Calorimeters in HEP, II

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A very useful review

Claude Leroy and Pier-Giorgio Rancoita

Physics of cascading shower generation and propagation in matter: principles of high-energy, ultrahigh-energy and compensating calorimetry

Rep. Prog. Phys. **63** (2000) 505–606

Energy resolution

- For EM calorimeters we can parameterise the resolution as

$$\boxed{\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{a_0}{E}\right)^2 + \left(\frac{a_1}{\sqrt{E}}\right)^2 + b^2}$$

Systematic (or “constant”) term

Electronic noise summed over a few channels (3x3 or 5x5 typically)

Photoelectron statistics (Poisson)

Systematic effects

- The systematic term has a number of distinct contributions:
  - Shower leakage, usually not less than about 0.3%
  - Interchannel calibration, again of order 0.3%
  - Channel non-uniformity
    - Optical attenuation length (intrinsic and known)
    - radiation-induced optical attenuation (induced and changing)
  - Pile-up due to extremely high luminosity, a major effect at hadron colliders such as the LHC
  - Fluctuations in the EM component in hadronic showers

Relative contributions at GEM - projected energy resolution (%)

E(GeV)	***5***	***10***	***20***	***50***	***100***	***200***	***500***
Electronic noise	0.4	0.2	0.1	0.04	0.02	0.01	0.004
p.e.	0.2	0.14	0.1	0.063	0.045	0.03	0.02
Leakage	0.6	0.43	0.32	0.3	0.3	0.3	0.36
Intercalibration	0.4	0.4	0.4	0.4	0.4	0.4	0.4
TOTAL	0.85	0.63	0.53	0.51	0.50	0.50	0.54

Table shows the GEANT simulation results for the BaF_2 ECAL of the proposed GEM detector for the SSC

Homogenous calorimeters

- Based on dense materials that are also active in generating the signal
- Archetype is the crystal calorimeter
  - Scintillating crystals (or glasses) such as BaF_2, $PbWO_4$, CsI
  - Cherenkov radiators such as Pb-glass (e.g. OPAL ECAL)
- Almost without exception used for EM calorimetry due to cost and technical difficulty of growing 9λ long crystals (this is *not* such a problem for glasses however)

Dense scintillator properties

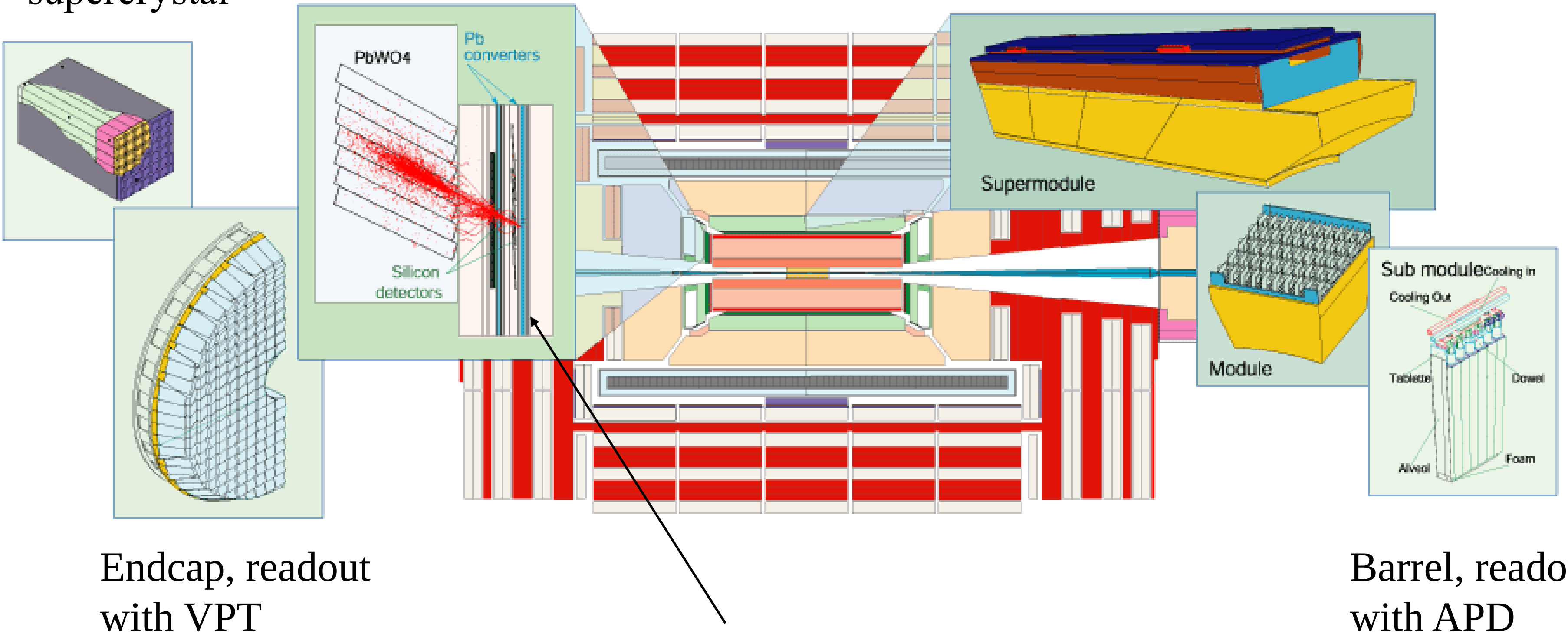
	NaI(Tl)	***CsI(Tl)***	***CsI***	***BaF_2***	***BGO***	***$PbWO_4$***
Density (g.cm^{-3})	3.67	4.51	4.51	4.89	7.13	8.3
X_0 (cm)	2.6	1.9	1.9	2.1	1.1	0.9
R_M (cm)	4.8	3.5	3.5	3.4	2.3	2.2
Decay (ns)	230	1000	35	600/1	300	10
Light	100%	45%	5%	20/4%	13%	1%

BaBar

L3 (LEP)

CMS (at LHC)

CMS Electromagnetic calorimeter



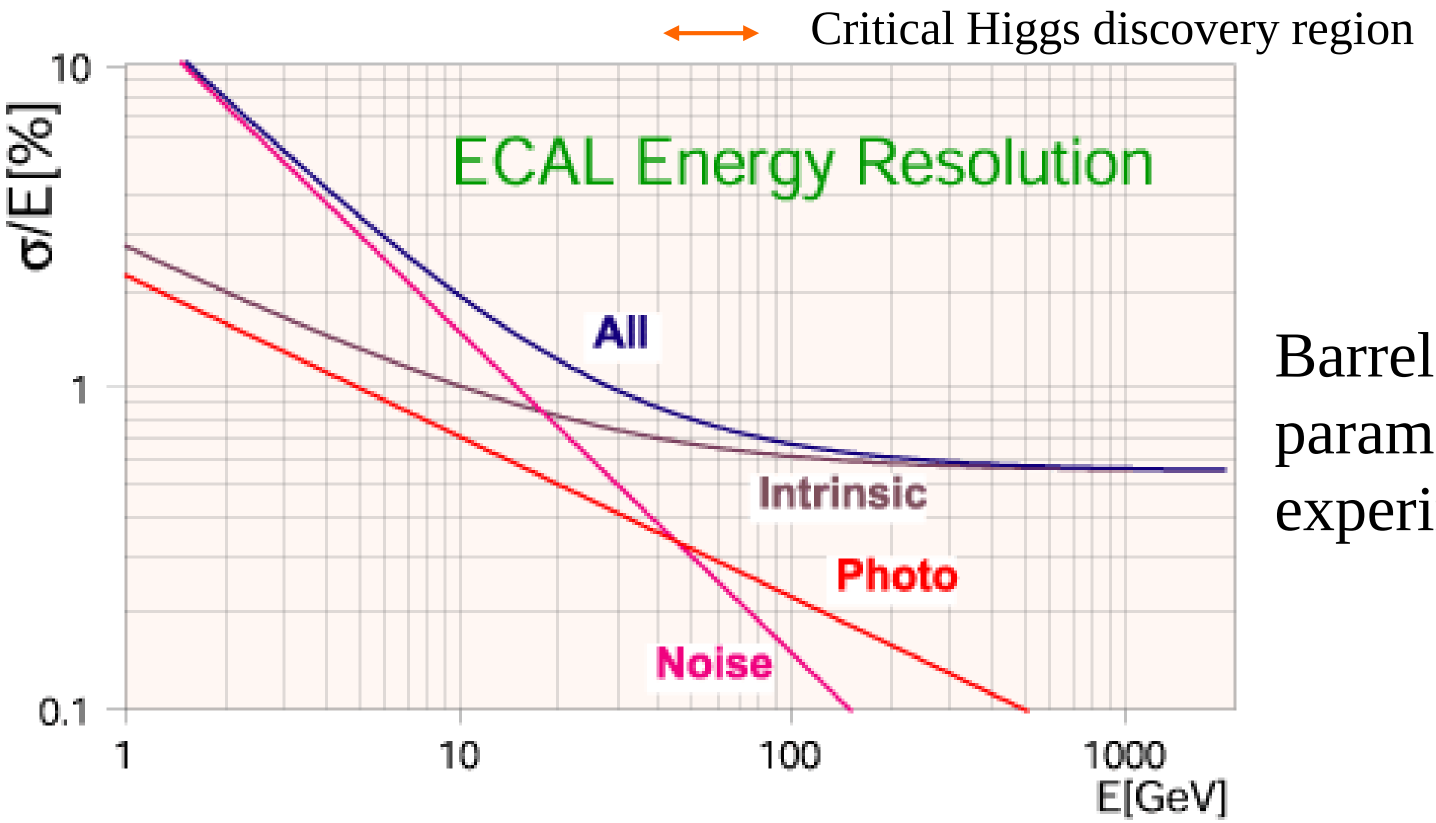
5x5 “supercrystal”

Endcap, readout
with VPT

Preshower

Barrel, readout
with APD

Energy resolution for CMS



Barrel calorimeter, parameterisation from experimental data

Sampling calorimeters

- Layers of inactive, dense material (e.g. Pb, W, U) mixed with active layers
- Active layers can be
  - Scintillators (plates or fibres) or Cherenkov in SiO_2 fibres
  - Silicon strips
  - Cryogenic noble liquids (Ar, Kr)
  - Gaseous detectors (e.g. Iarocci tubes in OPAL HCAL)
- The technology for HCAL, but also used in ECAL (e.g. the ATLAS ECAL)

Energy resolution

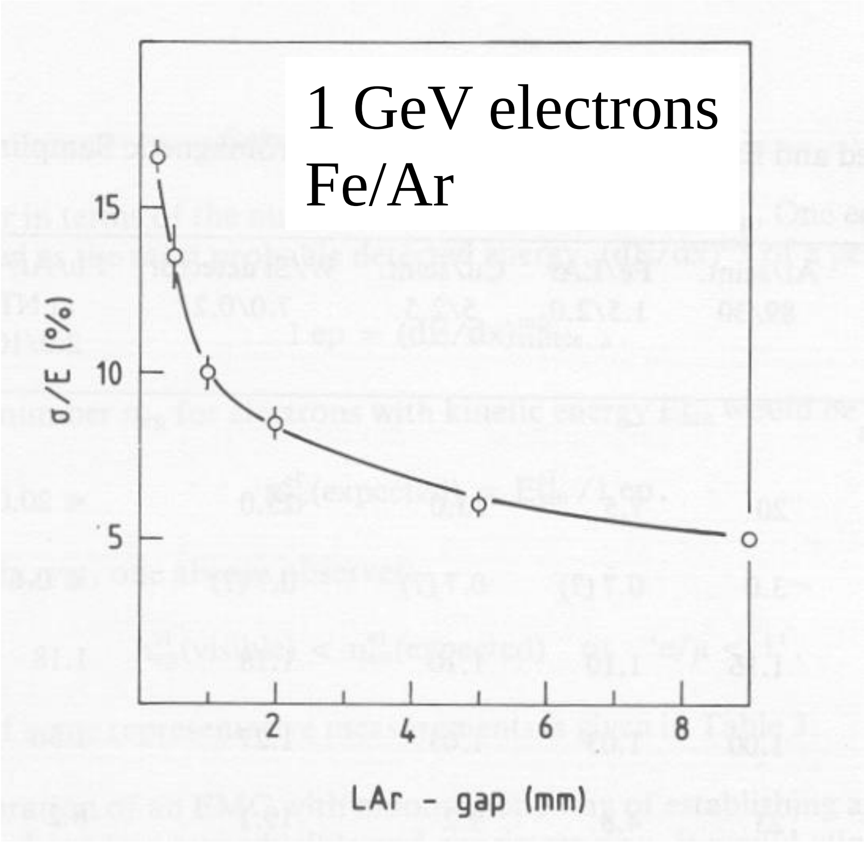
- Only a fraction of the deposited energy is sampled.
- Intrinsic sampling fluctuations reflect fluctuations in the number of electron/positron pairs traversing the active planes. A *lower bound* is given by

$$\sigma(E)/E = \sigma(N_x)/N_x = 3.2\%\left[\Delta E(\mathrm{MeV})/E(\mathrm{GeV})\right]^{1/2}$$

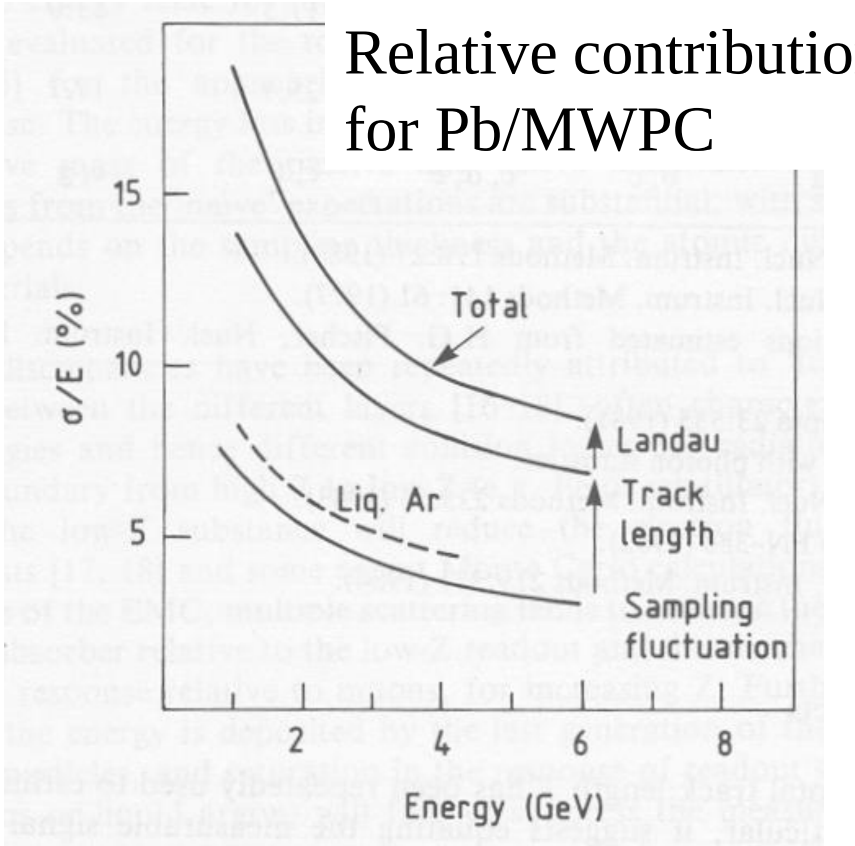
where N_x is the number of pairs crossing the active plates and ΔE is the energy loss per unit cell.

This expression ignores “Landau” losses in the active planes which may be significant in thin detectors (e.g. silicon or gaseous detectors). It also ignores the effects of multiple scattering.

Sampling effects



1 GeV electrons
Fe/Ar

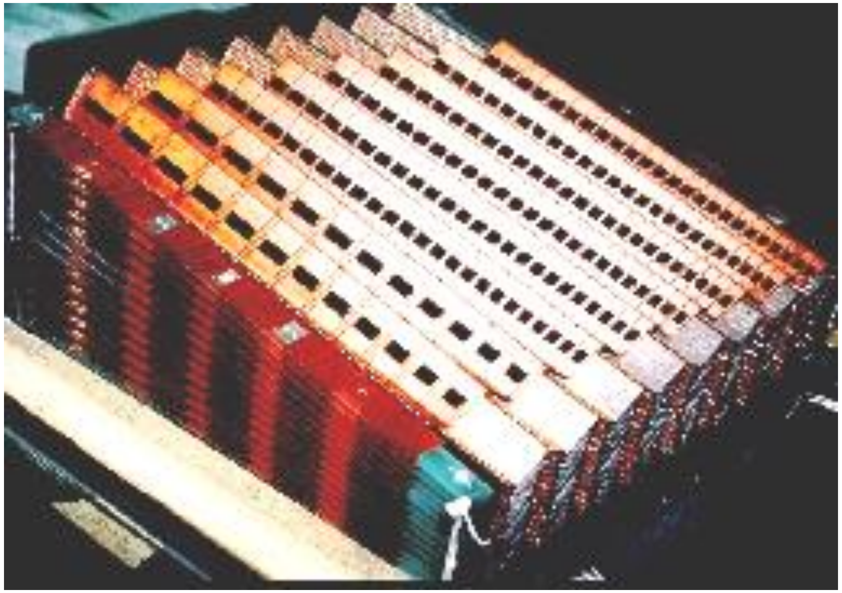


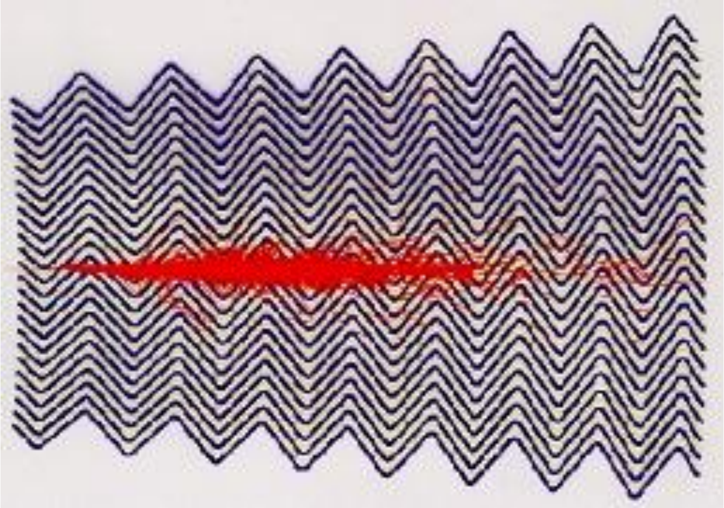
Relative contributions
for Pb/MWPC

Figures 7a and 7b from Fabjan C in Ferbel 1987

ATLAS Calorimeter

- Liquid argon as the active medium with lead (in an "accordion" arrangement) as the dense absorber.



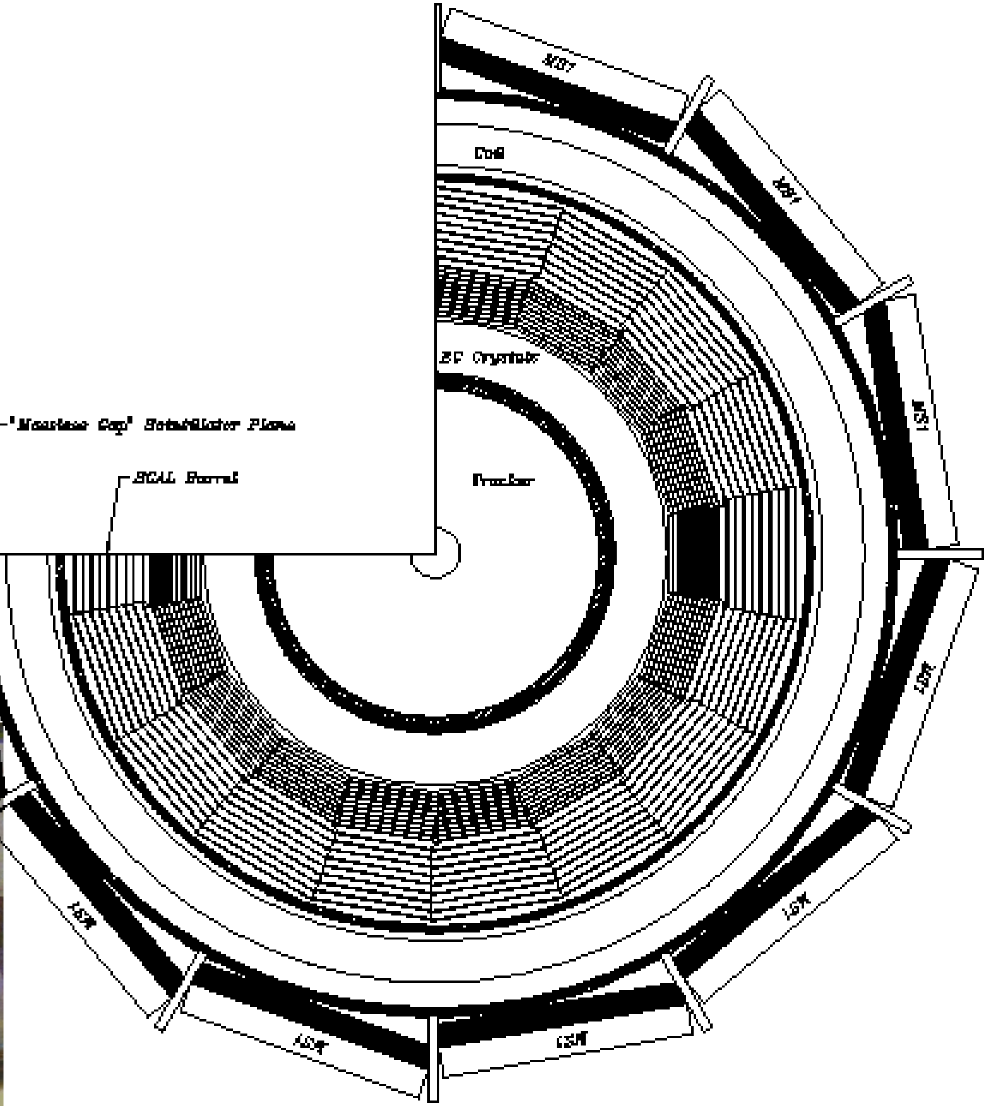


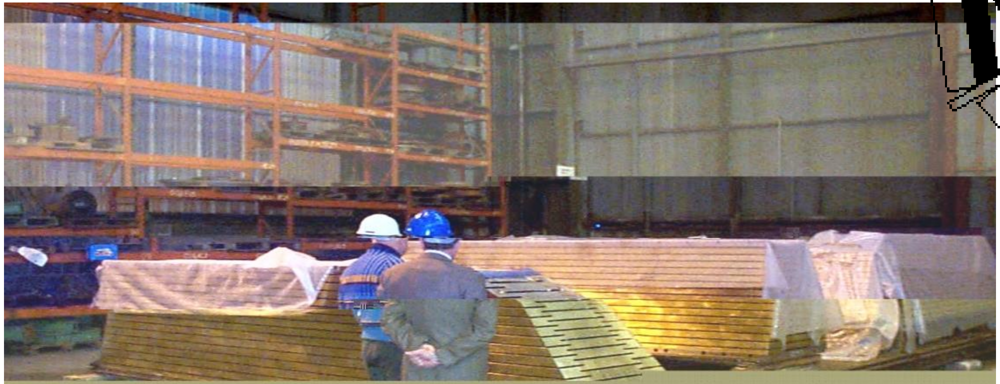
Hadronic shower

CMS HCAL

- Sampling with copper

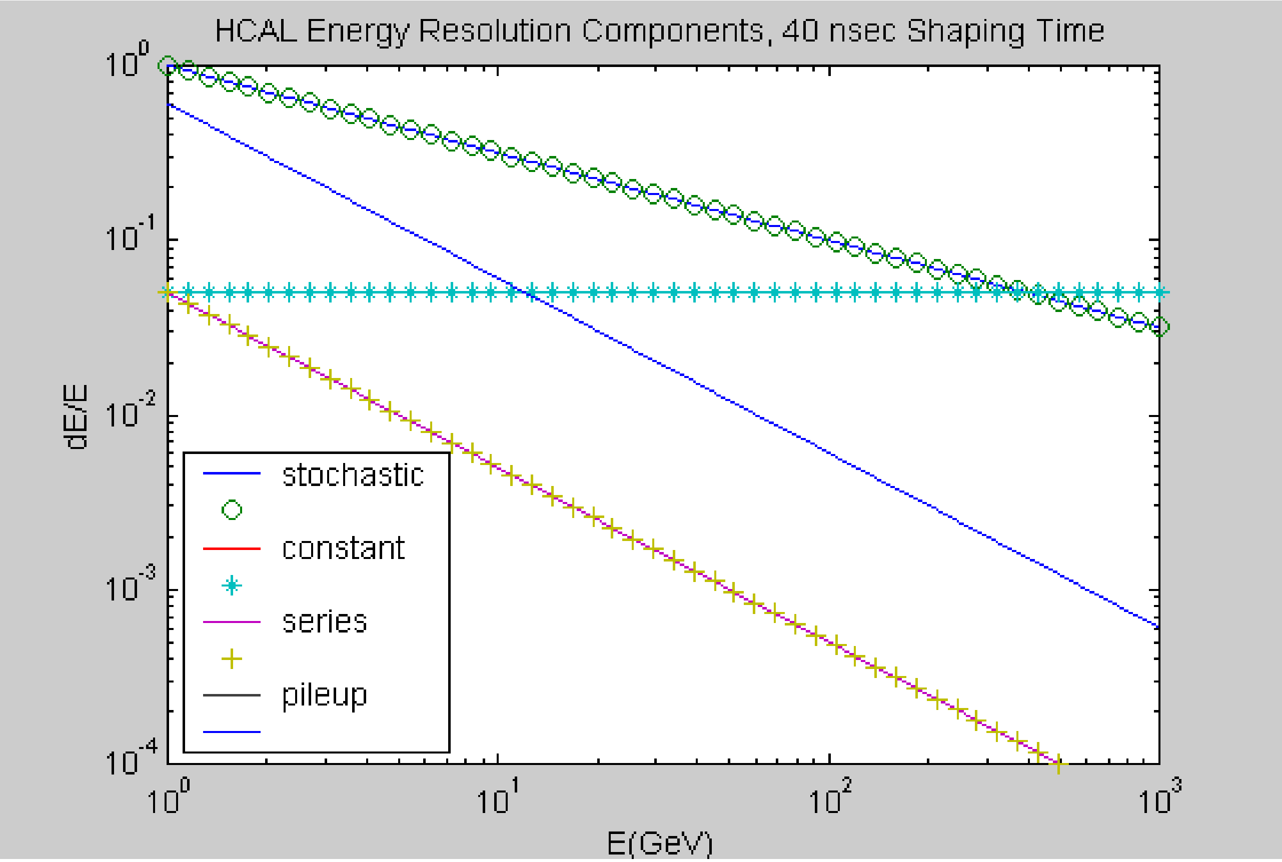
as the dense absorber



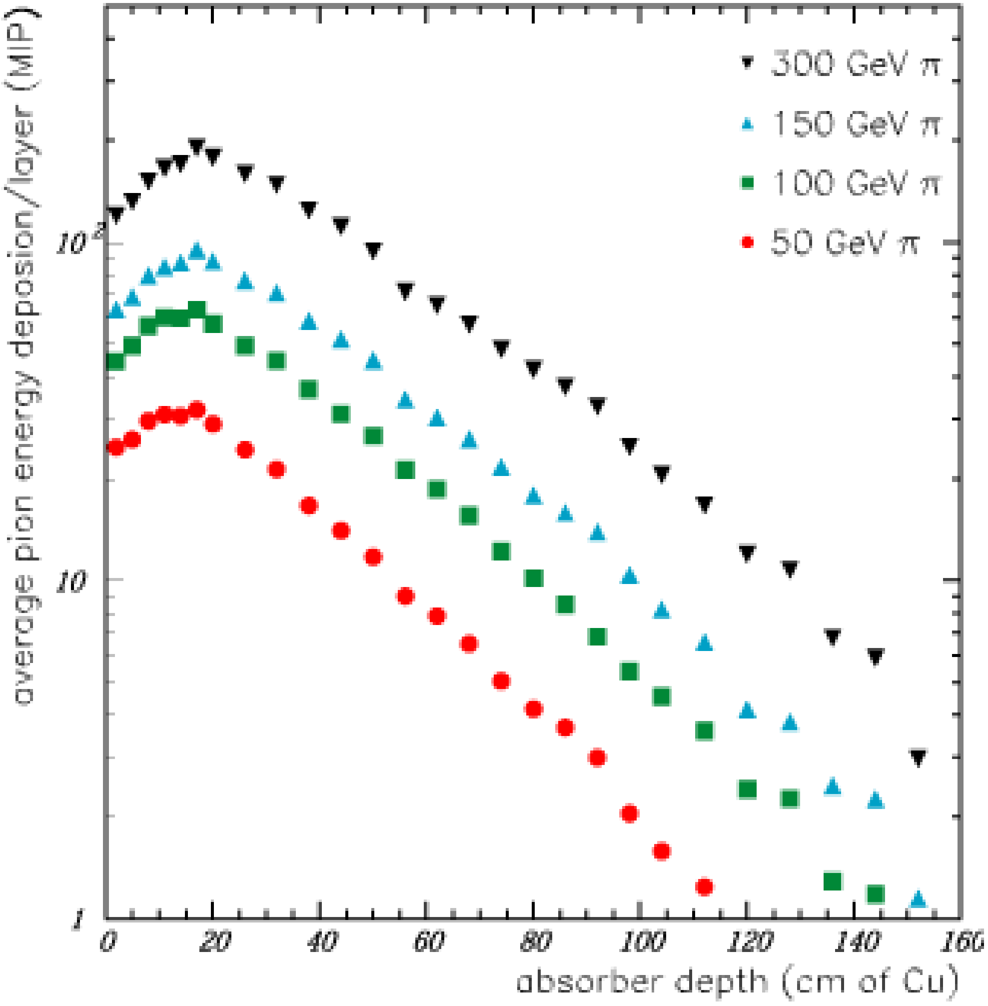


Barrel wedges

CMS HCAL resolution



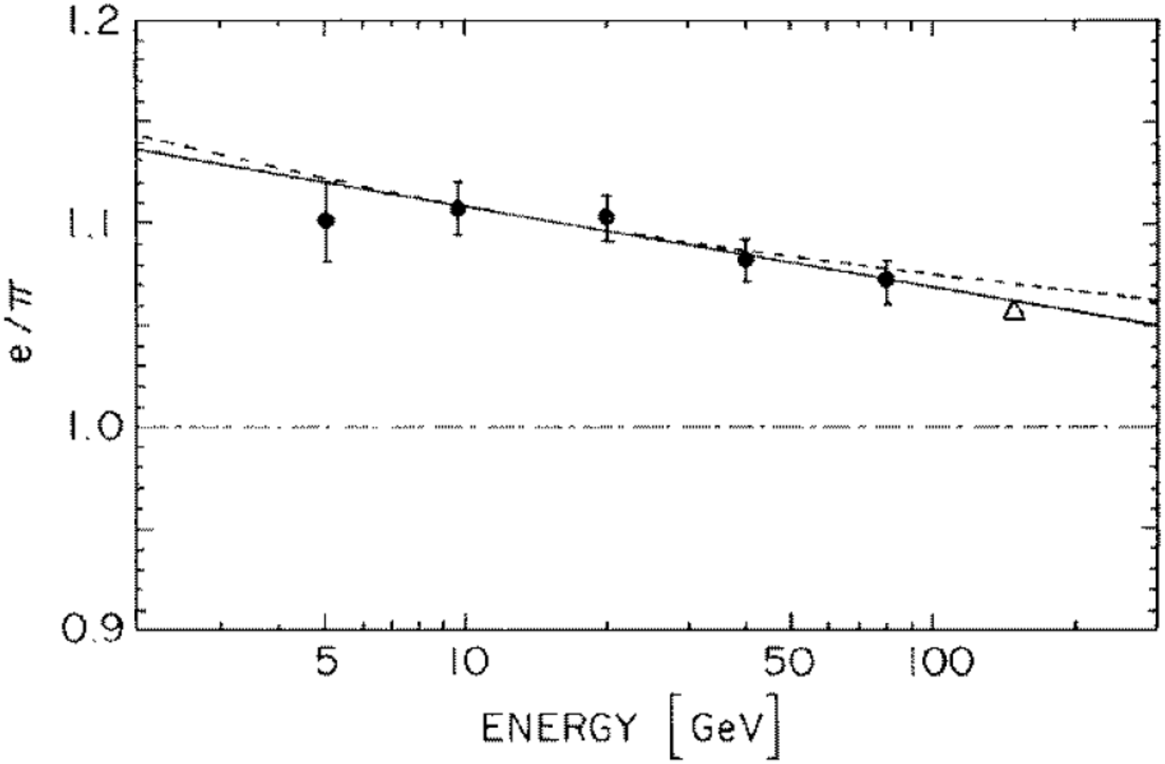
Pion energy deposition in CMS HCAL



Compensation in HCAL

- Hadronic showers have an EM component F_0 determined essentially by the *first* interaction.
- Roughly 1/3 of the mesons provide the neutral EM component, f_0
- Thus at generation 1) we have $F_0 = f_0$
- At generation 2) we have $F_0 = f_0 + f_0(1-f_0)$ etc.
- This leads to F_0 tending to one for very high energies. The response of most HCAL to electrons is different to hadrons; the ratio of these responses, known as e/h is critical to achieve compensation.

e/π ratio



- Lead/scintillating-fibre calorimeter

Contributions to energy deposition

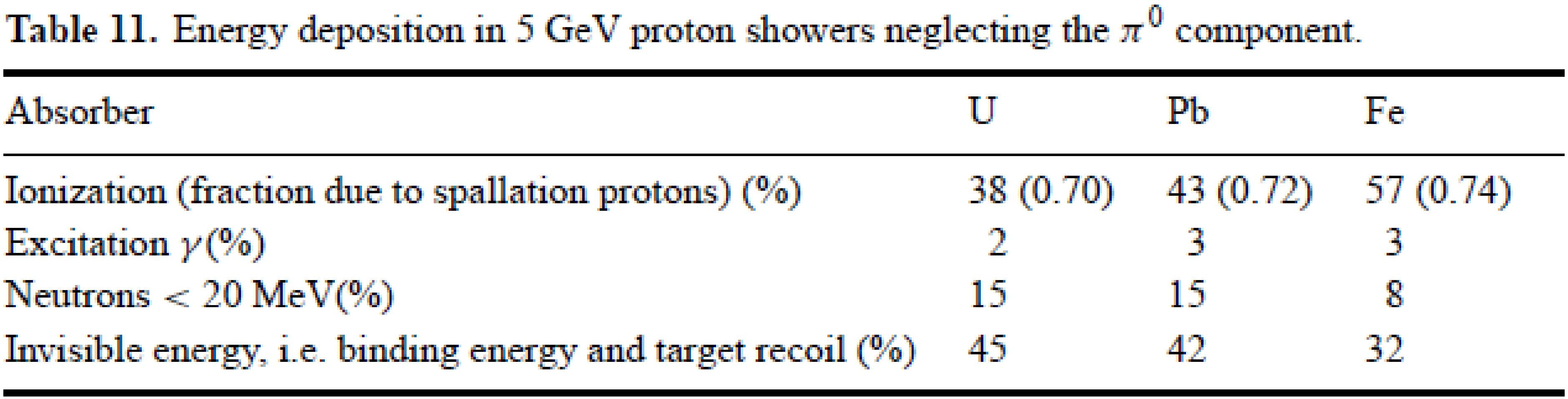


Table 11. Energy deposition in 5 GeV proton showers neglecting the π^0 component.

Absorber	U	Pb	Fe
Ionization (fraction due to spallation protons) (%)	38 (0.70)	43 (0.72)	57 (0.74)
Excitation γ (%)	2	3	3
Neutrons $<$ 20 MeV(%)	15	15	8
Invisible energy, i.e. binding energy and target recoil (%)	45	42	32

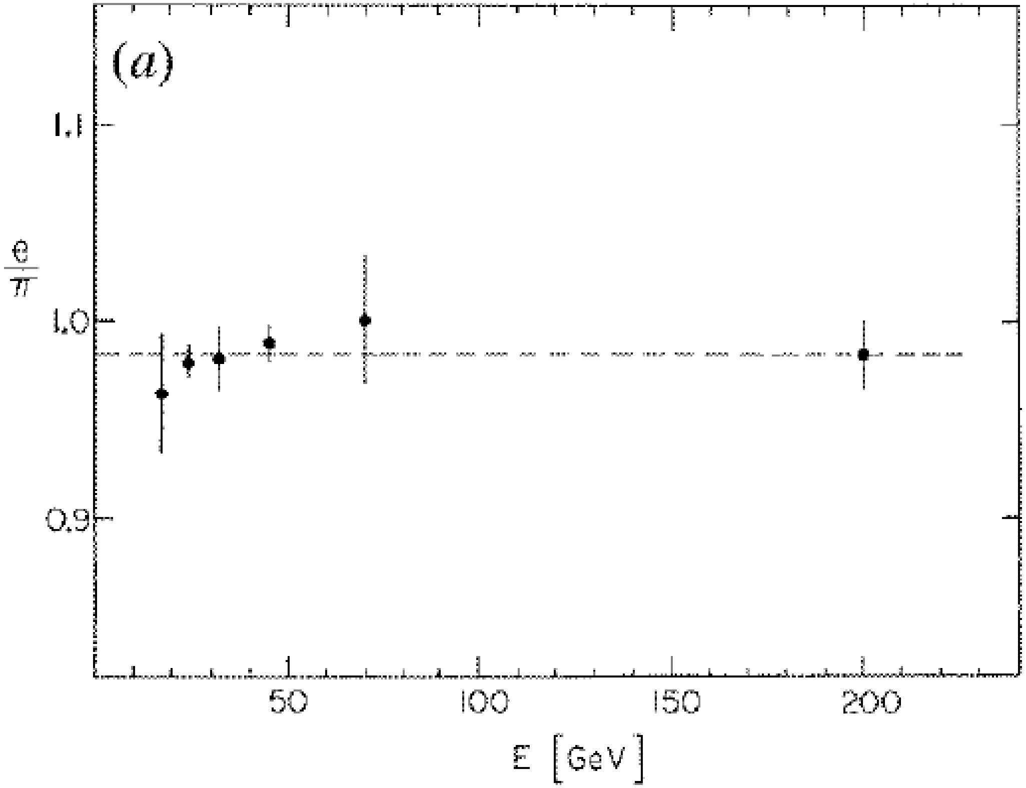
Compensation, problems and solutions

- If e/h is not close to 1.0 then
  - Non-Gaussian response to mono-energetic hadrons
  - e/h ratio changes with energy
  - Additional component that degrades energy resolution
  - σ/E does **not** improve as $1/\sqrt{E}$
- Solution, compensate by
  - Boosting the non-EM response using Uranium
  - Suppressing the EM response
  - Boosting the response to low energy neutrons (increase hydrogen)
- Warning! Good EM energy response is *not* compatible with compensation.

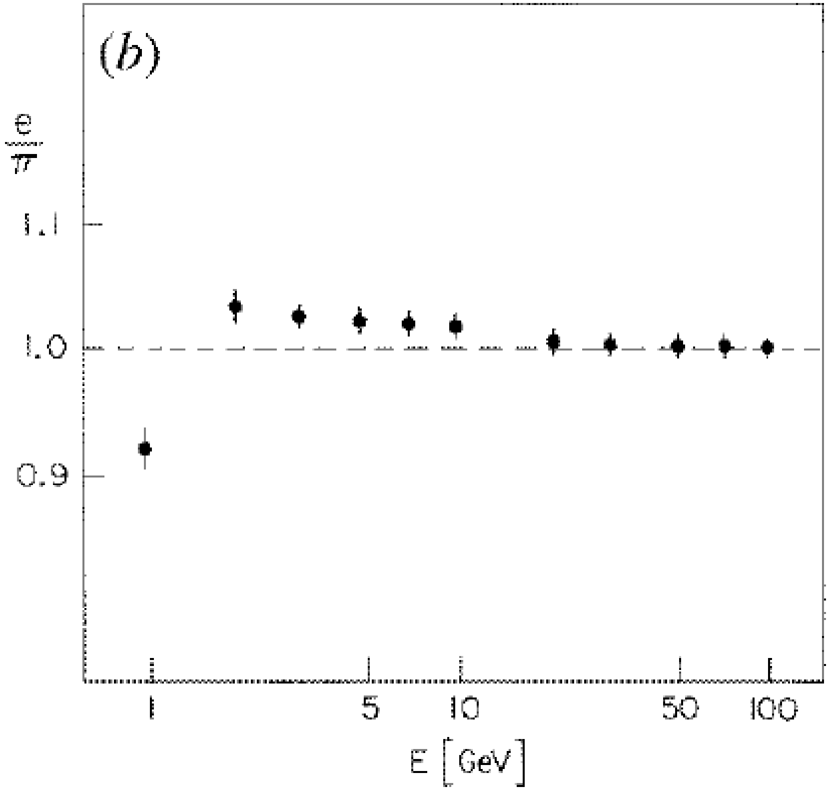
Example - ZEUS

- U/scintillator or Pb/scintillator?
- If U, then 1:1 absorber/scintillator ratio is compensating, if Pb then a 4:1 ratio is required
- The *intrinsic* fluctuations in a Pb sampling calorimeter are smaller than those for a U calorimeter
  - Pb: 13% vs U: 20% for hadrons
  - Pb: 0.3% vs U: 2.2% for EM
- However the much poorer sampling ratio for Pb resulted in the choice of Uranium.

Uranium compensation in practice



HELIOS



ZEUS