Calorimeters

Alexander Khanov

PHYS6260: Experimental Methods is HEP
Oklahoma State University

September 25, 2017
Calorimeters and trackers

- Modern HEP detectors have an “onion”-like structure: they consist of trackers and calorimeters.

<table>
<thead>
<tr>
<th>Trackers</th>
<th>Calorimeters</th>
</tr>
</thead>
<tbody>
<tr>
<td>measure particle momenta</td>
<td>measure particle energies</td>
</tr>
<tr>
<td>massless (ideally)</td>
<td>massive</td>
</tr>
<tr>
<td>resolution deteriorates with momentum</td>
<td>resolution improves with energy</td>
</tr>
</tbody>
</table>

- Tracker: $\frac{\sigma(p_T)}{p_T} \sim p_T$
  - this is asymptotic at large momenta, $\sigma(p_T)/p_T^2$ increases below few GeV due to multiple scattering.

- Calorimeter: $\frac{\sigma(E)}{E} \sim \frac{1}{\sqrt{E}}$
  - resolution improves at high $E$ due to increasing multiplicity of secondary particles.
Particles which can be measured by calorimeters

- Calorimeters measure both charged and neutral particles (unlike the trackers)
- Calorimeters can’t measure energies of muons (they still get registered with minimum ionization energy but escape the calorimeter volume)
- Neutrinos always escape detection (by both calorimeters and trackers)
- Calorimeters are great for measuring jets (collimated packs of many particles), they measure their total energy without separating the particles
  - as the jets are typically created in hadronization of energetic quarks and gluons, calorimeters provide a good proxy for quark/gluon energy
  - we still need the tracker to learn about the jet properties, e.g. to figure out the flavor of the quark that gave rise to the jet
Electromagnetic and hadronic calorimeters

- The particles that enter the calorimeter create a cascade, or a “shower”
- Electrons and photons create electromagnetic showers that are characterized by the radiation length $X_0$
- Hadrons (pions, kaons, protons, neutrons) create hadronic showers that are characterized by the nuclear interaction length $\lambda$

<table>
<thead>
<tr>
<th>material</th>
<th>$X_0$ [g/cm$^2$]</th>
<th>$\lambda$ [g/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>13.8</td>
<td>132</td>
</tr>
<tr>
<td>U</td>
<td>6.0</td>
<td>209</td>
</tr>
</tbody>
</table>

- To contain the shower, the calorimeters must be many interaction lengths deep
  - “many” = $15 - 30X_0$ for electromagnetic, $5 - 8\lambda$ for hadronic
- In practical setups there are usually two calorimeters, electromagnetic followed by hadronic
Electromagnetic cascade development

- High energy electrons produce photons through bremsstrahlung, and high energy photons produce electron-positron pairs.
- As the depth increases, the number of secondary particles increases, but their energy decreases.
- Eventually, the multiplication ceases as all particles fall below the critical energy and dissipate the rest of their energies through ionization and excitation.
- A simple EM shower model includes two parameters: radiation length $X_0$ and critical energy $E_c$ ($E_c=24$ MeV for Fe, 6 MeV for U).
- If $t = \frac{x}{X_0}$, $y = \frac{E}{E_c}$, then the particle energy $e(t) = \frac{E}{2^t}$ and the number of particles $n(t) = 2^t$.
  
  $n(t_{max}) = y$
Lateral shower development

- As the shower develops, it broadens laterally due to multiple scattering
  - The characteristic size of the shower is Moliere radius, \( R_m \sim 7A/Z \) [g cm\(^{-2}\)]

- Calorimeters are made of “cells” (small separately read out sections), with the size close to the Moliere radius
  - due to leakage to neighboring cells, the energy is read out by more that one cell which improves the energy resolution due to extrapolation
Hadronic cascade development

- Due to strong interactions, hadrons produce showers similar to those from electrons and photons
- One can develop a hadronic shower model similar to that for the electromagnetic showers
  - instead of critical energy, one can use pion production threshold $E_{th} \approx 2m_\pi$
- If $\nu = \frac{x}{\lambda}$, then the particle energy $e(\nu) = \frac{E}{\langle n \rangle_\nu}$, $e(\nu_{\text{max}}) = E_{th}$
- The number of particles is smaller than in the electromagnetic cascade by the ratio $E_{th}/E_c$
  - the resolution of hadronic calorimeter is worse
Homogeneous and sampling calorimeters

- How to measure the shower energy?
  - all methods we discussed so far are good
  - popular ways: measure ionization, scintillation, Cherenkov radiation

- The calorimeter can be designed in such a way that the medium where the showers occur is also used to produce the measured signal (scintillation, Cherenkov radiation): this is called homogeneous calorimeter (ECAL only)
  - CMS ECAL: scintillating crystals (PbWO$_4$) read out by VPT (Vacuum Photo Triods)
  - OPAL ECAL: cherenkov radiator (Pb glass)

- Alternatively, the calorimeter may consist of several layers of inactive material (Pb, W, U) mixed with active layers (scintillators, silicon strip detectors, gaseous detectors): this is called sampling calorimeter
  - ATLAS ECAL: liquid argon (active) and lead (passive) – “accordion” (ionization chamber)
  - CMS HCAL: scintillating optical fibers (active) and copper from Russian Navy shells (passive)
Compensation in HCAL

- Hadron showers always have electromagnetic component due to $\pi^0$ production ($\pi^0 \rightarrow 2\gamma$)
- A typical hadronic calorimeter does not have the same response to electrons and pions
- The ratio of detection efficiencies for electrons/photons and hadrons is known as the $e/h$ (or $e/\pi$) ratio
- $e/h \neq 1$ means problems
  - response depends on particle energies
  - resolution does not scale as $1/\sqrt{E}$
- by careful choice of the active/inactive medium combination, one can improve the $e/h$ ratio
  - ZEUS calorimeter: U/scintillator or Pb/scintillator?
    - choice: U (much better sampling)

<table>
<thead>
<tr>
<th>material</th>
<th>U</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>compensating absorber/scintillator ratio</td>
<td>1:1</td>
<td>4:1</td>
</tr>
<tr>
<td>intrinsic fluctuations (hadrons)</td>
<td>20%</td>
<td>13%</td>
</tr>
<tr>
<td>intrinsic fluctuations (EM)</td>
<td>2.2%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>