Calorimeters

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Calorimeters and trackers

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

Trackers	Calorimeters
measure particle momenta	measure particle energies
massless (ideally)	massive
resolution deteriorates with momentum	resolution improves with energy

- Tracker: $\dfrac{\sigma(p_T)}{p_T} \sim p_T$
  - this is asymptotic at large momenta, $\sigma(p_T)/p_T^2$ increases below few GeV due to multiple scattering
- Calorimeter: $\dfrac{\sigma(E)}{E} \sim \dfrac{1}{\sqrt{E}}$
  - 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
- Hadrond (pions, kaons, protons, neutrons) create hadronic showers that are characterized by the nuclear interaction length λ

material	X_0 [g/cm^2]	λ [g/cm^2]
Fe	13.8	132
U	6.0	209

- To contain the shower, the calorimeters must be many interaction lengths deep
  - "many" $= 15 - 30\, X_0$ 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 $\nu = \dfrac{x}{\lambda}$, then the particle energy $e(\nu) = \dfrac{E}{\langle n \rangle^\nu}$, $e(\nu_{\max}) = E_{th}$
- 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 π^0 production ($\pi^0 \to 2\gamma$)
- 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/π) 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?

material	U	Pb
compensating absorber/scintillator ratio	1:1	4:1
intrinsic fluctuations (hadrons)	20%	13%
intrinsic fluctuations (EM)	2.2%	0.3%

  - choice: U (much better sampling)