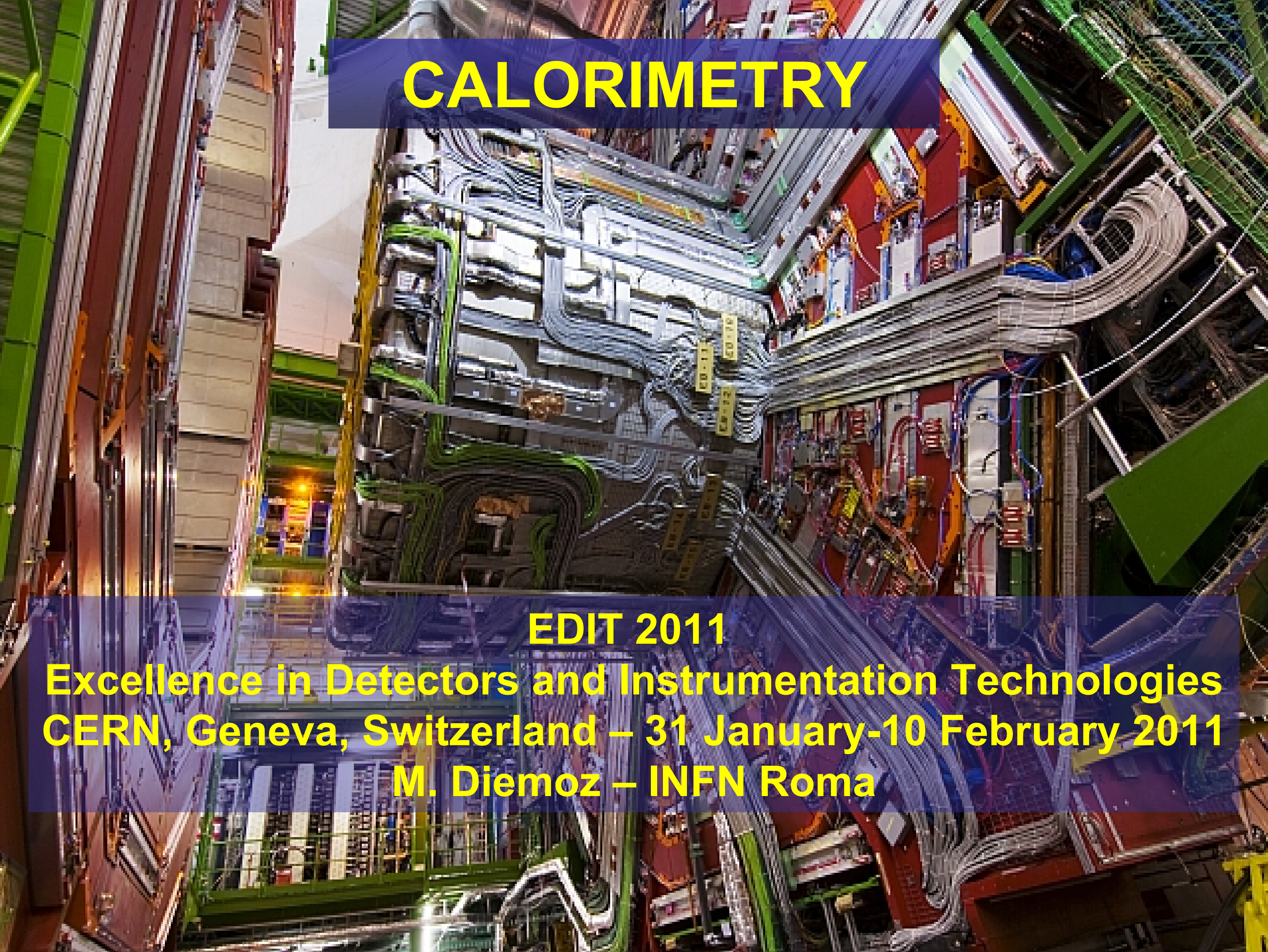


CALORIMETRY

EDIT 2011
Excellence in Detectors and Instrumentation Technologies
CERN, Geneva, Switzerland – 31 January-10 February 2011

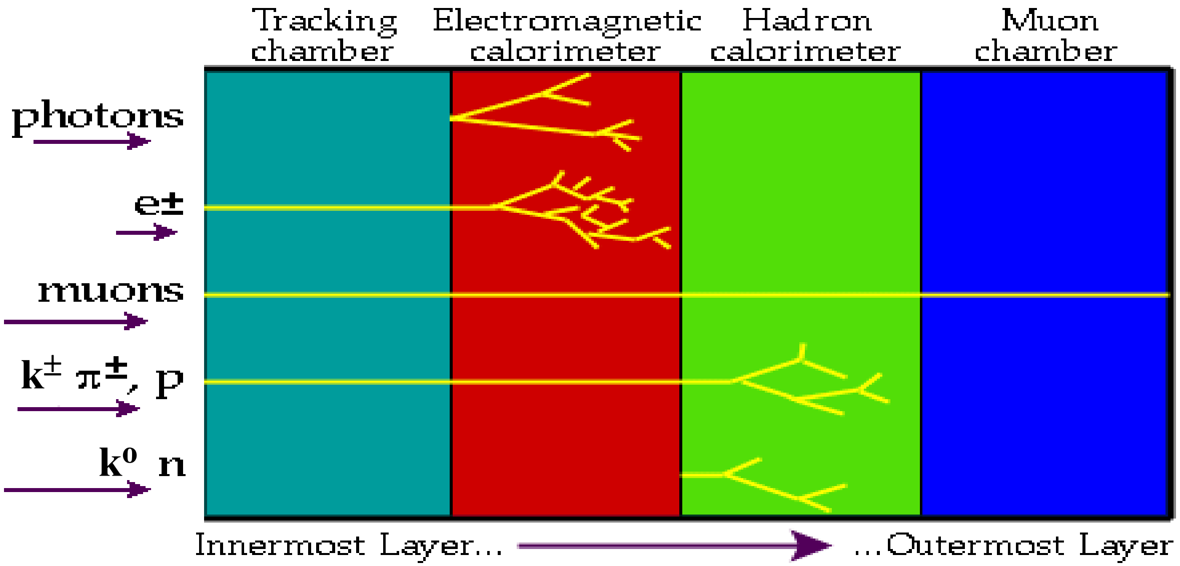
M. Diemoz – INFN Roma

Outline

- Introduction
- Interactions & showers (em&had)
- Basics of calorimetry
- Resolutions

Particle detection

Particles characteristics are measured through different type of detectors and identified thanks to specific behaviours due to their interaction with matter

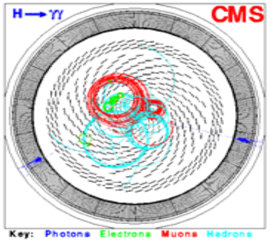


γ , e , jets (q,g), missing energy (e.g. ν), are detected with calorimeters

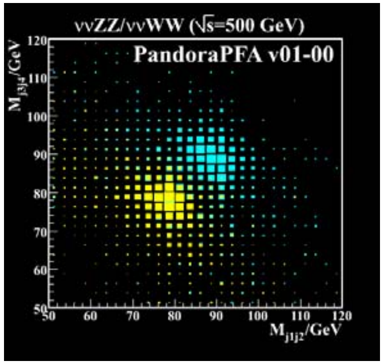
Which calorimetric system?

DEPENDS ON PHYSICS (and money…)!

Resolution on single objects (γ,e…)



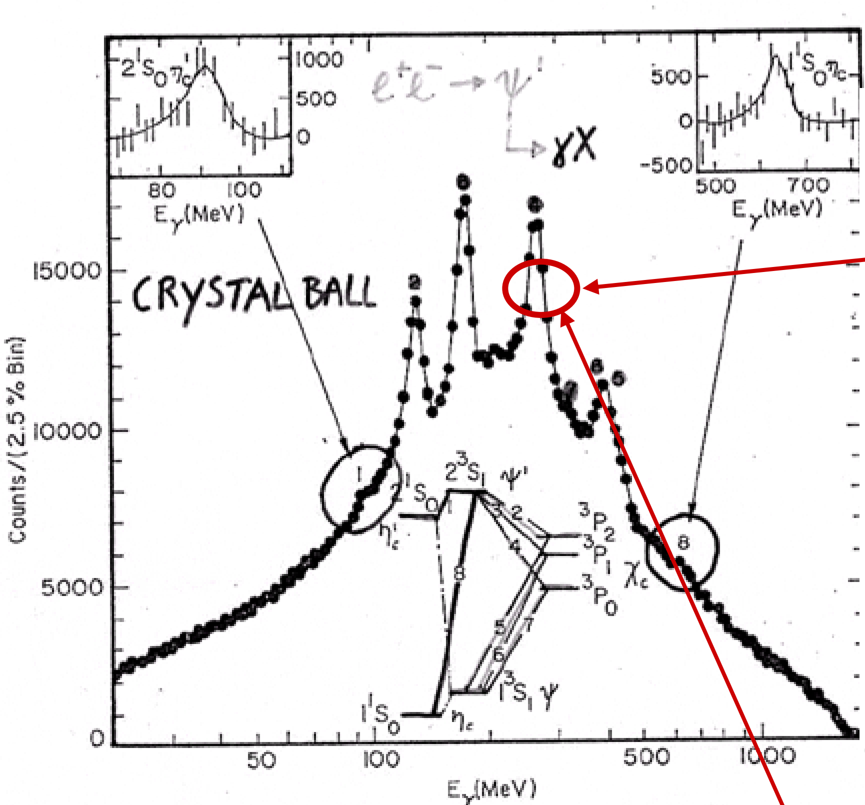
Resolution on complex objects (jets)

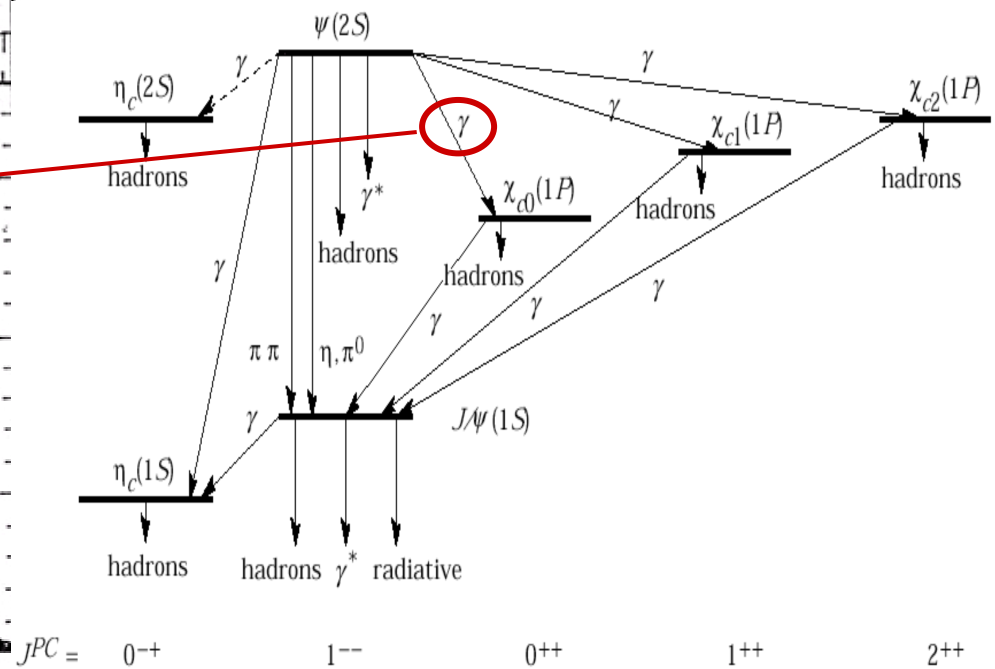


Resolution, resolution, resolution (and efficiency)… Energy, angle, time…

Often you would like ALL!

Crystal Ball: $c\bar{c}$ system transitions



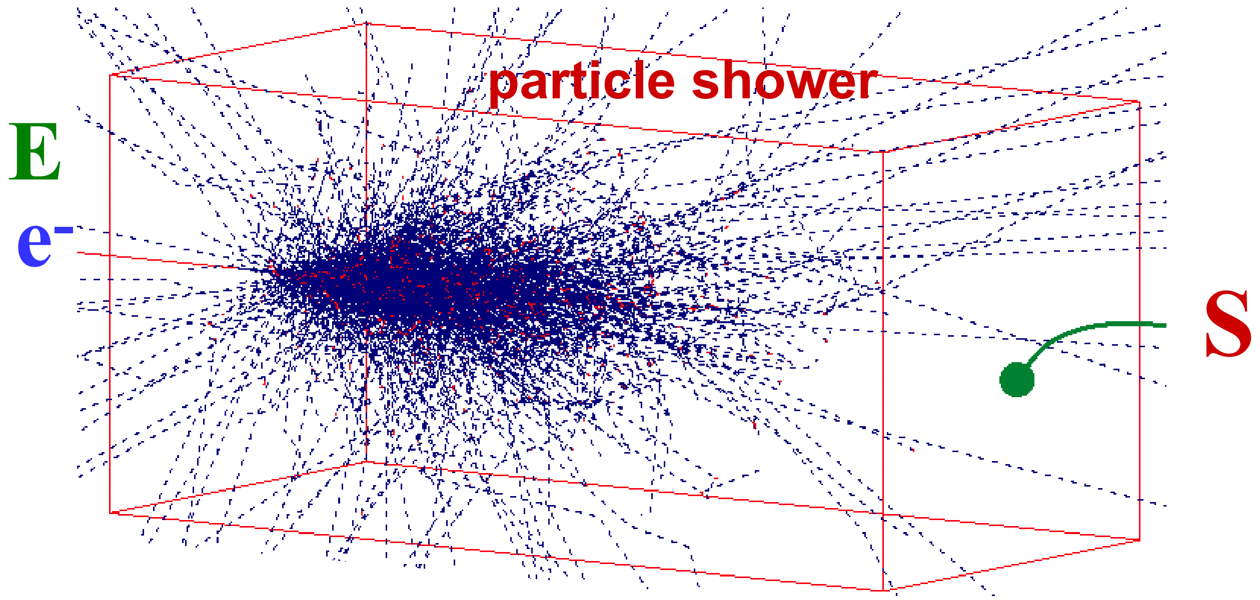


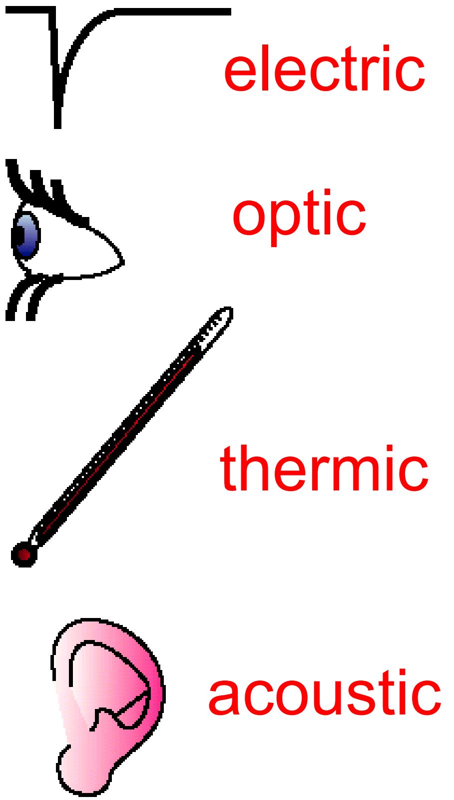
precision in γ energy: see peaks

1974: J/Ψ discovery

charmonium spectroscopy: e+e- $\to \Psi' \to \gamma X$

Calorimeters: a simple concept





Converts energy E of incident particles to detector response S:

$$S \propto E$$

Calorimetry is a "destructive" method. Energy and particle get absorbed !

Calorimeters: some features

- Detection based on stochastic processes

  precision increases with E

- Detection of both charged and neutral particles
- Dimensions necessary to containment $\propto \ln E$

  compactness

- Easy to be segmented

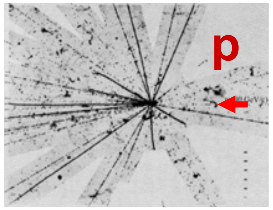
  measure of position and direction & particle id on topological basis

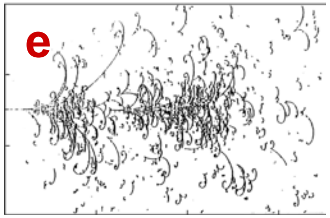
- Fast

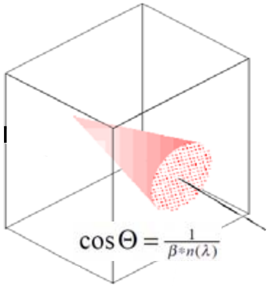
  high rate capability, trigger

Four steps

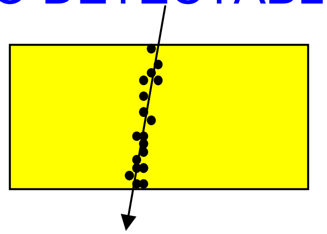
PARTICLE INTERACTION IN MATTER (depends on the impinging particle and on the kind of material)

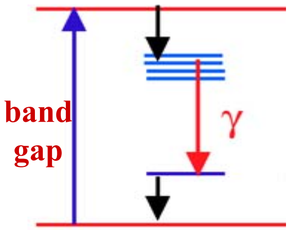




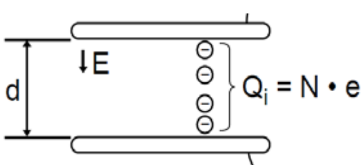


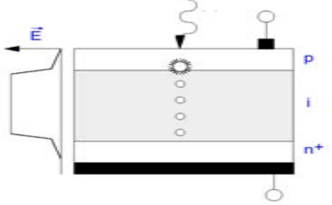
ENERGY LOSS TRANSFER TO DETECTABLE SIGNAL (depends on the material)



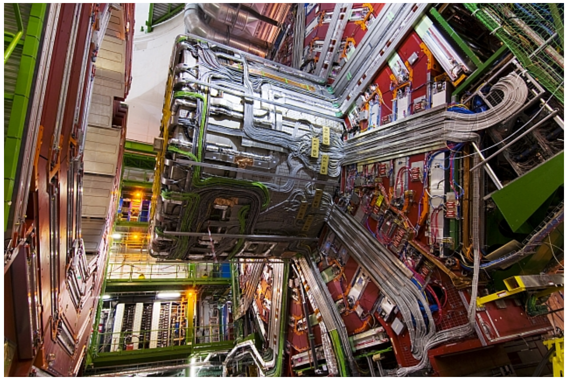


SIGNAL COLLECTION (depends on signal, many techniques of collection)





BUILD A SYSTEM

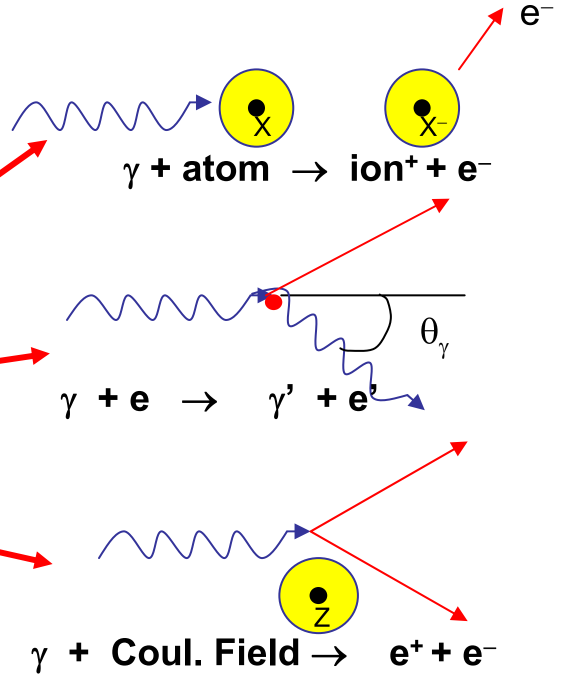


Energy losses by e & γ

In matter electrons and photons loose energy interacting with nuclei and atomic electrons

Electrons
- ionization (atomic electrons)
- bremsstrahlung (nuclear)

Photons
- photoelectric effect (atomic electrons)
- Compton scattering (atomic electrons)
- pair production (nuclear)



Above 1 GeV radiative processes dominate energy loss by e/γ

Electrons

- Ionization

$$-\frac{dE}{dx}\Big|_{ion} = N_A \frac{Z}{A} \frac{4\pi\alpha^2(\hbar c)^2}{m_e c^2} \frac{Z_i^2}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right]$$

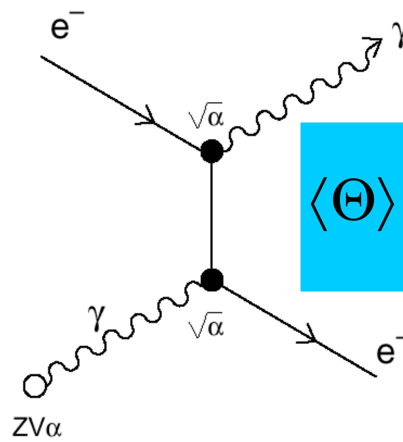
➢ $\sigma \propto Z$; $\sigma \propto \ln E/m_e$

- Bremsstrahlung

$$-\frac{dE}{dx}\Big|_{rad} = \left[4n\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2 c^4}\ln\frac{183}{Z^{1/3}}\right]E$$

$$-\frac{dE}{dx} \propto \frac{Z^2 E}{m^2}$$

$$X_0 = \left[4n\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2 c^4}\ln\frac{183}{Z^{1/3}}\right]^{-1}$$



$$\langle\Theta\rangle = \frac{1}{\gamma}$$

$$\frac{dE}{dx} = -\frac{E}{X_0} \qquad X_0 \approx \frac{180A}{Z^2}\ g.cm^{-2}$$

➢ $\sigma \propto Z(Z+1)$; $\sigma \propto A/X_0$ E>1 GeV, $\sigma \propto \ln E/m_e$ E<1 GeV

Radiation length: thickness of material that reduces the mean energy of a beam of high energy electrons by a factor e. For dense materials Xo ~ 1 cm.

Electrons

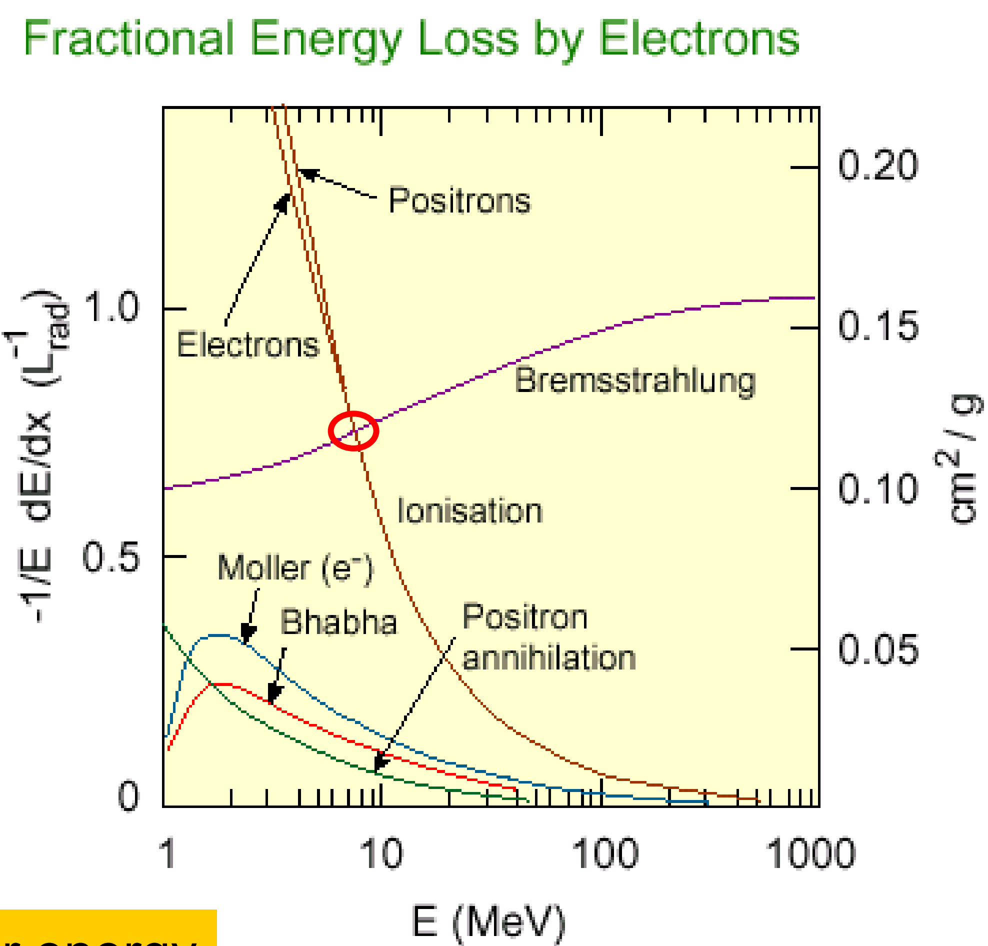
- **Critical energy E_c:**

$$\frac{(dE/dx)_{rad}}{(dE/dx)_{ion}} = 1$$

$$E_c \approx \frac{610\,\text{MeV}}{Z+1.24}$$

(solids, liquids)

Strongly material dependent,
it scales as 1/Z (eg. 7 MeV for lead)



Electrons irradiate photons until their energy becomes less than critical energy **Ec**

Photons

- photo-electric effect

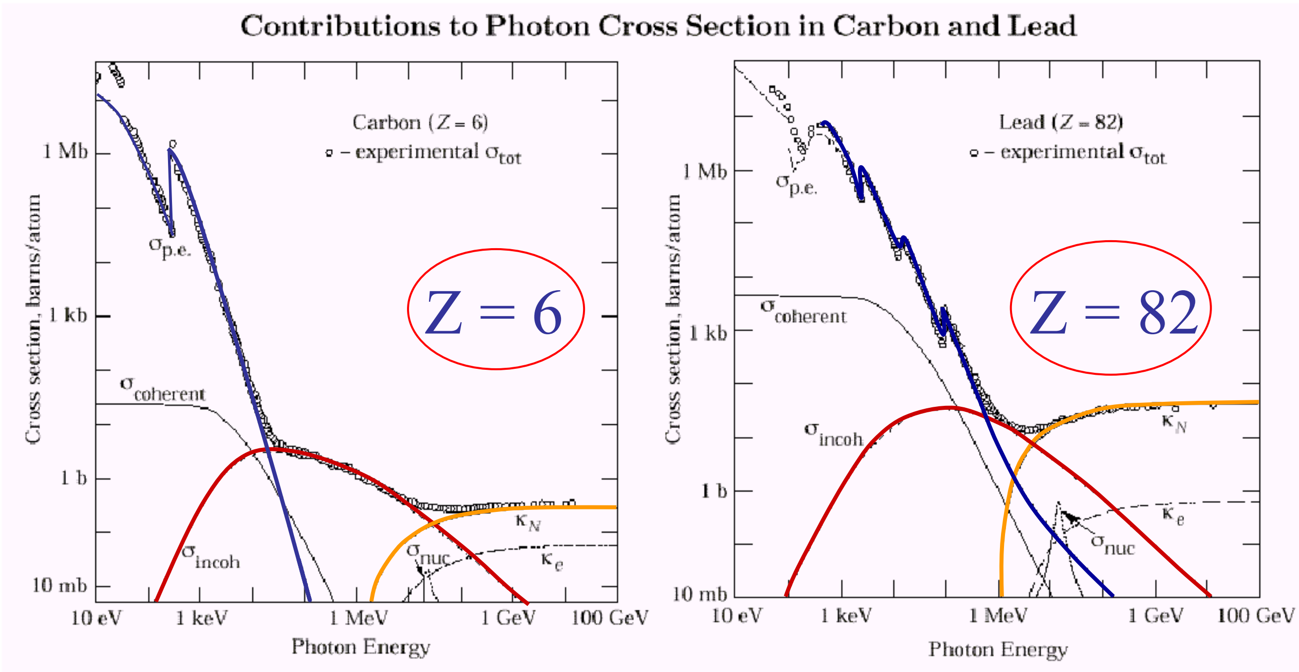
$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma} \right)^{\frac{7}{2}}$$

$$\sigma \propto Z^5 \;,\; E^{-3.5}$$

- Compton scattering

$$\sigma_c \approx Z \frac{\ln E_\gamma}{E_\gamma}$$

$$\sigma \propto Z \,,\; E^{-1}$$



- pair production occours if $E_\gamma > 2m_e c^2$

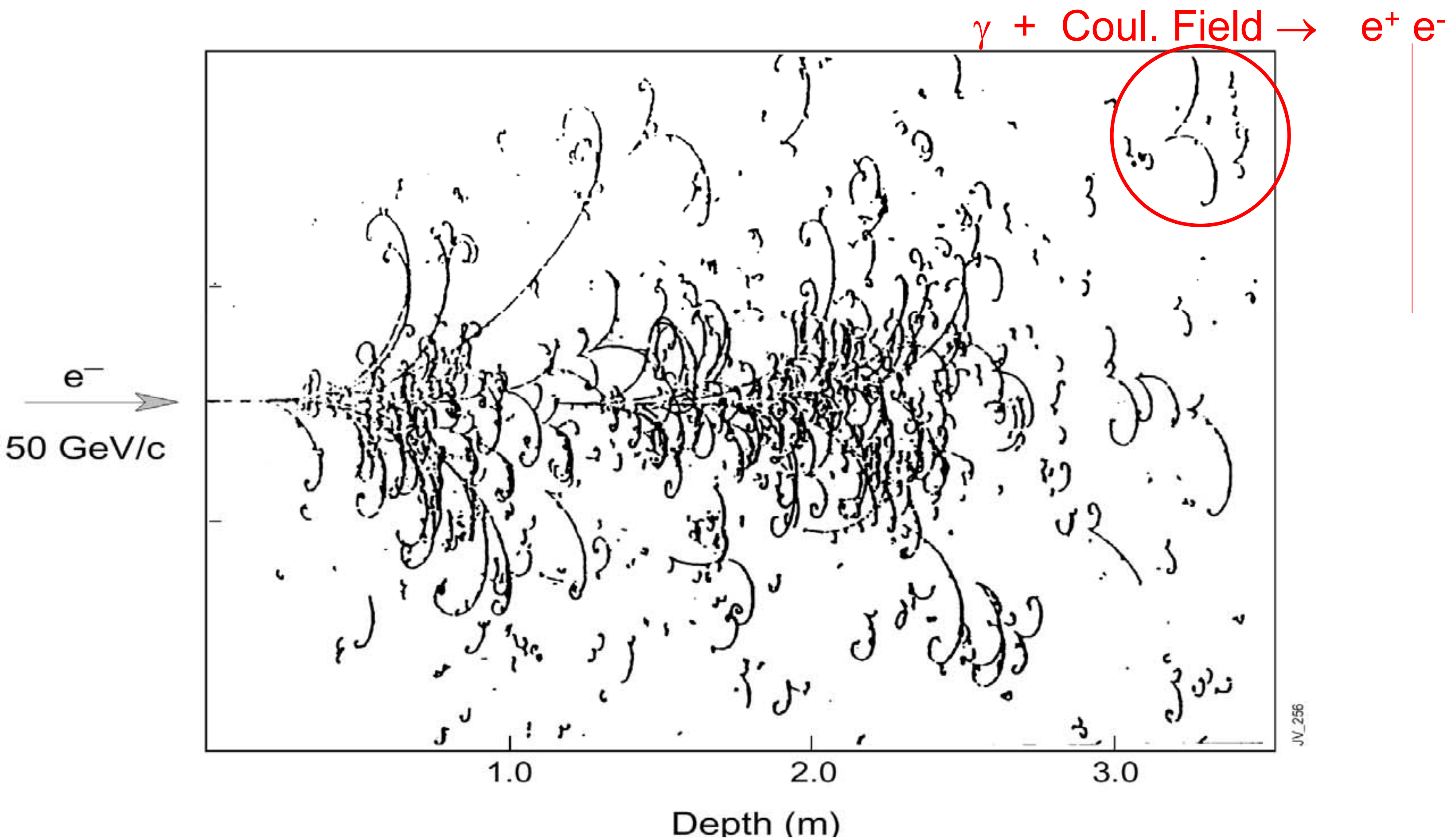
$$\sigma_{pair} \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

$\sigma \propto Z(Z+1)$; $\propto \ln E/m_e$ for E< 1GeV, constant E >1GeV

Probability of conversion in $1X_0$ is $e^{-7/9}$

Define a m.f.p. $L_{pair} = 9/7\, X_0$ (γ disappears)

Electromagnetic showers



Big European Bubble Chamber filled with Ne:H_2 = 70%:30%,

3T Field, L=3.5 m, $X_0 \approx 34$ cm, 50 GeV incident electron

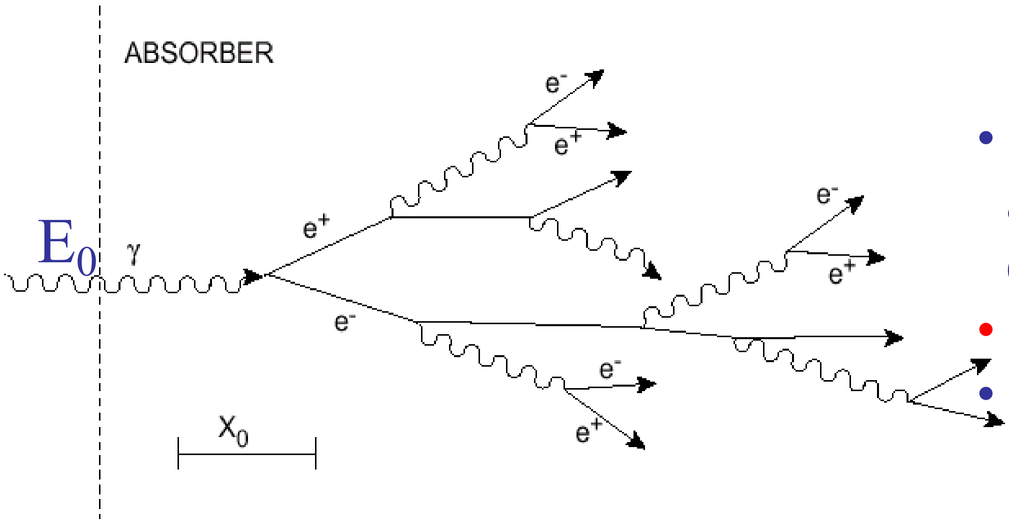
Electromagnetic showers

Above 1 GeV the dominant processes, bremsstrahlung for e^+ and e^- and pair production for γ, become energy independent

Through a succession of these energy losses an e.m. cascade is propagated until the energy of charged secondaries has been degraded to the regime dominated by ionization loss (below E_c)

Below E_c a slow decrease in number of particles occurs as electrons are stopped and photons absorbed

EM showers: a simplified model



- In $1X_0$ an e loses about 2/3 of its E and a high energy γ has a probability of 7/9 of pair conversion
- Assume X_0 as a generation length
- In each generation the number of particles increases by a factor 2

@ $\Delta x = X_0$ $\quad \gamma \to e+\ e-$ $\quad E = E_0/2$

@ $\Delta x = 2X_0$ $\quad e \to \gamma\ e'$ $\quad E' = E_0/4$

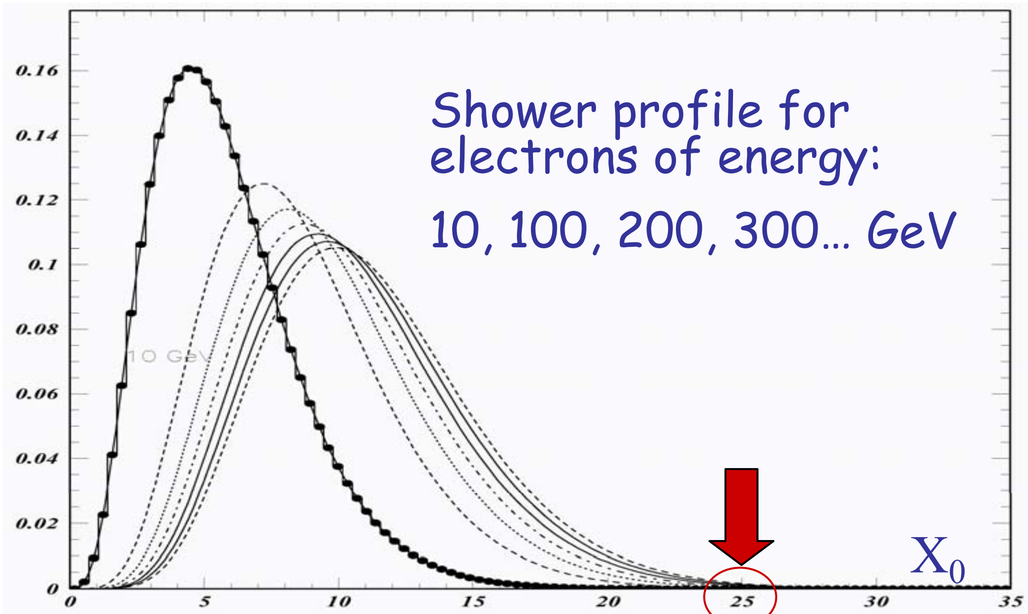
@ $\Delta x = tX_0$ $\quad N(t) = 2^t$ $\quad E(t) = E_0 / 2^t$

$E(t_{max}) = E_c \qquad E_0 / 2^{t_{max}} = E_c$

$$t_{max} = \ln(E_0/E_c)/\ln(2)$$

$$N(t_{max}) \sim E_0/E_c$$

EM showers: longitudinal profile



Shower energy dep parametrization:

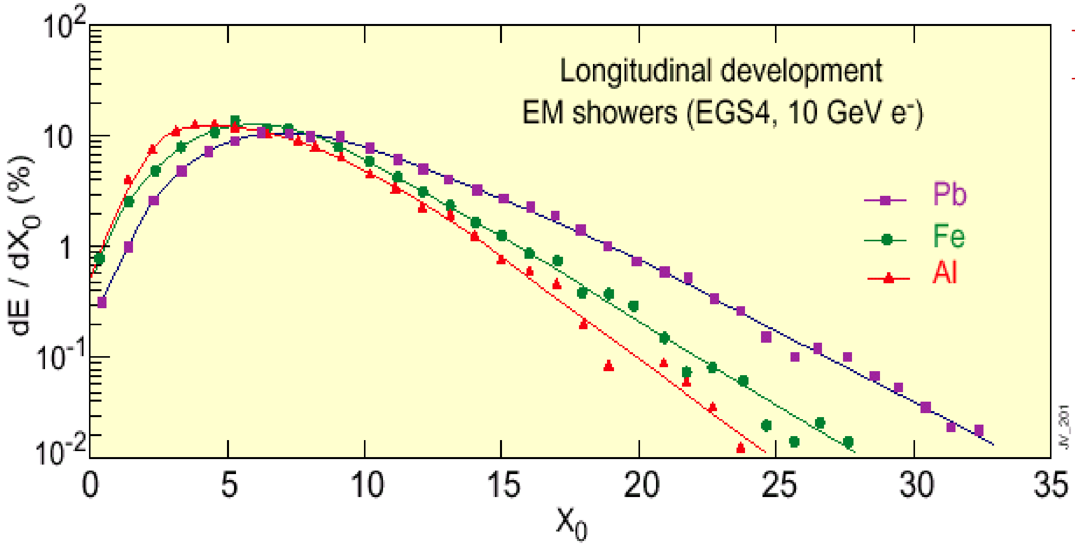
$$\frac{dE}{dt} \propto E_0 t^{\alpha} e^{\beta t}$$

E.Longo & I.Sestili NIM 128 (1975)

β material dependent

$$t_{max} = 1.4 \ln(E_0/E_c)$$

$$N_{tot} \propto E_0/E_c$$



E_c α 1/Z ➡

- shower max
- shower tail

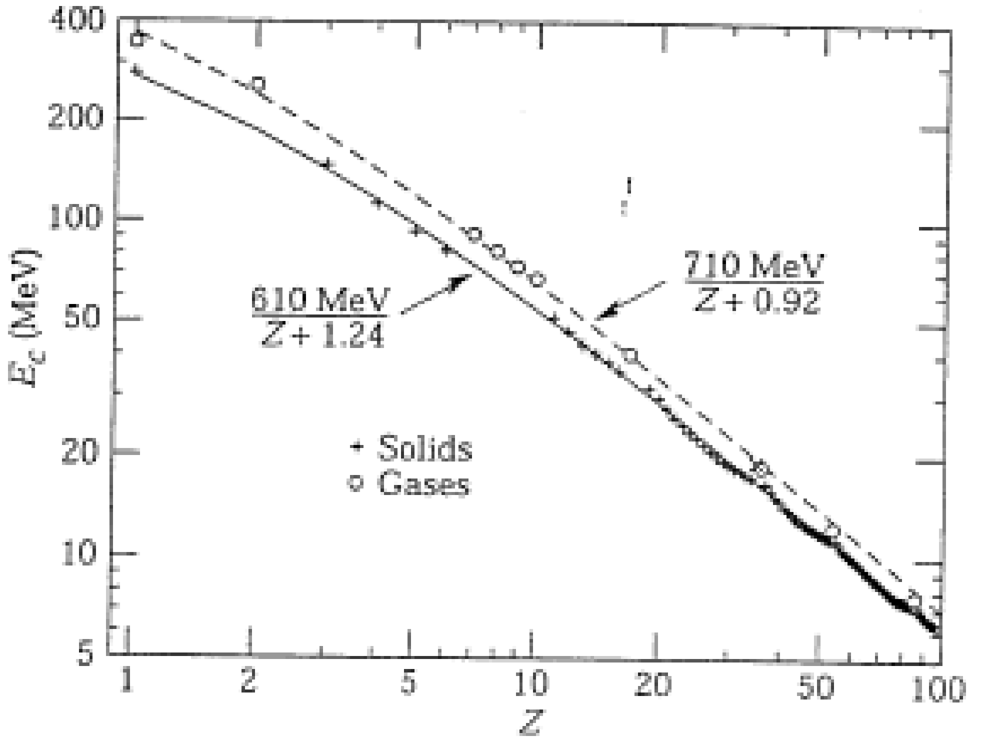
Longitudinal containment:

$$t_{95\%} = t_{max} + 0.08Z + 9.6$$

EM showers: some numbers

BASIC PARAMETERS

Material	Atomic No. (Z)	Critical Energy (E_c) (MeV)	Radiation Length (X_0) (g/cm^2)	(cm)	Moliere Radius (R_M) (cm)
Beryllium	_4	116._	65.19	35.28	6.4
Carbon	_6	84._	42.70	18.8_	4.7
Aluminum	13	43._	24.01	8.9_	4.4
Iron	26	22._	13.84	1.76	1.7
Copper	29	20._	12.86	1.43	1.5
Tungsten	74	8.1	6.76	0.35	0.9
Lead	82	7.3	6.37	0.56	1.6
Uranium	92	6.5	6.00	0.32	1.0



EM showers: transverse profile

Transverse shower profile

- Multiple scattering make electrons move away from shower axis
- Photons with energies in the region of minimal absorption can travel far away from shower axis

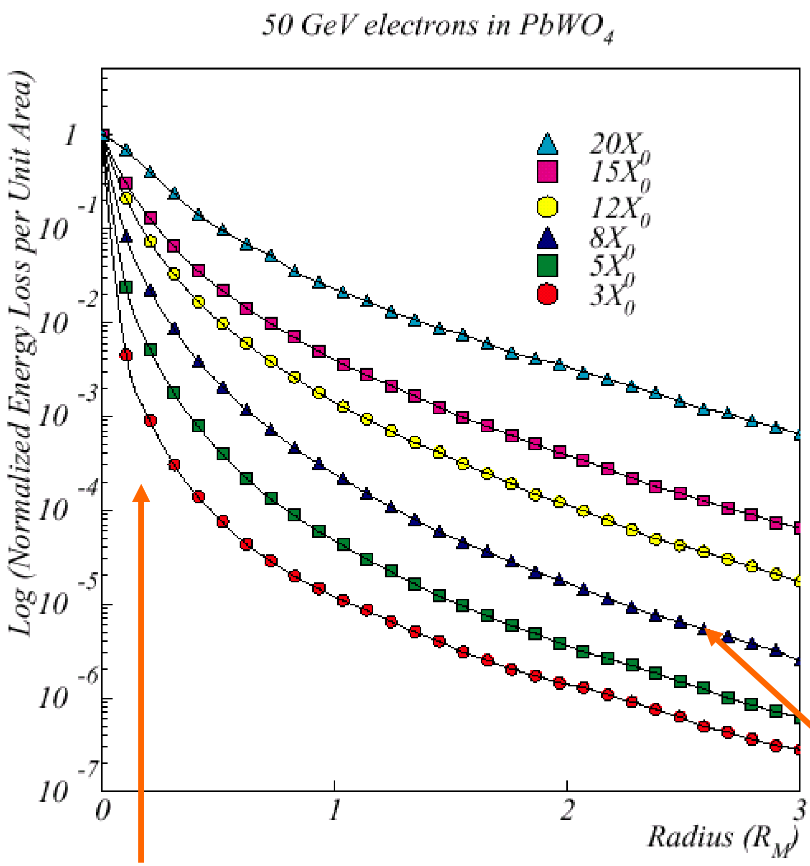
Molière radius sets transverse shower size, it gives the average lateral deflection of critical energy electrons after traversing $1X_0$

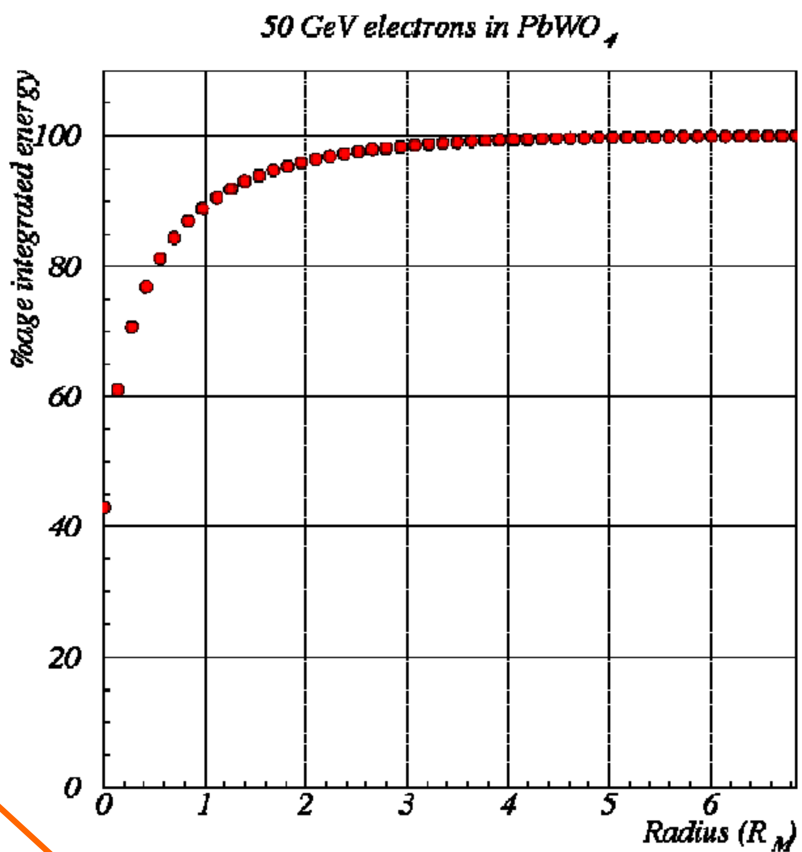
$$R_M = \frac{21\,\mathrm{MeV}}{E_C} X_0$$

$$R_M \propto \frac{X_0}{E_C} \propto \frac{A}{Z} \left(Z >> 1\right)$$

90% E_0 within $1R_M$, 95% within $2R_M$, 99% within $3.5R_M$

EM showers: transverse profile





Central core: multiple scattering

Peripheral halo: propagation of less attenuated photons, widens with depth of of the shower

EM showers: energy loss detection

The energy deposited in the calorimeters is converted to active detector response

- $E_{vis} \leq E_{dep} \leq E_0$

Main conversion mechanism

- Cerenkov radiation from e
- Scintillation from molecules
- Ionization of the detection medium

Different energy threshold E_{th} for signal detectability

EM calorimeters: energy resolution

Intrinsic limit **You are not going to do better!**

Detectable signal is proportional to the total track length of e+ and e- in the active material, intrinsic limit on energy resolution is given by the fluctuations in the fraction of initial energy that generates detectable signal

$$N_{tot} \propto \frac{E_0}{E_C}$$

Total track length →

$$T_0 = N_{tot} X_0 \approx \frac{E_0}{E_C} X_0$$

Detectable track length $T_r = f_s\, T_0$

f_s fraction of N_{tot} with kin $E > E_{th}$

Fluctuations in track length: Poisson process →

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(T_r)}{T_r} \propto \frac{1}{\sqrt{T_r}} \propto \frac{1}{\sqrt{E_0}}$$

Fix E_0 →

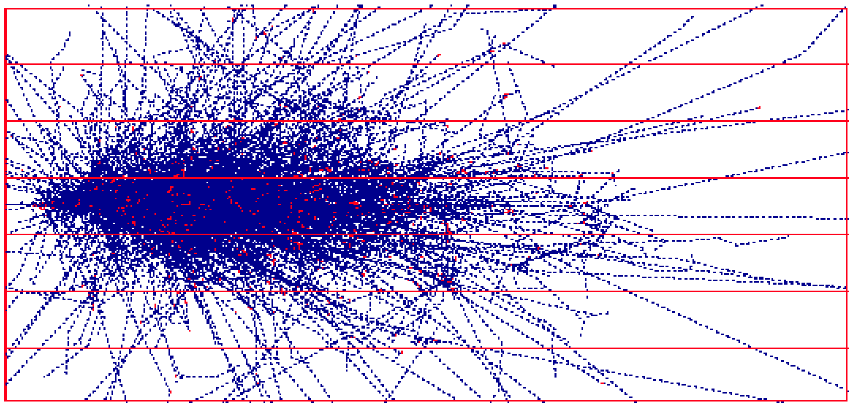
$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{f_s}}\sqrt{\frac{E_C}{X_0}} \propto \frac{1}{\sqrt{f_s}}\sqrt{\frac{Z}{A}}$$

→

- maximize f_s
- minimize Z/A

EM calorimeters: homogeneous

Homogeneous calorimeters: all the energy is deposited in the active medium. Absorber ≡ active medium



- **Excellent energy resolution (+)**
- **No information on longitudinal shower shape (-)**
- **Cost (-)**

All e+ and e- over threshold produce a signal

$$f_s = \frac{E_0 - N_{max} E_{th}}{E_0}$$

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{f_s}}$$

EM calorimeters: energy resolution

Homogeneous calorimeters: all the energy is deposited in an active medium.
Absorber ≡ active medium ➡ All e+e- over threshold produce a signal
Excellent energy resolution

Compare conversion processes with different energy threshold

Scintillating crystals

$$E_s \cong \beta E_{gap} \sim eV$$

$$\approx 10^2 \div 10^4 \gamma / MeV$$

$$\sigma / E \sim (1 \div 3)\% / \sqrt{E(GeV)}$$

Cherenkov radiators

$$\beta > \frac{1}{n} \rightarrow E_s \sim 0.7 MeV$$

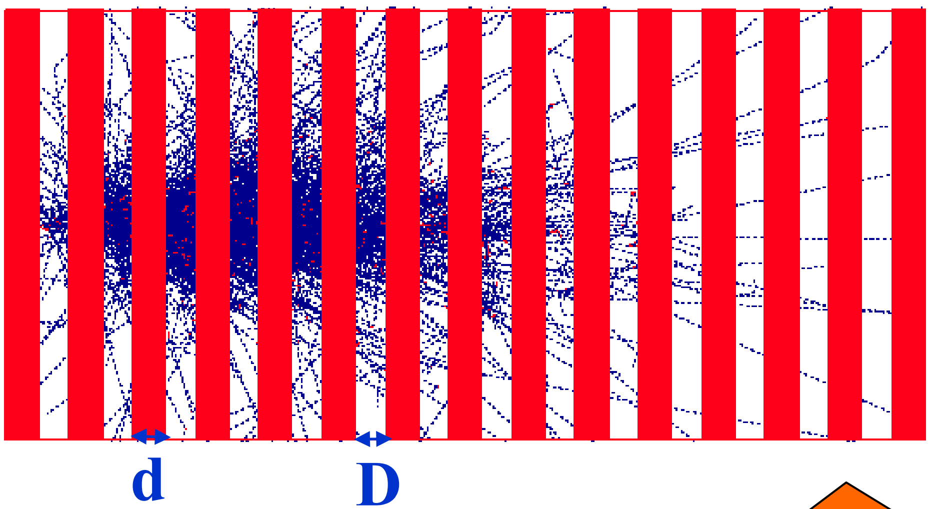
$$\approx 10 \div 30 \ \gamma / MeV$$

$$\sigma / E \sim (5 \div 10)\% / \sqrt{E(GeV)}$$

Lowest possible limit in em calorimetry

EM calorimeters: sampling

Sampling calorimeters: shower is sampled by layers of active medium (low-Z) alternated with dense radiator (high-Z) material.



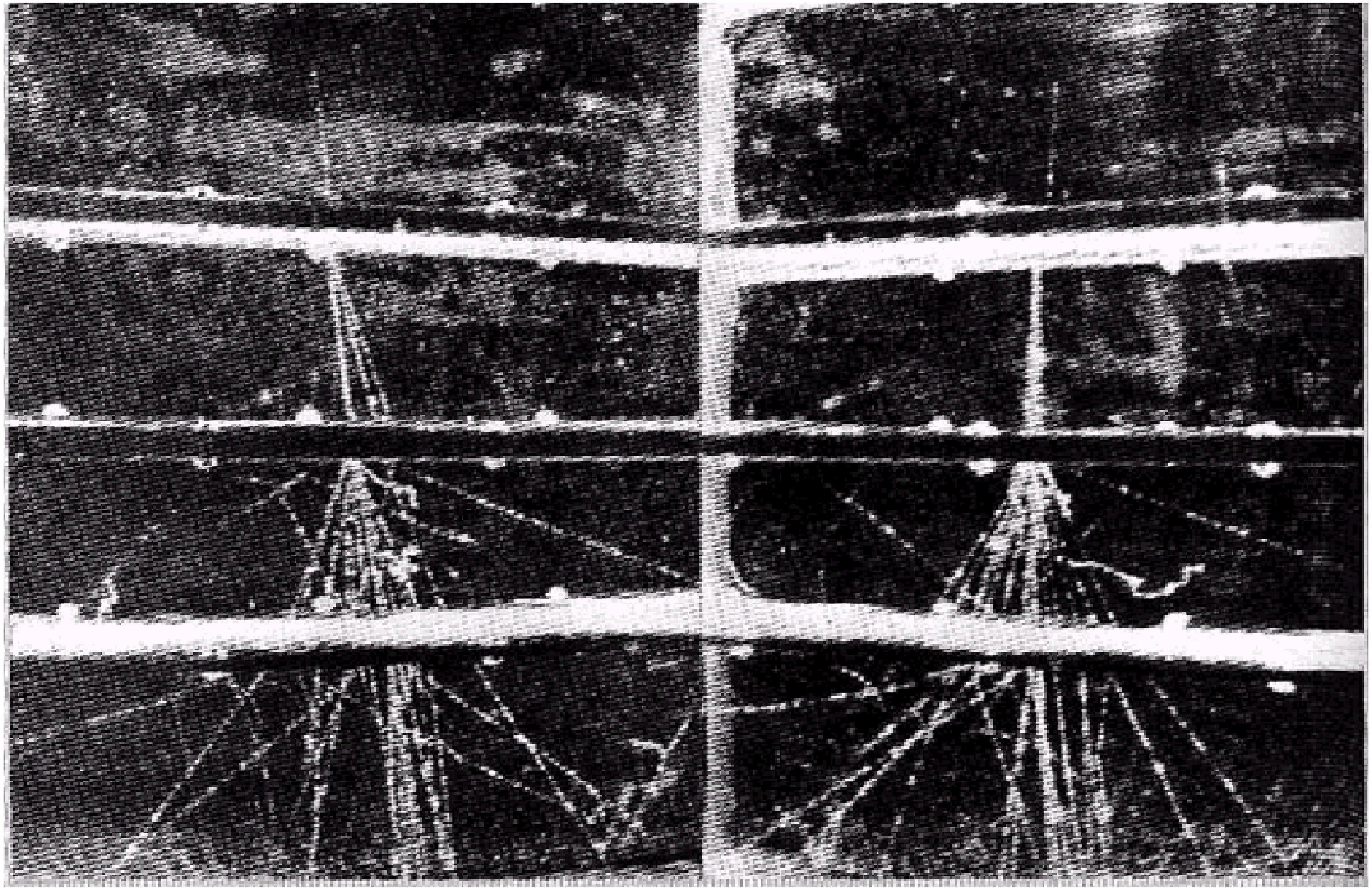
- Limited energy resolution
- Detailed shower shape information
- Cost

absorber=shower generator
active layers (scintillators, wire chambers…) negligible in the shower development

- only a fraction of the shower energy is dissipated in the active medium
- energy resolution is dominated by fluctuations in energy deposited in active layers: sampling fluctuations
- intrinsic resolution irrelevant

$$\sigma / E \sim (10 \div 20)\% / \sqrt{E(GeV)}$$

Sampling electromagnetic showers



Cloud chamber photograph of e.m. shower developing in lead plates (thickness from top down 1.1, 1.1, 0.13 X_0) exposed to cosmic radiation

Sampling fluctuations

Fluctuations in the number of shower particle traversals of the sampling elements

Total track length ($\Delta E_{abs} >> \Delta E_{act}$):

$$T_r = f_s T_0 = f_s N_{tot} X_0^{abs} \approx f_s \frac{E}{E_C^{abs}} X_0^{abs}$$

Number of crossings of active layers at distance **d**

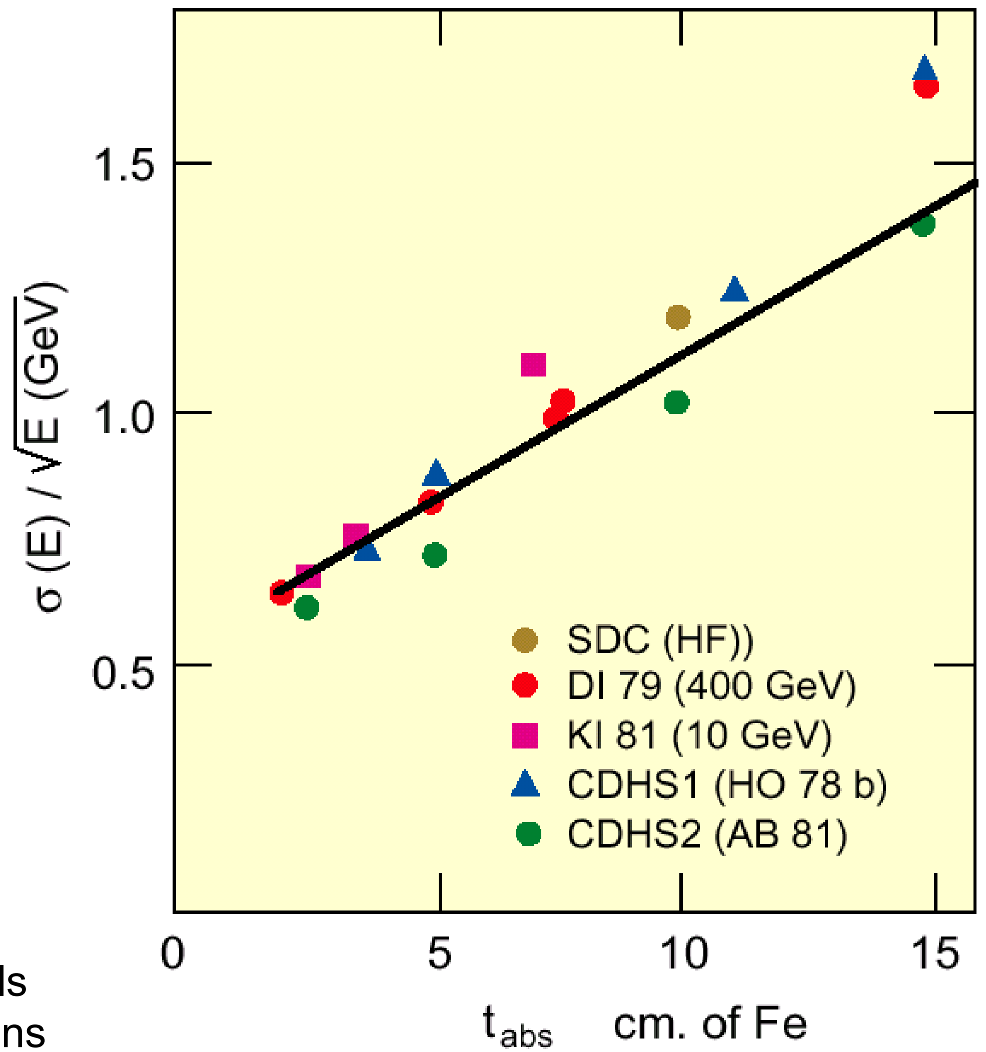
$$d \geq X_0^{abs}$$

$$N_r = \frac{T_r}{d} = f_s \frac{E}{E_C^{abs}} \frac{X_0^{abs}}{d}$$

Resolution scales with absorber thickness (t_{abs}= d/X_o)

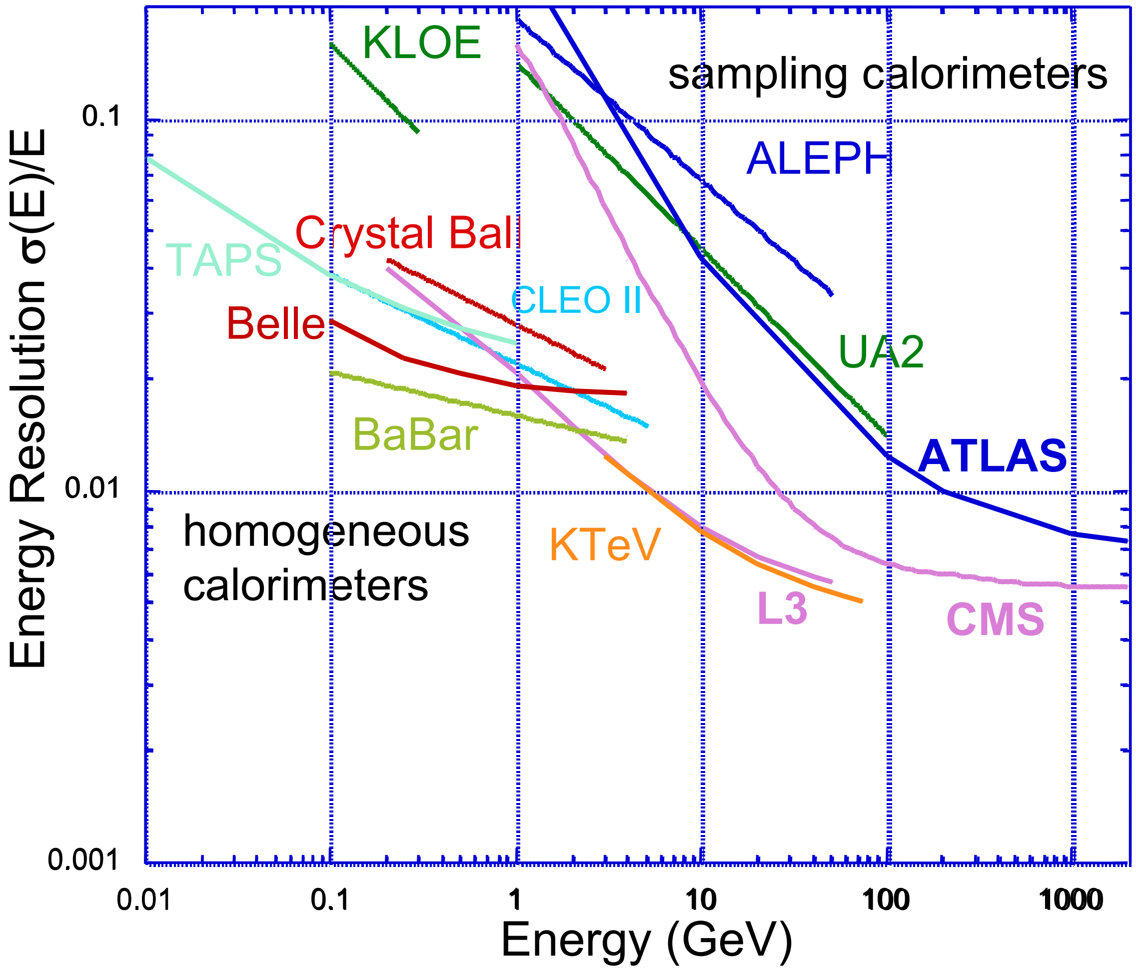
$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{N_r}} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{E_C t_{abs}}{E}}$$

NB. Crude approx. valid for solid active materials like plastic scintillators, no path length fluctuations



Calorimeters: a comparison

EACH SYSTEM OPTIMIZED FOR THE ENERGY RANGE OF INTEREST FOR THE EXP



EM calorimeters: energy resolution

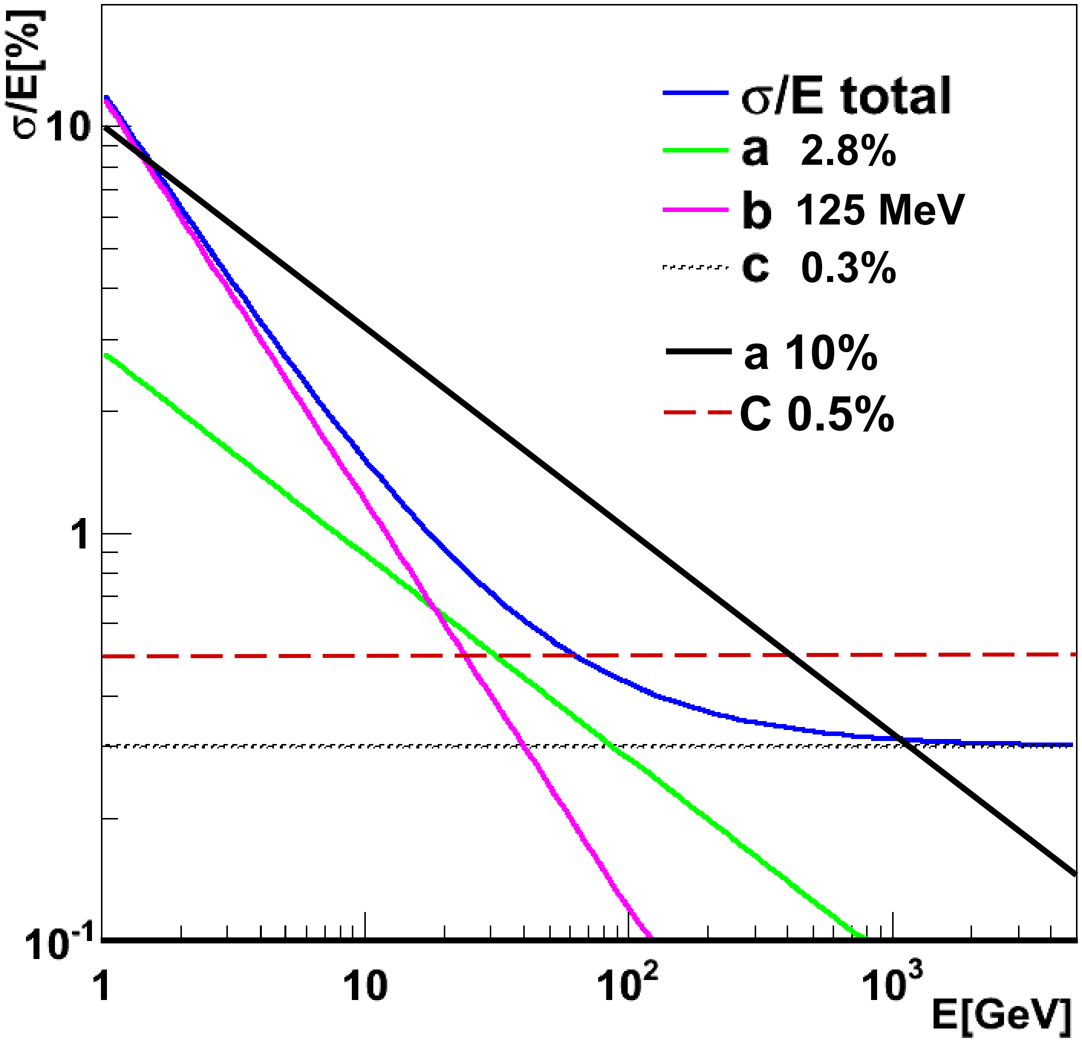
Energy resolution of a calorimeter can be parameterized as

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

$\oplus$ means sqrt (quadratic sum)

- a the *stocastic term* accounts for any kind of Poisson-like fluctuations
  - natural merit of homogeneous calorimeters
  - several contributions add to the “intrinsic one”
- b the *noise term* responsible for degradation of low energy resolution
  - mainly the energy equivalent of the electronic noise
  - contribution from pileup: the fluctuation of energy entering the measurement area from sources other than the primary particle
- c the *constant term* dominates at high energy
  - its relevance is strictly connected to the small value of a
  - it is mostly dominated by the stability of calibration
  - contributions from energy leakage, non uniformity of signal generation and/or collection, loss of energy in dead materials,…

When do you have to worry about c?



The constant term

c = (leakage)⊕(intercalibration)⊕(system instability)⊕(nonuniformity)

To have c ~ 0.5 % all contributions must stay below 0.3 %

- Leakage
  - front: negligible at high energies
  - rear: dangerous

    increases with $\ln(E)$

    fluctuations are due to interactions in the first X_0 $\not\propto 1/\sqrt{E}$

    but simple to remove ⇒ increase number of X_0

    an empirical parametrization (fraction of energy lost $f<0.1$)

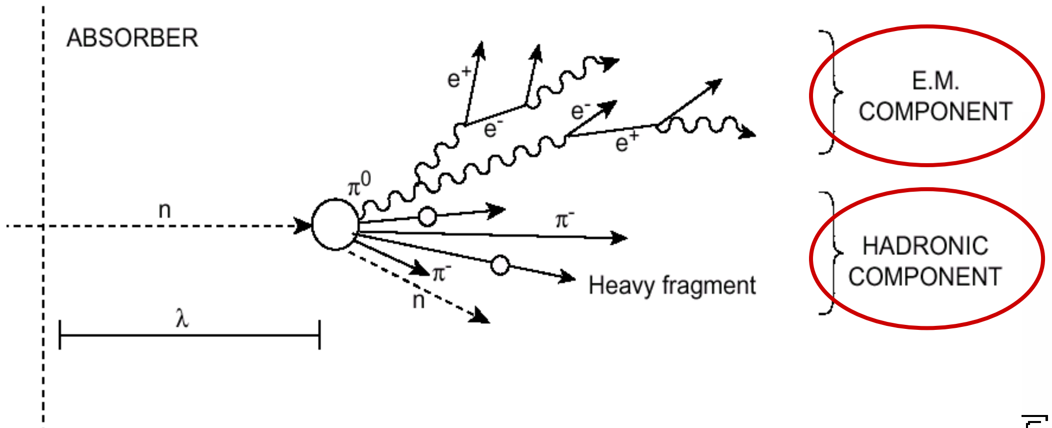
$$\frac{\sigma}{E} \approx \left[\frac{\sigma}{E}\right]_{L=\infty} \cdot (1 + 4f + 50f^2)$$

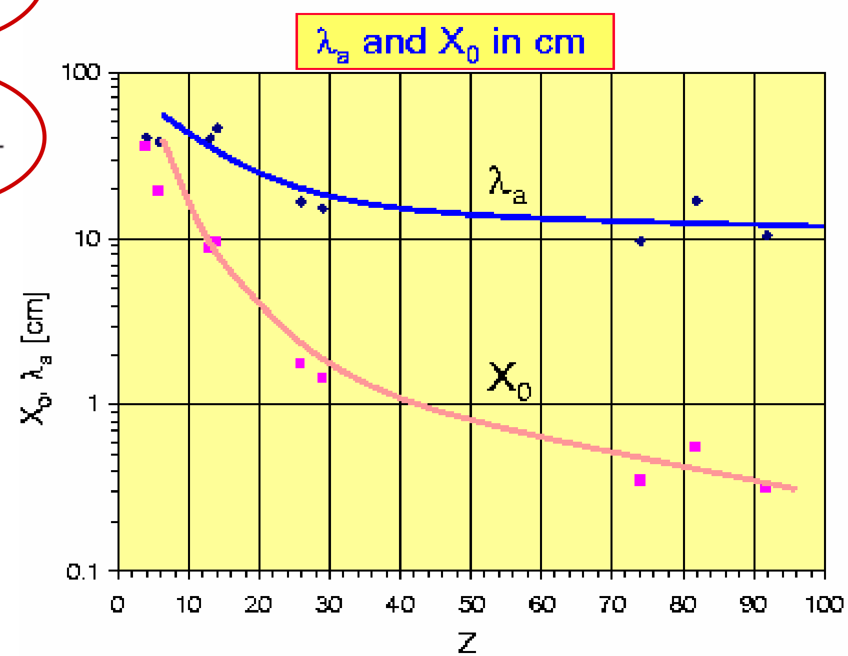
- Blind material: walls, gaps etc.

  (CMS full shower simulation: total contribution < 0.2%)

Hadron showers (a complicated story)

- Strong interaction is responsible for shower development
- A high energy hadron interacting with matter leads to multi-particle production, typically mesons $\pi^{\pm}$, π^{o}, K etc., these in turn interact with further nuclei
- Nuclei breakup leading to spallation neutrons/protons
- Multiplication continues until the pion production threshold, $E \sim 2m_{\pi} = 0.28$ GeV





Nuclear interaction length:

$$\lambda_{int} = \frac{A}{N_A \sigma_{int}} \propto A^{1/3}$$

$\lambda \sim 35\, A^{1/3}$ g cm^{-2}

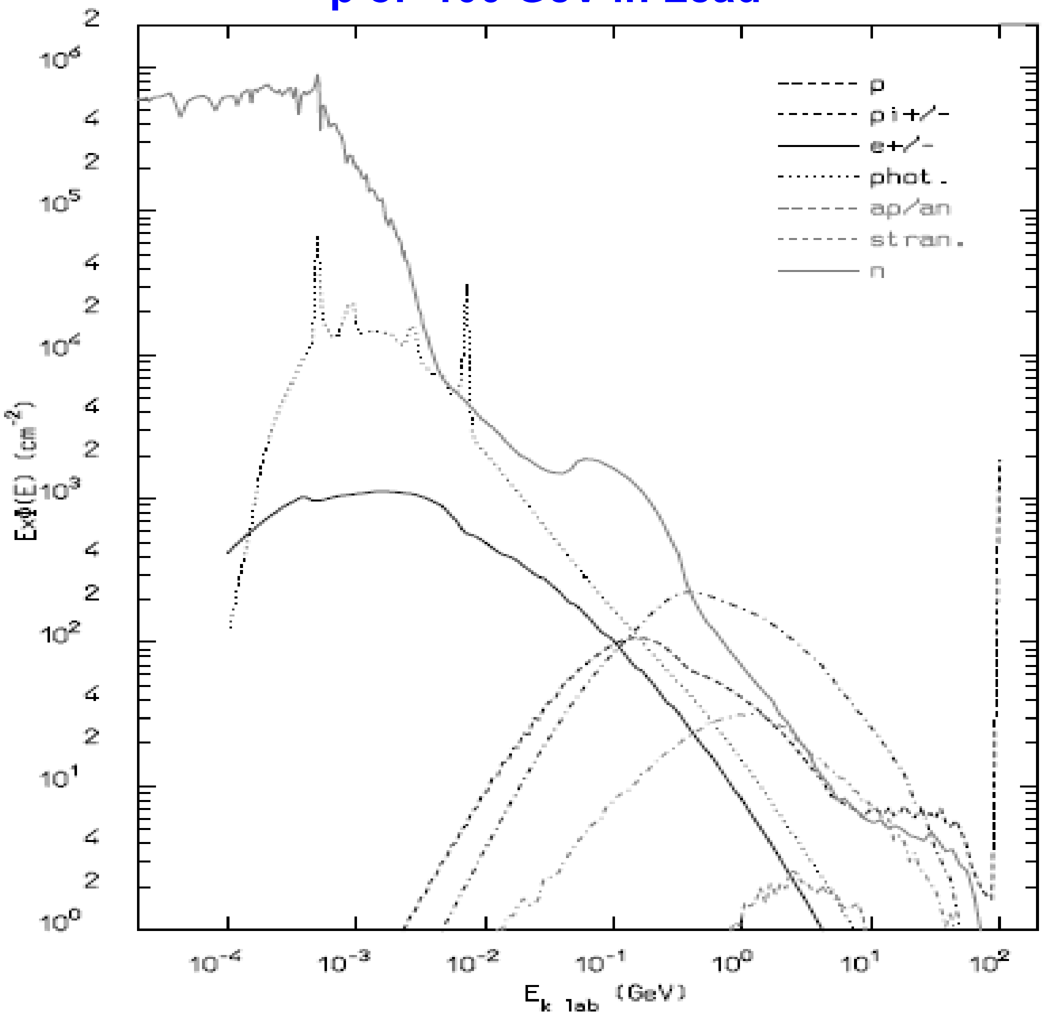
$$\sigma_{int} = \pi R^2 \;\alpha\; A^{2/3}$$

Hadron showers

Hadron shower induced by a 100 GeV proton in Lead: energy spectra of the major shower components weighted by their track lenght in the shower (average)

- **Soft spectra dominated by neutrons and photons**
- **Hard spectra dominated by charged pions**

p of 100 GeV in Lead



Hadron showers

All the fluctuations described in em case plus more and more significant

- Breakdown of ***non-em*** energy deposit in lead absorber:
  - *Ionizing particles* *56%* (2/3 from spallation protons)
  - *Neutrons* *10%* (37 neutrons per GeV!)
  - *Invisible* *34%*

  Spallation protons carry typically 100 MeV,
  Evaporation neutrons 3 MeV

An important fraction of energy goes in nuclear binding: not detectable!

FLUCTUATIONS OF E_{vis} : INTRINSIC LIMIT TO HADRONIC ENERGY MEASUREMENT

- Hadron showers contain em component (π^o, η)
- Size of em component F_{em} is mainly determined by the first interaction
- On average 1/3 of mesons produced in the 1° interaction will be a π^o, this fraction fluctuates in a significant way
- The 2° generation $\pi^\pm$ will produce π^o if enough energetic

An important fraction of energy goes in em deposits and strongly varies

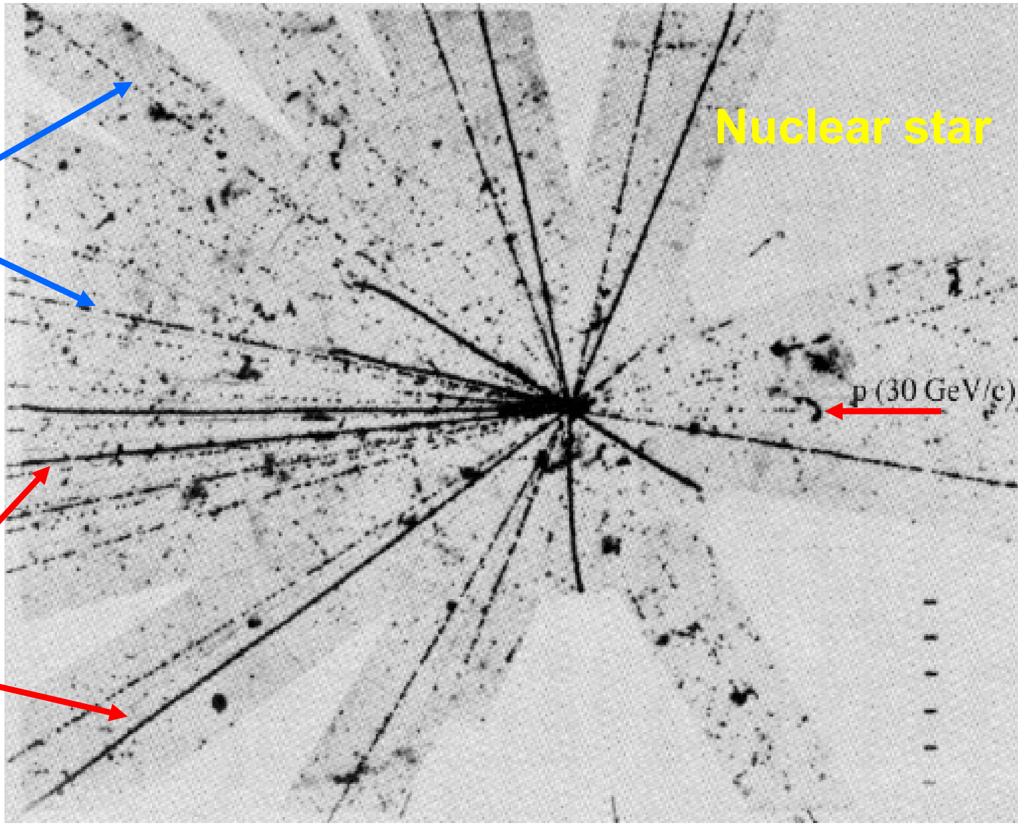
Hadron showers

Proton (30 GeV/c) – nucleus interaction in a photographic emulsion

Pions and fast spallation protons (less dense ionization) follow the motion of impinging proton

Neutrons are not visible but emitted in significant number

Protons (dense ionization) almost isotropic emission

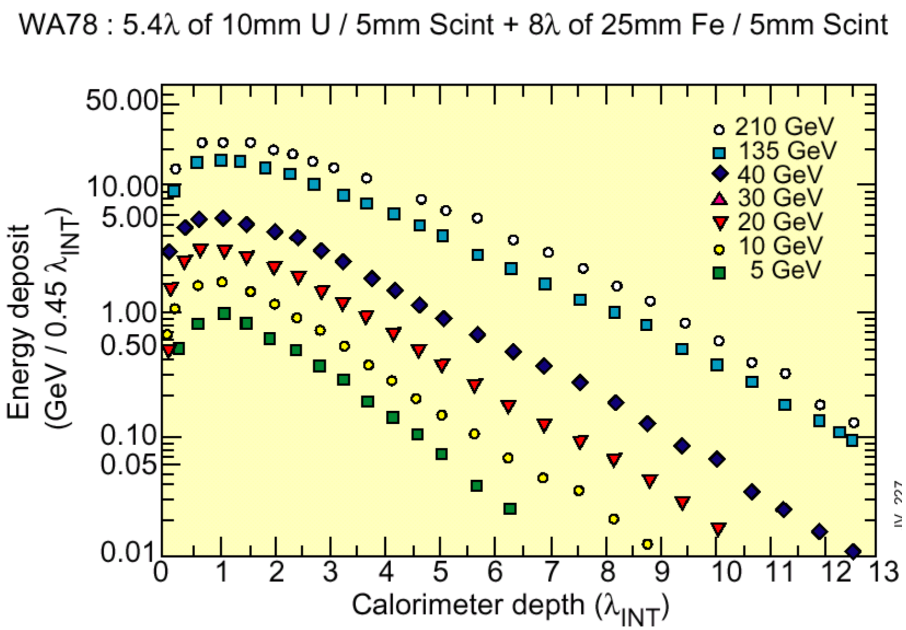


The energy needed to release these nucleons, ~nuclear binding energy, does not contribute to the calorimetric signal: invisible

Hadron shower profile

LONGITUDINAL

- **Sharp peak from π^o from the 1° interaction**
- **Gradual extinction with typical scale λ_{int}**

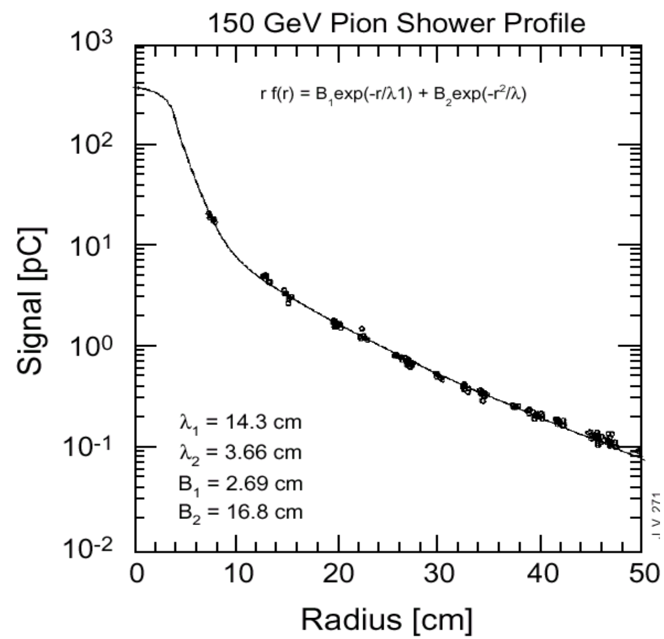


~10 λ needed to contain 99% E of 200 GeV π (about 1 – 2 m of heavy absorber)

Need to sample

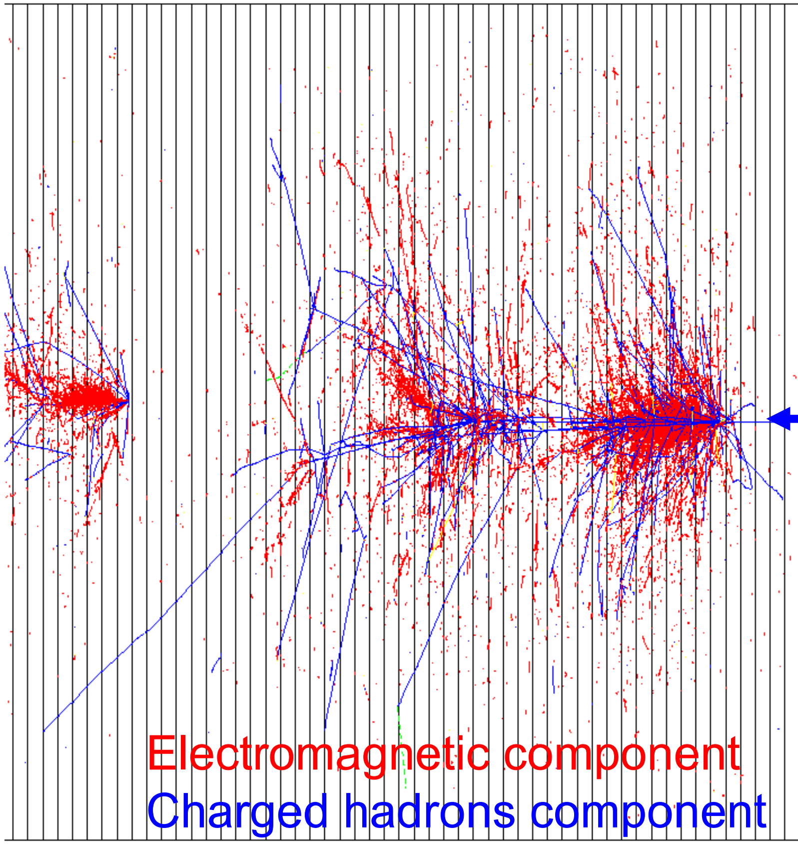
LATERAL

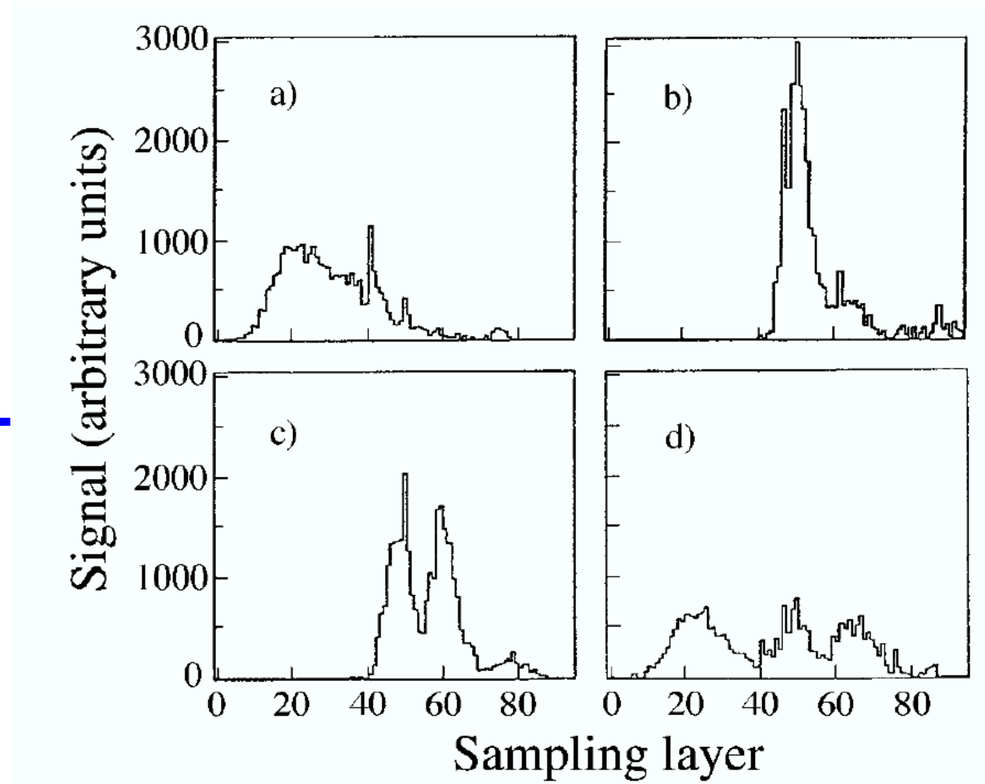
- **Average p_t secondaries ~ 300 MeV**
- **Typical transverse scale λ_{int}**
- **Dense core due to π^o**



Transverse radius for 95%E containment ~1λ

Hadron shower profile





Longitudinal measured profiles induced by 270 GeV π

Large fluctuations also in longitudinal profiles of hadron showers

Hadron showers

- A priori e and h in a calorimeter give a different response, e.g. e/h > 1
- The fluctuations in the fraction of energy deposited by e and h limitis resolution moreover in average this fraction is energy dependent (non linearity in detector response)

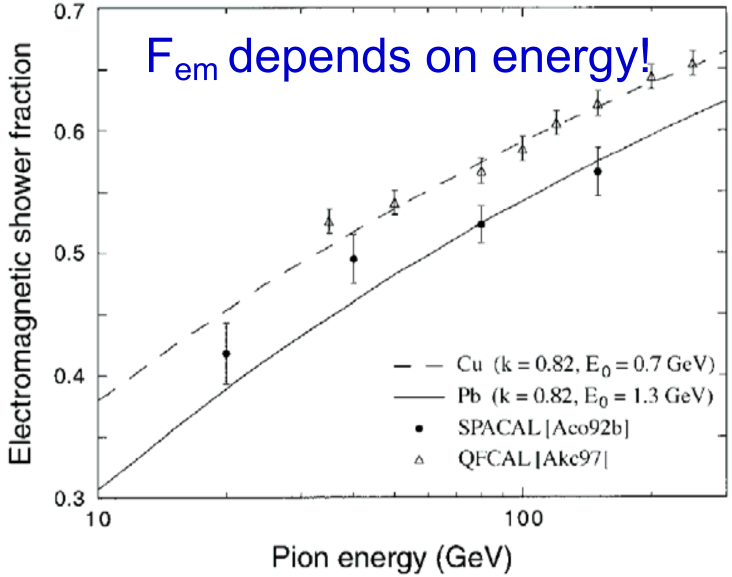


FIG. 2.22. Comparison between the experimental results on the em fraction of pion-induced showers in the (copper-based) QFCAL and (lead-based) SPACAL detectors. Data from [Akc 97] and [Aco 92b].

Elements to obtain e/h=1 (compensation)

- **Suppress em component (high Z abs.)**
- **enhance n production through fission**
- **enhance response to n using active materials hydrogen reach**

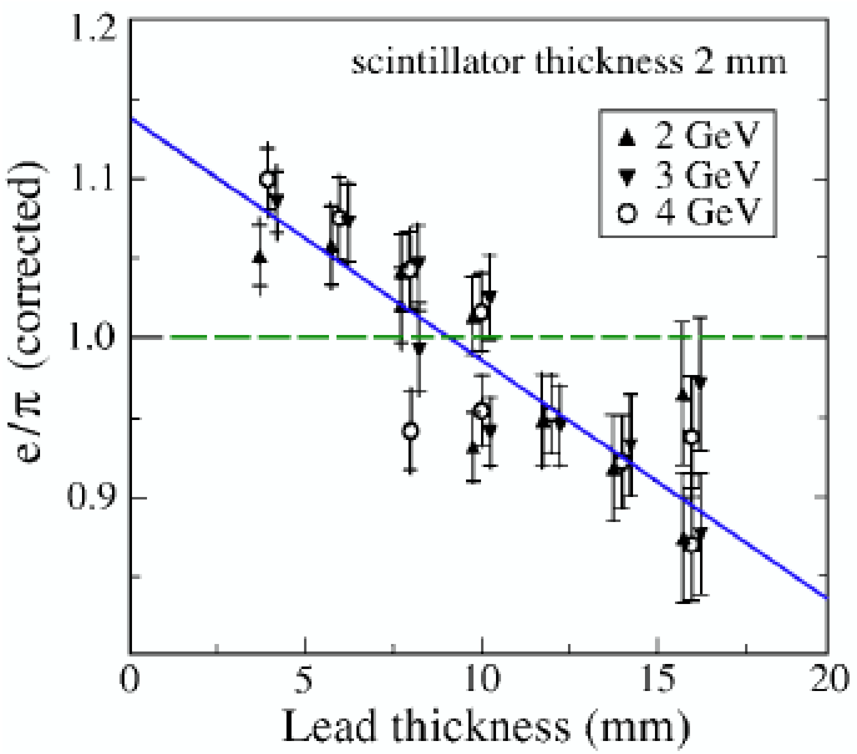
Intrisic hadronic resolution due to fluctuations of invisible energy and electromagnetic component (no compensation):

$$\sigma / E \sim (20 \div 40)\% / \sqrt{E(GeV)}$$

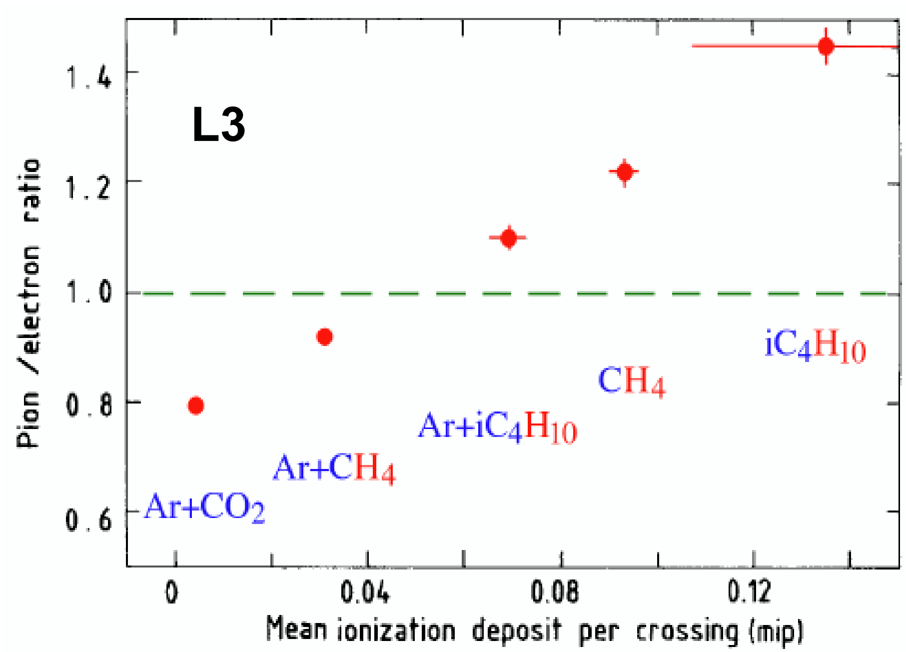
+ sampling…+…

Compensation

Pb/Scintillator



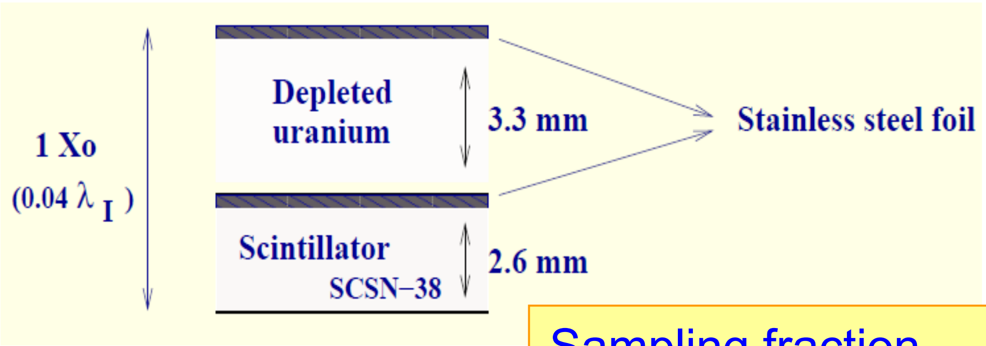
Hydrogen in active material (gas mixture)



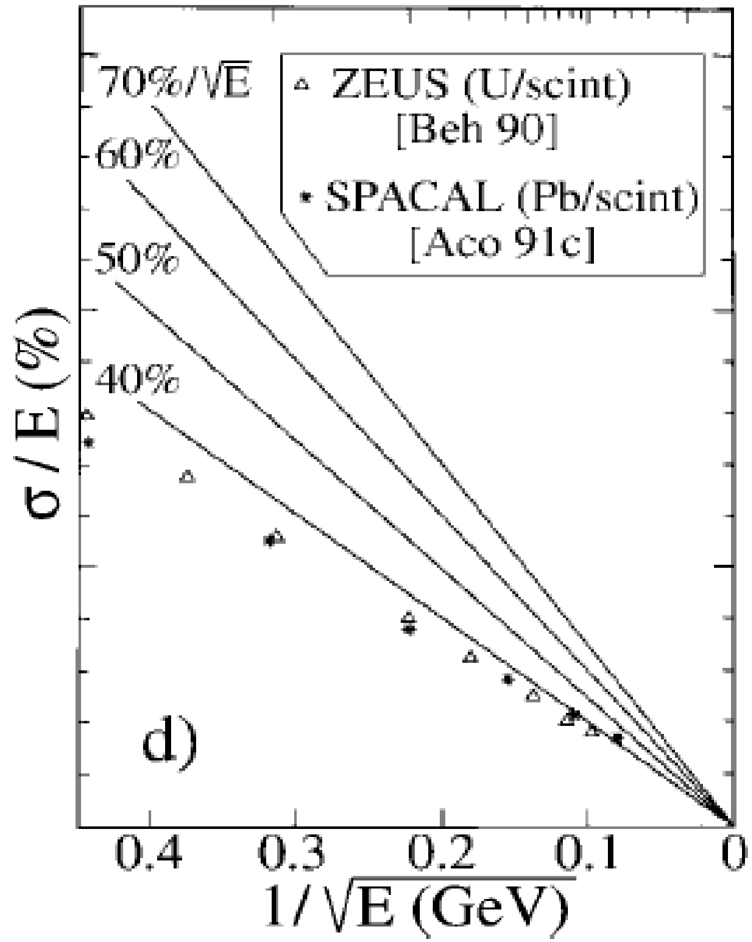
Sampling fraction can be tuned to achieve compensation

Elastic n-p scattering:
efficient sampling of neutrons through the detection of recoiling protons!

Compensation - ZEUS



Sampling fraction tuned to have $e/\pi = 1$



Excellent hadron resolution:

σ/E (hadrons) = 0.35/√E(GeV

σ/E (electrons) = 0.18/√E(GeV)

Ideas in hadron calorimetry (Dual Redout)

How to improve energy measurement in hadron calorimetry?

Measure F_{em} event by event using Čerenkov light emission

Čerenkov light emission threshold: **β>1/n**
e.g. quartz n=1.45 E_{th} = 0.2 MeV for electrons, 400 MeV for protons
Enhance electromagnetic response (in a quartz fiber calorimeter e/h ~ 5)

DUAL READOUT

Cerenkov radiator:
sample em part of the shower

Scintillator:
sample all components

Take electrons signal as reference

$$\boxed{C = [f + c(1-f)]\,E} \quad c = (h/e)_C$$

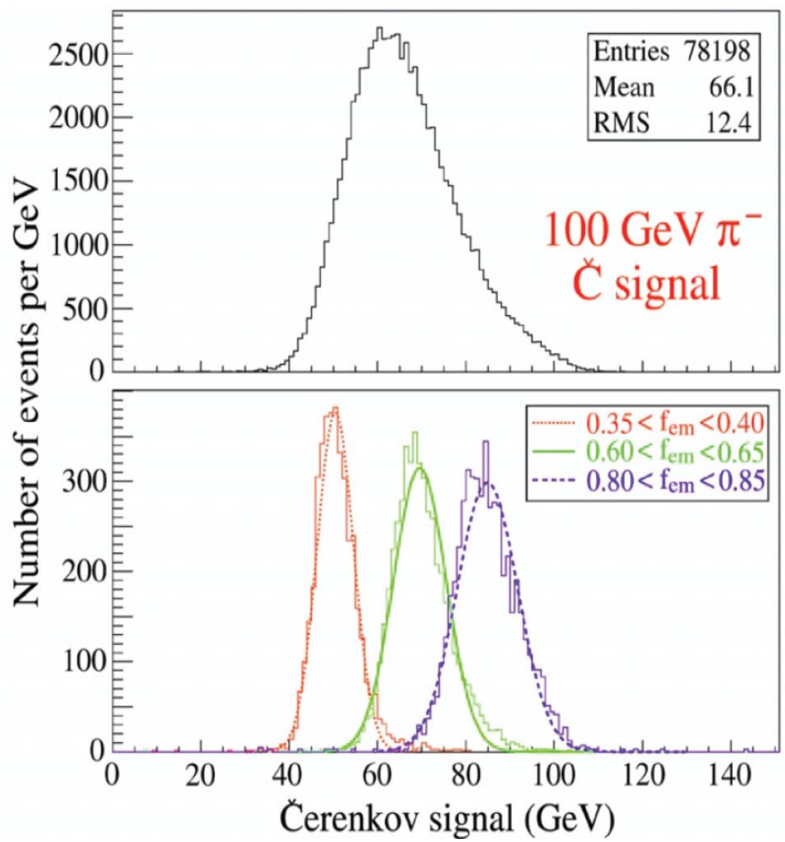
$$\boxed{S = [f + s(1-f)]\,E} \quad s = (h/e)_S$$

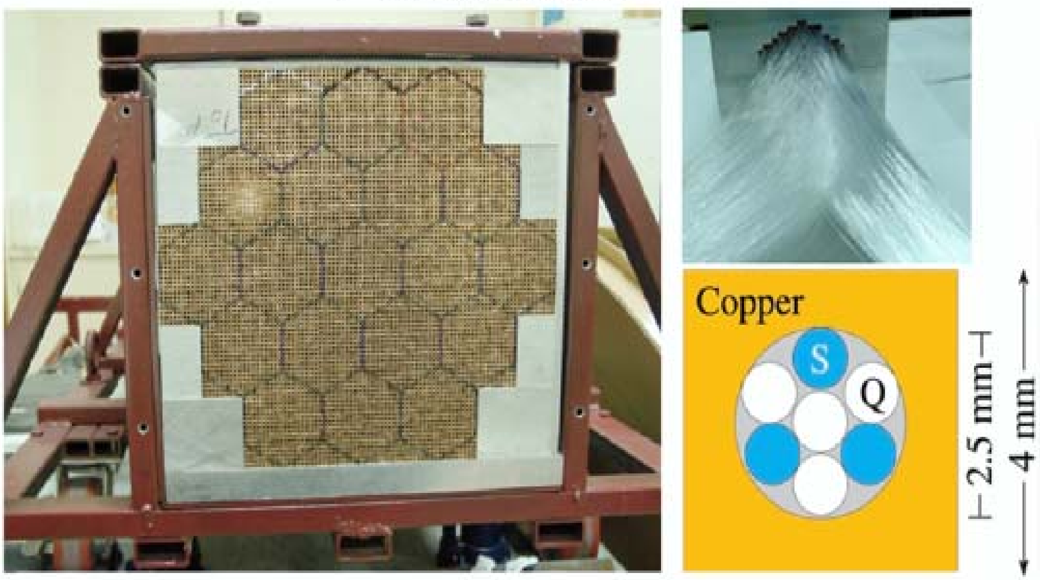
Combine information and get F_{em} (f) and E !

$$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)} \qquad E = \frac{S - \lambda C}{1 - \lambda} \qquad \lambda = \frac{1-s}{1-c}$$

Constant of the calorimeter

Dual readout: DREAM

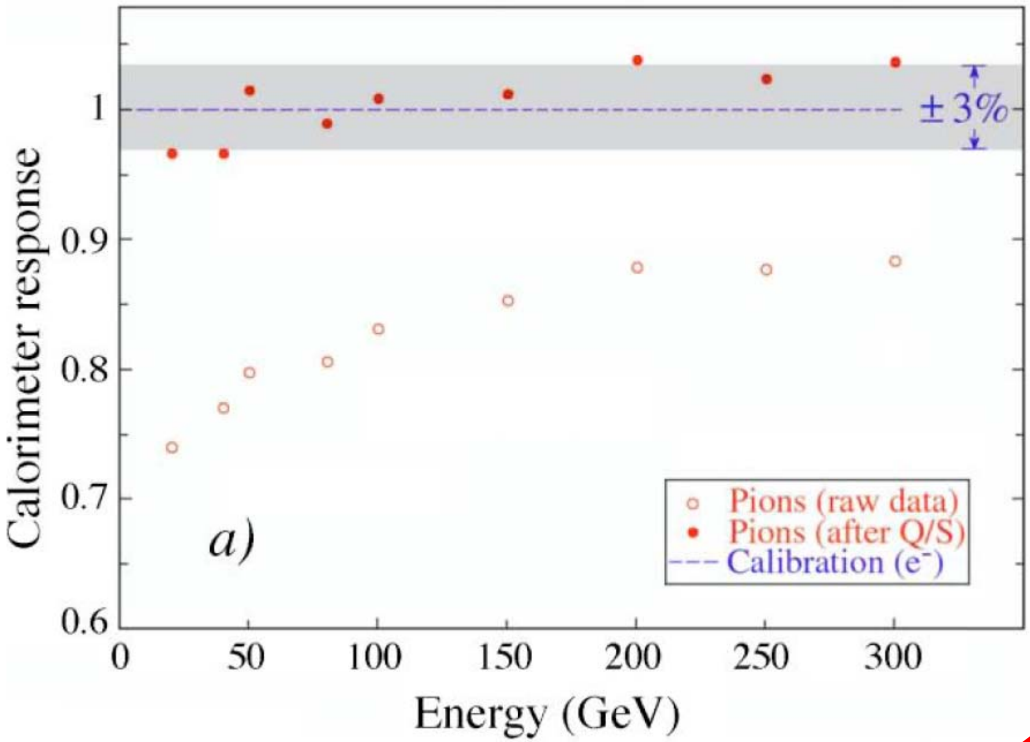


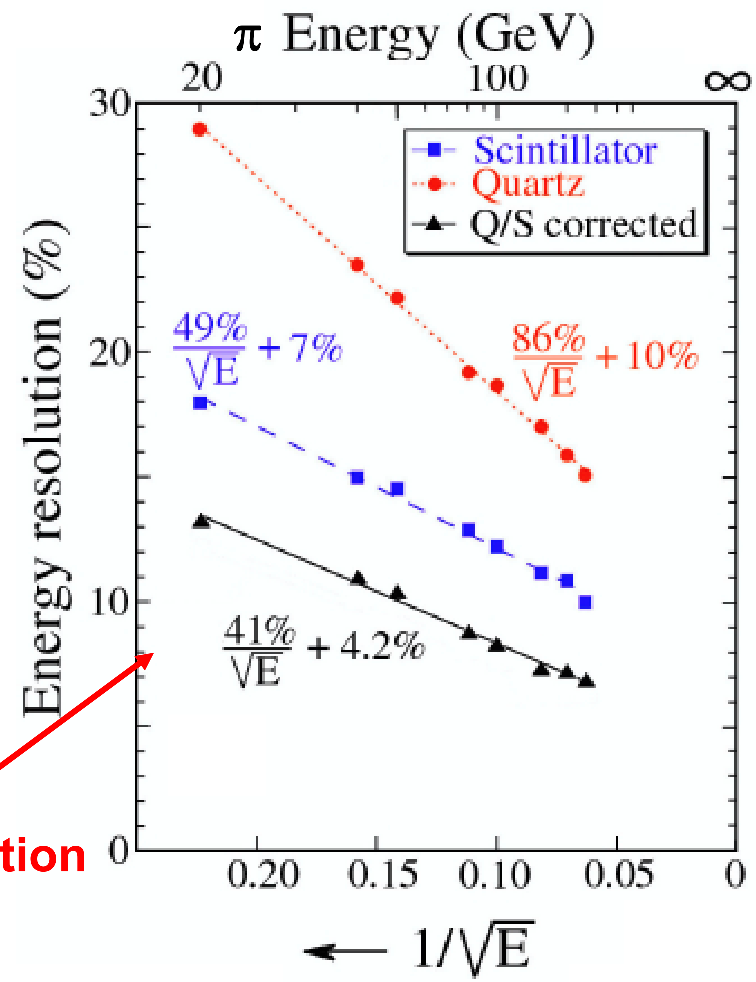


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

Dual readout: DREAM

Hadronic response after C/S correction





NB contains leakage contribution

NICE IDEAS AND STUDIES GOING ON, NEXT STEP TRANSITION TO A SYSTEM?

In summary

Electromagnetic calorimetry

Homogeneous, if well done a ~ 3% (take care of c!)

Sampling, if well done a ~ 10%

Hadron calorimetry (non compensating)

a ~ 50%-100%

Hadron calorimetry (compensating)

a ~ 35%

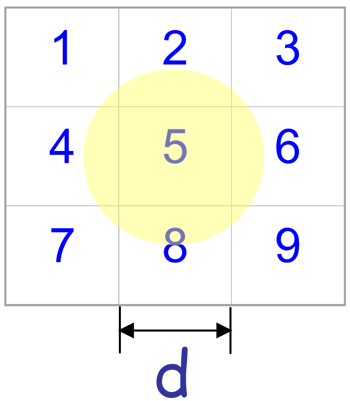
Dual Readout (R&D) calorimetry

a ~ 15% (potentially)

Position resolution - EM

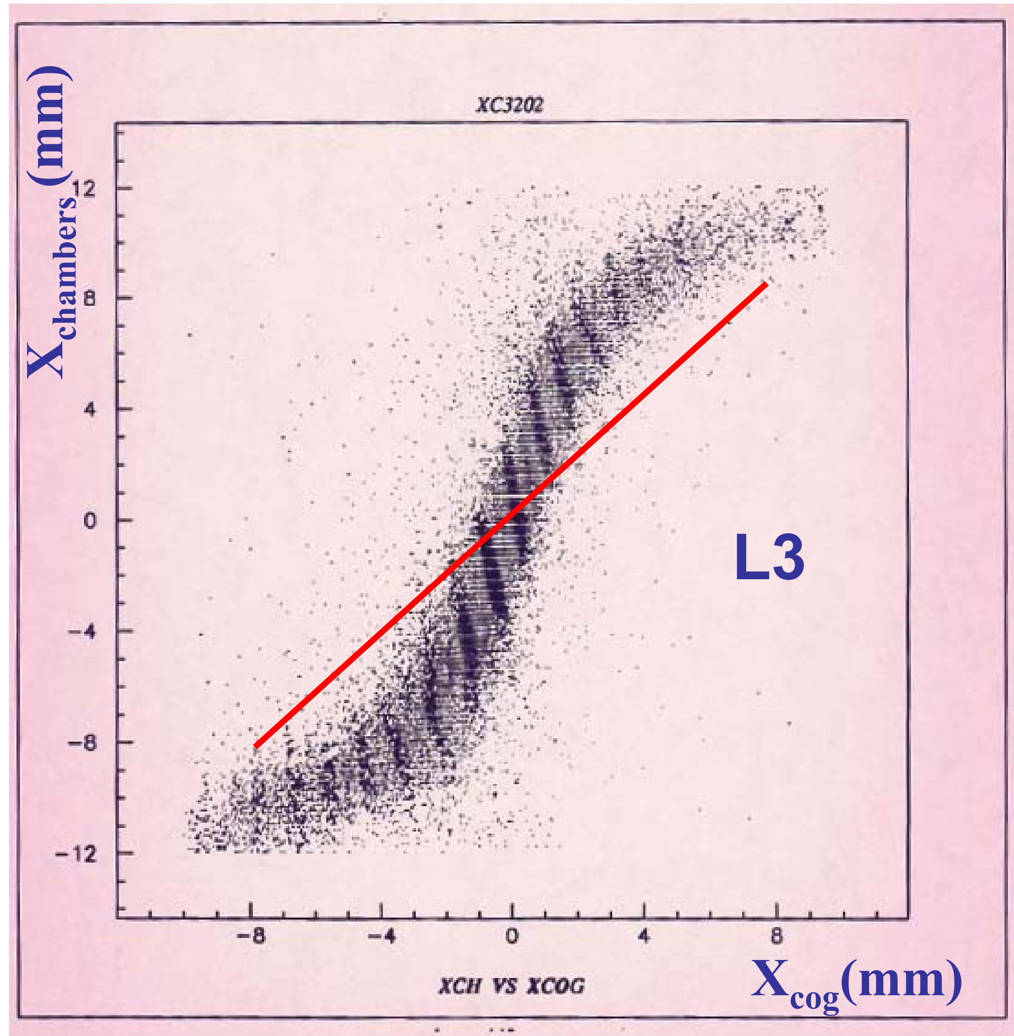
- Reconstruction of invariant masses of particles decaying into photons, electron identification using match with track measured in tracking devices
- Impact position of showers is determined using the transverse (and longitudinal) energy distribution in calorimeter cells
- Method based on center of gravity (COG) calculation
  - works for projective geometry and particles coming from the interaction vertex
  - calorimeter cell size $d \leq 1R_M$
- Typical resolutions: few mm/$\sqrt{E}$

Position resolution - EM

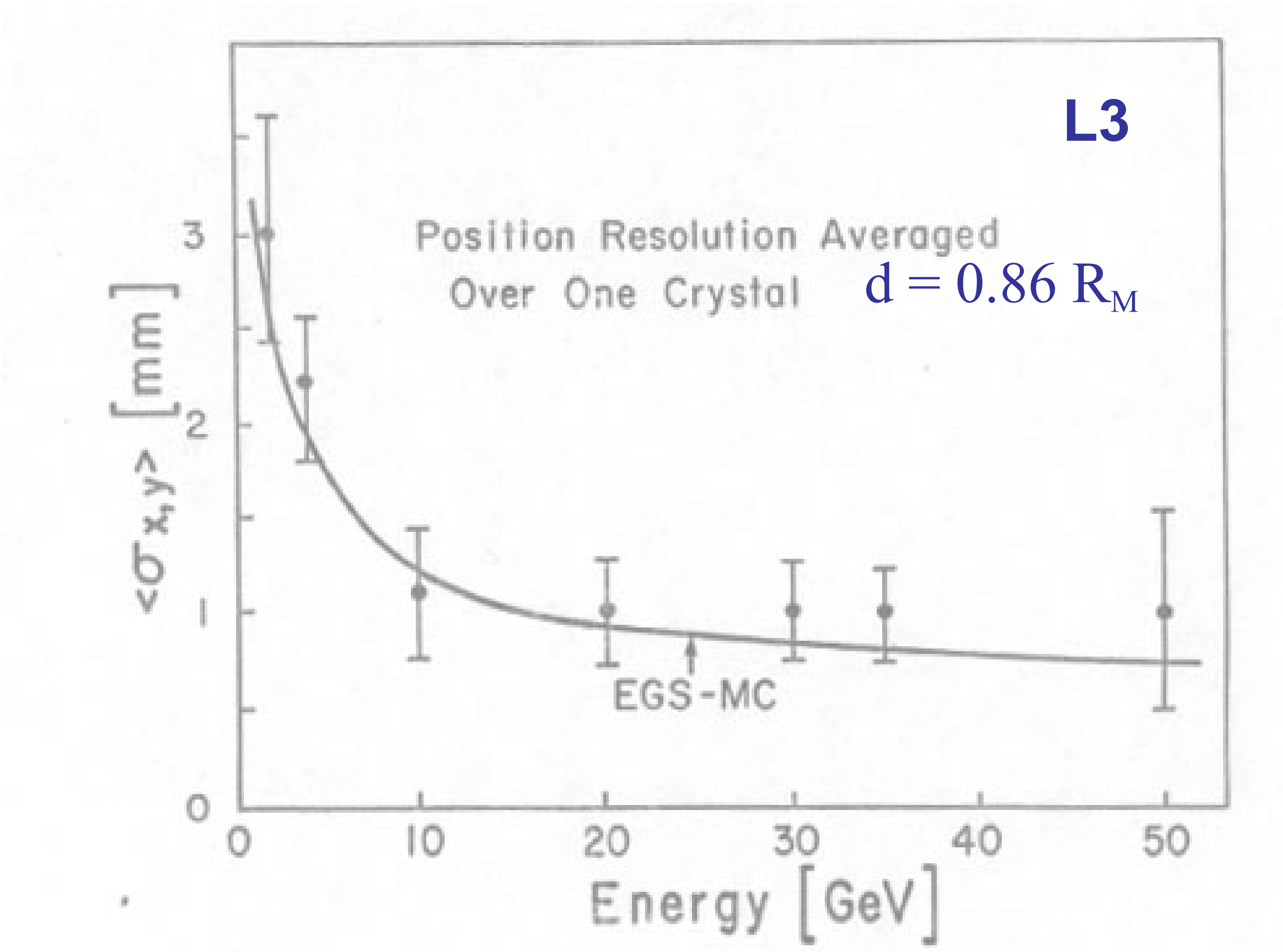


$$X_{cog} = \frac{\sum_1^9 E_i x_i}{\sum_1^9 E_i}$$

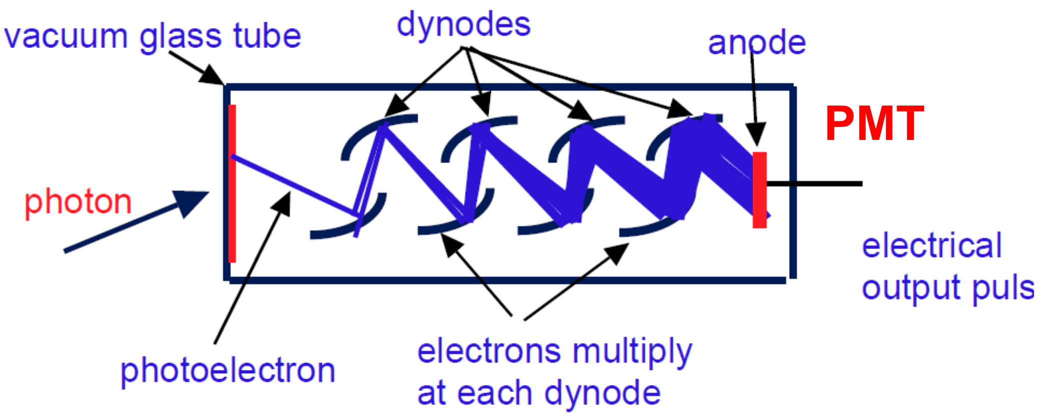
- Needs empirical corrections to account for finite cell size effect

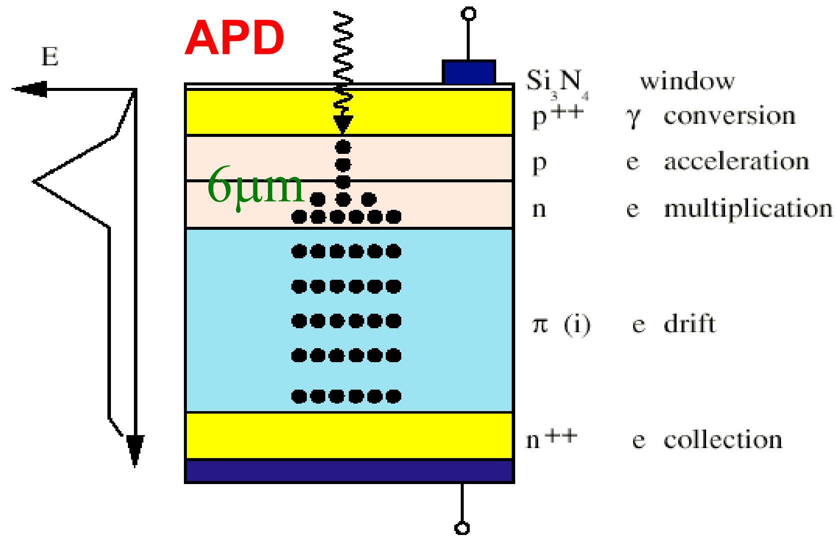


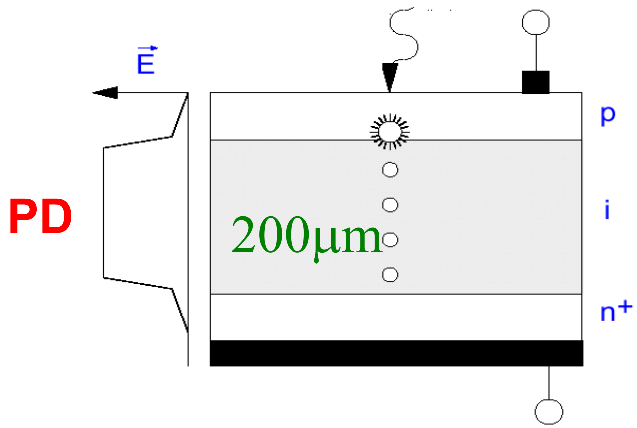
Position resolution - EM

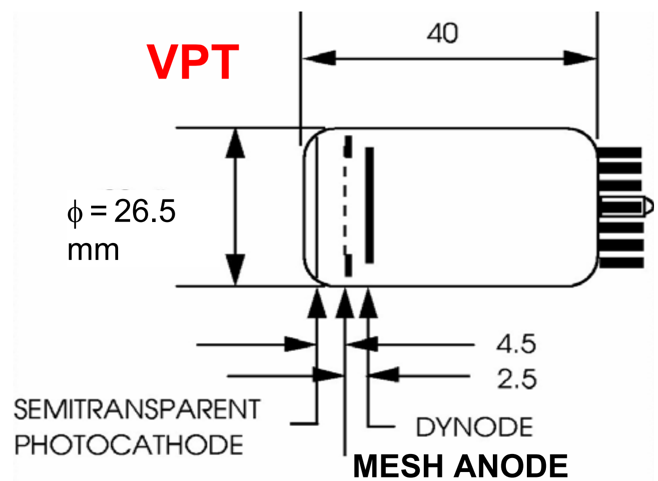


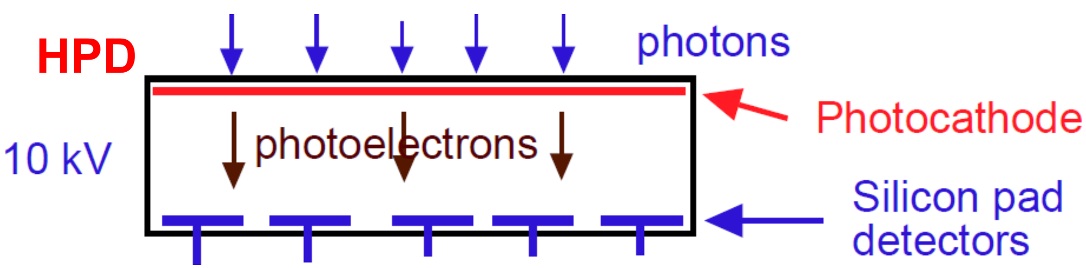
Readout of detector signal (light)











Time resolution (KLOE)

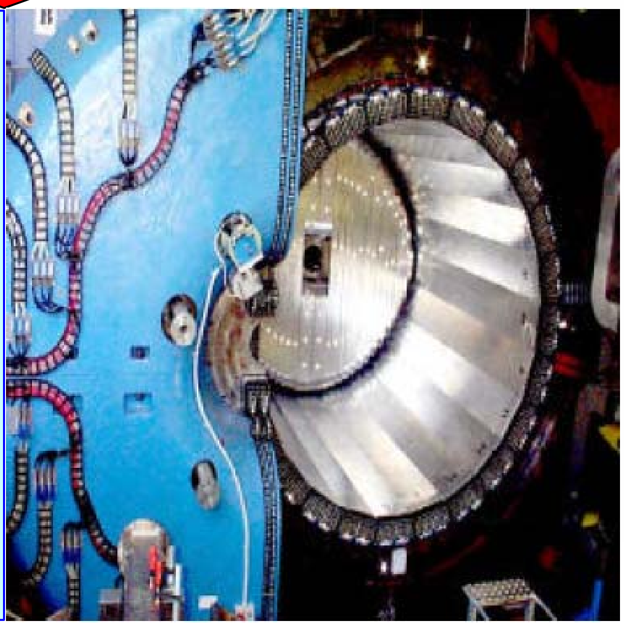
The KLOE design was driven by the measurement of direct CP̸ through the double ratio: $R = \Gamma(K_L \to \pi^+\pi^-)\,\Gamma(K_S \to \pi^0\pi^0) / \Gamma(K_S \to \pi^+\pi^-)\,\Gamma(K_L \to \pi^0\pi^0)$

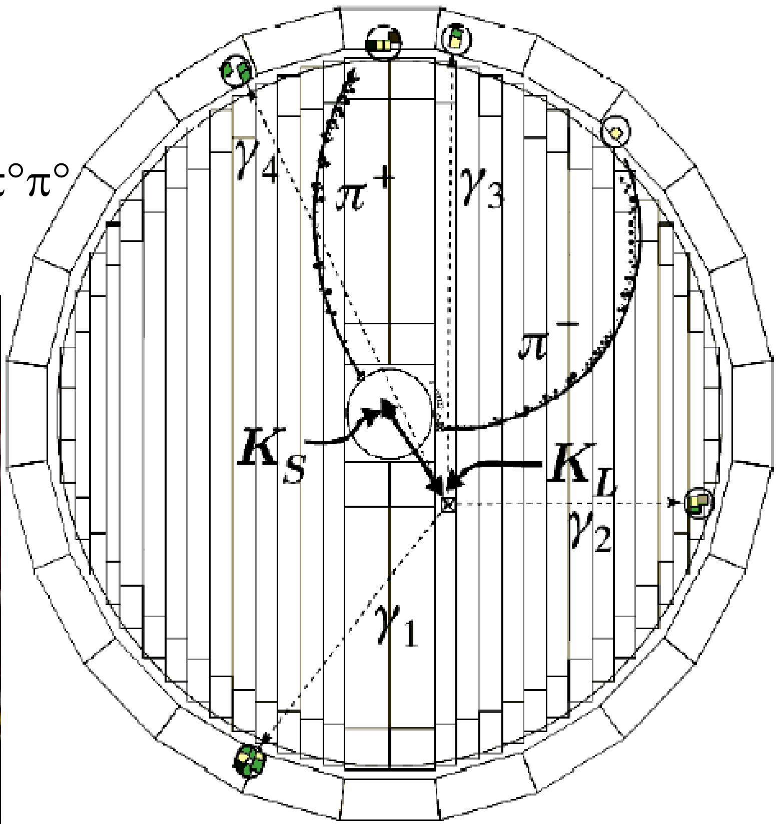
- Determine the $K_{L,S} \to \pi^\circ\pi^\circ$ with few mm precision
- Discriminate $K_L \to \pi^\circ\pi^\circ$ from $K_L \to \pi^\circ\pi^\circ\pi^\circ$
- Particle id. via time of flight (e .vs. μ vs. π)

Good energy & time resolution

$\phi \to K_S K_L \to \pi^\circ\pi^\circ$
$\quad \hookrightarrow \pi^+\pi^-$

- **$\sigma(E)/E \sim 5\% / \sqrt{E(\mathrm{GeV})}$**
- **High efficiency $20 < E_\gamma < 300$ MeV**
- **$\sigma(t) \sim 70$ ps / $\sqrt{E}$ (GeV)**
- **$\sigma_{x,y,z} \sim 1$ cm for photon conversion point**
- **Hermeticity**

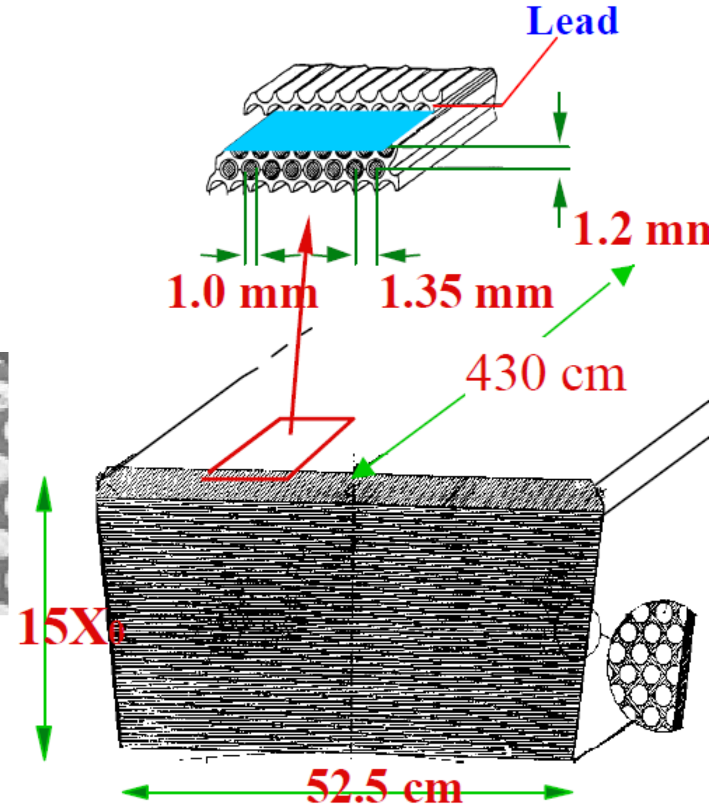




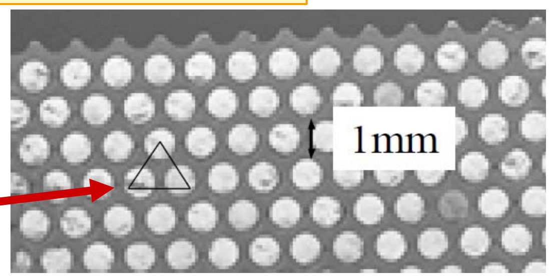
Time resolution (KLOE)

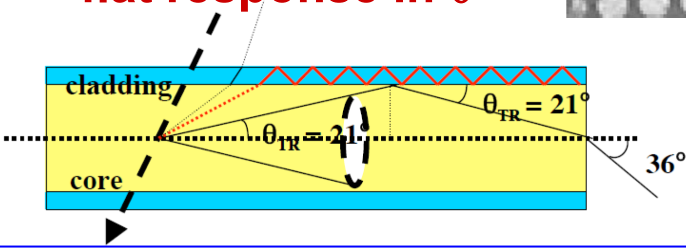
Fine sampling lead/scintillating fibers calorimeter

- Volume Ratio Fiber:Lead 50:50
- Energy sampling fraction 13 %
- X_0 = 1.6 cm ρ=5.3 g/cm^3



Triangular shape: high sampling frequency & flat response in θ



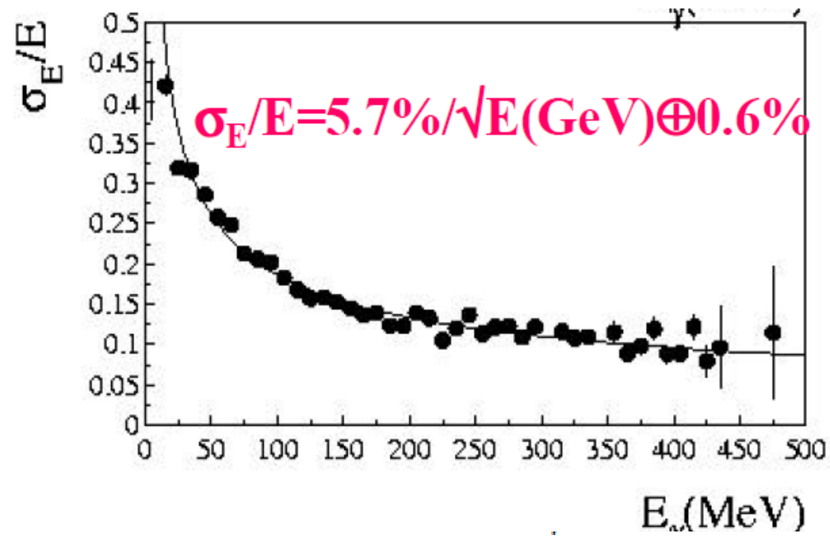


n_polystirene = 1.6 ; n_plexiglass(cladding) = 1.5 ; trapping angle 21°
Light Yeld 5*10^3 photons/MeV, λ_peak = 460 nm
Fiber emission time t = 2.2 ns; 50% absorption @ 2 m
Light collected with plexiglass light guide to fine mesh PM Q.E. 25% G ~5*10^6
Light output ~1 p.e./MeV/side at 2 m distance

Time resolution (KLOE)

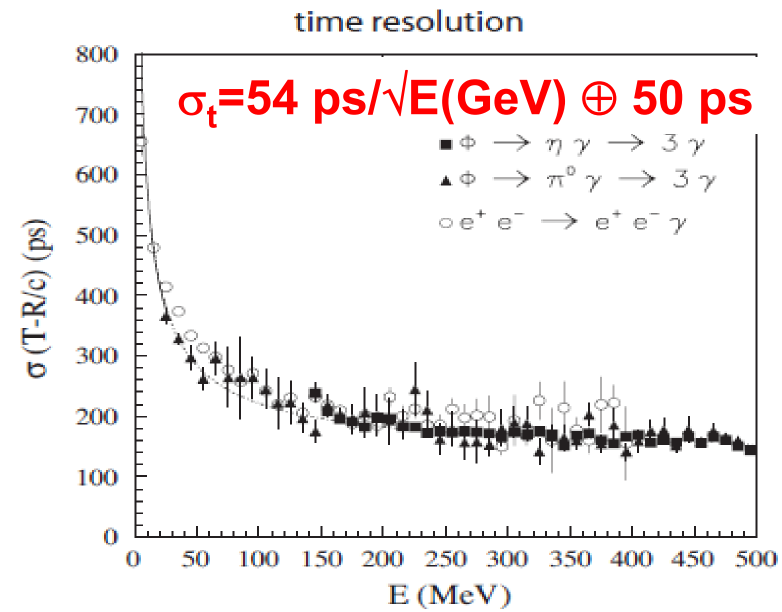
Energy resolution:
dominated by sampling fluctuations

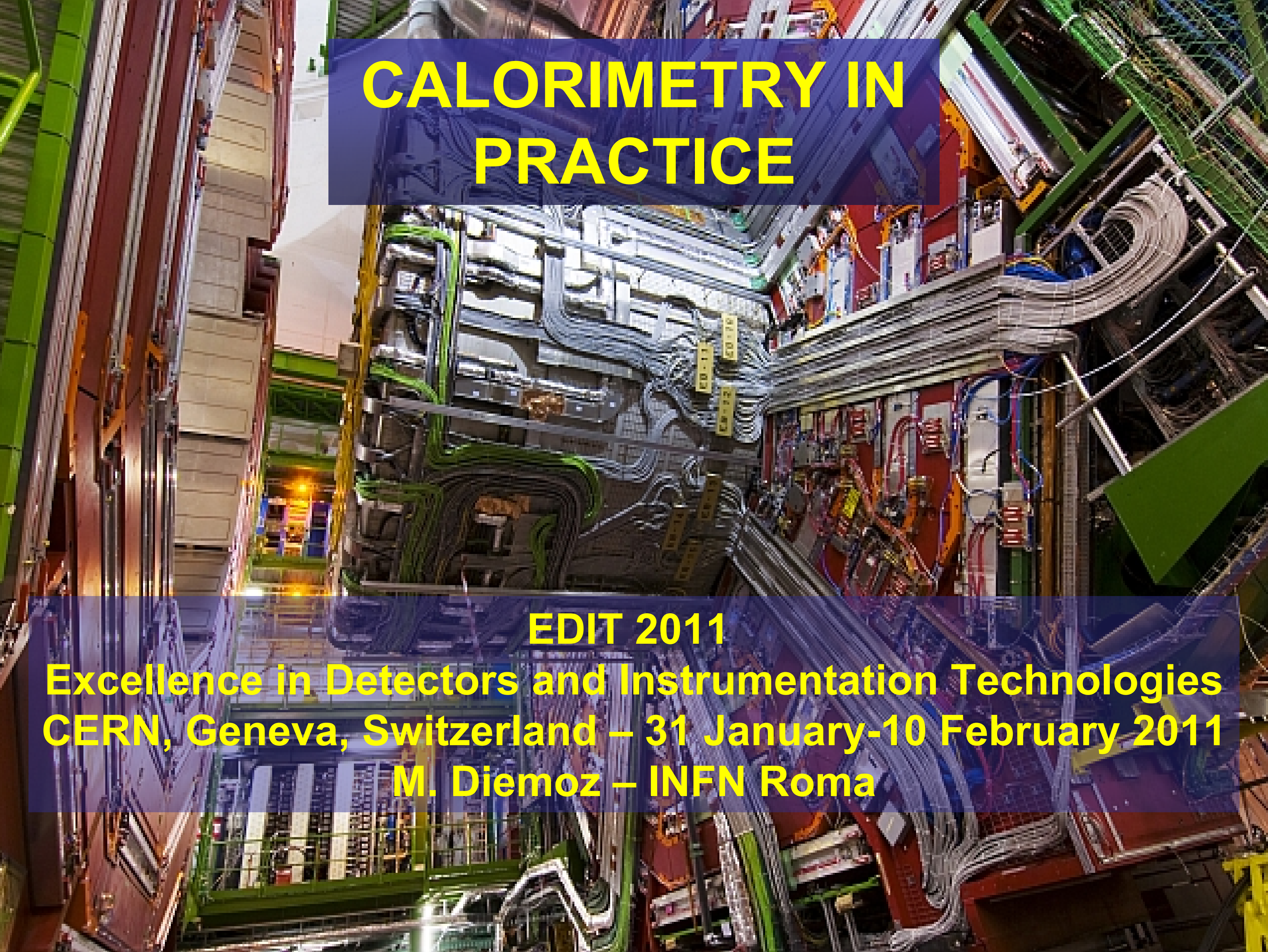
$$\frac{\sigma_E}{E} = \left(\frac{4.2\%}{\sqrt{E(GeV)}}\right)_{sampling} \oplus \left(\frac{2.5\%}{\sqrt{E(GeV)}}\right)_{p.e.} \oplus \ldots$$



Time resolution:
dominated by photo electron statistics

$$\sigma_t = \frac{\tau_{decay} \oplus \sigma_{fiber} \oplus \sigma_{l.g.}}{\sqrt{N(p.e.)}} \approx \frac{2.2ns}{\sqrt{N(p.e.)}} \approx \frac{50\,ps}{\sqrt{E(GeV)}}$$





CALORIMETRY IN PRACTICE

EDIT 2011
Excellence in Detectors and Instrumentation Technologies
CERN, Geneva, Switzerland – 31 January-10 February 2011

M. Diemoz – INFN Roma

Outline

- **Big Systems (ATLAS&CMS)**
- **Calibration**
- **Detection of physics objects**

Large Hadron Collider: Higgs hunt

Natural width (GeV)

0.001 | 0.004 | 1.4 | 30

0 | 50 | 100 | 200 | 400

Higgs Mass (GeV)

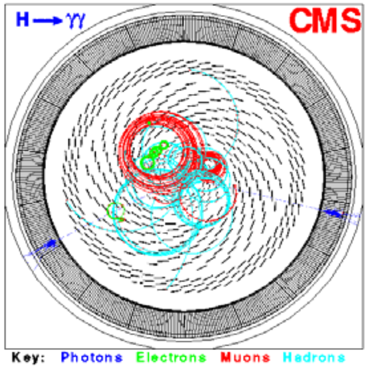
LEP | LHC

$H \to \gamma\gamma$

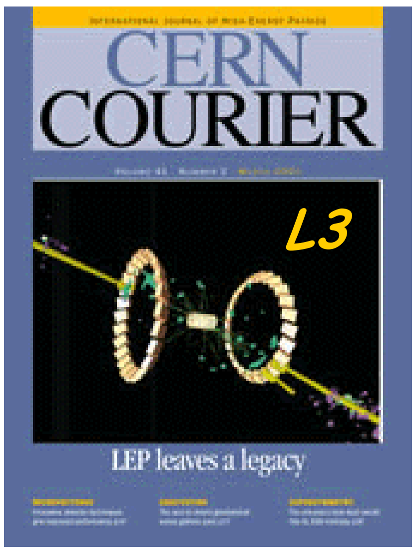
$H \to ZZ^* \to$ 4 leptons

$H \to ZZ \to$ 4 leptons

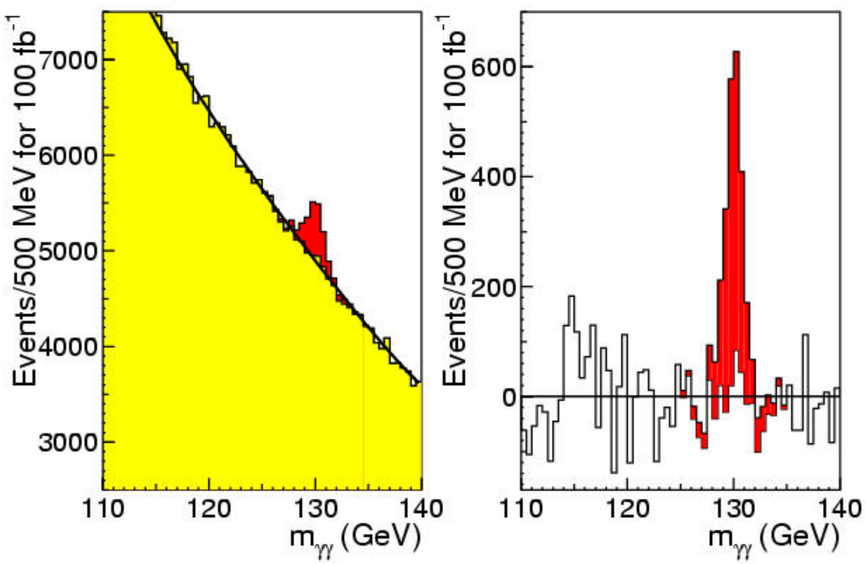
$H \to$ WW or ZZjj



μ, e, γ



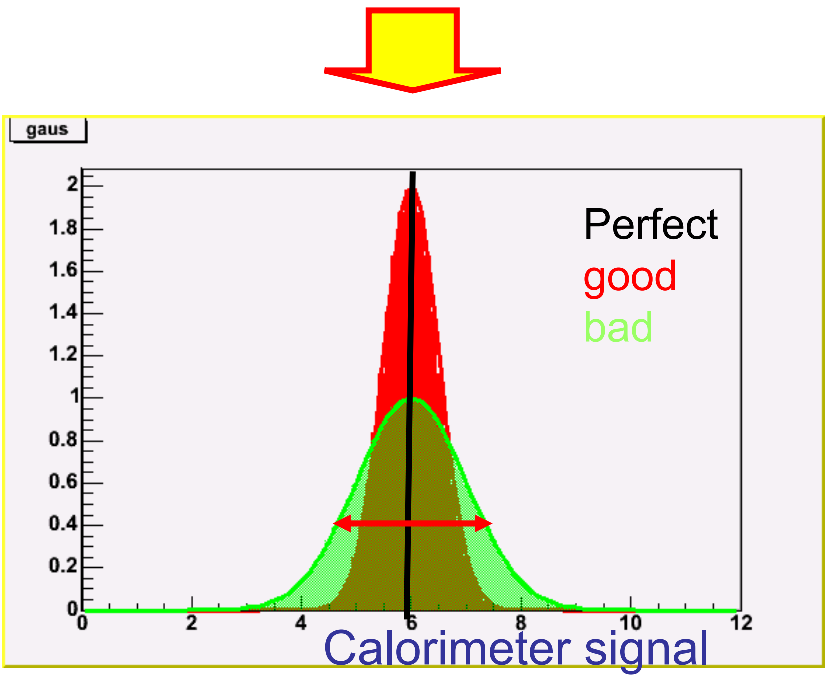
LEP observed an excess of events around 115 GeV



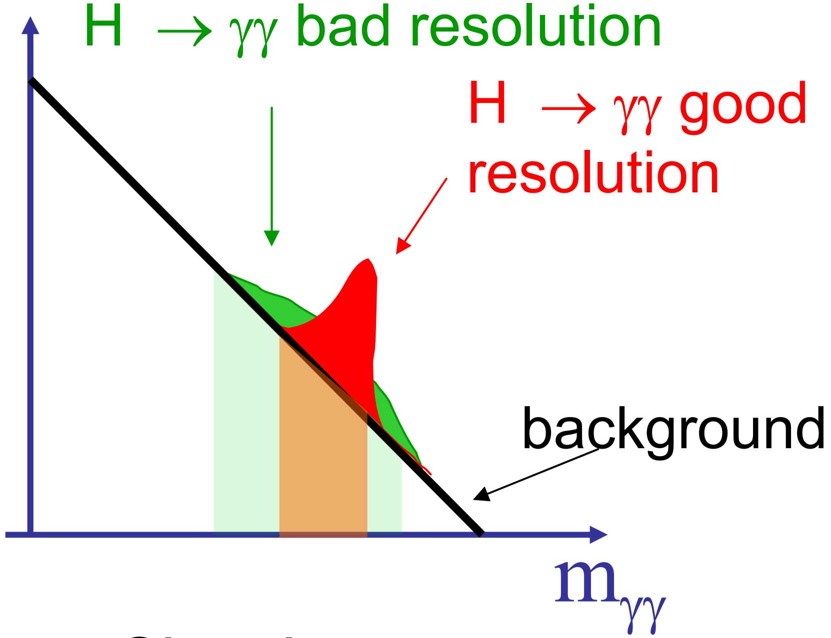
Only precision in γ detection will tell a peak ($H \to \gamma\gamma$ signal) from a huge background

Why precision matter so much?

Response to monochromatic source of energy E



σ(calo) defines the energy resolution for energy E.



Signal = constant

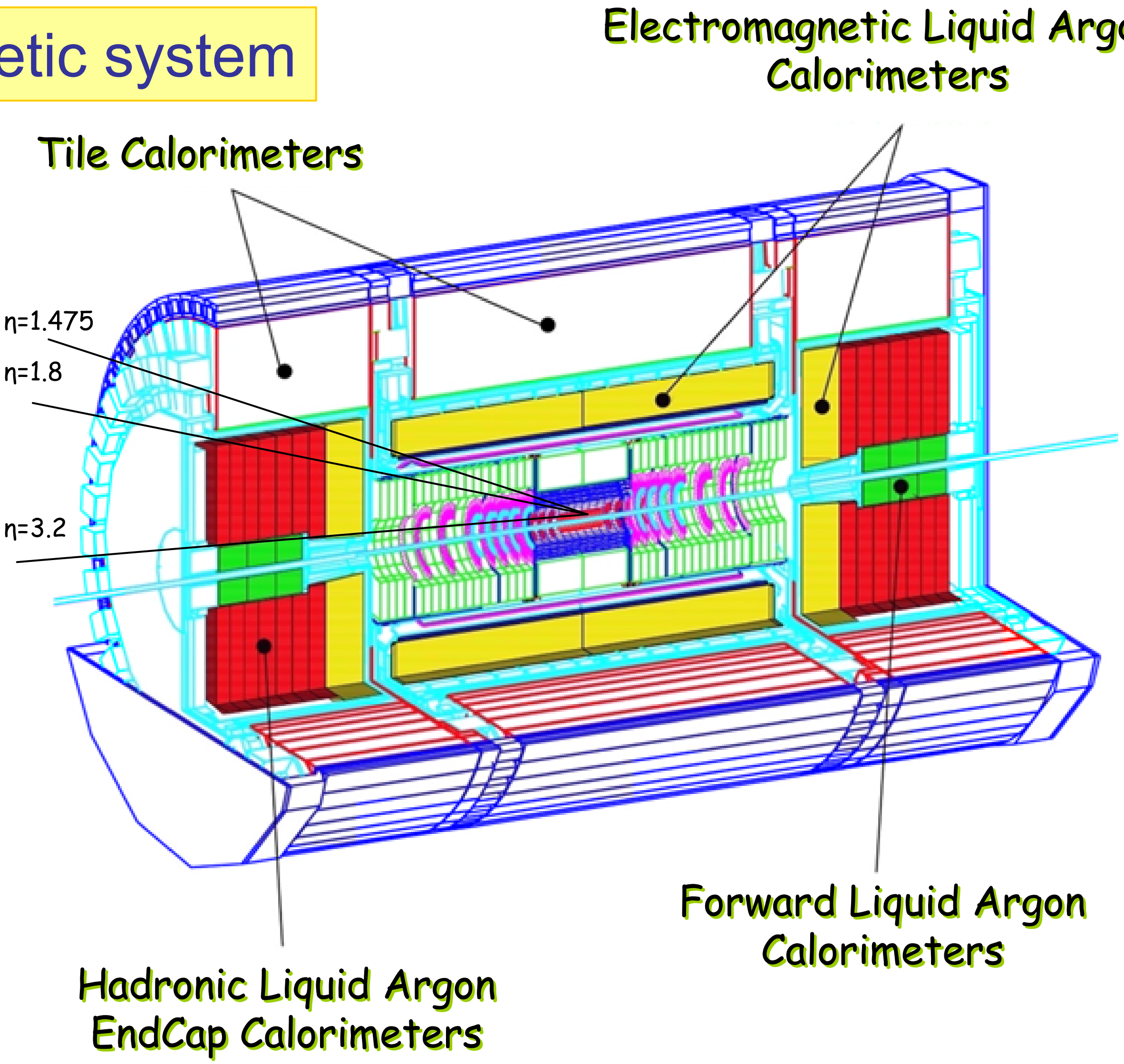
integrated B $\propto \sigma_{\gamma\gamma} \rightarrow$

$S/\sqrt{B} \propto 1/\sqrt{\sigma\gamma\gamma}$

… but $\sigma_{\gamma\gamma} = f(\sigma \text{calo})$

ATLAS CALORIMETERS

Hermetic system



CMS CALORIMETERS

Em Barrel : EB

Em Endcap : EE

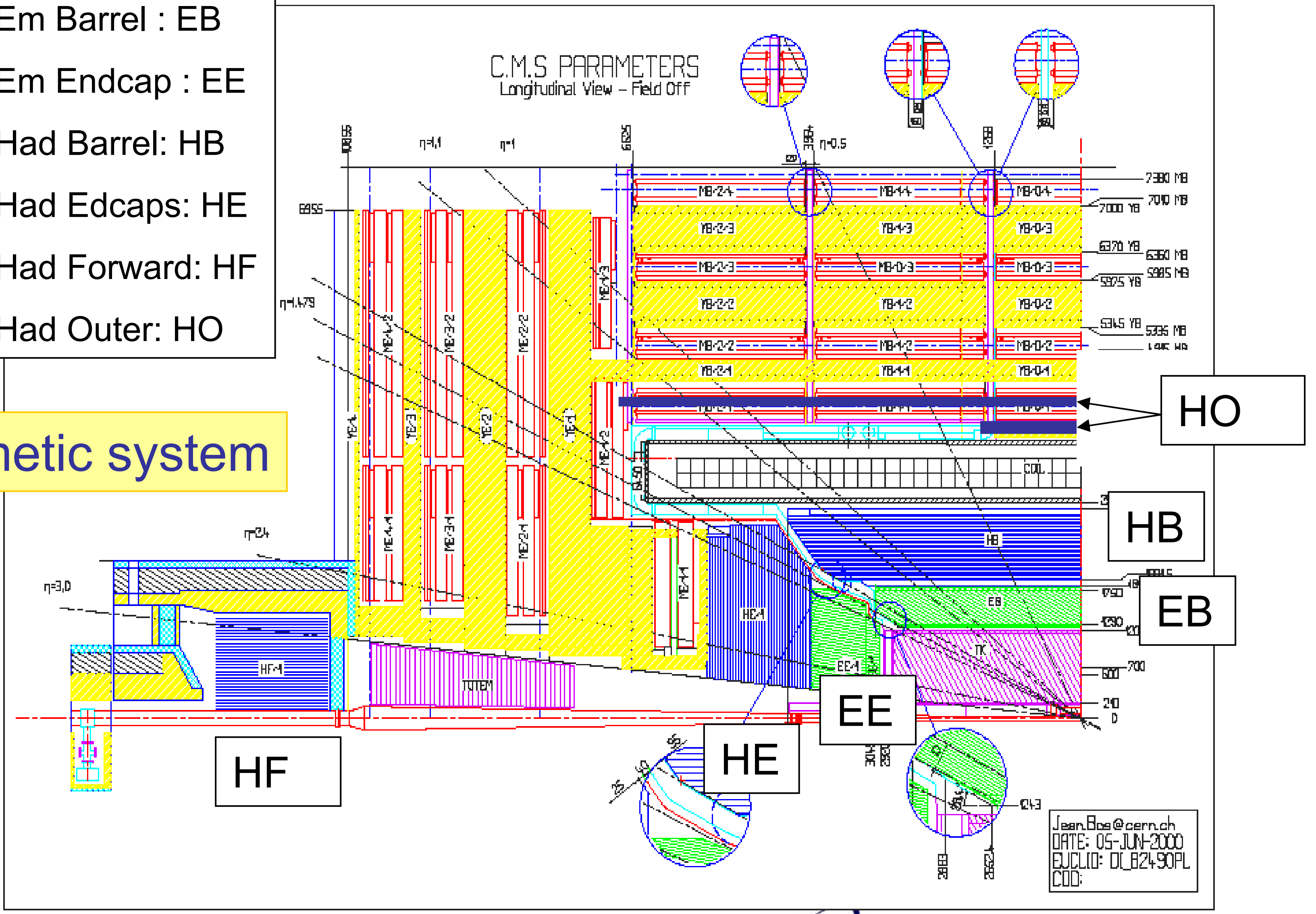
Had Barrel: HB

Had Edcaps: HE

Had Forward: HF

Had Outer: HO

Hermetic system



ATLAS & CMS EM calorimetry

- Compact
- Excellent energy resolution
- Fast
- High granularity
- Radiation resistance
- E range MIP → TeV

•Homogeneous calorimeter made of 75000 $PbW0_4$ scintillating crystals + PS FW

- Good energy resolution
- Fast
- High granularity
- Longitudinally segmented
- Radiation resistance
- E range MIP → TeV

•Sampling LAr-Pb, 3 Longitudinal layers + PS

ATLAS and CMS makes different choices:

- sampling calorimeter allow to have redundant mesurement of γ angle
- homogenous calorimeter with very low stochastic term aims to excellent energy resolution, the mesure of γ angle relies on vertex reconstruction from tracking.

$H \rightarrow \gamma\gamma$: ECAL benchmark

$\Gamma_H (m_H \cong 100 \text{ GeV}) \sim 2 - 100 \text{ MeV}$ → $\Gamma_H / m_H \leq 10^{-3}$

$m_{\gamma\gamma} = 2 E_1 E_2 (1 - \cos\theta_{\gamma\gamma})$ Precision given by experimental resolution

$$\frac{\sigma_m}{m} = \frac{1}{2}\left[\left(\frac{\sigma_1}{E_1}\right)^2 + \left(\frac{\sigma_2}{E_2}\right)^2 + \left(\frac{\sigma_\theta}{\text{tg}\theta/2}\right)^2 + \right]^{1/2}$$

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Homogeneus calo **a** can be ~ 2%, to match it for E_γ ~ 50 GeV:

CMS

$c \sim 0.5\%$

$b \sim 200$ MeV

and an angular resolution

$\sigma_\theta \sim 50 \text{ mrad}/\sqrt{E}$

Sampling calo **a** can be ~ 10%, to match it for E_γ ~ 50 GeV:

ATLAS

$c \sim 0.7\%$

$b \sim 300$ MeV

and an angular resolution

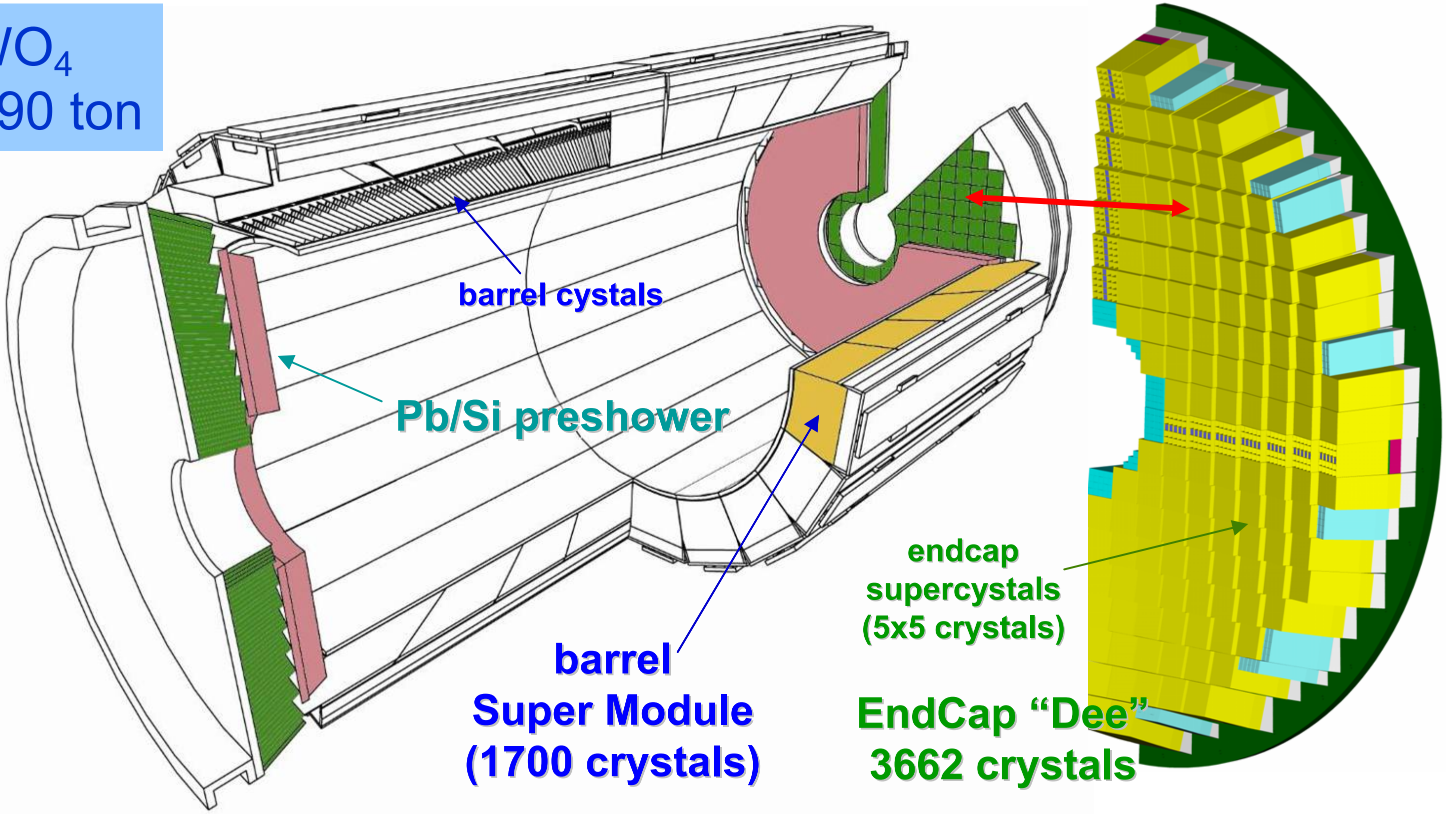
$\sigma_\theta \sim 50 \text{ mrad}/\sqrt{E}$

ECAL @ CMS

Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: $PbWO_4$
about 10 m^3, 90 ton

Previous
Crystal
calorimeters:
max 1m^3



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2x2x23cm^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3x3x22cm^3$)

Aiming at precision

Precision has a price… a long list to take care:

- Longitudinal and lateral shower containment
- Light production and collection
- Light collection uniformity
- Nuclear counter effect (leakage of particles in PD)
- Photo Detector gain (if any) stability
- Channel to channel intercalibration
- Electronic noise
- Dead material (energy loss and γ conversions)
- Temperature stability and uniformity
- Radiation damage
- Pileup

The choice of the crystal

Crystal's catalog

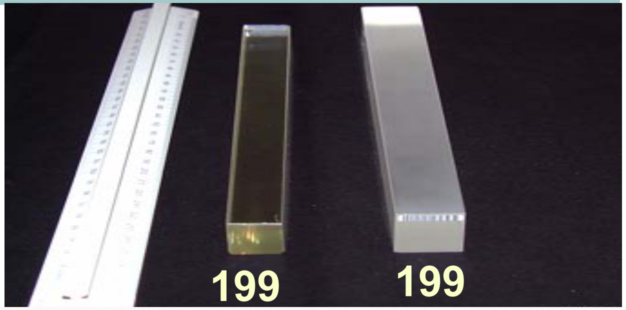
	NaI(Tl)	BaF_2	CsI(Tl)	CsI	CeF_3	BGO	PWO	
ρ	3.67	4.88	4.53	4.53	6.16	7.13	8.26	g/cm^3
X0	2.59	2.05	1.85	1.85	1.68	1.12	0.89	cm
RM	4.5	3.4	3.8	3.8	2.6	2.4	2.2	cm
τ	250	0.8/620	1000	20	30	300	15	ns
λp	410	220/310	565	310	310/340	480	420	nm
n (λp)	1.85	1.56	1.80	1.80	1.68	2.15	2.29	
LY	100%	15%	85%	7%	5%	10%	0.2%	%NaI

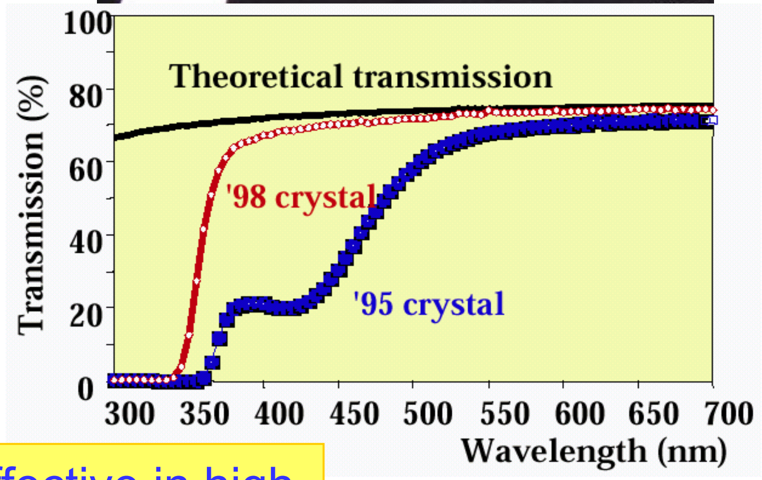
Typical light yield of NaI ~ 40000 γ/MeV

CMS developed a new crystal

Lead Tungstate Crystals (PWO) for CMS

Parameter		Value
Radiation length	cm	0.89
Moliere radius	cm	2.2
Hardness	Moh	4
Refractive index		2.3
Peak emission	nm	440
% of light in 25 ns		80%
Light yield (23 cm)	γ/MeV	100



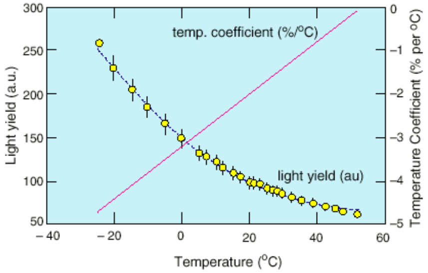


Very low light output

Hard light extraction

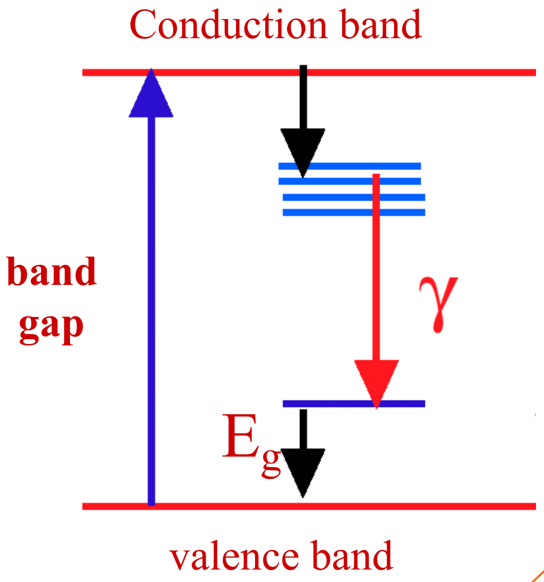
Very effective in high energy γ containment

T dependent: -2%/°C



23 cm to contain em showers!

PWO: a scintillating crystal



$E_{dep} \rightarrow$ e-h

$E_s = \beta\, E_g \quad \beta > 1$

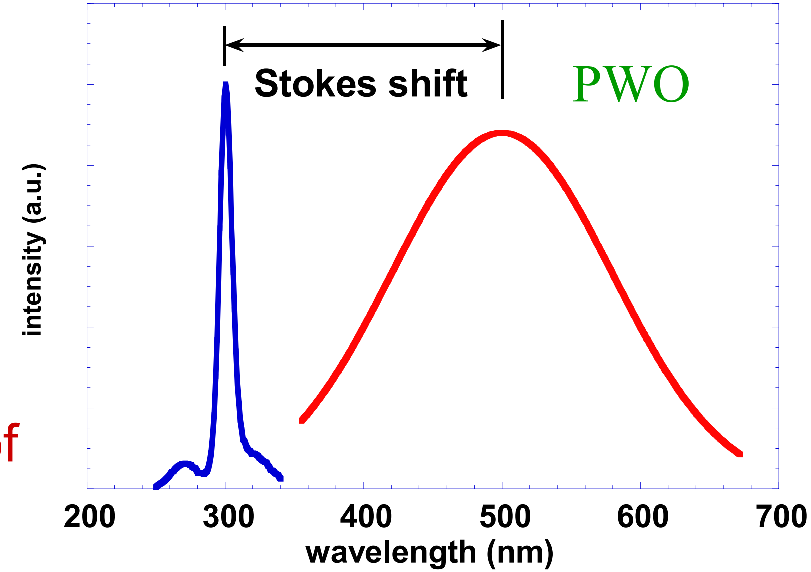
$N_{eh} = E_{dep} / \beta E_g$

$N_\gamma = SQN_{eh}$

Radiative efficiency of luminescent centres

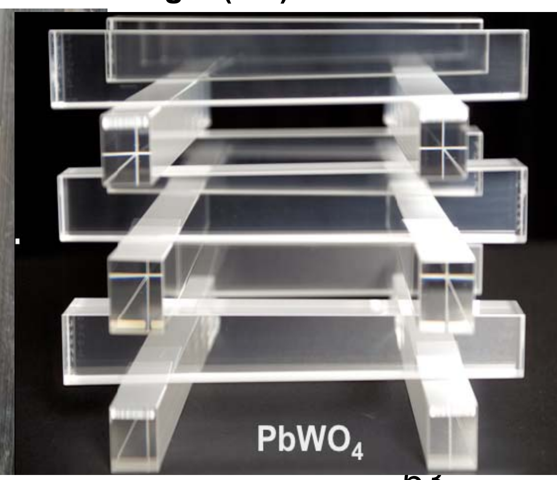
Efficiency of transfer to luminescent centres

$PbWO_4$: λ_{excit}=300nm ; λ_{emiss}=500nm



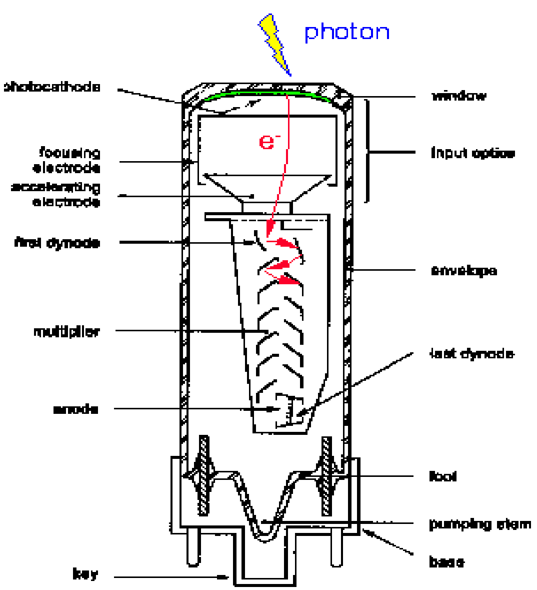
$$\eta_\gamma = N_\gamma / E_{dep} = SQN_{eh} / E_{dep} = SQ / \beta E_g$$

- **S, Q ≈ 1** , βE_g as small as possible
- medium transparent to λ_{emiss}

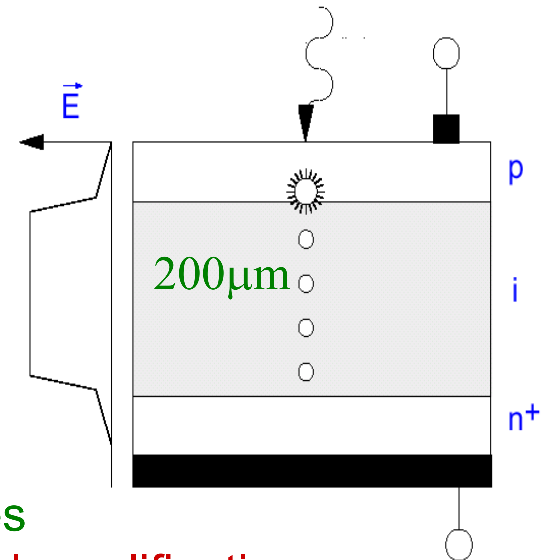


Photon detectors for PWO

- Not sensitive to 4T magnetic field
- High quantum efficiency for λ 400 – 500 nm
- Internal amplification (low PWO LY)
- Fast and good for high rate (40MHz)
- Radiation hard
- Not (too much) sensitive to charged particles

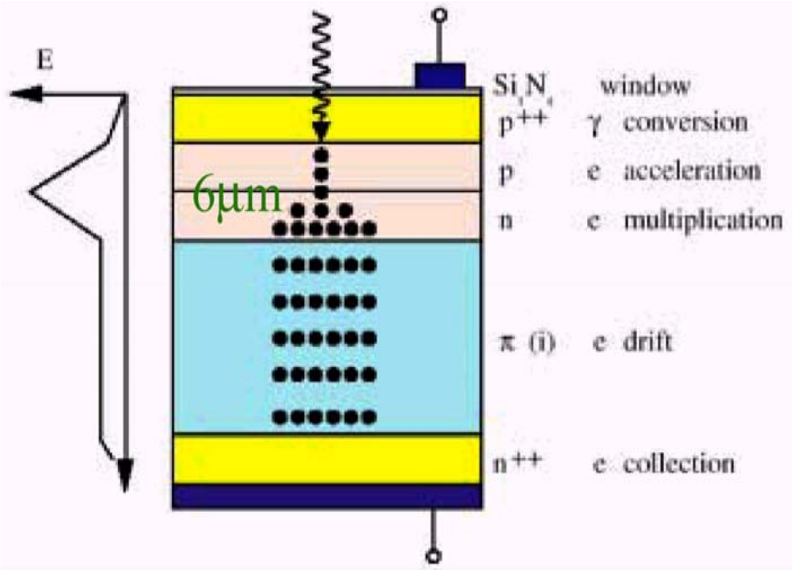


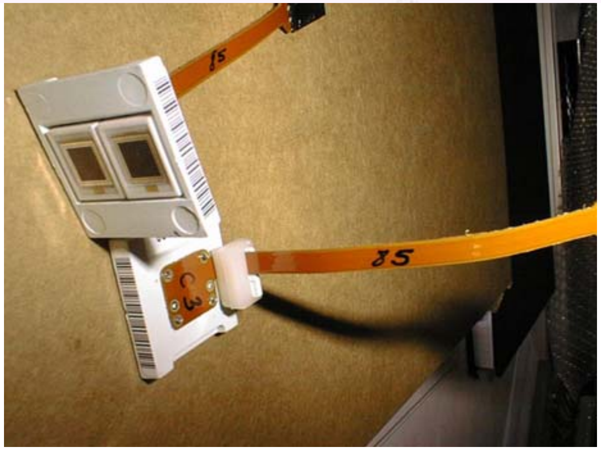
Photomultipliers
- affected by magnetic field
- large volume



PIN photodiodes
- no internal amplification
- too sensitive to charged particles (Nuclear Counter Effect)

Avalanche Photo Diodes





2 APDs per crystal: 50 mm^2 active area

Barrel: Avalanche Photodiodes (APD, Hamamatsu)

Characteristics optimized with an extensive R&D Program

- **insensitive to B-field as PIN diodes**
- **Internal gain (M=50 used)**
- **good match to Lead Tungstate scintillation spectrum (Q.E. ~ 80%)**
- **dM/dV = 3%/V and dM/dT = -2.3%/°C :**

→T and V stabilization needed

- **bulk current increase & recovery with irradiation measured over 1 year: expect doubling of initial noise after 10 years running, OK**
- **Capacitance 75 pF**
- **Excess noise factor F=2.2 (→ fluctuations in multiplication)**
- **Effective $d_{eff} \cong 6\ \mu m$ (→ small response to ionizing radiation)**

Energy resolution: a , b , c

In scintillating crystals the only intrinsic source of fluctuations is photostatistics:

Light Yield of the crystal is one of the factors but not the only one

$$\frac{\sigma}{E} = \frac{1}{\sqrt{N_{pe}}} = \frac{1}{\sqrt{E(GeV) \cdot N_{pe}/GeV}}$$

Npe/GeV= (γ/GeV)•(light collection eff.)•(geometrical PD eff.)•(photocathode eff.)

a = (photostatistics)⊕(lateral containment)⊕(e multiplication in PD)

N_{pe}/GeV=4000
1.6%/ √E(GeV)

Electronic noise (1/E):

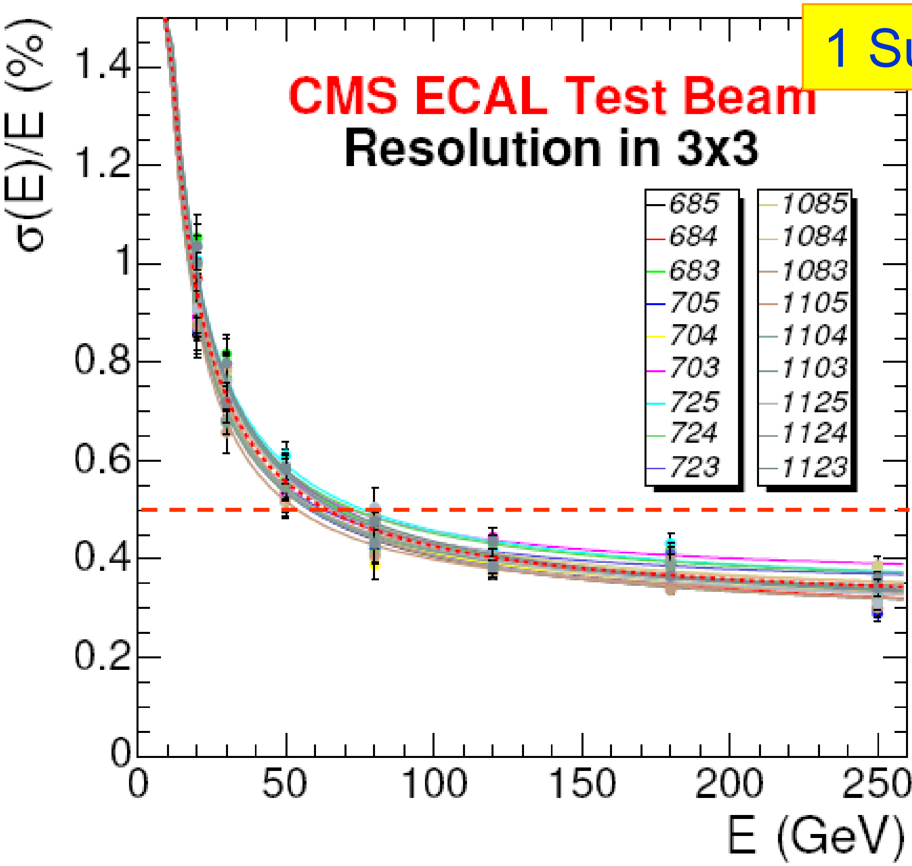
b = (pd capacitance)⊕(dark current)⊕(physics pileup)

$\propto 1/\sqrt{t_{shaping}}$ $\propto \sqrt{t_{shaping}}$

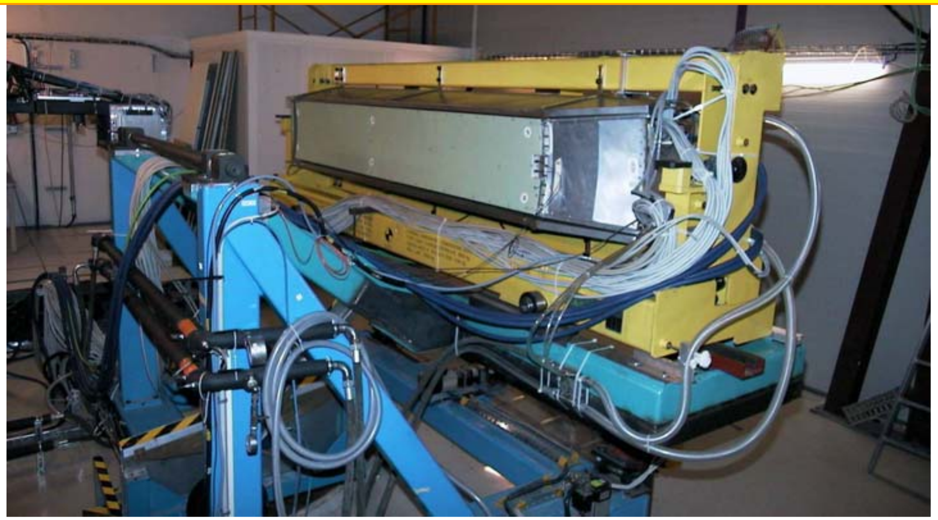
c = (leakage)⊕(intercalibration)⊕(system instability)⊕(nonuniformity of xl)

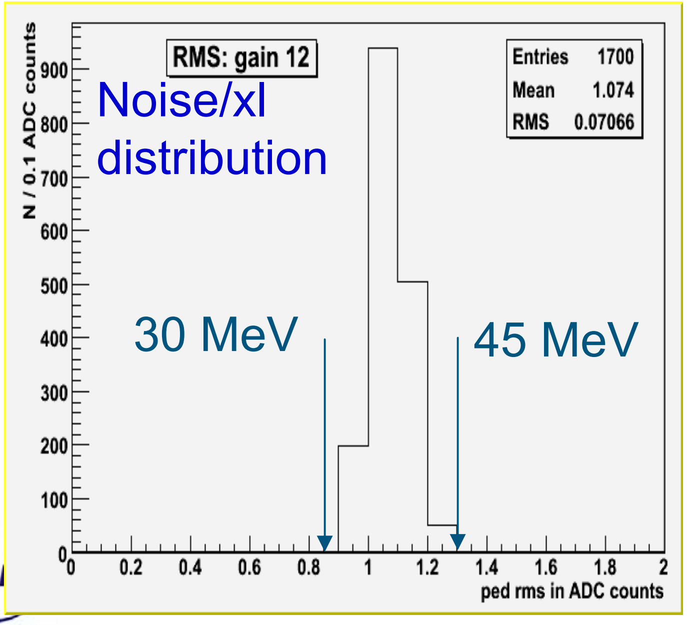
To have c ~ 0.5 % all contributions must stay below 0.3 %

CMS ECAL: the performance



1 Super Module 1700 xl on test beam in 2004





$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

Energy resolution: how to keep it?

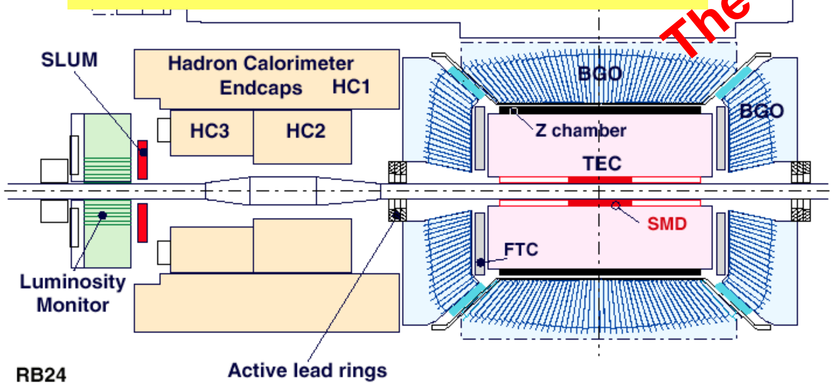
- **Intercalibration**

  requires several steps before, during and after data taking
  - test beam precalibration
  - continuous monitor during data taking
  - absolute calibrations by physics reactions during the experiment lifetime

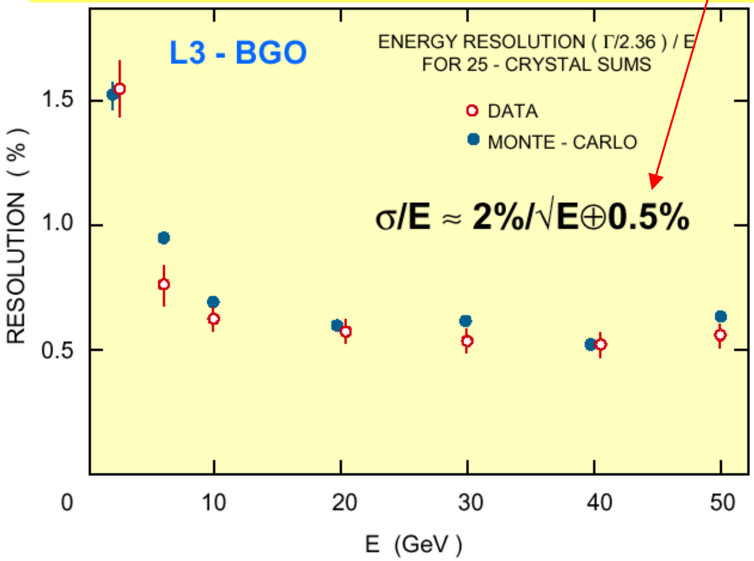
THIS IS THE KEY ISSUE TO MAINTAIN PHYSICS PERFORMANCE

The case of L3

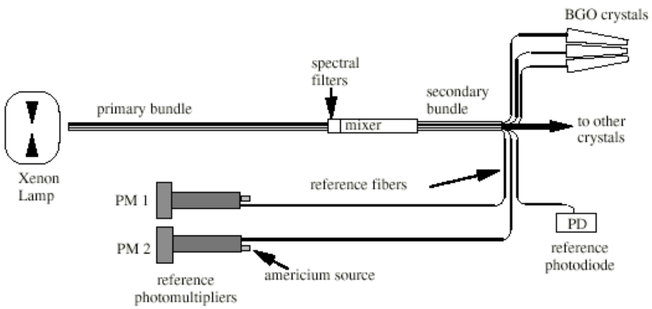
- **7680 EB + 3640 EC BGO crystals**
- **PIN diode read-out (no gain)**
- **Noise level around 1 MeV**



Individual calibration constants determined on test beams to a precision of 0.4%.

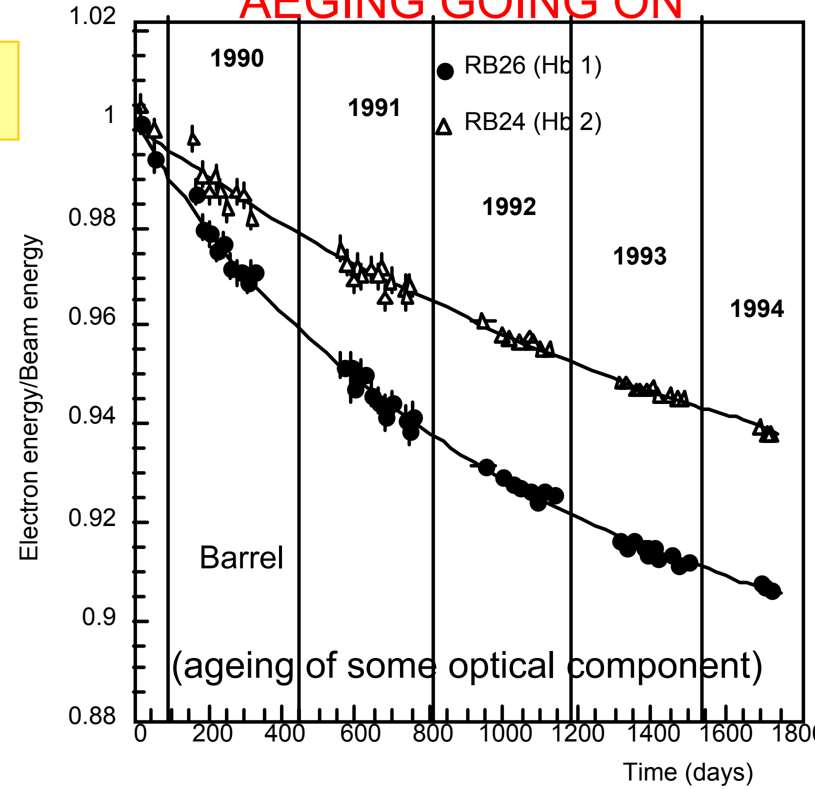


Things may change unexpectedly…

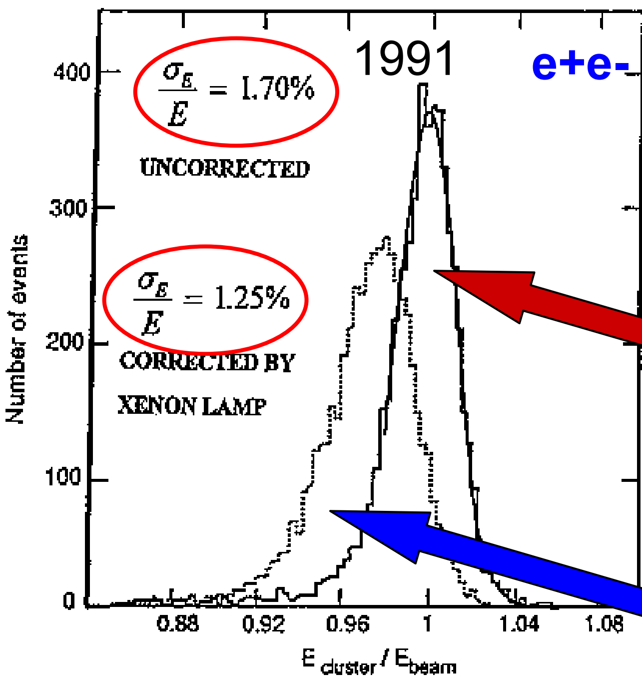


L3 BGO

AEGING GOING ON



- **System able to track the BGO response decrease (few %/year) with light injection**

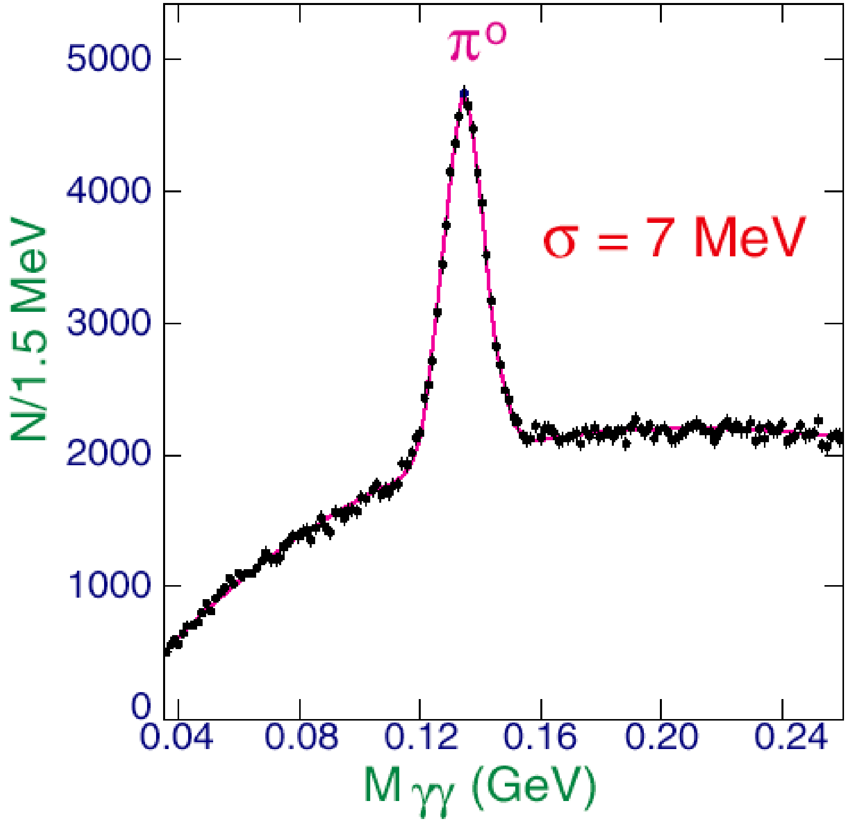


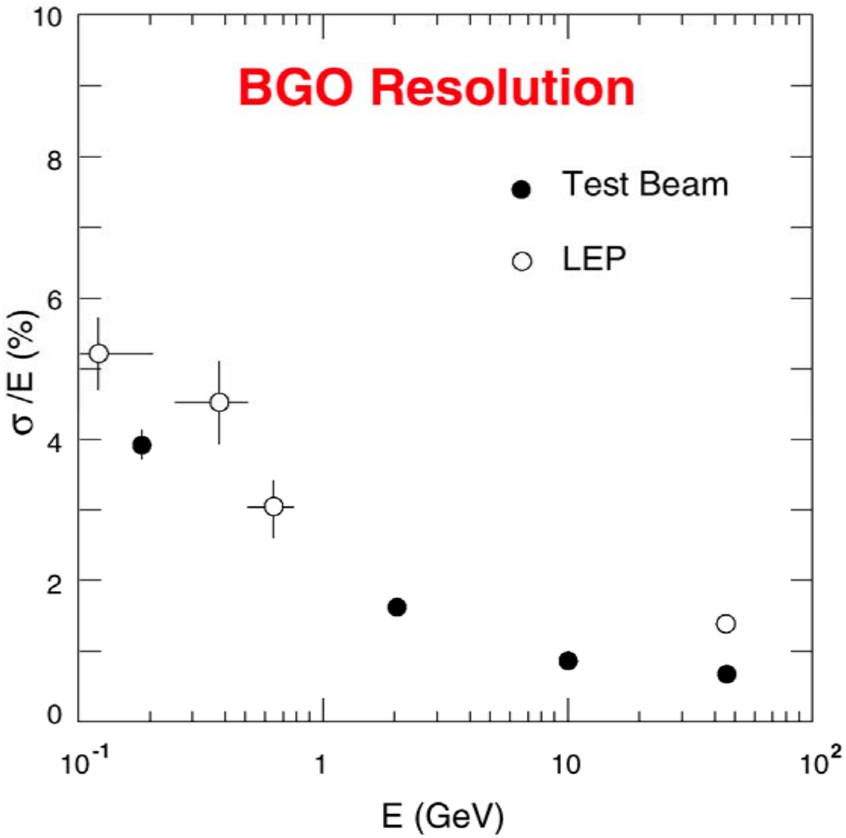
e+e-→ Z→e+e-

After light correction

Before light correction

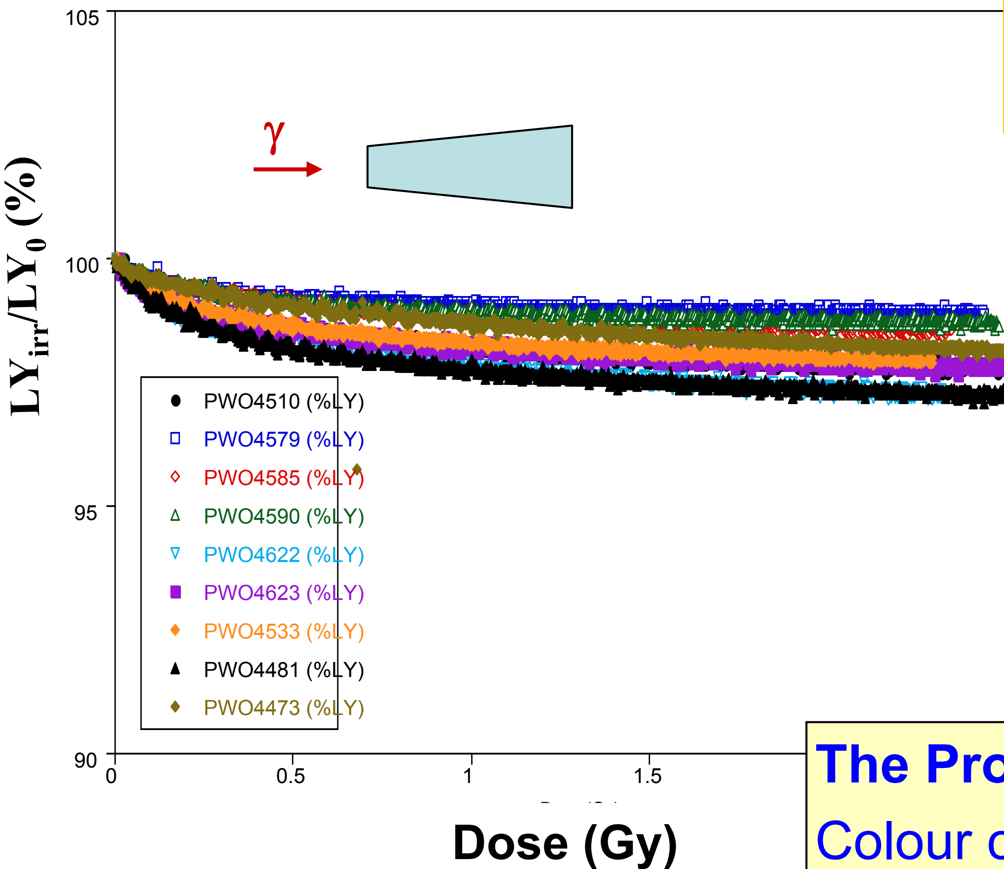
L3 BGO ECAL: calibration



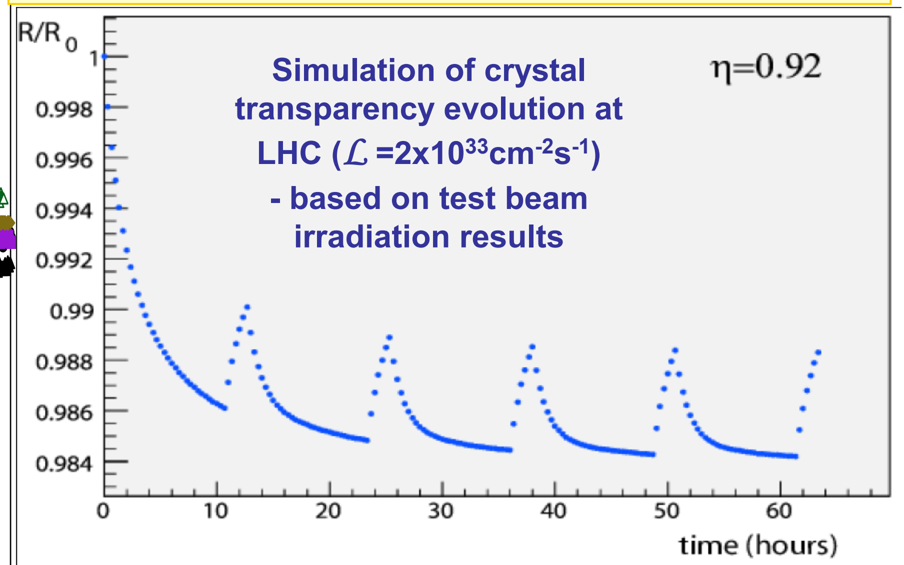


CMS PWO γ induced radiation damage

Front irrad., 1.5Gy, 0.15Gy/h



We know PWO response will change with irradiation!



The Problem:

Colour centres form in PWO under irrad$^{\underline{n}}$

Transparency loss depends on dose rate

Equilibrium is reached after a low dose

Partial recovery occurs in a few hours

CMS ECAL monitoring system

The Solution:

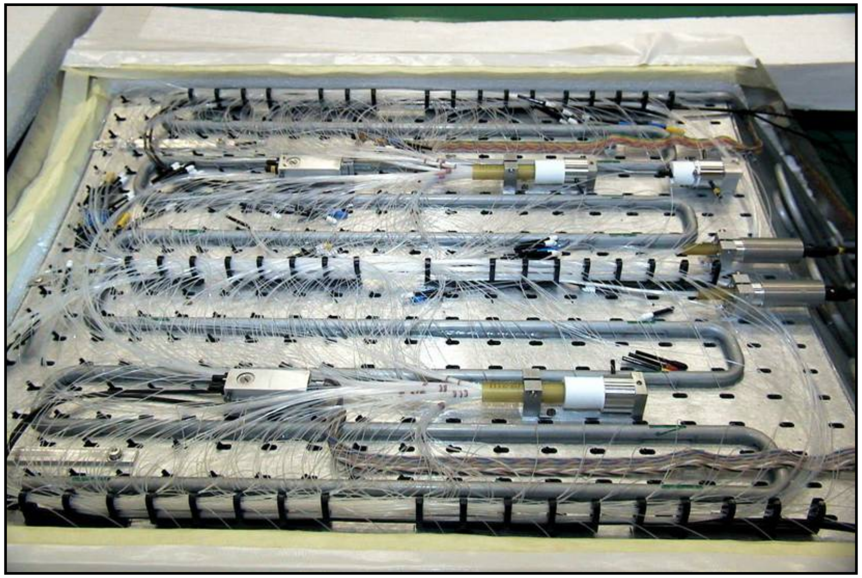
Damage and recovery during LHC cycles tracked with a laser monitoring system

2 wavelengths are used:

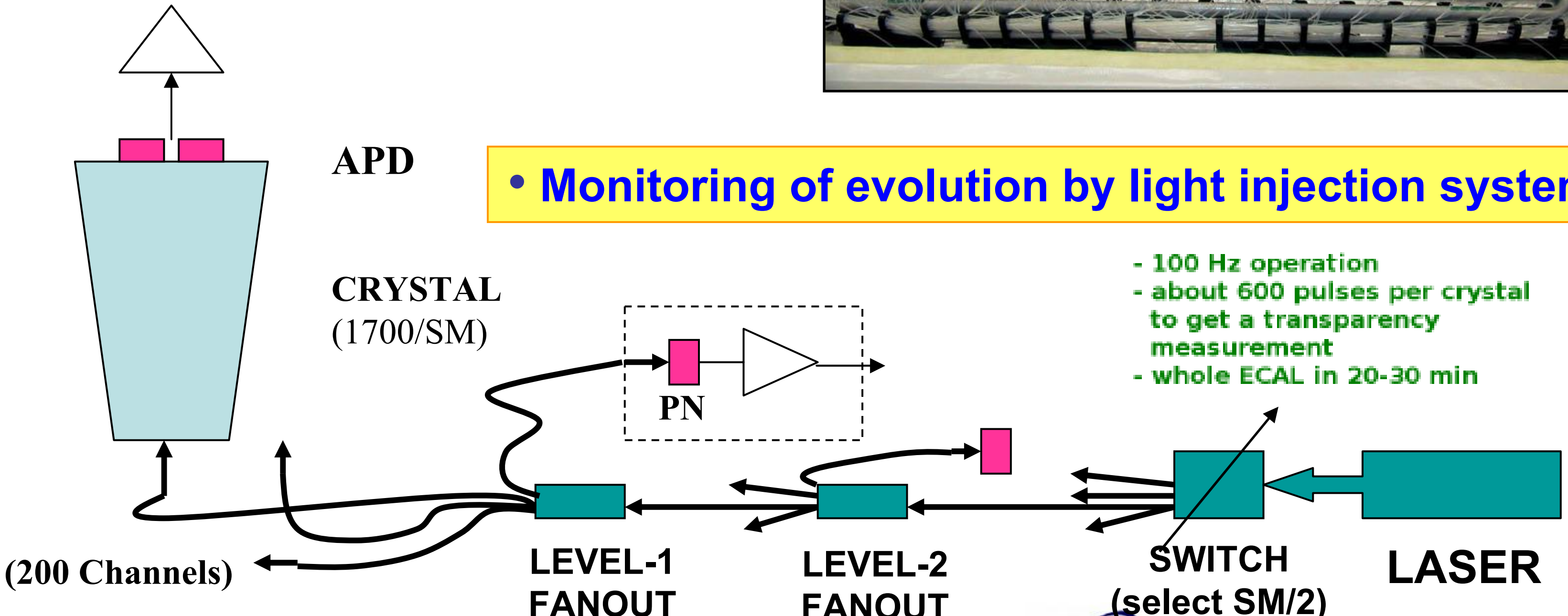
440 nm and 796 nm

Light is injected into each crystal

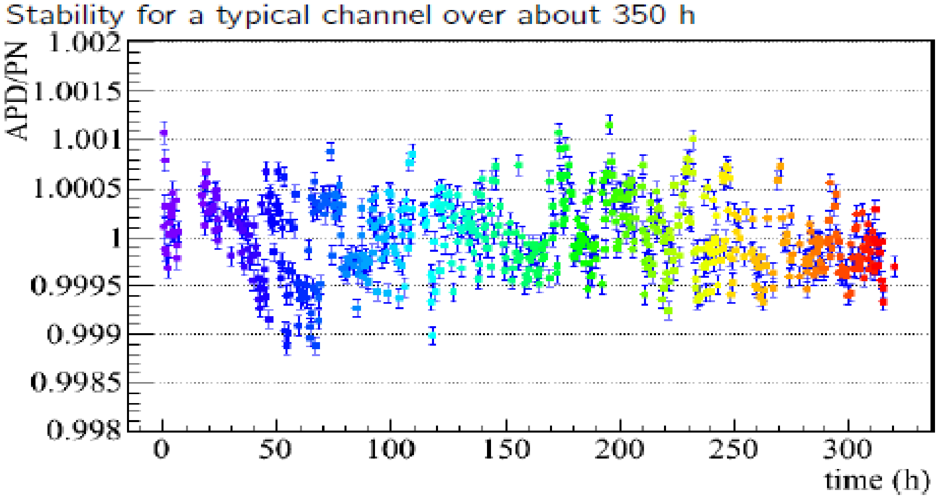
Normalisation given by PN diodes (0.1%)



- **Monitoring of evolution by light injection system**



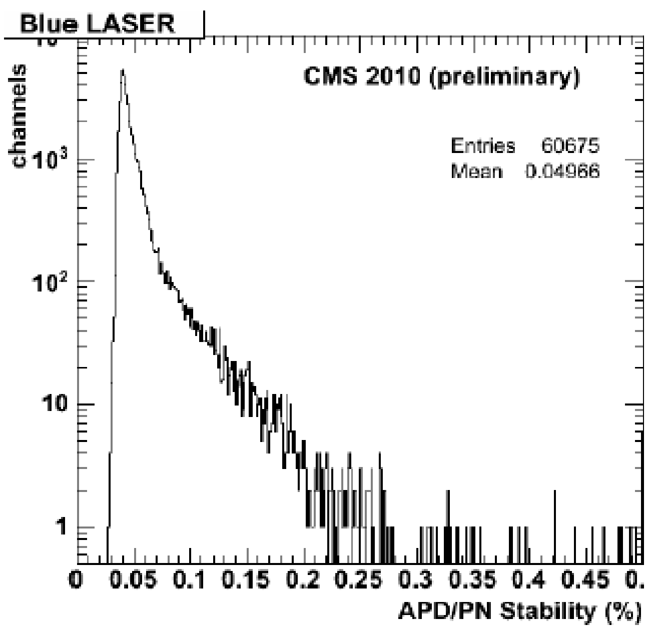
ECAL monitoring system

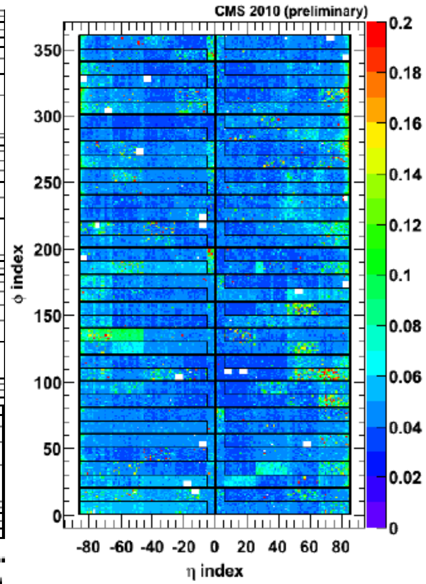


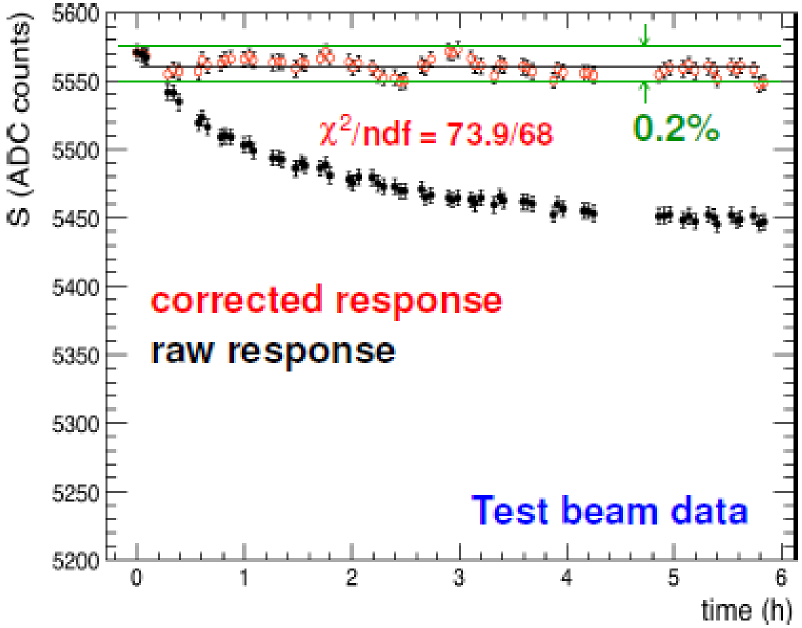
Measure a loss of transparency:
S (particle signal) and R(laser signal)

$$S_{cor} = S\left(\frac{R}{R_0}\right)^{\alpha}$$

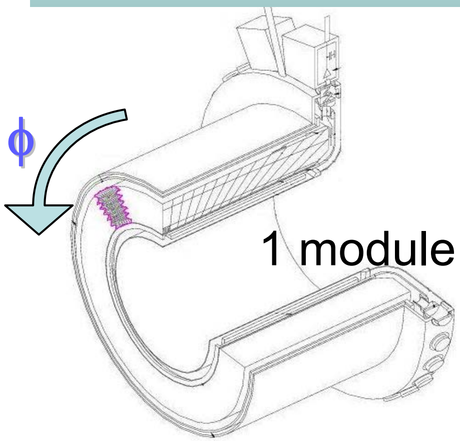
NB: α is ~ the same for all crystals!



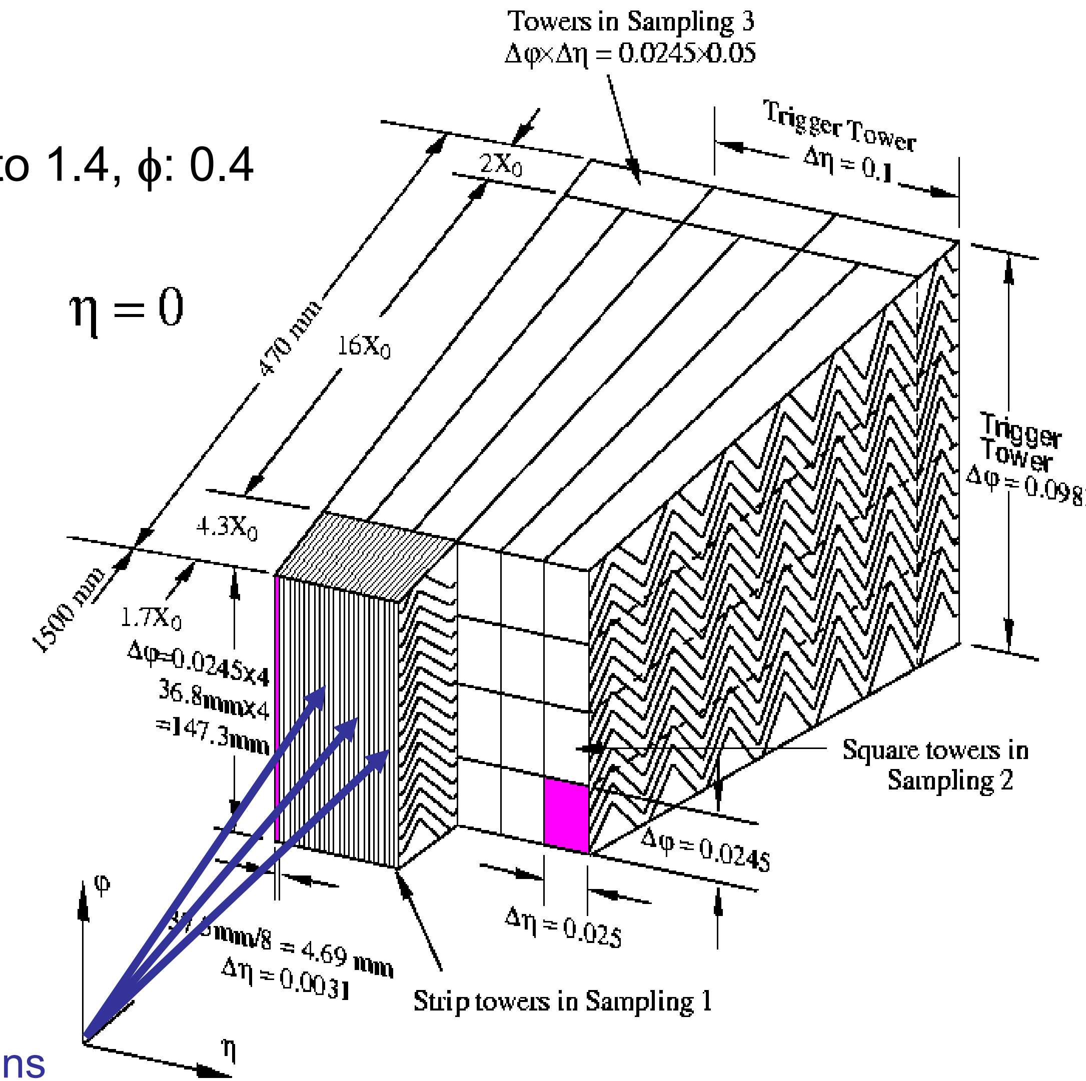




ECAL @ ATLAS



1 module covers η: 0 to 1.4, ϕ: 0.4



- Longitudinal dimension:

$\approx$25 X_0 = 47 cm (CMS 22 cm)

- 3 longitudinal layers

4 X_0 π^0 rejections separation of 2 photons very fine grain in η

16 X_0 for shower core

2 X_0 evaluation of late started showers

- Total channels $\approx$ 170000

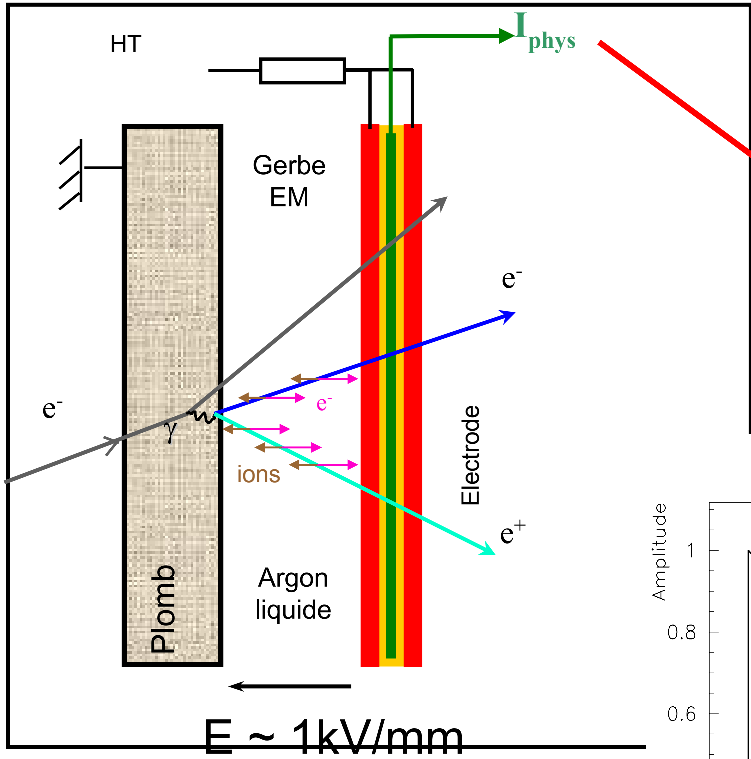
Particles from collisions

ATLAS: the choice of LAr

- High number of electron-ion pair produced by ionization
- No amplification neeeded of signal, low fluctuations
- Liquid → Very uniform response (purification)
- Stability with time
- Main fluctuations are due to sampling fluctuations
- Intrinsically radiation hard
- cheap
- slow time response 400 ns
- boling temperature 87°K
  → criogeny needed
- Temperature sensitivity
  2% signal drop for $\Delta T=1°C$

Properties of Noble Liquids		LAr
Z/A		18/40
Density	g/cm^3	1.39
dE/dx <mip>	MeV/cm	2.11
Critical energy	MeV	41.7
Radiation Length	cm	14.3
Moliere Radius*	cm	7.3
W value	eV	23.3
Drift vel (10kV/cm)	cm/µs	0.5
Dielectric Constant		1.51
Triple Point Temp	K	84

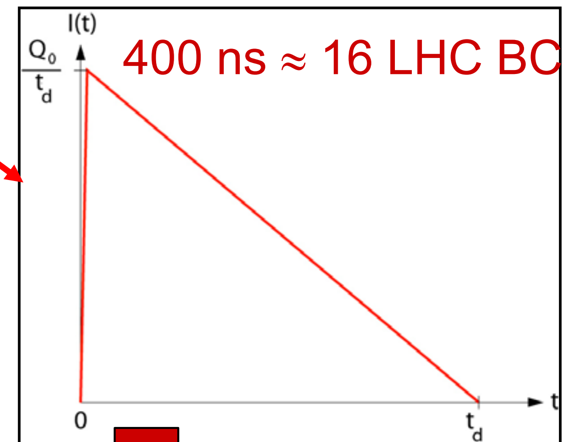
ATLAS EM LAr

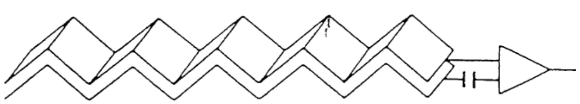


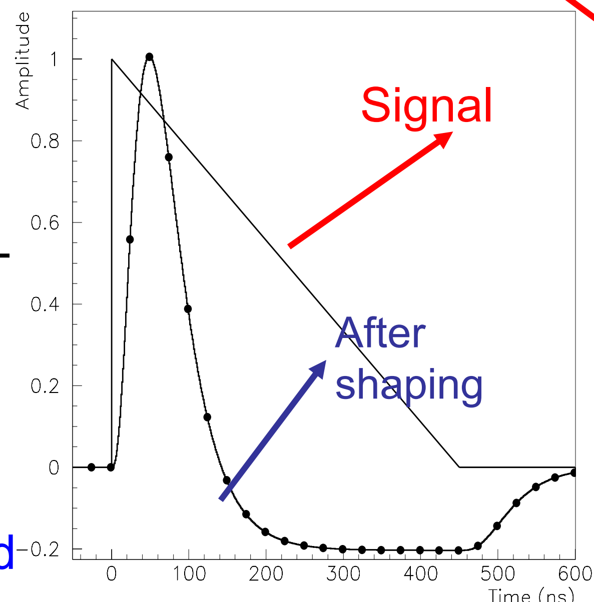
Signal is given from collection of released electrons

Drift velocity depends on electron mobility and applied field. In ATLAS :

Lar gap 2 mm, ΔV = 2kV



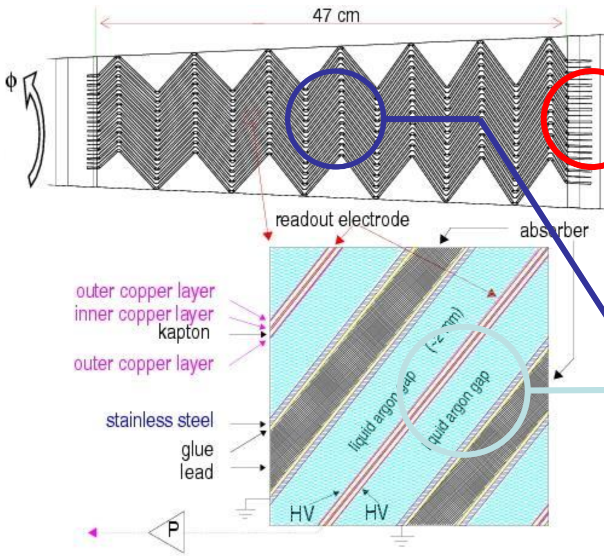


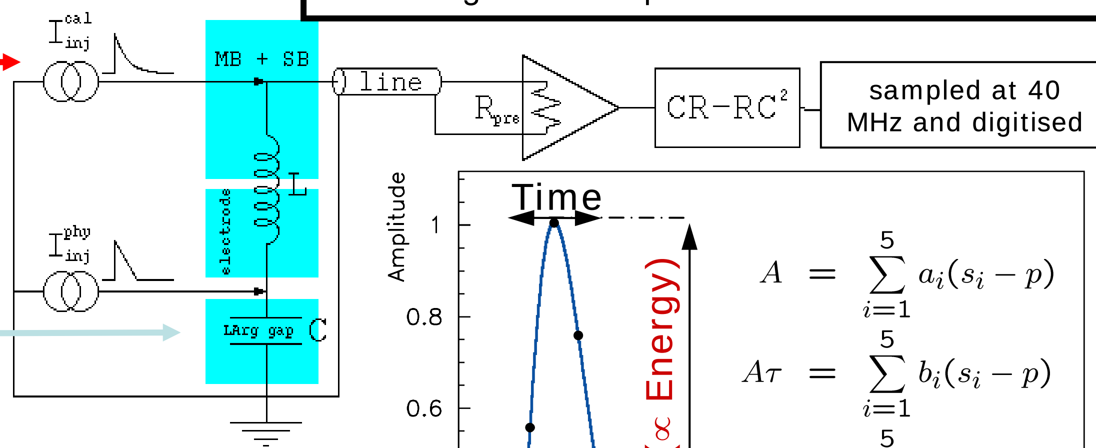


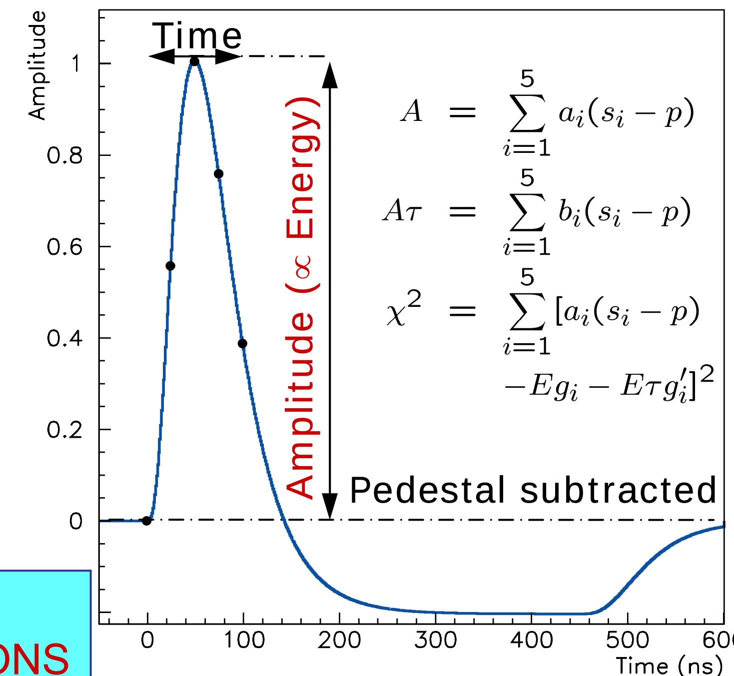
Pulse is shaped and sampled each 25 ns, has 0 time integral → mean value of pileup is cancelled (no baseline shift).

LAr electronics calibration

The ionization signal is sampled every 25 ns by a 12 bits ADC in 3 gains. 5 samples are recorded at at ATLAS.



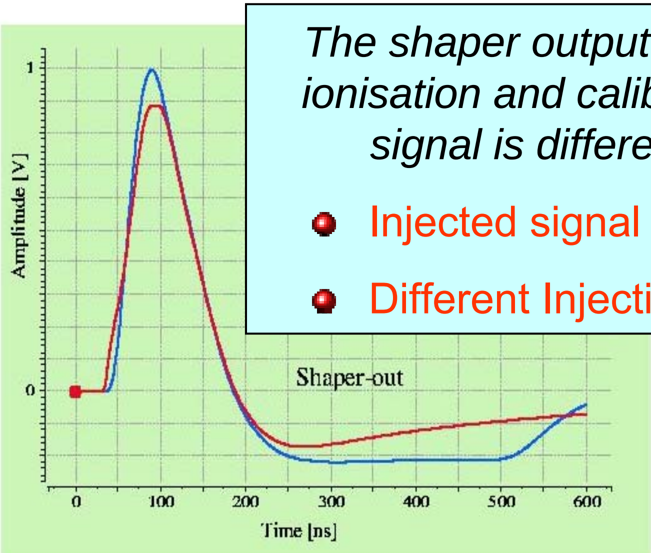




The shaper output of the ionisation and calibration signal is different!

- Injected signal shape
- Different Injection point

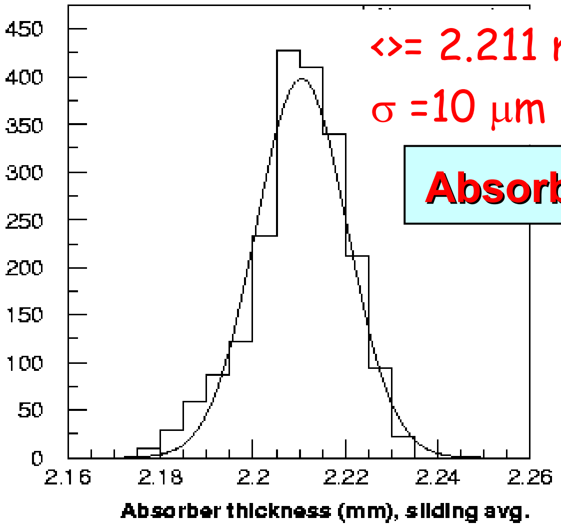
NEED CORRECTIONS



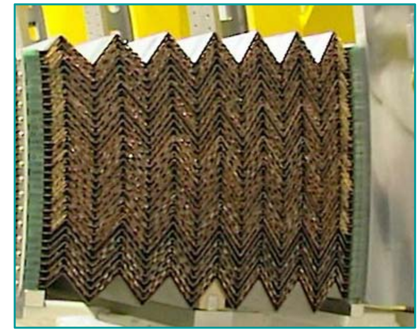
The equalization of the electronic readout. Requires to know the shaping function of each cell at few percent level

→ equalization with an electronic control signal

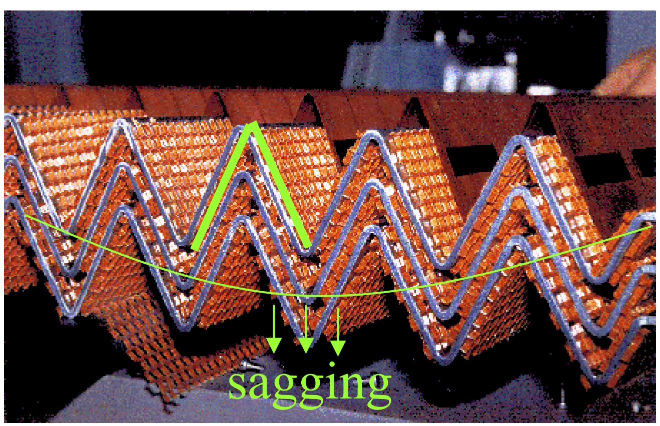
The challenge of LAr



Mechanical non uniformities: modifies electric field and detector response. Take care during construction, try to reproduce effects and apply corrections.



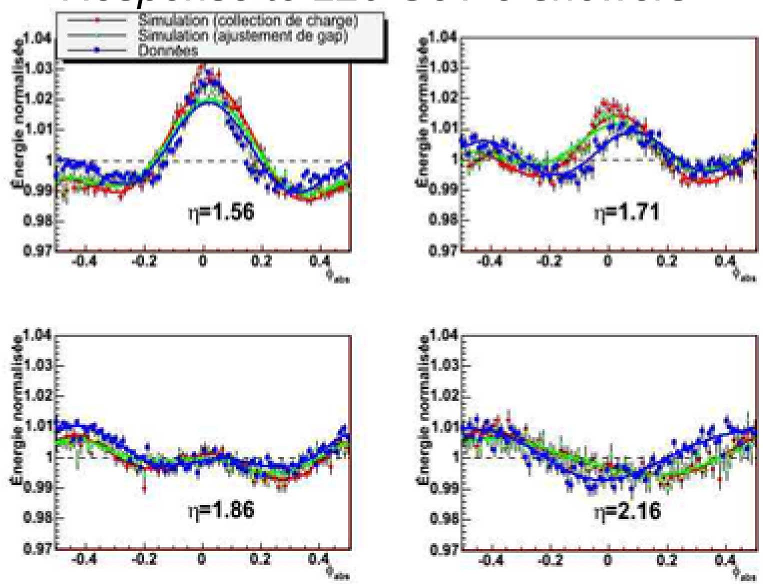
1% Pb variation → 0.6% drop in response
Measured dispersion σ = 9 μm (calo)
translates to < 2 ‰ effect on constant term



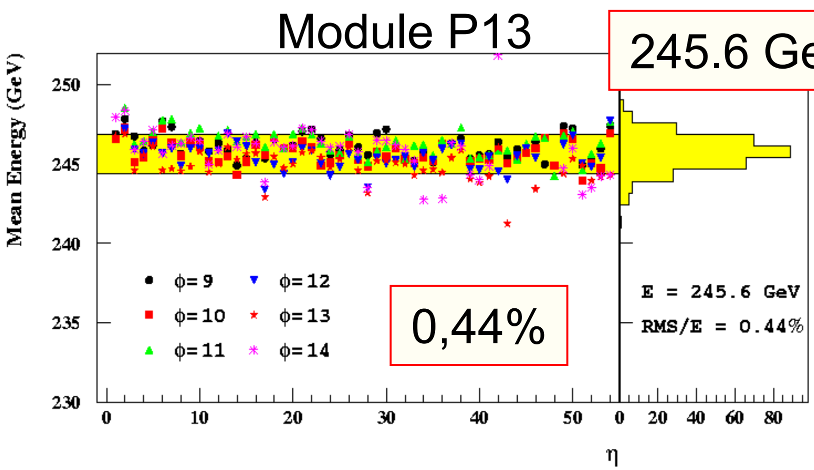
ϕ-modulations in the EMEC →

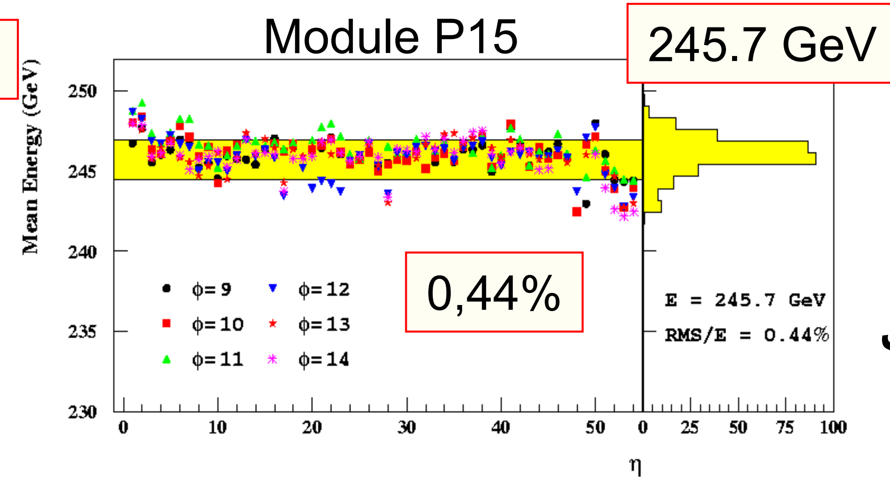
Calorimeter response is affected ~ 3 %

Response to 120 GeV e-showers



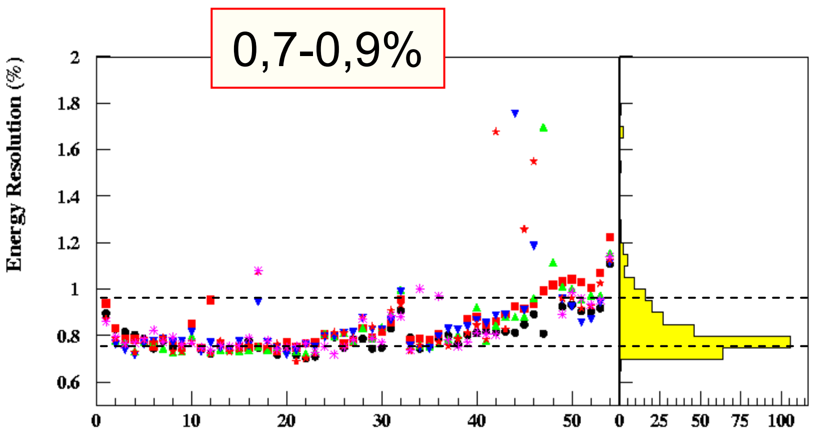
ATLAS EM uniformity

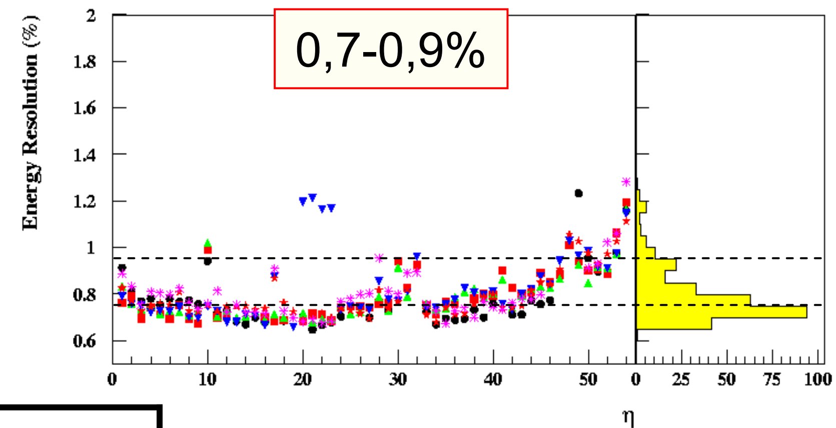




Uniformity

Scan modules with monochromatic electrons





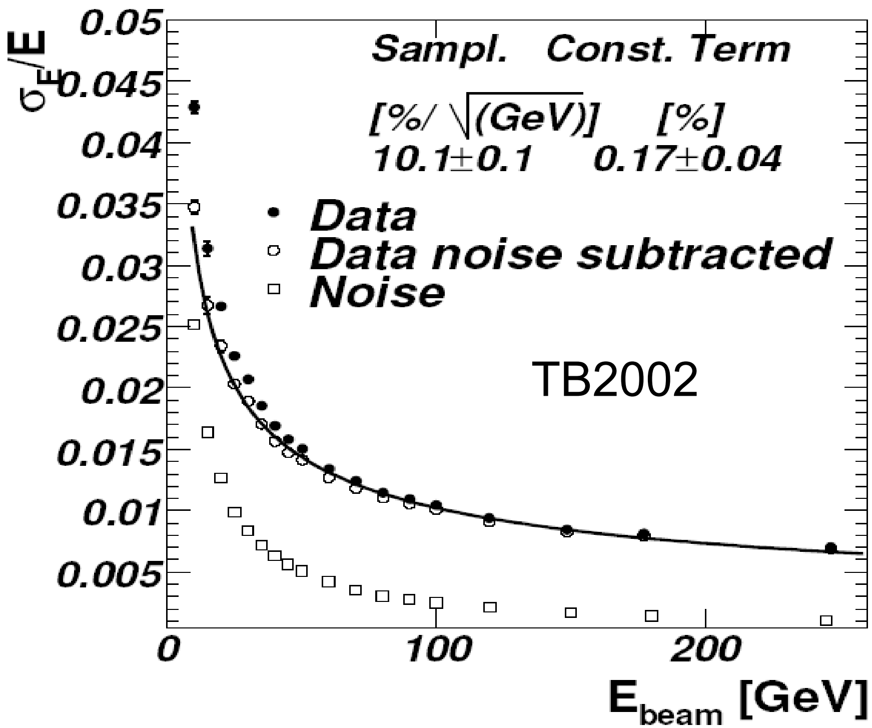
Resolution

Module	**P13**	**P15**
Global constant term	**0.62%**	**0.56%**

P13/P15 ~ 0.05%

Ratio of absolute response

ATLAS EM: the performance



LOCAL RESOLUTION

•The constant term in the resolution is dominated by:

- the equalization of the electronic readout.
- the non uniformity in the electric field and in the sampling fraction introduced by the accordion structure.

The calibration

From single channel electrical signal to $E_{e,\gamma}$

(The case of CMS)

TBD

E_i

x G

$$E_{e,\gamma} = G \times \mathcal{F} \times \sum_{i}^{\text{Cluster}} c_i \times A_i,$$

absolute energy scale

amplitudes

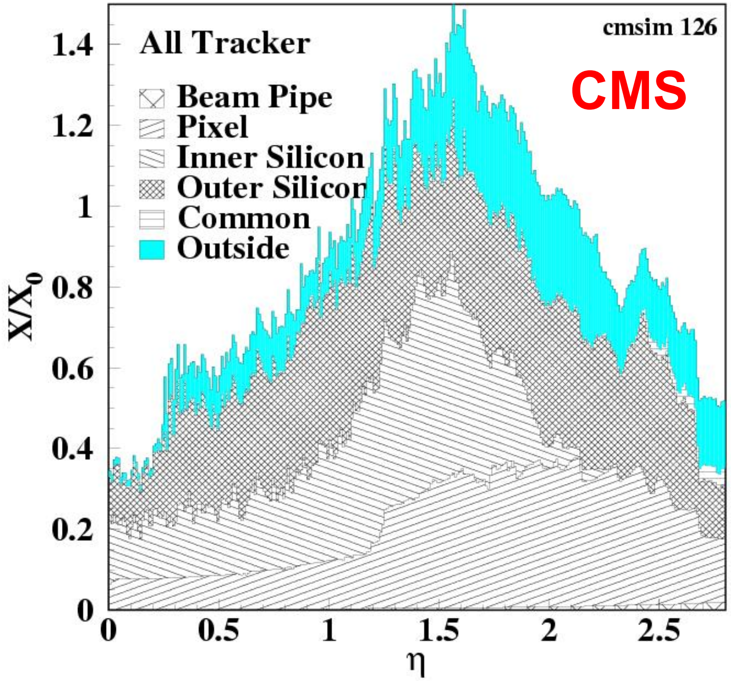
inter-calibration constants

algorithmic corrections

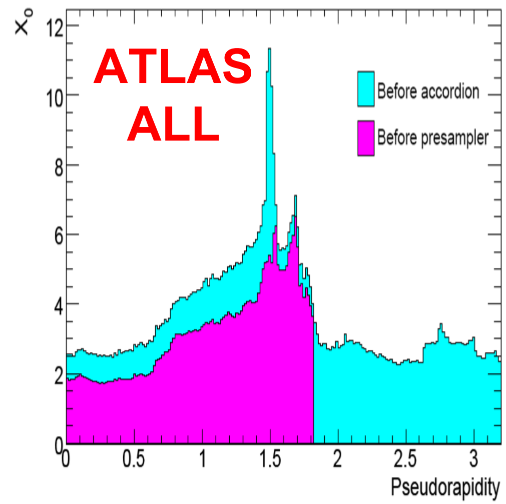
(particle type, momentum, position & clustering algo)

Account for energy losses due to containment variations

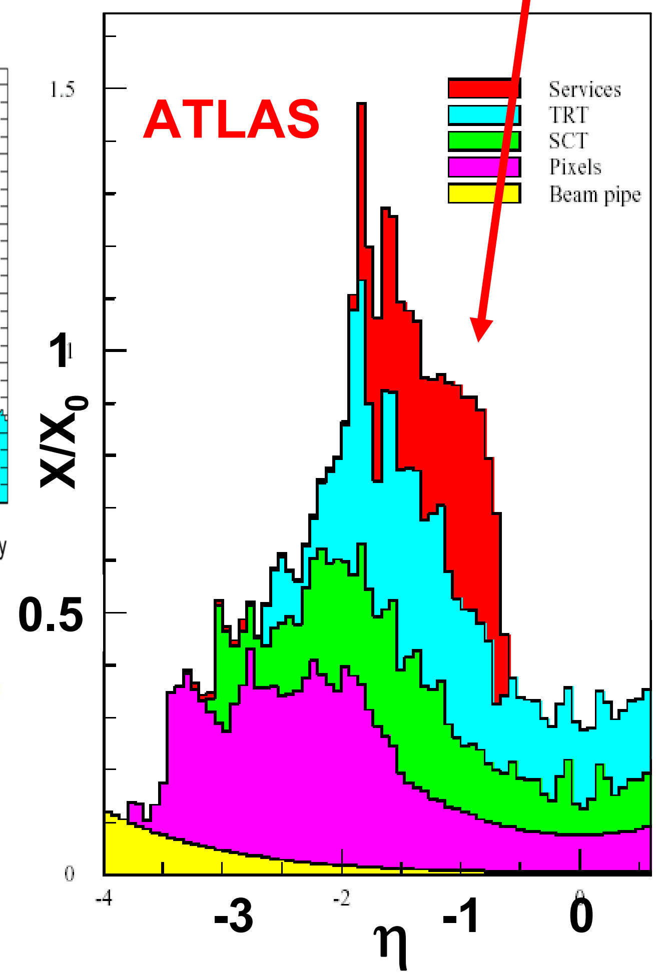
The tough point: material in Trackers

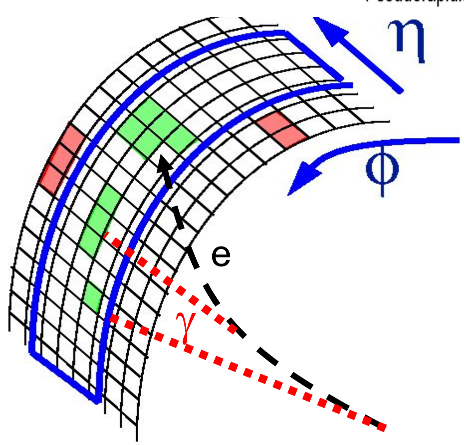


Tough for both experiments…



+ THE SOLENOID





Tracker material :

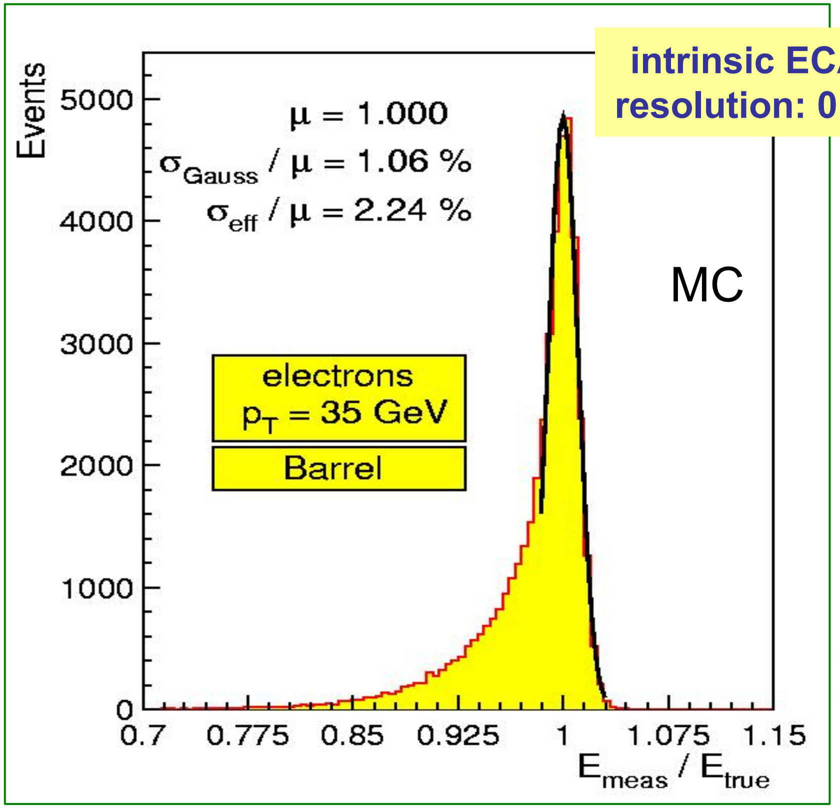
- electrons loose energy via bremsstrahlung
- photons convert

4T (2T) solenoidal B field :

Electrons bend $\Rightarrow$ radiated energy spread in φ

Calibration: effect of material

EFFECT IN CMS

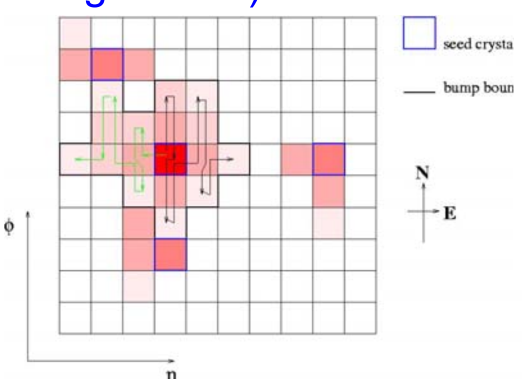


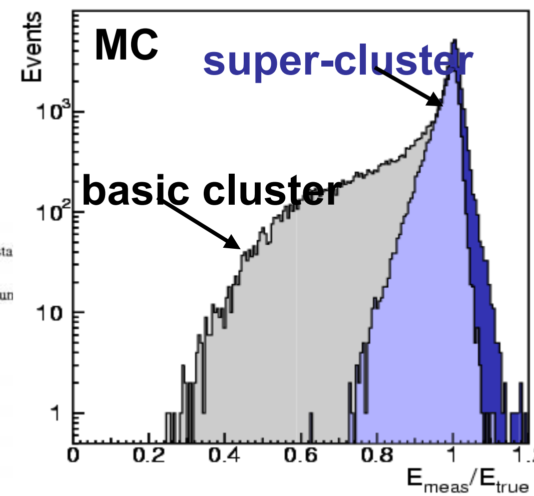
intrinsic ECAL resolution: 0.7%

- 50% e $\rightarrow$ not negligible brem
- definition of algorithm and selection efficiency for e with "no brem"
- e track reconstruction (dedicated)
- e reconstruction quality f(η,ϕ)

The size of the tail is eta depending !

(SuperCluster from dynamic clustering algorithms)



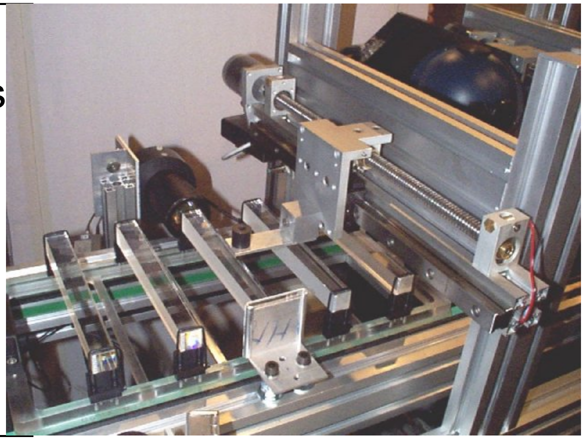


Calibration before LHC Start Up

<u>A very intense 10 years long pre-calibration campaign.</u> Several orders of magnitude in energy: from 1 MeV of Co^{60} source to 120 GeV electron beam.

Laboratory measurements during crystal qualification phase.

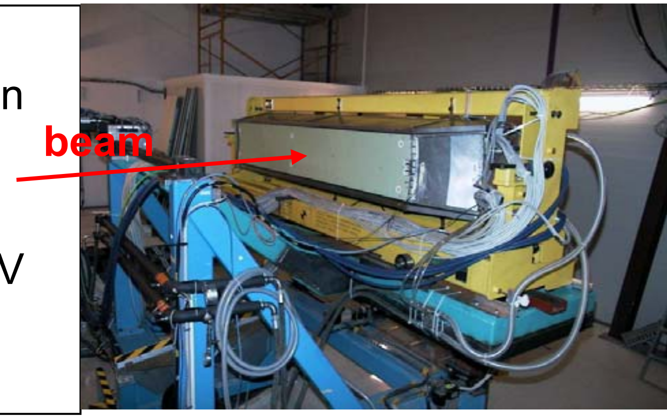
(2000-2006)



Test Beam: Cern electron beams.

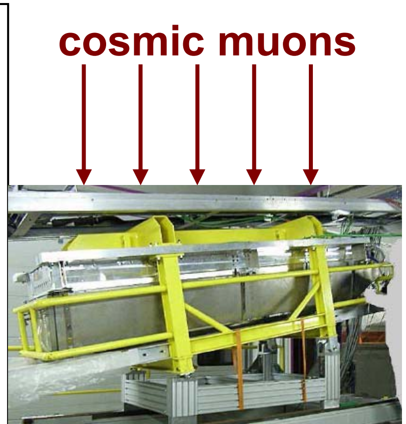
From 15 GeV to 250 GeV.

(2004-2007)

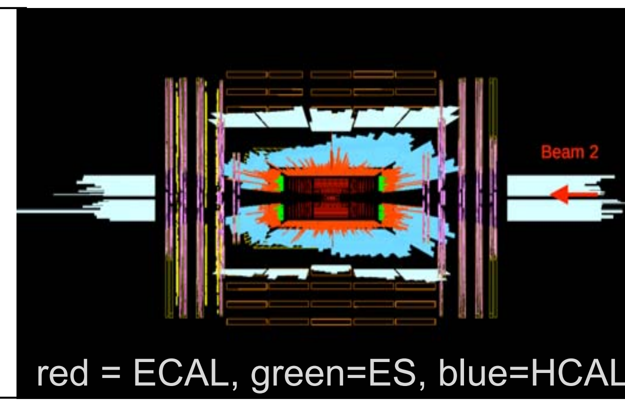


Channel intercalibration with cosmic muons (only Barrel SMs)

(2006-2007)



Beam Splash: In September 2008 and November 2009, beam was circulated in LHC, stopped in collimators 150m away from CMS

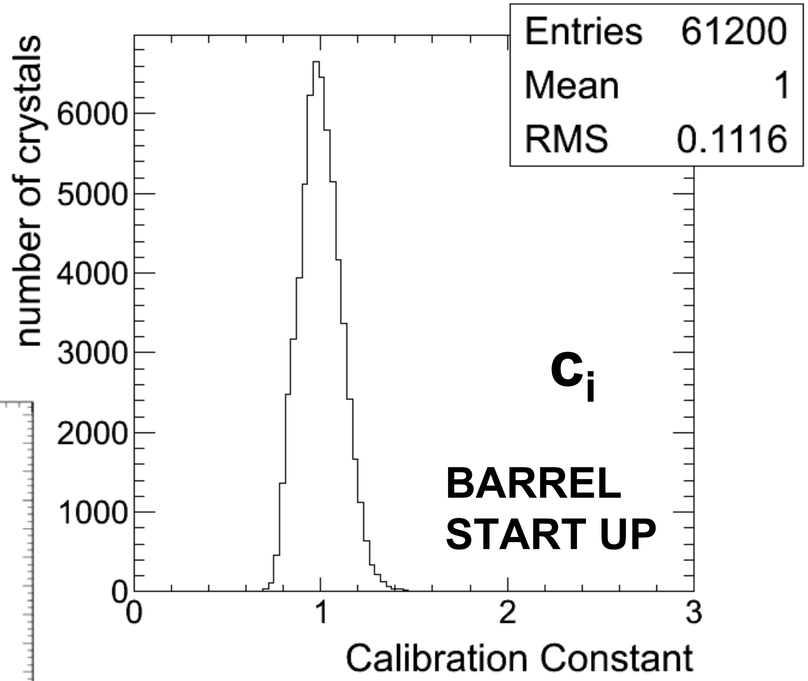


Calibration @ Start Up

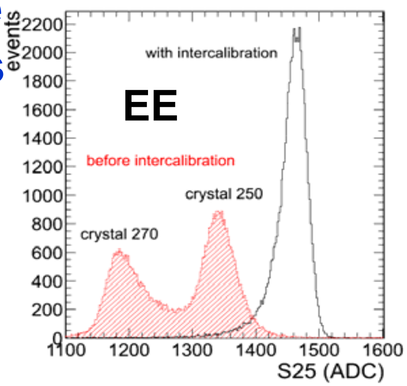
Problem: delay in crystals delivery, can not expose all ECAL on Test Beam

- Test Beam at Cern (50 GeV)
  - 10 Supermodules on electron beam (intercalibration accuracy ~0.3%)
- Cosmics Calibration (20 MeV)
  - 36 SMs (~1.4-2.2%)
- Light Yield Measurements (LAB Co^{60} 1 MeV)
  - 36 SMs (~4.5-6.0%)

Inhomogeneity at the construction:
11.2% due to xl different Light Yield
pre-calibration precision of **0.3%-2.2%**



Combination strategy:
- **Select best calibration available**
- **Combine when comparable precision from two sources**

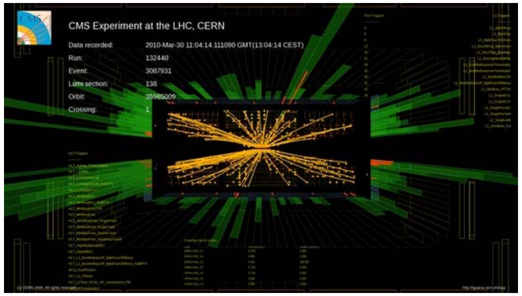


Energy scale set at Test Beam with electrons of known energy

Calibration in Situ (use physics)

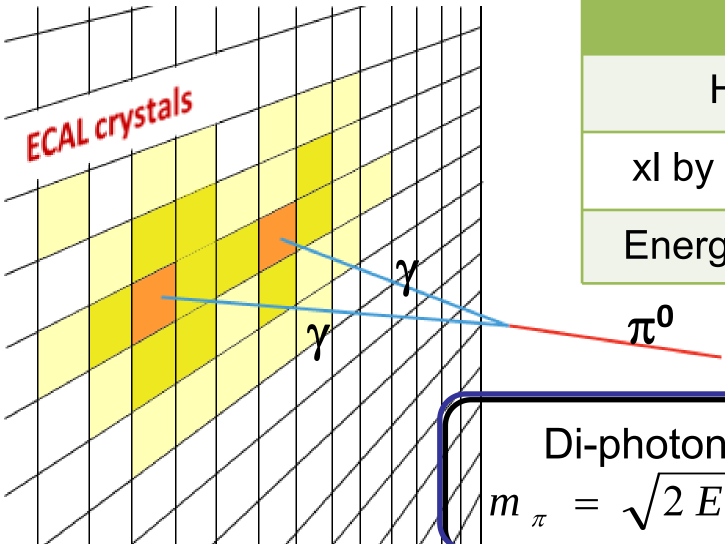
Intercalibration precision goal is 0.5%. Main contribution to the constant term of energy resolution (all the others minimized!).

- Several methods to calibrate in-situ:
  - φ-symmetry calibration: invariance around the beam axis of energy flow in minimum bias events. Intercalibrate crystals at the same pseudorapidity, other methods are needed to intercalibrate regions at different pseudorapidity.



  - π^0 and η calibration: mass constraint on photon energy, use unconverted γ's reconstructed in 3x3 matrices of crystals.
  - High energy electron from W and Z decays (E/p with single electrons and invariant mass with double electrons). High luminosity required. Helpful at the startup only for energy scale. Testing also J/ψ.

π° calibration



Pros
High Statistics
xl by xl inter-calibration
Energy scale calibration

Cons
Reco of low energy γ
High energy γ overlap
Sizeable background

Di-photon invariant mass

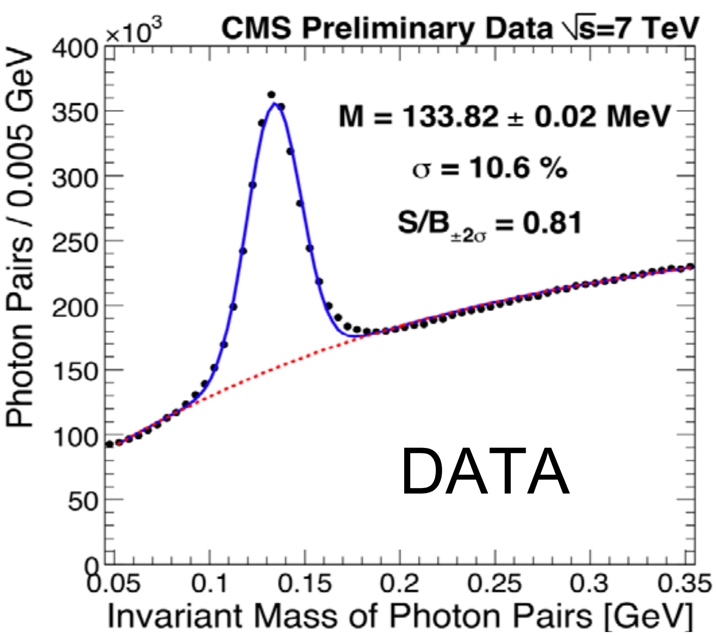
$$m_\pi = \sqrt{2 E_1 E_2 (1 - \cos\vartheta)}$$

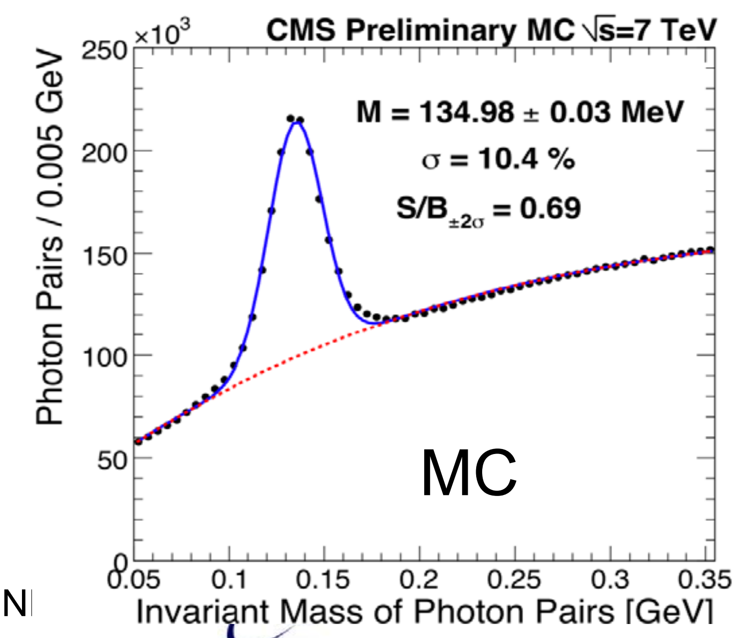
Calibrated photon energy

⇓

π^0 mass peak at right position

Minimum peak spread



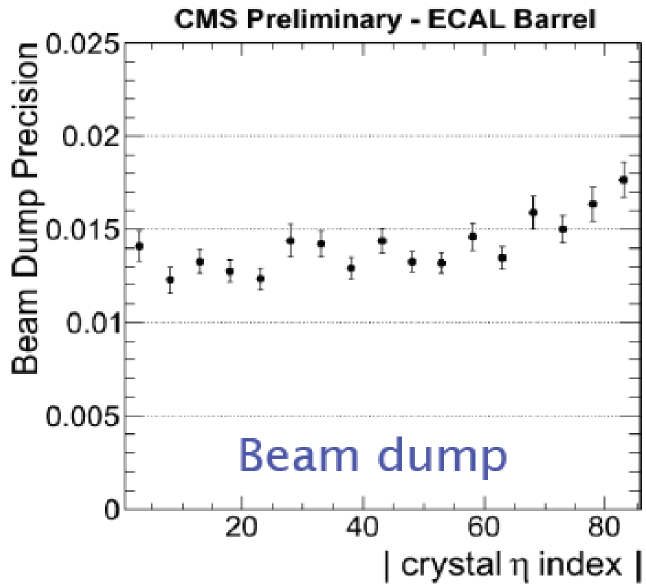


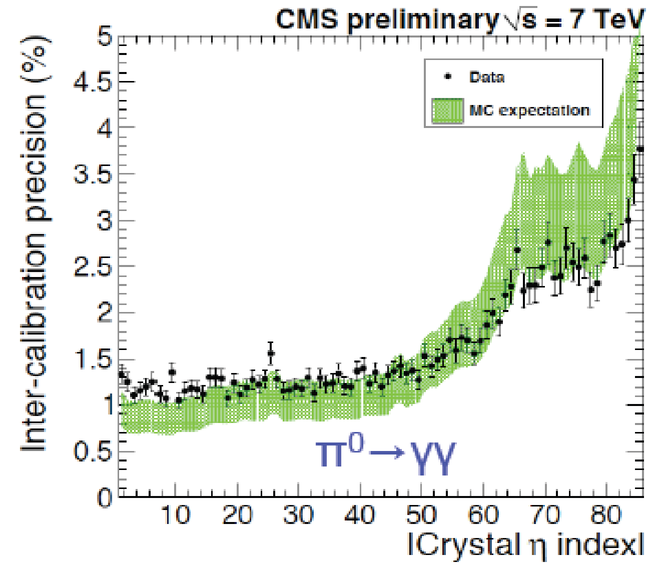
Combine available methods

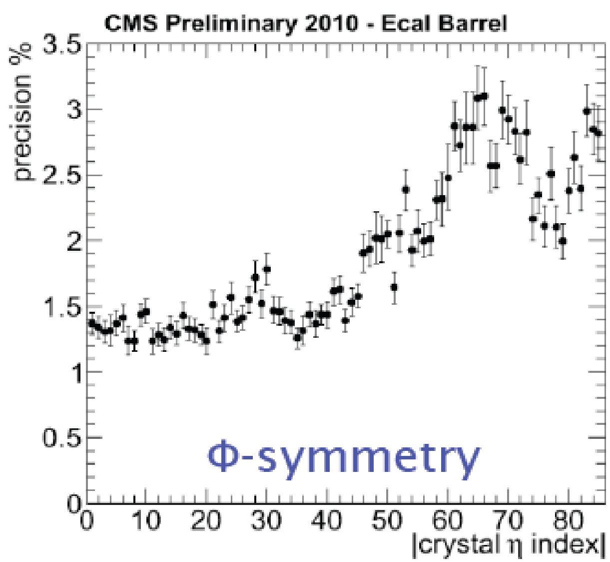
By combining methods the inter calibration precision reach 0.5% in the region with less material in front.

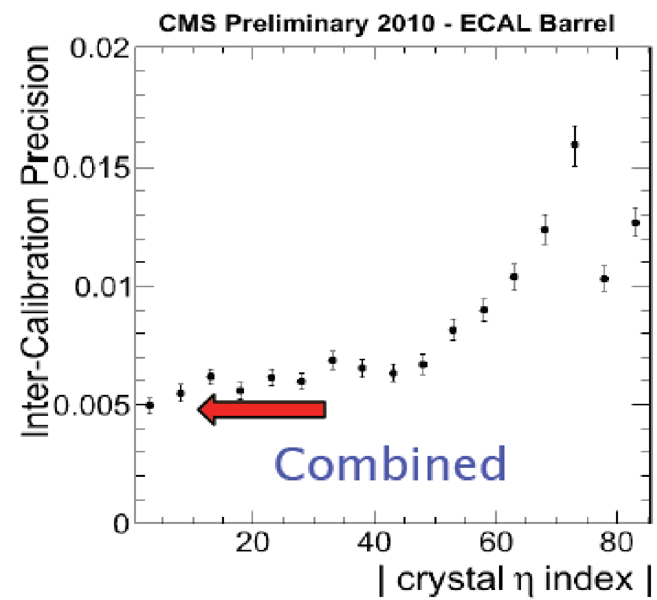
Of course this precision will improve with time (collected statistics).

But remember, monitoring the variation of the crystal's response is essential!





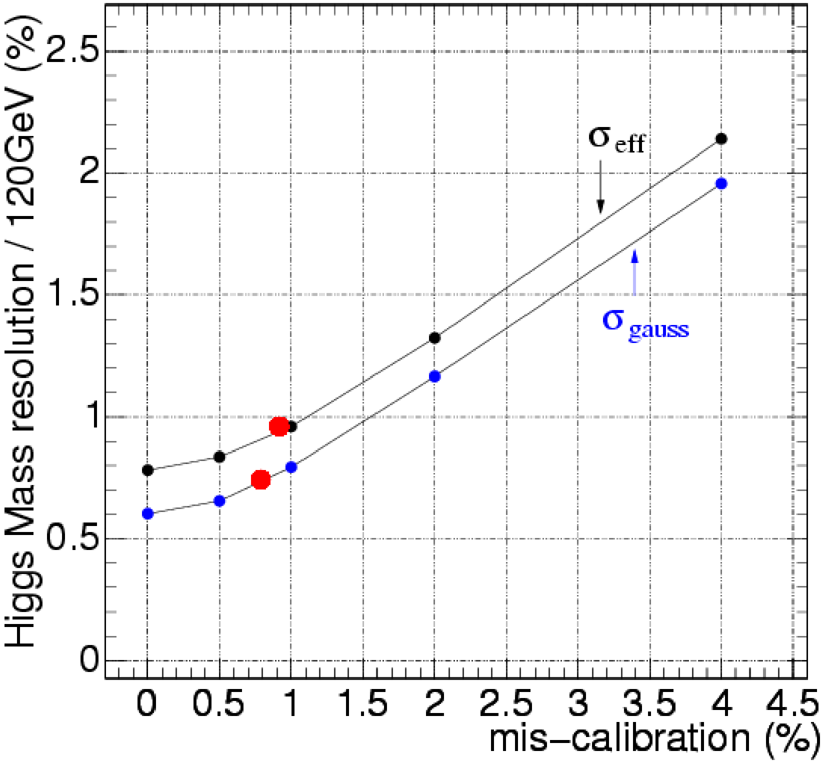




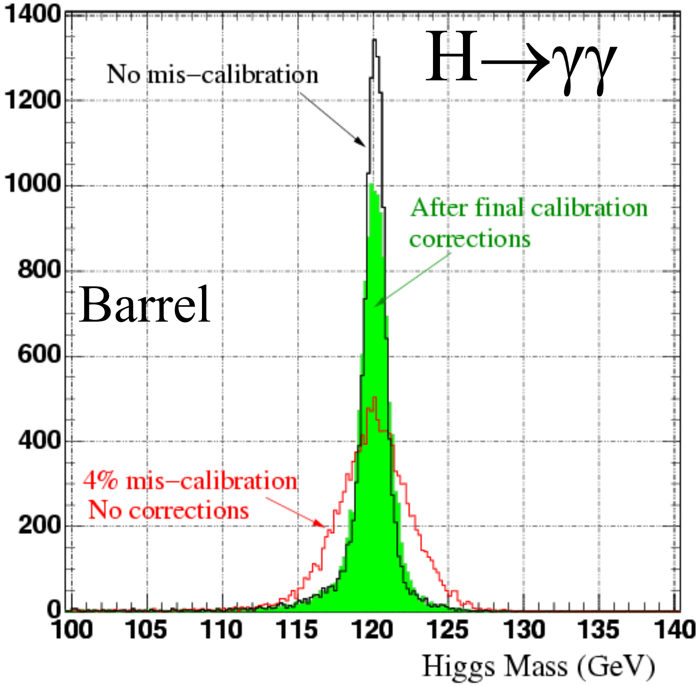
And the Higgs?

If light, it will take a while…

Relative Higgs mass resolution versus mis-calibration.

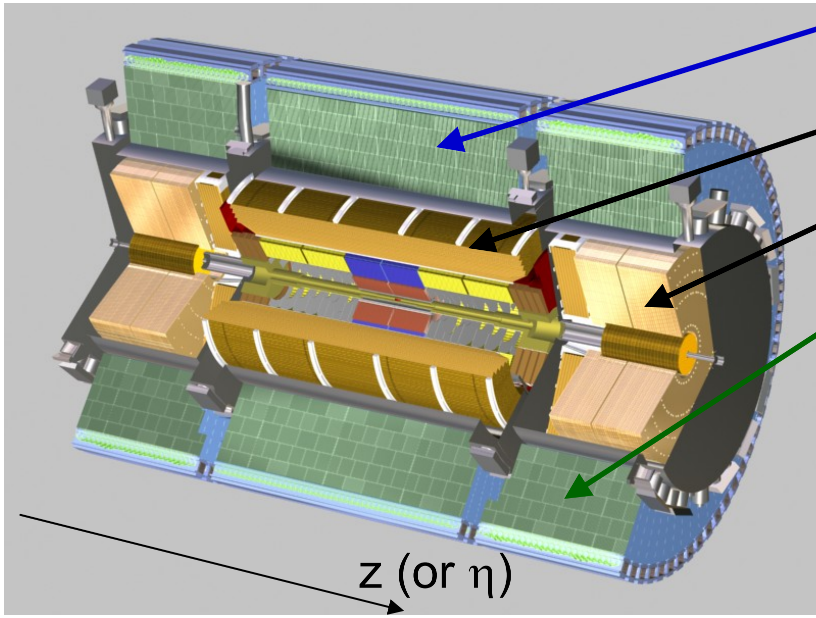


Higgs Boson Mass Resolution



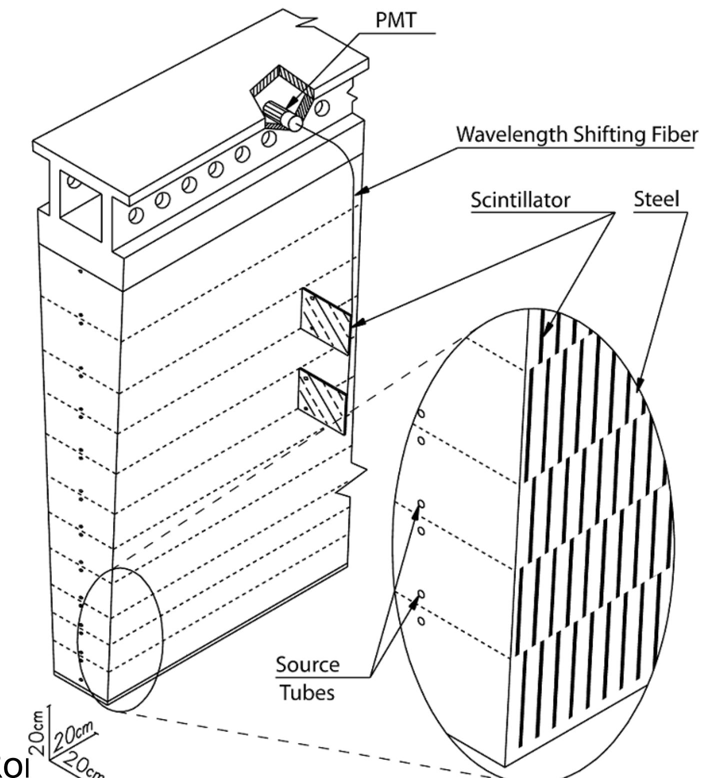
On paper resolution on $\gamma\ \gamma$ invariant mass:
- CMS 0.7 GeV
- ATLAS 1.2 GeV

HCAL @ ATLAS

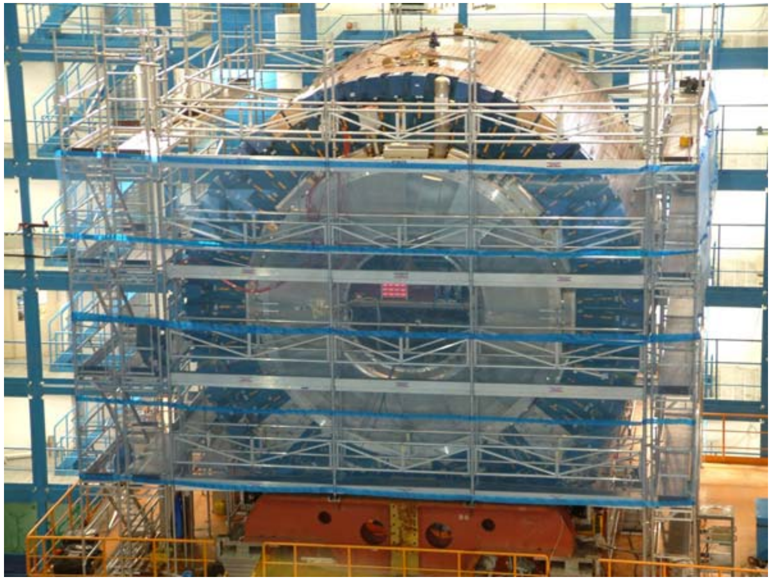


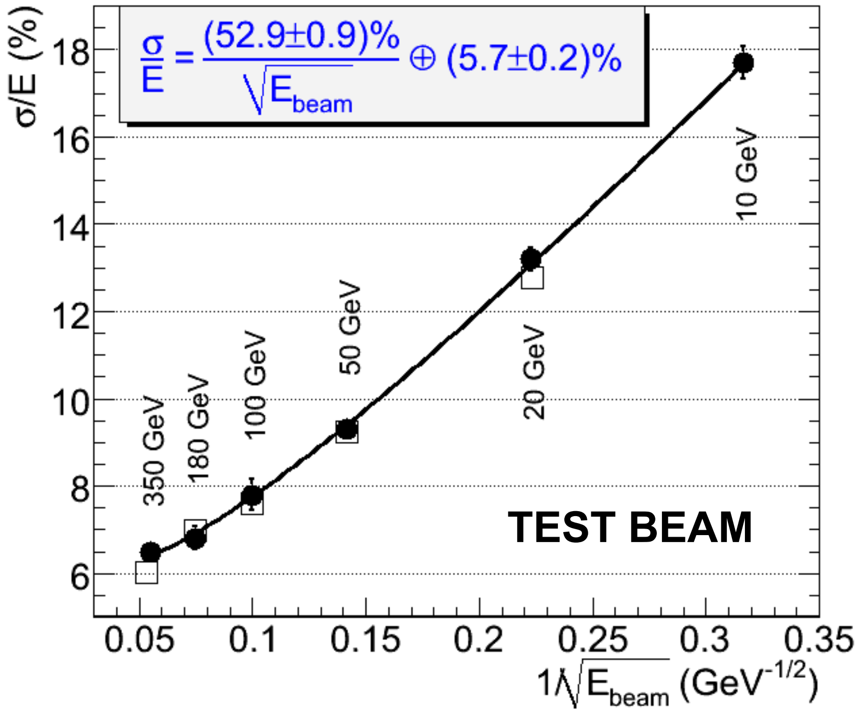
- Tiles perpendicular to beam axis
- Wavelength shifting fibers carry light to PMTs
- Covers $|\eta|<1.7$

Hadronic Calorimeter:
Iron/Plastic scintillator sampling calorimeter

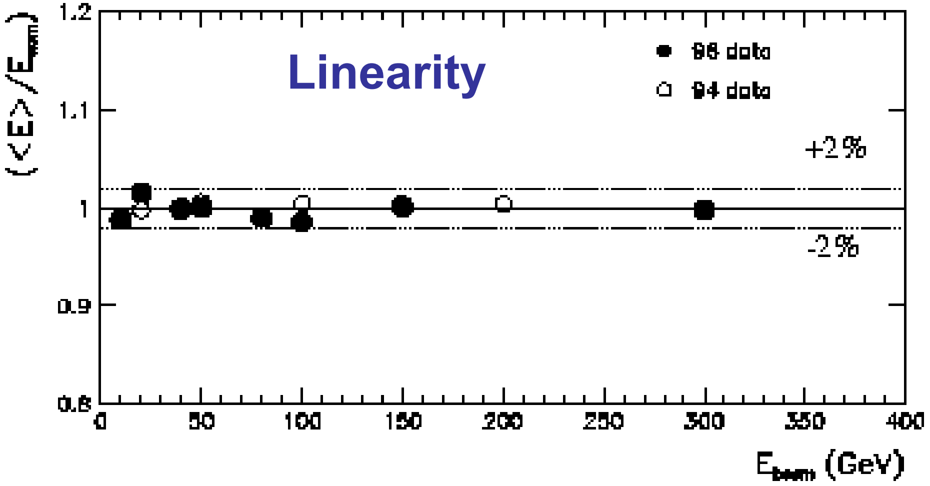


ATLAS HCAL



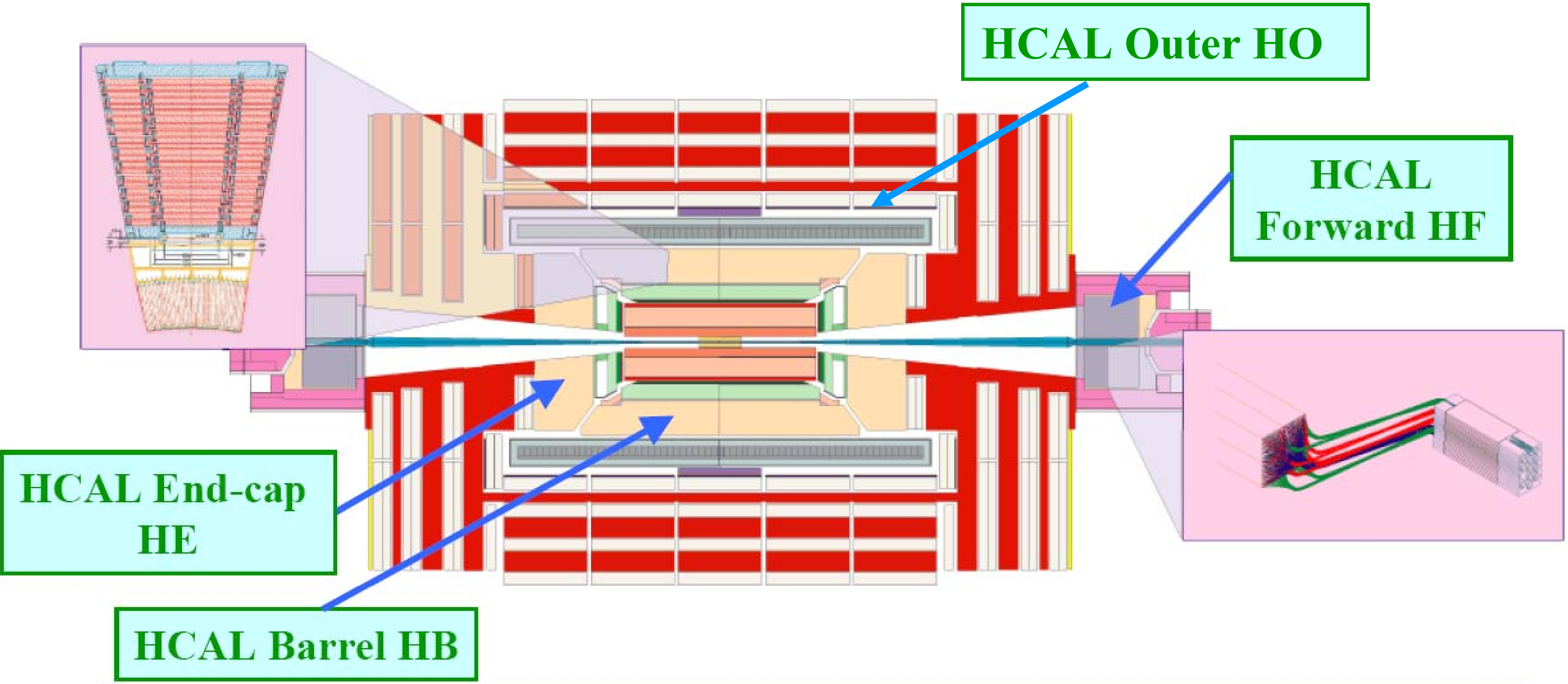


$\frac{\sigma}{E} = \frac{(52.9\pm0.9)\%}{\sqrt{E_{beam}}} \oplus (5.7\pm0.2)\%$
σ/E (%)
10 GeV
20 GeV
50 GeV
100 GeV
180 GeV
350 GeV
TEST BEAM
$1/\sqrt{E_{beam}}$ $(GeV^{-1/2})$



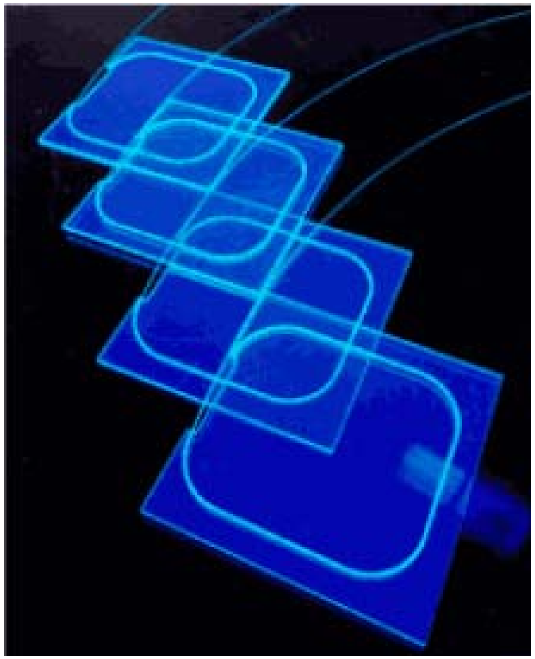
Linearity
96 data
94 data
+2%
-2%
$(<E>/E_{beam})$
E_{beam} (GeV)

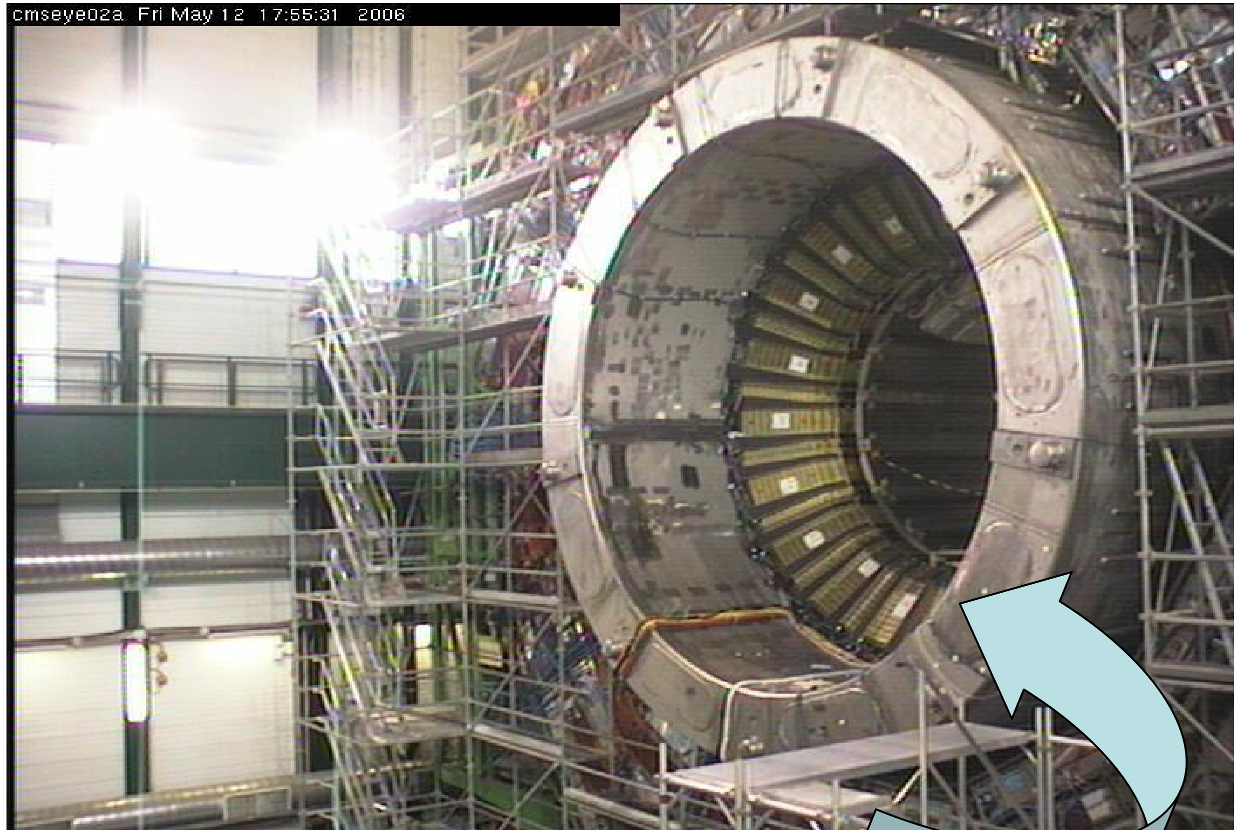
HCAL @ CMS



- Hadronic Barrel and End-cap calorimeters are sampling calorimeters with 50 mm thick **brass** absorber plates interleaved with 4 mm thick scintillator sheets.
- Hadronic Forward calorimeters are sampling calorimeters with steel absorbers and quartz fibers for read-out oriented ~parallel to the beam axis.

CMS HCAL

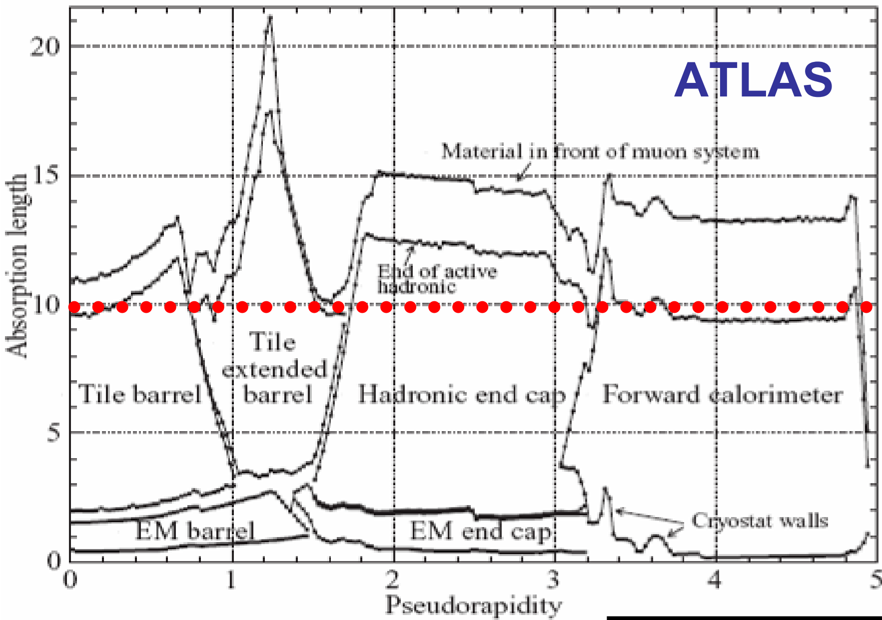


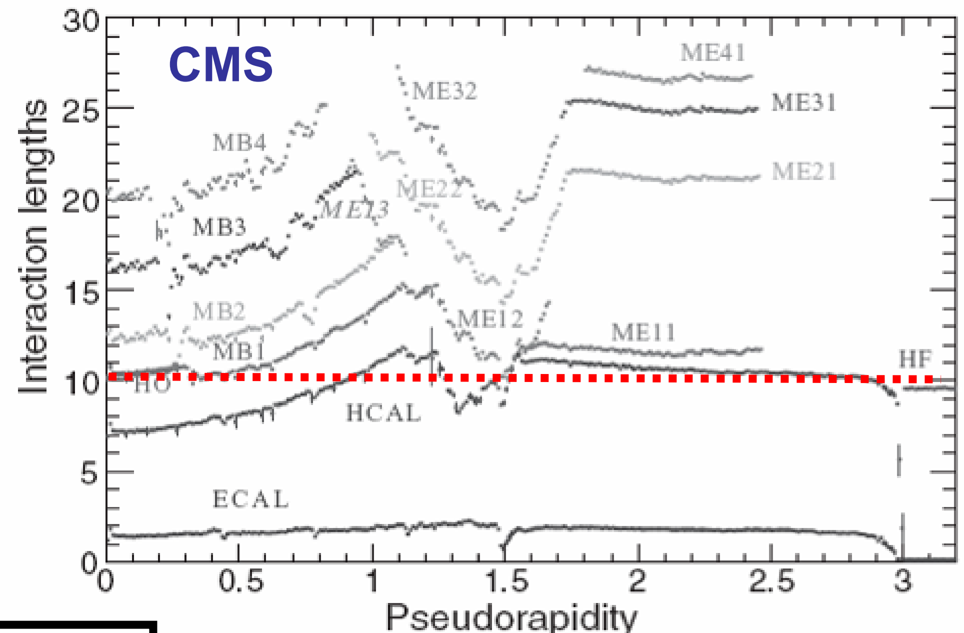


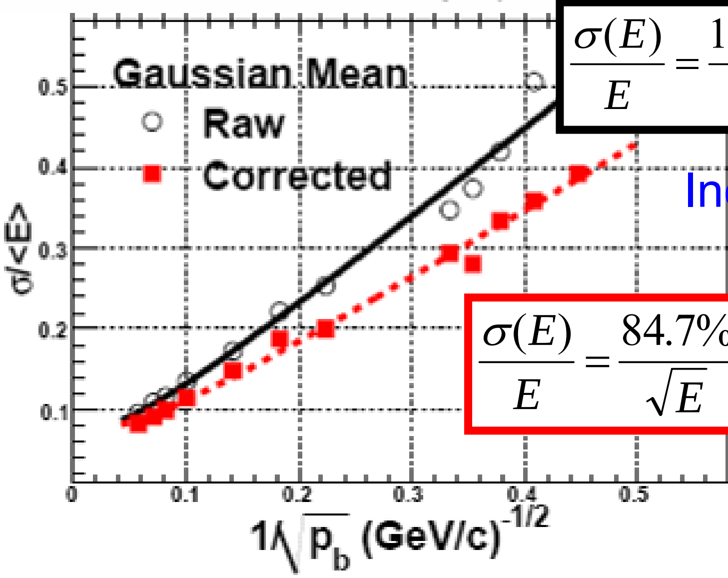
~ 5% of a 300 GeV π energy is leaked outside the HB (inside coil)

HB inside the coil not enough thick for shower containment: scintillator layers just after the coil (HO) improves π resolution by ~10% at 300 GeV & linearity

CMS HCAL



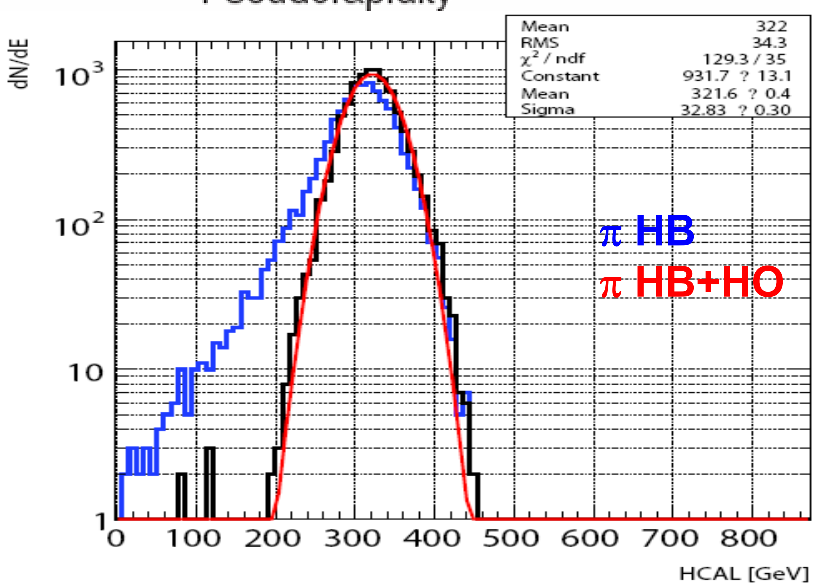




$$\frac{\sigma(E)}{E} = \frac{110.7\%}{\sqrt{E}} \oplus 7.3\%$$

Includes 1st λ of PWO

$$\frac{\sigma(E)}{E} = \frac{84.7\%}{\sqrt{E}} \oplus 7.4\%$$



HCAL: compare parameters

	ATLAS	CMS
Technology		
Barrel / Ext. Barrel	14 mm iron / 3 mm scint	50 mm brass / 4 mm scint
End-caps	25 mm (front) - 50 mm (back) copper / 8.5 mm LAr	80 mm brass / 4 mm scint.
Forward	Copper (front) - Tungsten (back) 0.25 - 0.50 mm LAr	4.4 mm steel / 0.6 mm quartz
# Channels		
Barrel / Ext. Barrel	9852	2592
End-caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta \times \Delta\phi$)		
Barrel / Ext. Barrel	0.1 x 0.1 to 0.2 x 0.1	0.087 x 0.087
End-caps	0.1 x 0.1 to 0.2 x 0.2	0.087 x 0.087 to 0.35 x 0.028
Forward	0.2 x 0.2	0.175 x 0.175
# Longitudinal Samplings		
Barrel / Ext. Barrel	Three	One
End-caps	Four	Two
Forward	Three	Two
Absorption lengths		
Barrel / Ext. Barrel	9.7 - 13.0	5.8 - 10.3 10 - 14 (with Coil / HO)
End-caps	9.7 - 12.5	9.0 - 10.0
Forward	9.5 - 10.5	9.8

HCAL

- The choices made for the hadronic central section by ATLAS and CMS are similar: sampling calorimeters with scintillator as active material.
- In both cases the dominant factor on resolution and linearity is the $e/h \neq 1$
- ATLAS & CMS: $e/h_{had} \approx 1.4$
- ATLAS higher segmentation and containment gives better total resolution

Missing E_T

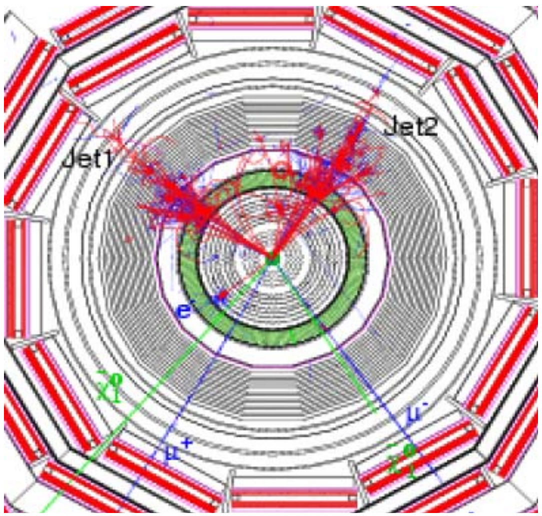
$$\vec{E}_T^{miss} = -\sum_i \vec{E}_T^{i}$$

$$\text{METX, METY} = E_T^{miss}{}_{x,y} = -\sum_i \left(E_T^i\right)_{x,y}$$

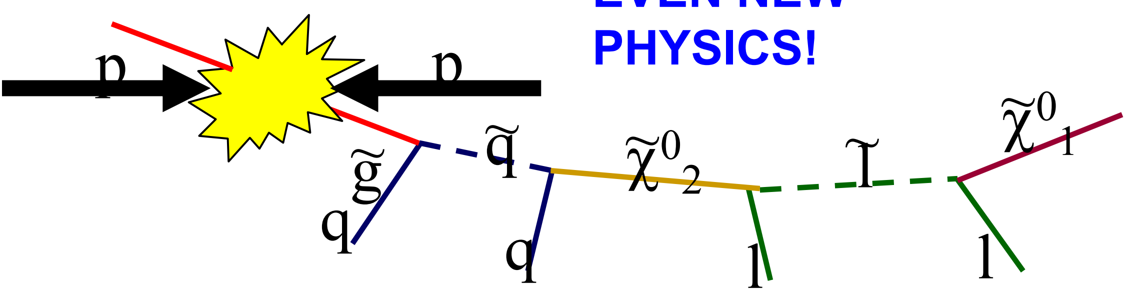
$$\Sigma E_T = \sum_i E_T^i$$

very challenging
(calorimeter noise adds up)

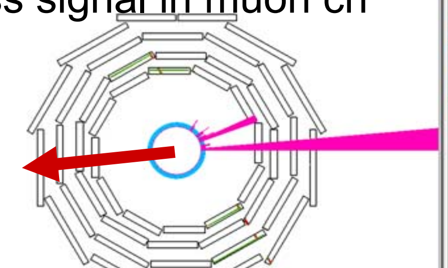
E_T^{miss} CAN COME FROM CALORIMETRIC MEASUREMENT FLUCTUATIONS, THE WORSE YOUR RESOLUTION IS THE MORE E_T^{miss} YOU WILL FIND. HOW TO TELL NEW PHYSICS FROM INSTRUMENTA EFFECTS?!



E_T^{miss} CAN BE DUE TO PHYSICS (ν). EVEN NEW PHYSICS!



Take a cosmic μ, if you miss signal in muon ch

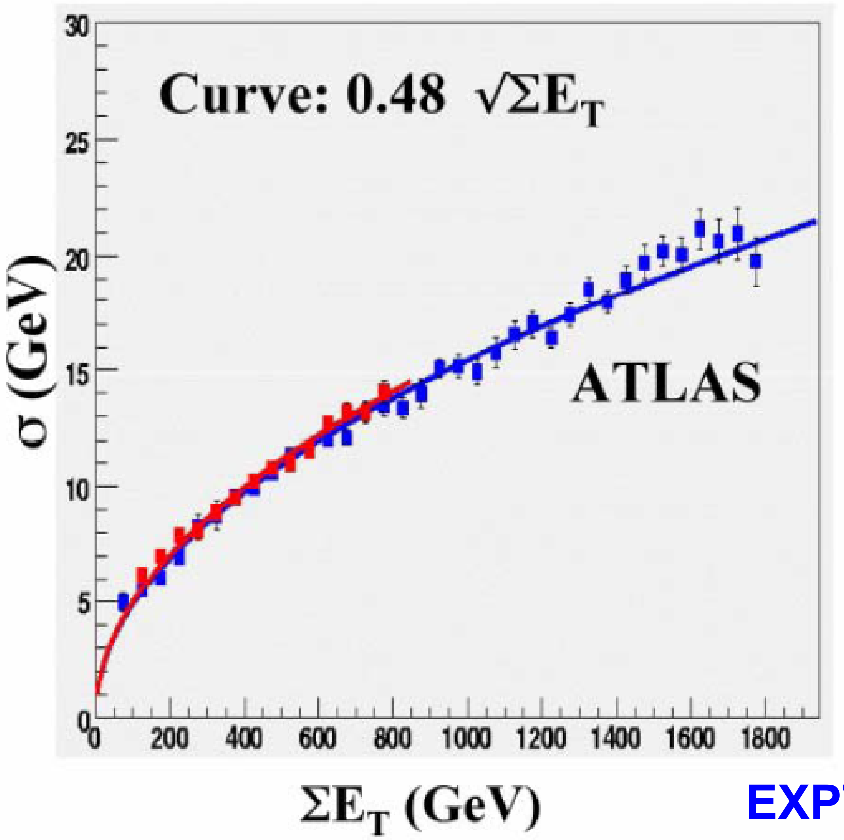


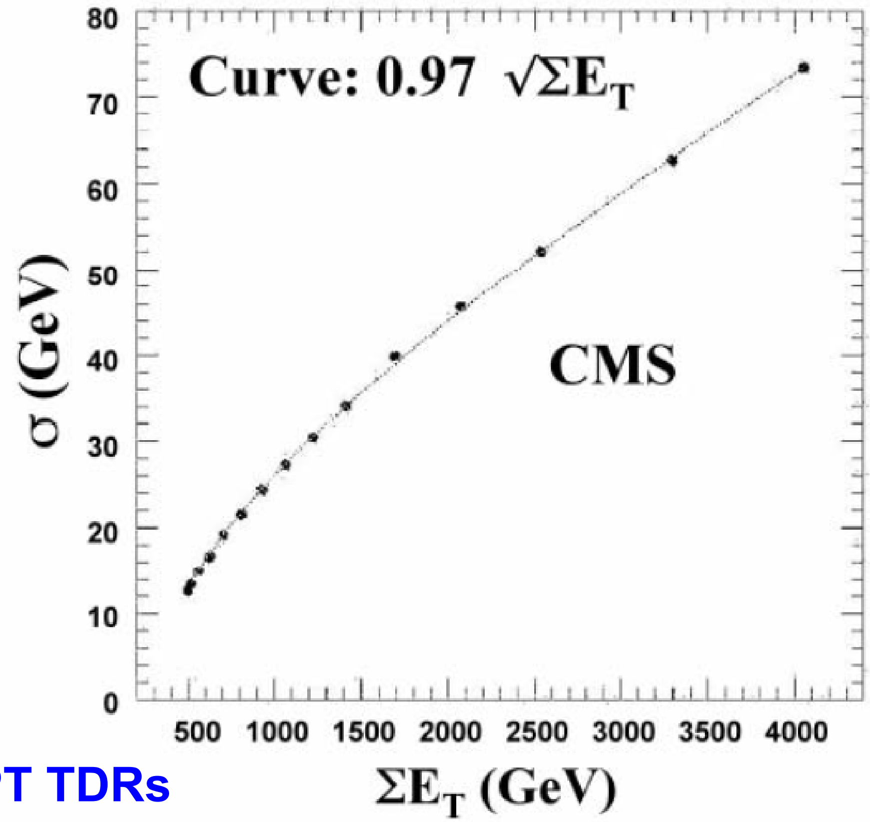
Not in time with beam collision!

Missing E_T: expected performances

Expected precision of measurement of missing ET as function of ET measured per event.

SHOULD BE 0 IN QCD EVENTS





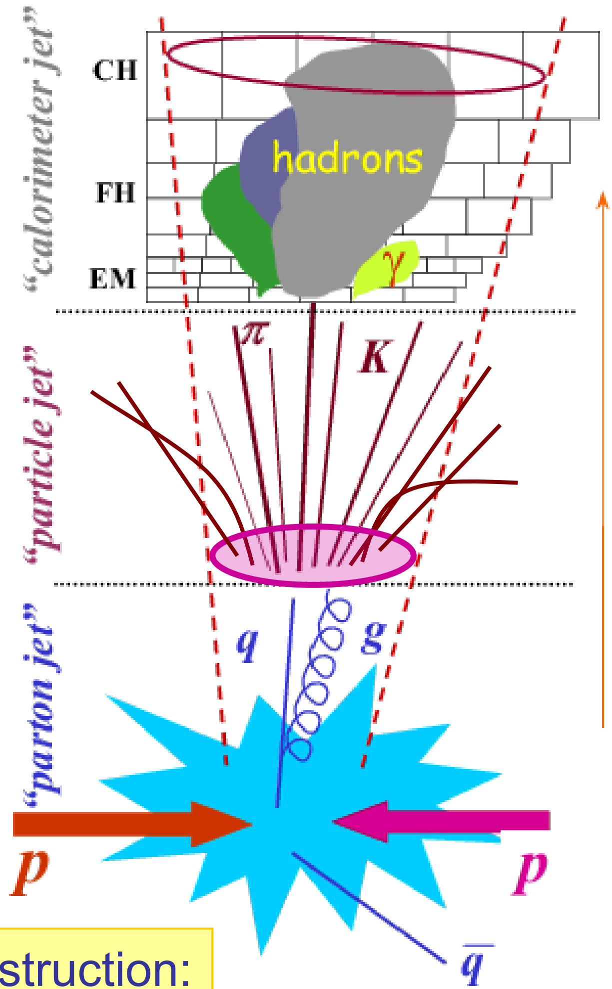
EXPT TDRs

Physics objects

We are not going to measure single hadrons…

Contribution from

- Physics:
  - Parton shower & fragmentation
  - Underlying events
  - Initial State Radiation & Final State Radiation
  - Pileup form minimum bias events
- Detector:
  - Resolution
  - Granularity
- Clustering:
  - Out of "cone" energy losses



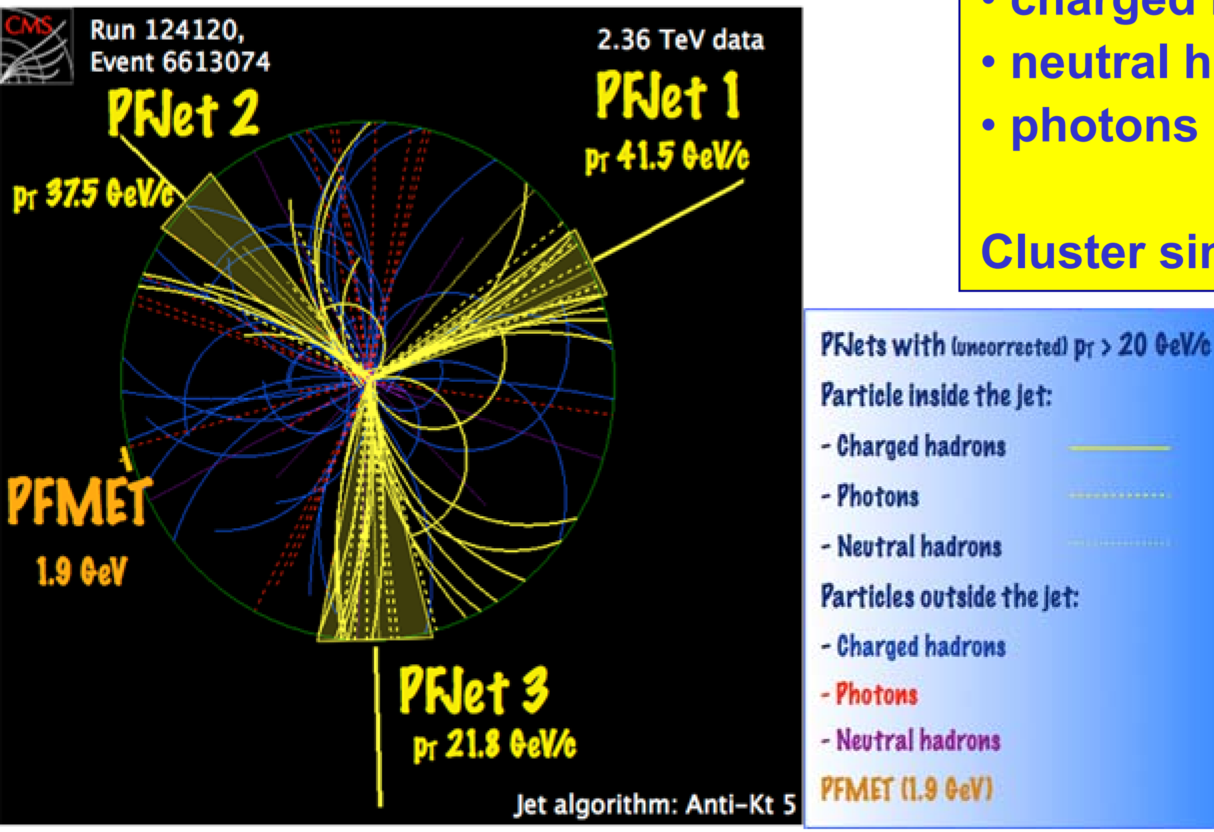
Use physics events to understand jet energy reconstruction:
γ / Z (→ ll) + jet, W → jet jet, ...

Particle Flow (ALEPH, CMS,…, R&D)

Use the best system you have to measure all particles in the event

Identification and reconstruction of:
- **charged hadrons (~ 65%E_{jet})**
- **neutral hadrons (~ 20% E_{jet}))**
- **photons (~ 15% E_{jet})**

Cluster single particles in Jets

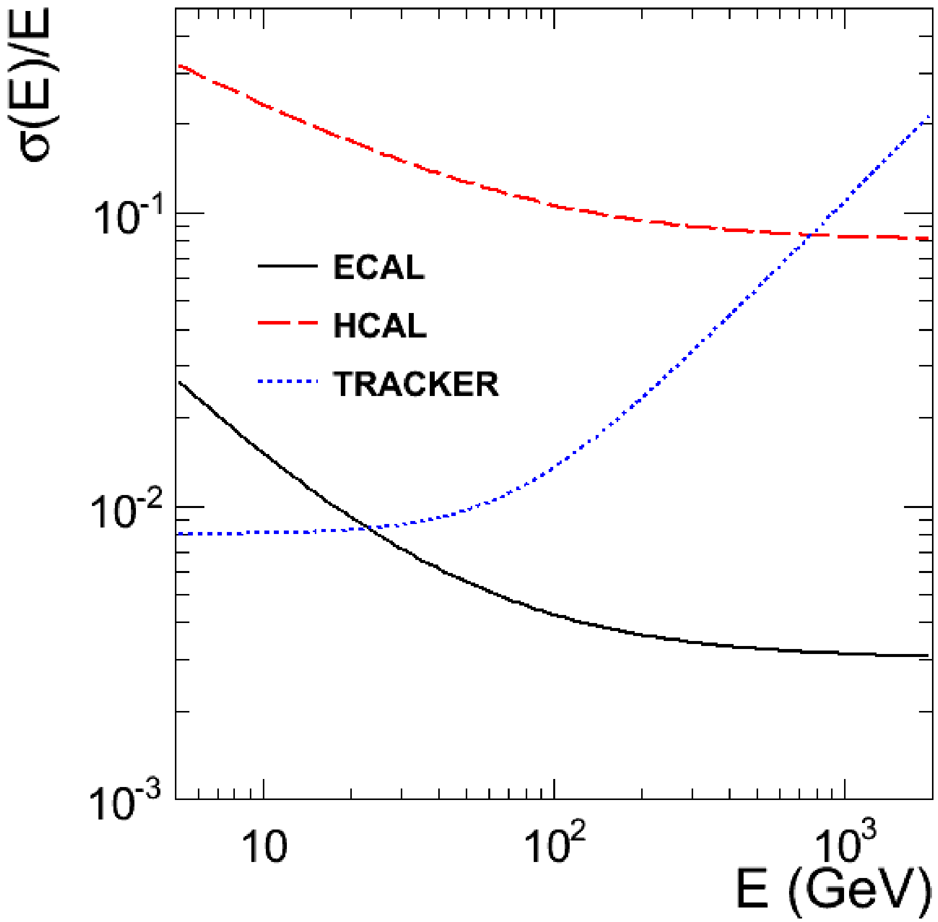


Multijet @ 2.36 TeV

CMS:
- **high B**
- **excellent TK**
- **granular ECAL**

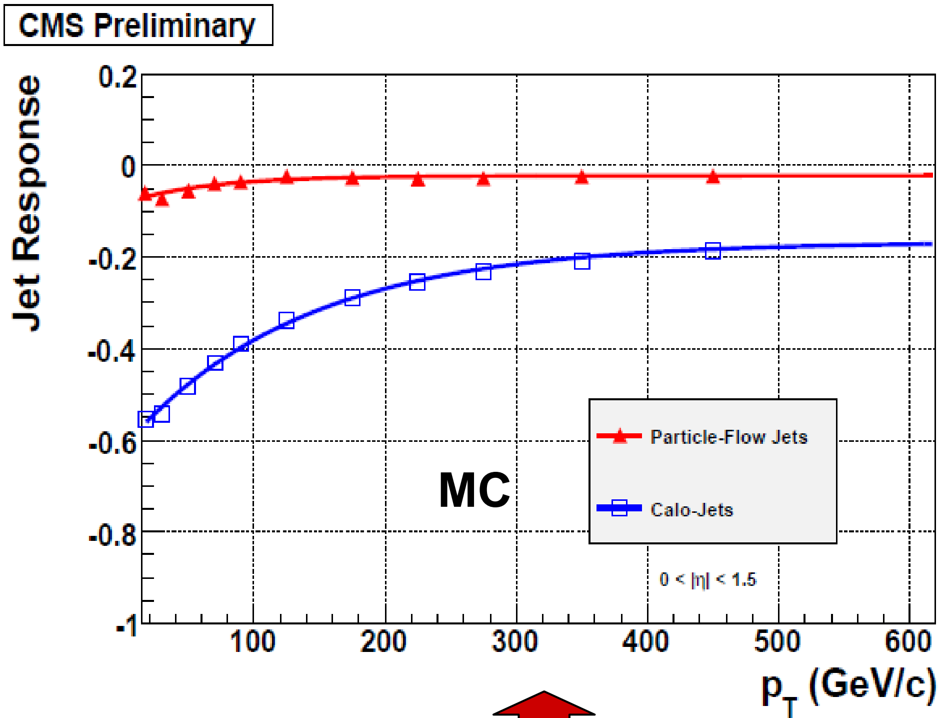
Strong improvement in JET/MET resolution

PF: combine detectors

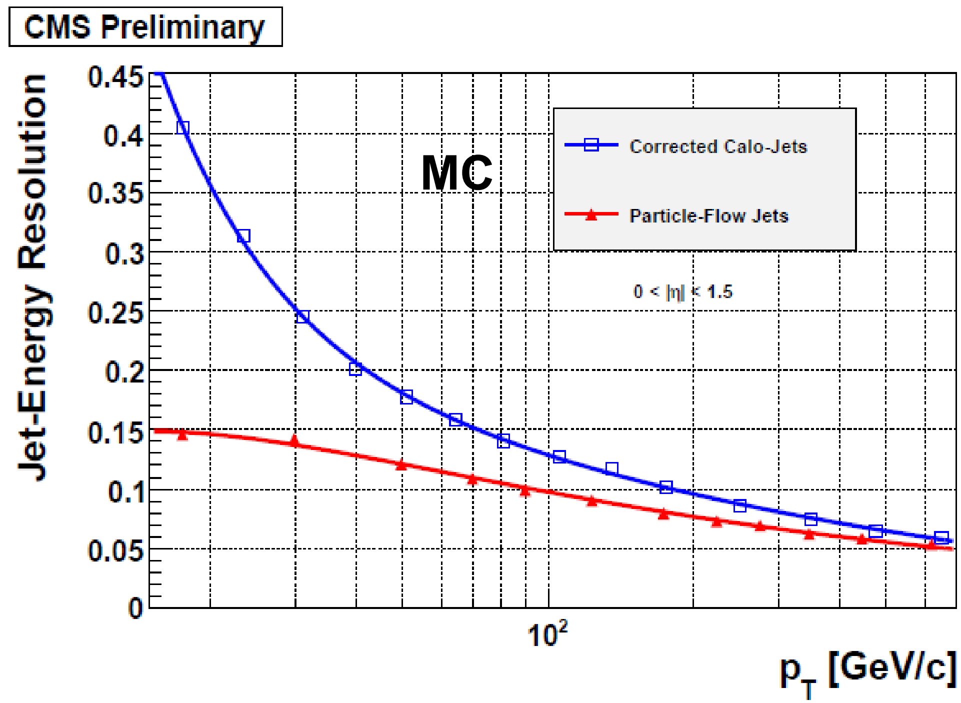


CALORIMETERS IMPROVE THEIR PRECISION WITH ENERGY ON THE CONTRARY OF TRACKING DEVICES. TO USE THIS FITURE YOU MUST BE ABLE TO ASSOCIATE A TRACK TO THE RIGHT CLUSTER AND TO SEPARATE CLUSTERS OF DEPOSITED ENERGY IN A DENSE ENVIRONMENT LIKE A JET.

Particle Flow.vs.CALO JETS



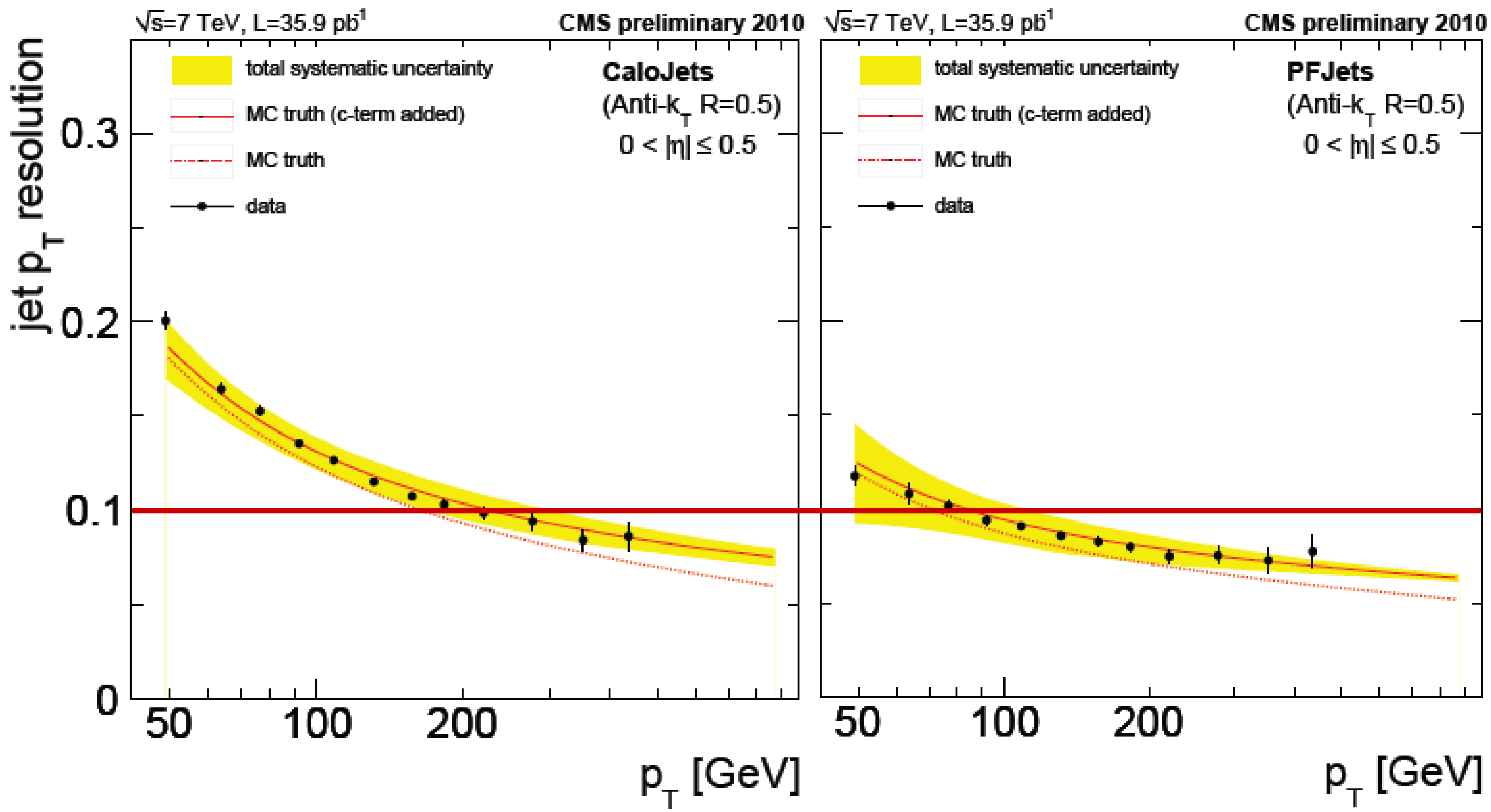
Jet resolution: profits of Tracker excellent momentum resolution, The benefit is lost for very high energy Jets.



Jet response: $(p_T^{rec} - p_T^{gen}) / p_T^{gen}$

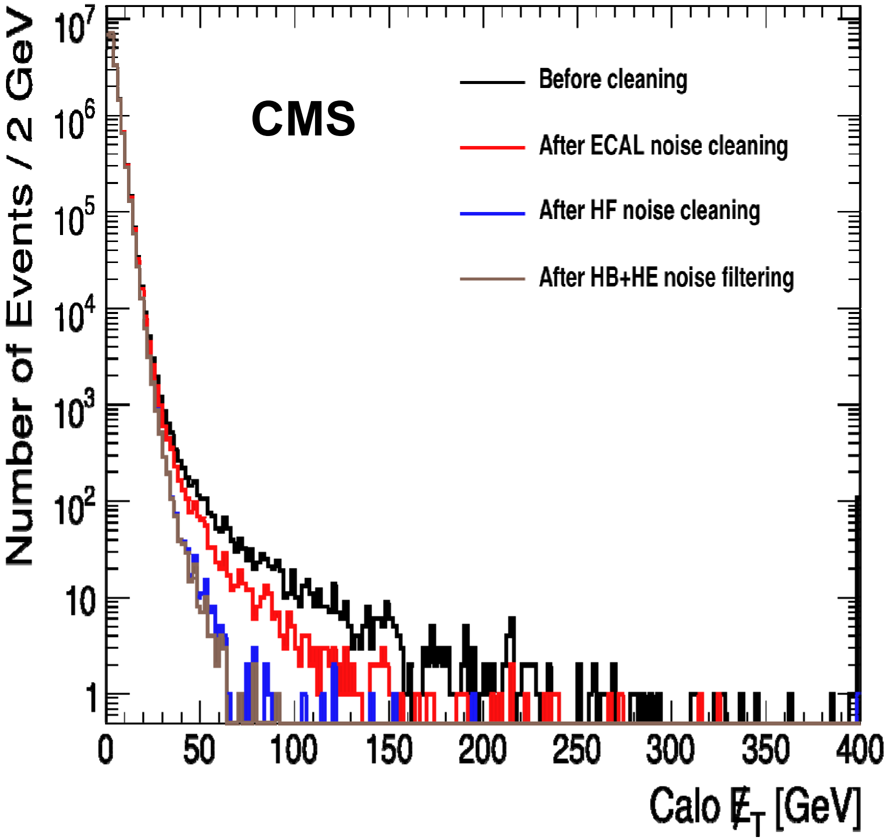
About 65% of Jet Energy measured with tracks. No invisible energy and no energy dependent Fem.

Particle Flow.vs.CALO JETS

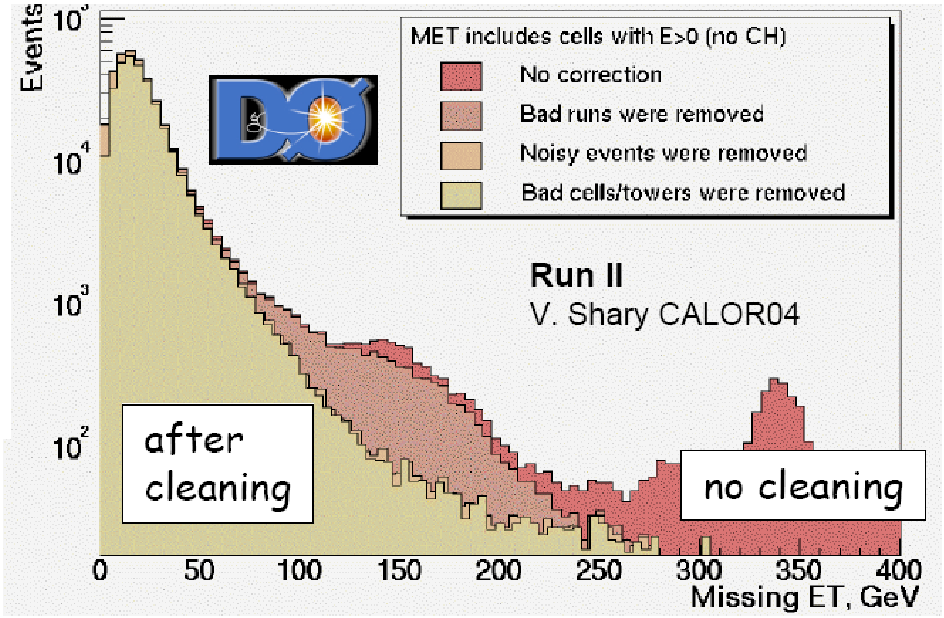


Measure jet response and jet pt resolution balancing 2jet events or γ+jet

Missing E_T (MET) & Detector

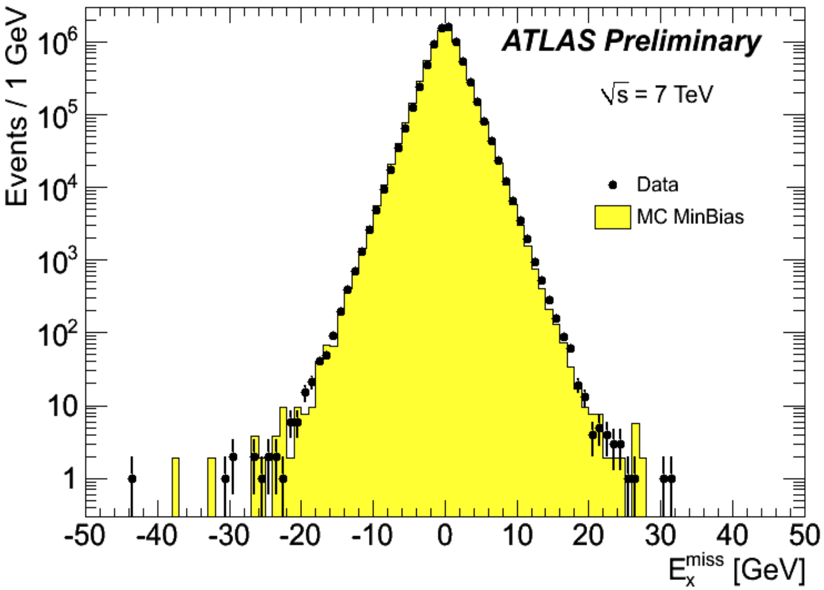


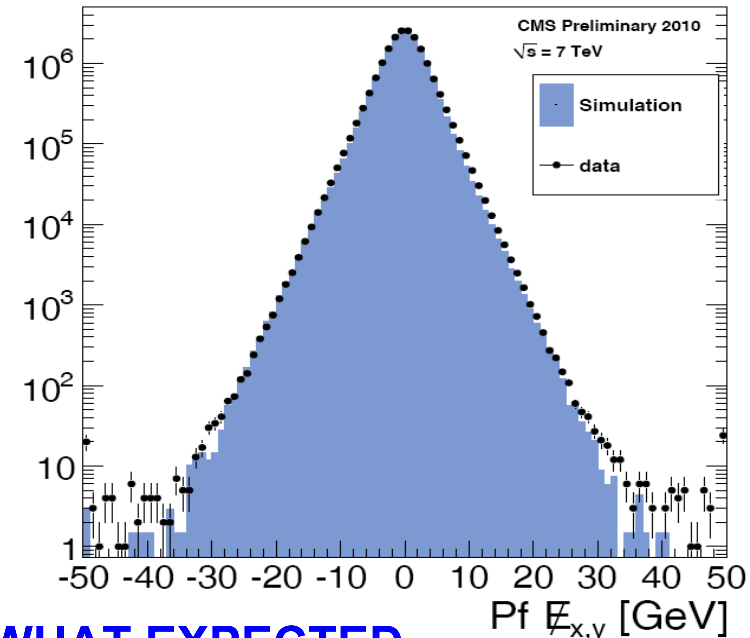
First step to measure MET: understand what is going on in your detector!
Beam background, cosmics, various kind of noise some of which not really expected.



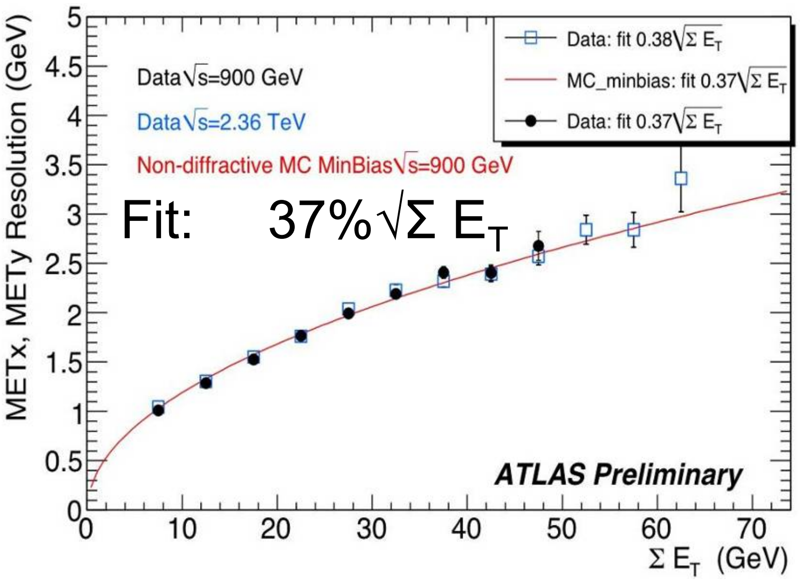
CLEAN YOUR DATA

Missing E_T (MET): the performance



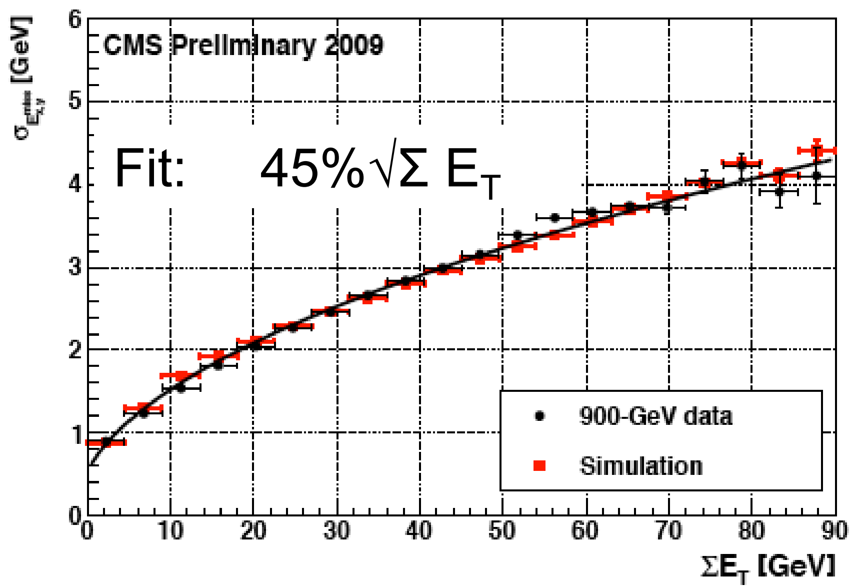


MUCH BETTER THAN WHAT EXPECTED



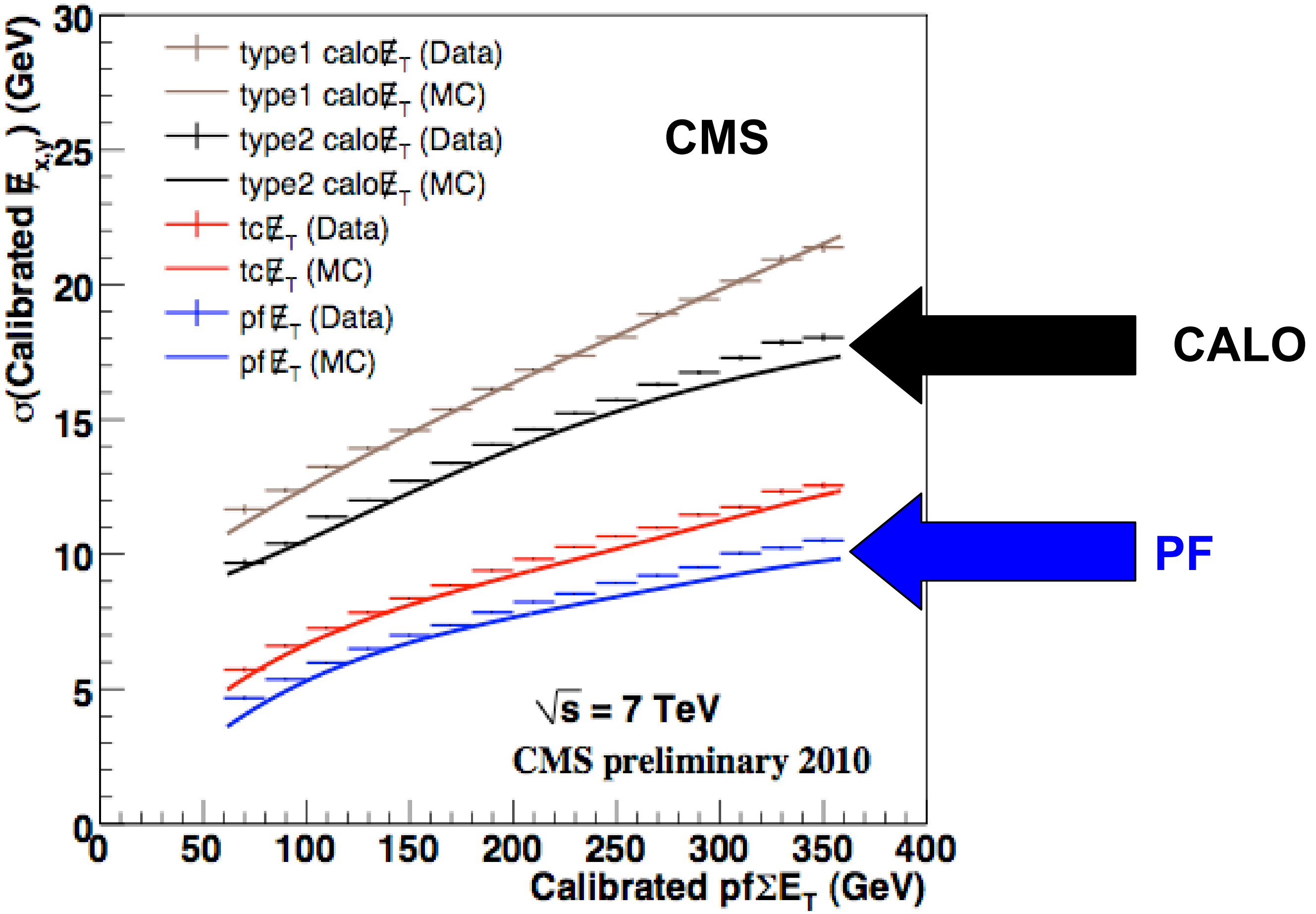
Fit: $37\%\sqrt{\Sigma E_T}$

oz, INF



Fit: $45\%\sqrt{\Sigma E_T}$

Missing E_T (MET)



Few references

- R. Wigmans, “Calorimetry, Energy Measurements in Particle Physics” , Oxford science publications
- U.Amaldi, “Fluctuations in Calorimetry measurements” 1981 Phys.Scr.23 409
- ATLAS & CMS TDRs