Calorimetry

concept & examples

European School of Instrumentation
in Particle & Astroparticle Physics
ESIPAP 2015

Lecture 2

Programme

Lesson 1

Why build calorimeters ?

Electromagnetic showers

Detection processes

Lesson 2

Recap

EM calorimeters

Hadronic showers

Jets & Missing Transverse Energy

CMS & ATLAS calorimeters

Lesson 3

Other calorimeters

Calorimeter R&Ds for future colliders

Tutorial

Detecting EM showers - $H \rightarrow \gamma\gamma$

A few numbers

RECAP: ELECTROMAGNETIC SHOWERS

The shower develops as a cascade by energy transfer from the incident particle to a multitude of particles ($e^{\pm}$ and γ).

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 is a function of the material (Z)

The radiation length (X_0) allows to universally describe the shower development

A SIMPLE EM SHOWER MODEL

Simple shower model:
[from Heitler]

Only two dominant interactions:
Pair production and Bremsstrahlung ...

γ + Nucleus ➤ Nucleus + e^+ + e^-
[Photons absorbed via pair production]

e + Nucleus ➤ Nucleus + e + γ
[Energy loss of electrons via Bremsstrahlung]

Shower development governed by X_0 ...

After a distance X_0 electrons remain with only $(1/e)^{th}$ of their primary energy ...

Photon produces e^+e^--pair after $9/7X_0 \approx X_0$ ...

Assume:

$E > E_c$: no energy loss by ionization/excitation

$E < E_c$: energy loss only via ionization/excitation

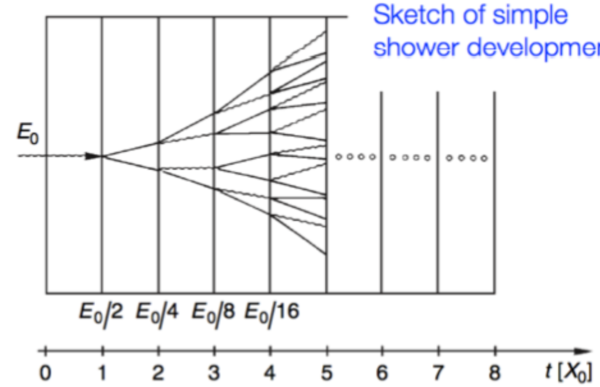
Use
Simplification:

$E_\gamma = E_e \approx E_0/2$
[E_e looses half the energy]

$E_e \approx E_0/2$
[Energy shared by e^+/e^-]

... with initial particle energy E_0

A SIMPLE EM SHOWER MODEL



Simple shower model:
[continued]

Shower characterized by:

- Number of particles in shower
- Location of shower maximum
- Longitudinal shower distribution
- Transverse shower distribution

Longitudinal components; measured in radiation length ...

... use: $t = \frac{x}{X_0}$

Number of shower particles after depth t:

$$N(t) = 2^t$$

Energy per particle after depth t:

$$E = \frac{E_0}{N(t)} = E_0 \cdot 2^{-t}$$

$$\rightarrow \quad t = \log_2(E_0/E)$$

Total number of shower particles with energy E_1:

$$N(E_0, E_1) = 2^{t_1} = 2^{\log_2(E_0/E_1)} = \frac{E_0}{E_1}$$

Number of shower particles at shower maximum:

$$N(E_0, E_c) = N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c} \propto E_0$$

Shower maximum at:

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

A SIMPLE EM SHOWER MODEL

Simple shower model:
[continued]

Longitudinal shower distribution increases only logarithmically with the primary energy of the incident particle ...

Some numbers: $E_c \approx 10$ MeV, $E_0 = 1$ GeV ➛ $t_{max} = \ln 100 \approx 4.5$; $N_{max} = 100$
$E_0 = 100$ GeV ➛ $t_{max} = \ln 10000 \approx 9.2$; $N_{max} = 10000$

$$t_{\mathrm{max}}[X_0] \sim \ln \frac{E_0}{E_c}$$

EM LONGITUDINAL DEVELOPMENT

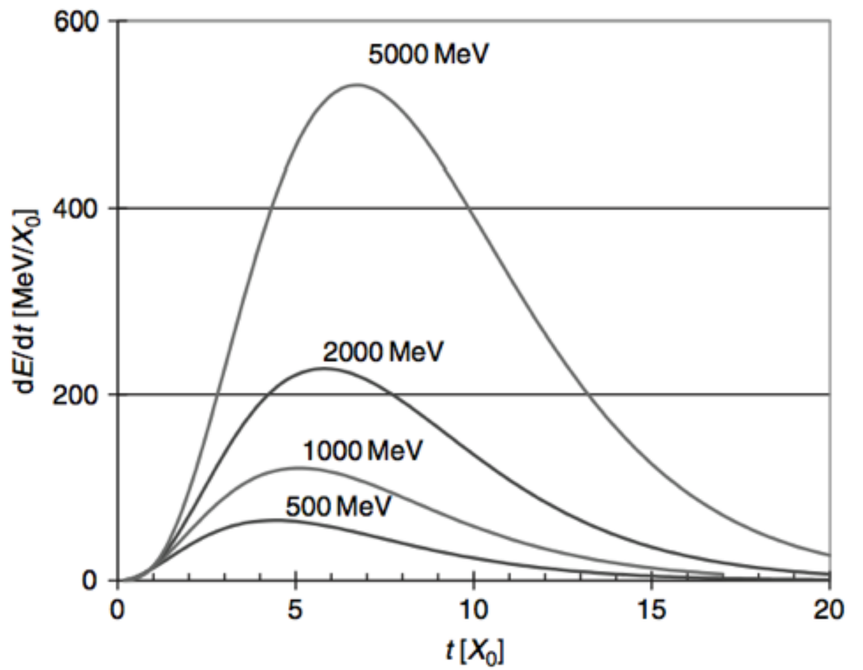
Longitudinal profile

Parametrization:
[Longo 1975]

$$\frac{dE}{dt} = E_0\, t^{\alpha} e^{-\beta t}$$

α,β : free parameters
t^{α} : at small depth number of secondaries increases ...
$e^{-\beta t}$: at larger depth absorption dominates ...

Numbers for E = 2 GeV (approximate):
α = 2, **β** = 0.5, t_{max} = **α/β**



More exact
[Longo 1985]

$$\frac{dE}{dt} = E_0 \cdot \beta \cdot \frac{(\beta t)^{\alpha-1} e^{-\beta t}}{\Gamma(\alpha)}$$

[Γ: Gamma function]

$$\rightarrow \quad t_{max} = \frac{\alpha - 1}{\beta} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

with:

$C_{e\gamma} = -0.5$ [γ-induced]

$C_{e\gamma} = -1.0$ [e-induced]

CALORIMETER ENERGY RESOLUTION

Calorimeter energy resolution determined by fluctuations ...

Homogeneous calorimeters:

- Shower fluctuations
- Photo-electron statistics
- Shower leakage
- Instrumental effects (noise, light attenuation, non-uniformity)

(Shower fluctuations and photo-electron statistics: Quantum fluctuations)

In addition for

Sampling calorimeters:

- Sampling fluctuations
- Landau fluctuations
- Track length fluctuations

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Quantum fluctuations	$\sim {}^1/\sqrt{E}$
Electronic noise	$\sim {}^1/E$
Shower leakage*	$\approx$ const
Sampling fluctuations	$\sim {}^1/\sqrt{E}$
Landau fluctuations	$\sim {}^1/\sqrt{E}$
Track length fluctuations	$\sim {}^1/\sqrt{E}$

* Different for longitudinal and lateral leakage ...
Complicated; small energy dependence ...

EM ENERGY RESOLUTION

Detectable signal is proportional to the number of potentially detectable particles in the shower $N_{tot} \prec E_0/E_c$

Total track length $T_0 = N_{tot} . X_0 \sim E_0/E_c . X_0$

The ultimate energy resolution

$$\frac{\sigma(E)}{E} \prec \frac{1}{\sqrt{T_0}} \prec \frac{1}{\sqrt{E}}$$

Detectable track length $T_r = f_s . T_0$ where f_s is the fraction of N_{tot} which can be detected by the involved detection process (Cerenkov light, scintillation light, ionisation) $E_{kin} > E_{th}$

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

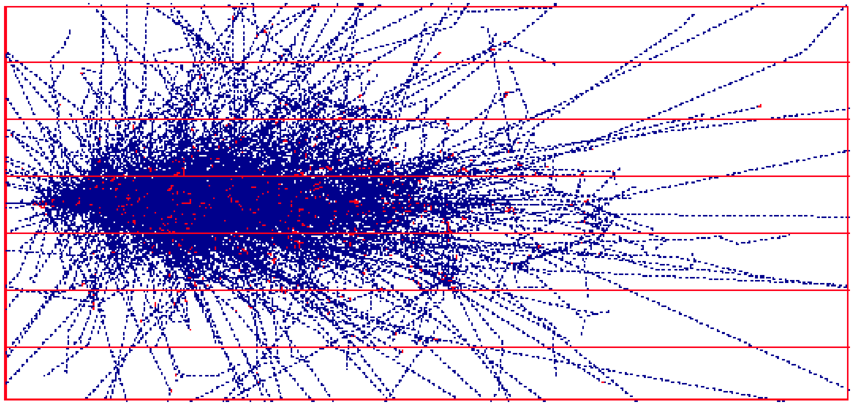
Converting back to materials ($X_0 \prec A/Z^2$, $E_c \prec 1/Z$) and fixing E

Maximise detection f_s

Minimise Z/A

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

HOMOGENEOUS CALORIMETERS



All the energy is deposited in the active medium

- Excellent energy resolution
- No longitudinal segmentation

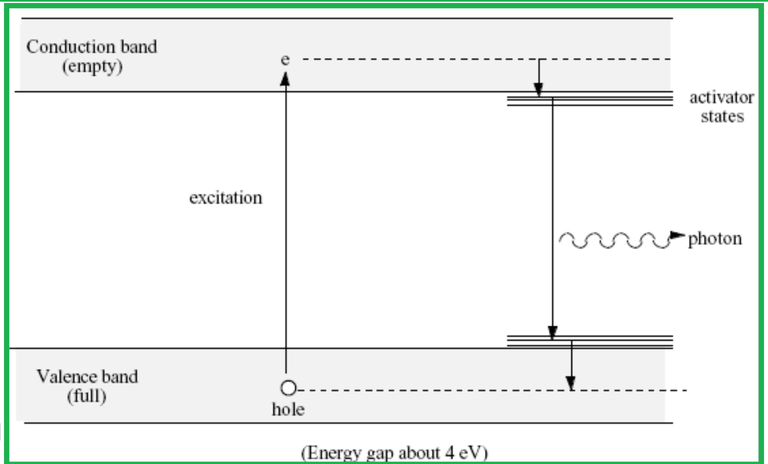
All $e^{\pm}$ with $E_{kin} > E_{th}$ produce a signal

Scintillating crystals

$E_{th} \approx \beta . E_{gap} \sim$ eV

$\rightarrow 10^2 \div 10^4$ γ/MeV

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

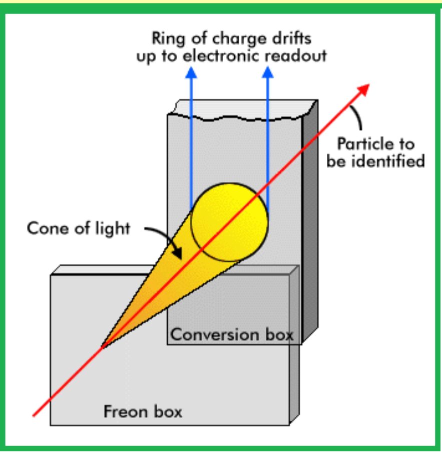


Cerenkov radiators

$\beta > 1/n \rightarrow E_{th} \approx 0.7$ MeV

$\rightarrow 10 \div 30$ γ/MeV

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



EXAMPLE

Take a Lead Glass crystal

E_c = 15 MeV

produces Cerenkov light

Cerenkov radiation is produced par $e^{\pm}$ with $\beta > 1/n$, i.e $E > 0.7$MeV

Take a 1 GeV electron

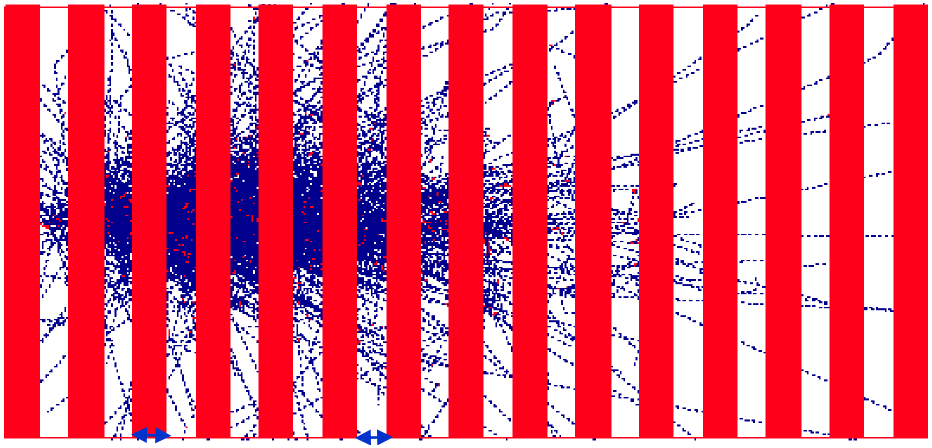
At maximum 1000 MeV/0.7 MeV $e^{\pm}$ will produce light

Fluctuation $1/\sqrt{1400} = 3\%$

In addition, one has to take into account the photon detection efficiency which is typically 1000 photo-electrons/GeV: $1/\sqrt{1000} \sim 3\%$

Final resolution $\sigma/E \sim 5\%/\sqrt{E}$

SAMPLING CALORIMETERS



Shower is sampled by layers of an active medium and dense radiator

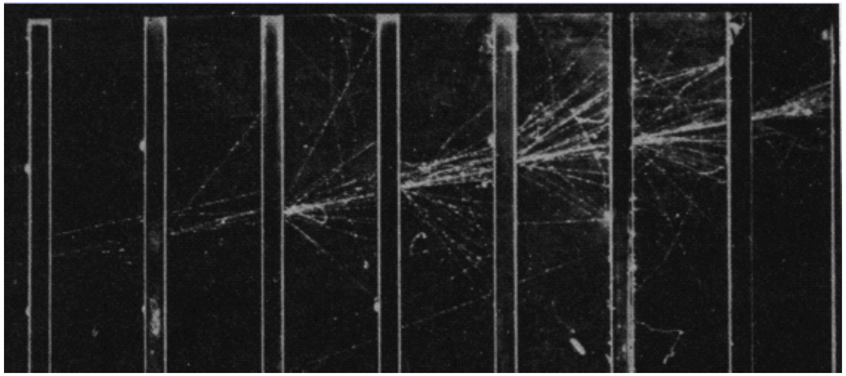
- Limited energy resolution
- Longitudinal segmentation

Only $e^{\pm}$ with $E_{kin} > E_{th}$ of the active layer produce a signal

Absorber (high Z): typically Lead, Uranium

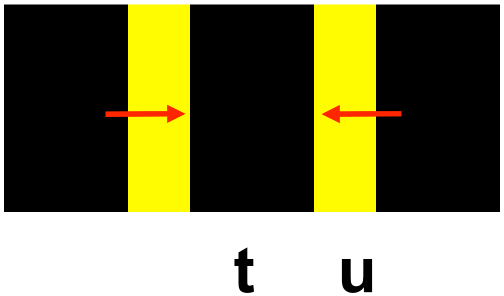
Active medium (low Z): typically Scintillators, Liquid Argon, Wire chamber

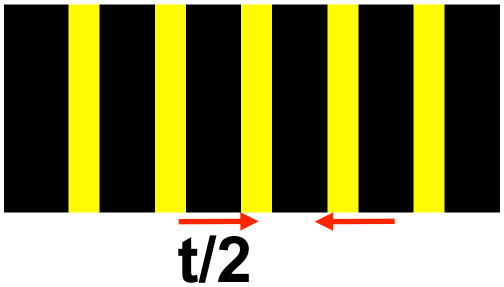
Energy resolution of sampling calorimeter dominated by fluctuations in energy deposited in the active layers



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

SAMPLING CALORIMETERS





Sampling frequency is defined by the the thickness t (in units of X_0) of the passive layers: number of times a high energy electron or photon shower is sampled

The thinner the passive layer, the better

Sampling fraction is defined by the thickness of the active layer

$$f_S = u.dE/dx_{active}/[u.dE/dx_{active} + t.dE/dx_{passive}] \quad (u,t \text{ in } gcm^{-2}, dE/dx \text{ in } MeV/gcm^{-2}).$$

for minimum ionising particles.

SAMPLING CALORIMETERS

Most of detectable particles are produced in the absorber layers

Need to enter the active material to be counted/measured

The number of crossing of a unit "cell" N_x, using the Total Track Length

N_x = TTL/(t+u) =E/E_c(t+u) = E/ΔE where ΔE is the energy lost in a unit cell t+u

Assuming the statistical independence of the crossings, the fluctuations on Nx represent the "sampling fluctuations" $\sigma(E)_{samp}$

$$\sigma(E)_{samp}/E=\sigma(N_x)/N_x=1/\sqrt{N_x}= [\Delta E(GeV)/E(GeV)]^{1/2} =a/\sqrt{E}$$

a is called the sampling term

SAMPLING FRACTION

The actual signal produced by the calorimeter is proportional

$E.f_s = \sum u.dE/dx$

If f_s is too small, the collected signal will be affected by electronics noise.

The dominant part of the calorimeter signal is not produced by minimum ionising particles (m.i.p.), but by low-energy electrons and positrons crossing the signal planes.

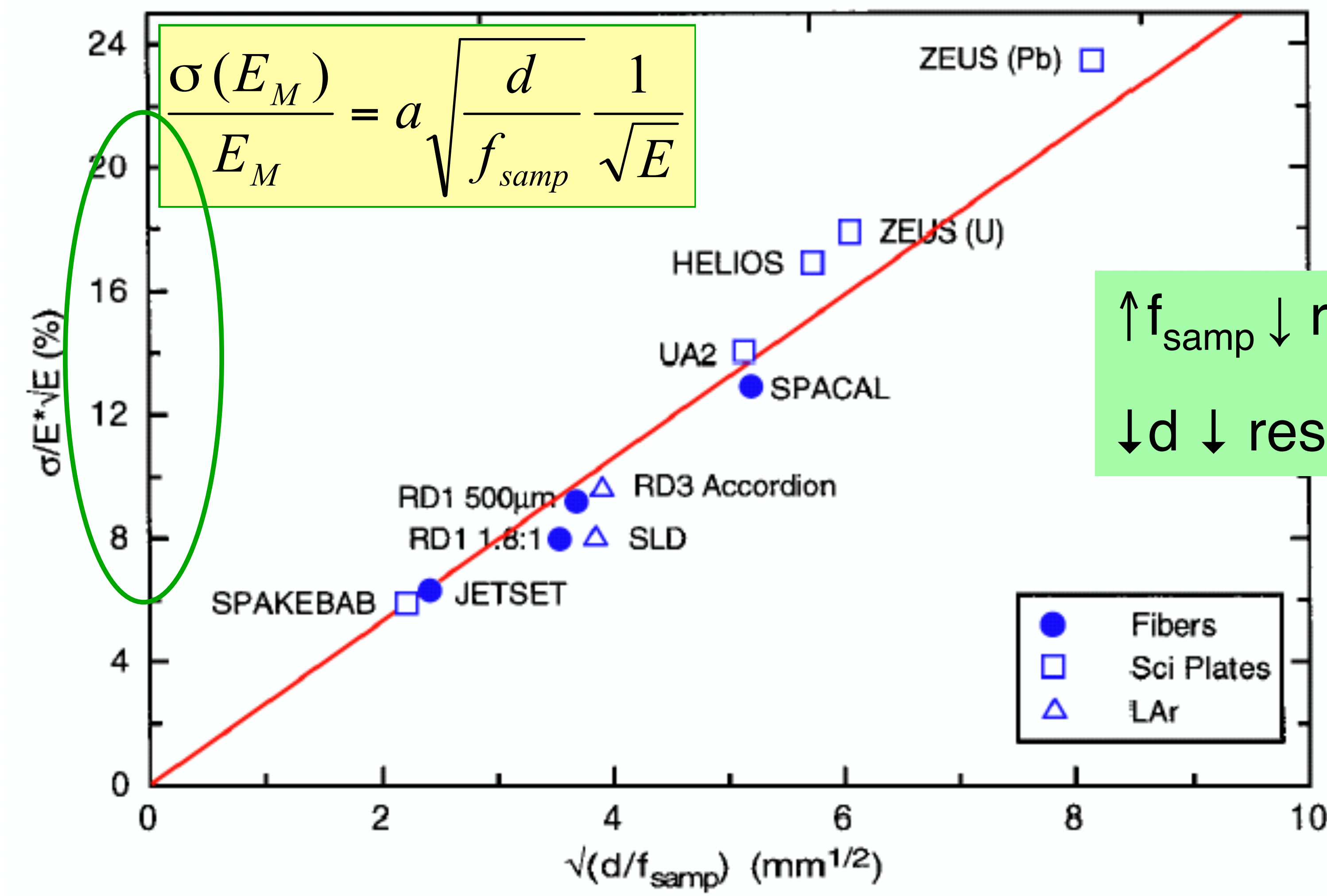
One defines the fractional response f_R^i of a given layer i as the ratio of energy lost in the active and of sum of active+passive layers:

$f_R^i = E^i_{active}/(E^i_{active} + E^i_{passive})$ with $\sum^i(E^i_{active} + E^i_{passive}) = E_0$

$f_R/f_s \sim e/mip \sim 0.6$ when $Z_{passive} >> Z_{active}$
due to transitions effects & low energy particles not reaching the active medium

ENERGY RESOLUTION for SAMPLING CALORIMETERS

$$\frac{\sigma(E_M)}{E_M} = a\sqrt{\frac{d}{f_{samp}}}\frac{1}{\sqrt{E}}$$



↑ f_{samp} ↓ resolution

↓ d ↓ resolution

ENERGY RESOLUTION

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

a the stochastic term accounts for Poisson-like fluctuations

naturally small for homogeneous calorimeters

takes into account sampling fluctuations for sampling calorimeters

b the noise term (hits at low energy)

mainly the energy equivalent of the electronics noise

at LHC in particular: includes fluctuation from non primary interaction (pile-up noise)

c the constant term (hits at high energy)

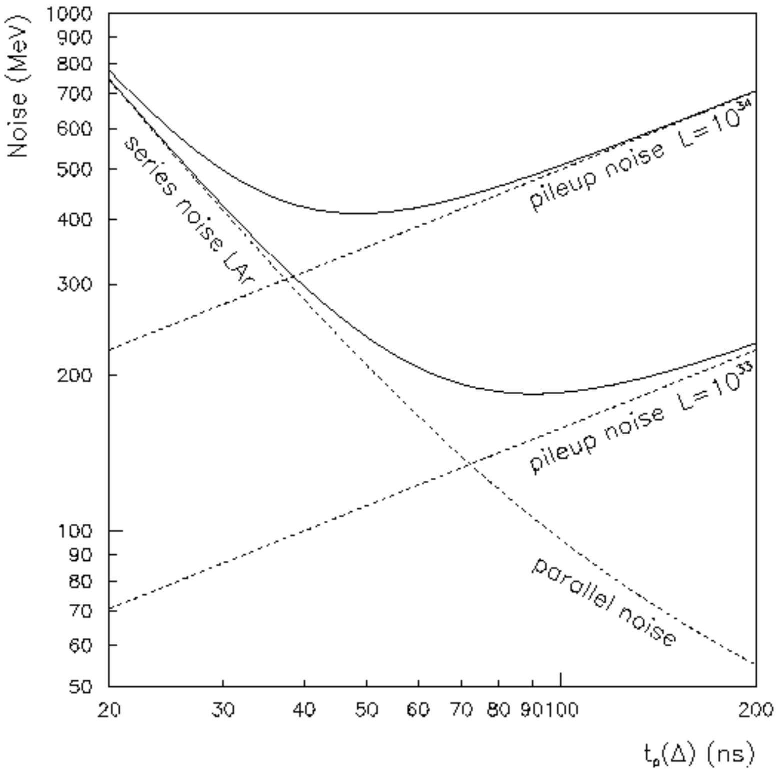
Essentially detector non homogeneities like intrinsic geometry, calibration but also energy leakage

NOISE TERM WITH PILE-UP

Electronics noise vs pile-up noise

Electronics integration time was optimized taking into account both contributions for LHC nominal luminosity if $10^{34} cm^{-2} s^{-1}$

Contribution from the noise to an electron is typically ~ 300-400 MeV at such luminosity



THE CONSTANT TERM

The constant term describes the level of uniformity of response of the calorimeter as a function of position, time, temperature and which are not corrected for.

- Geometry non uniformity
- Non uniformity in electronics response
- Signal reconstruction
- Energy leakage

Dominant term at high energy

ATLAS LAr EMB testbeam

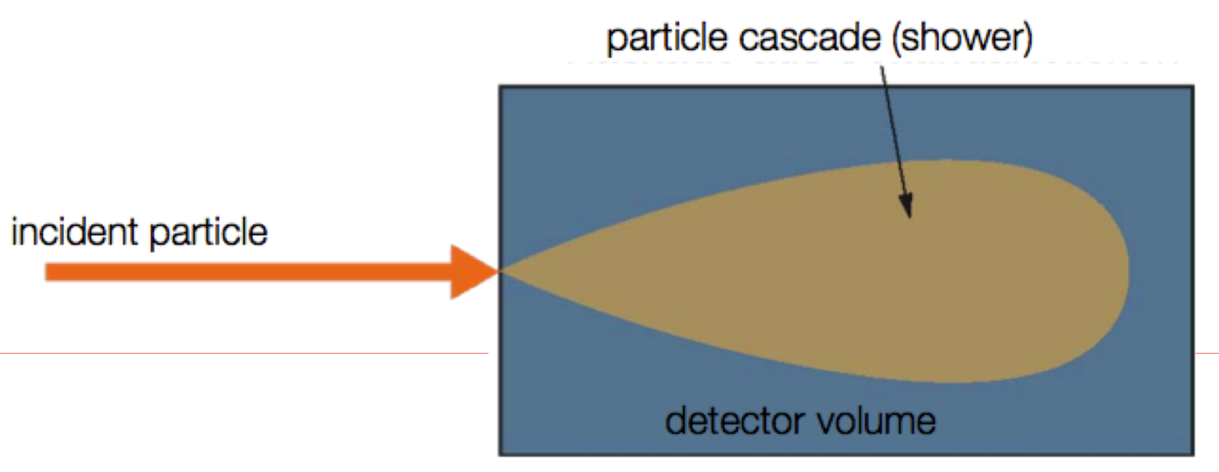
Correlated contributions	Impact on uniformity	
Calibration	0.23%	
Readout electronics	0.10%	
Signal reconstruction	0.25%	
Monte Carlo	0.08%	
Energy scheme	0.09%	
Overall (**data**)	0.38% (**0.34%**)	
Uncorrelated contribution	P13	P15
Lead thickness	0.09%	0.14%
Gap dispersion	0.18%	0.12%
Energy modulation	0.14%	0.10%
Time stability	0.09%	0.15%
Overall (**data**)	0.26% (**0.26%**)	0.25% (**0.23%**)

CALORIMETERS

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



CALORIMETERS CAN:

Calorimeters can be built as 4π-detectors

- They can detect particles over almost the full solid angle
- Magnetic spectrometers: anisotropy due to magnetic field

Calorimeters are often also sensitive to particle position

- Important for neutral particles: no track in inner detector

Calorimeters can provide fast timing signal

- 0.1 to 10 ns
- They can be used for triggering

Calorimeters can measure the energy of both charged and neutral particles

- Magnetic spectrometer: only charged particles

Segmentation in depth allows particle separation

- e.g. separate hadrons from particles which only interact electromagnetically

USEFUL QUANTITIES

Radiation length

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

Radiation length
for a composite material

$$1/X_0 = \Sigma\, w_j / X_j$$

Moliere Radius

$$R_M = \frac{21MeV \times X_0}{E_c} \approx \frac{7A}{Z} g \times cm^{-2}$$

Energy resolution

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

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]

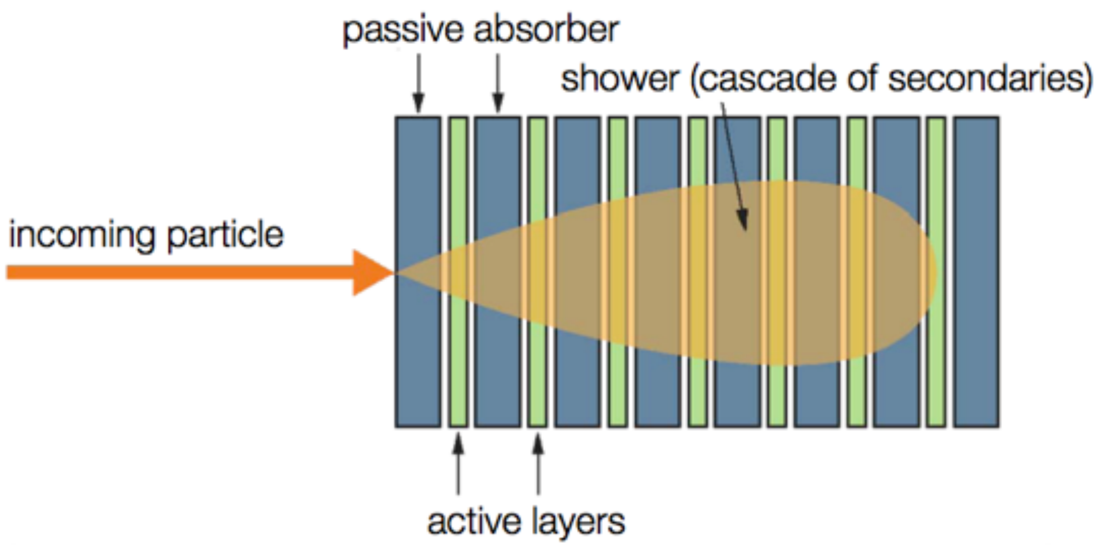
Absorber materials:
[high density]

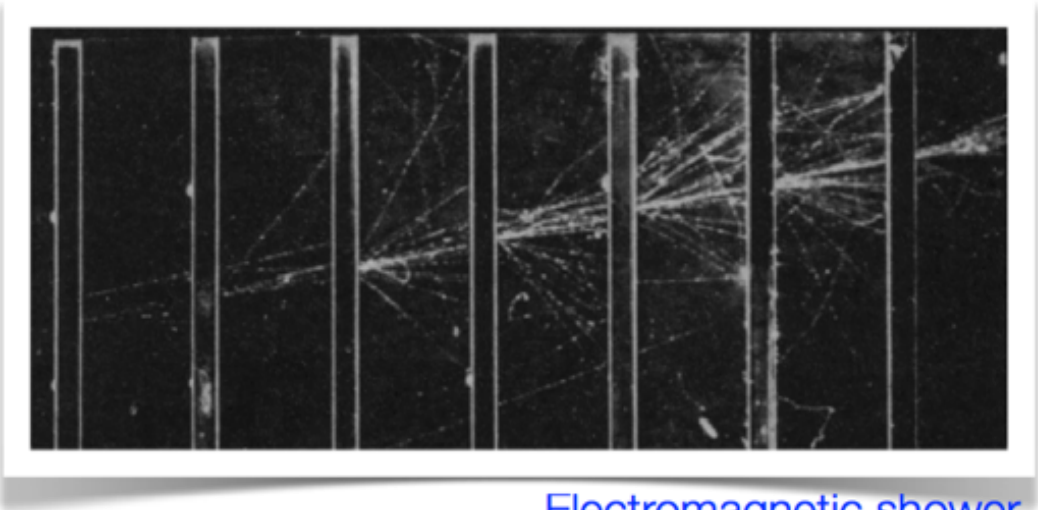
- Iron (Fe)
- Lead (Pb)
- Uranium (U)
  [For compensation ...]

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:

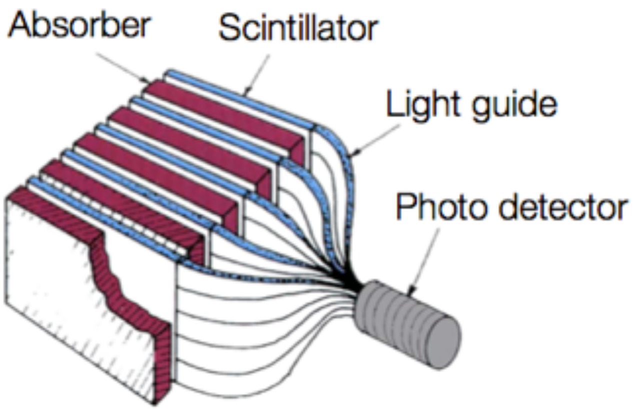
Only part of the deposited particle energy is actually detected in the active layers; typically a few percent [for gas detectors even only $\sim 10^{-5}$] ...

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

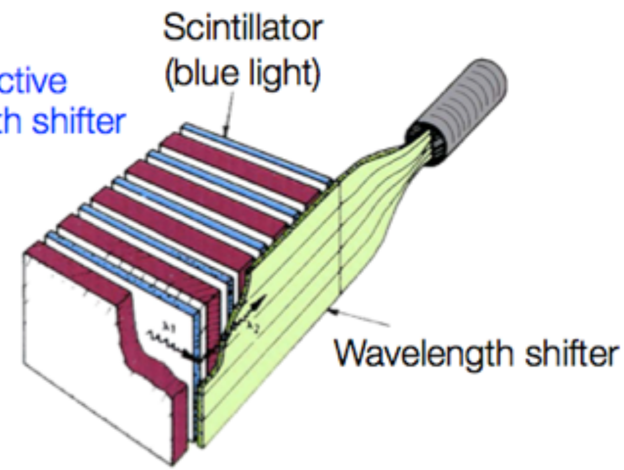
SAMPLING CALORIMETER

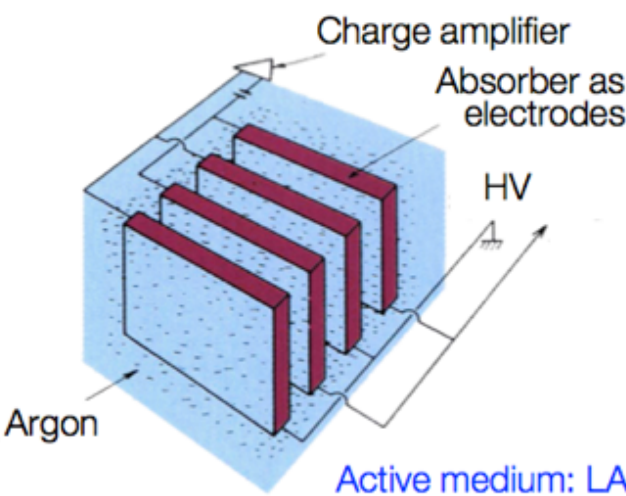
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



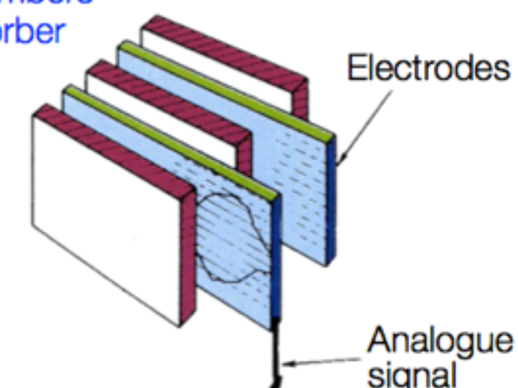
Scintillators as active layer; wave length shifter to convert light





Active medium: LAr; absorber embedded in liquid serve as electrods

Ionization chambers between absorber plates



HOMOGENEOUS vs SAMPLING CALORIMETERS

Resolution of typical electromagnetic calorimeter
[E is in GeV]

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	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

Homogeneous

Sampling

Hadronic Showers

Hadron showers

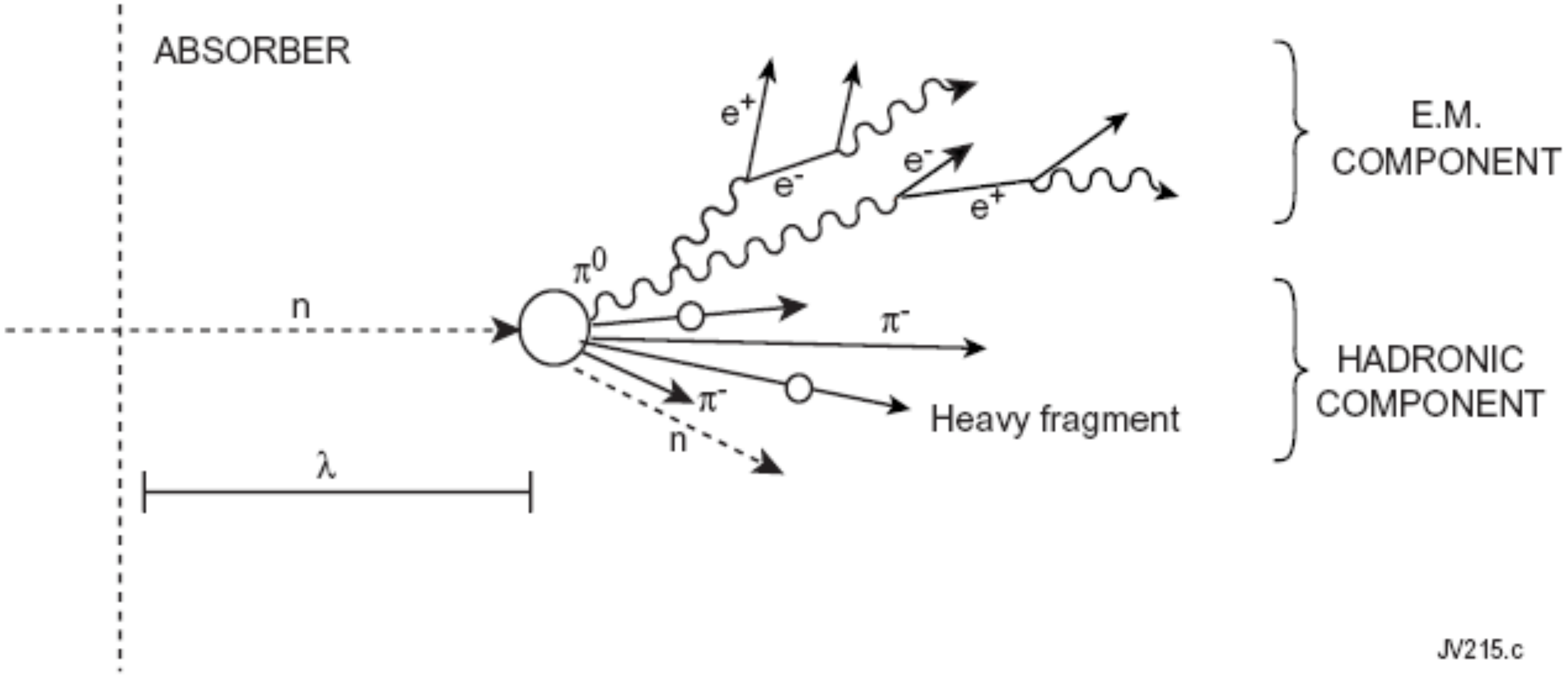
Hadronic cascades develop in an analogous way to e.m. showers

- 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 cascade



As compared to electromagnetic showers, hadron showers are:

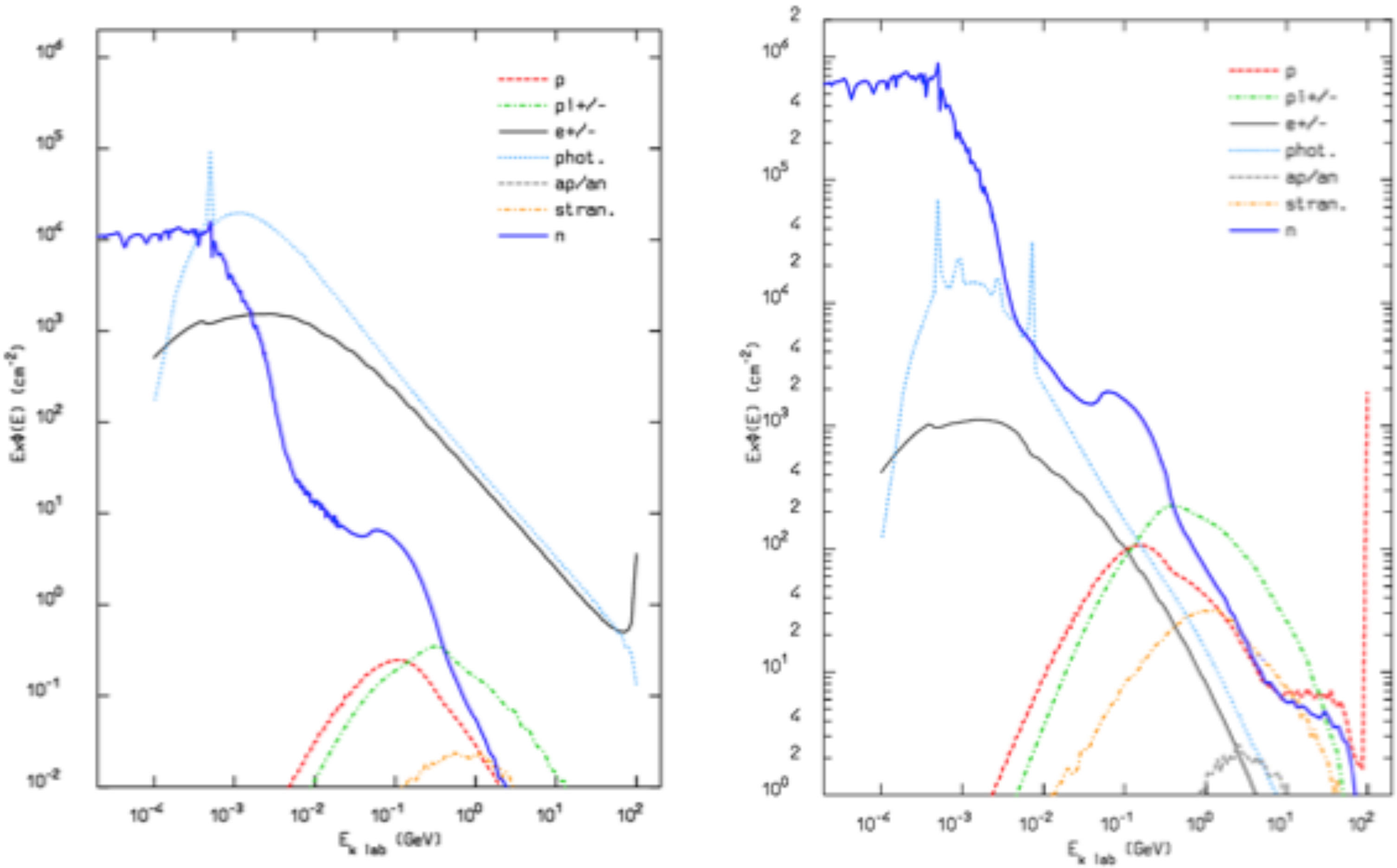
- Larger/more penetrating
- Subject to larger fluctuations – more erratic and varied

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.



E[GeV]

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

Hadronic shower development

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

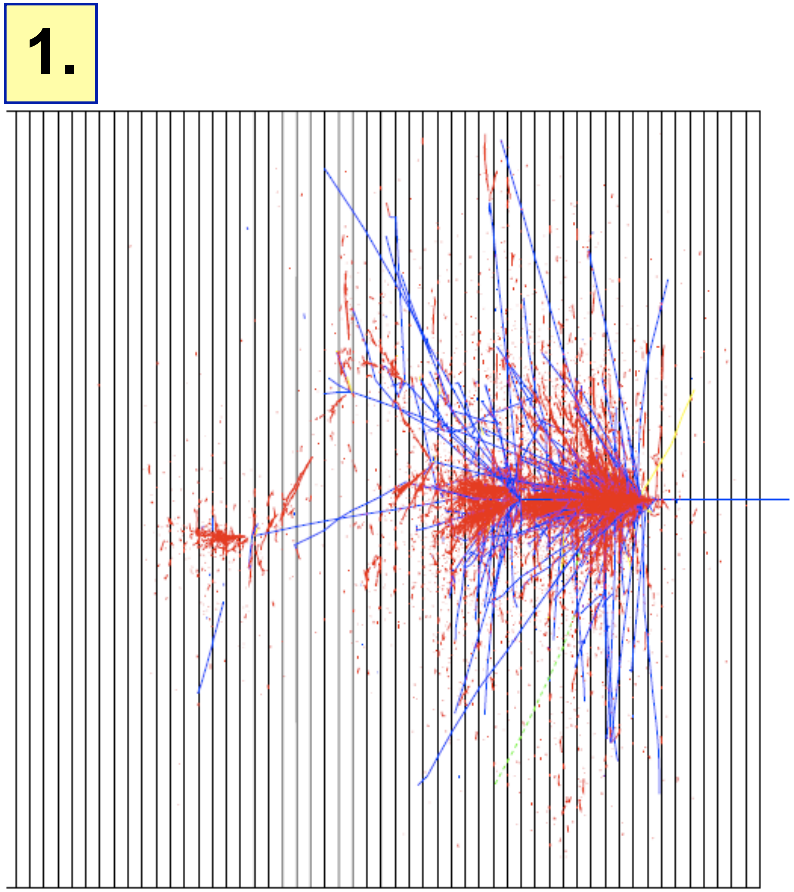
$\sigma_{inel} \approx \sigma_0 A^{0.7}$, $\sigma_0 = 35$ mb

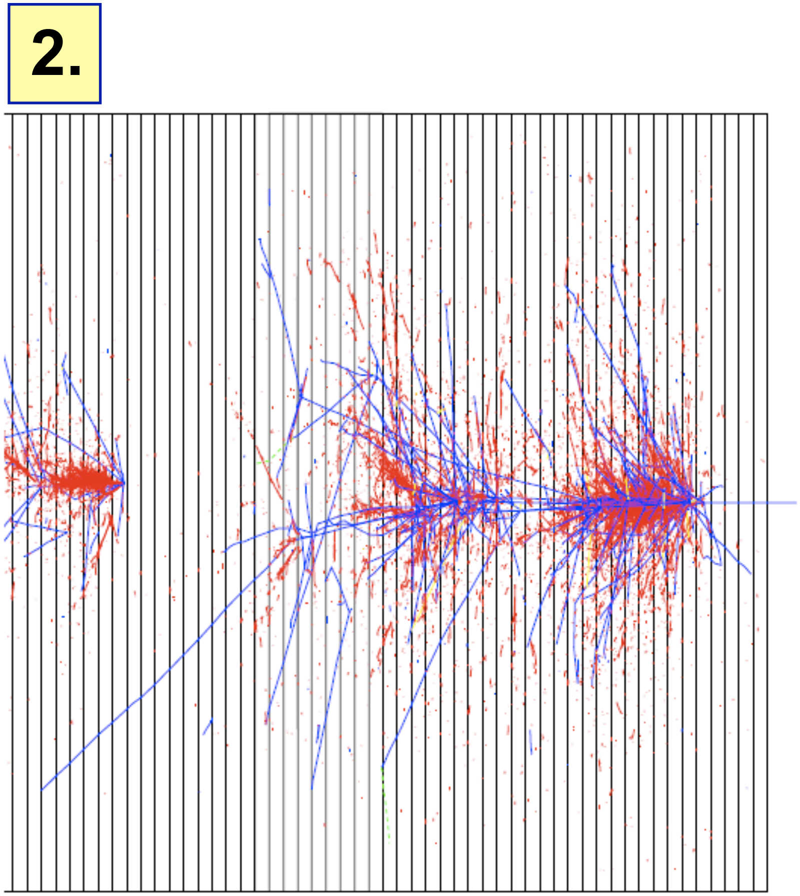
Nuclear interaction length: mean free path before inelastic interaction

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

	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	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

Hadron showers





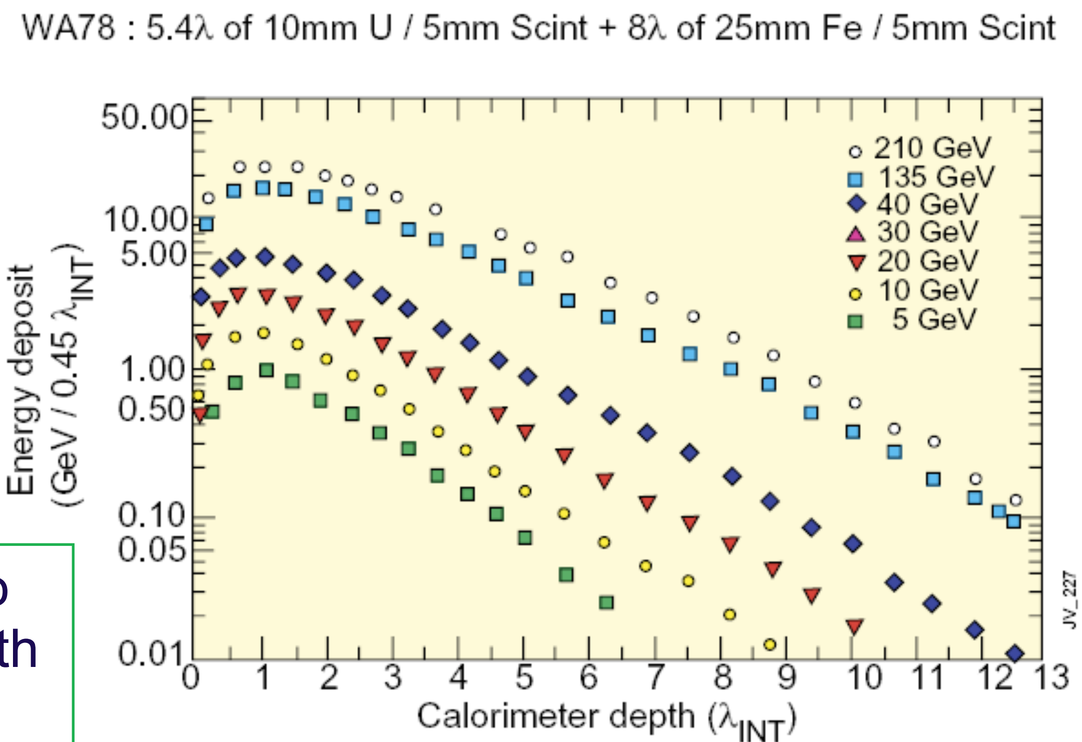
red - e.m. component
blue - charged hadrons

- Individual hadron showers are quite dissimilar

Hadron shower longitudinal profiles

Longitudinal profile

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



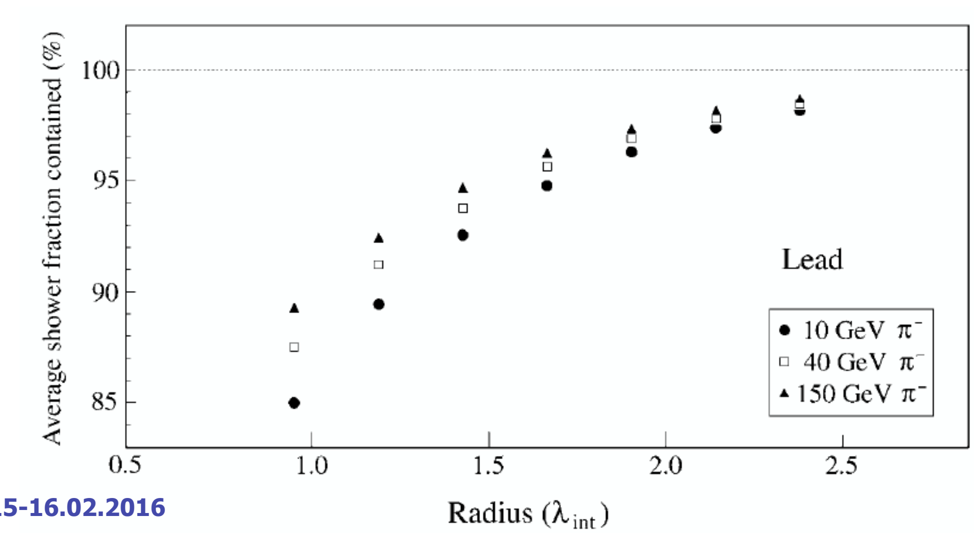
As with e.m. showers: depth to contain a shower increases with log(E)

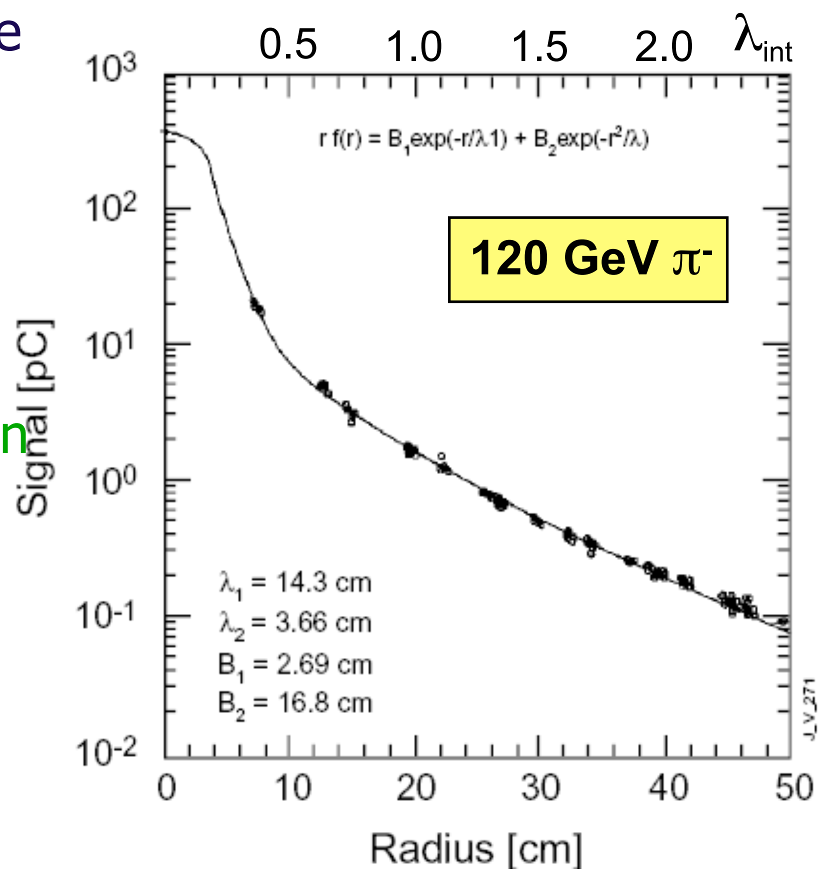
Hadron shower transverse profiles

Mean transverse momentum from interactions, $\langle p_T \rangle \sim 300$ 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

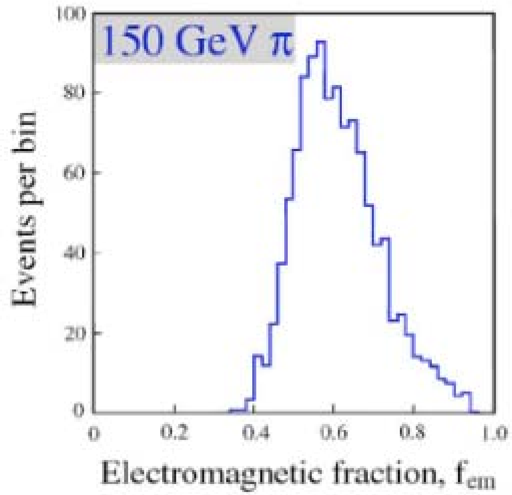
The π^0 component of the cascade results in an electromagnetic core

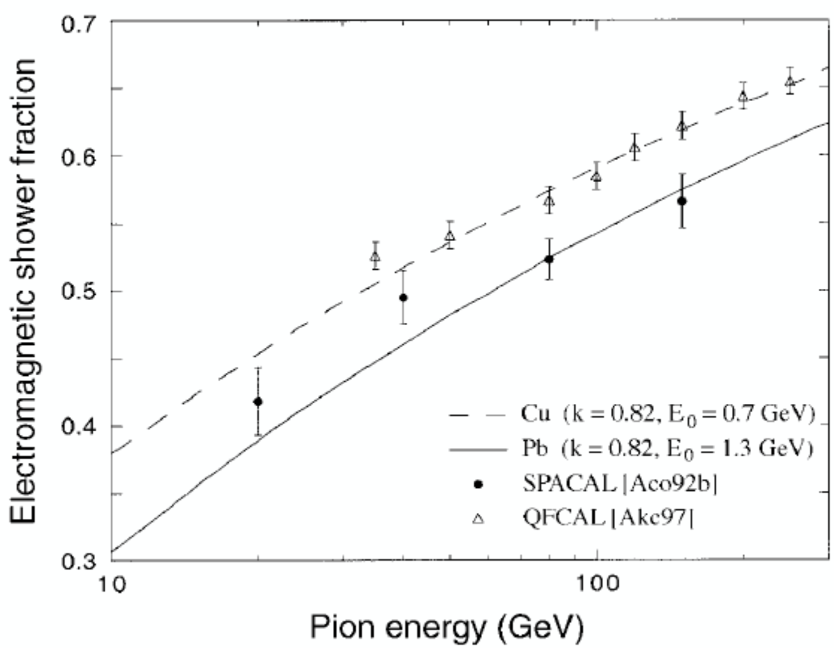




Lateral containment increases with energy

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

$50\text{-}100\%/\sqrt{E} \oplus$ a few %

Hadronic shower and non compensation

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

- R_h: Response to hadrons
- ε_e: fract. of detected EM energy
- E_e: shower EM energy
- ε_h: fract. of detected HAD energy
- E_h: shower HAD enerrgy

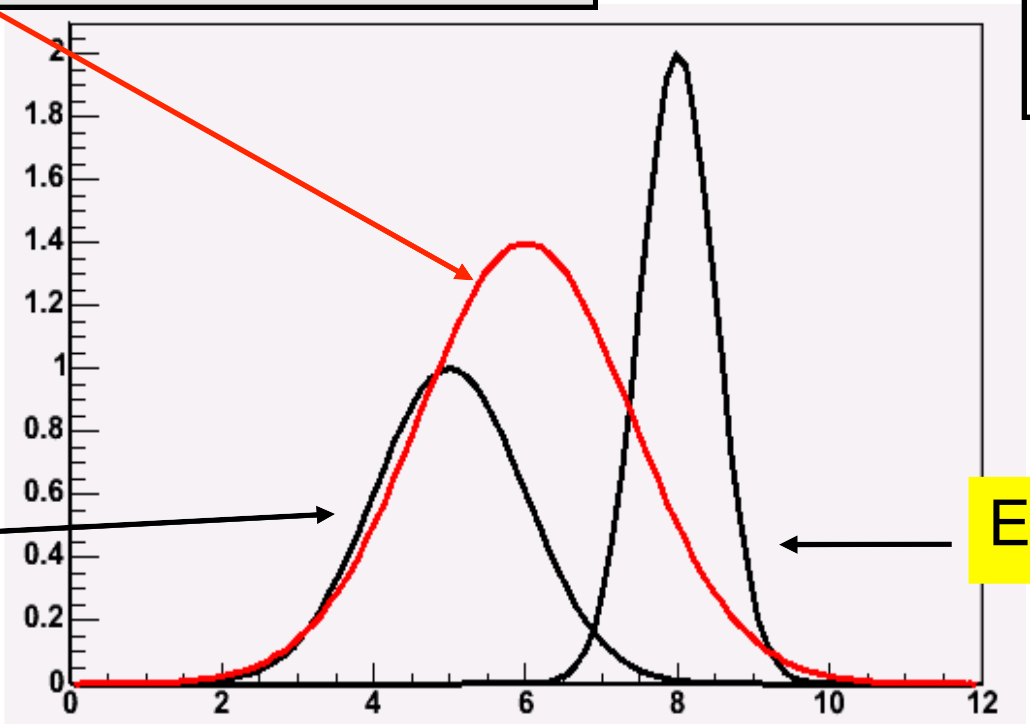
$$\frac{e}{h} = \frac{\varepsilon_e}{\varepsilon_h}$$

- ≈ 1 : compensating calorimeter
- > 1 : non compensating calorimter

Hadronic showers: non compensation

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

$\varepsilon_e > \varepsilon_h$



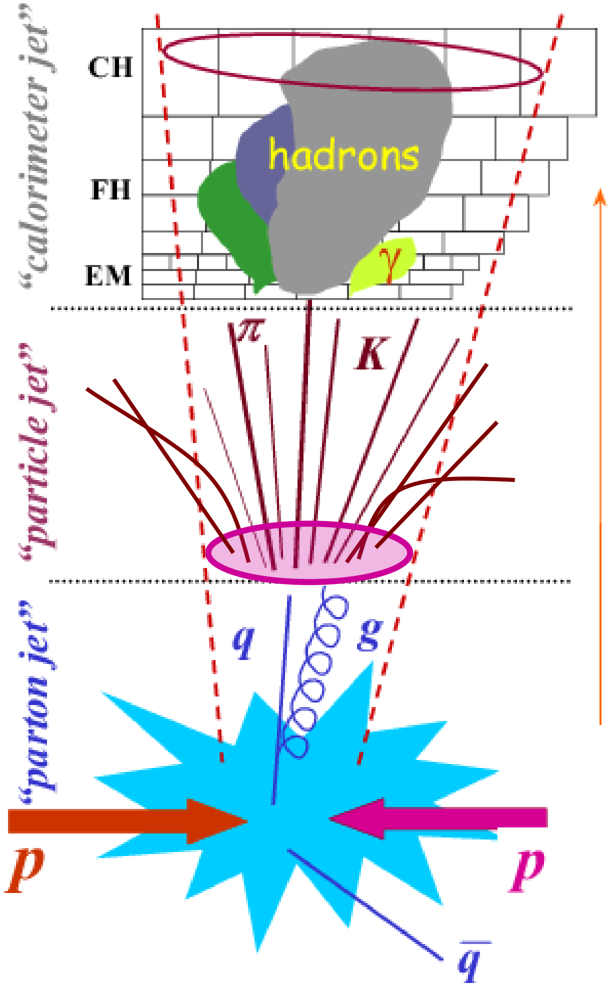
$E_e << E_h$

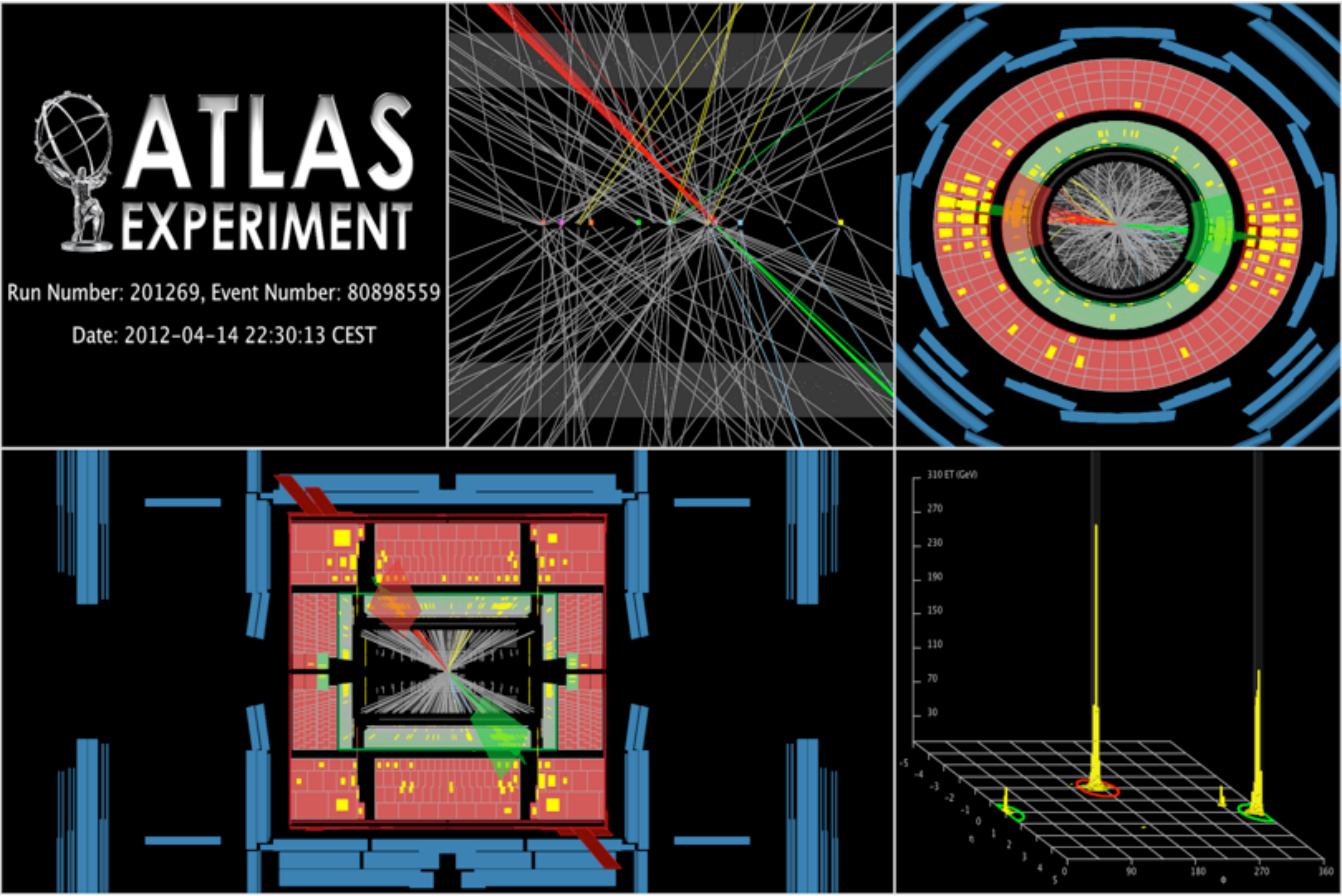
$E_e >> E_h$

Jets

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

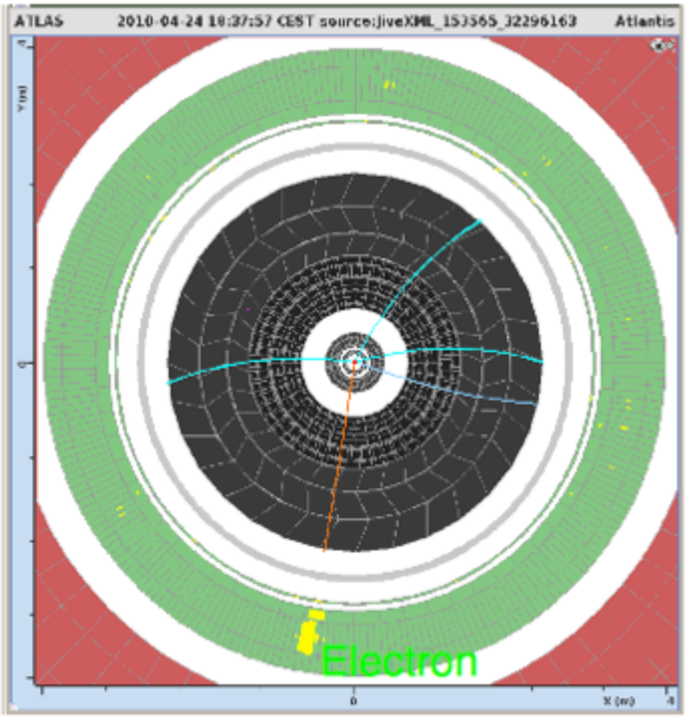
- In a cone around the initial parton: high density of hadrons
- LHC calorimeters cannot separate all the incoming hadrons
  - Use dedicated calibration schemes (based on simulation in ATLAS)
  - Use tracking system to identify charged hadrons (Particle Flow in CMS)

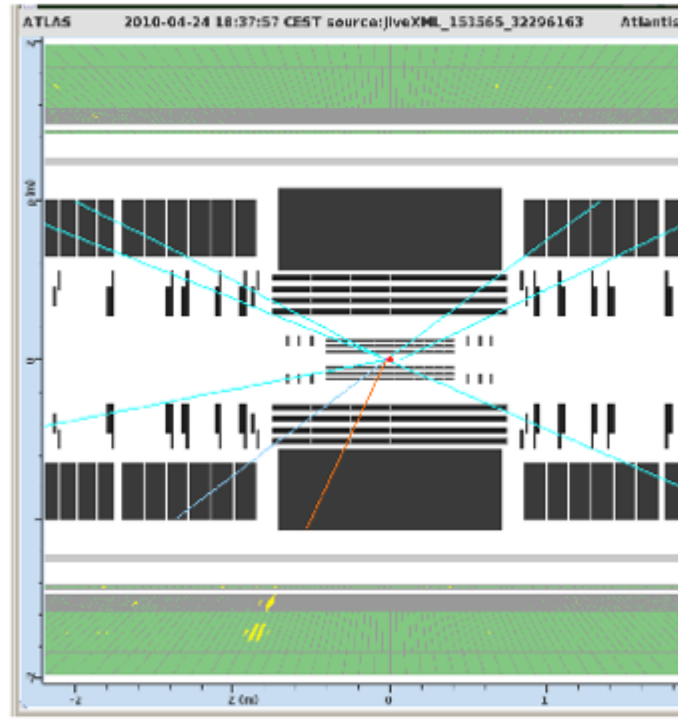



ATLAS
EXPERIMENT
Run Number: 201269, Event Number: 80898559
Date: 2012-04-14 22:30:13 CEST
310 ET (GeV)
270
230
190
150
110
70
30
0
90
180
270
360

Missing Transverse Energy

Missing transverse energy : $W \to e\,\nu$ candidate

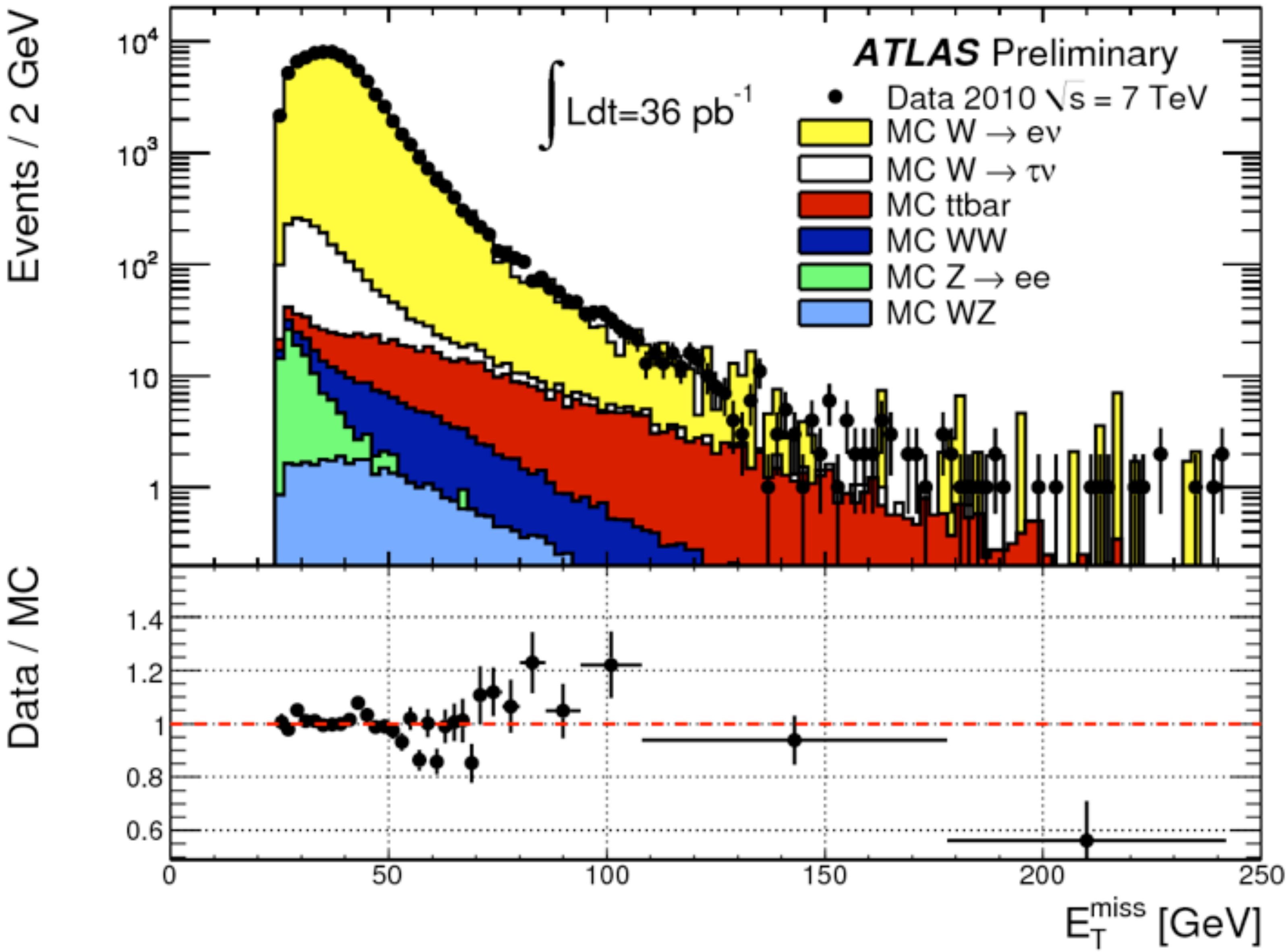




- hight pt electron (pt = 29 GeV); several low pt tracks (1 GeV)
- transverse momentum is a tool for selecting events in which a W boson has occured
- the total transverse momentum vector is not ballanced $\Longrightarrow$ missing energy
- the Missing Energy vector: $$\vec{E}^{miss} = - \sum_{\text{calorimeter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

where $\vec{u}_i$ 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_μ=105,66 MeV/c^2

} $m\mu / m_e$ ~ 200 ➔ $(m\mu / me)^2$ ~ 40000

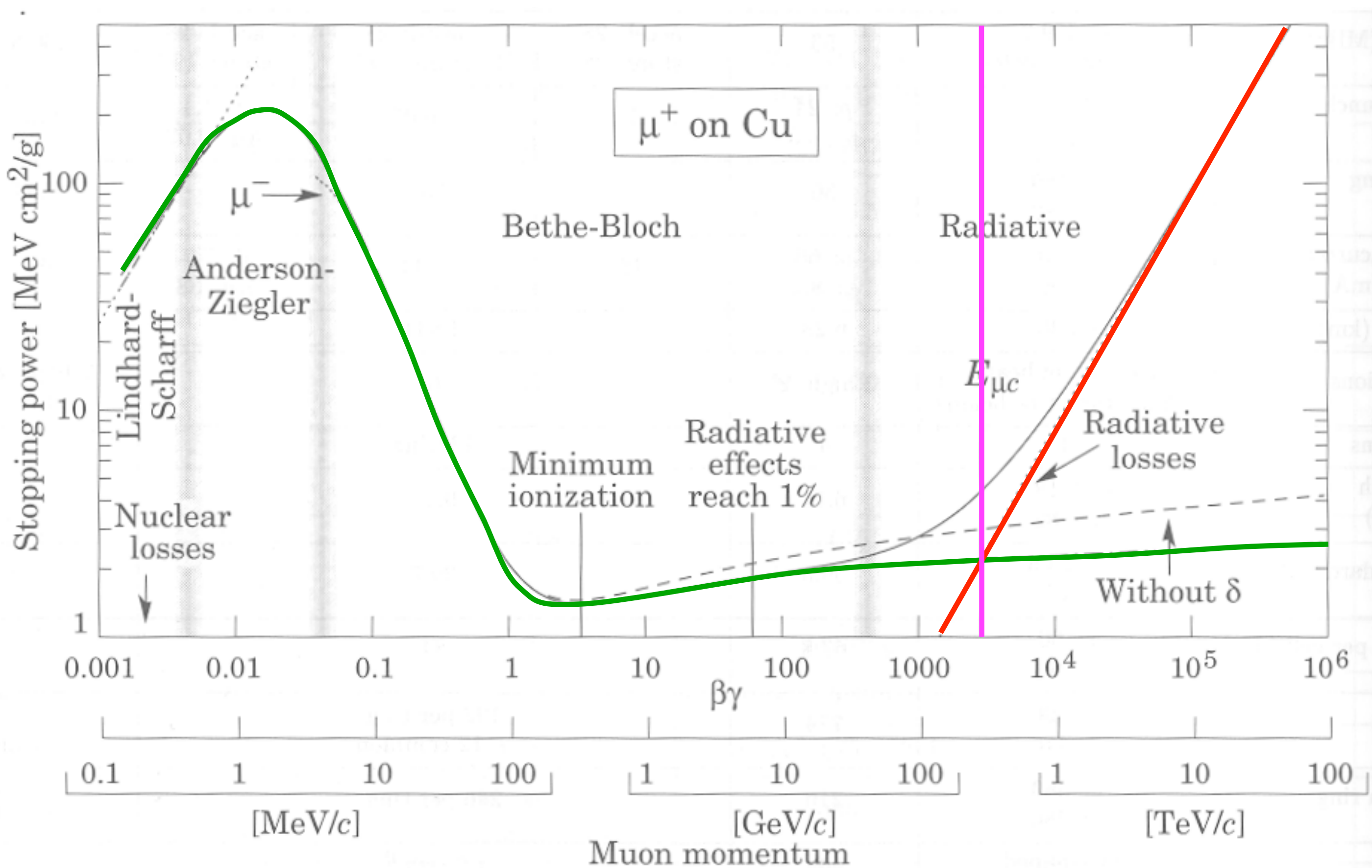
Contrary to electrons, muons (E<100GeV) loose energy mainly via ionization with

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

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

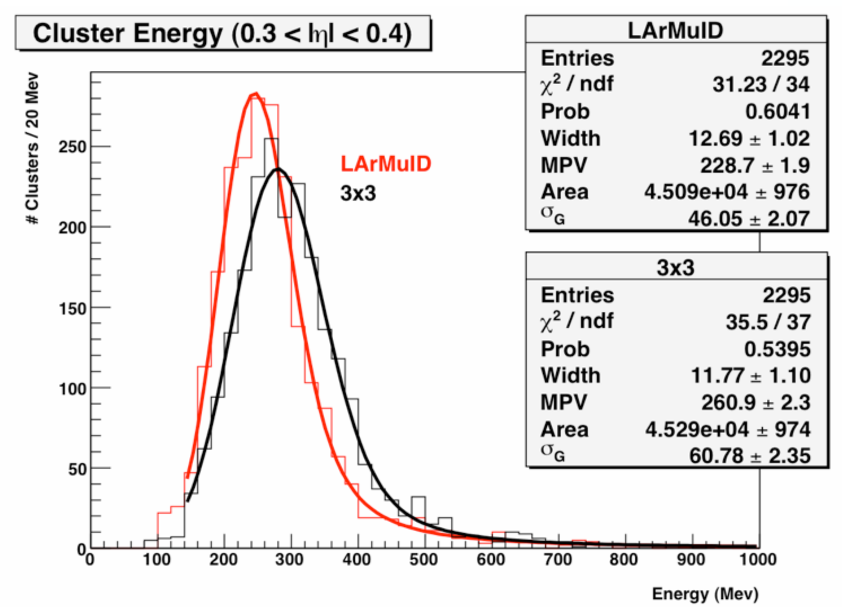
Muons in matter

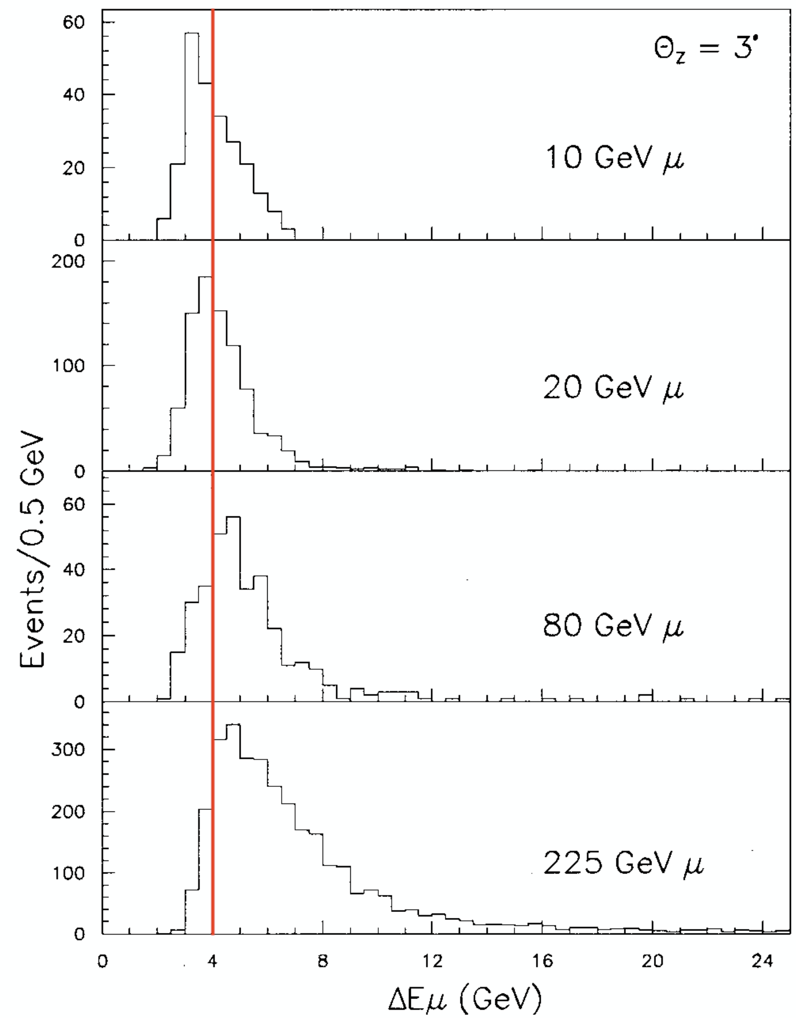
dE/dx



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

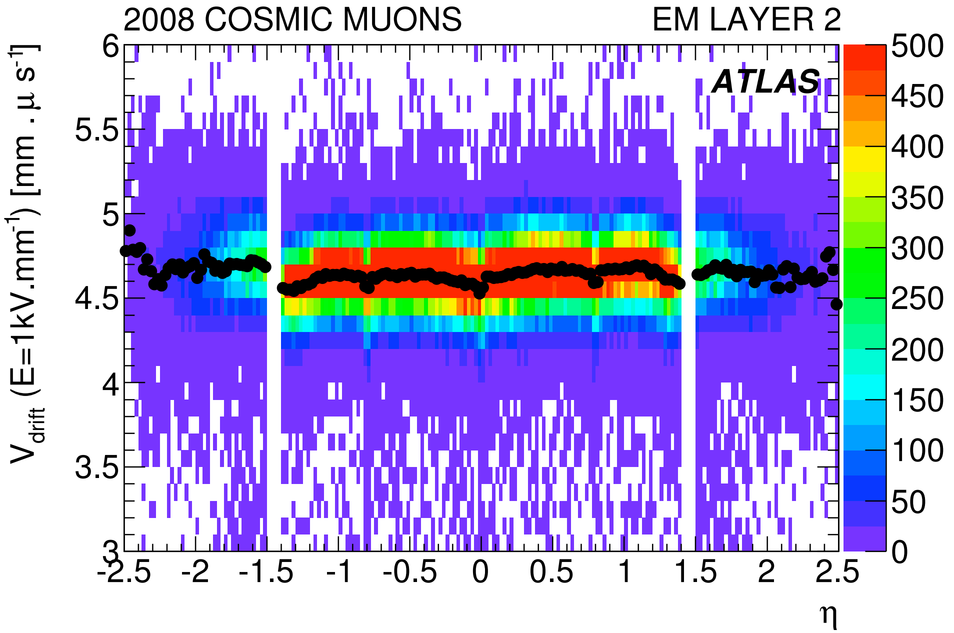
Muons deposit very little energy in calorimeter: dE/dx . x

- Except for catastrophic energy loss (γ emission)

They are nice tools to assess calorimeter response uniformity

- at low energy

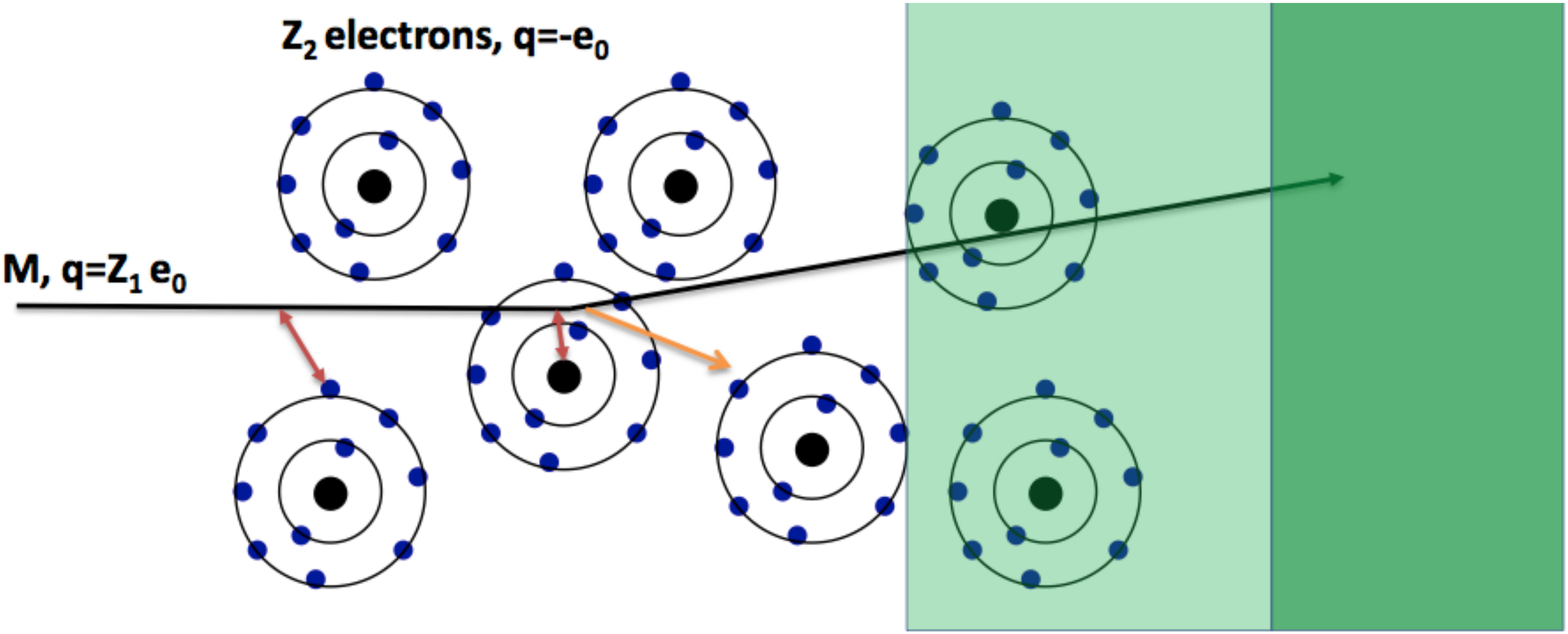
They are nice clean probes to analyse the calorimeter geometry



(b) Drift velocity

ELECTROMAGNETIC INTERACTIONS OF PARTICLES WITH MATTER

INTERACTIONS → DETECTORS



Interaction with the atomic electrons.
The incoming particle loses energy and the atoms are **exited** or **ionised**.

Interaction with the atomic nucleus.
The incoming particle is deflected causing **multiple scattering** of the particle in the material.
During this scattering a **Bremsstrahlung photon** can be emitted

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as **Cherenkov radiation.**
When the particle crosses the boundary between two media, there is a probability of 1% to produce an Xray photon called **Transition radiation.**

INTERACTIONS OF PARTICLES WITH MATTER

IONISATION AND EXCITATION

Charged particles traversing material and exciting and ionising atoms.

The average energy loss of the incoming particle by the process is to a good approximation described by the Bethe-Block formula.

CHERENKOV RADIATION

If a particle propagates in a material with velocity > speed of light in this material, C radiation is emitted at a characteristic angle that depends on the particle velocity and the refractive index of the medium

TRANSITION RADIATION

If a charged particle is crossing the boundary between two materials of different dielectric permittivity, there is a certain probability for emission of an X-ray photon.

MULTIPLE SCATTERING AND BREMSSTRAHLUNG

Incoming particles are scattering off the atomic nuclei which are partially shielded by the atomic electrons.

This scattering imposes a lower level on the momentum resolution of the spectrometer, when measuring the particle momentum by deflection of the particle trajectory in the magnetic field.

The deflection of the particle on the nucleus results in an acceleration that causes the emission of Bremsstrahlung photons.
The photons in turn produce e+e- pairs in the vicinity of the nucleus, which causes the EM cascade.
This effect depends on m^{-2}: only relevant for electrons.

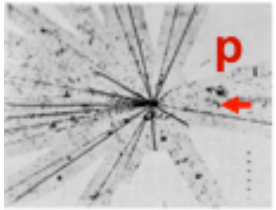
HADRONIC INTERACTION

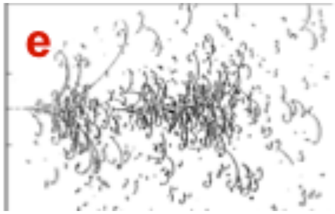
Incoming hadrons on a material will interact with the nucleus and create a shower composed of hadrons, electrons, photon.
A fraction of the energy is *lost* in the form of binding energy or neutrinos.

INTERACTIONS → DETECTORS

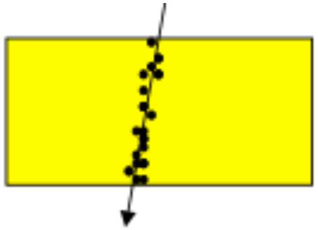
FOUR STEPS

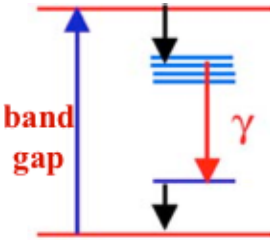
1. Particles interact with matter
   depends on particle and material

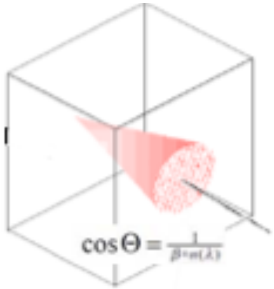




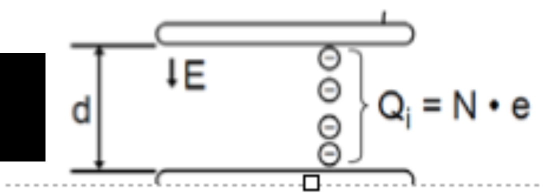
2. Energy loss transfer to detectable signal
   depends on the material

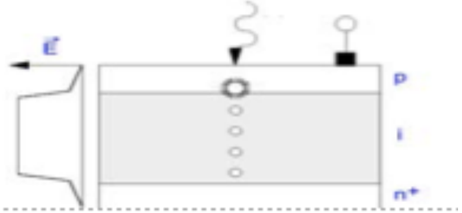






3. Signal collection
   depends on signal and type of detection



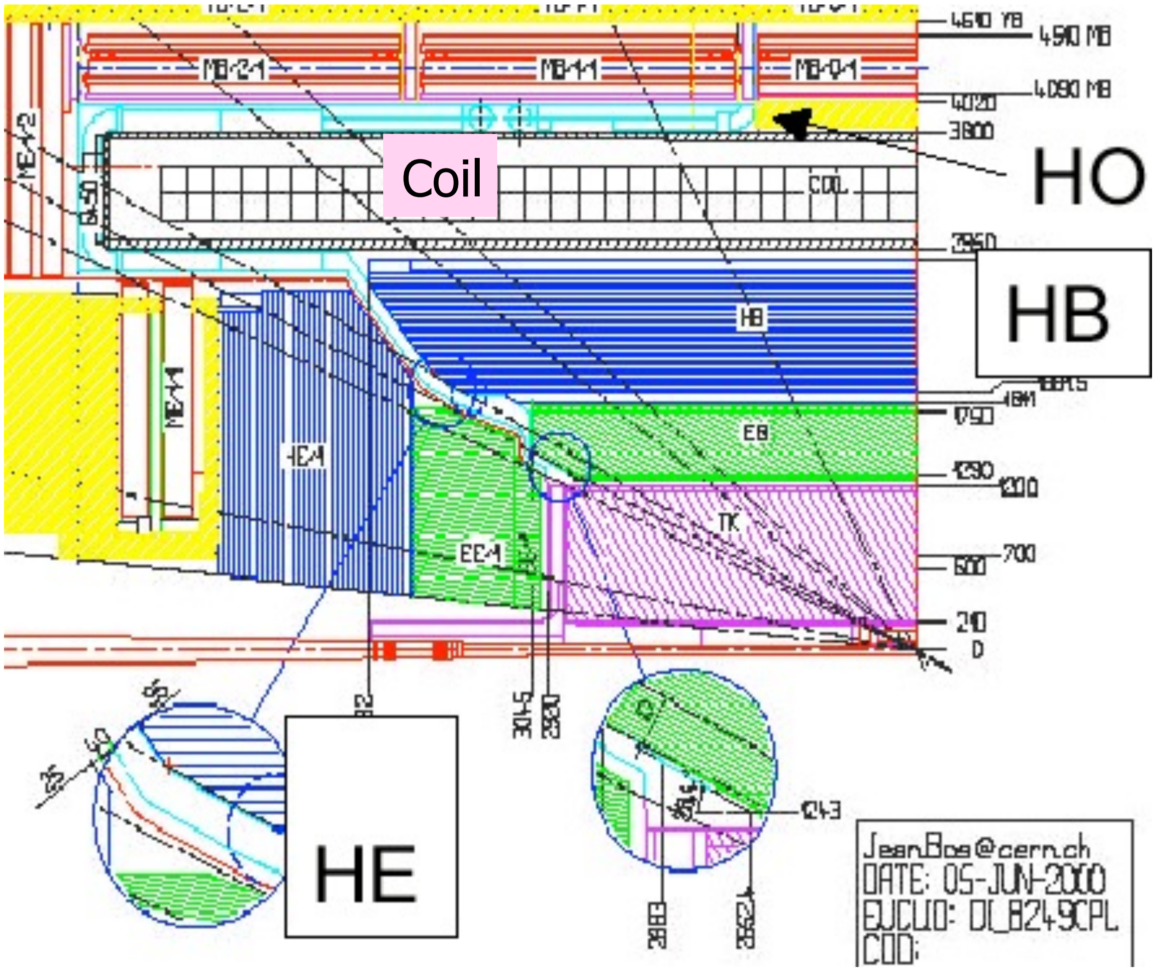


4. BUILD a SYSTEM
   depends on physics, experimental conditions,….

Two Examples
CMS
ATLAS

CMS calorimeter

The CMS calorimeter



The CMS choices

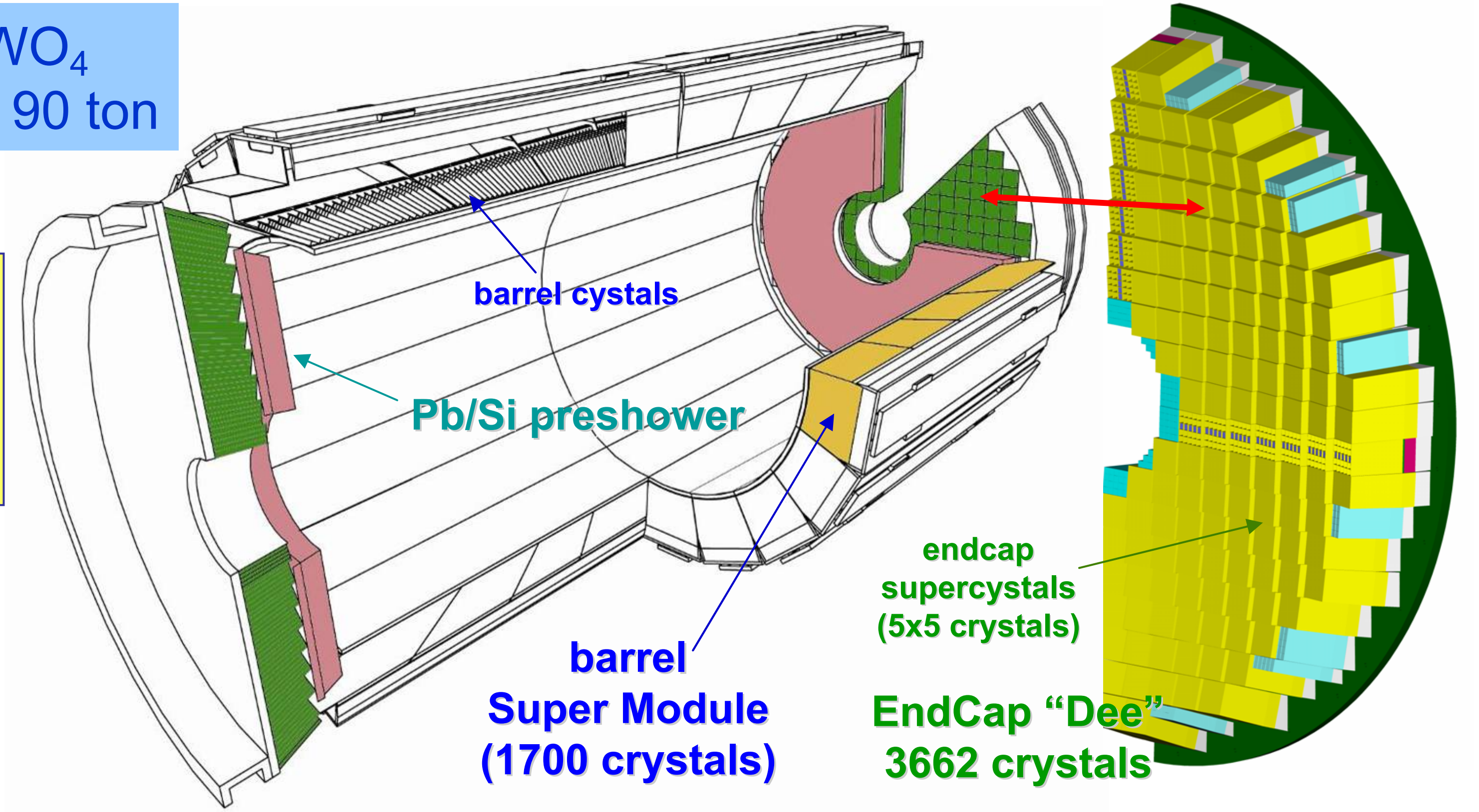
- Solenoidal Magnetic Field: 4T
- Outside the calorimeter
  - “Compact” calorimeter
- Very precise EM calorimeter
  - PbWO crystal (very dense)
- “Thin” HAD calorimeter

ECAL @ CMS

Precision electromagnetic calorimetry: 75848 PWO crystals

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

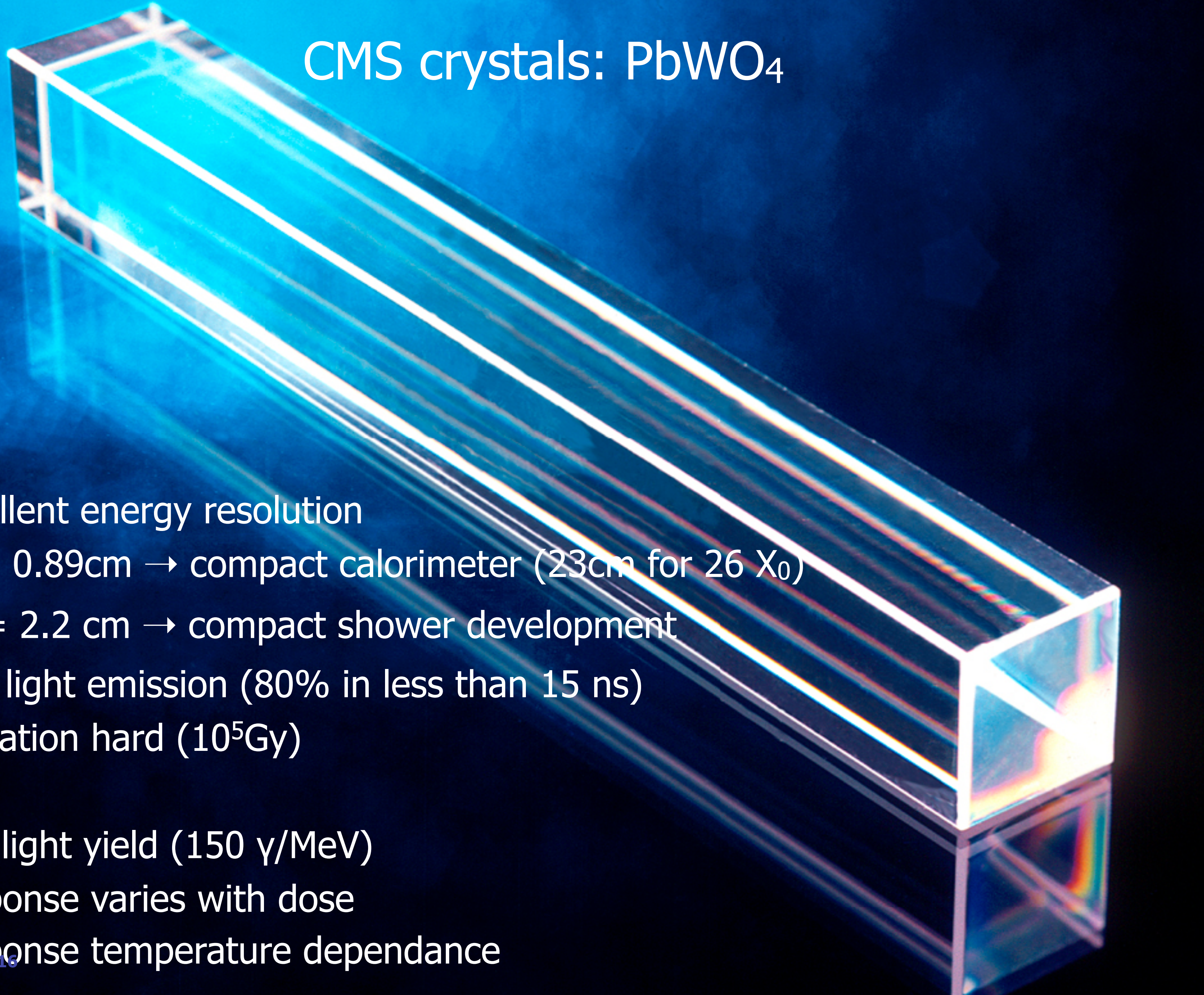
Previous Crystal calorimeters: max $1m^3$



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

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

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)

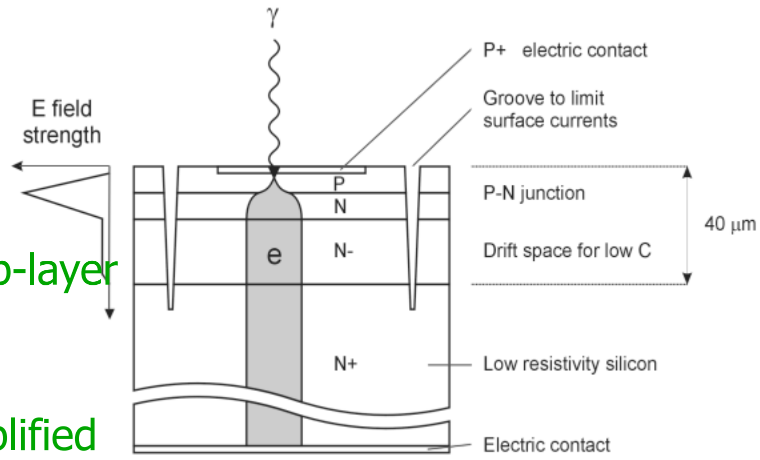
Response varies with dose

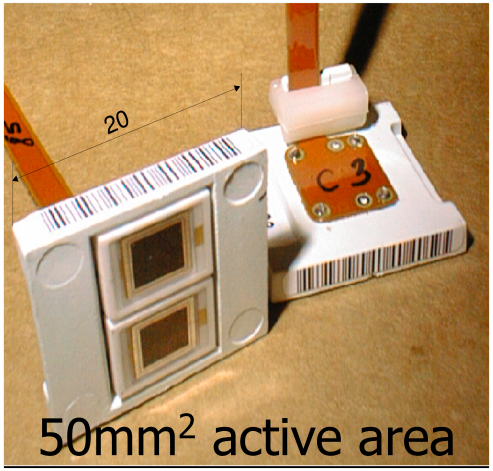
Response temperature dependance

Light Collection: APD & VPT

APD: ECAL barrel

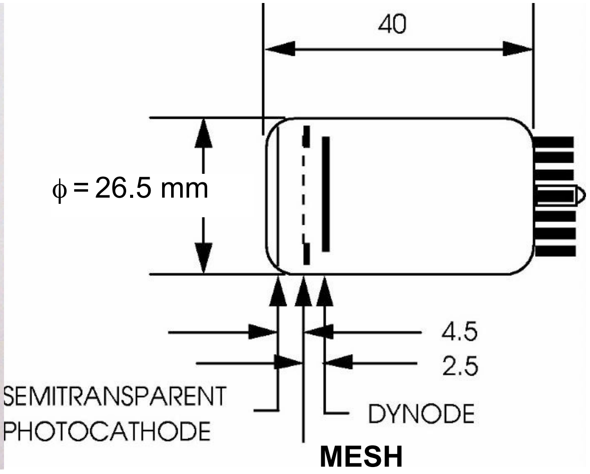
- Photo-eletrons from THIN 6μm p-layer induce avalanche in p-n junction
- Electrons from ionising particles traversing the bulk are NOT amplified



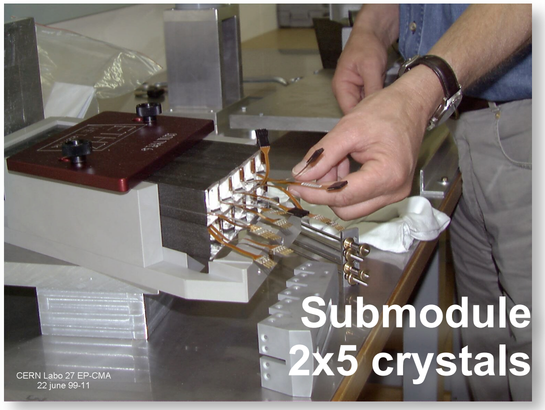


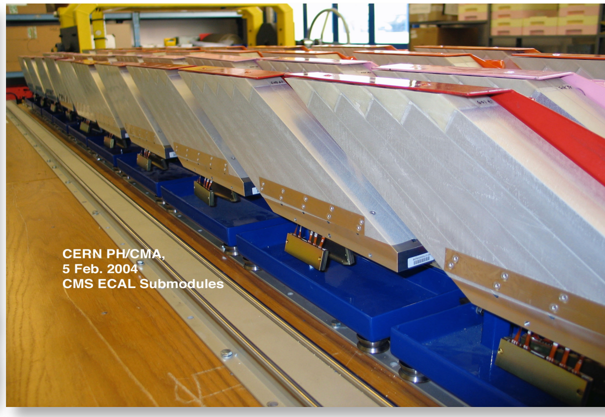
Vacuum Phototriodes: ECAL Endcaps

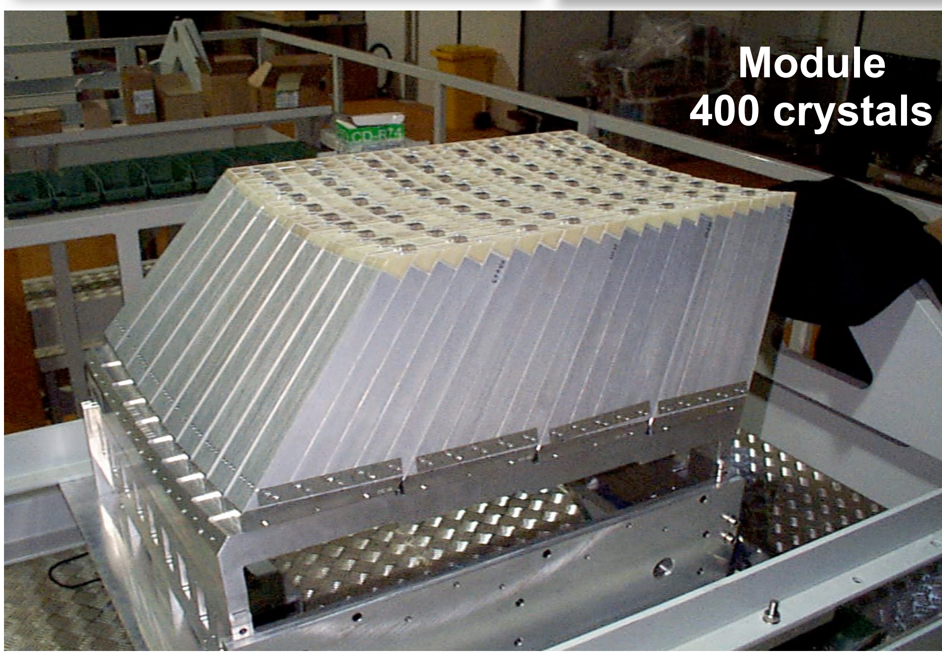
- Single stage PM tube with fine metal grid anode (insensitive to axial magnetic fields)
- Favourable for EC-ECAL
- Q.E. ~20% at 420nm

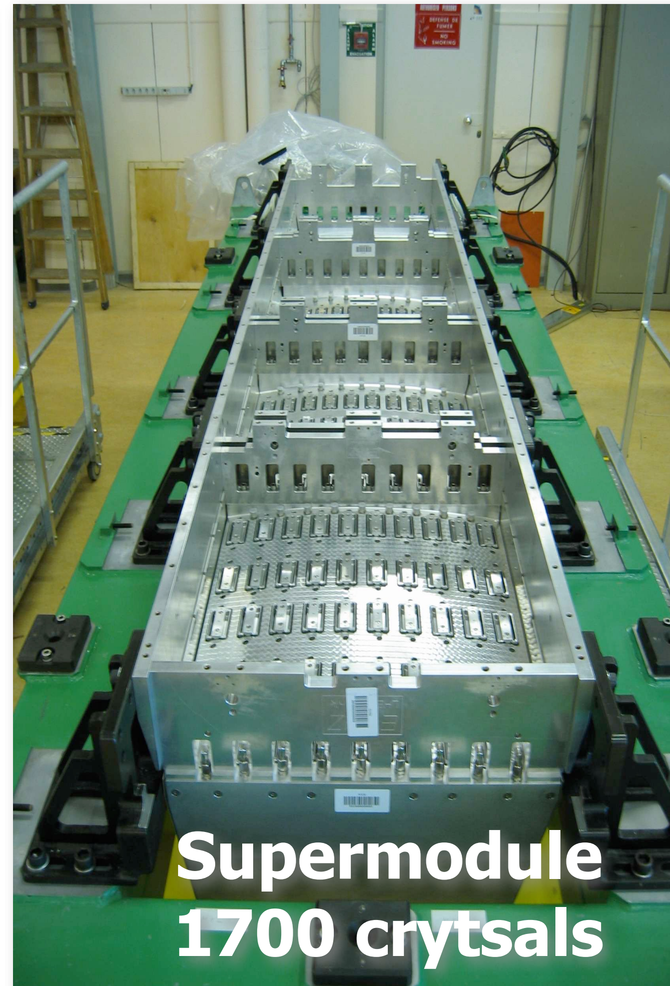


CMS ECAL Construction

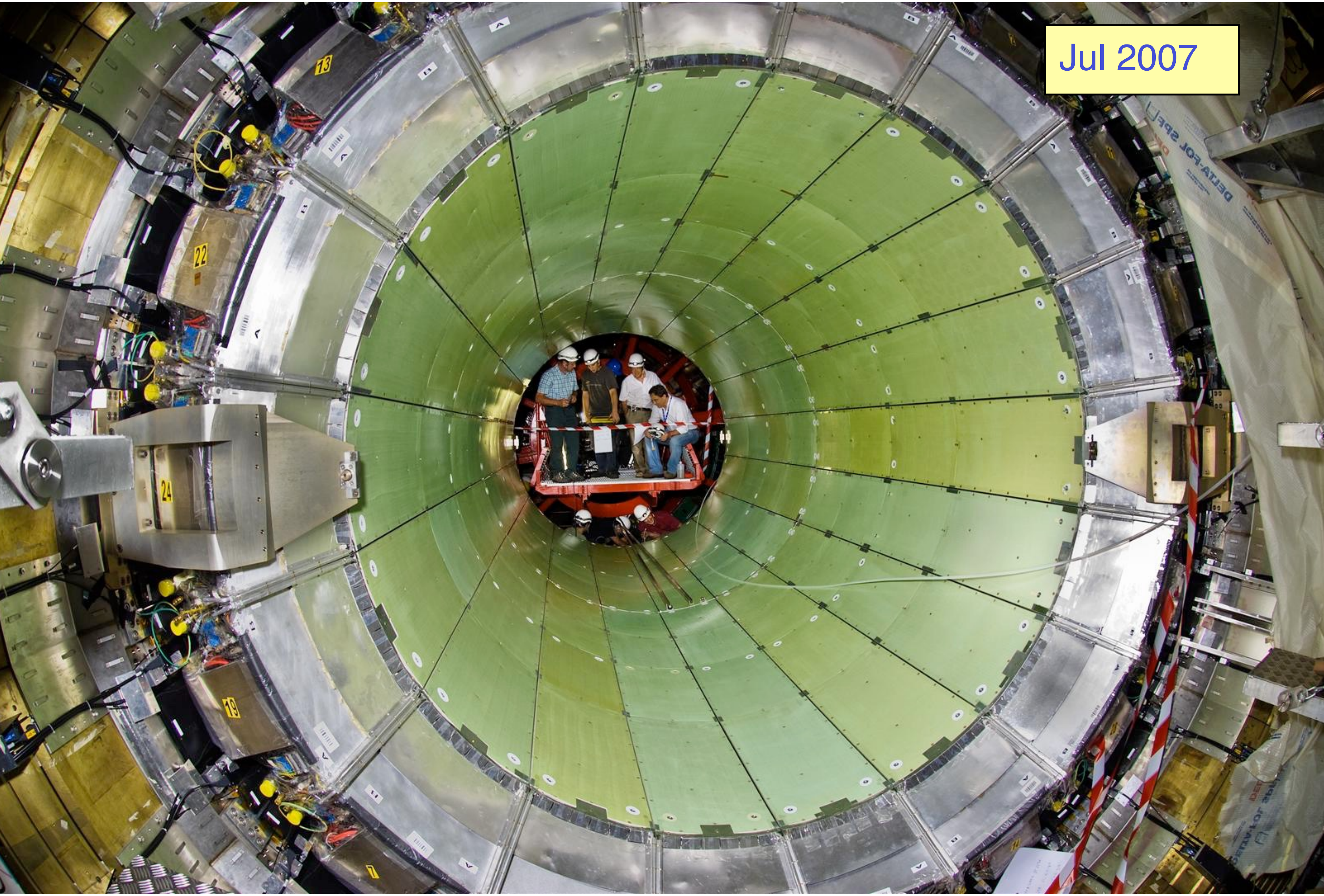




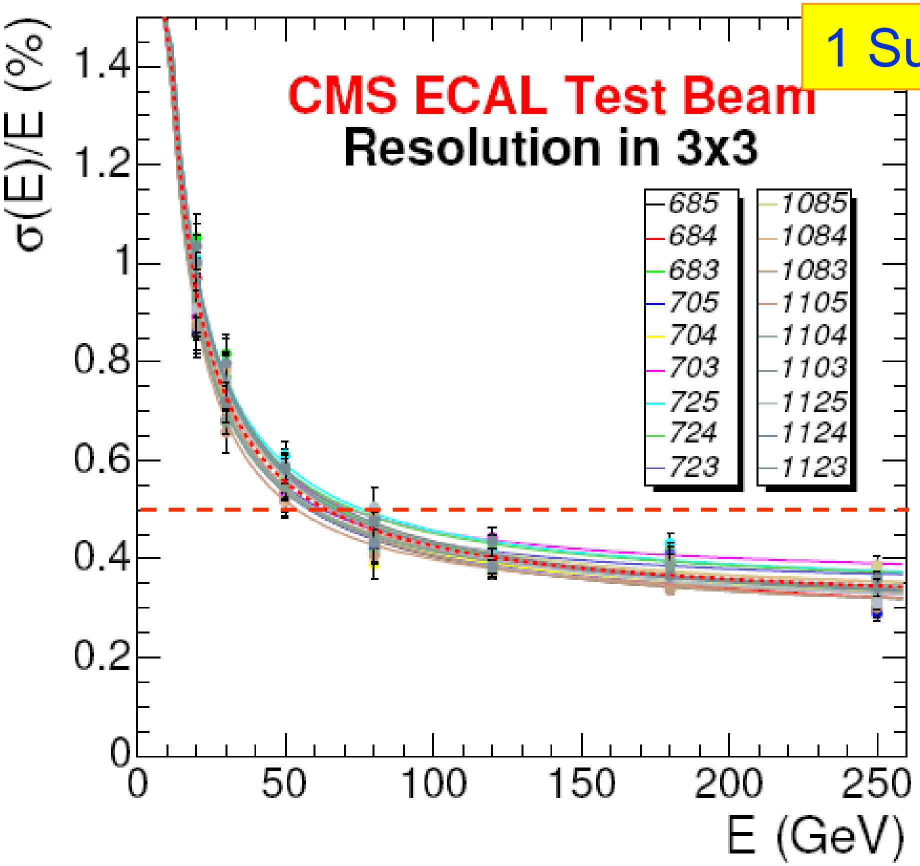




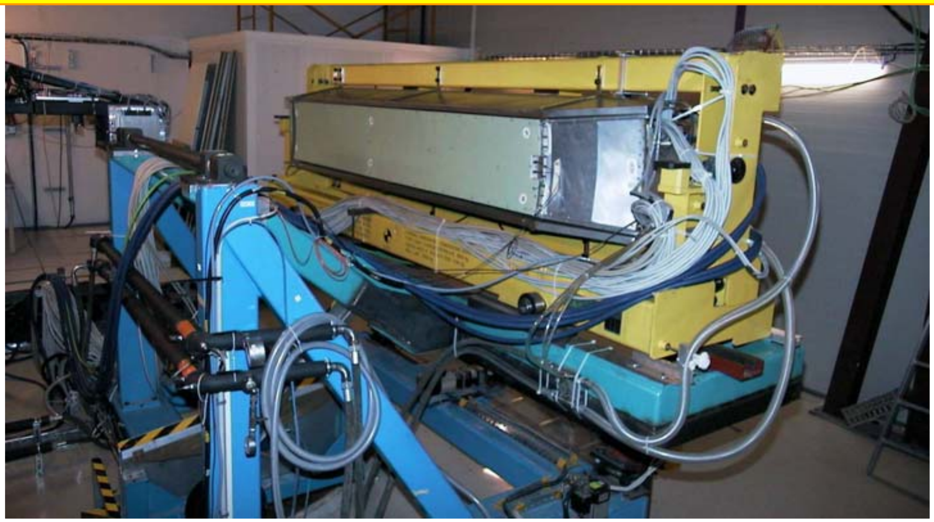
Total 36 Supermodules


Jul 2007

CMS ECAL: Performance in testbeam



1 Super Module 1700 xl on test beam in 2004



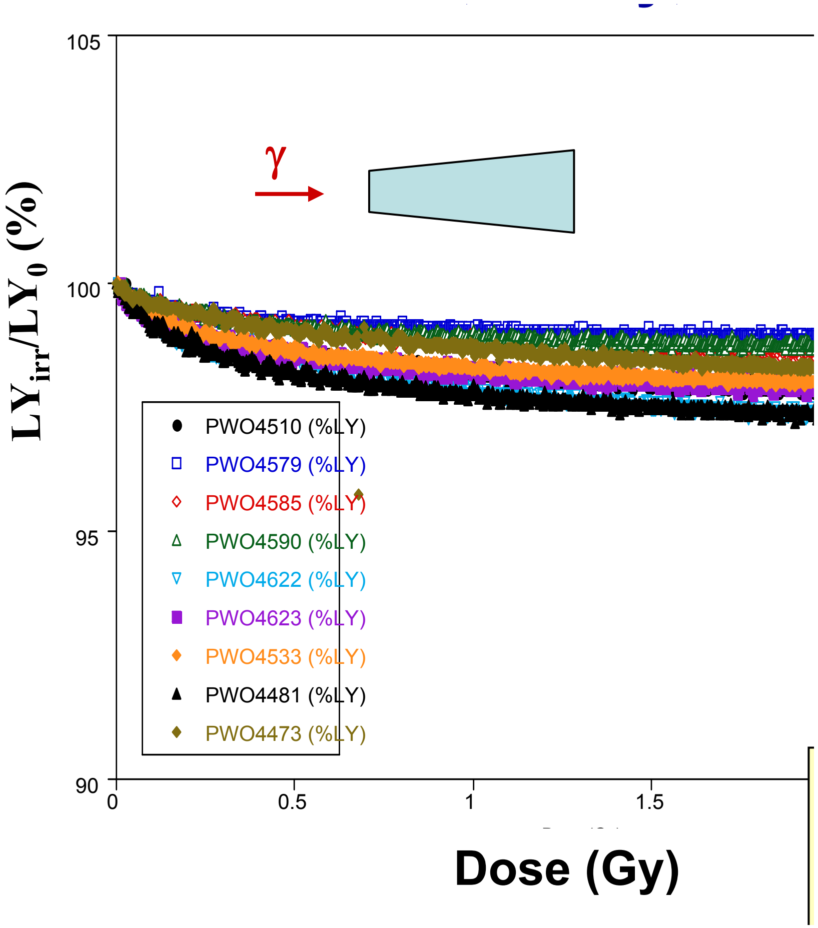
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

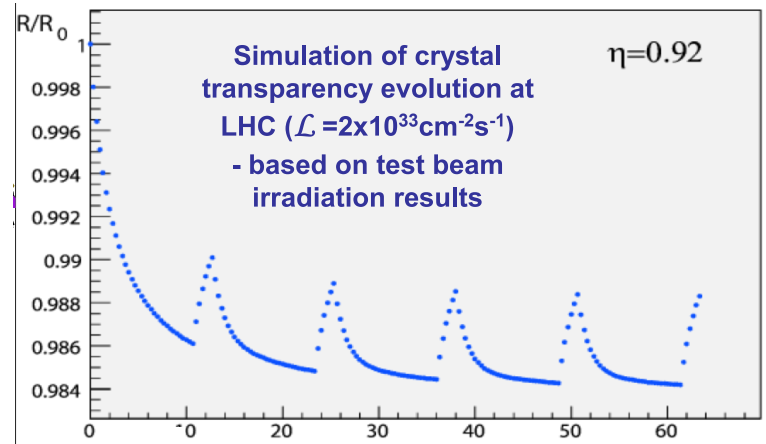
Excellent performance obtained in testbeam

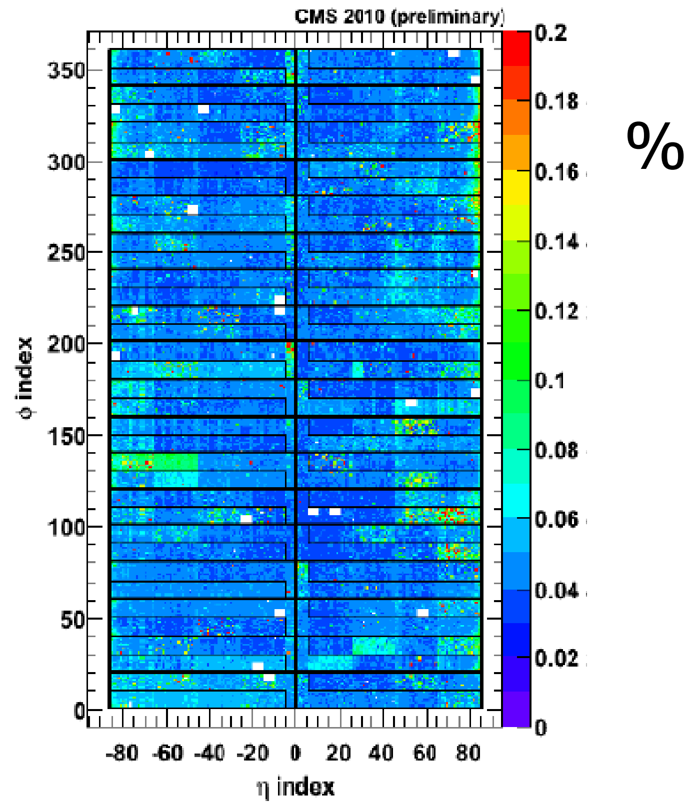
1/4 of barrel modules

How to preserve it at LHC ?

Sensitive to radiation dose







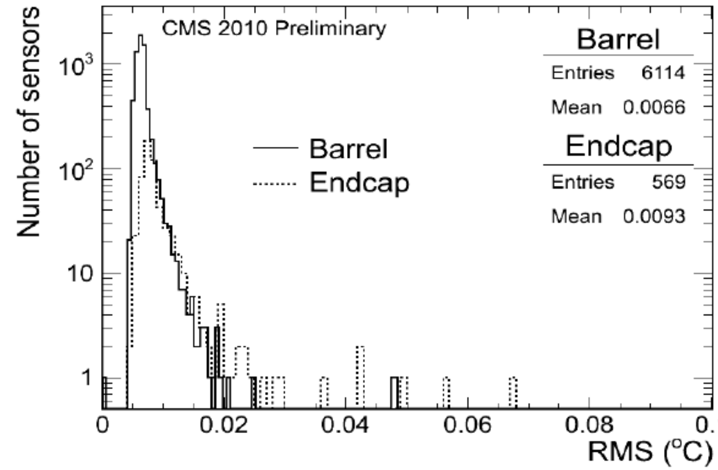
Large effect which needs to be corrected for

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

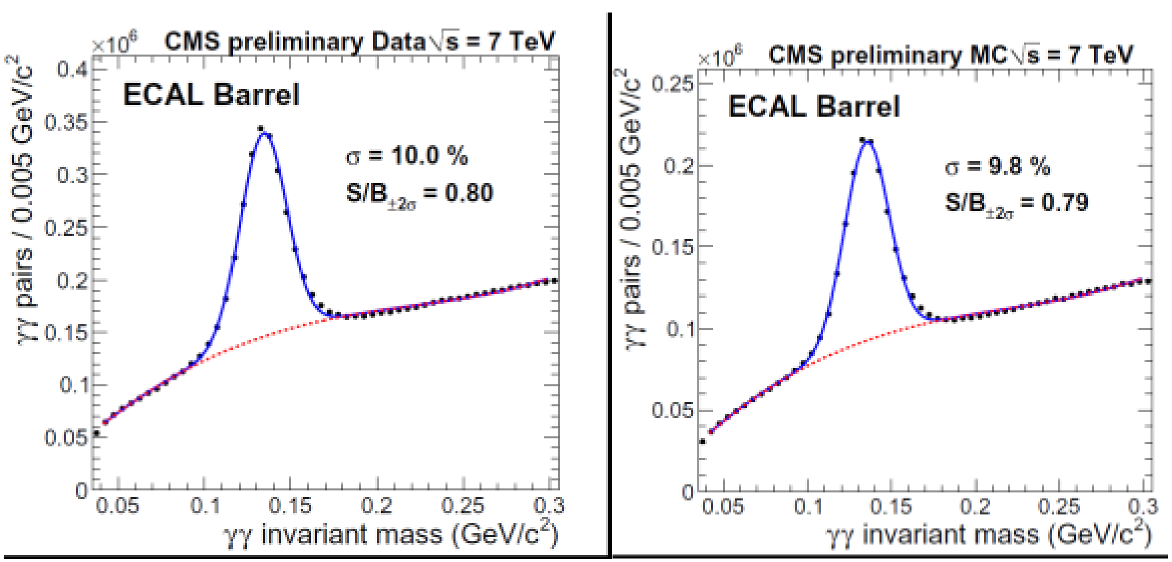
Crystal calibration in CMS

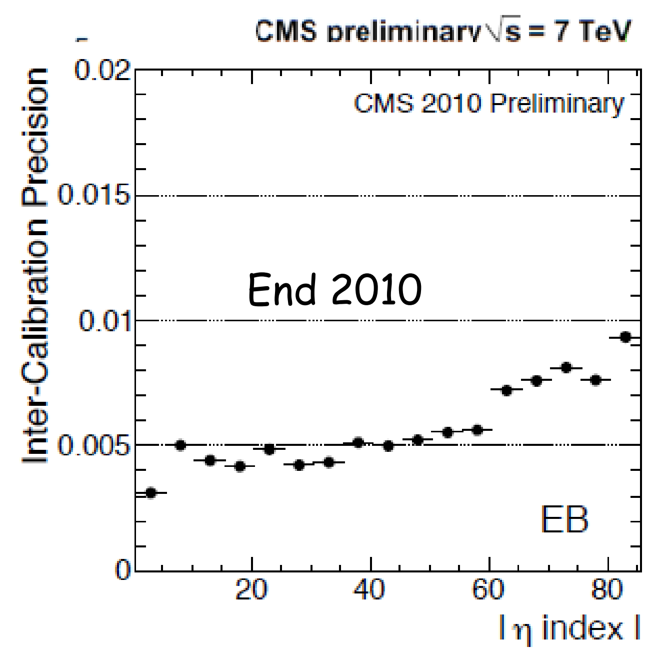
Inter-calibration: several steps

- 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

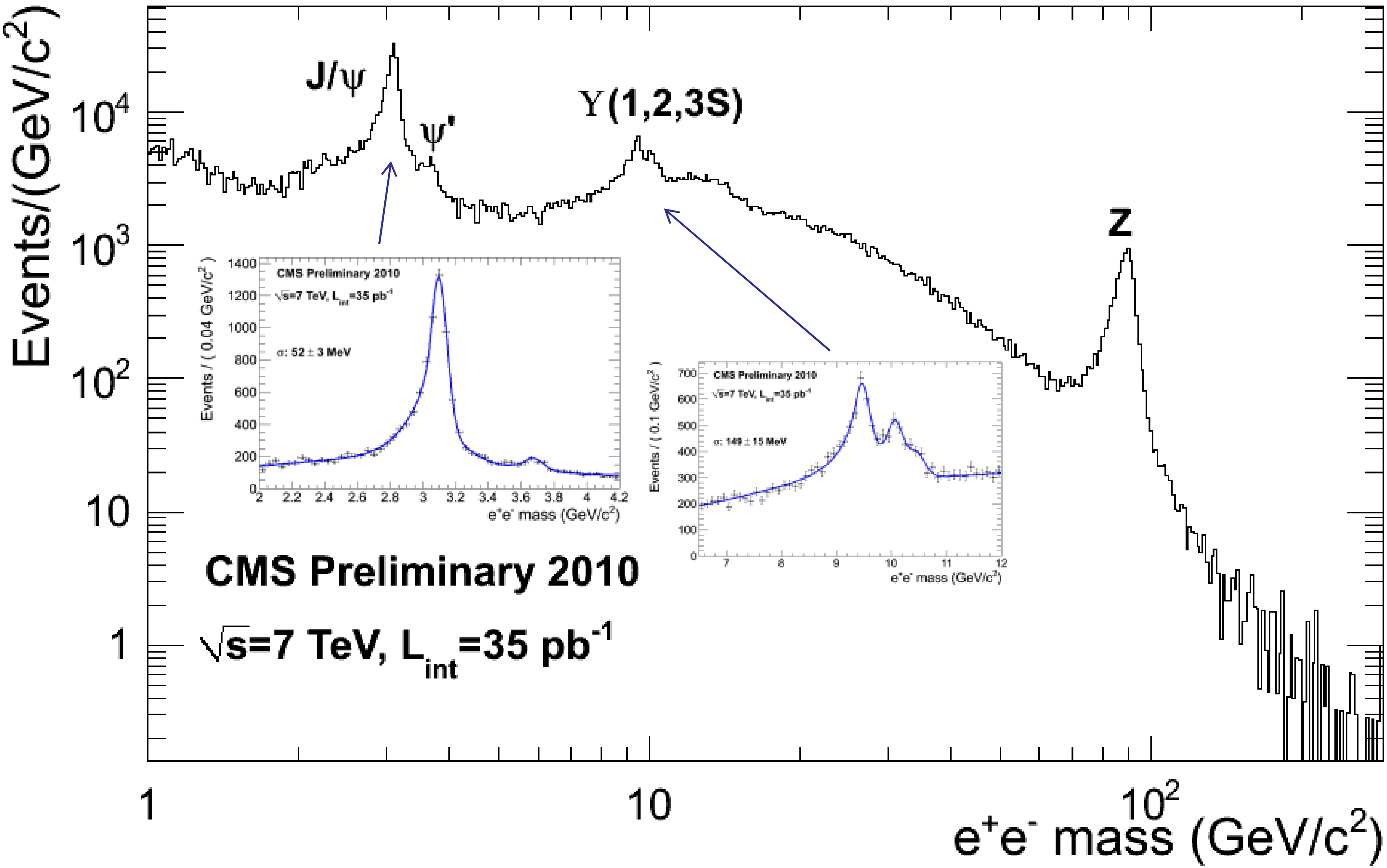


June 2010 - Dec 2010

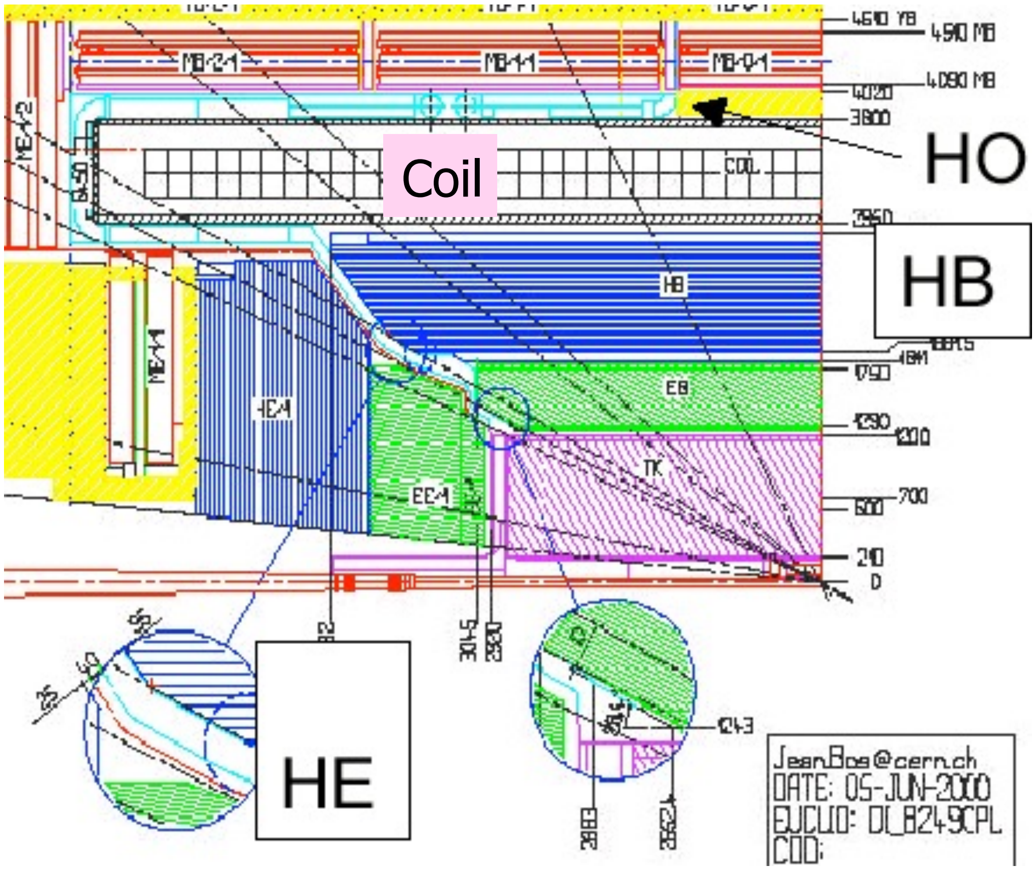




Performance in-situ CMS



CMS Hadronic calorimeter



Central : $|\eta| < 1.7$ Cu/scintillator + WLS

2 + 1 (HO) layers

5.9 + 3.9 λ ($|\eta| = 0$)

Endcap $1.3 < |\eta| < 3$ Cu/scintillator + WLS

2/3 layers

Forward $2.85 < |\eta| < 5.19$

Fe/quartz fibers (radiations)

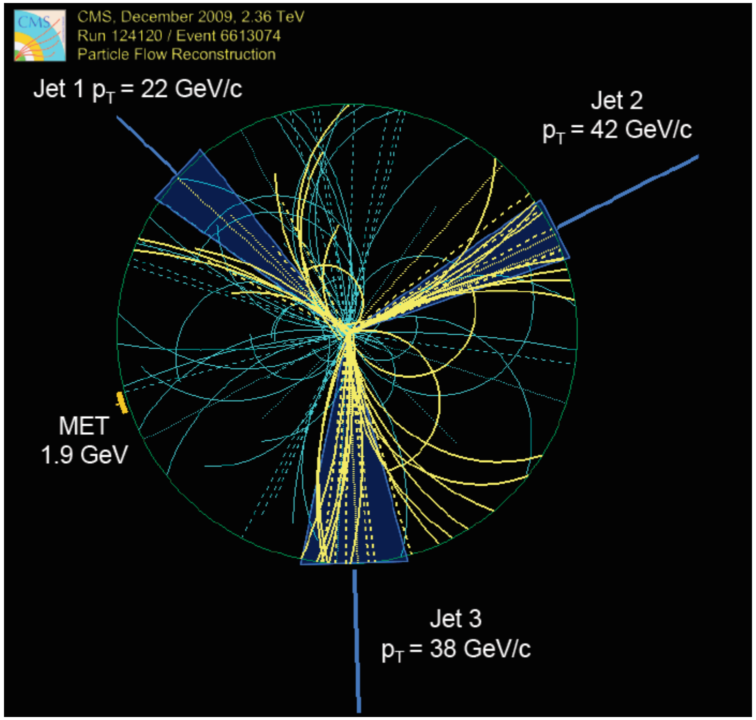
Copper: non magnetic material

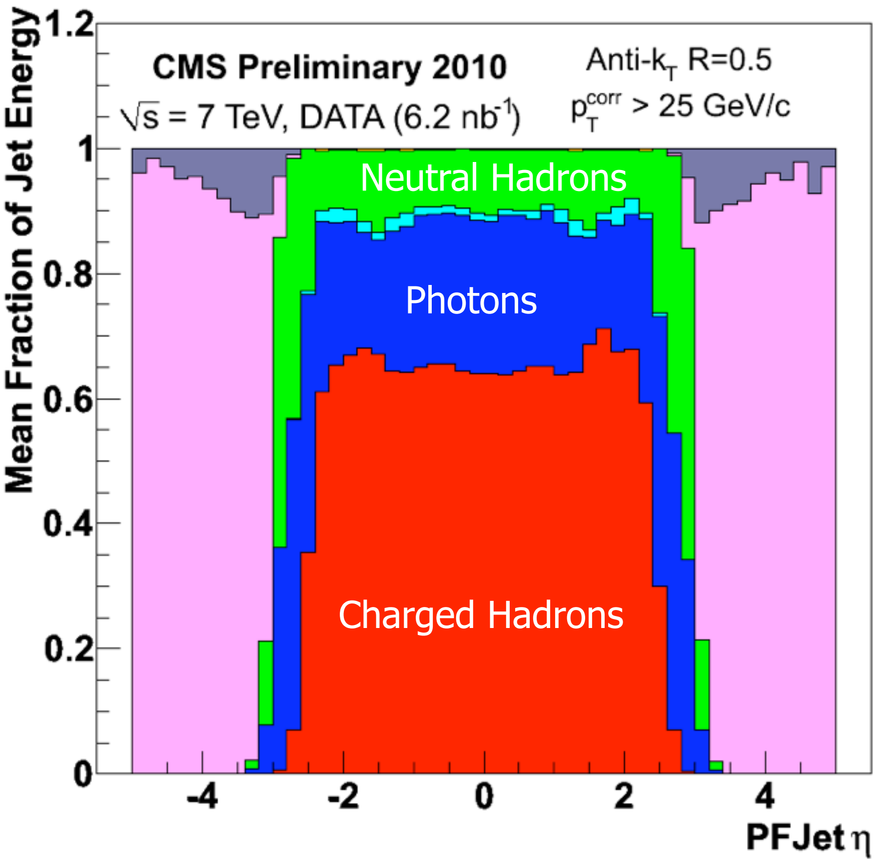
CMS Hadronic Response

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

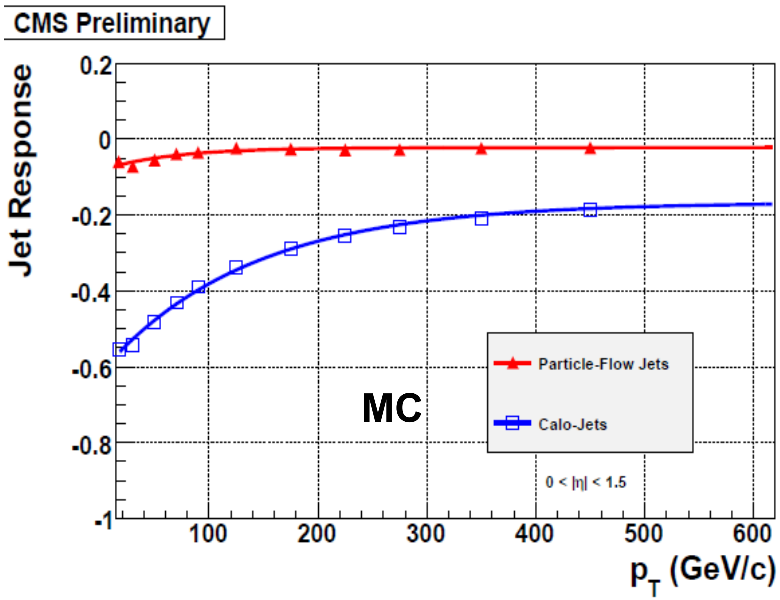
use the best measurement for each component

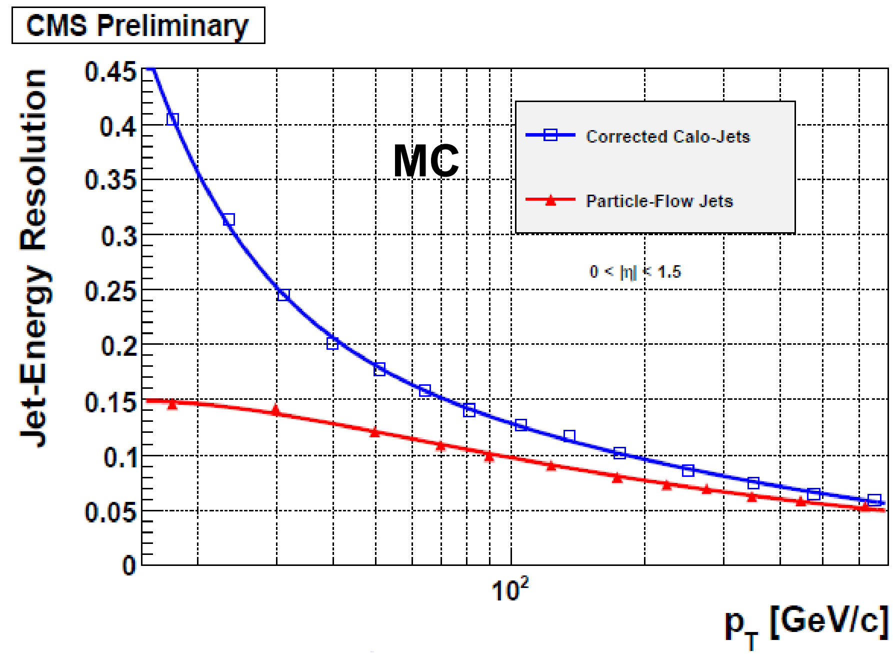
- Tracker for charged hadron
- ECAL for electrons & photons
- HCAL for neutral hadrons

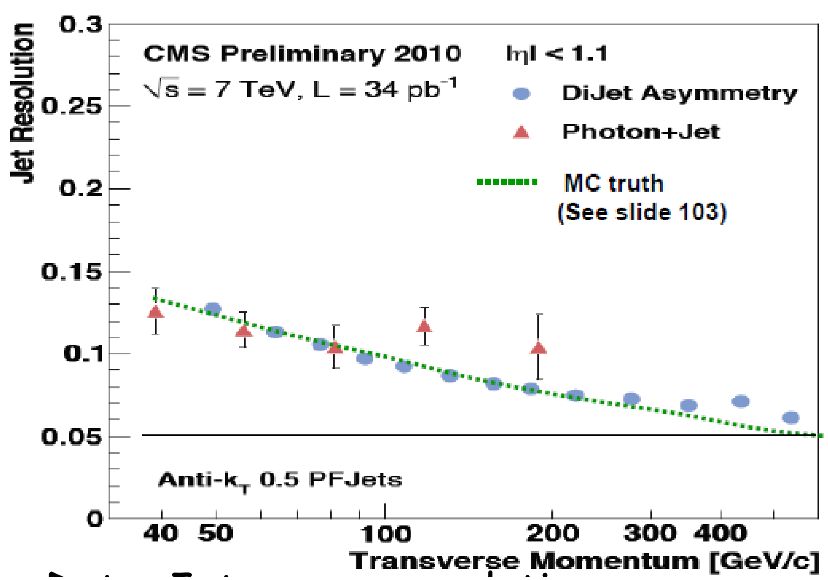




CMS-Particle Flow Jet Reconstruction Performance

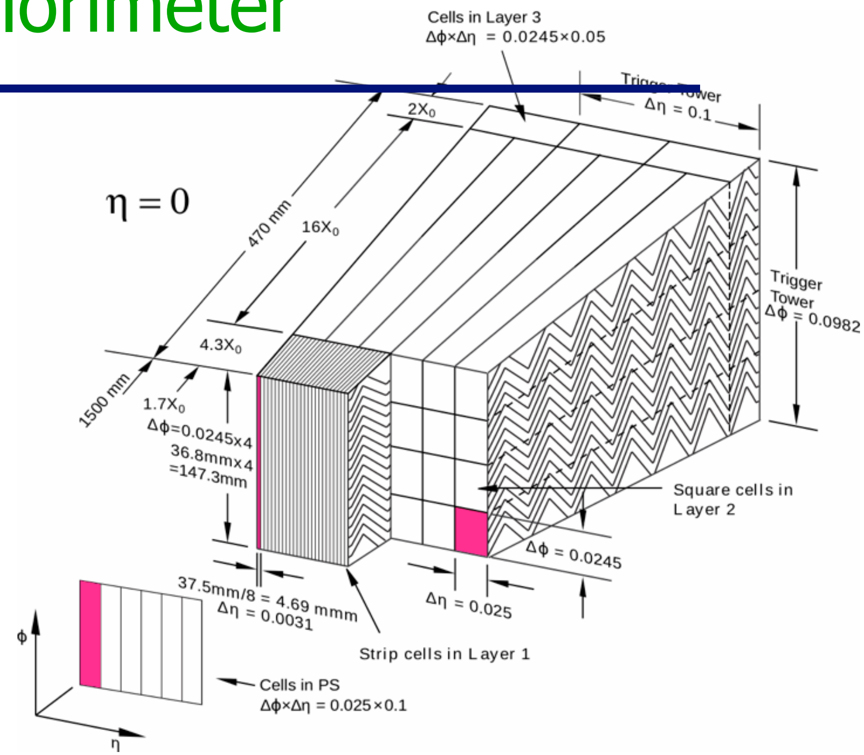






ATLAS calorimeter

ATLAS EM calorimeter



Accordion Pb/LAr $|\eta|<3.2$ ~170k channels

- Precision measurement $|\eta|<2.5$

3 layers up to $|\eta|=2.5$ + presampler $|\eta|<1.8$

2 layers $2.5<|\eta|<3.2$

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

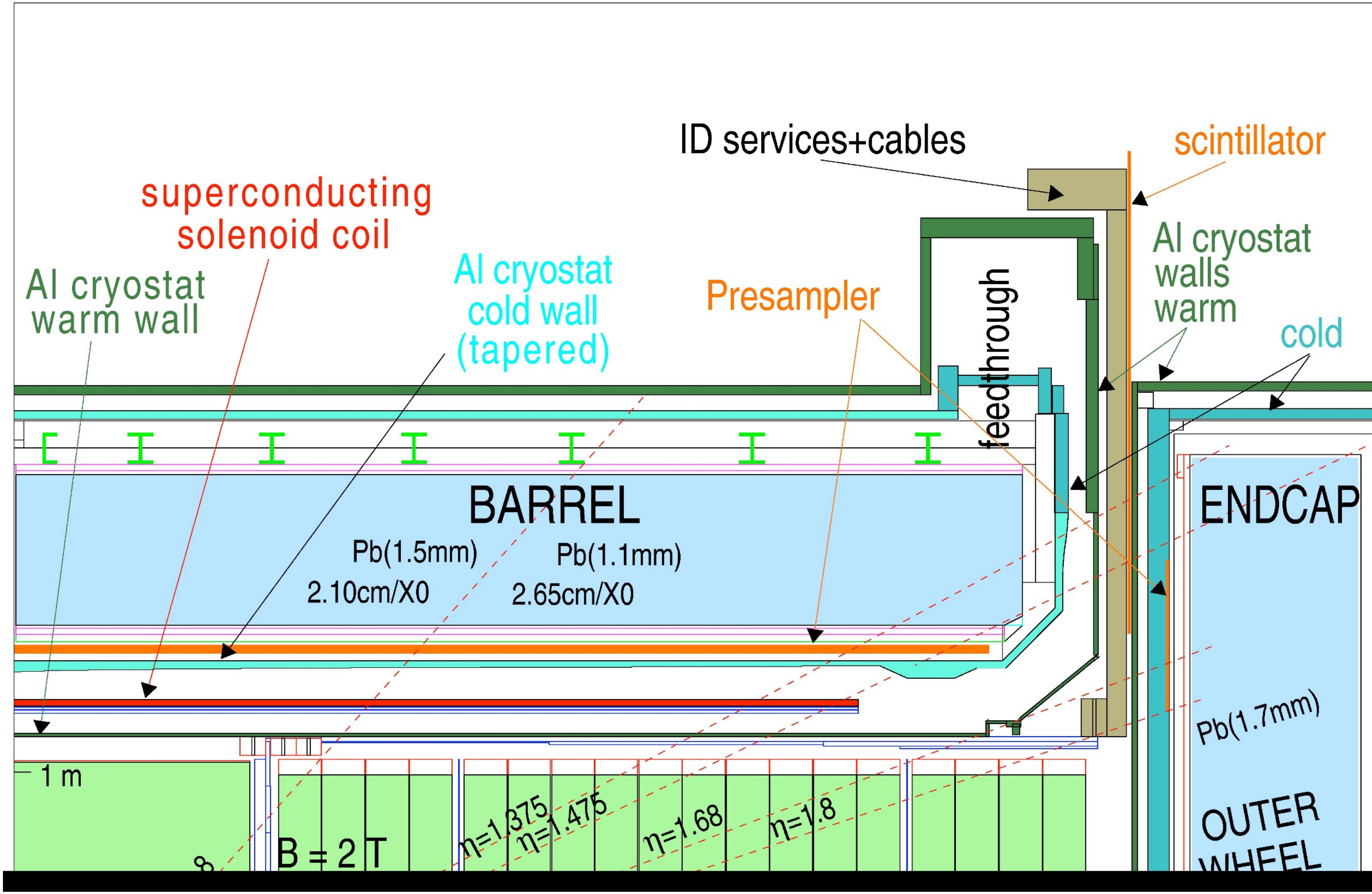
Energy Resolution: design for η~0

- $\Delta E/E \sim 10\%/\sqrt{E} \oplus 150\ \mathrm{MeV}/E \oplus 0.7\%$

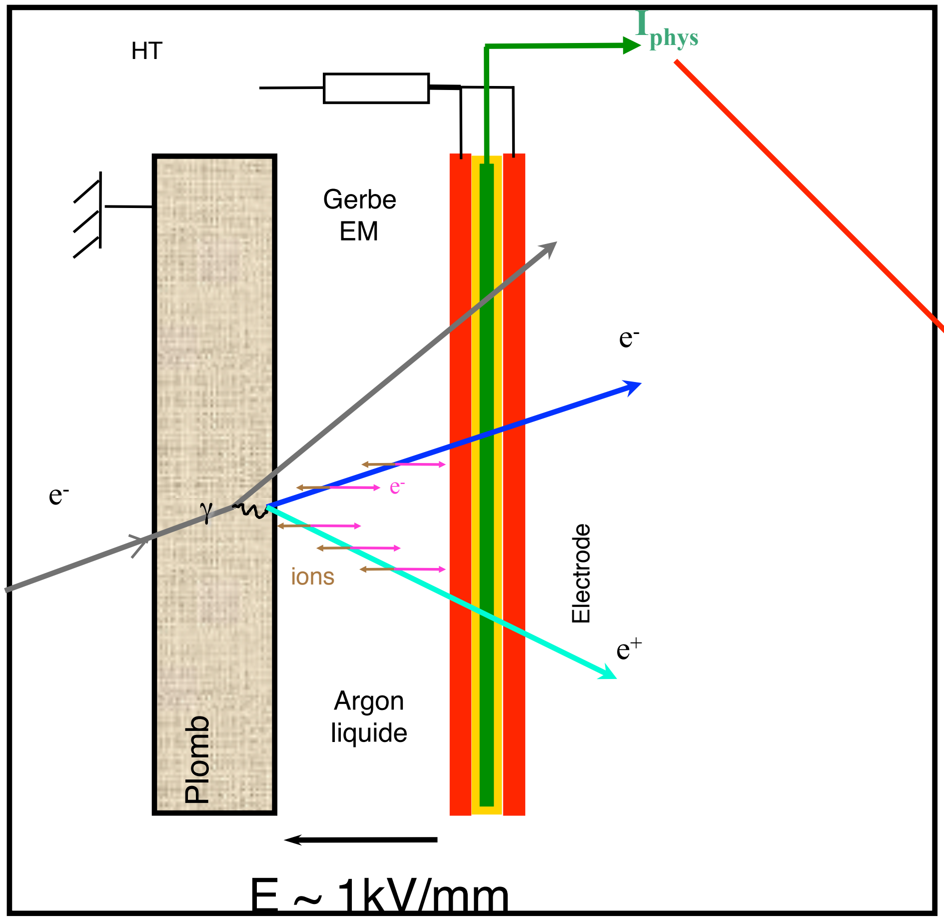
Angular Resolution

- 50mrad/$\sqrt{E(\mathrm{GeV})}$

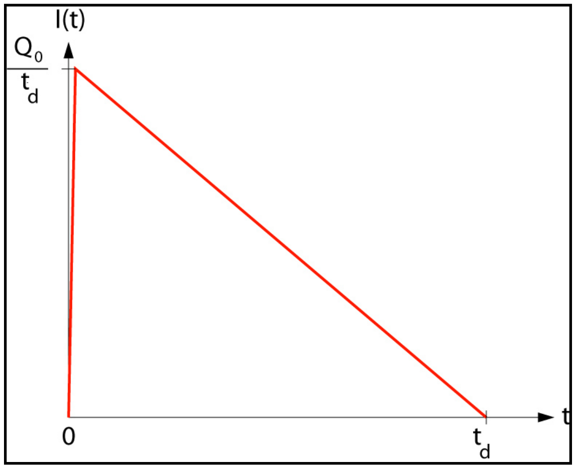
The cryostat structure



Principle



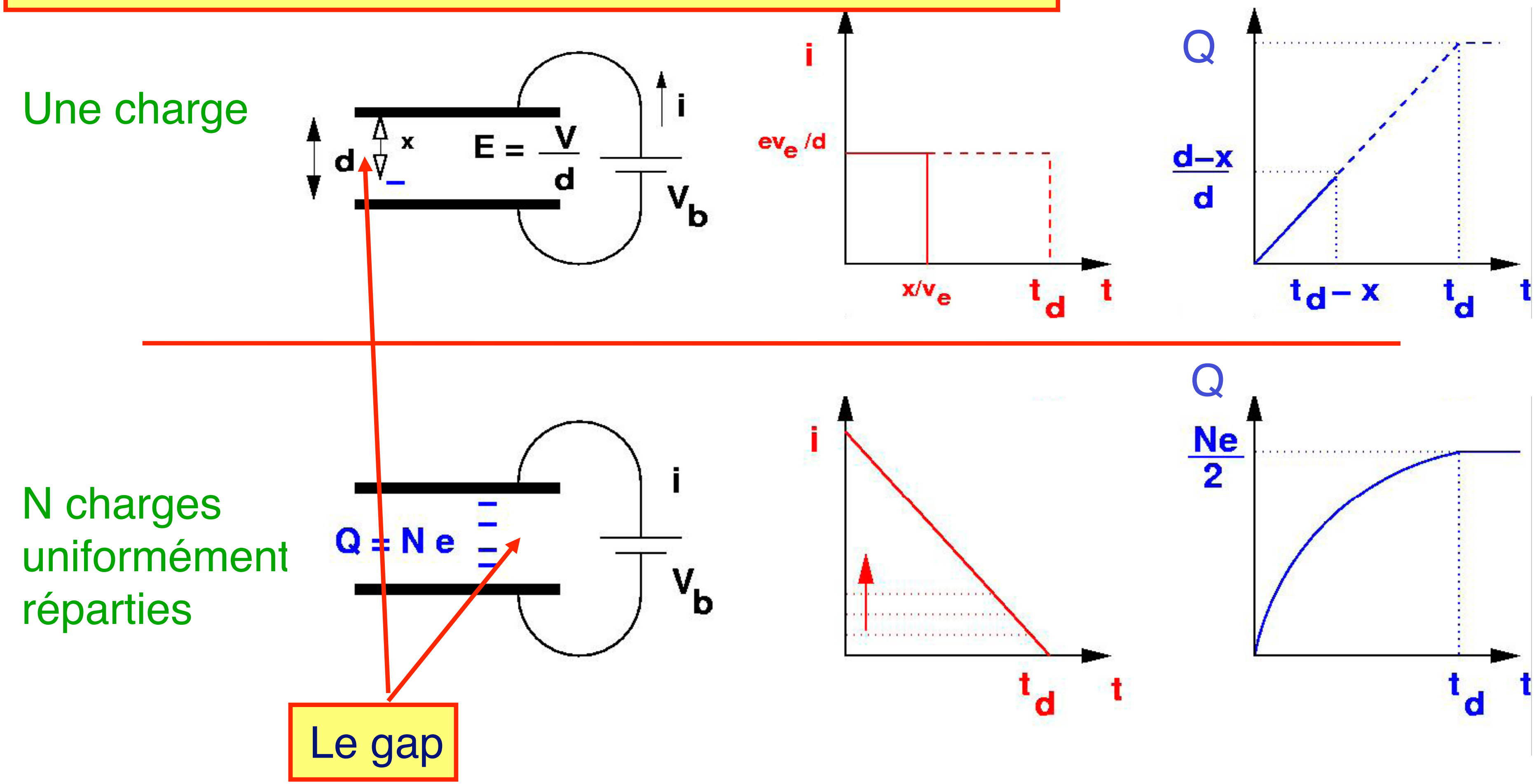
Pic ∝ ∫ signal déposé



400 ns ≈ 16 LHC BC

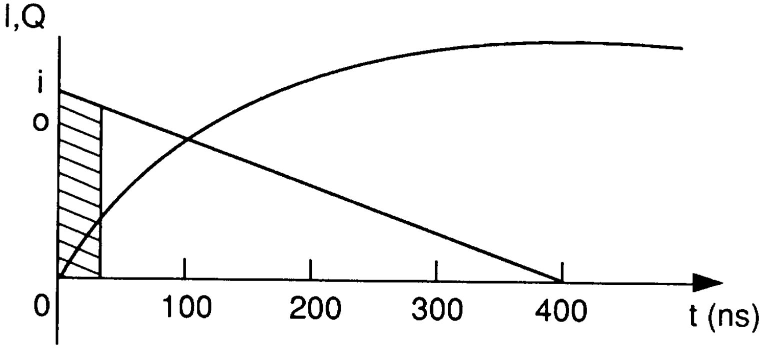
Collection du signal dans l'argon liquide

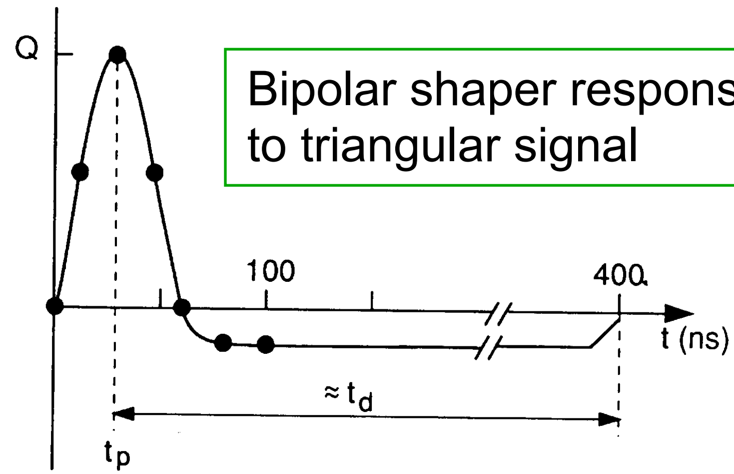
Collection des électrons induits par l'ionisation des atomes due au passage des particules chargées de la gerbe dans le liquide noble



Obtaining a fast response

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





Bipolar shaper response to triangular signal

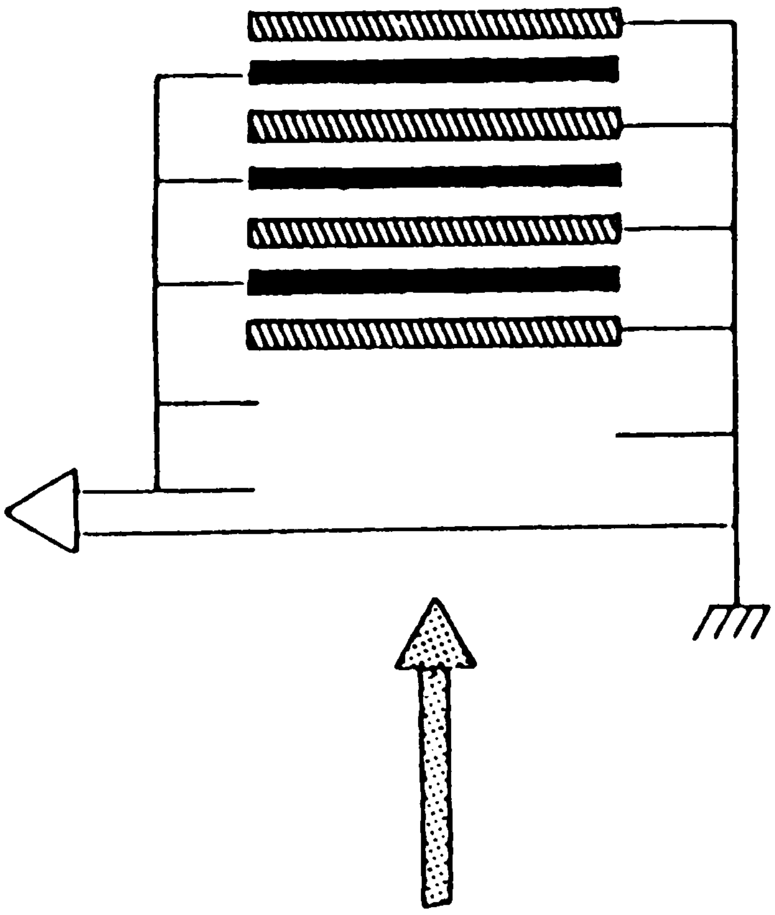
S/N is smaller than in the case $t_p = t_D$

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

→ detector response time is not t_d but t_p

~30 smaller for 40 ns than for 400 ns

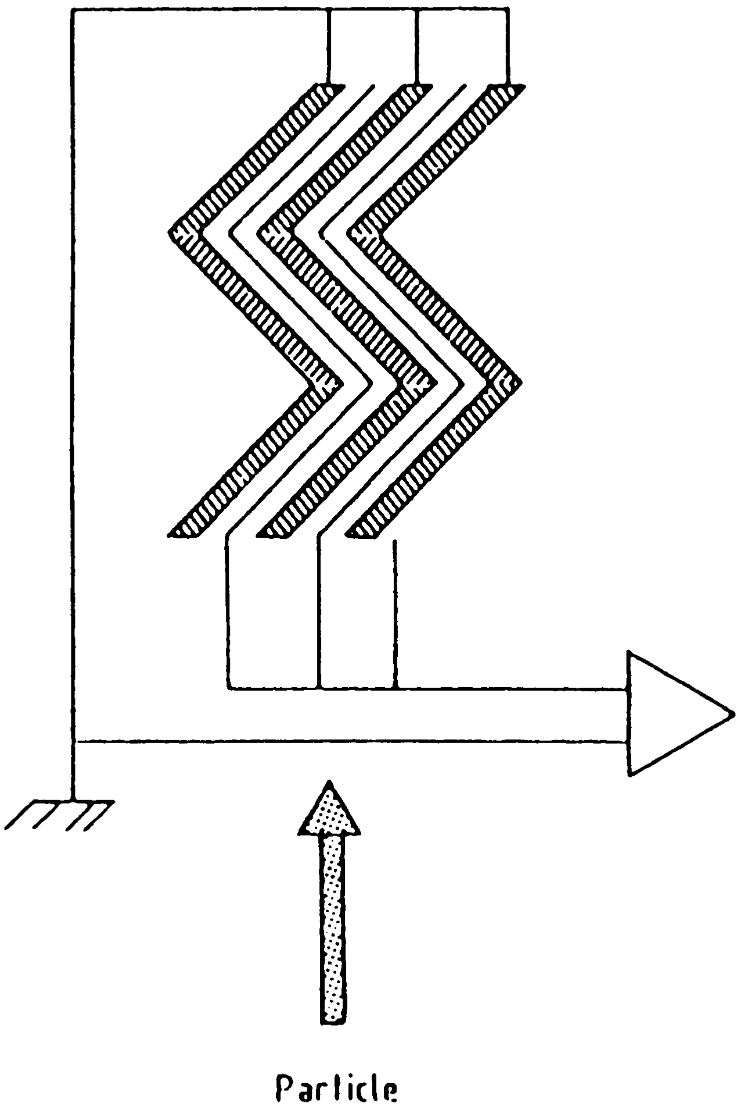
Parallel plates geometry



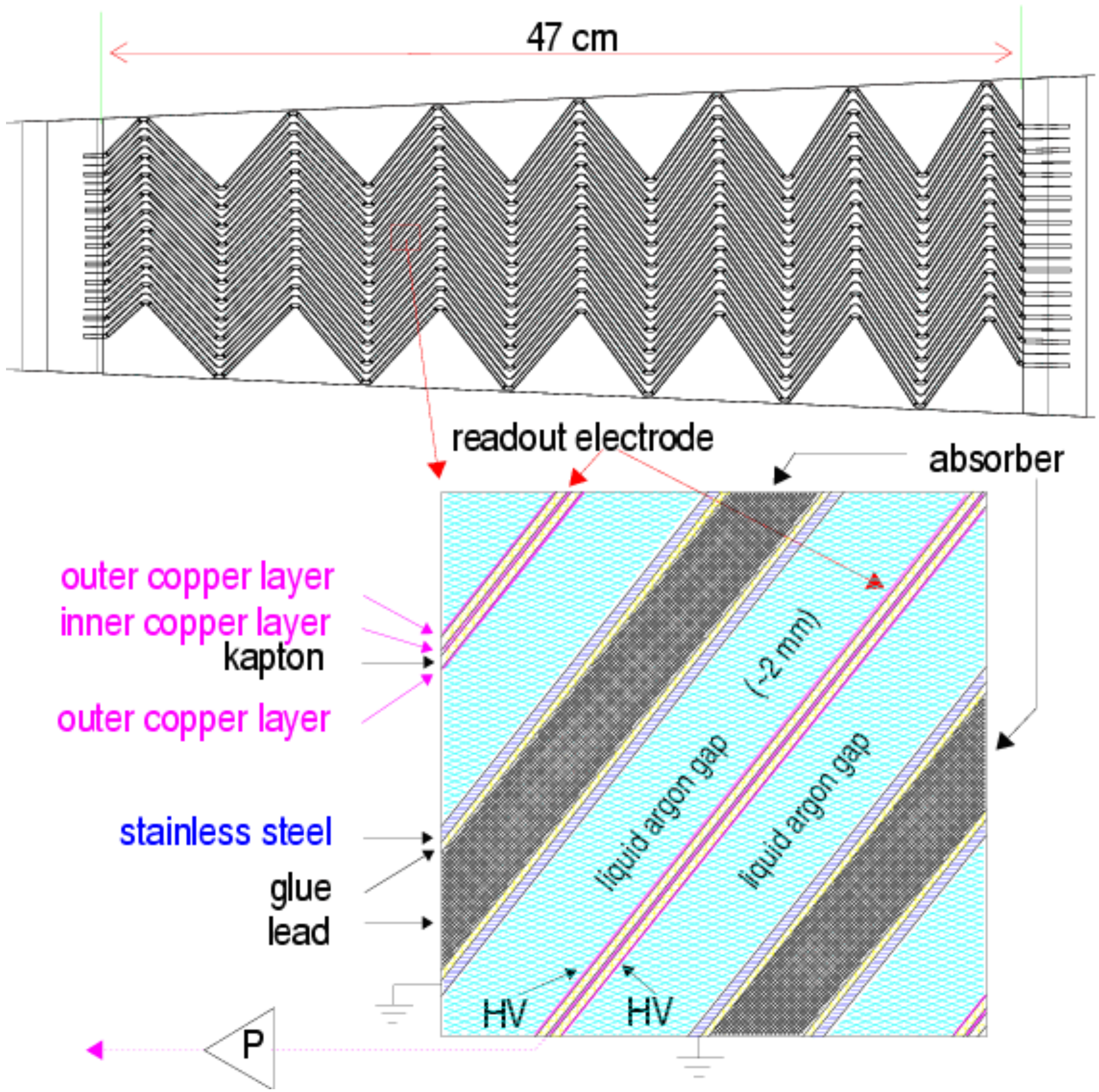
- Les anciens calorimètres à argon liquide avaient un temps de réponse lent (intégration du signal).
- Electrodes perpendiculaires aux particules
- Longs câbles
    - pour emmener les signaux vers les preamplis (transfert ~qques ns)
    - regrouper ensemble des gaps
- Zones mortes dues aux câbles

Accordeon geometry

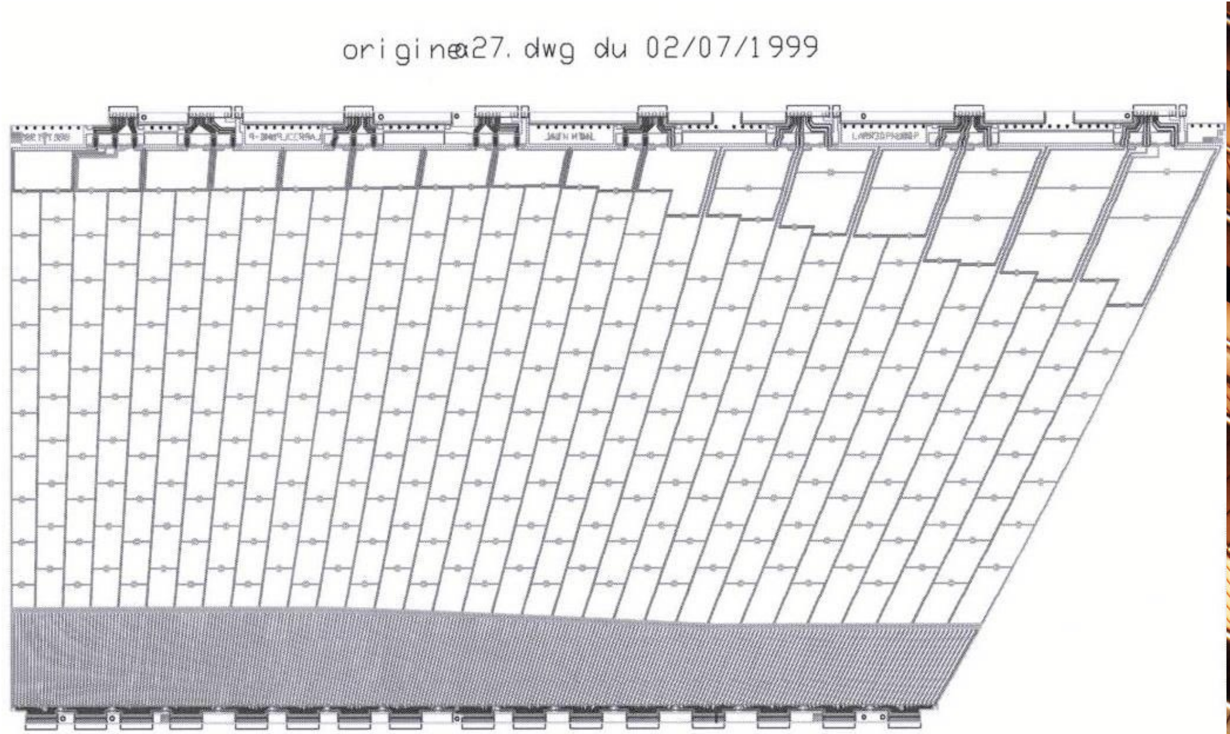
- Géométrie à accordéon: rapide
- Les électrodes sont parallèles aux particules incidentes
  - lectures des signaux à l'avant et à l'arrière
  - pas de longues connexions
- Le découpage en profondeur est dessiné sur les électrodes
- Pas d'espace sans détection

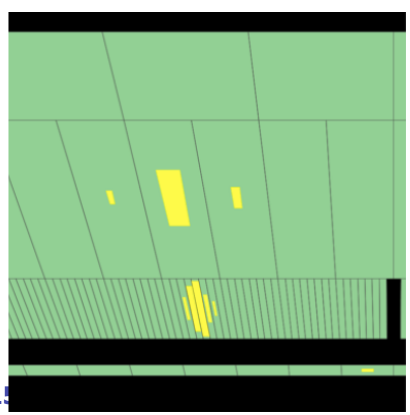


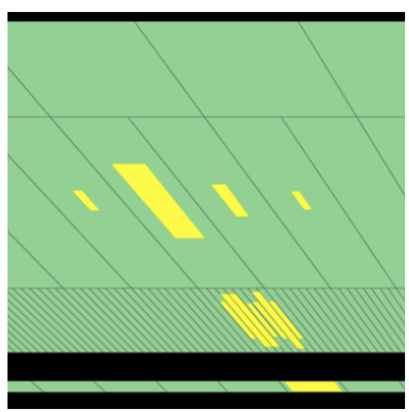
ATLAS EM calorimeter

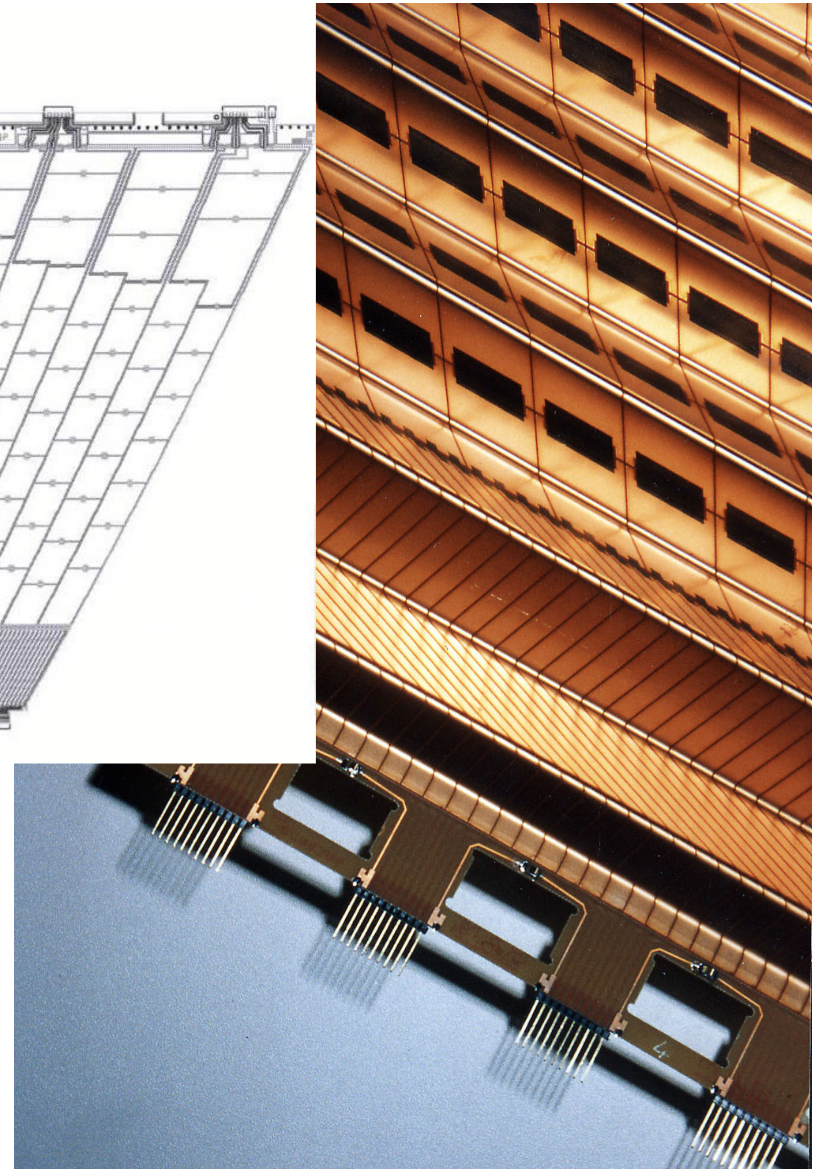


The segmentation

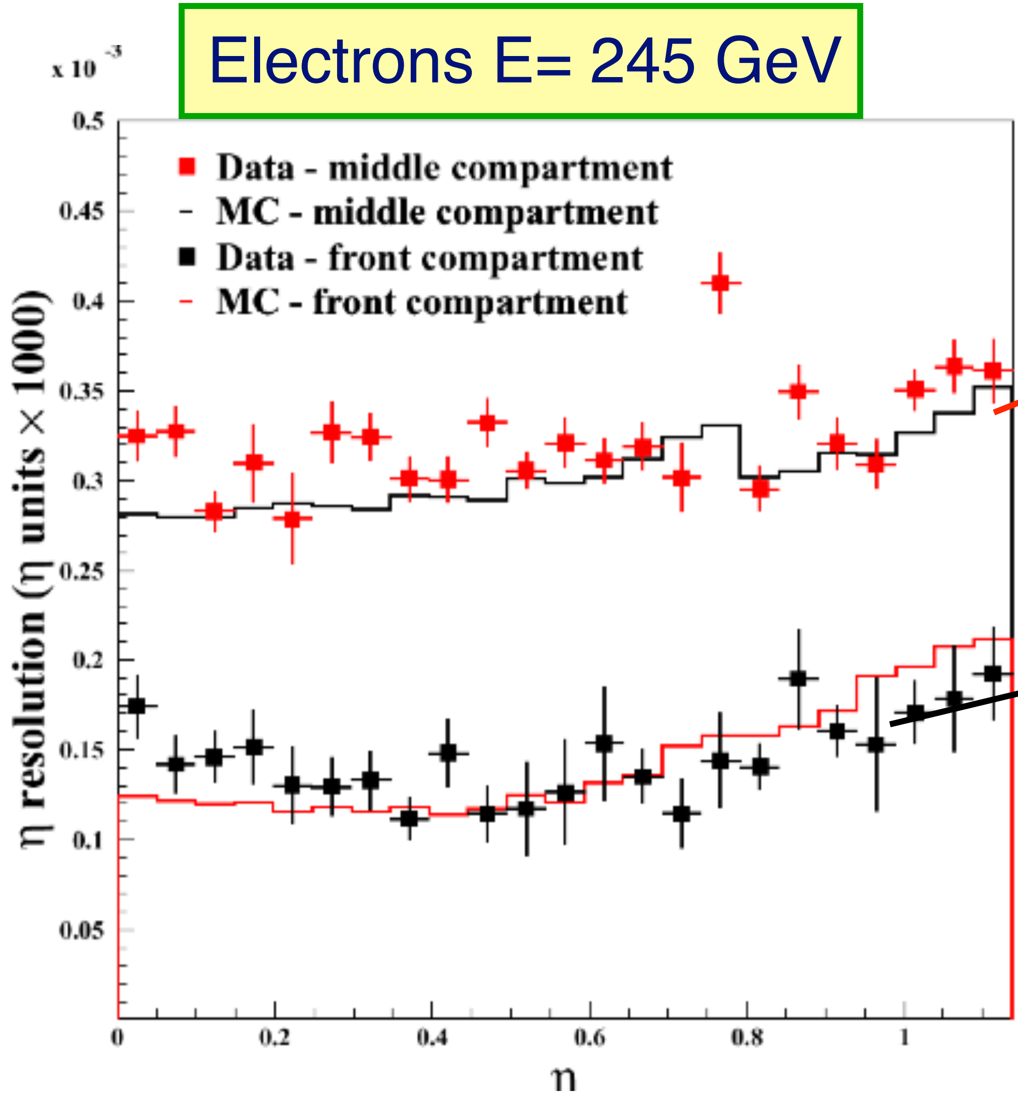


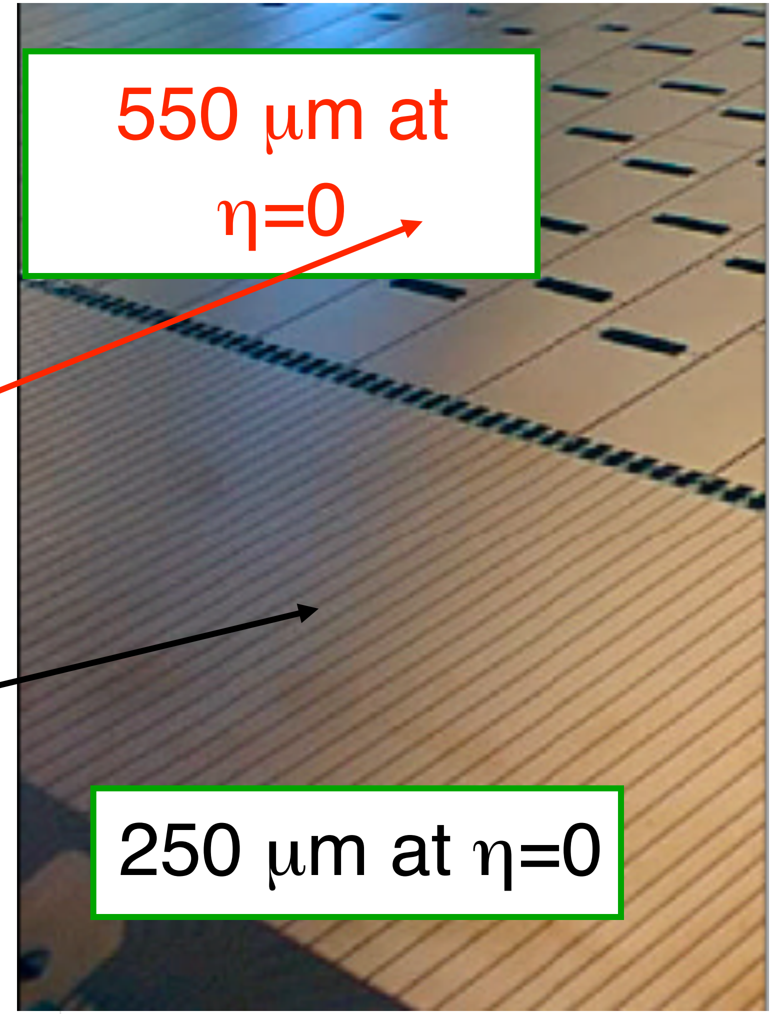






Position resolution





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

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

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