Hadron showers

Hadrons (think mainly π^+,π^-) interact with nuclei in material with characteristic interaction length $\lambda = 35\ (\mathrm{g\ cm^{-2}})\ A^{1/3} / \rho$. Exercise: What assumptions about nuclear matter and hadrons will lead you to expect that $\rho\lambda$ scales with $A^{1/3}$?

Element	λ (cm)	X_0 (cm)
Be	41	35
Si	45	9.4
Fe	17	1.8
Pb	10.5	0.56

Typical hadron interaction lengths, with radiation length for comparison.

When a high energy hadron hits material a shower develops. Hadron showers are complex. Many possible interactions (compared with just brems and pair prod for EM shower). Hadron interactions generally produce many products (EM are all $1\rightarrow2$). Even in dense materials λ is ~10 cm, many interaction lengths are required to absorb a hadron shower; hadron calorimeters need to be massive. Width of hadron shower is of order λ. Among the products of hadron collision with a nucleus can be:

• π^+,π^-, p • π^0 (promptly followed by $\pi^0 \rightarrow \gamma\gamma$) • n, K^0
• nuclear decay products (α,β or γ), maybe prompt or delayed • recoiling nucleus

Hence limitation of hadron calorimeter: no sensor can be made equally sensitive to all these. Main effect is fluctuations in the electromagnetic component of hadron induced showers.

Calorimeters

- Designed to contain EM or H showers and produce a signal proportional to the energy of the incident particle (or jet of particles).
- Cover a portion of the solid angle around the interaction point, often nearly 4π.
- Subdivided into cells, so giving energy and direction; momentum measurement.
- Normally one places a calorimeter designed for EM showers in front of one designed for hadronic showers.

Types	**Homogeneous**	**Sampling**. Layers of passive dense material (absorber) alternating with sensitive layers.
Optimised for **electromagnetic** showers. Cell size ≈ (few cm)²	**Dense scintillating crystals**; Bismuth Germanium Oxide, Lead Tungstate, Caesium Iodide. Old tech is lead glass producing Cerenkov. All producing light; readout by PM , photodiode, etc.	Absorber usually **lead**. Tungsten if you have the money. Absorber layer thickness ~0.5 X_0 to produce a significant but not large development of the shower between samples. Sensors: • plastic scintillator > PM etc • **Liquid argon** ionisation chamber • Silicon (expensive).
Optimised for **hadronic** showers. Cell size ≈ (few x 10 cm)²	Not feasible to make such large crystals.	Absorber usually **iron** (cheap, dense, also acts as magnetic field return yoke). Absorber layer thickness ~0.5 λ. Sensor layers: • **plastic scintillator** > PM etc • Liquid argon ionisation chamber • Wire chambers

Calorimeter energy resolution

Conversion of energy to an electrical signal in a calorimeter always ends up being a statistical process. At some point there is a number N that has a Poisson distribution, so resolution = **uncertainty = √N** for large N. N may be number of photons entering a photomultiplier, number of ionising tracks segments crossing sensitive layers in a sampling calorimeter, etc. There is an additional uncertainty due to **imperfect inter-calibration** between; different calorimeter cells, different positions or depths within one calorimeter cell or the response of one cell at different times. This uncertainty, B, is independent of energy and can be kept down to ≤1%, given enough effort. So $\sigma_E/E = A/\sqrt{E(\mathrm{GeV})} \oplus B$. The A term depends a lot of the type of calorimeter:

	Homogeneous	Sampling
EM	2 – 3 %	10 – 20 %
Hadronic		40 – 80 %

In a sampling calorimeter most of the ionisation energy is deposited in the passive layers, only a fraction is deposited in the active layers where it can be measured, so N is smaller and energy resolution is poorer. The proportion of the radiation length made from the active material is called the **sampling fraction**. Can be from <1% for Aleph Lead/gas calorimeter to 5% for Atlas lead/liquid argon calorimeter.

Hadron calorimeters have further difficulties; the many different ionising particles from slow alphas to fast e^+e^-. Alphas, slow protons and fission fragments have very short range - usually do not escape the absorber where they were produced. If they do get into the sensitive layer their high dE/dx may saturate the dynamic range of the amplifier. Some energy deposit is delayed too late to be counted. Some energy ends up as changes to nuclear binding energy which are completely hidden. All this gives hadron calorimeters poorer resolution than EM, but even so they are an important part of high energy collider detectors, essential for jet and missing energy (neutrino) measurement.

Particle Identification

The main tool of particle identification is the multi-layered general purpose particle detector that has evolved over the years. It gives signatures that you probably know already:

	Inner tracker	EM calorimeter	Hadron calo	Muon tracker
Photon	-	Dense shower	-	-
e+ or e-	Track, measure p	Dense shower, position and energy matches track p	-	-
Charged hadron	Track, measure p	Start of diffuse shower	Remainder of diffuse shower, approximate energy match	Maybe some remnants of shower but not well matched to inner track
μ+ or μ-	Track, measure p	Small signal consistent with m.i.p.	Small signal consistent with m.i.p.	Track matches in position and momentum with inner track
jet	Many tracks.	Several showers close together. Sum their energy.	Several showers close together. Sum their energy.	Tails of showers. Rarely muons that match to inner track.

Charged particle identification

Trackers measure charged particle p, which is $m_0\beta\gamma c$. If we have an independent measurement of β then we can calculate m_0 and identify the particle. Usual requirement is either e/π or π/K separation.

Time-of-flight

Conceptually simple, measure flight time over known distance and calculate β. Distances of a few metres, flight times ~10 ns. Practical timing resolution is tenths of ns. Beta resolution will be a few %. Stable particle masses are all < 1 GeV/c^2, hence TOF is only useful **at low energies**.

dE/dx

< dE/dx> is a function of β, independent of m_0, as described by the Bethe-Bloch equation. Because of Landau shape, we need to use statistical tricks to make accurate estimate of <dE/dx> : use **many samples**, eg from a TPC. Use **truncated mean**; rank the sample values and use only the lowest 60% of them in the mean, thus throwing away some of the variability associated with the Landau tail. Can be very effective in momentum range up to 10 GeV/c.

Cerenkov radiation

A particle traversing a transparent medium faster than the speed of light in that medium (c/n) radiates Cerenkov light. Negligible contribution to dE/dx. A weak light source spread over a large frequency range, detectable in the visible to UV. Cerenkov angle **$\cos(\theta_C) = 1/n\beta$**. Wide range of n (and therefore β) is available; gas n=1.001, silica aerogel n=1.007 to 1.13, water n=1.3, quartz n=1.5 . **Imaging Cerenkov: θ_C is measured** by focussing the light, **Threshold Cerenkov**: only presence/absence of light is detected. If $n\beta<1$ no light is produced. Babar application uses quartz bars, total internal reflection, angle measurement when light leaves bar at end.

Transition radiation

A relativistic charged particle crossing a boundary between media with different plasma frequencies (=different electron densities) produces radiation with a probability proportional to relativistic γ. A very weak effect; a high energy electron has O(1%) probability of producing a photon per boundary crossed. Need many boundaries – use foil or foam. TR photons are in X-ray energy range 2-20 keV. Detect with proportional gas counter filled with Xe for its high Z, high X-ray absorption cross section. Atlas application uses straw drift tubes with two pulse height thresholds. Normal mip tracks cross low threshold, electrons accompanied by their TR photons sometimes pass high threshold.