{E_0}{2^{t_{\text{max}}}} ,$$

or

$$t_{\text{max}} \sim \ln \left( \frac{E_0}{E_c} \right)$$
EM Showers: Longitudinal Development (cont.)

- Approximate formula \((t=x/X_0)\):

\[
dE/dt = E \frac{b^{\alpha+1} t^\alpha e^{-bt}}{\Gamma(\alpha+1)}
\]

\(b \sim 0.5\) (material dependent)
\(\alpha = 0.5 \ln(E_0/E_c) - 1.1\)
\(+0.8 \text{ for } \gamma\)

So \(t_{\text{max}} = \frac{\alpha}{b} \sim \ln(E_0/E_c) - \)

\(t_{95\%} \approx t_{\text{max}} + 0.08Z + 9.6\)
- Best fits are achieved with $b$ adjusted for material and energy

\[ b = \frac{E}{E_c}, \]
Longitudinal development (cont.)

An example of longitudinal development (30 GeV electron induced shower in iron)
- Effect of critical energy on longitudinal energy distribution
  - shower maximum
  - shower tail

Figure 2.19  Longitudinal distribution of energy deposition in a 6-GeV electron shower (after Bathow et al. 1970).
Electromagnetic Showers: Radial distribution

- Scales with Moliere radius
  \( \text{Al}(Z=13) \quad R_M = 4.4 \text{ cm} \)
  \( \text{Cu}(Z=29) \quad R_M = 1.5 \text{ cm} \)
  \( \text{Pb}(Z=82) \quad R_M = 1.6 \text{ cm} \)
- \(~90\%\) of energy is within \(R_M\), and
  \(~95\%\) of energy is within \(2R_M\).
Electromagnetic Showers: Calorimetry

- The energy of the incident electron or photon is proportional to the total track length of the electrons and positrons in the EM shower.
- Therefore, by measuring the electron+ positron track lengths, one measures a variable which is proportional to energy.
- Measurements of:
  - Cerenkov radiation from e⁻ & e⁺
  - Scintillation from molecules in calorimeter
  - Ionization of the detection medium
Electromagnetic Showers: Calorimetry (homogeneous or sampling)

- **Homogeneous calorimeter:**
calorimeters in which the shower is "observed" throughout the detector
  
  examples: lead glass, NaI, CsI, BGO, BaF

- **Sampling calorimeter:**
calorimeters in which the shower is sampled by an "active" readout medium alternated with denser radiator material
  
  examples: scintillator sandwich, scintillating fiber, liquid argon, silicon, liquid scintillator
Electromagnetic Calorimetry: homogeneous vs. sampling tradeoffs

- **Homogeneous**
  - better energy resolution
  - observation of full shower
  - limited spatial resolution
  - segmentation is limited to preserve energy resolution

- **Sampling**
  - limited energy resolution
  - sampling fluctuation
  - good spatial resolution
  - segmentation gives detailed shower shape information
Electromagnetic Showers: Fluctuations

- The measurement of energy will be limited in precision by fluctuations in the EM shower and in the measurement process.
- The shape of an EM shower fluctuates only modestly, and resolution of an EM calorimeter is usually limited by other effects (assuming full containment has been achieved).
- Dominant fluctuation in the shower is the depth of the first pair conversion.
EM Calorimeters: Energy Resolution

- Sampling Fluctuations (a)
- Noise (b)
- Pedestal Fluctuations (b)
- Nonuniformities (c)
- Calibration errors (c)
- Incomplete shower containment (leakage) (c)

\[ \sigma/E = a/\sqrt{E} \oplus b/E \oplus c \]
The calorimeter is measuring total track length. This track length \( S \) will fluctuate as \( S^{1/2} \) so that the energy measurement will have an error which scales as (since \( E \sim S \) )

\[
\frac{\sigma}{E} \sim E^{-1/2}
\]

In a sampling calorimeter we have the further scaling law that the resolution will scale with the sampling thickness

\[
\frac{\sigma}{E} \sim t^{1/2} / E^{1/2}
\]

The limiting resolutions are

\[
(\frac{\sigma}{E})_{\text{shower}} \sim 0.005 \; E^{-1/2}
\]

\[
(\frac{\sigma}{E})_{\text{sampling}} \sim 0.04 \left(1000 \; \Delta E / E \right)^{1/2}
\]
EM Calorimeters: Energy Resolution (longitudinal leakage)
50 GeV
EM Shower
Examples of EM Calorimeters (pdg)

- NaI(Tl) \[ 2.7\% / E^{1/4} \]
- Lead Glass \[ 5\% / E^{1/2} \]
- Lead-liq. argon \[ 7.5\% / E^{1/2} \]
- Lead-scin. sand. \[ 9\% / E^{1/2} \]
- Lead-scin. spaghetti \[ 13\% / E^{1/2} \]
- Prop. wire chamber \[ 23\% / E^{1/2} \]

- most of these resolutions must be added in quadrature with the appropriate constant term, typically on the order of 1\%, or a bit smaller.
- Better resolution has been achieved with most advanced crystals (eg. CsI)
Position and Pointing Resolution

- The measurement of the impact point of a photon entering an EM calorimeter is limited by the transverse fluctuations in the shower, and the measurement errors of this measurement.

- This measurement involves determining the centroid of the shower as a function of depth in the calorimeter.

- Typically, the achievable resolution is: few mm / E^{1/2}
Position and Pointing Resolution (cont.)

- More challenging than position impact position measurement, is a measurement of the direction of the incident particle
  - This is particularly important at high luminosity colliders where multiple event occur within the same beam crossing (or readout window)
- Atlas has achieved about
  - 40 mrad / $E^{1/2}$ (see figure)
- Position resolution often reflects on the electron identification performance
Examples of Recent Advances in EM Calorimeters

• Accordion liquid argon calorimeter
• Radiation resistant crystals
• Silicon luminosity monitors
• Scintillating Fiber
• CsI
  • CLEO
  • KTeV
  • BaBar (thallium doped)
  • BELLE (thallium doped)
Accordion Liquid Argon Calorimeter

- fast readout
  - combines electrode and transmission line
- amenable to very fine readout
Excellent performance has been demonstrated in beam tests.

\[ \eta = 0.28 \]
\[ a = (9.99 \pm 0.29) \% \]
\[ b = (282.2 \pm 16.9) \text{ MeV} \]
\[ c = (0.35 \pm 0.04) \% \]

\[ \eta = 0.9 \]
\[ a = (10.42 \pm 0.33) \% \]
\[ b = (386.6 \pm 15.6) \text{ MeV} \]
\[ c = (0.27 \pm 0.08) \% \]
• Atlas measures the position of the shower at front and back of calorimeter to get a vector.
Liquid Krypton (in ATLAS tests)

- better sampling fraction
- double to signal
- saturated drift velocity
CMS Plans a 83,000 crystal calorimeter in the hostile environment of the LHC

- 1 krad/day
Radiation resistant Crystal Calorimeters (cont.)

- \( \text{PbWO}_4 \) (Lead Tungstate)
  - very dense
  - fast
  - intrinsically rad hard
- Radiation damage mechanism now better understood
  - scintillation light yield is not significantly damaged by radiation
  - predominant radiation damage effect is radiation induced absorption
- Rad-hard crystal R&D continues
Silicon Calorimetry: Luminosity Monitors

- SLD built first silicon luminosity monitor (installed in 1991); it has provided reliable performance.
- OPAL improved on the design with a silicon calorimeter that achieves < 0.04% luminosity measurement.
Silicon Calorimetry: OPAL Luminosity Monitor (cont.)

OPAL SW
RUN 4396 EVENT 101432

LEFT END (-Z)

Longitudinal Shower Profile
Lateral Shower Profile

RIGHT END (+Z)

Cluster Energy 44.998 GeV
Layer with max. Shower 5
Tower with max. Shower 12
Row with max. Shower 9

Cluster Energy 44.836 GeV
Layer with max. Shower 7
Tower with max. Shower 4
Row with max. Shower 10
Silicon Calorimetry: OPAL Luminosity Monitor (cont.)

45 GeV Electron Lateral Shower Profiles

Shower at 4 $X_0$

Shower at 6 $X_0$

Shower at 8 $X_0$

54
Scintillating Fiber EM Calorimeters

- Latest application - KLOE:
  - scintillating fiber (1 mm diameter) - lead calorimeter at DAFNE, the phi factory at Frascati
  - Fiber:Lead:Glue = 50:40:10

- Beam test performance:

  \[ \sigma/E = (4.96 \pm 0.01)\% / \sqrt{E} \]

- Very fast:

  \[ \sigma_T = 71.7 \pm 1.0 \text{ psec} / \sqrt{E} \]
Cesium Iodide

- CLEO has an excellent history with CsI and BaBar and BELLE will soon.

- KTeV has completed physics run with CsI
  - outstanding performance has been achieved.

\[ \sigma / E = 2\% \sqrt{E} \oplus 0.2\% \oplus 0.4\% \]

- The π/e rejection is 680/1, based on a shape \( \chi^2 \)
Compact, Highly Segmented Calorimeter for the NLC

- Highly segmented silicon/tungsten EM calorimeter for the NLC
  - motivated by desire to separate EM showers from charged tracks in the jet environment
  - 4 million readout cells, very dense
Summary

- Electromagnetic Showers are very well understood theoretically.
- Electromagnetic Calorimeters are continuing to advance many varieties. For example:
  - crystals
  - accordion liquid argon
  - silicon sampling
  - scintillating fibers
- Optimization is always a trade-off between competing constraints.
100 GeV
Hadronic Shower
Hadronic Showers

- Hadronic Showers are much more complex than EM showers, and hadron resolution is more limited (eg. the best performance of hadron calorimeters is $\sim 30\% / E^{1/2}$)
- Next week - Hadronic Calorimetry
References