Calorimetry

concept & examples

European School of Instrumentation
in Particle & Astroparticle Physics
ESIPAP 2014

Lecture 2

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European Scientific Institute

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in Particle & Astroparticle Physics

Programme

Lesson 1

Why build calorimeters ?

Electromagnetic showers

Detection processes

EM calorimeters

Lesson 2

Hadronic showers & calorimeters

Jets

Missing Transverse Energy

Lesson 3

Existing calorimeters

R&Ds for future calorimeters

Lesson 4

Detecting EM showers

ATLAS & CMS calorimeters

Hadronic Showers

Hadron showers

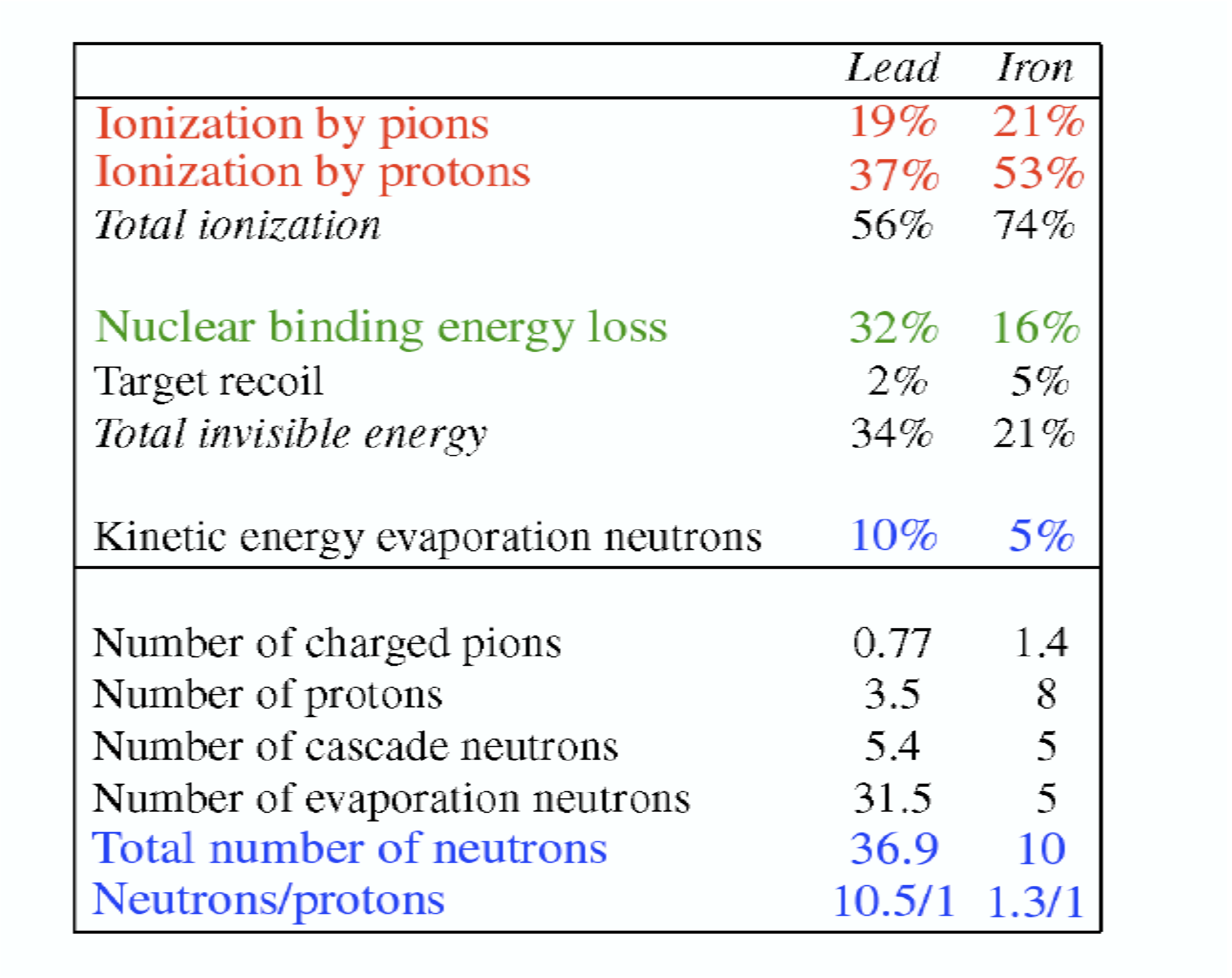
Hadronic cascades develop in an analogous way to e.m. showers

- Strong interaction controls overall development
- High energy hadron interacts with material, leading to multi-particle production of more hadrons
- These in turn interact with further nuclei
- Nuclear breakup and spallation neutrons
- Multiplication continues down to the pion production threshold
  - $E \sim 2m_\pi = 0.28\ \mathrm{GeV}/c^2$
- Neutral pions result in an electromagnetic component (immediate decay: $\pi^0 \rightarrow \gamma\gamma$) (also: $\eta \rightarrow \gamma\gamma$)

Energy deposited by:

- Electromagnetic component (i.e. as for e.m. showers)
- Charged pions or protons
- Low energy neutrons
- Energy lost in breaking nuclei (nuclear binding energy)

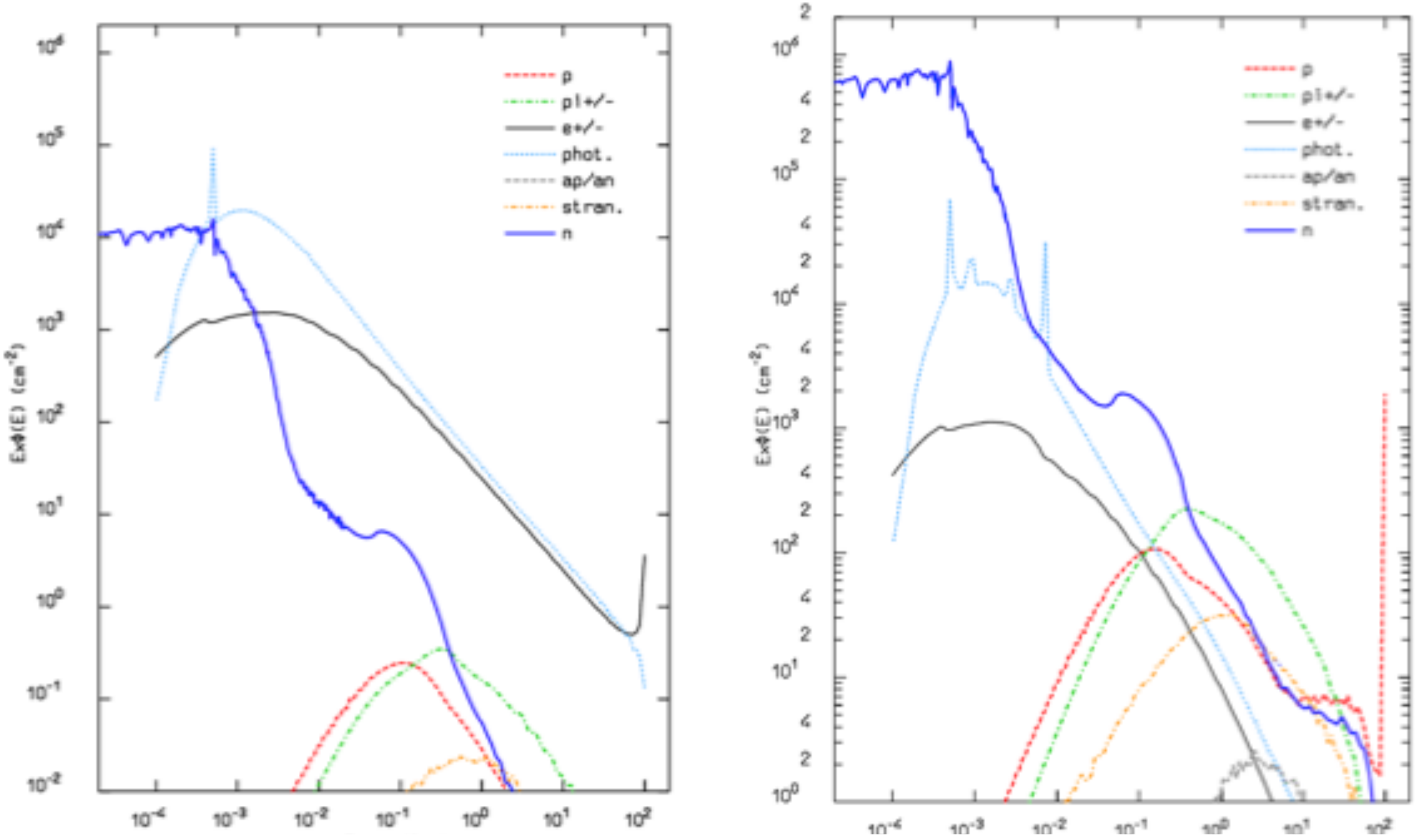
Hadronic Showers: Where does the energy go?



	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

Em vs HAD shower development

These spectra are dominated by electrons, positrons, photons, and neutrons at low energy. The structure in the photon spectrum at approximately 8 MeV reflects an (n, γ) reaction and is a fingerprint of nuclear physics; the line at 511 keV results from e+e− annihilation photons. These low-energy spectra encapsulate all the information relevant to the hadronic energy measurement.



Fluences in Electromagnetic(left) and hadronic(right) showers from FLUKA

Hadronic shower development

Simple model of interaction on a disk of radius R: $\sigma_{int} = \pi R^2 \propto A^{2/3}$

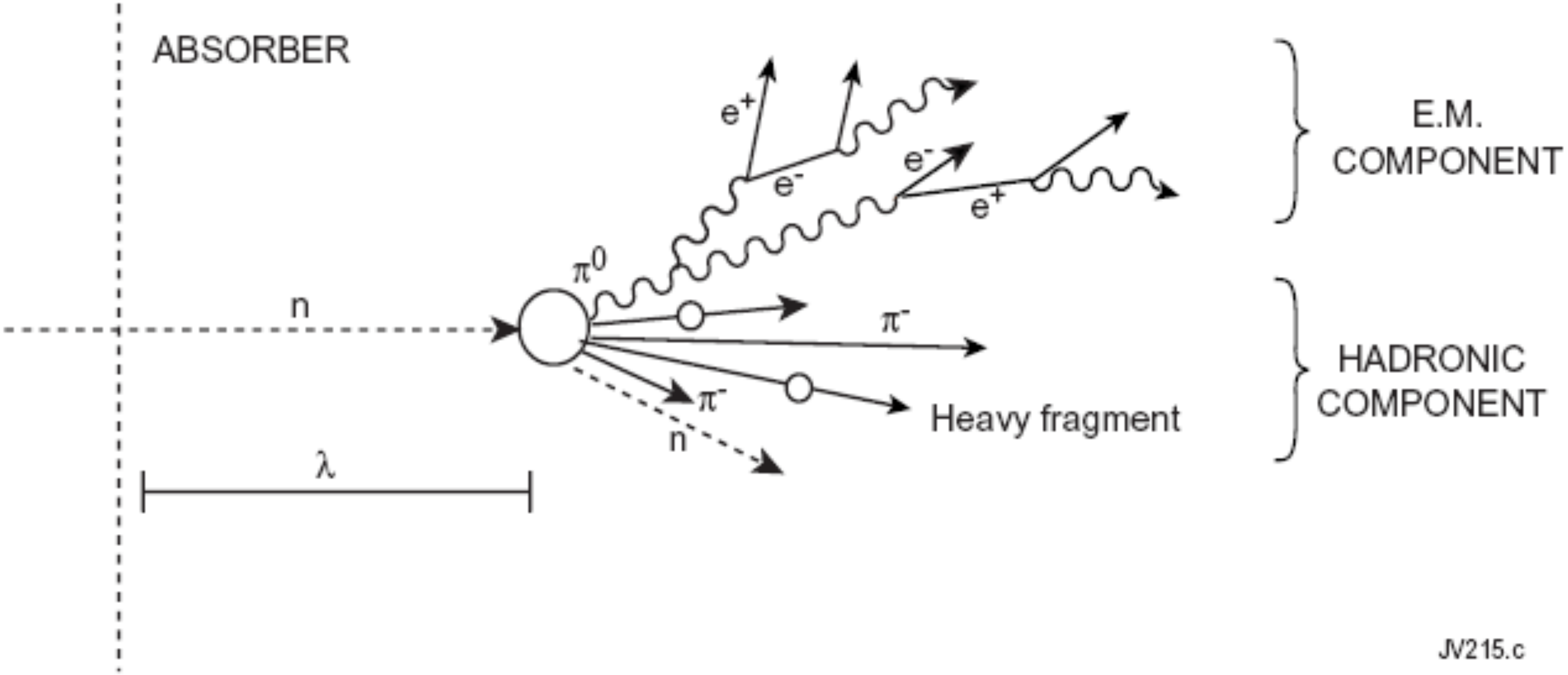
$\sigma_{inel} \approx \sigma_0 A^{0.7}$, $\sigma_0 = 35$ mb

Nuclear interaction length: mean free path before inelastic interaction

$$\boxed{\lambda_{int} \approx \frac{A}{N_A \sigma_{int}} \approx 35 A^{1/3} g \times cm^{-2}}$$

	Z	ρ (g.cm^{-3})	E_c (MeV)	X_0 (cm)	λ_{int} (cm)
Air				30 420	~70 000
Water				36	84
$PbWO_4$		8.28		0.89	22.4
C	6	2.3	103	18.8	38.1
Al	13	2.7	47	8.9	39.4
L Ar	18	1.4		14.0	84.0
Fe	26	7.9	24	1.76	16.8
Cu	29	9.0	20	1.43	15.1
W	74	19.3	8.1	0.35	9.6
Pb	82	11.3	6.9	0.56	17.1
U	92	19.0	6.2	0.32	10.5

Hadronic cascade

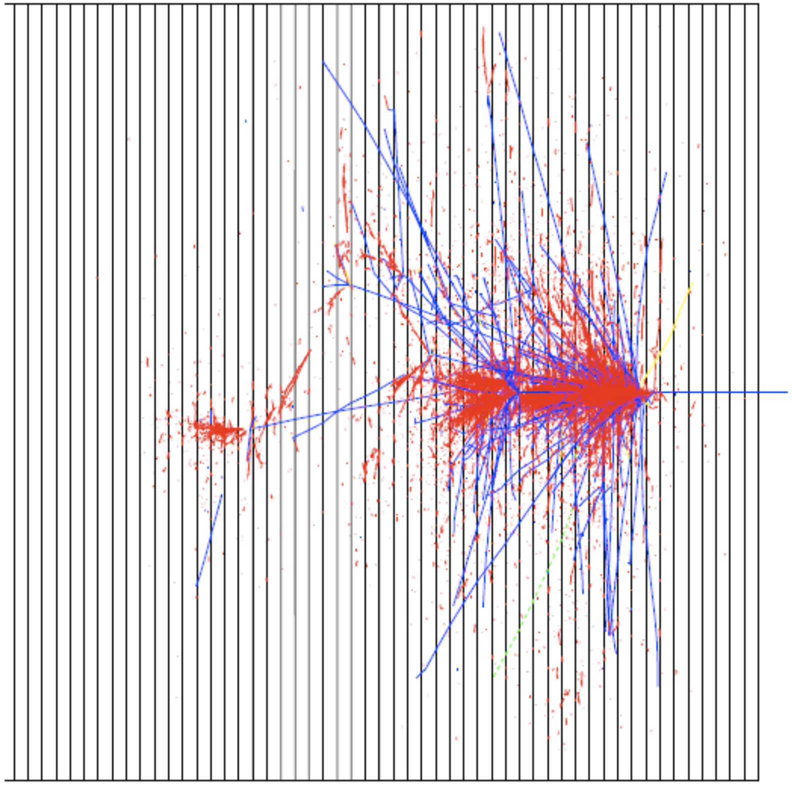


As compared to electromagnetic showers, hadron showers are:

- Larger/more penetrating
- Subject to larger fluctuations – more erratic and varied

Hadron showers

1.



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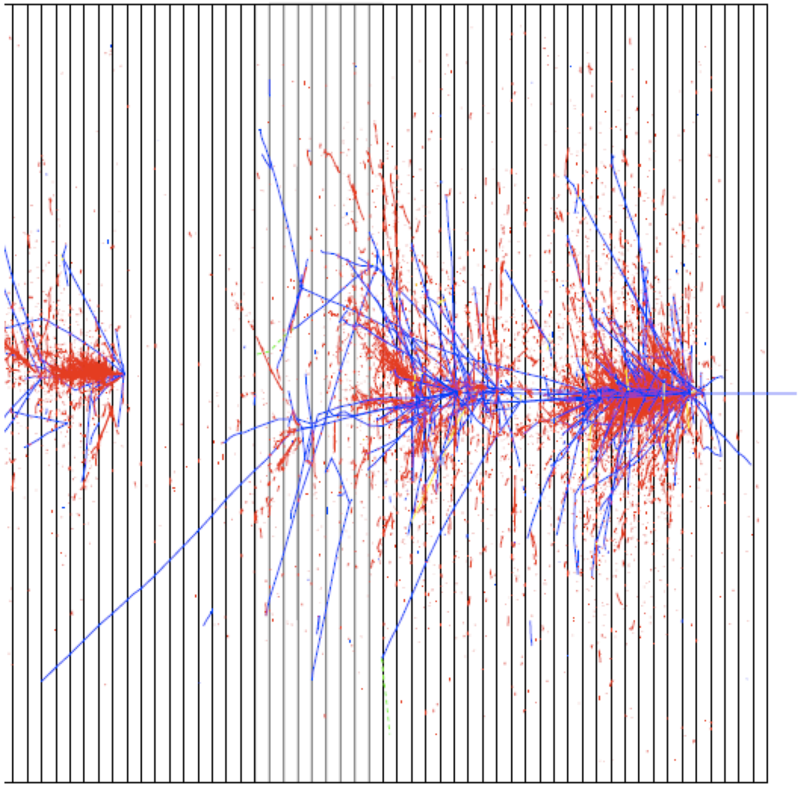


red - e.m. component
blue - charged hadrons

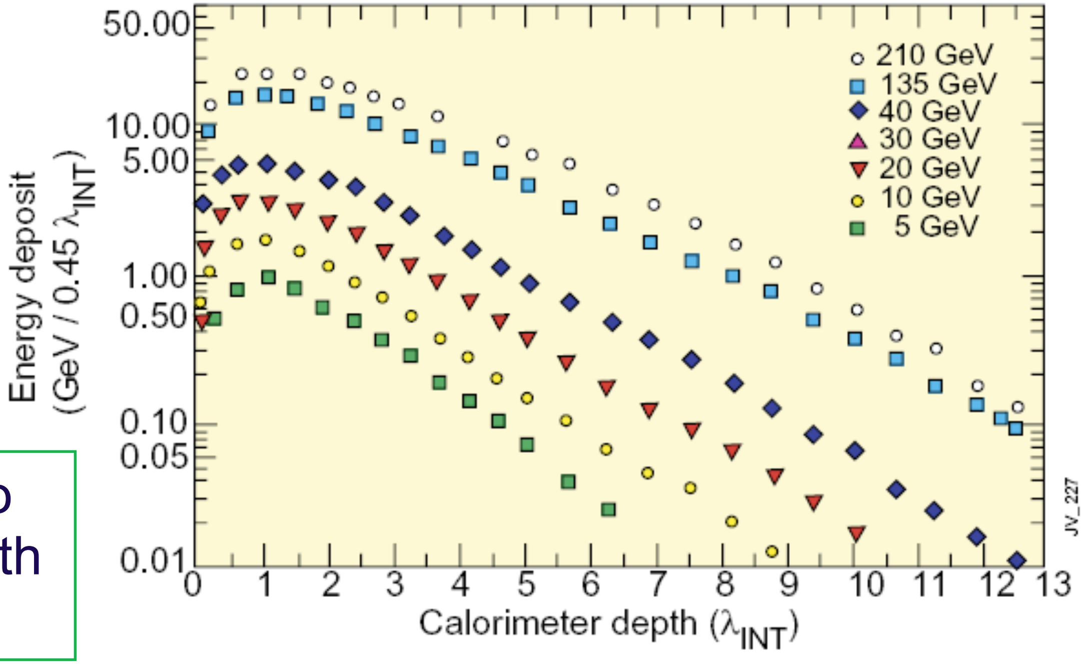
- Individual hadron showers are quite dissimilar

Hadron shower longitudinal profiles

Longitudinal profile

- Initial peak from π^0s produced in the first interaction
- Gradual falloff characterized by the nuclear interaction length, λ_{int}

WA78 : 5.4λ of 10mm U / 5mm Scint + 8λ of 25mm Fe / 5mm Scint



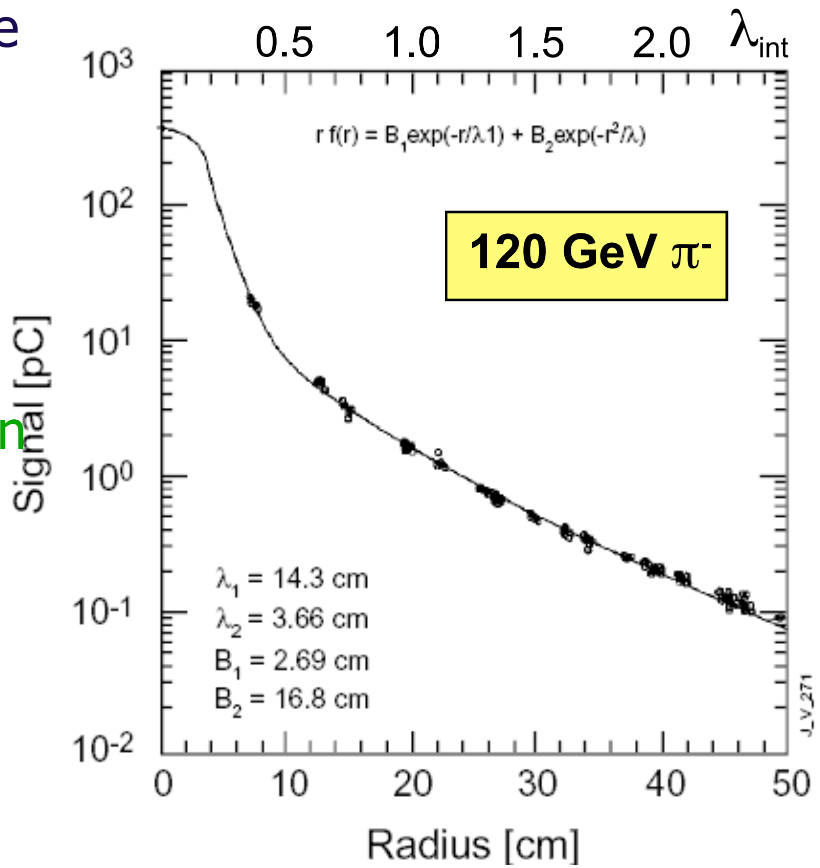
As with e.m. showers: depth to contain a shower increases with log(E)

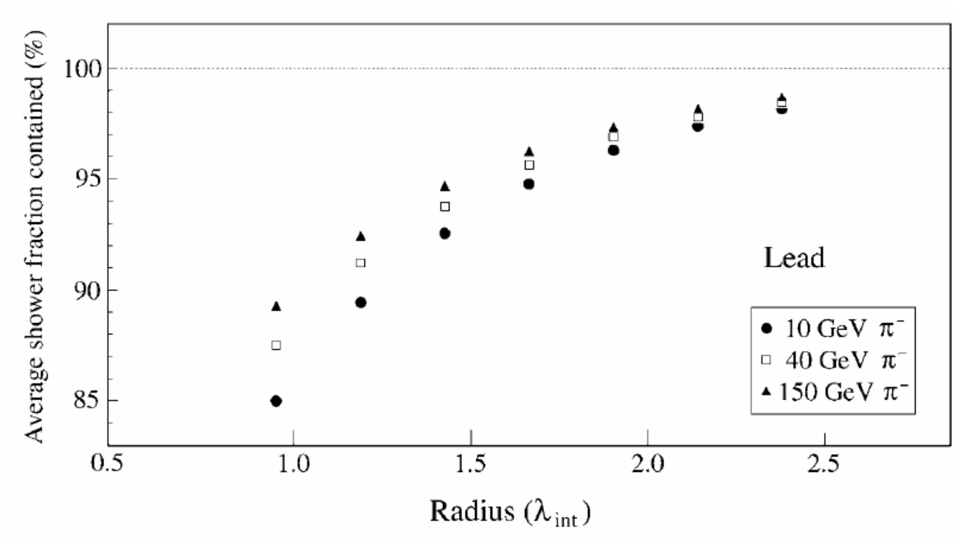
Hadron shower transverse profiles

Mean transverse momentum from interactions, $<p_T>$ ~ 300 MeV, is about the same magnitude as the energy lost traversing 1λ for many materials

So radial extent of the cascade is well characterized by λ

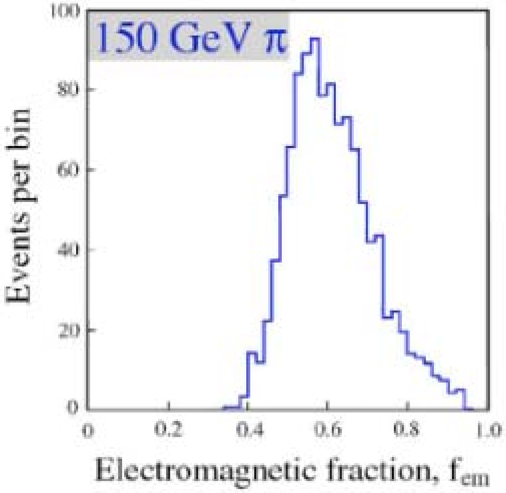
The π^0 component of the cascade results in an electromagnetic core

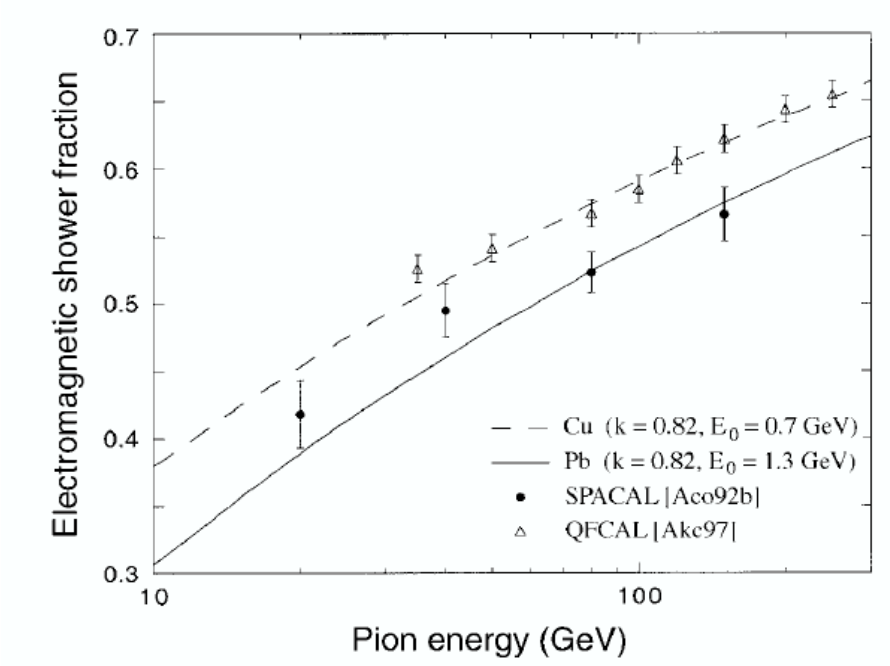




Lateral containment increases with energy

Hadronic Showers: EM fraction





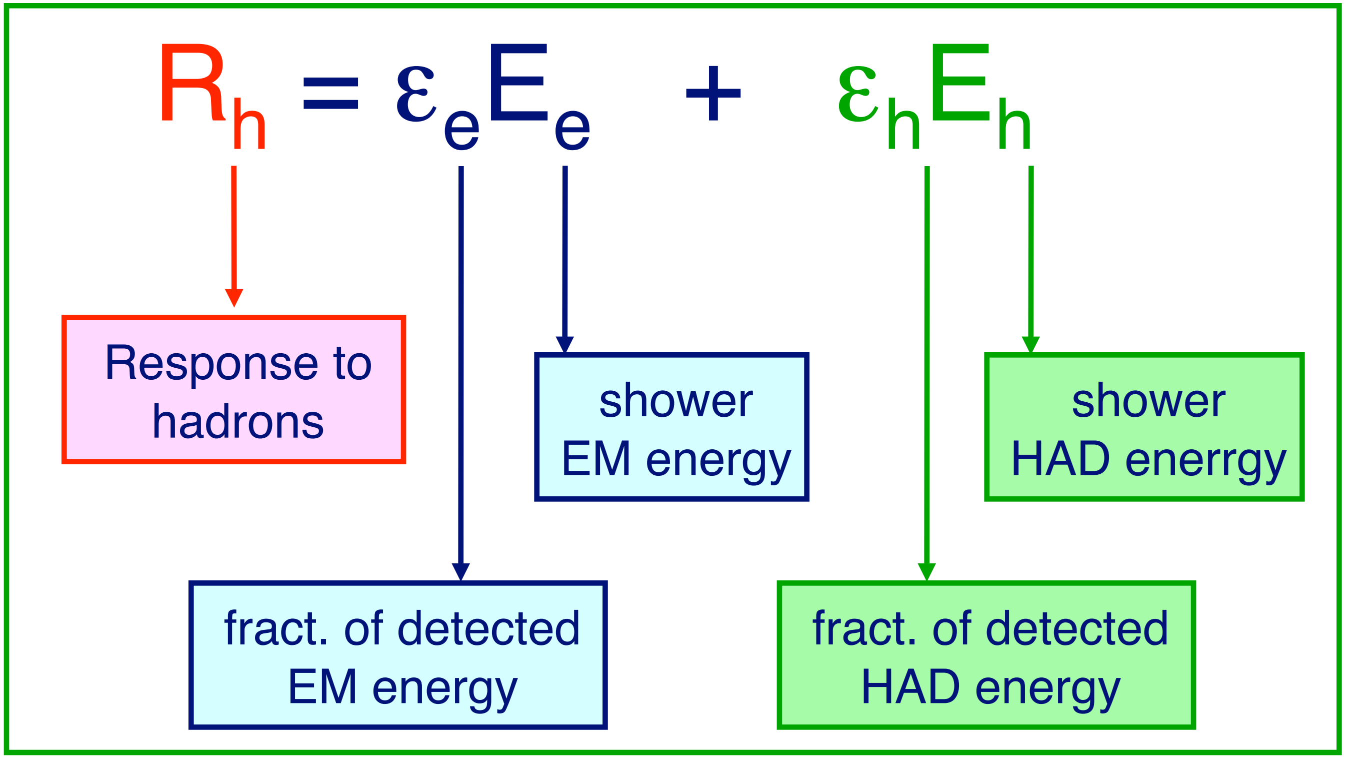
Large fluctuation of the EM component from one shower to the other

Varies with energy

Energy resolution is degraded w.r.t. EM showers

50-100%/√E ⊕ a few %

Hadronic shower and non compensation



$$R_h = \varepsilon_e E_e \quad + \quad \varepsilon_h E_h$$

R_h: Response to hadrons

E_e: shower EM energy

E_h: shower HAD enerrgy

ε_e: fract. of detected EM energy

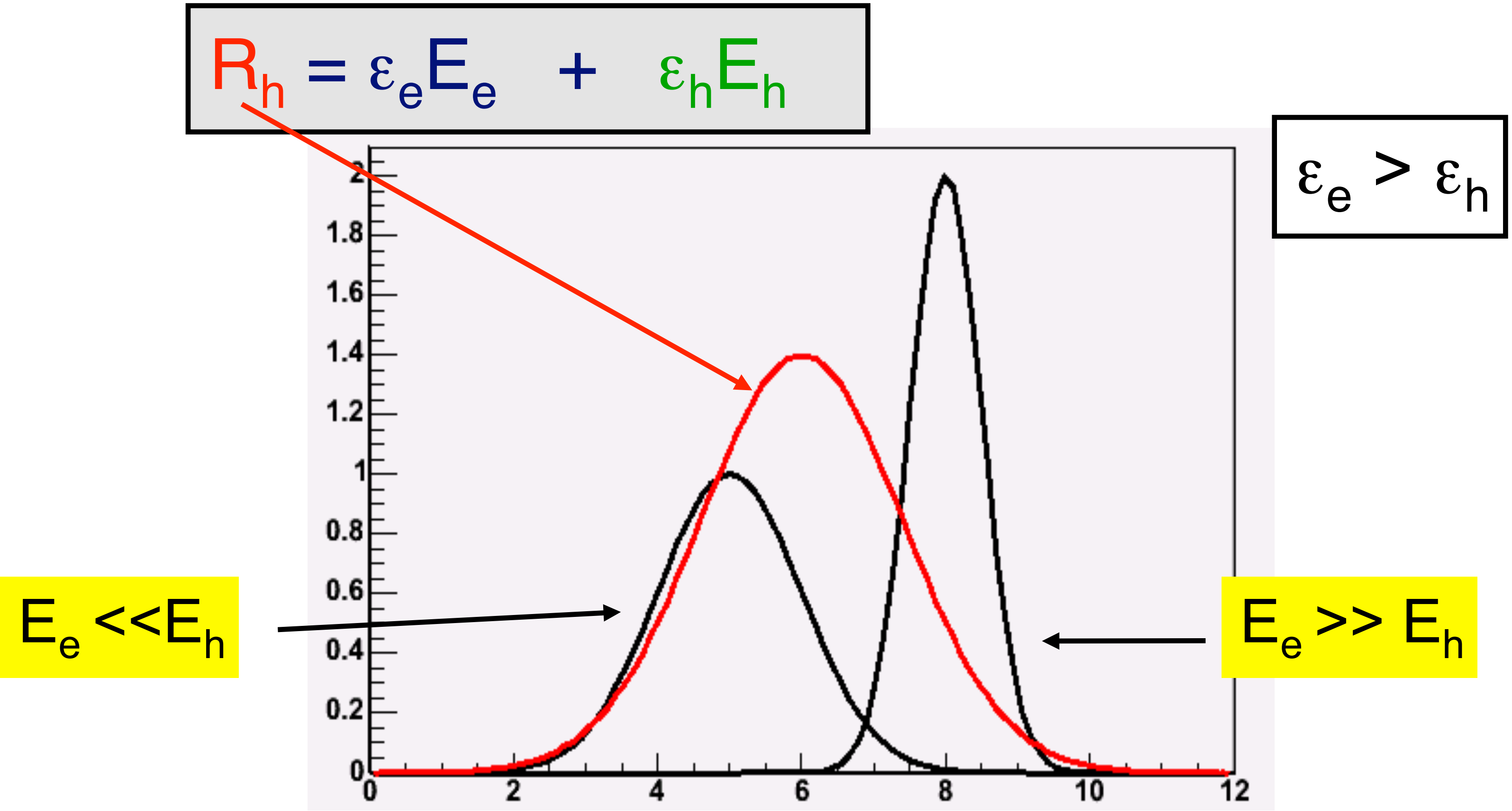
ε_h: fract. of detected HAD energy

$$\boxed{\frac{e}{h} = \frac{\varepsilon_e}{\varepsilon_h}}$$

≈ 1 : compensating calorimeter

> 1 : non compensating calorimter

Hadronic showers: non compensation



$$R_h = \varepsilon_e E_e \;+\; \varepsilon_h E_h$$

$$\varepsilon_e > \varepsilon_h$$

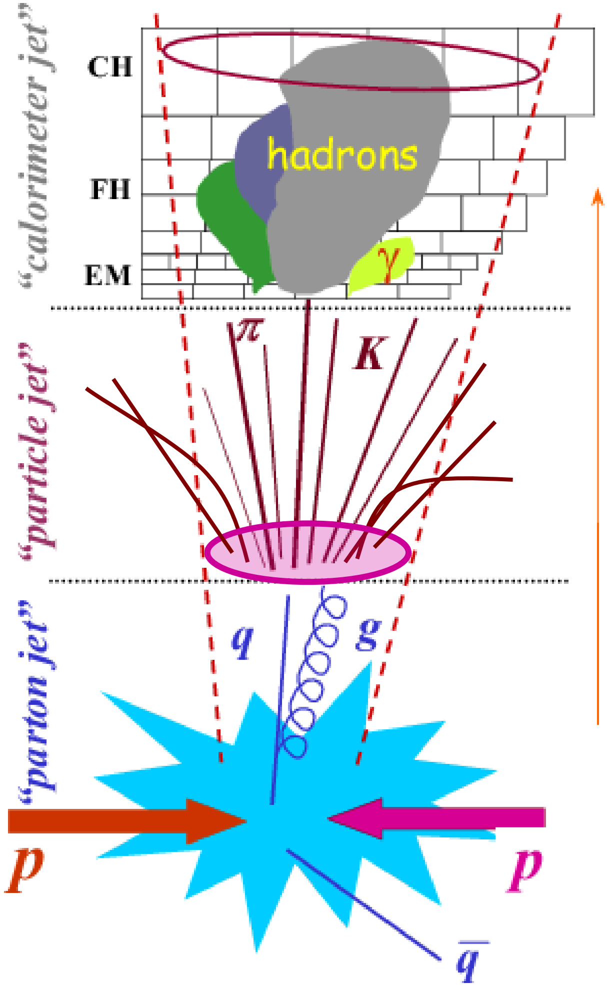
$E_e \ll E_h$

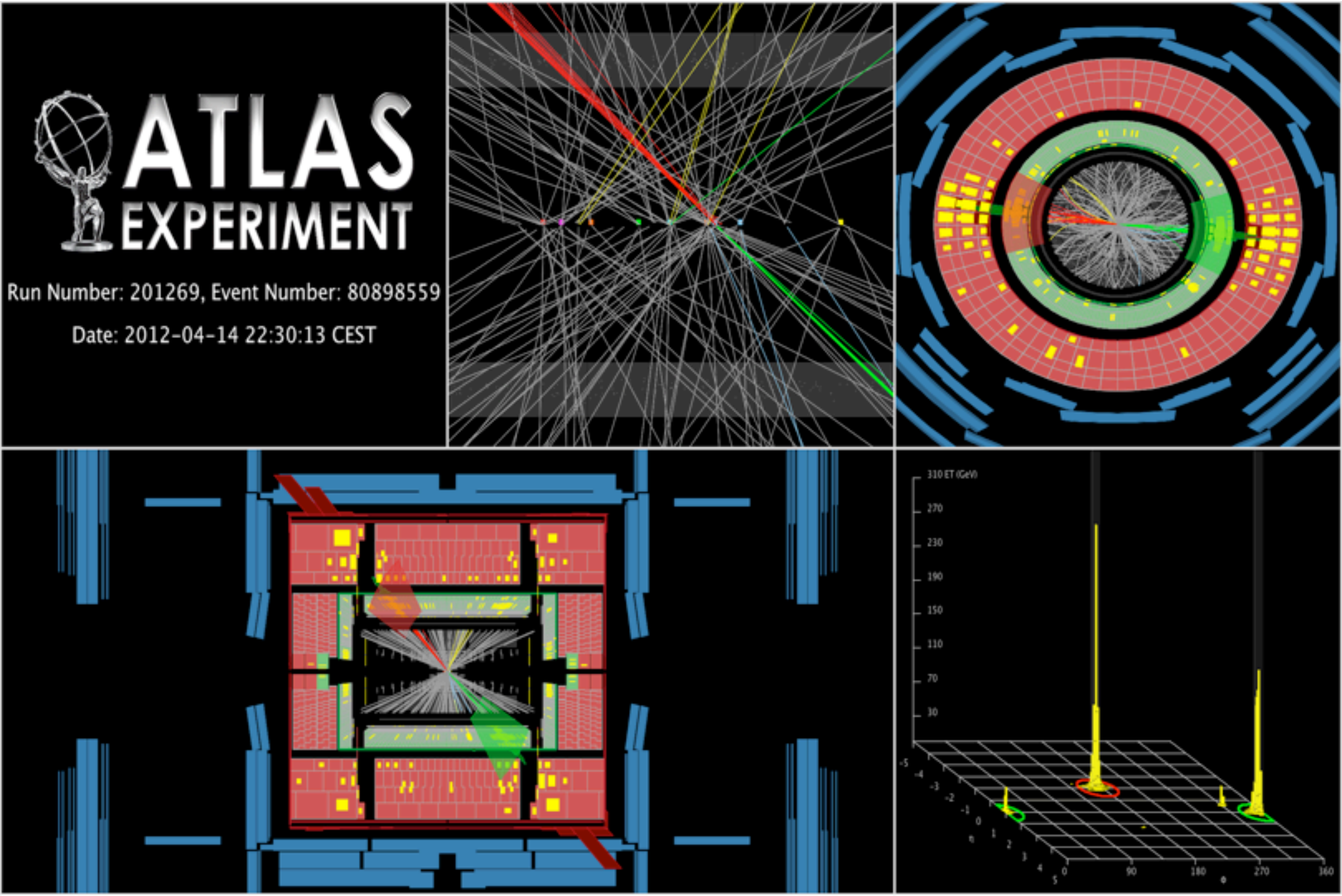
$E_e \gg E_h$

Jets

At Hadronic Colliders, quarks & gluons produced, evolves (parton shower, hadronisation) to become jets

- In a cone around the initial parton: high density of hadrons
- LHC calorimeters cannot separate all the incoming hadrons
  - Use dedicated calibration schemes (based on simulation in ATLAS)
  - Use tracking system to identify charged hadrons (Particle Flow in CMS)





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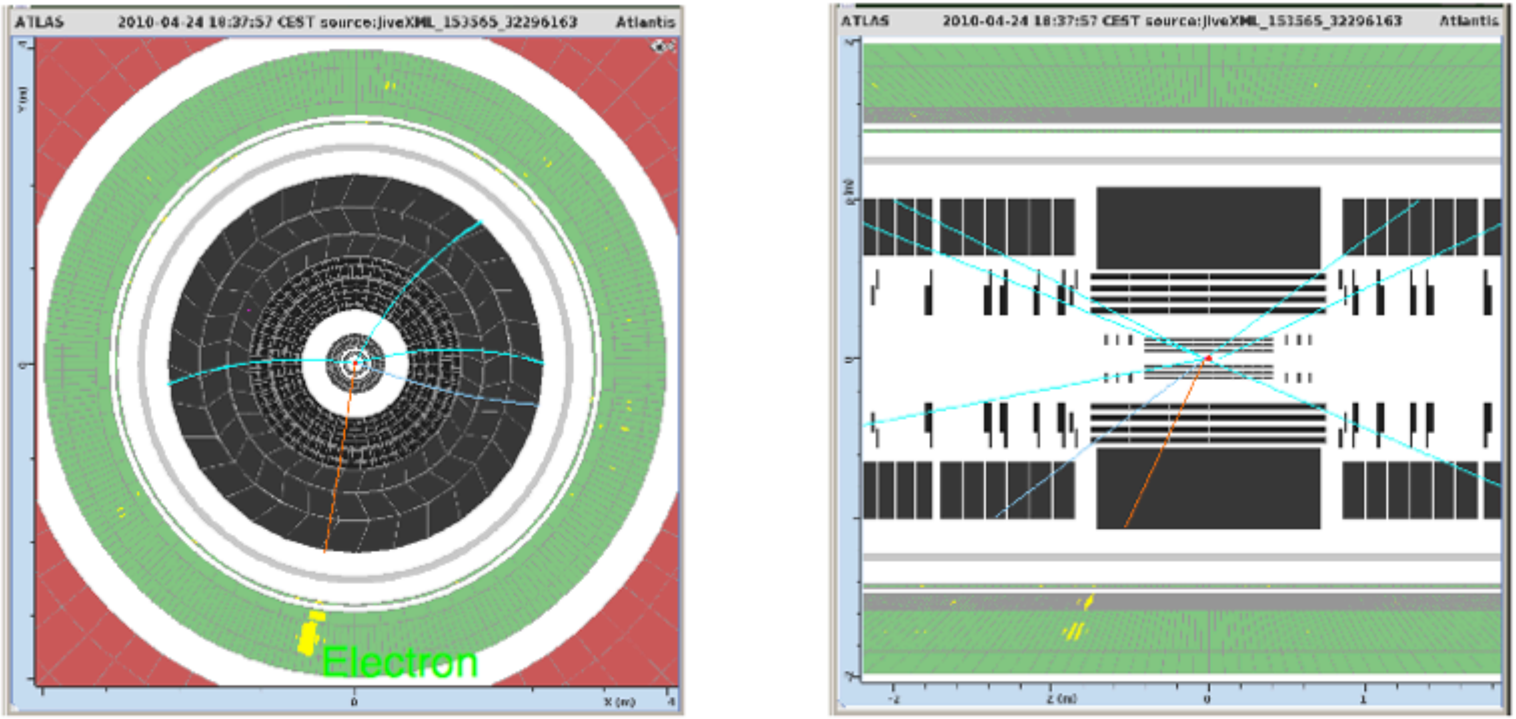
Missing Transverse Energy

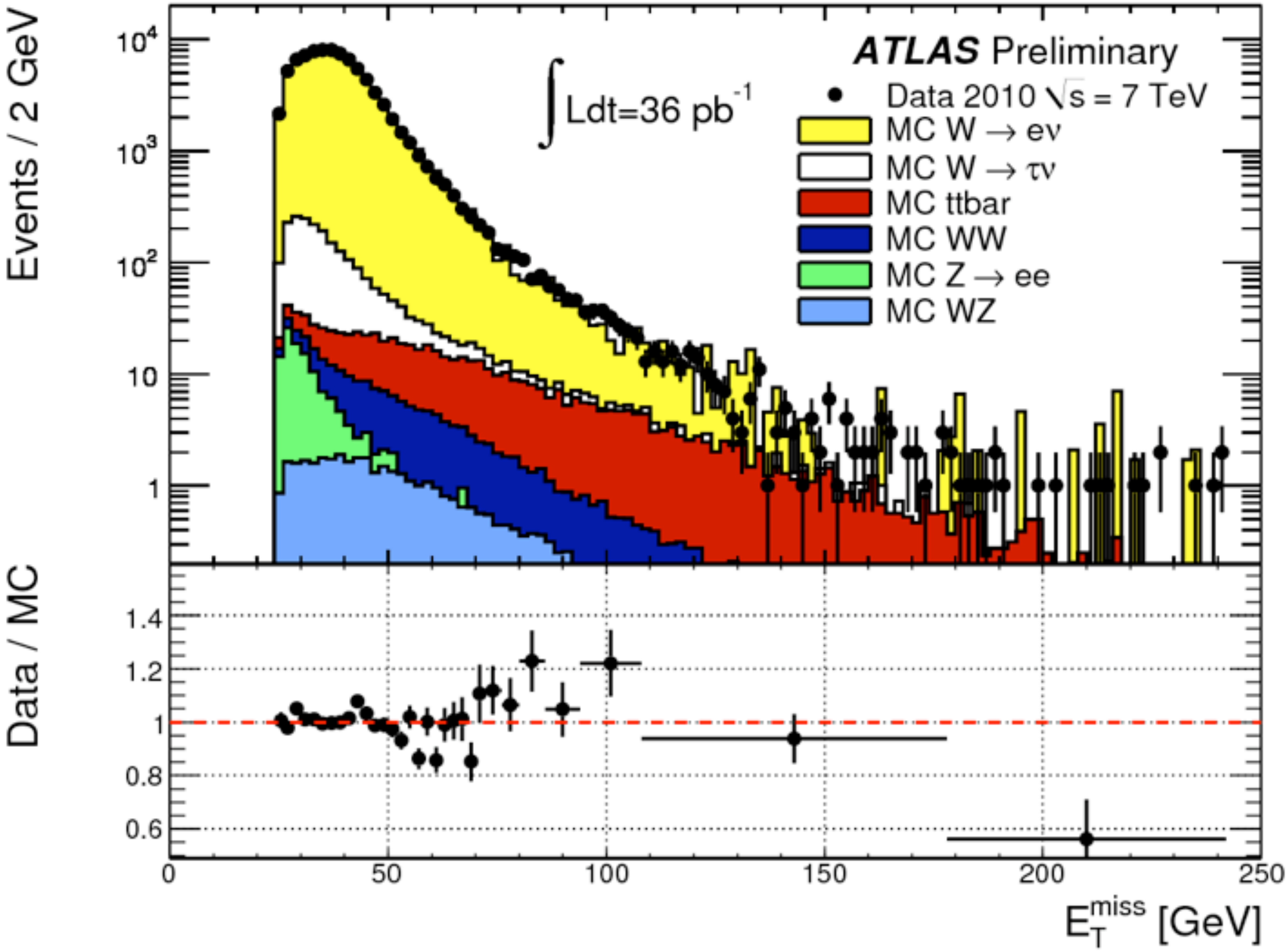
Missing transverse energy : $\mathrm{W} \rightarrow e\,\nu$ candidate



- hight pt electron (pt = 29 GeV); several low pt tracks (1 GeV)
- transverse momentum is a tool for selecting events in which a W boson has occured
- the total transverse momentum vector is not ballanced $\Longrightarrow$ missing energy
- the Missing Energy vector: $\boxed{\vec{\mathrm{E}}^{\mathrm{miss}} = -\sum_{\text{calorimeter cells}} \mathrm{E_i}\,\vec{\mathrm{u}}_{\mathrm{i}}}$

  where $\vec{\mathrm{u}}_{\mathrm{i}}$ is the unit vector between the collision point and the position of the energy deposition observed in the i^{th} cell of the calorimeter

ATLAS E_T^{miss} calibration



Interlude:
muons

Muons interacting with matter

Muons are like electrons but behave differently when interacting with matter (at a given energy).

Bremsstralhung process is ~ $1/m^2$

$m_e = 0.519$ MeV/c^2

$m_\mu = 105{,}66$ MeV/c^2

$\Big\}$ $m\mu / m_e \sim$ **200** ➔ $(m\mu / me)^2 \sim$ **40000**

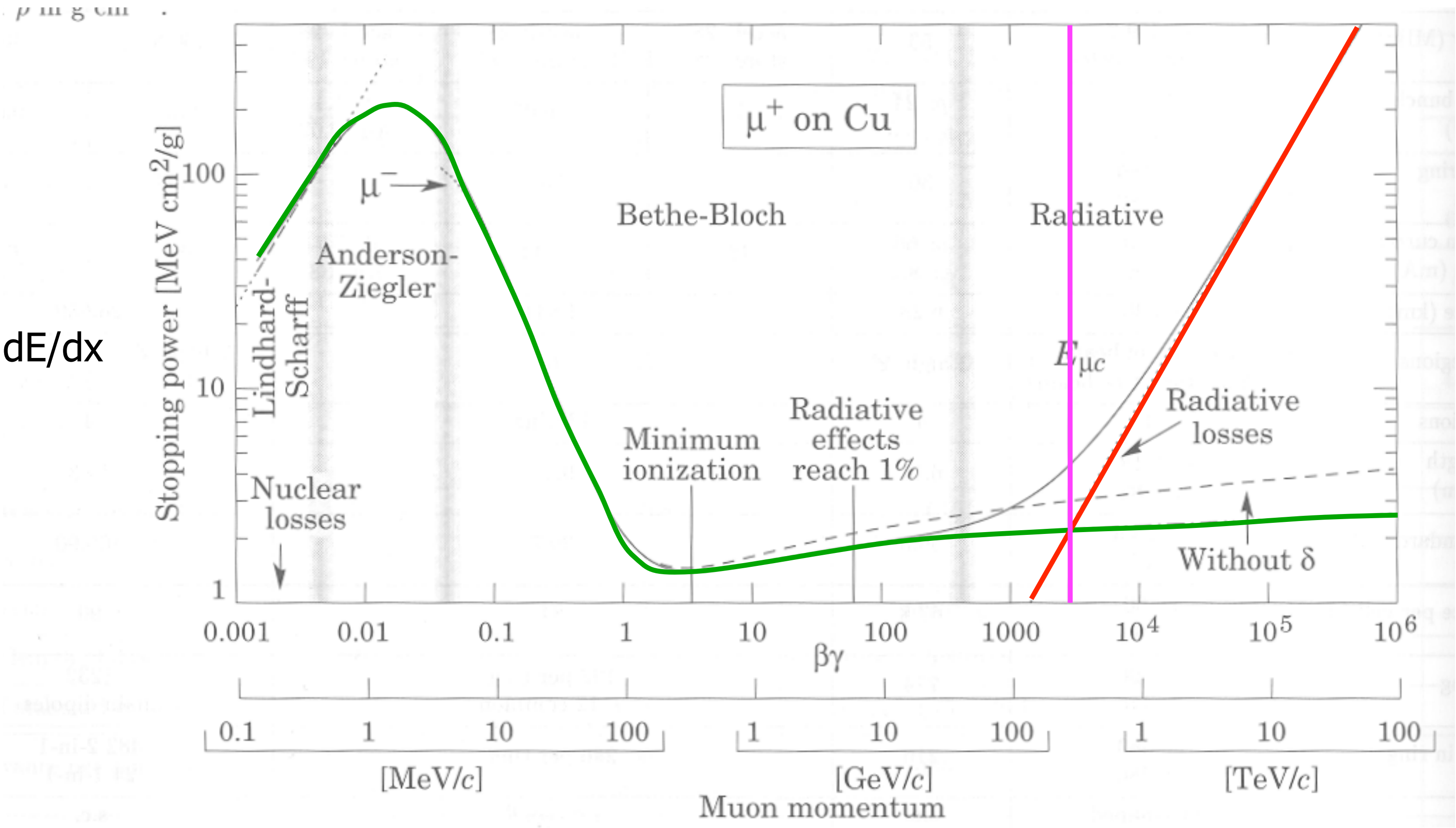
Contrary to electrons, muons (E<100GeV) loose energy mainly via ionization with

$E_c(\mu) = (m_\mu / m_e)^2 \times E_c(e)$

$E_c(\mu) \approx 200$ GeV in lead

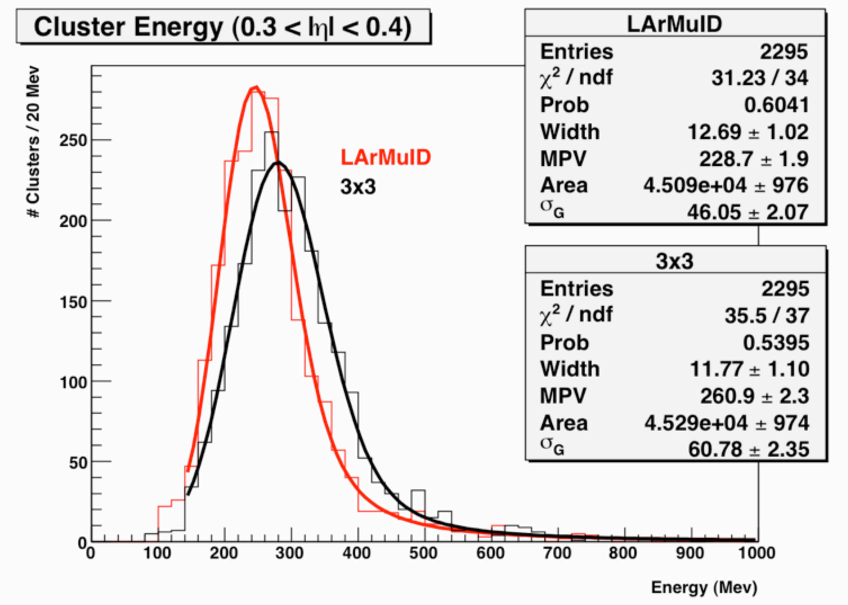
Muons in matter

dE/dx

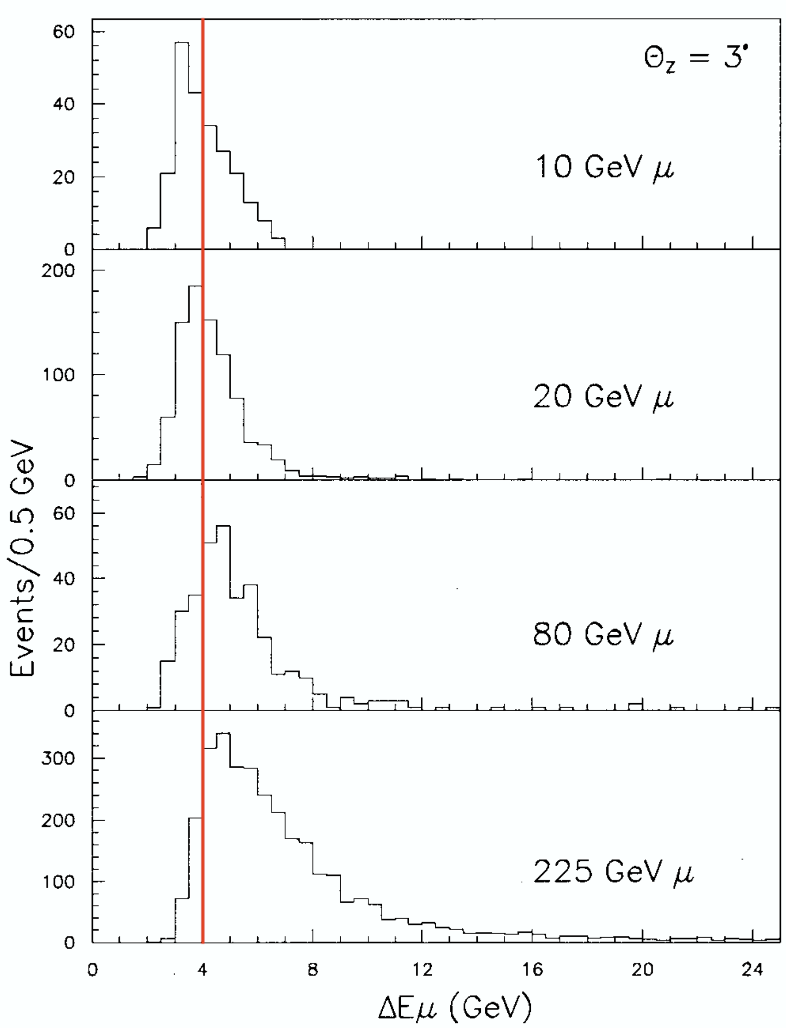


Energy deposit of muons in matter

Muons energy deposit in matter is not proportional to their energy.



Cosmic μ in ATLAS LAr EM barrel



Muons for calorimeters

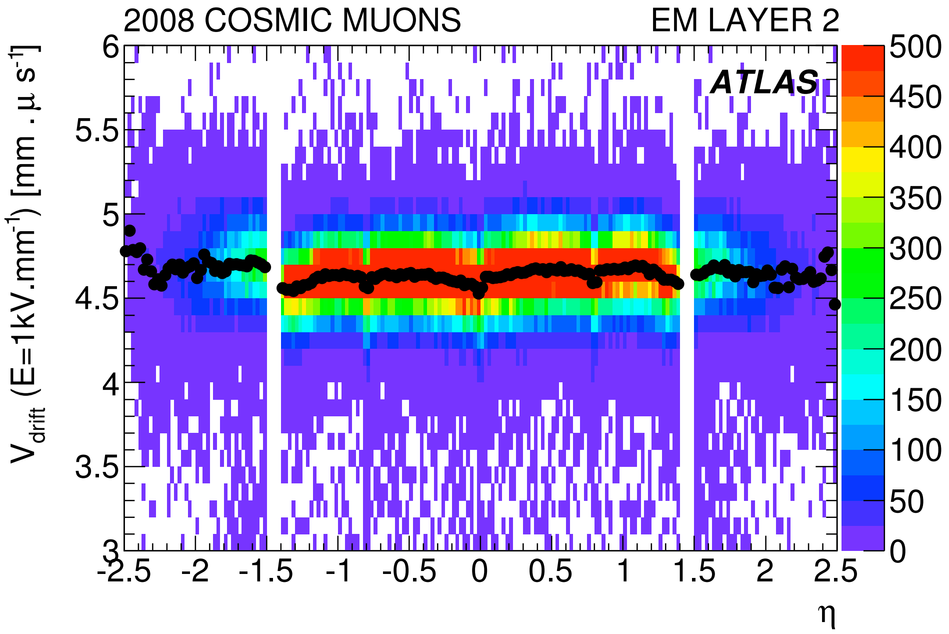
Muons deposit very little energy in calorimeter: dE/dx . x

  Except for catastrophic energy loss (γ emission)

They are nice tools to assess calorimeter response uniformity

  at low energy

They are nice clean probes to analyse the calorimeter geometry

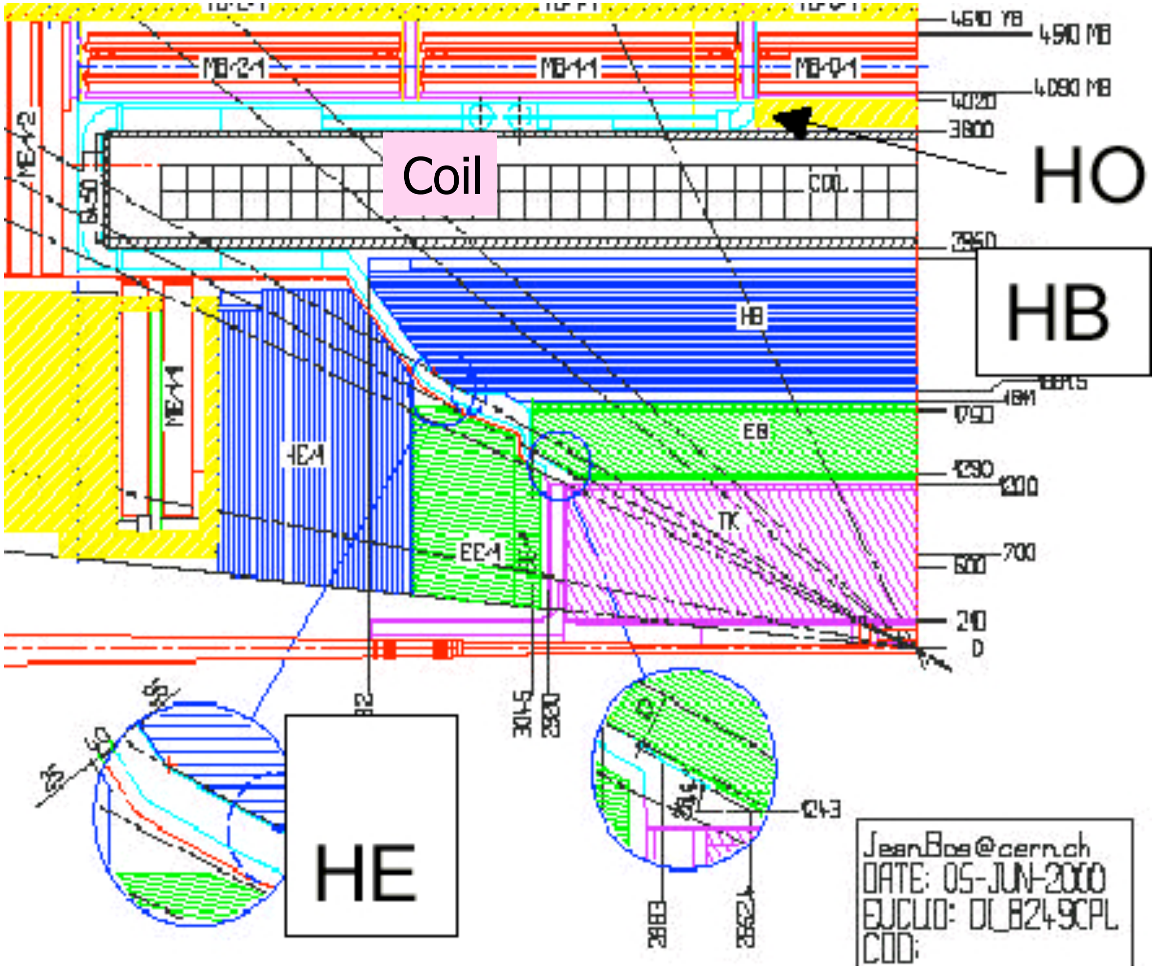


(b) Drift velocity

Two Examples
CMS
ATLAS

CMS calorimeter

The CMS calorimeter



The CMS choices

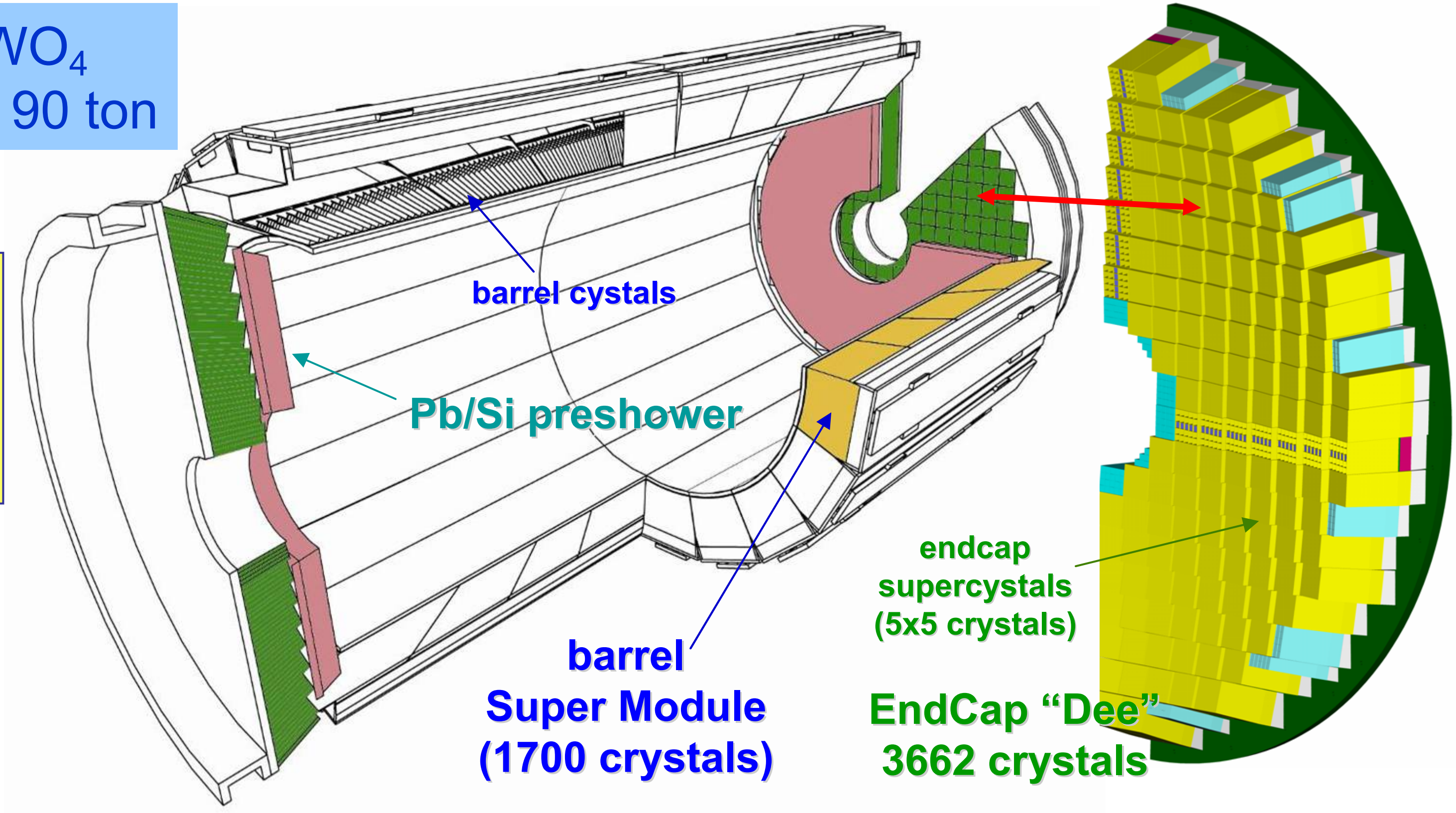
- Solenoidal Magnetic Field: 4T
- Outside the calorimeter
  - “Compact” calorimeter
- Very precise EM calorimeter
  - PbWO crystal (very dense)
- “Thin” HAD calorimeter

ECAL @ CMS

Precision electromagnetic calorimetry: 75848 PWO crystals

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

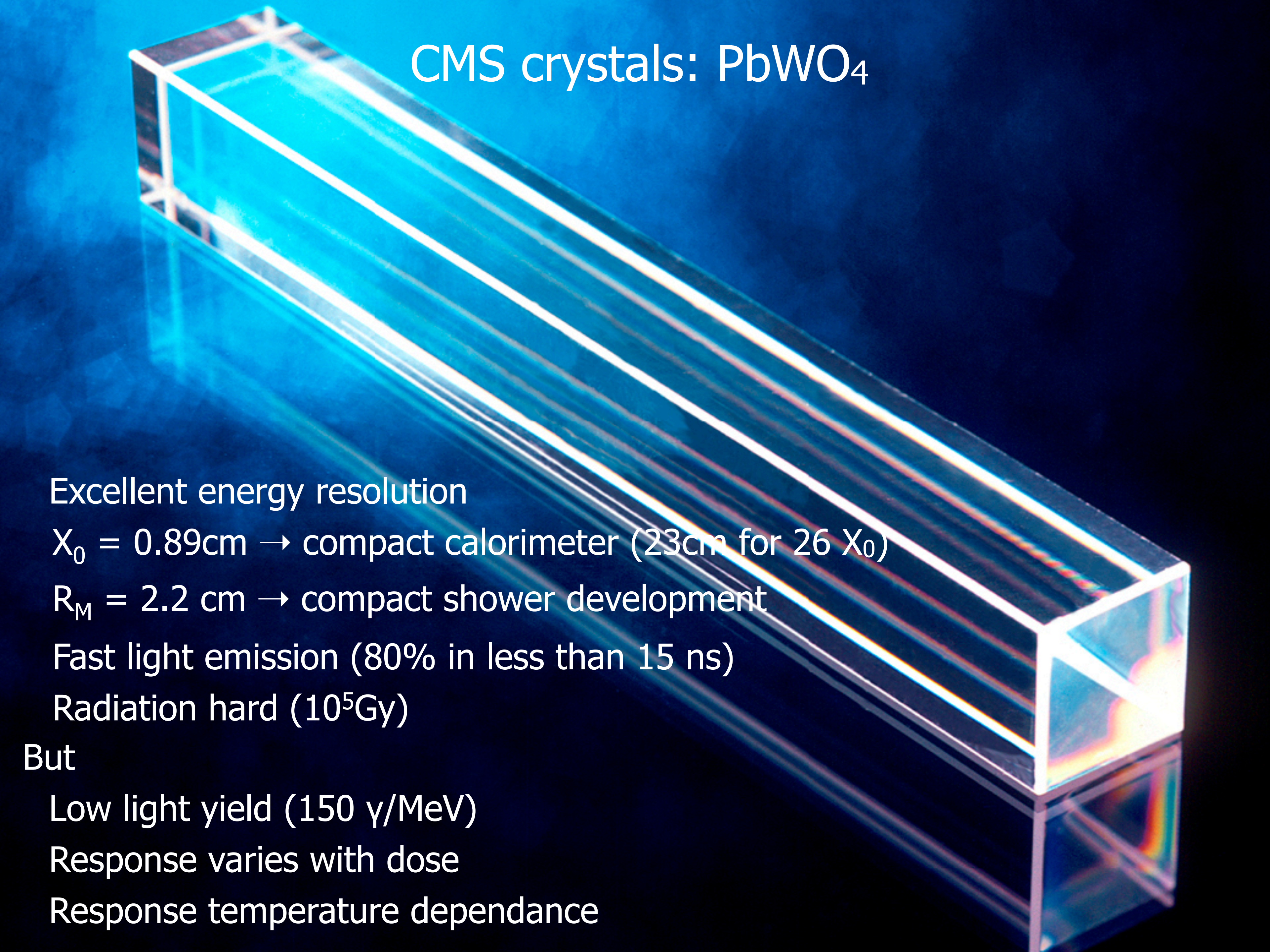
Previous Crystal calorimeters: max $1 m^3$



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2x2x23 cm^3$)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3x3x22 cm^3$)

CMS crystals: $PbWO_4$



Excellent energy resolution

X_0 = 0.89cm → compact calorimeter (23cm for 26 X_0)

R_M = 2.2 cm → compact shower development

Fast light emission (80% in less than 15 ns)

Radiation hard (10^5Gy)

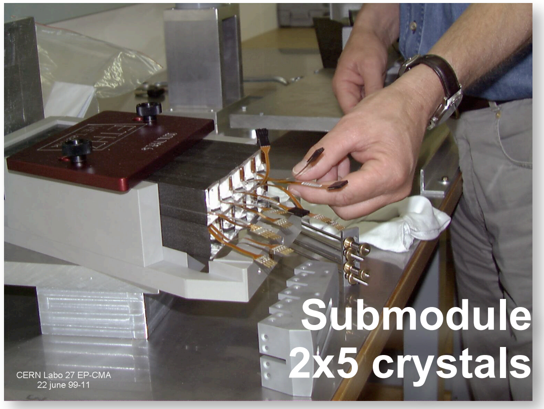
But

Low light yield (150 γ/MeV)

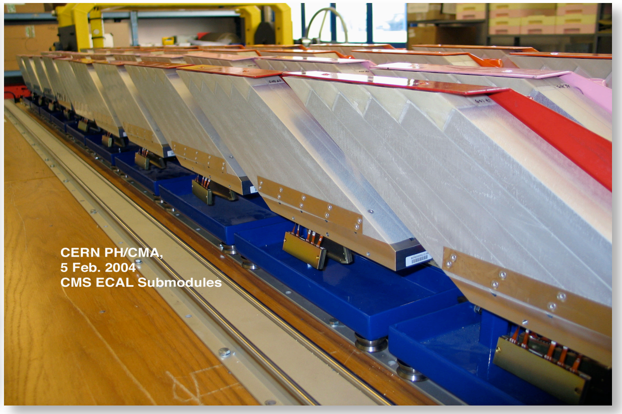
Response varies with dose

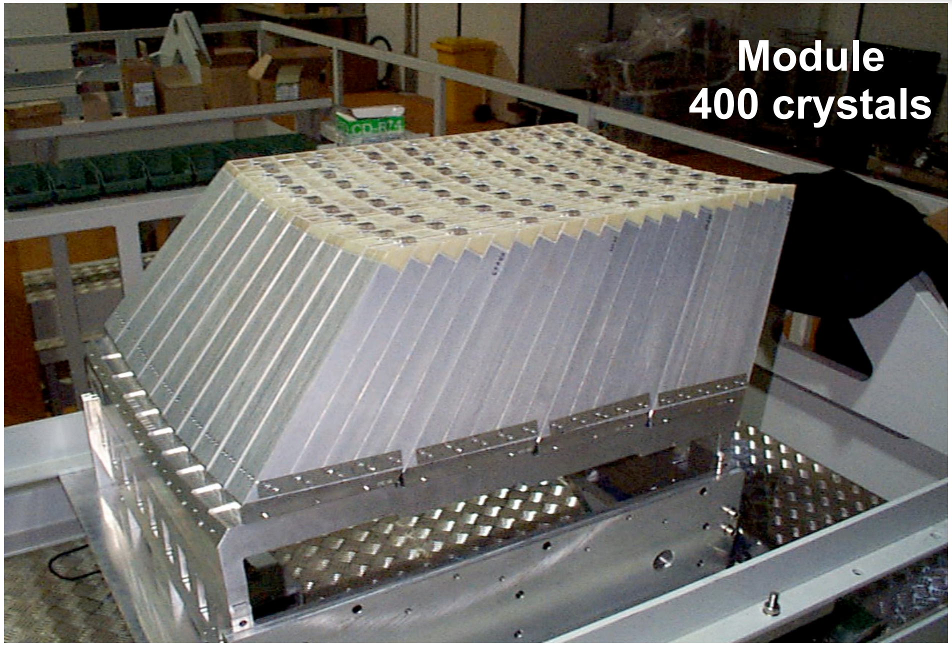
Response temperature dependance

CMS ECAL Construction

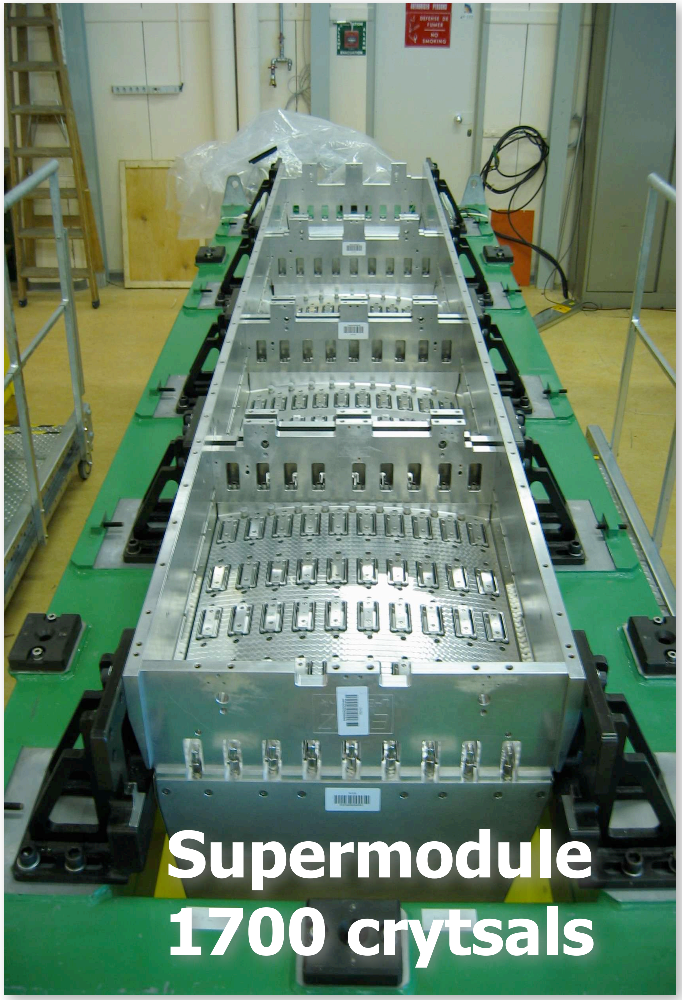


Submodule
2x5 crystals



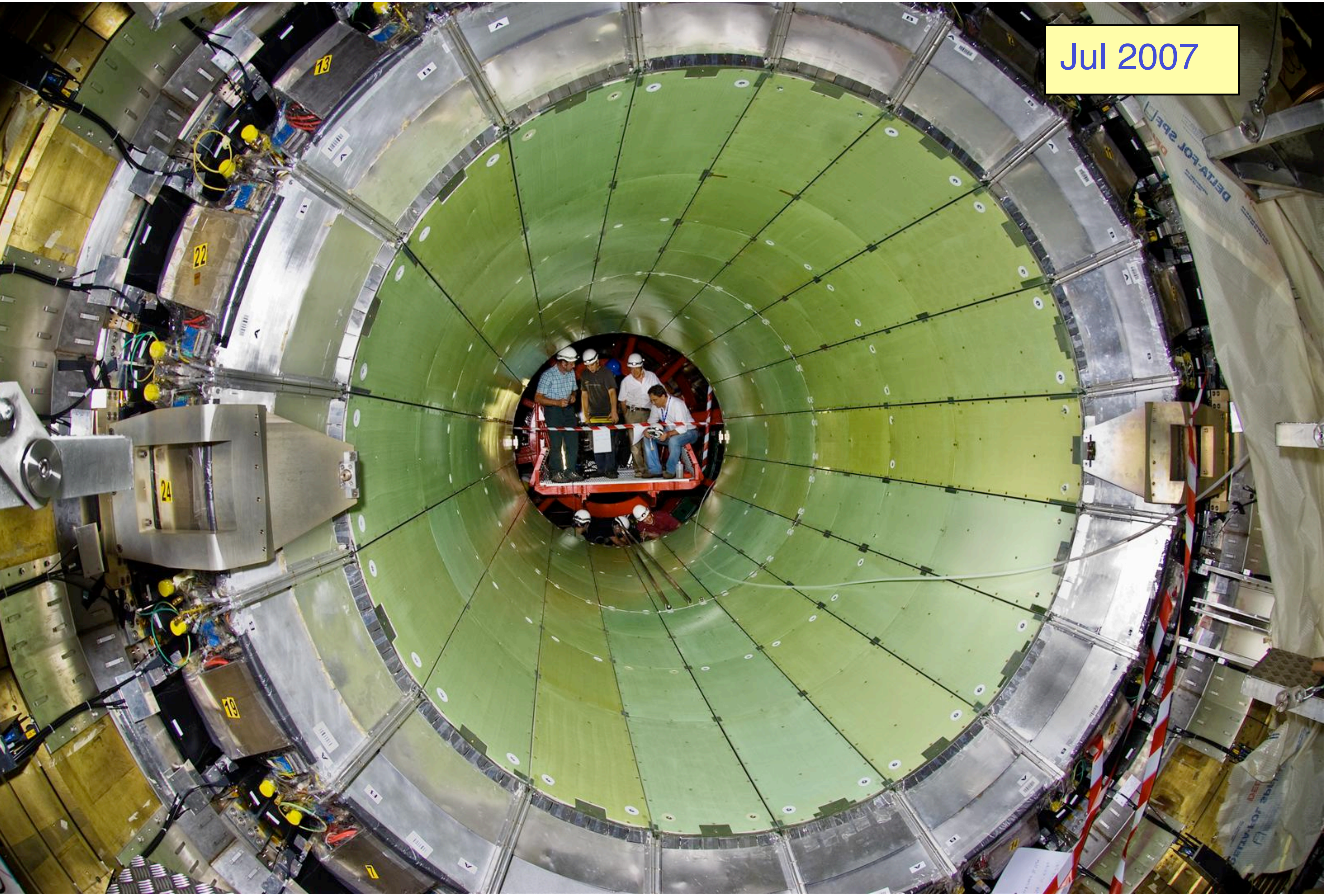


Module
400 crystals

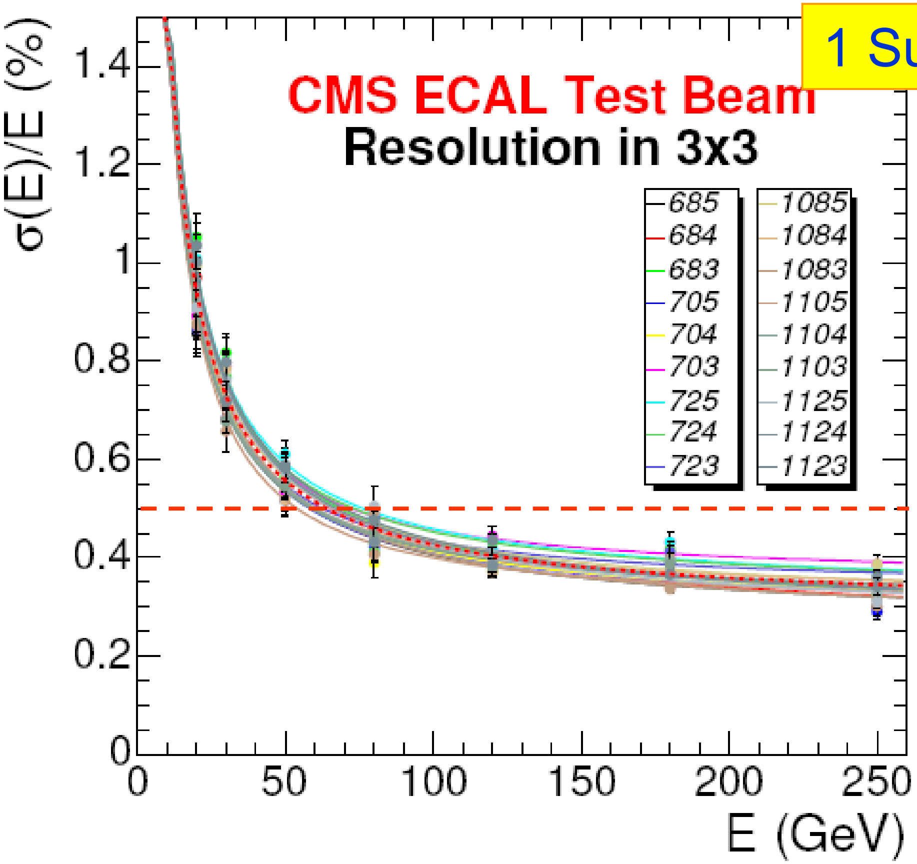


Supermodule
1700 crytsals

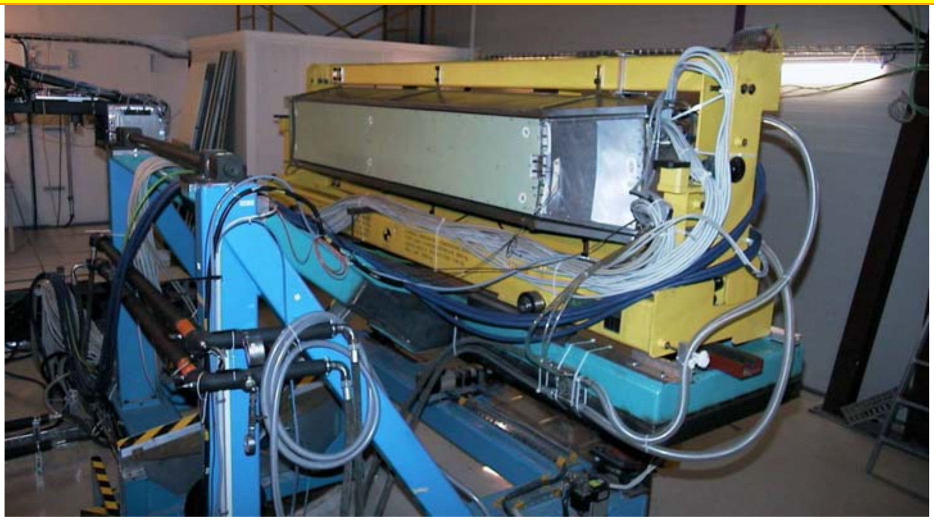
Total 36 Supermodules


Jul 2007

CMS ECAL: Performance in testbeam



1 Super Module 1700 xl on test beam in 2004



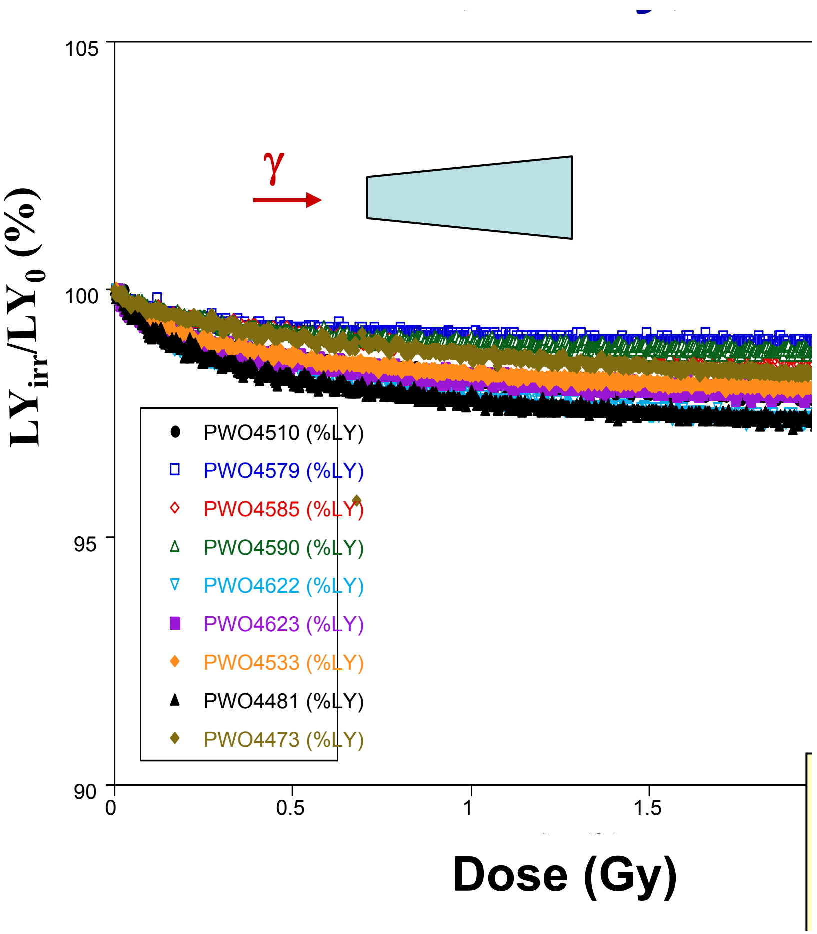
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

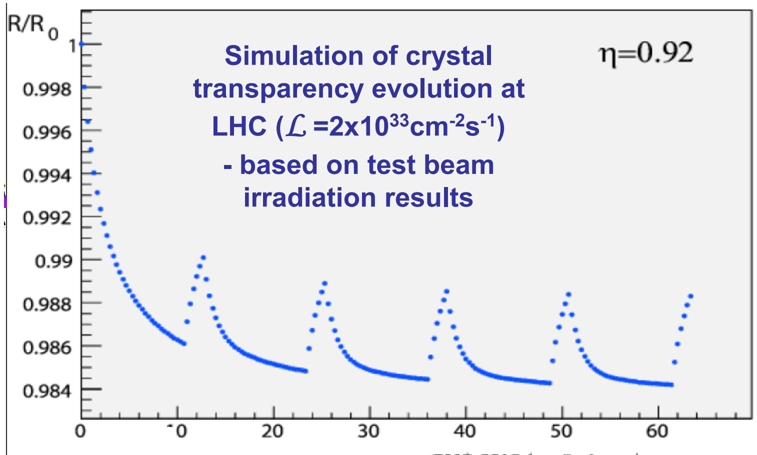
Excellent performance obtained in testbeam

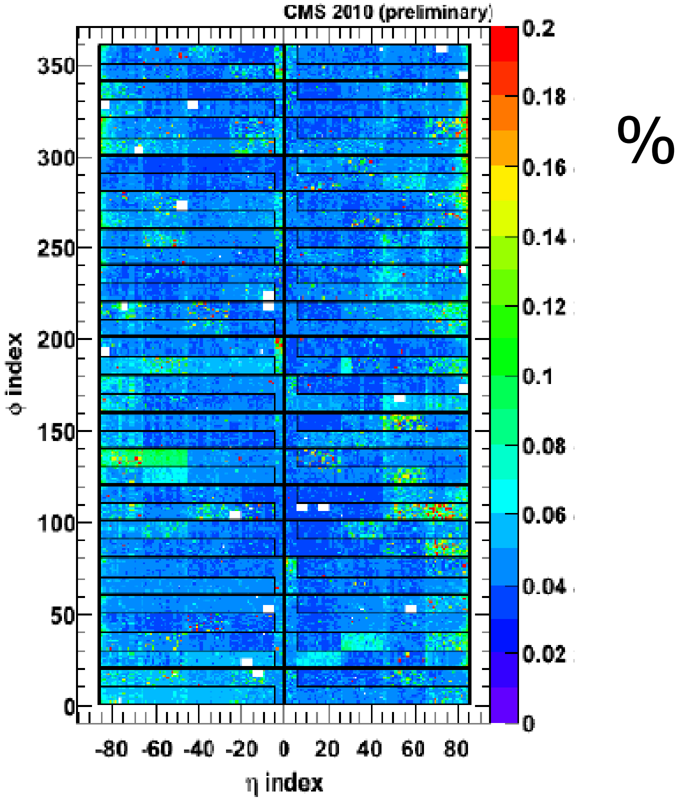
1/4 of barrel modules

How to preserve it at LHC ?

Sensitive to radiation dose




Simulation of crystal transparency evolution at LHC ($\mathcal{L}$ =2x10^{33}cm^{-2}s^{-1}) - based on test beam irradiation results



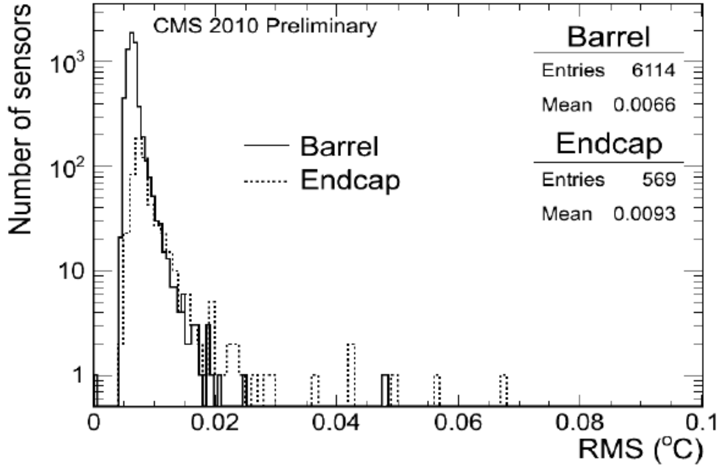
Large effect which needs to be corrected for

- Laser system which sends light to each crystal during beam (LHC abort gap)

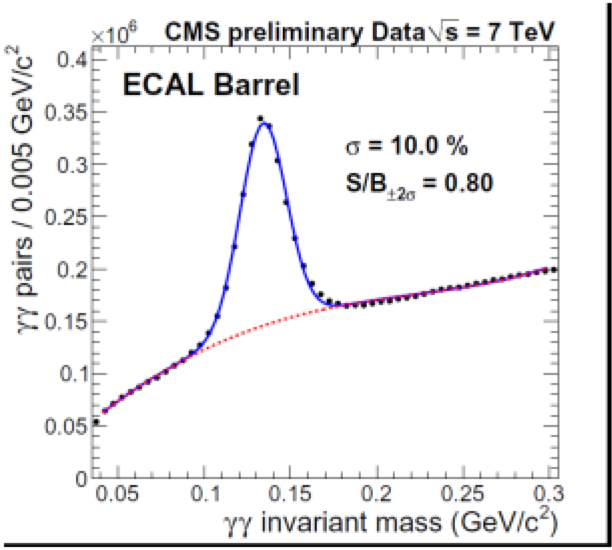
Crystal calibration in CMS

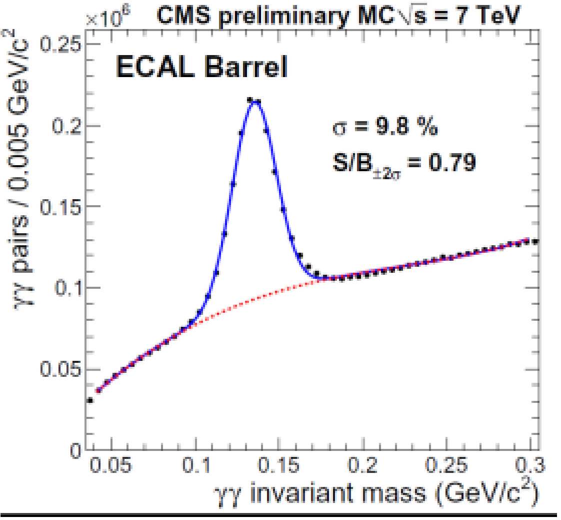
Inter-calibration: several steps

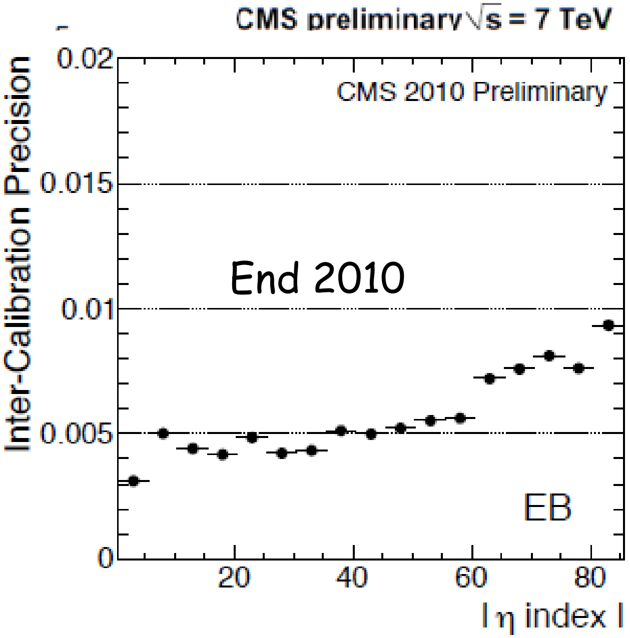
- testbeam (1/4 of barrel ECAL)
- cosmic muons in situ
- Laser pulsing: tracks variations during data taking
- Temperature stability: $\Delta E/E = -2\%/^{0}C$
- Using particles: π^0, η^0



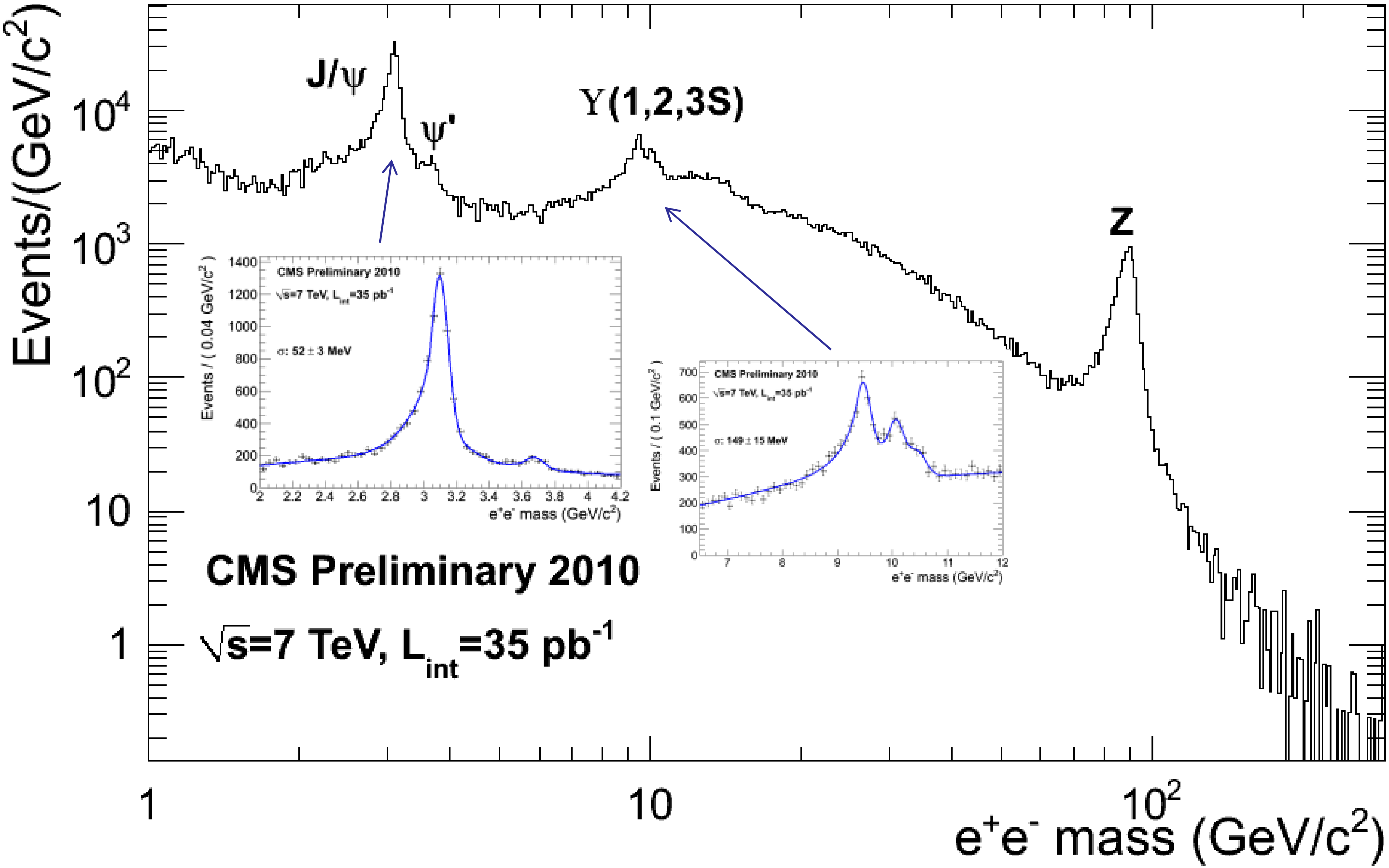
June 2010 - Dec 2010



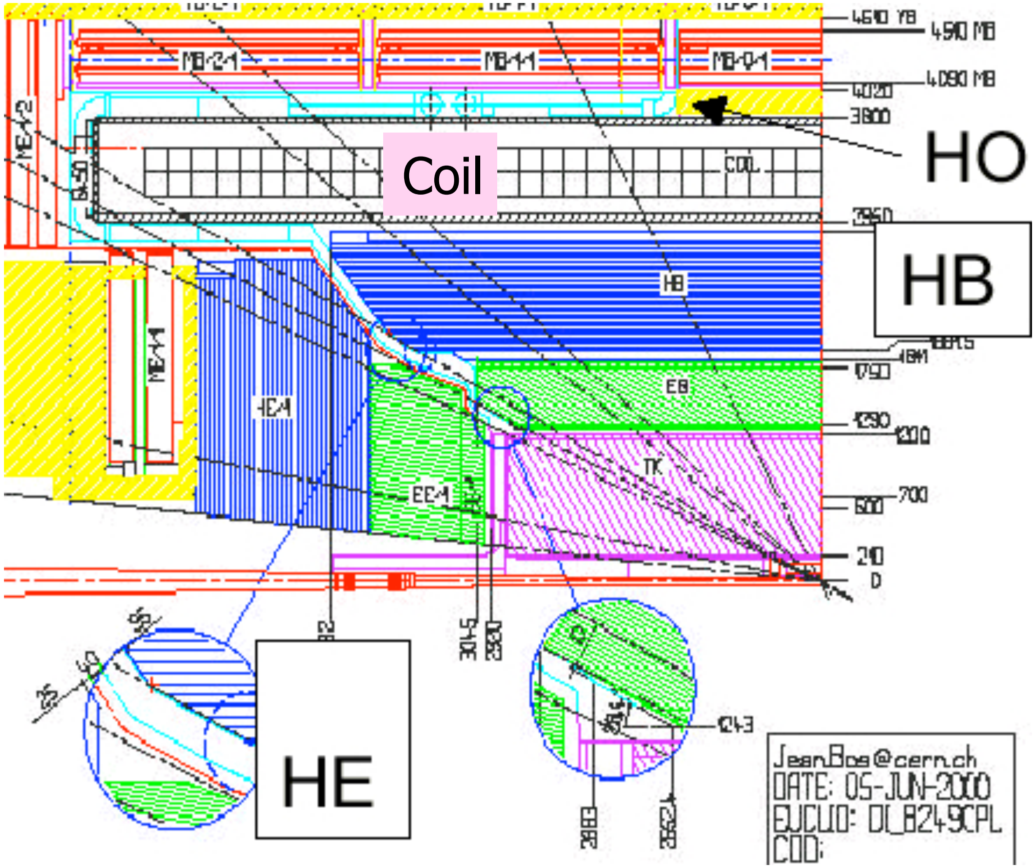




Performance in-situ CMS



CMS Hadronic calorimeter



Central : lηl < 1.7 Cu/scintillator + WLS

2 + 1 (HO) layers

5.9 + 3.9 λ (lηl =0)

Endcap 1.3< lηl < 3 Cu/scintillator + WLS

2/3 layers

Forward 2.85 < lηl < 5.19

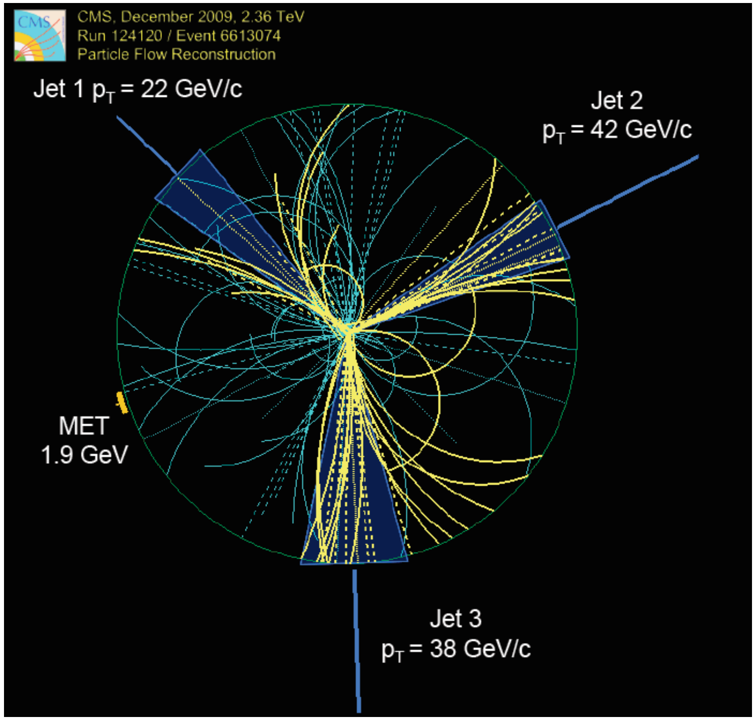
Fe/quartz fibers (radiations)

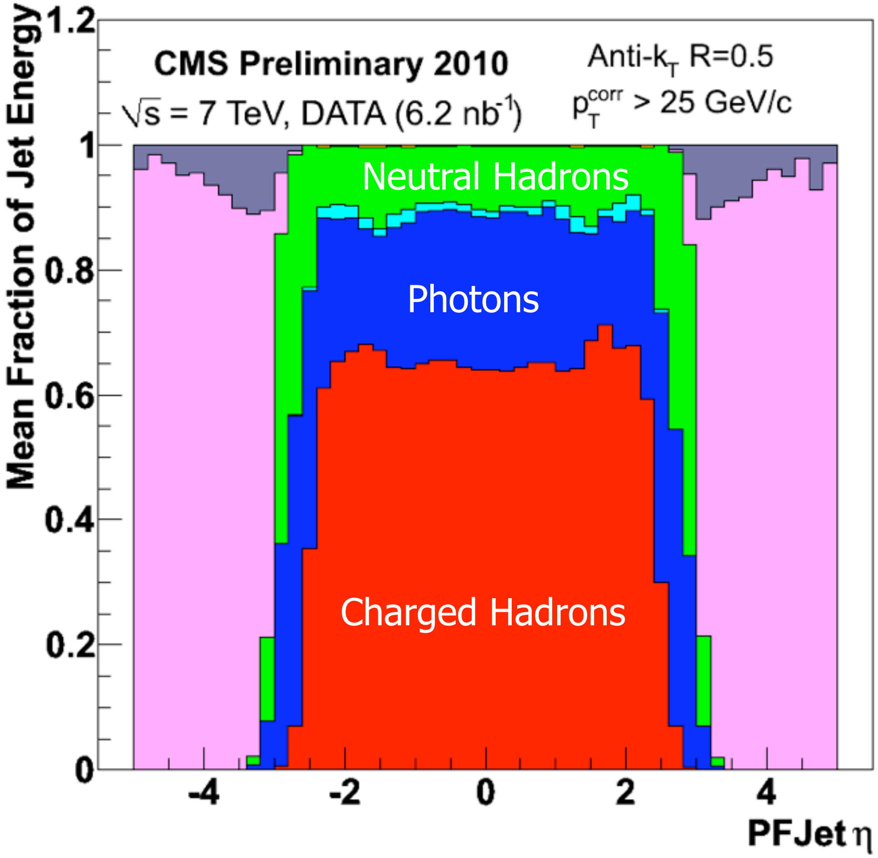
Copper: non magnetic material

CMS Hadronic Response

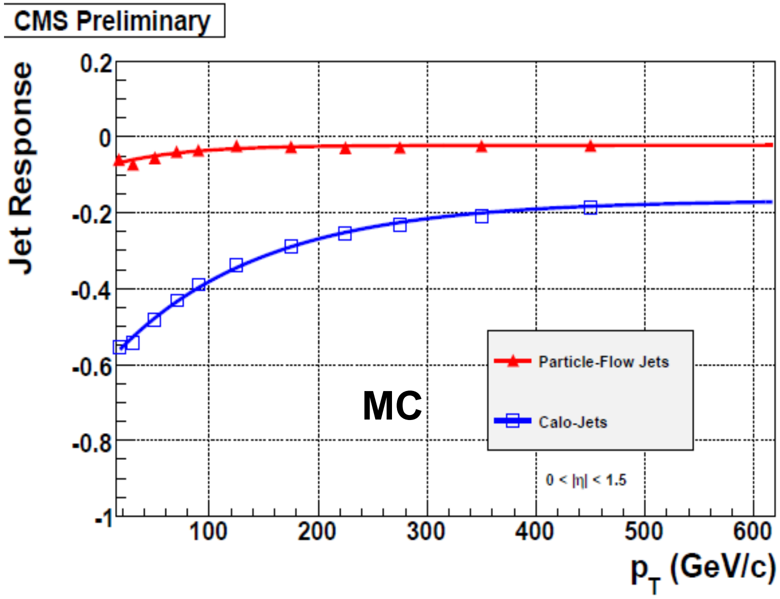
CMS is using a Particle Flow Technic to reconstruct Jets and Missing Transverse Energy

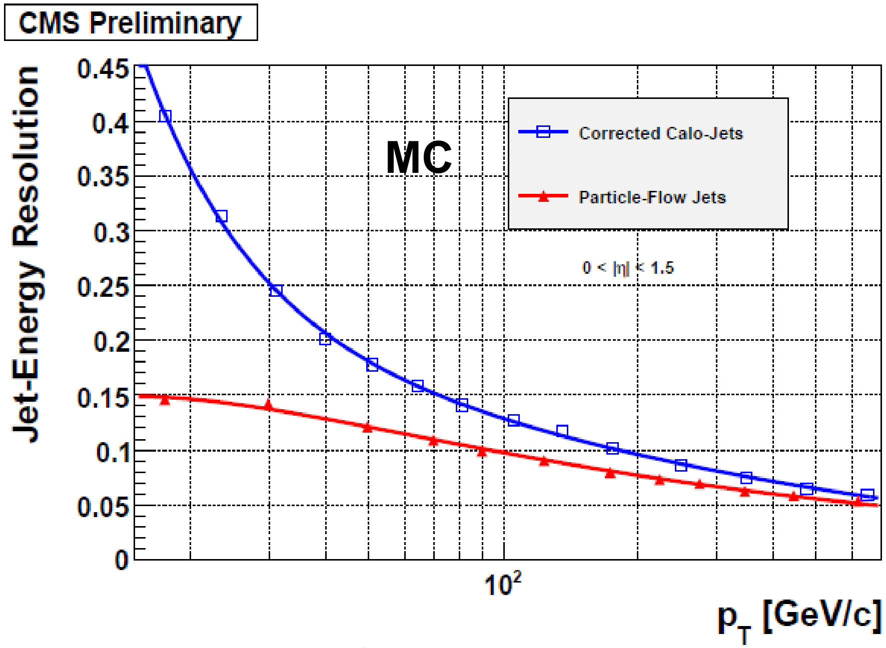
- use the best measurement for each component
  - Tracker for charged hadron
  - ECAL for electrons & photons
  - HCAL for neutral hadrons

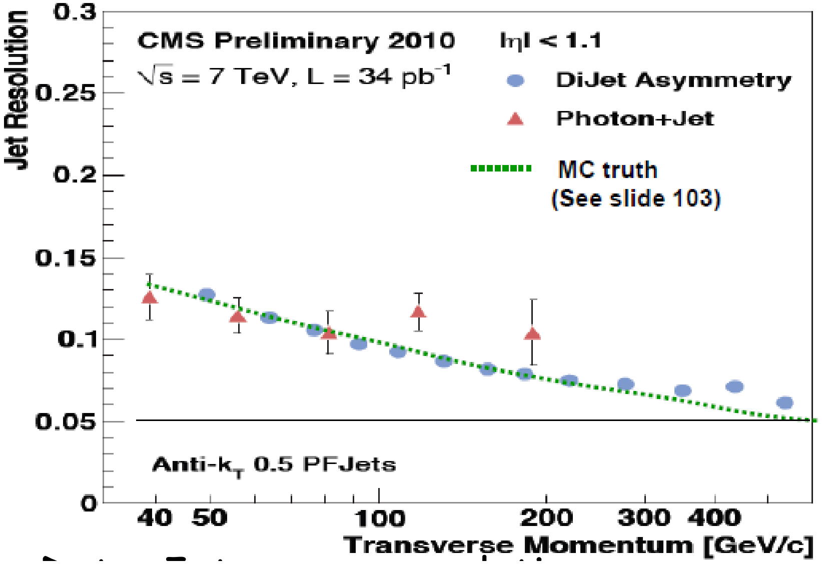




CMS-Particle Flow Jet Reconstruction Performance

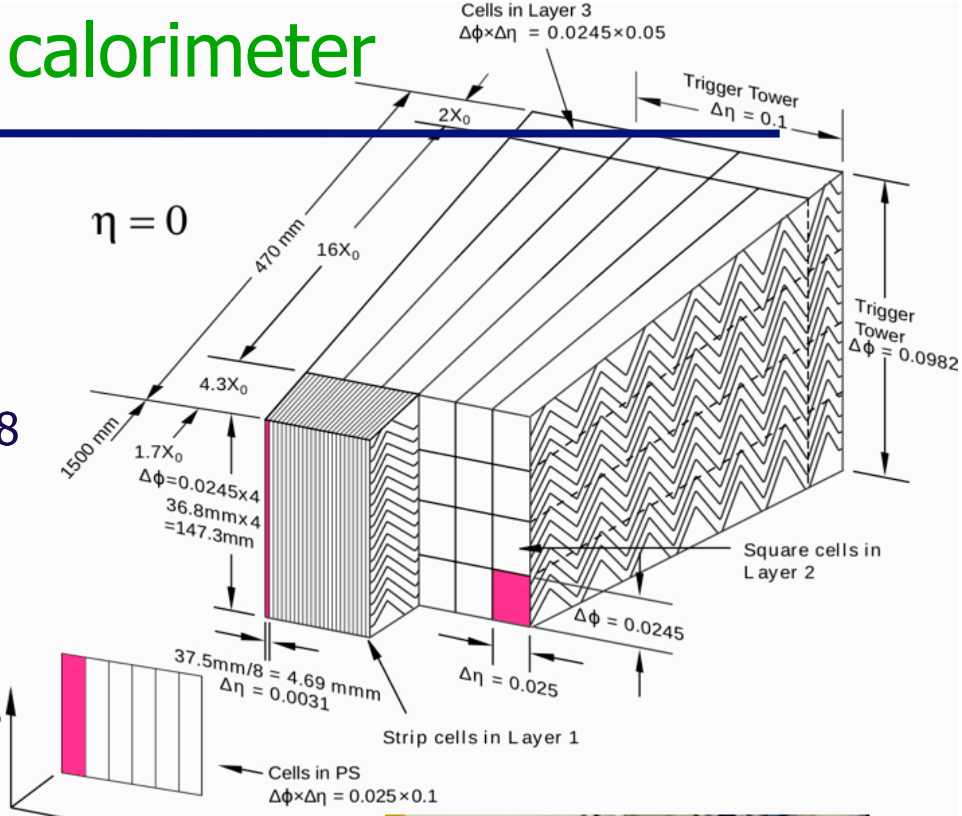






ATLAS calorimeter

ATLAS EM calorimeter



Accordion Pb/LAr |η|<3.2 ~170k channels

- Precision measurement |η|<2.5

3 layers up to |η|=2.5 + presampler |η|<1.8

2 layers 2.5<|η|<3.2

- Layer 1 (γ/π^0 rej. + angular meas.)
- Δη.Δφ = 0.003 x 0.1
- Layer 2 (shower max)
- Δη.Δφ = 0.025 x 0.0.25
- Layer 3 (Hadronic leakage)
- Δη.Δφ = 0.05 x 0.0.025

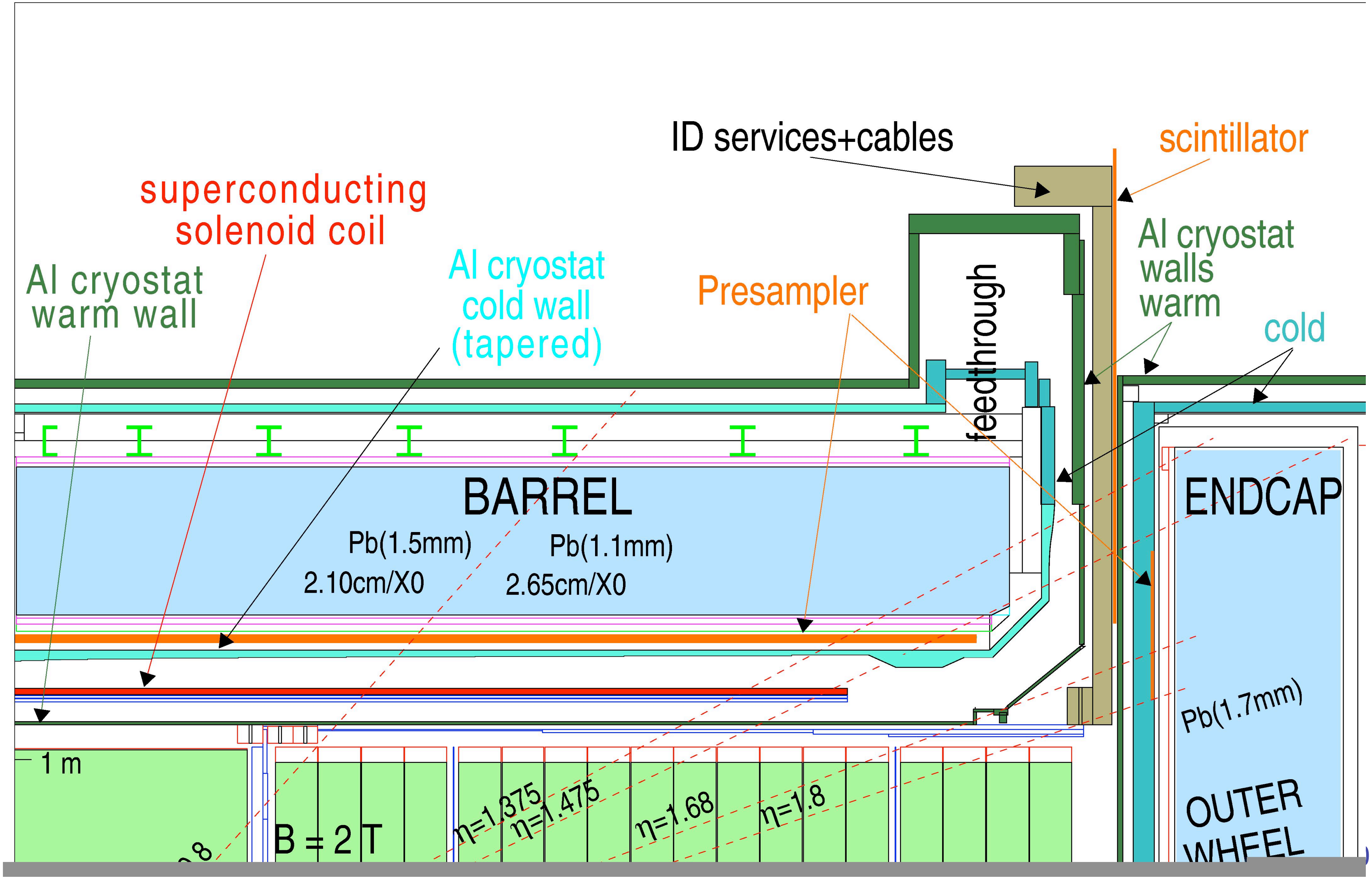
Energy Resolution: design for η~0

- ΔE/E ~ 10%/√E ⊕ 150 MeV/E ⊕ 0.7%

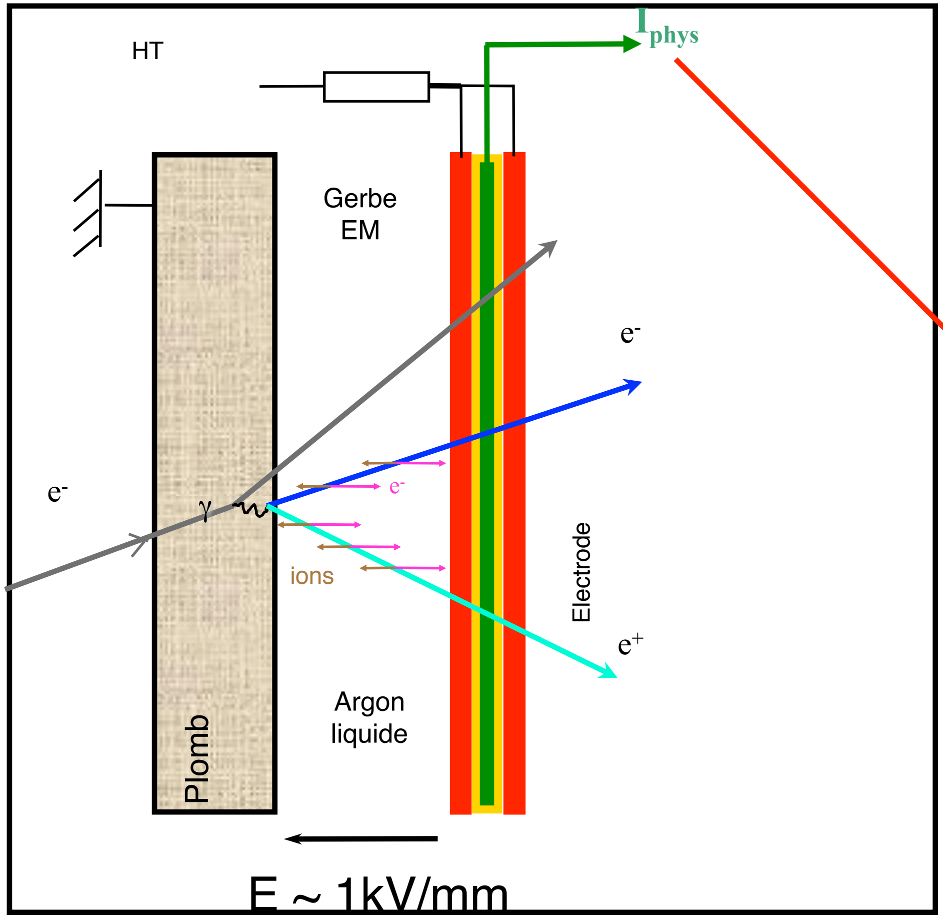
Angular Resolution

- 50mrad/√E(GeV)

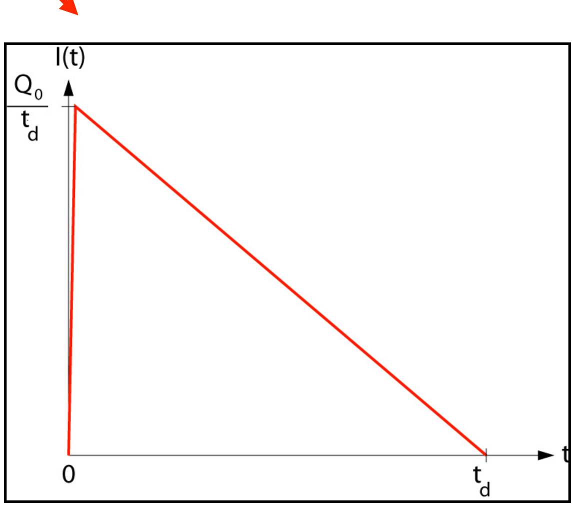
The cryostat structure



Principle



Pic ∝ ∫ signal déposé



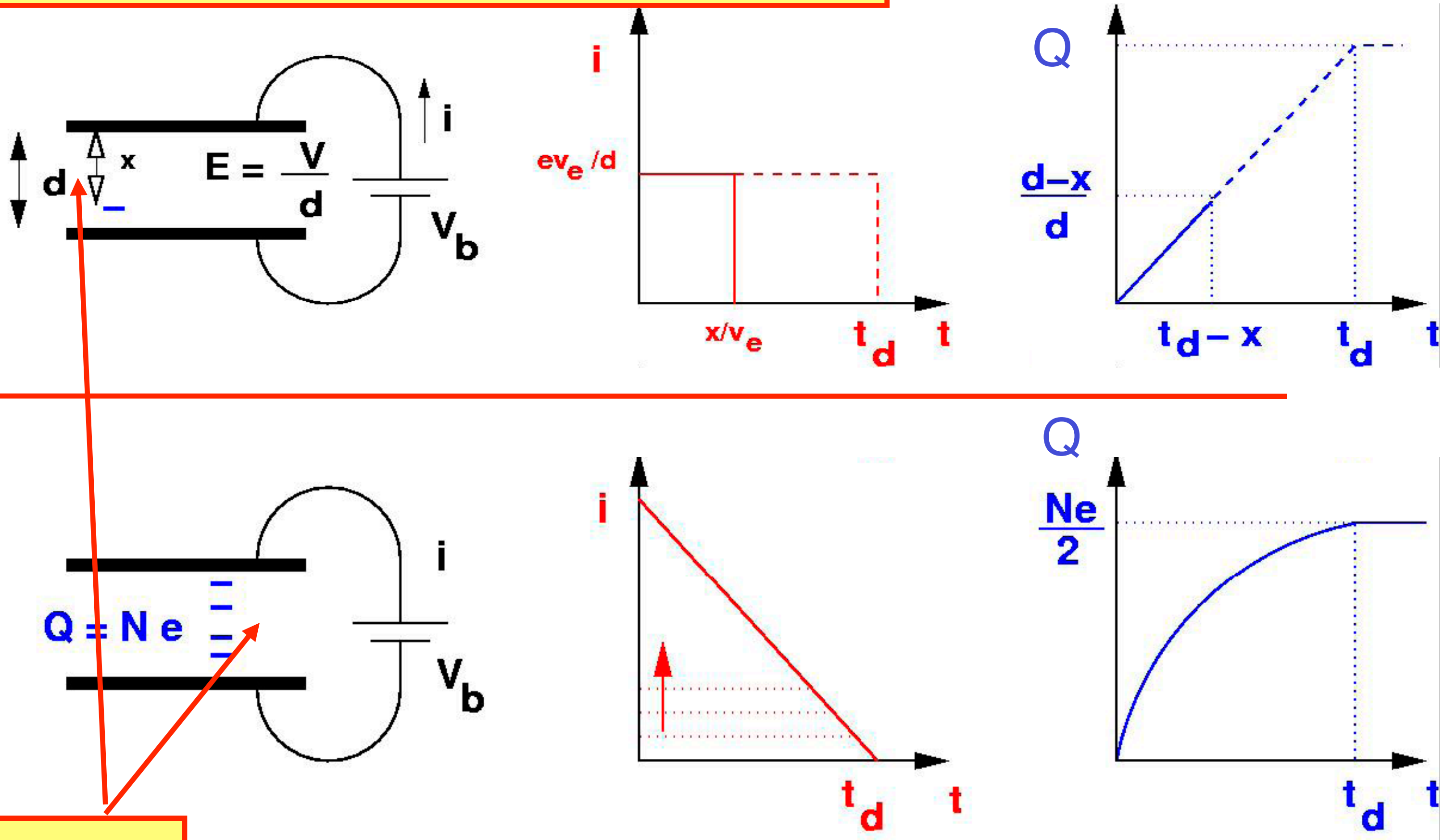
400 ns ≈ 16 LHC BC

Collection du signal dans l’argon liquide

Collection des électrons induits par l’ionisation des atomes due au passage des particules chargées de la gerbe dans le liquide noble

Une charge

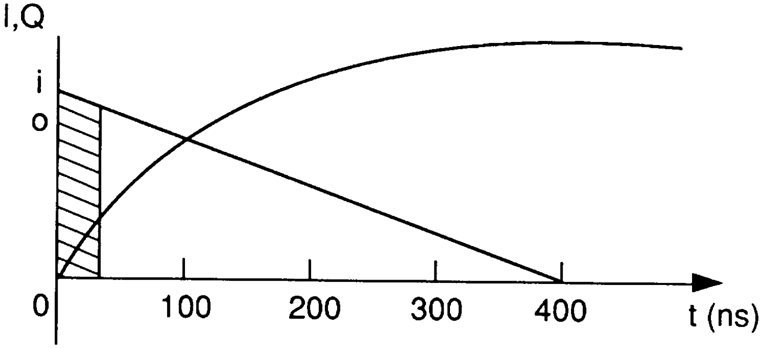
N charges uniformément réparties

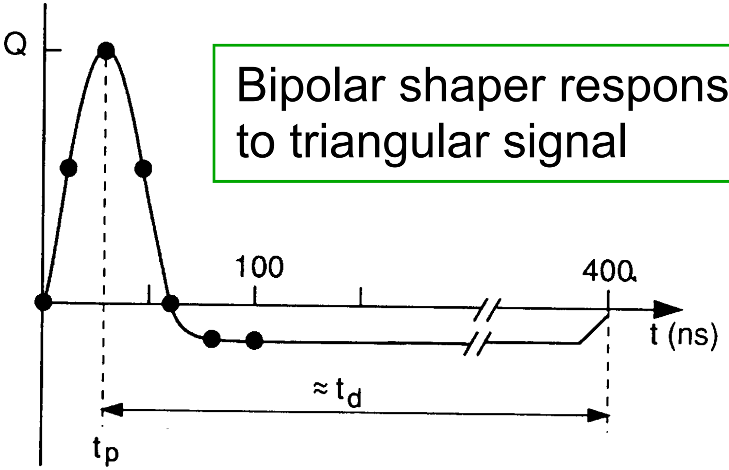


Le gap

Obtaining a fast response

Integrate the current over time $t_p << t_D$ ($t_p \sim 40$ ns)





Bipolar shaper response to triangular signal

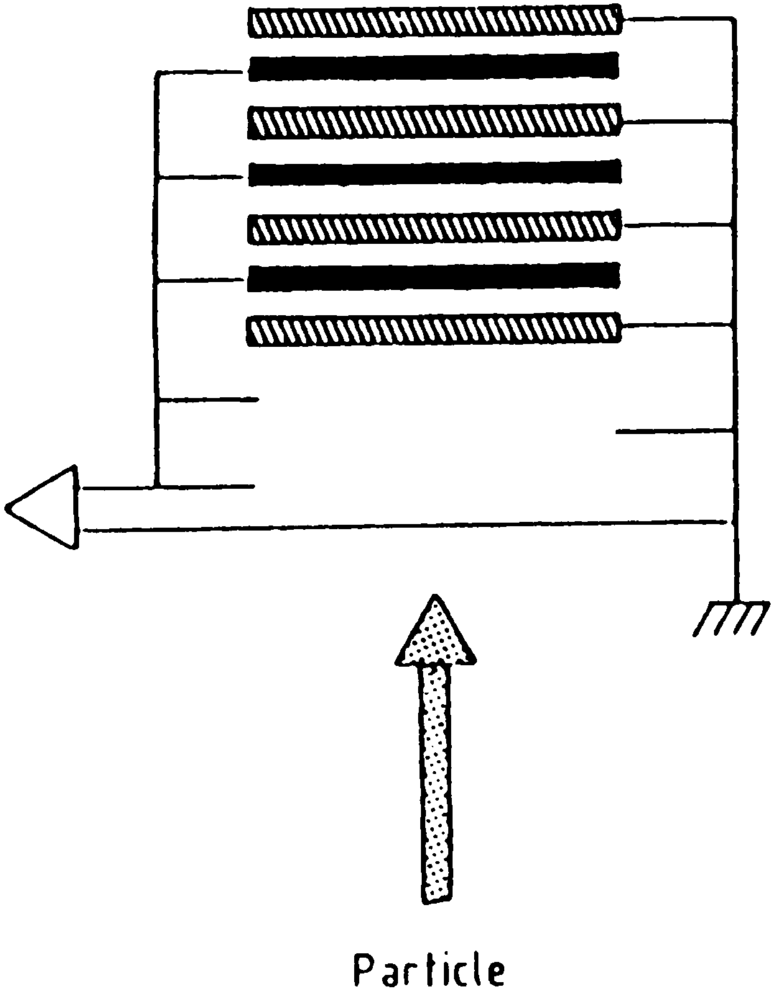
S/N is smaller than in the case t_p=t_D

$$S \sim t_p, N \sim \frac{1}{\sqrt{t_p}} \Rightarrow \frac{S}{N} \sim t_p^{3/2}$$

→ detector response time is not t_d but t_p

~30 smaller for 40 ns than for 400 ns

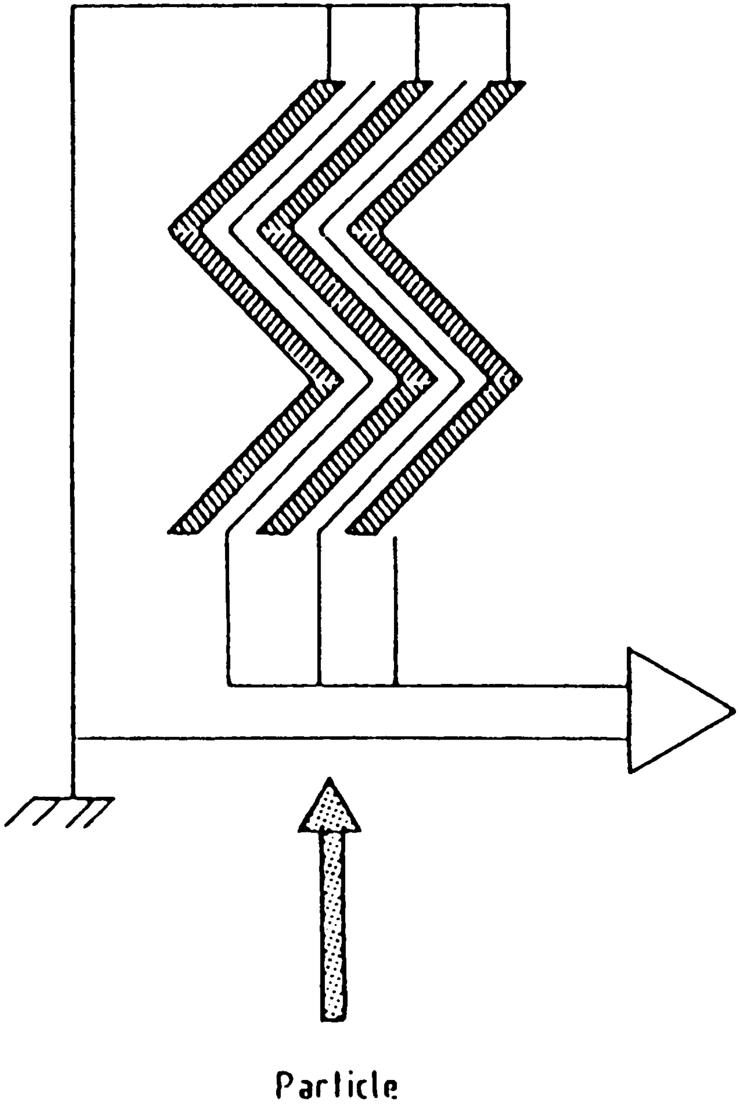
Parallel plates geometry



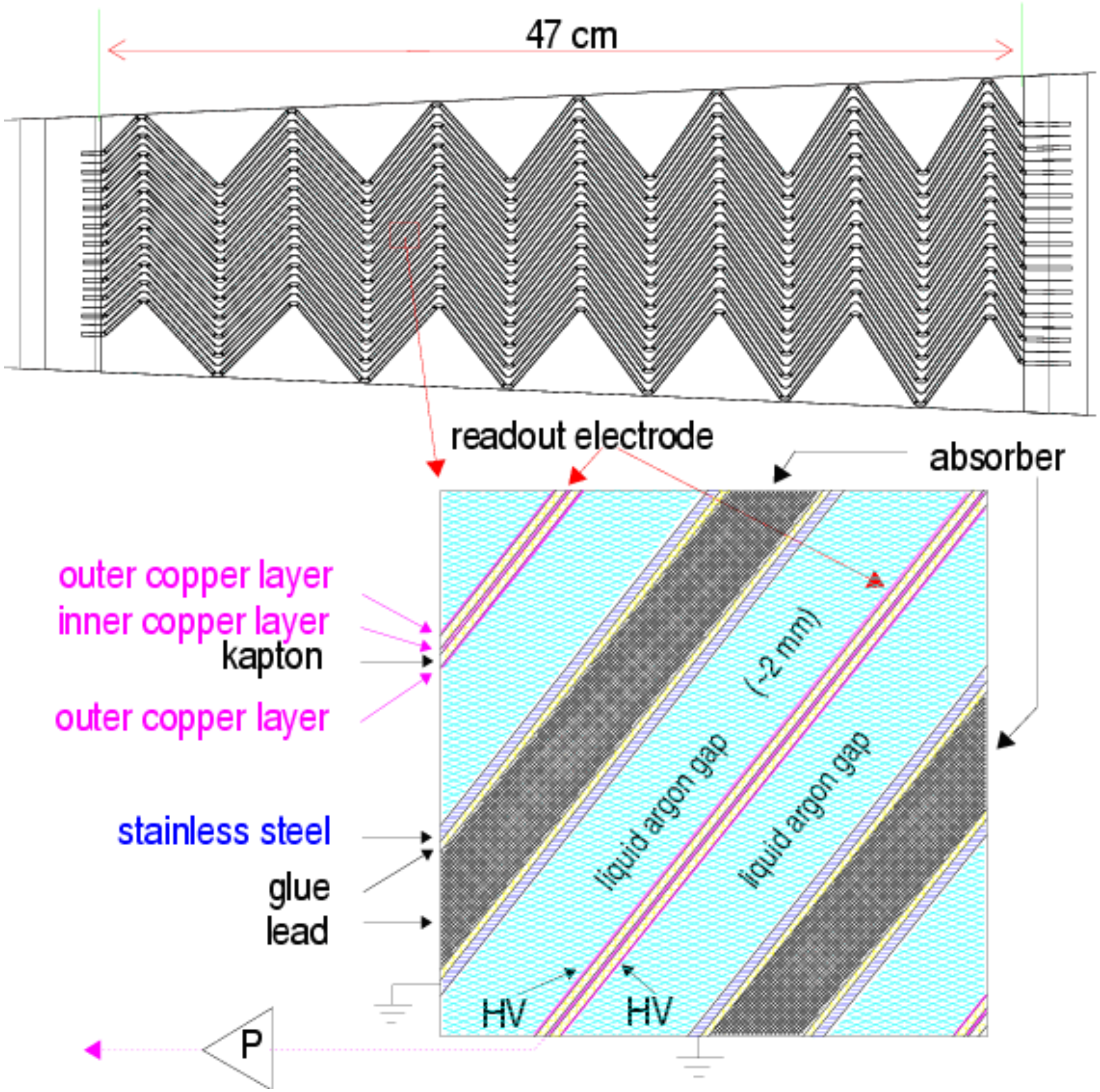
- Les anciens calorimètres à argon liquide avaient un temps de réponse lent (intégration du signal).
- Electrodes perpendiculaires aux particules
- Longs câbles
  - pour emmener les signaux vers les preamplis (transfert ~qques ns)
  - regrouper ensemble des gaps
- Zones mortes dues aux câbles

Accordeon geometry

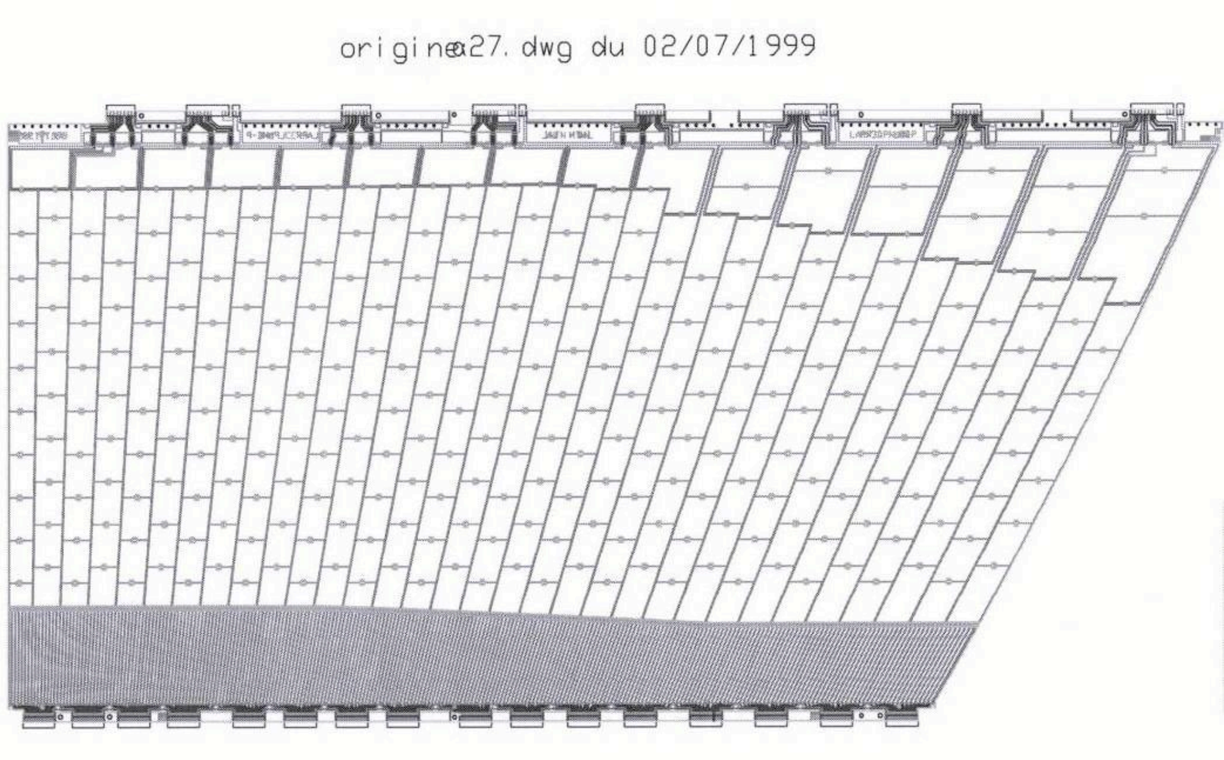
- Géométrie à accordéon: rapide
- Les électrodes sont parallèles aux particules incidentes
  - lectures des signaux à l'avant et à l'arrière
  - pas de longues connexions
- Le découpage en profondeur est dessiné sur les électrodes
- Pas d'espace sans détection

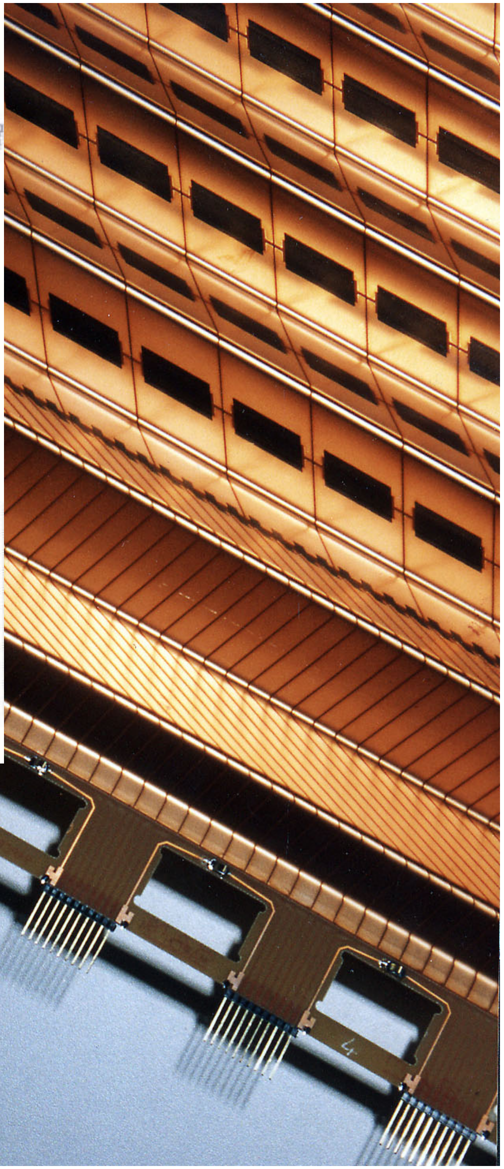


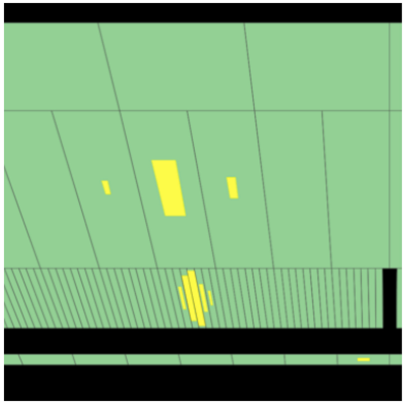
ATLAS EM calorimeter

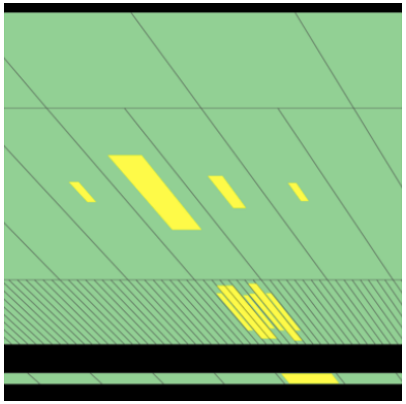


The segmentation



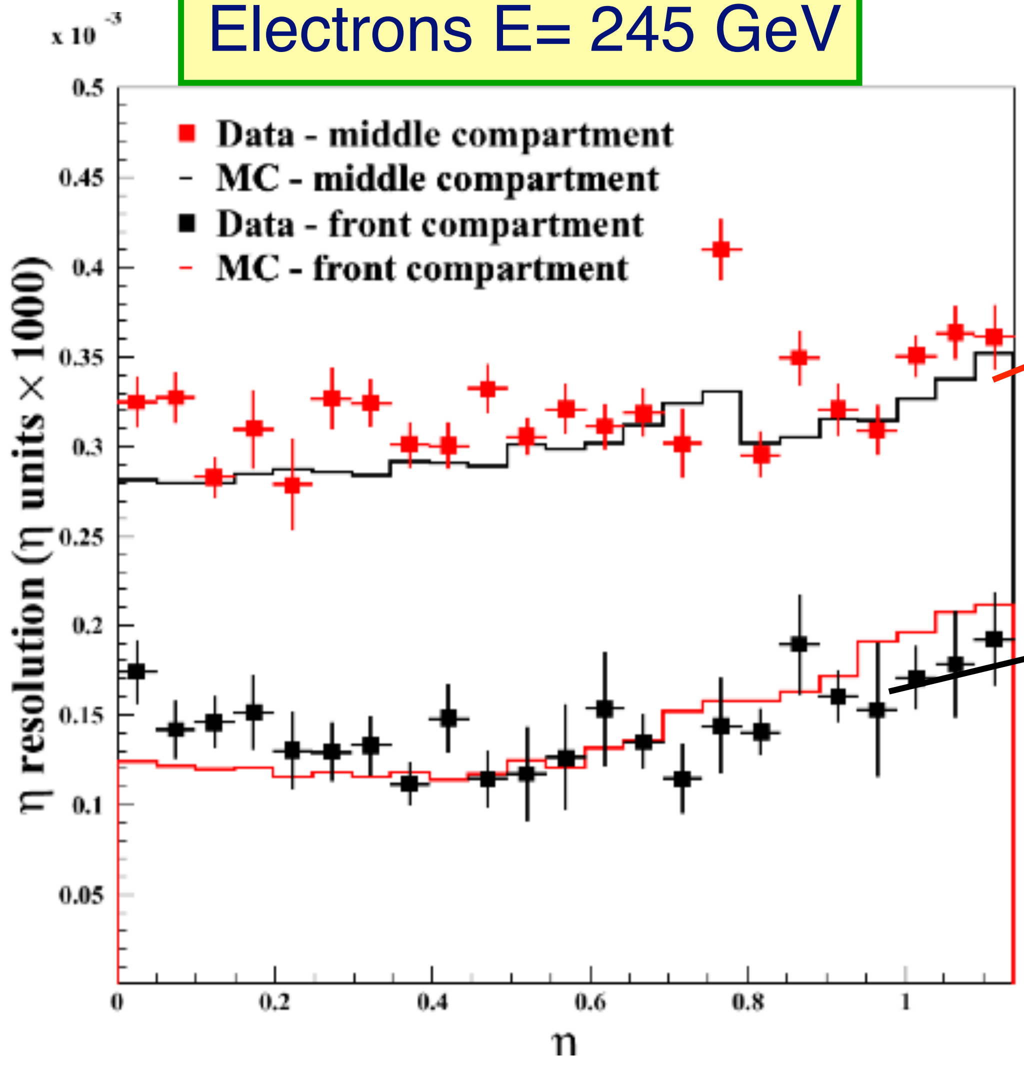


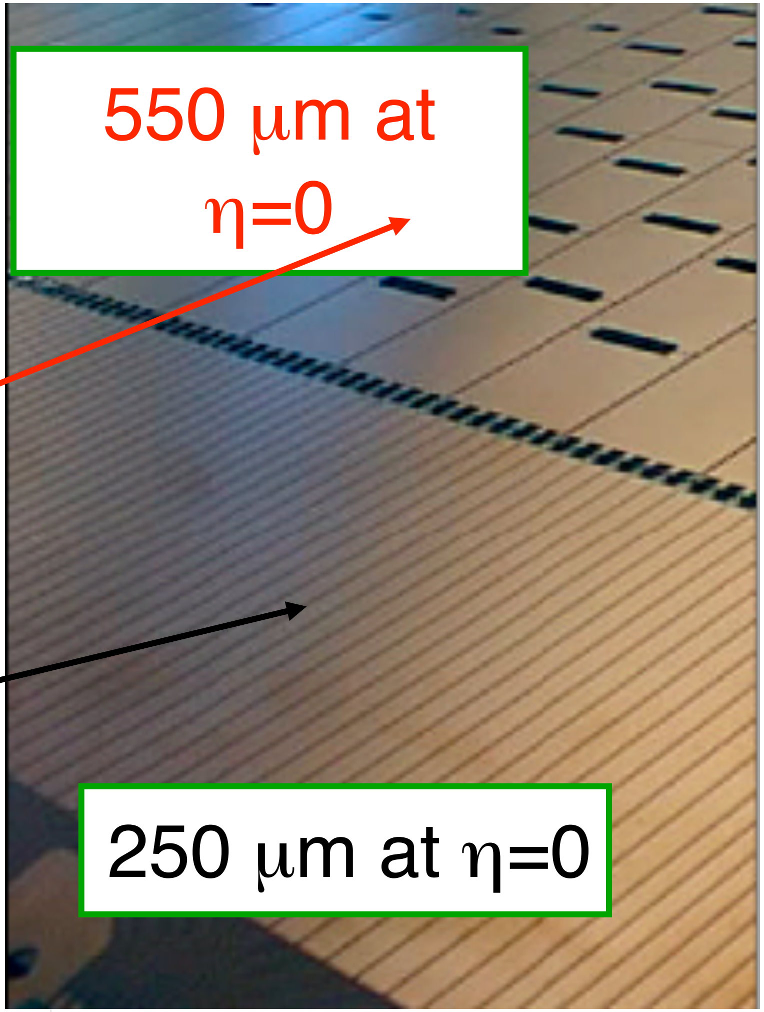




Position resolution

Electrons E= 245 GeV





550 μm at η=0

250 μm at η=0

Energy Resolution CMS vs ATLAS

CMS ($PbW0_4$) / ATLAS (Pb/LAr)			
	10 GeV	100 GeV	1000 GeV
Stochastic (GeV)	0.095 / 0.32	0.3 / 1	0.949 / 3.2
Noise (GeV)	0.3 / 0.3	0.3 / 0.3	0.3 / 0.3
Constant (GeV)	0.05 / 0.07	0.5 / 0.7	5 / 7
σ(E) (GeV)	0.30 / 0.44	0.65 / 1.26	5.1 / 7.7
σ(E)/E (%)	3 / 4.4	0.65 / 1.26	0.51 / 0.77

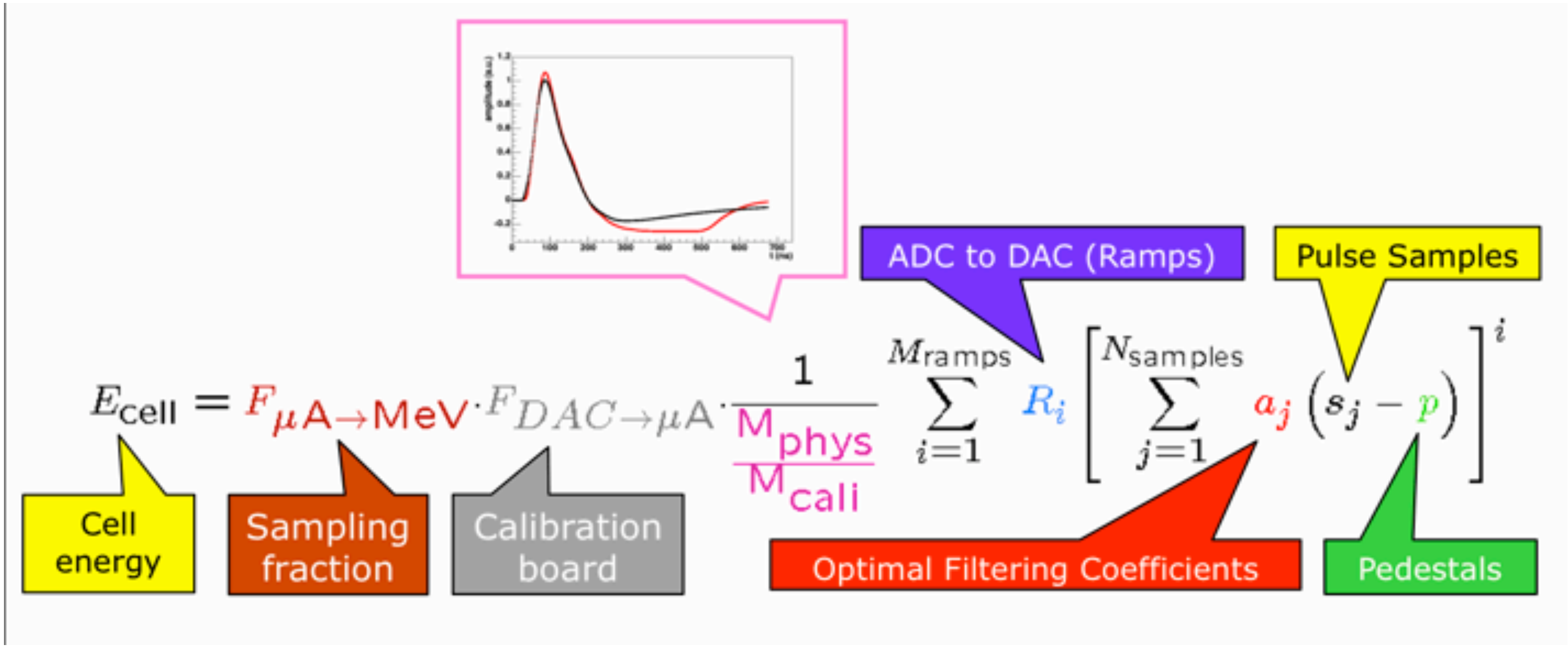
$$\frac{\sigma(E)}{E} = \frac{0.03}{\sqrt{E(GeV)}} \oplus \frac{0.3}{E(GeV)} \oplus 0.005$$

$$\frac{\sigma(E)}{E} = \frac{0.1}{\sqrt{E(GeV)}} \oplus \frac{0.3}{E(GeV)} \oplus 0.007$$

ATLAS LAr cell calibration

Cell to cell calibration from electronics calibration system

- Inject a known signal amplitude
- Correct for the difference between calibration signal and ionisation signal shapes
- Correct for the sampling fraction
- Apply calibration factor



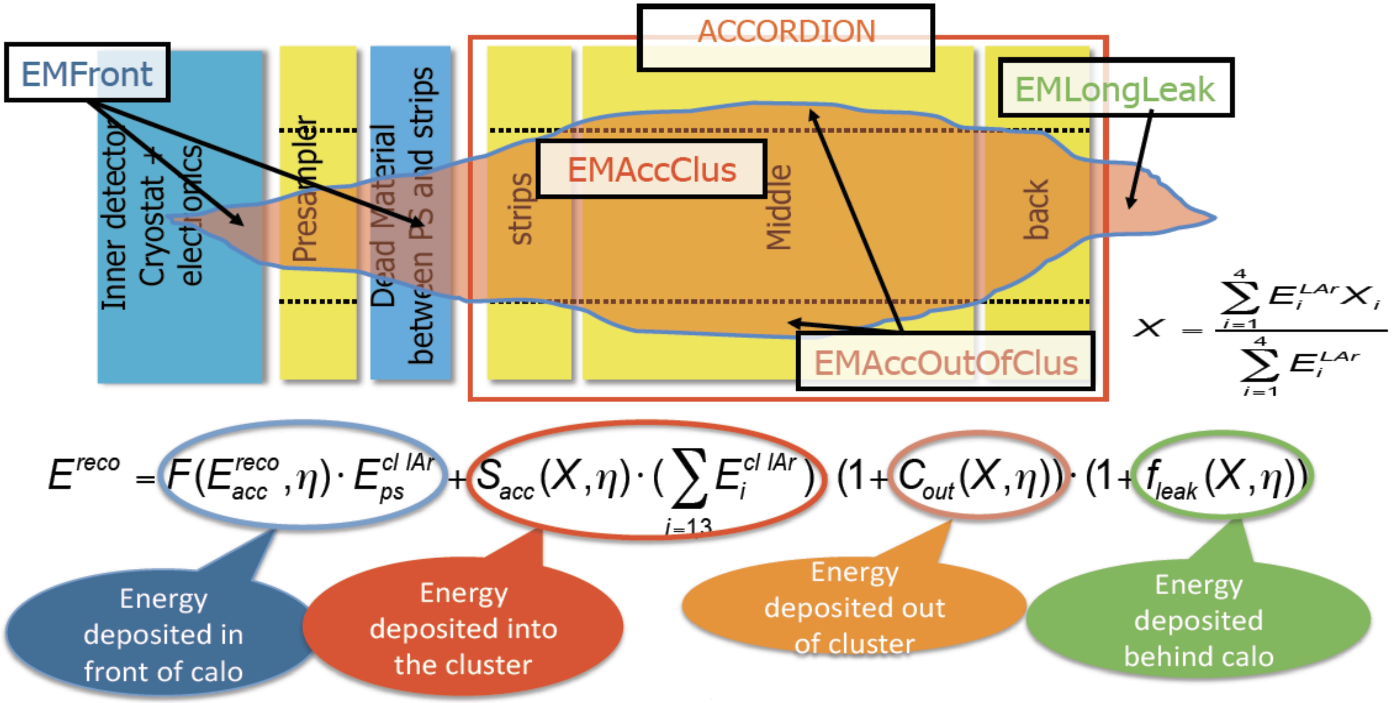
$$E_{\text{cell}} = F_{\mu\text{A}\rightarrow\text{MeV}} \cdot F_{DAC\rightarrow\mu\text{A}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \sum_{i=1}^{M_{\text{ramps}}} R_i \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]^i$$

ATLAS cluster correction

- Make use of simulation
  - compare energy deposited in the calorimeter to the one reconstructed
  - takes into account un-detected energies in
    - dead region of the detector
    - energy deposited outside the cluster
  - parametrize corrections as a function of energy and η
    - dedicated correction factors for electrons, photons, jets
- In situ, use precise knowledge of M_Z to set absolute energy scale (correct to ~% from testbeam)
- Method developed during testbeam campaigns and now applied in ATLAS

Cluster Energy Reconstruction

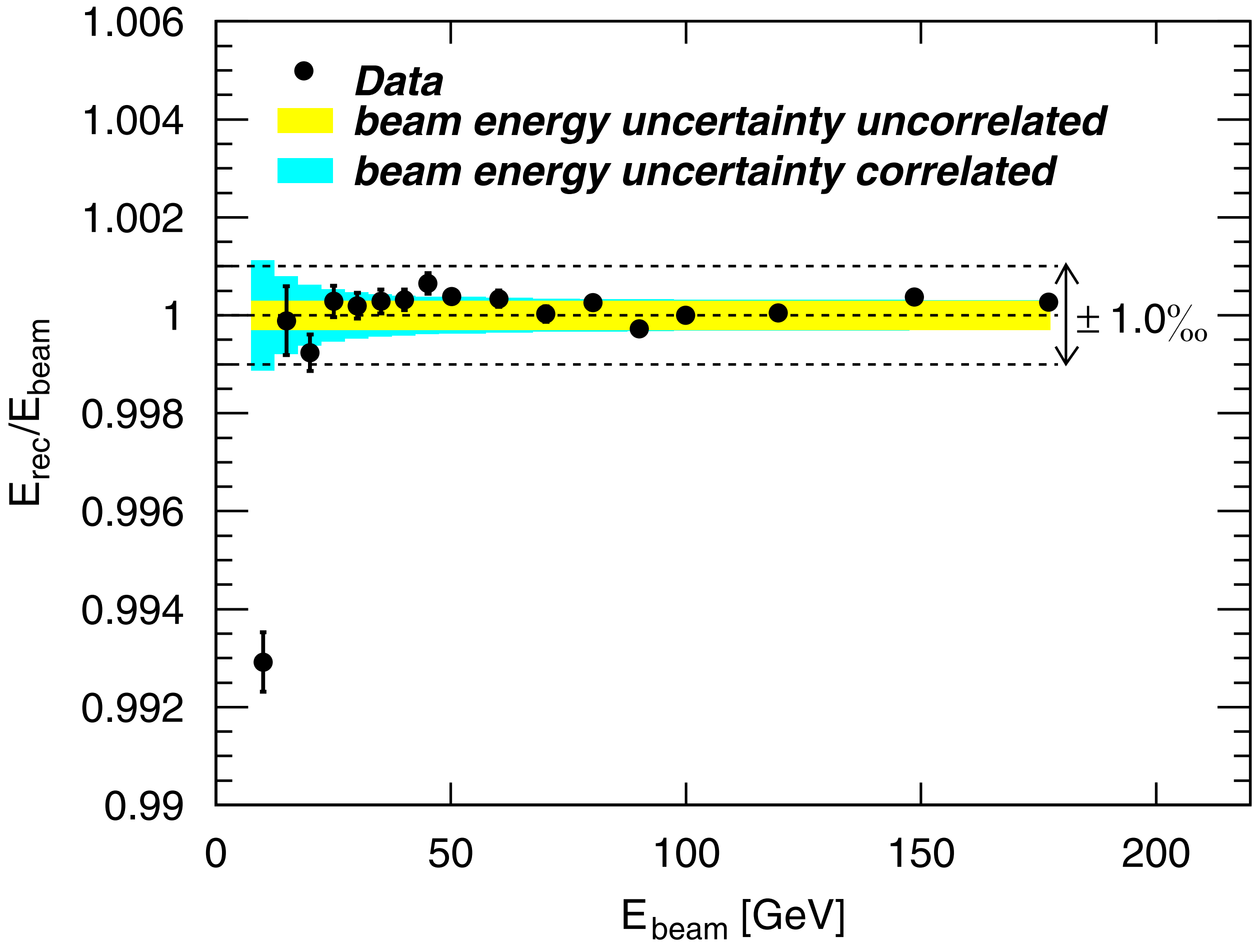
- E_{rec}: Need to correct E_{acc} for losses
  - in matter in front of calorimeter (IDI + cryostat)
  - Between Crysotat & Accordion
  - Loss outside the cluster $E_{outcluster}$
  - Rear leakage E_{leak}
- Use MC



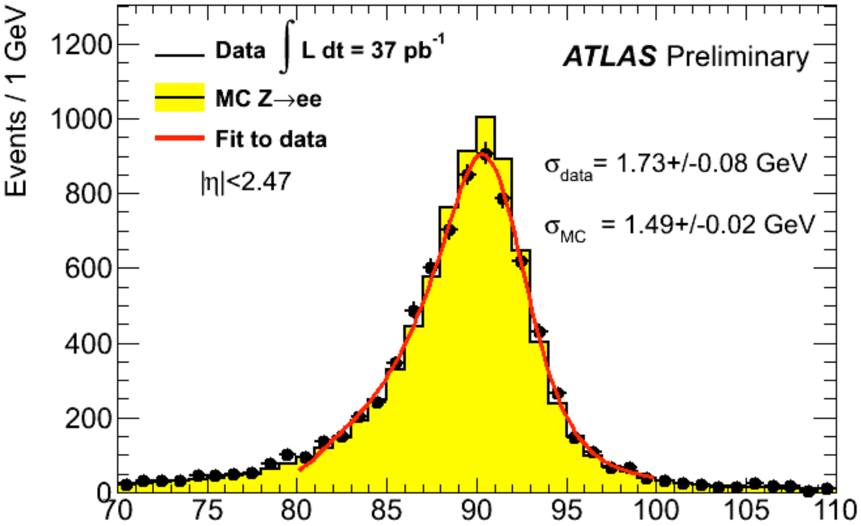
$$X = \frac{\sum_{i=1}^{4} E_i^{LAr} X_i}{\sum_{i=1}^{4} E_i^{LAr}}$$

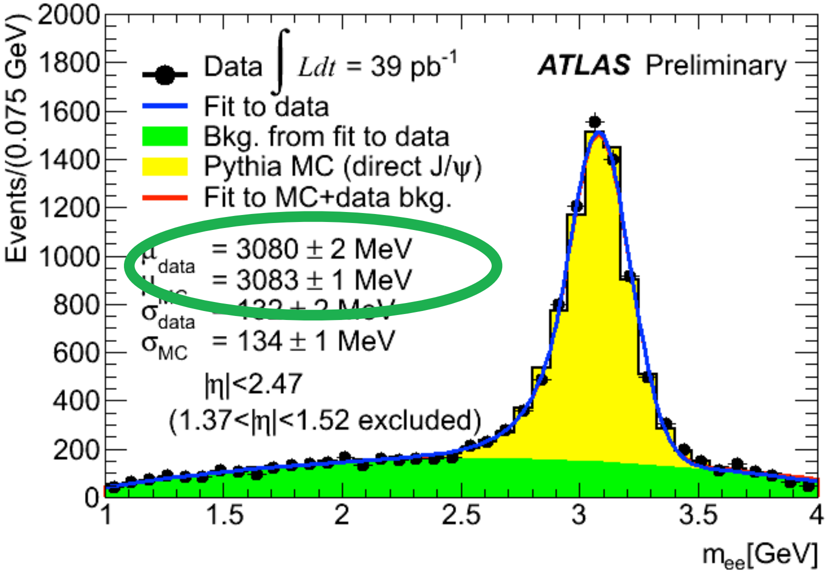
$$E^{reco} = F(E^{reco}_{acc},\eta)\cdot E^{cl\ lAr}_{ps} + S_{acc}(X,\eta)\cdot\left(\sum_{i=1}^{3} E_i^{cl\ lAr}\right)(1+C_{out}(X,\eta))\cdot(1+f_{leak}(X,\eta))$$

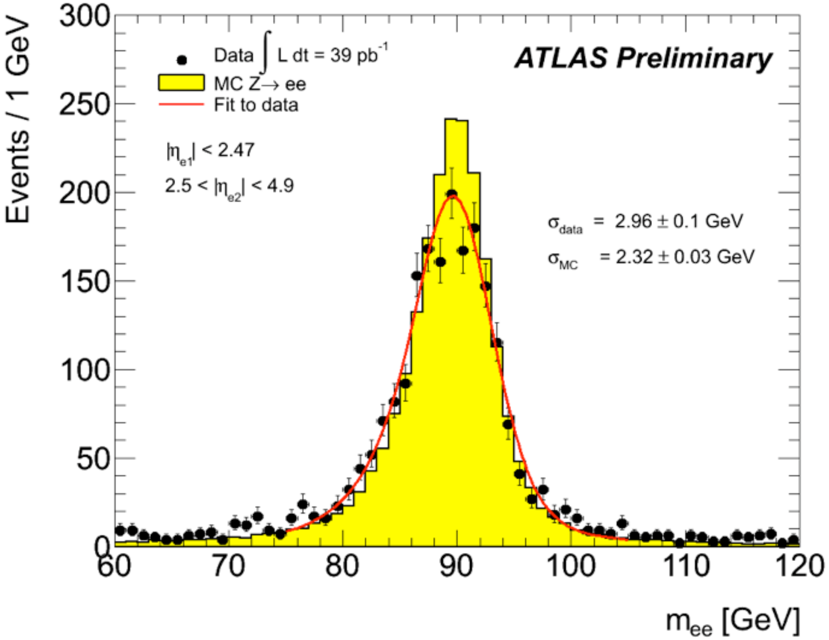
ATLAS EM calorimeter linearity



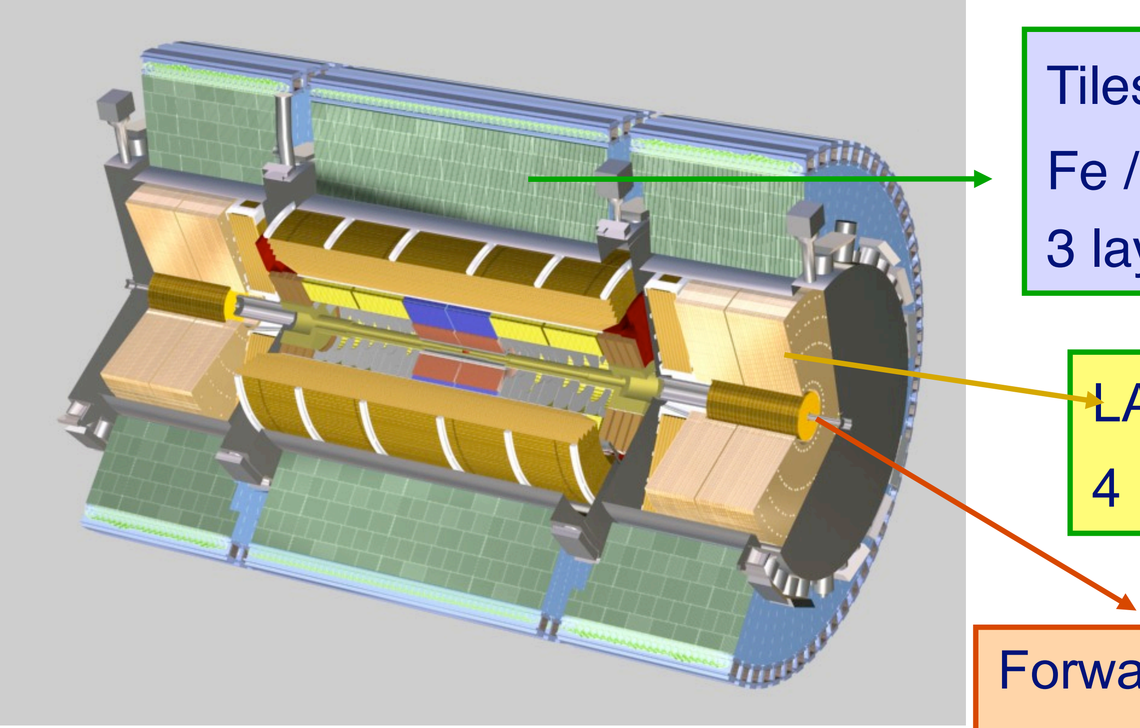
ATLAS Linearity with data







ATLAS Hadronic calorimeters



Tiles Calorimeter $|\eta| < 1.7$

Fe / Scintillator

3 layers in depth

LAr/Cu $1.7 < |\eta| < 3.2$

4 layers in depth

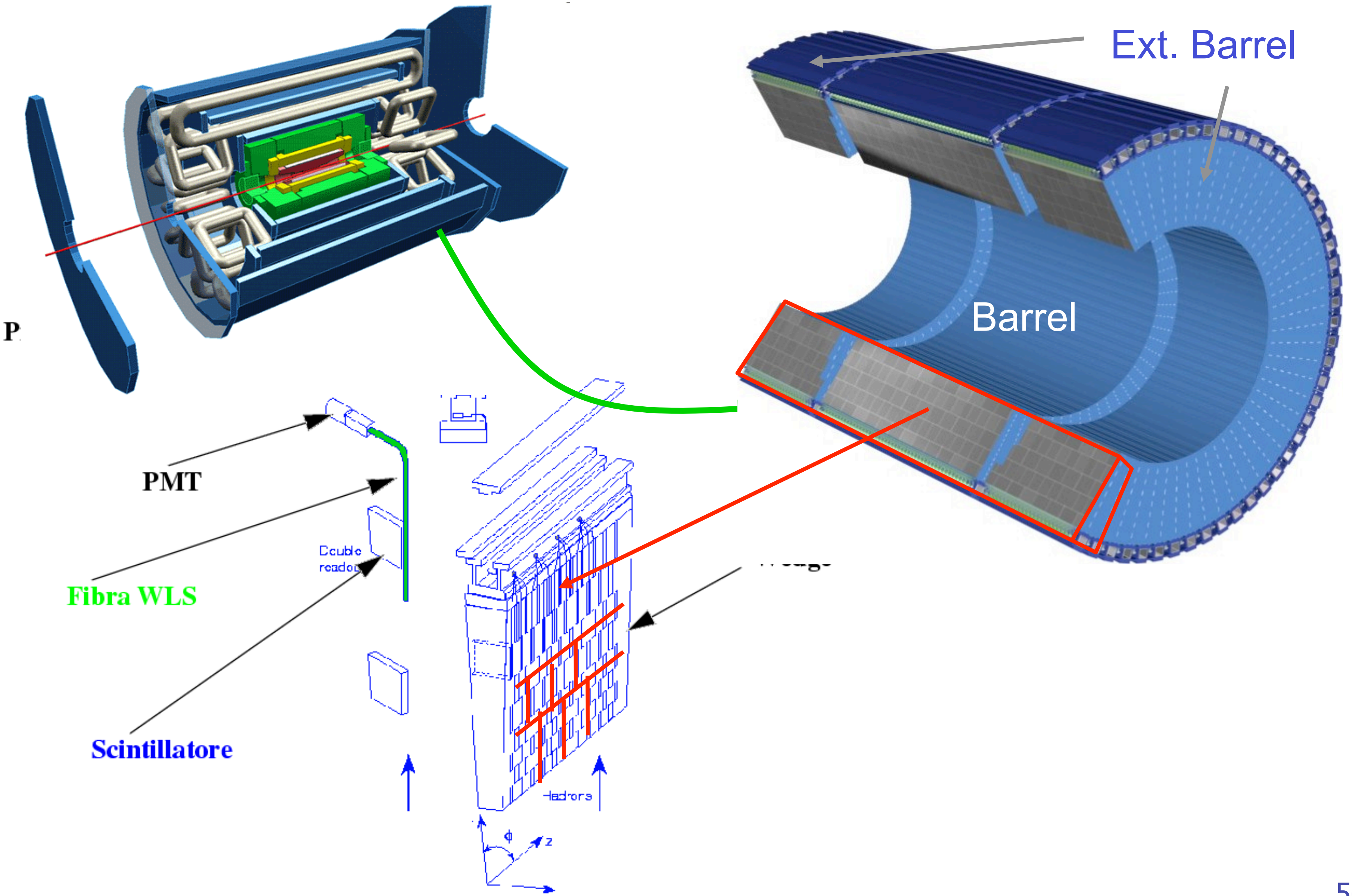
Forward: 1 layer EM, 2 HAD

LAr/Cu or W $3.2 < |\eta| < 4.9$

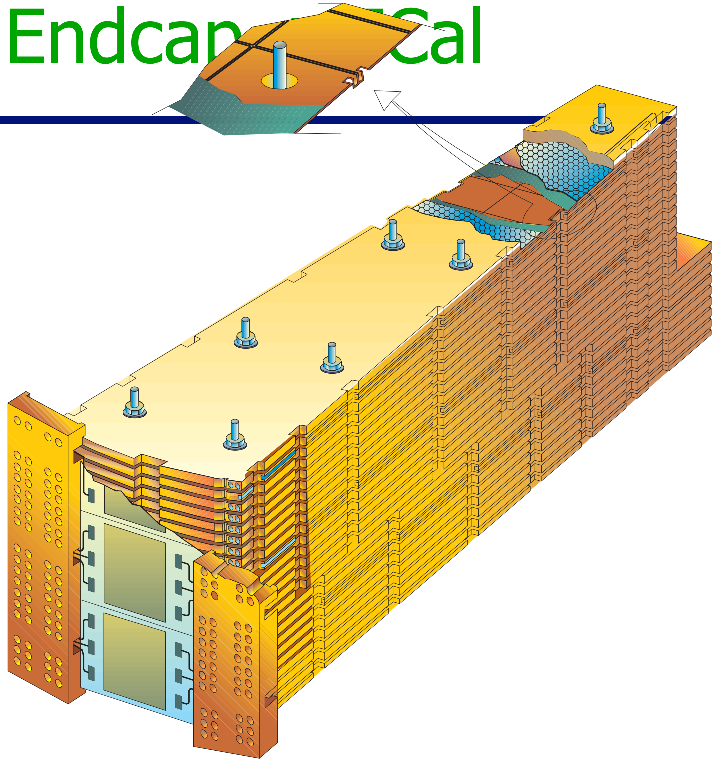
Total thickness: ~ 8 -10 λ

Use of different technics: cope with radiations in forward region

ATLAS Hadronic Tiles calorimeter



ATLAS LAr Hadronic Endcap Cal



HEC Cu/LAr

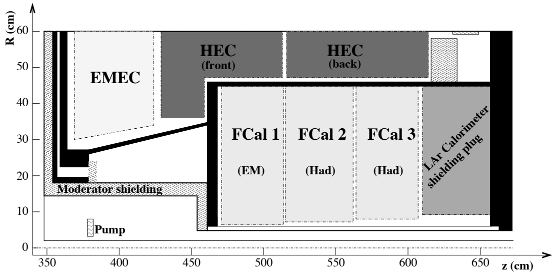
1.5< |η|<3.2 ~5600 channels

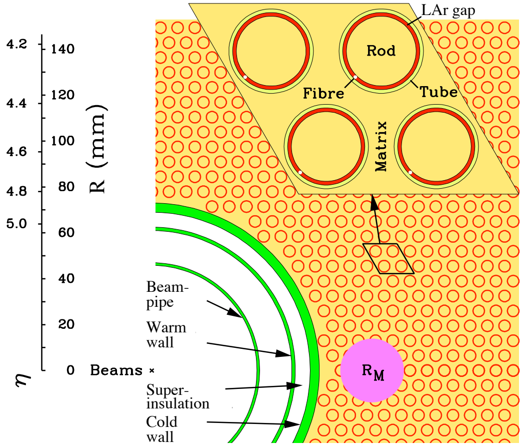
4 layers Δη.Δφ = 0.1 x 0.1 & 0.2x0.2

FCal Cu-W/LAr

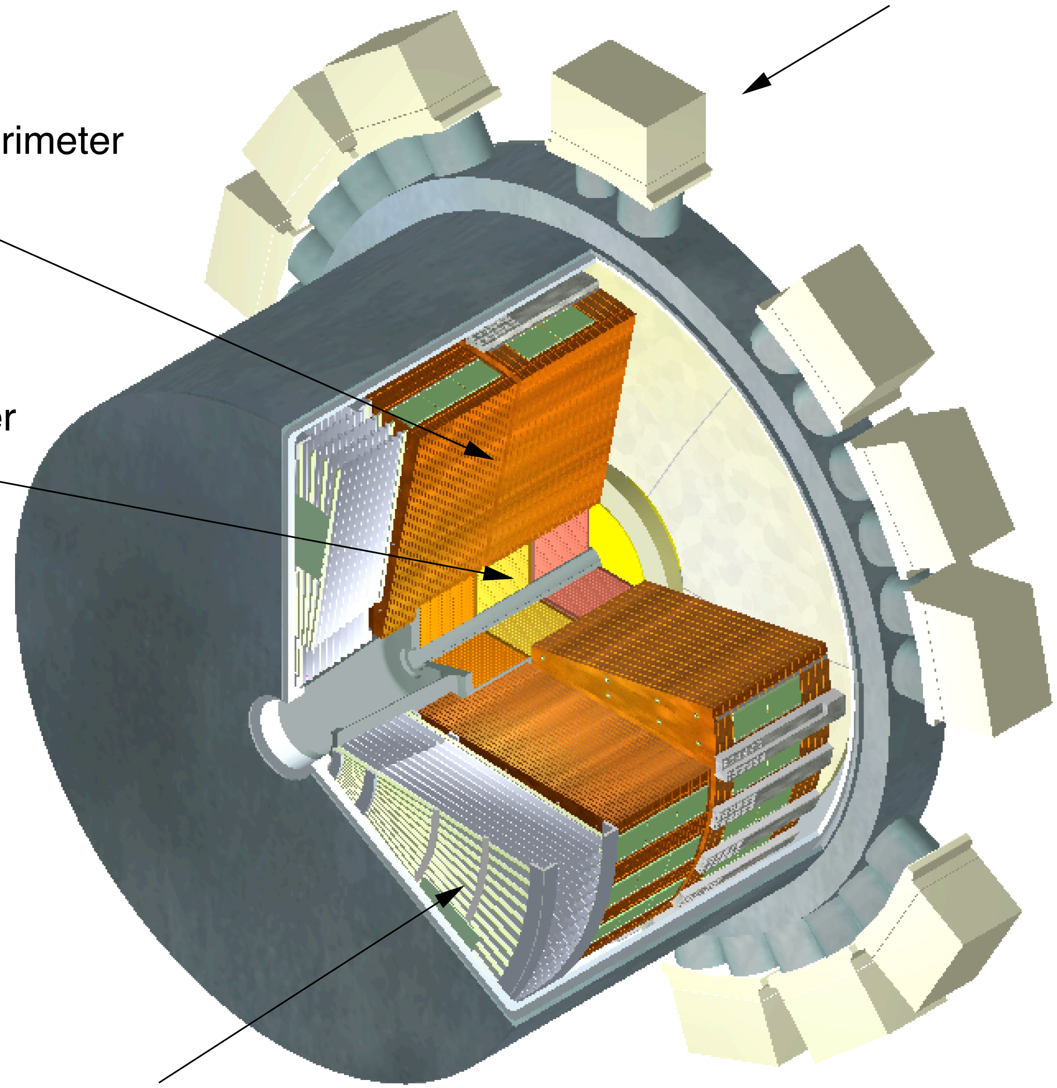
3.1<|η|<4.9 ~3500 channels

3 layers Δx.Δy 3x2.6 cm^2 - 5.4x4.7 cm^2





Endcap cryostat view



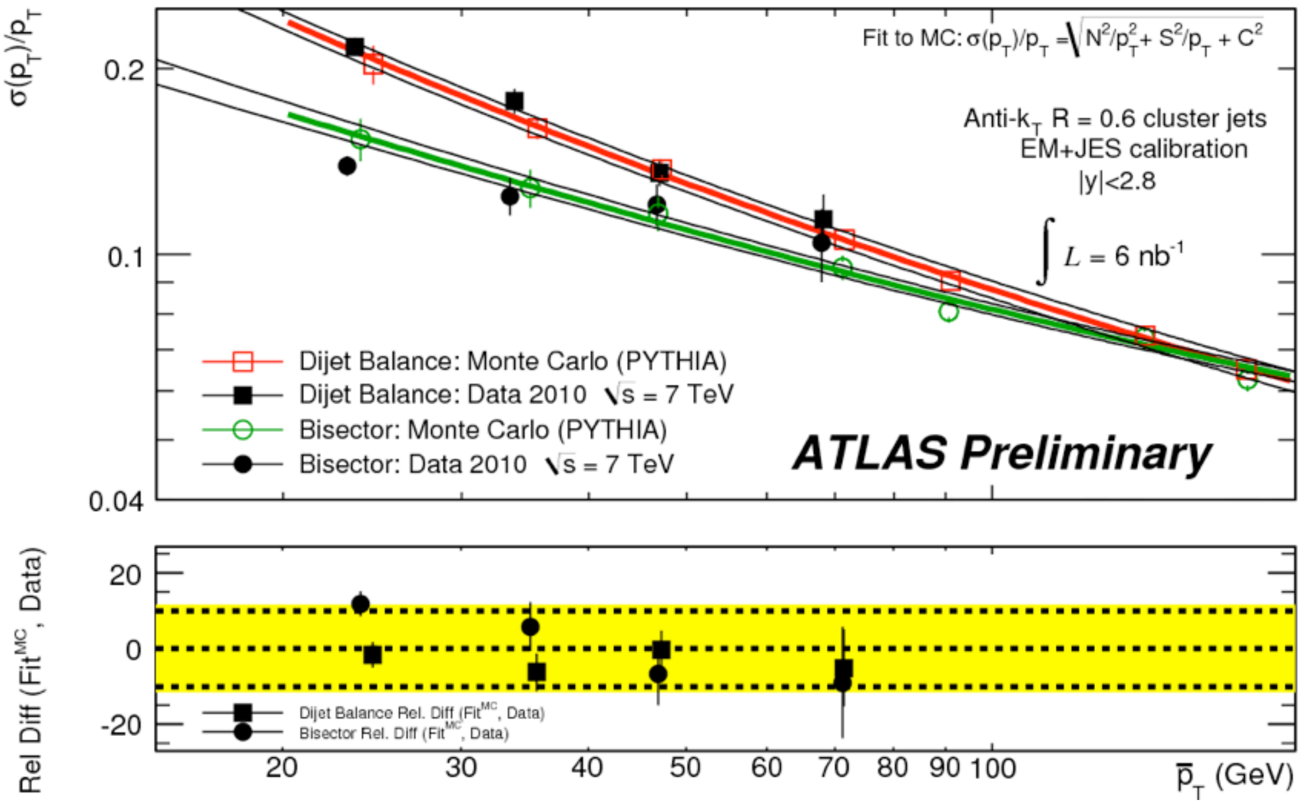
Feed-throughs and front-end crates

Hadronic end-cap calorimeter

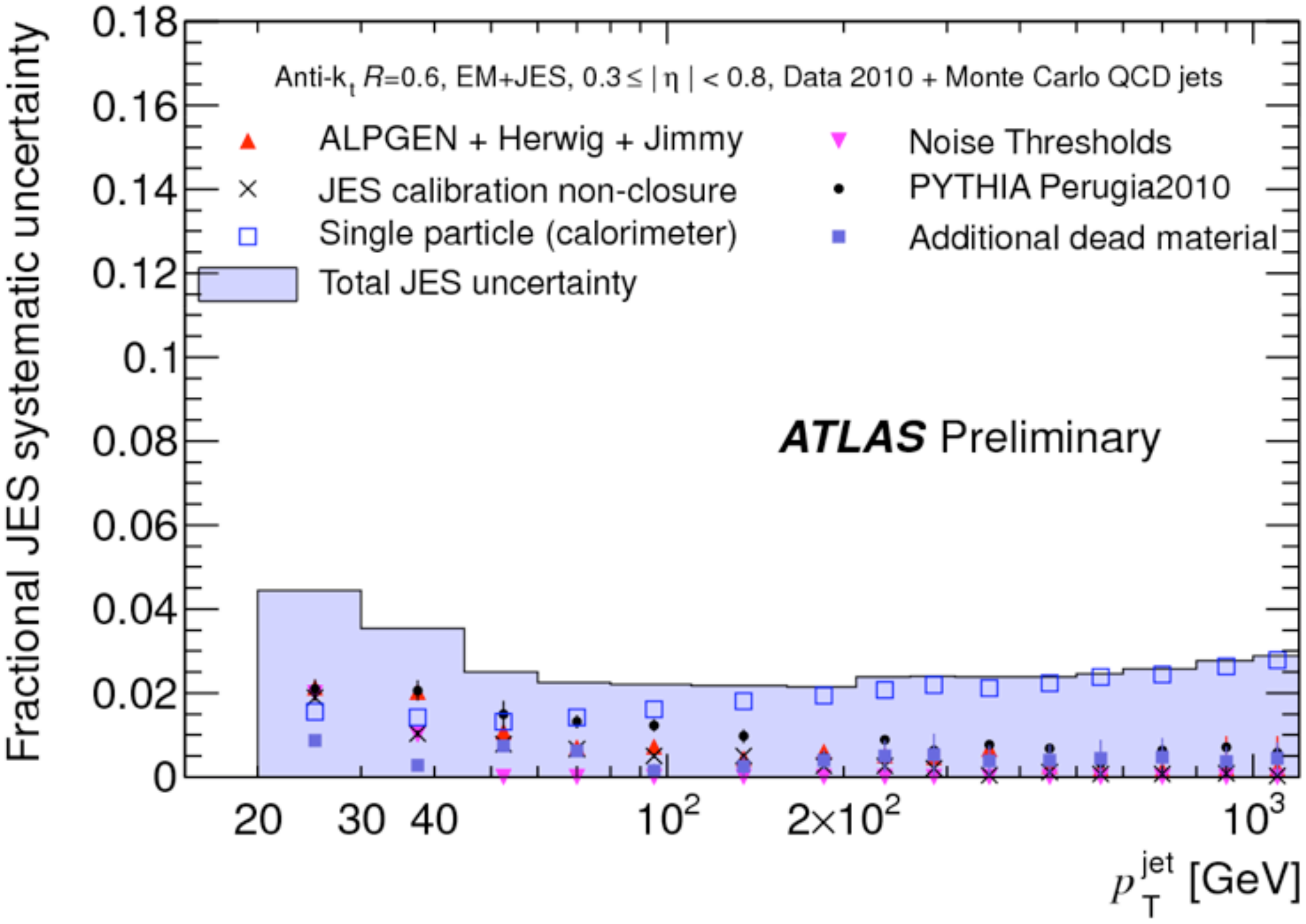
Forward calorimeter

Electromagnetic end-cap calorimeter

ATLAS Jets Performance

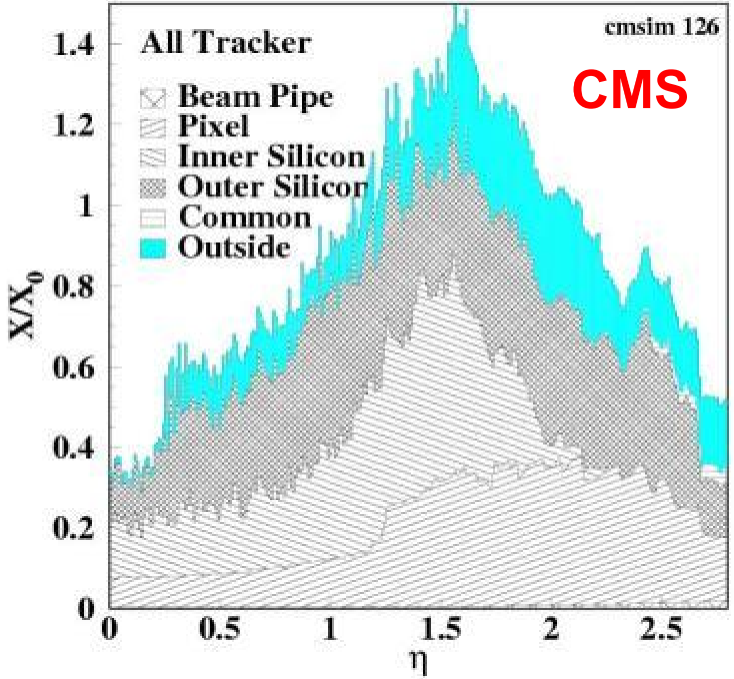


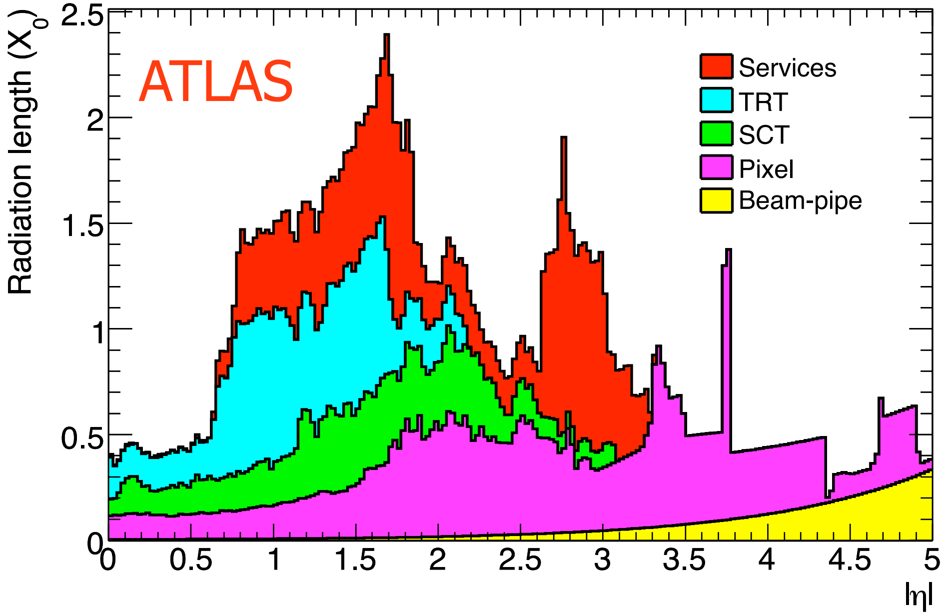
$\sigma(E)/E$ (50 GeV) ~ 15 %


Anti-k$_t$ R=0.6, EM+JES, 0.3 ≤ | η | < 0.8, Data 2010 + Monte Carlo QCD jets
ALPGEN + Herwig + Jimmy
JES calibration non-closure
Single particle (calorimeter)
Total JES uncertainty
Noise Thresholds
PYTHIA Perugia2010
Additional dead material
ATLAS Preliminary
Fractional JES systematic uncertainty
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
20
30
40
10^2
2×10^2
10^3
p_T^{jet} [GeV]

Calorimeters: behind the Inner Detector

Material in front of calorimeters



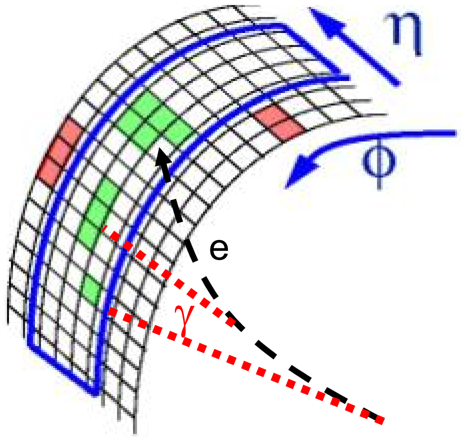


Electron Brem

Photon conversions

Proper description of material (ID weighting during construction)

Taken into account for event reconstruction



Understanding material in front of calorimeter