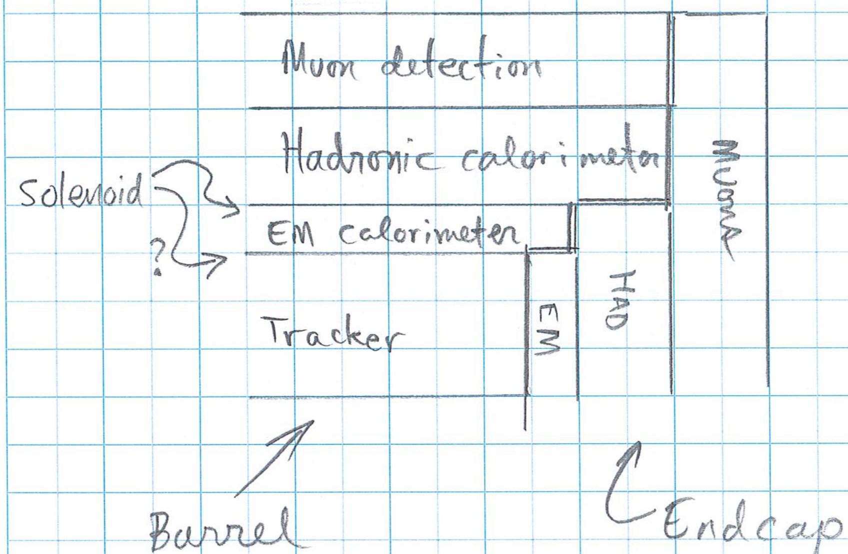
Jet Clustering (in practice)

Typical experimental configuration:



Passive material:

The solenoid could be inside (as in the case of CDF / DØ / ATLAS) or outside (as in the case of CMS)

There is additional structural material and cracks in the overlap region between the barrel and endcap.

The tracker reconstructs the direction of charged particles precisely. Momentum resolution ~

$$\frac{\sigma_{p_T}}{p_T} \sim 1\text{-}2\%$$

Calorimeter energy resolution $\sigma_E \propto \sqrt{E}$ (roughly). Segmented in y and φ into "towers". Given an event vertex, this defines the direction of particles depositing energy.

Composition of jets:

- Primarily hadrons, $\pi^\pm$
- Isospin symmetry $\Rightarrow n(\pi_0) \simeq n(\pi^\pm)$
- $\pi^0 \rightarrow \gamma\gamma$
- Charged kaons (of order 10-20%)
- Neutral kaons (K^0_L and K^0_S)
- protons, neutrons, Λ
- hyperons (may decay in the tracker)

Contributions to jet energy resolution:

- electronic noise, energy offsets
- fluctuations in EM / hadronic components
- uncorrelated energy from underlying event
- uncorrelated energy from pileup

Why do we need good jet energy resolution?

- di-jet mass reconstruction
- efficient selections on jet energy
- jet spectra are usually sharply falling functions of jet p_T. Upward fluctuations can be significant backgrounds to new physics at high jet p_T.

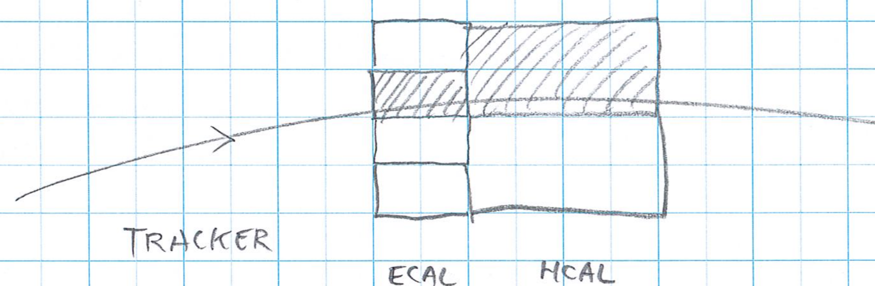
- Important to match / understand response in data and Monte Carlo.

Particle Flow in CMS

Counting both a charged pion detected in the tracker and the energy it deposits in the calorimeter results in double-counting.

On average, 60% of the energy is charged particles
30% is from photons
10% is neutral hadrons.

Basic idea:



1. Extracpolate tracks to the EM and hadronic calorimeters
2. If the energy is consistent with expected energy deposit use the track parameters.
3. Otherwise, subtract the expected energy from the EM and HAD calorimeter clusters.
4. Remaining energy in EM calorimeter are photon candidates, remaining energy in hadronic calorimeter are neutral hadron candidates.

(Muons and electrons receive special treatment)

Pileup

The inelastic pp cross section is about 70 mb at high energies.

$$70 \text{ mb} = 70 \times 10^{-27} \text{ cm}^2$$

Typical LHC luminosity $L = 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

$$N_{inel} = 70 \times 10^{7} \text{ s}^{-1}$$

Time between collisions is 25 ns

$$N_{inel}/\text{collision} = (70 \times 10^{7} \text{ s}^{-1})(25 \times 10^{-9} \text{ s})$$
$$= 17.5$$

This is a crude calculation but it illustrates the problem we face.

In practice, we expect a large number of inelastic collisions in each event.

Proton bunches in the LHC are gaussian in shape with $\sigma_z \sim 10$ cm.

Collisions are spread out over a luminous region that is ~ 20 cm in length along the beam axis.

Precision tracking allows the reconstruction of individual inelastic collisions.

Because the primary vertices of charged particles can be identified, jet clustering is performed using only the particles associated with the vertex of interest.

Pileup subtraction attempts to estimate the average (median) p_T density in the $\eta \times \varphi$ plane due to pileup events and subtract this from reconstructed jets.

$$p_T^{corr} = p_T^{jet} - \rho A^{jet}$$

A^{jet} is the jet area in the $\eta \times \varphi$ plane.

Pileup jet subtraction attempts to correlate charged particles from pileup vertices with clustered jets.

$$\text{"jet-vertex-fraction"} = \frac{p_T(\text{tracks in jet})}{p_T(\text{jet})}$$

Jets with low JVF may be due to pileup jets that were not removed by charged hadron subtraction.

Jet Energy Scale

Using Monte Carlo, calculate the jet response:

$$R(E,\eta) = \left\langle \frac{E^{reco}}{E^{true}} \right\rangle$$

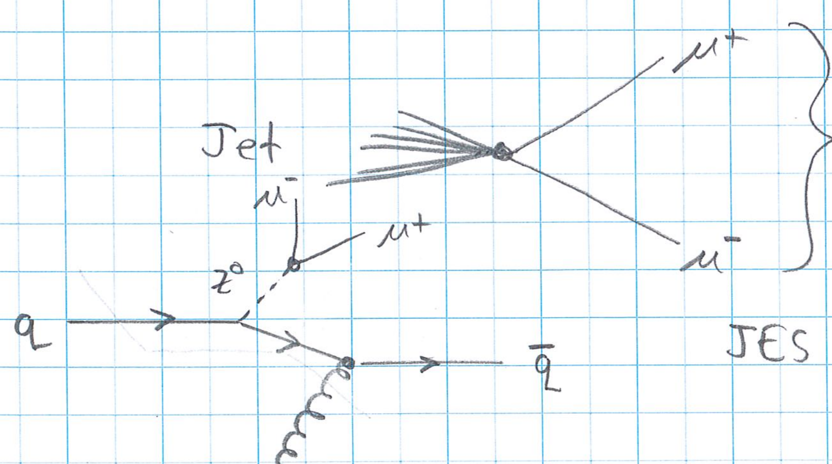
Jet Energy Scale corrections divide the measured jet energy by $R(E,\eta)$ to estimate the "true" jet energy.

This accounts for dead regions (eg in the barrel/endcap overlap region) shower leakage, and EM/hadronic energy fluctuations.

In-Situ Corrections.

The Monte Carlo model might not be perfect.

1. Reconstruct a reference object (Z, γ, other jets) with known energy
2. This energy should be balanced by the recoiling jet



$Z^0 \to \mu^+\mu^-$

$$JES = \frac{\langle p_T^{jet}/p_T^{ref}\rangle_{MC}}{\langle p_T^{jet}/p_T^{ref}\rangle_{data}}$$

Other jet corrections and uncertainties

gluon jets are found to be broader than quark jets, so in principle, the corrections for quark and gluon jets could be different.

b-jets can also be different: b-quarks are massive and can decay semileptonically to c and to s. Neutrinos reduce the visible energy. Particle content may be different compared to a light-flavor jet.

Missing Energy

Once jets associated with an event have been reconstructed, define

$$\cancel{E}_T = \left| -\sum_i \vec{p}_{T_i}^{\,jet} \right| \qquad \vec{\cancel{p}}_T = -\sum_i \vec{p}_{T_i}^{\,jet}$$

Corresponds to the transverse momentum of invisible particles (eg, neutrinos)