Calorimetry at Colliders

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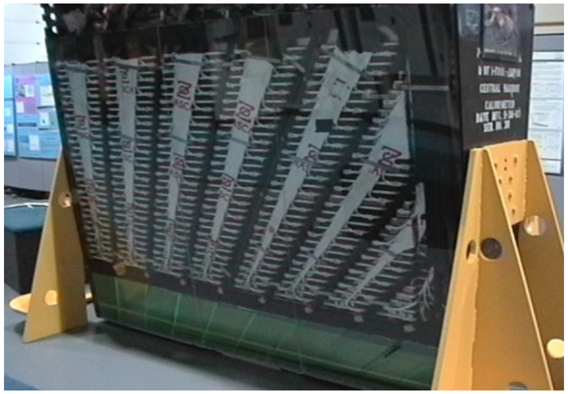
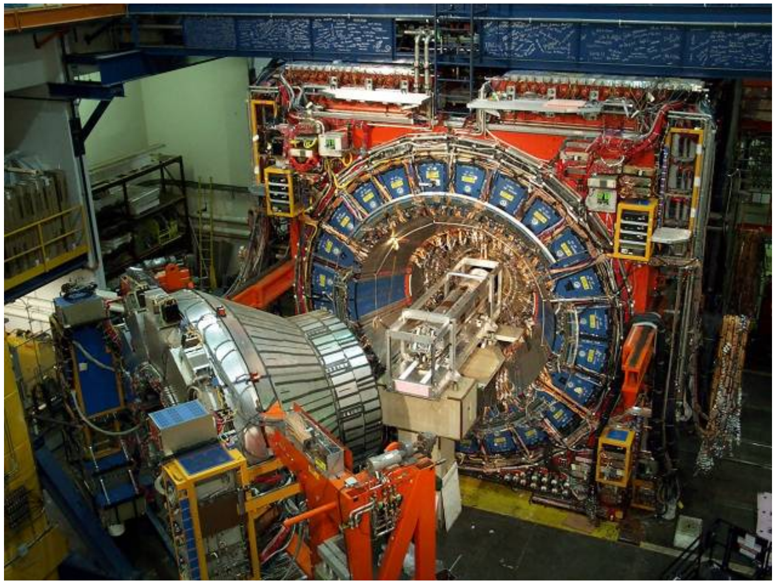
A bit about myself





Calorimetry in Particle Physics

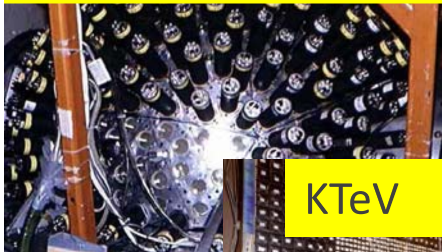
I will give 2 lectures at this summer school:

Part 1: Calorimeter basic principals and general features of electromagnetic and hadronic showers

Part 2: Precision measurement with calorimeters – with focus on hadron colliders

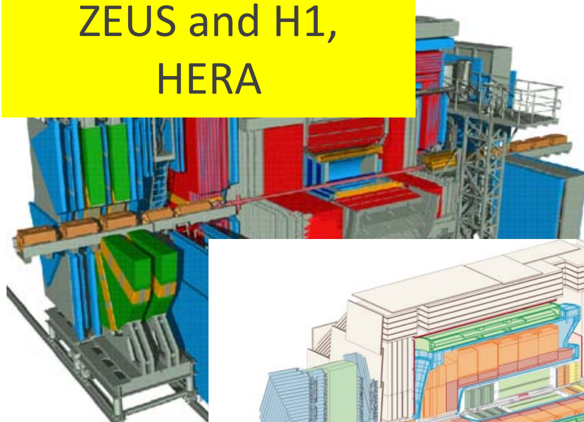
Calorimeters are ubiquitous.. e.g. from 1979 - 2012

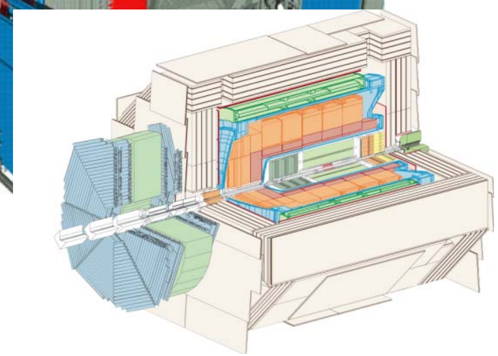
Crystal Ball, SLAC



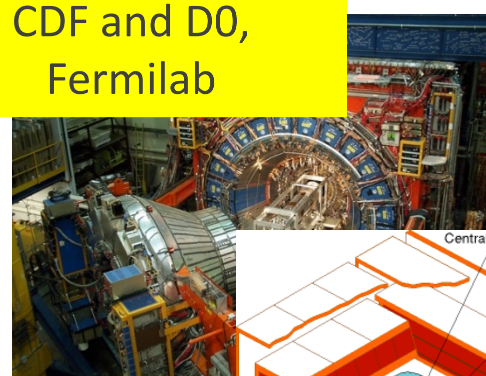
KTeV

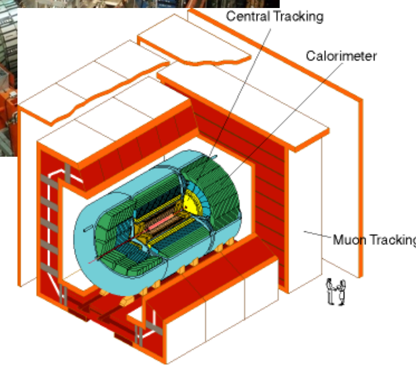
ZEUS and H1, HERA



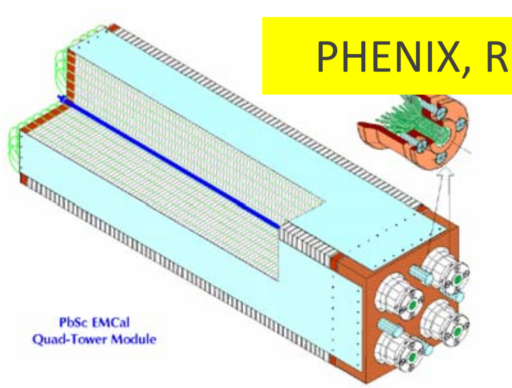


CDF and D0, Fermilab

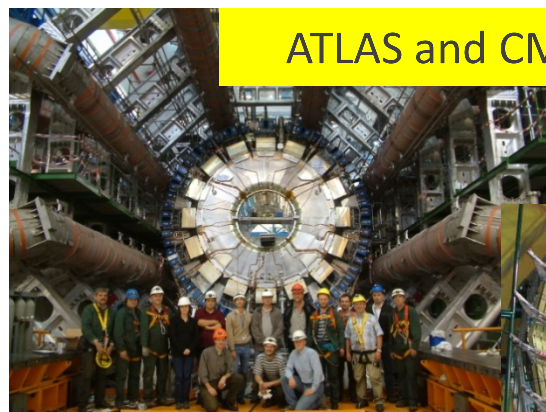




PHENIX, RHIC



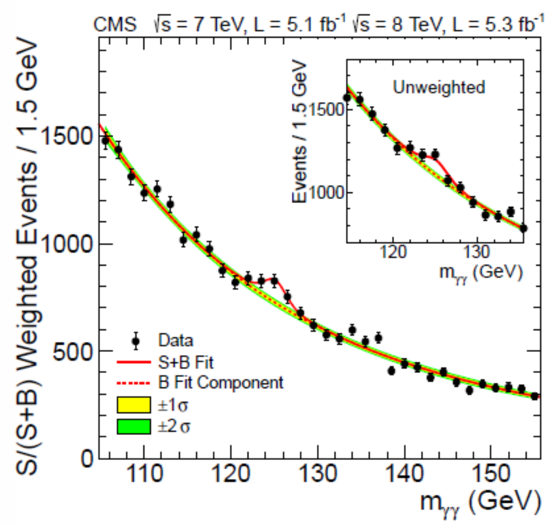
ATLAS and CMS, CERN

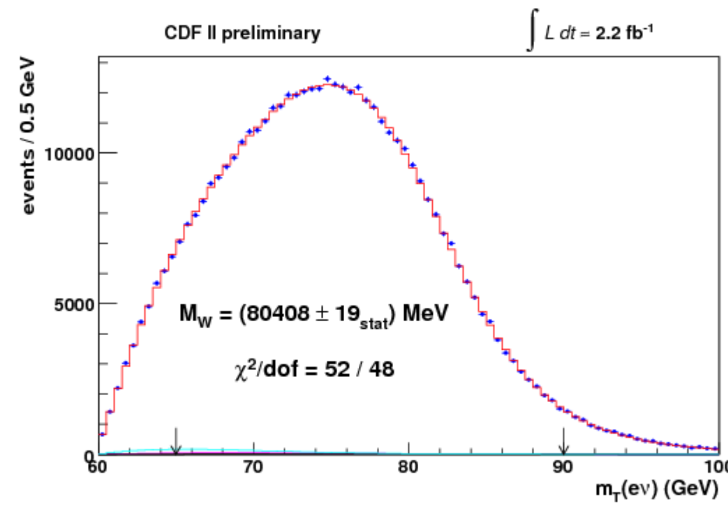


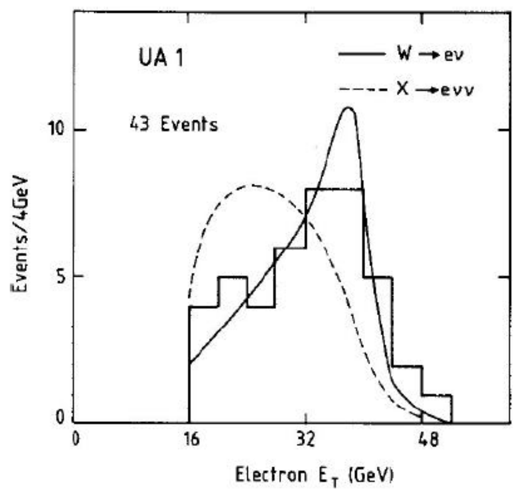
and there are many, many more…

And they have made some amazing measurements

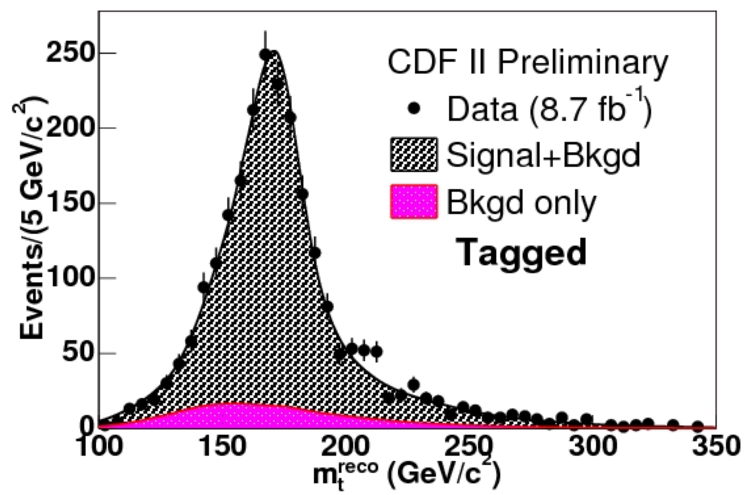
New boson decaying to $\gamma\gamma$







Discovery of the W and Z Bosons by UA1 and UA2 at the SppS

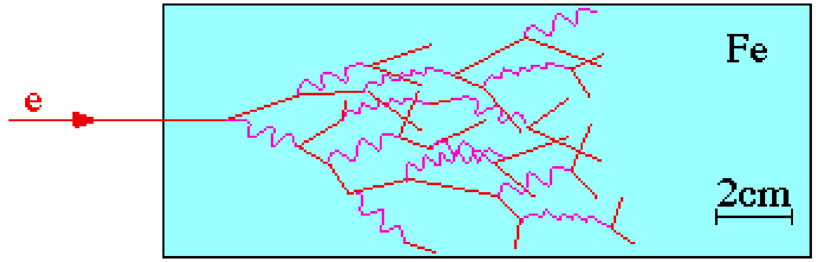


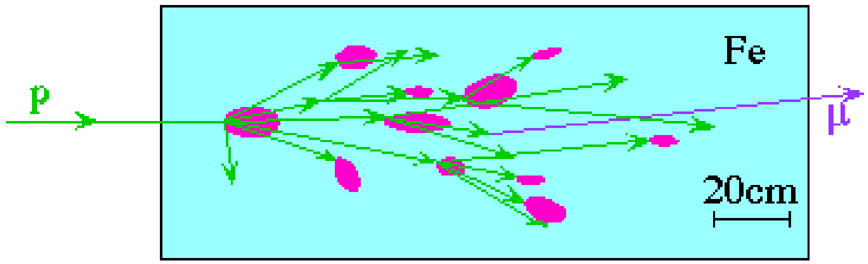
And many more

Calorimeters in Particle Physics

- **Advantages**
  - Measure neutrals as well as charged hadrons and photons
  - Resolution improves with particle energy (unlike the case for the measurement of a particle momentum in a magnetic field)
  - If hermetic (i.e. covers a large fraction of the kinematic acceptance for the process in question) can be used to infer the presence of ***neutrinos*** in the final state
  - Can provide a fast trigger
- **Disadvantages**
  - Generally, calorimeters have a non-linear response to charged hadrons
  - Hadron calorimeters need to be BIG to provide adequate containment for high energy particles. Cost vs performance compromises must be made
  - Design and construction of these devices and providing the physical space to extract the signals from them presents a non-trivial engineering challenge

But what are they and how do they work exactly?



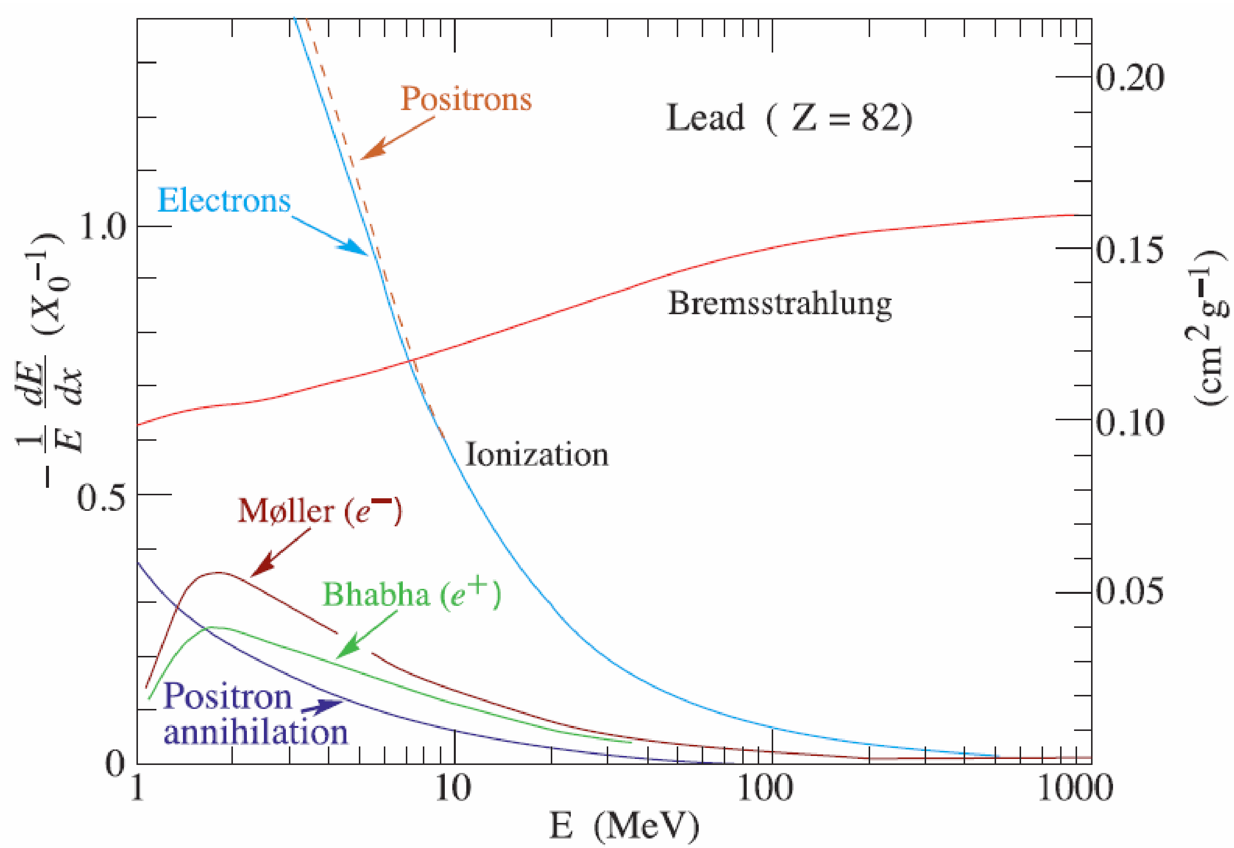


Fundamentally they are blocks of matter which degrade the energy of high energy particles to the levels of atomic ionization and excitation and are instrumented to detect the ionization and de-excitation of the exited states produced and convert this into an electrical signal

The key feature is that the signal detected should be proportional to the energy of the incident particle

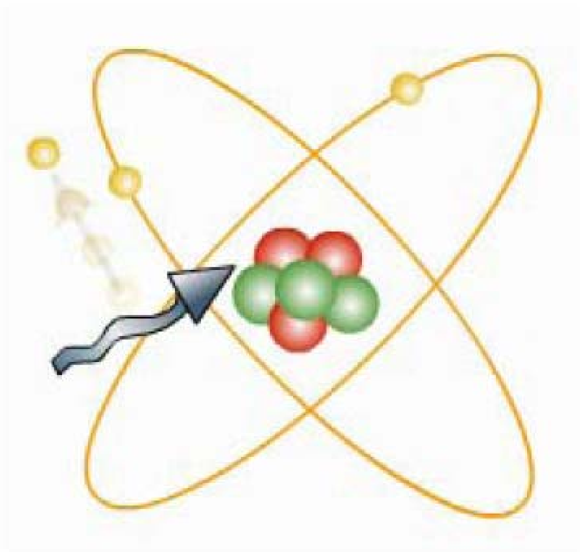
First the “easy” part - electromagnetic calorimeters

Interactions of particles with matter: PDG PR D86, 010001 (2012) – electromagnetic processes

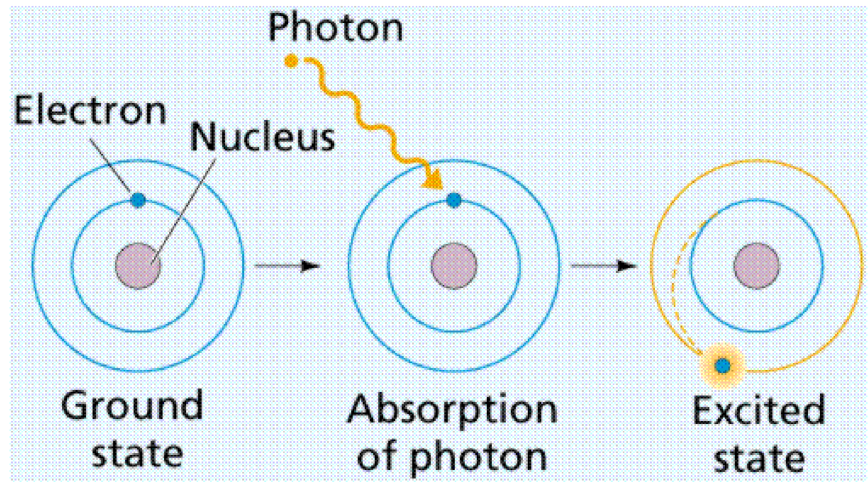


Fractional energy loss per radiation length in lead as a function of electron or positron energy, using X0(Pb) = 6.37 g/cm2

Ionization and Excitation



Charged particles with sufficient energy can ionize atoms when passing through a medium – i.e. remove or add electrons to them.



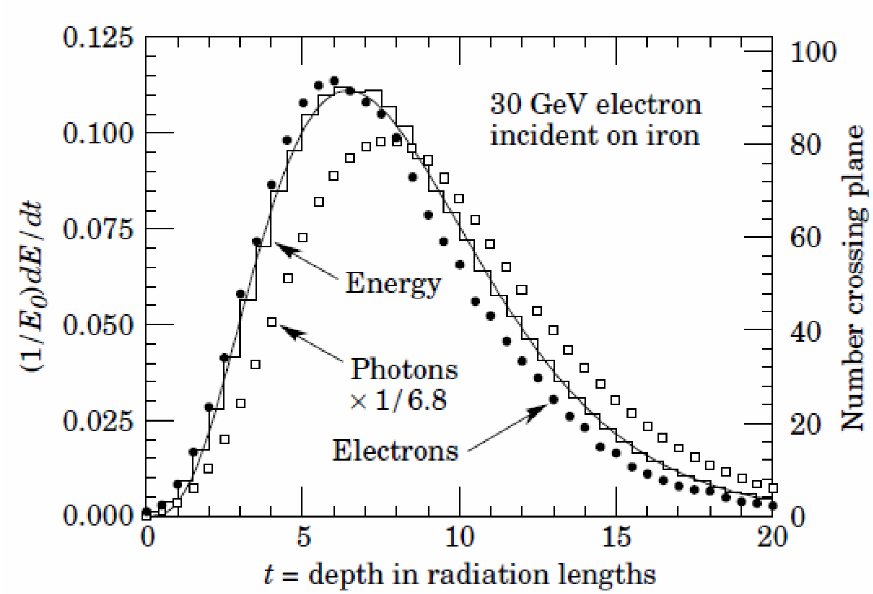
Photons can interact with electrons in a lower orbital and convert them to an excited state. Typically this excited state lives for a very short time before decaying the ground state by emitting photon(s)

Longitudinal Shower development (I)

high energy electrons and photons interact primarily through electromagnetic interactions with the nucleus => the longitudinal development of the shower is dominated by bremsstrahlung and pair production to generate a cascade of particles: this scales with radiation length X_0 ~*180* A / Z^2 g/cm^2

The radiation length X_0 is the mean distance over which electron loses all but *1/e* of its energy by bremsstrahlung

Eventually the electron energy falls below the so-called critical energy at which the ionization loss per radiation length is equal to the electron energy and the electron then dissipates its energy by ionization



An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The circles indicate electrons with energy > 1.5MeV

Lateral Shower development

Transverse shower size set by the Moliere radius $R_M \sim X_0$ (21 MeV/E_c) – the radius containing 90% of the electromagnetic cascade – though there are long tails.

Some examples of R_M:

Lead: 1.6cm

Lead-Tungstate: 2.0cm

Iron: 1.7cm

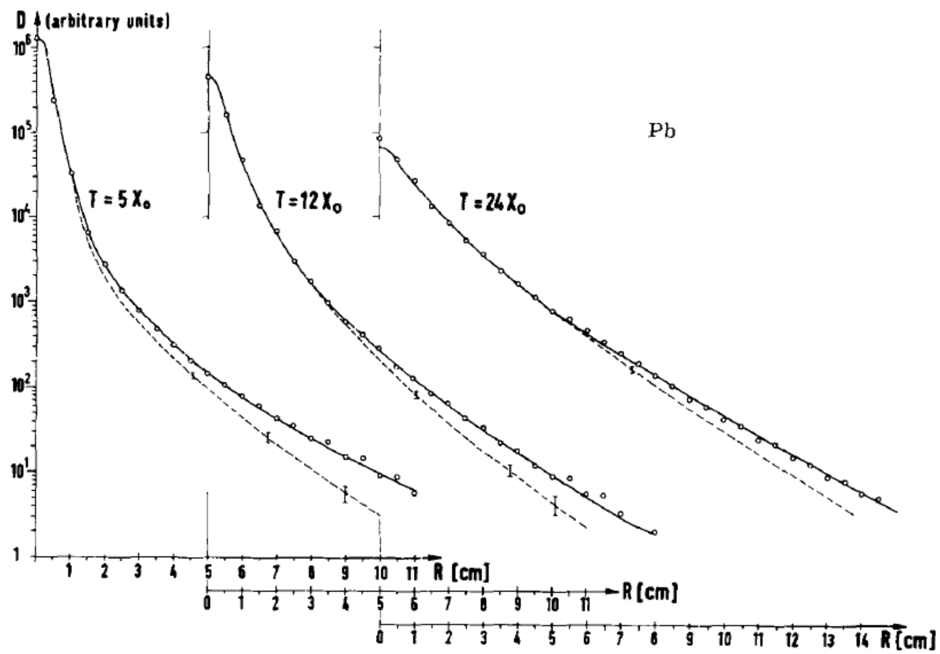
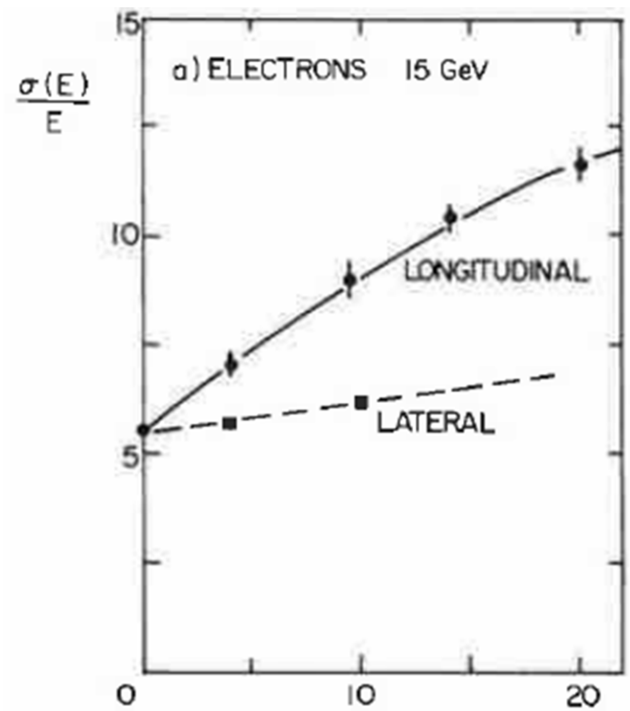


Fig. 4. Measured lateral distribution for lead (circles) in comparison with Monte-Carlo results (dotted line with error bars).

(*BATHOW*)



% of energy lost

(*AMALDI*)

Measurement of the shower

Either using

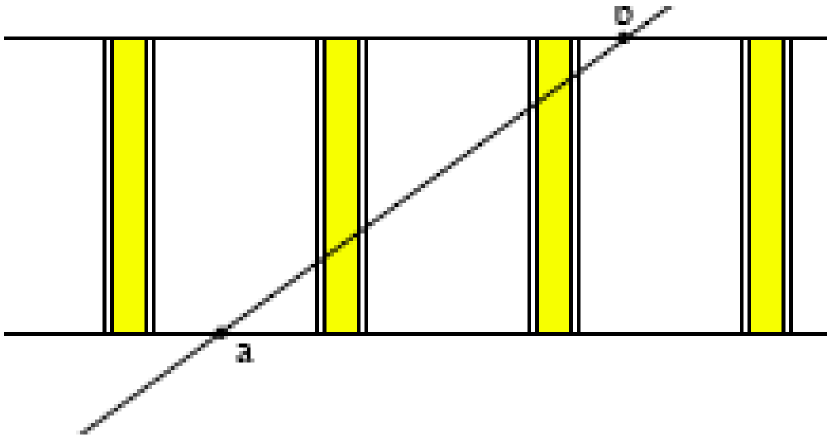
sampling calorimeters where layers of passive absorber are interspersed with layers of a detector to sample the ionization energy.

Or

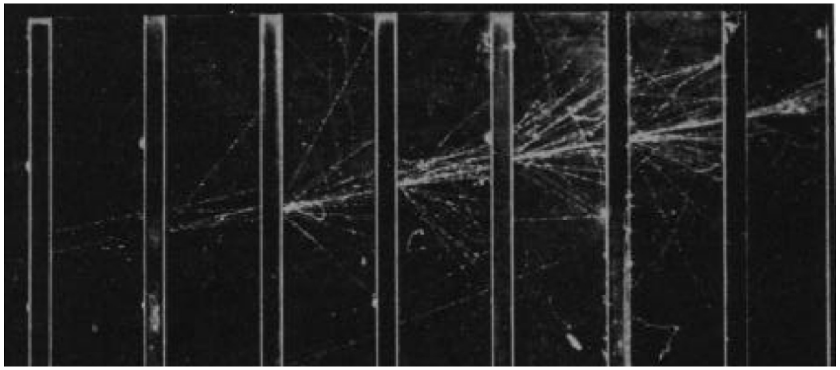
Homogeneous (crystal/glass) calorimeters (such as lead-tungstate calorimeter of CMS) in which the active and passive material are combined for the measurement of photons and electrons. Offer exceptional energy resolution (few $\%/\sqrt{E}$ for photons and electrons)

$\Rightarrow$These are costly and therefore only used to measure EM showers

Sampling Calorimeters



Cloud chamber + Passive Absorber



These calorimeters sample the showers produced by high energy particles at regular intervals.

The passive absorber is selected based on the type of particle to be detected
The sensitive detector is typically chosen to match cost and required performance

Sampling Calorimeter - Energy response and resolution

- It is the ionization energy, dE/dx, deposited in the sensitive detector which we measure, all other ionization energy is deposited in the passive absorber
- Sampling fraction is $\sum(dE/dx)_{active\ medium} / \sum(dE/dx)_{absorber}$
- The energy measurement is in principal linear, so for an infinitely deep detector:
  - $E_{particle} = k * \{(dE/dx)_{absorber}/(dE/dx)_{active\ medium}\} * \sum(dE/dx)_{active\ medium}$
- Energy deposition is statistical and depends on the number of particles in the shower which contribute to ionization
  - $N_{shower} \sim E_{particle}/E_{critical}$
  - For an electromagnetic cascade the critical energy, $E_{critical}$,is characterized by the energy at which ionization dominates over pair production
  - For a hadronic cascade the critical energy is characterized by the energy for Pion multiplication (e.g. $\pi p \to \pi\pi p$
- Resolution $\sigma_E \sim 1/\sqrt{N_{shower}}$ => $\sigma_E \sim 1/\sqrt{E_{particle}}$

Sampling Fluctuations

- **Path length fluctuations also affect the measurement resolution of a sampling calorimeter**
- **Numerically, this term in the resolution function is dependent on the type of showering particle**
  - For electromagnetic showers $\sigma(E)/E = k \sqrt{(t_{em}/E)}$, where t_{em} is the absorber thickness expressed in radiation lengths
  - For hadronic showers $\sigma(E)/E = k \sqrt{(t_{had}/E)}$, where t_{had} is the absorber thickness expressed in interaction lengths

For a much more detailed discussion, see the beautiful paper by [AMALDI]

Sensitive detectors used in sampling calorimeters

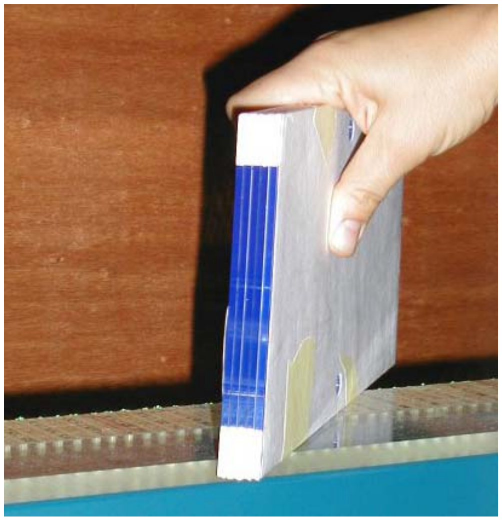
More Common

- Scintillator (solid and liquid)
- Liquid Argon

Less Common

- Gas proportional tubes
- Silicon

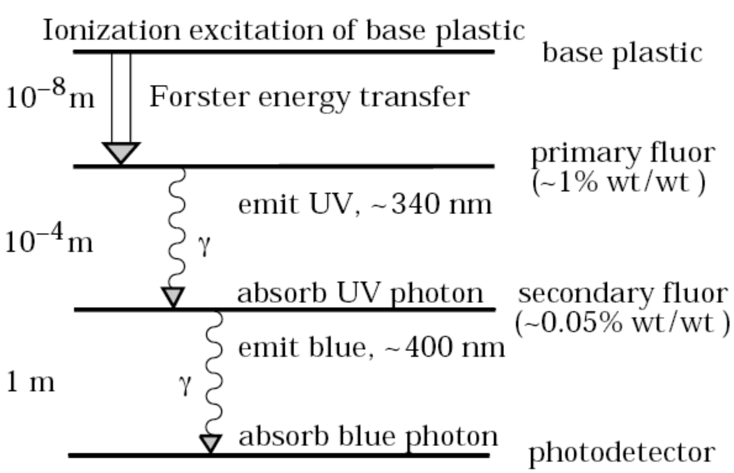
Scintillator as the Sensitive Medium (here solid)

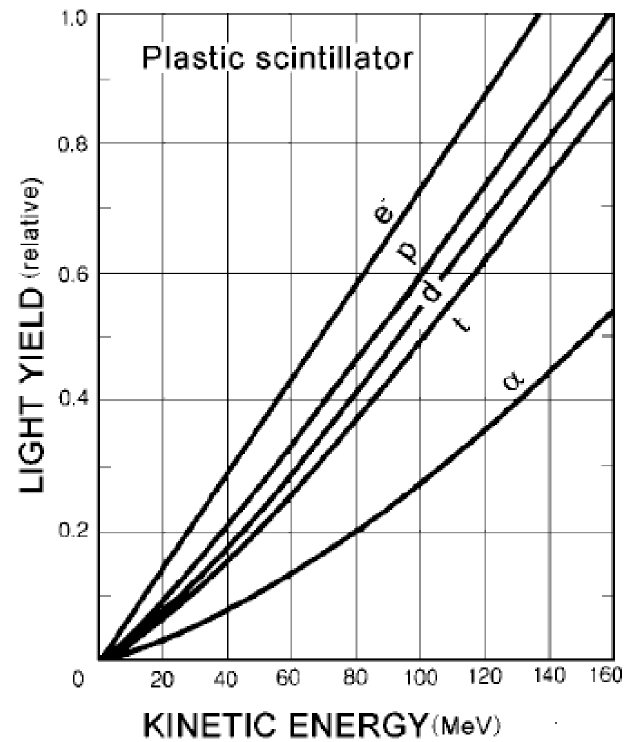


Birk's Law

Ionization Quenching

$$\frac{d\mathscr{L}}{dx} = \mathscr{L}_0 \frac{dE/dx}{1 + k_B\, dE/dx}$$

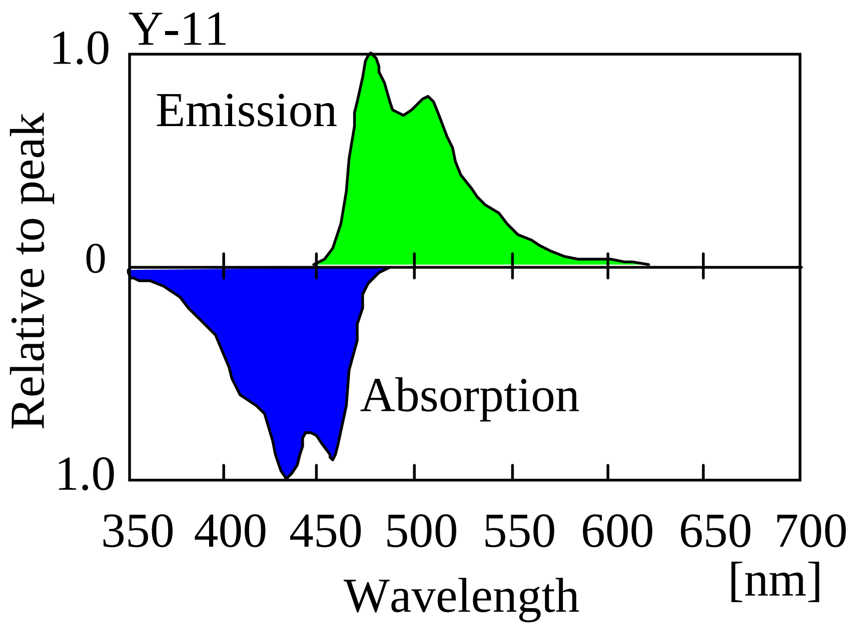




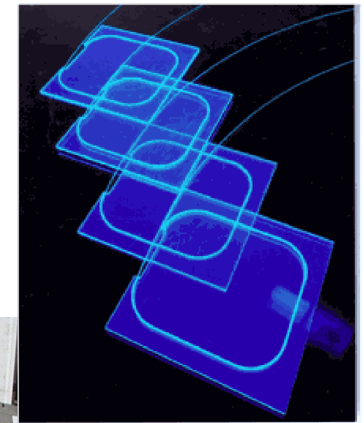
Signal Pulse Length 2-60 nsec

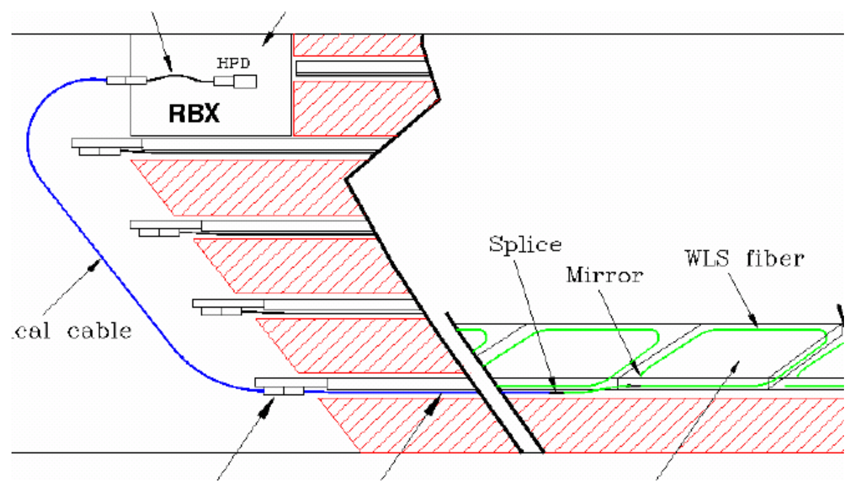
[KOEN]

Getting the light out



CMS HCAL

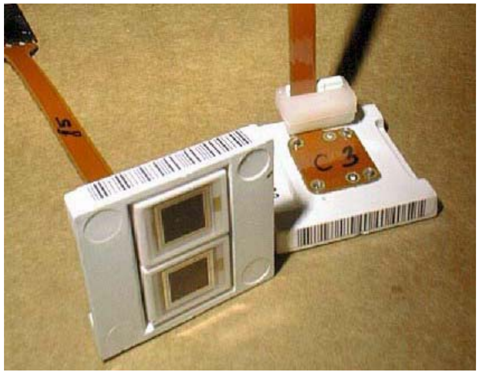




Shown here is the tile-fiber readout concept. In earlier detectors, wavelength-shifter plates were edge coupled to scintillator tiles – but at the cost of reduced sensitive detector volume

From light to an electrical signal

The light collected by the fiber from the scintillator is transported by total internal reflection along the fiber until it is coupled to a photon sensor. Many types of sensor are used – by all use some sort of photo-cathode together with an amplification structure., e.g.
Photo-multiplier tube, or avalanche photo-diode



And the signal is FAST

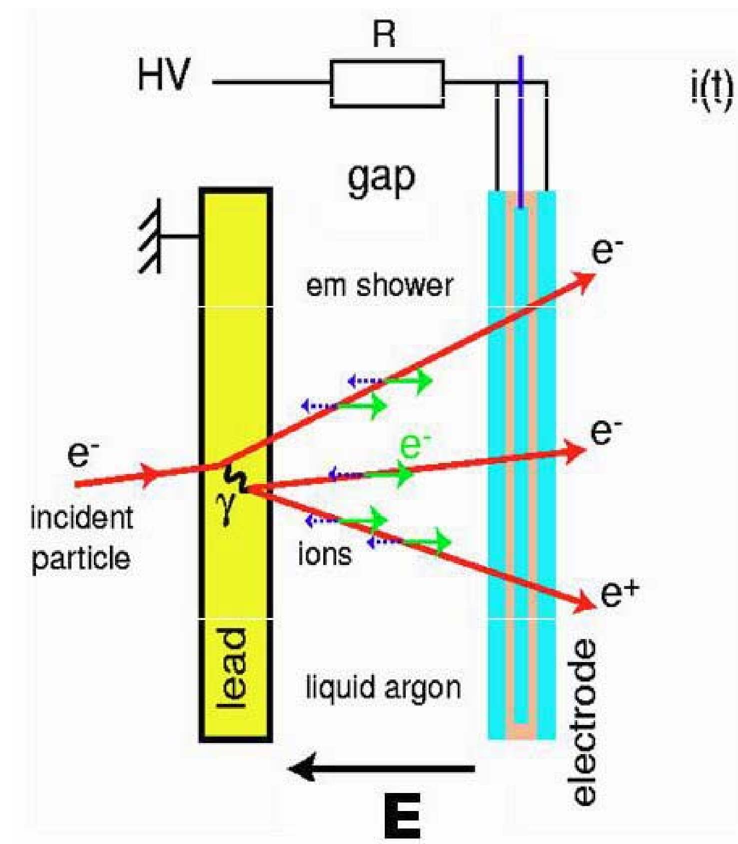
But, there is a price to pay:
~3% sampling fraction, 3% light collection rom tile to fiber, 50% attenuation in transport along the fiber and finally the Quantum Efficiency of the photon-sensor

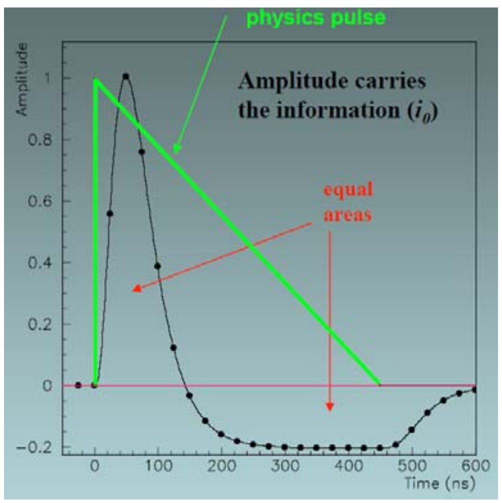
From ionization signal to electrical signal

The ions have a much smaller drift velocity compared to electrons, therefore a track crossing a gap (and depositing charge uniformly) will give rise to a triangular current. For liberated charges $+Q_0$ and $-Q_0$, gap d, and drift velocity v of electrons:

$I(t) = Qv/d$ with $Q = Q_0 (1 - vt/d)$.

Lead-liquid argon sampling calorimeter basic unit





Bi-polar pulse shaping, followed by digitization

Homogenous electromagnetic calorimeter

The fundamental energy degradation processes are identical to those in a sampling calorimeter, then ionization -> scintillation light -> APD -> electrical signal

Table 1. Crystal Calorimeter in High Energy Physics: Past and Present

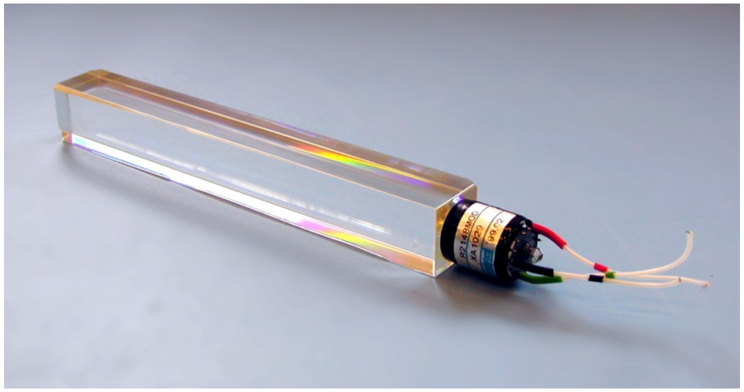
Experiment	C. Ball	L3	CLEO II	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	Tevatron	PEP II	KEK	LHC
Date	75–85	80–00	80–00	90–10	94–10	94–10	95–20
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (Tesla)	-	0.5	1.5	-	1.5	1.0	4.0
Inner Radius (m)	0.254	0.55	1.0	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	2	5.9	9.5	11
L. Yield (p.e./MeV)	350	1,400	5,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	PMT	Si PD	Si PD	APD†
Photosensor Gain	Large	1	1	4,000	1	1	50
Noise/Chan. (MeV)	0.05	0.8	0.5	Small	0.15	0.2	30
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^5

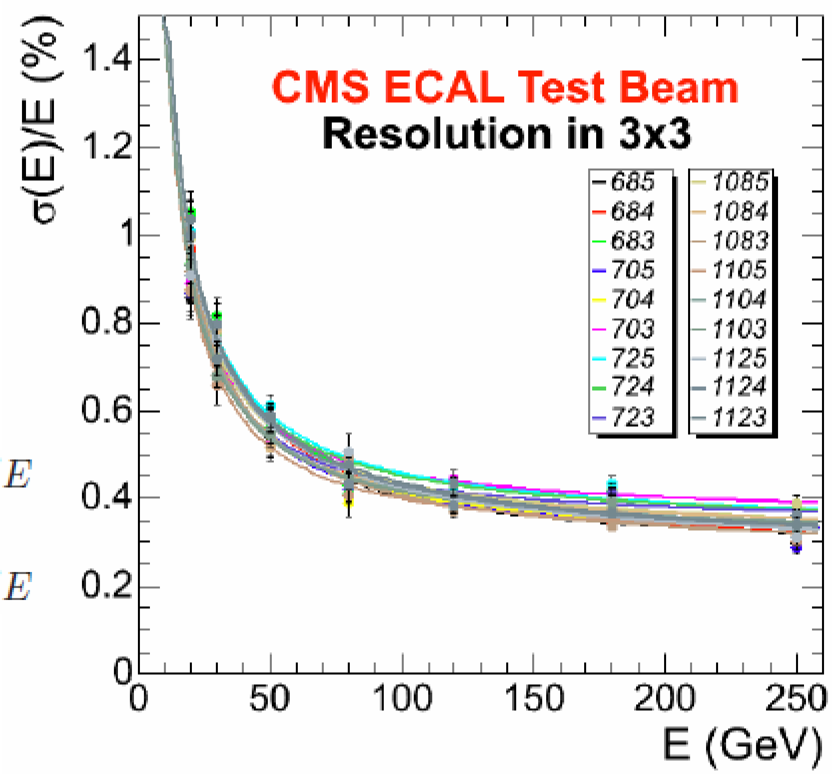
† Avalanche photo-diode.

Note light yield is huge relative to a sampling scintillator calorimeter:
CMS ECAL is 2000pe/GeV, to be compared with ATLAS Tile Cal of ~60pe/GeV

Energy resolution of a crystal calorimeter

CMS Lead-Tungstate Calorimeter – response to high energy electrons

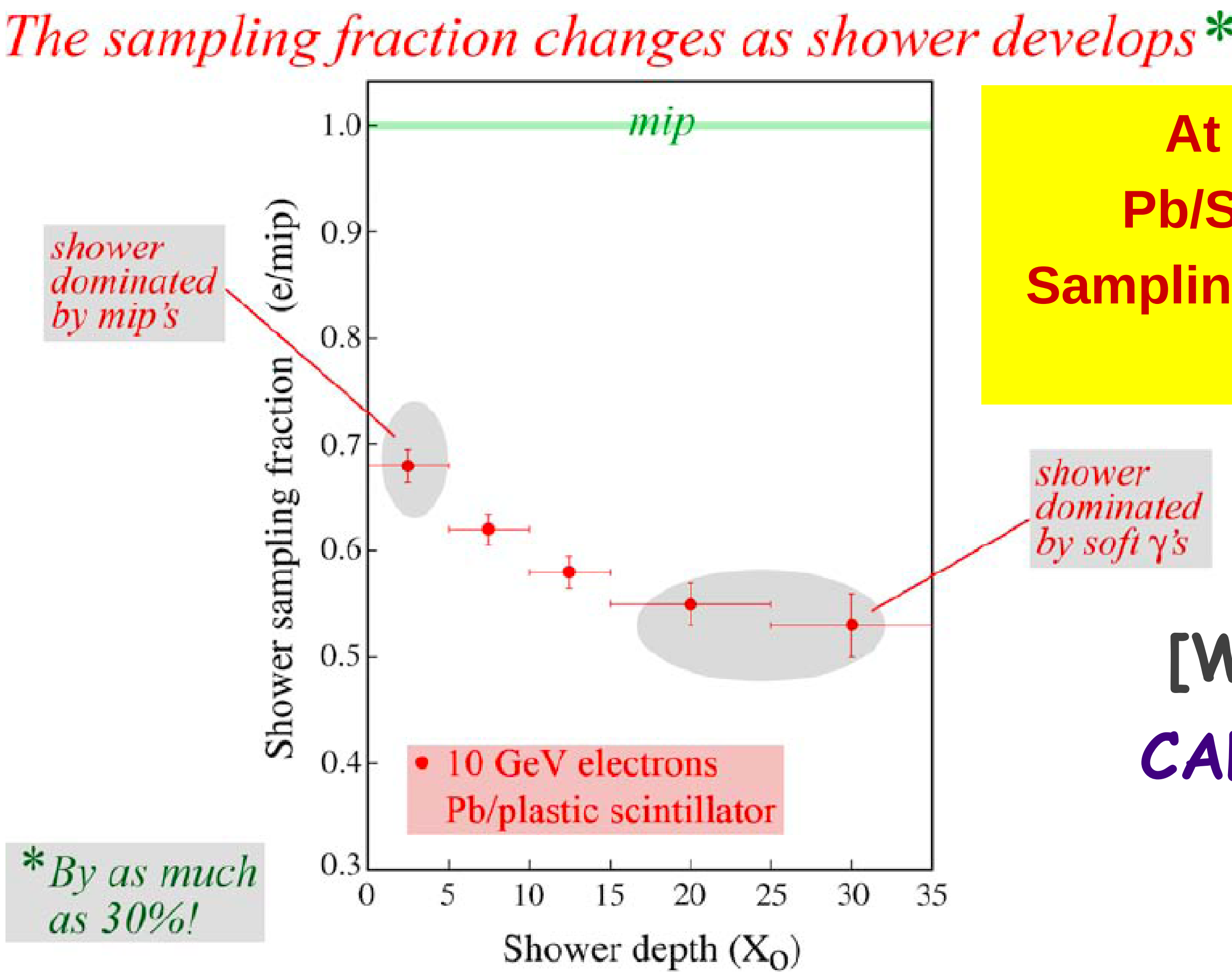




For Barrel: $\sigma_E/E = 2.7\%/\sqrt{E} \oplus 0.55\% \oplus 0.16/E$

For Endcaps: $\sigma_E/E = 5.7\%/\sqrt{E} \oplus 0.55\% \oplus 0.77/E$

BUT even Electromagnetic Showers Are not Simple



At Least in Pb/Scintillator Sampling Calorimeter

[Wigmans]

CALOR2006

Simple picture is only a useful approximation – more later in the discussion on calibration

One last point - the preshower detector

Electromagnetic calorimeters are the detector which must also IDENTIFY photons and differentiate them from p0's for example.

Typically, the initial few radiation lengths of the detector is instrumented with fine granularity and readout separately to accomplish this either on a statistical basis or on an event-by-event basis.

Hadron Calorimetry

$\Rightarrow$Our ansatz "Measured Ionization" = *F* ($E_{particle}$)

$\Rightarrow$In an ideal world this would be linear

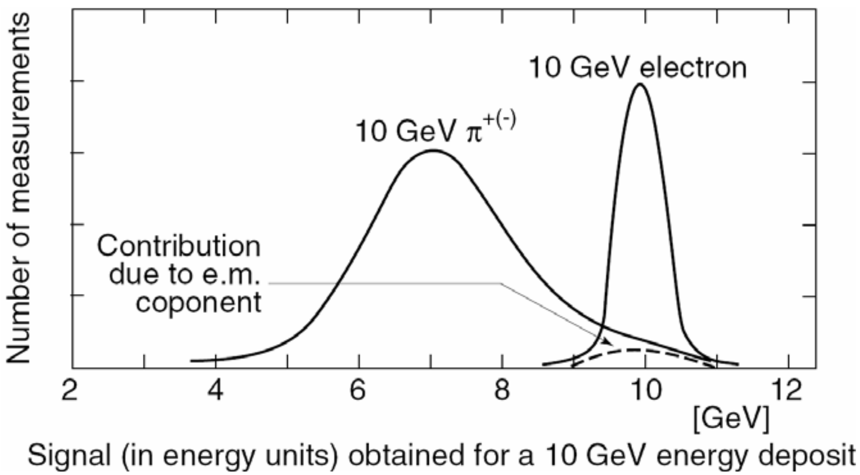
$\Rightarrow$In an ideal world the signal response for any given detector layer would be uniform

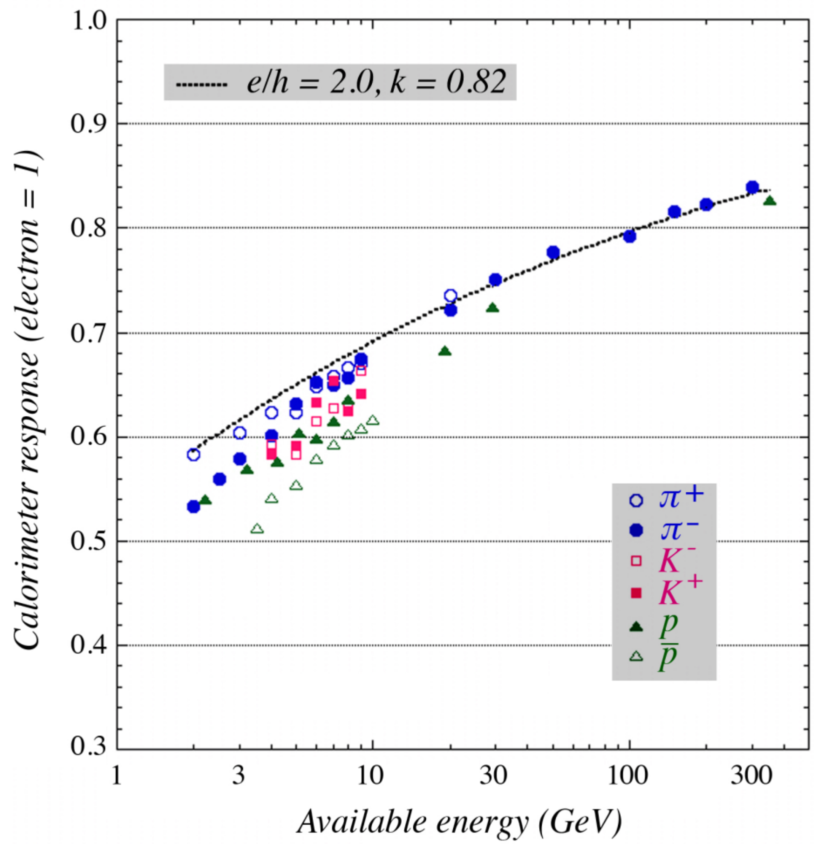
$\Rightarrow$In the real world *F* is non-linear and inverting this to obtain the most accurate estimate of the incident particle is THE major issue for both the resolution and linearity of any calorimeter

$\Rightarrow$And this is the case for both electromagnetic showers and shower produced by high energy hadrons

And response is dependent on particle type and energy

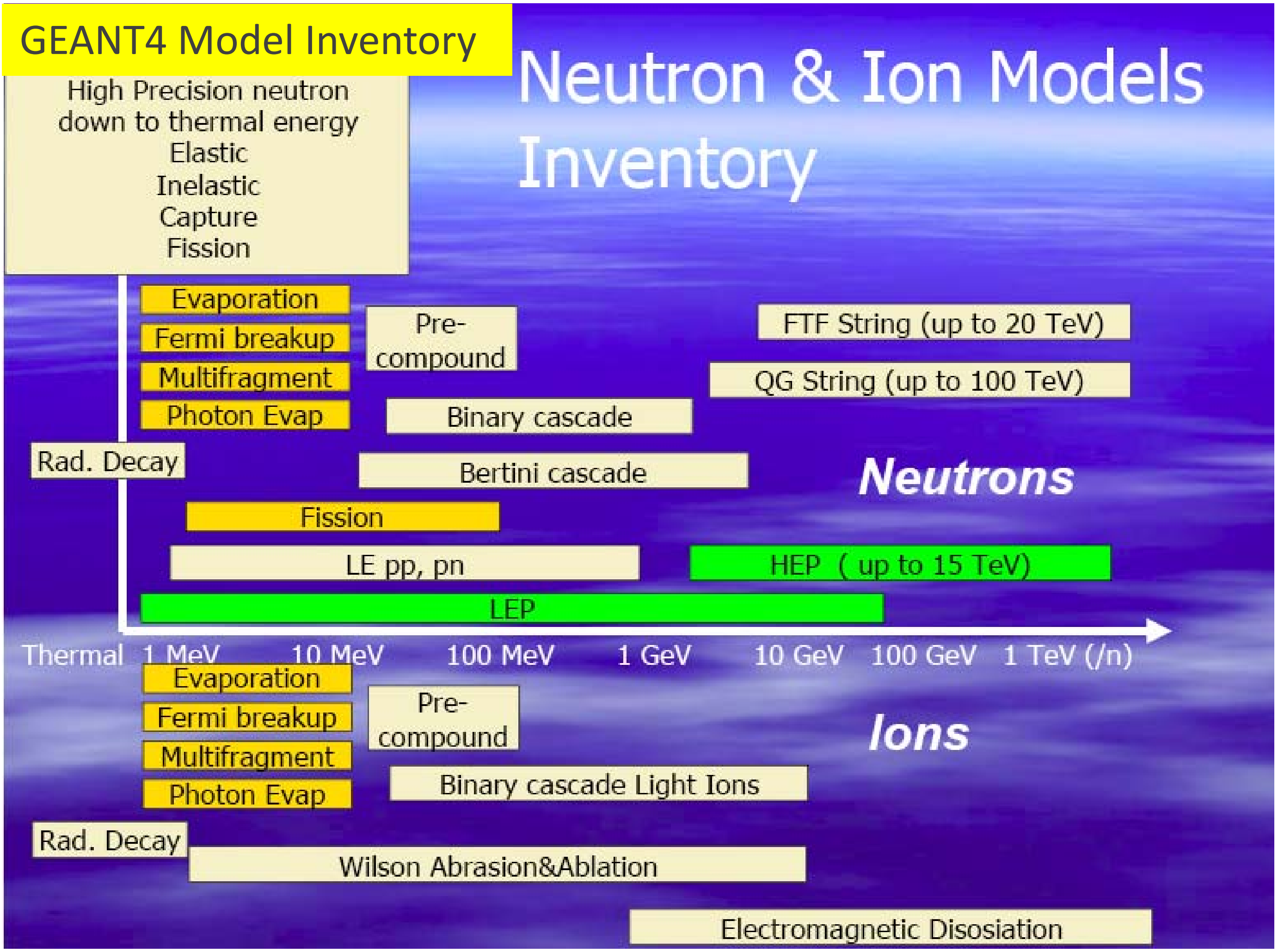
Cartoon showing effect of e/h != 1





The response of the CMS calorimeter system to different types of particles as a function of energy

Hadronic calorimetry – NOT simple to model!



More on this later

Ionization energy deposition for hadrons in Fe

CALOR Monte Carlo Code circa 1990-based on codes used for shielding calculations

The key factor:
Binding energy losses are at the level of 25% and are “invisible”

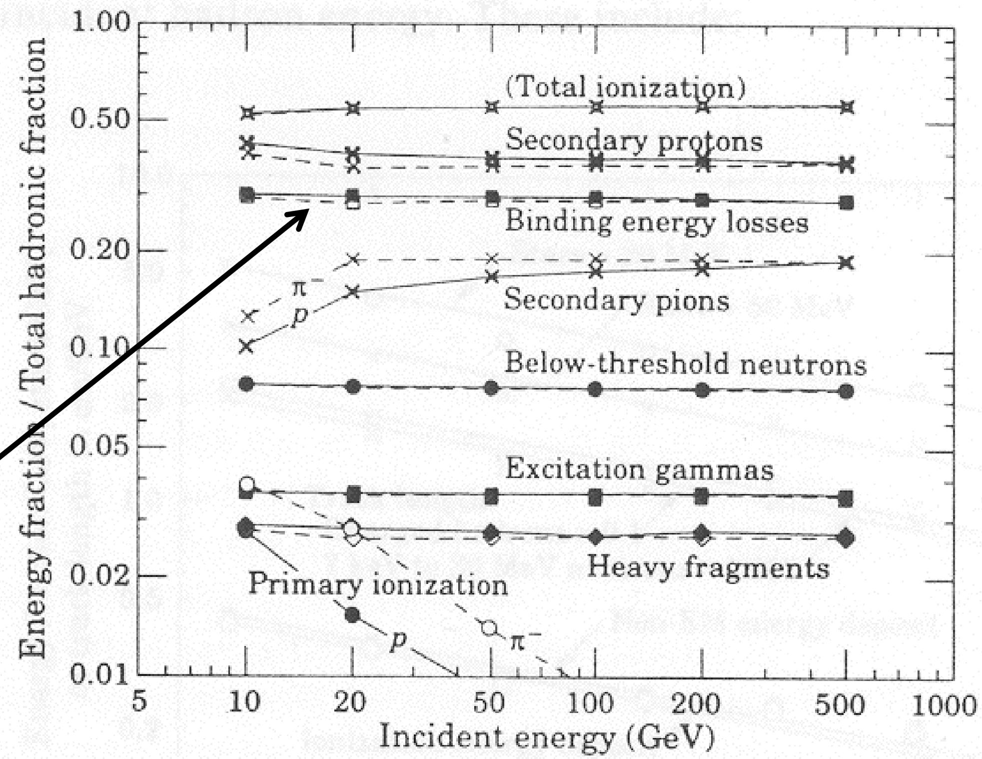


Fig. 5. Hadronic energy loss by various mechanisms in cascades initiated by protons (solid lines) and negative pions (dashed lines) in iron, as simulated with CALOR. Energy deposits are given as fractions of the energy not carried by π^0's. “Total ionization” is the sum of primary and secondary ionization by pions and protons, and is shown to demonstrate the constancy of the sum of all ionization contributions. Exclusive of this subtotal, the sum of the contributions at each energy is unity.

[GABRIEL]

Hadronic Calorimeters - some issues

As far as I know, all hadron calorimeters are sampling calorimeters

⇒Choice of passive absorber (Pb/Fe/Cu/W/quartz are among the many possibilities) – not that important

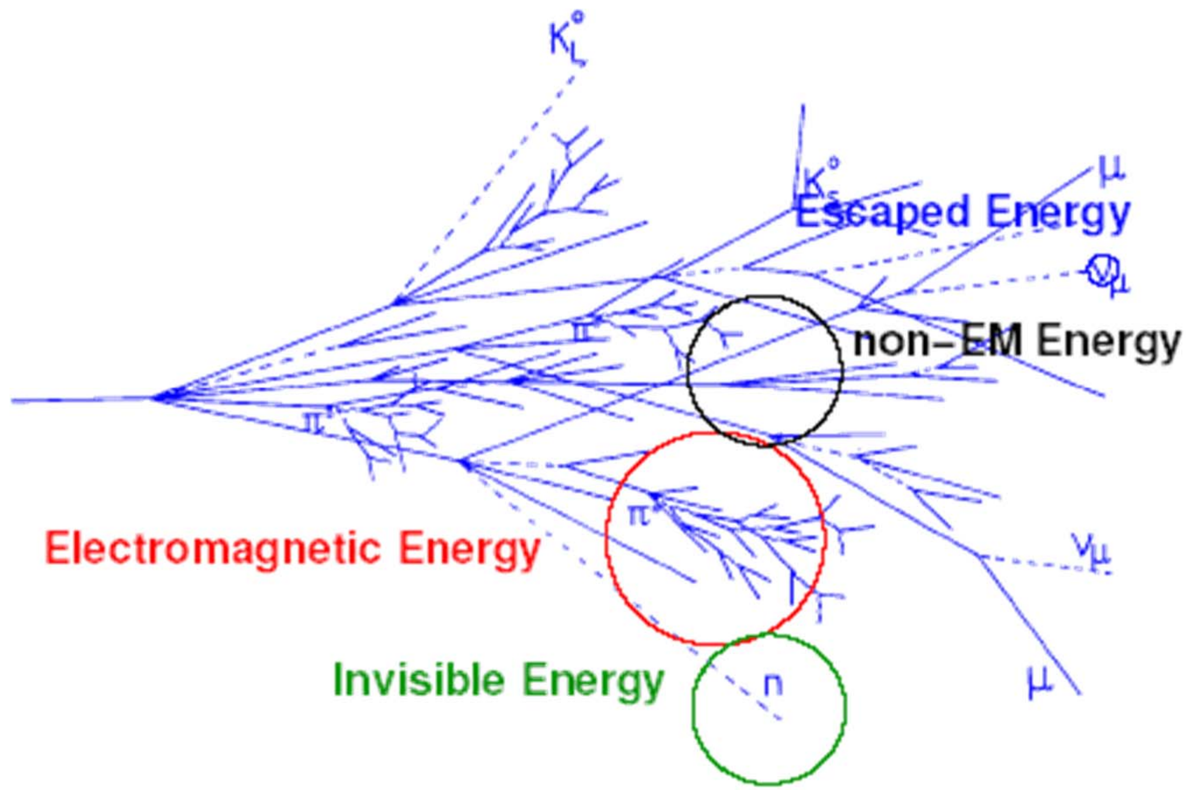
⇒Choice of sensitive medium (taste and prior experience plays a big role here)

⇒e/h and fraction of energy deposited by π^0's in the shower

⇒The role of neutrons

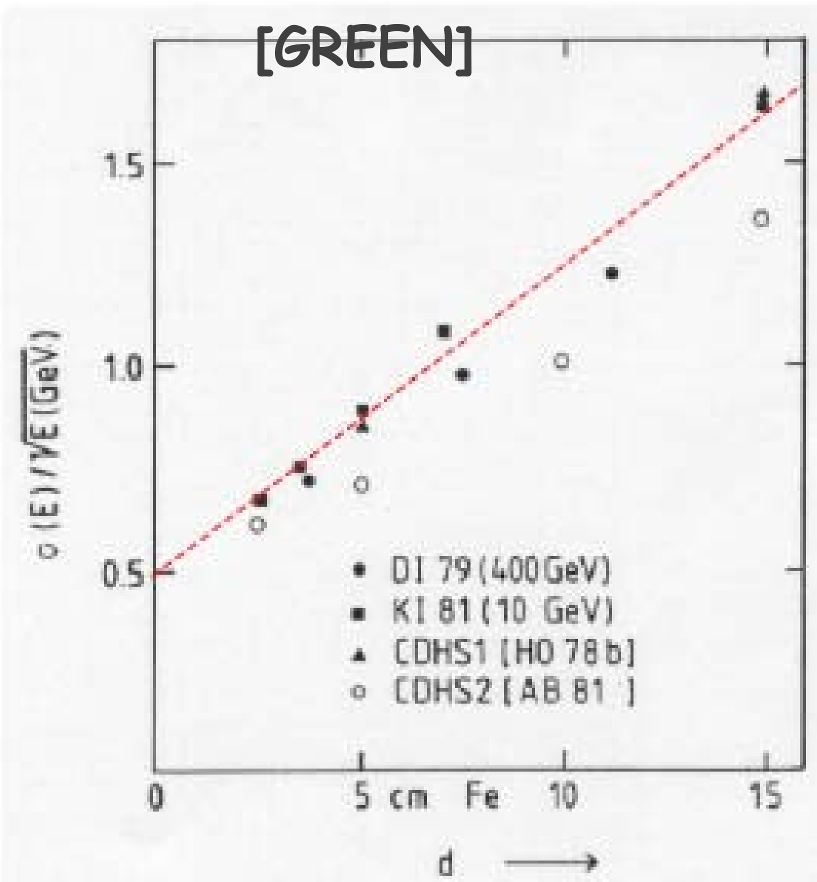
  - ⇒compensation
  - ⇒By nuclear fission (e.g. ZEUS)
  - ⇒By sampling fraction (decrease EM response)
  - ⇒by energy flow techniques

Response for Single Hadrons: $F(E_{particle})$



- EM energy (eg $\pi^0 \rightarrow \gamma\gamma$) : *O*(50%)
- Visible non-EM energy (eg dE/dX) : *O*(25%)
- Invisible non-EM energy (eg nuclear breakup) :*O*(25%)
- Escaped energy (eg ν) :*O*(1%)

Binding Energy Fluctuations



Sampling Thickness

The Stochastic coefficient scales as t_{had} as expected.

The non-zero intercept indicates that this is not the full story =>

(nuclear) binding energy fluctuations

The role of neutrons - a lecture in its own right

Mentioned here for completeness: as far as I know this is not relevant in any operating calorimeters (it was relevant for D0 and ZEUS)

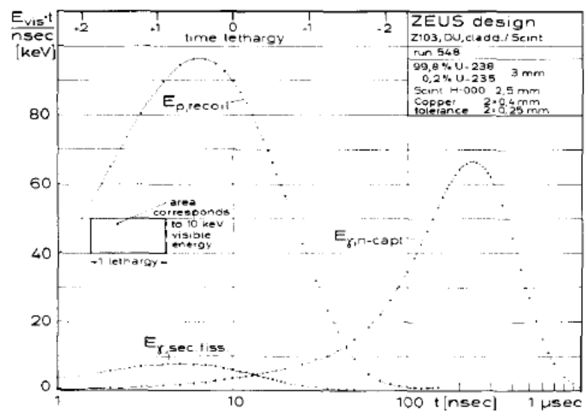
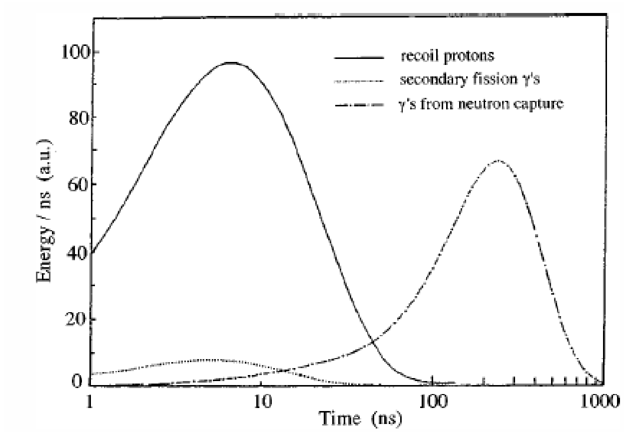
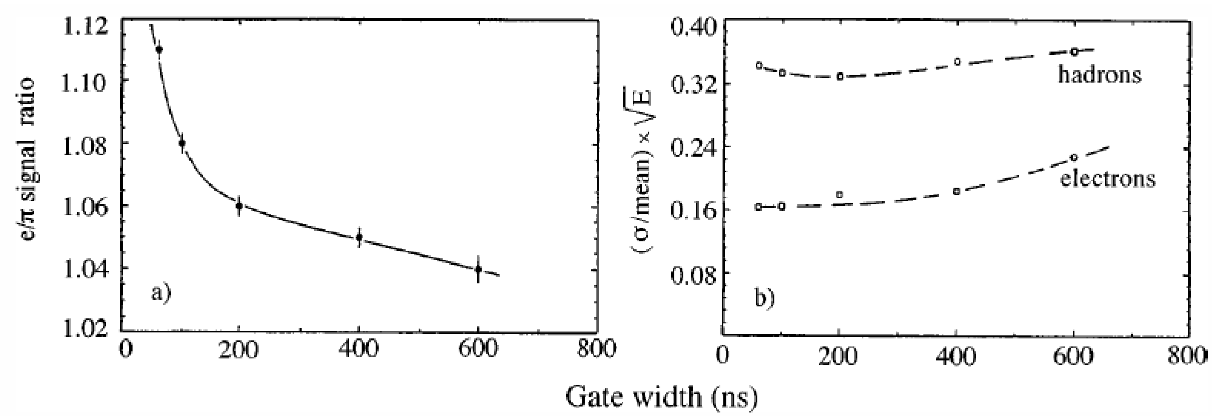


Fig. 11. The contributions to "visible" energy from proton recoils and from the nuclear processes. In the lethargy-plot, areas are directly proportional to an amount of energy contributed.

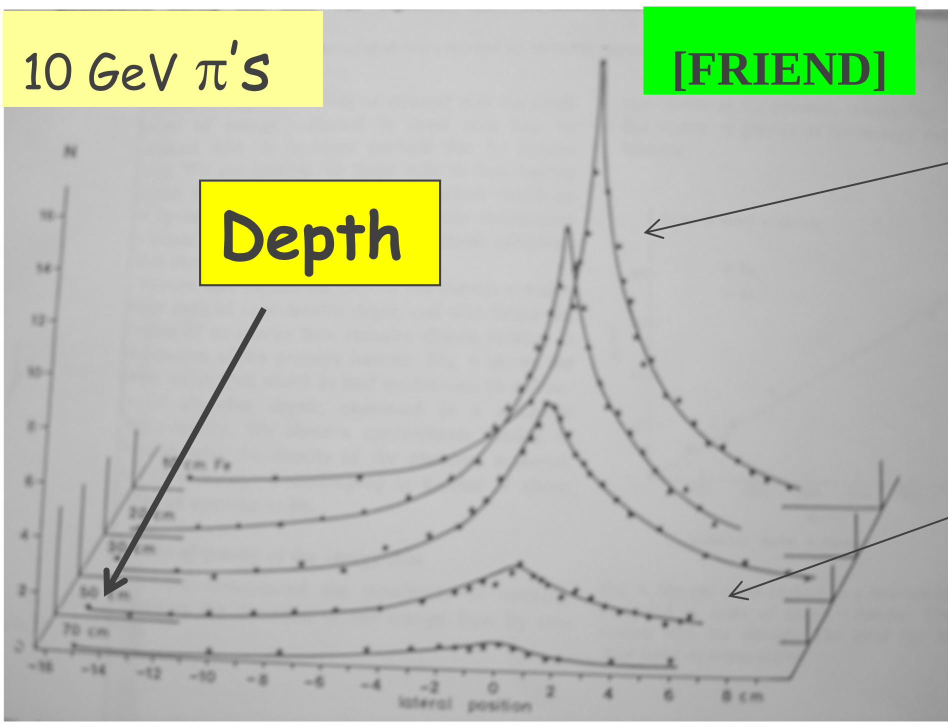




Active Compensation: ZEUS Calorimeter using U/Scint

Hadron Shower Development

Hadronic showers are defined by the fraction of energy transferred to the electromagnetic sector by the production of π^0's – 1/3rd of the energy on each interaction (isospin).Once transferred it doesn't return to the hadronic sector.



Dense core associated with deposition of electromagnetic energy

Tail associated with deposition of hadronic energy

Contribution from electromagnetic energy diminishes with shower depth

Shower width increases linearly with depth x density

Fraction of Energy Carried by π^0's

[AMARAL]

Integrate the contribution for the first component to obtain the fraction of energy carried by π^0's

$$f_{\pi^0} = \frac{a_1 \lambda_1}{\sum_{i=1}^{3} a_i \lambda_i}. \quad (29)$$

For the entire Tile Calorimeter this value is $(53 \pm 3)\%$ at 100 GeV.

The observed π^o fraction, f_{π^0}, is related to the intrinsic actual fraction, f'_{π^0} by the equation

$$f_{\pi^0}(E) = \frac{eE'_{\rm em}}{eE'_{\rm em} + hE'_{\rm h}} = \frac{e/h\, f'_{\pi^0}(E)}{(e/h - 1)f'_{\pi^0}(E) + 1} \quad (30)$$

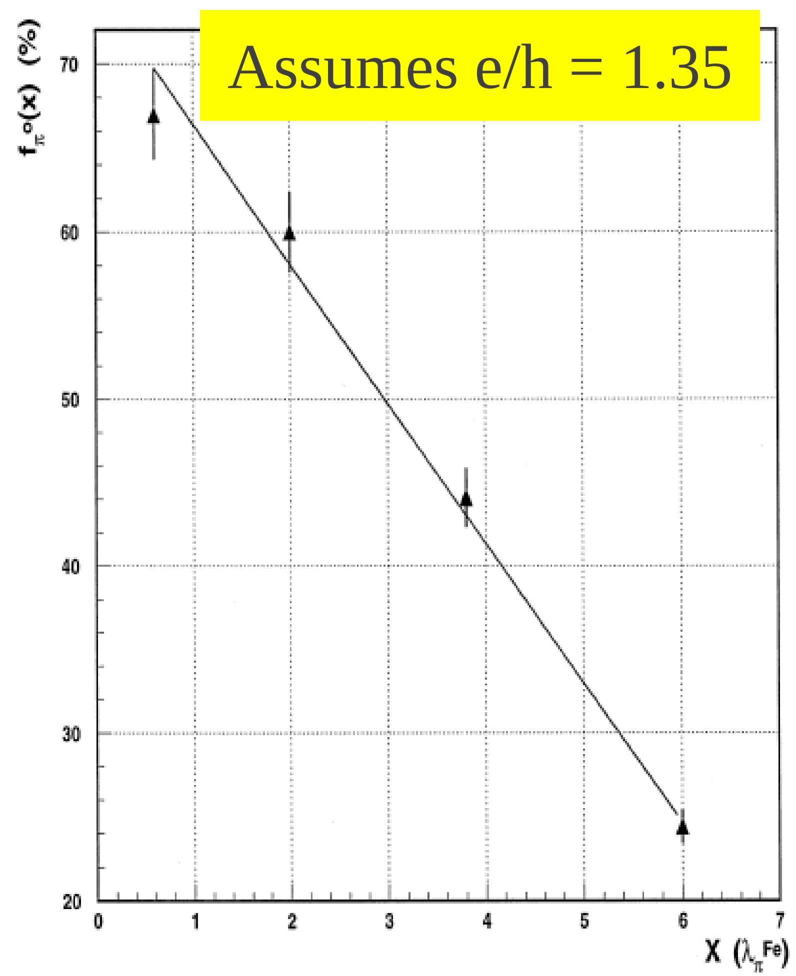
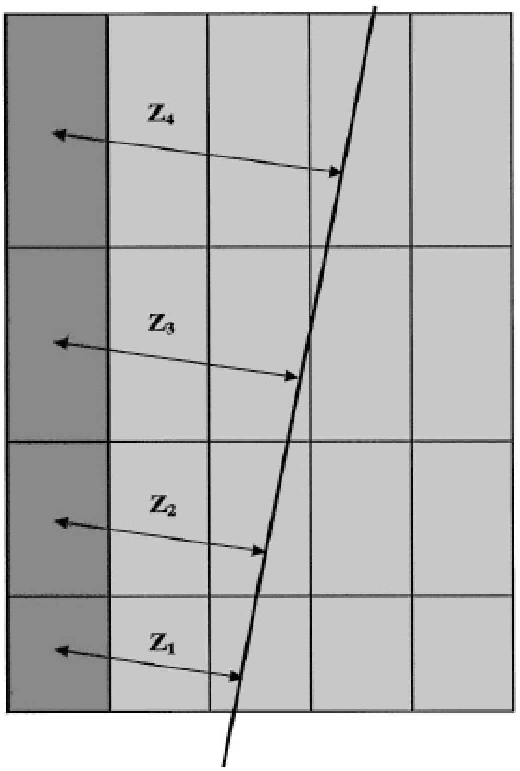


Fig. 20. The $f_{\pi^0}(x)$ fractions of hadronic showers as a function of x.

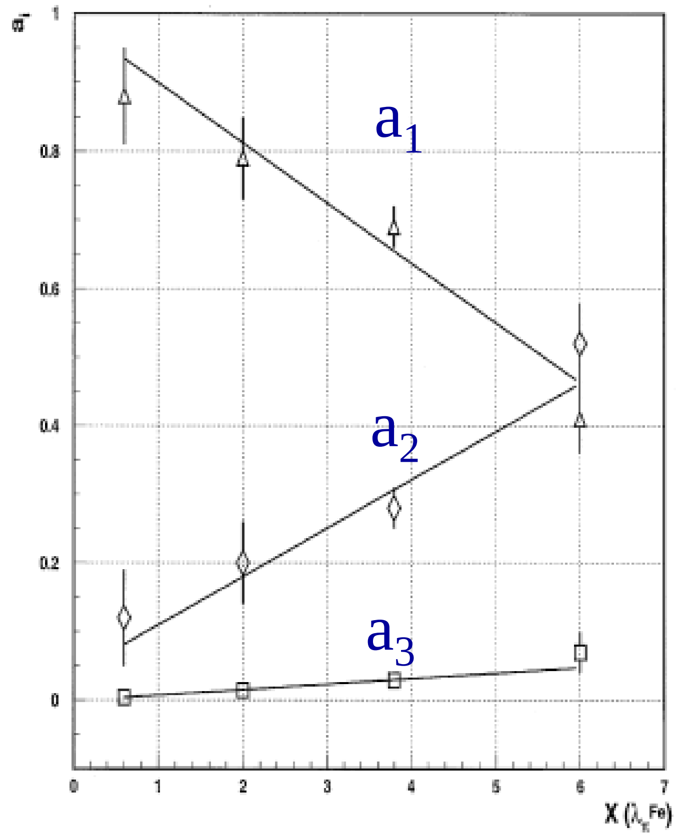
Tile Calorimeter Prototype

$$f(z) = \frac{E_0}{2B} \sum_{i=1}^{3} a_i e^{-|z|/\lambda_i}$$



[AMARAL]

Same story…



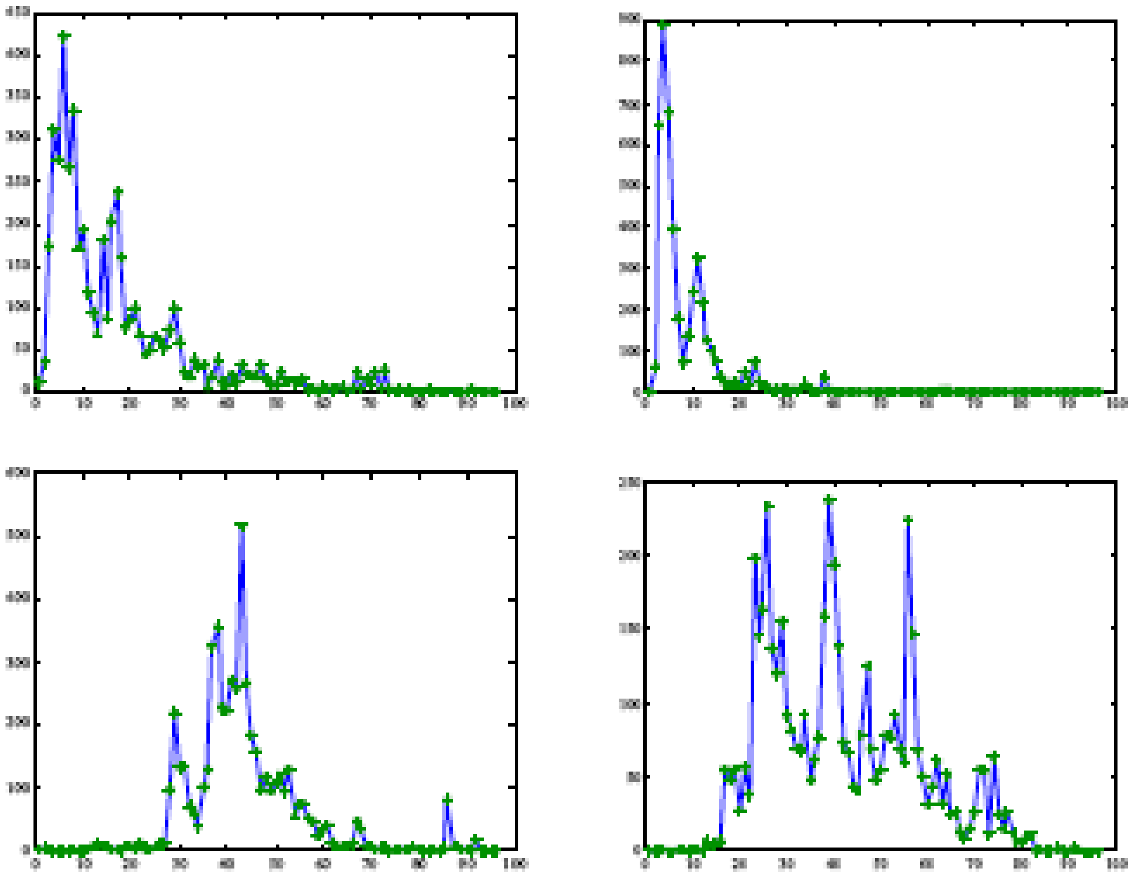
$<\lambda_1>$=23mm , $<\lambda_2>$=58mm, $<\lambda_3>$~250mm

Hadron Shower Development (II)

96 Layers of Pb/Scintillator Sampling Depth is 0-6 λ [GREEN]

Fluctuations in depth are indicative of the fluctuations associated with the deposition of electromagnetic energy

Substantial event-to-event variation. Therefore any useful correction must be event-by-event



Sample-to Sample Correlations

Relevant for the correction of the measured energy for dead material (coils, cryostats and the like)

Flat => No Correlation

Proportional => Strong Correlation

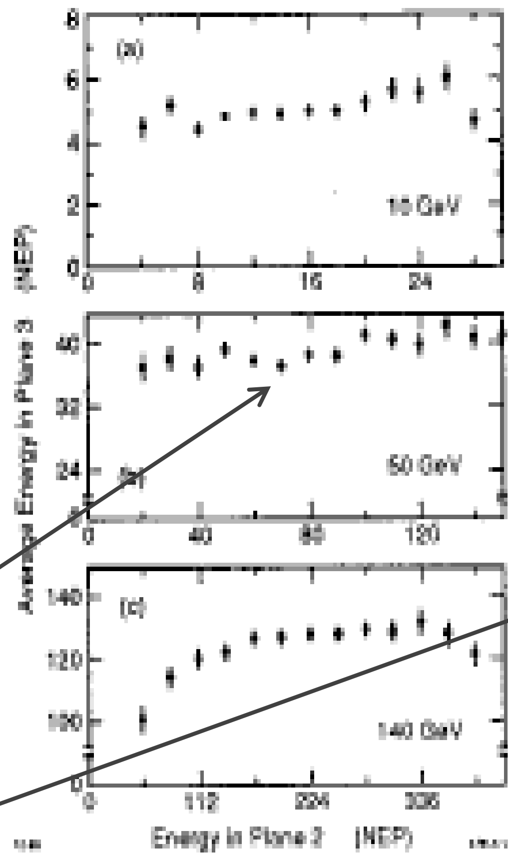


Fig. 13. Average shower energy deposited in the third plane from the vertex as a function of the shower energy ...

Plane 3 vs 2

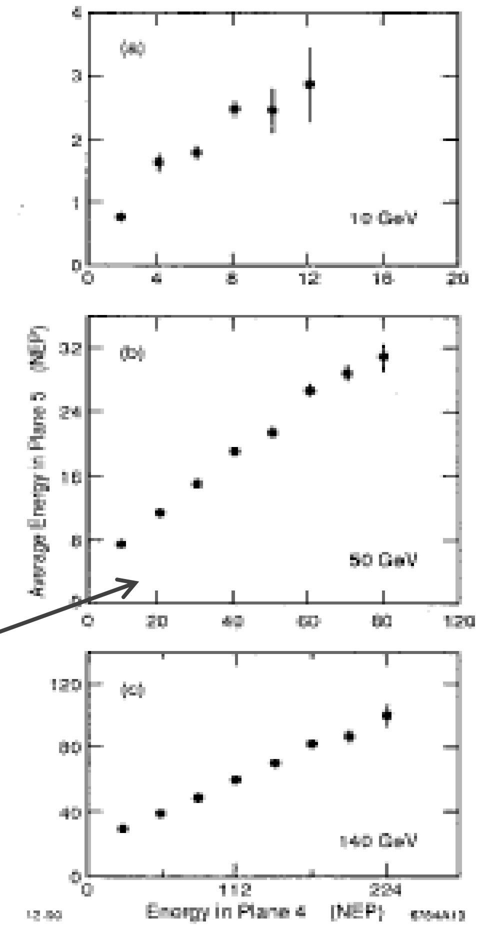


Fig. 14. Average shower energy deposited in the fifth plane from the vertex as a function of the shower energy deposited in the fourth

Plane 5 vs 4

[HUGHES]

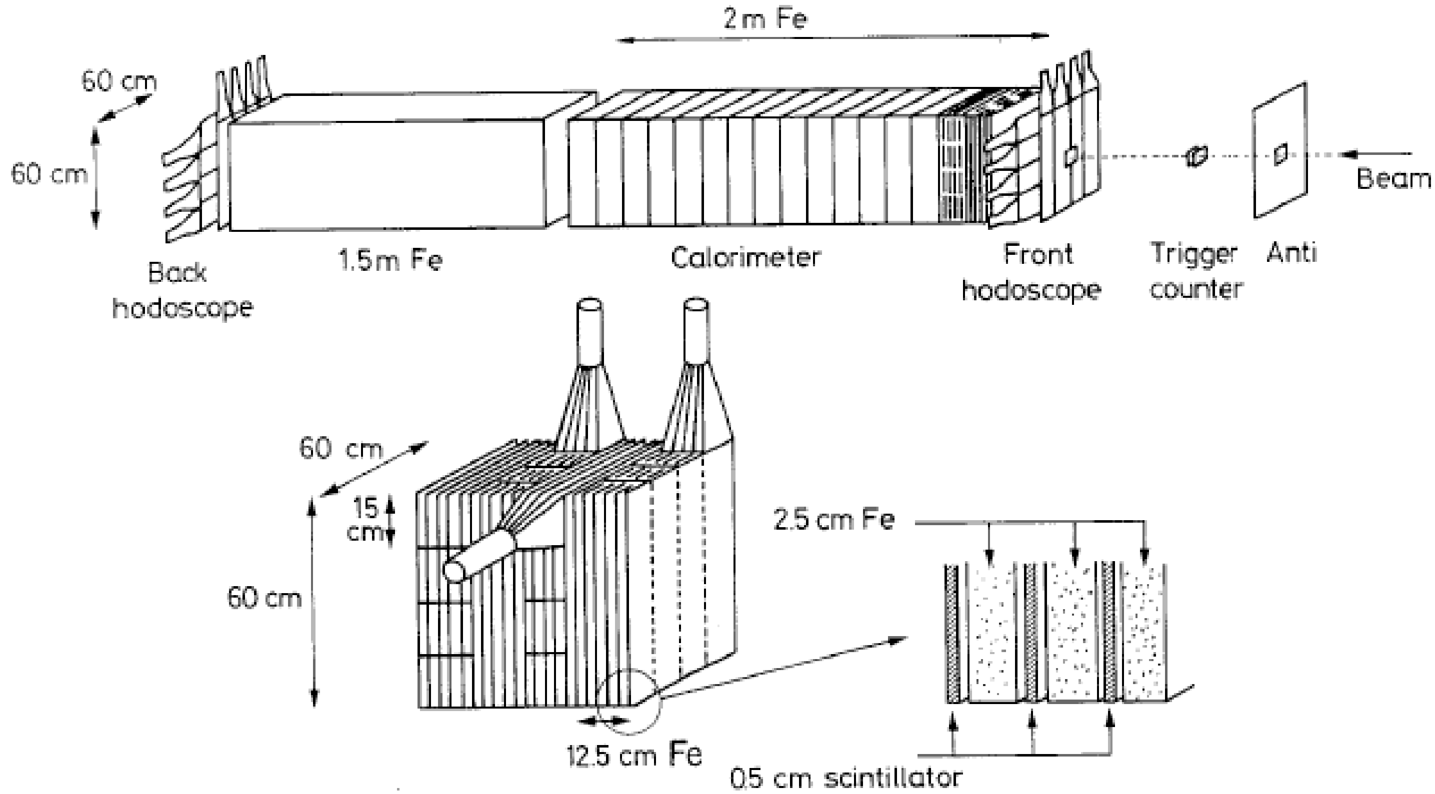
Features of Hadronic Showers: Recap

We have now established several of the important "well-known" features of hadronic showers:

- In general e/p relative response is not equal to 1
- A large fraction of the energy is deposited through em showers (π^0's)
- The starting point for the em component various wildly (little sample to sample correlation early in cascade)
- Fluctuations in binding energy appear to be the principal mechanism which limit the precision of the measurement of the energy of the incident particle
- The transverse shower shape is a function of the depth of the shower

The Way to Address These Issues (I)

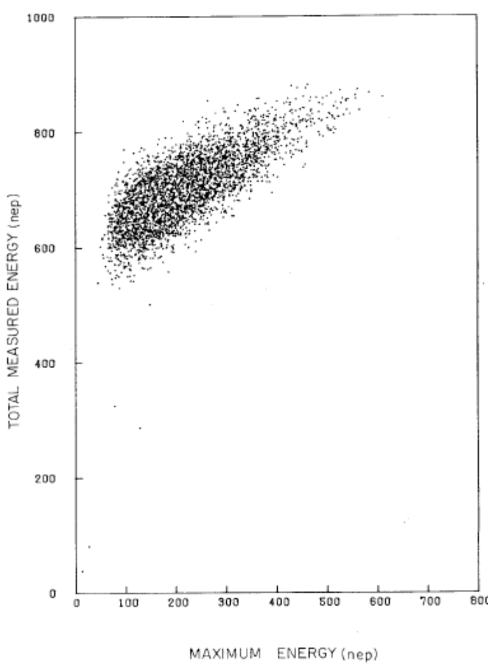
Use Longitudinal Segmentation

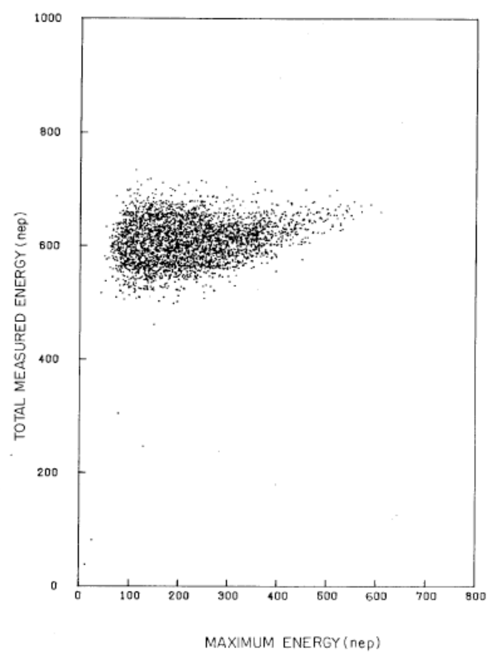


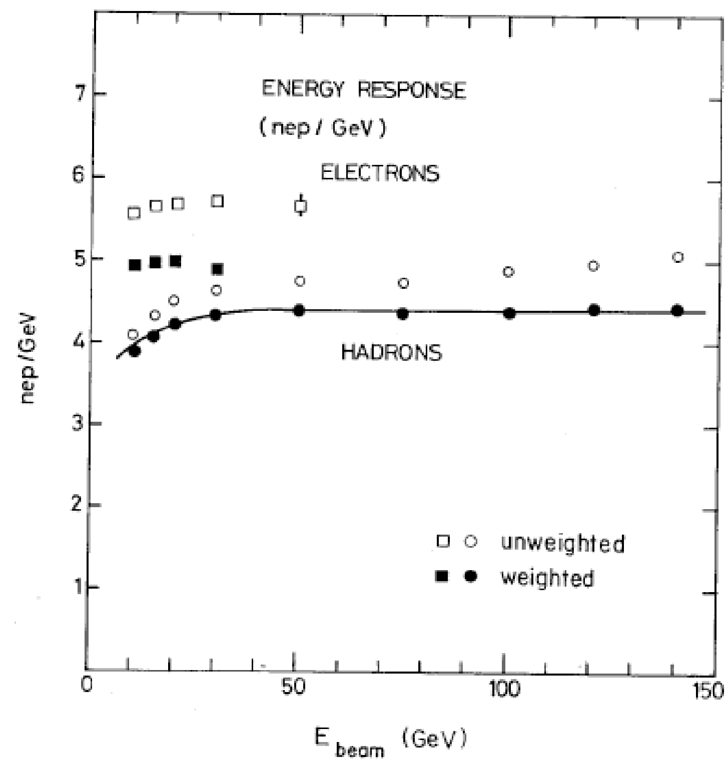
[ABRAMOWICZ]

The Way to Address These Issues (II)

Weight Signals as a Function of Depth to Minimize resolution







Response to electrons is not equal to the response to hadrons

Some examples of calorimeters

CDF

ATLAS

D0

CMS BCAL

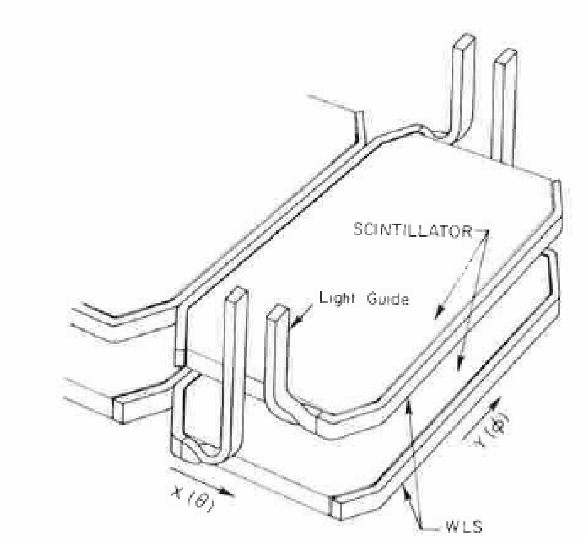
CMS HCAL

CMS HF

CDF EM and Hadronic Calorimeter

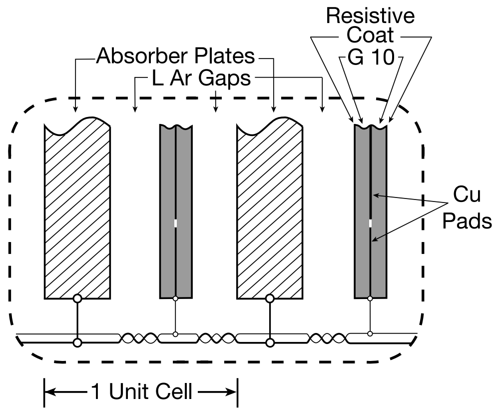
HAD Section:
25mm Fe, 10mm scintillator

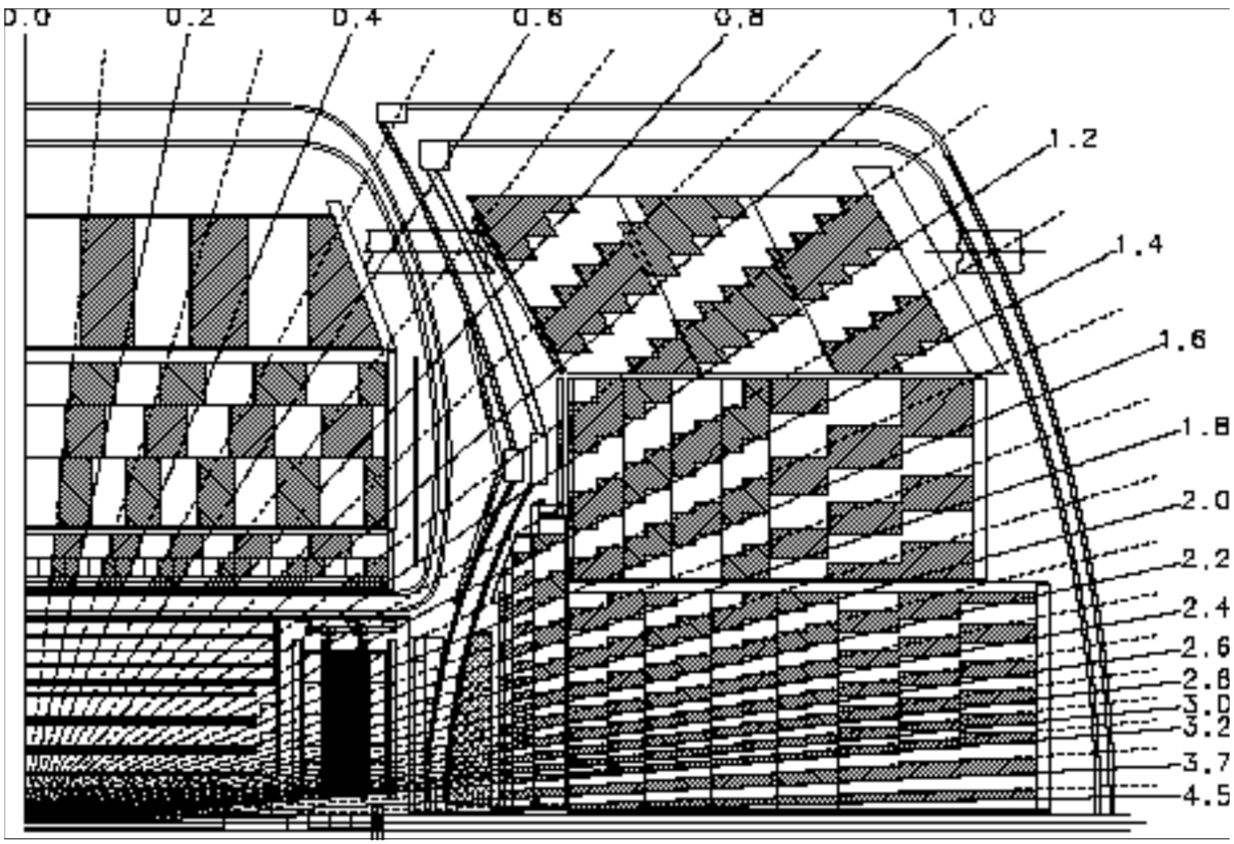
Readout by wls fingers



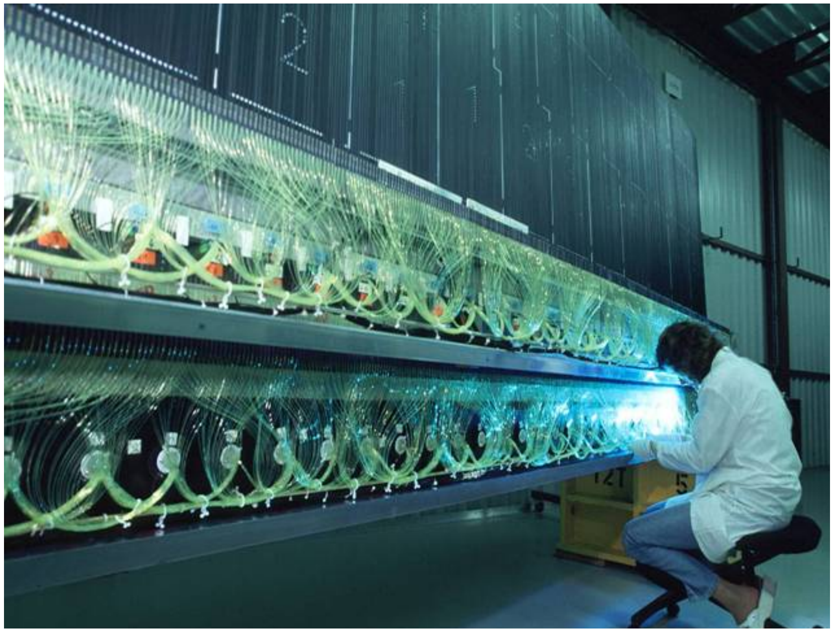
EM Section:
3mm Pb, 5mm scintillator, 3mm Y7 waveshifter plate

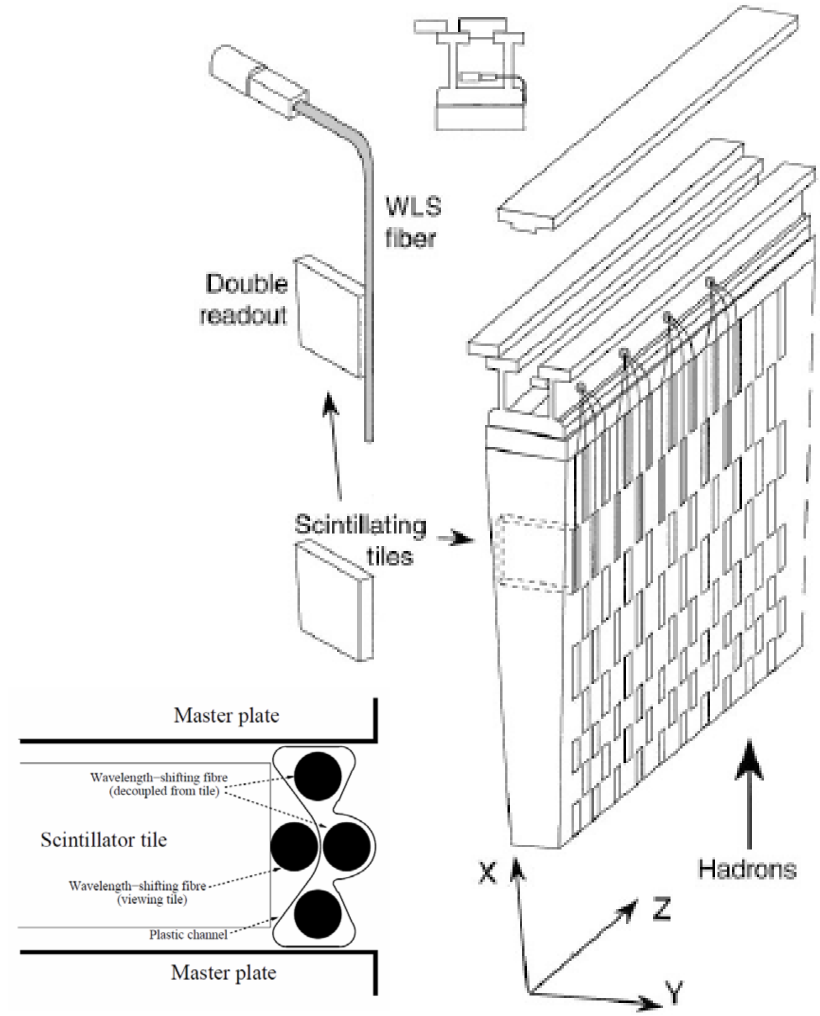
D0 Calorimeter





ATLAS Barrel Hadron Calorimeter

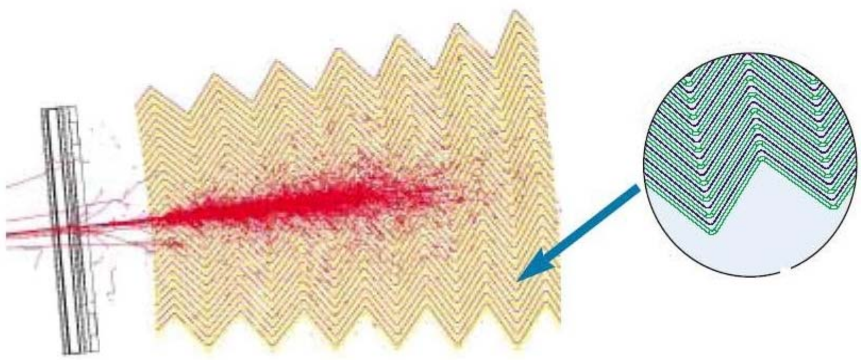


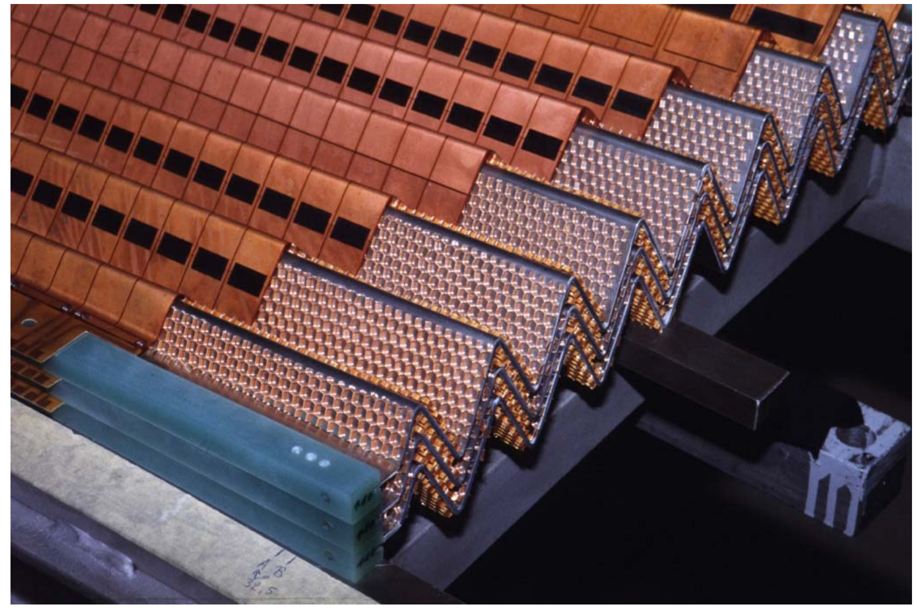


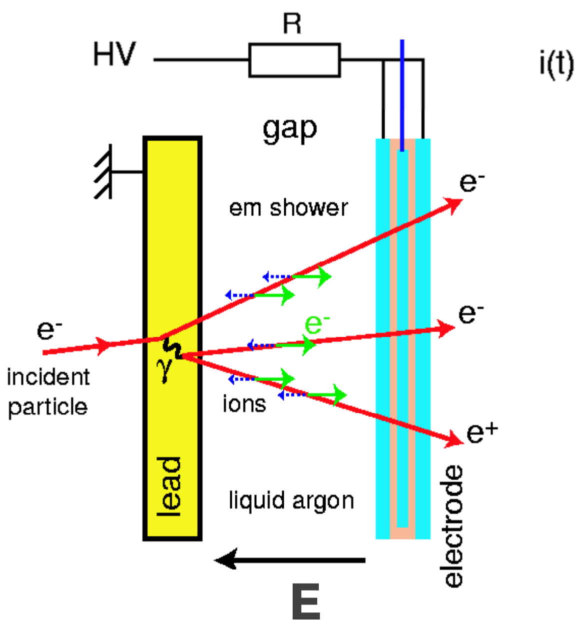
The iron structure supporting the calorimeter (girder) is contains the return field of the ATLAS 2 Tesla solenoidal field. The photon-sensors are inside the girder and in a modest B-field

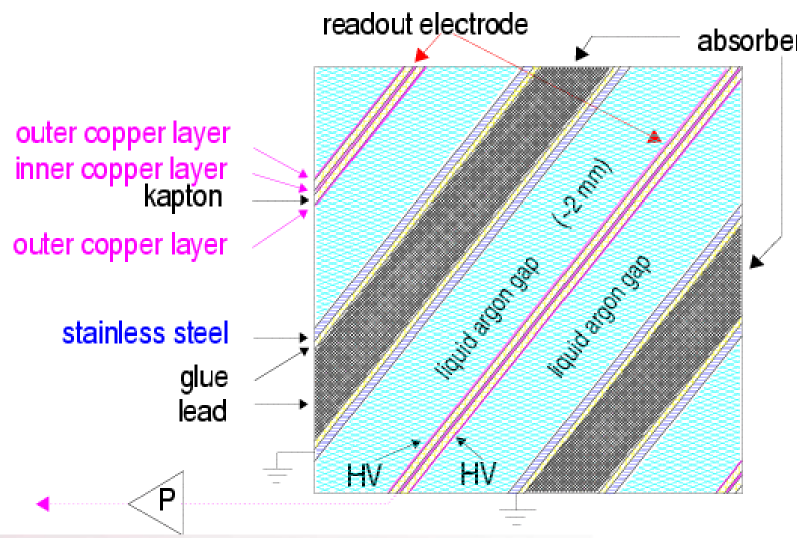
Tile Cal a Fe/Scint with WLS fiber Readout via PMT

ATLAS Barrel Liquid Argon Calorimeter

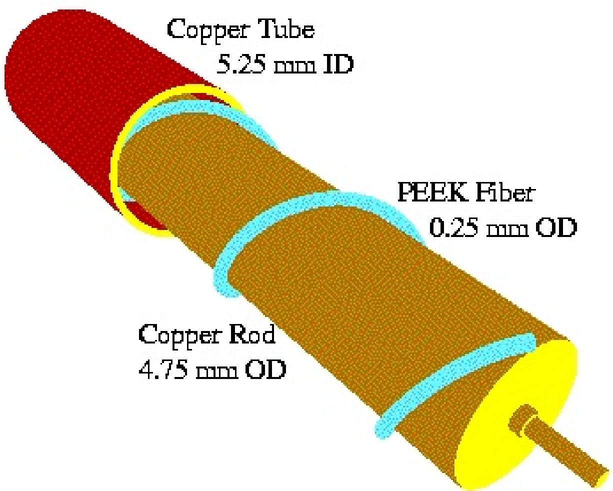


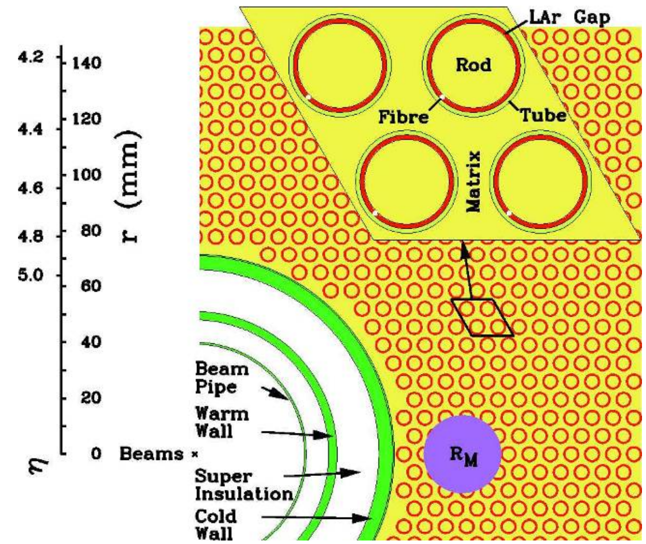


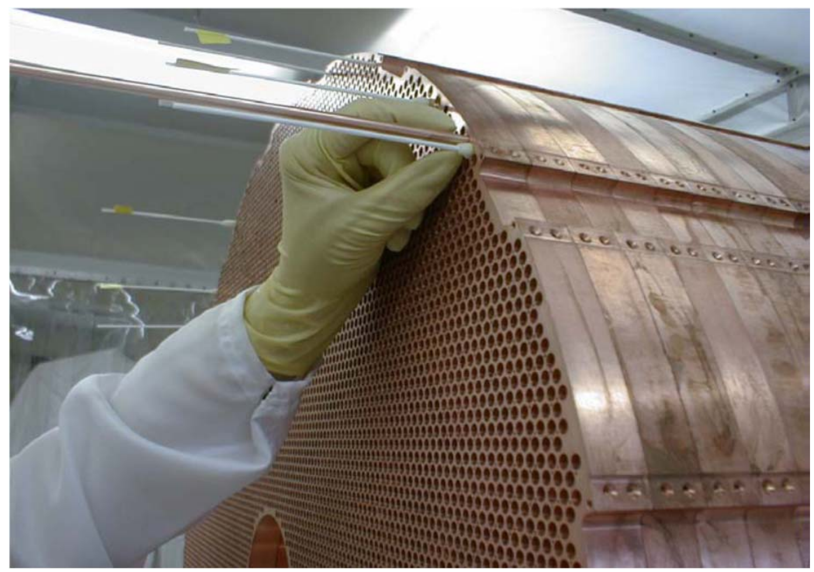




ATLAS FCAL

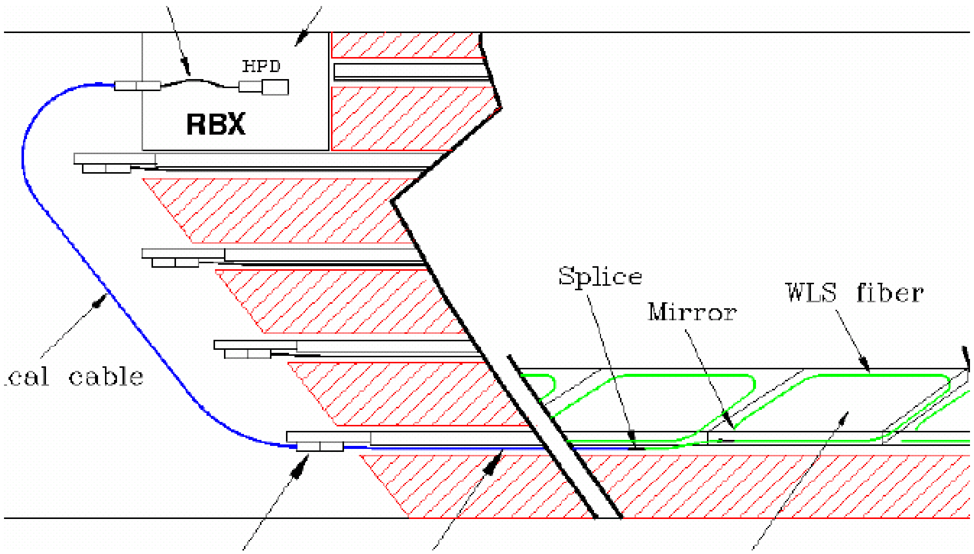

Copper Tube
5.25 mm ID
PEEK Fiber
0.25 mm OD
Copper Rod
4.75 mm OD


LAr Gap
Rod
Fibre
Tube
Matrix
4.2
4.4
4.6
4.8
5.0
η
140
120
100
80
60
40
20
0
r (mm)
Beams
Beam Pipe
Warm Wall
Super Insulation
Cold Wall
R_M



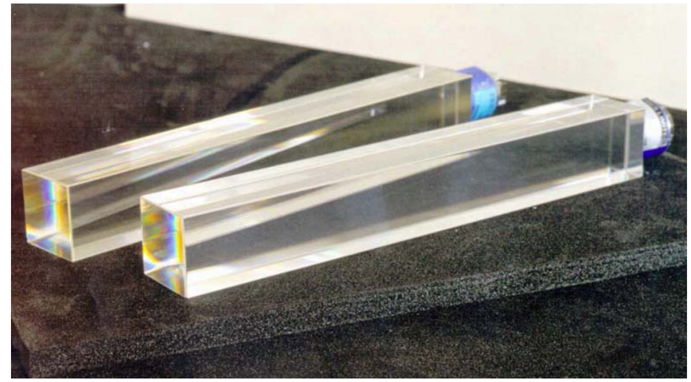
CMS HCAL

Brass/Scintillator Sampling Plate Calorimeter



NB. The detector and photo-detectors are inside the CMS 4 Tesla Magnetic Field

CMS ECAL

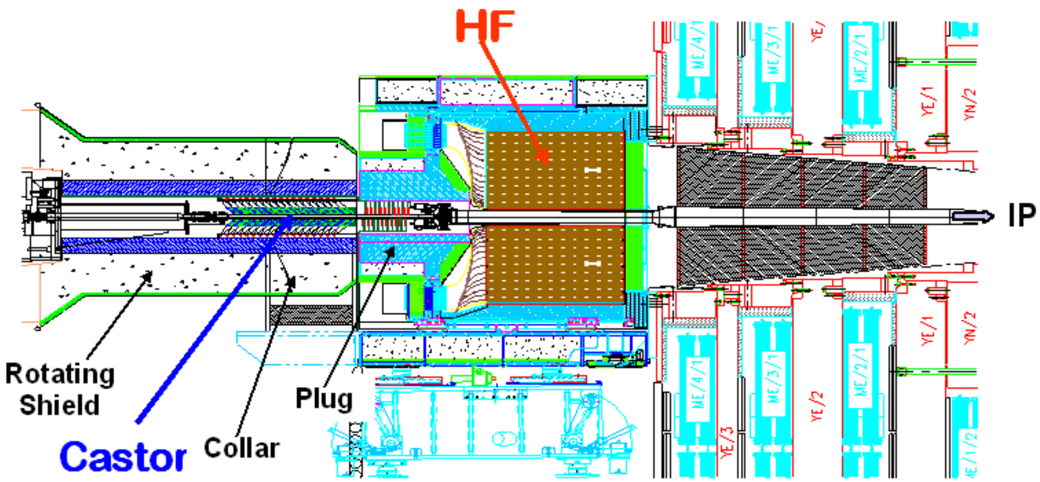


Looks simple, but requires significant development to grow crystals of sufficient size, transparency and light yield

Light detection via APD

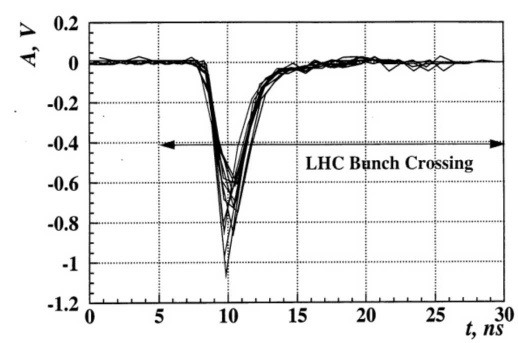
CMS HF

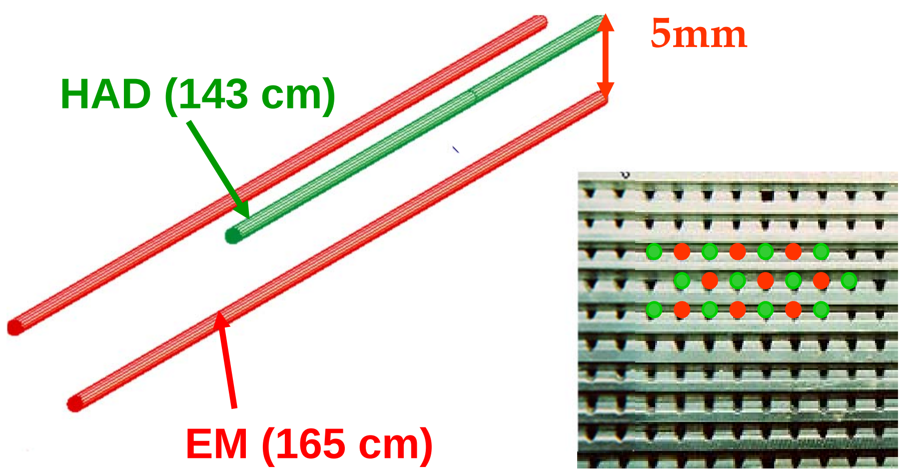
Quartz fiber Cerenkov
Calorimeter with Steel Absorber



Forward CMS Region

350 GeV Pion Signal





Lecture 2

Precision measurements with calorimeters at hadron colliders – turning them into scientific instruments

Some Reference Material

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