Calorimetry (for pedestrians)

- Concept
- Electromagnetic calorimetry
  - Electromagnetic (em) showers properties
  - Energy resolution of em calorimeters
  - Two examples: ATLAS and CMS.
    - different approaches, challenges,
    - test beam performance
    - the bitter reality (material budget)
    - Performance in situ
- Hadronic calorimetry
  - Hadronic showers properties. Compensation.
  - Example: ATLAS TileCal
  - Future (or current?) trends
    - Dual readout
    - Particle Flow

Before I start

A great thanks to the Professors of the EDIT 2011 instrumentation school
(Marcella Diemoz, Daniel Fournier, Patrick Janot, Felix Sefkow, Richard Wigmans)

http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=96989

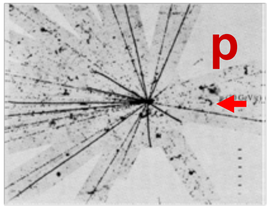
I have shamelessly used many of their inputs for this lecture !

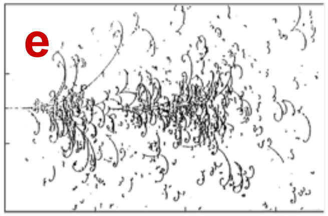
Another excellent reference:
C.Fabjan & F.Gianotti : Calorimetry for Particle Physics
Rev. Mod. Phys. 75 (2003) 1243-1286 and CERN-EP-2003-075

Calorimetry Concept

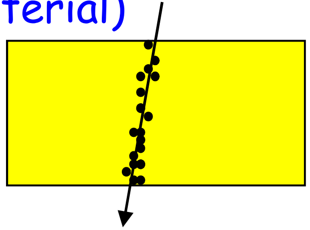
PARTICLE INTERACTION IN MATTER (depends on the impinging particle and on the kind of material)

Destructive interaction

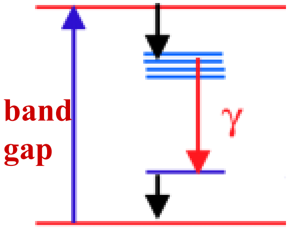




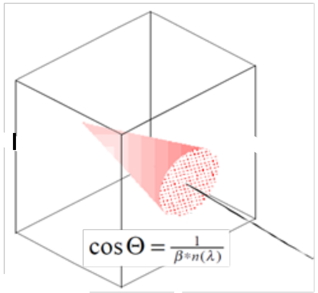
ENERGY LOSS TRANSFER TO DETECTABLE SIGNAL (depends on the material)



Ionisation



scintillation



Cerenkov

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

- Electric: charge collection
- Optic : light collection
- Thermal : temperature

$S \propto E$

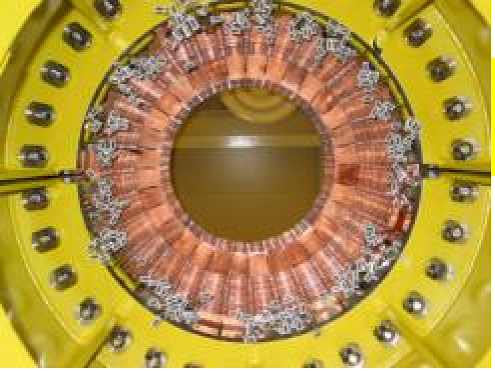
Why calorimeters ?

Calorimeters have been introduced mainly to measure the total energy of particles

- Versatile detectors, can measure also position, angle, timing for charged & neutral particles (even neutrinos through missing E if hermetic)
- Compact detectors: shower length increase only logarithmically with E
- Unlike spectrometers, E resolution improves with increasing E
- Provide fast signals which can be used for triggering

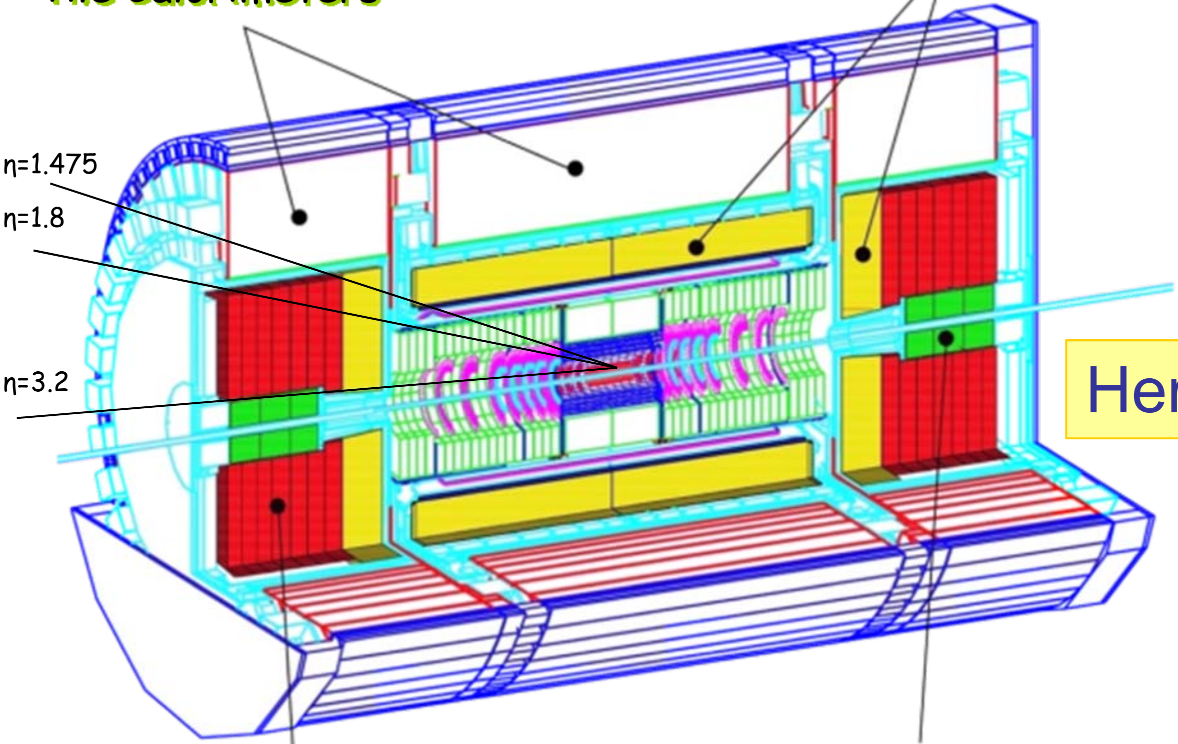
Calorimeters are present in practically all experiments

ATLAS CALORIMETERS



LAr

TileCal



Electromagnetic Liquid Argon Calorimeters

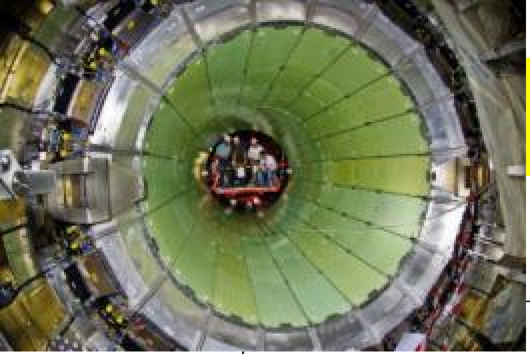
Tile Calorimeters

Hadronic Liquid Argon EndCap Calorimeters

Forward Liquid Argon Calorimeters

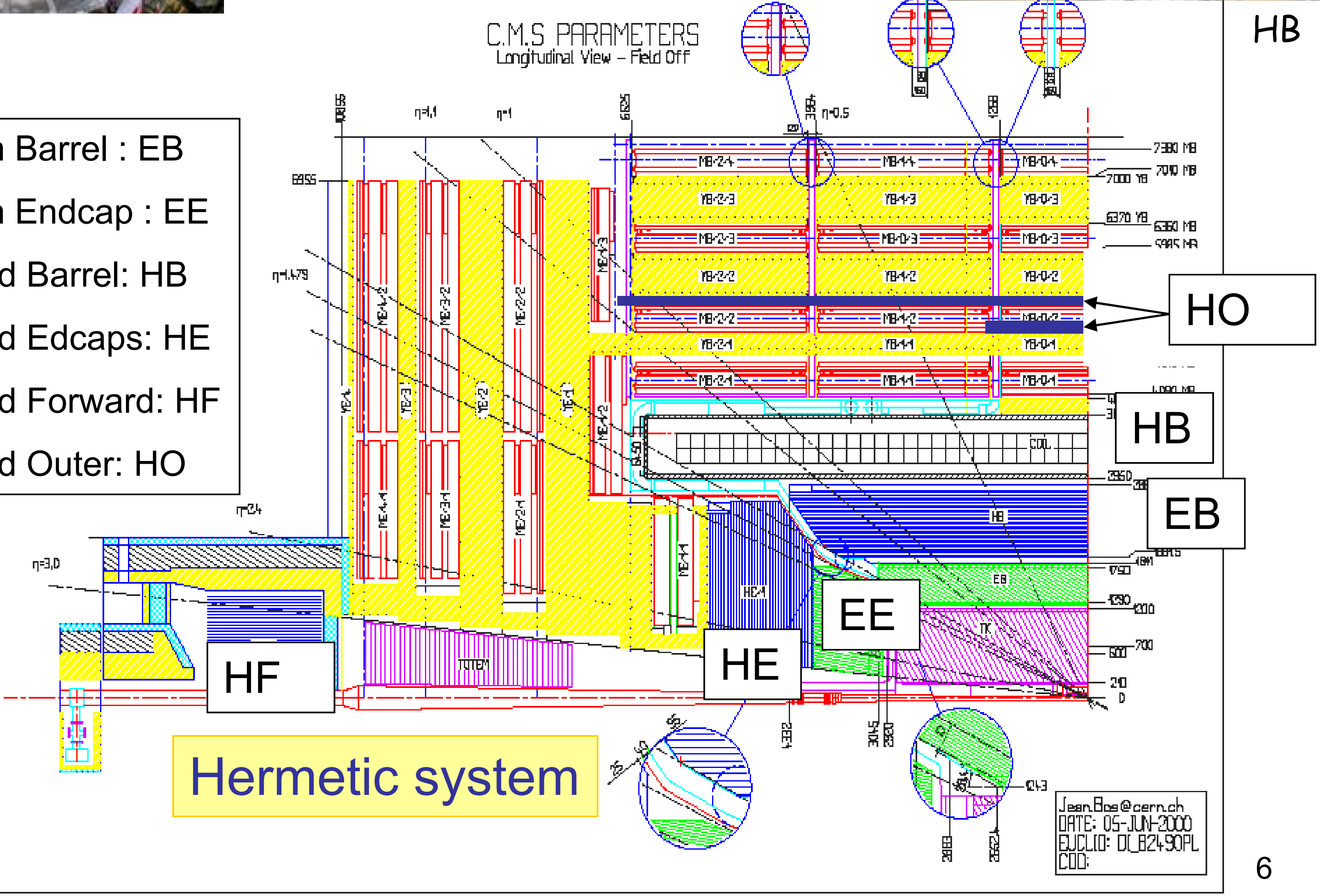
Hermetic system

CMS CALORIMETERS


EB


HB

- Em Barrel : EB
- Em Endcap : EE
- Had Barrel: HB
- Had Edcaps: HE
- Had Forward: HF
- Had Outer: HO

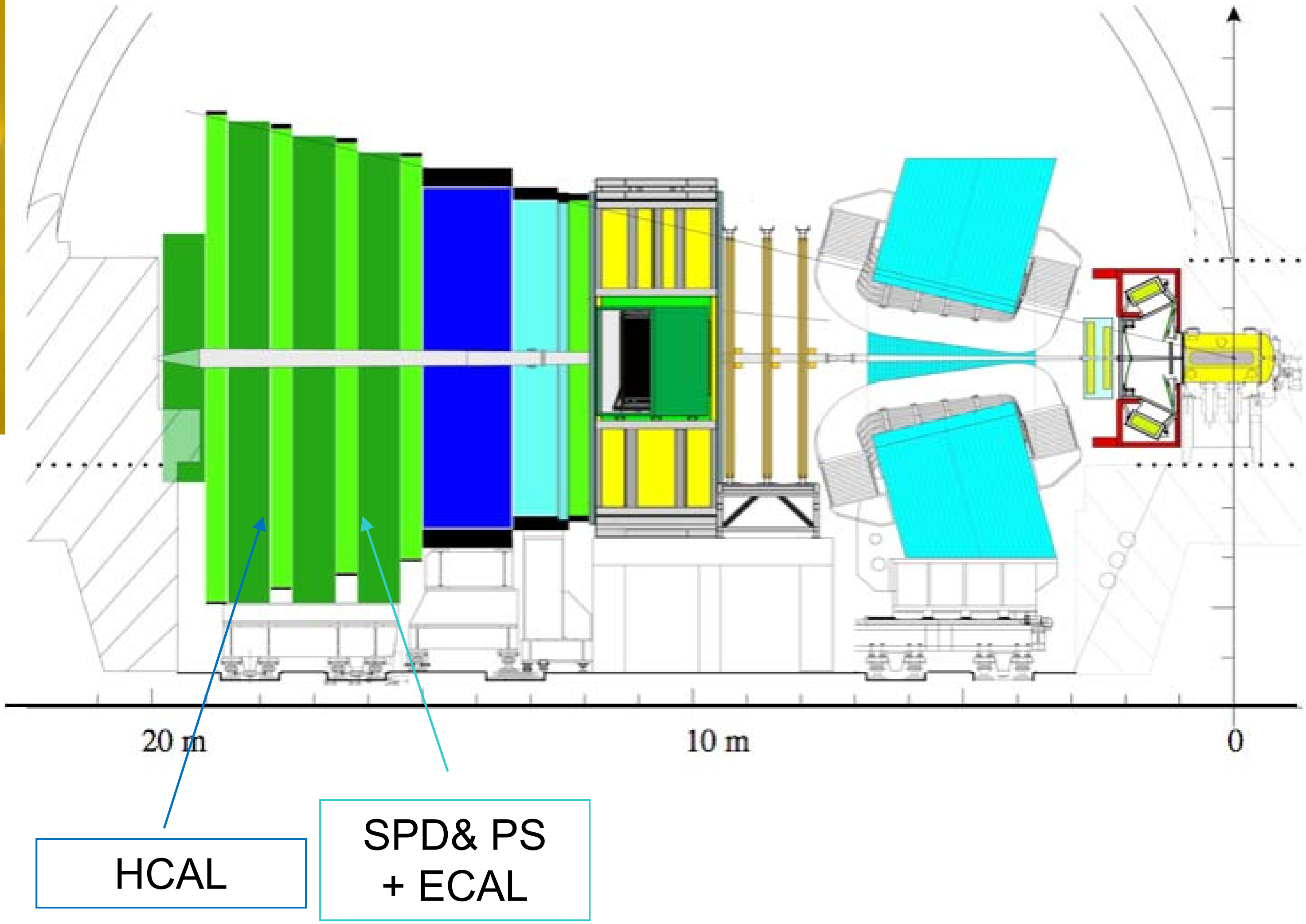


Hermetic system

LHCb calorimeters

ECAL

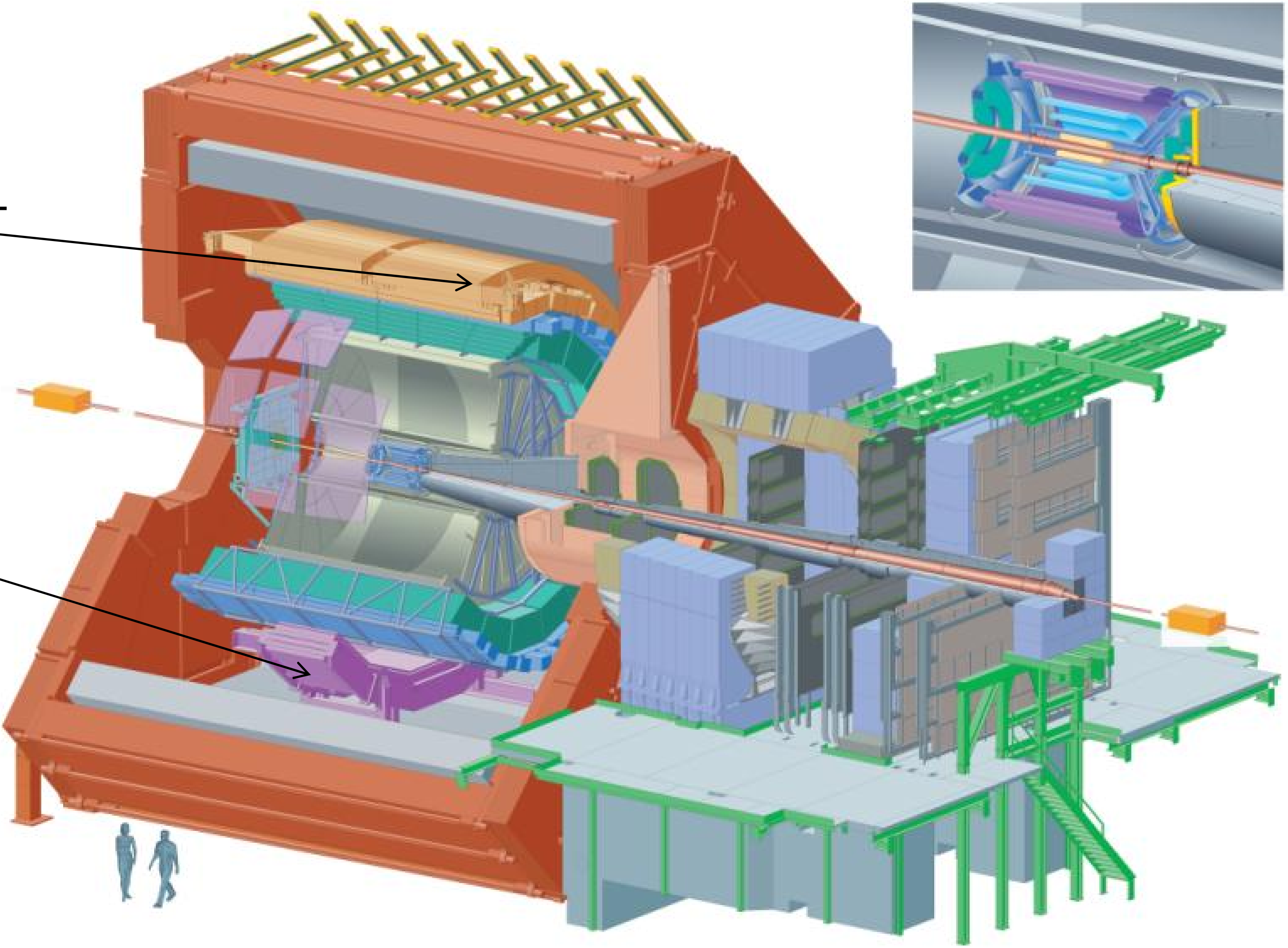
HCAL



HCAL

SPD& PS
+ ECAL

ALICE calorimeters

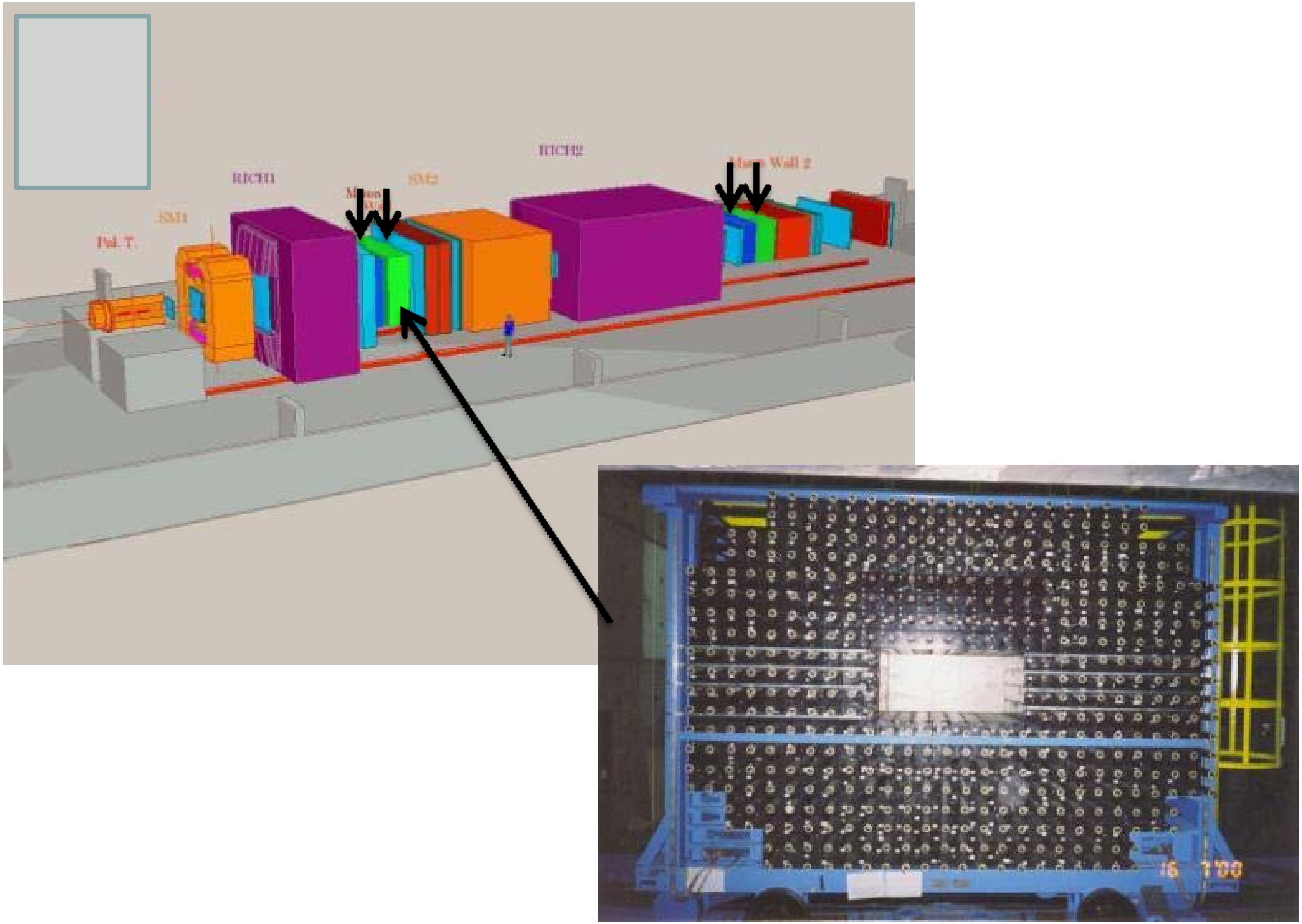


EMCAL

PHOS
emcal

Fixed target experiments

Example : COMPASS



Electromagnetic Calorimetry

Energy losses by e & γ

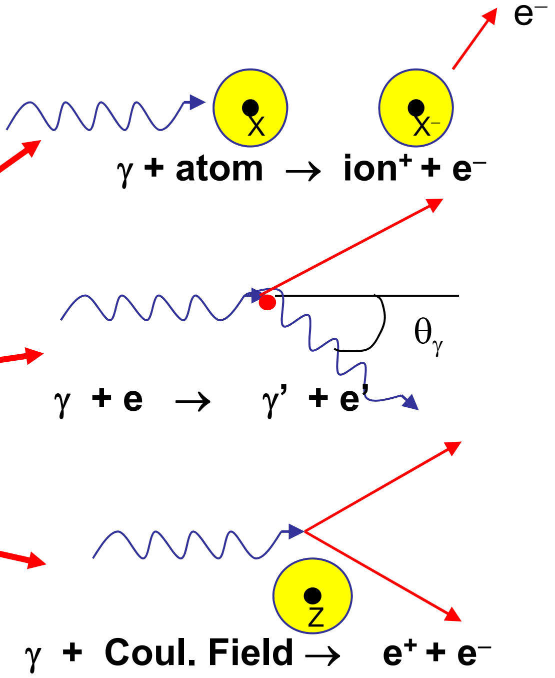
In matter electrons and photons loose energy interacting with nuclei and atomic electrons

Electrons

- ionization (atomic electrons)
- bremsstrahlung (nuclear)

Photons

- photoelectric effect (atomic electrons)
- Compton scattering (atomic electrons)
- pair production (nucleus+ electrons)



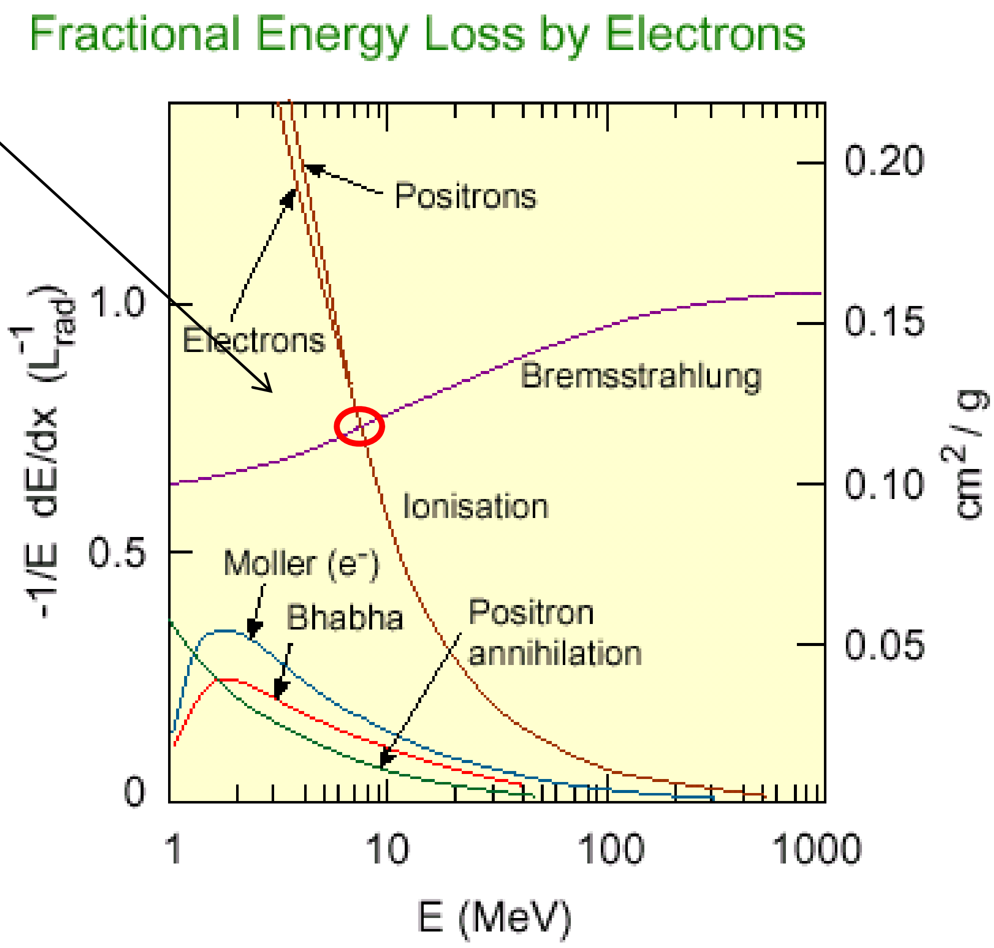
Electrons

Critical energy E_c:
when radiation overcomes ionisation

$$E_c \approx \frac{610[710]MeV}{Z+1.24[0.92]}$$

(solids, liquids [gas])

7 MeV for lead


Fractional Energy Loss by Electrons

Radiation length: thickness of material that reduces the mean energy of an electron beam of high energy electrons by a factor e

$$X_0 \approx \frac{716\,g\,cm^{-2}A}{Z(Z+1)\ln\left(287/\sqrt{Z}\right)}$$

6.4 g cm^{-2} (= 0.56 cm) for lead

Photons

- photo-electric effect

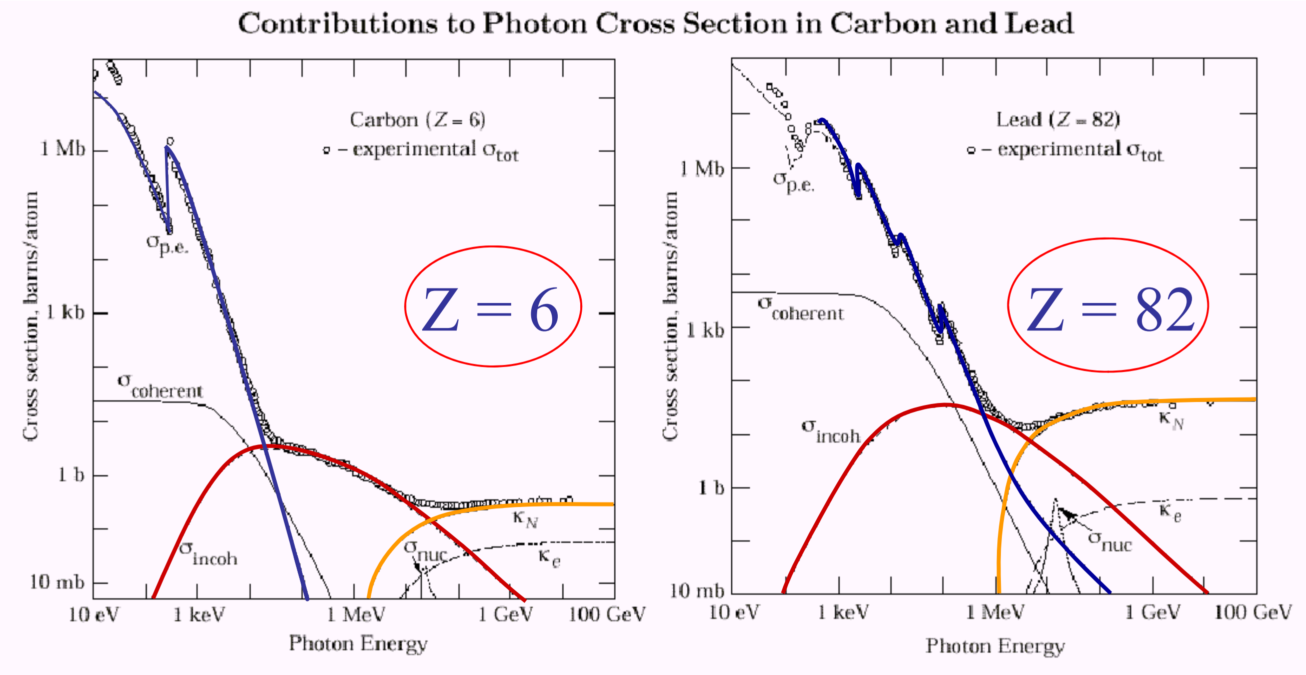
$$\sigma_{pe} \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma} \right)^{\frac{7}{2}}$$

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

- Compton scattering

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

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


Contributions to Photon Cross Section in Carbon and Lead

Legend
K_n = pair on nucleus field
K_e = pair on electrons field
Incoh =Compton

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

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

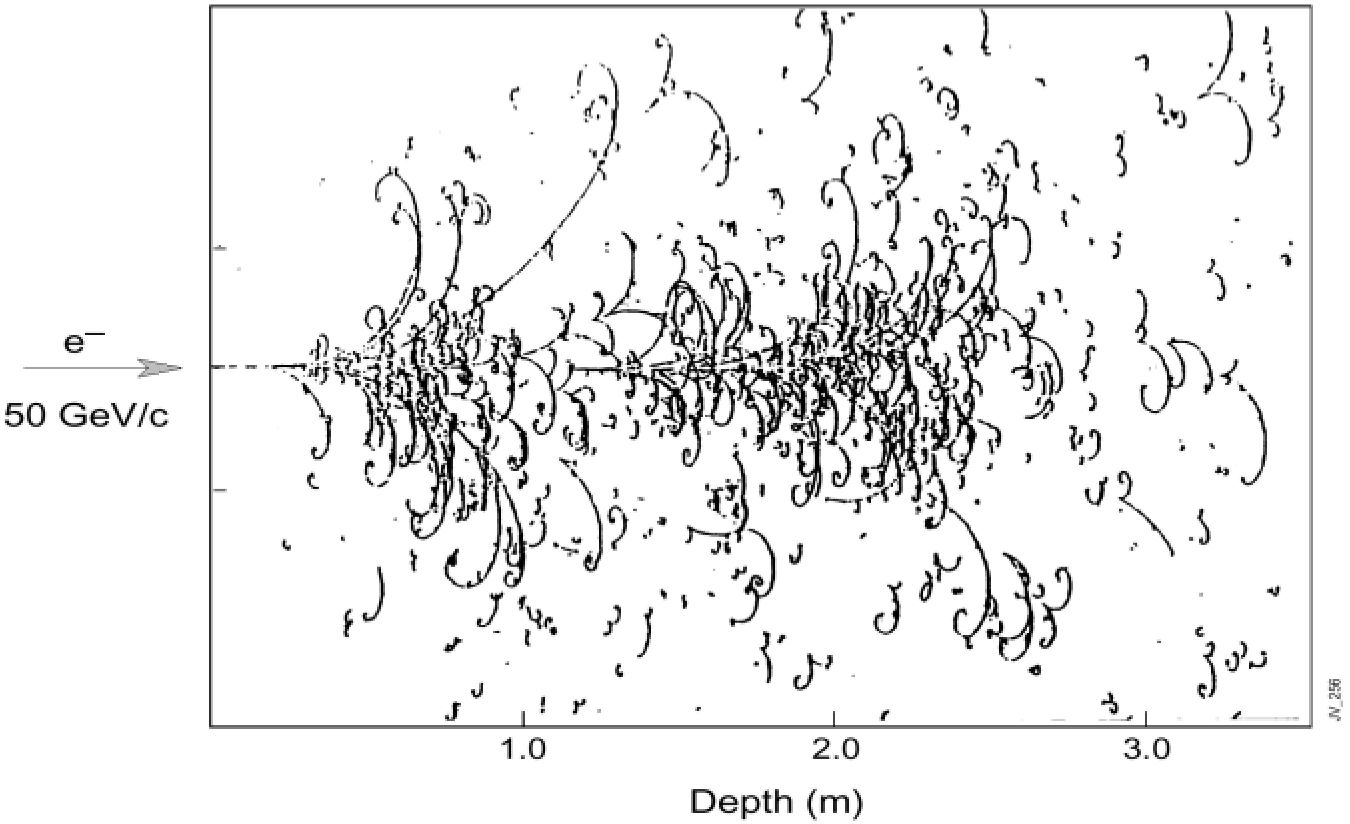
constant E >1GeV

$\propto Z\,(Z+1)$

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

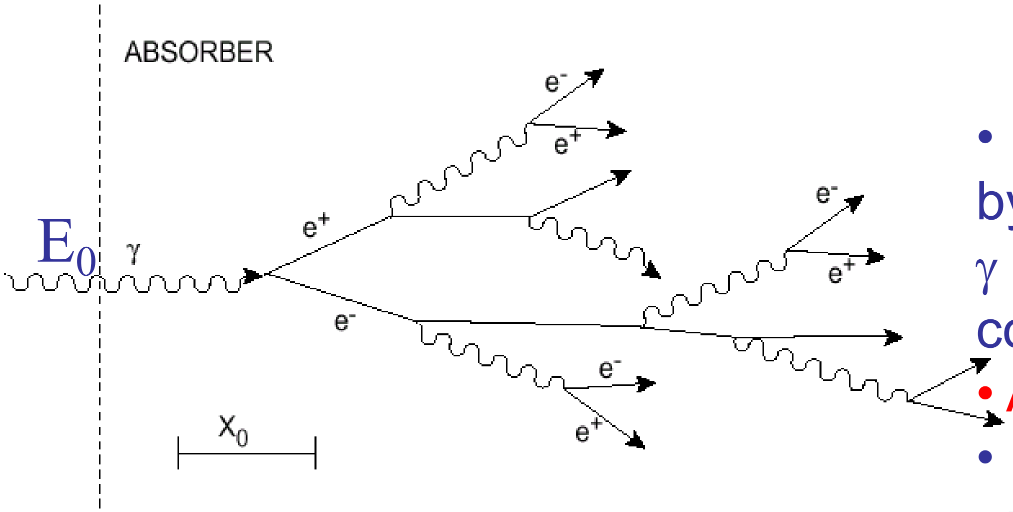
Electromagnetic showers

In a dense material, cascade of pair production + Bremsstrahlung until the energy of charged secondaries has been degraded to an energy dominated by ionization loss (below E_c)



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

EM showers: a simplistic model



- In $1X_0$ an e loses about 2/3 of its E by bremsstrahlung 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

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

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

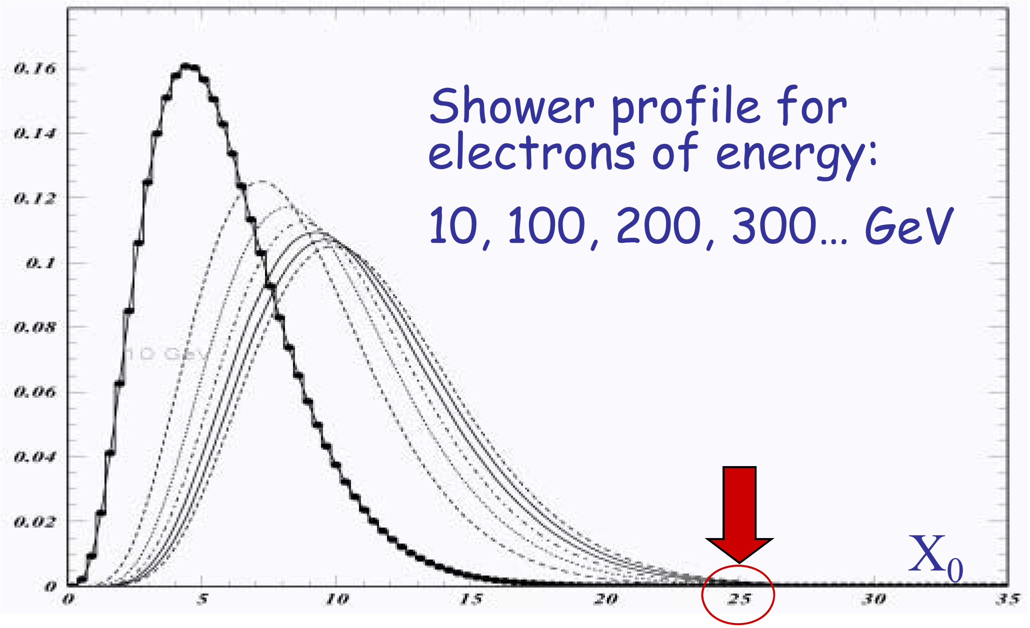
@$\Delta x = tX_0$ $N(t) = 2^t$ $E(t) = E_0/2^t$

Cascade increases until E~Ec

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

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

EM showers: longitudinal profile



Shower profile for electrons of energy:

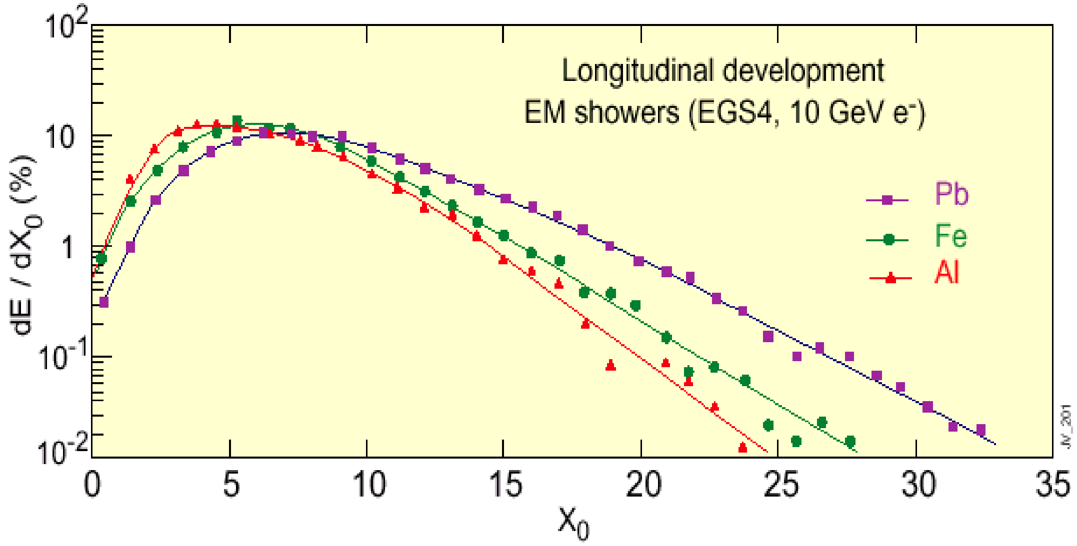
10, 100, 200, 300… GeV

Shower energy dep parametrization:

$$\frac{dE}{dt} \propto E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

$t_{max} \sim \ln(E_0/E_c) + t_0$

$t_0 = -0.5$ (electrons) or $+0.5$ (photons)



Longitudinal containment:

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

With 25 X_0, < 1% up to 300 GeV

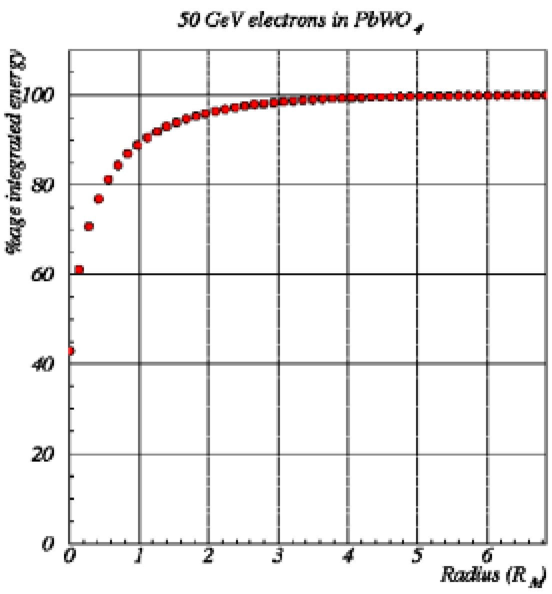
EM showers: transverse profile

- Multiple scattering make electrons move away from shower axis
- Photons with energies in the region of minimal absorption (10 MeV for lead) can travel far away from shower axis

Molière Radius R_M sets transverse shower size, it gives the average lateral deflection at the critical energy electrons after traversing one radiation length

$$R_M = \frac{21\,MeV}{E_C} X_0 \quad \prec \frac{A}{Z}$$

90% of shower energy within $1R_M$,
95% within $2R_M$,
99% within $3.5R_M$



Summary of em showering process

- Electromagnetic showering process is
  - well understood
  - very linear
- Simulations reproduce in general very well the observed distributions
  - Optimization by tuning of multiple scattering and lower energy cuts

Energy resolution of em calorimeters (1)

Energy resolution of a calorimeter can be parameterized as

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \qquad \oplus \text{ means quadratic sum}$$

a is the *stochastic term* *and* accounts for fluctuations related to physical development of the shower, i.e. the fluctuation s of the total detectable track length (ideal situation)

Total track length $T_0 \approx \frac{E}{E_C} X_0 \Rightarrow \frac{\sigma(E)}{E} \prec \frac{1}{\sqrt{T_0}} \prec \frac{1}{\sqrt{E}}$

Threshold for detection

where f_S = fraction of T_0 with kin $E > E_{th}$ (typical example is Cerenkov detector)

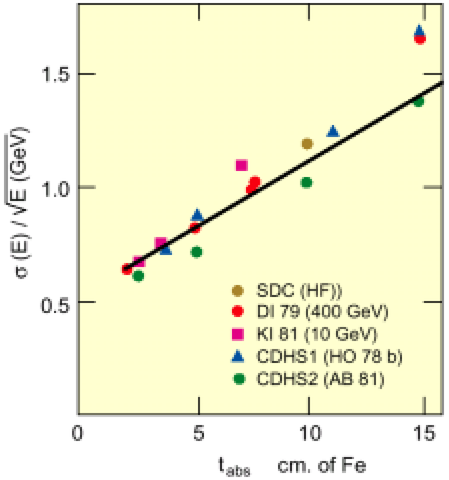
$$\frac{\sigma(E)}{E} \prec \frac{1}{\sqrt{E}} \frac{1}{\sqrt{f_S}}$$

Sampling calorimeter

Fluctuation on number of tracks crossing the active layers

N_cross ~ T_0 / (d/ X_0) (d =thickness of absorber plate)

$$\frac{\sigma(E)}{E} \prec \sqrt{\frac{d/X_0}{E}}$$



Examples of stochastic performance

Scintillating crystals

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

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

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

In practice dictated by light collection and fluctuations (ENF) at photocathode of photodetector

Cherenkov radiators

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

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

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

Homogeneous LKr calorimeter NA48/62

Ionisation signal

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

ATLAs Pb-LAr sampling

$$t = d/X_0 \approx 0.4$$

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

Energy resolution of em calorimeters (2)

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

- b the *noise term* responsible for degradation of low energy resolution
  - mainly the energy equivalent of the electronic noise
  - or contribution from pileup in the shower area

- c the *constant term* dominates at high energy

  all kind of nuisances :
  - stability of calibration
  - radiation effects
  - energy leakage
  - non uniformity of signal
  - loss of energy in dead materials
  - …

ATLAS & CMS em calorimetry

Homogeneous calorimeter made of 75000 **$PbWO_4$ scintillating crystals** + PS FW

- Very compact R_M=2.0cm
- Excellent energy resolution
- Fast << 100 ns
- High granularity
- No longitudinal segmentation
- No angular measurement
- Radiation tolerance : needs follow up
- Room Temperature
- T sensitive 5%/°K
- Requires uniformisation by calibration

Sampling LAr-Pb, 3 Longitudinal layers + PS

- R_M=7.3cm
- Good energy resolution
- Not so fast (450 ns), requires shaping
- High granularity
- Longitudinally segmented
- Angular measurement
- Radiation resistance

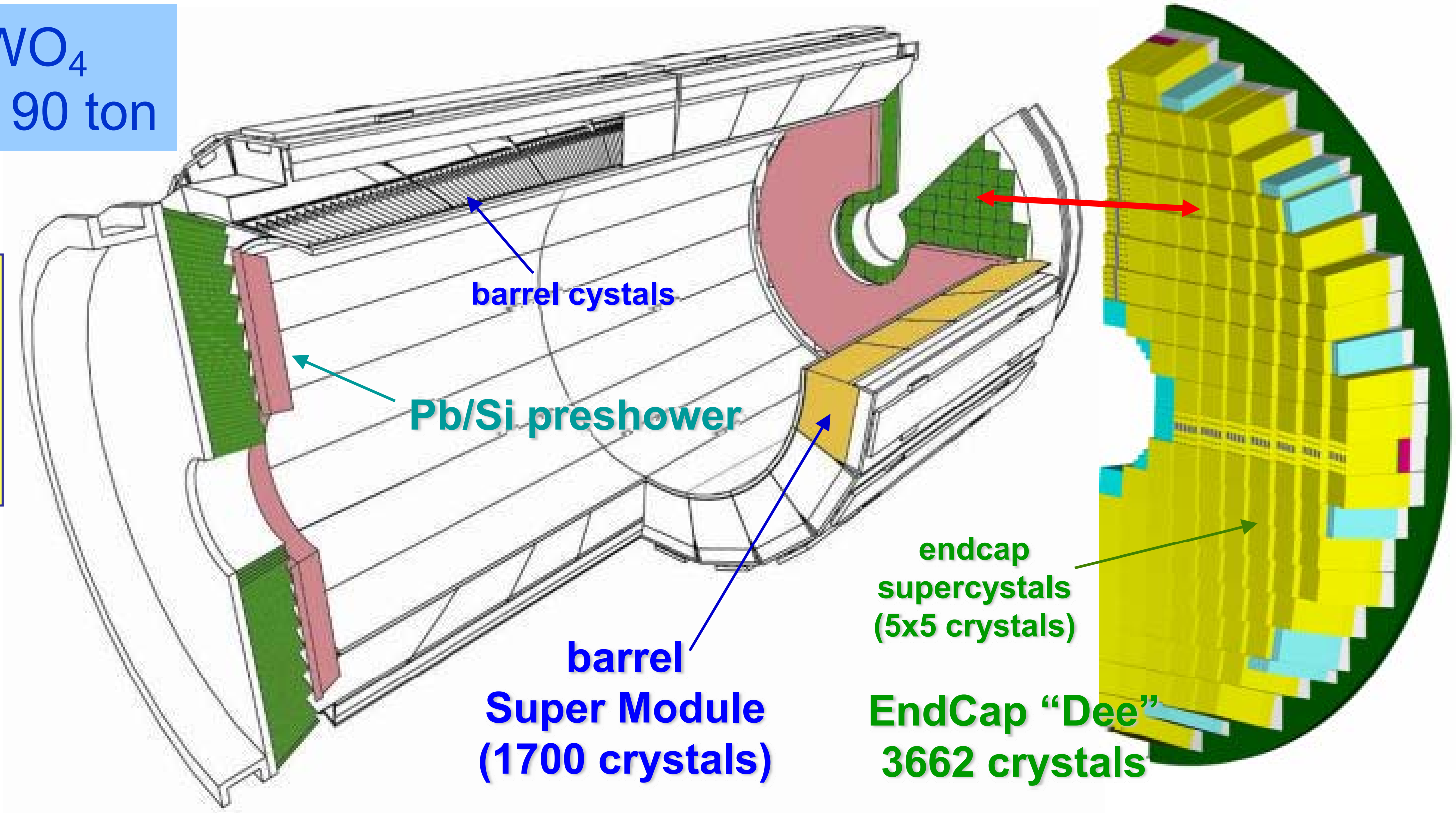
- Cryogenic detector (cryostat)
- T sensitive 5%/°K
- Instrinsically uniform

CMS em Calorimeter

Precision electromagnetic calorimetry: 75848 PWO crystals

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

Previous
Crystal
calorimeters:
max 1m^3



barrel cystals

Pb/Si preshower

barrel
Super Module
(1700 crystals)

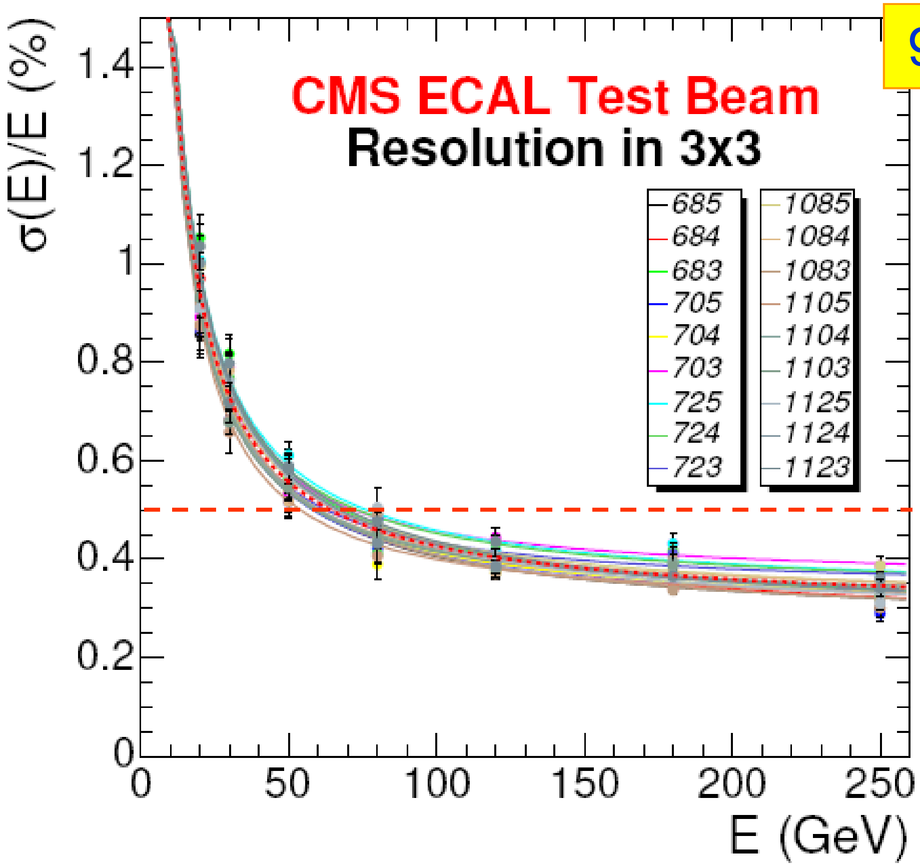
endcap
supercystals
(5x5 crystals)

EndCap “Dee”
3662 crystals

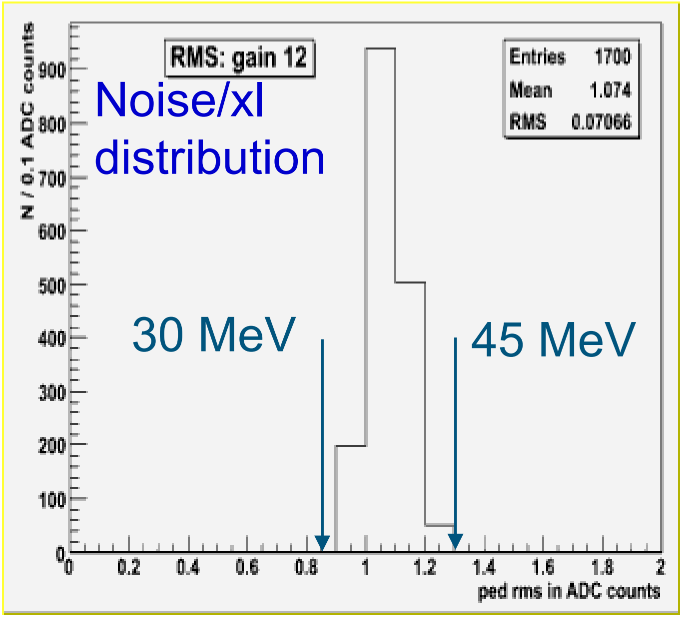
Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23cm³)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3x3x22cm³)

CMS ECAL: the performance in test beam



9 Super Modules 1700 xl on test beam



Noise/xl distribution

30 MeV

45 MeV

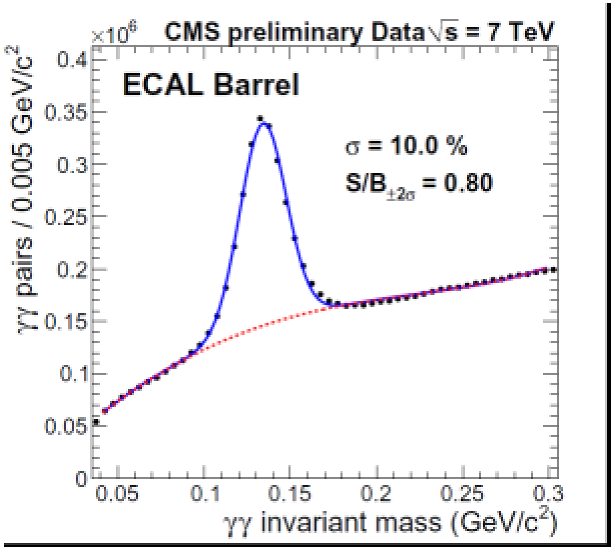
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

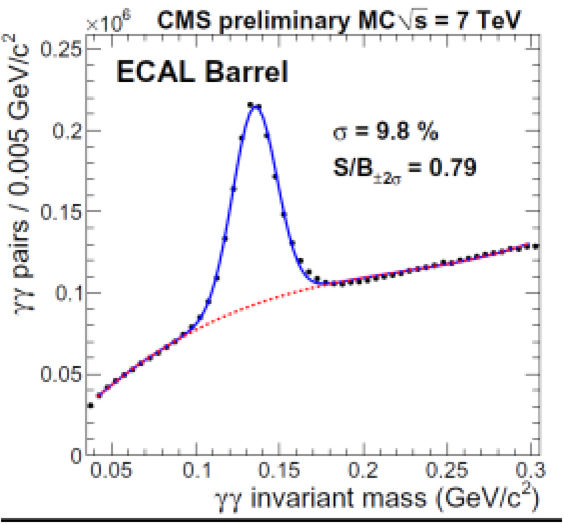
Local resolution

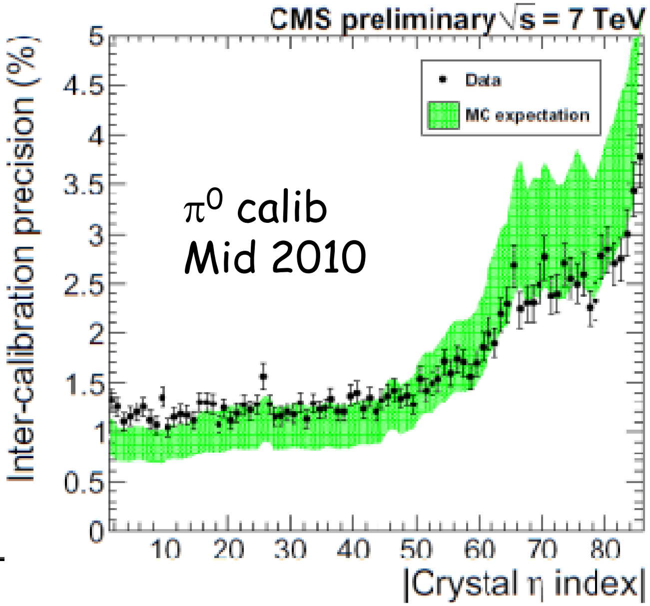
Energy resolution: how to keep it?

- **Intercalibration**

  requires several steps before, during and after data taking
  - test beam precalibration
  - continuous monitoring during data taking (short term changes)
  - Intercalibration by physics reactions during the experiment (π^0, η) with specialized data-stream or ϕ symmetry





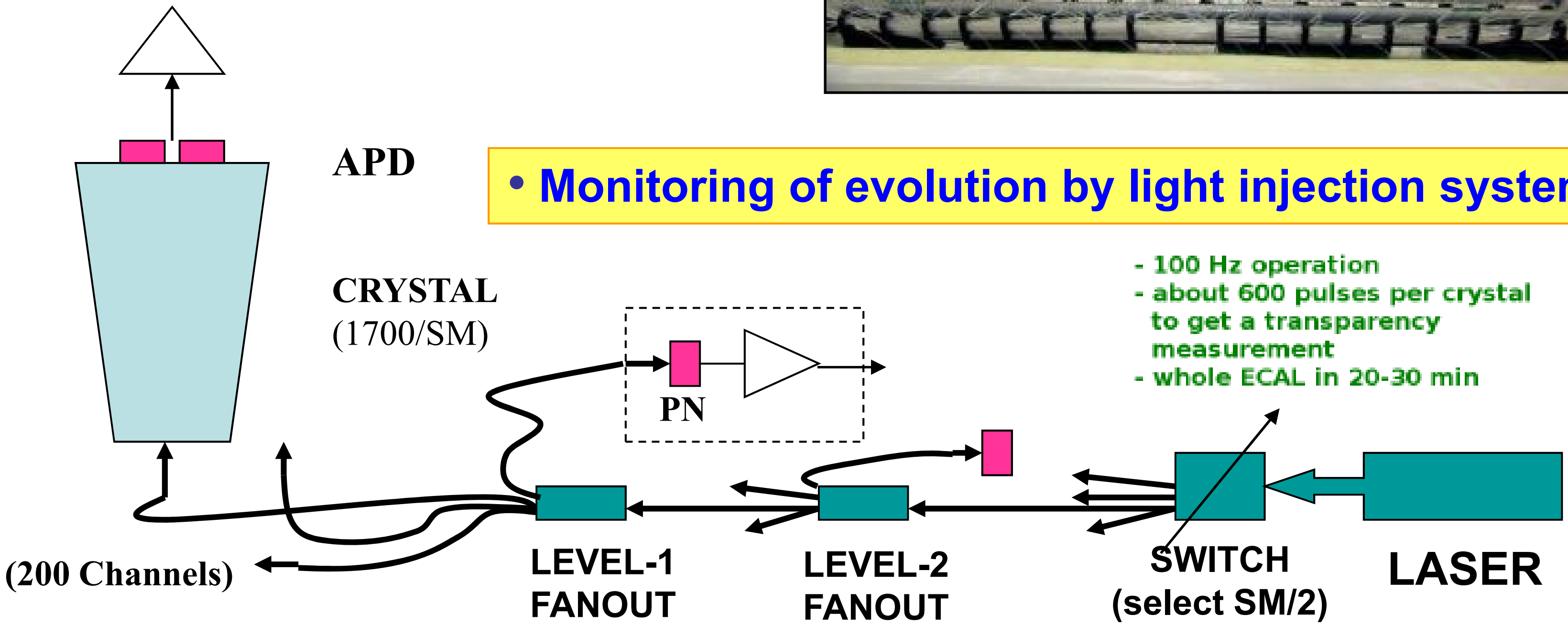


π^0 calib
Mid 2010

CMS ECAL monitoring system

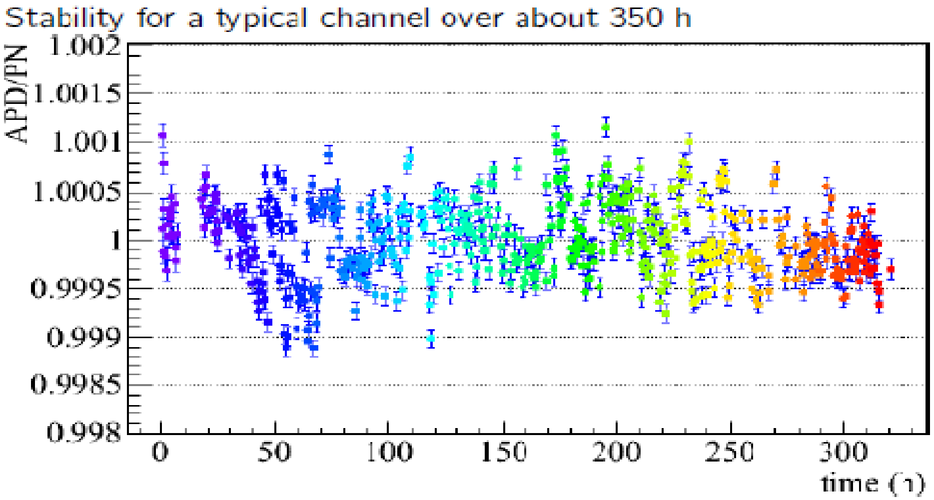
The Solution:
Damage and recovery during LHC cycles
tracked with a laser monitoring system
2 wavelengths are used:
440 nm and 796 nm
Light is injected into each crystal
Normalisation given by PN diodes (0.1%)

- Monitoring of evolution by light injection system



- 100 Hz operation
- about 600 pulses per crystal to get a transparency measurement
- whole ECAL in 20-30 min

ECAL monitoring system

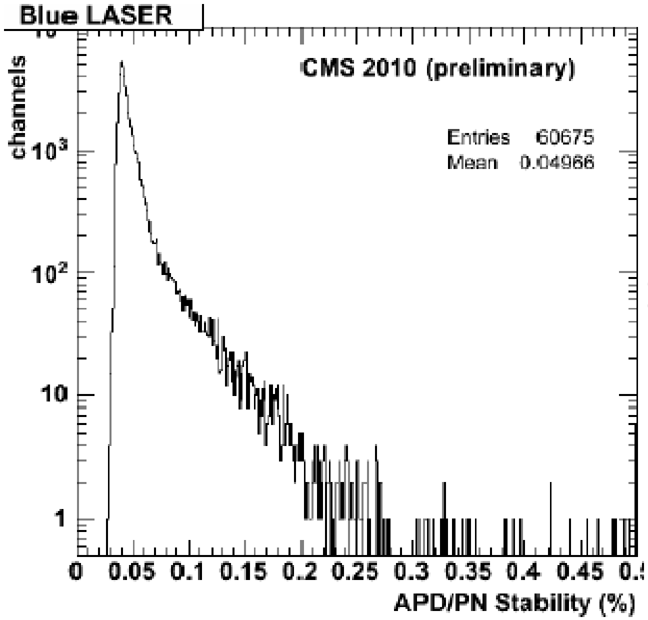


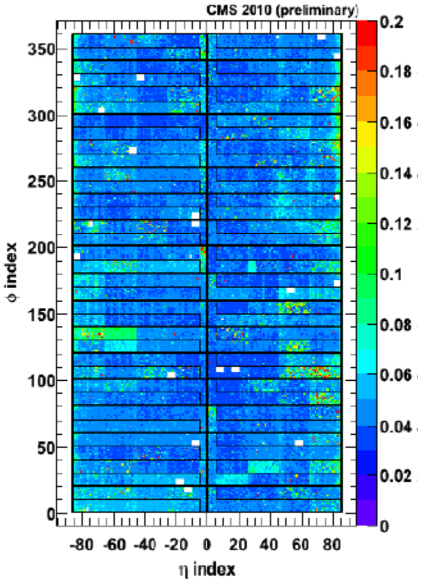
Stability for a typical channel over about 350 h

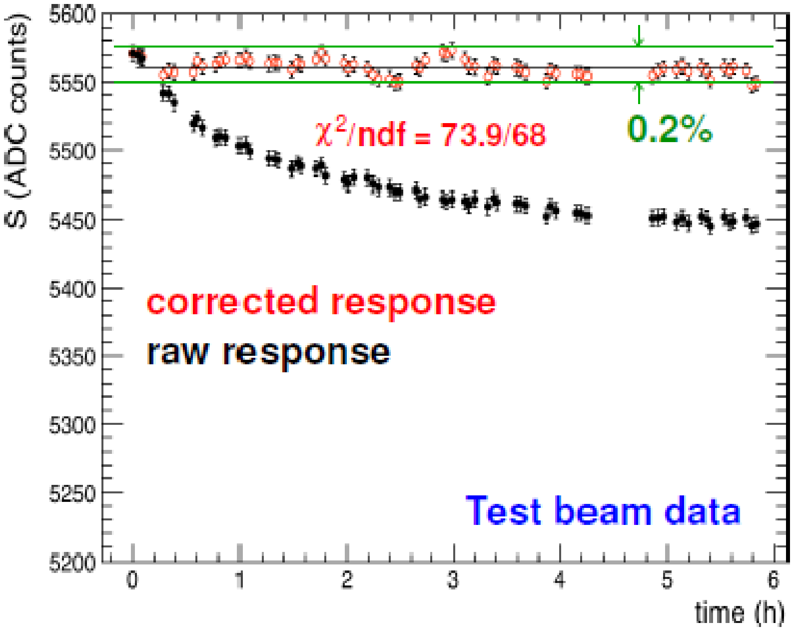
Measure a loss of transparency:
S (particle signal) and R(laser signal)

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

NB: α is ~ the same for all crystals!





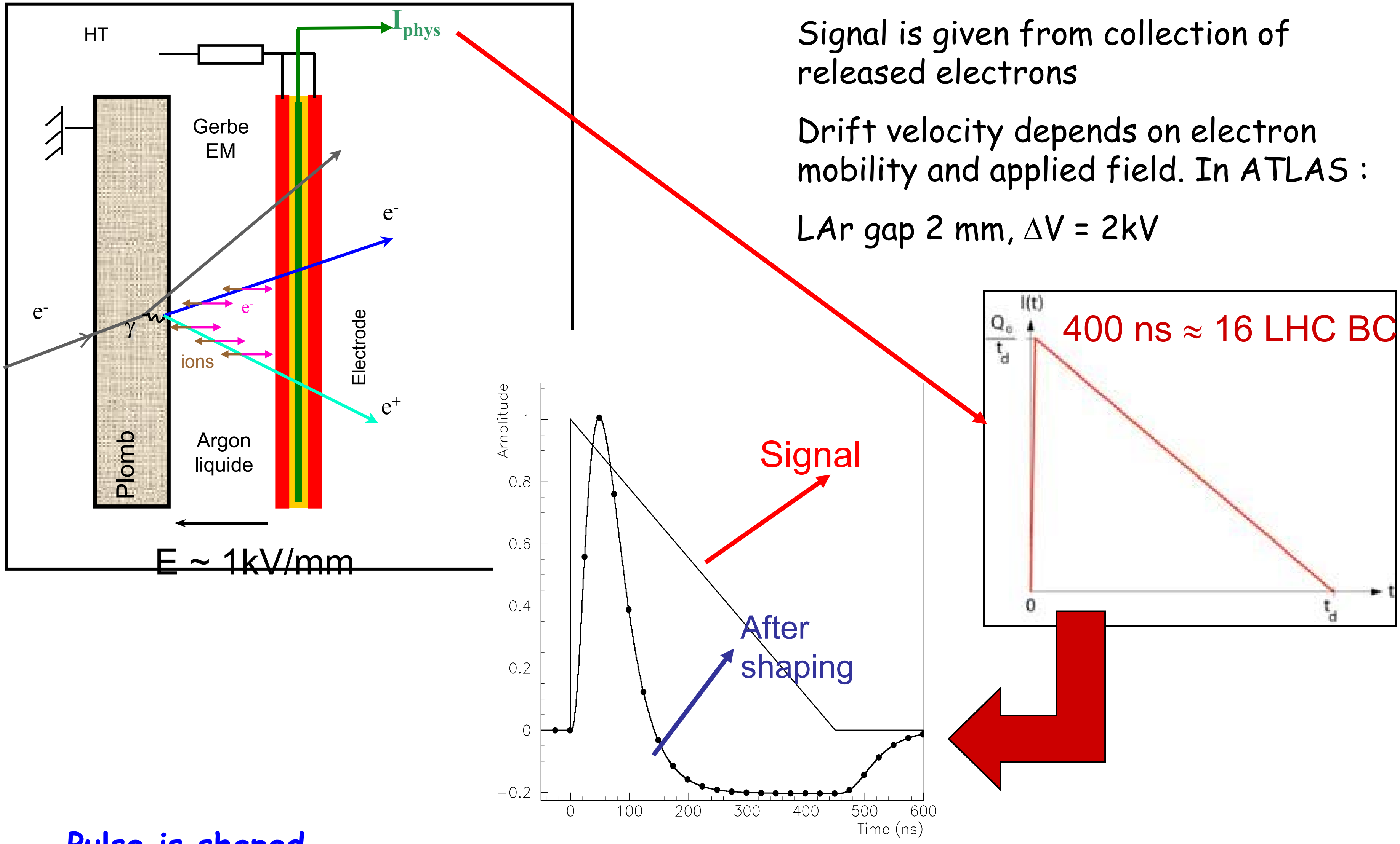


ATLAS em LAr

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

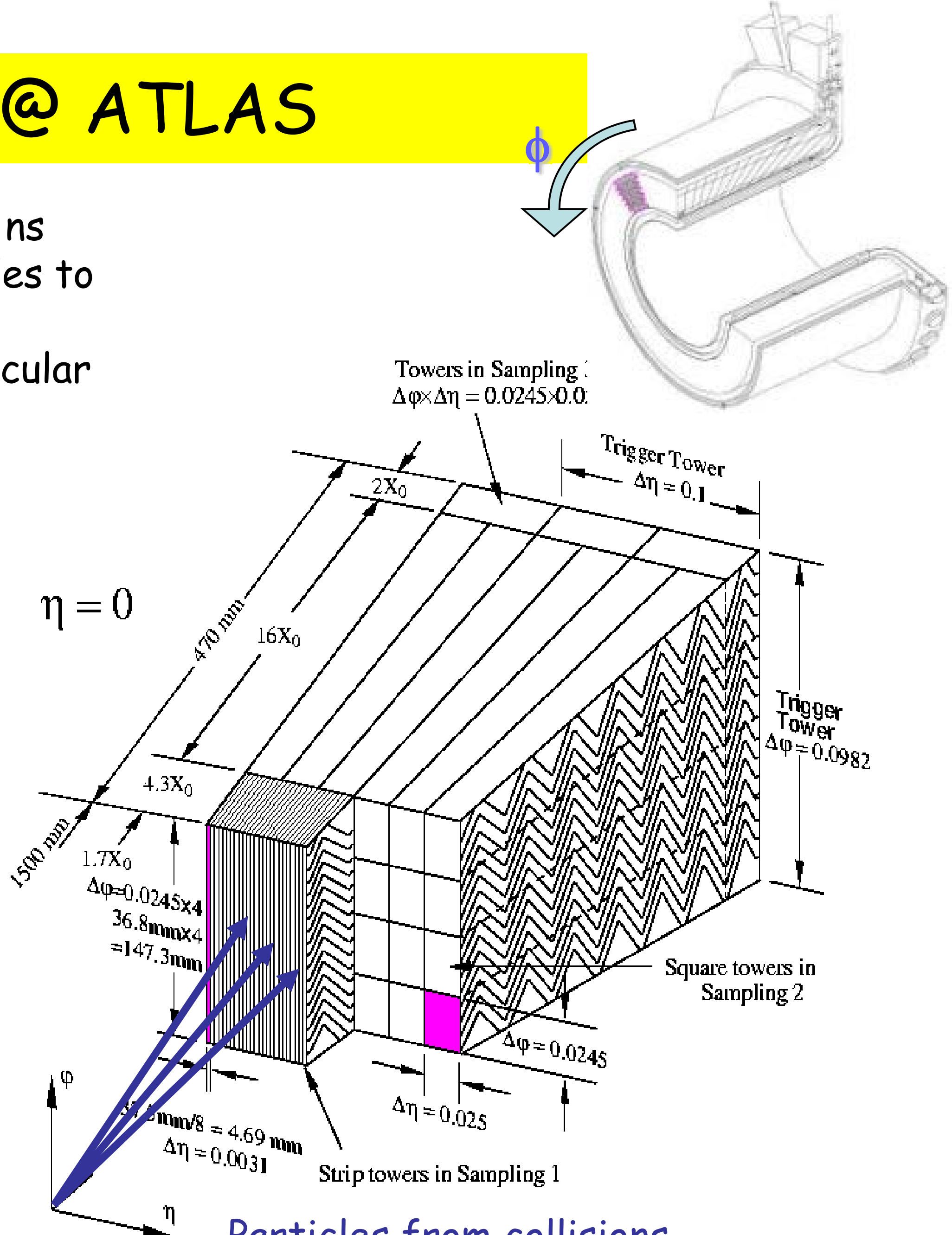


Pulse is shaped

has 0 time integral → mean value of pileup is cancelled (no baseline shift).

ECAL @ ATLAS

Shaping = integrate current over t_p =50 ns
→ requires transfer time from electrodes to readout chain < t_p = short cables
→ absorber and gap layers are perpendicular to particle direction → cracks
→ Avoided with accordion geometry



Particles from collisions

- Longitudinal dimension:

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

- 3 longitudinal layers

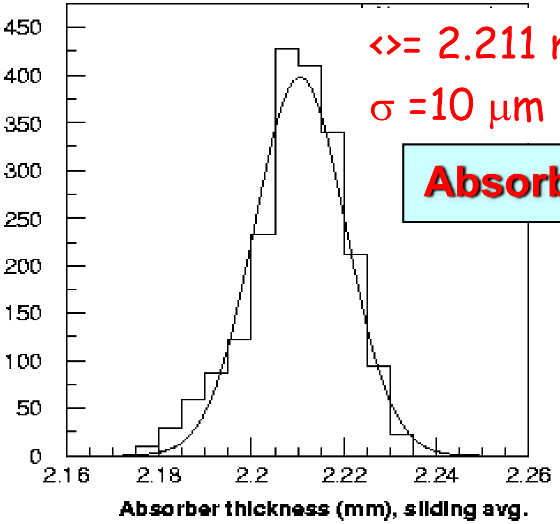
  $4\ X_0$ π^0 rejections separation of 2 photons very fine grain in η

  $16\ X_0$ for shower core

  $2\ X_0$ evaluation of late started showers

- Total channels ≈ 170000

The challenge of LAr accordion



<>= 2.211 mm

σ =10 μm

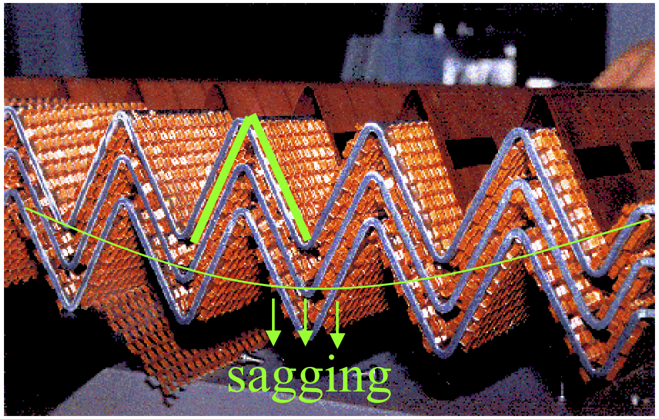
Absorber thickness

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 = 10 μm

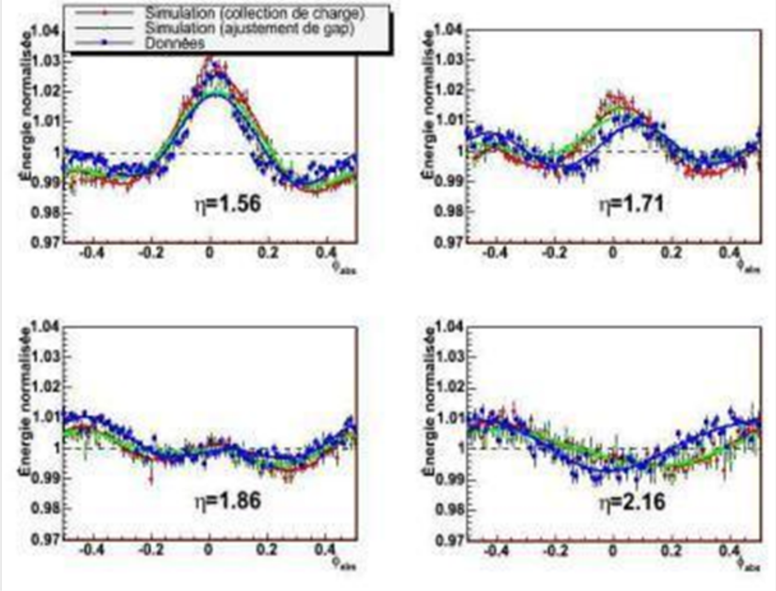
translates to<2 ‰ effect on constant term



ϕ-modulations in the EMEC

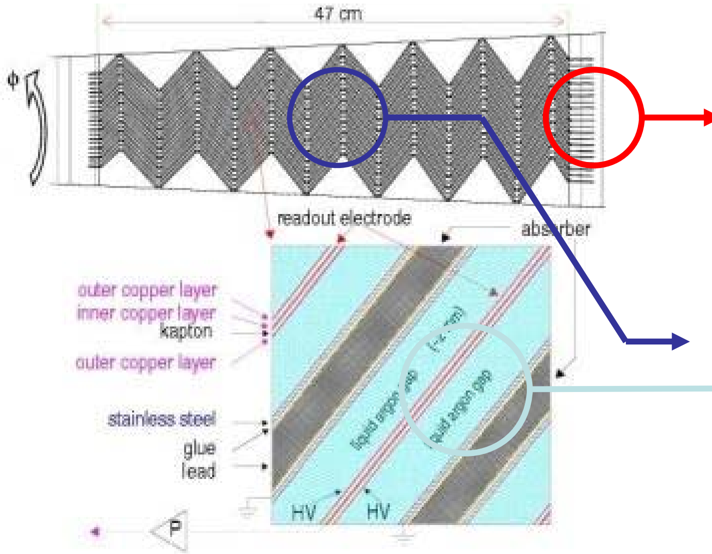
Calorimeter response is affected ~ 3 %

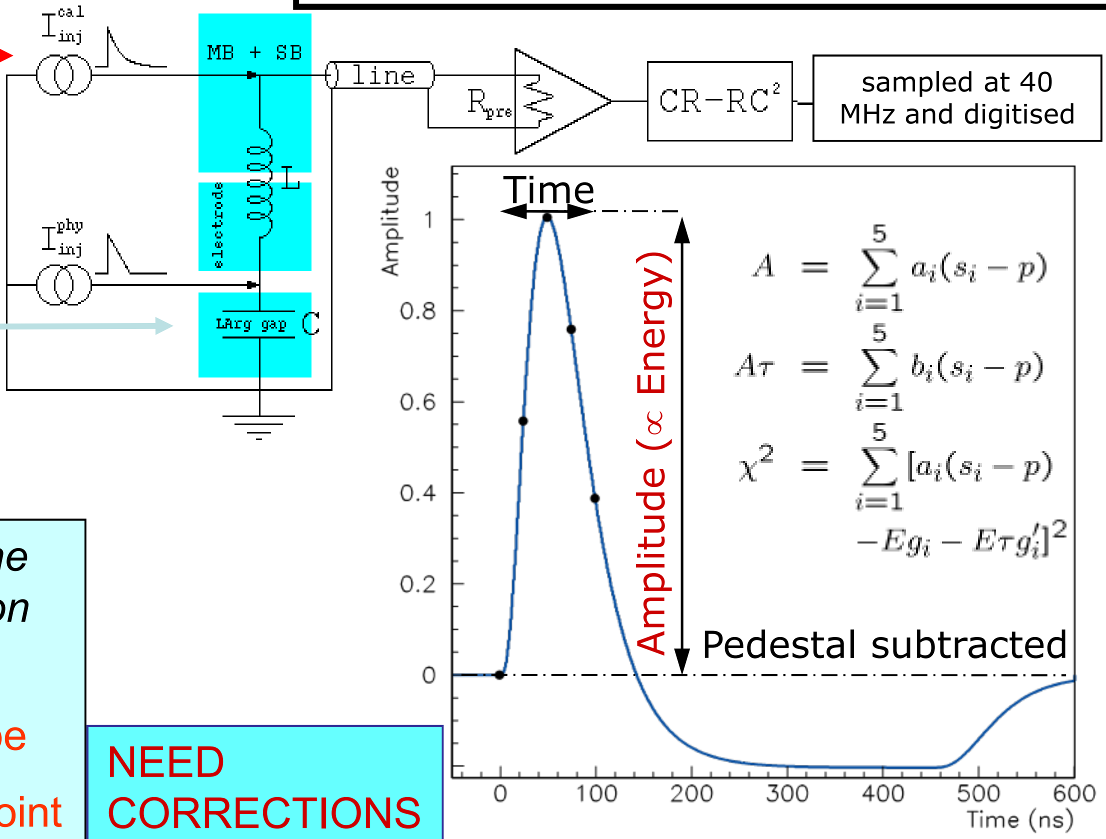
Response to 120 GeV e-showers



LAr electronics calibration

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





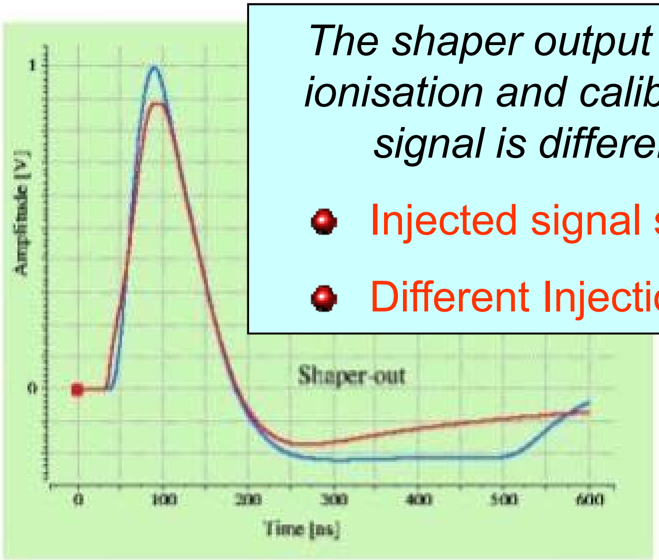
$$A = \sum_{i=1}^{5} a_i(s_i - p)$$

$$A\tau = \sum_{i=1}^{5} b_i(s_i - p)$$

$$\chi^2 = \sum_{i=1}^{5} [a_i(s_i - p) - Eg_i - E\tau g_i']^2$$

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

- Injected signal shape
- Different Injection point

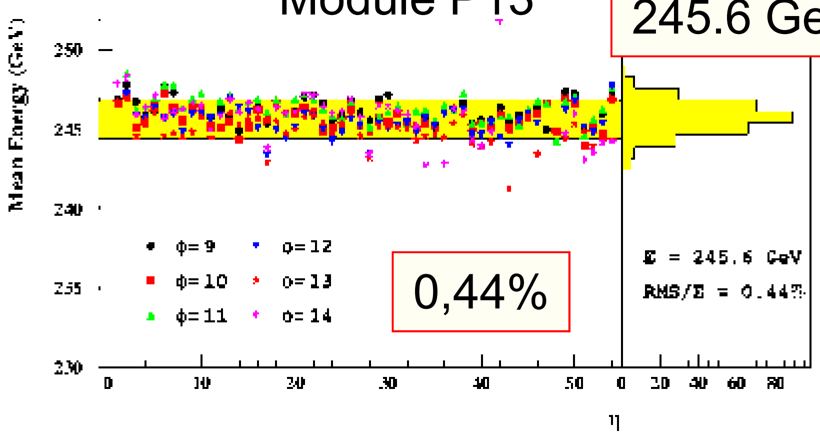


NEED CORRECTIONS

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

ATLAS EM uniformity (test beam)

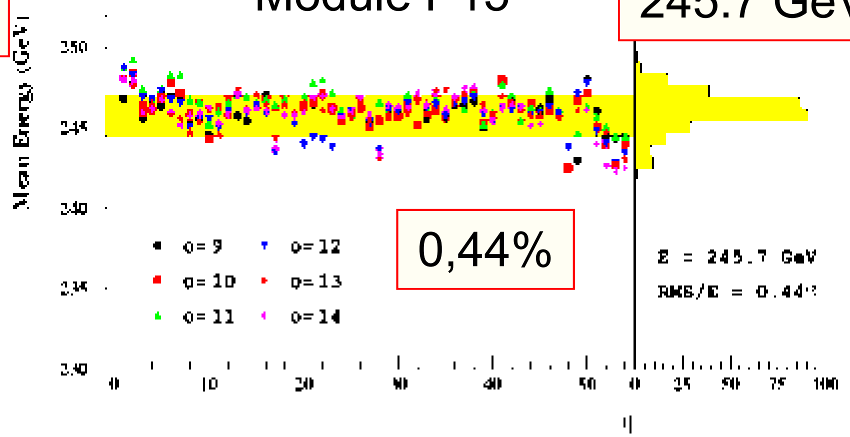
Module P13



245.6 GeV

0,44%

Module P15

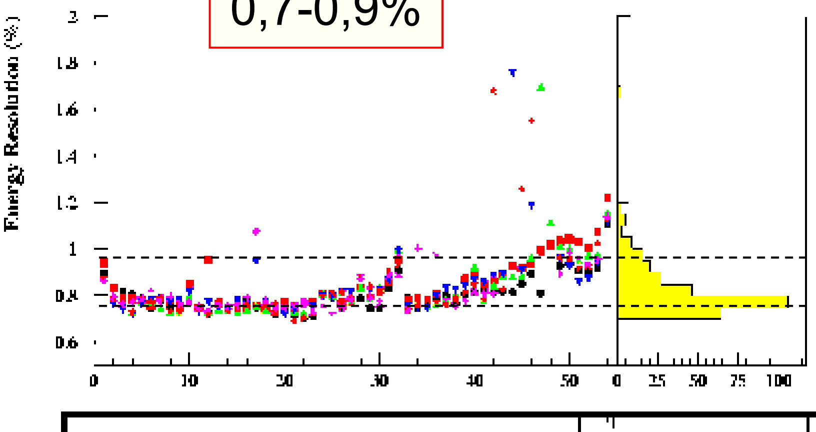


245.7 GeV

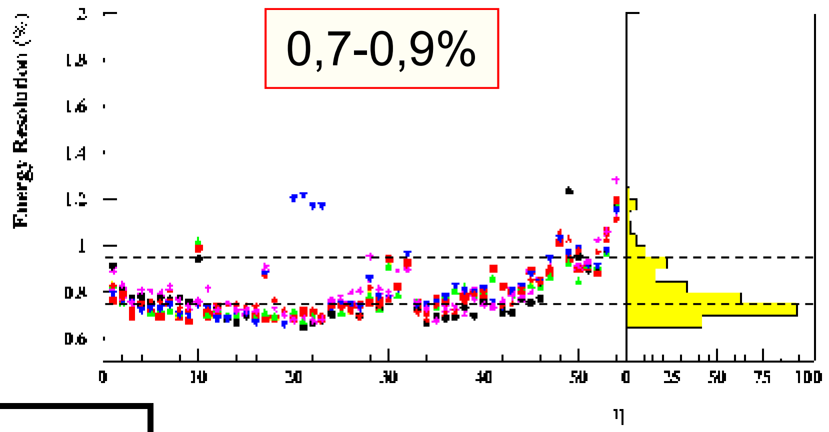
0,44%

Uniformity

Scan modules with monochromatic electrons



0,7-0,9%



0,7-0,9%

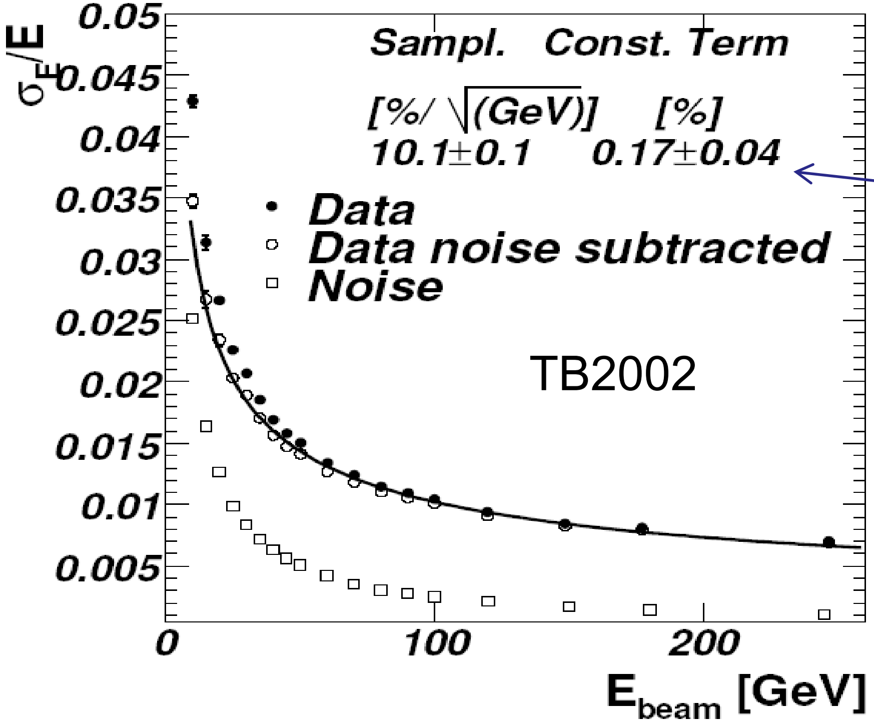
Resolution

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

P13/P15 ~ 0.05%

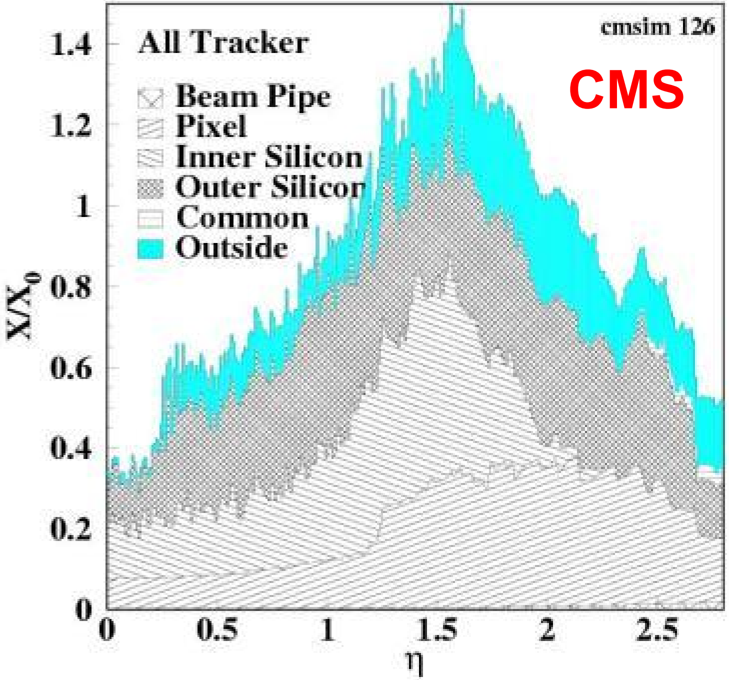
Ratio of absolute response

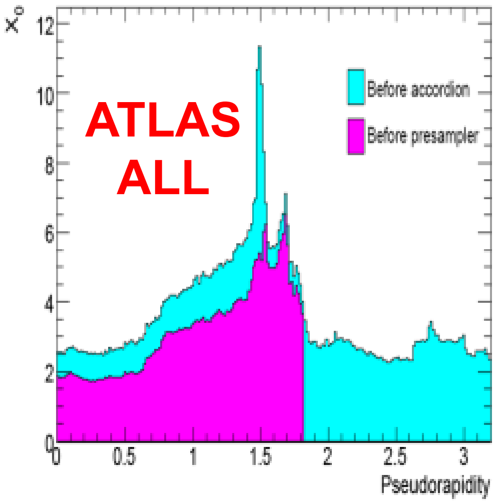
ATLAS EM: resolution in test beam

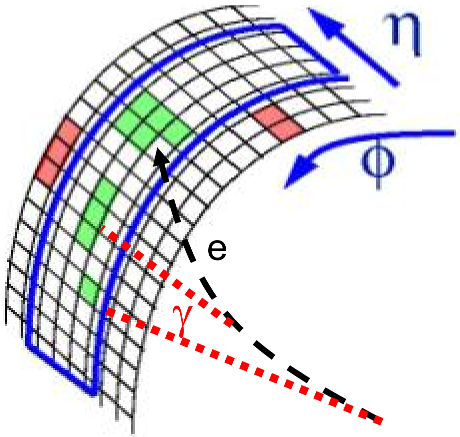


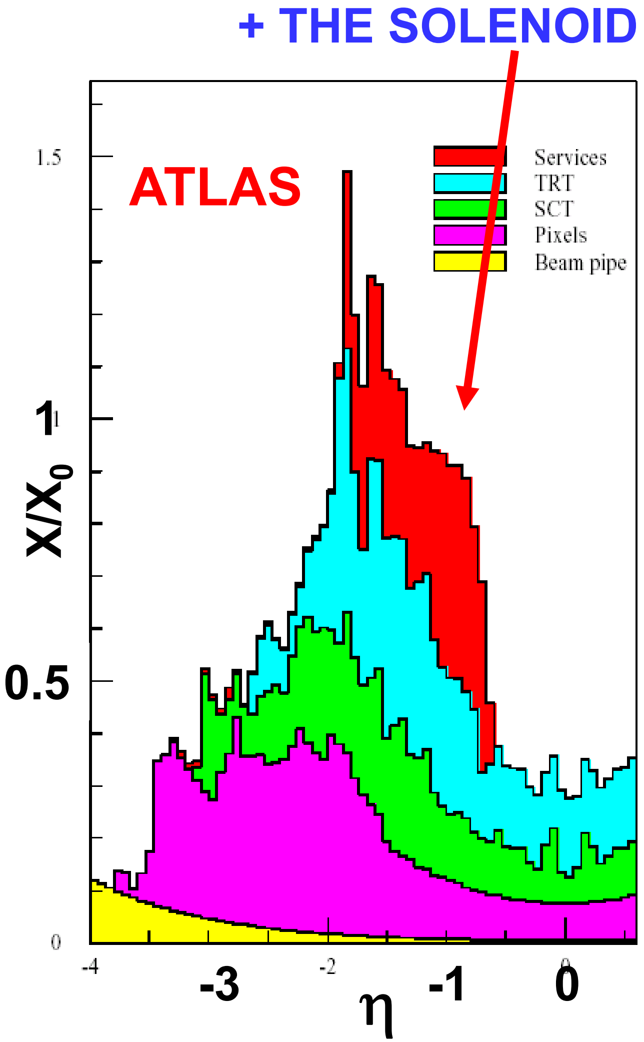
LOCAL RESOLUTION

The bitter reality: material in front









Tracker material :

- electrons loose energy via bremsstrahlung
- photons convert

4T (2T) solenoidal B field :

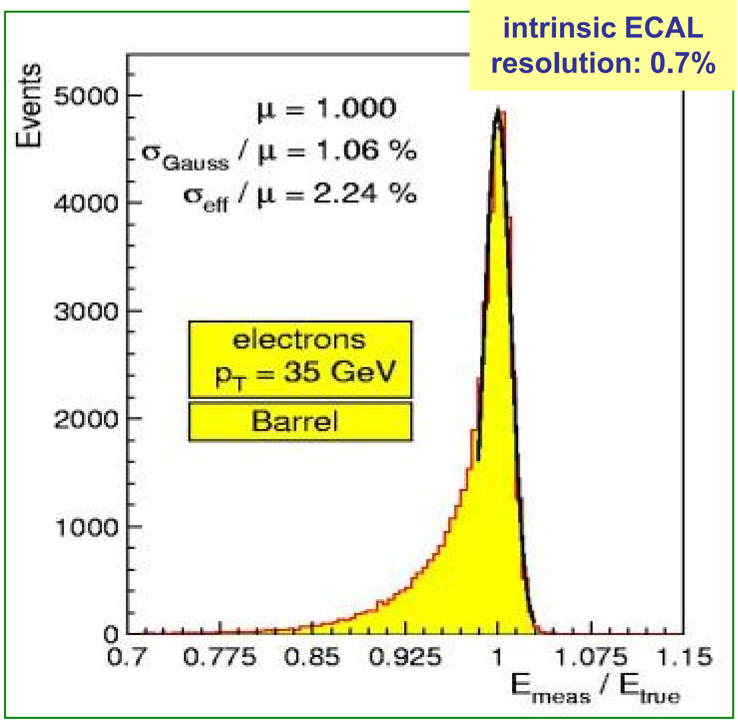
Electrons bend ⇒ radiated energy spread in φ

Blur sharpness of Trigger thresholds

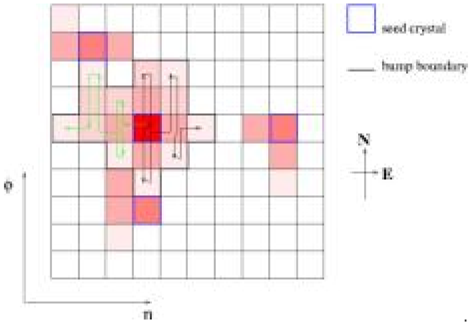
The bitter reality (2)

Solutions

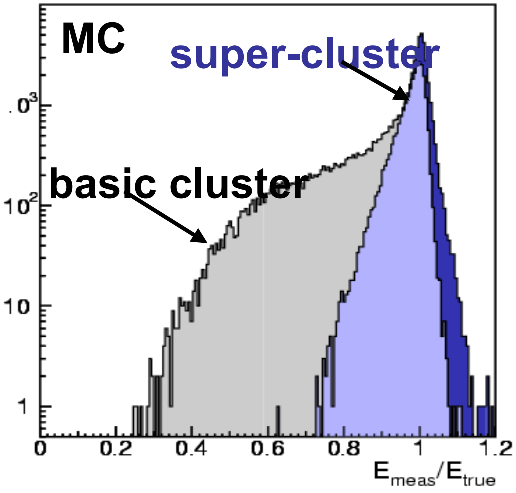
- Increase clustering in ϕ to collect all energy
- or dynamic cluster algorithm to find the “bits and pieces”
- or identify brems following track kinks (PFlow in CMS)
- or tag high quality (low brems) electrons, using Tracker curvature info or E/p



intrinsic ECAL resolution: 0.7%

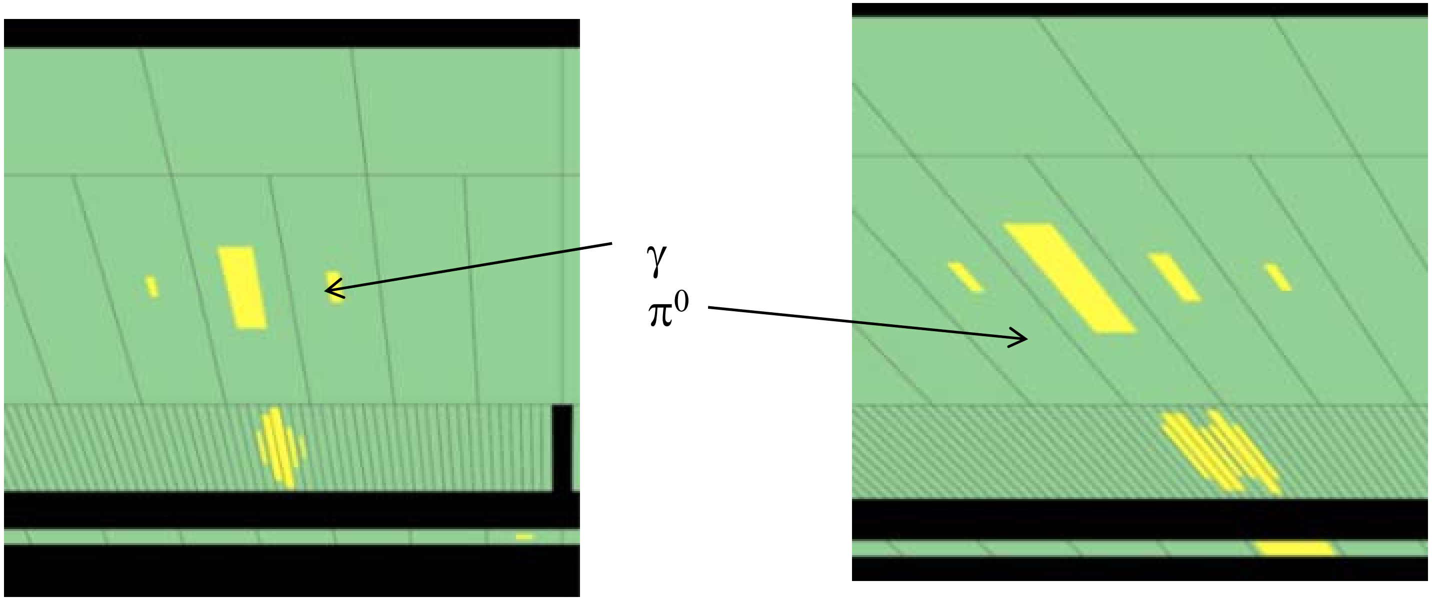


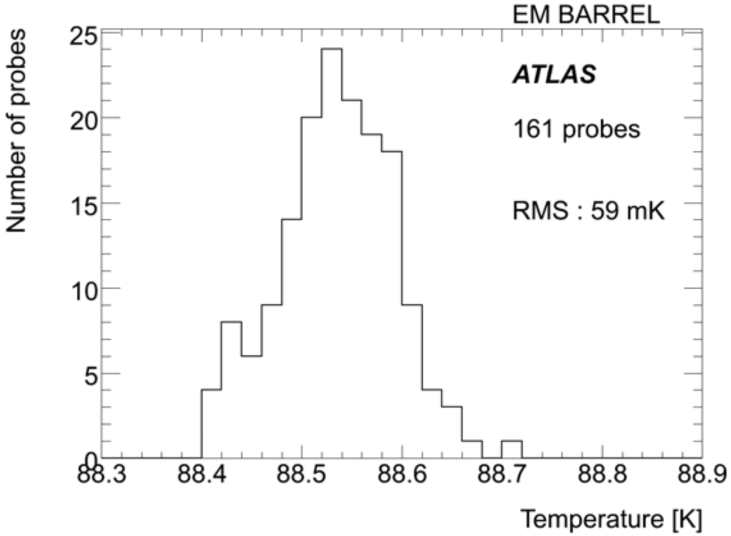
Dynamic super-cluster



CMS example

Performance in situ : ATLAS

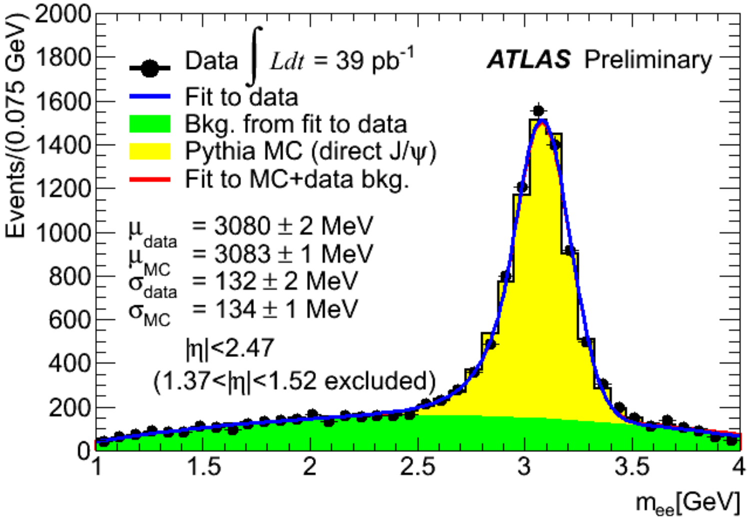


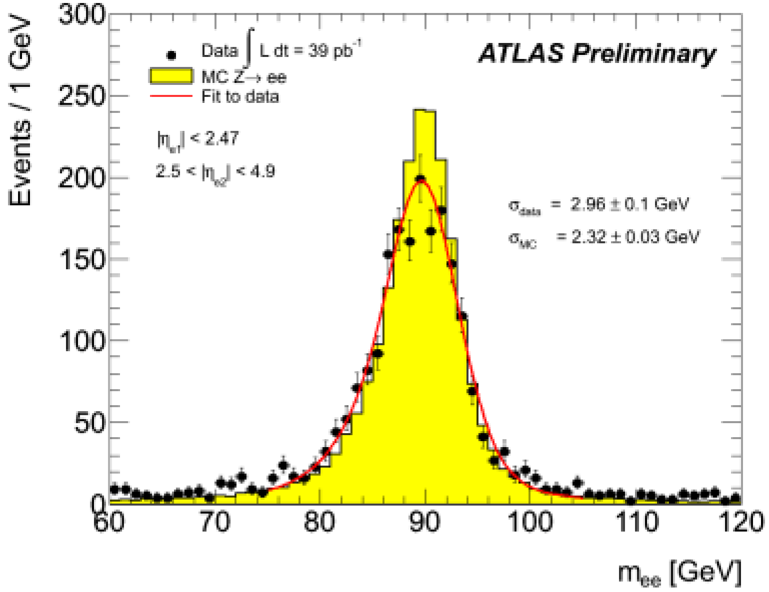


Temperature stability

$\varepsilon_{\text{Barrel LAr}}$ 97.9% in 2010

Performance in situ: ATLAS



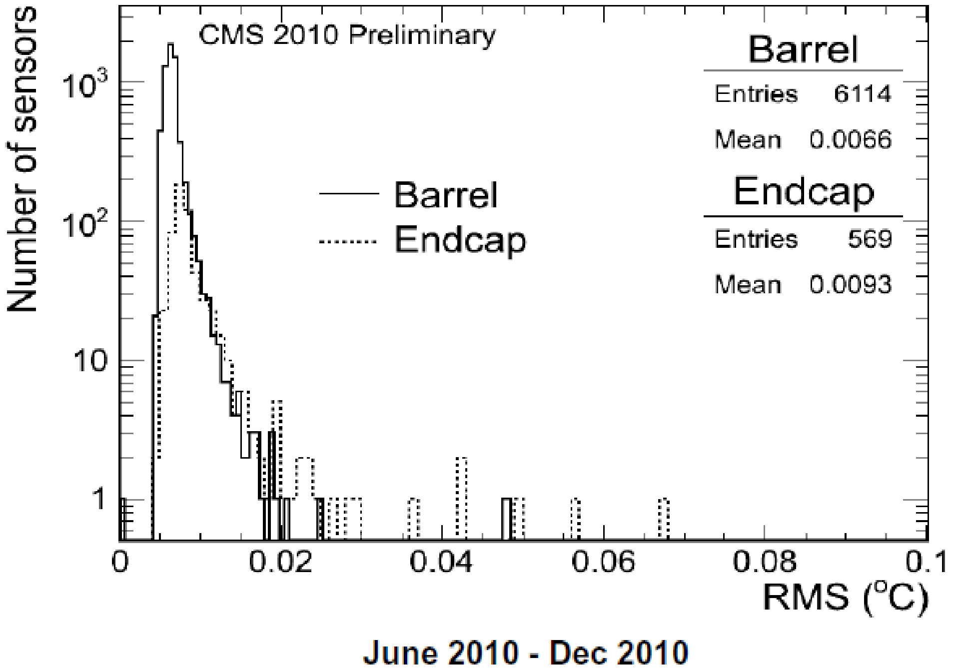


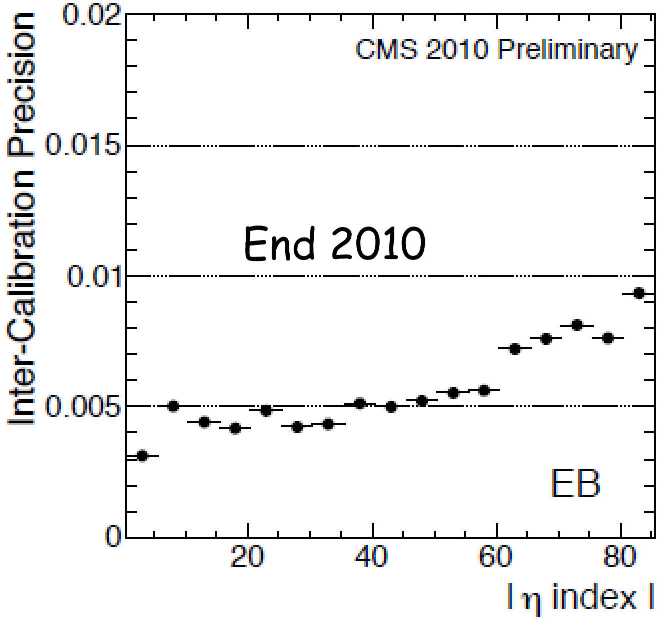
Excellent agreement with expectations from simulation

Performance in situ CMS

$\varepsilon_{\text{Barrel ECAL}}$ 99.1% in 2010

$\varepsilon_{\text{Endcap ECAL}}$ 98.6% in 2010

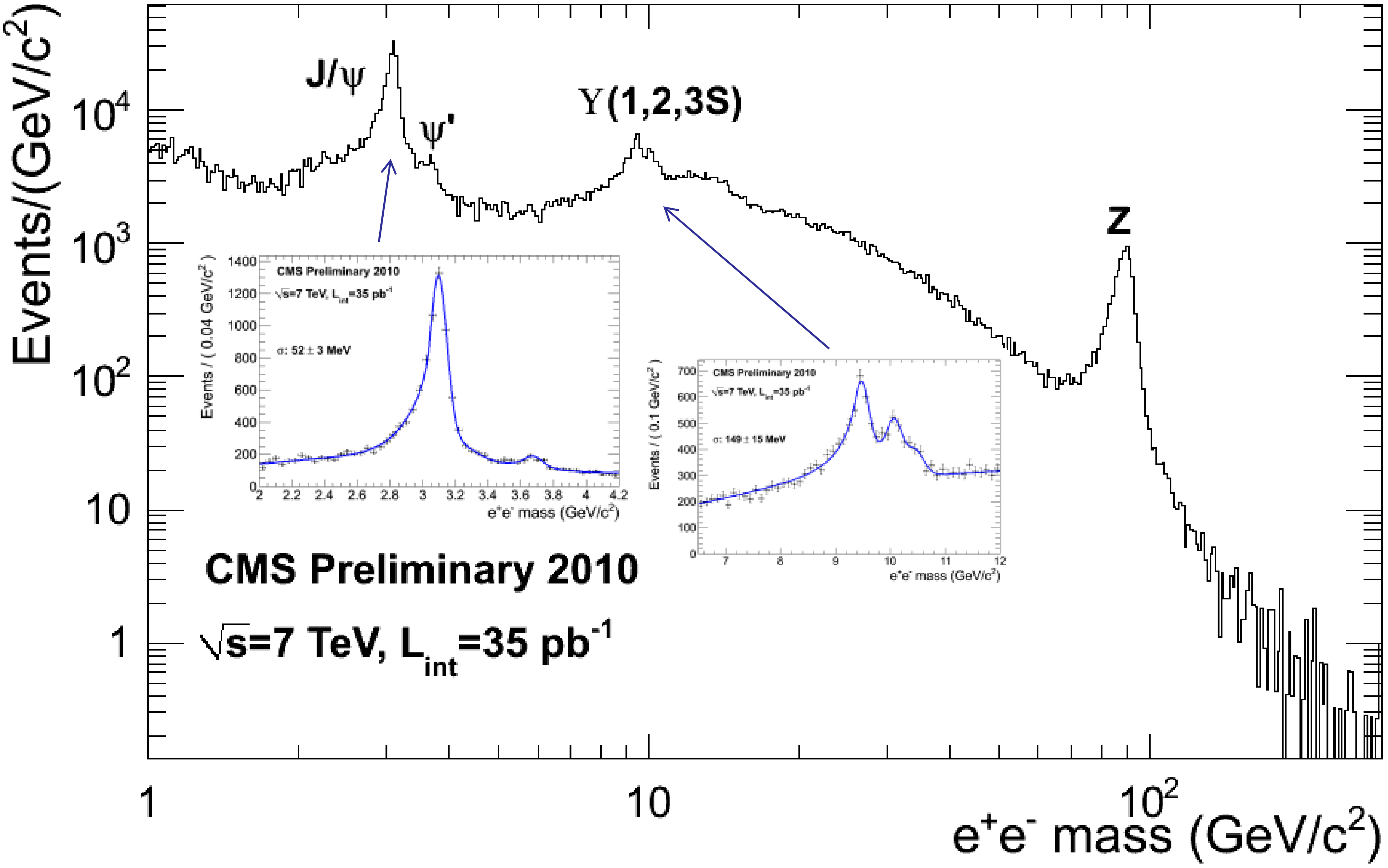




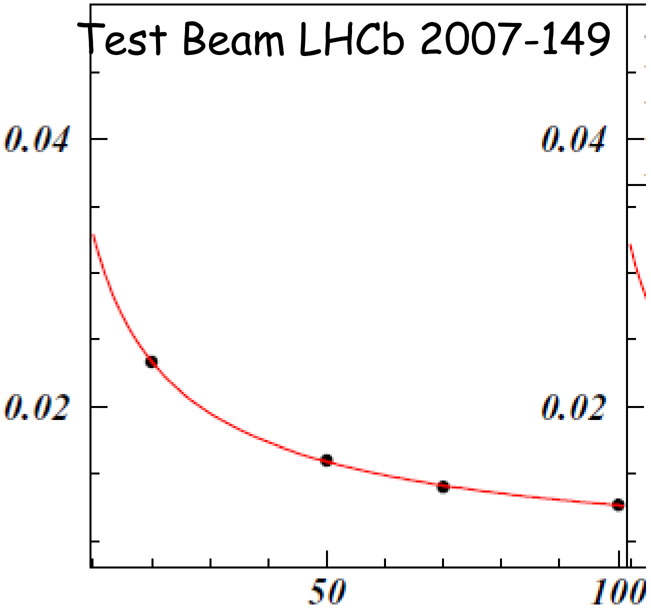
Temperature stability

Intercalibration precision

Performance in situ: CMS

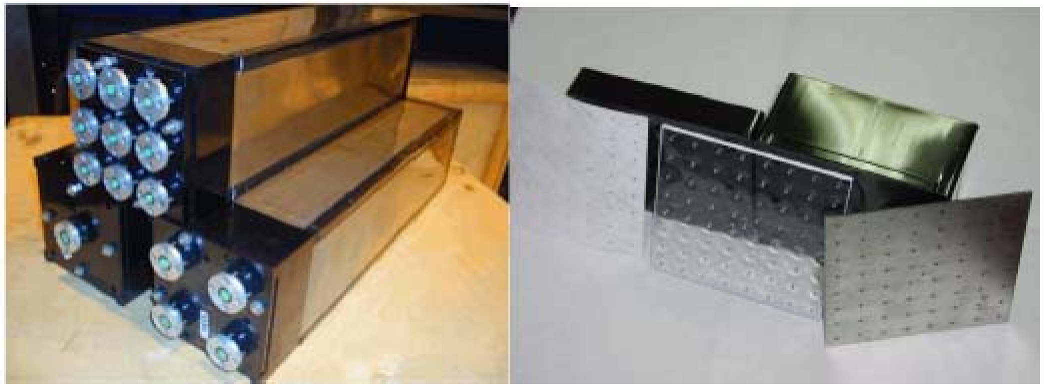


Performance LHCb



Shashlik (scint fiber-lead)
66 layers, total 25 X0
6016 channels
ε_{ECAL} 99.8% in 2010

$$\sigma/E \sim \frac{9.5\%}{\sqrt{E(GeV)}} \oplus \frac{0.11}{\mathrm{E}(GeV)} \oplus 0.83\%$$



2009 LHC data

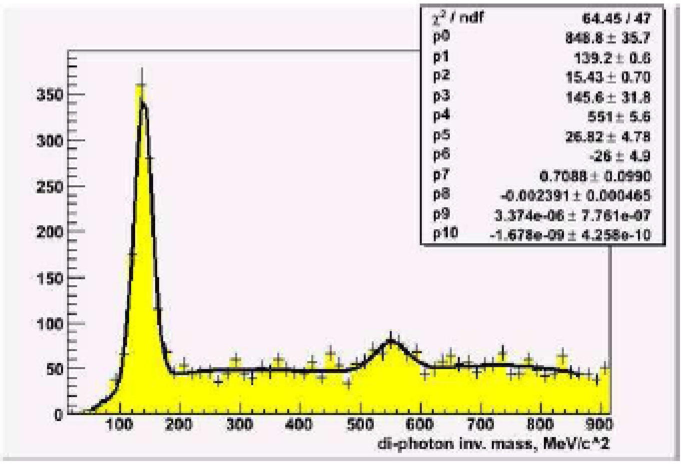


Figure 6: π^0 and η reconstructed from proton proton collisions.

Hadronic Calorimetry

Hadron calorimeter are essential to detect jets, which are fragments of fundamental constituents like quark and gluons.

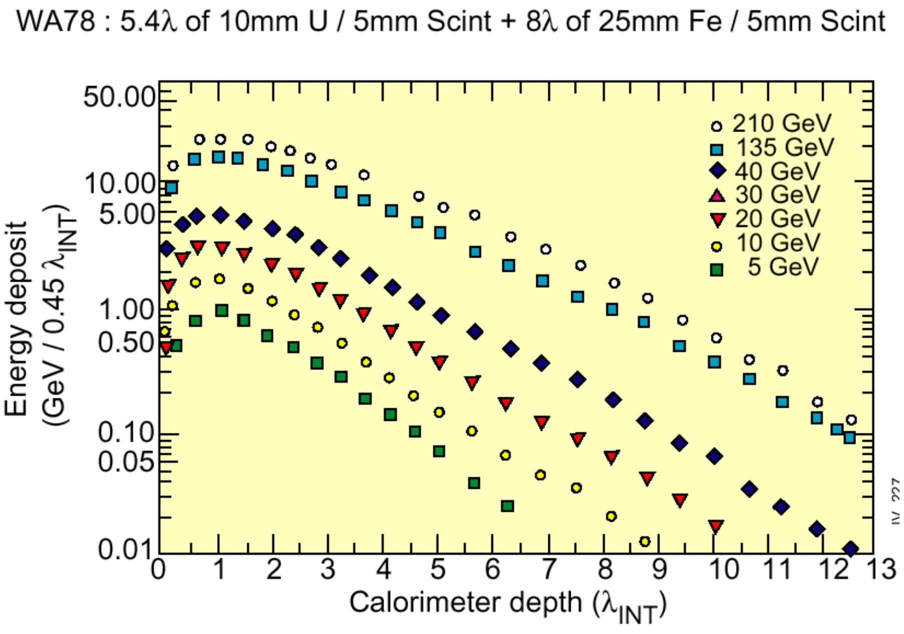
(a far more complicated story)

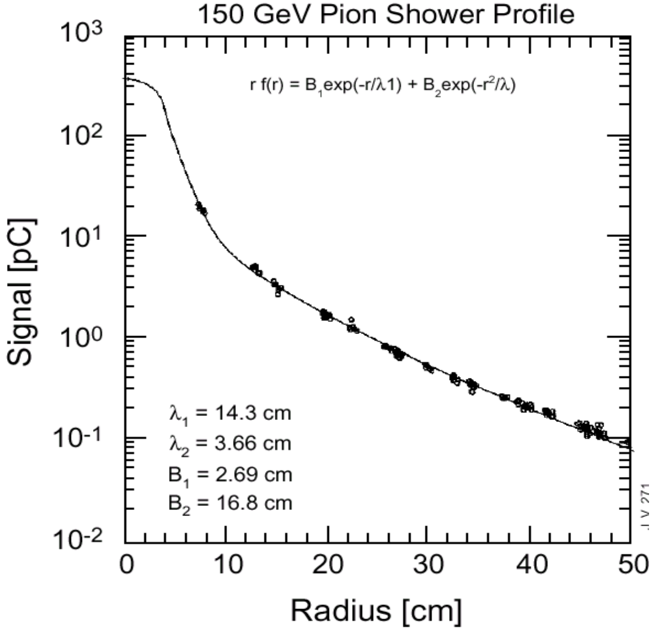
Hadron shower development

- Strong interaction is responsible for shower development
- A high energy hadron interacting with matter leads to multi-particle production, these in turn interact with further nuclei or decay (π^0)
- Multiplication continues until the pion production threshold.

Typical scale: interaction length $\lambda = 35\ A^{1/3}$ g cm-2 = 17 cm for iron

Good containment → 10 λ thickness → large size → sampling calorimeters



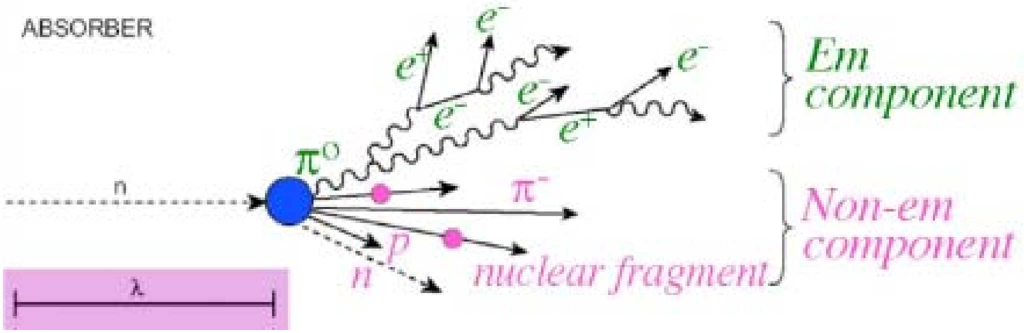


Longitudinal development

Transverse development

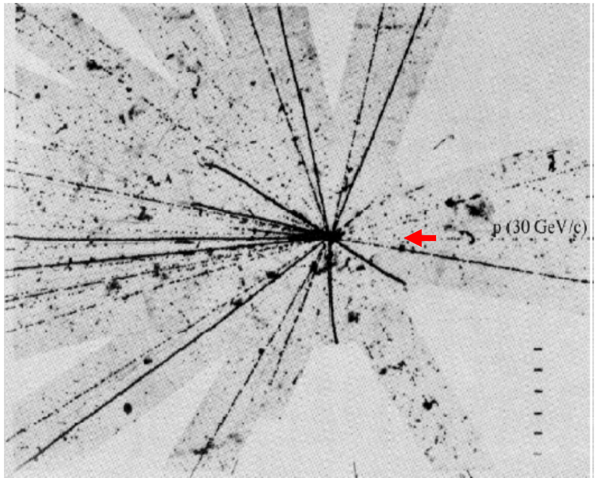
Hadron showers composition is complex

- π^0s decay before interacting
- Nuclei breakup leading to spallation neutrons/protons



Electrons, photons
$\pi^0 \rightarrow 2\gamma$

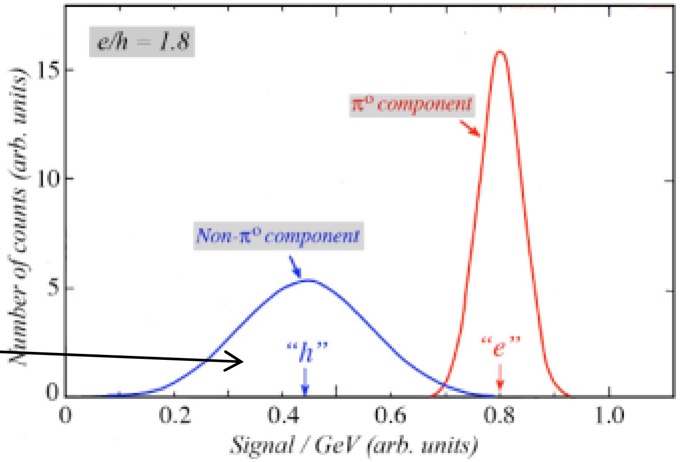
Charged hadrons	(20%)
Nuclear fragments , p	(25%)
Neutrons, soft γ's	(15%)
Breakup of nuclei	(40%)



Either not detected or often to slow to be within detector time window

= Invisible energy

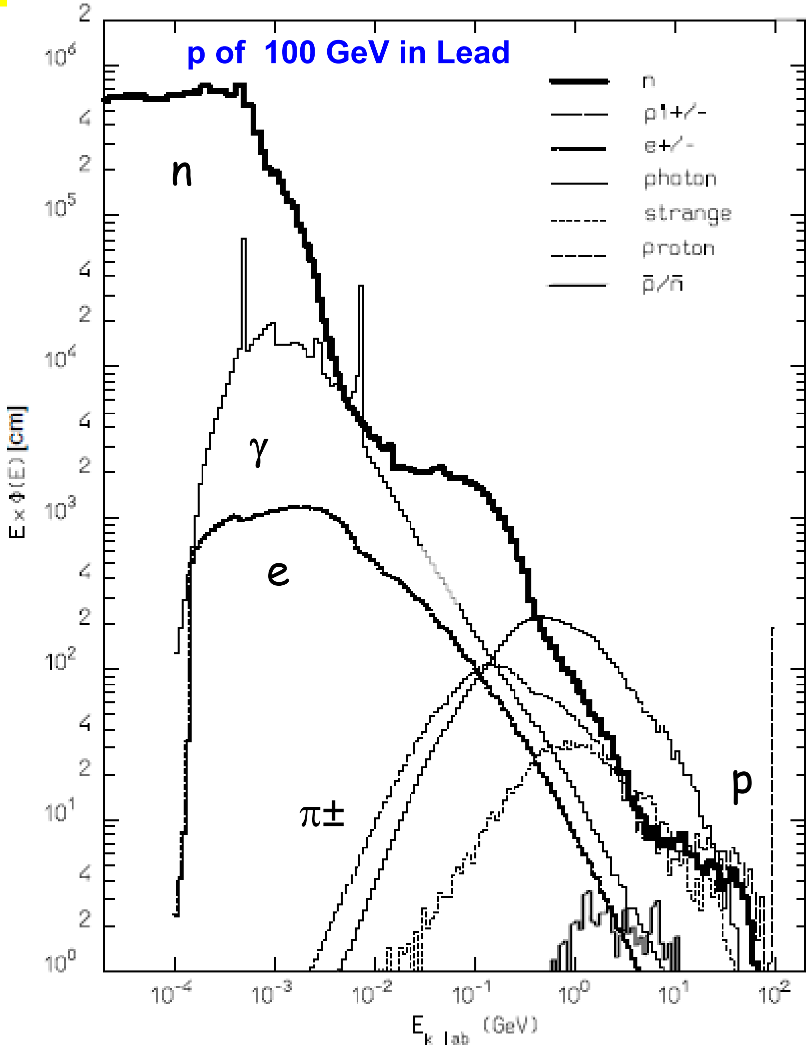
e/h > 1



Hadron showers composition is complex

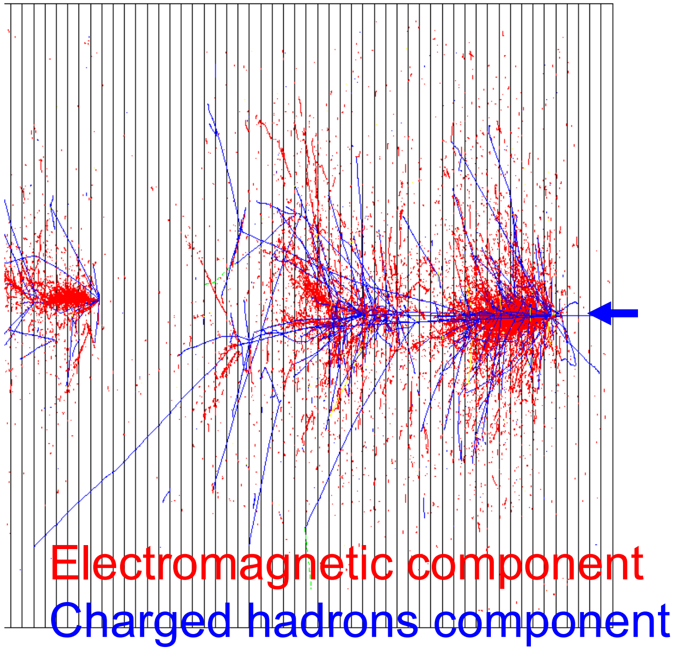
The fractions fluctuate in a non-Gaussian way
They are energy dependent
They depend of initial particle (π, p)

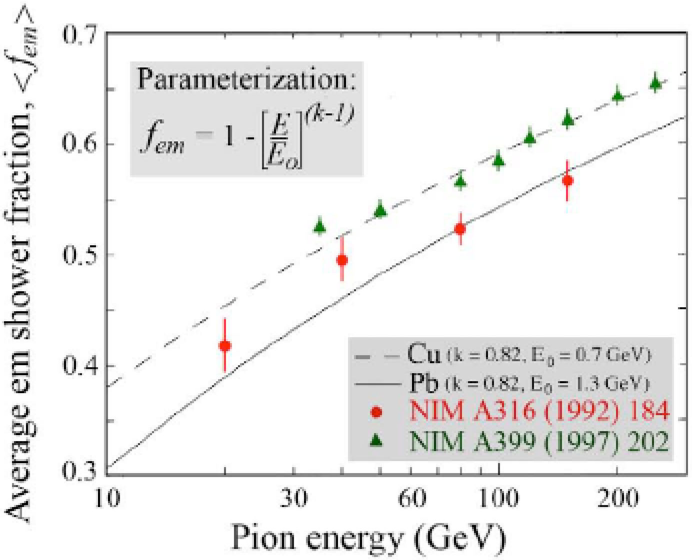
This makes also the simulations very difficult as the number of physical processes is large and spans from high (GeV) to low (< MeV) energies

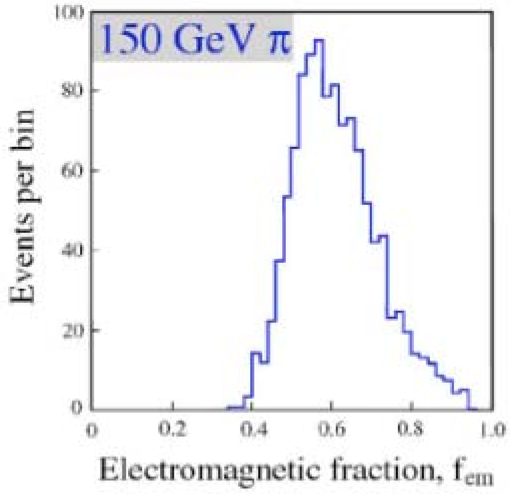


Hadron shower induced by a 100 GeV proton in Lead: energy spectra of the major shower components weighted by their track length in the shower (average) ref Ferrari 2001

electromagnetic component variation





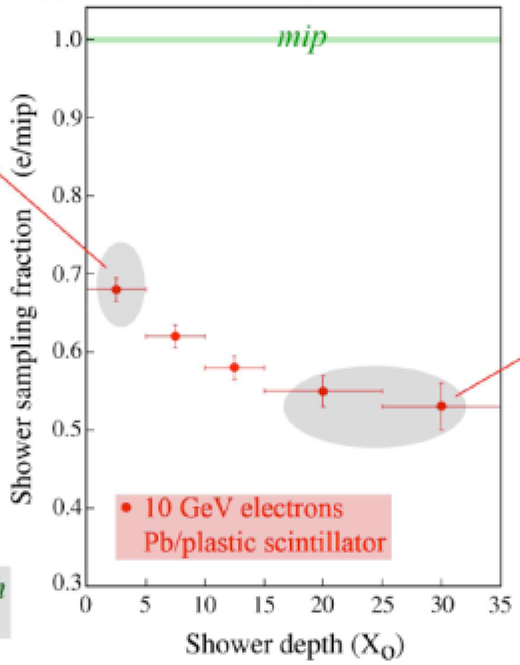


The em fraction f_{em} :

- is large and varies with energy
- fluctuates with non Gaussian tails
- gives a different answer as pure hadronic one

→ non linearity
→non Gaussian response function
→poor energy resolution

Dependence on shower starting point

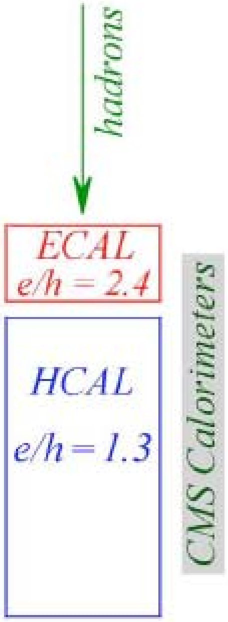


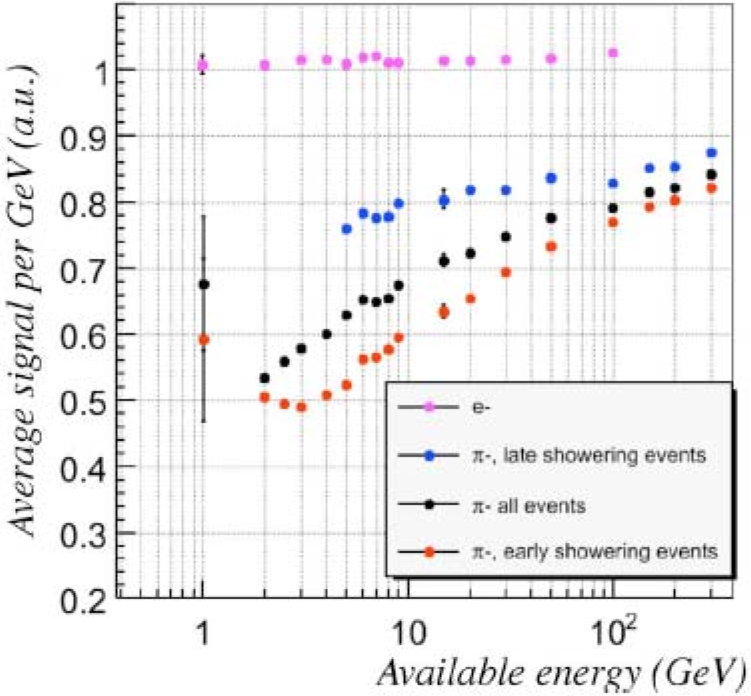
shower dominated by mip's

shower dominated by soft γ's

**By as much as 30%!*

The composition varies along the shower development





Way out?

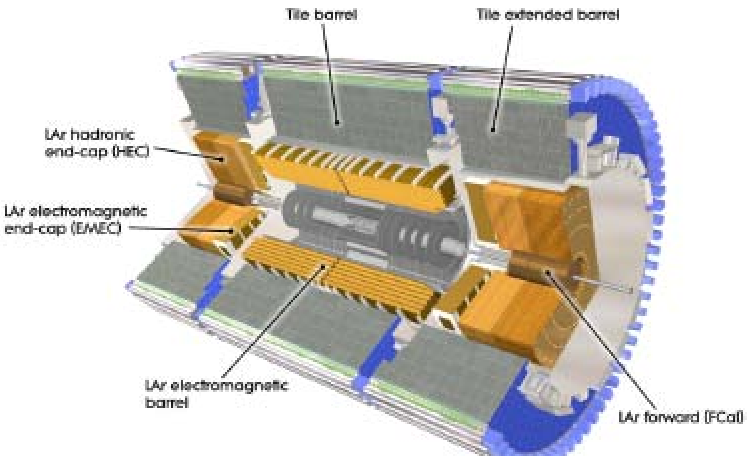
Different approaches can be used to solve this problem

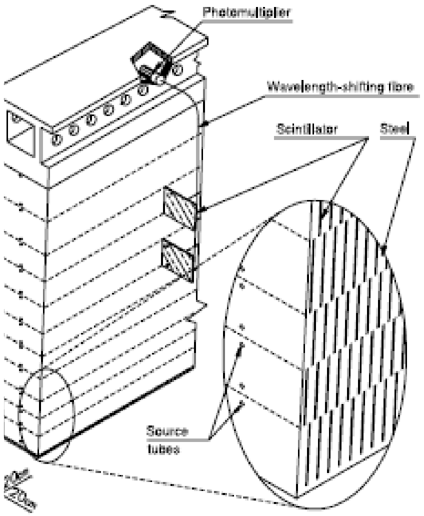
1. Compensation
   - Software: Identify em hot spots and down-weight Requires high 3D segmentation ex: H1, (ATLAS)
   - Hardware : Bring the response of hadrons and electrons to the same level (e/h =1) to that fluctuations do not matter ex: Zeus
2. Dual (or triple) readout

   Evaluate the 2 components (+ possibly slow neutrons)
3. Particle flow

   Use only the calorimeter for the neutral hadron component

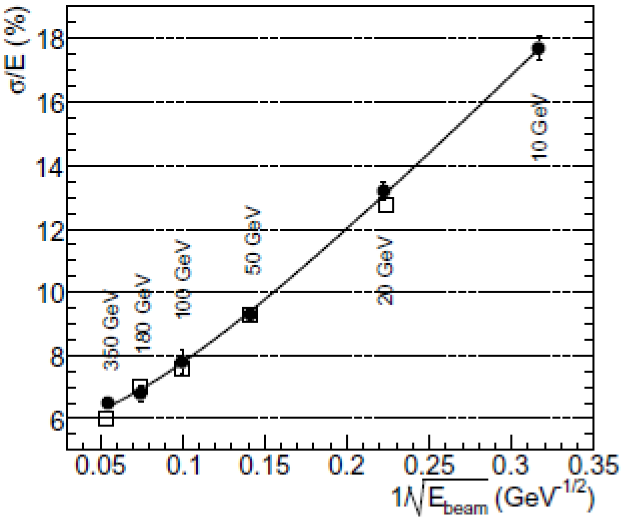
Example : ATLAS TileCal

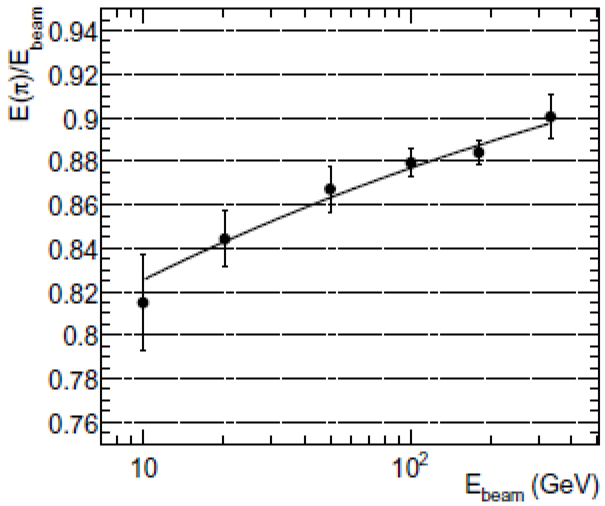




TileCal 9836 channels

4 radial segmentations





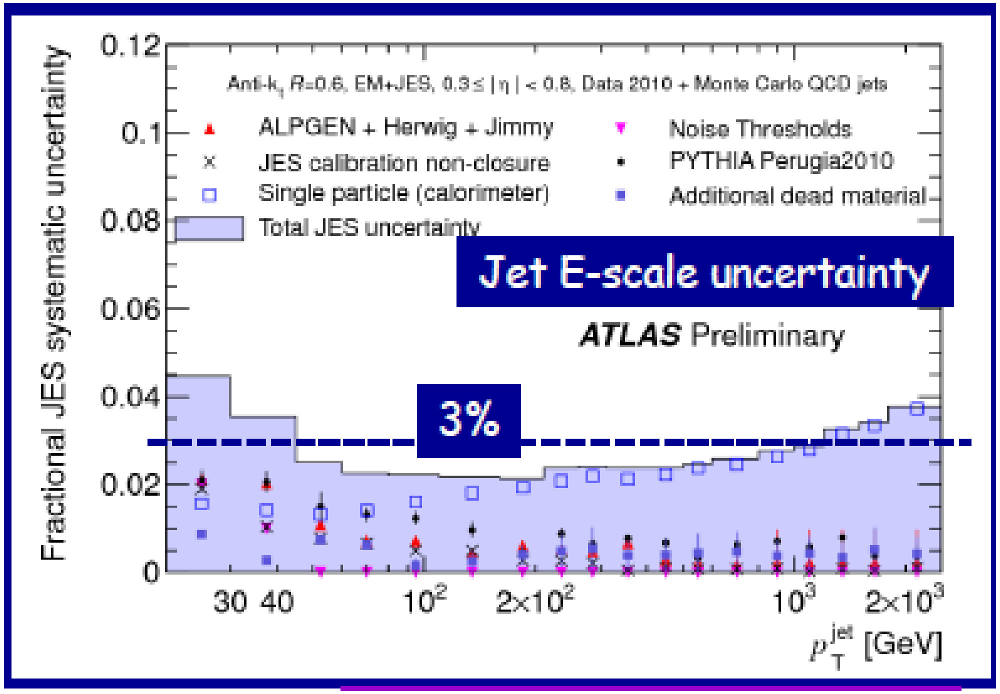
$$\frac{E(\pi)}{E_{\mathrm{beam}}} = (1 - F_{\mathrm{h}}) + F_{\mathrm{h}} \times \left(\frac{\mathrm{e}}{\mathrm{h}}\right)^{-1}$$

$$\frac{\sigma(E)}{E} = \frac{52\%}{\sqrt{E}} \oplus 5.7\%$$

e/h = 1.33

Nucl. Instrum. Methods Phys. Res., A 606 , 3 (2009) 362-394

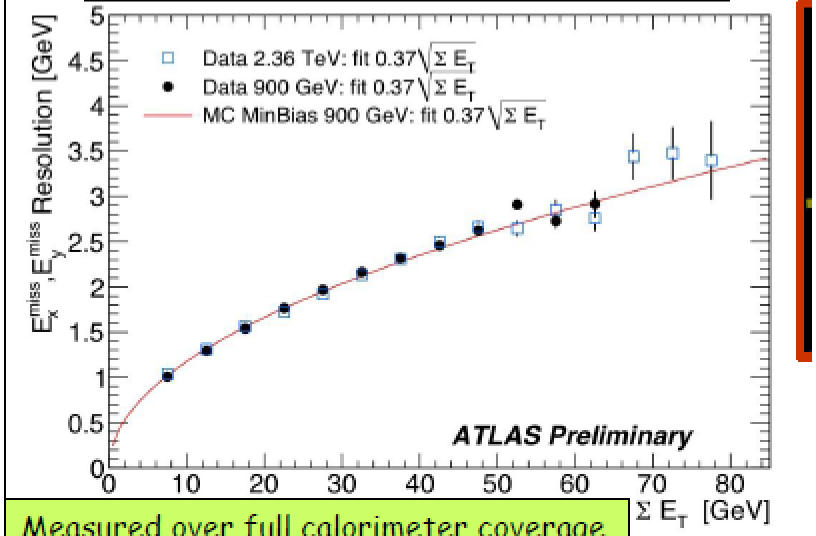
ATLAS : final product performance in situ



Jet E-scale uncertainty

3%

Missing transverse energy resolution

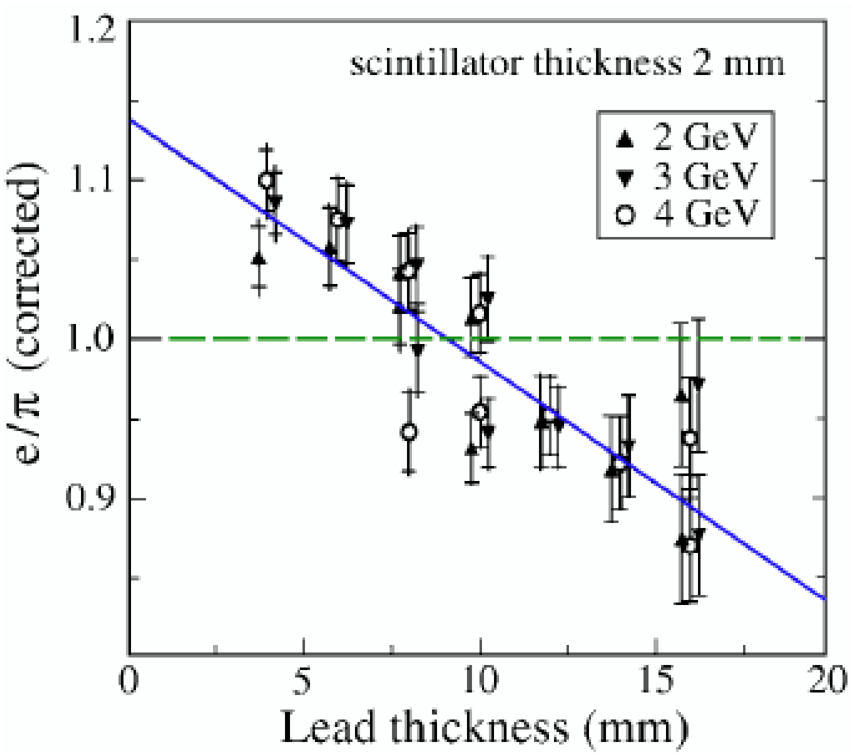


Measured over full calorimeter coverage
(360⁰ in φ, |η| < 5, ~ 200k cells)

Hardware Compensation

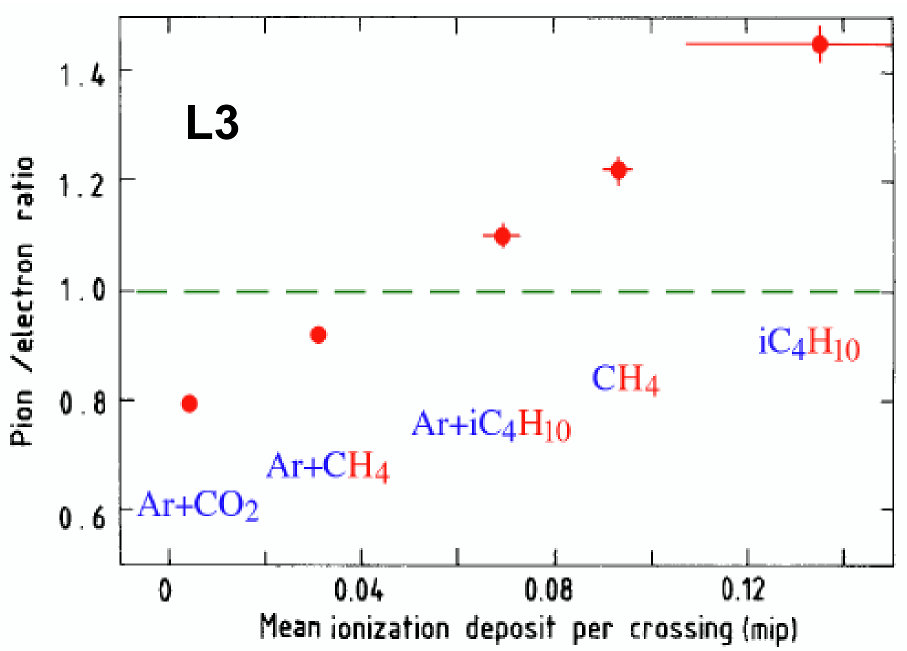
- enhance n production through fission (^{238}U calo: initial idea of Willis)
- Suppress em component (high Z abs.)
- enhance response to n using active materials hydrogen reach

Pb/Scintillator



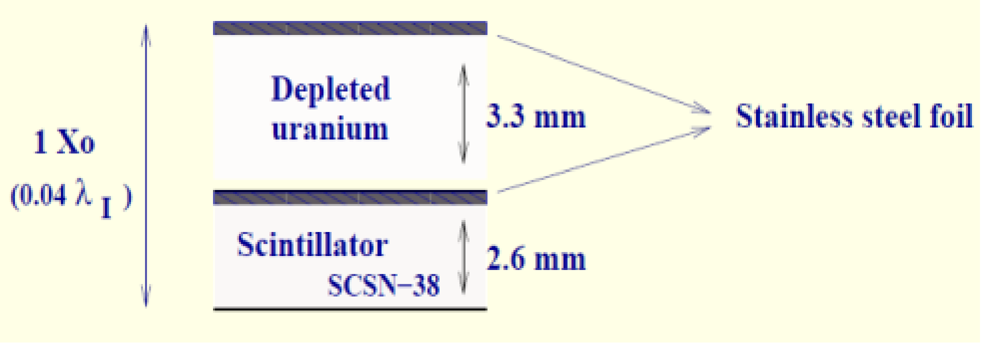
Sampling fraction can be tuned to achieve compensation

Hydrogen in active material (gas mixture)

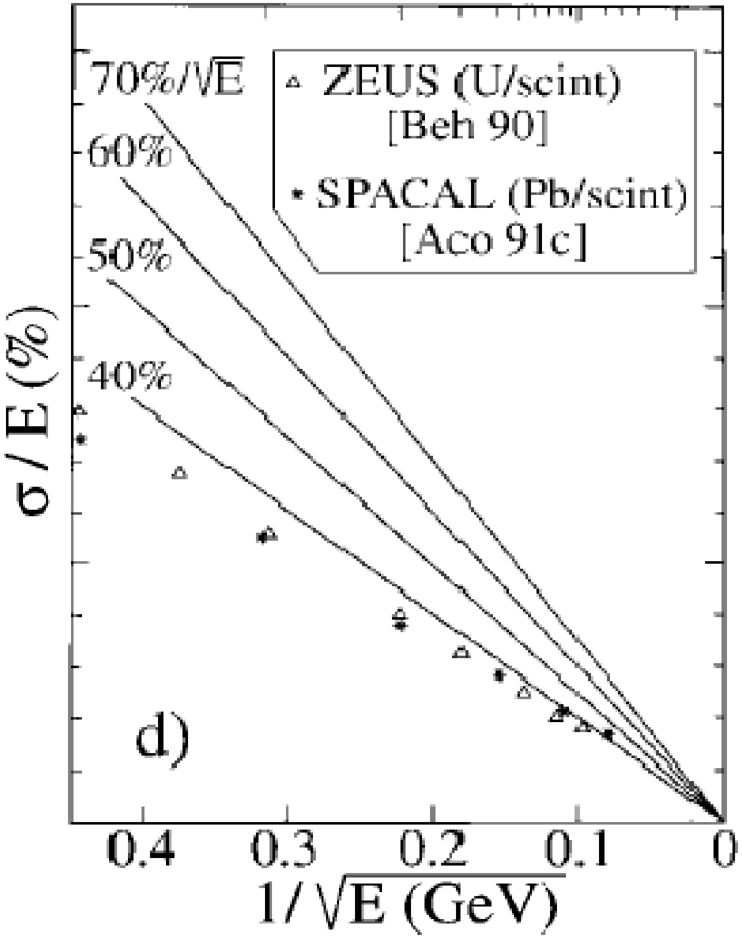


Elastic n-p scattering:
efficient sampling of neutrons through the detection of recoiling protons!

Hardware Compensation – ZEUS, SPaCal



Sampling fraction tuned to have e/π = 1



Excellent energy resolution with Hadrons
Cons:

- small sampling fraction poor em resolution
- Long integration time > 50ns for neutrons

σ/E (hadrons) = $0.35/\sqrt{E(\text{GeV})}$

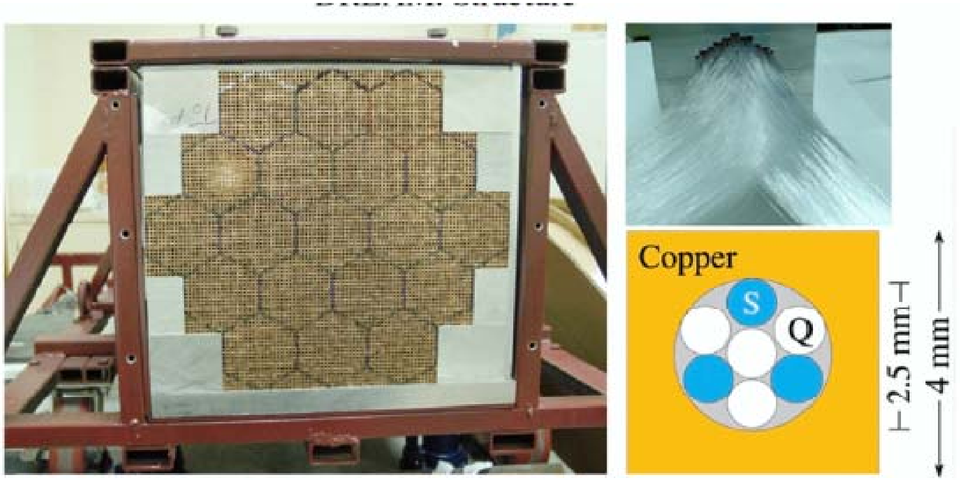
Dual Readout : DREAM

Proposed by R. Wigmans.

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

Cerenkov radiator:
sample em part of the shower

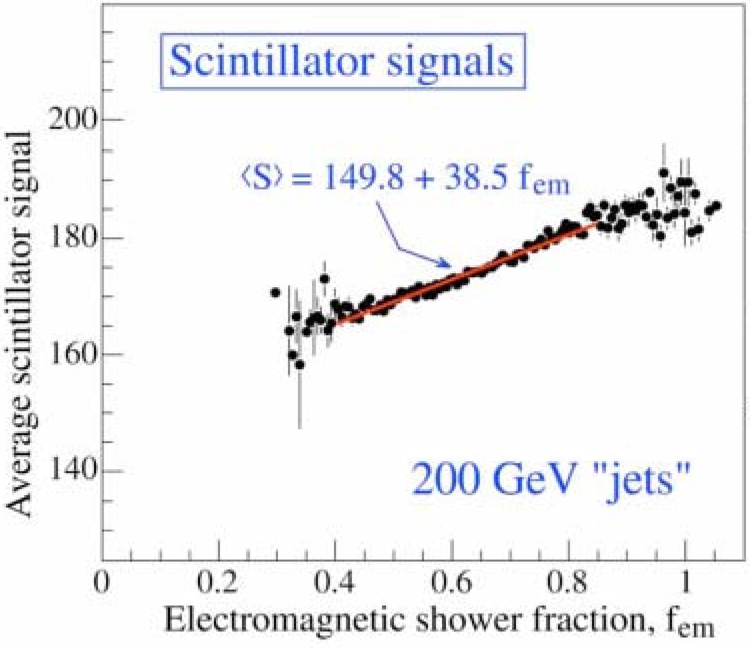
Scintillator:
sample all components

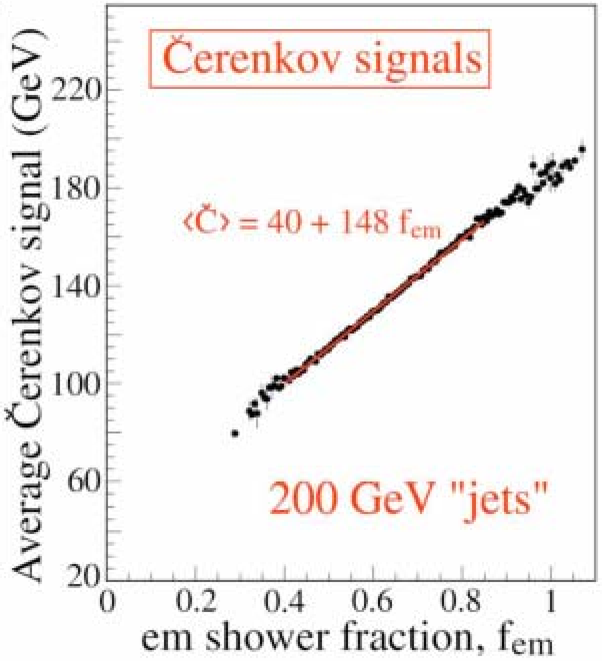


Q=quartz =Cerenkov
S=scintillator

- *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





In practice the two systems respond differently to hadrons

$(e/h)_S = 1.3$

$(e/h)_C = 4.7$

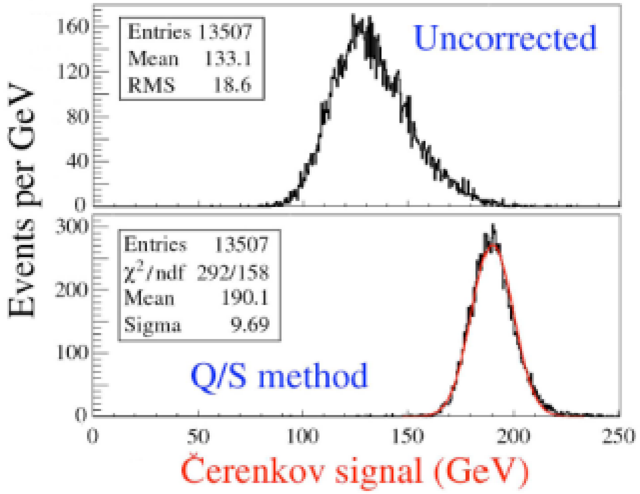
From:
NIM A537 (2005) 537

$$C = E \quad [f_{em} + \frac{1}{(e/h)_C} \times (1 - f_{em})$$

$$S = E \quad [f_{em} + \frac{1}{(e/h)_S} \times (1 - f_{em})$$

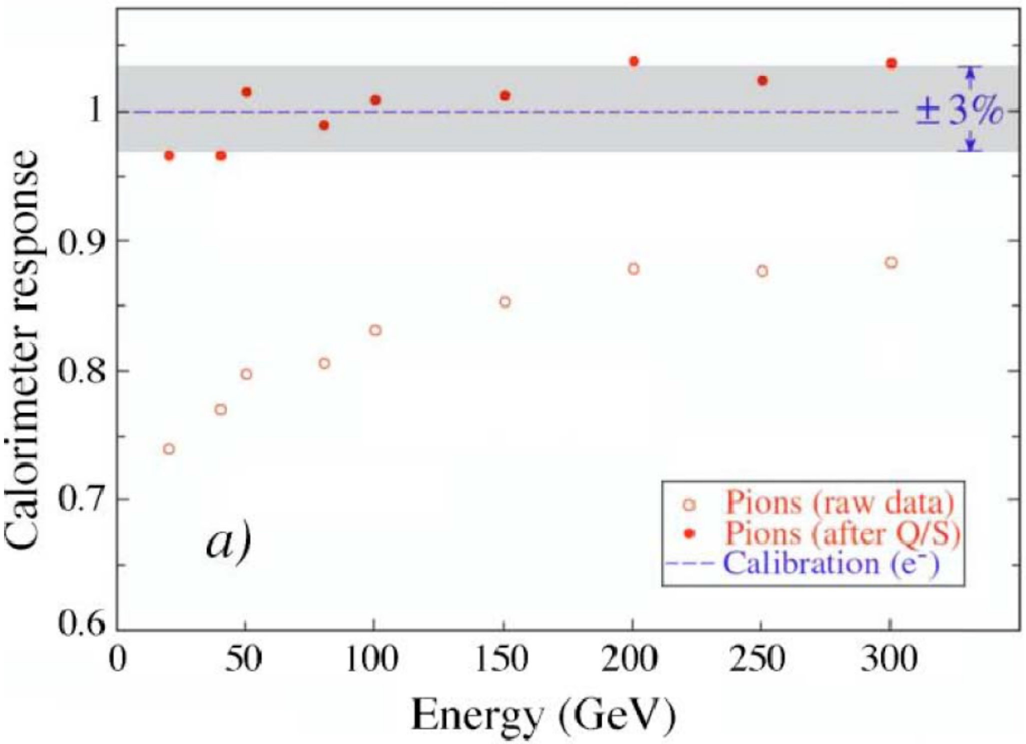
$$E = \frac{S - \chi C}{1 - \chi}$$

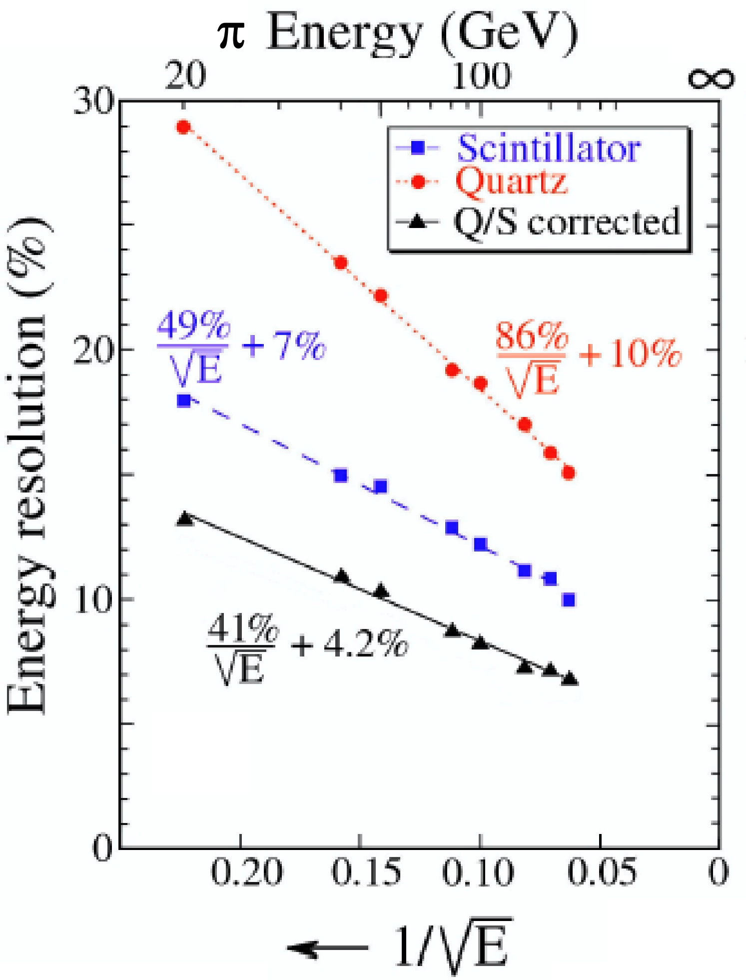
where $$\chi = \frac{1 - 1/(e/h)_S}{1 - 1/(e/h)_C}$$



Dual readout: DREAM

Hadronic response after C/S correction



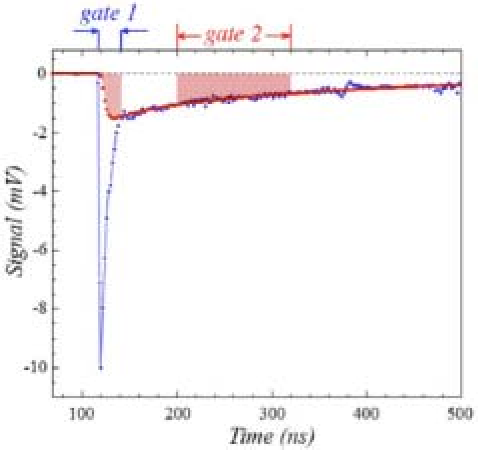


- Gaussian response
- Linear
- Correct energy scale
- Can be further improved by looking at timing (n component)

Dual readout : future work

Dream work continuing

can be applied to crystals by using timing structure



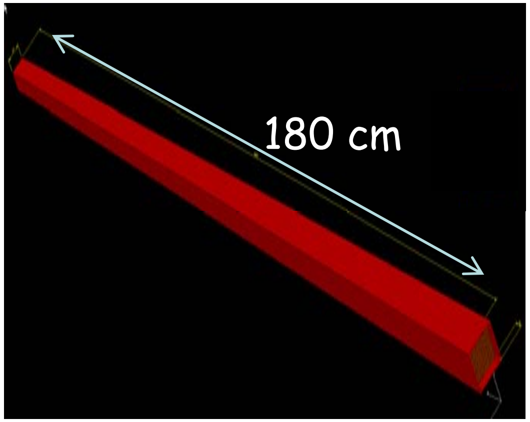
BGO crystal
UG 11 (UV) filter

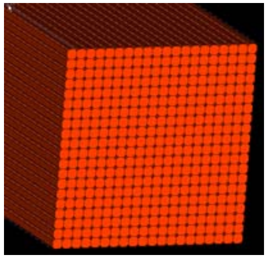
From:
NIM A595 (2008) 359

Other investigators:

TWICE collaboration, funded by INFN

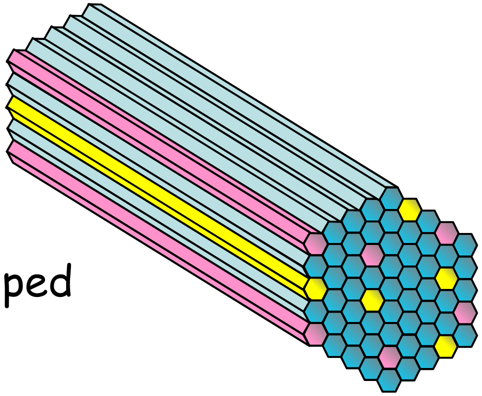
Heavy Glass SF57 HHT + scintillating fibers





Crystal Clear collaboration (CERN)

Meta cables of crystal fibers differently doped

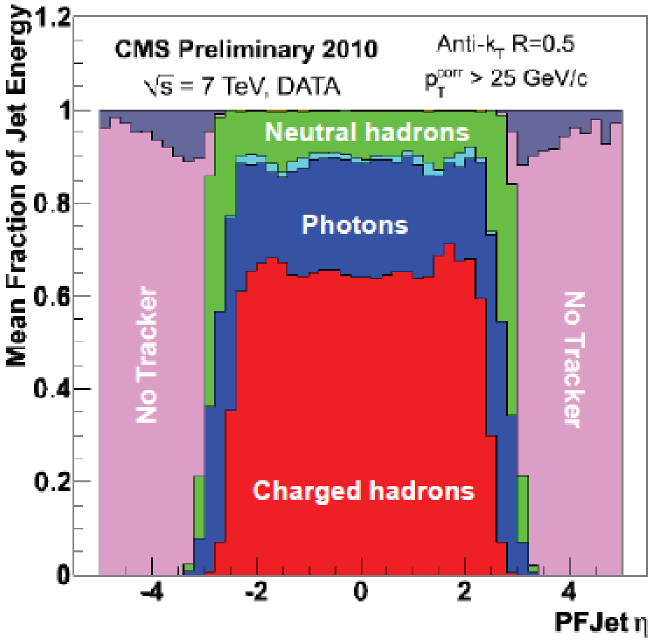


Particle flow

Use "best measurement" of each component
Charged tracks = Tracker
e/photons = Electromagnetic E calorimeter
Neutral hadrons from HCAL: only 10%

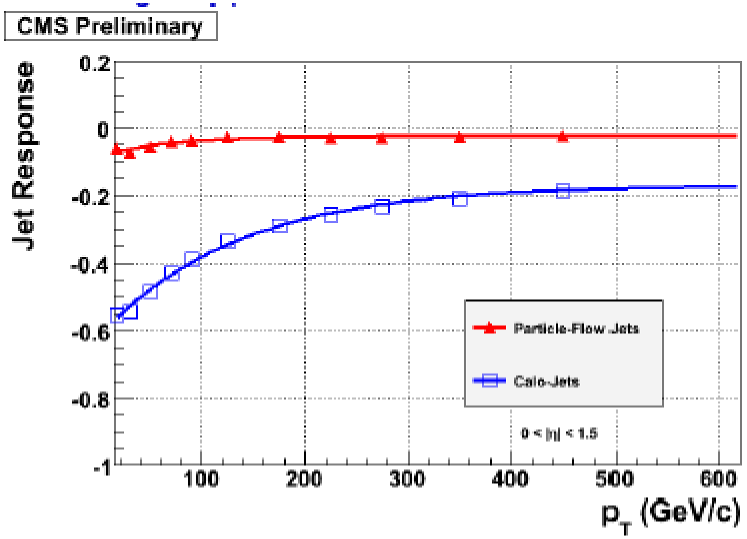
Critical points:
Very fine granularity
Confusion due to shower overlaps in calorimeter
Very large number of channels

- Successfully used for ALEPH experiment and now by CMS experiment (in both case rather poor HCAL)

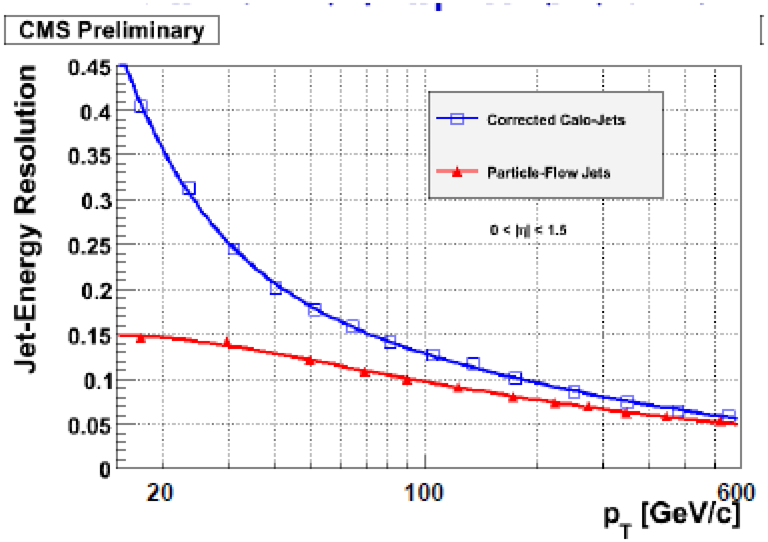


CMS real data !

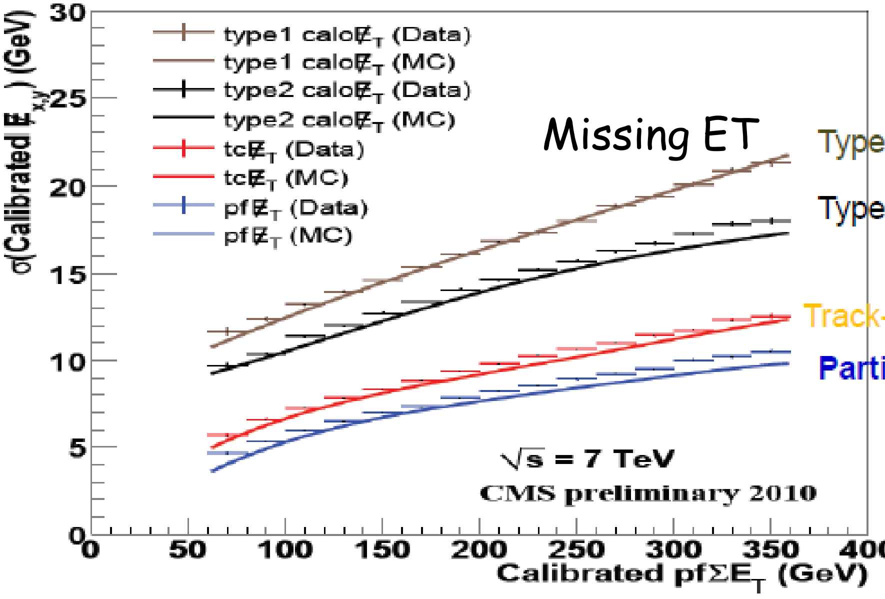
Particle Flow : CMS case (2010 data)



Simulation: energy scale



Simulation: Jet energy resolution



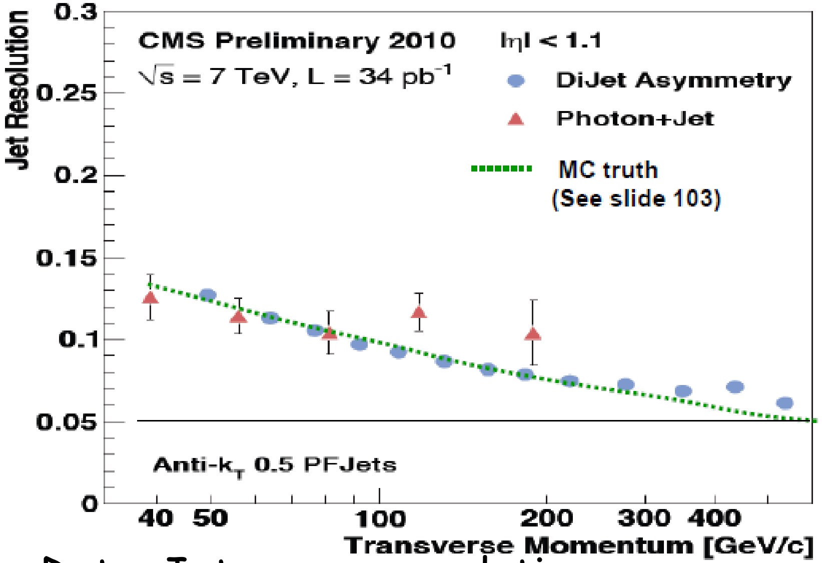
Missing ET

Type I corrected

Type II correctec

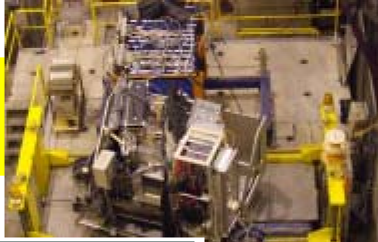
Track-corrected

Particle Flow



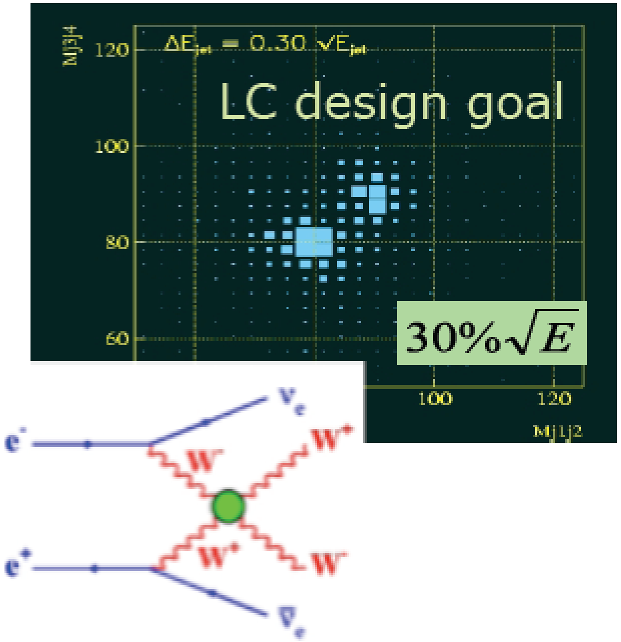
Data: Jet energy resolution

Particle Flow : Calice ILC/CLIC



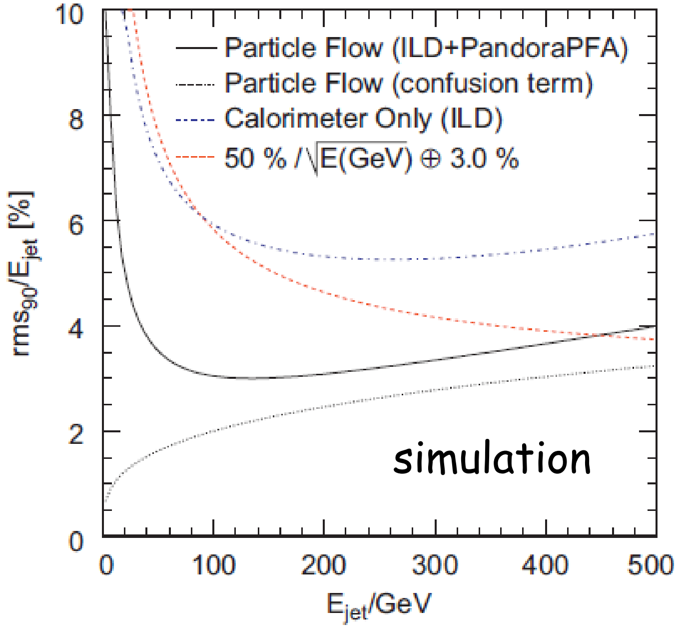
Challlenge : separate W and Z hadronic decays

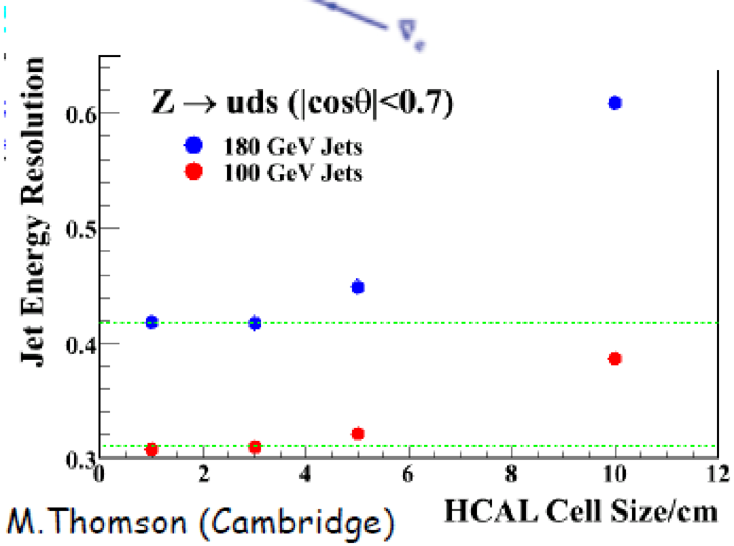
Large radius: to separate the particles
Large B field to sweep out charged tracks
Small Moliere radius to separate showers
Very small granularity



$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3} \%$$

Resolution Tracking Leakage Confusion





M.Thomson (Cambridge)

Optimum: 3x3 cm^2 cells

Conclusions

- Calorimeters are key components of HEP detectors.
- Electromagnetic calorimetry is well understood. This has allowed the design of large, sophisticated, high resolution detectors.
- Hadronic calorimetry becomes more and more important in HEP to detect jets, which are fragments of fundamental constituents like quark and gluons. But the physics of hadron showers is complex and the battle to reach high resolution is still going on.