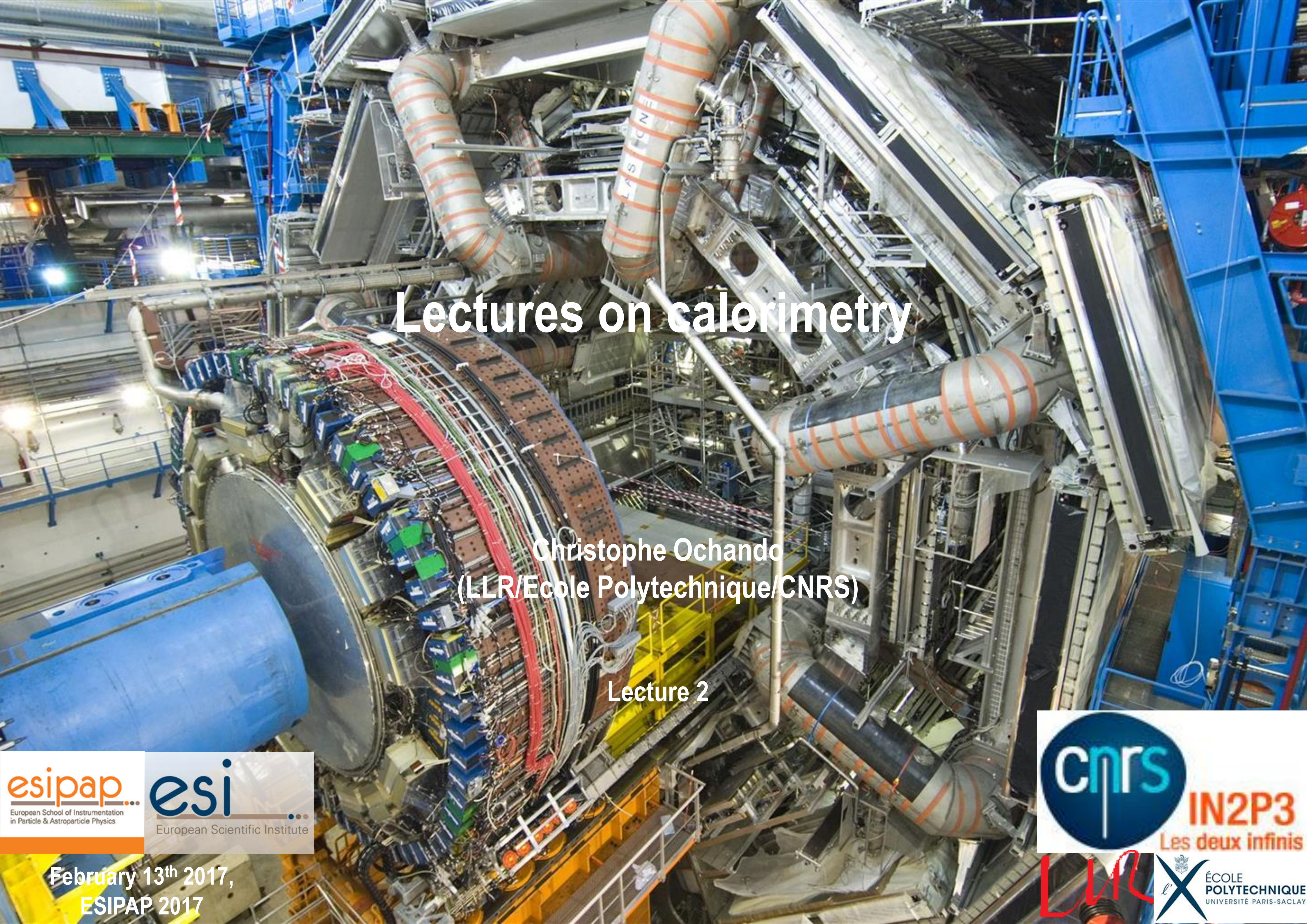

Lectures on calorimetry

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Lecture 2

esipap
European School of Instrumentation in Particle & Astroparticle Physics

esi
European Scientific Institute

February 13th 2017,
ESIPAP 2017

CNRS IN2P3 Les deux infinis

LLR

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Plan of lectures

Lecture 1

- Why/what calorimeters ?
- Physics of EM showers
- Calorimeter Energy Resolution

Lecture 2

- Physics of hadronic showers
- ATLAS & CMS calorimeters
- Calorimeter Objects

Lecture 3

- Example of calorimeters (suite)
- Future of calorimetry

Lecture 4

- Tutorial
- Exercises

KEEP
CALM
AND
RECAP

Electromagnetic shower: summary

- High-energy electrons or photons interact with dense material from calorimeter:
  ↷ **cascade of secondary particles**

- The number of cascade particles is **proportional to the energy** deposited by the incident particle

- The role of the calorimeter is to **count** these cascade particles

- The relative occurrence of the various processes creating the cascade particles **depends on Z.**
  - Above 1 GeV, bremsstrahlung radiation and pair production dominates
  - The shower develops like this until secondary particles reaches E_C where loss by ionization dominated
  - Below E_C, the number of secondary particles slowly decreases as electrons (photons) are stopped (absorbed)

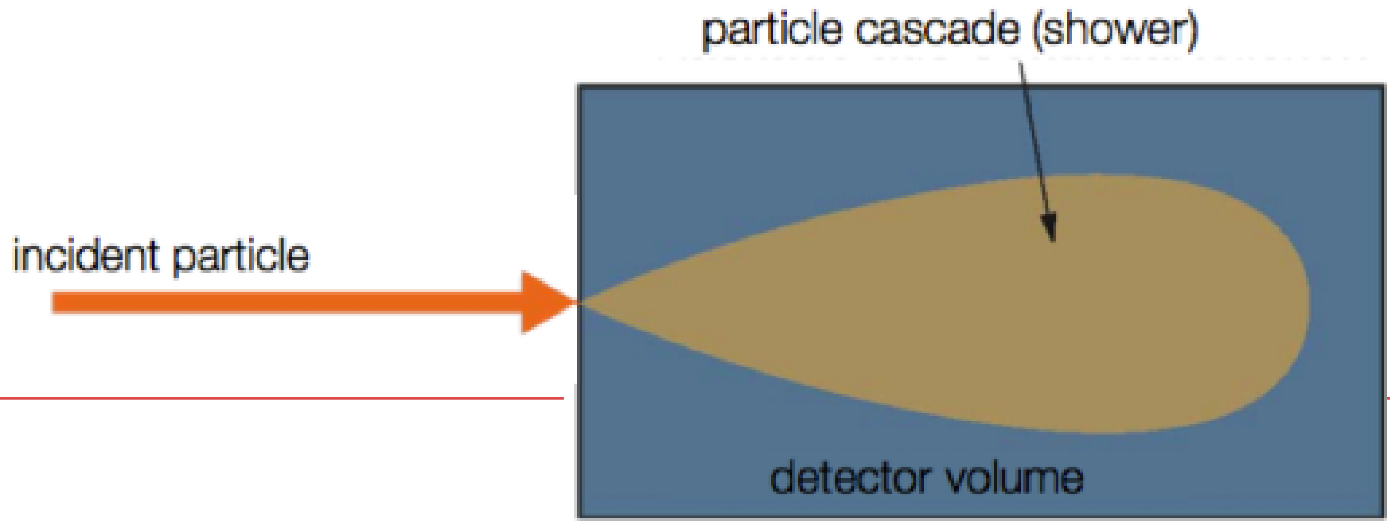
> - **The shower development is governed by the "radiation length" X_0**
> - **Needs about 25 X_0 to contain most of the EM showers.**
> - **Shower max grows with ln(E)**
> - **90% of showe energy contained in a cylinder of radius R_M**

Calorimeters Principles

Detector for energy measurement via total absorption of particles

Principle of operation

- Incoming particle initiates particle shower
  - Electromagnetic, hadronic
  - Shower properties depend on particle type and detector material
- Energy is deposited in active regions
  - Heat, ionisation, atom excitation (scintillation), Cerenkov light
  - Different calorimeters use different kind of signal
- Signal is proportional to energy released
  - Proportion → calibration
  - Shower containment



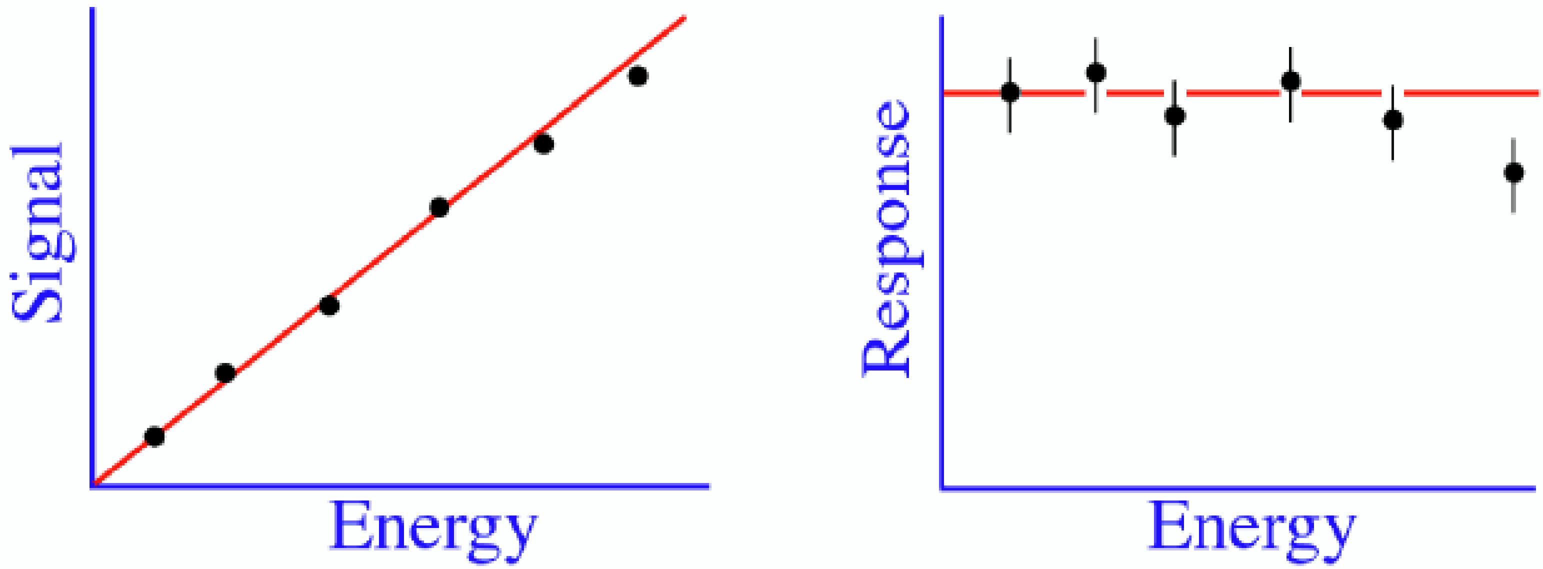
Calorimeter Features

- Measure energy of charged (p, π, K, e, …), and neutral (γ, n,…) particles
- Precision improves with energy
- Position Measurement
  - Important for neutral particles
- Particle ID
  - Longitudinal (if sampling calorimeter) and lateral profiles different for e and π.
- Timing
- Triggering
- Can be built at 4π detectors
  - Hermiticity ! Important for missing energy measurement (see later)

LINEARITY

Response: mean signal per unit of deposited energy
e.g. # of photons electrons/GeV, pC/MeV, µA/GeV

➔A linear calorimeter has a constant response



Electromagnetic calorimeters are in general linear.
All energies are deposited via ionisation/excitation of the absorber.

Useful Quantities

Radiation Length:

$$X_0 \approx \frac{180A}{Z^2}$$ (g.cm^{-2})

Radiation Length for composite material:

$$\frac{1}{X_0} = \sum \frac{w_j}{X_j}$$

w_j: fraction of material j
X_j: radiation length of material j (in g.cm-2)

Moliere Radius:

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

Moliere Radius for composite material:

$$\frac{1}{R_M} = \sum \frac{w_j}{R_{M\,j}}$$

w_j: fraction of material j
R_{Mj}: Moliere Radius of material j (in g.cm-2)

Energy Resolution:

$$\frac{\sigma}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

$\oplus$: quadratic sum
S: Stochastic
N: noise
C: constant

HOMOGENOUS CALORIMETERS

★ In a homogeneous calorimeter the whole detector volume is filled by a high-density material which simultaneously serves as absorber as well as as active medium ...

Signal	Material
Scintillation light	BGO, BaF_2, CeF_3, ...
Cherenkov light	Lead Glass
Ionization signal	Liquid nobel gases (Ar, Kr, Xe)

★ Advantage: homogenous calorimeters provide optimal energy resolution

★ Disadvantage: very expensive

★ Homogenous calorimeters are exclusively used for electromagnetic calorimeter, i.e. energy measurement of electrons and photons

SAMPLING CALORIMETERS

Principle:

Alternating layers of absorber and active material [sandwich calorimeter]

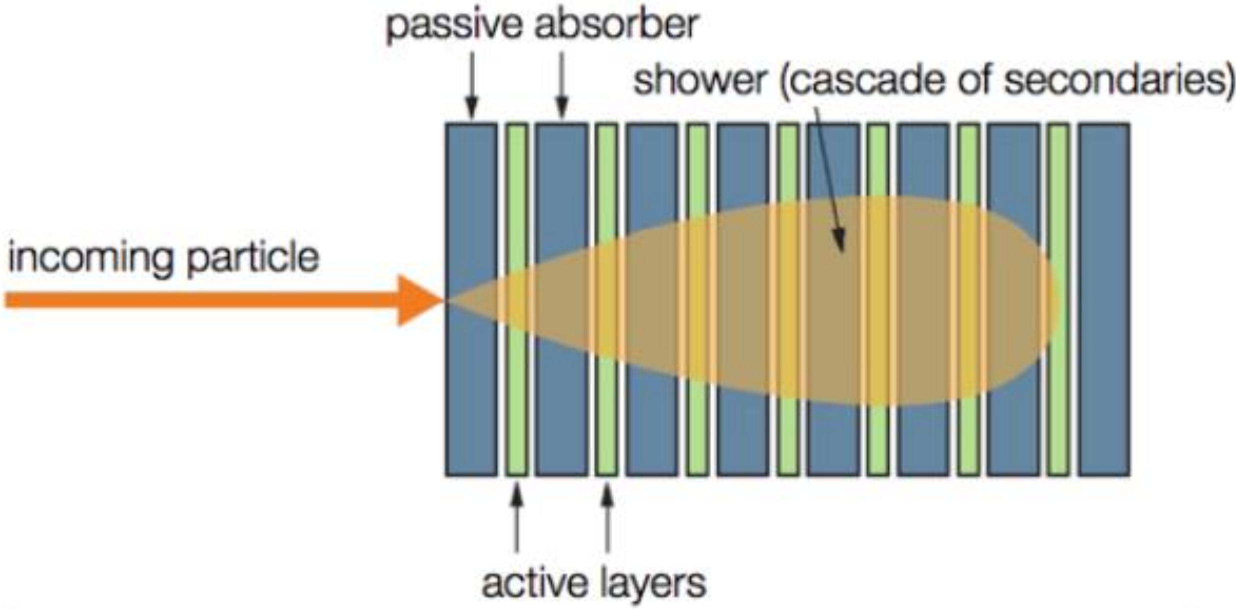
Absorber materials:
[high density]

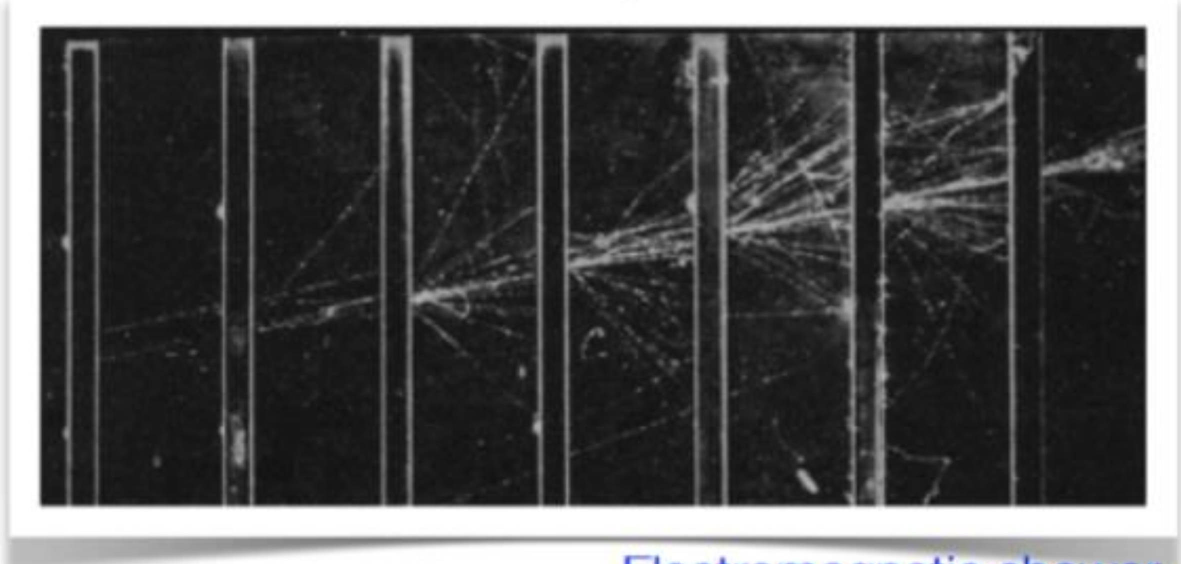
- Iron (Fe)
- Lead (Pb)
- Uranium (U)
  [For compensation ...]

Active materials:

- Plastic scintillator
- Silicon detectors
- Liquid ionization chamber
- Gas detectors

Scheme of a sandwich calorimeter





Electromagnetic shower

SAMPLING CALORIMETERS

★ Advantages:

By separating passive and active layers the different layer materials can be optimally adapted to the corresponding requirements ...

By freely choosing high-density material for the absorbers one can built very compact calorimeters ...

Sampling calorimeters are simpler with more passive material and thus cheaper than homogeneous calorimeters ...

★ Disadvantages:

Only part of the deposited particle energy is actually detected in the active layers; typically a few percent [for gas detectors even only ~10^{-5}] ...

Due to this sampling-fluctuations typically result in a reduced energy resolution for sampling calorimeters ...

Homogenous vs Sampling EM calorimeter Resolution

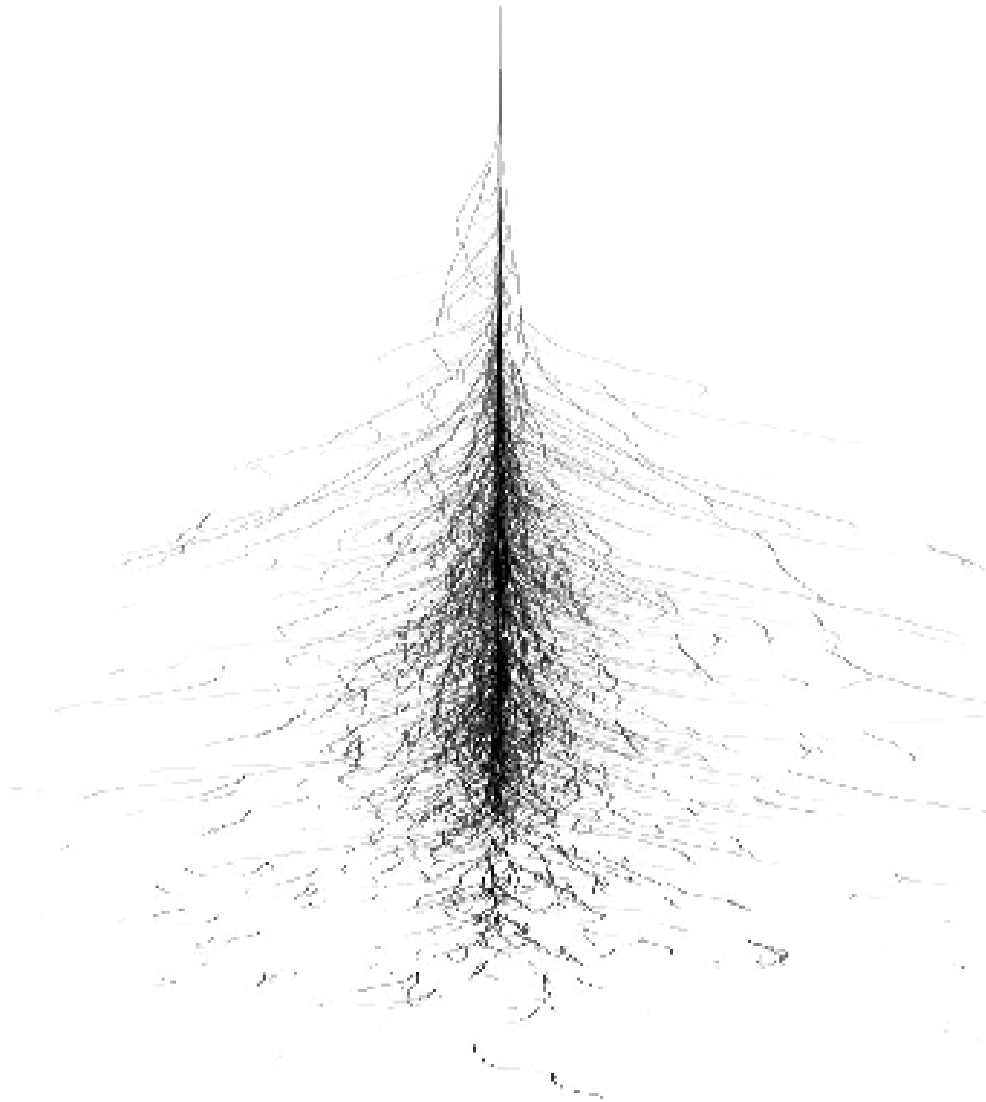
Table 33.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20–30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20–30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

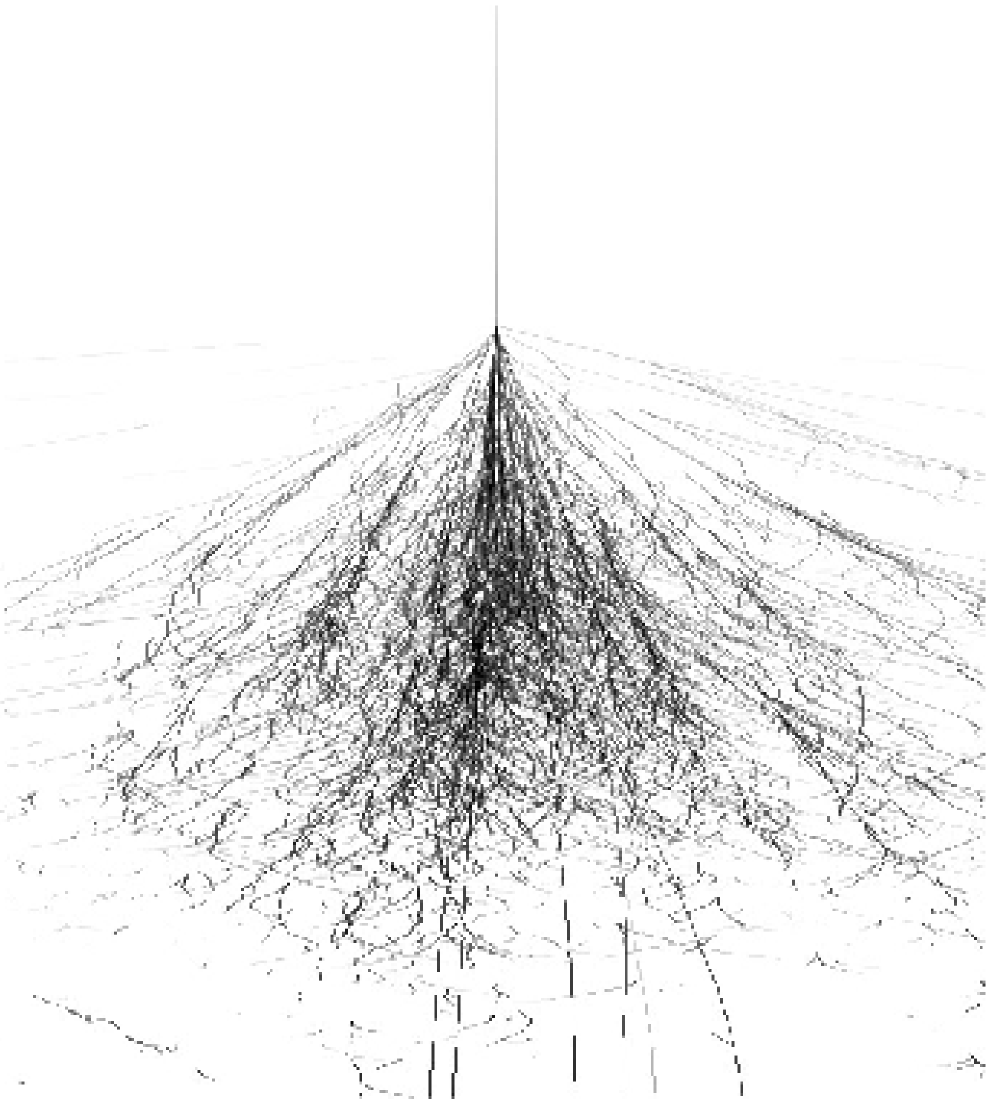
Homogenous

Sampling

Physics of Hadronic Showers



Gamma shower



Hadronic shower

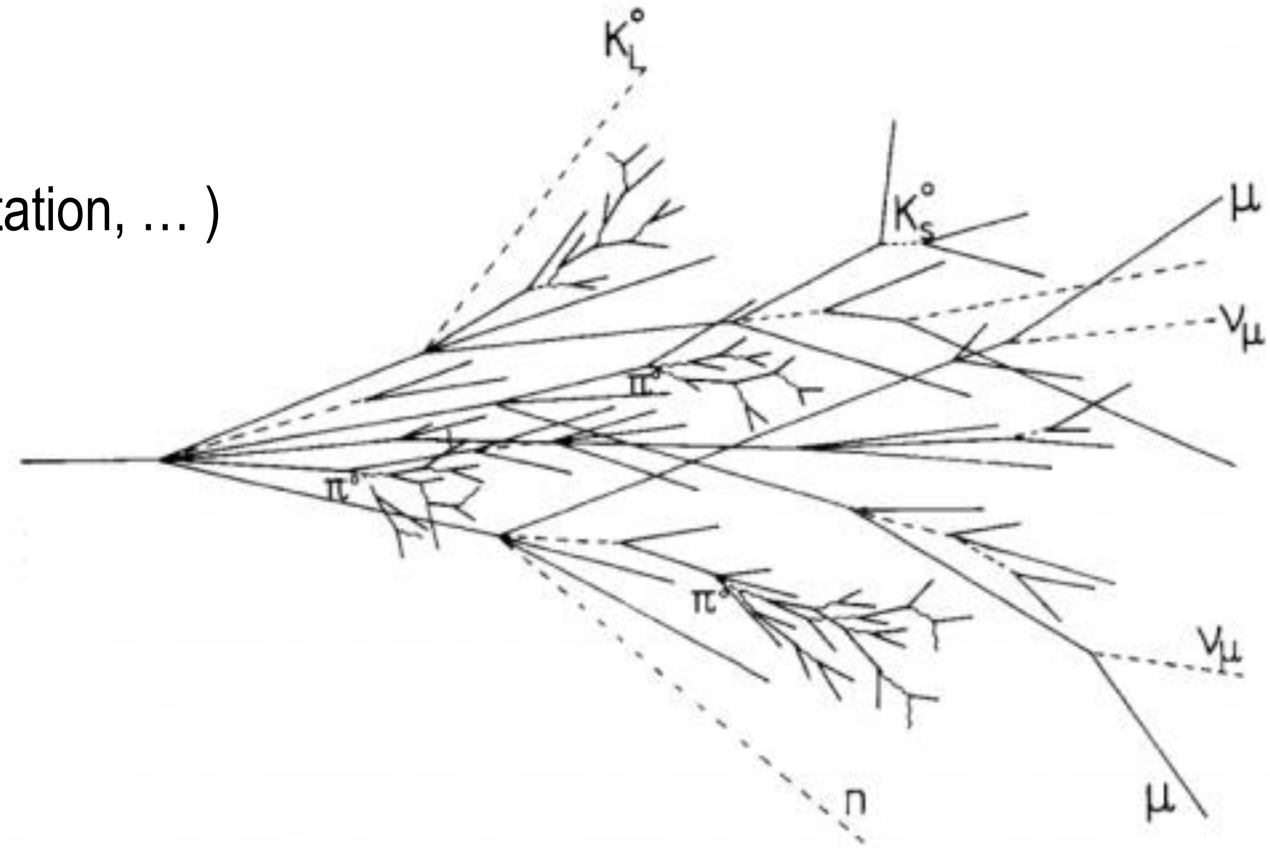
1. Particles interact with matter
   depends on particle and material

Hadronic Showers

An Hadronic (HAD) shower is a cascade of secondary particles initiated by the interaction with matter (ie, energy loss) of an incoming of hadron.

- HAD showers are like EM showers… but **more complicated**, due to **strong interaction** of hadrons with absorber.

- Many processes involved:
  - Ionization,
  - hadron production (fragmentation, …)
  - Charge exchange
    $\pi^{+/-}n \rightarrow \pi^{0}p/pbar$
  - nuclear de-excitation,
  - nuclear breakup,
    $\rightarrow$ spallation neutrons,
  - muon and pion decay,
  - …



Hadronic showers

Hadronic interaction:

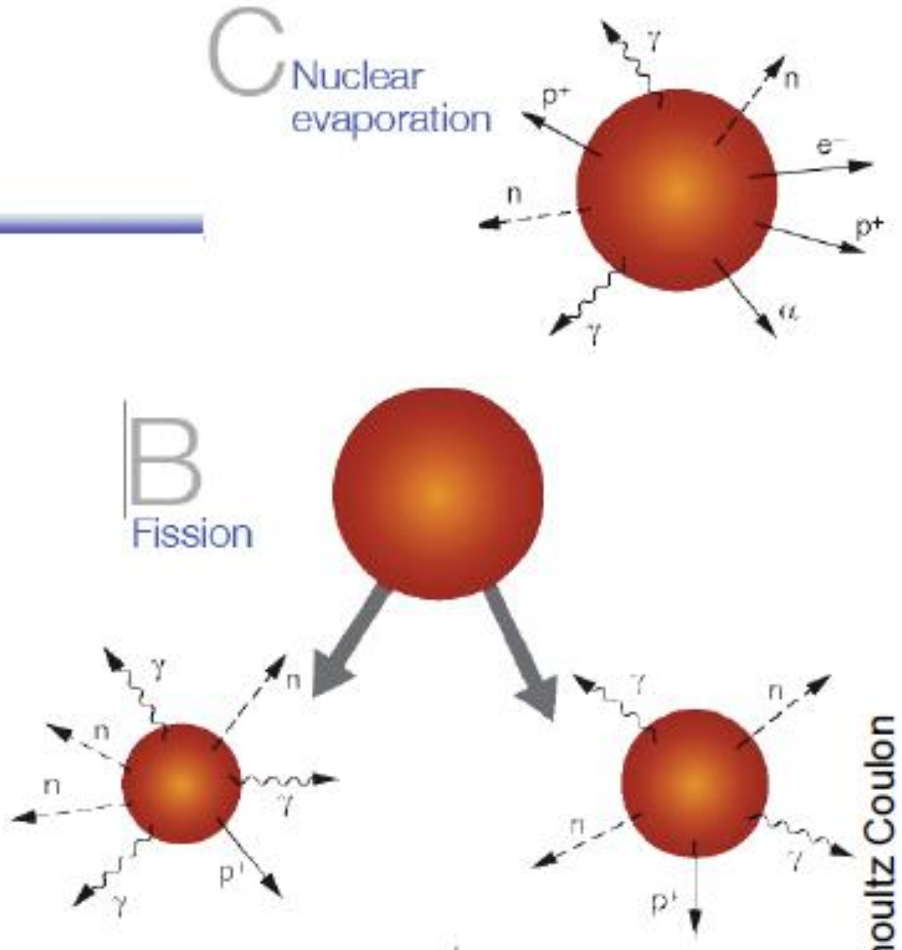
Elastic:

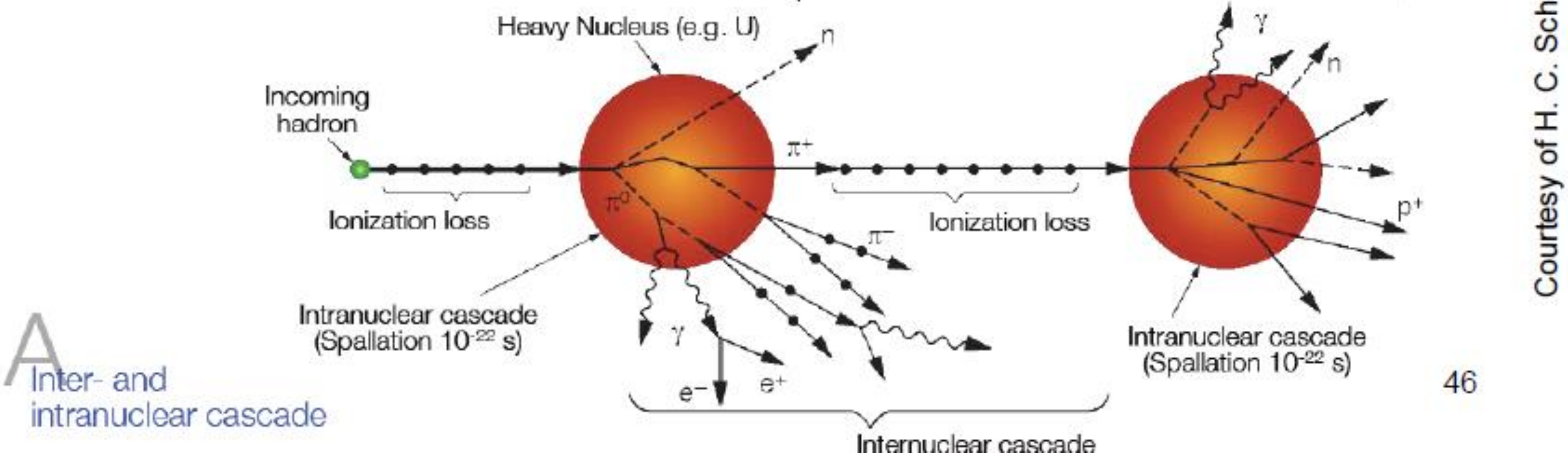
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

Inelastic:

$$p + \text{Nucleus} \rightarrow$$
$$\pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

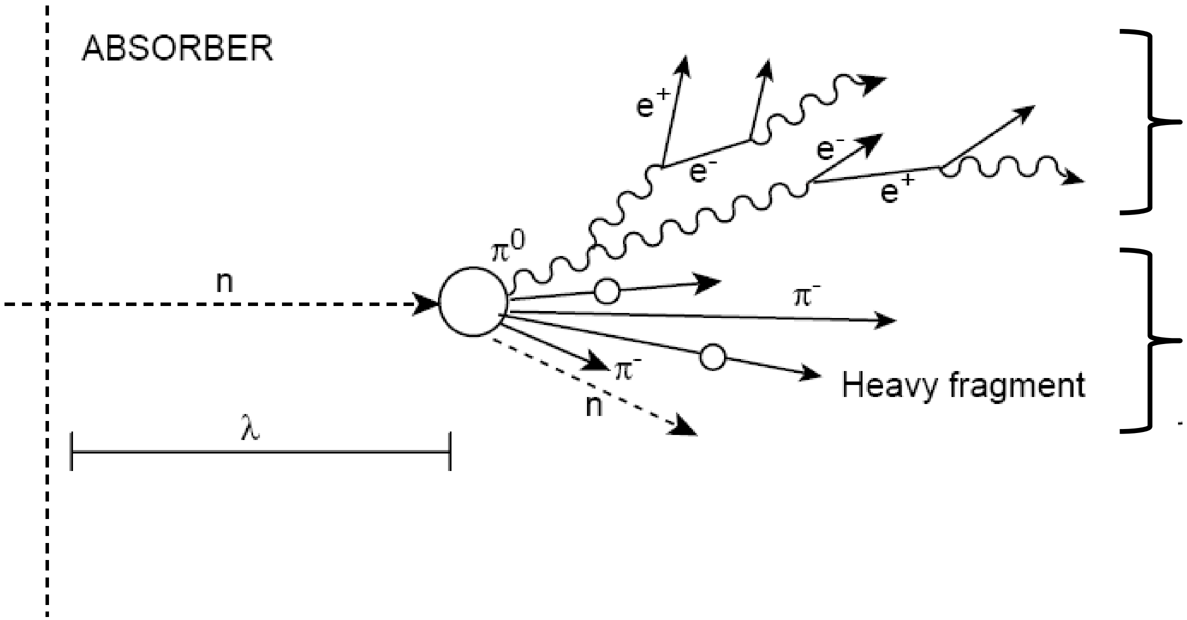
$$\left[\begin{array}{l} \text{Nucleus}^* \rightarrow \text{Nucleus A} + n, p, \alpha, \ldots \\ \qquad\qquad \rightarrow \text{Nucleus B} + 5p, n, \pi, \ldots \\ \qquad\qquad \rightarrow \text{Nuclear fission} \end{array}\right]$$





Hadronic Showers

HAD showers have thus **two components**:



Electromagnetic component:

- Electrons, photons (from excitation, radiation, decay of hadrons, photo-effect, …)
- Neutral pions (eg, $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$)

Hadronic component:

- Charged hadrons $\pi^\pm$, $K^\pm$, p, …
  - ionization, excitation, nuclei interaction (spallation p/n production, evaporation n, spallation products)
- Neutrons,
  - Elastic collisions, thermalization+capture (=>γ's)
- Break-up of nuclei

➢ Part of the energy is lost in breaking nuclei (nuclear binding energy)
⇒ **Invisible part** of the shower ! **Only part of the shower energy is sampled !**

- Large, **non-Gaussian** fluctuations of each component (EM vs non-EM)
- Large, **non-Gaussian** fluctuations in "invisible" energy losses.

Interaction Length

- The hadronic shower is governed by the interaction length λ_{int}
  - λ_{int}: Mean free path between inelastic interaction

$$\lambda_{int} \approx 35A^{1/3}(g.cm^{-2})$$

	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	84
Fe	26	7.9	24	1.76	16.8
Cu	29	9	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	6.2	0.32	10.5

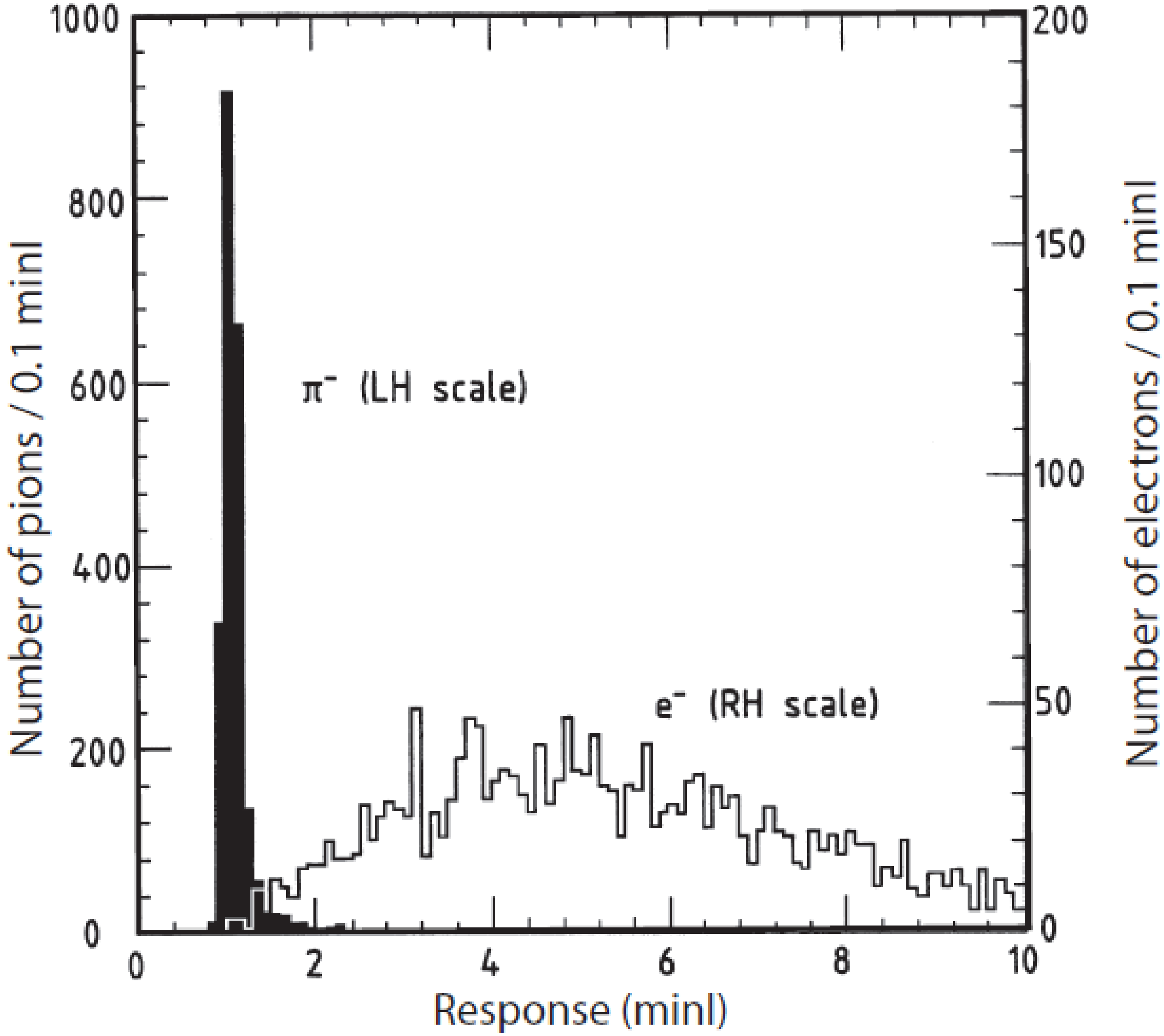
Hadronic shower are longer than EM shower…

Particle ID

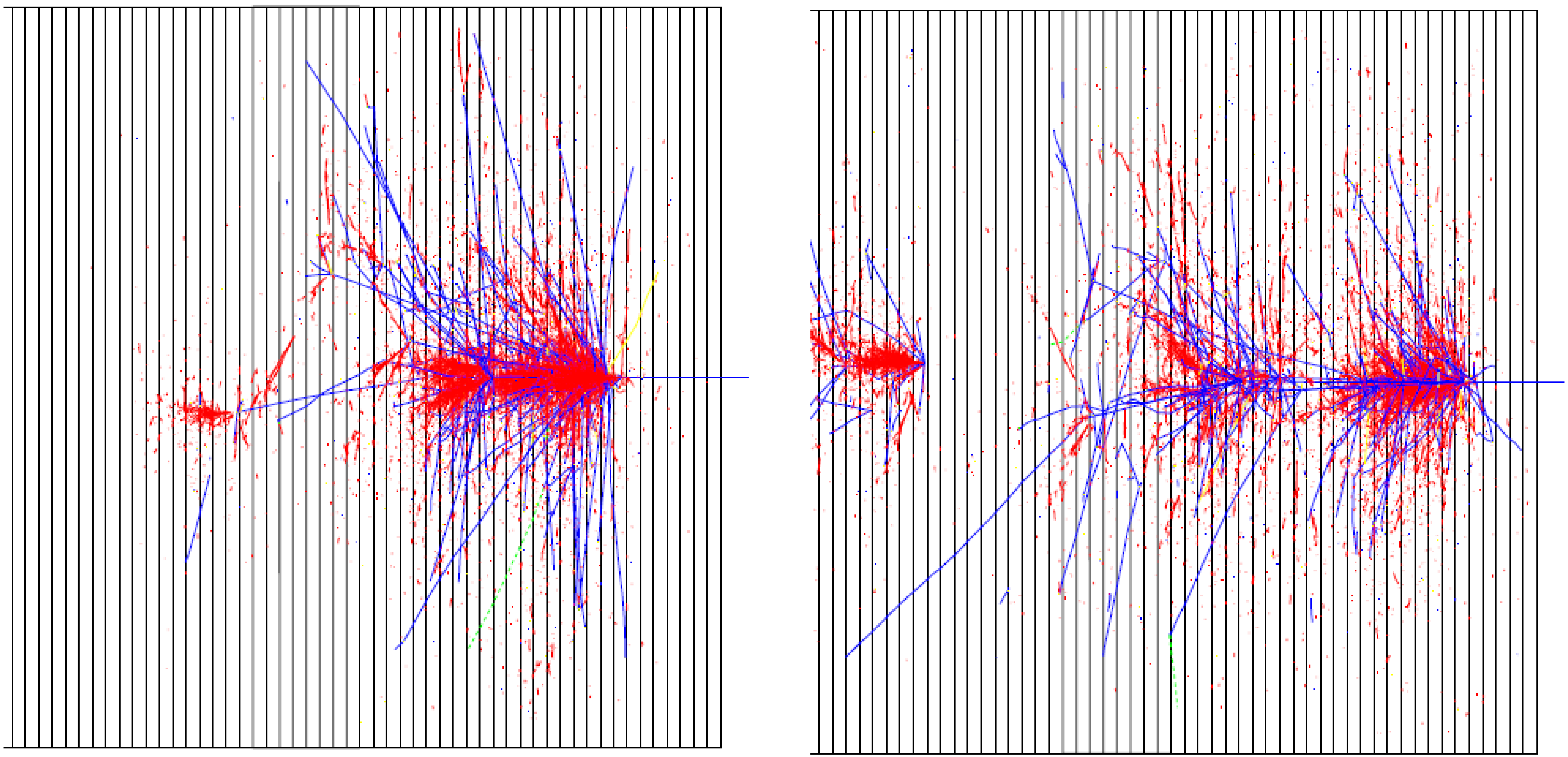
The ratio $R=\lambda_{int} / X_0$ is important for Particle Identification

In high-Z material, R~30 => **excellent e/π separation !**

1 cm Pb + scintillator plates makes an excellent “Pre-Shower”



Hadron shower in Cu



red - e.m. component
blue - charged hadrons

HAD showers: intrinsic fluctuations

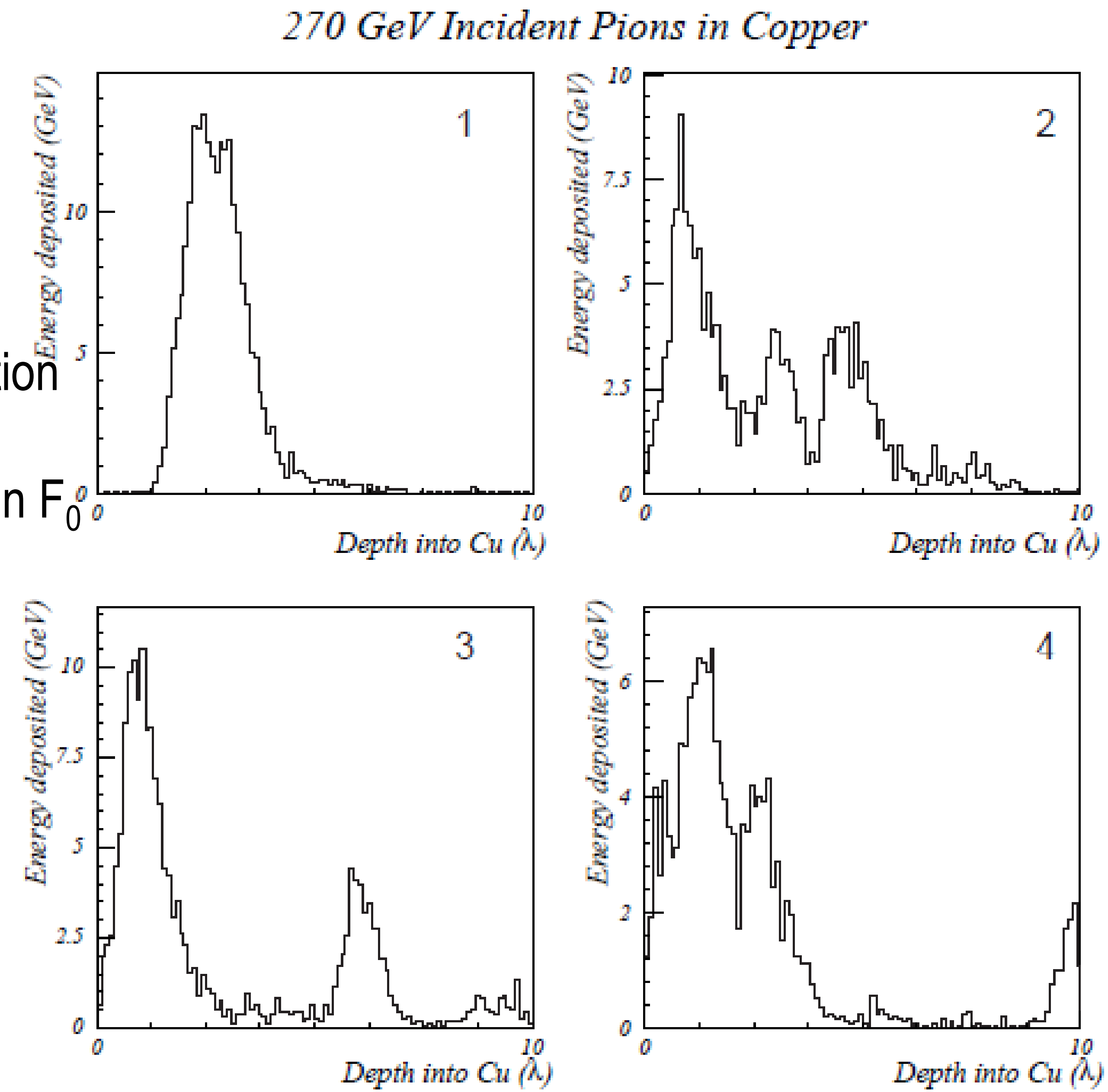
No "characteristic" profile…

Size of the EM component (F_0) is essentially determined by the 1st interaction

Considerable event-to-event fluctuation in F_0

On average 1/3 of mesons produced in the first interaction with be π^0's

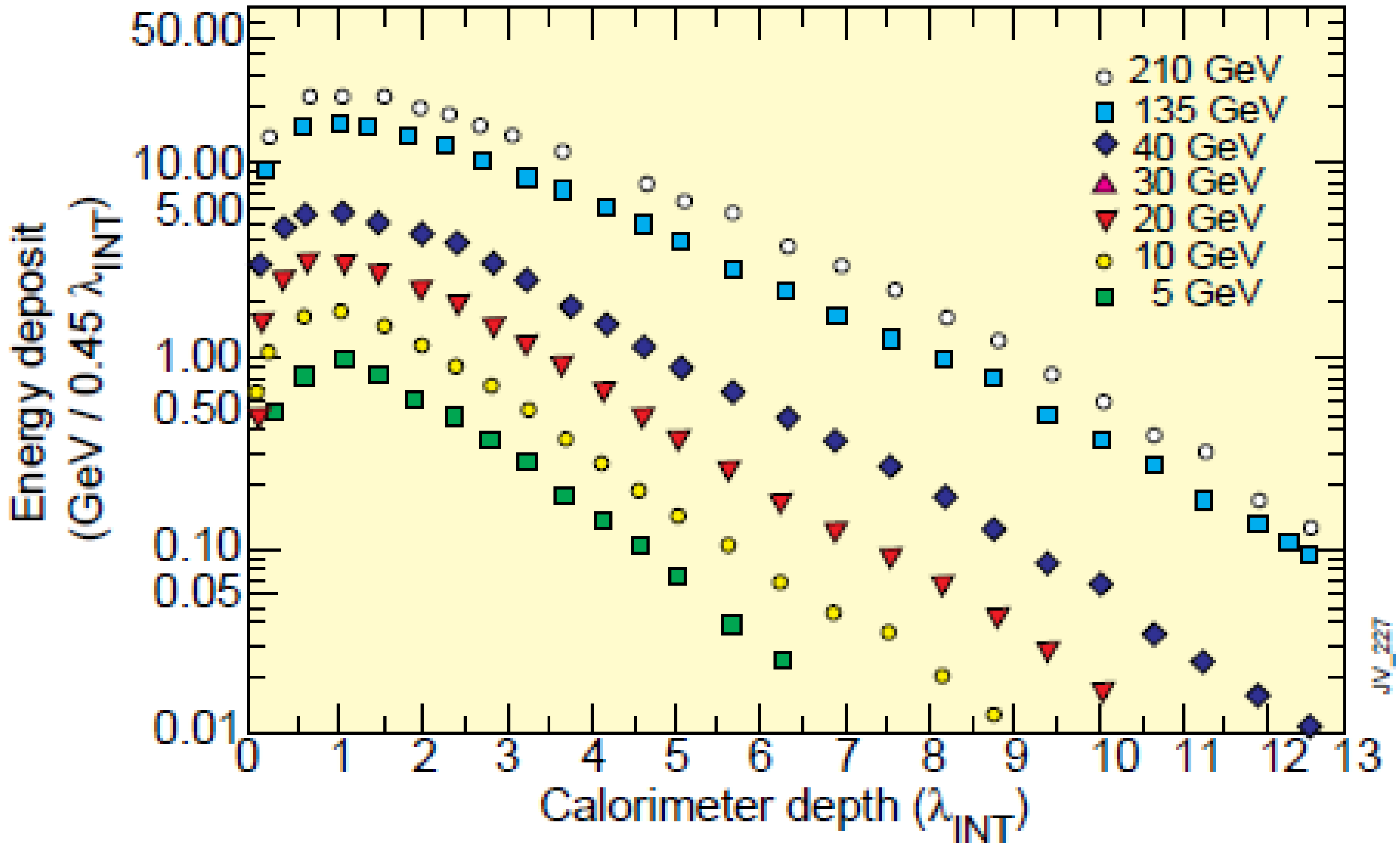
The 2nd generation $\pi^{\pm}$'s also produced π^0's if sufficiently energetic.



HAD showers: Longitudinal Profile

- As for EM showers, **depth to contain an HAD shower increase with ln(E)**

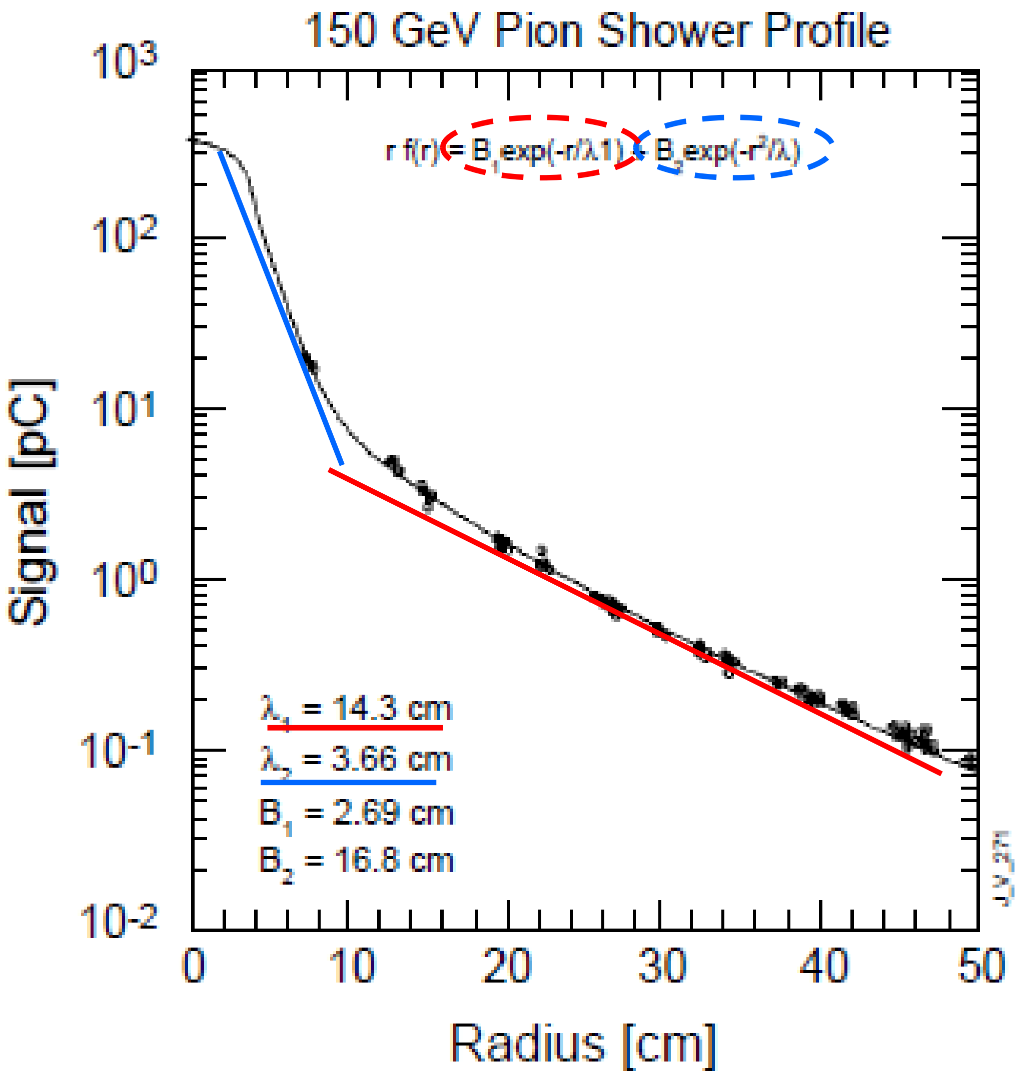
WA78 experiment: 5.4 λ (10mm U/5mm Scint), 8 λ (25 mm Fe / 5mm Scint.)



- sharp peak near the 1st interaction point (from π^0's produced in the 1st interaction)
- Then more gradual falloff (characterized by λ_{int})

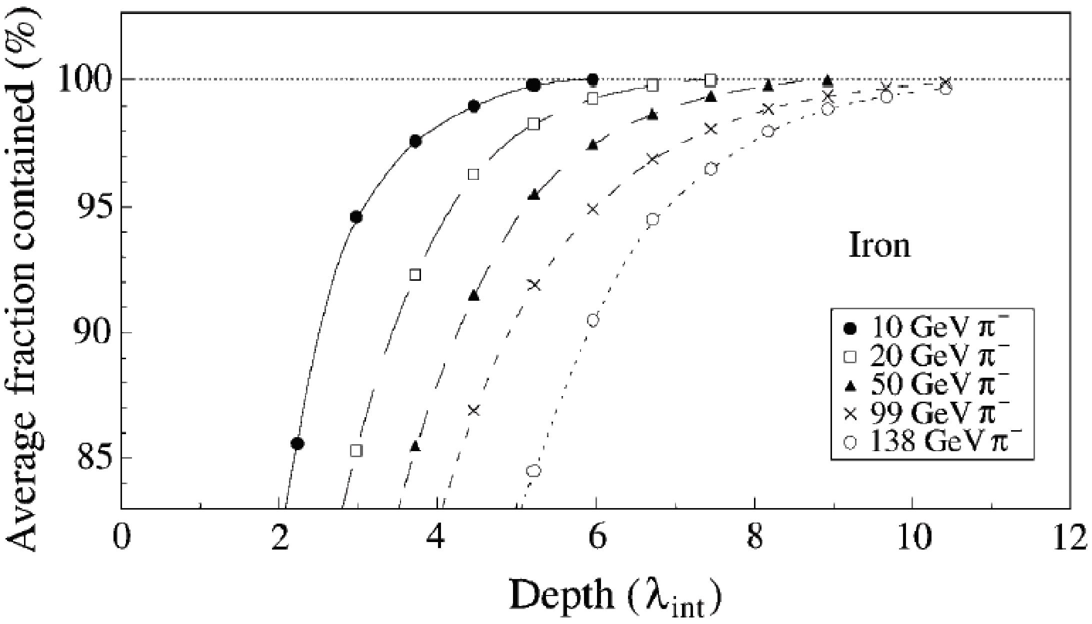
HAD showers: Lateral Profile

- Lateral shower profile has two components:
  - **Electromagnetic core** (from $\pi^0 \rightarrow \gamma\gamma$)
  - **Non-EM halo** (mainly non-relativistic shower particles)

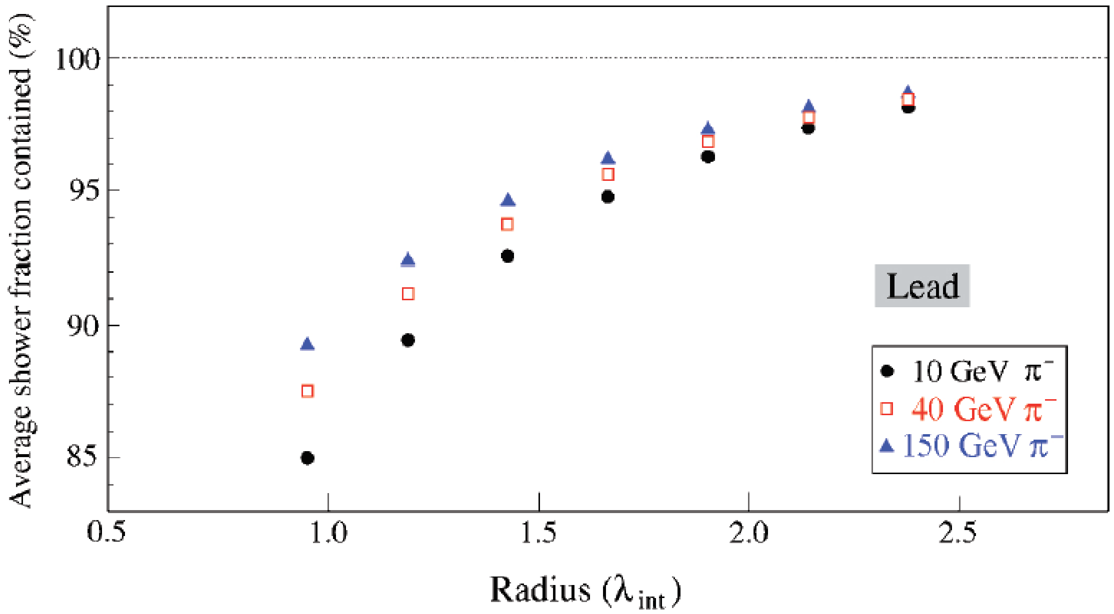


HAD showers: containment

Longitudinal



Lateral



Need about **~10 λ_{int}** to contain most of the hadronic showers

Lateral containment increases with energy ! (*)
Transverse radius for 95% containement ~ 1.5 λ_{int}

(*) f_{EM} increase with E, and γ from π^0 emitted along the π^0 axis.

Non-EM fraction breakdown

- In Lead, non-EM component energy breakdown:
  - ~56% ionizing particle
    - 2/3 are protons (from spallation). <E>~50-100 MeV
  - **~10% neutrons,**
    - very soft (3 MeV typically),
    - on average 37 n per deposited GeV !
  - **~34% invisible**

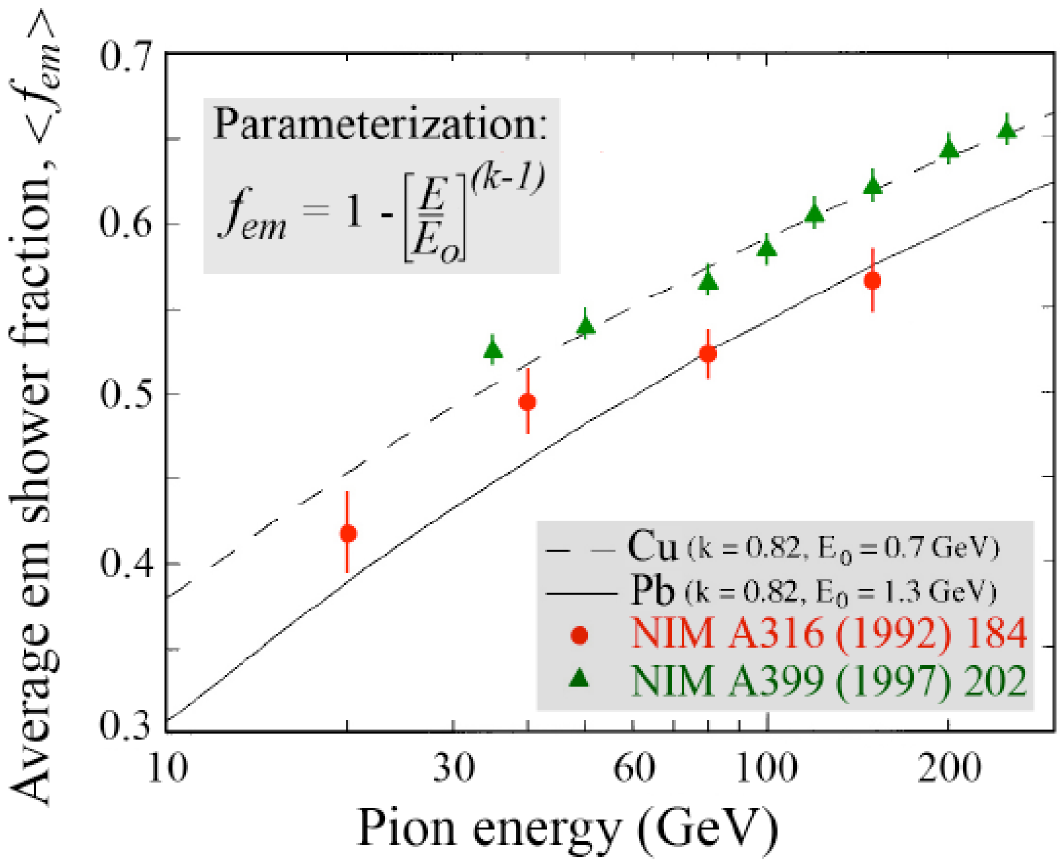
	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	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 fraction (1)

- **EM fraction ($f_{EM}=E_{EM} / E_{tot}$)** due to $\pi^0/\eta\rightarrow\gamma\gamma$.
  - In first interaction, ~1/3 of produced particles are π^0.
  - Remaining hadrons may undergo neutral pions too.

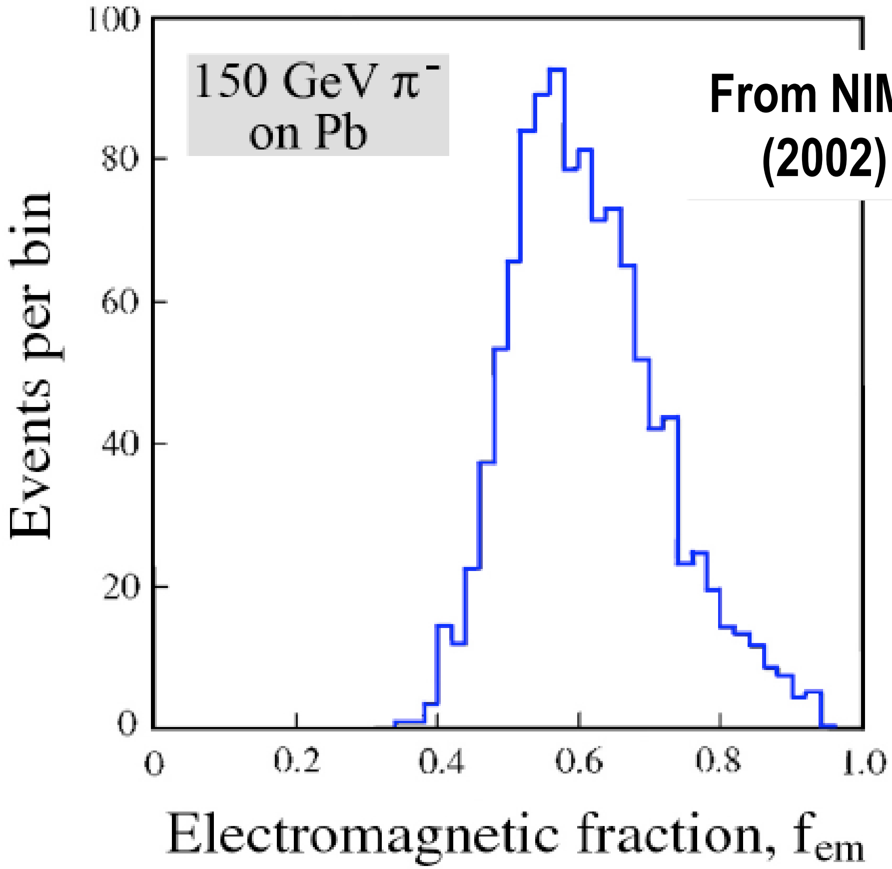
- **Considerable variations from shower to shower**

- On average, f_{EM} increase with shower energy (typically ~30% at 10 GeV, ~50% at 100 GeV)

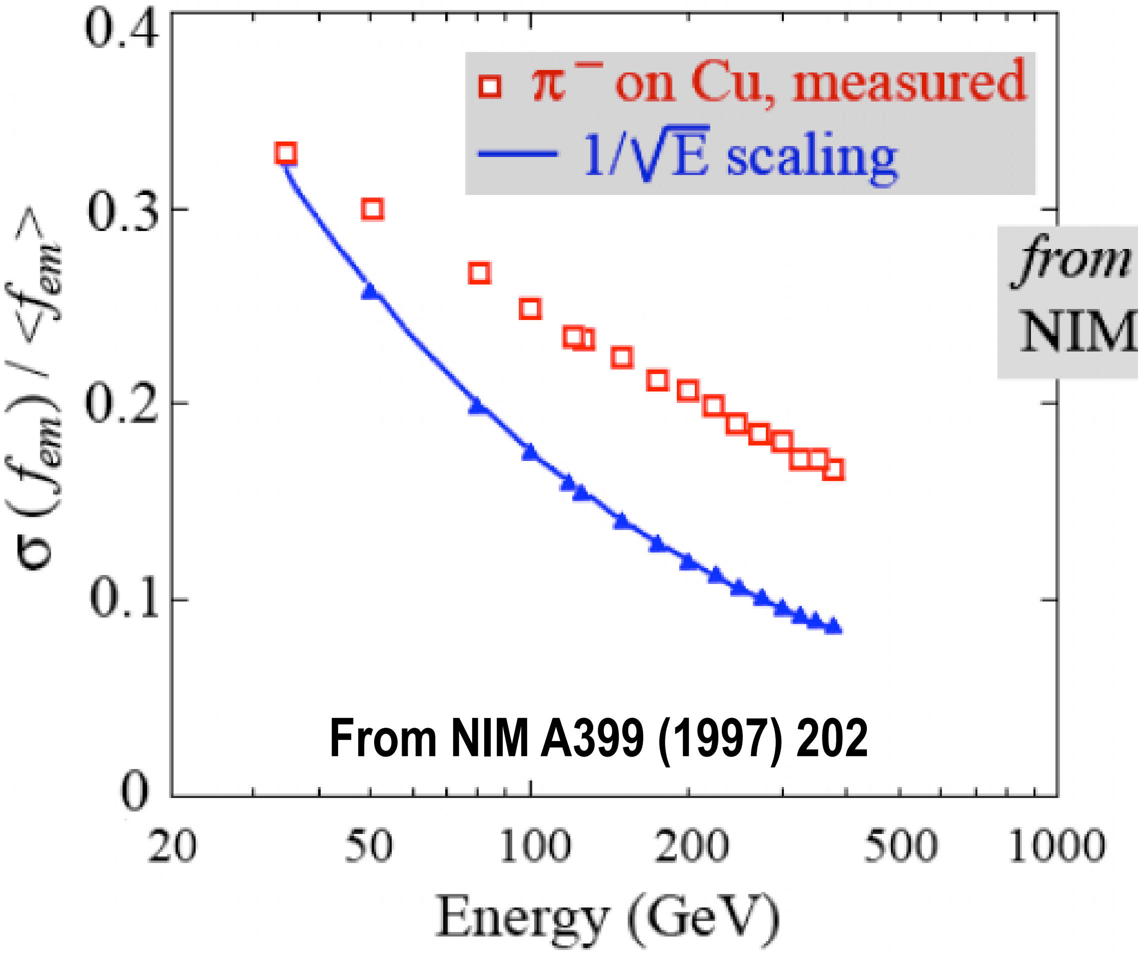


$\langle f_{EM}\rangle$ is large, energy dependent and material dependent

EM fraction (2)



From NIM A316 (2002) 184



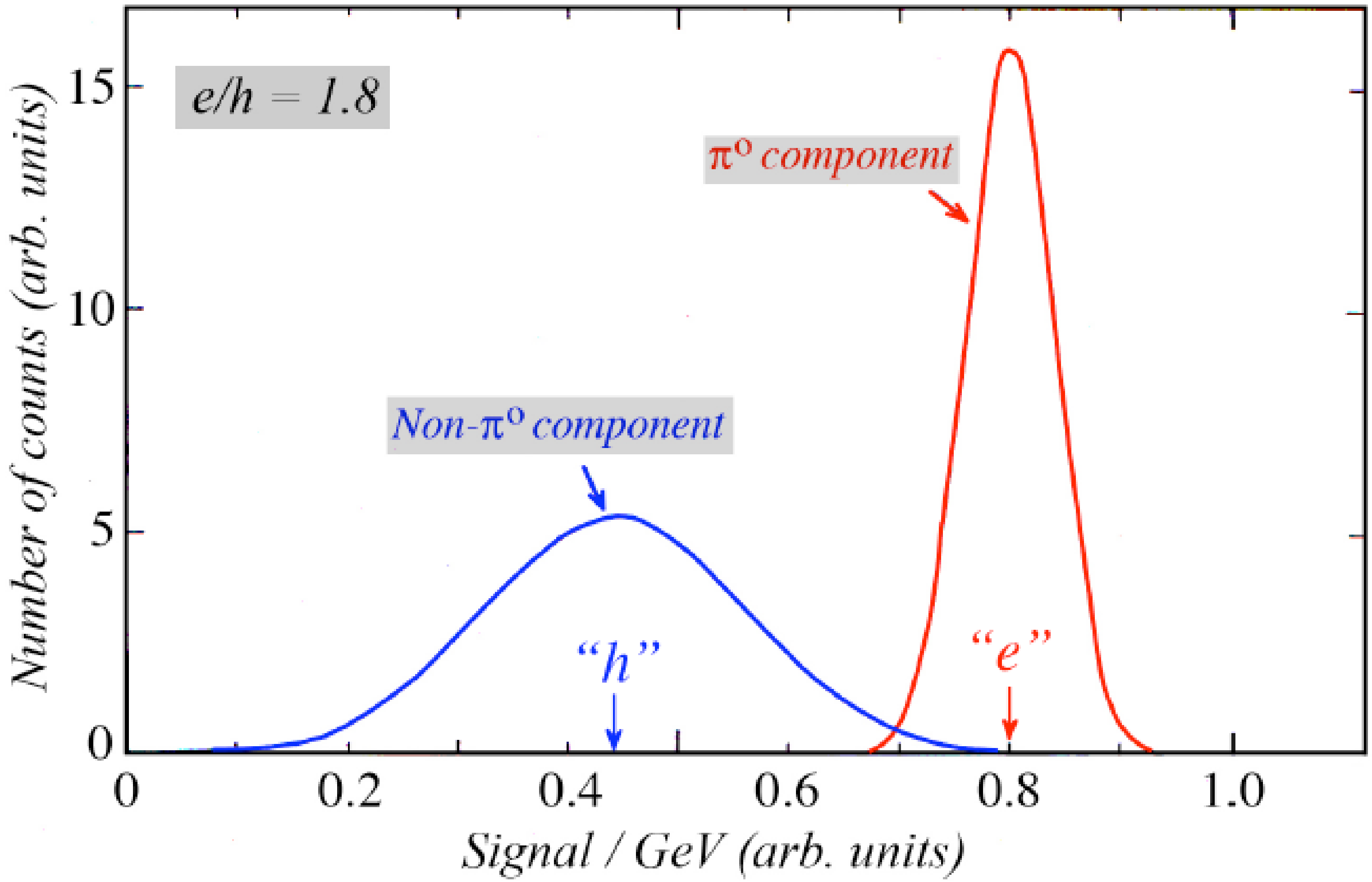
From NIM A399 (1997) 202

- **Fluctuations in f_{EM} are non-Poissonian**
- Deviations from E-1/2 scaling

HAD shower response (1)

- The response to the **HAD part (h)** of a hadron-induced shower is usually smaller than that of the **EM part (e)** (due to invisible energy: energy used to release nucleons from nuclei, neutrinos, …)
  $\Rightarrow$ **"non-compensation"** (see next)

- Moreover, as $\langle f_{EM} \rangle$ varies with energy, **hadron calorimeters are non-linear.**



HAD shower response (2)

$$\pi = f_{EM} e + (1 - f_{EM}) h$$

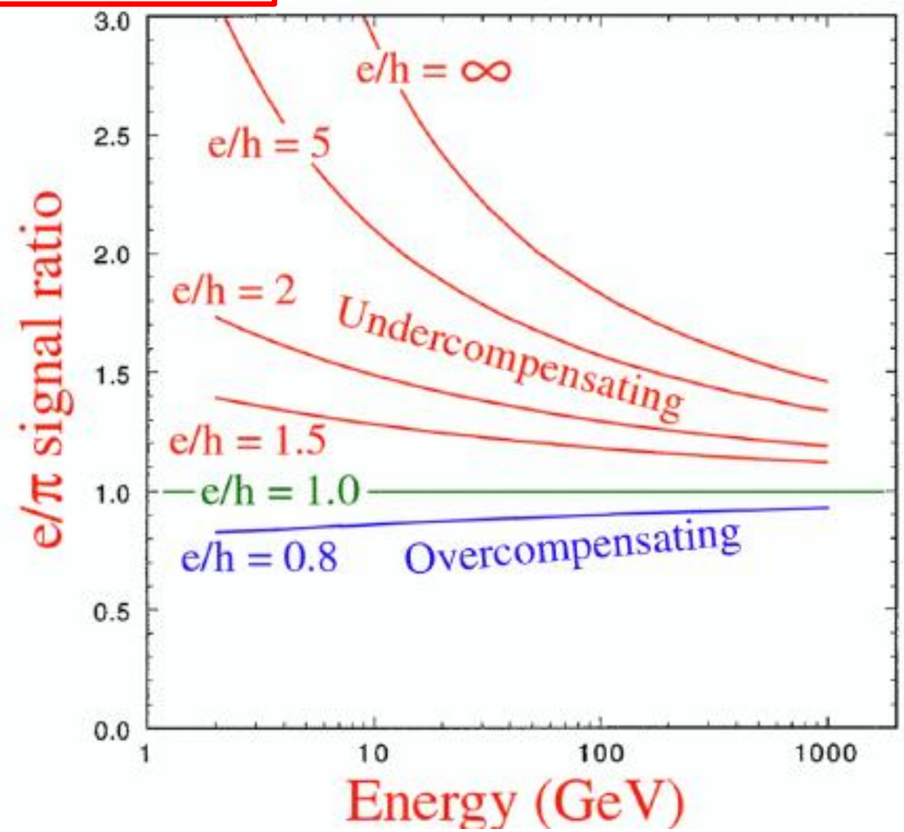
$$\frac{e}{\pi} = \frac{e}{f_{EM} e + (1 - f_{EM}) h}$$

π: response to pions-induced showers
e: response to em shower component
h: response to non-em shower component

$$\frac{e}{\pi} = \frac{(e/h)}{1 - f_{EM}(1 - e/h)}$$

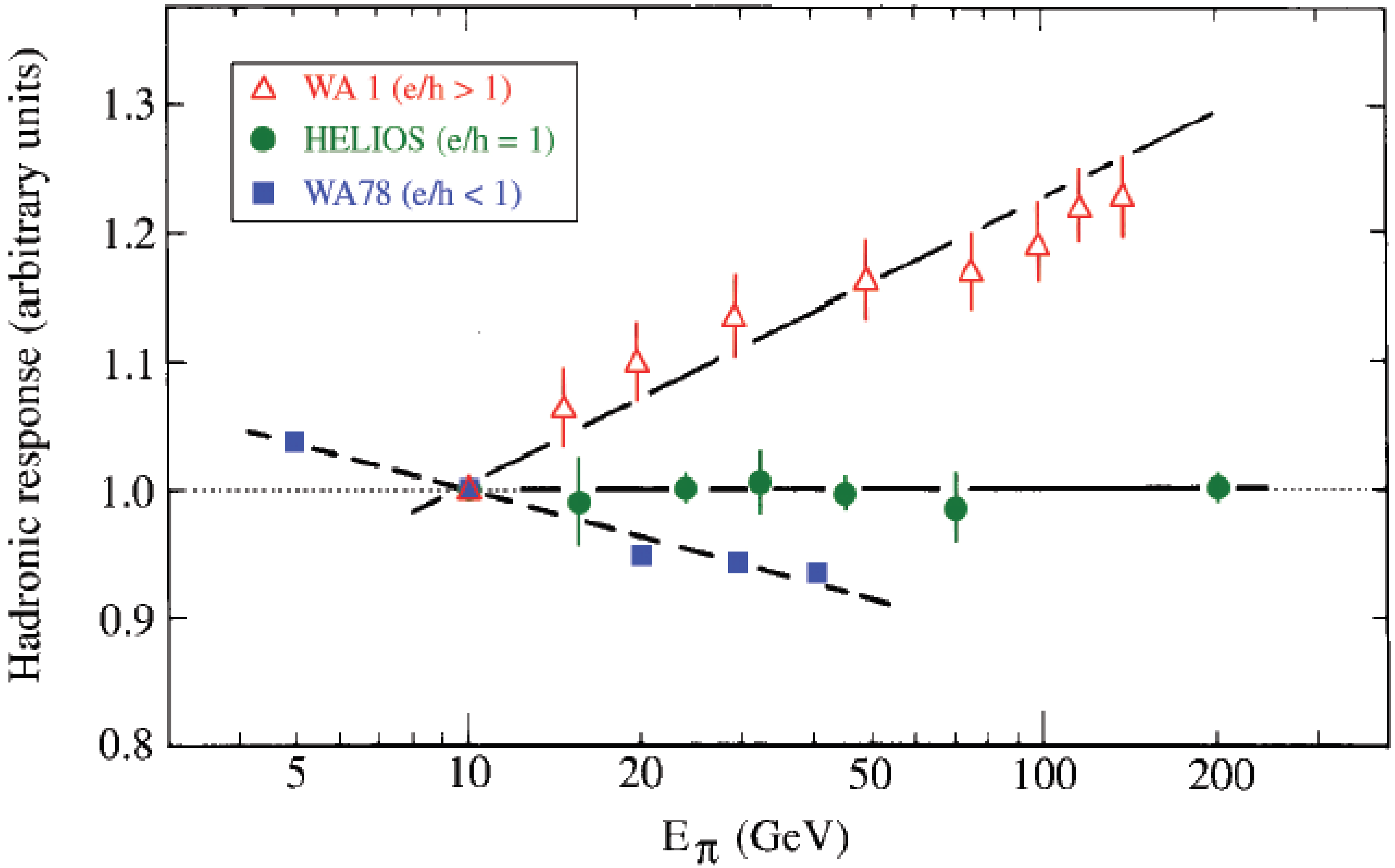
- **e/h**: energy independent way to characterize hadron calorimeters
  - Cannot be measured directly (inferred by e/π at several energies)

Calorimeters can be:
- under-compensating (e/h>1)
- over-compensating (e/h<1)
- **Compensating (e/h = 1)**



Consequences of (non-)compensation

- **(some) Consequences of non-compensation:**
  - Non-linearity of the hadronic calorimeter response
  - Degradation of the energy resolution
    - Event-by-event, fluctuations in em and non-EM fraction creates event-by-event signal fluctuations



How to achieve compensation ?

- Long-story… it took a lot of R&D to understand the underlying mechanisms of hadron calorimetry and identify several ways to achieve compensation:

- **Build a sampling calorimeter**
  - Compensation can never be achieved with homogenous calorimeter !

- **Boost the non-EM response**
  - Amplify neutron and soft photons component by:
    - Fission: usage of ^{238}U plates (depleted).
    - hydrogenous detector: optimize sampling fraction, integrate signal over a large enough window, …

- **Suppress EM response**
  - Usage of high-Z absorber (Pb, Ur,…) and low-Z active.
    - Photo-electric effect dominates ($\sigma_{photo\text{-}e} \propto Z^5$)
    - Suppress low energy photon detection (γ < 1 MeV captured in absorber)
  - Further suppression: shield active layers with thin sheets of passive low Z material.
    - e.g. Ur wrapped with Stainless Steel sheets in ZEUS.

- **Offline compensation:**
  - Recognize, event-by-event, cells rich in EM and non-EM deposits, and weight their energy accordingly
    - Need fine segmentation

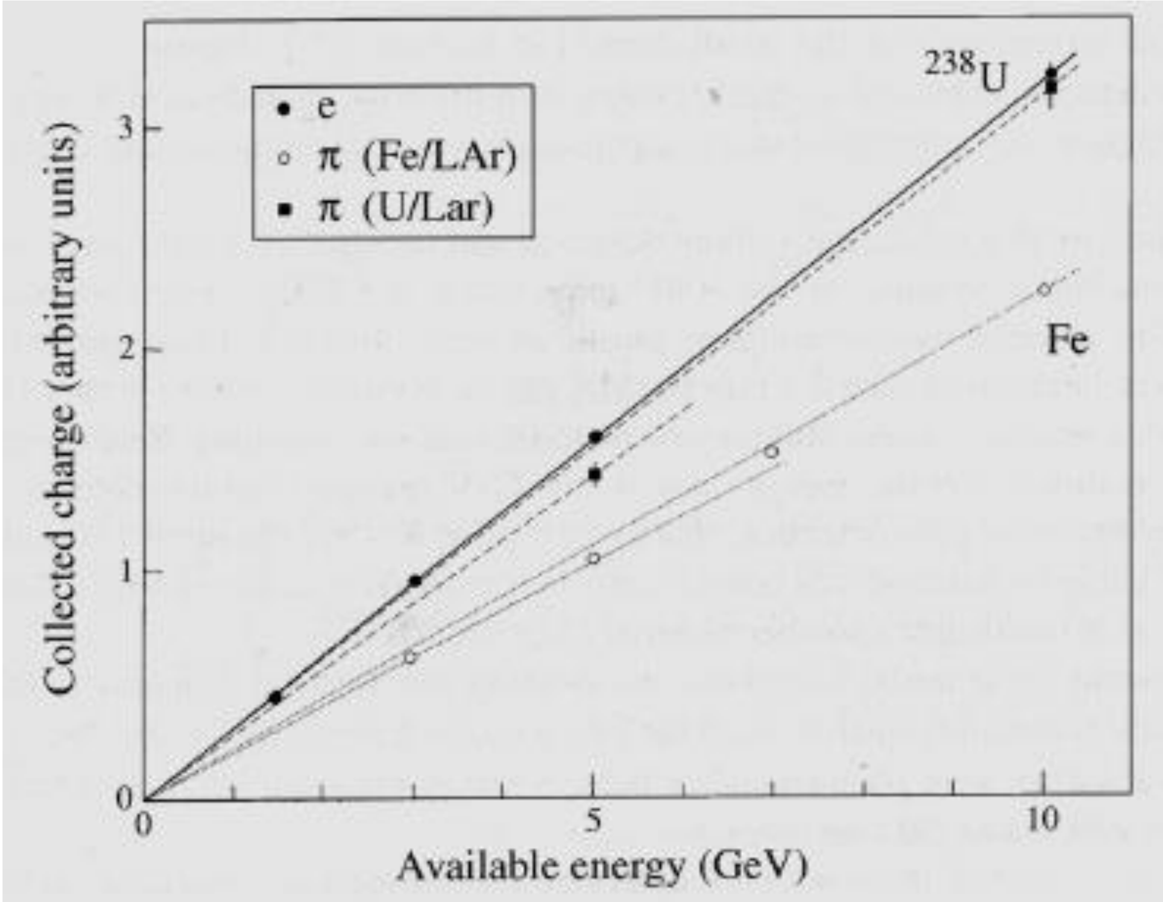
First “compensating” calorimeter

- First Uranium calorimeter by Fabjan & Willis

250 ^{238}U plates (1.7mm thick)
+ LAr (20mm gap between plates)

- Compensation almost achieved

=> e/h ~1.1 – 1.2



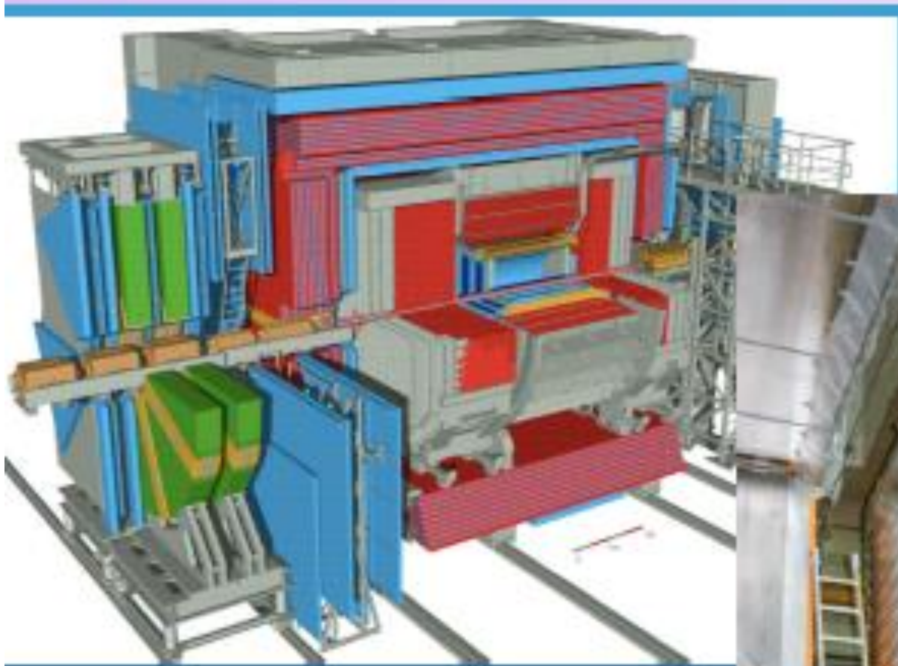
- **Mechanism: nuclear fission**
  - Extra energy from fission fragment: carries a lot of energy (nuclear γ's and soft evaporation neutrons.
  - Should “compensate” for losses in nuclear binding energy

- For a long time, thought to be the solution to compensation…

Compensated calorimeter: example

ZEUS experiment (HERA e-p collider DESY, Germany)

ZEUS at HERA had an intrinsically compensated ^{238}U/plastic scintillator calorimeter. The ratio of ^{238}U thickness (3.3 mm) to scintillator thickness (2.6 mm) was tuned such that $e/p = 1.00 \pm 0.03$ (implying $e/h = 1.00 \pm 0.045$)
For this calorimeter the intrinsic energy resolution was: $\sigma/E = 26\%/\sqrt{E}$



excellent overall energy resolution for hadrons:
$\sigma/E\ (HAD) \sim 35\%/\sqrt{E}$

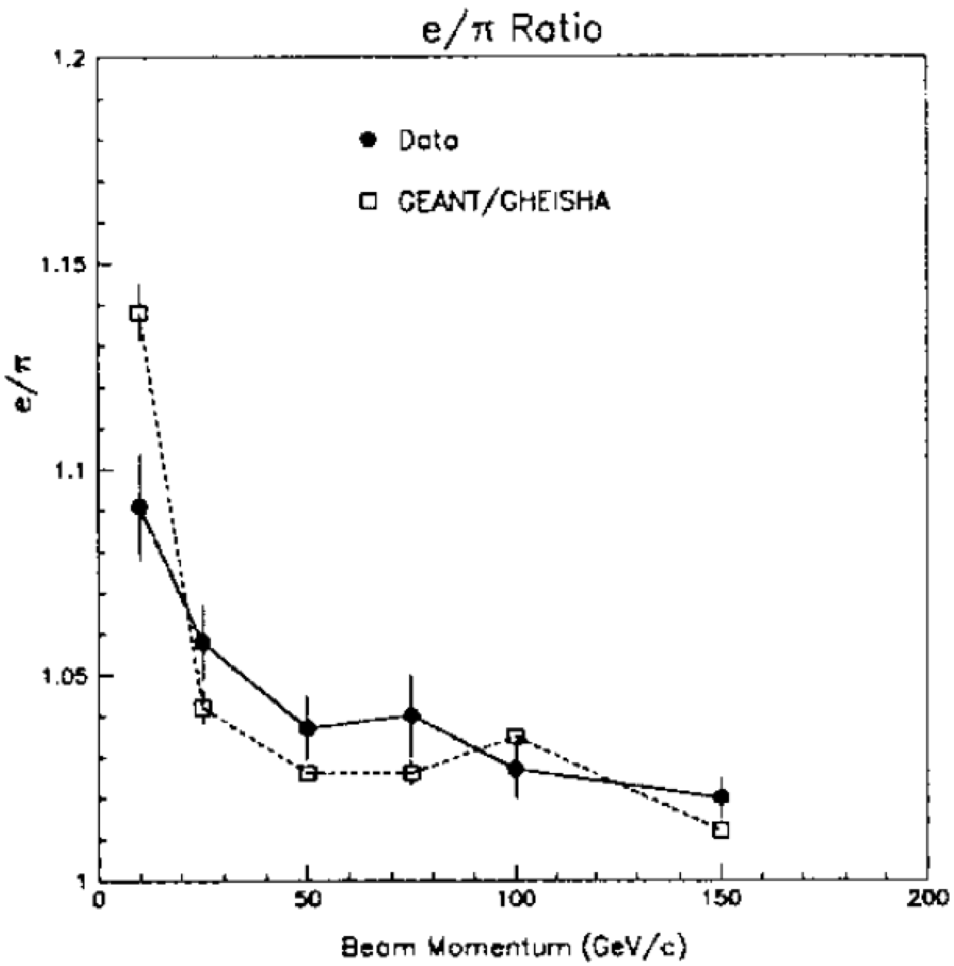
The downside is that the ^{238}U thickness required for compensation (~ $1X_0$) led to a rather modest EM energy resolution:
$\sigma/E\ (EM) \sim 18\%/\sqrt{E}$

BCAL 20x20 cm² cells
EM 25 X_0
HAD ~5 λ_I

Compensation: examples

DØ Ur/LAr calorimeter

Almost compensated during Run I (1992-1996)



- During Tevatron Run II (2001-2011):
  - bunch crossing 3200->396 ns
  - => Smaller ~0.45ms (vs~2ms) charge integration window

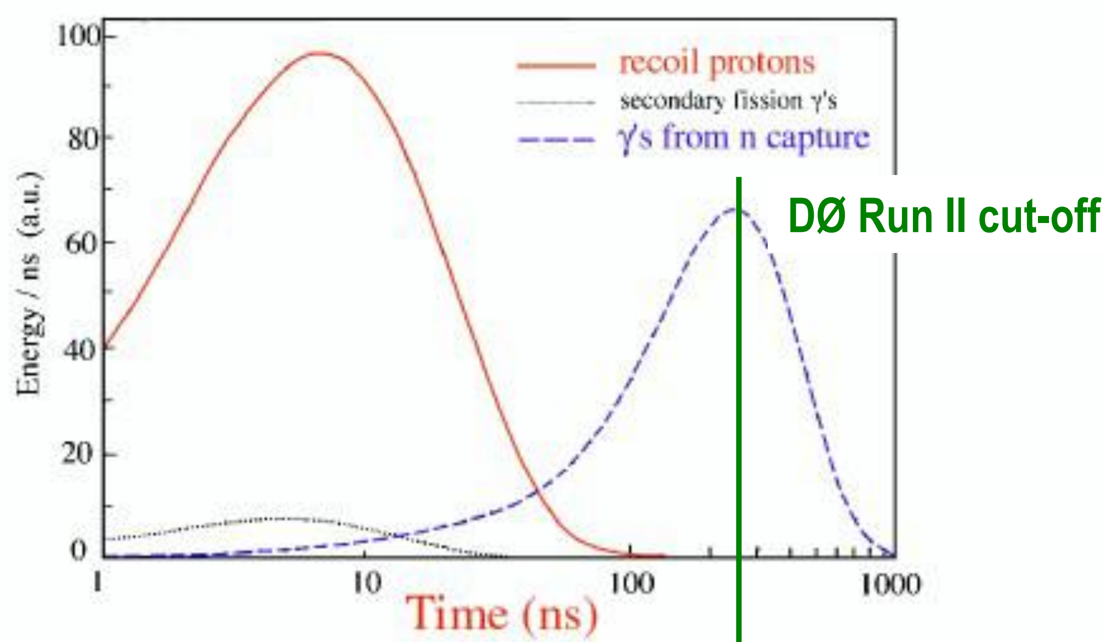


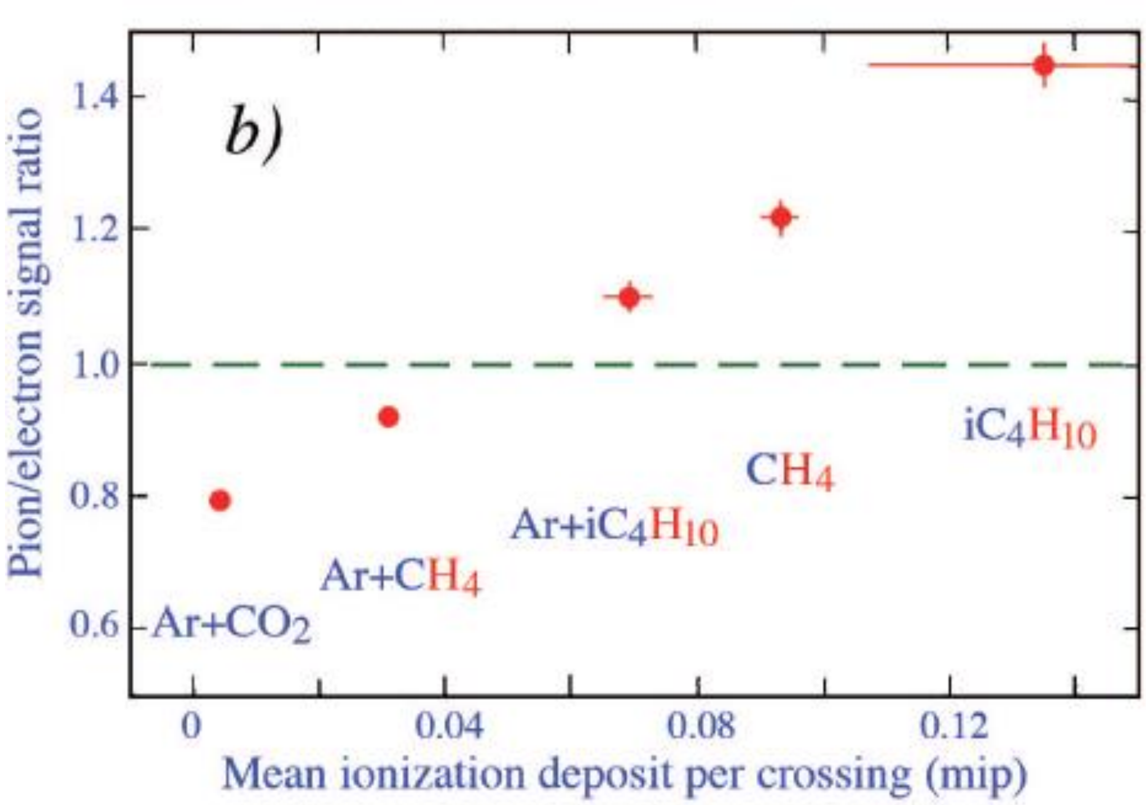
FIG. 3.22. Time structure of various contributions from neutron-induced processes to the hadronic signals of the ZEUS uranium/plastic-scintillator calorimeter [Bru 88].

Decays of excited uranium nuclei happen long after shower development and corresponding charge not captured with short integration time.

=> **Compensation deteriorated and thus resolution for Run II**.

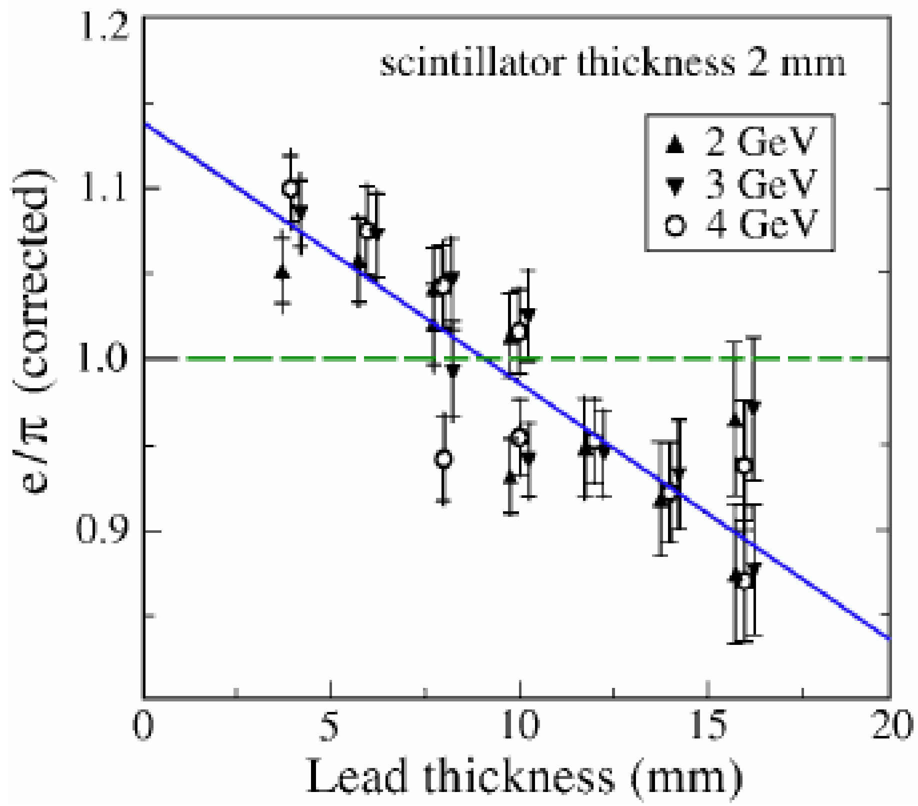
Compensation: examples

Hydrogen in active material (gas mixture)



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

Lead / Scintillator



Sampling fraction can be tuned to achieve compensation

e/h not determined by absorber but by active medium (and in particular its H-content)

Pros & Cons of Compensating Calorimeters

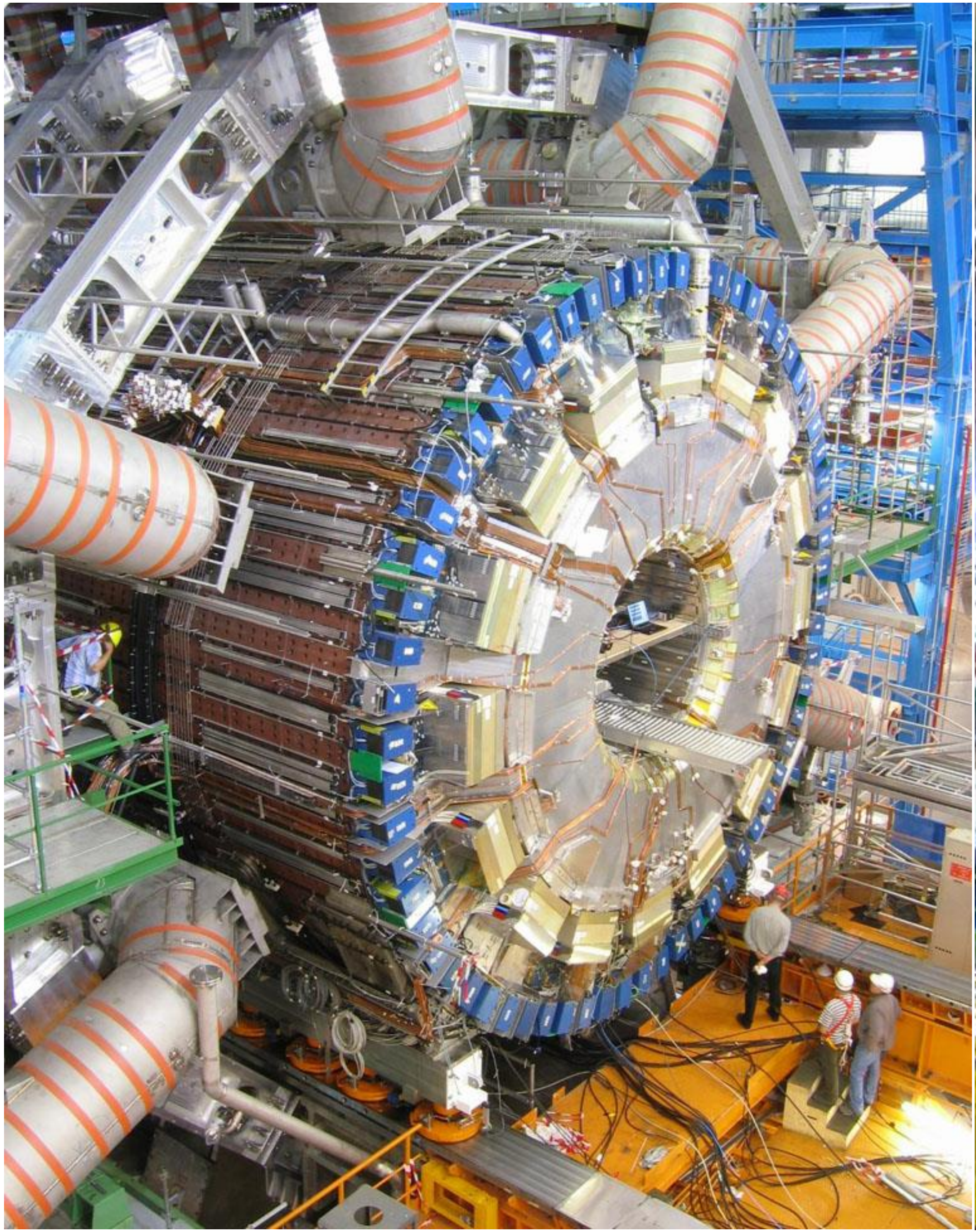
Pros

- Same *energy scale* for electrons, hadrons and jets. No ifs, ands or buts.
- *Calibrate* with electrons and you are done.
- Excellent hadronic *energy resolution* (SPACAL: $30\%/\sqrt{E}$).
- *Linearity,* Gaussian *response function* and all that good stuff.
- Compensation fully understood.
  We know how to build these things, even though GEANT doesn't

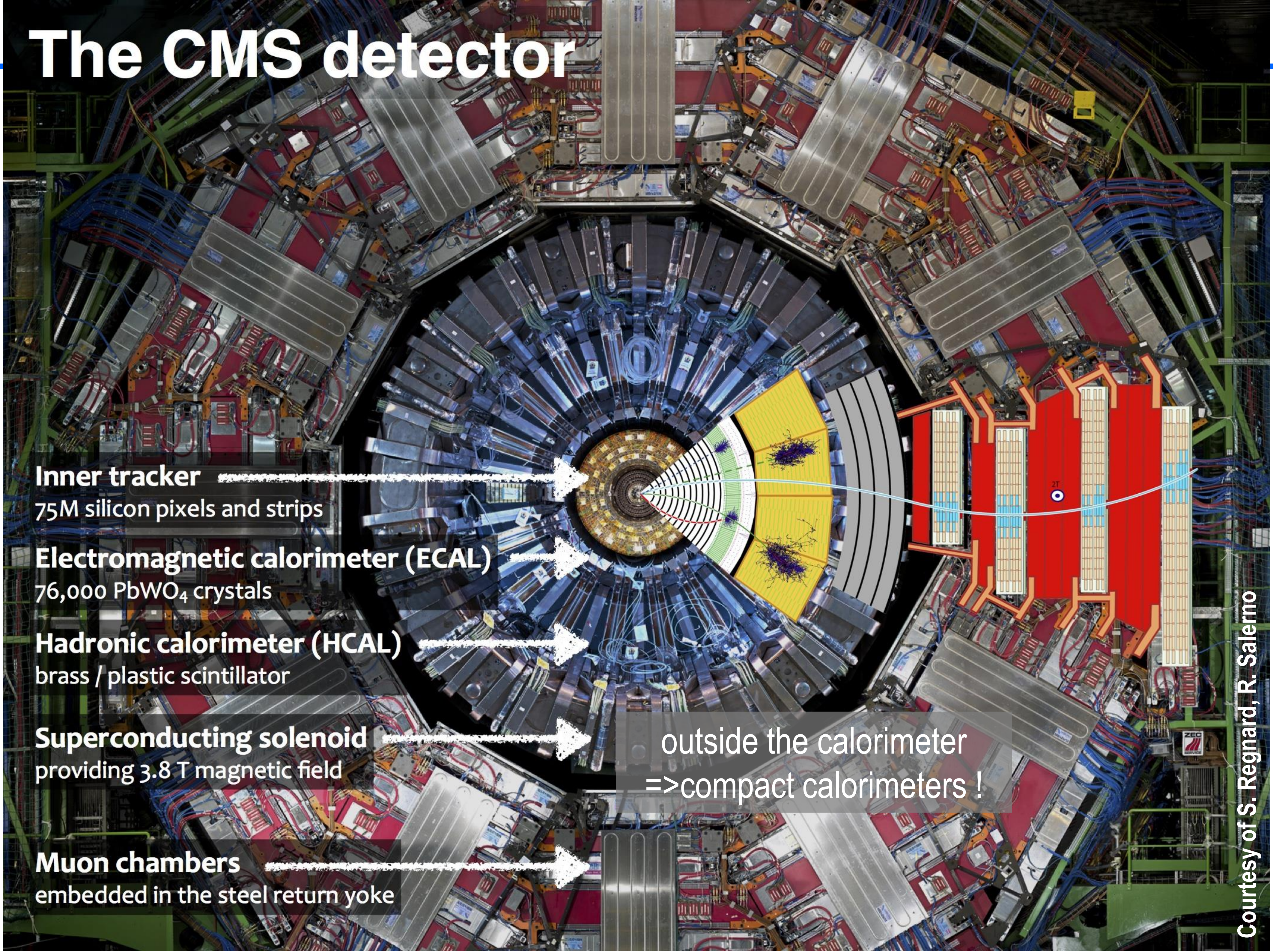
Cons

- Small sampling fraction (2.4% in Pb/plastic)
  ⟶ *em energy resolution limited* (SPACAL: $13\%/\sqrt{E}$, ZEUS: $18\%/\sqrt{E}$)
- Compensation relies on detecting neutrons
  ⟶ Large *integration volume*
  ⟶ Long *integration time* (~50 ns)

ATLAS & CMS calorimeters

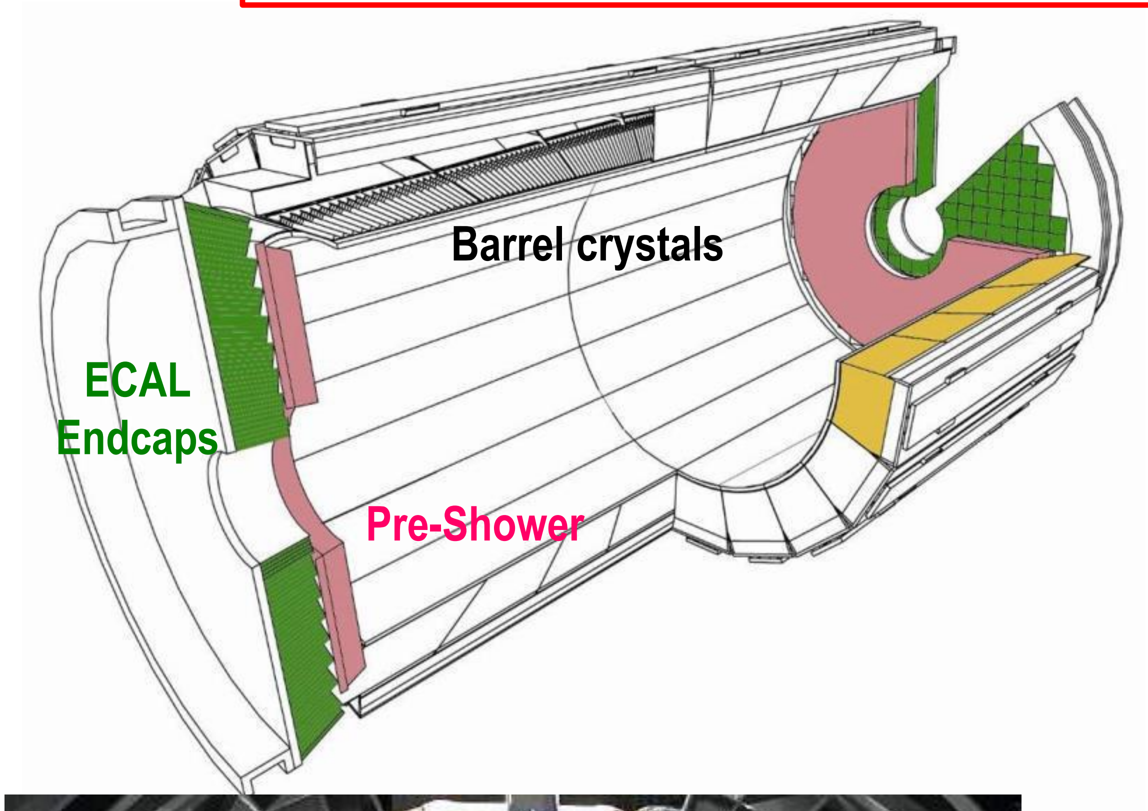


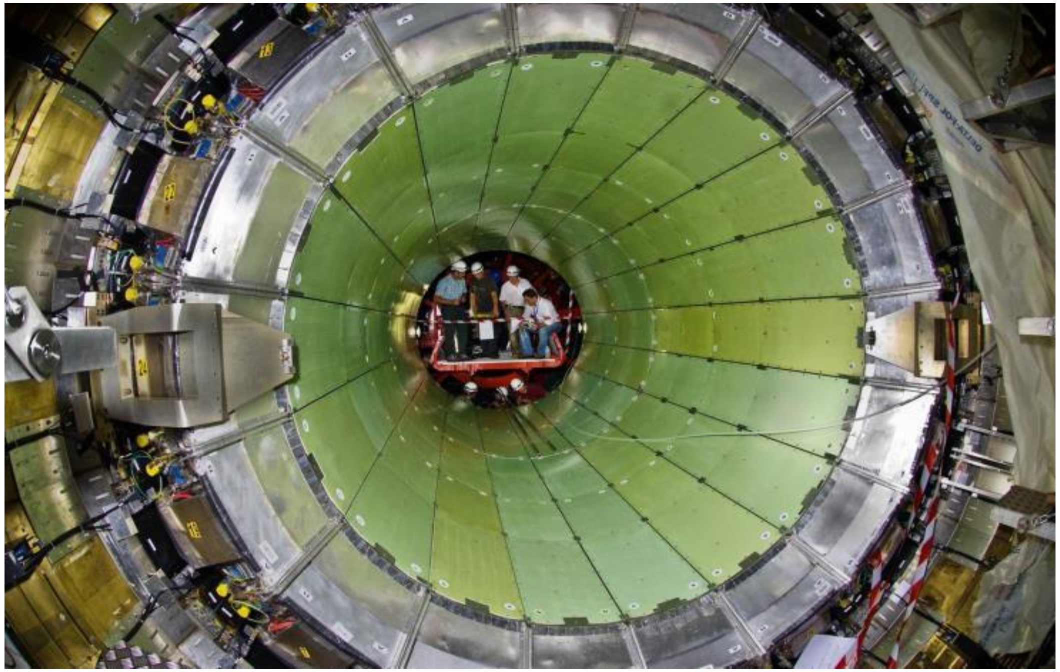
The CMS detector



CMS ECAL

Homogenous calorimeter made from 75848 $PbWO_4$ scintillating crystals

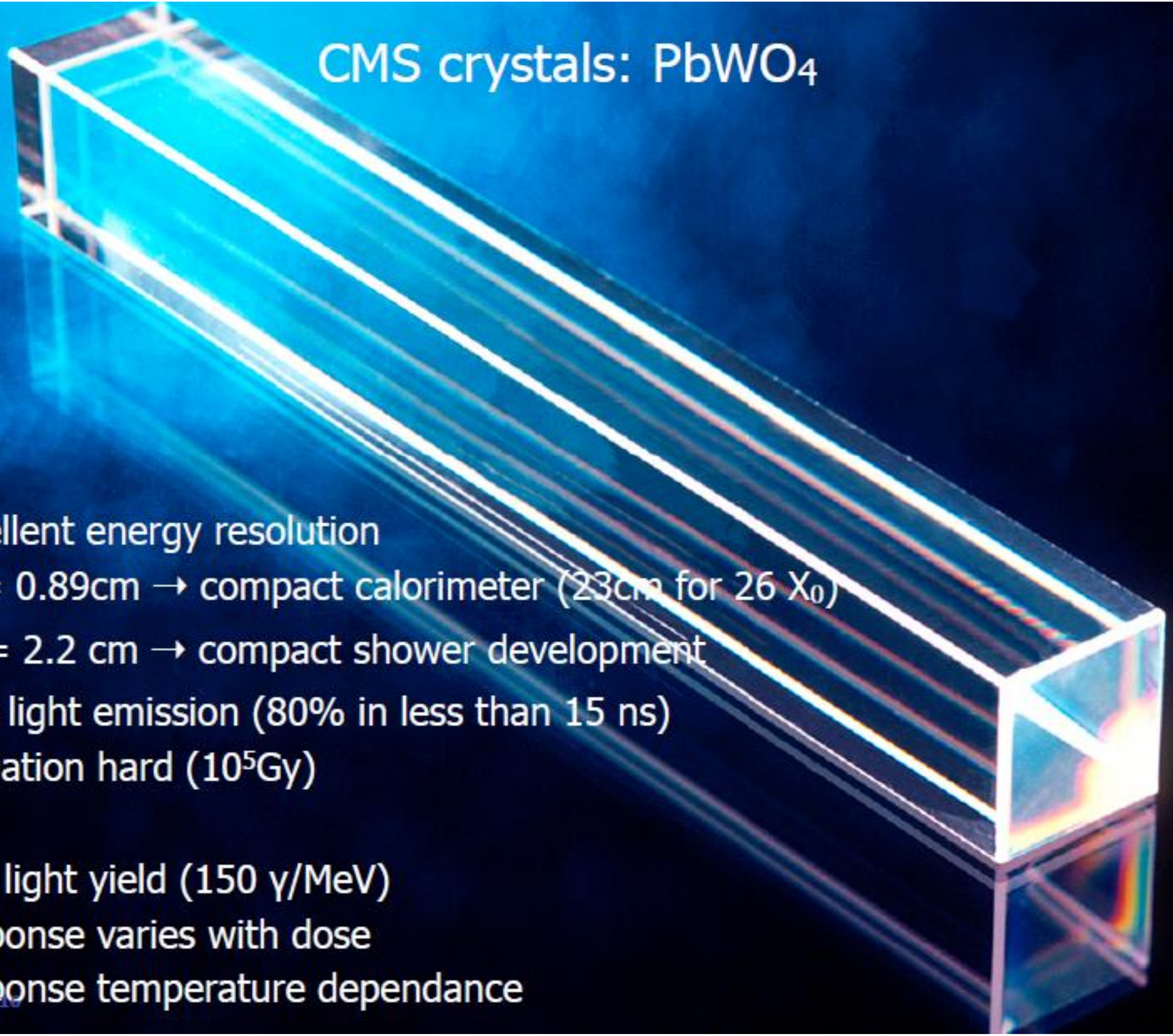




- Barrel ($|\eta|<1.48$), ~67 t
- 61200 crystals over 36 super-modules

- Endcaps ($1.48<|\eta|<3$), ~23 t
- 14648 crystals over 4 Dees (2 per endcap)
- Preceded by Pb/Si Pre-Shower

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)

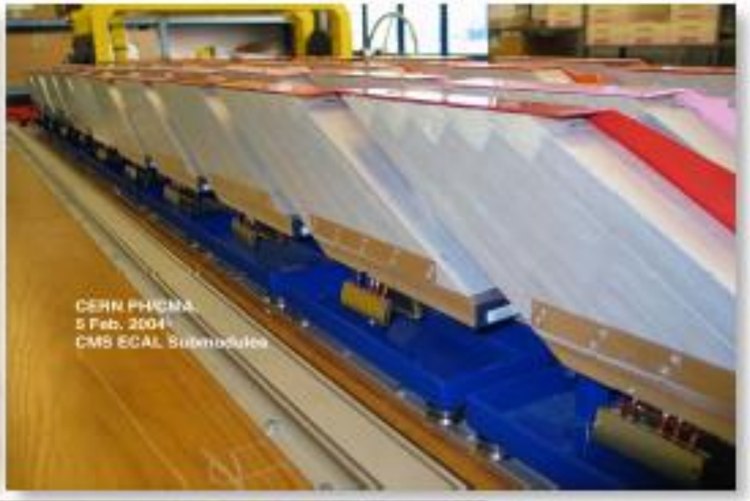
But

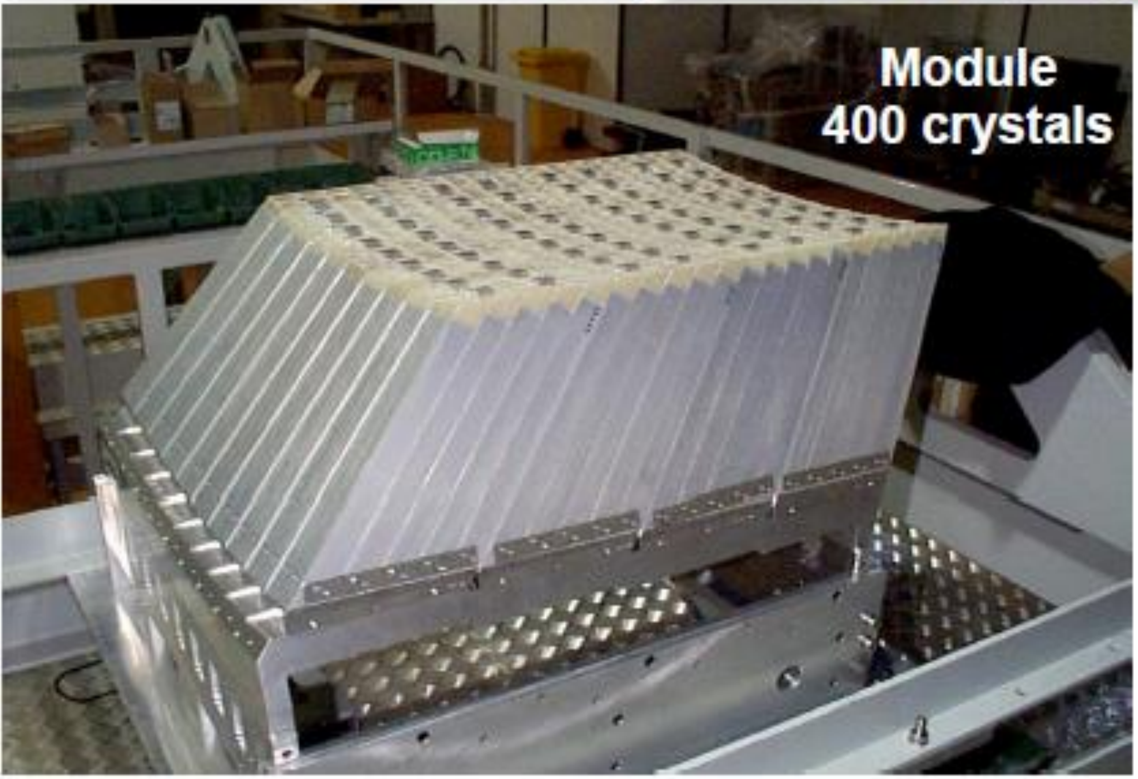
Low light yield (150 γ/MeV)

Response varies with dose

Response temperature dependance

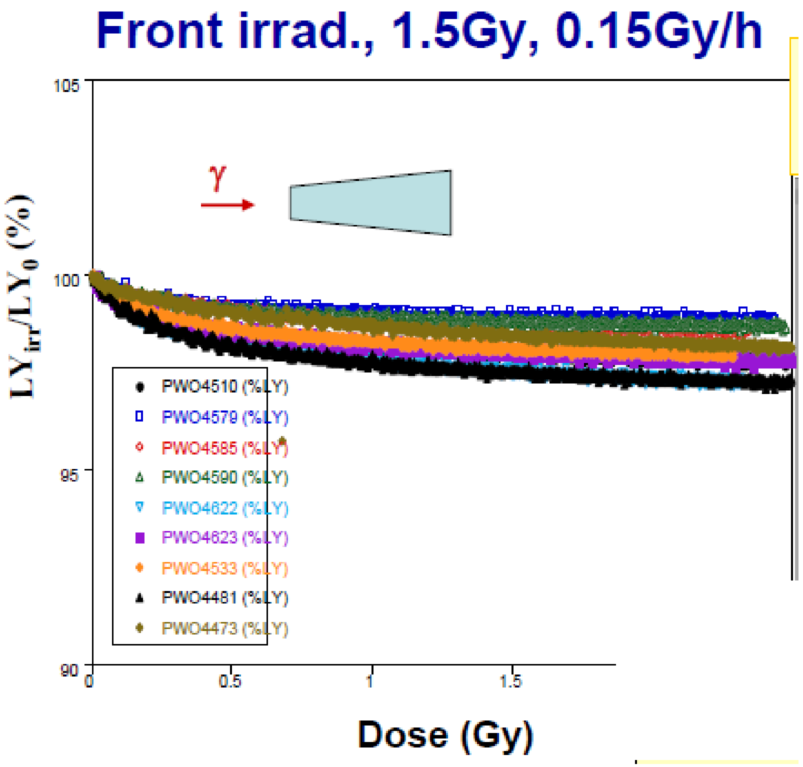
CMS ECAL Construction





Total 36 Supermodules

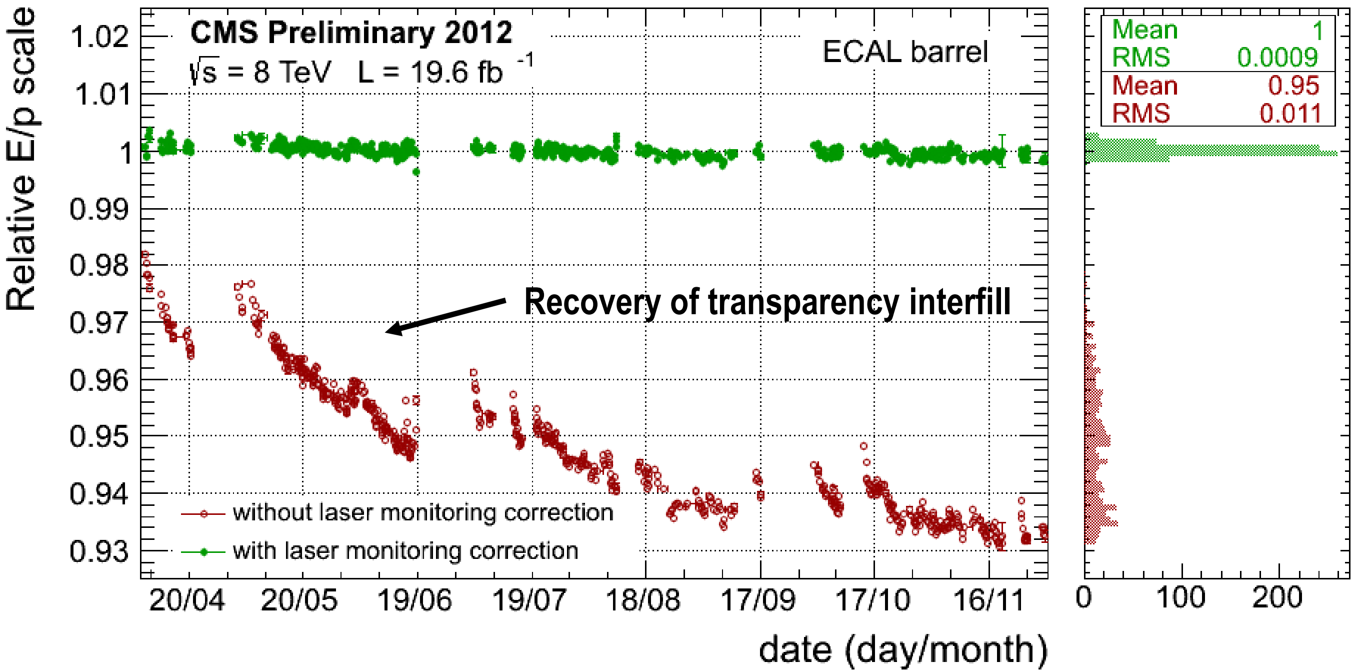
CMS ECAL: monitoring



- Response of $PbWO_4$ crystal change with irradiation
  - Loss of transparency

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

E/p with W→eν events

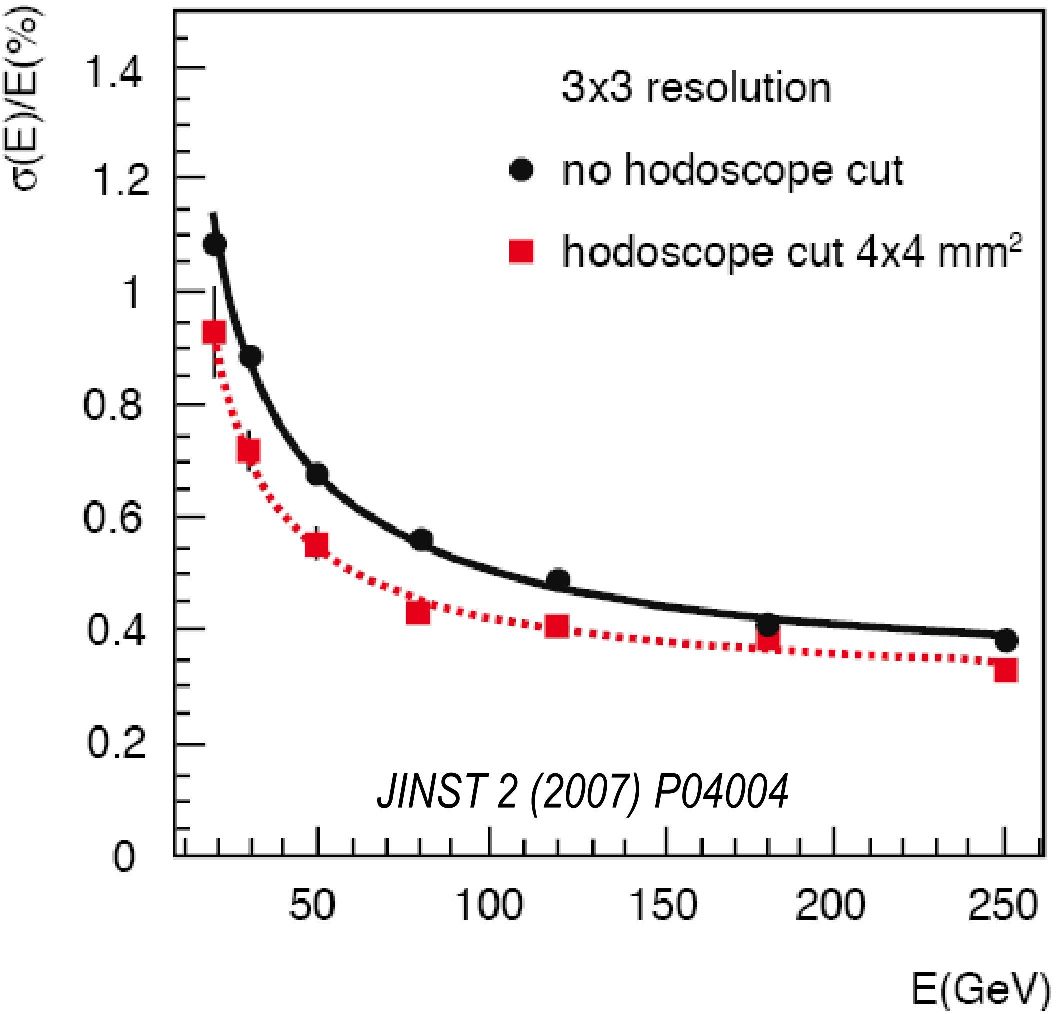


After laser correction

Before laser correction

CMS ECAL: performance

Stand-alone performance assessed during extensive test Beam campaigns at CERN...

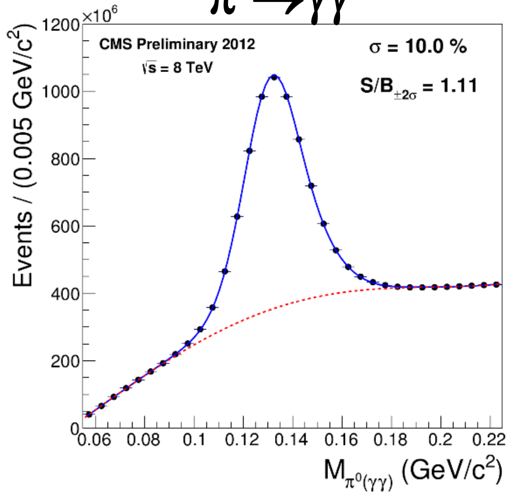


$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

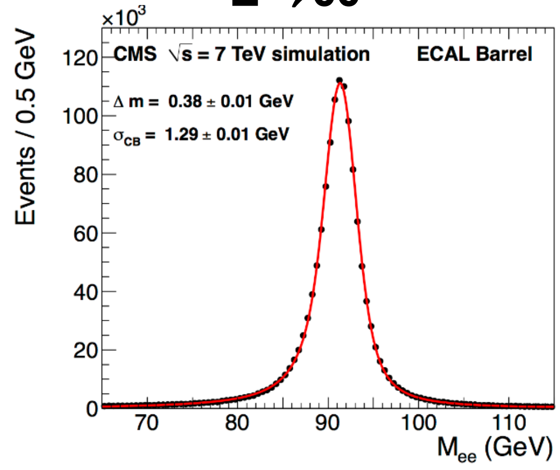
(test beam)

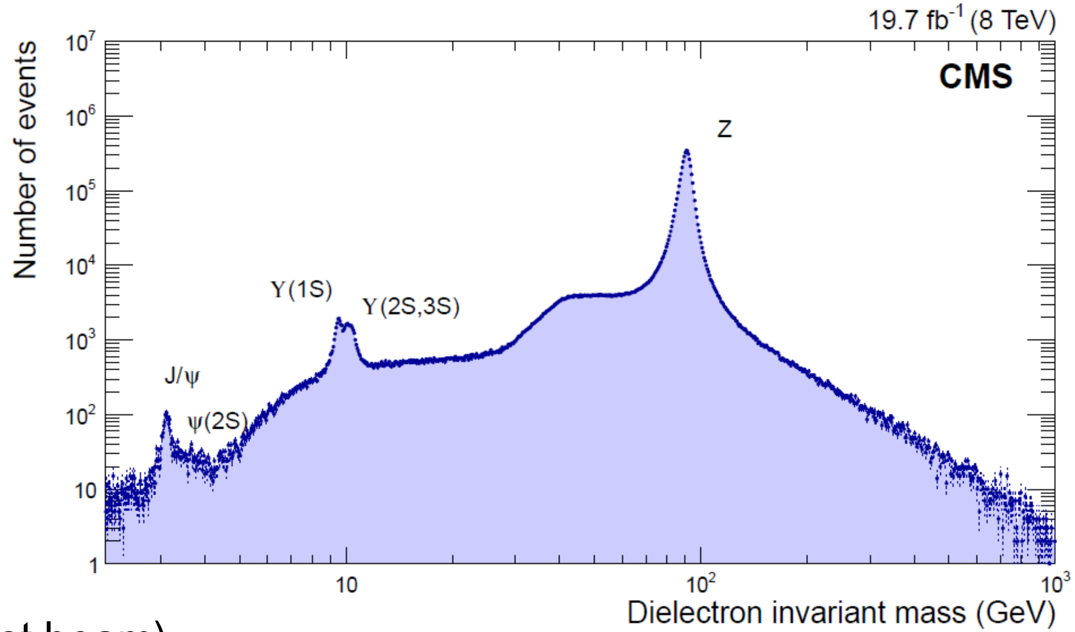
Combined performance measured in-situ

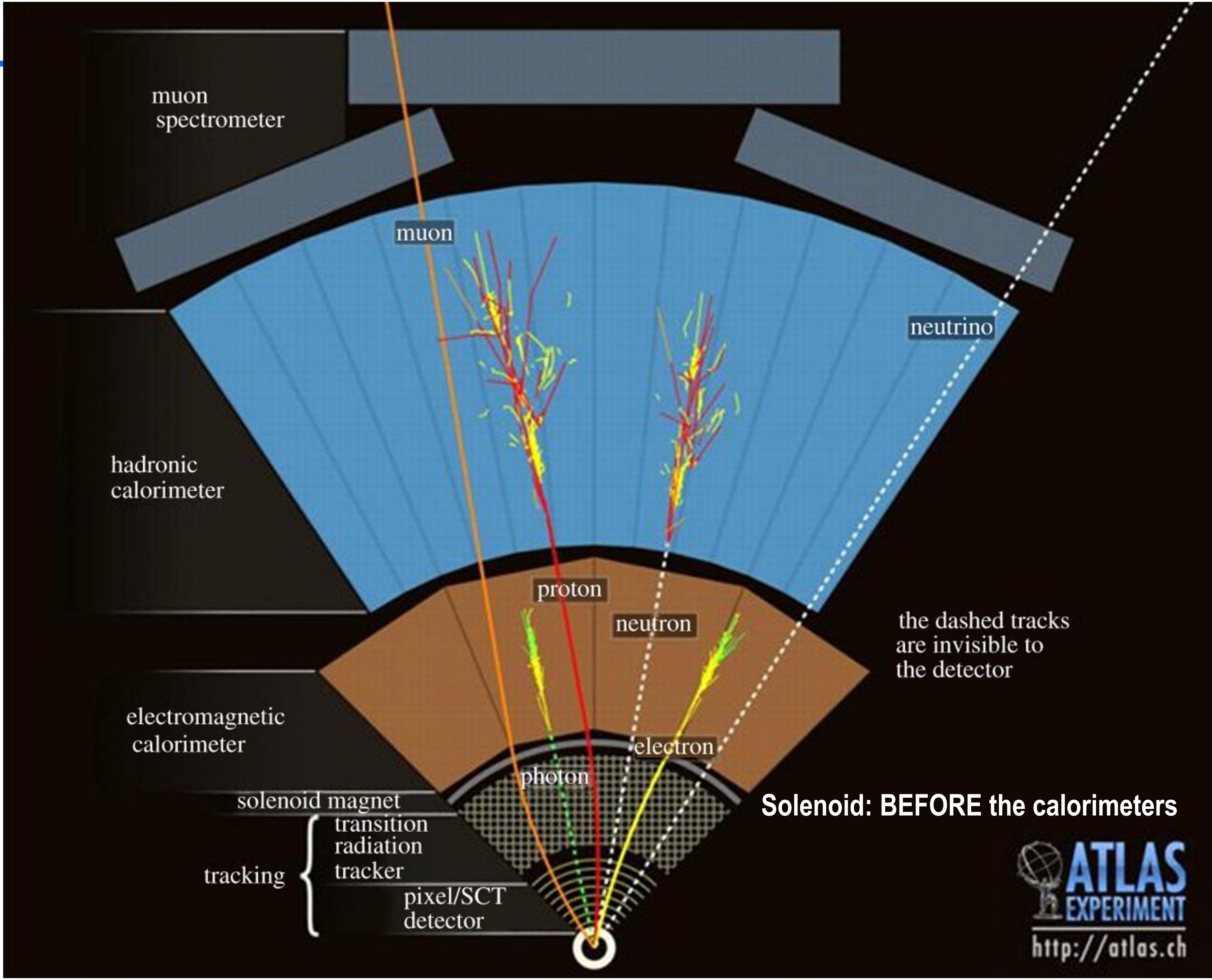
$\pi^0 \to \gamma\gamma$



$Z \to ee$



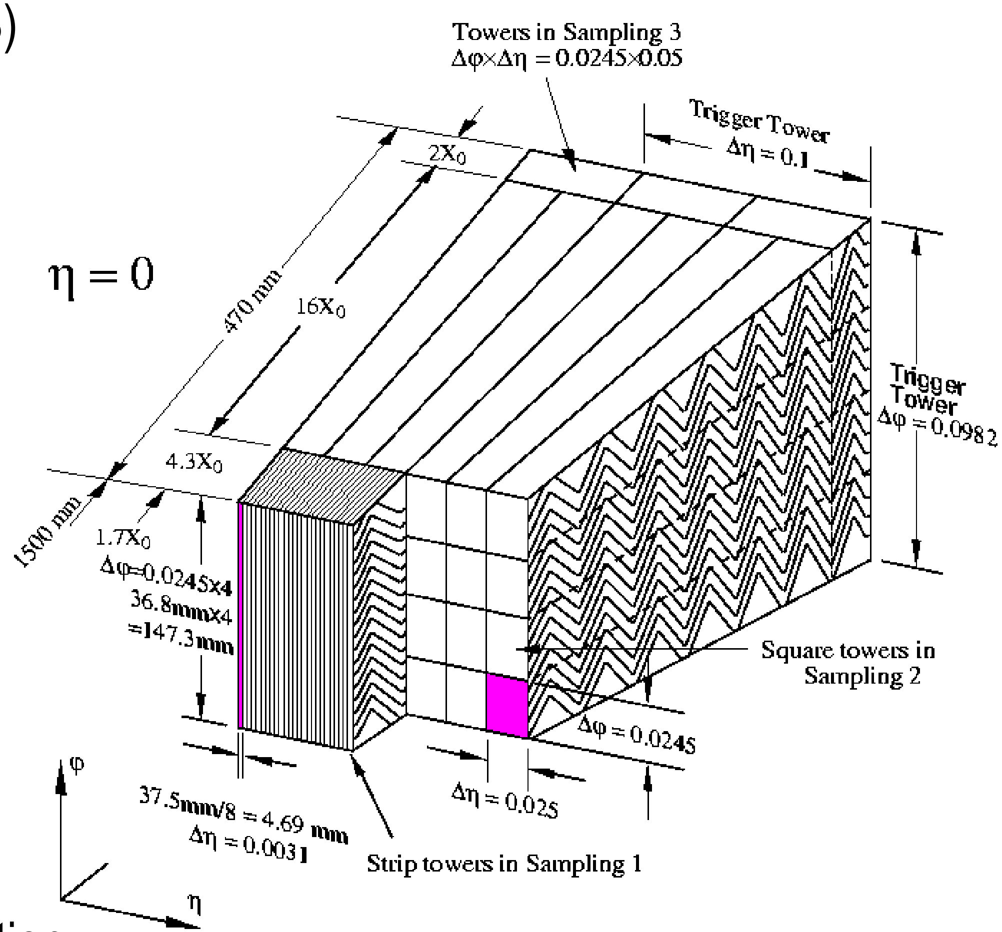



muon
spectrometer
muon
neutrino
hadronic
calorimeter
proton
neutron
the dashed tracks
are invisible to
the detector
electromagnetic
calorimeter
electron
photon
solenoid magnet
transition
radiation
tracker
tracking
pixel/SCT
detector
Solenoid: BEFORE the calorimeters
ATLAS
EXPERIMENT
http://atlas.ch

The ATLAS ECAL

Sampling Pb/LAr calorimeter with innovative "accordion" geometry

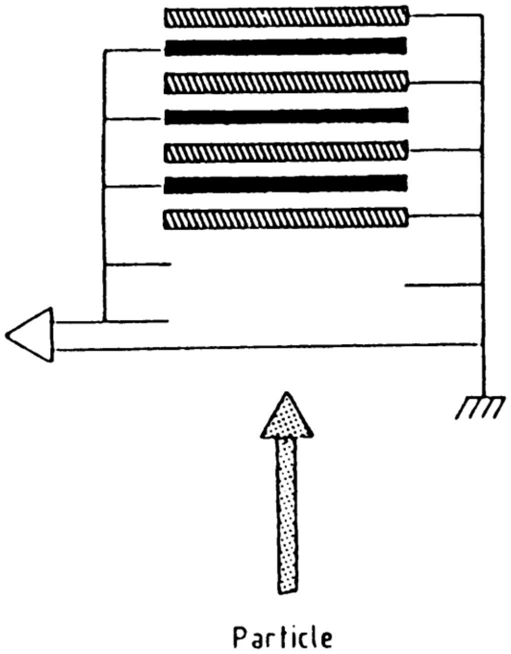
- Longitudinal dimension ~25 X0, 47 cm (vs 22 cm for CMS)
  - 3 layers up to |η|=2.5 + presampler |η|<1.8
  - 2 layers 2.5<|η|<3.2
    - Layer 1 (γ/π⁰ rej. + angular meas.)
    - Δη.Δφ = 0.003 x 0.1
    - Layer 2 (shower max)
    - Δη.Δφ = 0.025 x 0.0.25
    - Layer 3 (Hadronic leakage)
    - Δη.Δφ = 0.05 x 0.0.025



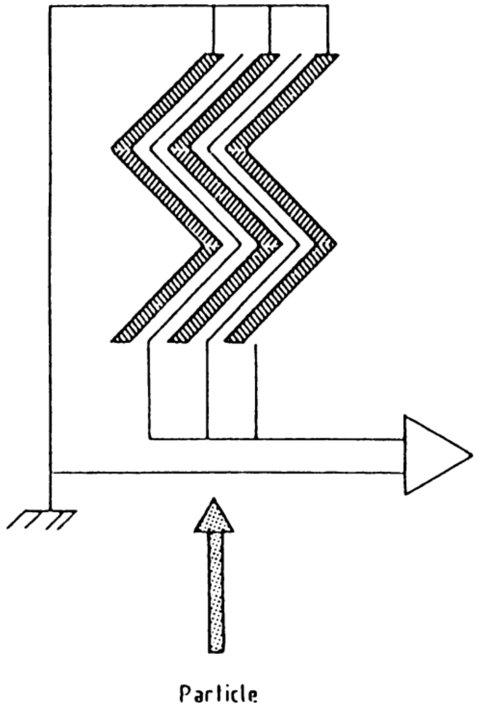
- ~170 000 channels
- **Usage of Liquid Argon**
  - Radiation Hard
  - High number of electron-ion pair produced by ionization (1 GeV deposit -> 5.10^6 e-)
  - Stable vs time
  - **BUT:**
    - Need a cryostat (90K)
    - Slow time response (400 ns vs 25 ns LHC bunch crossing)

ATLAS ECAL: accordion geometry (1)

Standard Liquid Argon



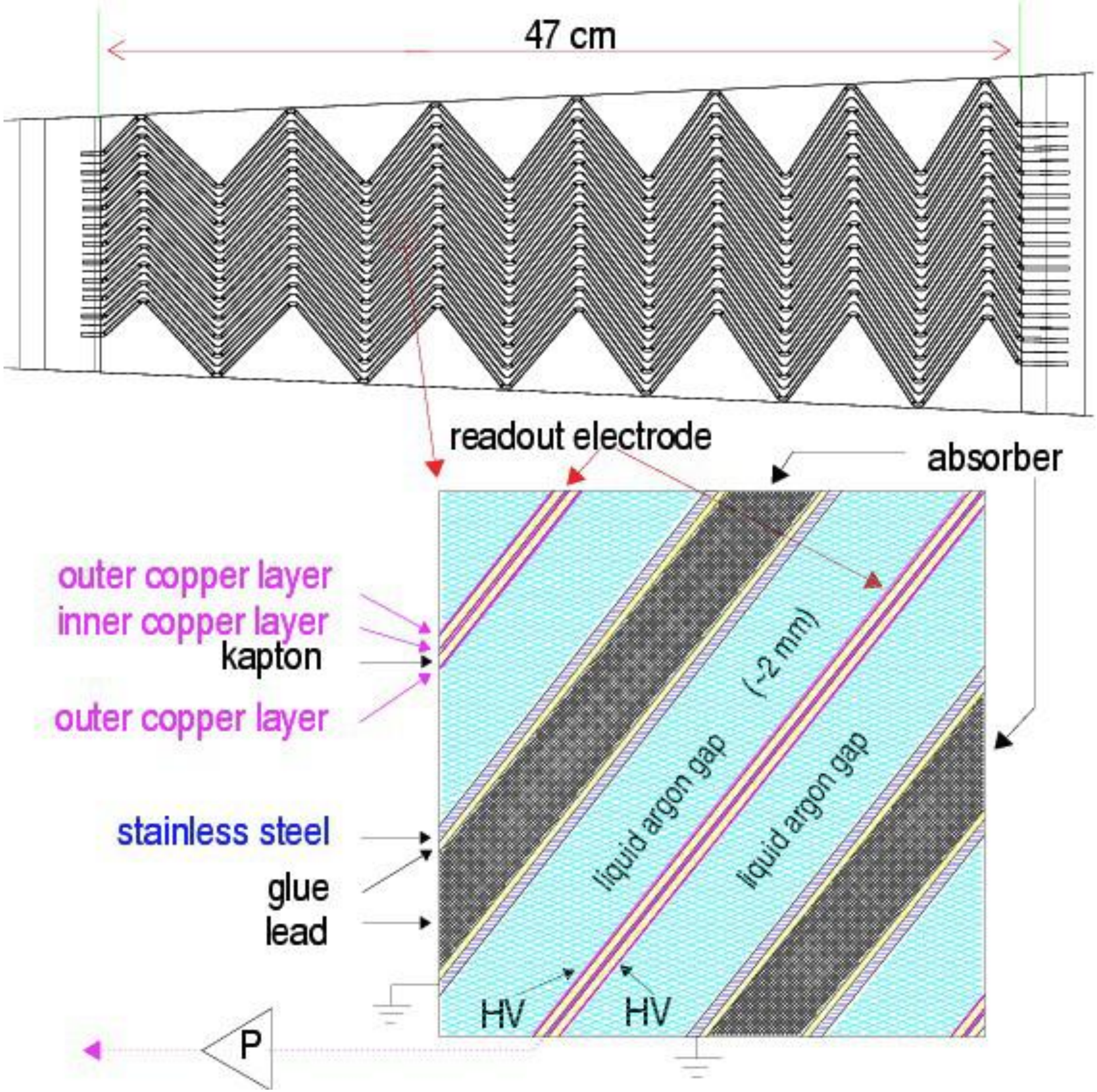
Accordion Liquid Argon

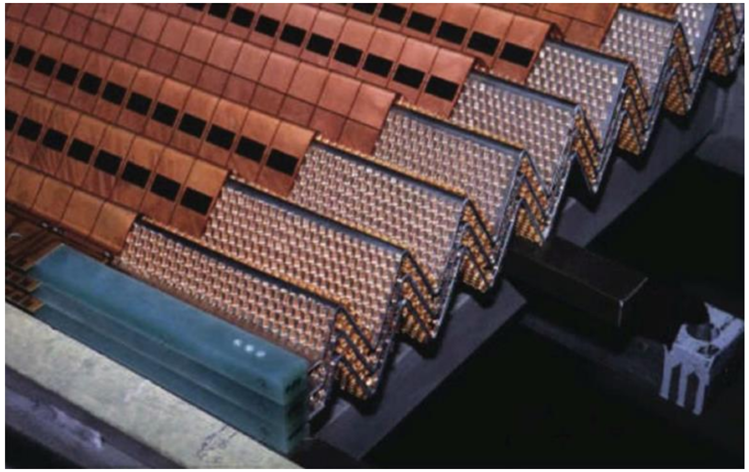


- Slow response (long integration time)
- Electrodes ⊥ particles
- Long cables
  - To bring signal to pre-amplifiers
  - Regroup gaps
- Dead zones due to cables

- Accordion geometry: **fast**
- Electrodes // to incident particles
  - Signal read out forward & backward
  - No long connection
- **No cracks (in azimuth)**

ATLAS ECAL: accordion geometry (2)

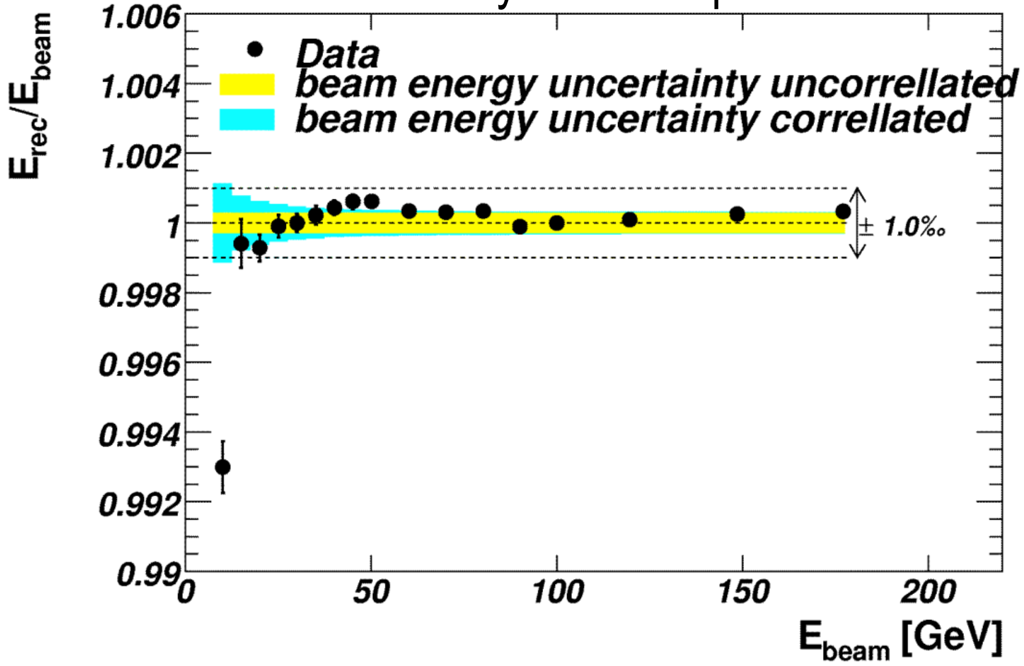




ATLAS ECAL: Performance

Stand-alone performance assessed during extensive test Beam campaigns at CERN...

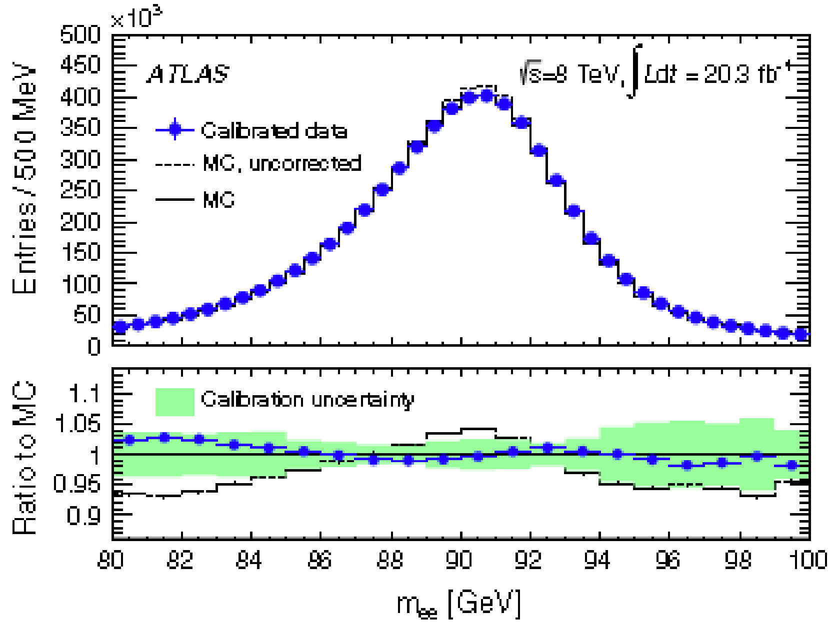
Linearity of the response

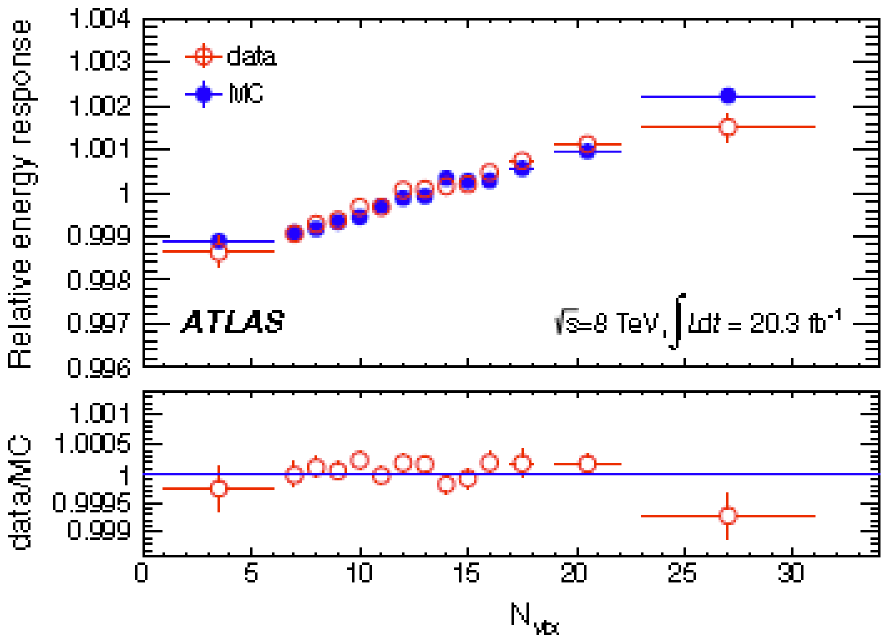


$$\frac{\sigma}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.3}{E} \oplus 0.7\%$$

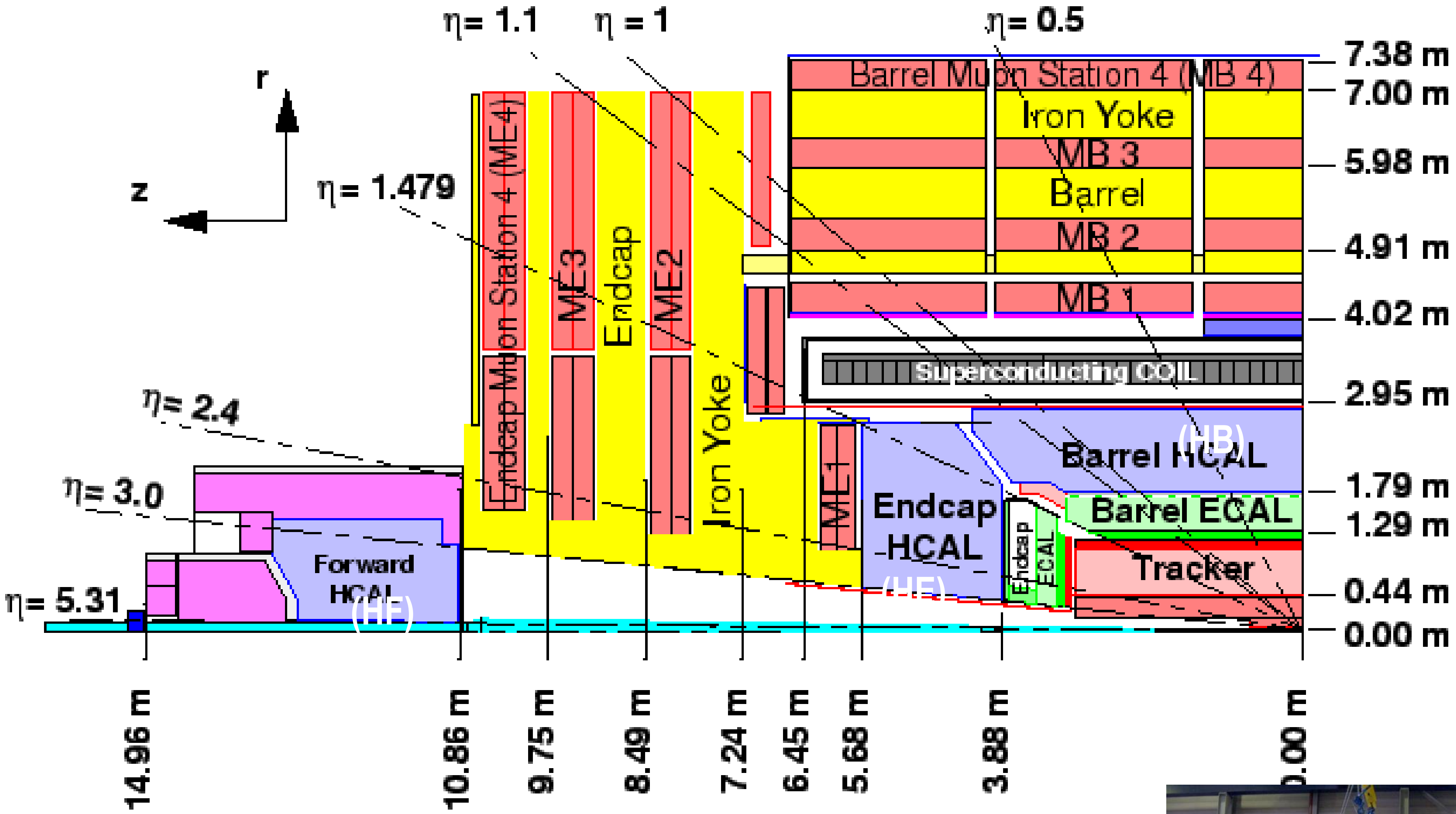
(test beam)

Combined performance measured in-situ





CMS HCAL



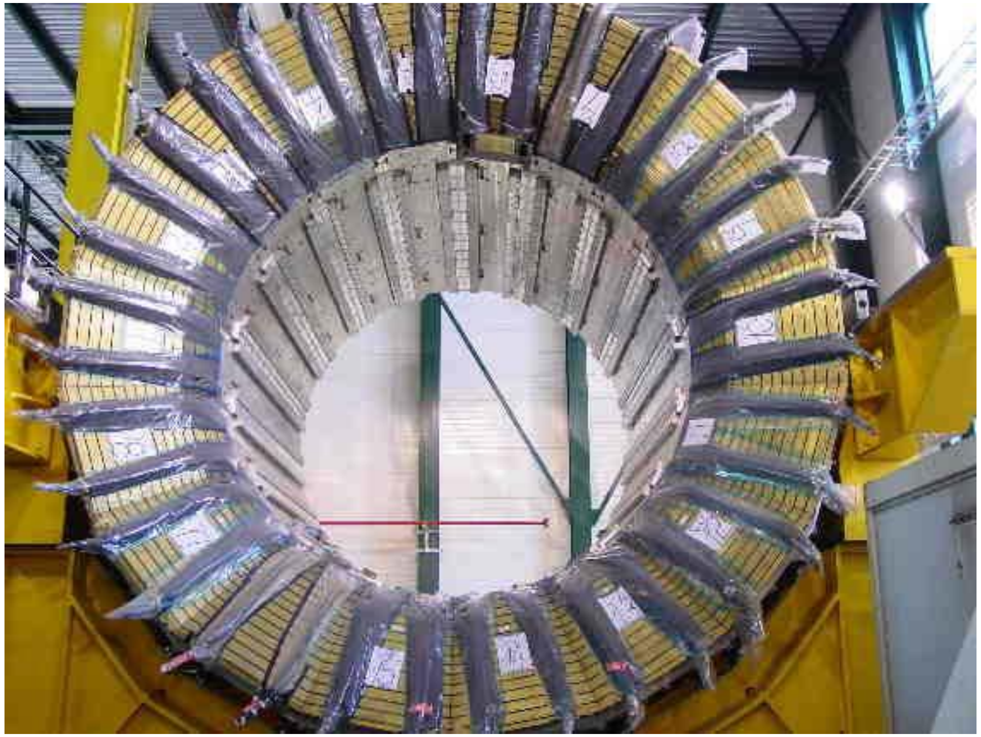
- HCAL Barrel (HB): |η|<1.3
- HCAL Endcap (HE): 1.3<|η|<3
- Forward HCAL (HF): 3<|η|<5, Fe+Quartz Fiber

See next

CMS HCAL

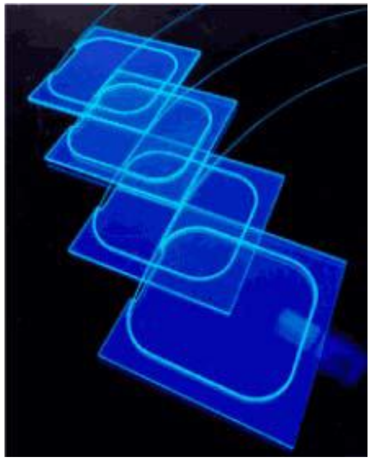
HB/HE: Sampling Brass/plastic scintillator calorimeter

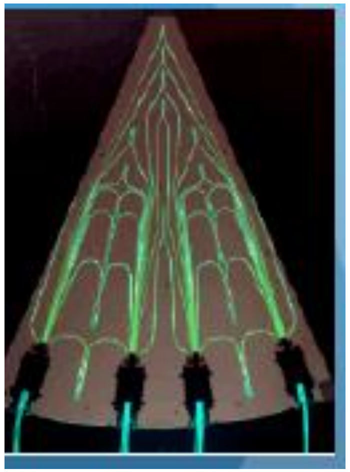
HB **(17 longitudinal layers)**



HE **(19 longitudinal layers)**

- Segmentation: $\Delta\eta x \Delta\phi$=0.087x0.087 (larger at high η)
- 18x20° "wedges" with alternate brass plates (5-8 cm) and "tiles" embedded with Wave Length Shifter (WLS).
  - Light from scintillator: blue-violet
  - WLS: absorb light then fluorescence in green
  - Green light read by Hybrid Photo Diode (HPD)





CMS HCAL: Brass absorber preparation

Workers in Murmansk sitting on brass casings of **decommissioned shells of the Russian Northern Fleet**

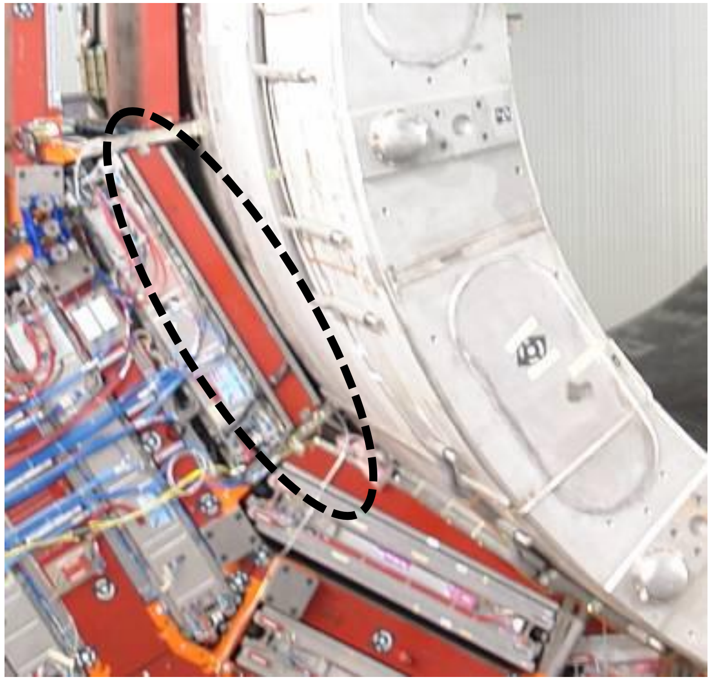
Explosives previously removed!

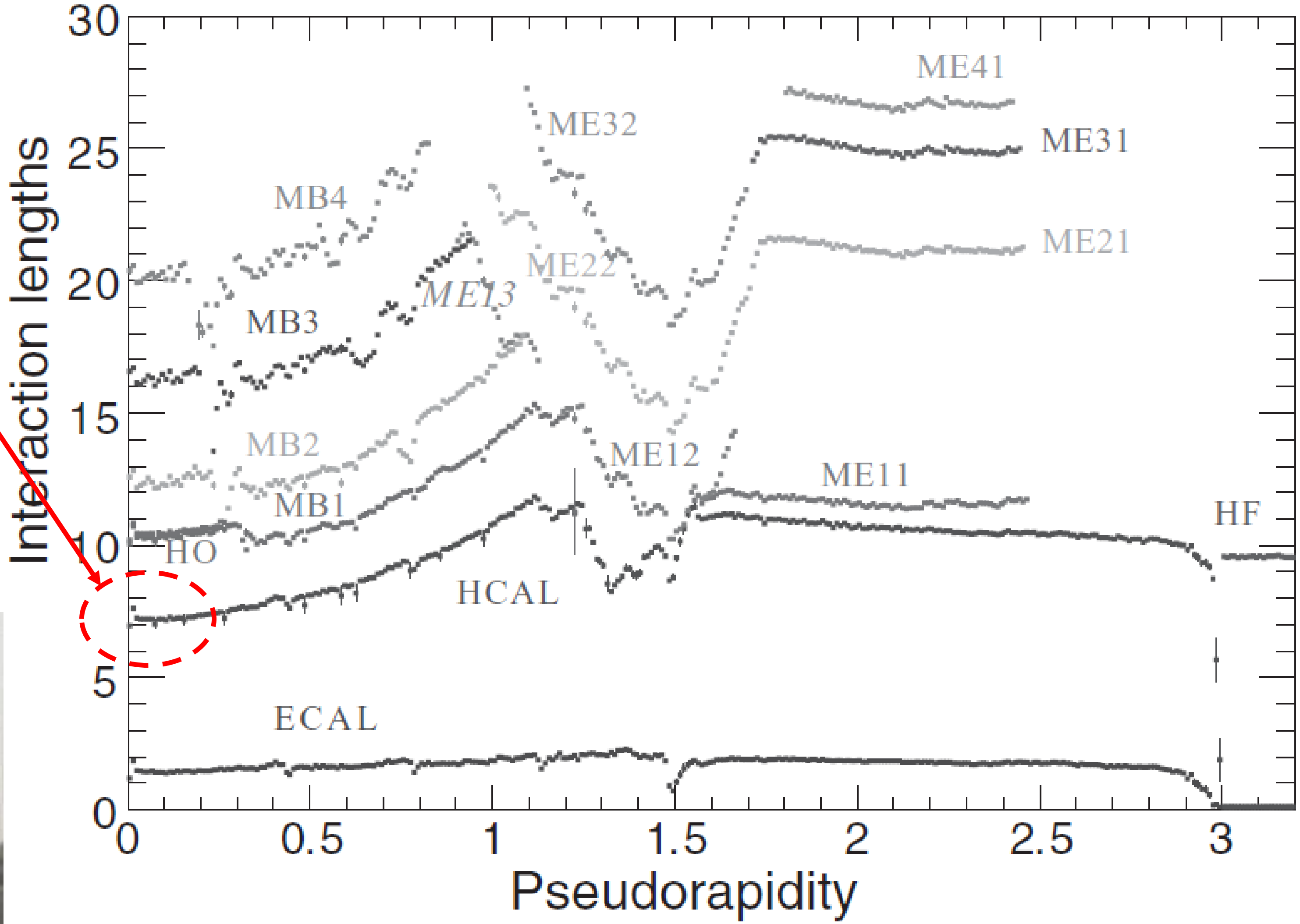
Casings melted in St Petersburg and turned into raw brass plates

Machined in Minsk and mounted to become absorber plates for the CMS Endcap Hadron Calorimeter

CMS HCAL: Containment

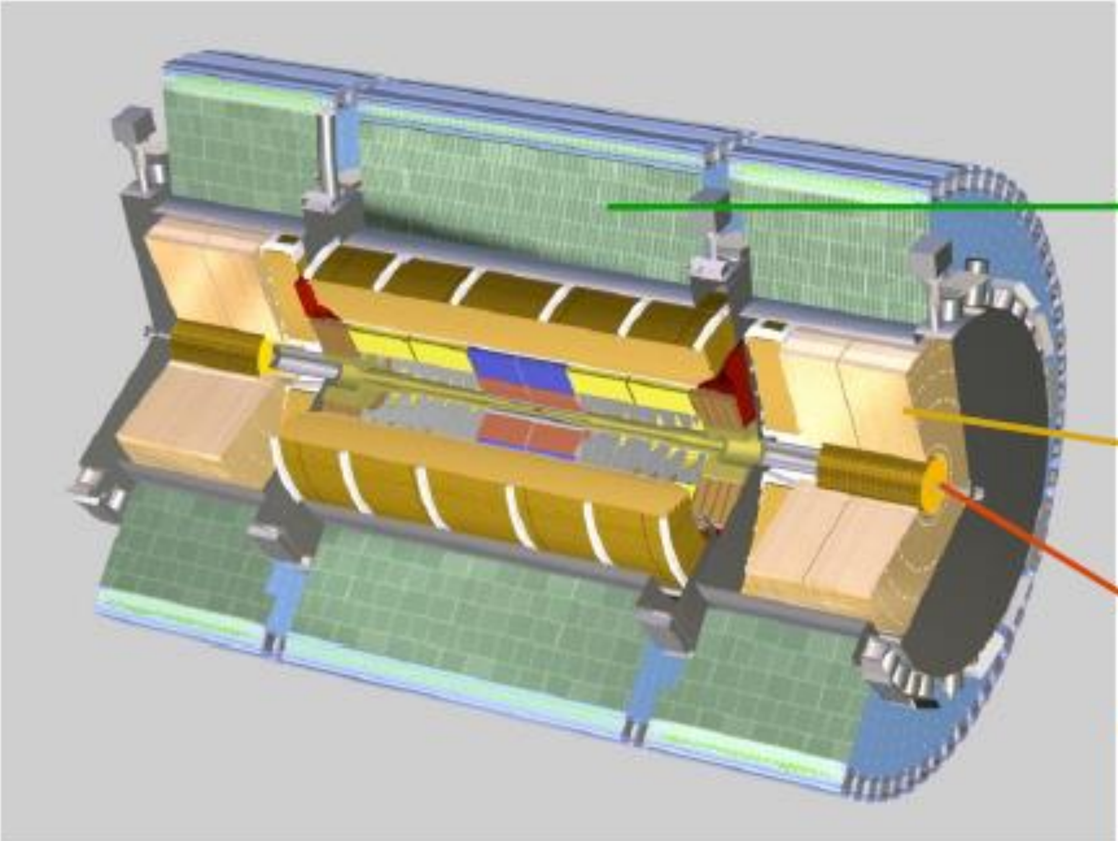
- At |η|=0, λint from HB =5.8 ! (7.2 with ECAL)
  - Large leakage…
- CMS adds HCAL Outer (HO):
  - Scintillator + WLS outside coil acting as "tail catcher".





Poor Resolution: ~100% / √E

ATLAS HCAL



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

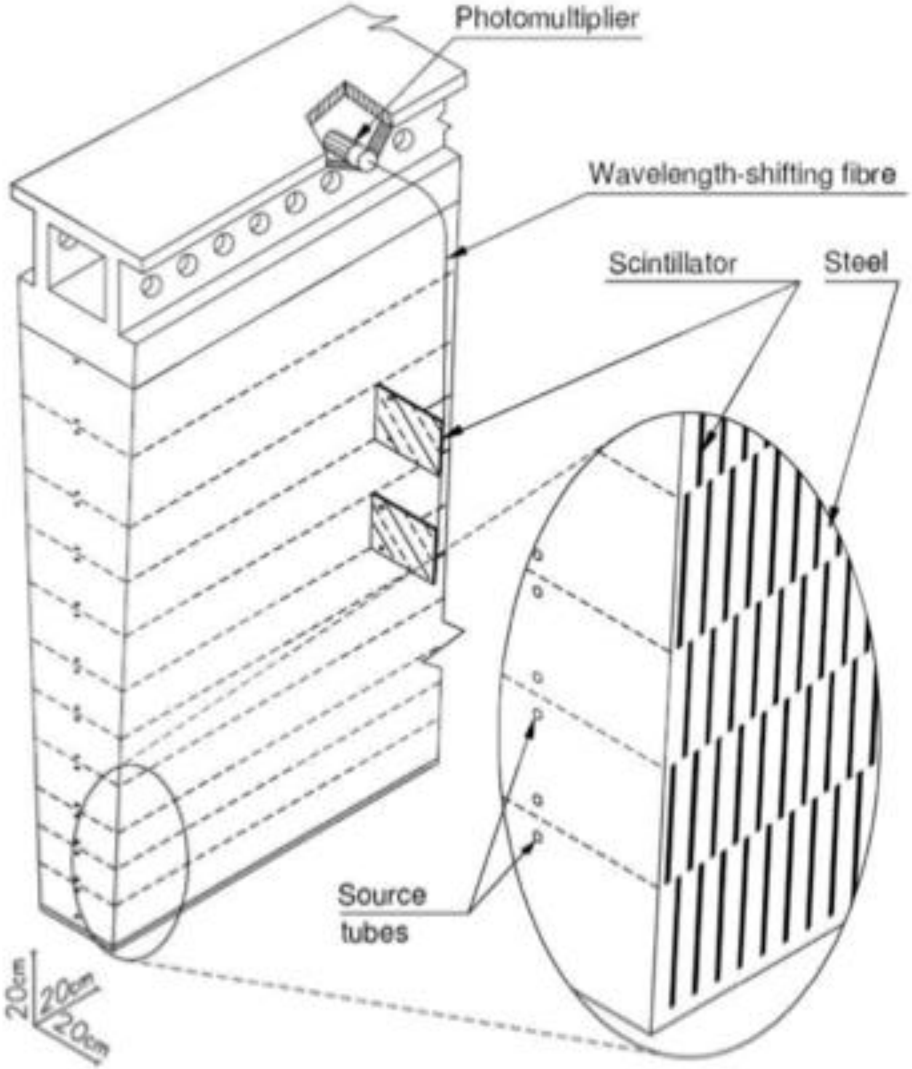
LAr/Cu or W $3.2 < |\eta| < 4.9$

Total thickness: ~ 8 -10 λ

Use of different technics: cope with radiations in forward region

ATLAS TileCal

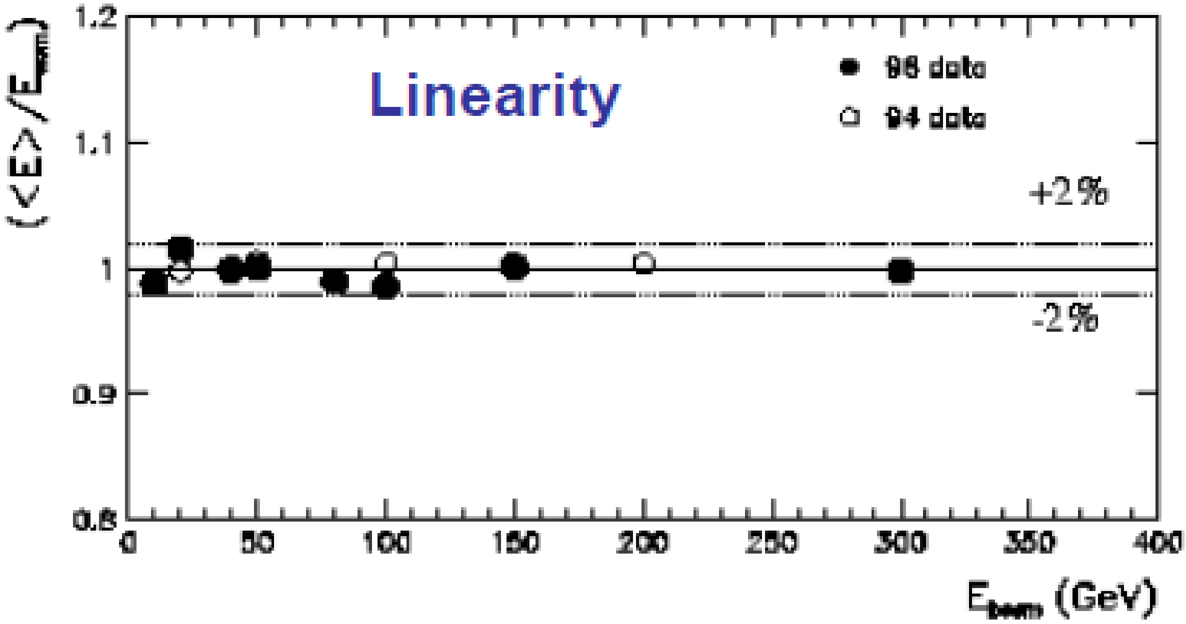
TileCal: Sampling Fe/plastic scintillator calorimeter

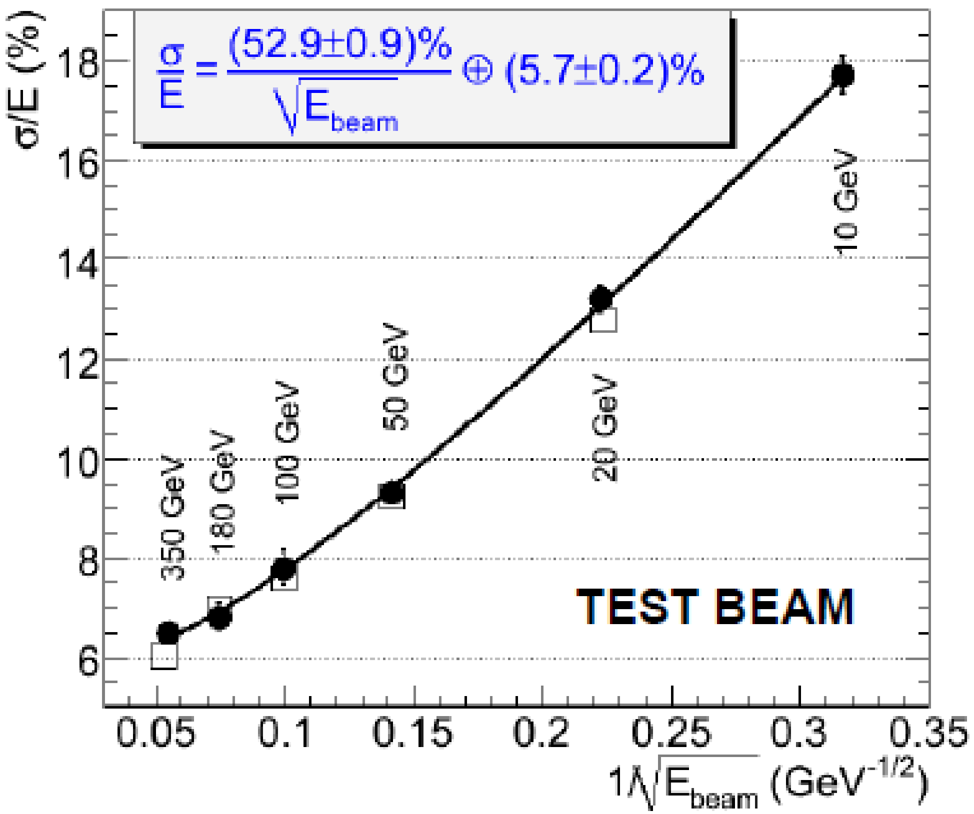


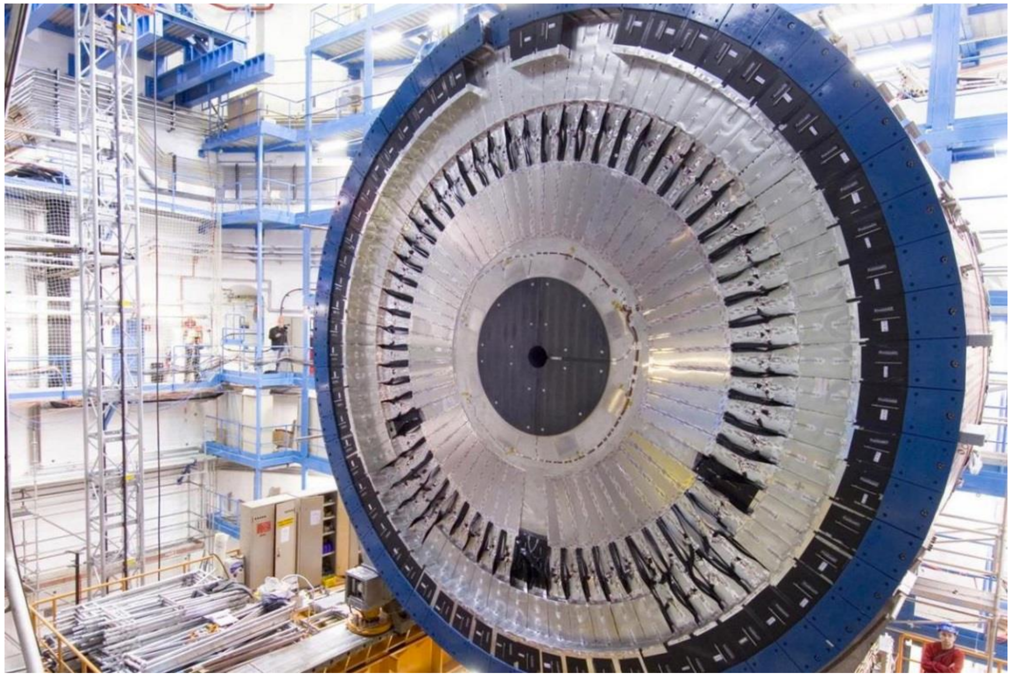
- Coverage: $|\eta|<1.7$
- 3 cylinders (1 barrel, 2 extended barrel)
- 3 longitudinal sampling
- Segmentation: $\Delta\eta x\Delta\phi=0.1$ (0.2) x0.1
- ~10 000 channels

➢ Key element: Tile
  - Perpendicular to beam axis
  - WLS carry light to PMT

ATLAS TileCal: Performance







Resolution: ~50% / √E

ATLAS/CMS ECAL Resolution

TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	ATLAS		CMS	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025 × 0.1	0.025 × 0.1		
Strips/ Si-preshower	0.003 × 0.1	0.003 × 0.1 to 0.006 × 0.1		32 × 32 Si-strips per 4 crystals
Main sampling	0.025 × 0.025	0.025 × 0.025	0.017 × 0.017	0.018 × 0.003 to 0.088 × 0.015
Back	0.05 × 0.025	0.05 × 0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2 × 2 mm		
Strips/ Si-preshower	≈4.3 X_0	≈4.0 X_0		3 X_0
Main sampling	≈16 X_0	≈20 X_0	26 X_0	25 X_0
Back	≈2 X_0	≈2 X_0		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term *a*	10%	10 to 12%	3%	5.5%
Local constant term *b*	0.2%	0.35%	0.5%	0.5%

Note the presence of the silicon preshower detector in front of the CMS end-cap crystals, which have a variable granularity because of their fixed geometrical size of 29 × 29 mm^2. The intrinsic energy resolutions are quoted as parametrizations of the type $\sigma(E)/E = a/\sqrt{E} \oplus b$. For the ATLAS EM barrel and end-cap calorimeters and for the CMS barrel crystals, the numbers quoted are based on stand-alone test-beam measurements.

ATLAS/CMS HCAL Resolution

TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	ATLAS				CMS	
	Barrel LAr/Tile		End-cap LAr			
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

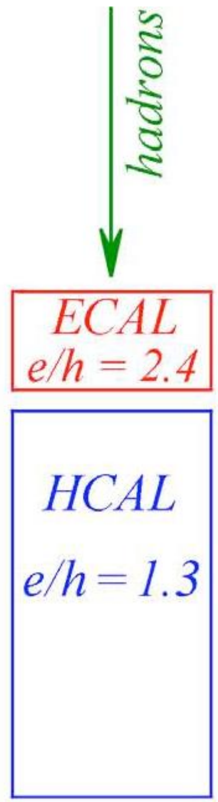
How can CMS can compete with ATLAS on the jet physics given these numbers ?
=> **Particle Flow** (**see next lecture**)

Last note on ATLAS / CMS Calorimeters

ATLAS and CMS are NON-compensating calorimeters

- **Numbers** (*):
  - ATLAS Tile Barrel e/h ~ 1.4

  - CMS ECAL: e/h ~ 2.4
  - CMS HCAL: e/h ~ 1.3
  - CMS HF: e/h ~ 4.7

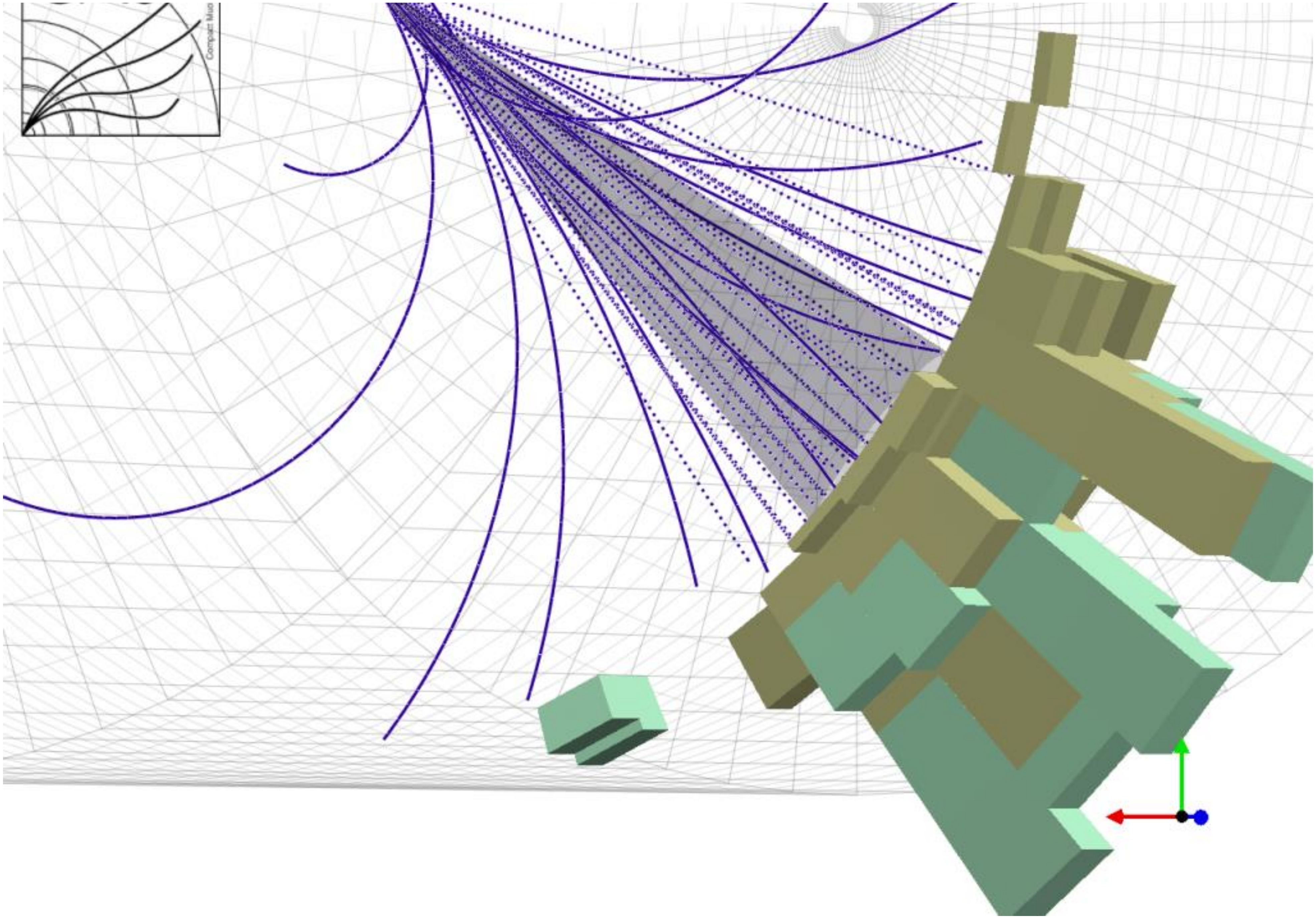


- Ex: CMS calibrates:
  - ECAL for electrons/photons
  - HCAL with pions non-interacting in ECAL
  - But pions DO interact with ECAL. And thus get wrong calibration.
  - Degrades the resolution.

Again, **Particle Flow technics will help there** (by separating charged and neutral pions). **See Lecture 3.**

(*) to be verified…

Calorimeter Objects



Calorimeter objects

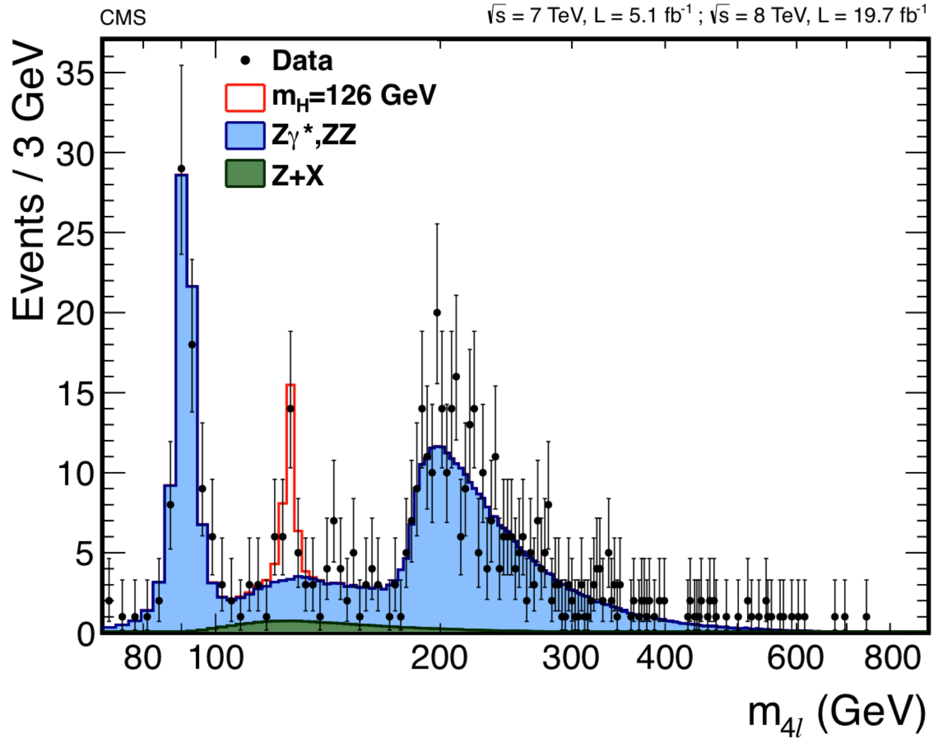
- In hadron colliders, calorimeters are meant to trigger, reconstruct, identify and measure energy of charged and neutral particles produced during the collisions:
  - Electrons & photons
  - Jets
  - Neutrinos (and other invisible particles)

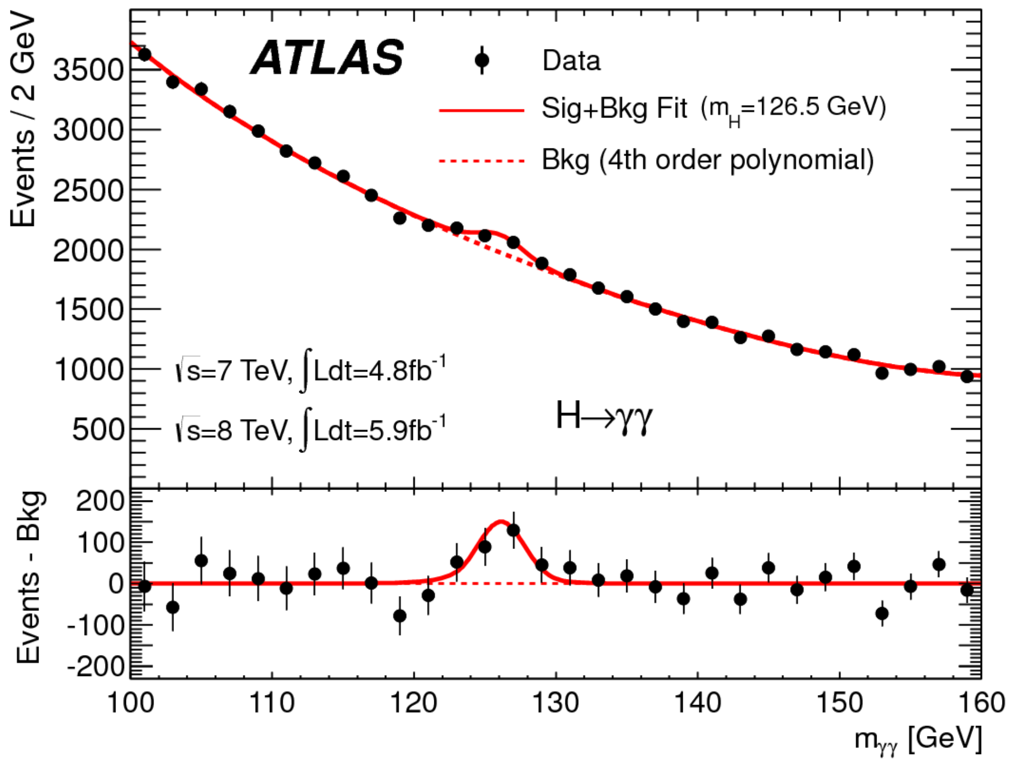
- Real conditions are different from standalone device or test beams:
  - Magnetic field (constraint for the readout electronics, photodetectors, …)
  - Material in front of the calorimeter
  - Radiations,
  - (inter-)calibrations,
  - Pile-up,
  - …

=> Degrade ultimate performance.

Electrons/Photons at LHC (1)

- Final states with electrons and photons are **major experimental signatures at LHC:**
  - $H \to \gamma\gamma$
  - $H \to ZZ^* \to$ 4 leptons (e, μ)
  - SUSY $\to$ multileptons cascade
  - …





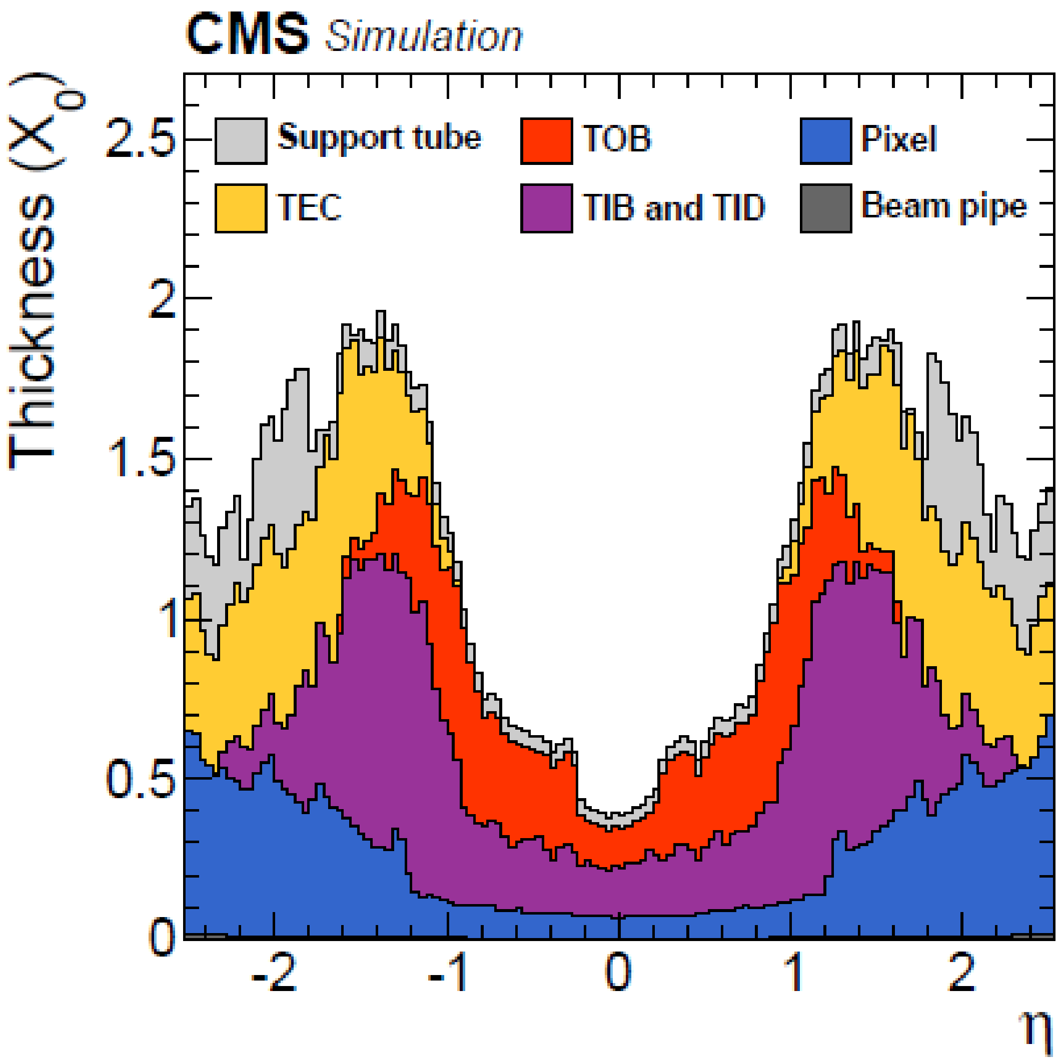
- **Naively:**

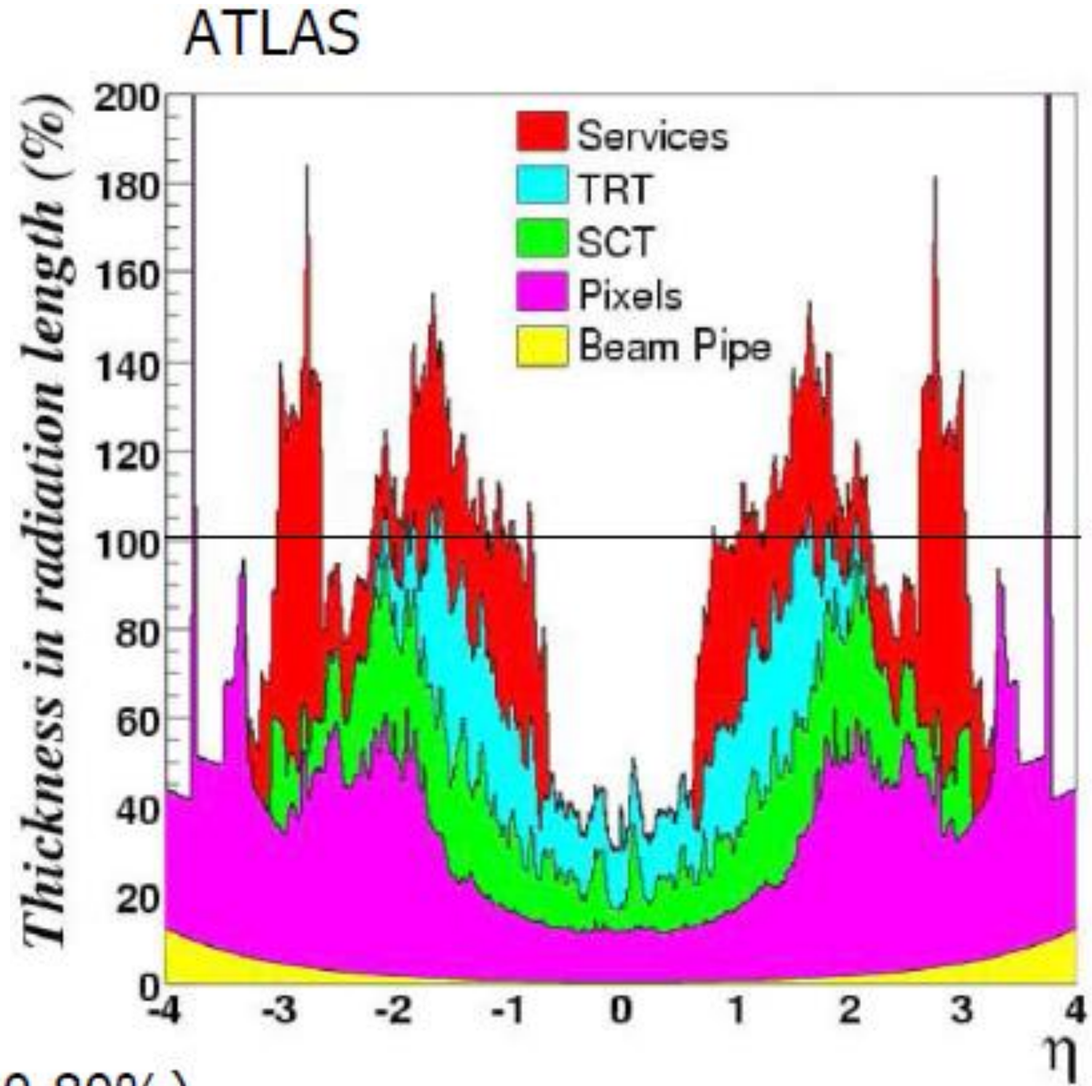
Photon = (isolated) energy deposited in ECAL only (not leakage in HCAL), no track

Electrons = (isolated) energy deposited in ECAL only + associated track (from Tracking detector)

Electrons/Photons at LHC (2)

➢ **Material in front of calorimeter:** cables, cooling, mechanical support, …
+ B-field (radiated energy spread in φ)





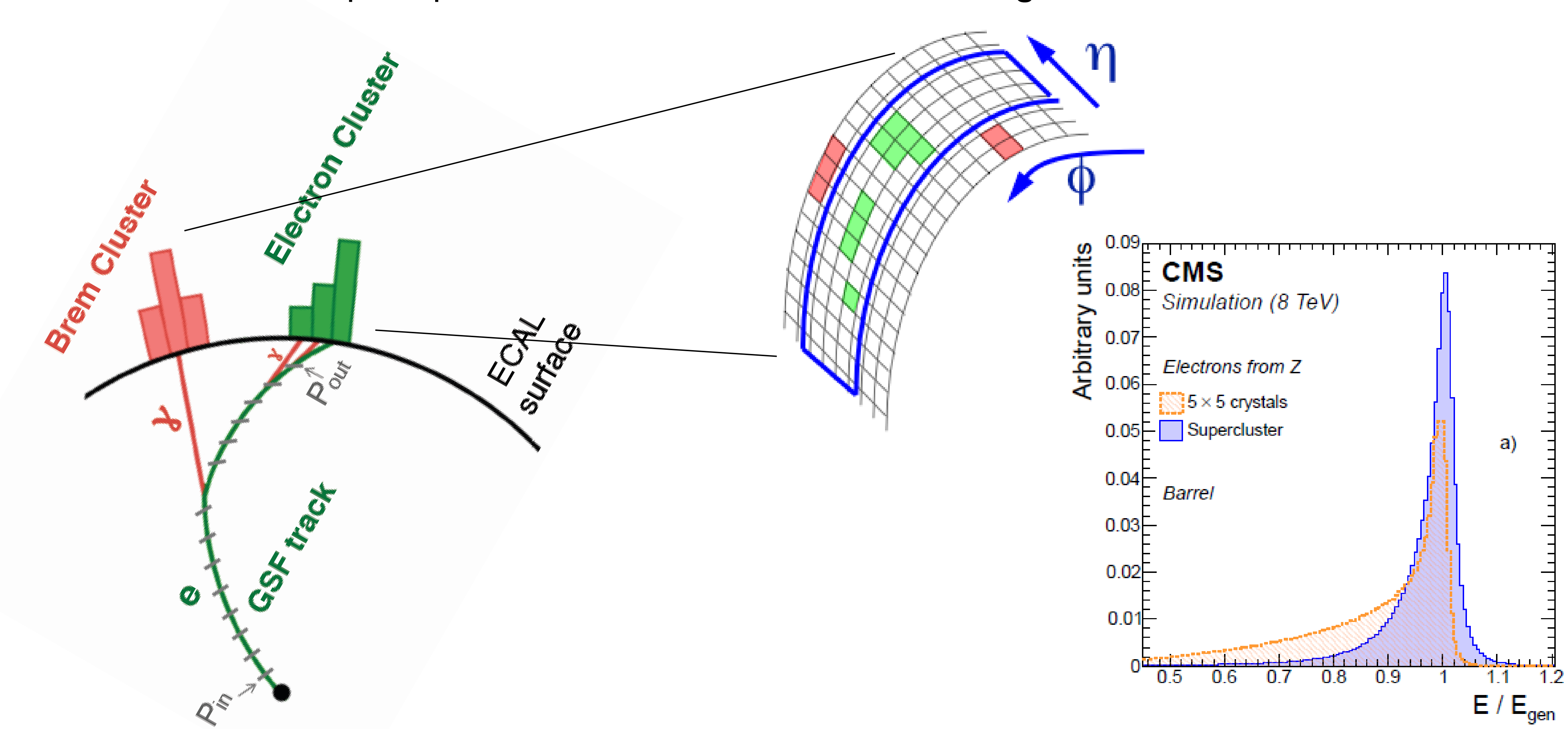
The electrons initiate showers (e.g. 40-80%)

⇒ Identification and efficiency problems, charge mis-identification

The photons convert (e.g. 20-40%) in e+e– pairs before reaching the ECAL

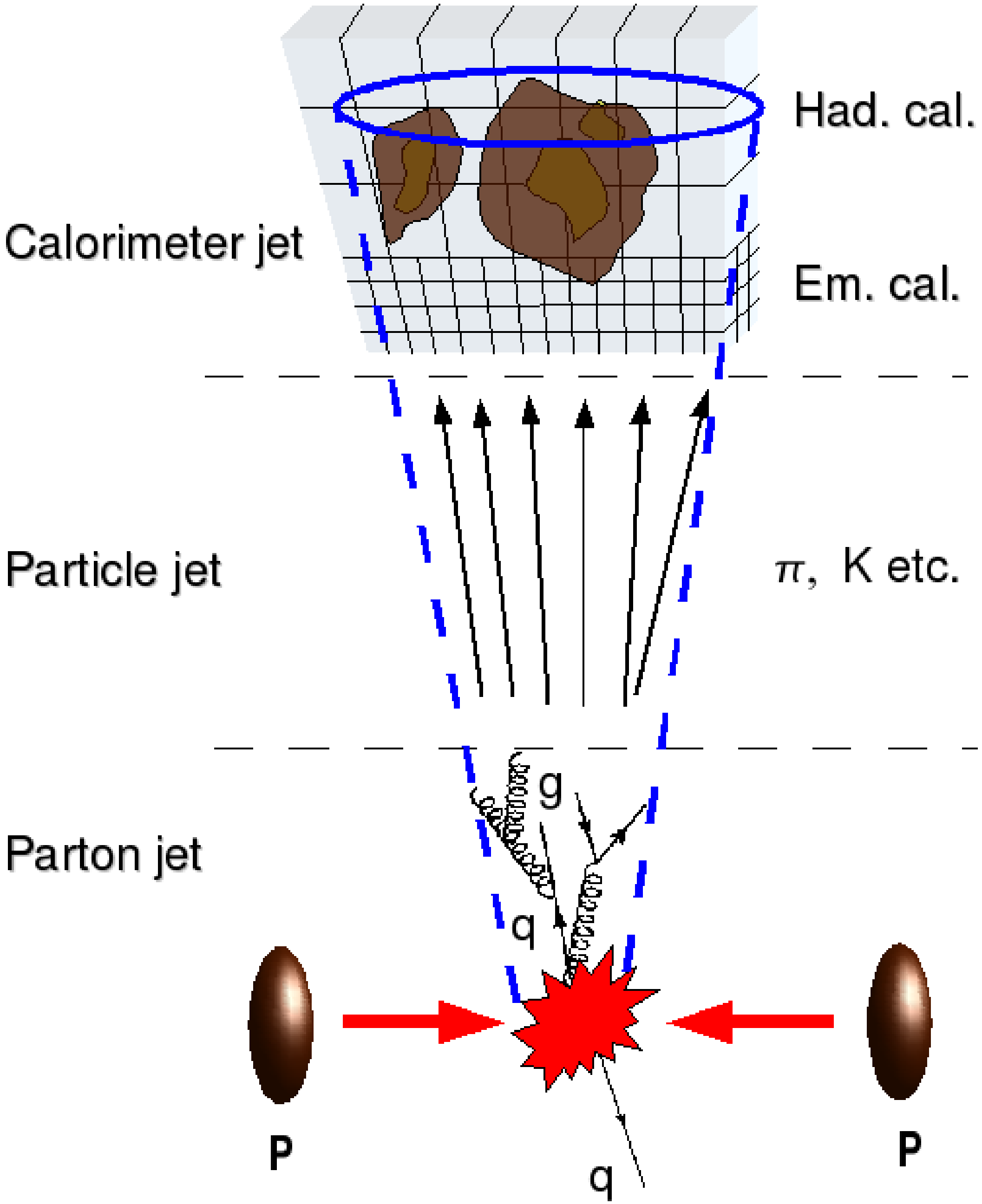
Electrons/Photons at LHC (3)

- Electrons (and photons) undergo **complicated pattern**:
  - electrons radiates brem photons, which may convert in e+e-, possibly also “breming”, and subsequent photon convert, … **BEFORE reaching the ECAL surface**



- Need to develop **complex reconstruction algorithm** to collect brem/conversion: super-clustering, extension of Kalman filter, …

From single hadrons to Jets

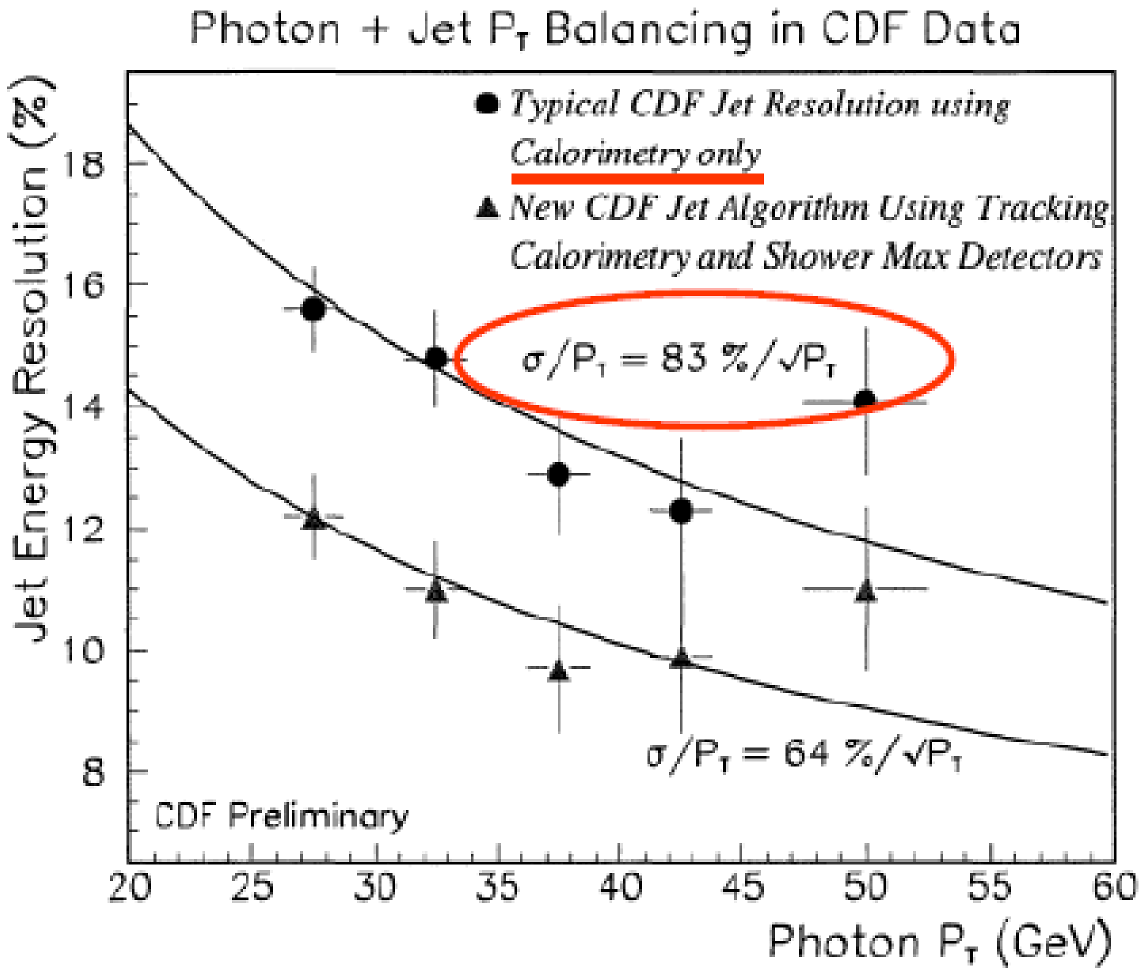


- At (hadrons) colliders, quarks & gluons produced a collection of particles via fragmentation.
- This **(collimated) sum of particles** (pions, kaons, p, n, electron/γ, ..) is **called a jet**.
- Reconstructed with “cone” algorithms
  - Various flavors…
- Jets are important signatures at LHC too (dijet resonance, VBF, …)

Jets vs single particle resolution

Jets at CDF @ TeVatron

		Central	Plug
EM	thickness	$19\,X_0,\ 1\lambda$	$21\,X_0,\ 1\lambda$
	sample(Pb)	$0.6\,X_0$	$0.8\,X_0$
	sample(scint.)	5 mm	4.5 mm
	wavelength sh.	sheet	fiber
	resolution	$\frac{13.5\%}{\sqrt{E_T}} \oplus 2\%$	$\frac{14.5\%}{\sqrt{E}} \oplus 1\%$
HAD	thickness	$4.5\,\lambda$	$7\,\lambda$
	sample(Fe)	25-50 mm	50 mm
	sample(scint.)	10 mm	6 mm
	wavelength sh.	finger	fiber
	resolution	$\frac{50\%}{\sqrt{E_T}} \oplus 3\%$	$\frac{70\%}{\sqrt{E}} \oplus 4\%$

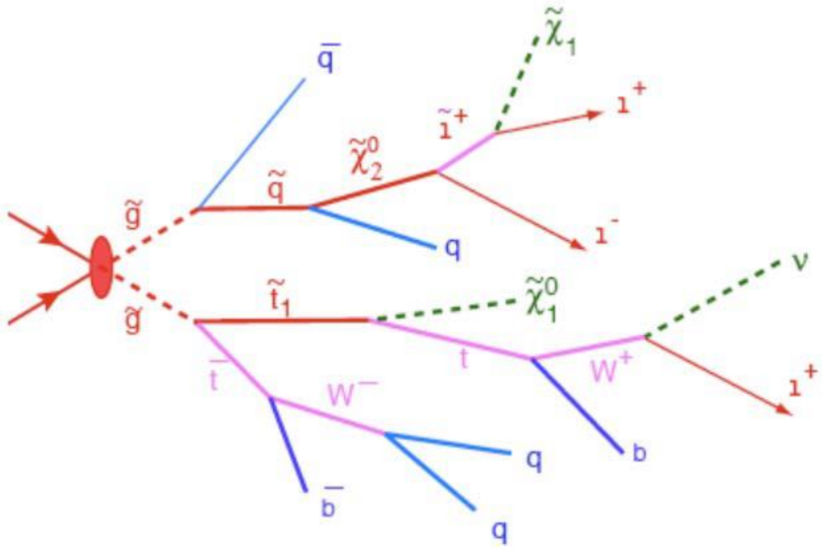


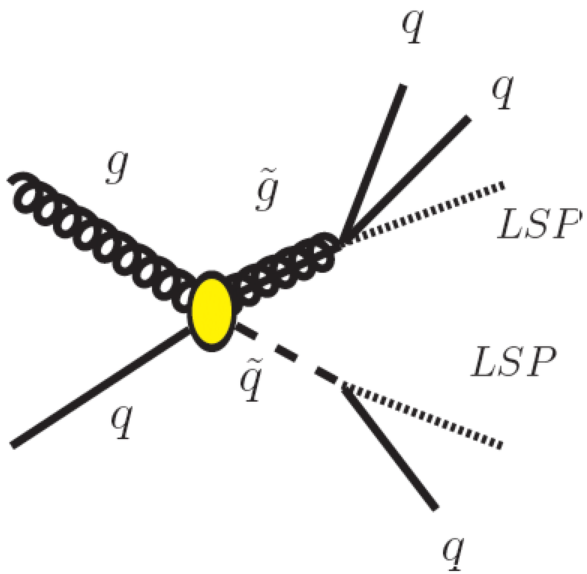
Jets performance in calorimeter worst than single hadron performance

Contribution from physics (parton shower/fragmentation, ISR/FSR, Underlying Event, …), detector (granularity, resolution, …) and clustering algorithm (out of "cone" energy losses) !

Measuring the invisible…

- Neutrinos produced in collisions escape detection: W→eν, Z→νν, …
- Many BSM processes involves “invisible” particles: Dark Matter, Neutralinos from SUSY, …





- Way to quantify these “invisible” particles, Missing Transverse Energy (MET):

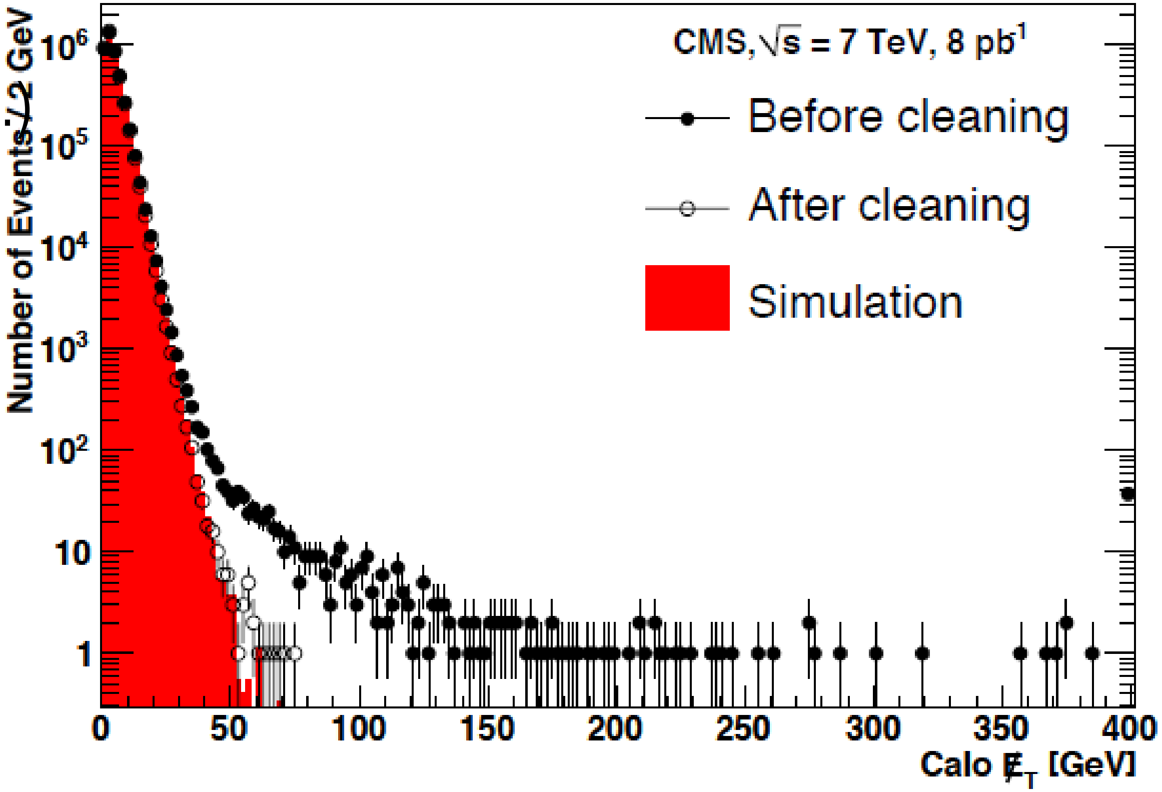
$$\vec{E}_T^{miss} = -\sum_i \vec{E}_T^{i}$$

final states particles transverse momenta
(or the way they are reconstructed in a given
device: calo cluster/tower, …)

Missing Transverse Energy (1)

- In practice, very difficult quantity to understand, calibrate, …

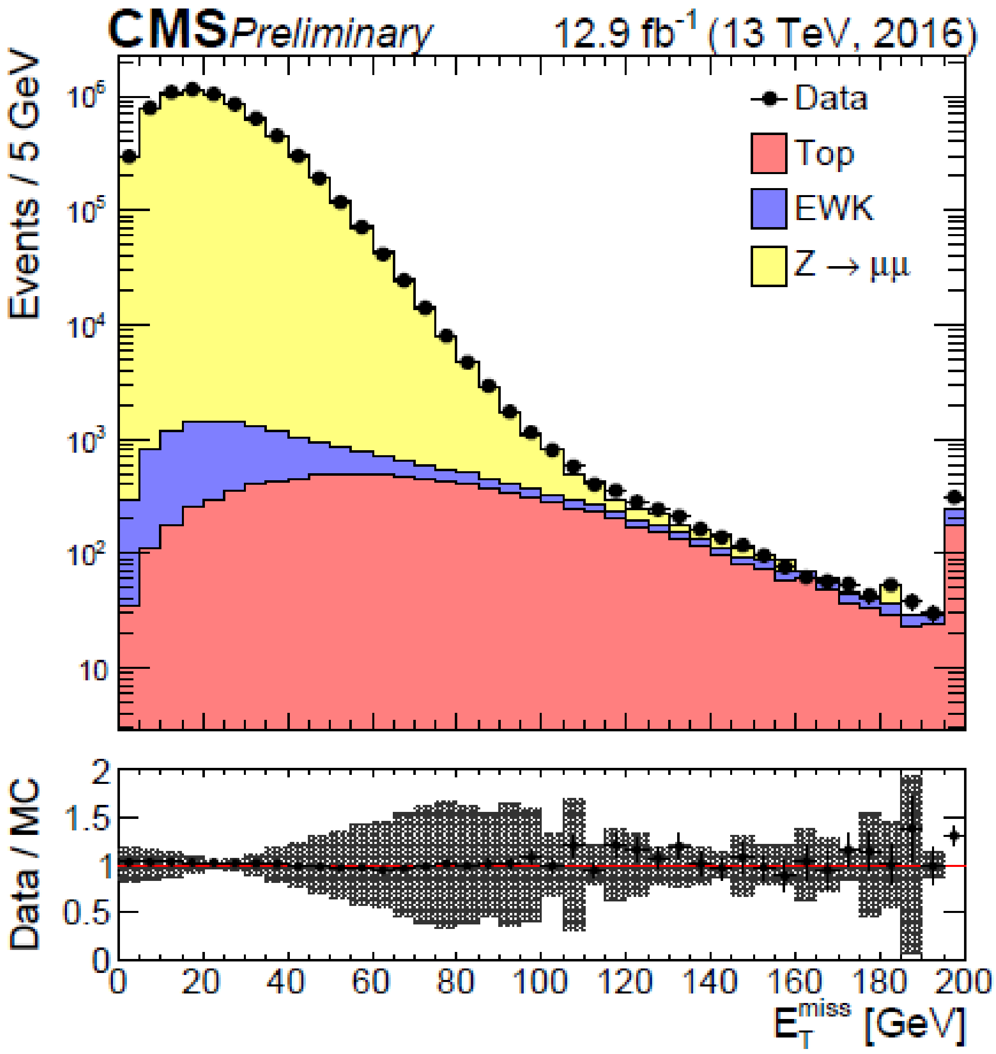
- **Affected by:**
  - Mis-reconstructed objects (e/g, jets, …)
  - Instrumental effects:
    - Noise
    - Dead of hot calorimeters cells
  - Cosmic ray brem,
  - beam halo,
  - Poorly instrumented area
  - Pile-up (PU),
  - ….



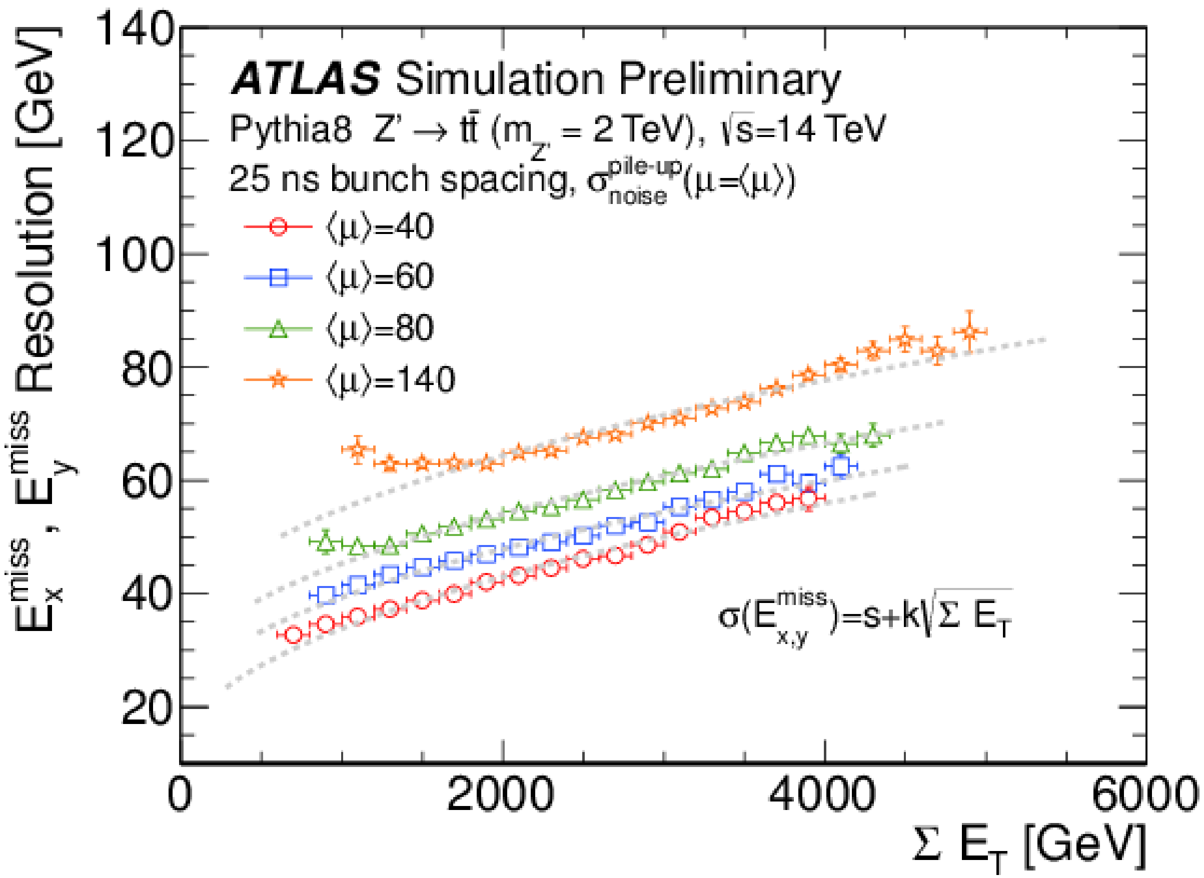
- Fake MET thus appears naturally from various sources.
  - **Need dedicated cleaning in order NOT to make fake discoveries**
    (e.g., BSM models tends to produced very high MET signals)

Missing Transverse Energy (2)

MET well understood



Effect of Pile-Up on MET resolution



BACK UP SLIDES

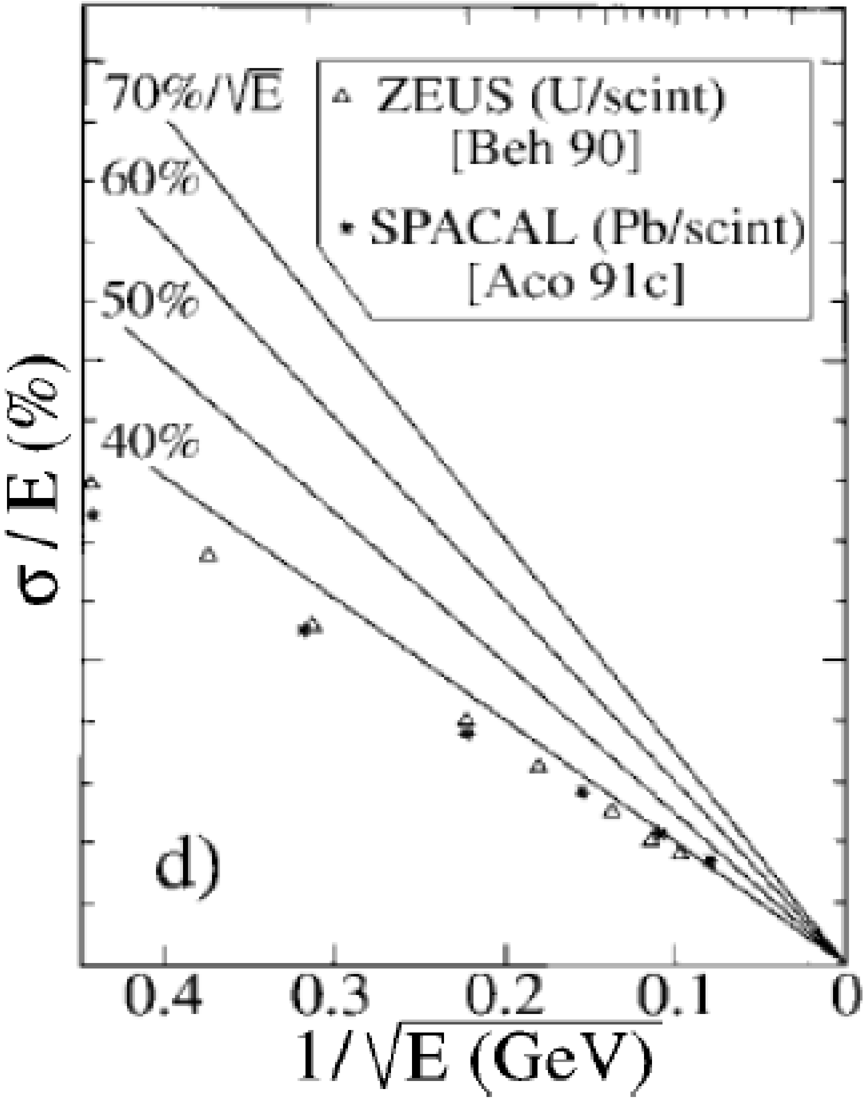
CMS ECAL: collecting the light

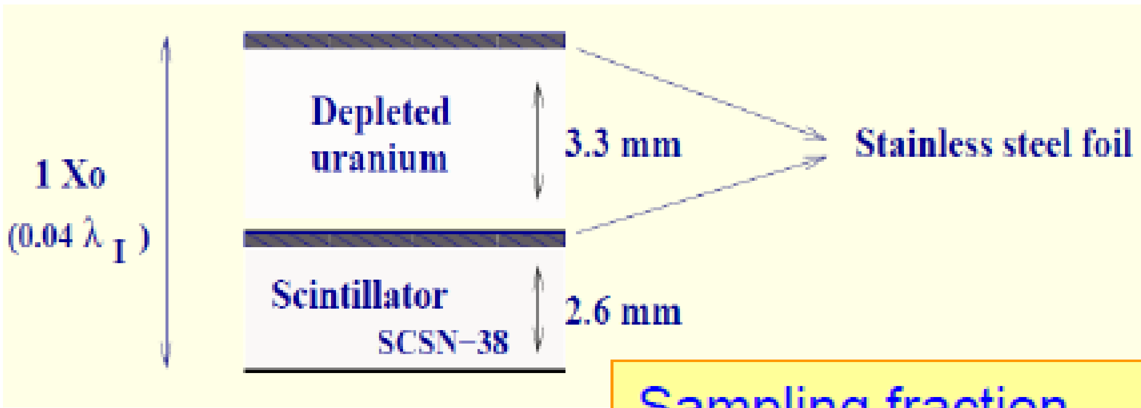
- Cannot use PMT (affected by magnetic field) or PIN photodiodes (no internal amplification, too sensitive to charged particles)

Barrel crystals read by
Avalanche Photo Diode

Endcap crystals read by
Vacuum Photo Triode

ZEUS calorimeter





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

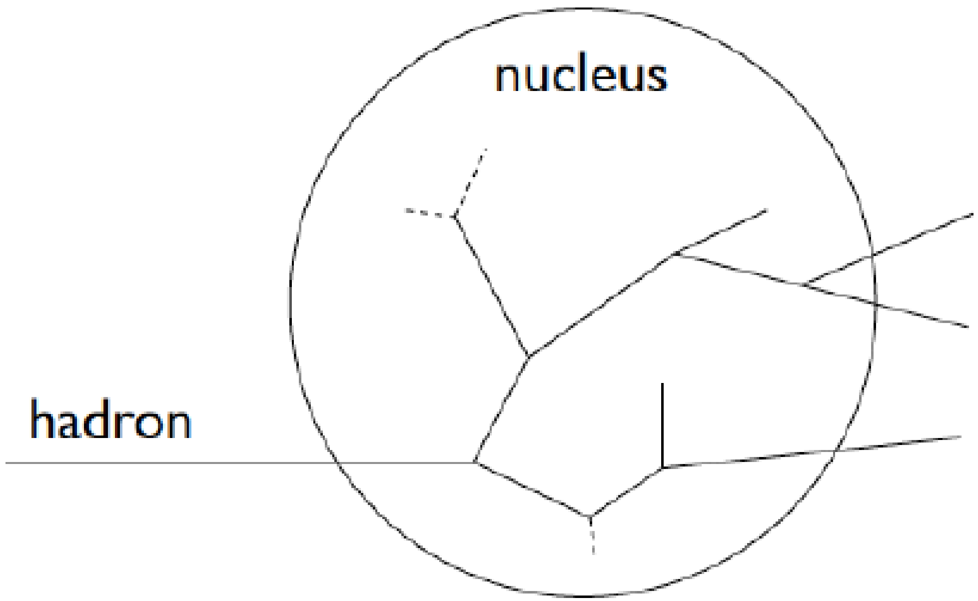
Excellent hadron resolution:

σ/E (hadrons) = $0.35/\sqrt{E}$(GeV

σ/E (electrons) = $0.18/\sqrt{E}$(GeV)

“naïve” model (simulation programs)

Interaction of hadrons with 10 MeV < E < 10 GeV via intra-nuclear cascades



- $\lambda_{deBroglie} \leq$ d nucleon
- nucleus = Fermi gas (all nucleons included)
- Pauli exclusion: allow only secondaries above Fermi energy

For E < 10 MeV only relevant are fission, photon emission, evaporation, …

De-excitation	Intra-nuclear Cascade	String Models

1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV ➡ 48