ÉCOLE DE PHYSIQUE
LES HOUCHES
XXVII

Detector at LHC : Calorimetry

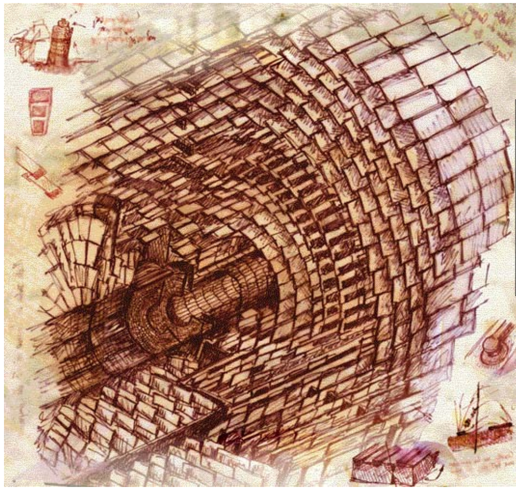
1. *Particles Energy Mesurements using Calorimeters*

2. *2.   Electron-Gamma*
3. *Electromagnetic Cascade*
4. *Energy resolution parameters.*

3. Hadron measurement
Hadronic Cascade
Hadronic Calorimeter Performances

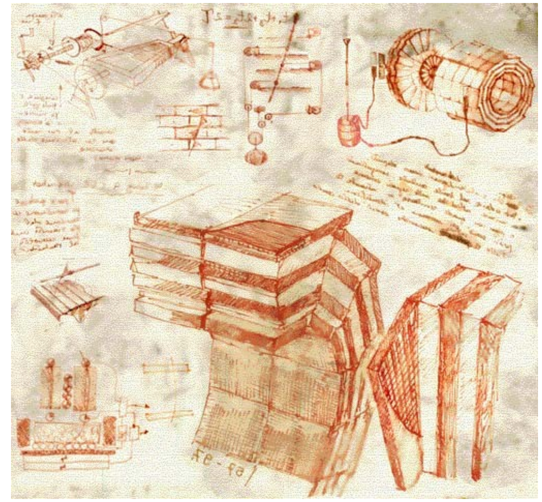
4.   Calorimeters
ATLAS
CMS
5. What was not address

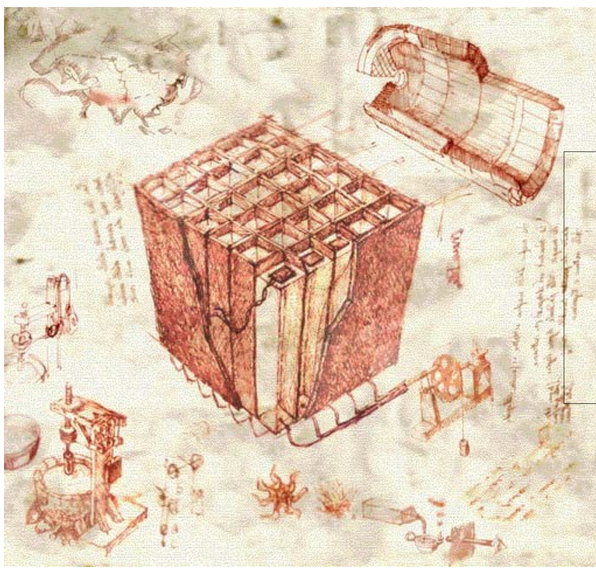
Outline



Yesterday

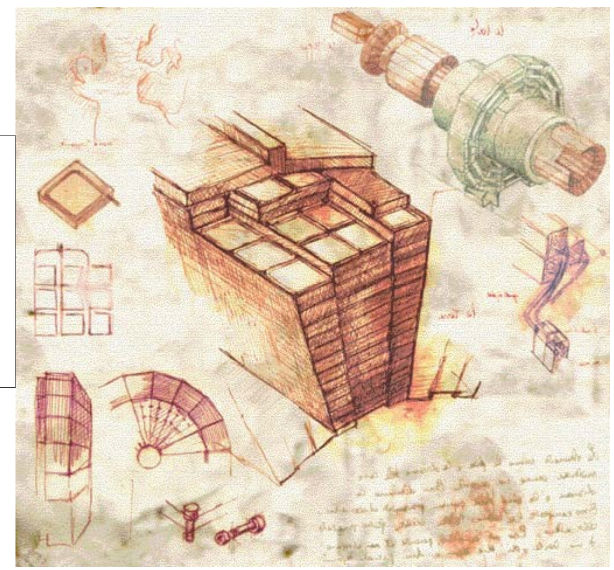
Traker Muon



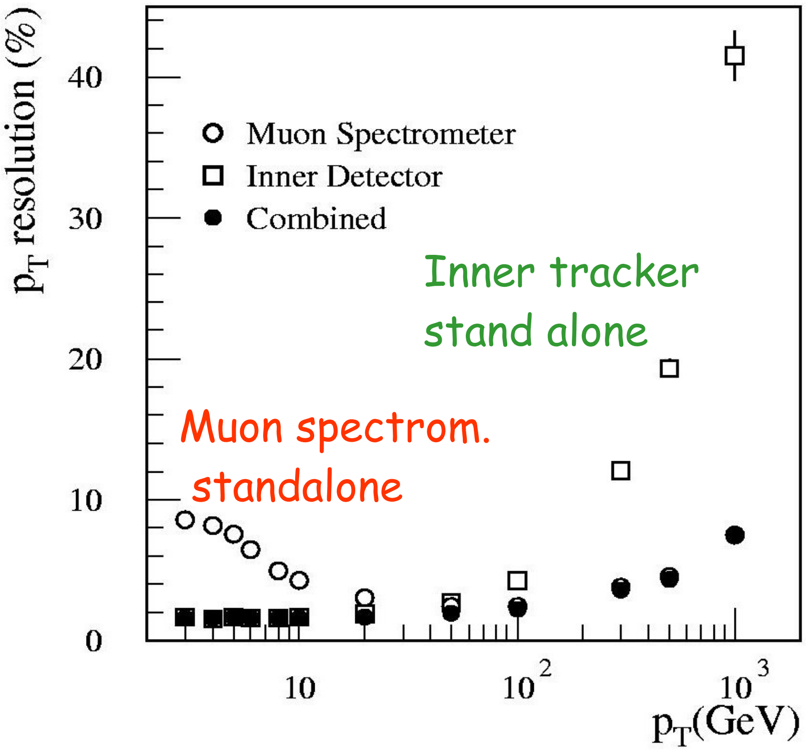


Today
Calorimetry

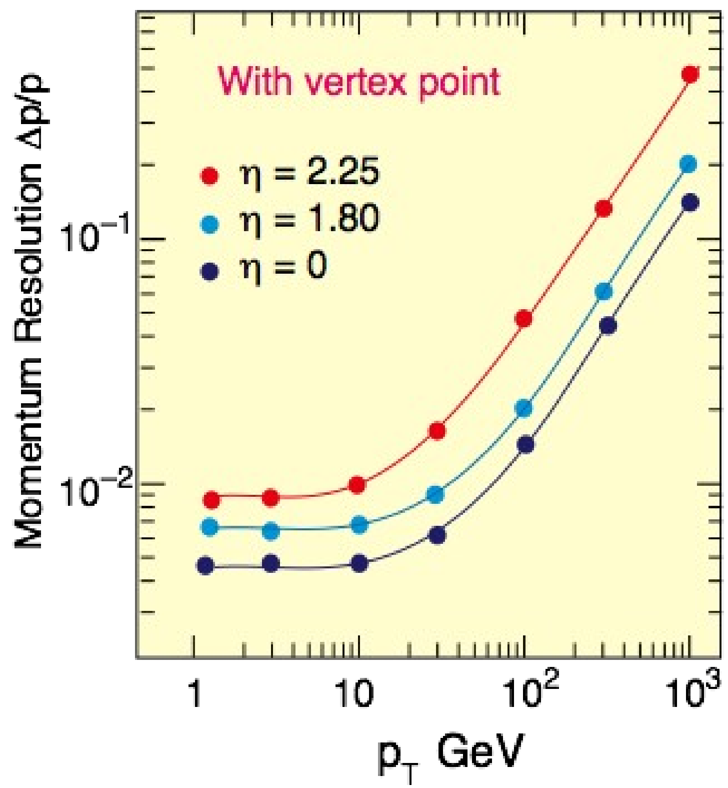
Ecal Hcal



Answer 1



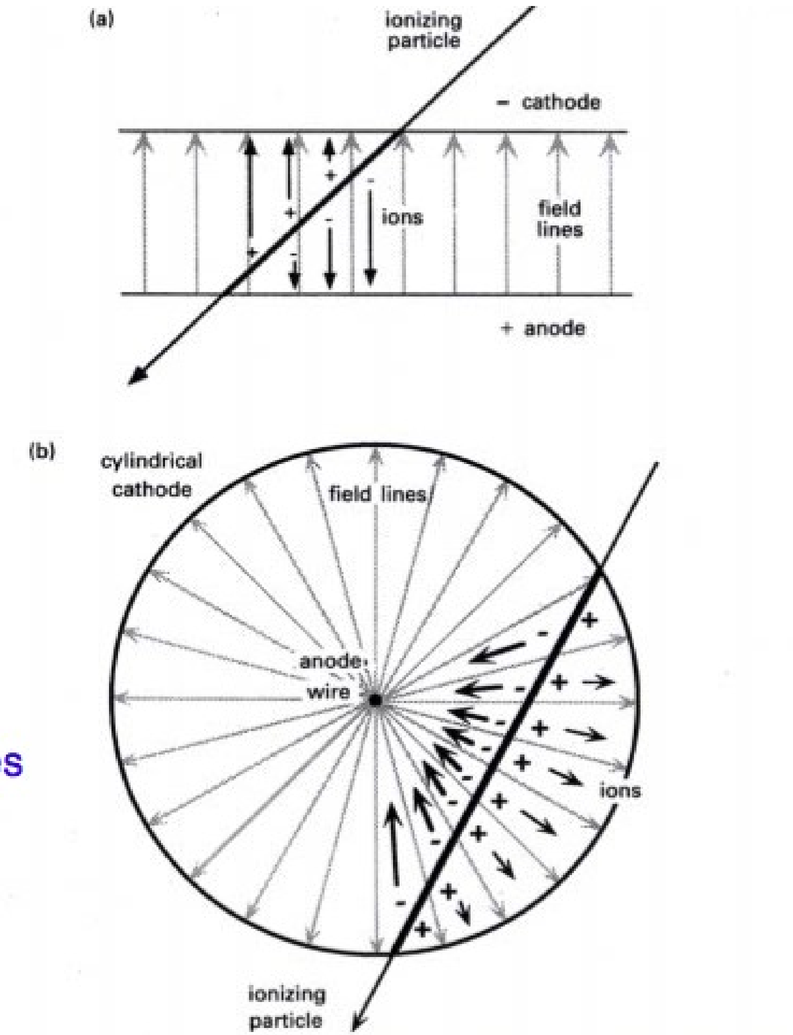
Estimated Momentum Resolution v/s p_T in CMS



Answer 2

e.g. ALICE Parallel Plate Chambers

e.g. ATLAS Straw Chambers
ATLAS Muon Monitored Drift Tubes



(a) A parallel plate ionization chamber; (b) a cylindrical ionization chamber.

Answer 3

For **"heavy" charged particles** ($M >> m_e$: p, K, π, μ), the rate of energy loss (or stopping power) in an inelastic collision with an atomic electron is given by the Bethe-Block equation:

$$-\frac{dE}{dx} = 2\pi N_A r_e^2 m_e c^2 \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta(\beta\gamma) - 2\frac{C}{Z}\right] \quad \left[MeV\ \frac{cm}{g}\right]$$

$\delta(\beta\gamma)$: density-effect correction

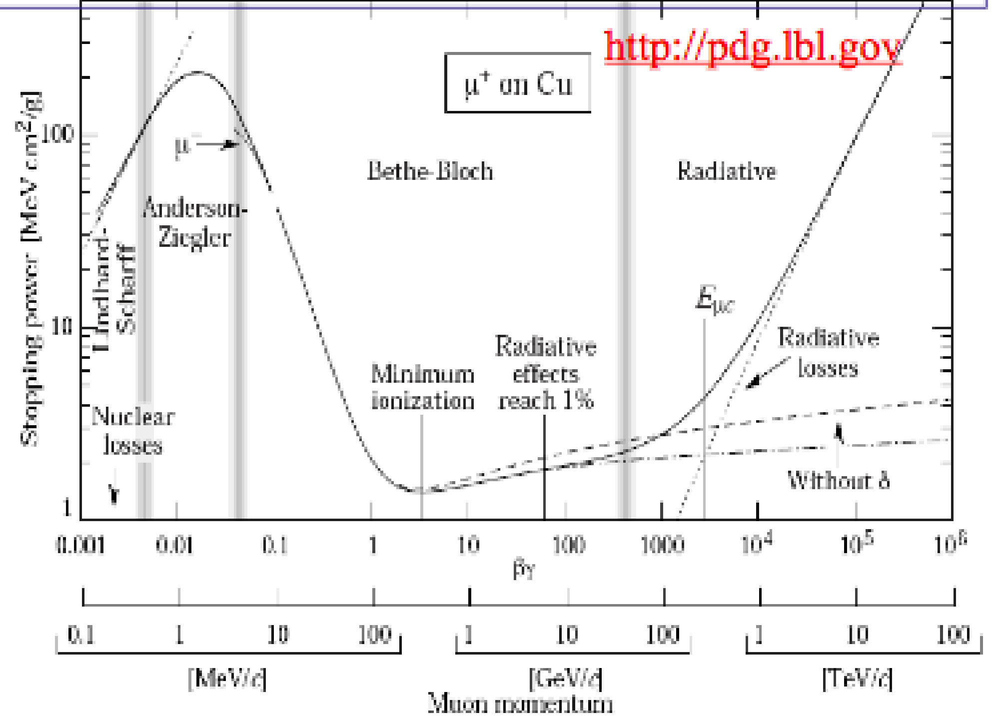
C: shell correction

z: charge of the incident particle

$\beta = vc$ of the incident particle ; $\gamma = (1-\beta^2)^{-1/2}$

W_{max}: maximum energy transfer in one collision

I: mean ionization potential



Notes

Bibliography

- ***Experimental Challenges in High-Luminosity Collider Physics***
  N. Ellis and T. Virdee (Ann. Rev. Nucl. Part. Sci. 44 (1994) 609

  D. Fournier and L. Serin, Experimental Techniques, European School of Particle Physics, CERN 96-04

- ***T. S. Virdee, Experimental Techniques, European School of Particle Physics, St. Andrews, CERN 99-04***

- ***CERN Academic Training Lectures***

- ***ATLAS and CMS outreach pages***

Important Lecture Note

- ***In this lecture I use many exemples from CMS , only because of my better knowledge of this experience. This must not be taken as a ranking between ATLAS and CMS.***

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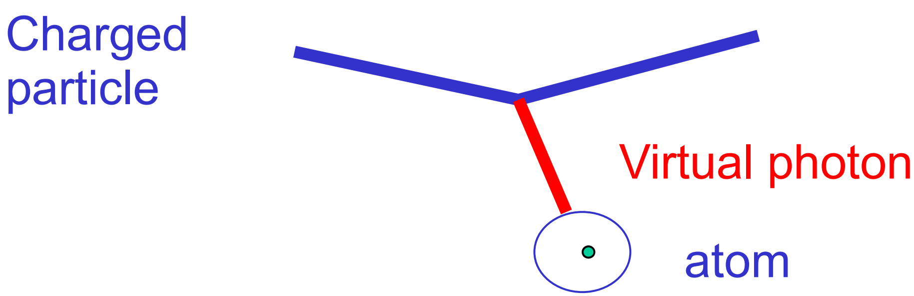
Particle Detection

To detect particles energy must be transferred to the detecting medium

Energy Loss by Charged Particles
Lose energy via interactions of virtual photons with atomic electrons



Can consider the medium as consisting of a gas of electrons

The energy transferred to the electrons causes them to be ejected from the parent atom **(ionization)** or to be excited to a higher energy state **(excitation)**

Particle detection is based on one or both of these processes

Measurement of Energy: Calorimeters

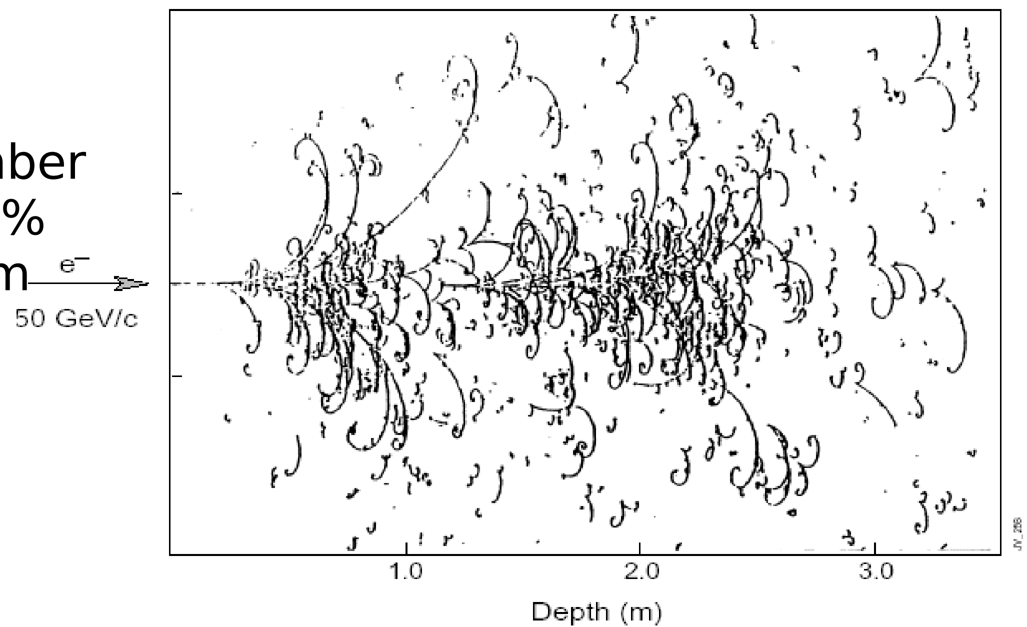
Neutral and charged particles incident on a block of material deposit their energy through destruction and creation processes

The deposited energy is rendered measurable by ionisation or excitation of the atoms of matter in the active medium.

The active medium can be the block itself *(totally active or homogeneous calorimeter)* or a sandwich of dense absorber and light active planes *(sampling calorimeters)*.

The measurable signal is usually linearly proportional to the incident energy.

Big European Bubble Chamber
filled with Ne:H2 = 70%:30%
3T field, L=3.5m, X0=34 cm
50 GeV incident electron

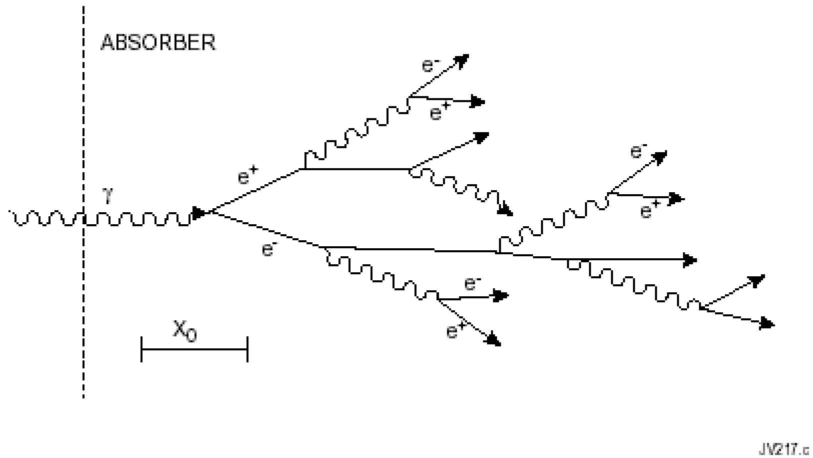


Part.II

Electron-Gamma
Electromagnetic Cascade
Energy resolution Parameters

Electromagnetic Cascade

A high energy e or γ incident on a thick absorber initiates a cascade of $e^{\pm}$'s, γ's via bremstrahlung and pair production.



The multiplication continues until the energies fall below the critical energy ε.

Simplemodel of shower development - use scaled variables

$$t = \frac{x}{X_0} \quad and \quad y = \frac{E}{\varepsilon}$$

In 1 X_0, an electron loses about 2/3rd of its energy and a high energy photon has a probability of 7/9 of pair conversion - **naively take X_0 as a generation length**.
Assume that after each generation the number of particles increases by a factor of 2.

Electromagnetic Cascade: longitudinal

After t generations,

$$energy\ \ of\ \ particles\ \ \ e(t) = \frac{E}{2^t}$$

$$number\ \ of\ \ particles\ \ \ n(t) = 2^t$$

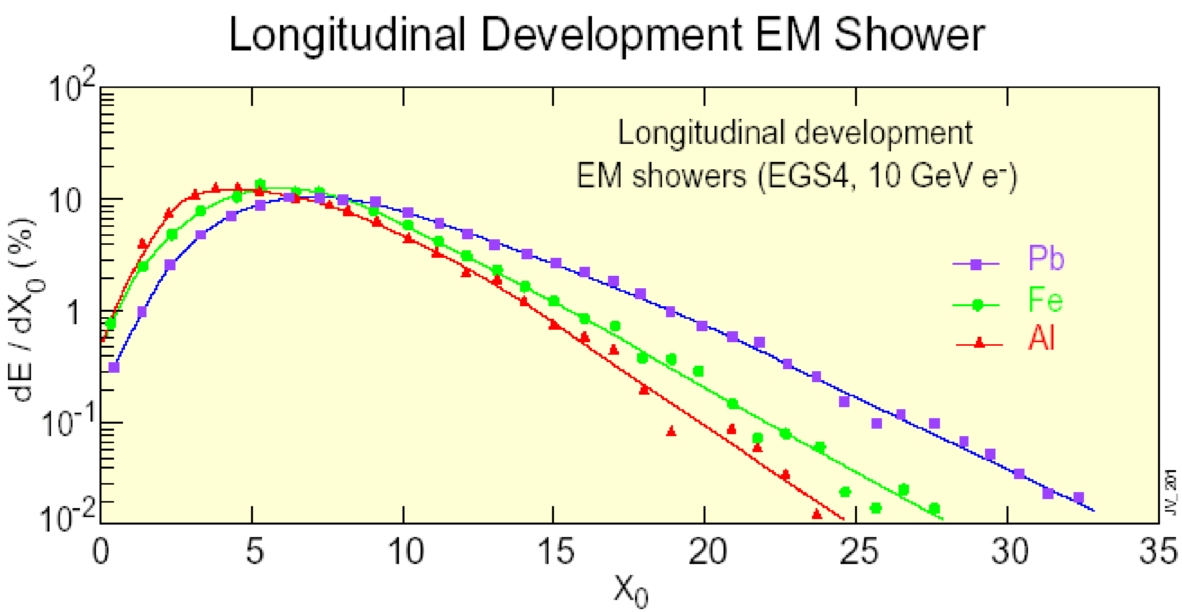
At shower max. where e ~ ε

$$no.\ of\ \ particles\ \ \ n(t_{\max}) \approx \frac{E}{\varepsilon} = y$$

$$and\qquad t_{\max} \approx \ln\frac{E}{\varepsilon} = \ln y$$

After shower maximum

remaining energy is carried forward by photons giving the typical exponential falloff



Need a depth of
> 25 X_0 to contain high
energy em showers

CSS99

Radiation Length and Moliere Radius

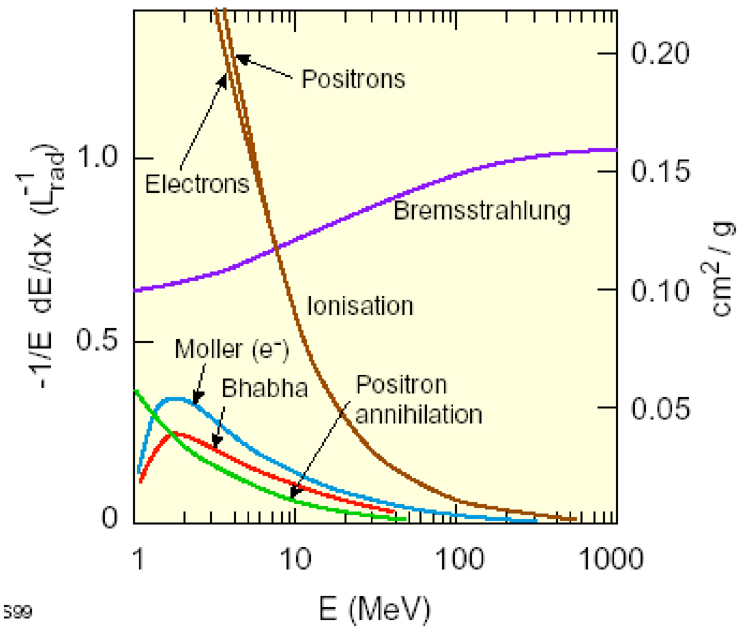
Critical Energy, ε

Defined to be the energy at which the energy loss due to ionisation* (at its minimum i.e. β≈0.96) and radiation are equal (over many trials)

$$i.e.\quad \frac{(dE/dx)_{rad}}{(dE/dx)_{ion}} = 1$$

$$\Rightarrow \quad \varepsilon = \frac{560}{Z} \quad (E \ \ in \ \ MeV)$$

Fractional Energy Loss by Electrons



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Moliere Radius, R_M

This gives the average lateral deflection of critical energy electrons after traversing 1 X_0 and can be parameterised as :

$$R_M = \frac{X_0 E_s}{\varepsilon} = \frac{21_{MeV} X_0}{\varepsilon} \approx \frac{7A}{Z} \quad g.cm^{-2}$$

	Z	ρ g.cm⁻³	I/Z eV	(1/ρ) dT/dx MeV/g·cm⁻²	X_0 cm	ε MeV	λint cm
C	6	2.2	12.3	1.85	~19	103	38.1
Al	13	2.7	12.3	1.63	8.9	47	39.4
Fe	26	7.87	10.7	1.49	1.76	24	16.8
Pb	82	11.35	10.0	1.14	0.56	6.9	15.1
U	92	18.7	9.56	1.10	0.32	6.2	10.5

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

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

Energy Resolution of Calorimeters

Parametrisation of the energy resolution of calorimeters:

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

symbol ⊕ implies the quadratic sum of the three terms on rhs

'stochastic or sampling' term (coeff. a) accounts for

- the statistical fluctuation in the number of primary signal generating processes

'noise' term (coeff. c) includes

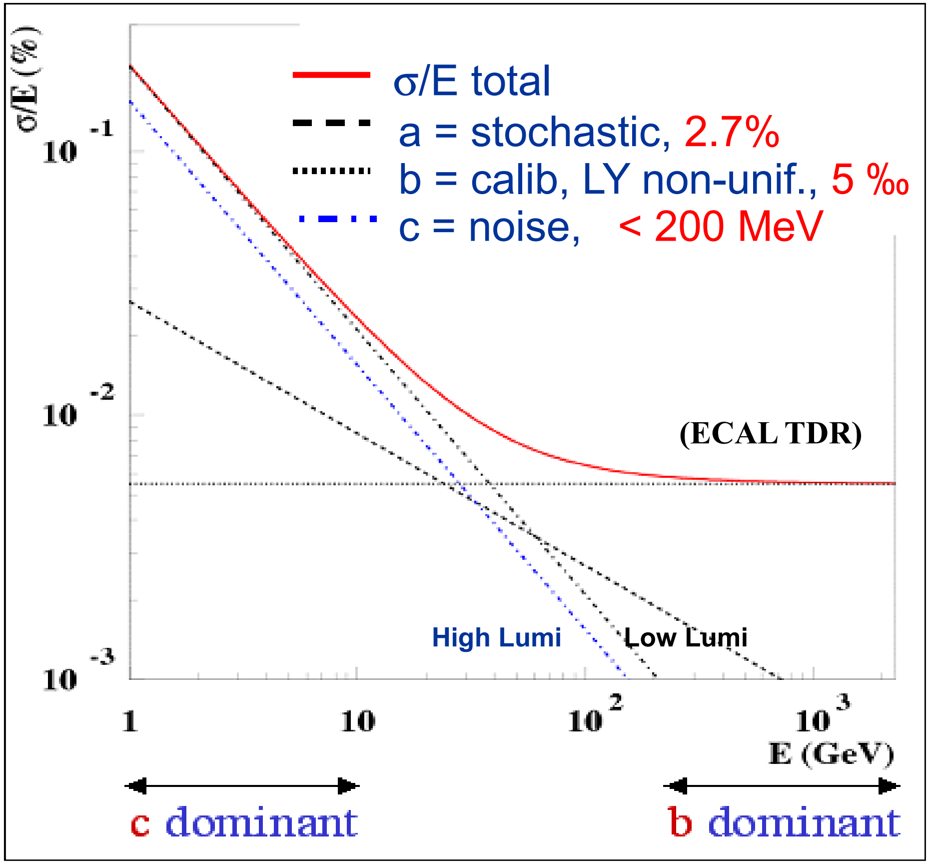
- the energy equivalent of the electronics noise and
- pileup - the fluctuation of energy entering the measurement area from other sources

'constant' term (coeff. b) accounts for

- non-uniformity of signal generation and/or collection
- the cell to cell inter-calibration error
- the fluctuation in the amount of energy leakage
- fluctuation in the e.m. component for hadronic showers

- The tolerable value of the 3 terms depends on the energy range of interest.
- Such parametrisations allow the identification of the causes of resolution degradation.
- Quadratic summation implies independent contributions which may not be the case.

Ecal : Resolution versus Energy



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

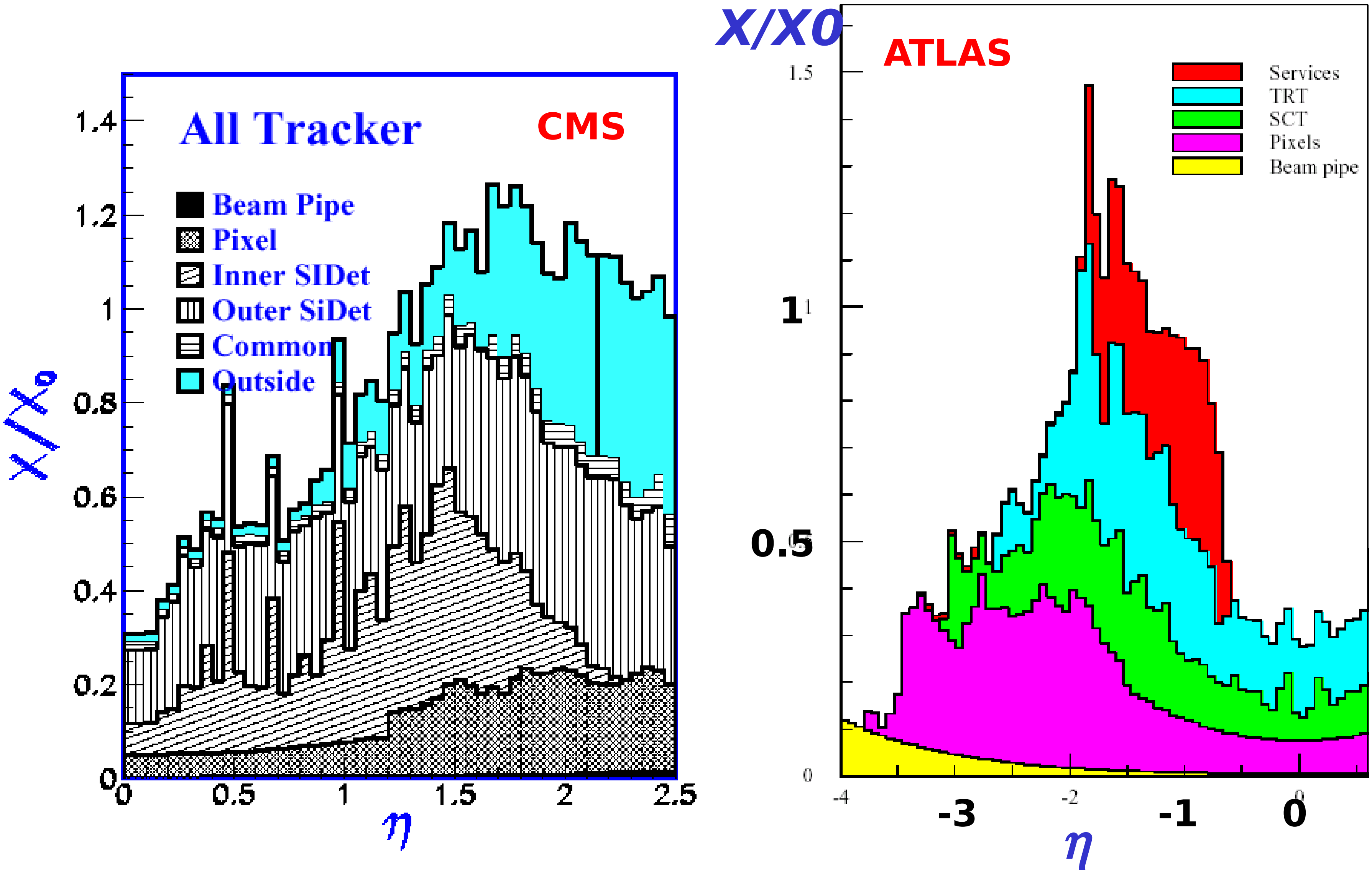
It is important to have a balance between each contribution to the resolution

Also important is the variation of b and c with time, mainly because of radiation.

Note that the scale refers the e or γ energy

For example for low mass Higgs we are looking to measure e, γ in the 20 -60 Gev energy range.

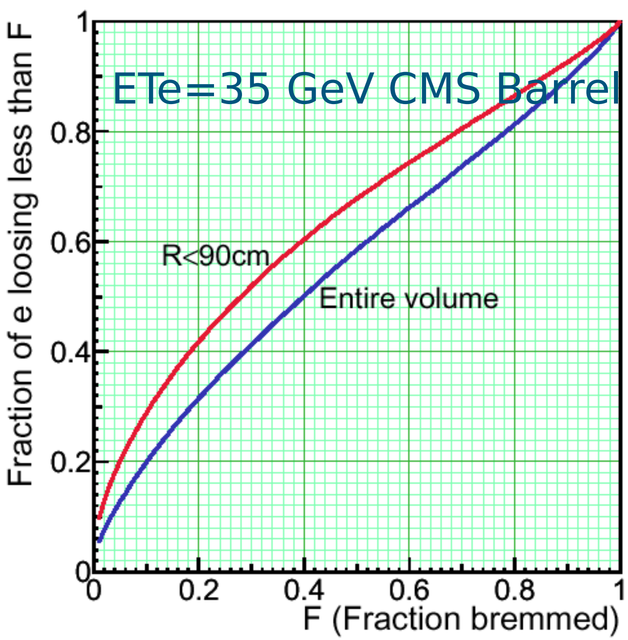
Effect of Material in Front of ECAL

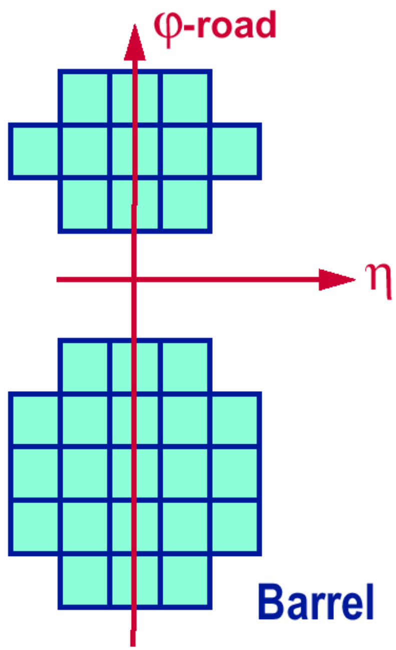


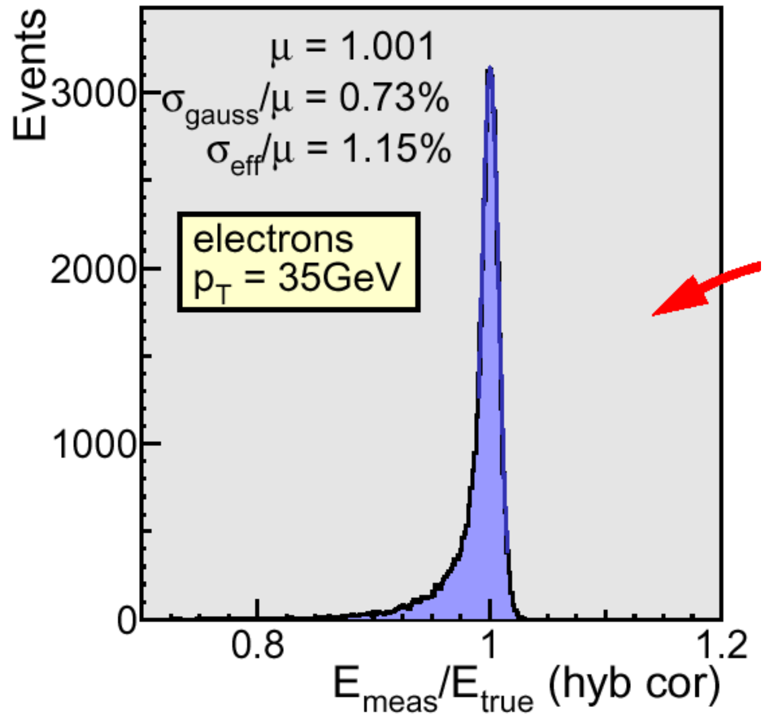
Electron Reconstruction

Reconstruction of electrons that radiate little (and unconverted γs) is simple : CMS - **collect energy in an array of 5 x 5 crystals** centred on ~ impact point

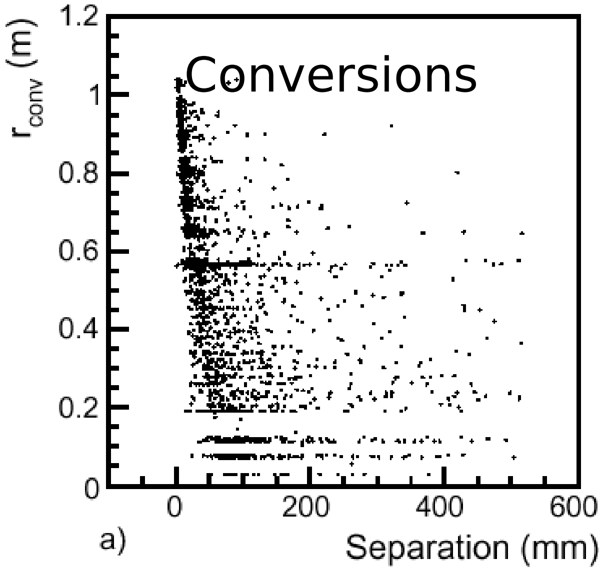
For 'bremming' e's and converting γ's, challenge is in coping with the combined result of tracker material and the 4T magnetic field (CMS) – problem is not energy loss but spraying/spreading of energy

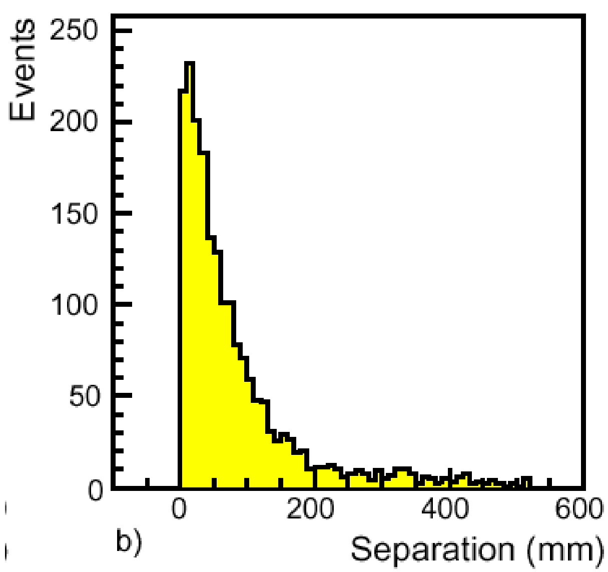






Photon Reconstruction



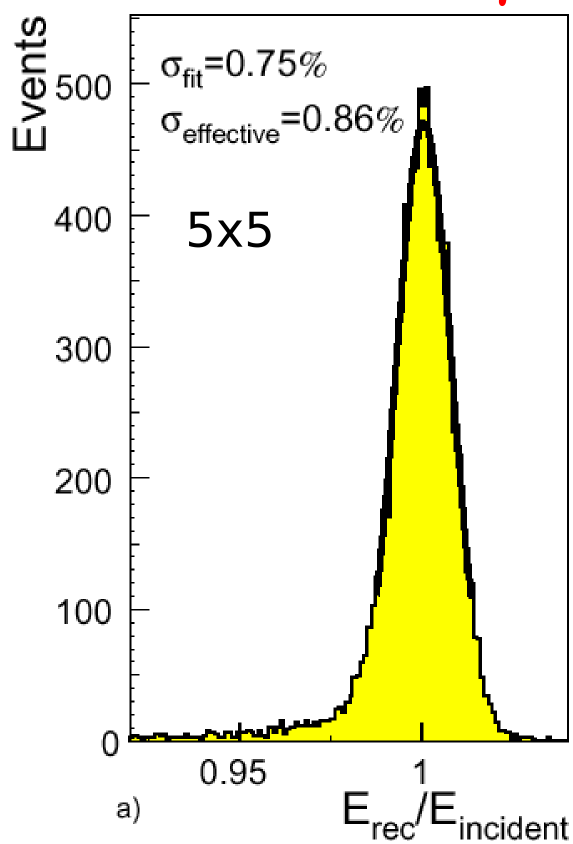


CMS 4T

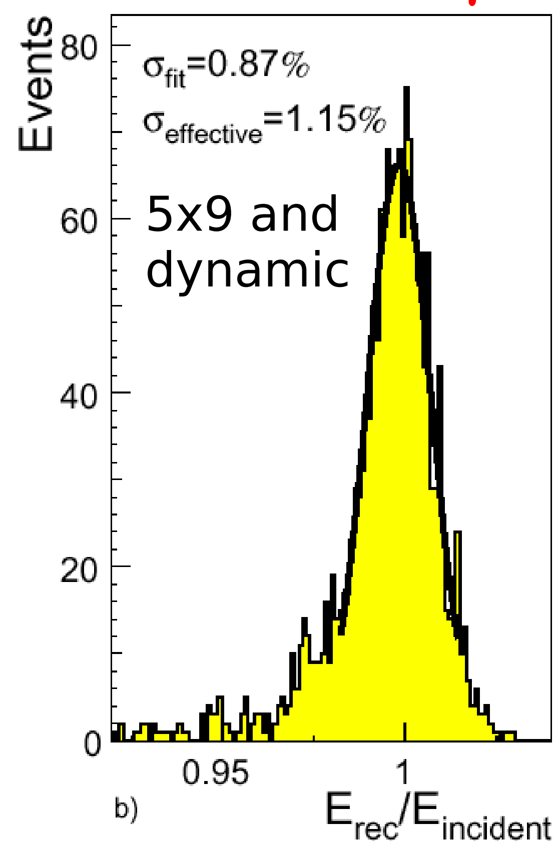
CMS Barrel
Higgs g γγ
εγ ~ 90%

¼ of conversions cannot be reconstructed

Unconverted γs



Converted γs

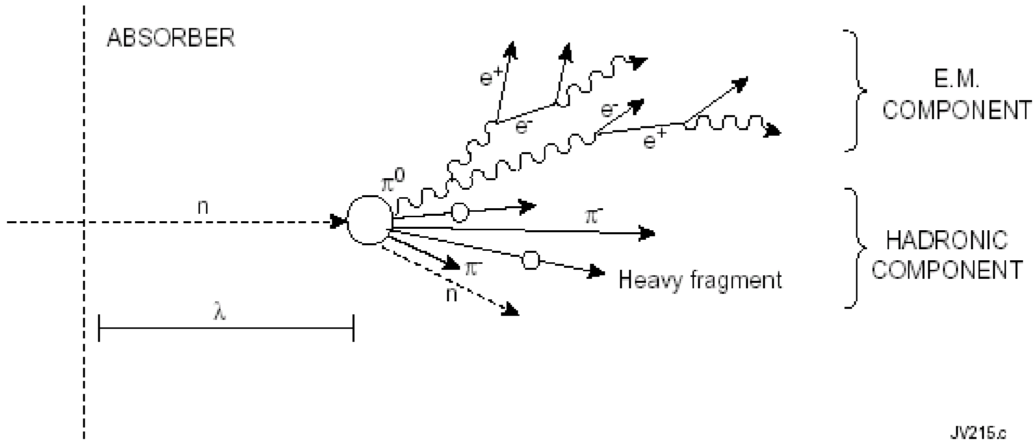


Part.II

Hadron measurement
Hadronic Cascade
Hadronic Calorimeter Performances

Hadronic Cascade

- Analogy with em showers. **Strong interaction** is responsible for shower development.
- A high energy hadron striking an absorber leads to multi-particle production consisting of mesons (e.g. $\pi^{\pm}$, π^0, K etc.). These in turn interact with further nuclei
- Nuclei breakup leading to spallation neutrons.
- Multiplication continues until the pion production threshold, $E_{th} \sim 2\, m_\pi = 0.28$ GeV



Simple model treats interaction on a black disc of radius R $\sigma_{int} = \pi R^2 \;\alpha\; A^{2/3}$

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

Defne nuclear interaction length $\lambda_{int} = \dfrac{A}{N_A \sigma_{int}} \propto A^{1/3}$ $\lambda \sim 35\, A^{1/3}$ g cm^{-2}

Cascade particles have a limited transverse momentum $\langle p_T \rangle \approx 300\text{-}400$ MeV

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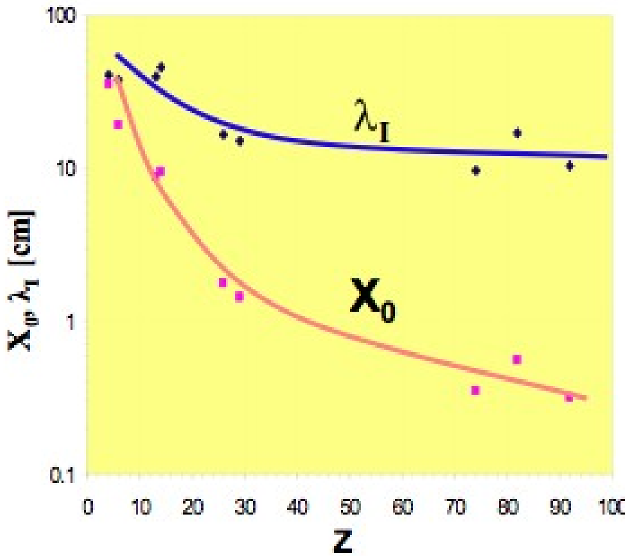
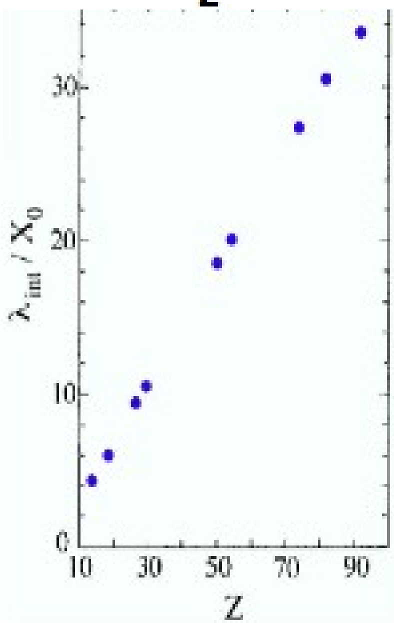
X0 versus λI

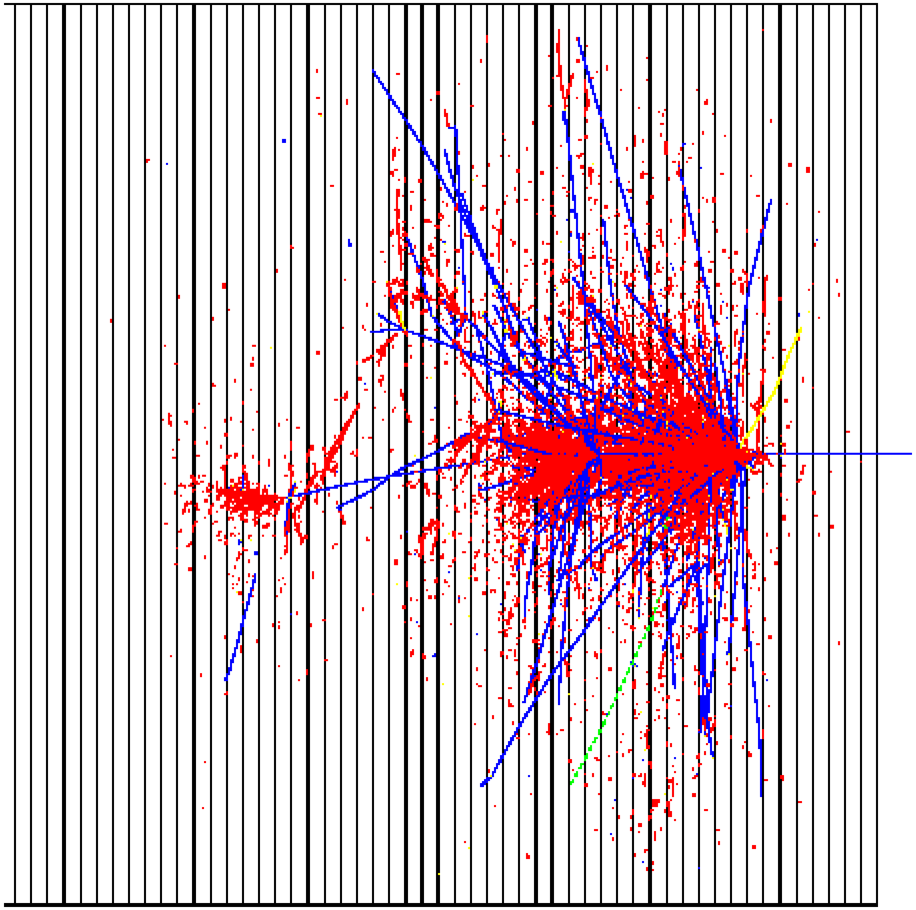


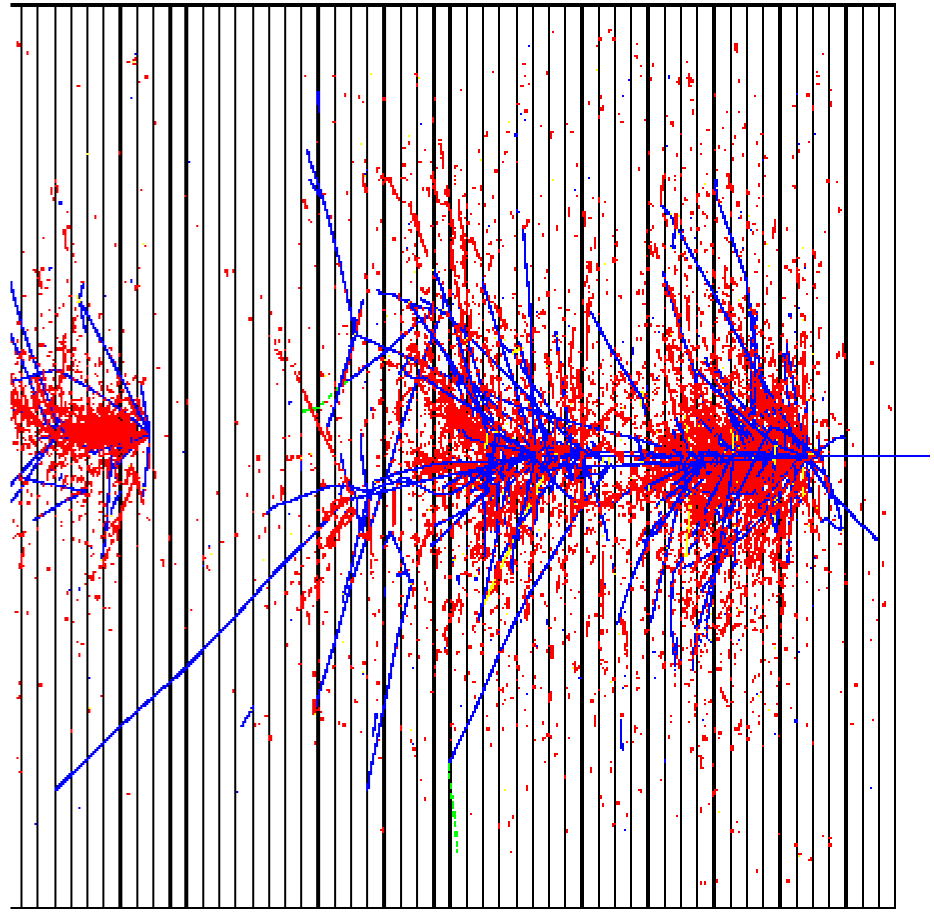


Material	Z	A	ρ [g/cm³]	X_0 [g/cm²]	λ_I [g/cm²]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

Comparing X0 and λI we understand why Hadronic Calorimeter are in general larger then EM calorimeters

150 GeV Pion Showers in Cu





Hadron shower not as well behaved as an em one

red - e.m. component
blue - charged hadrons

Hadron calorimeter are always sampling calorimeters

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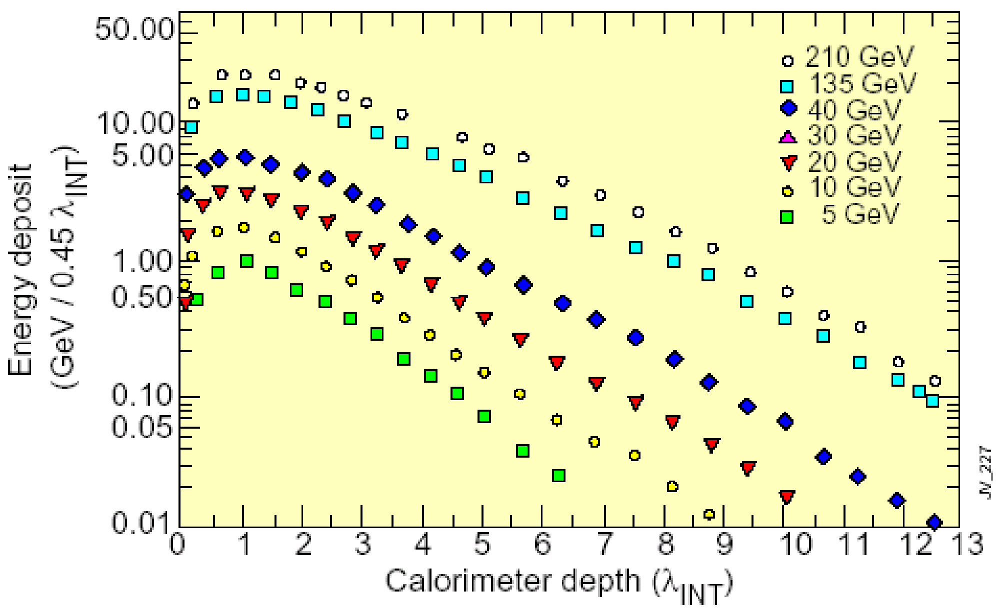
Hadronic Cascade: Profiles

Hadron shower profiles for single $\pi^{\pm}$

Longitudinal

- sharp peak from π^0's produced in the 1st interaction
- followed by a more gradual falloff with a characteristic scale of λ.

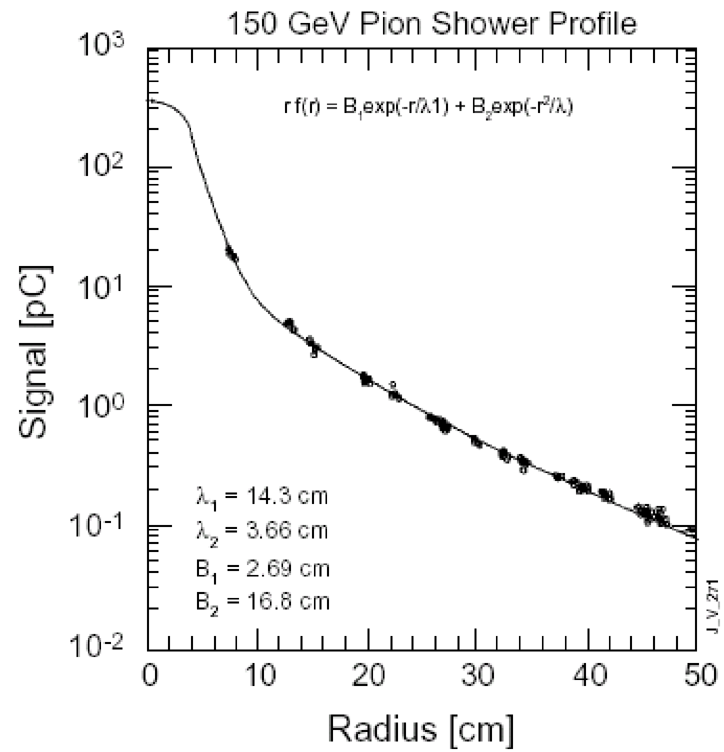
WA78 : 5.4λ of 10mm U / 5mm Scint + 8λ of 25mm Fe / 5mm Scint



Approx. 10 λ required to contain 99% of the energy of ≈ 200 GeV pions

Lateral

- Secondaries produced with $<p_t>$ ~ 300 MeV
-approx. energy lost in ≈ 1 λ in most materials.
- Characteristic transverse scale is $r_\pi \approx \lambda$.
- Pronounced core, caused by the π^0 component,



Transverse radius for 95% containment is $R_{0.95} \approx 1\ \lambda$

Compensation I

The efficiency (response) of HCAL in energy deposition due to EM interaction and energy deposition due to hadron is called **e/h**

The EM part of an Hadronic shower in mainly due to $\pi 0 \rightarrow \gamma\gamma$ with the subsequent EM photon interactions

The response of the calorimeter can be written as

$\pi\pm = fem\ e + fh\ h$

$fh = 1 - fem$

$\pi\pm$	response of the calorimeter to charge pion
e	EM response
h	Hadronic response
fem	fraction of EM energy
fh	fraction of Hadronic energy

The EM fraction of the shower is large (about 1/3 of the produced pions are $\pi 0$)

- Large fluctuations in EM shower
- fm depend on the energy of the primary particle

If $e/h \neq 1$ (> 10%) then

- $\sigma(E)/E$ is no more proportional to $1/\sqrt{E}$
- Hadron response non linear
- Energy deposition distribution “non Poisson”

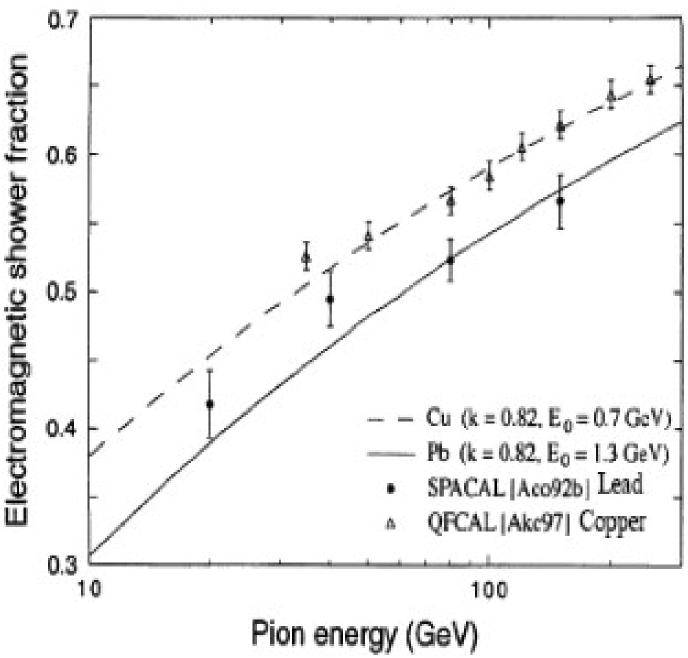
Compensation II

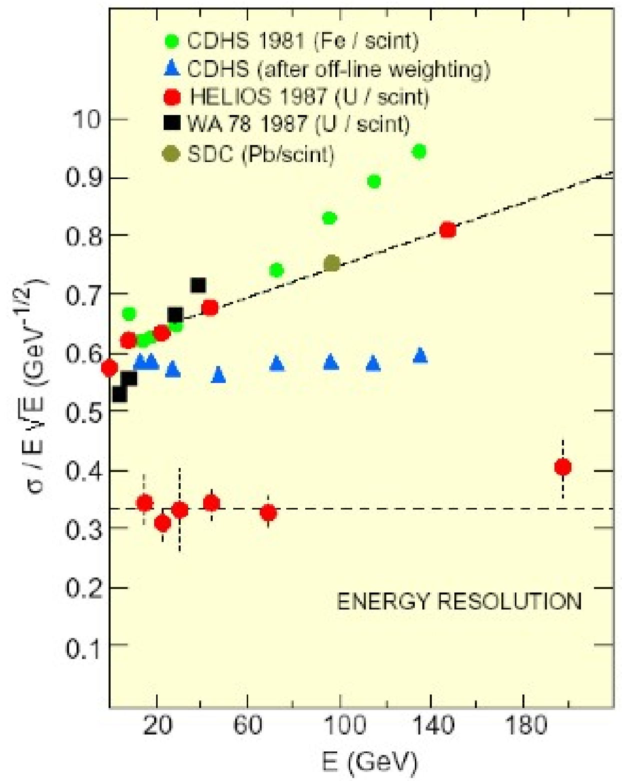
E_{em} - em component (π^0s)
E_{ch} - charged pions or protons
E_n - low energy neutrons
E_{nucl} -energy lost in breaking nuclei (binding energy)

$$E_{vis} = eE_{em} + \pi E_{ch} + nE_n + NE_{nucl}$$

N is normally v. small but E_{nucl} can be large (~ 40 % in Pb)

fem



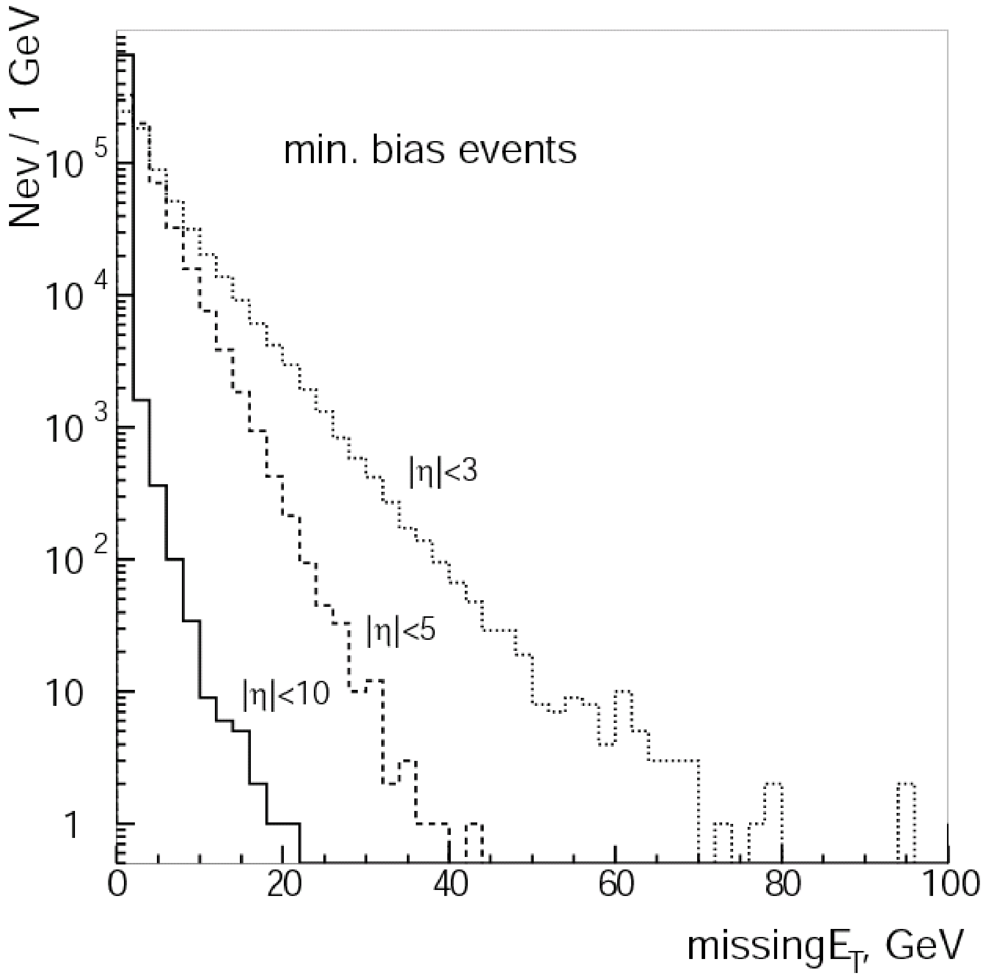


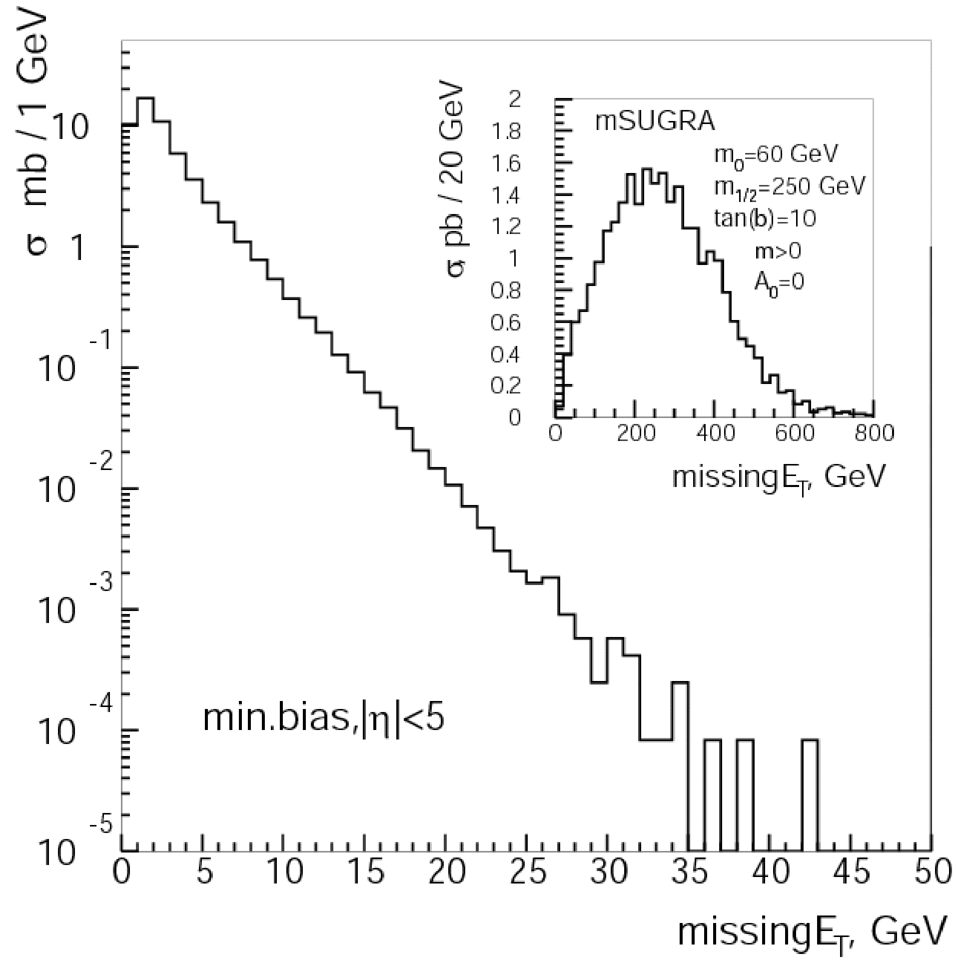
Compensation III

Hadronic Calorimetrv at LHC

- **Jet energy resolution**
  - Limited by jet algorithm, fragmentation, magnetic field and energy pileup at high luminosity
  - Can use the width of jet-jet mass distribution as a figure of merit
    - Low p_t jets: W, Z $\rightarrow$ Jet-Jet, e.g. in top decays
    - High p_t jets: W', Z' $\rightarrow$ Jet-Jet
  - Fine lateral granularity (≤ 0.1) high p_t W's, Z's
- **Missing transverse energy resolution**
  - Gluino and squark production
    - Forward coverage up to $|\eta| = 5$
    - Hermeticity - minimize cracks and dead areas
    - Absence of tails in the energy distribution is more important than a low value for the stochastic term
  - Good forward coverage is also required to tag processes initiated vector boson fusion

Missing ET

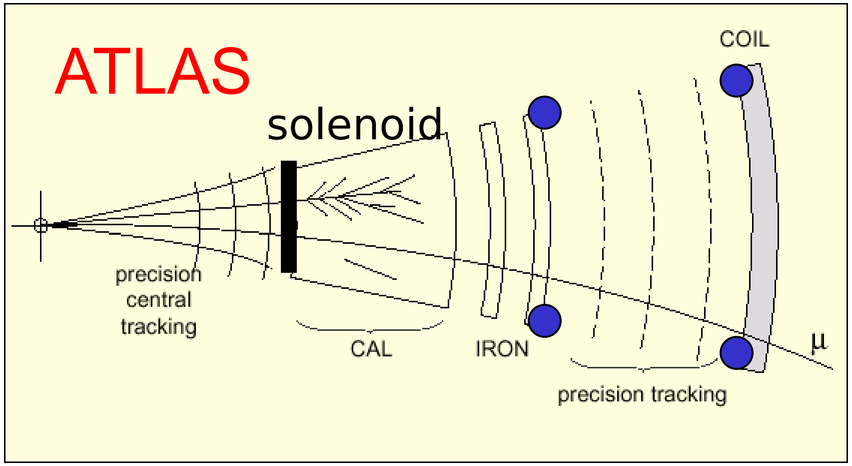




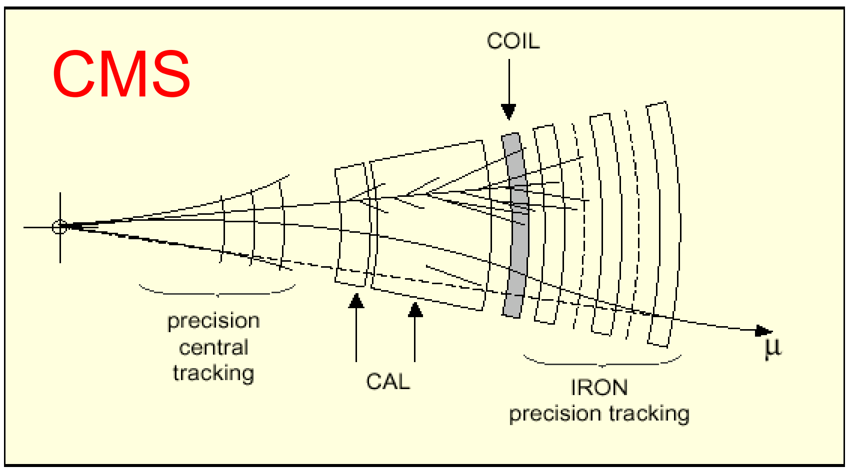
Require Calorimetry coverage $|\eta| > 5$

Designs of General Purpose Detectors

Complementary Conception



Identify and measure muons after full absorption of hadrons
Air-core toroid
Good stand-alone p_μ measurement
p_μ measurement safe at high multiplicities
solenoid needed for inner tracking
σp_T flat with η

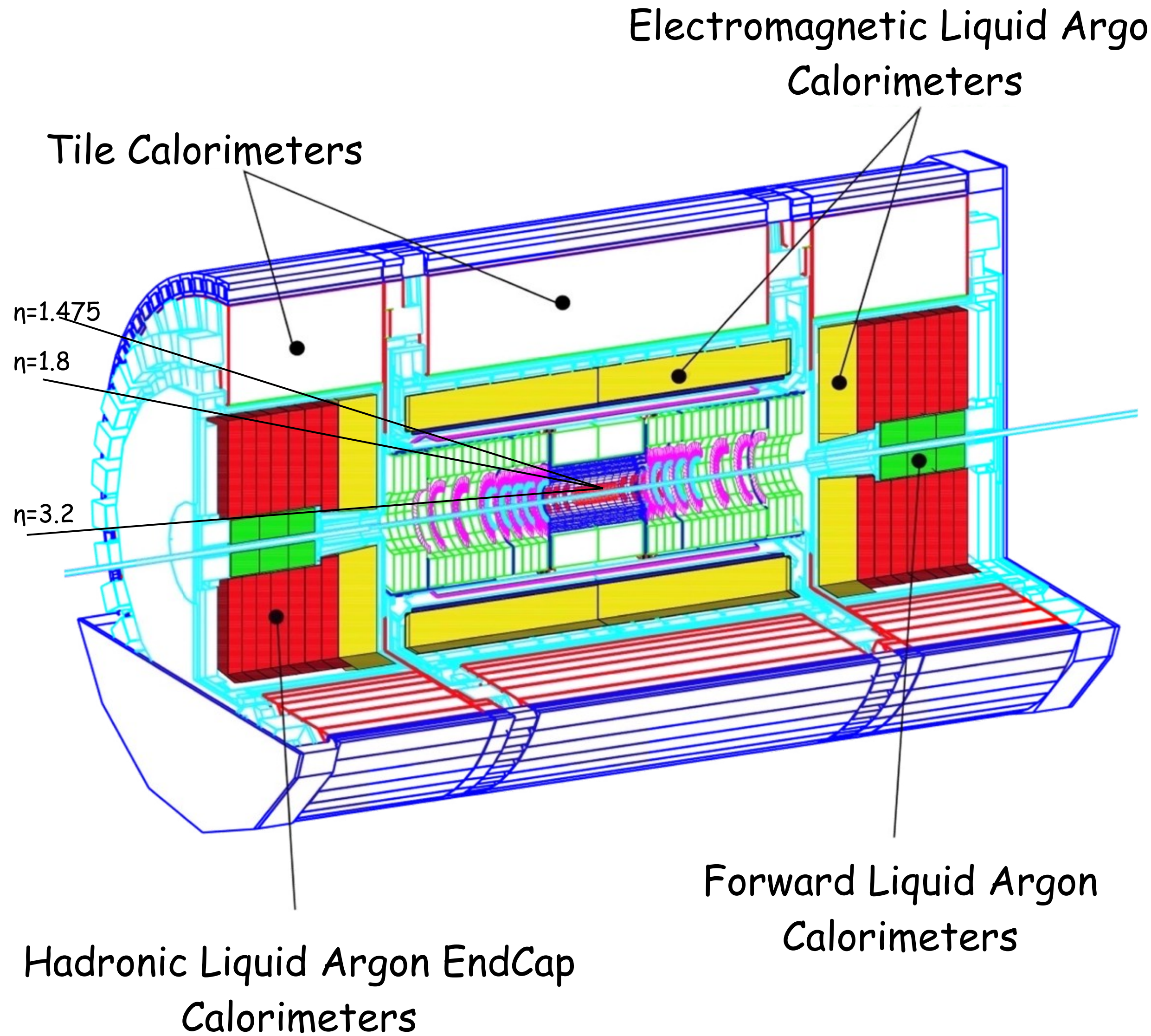


High field solenoid placed after calorimetry
Fe flux return
Measurement of p in tracker and B return with single magnet
Solenoid: High pT muon tracks point back to vertex
Reasonable stand-alone measurement
σp_T degrades progressively with η for tracks exiting the open end of the solenoid

Part.III.1

Calorimeters
ATLAS

ATLAS Calorimeters



ECAL

Accordion Pb/LAr

$|\eta|<3.2$, 3 samplings

S1: $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$

S2: $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$

S3: $\Delta\eta \times \Delta\phi = 0.05 \times 0.025$

HCAL

Barrel: Fe/Scintillator with WLS fibre readout

3 samplings - $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

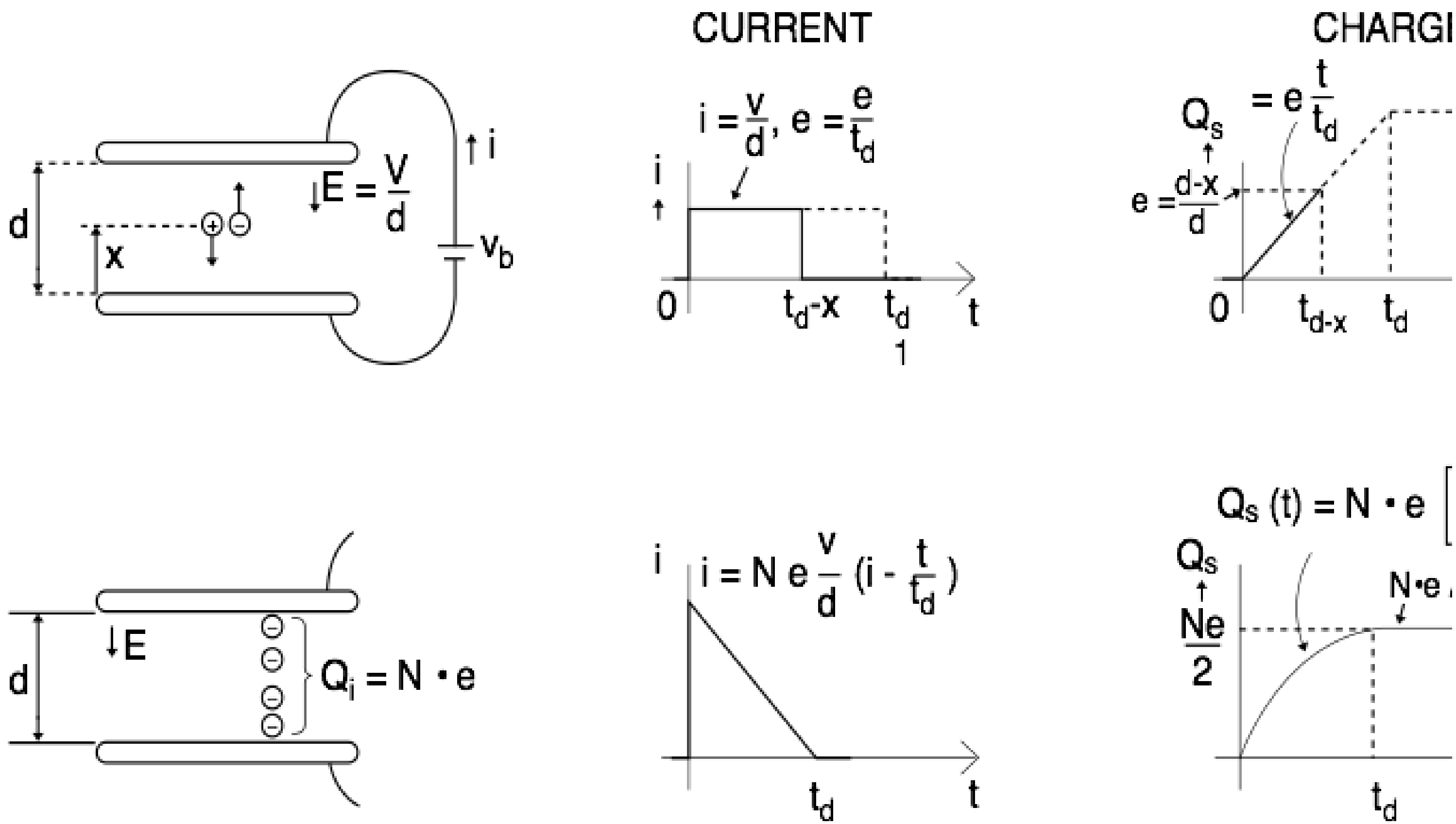
Endcap: Fe/LAr

Forward: W/LAr

$3.1<|\eta|<4.9$

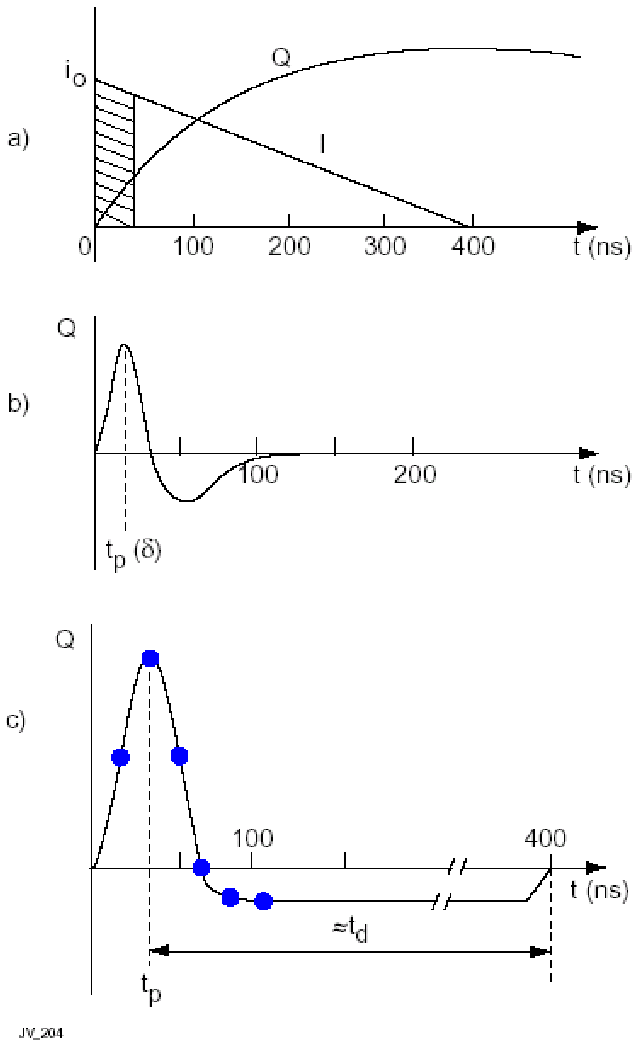
$\Delta\eta \times \Delta\phi = 0.2 \times 0.2$

Charge Collection in Lar Ionisation Volume



The current and charge for a) single electron-ion pair, b) uniformly distributed e-ion pairs

Liquid Ionisation Calorimeters



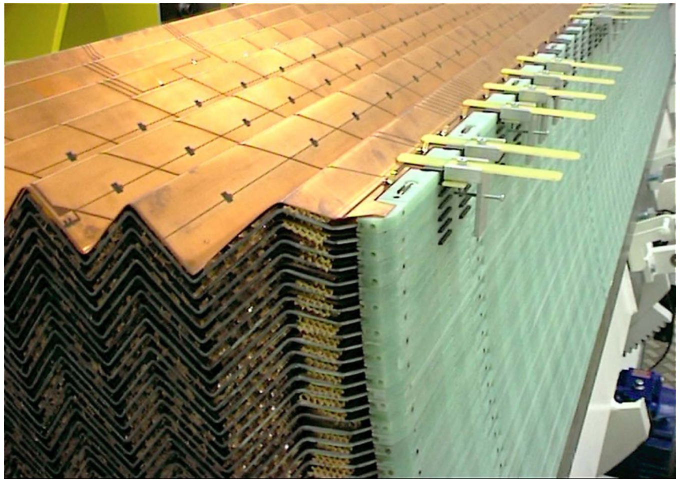
- Induced current duration = electron drift time t_d, with a triangular shape

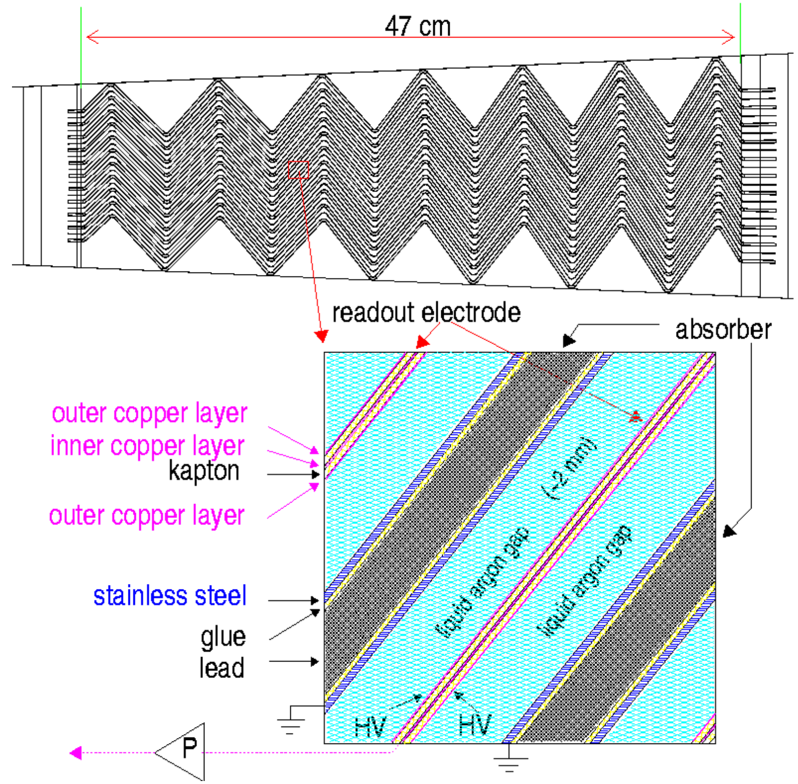
- bipolar impulse response of chamber-preamp-shaper, most important condition for pulse shaping at high rates is
  system impulse response should have zero area

  pileup then does not produce a baseline shift

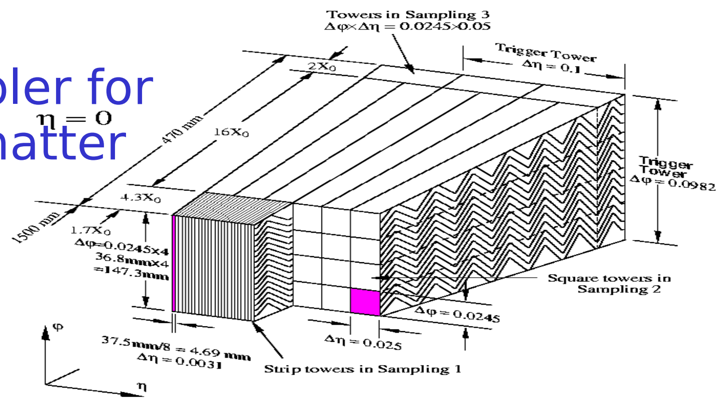
- for $t_p \ll t_d$, i.e. peaking time much faster than drift time, output response becomes 1st derivative of current pulse
  energy info. fully contained in the initial current i_0

ATLAS: LAr Calorimeter





Fine strips for /
0
Presampler for
dead matter



Accordion geometry benefits :

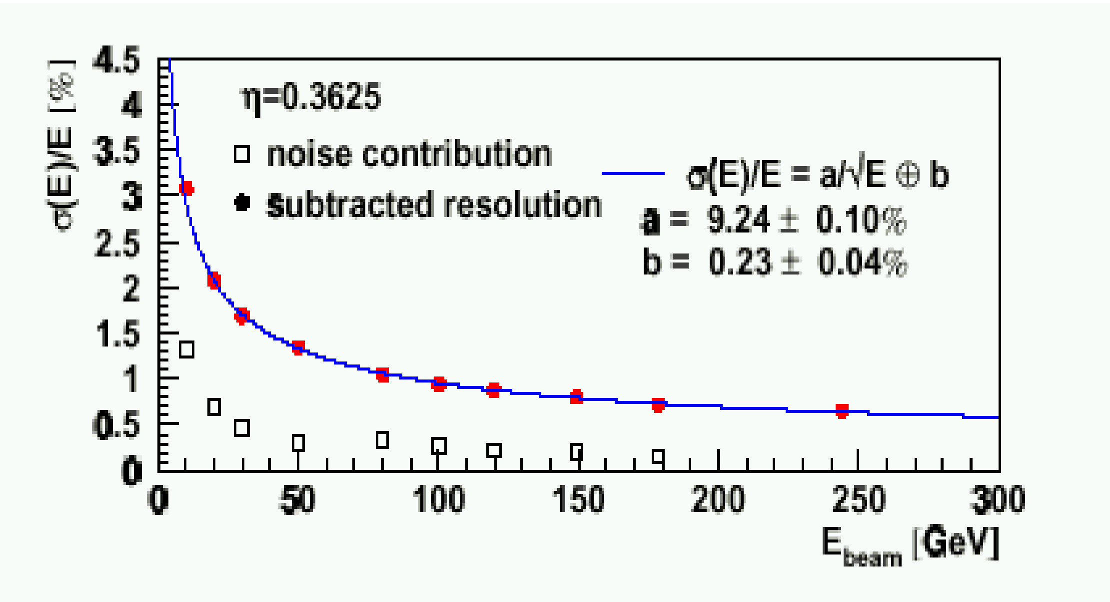
No cracks in õ

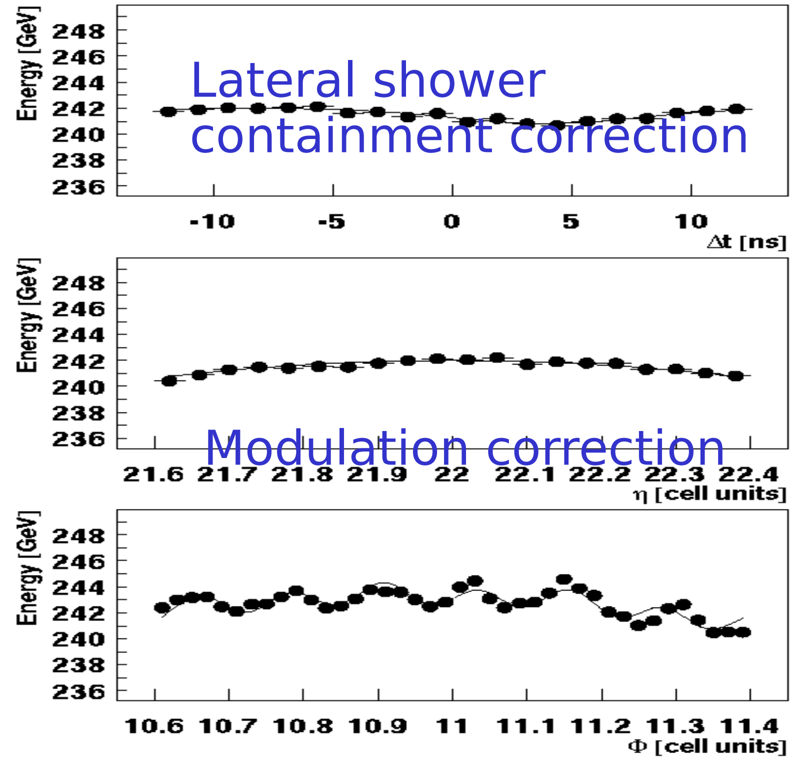
Small   modulation (few per mille)

Cabling on front and back only

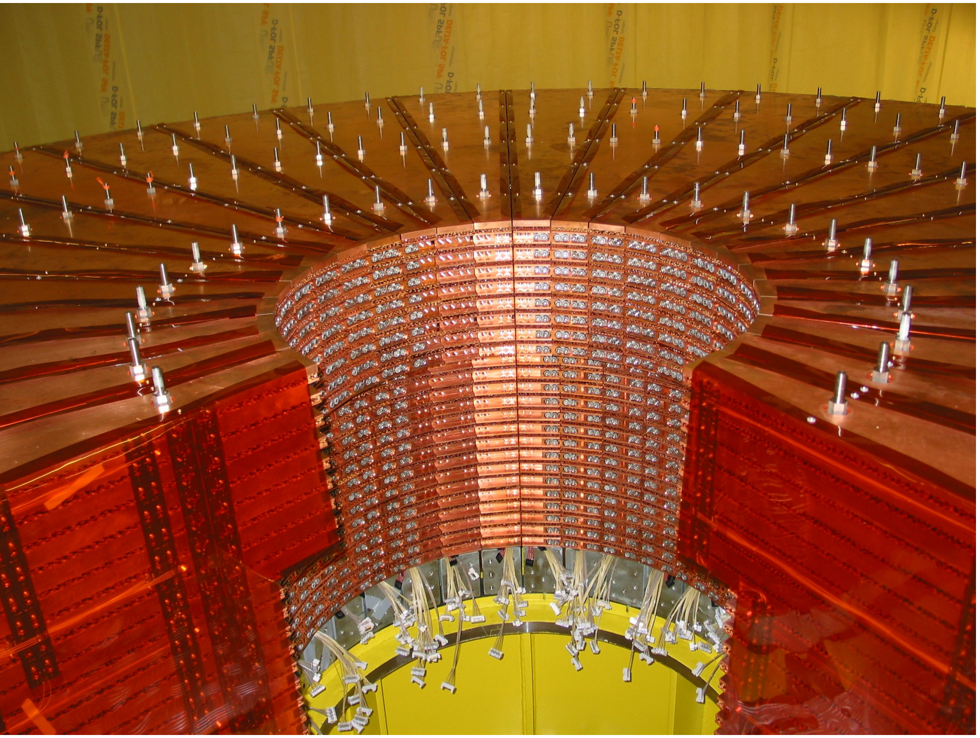
Low inductance

ATLAS: LAr Calorimeter

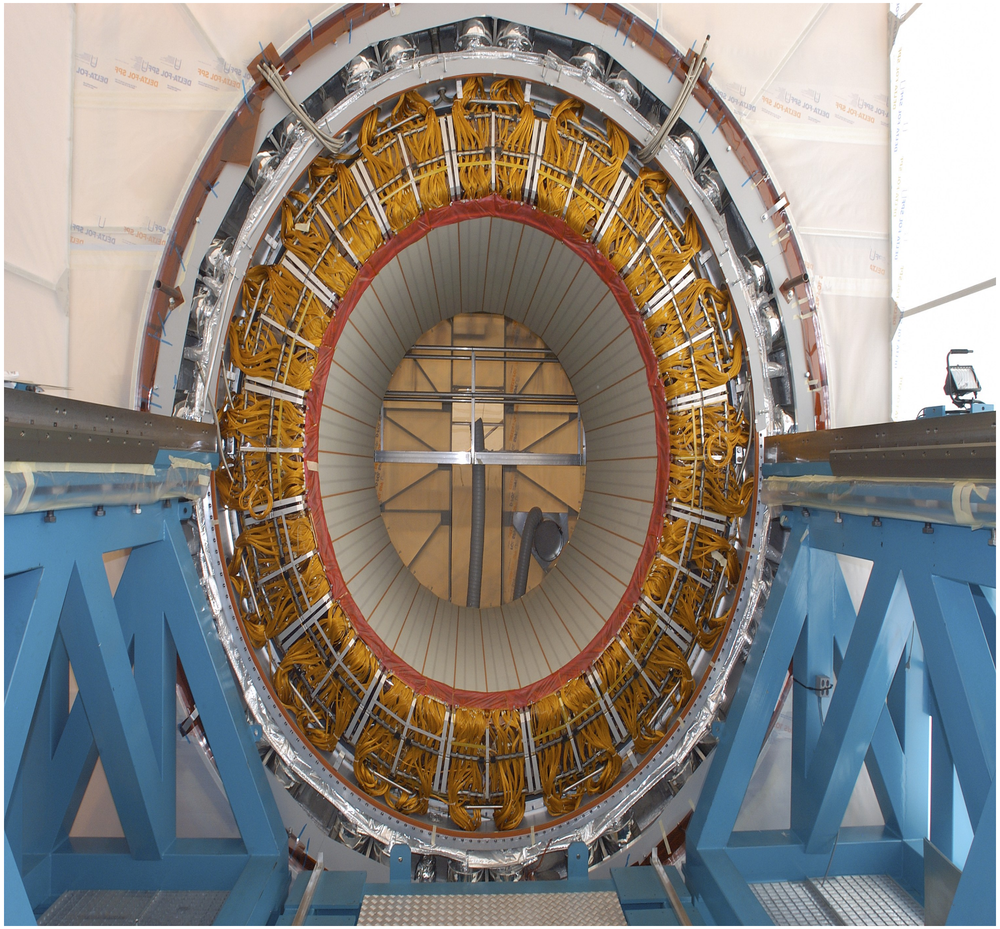




ATLAS: LAr Calorimeter



Assembly of the first HEC wheel (horizontal)

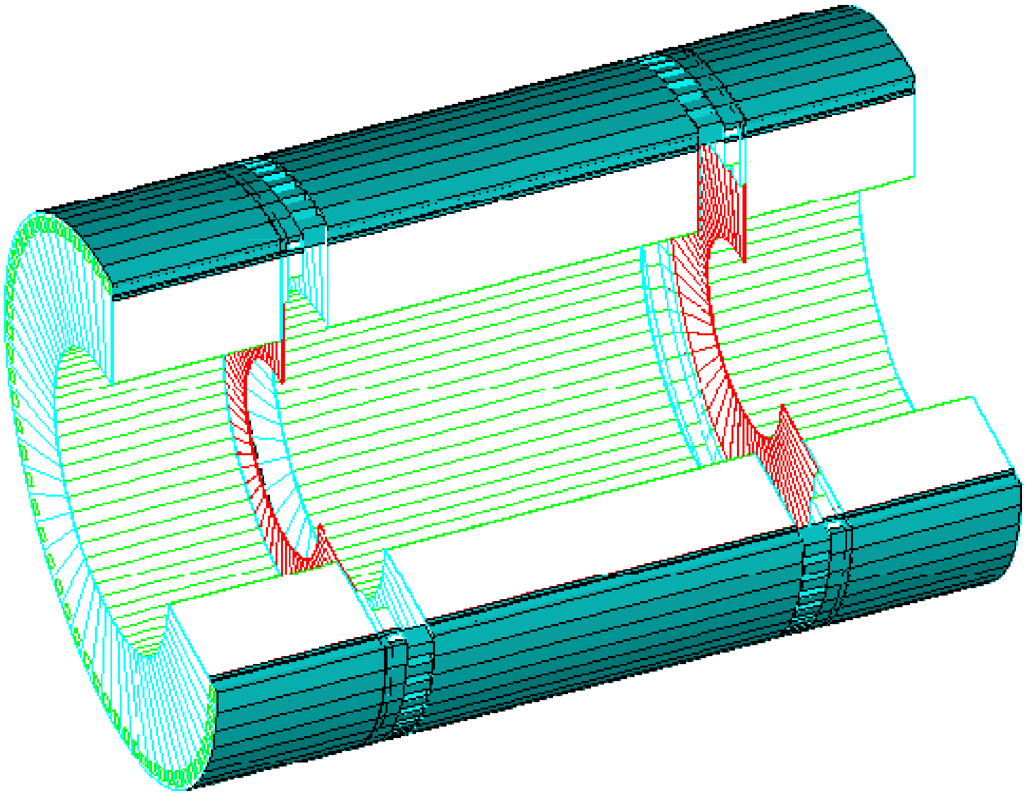


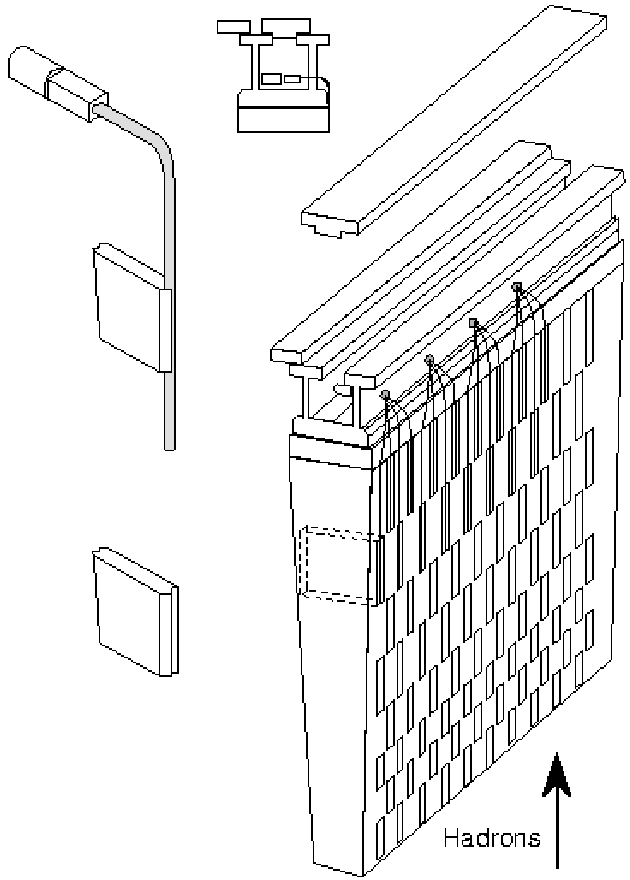
LAr EM half barrel after insertion into the cryostat

ATLAS: Tilecal

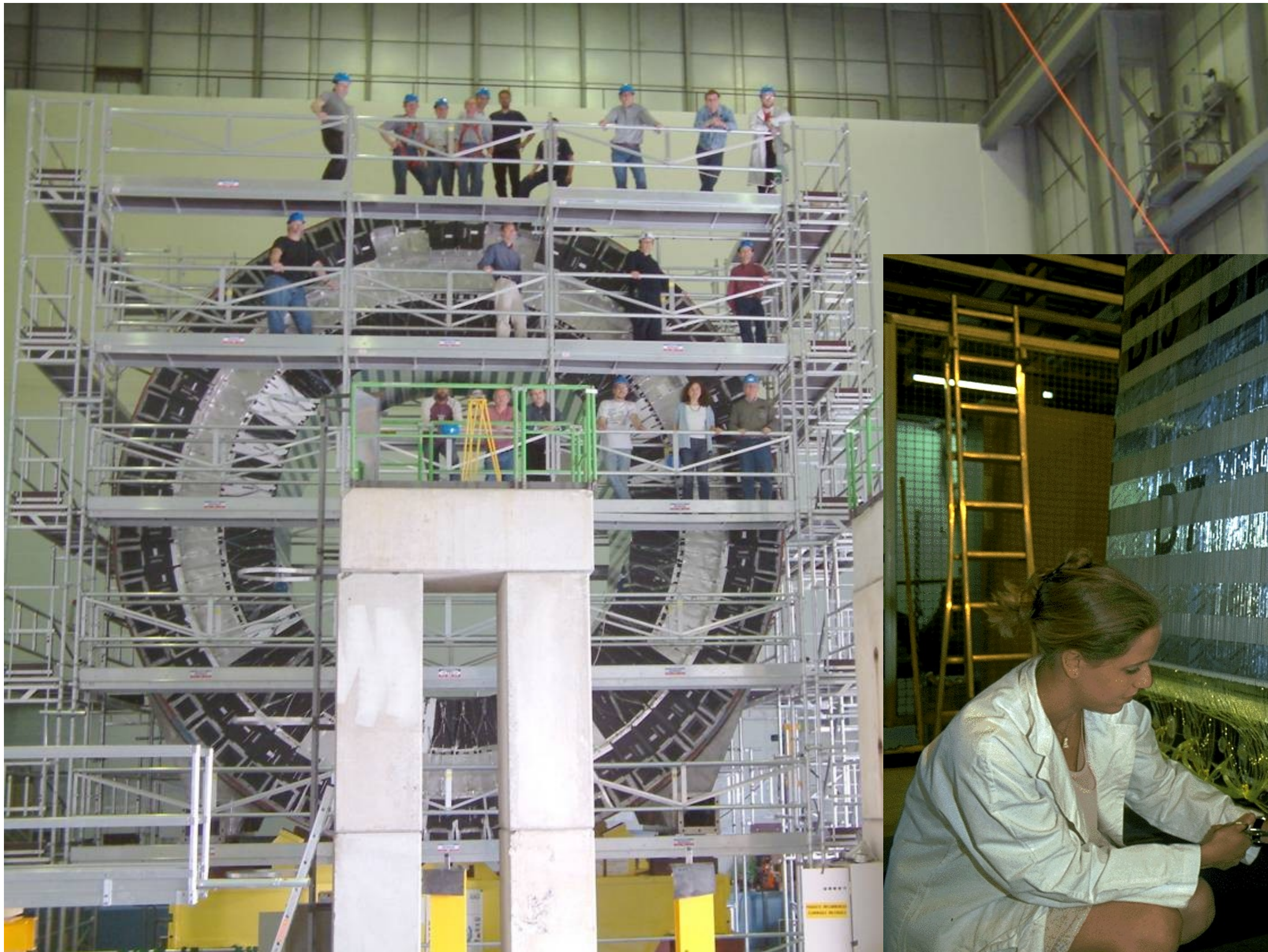
Fe absorber with scintillator tile readout with

$\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$, 3 longitudinal samplings, $|\eta| < 1.7$





ATLAS: Tilecal Assembly



ATLAS: Calorimeter Performance

Combined Test:

EM LAr and Hadronic Tile Calorimeter

 Energy Resolution

Compensation
e/h ~ 1.31

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

	a (%GeV1/2)	b (%)	c (GeV)
Data	69.8 ± 0.2	3.3 ± 0.2	1.8± 0.1
G-CALOR	61.7 ± 0.1	2.9 ± 0.3	1.5 fixed

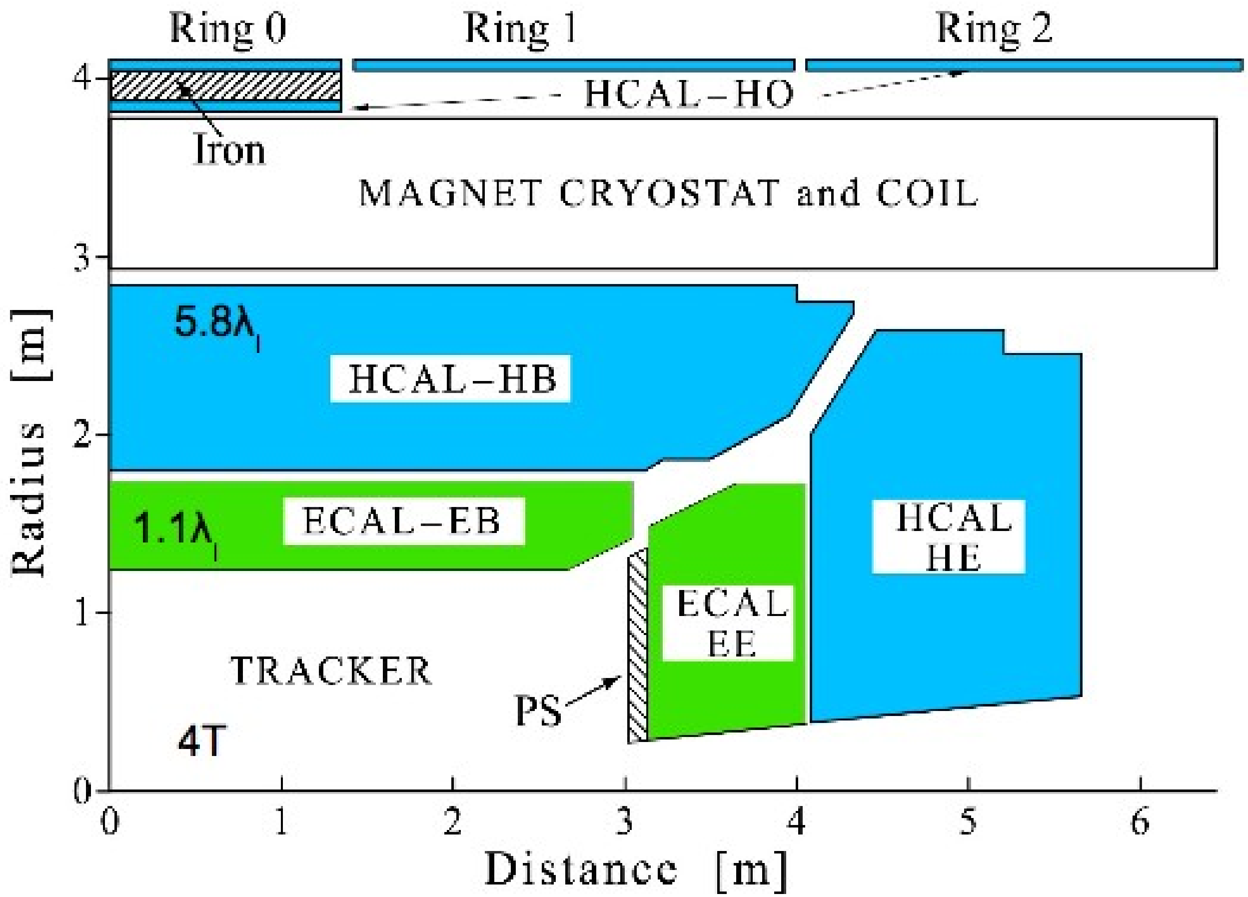
e/ ratio Degree of non-compensation *e/h*

$$e / \pi = \frac{e / h}{1 + (e / h - 1) \cdot F(\pi^0)}, F(\pi^0) = 0.11 \cdot \ln E$$

Part.III.2

Calorimeters
CMS

CMS Calorimeters

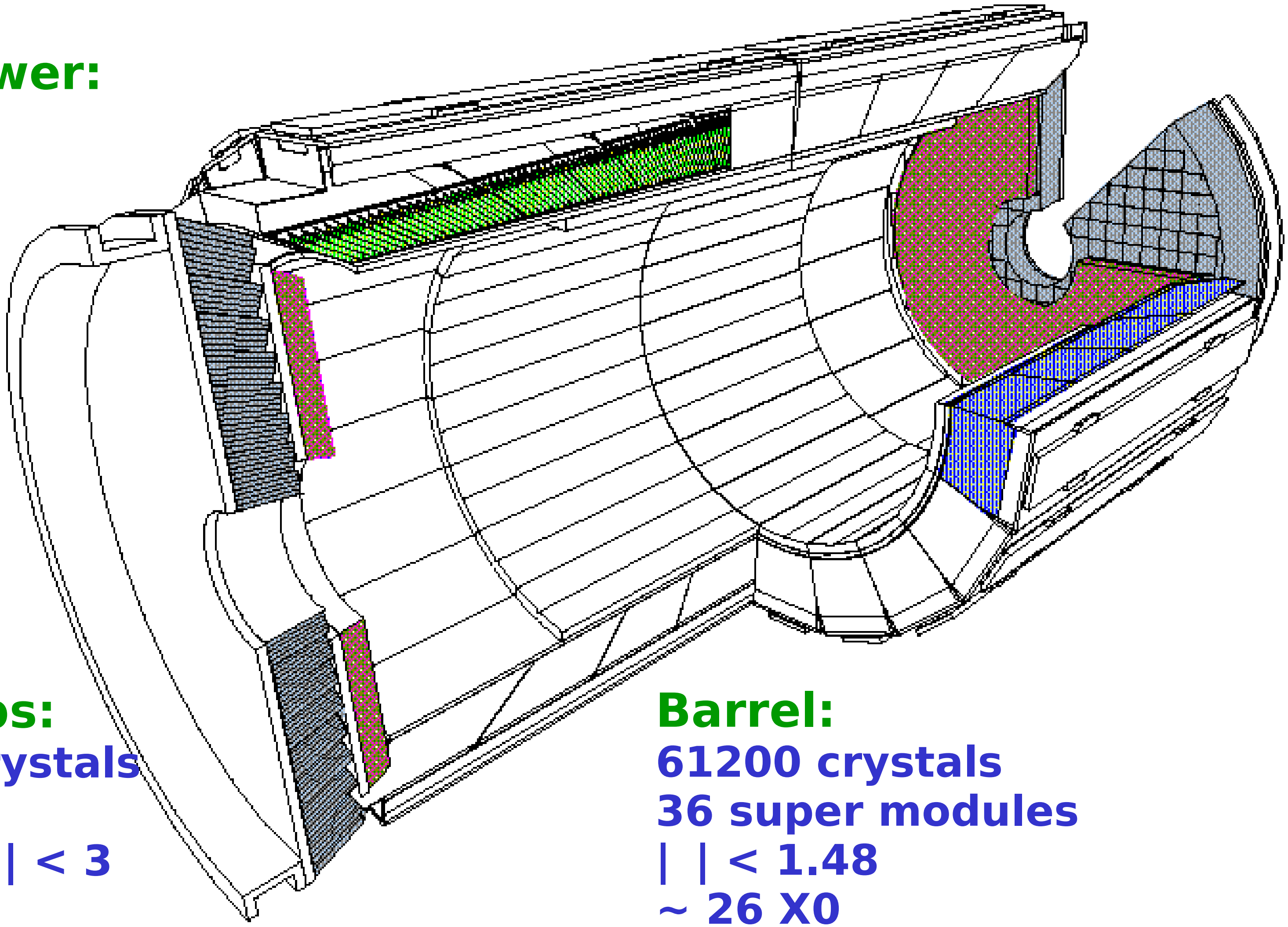


ECAL
Crystal Calorimeter
PbWo4 + Photodetector

PS PreShower
Pb/Si

HCAL
Brass/Scintillator
with WLS fibre
readout

CMS Electromagnetic Calorimeter



Preshower:
3 X0
Pb/Si

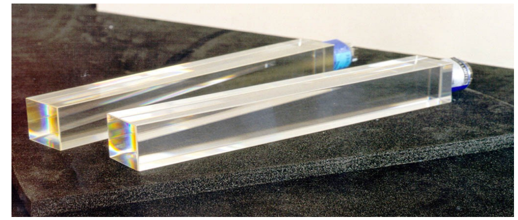
End Caps:
14648 crystals
4 Dees
1.48 < |ð| < 3
~ 25 X0

Barrel:
61200 crystals
36 super modules
| | < 1.48
~ 26 X0

CMS: Crystal Calorimeter

Advantages:
- Fast
- Dense
- Radiation hard
- Emission in visible

Disadvantages:
- Temperature dependence
- Low light yield
- a Photodetector with gain
- (in a strong magnetic field)



Density [g/cm^3]	8.28
Rad length, X_0 [mm]	8.9
Int length [mm]	224
Molière rad [mm]	21.9
Decay time [ns]	5(39%) 15(60%) 100 (1%)
Refractive index	2.30
Max emiss [nm]	420
Light yield [ph/MeV]	~50
Temp coeff [%/ºC]	-2

CMS Parameters

Parameter	Barrel	End caps
Xtal size (mm^3) Depth in X_0	21.8 × 21.8 × 230 25.8	30.0 × 30.0 × 220 24.7
No. crystals Volume (m^3) Xtal mass (t)	61200 8.14 67.4	14664 2.77 22.9

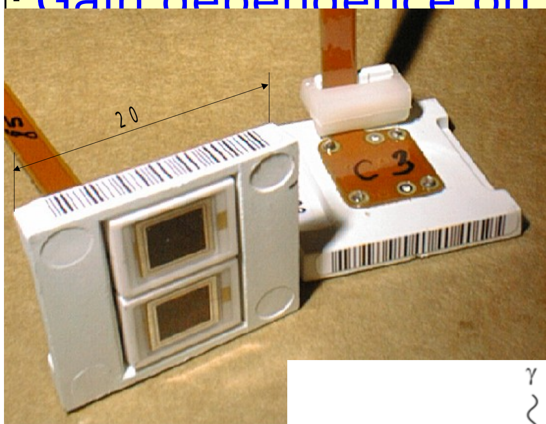
~ 75 % of shower energy in one crystal

Photodetectors for PWO

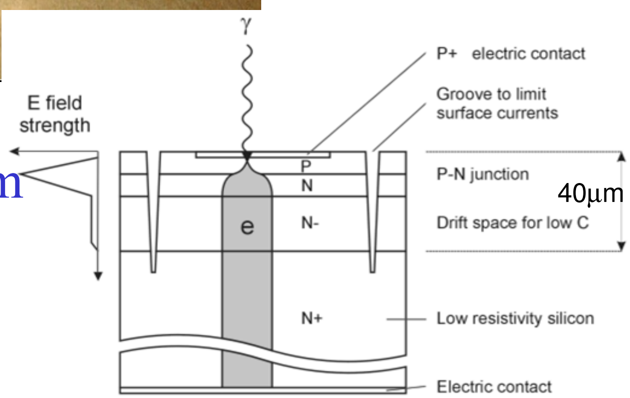
Barrel - Avalanche photodiodes (APD)

Two 5x5 mm2 APDs/crystal

- Gain: 50 QE: ~75% @ λpeak= 420 nm
- Temperature dependence: -2.4%/OC
- Gain dependence on bias V: 3%/V



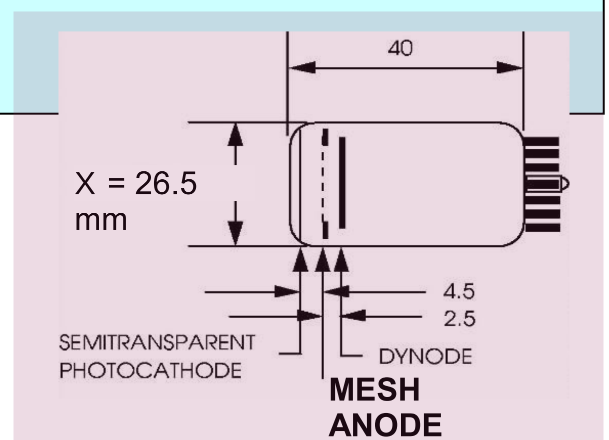
deff ~6µm



Endcaps: - Vacuum phototriodes (VPT)

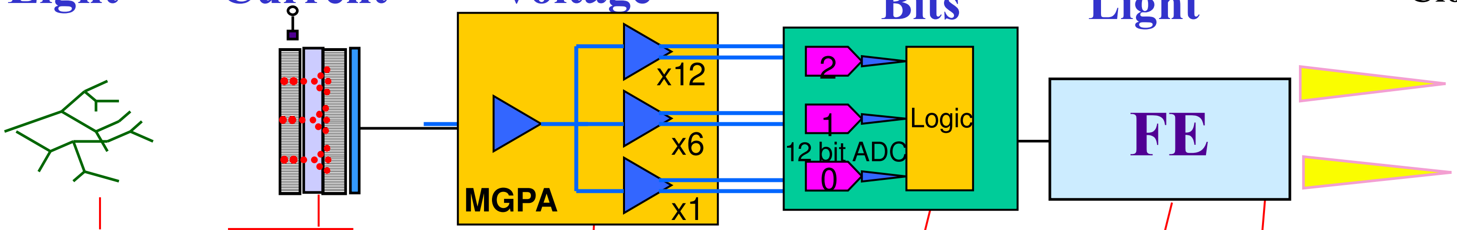
More radiation resistant than Si diodes (with UV glass window)

- Active area ~ 280 mm2/crystal
- Gain 8 -10 (B=4T) Q.E.~20% at 420 nm



CMS ECAL READOUT CHAIN

Energy → Light	Light → Current	Current → Voltage	Voltage → Bits	Bits → Light	Clock & Control



PbWO4 Crystal

APD VPT

Multi-Gain (x 1, x 6, x 12) Pre Amplifier

multi-channel 12-bit ADC 40 MHz

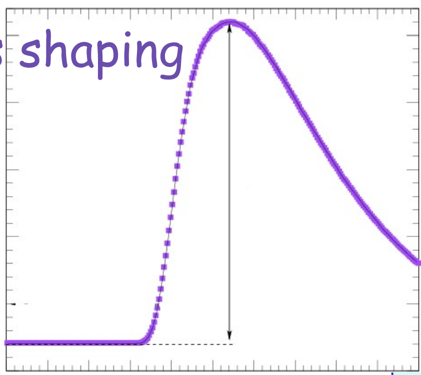
Data pipeline Trigger primitives

optical data link driver 800 Mbit/s

DAQ data

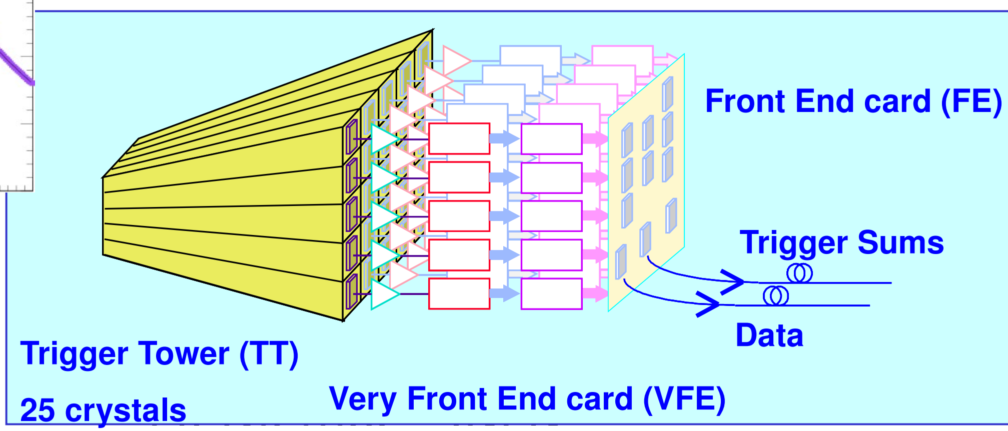
100 m Fibers to counting room

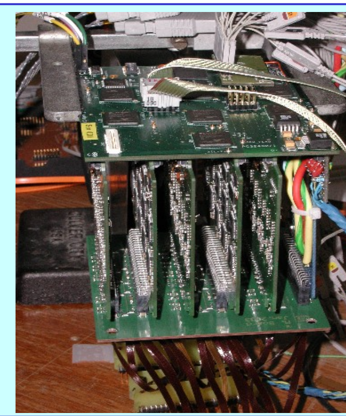
40 ns shaping



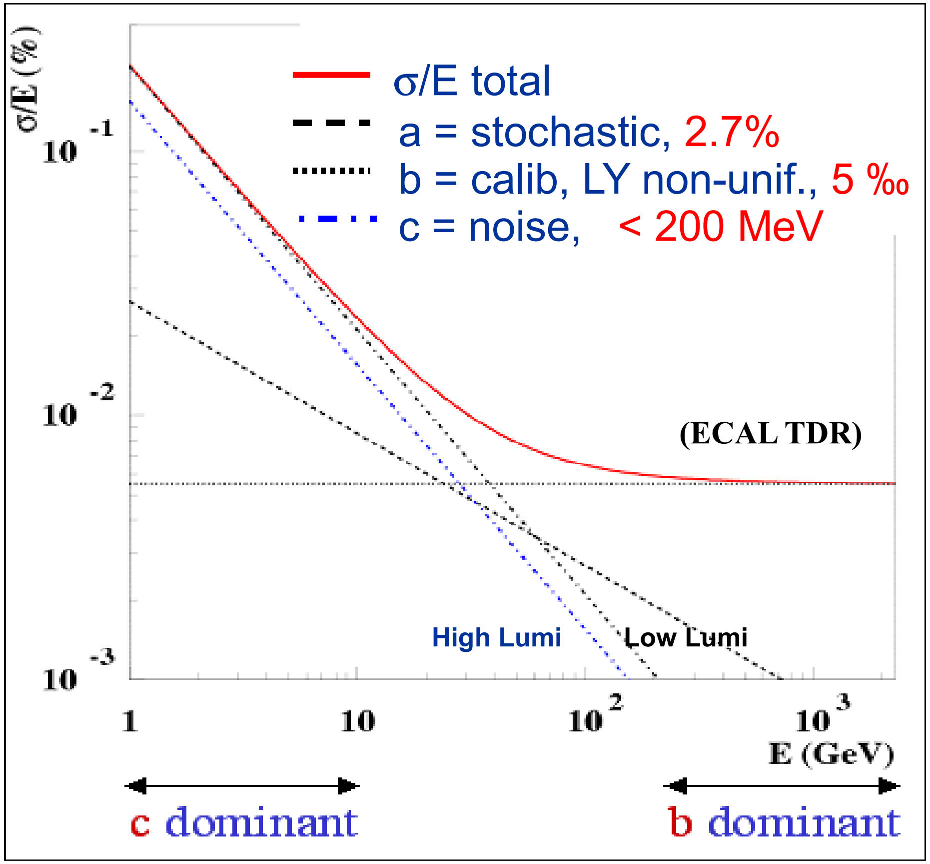
25 ns sampling

IBM CMOS 0.25 µm technology



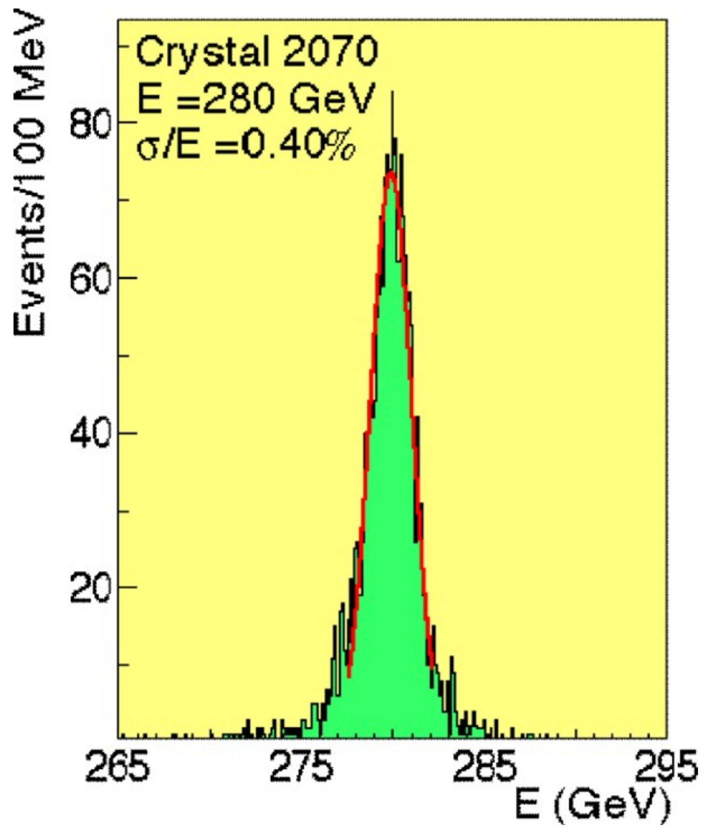


CMS ECAL: Performance



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

3 x 3 Crystals



Goal $$\frac{\sigma}{E} = \frac{2.7\%}{E} \oplus 0.5\% \oplus \frac{200\,MeV}{E}$$

CMS: ECAL Calibration

Precalibration:

- Lab measurements, **< 5%**
- Test beam, **< 2%**

but only a fraction of ECAL will be calibrated

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

intercalibration goes directly into
constant term
(most of the energy in a single crystal)

In-situ calibration: **at low Lumi**

A) Fast intercalibration using **Φ − σψμμετρψ**, ≈2% **φεω ηουρσ**

B) Υσε **Ζ → ε+ε−** φορ ιντερχαλιβ ιν η ανδ αβσολυτε Ε σχαλε **φεω δαψσ**

Χ) Ωηεν τραχκερ φυλλψ οπερατιοναλ : Ε/π φρομ **Ω → εν** **φεω μοντησ**

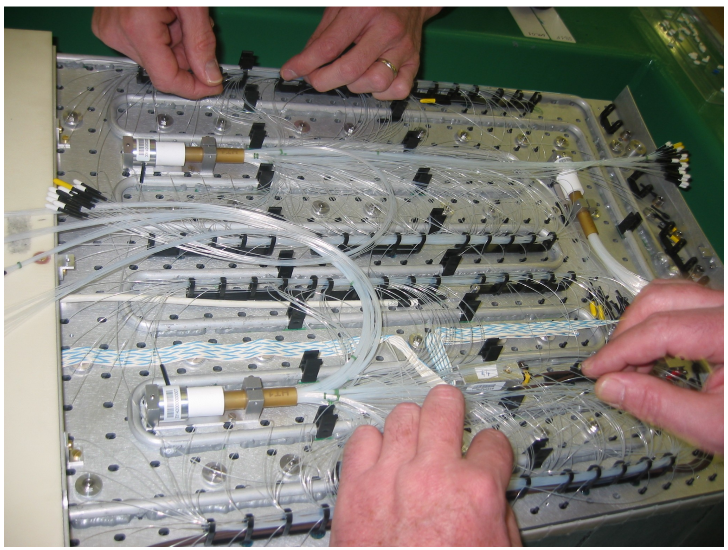
Φιναλ γοαλ : **0.5 %**

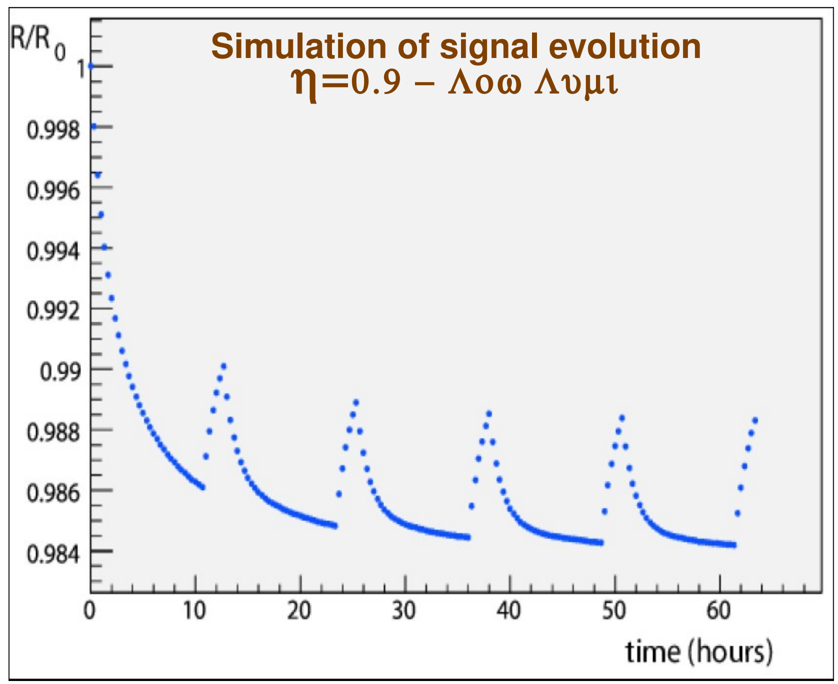
Laser monitoring:

Correct for variations in crystal transparency due to irradiation

CMS ECAL Crystal Monitoring

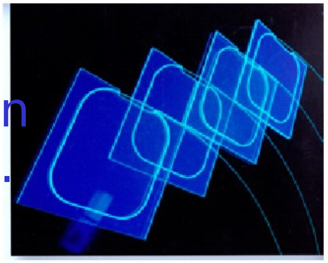
- Crystals light collected changes due to irradiation / modification of transparency
- ==> Monitor transparency using laser light of 440nm, 495nm and 700nm
- Relative response to electrons and laser light characterized by a single constant ¶



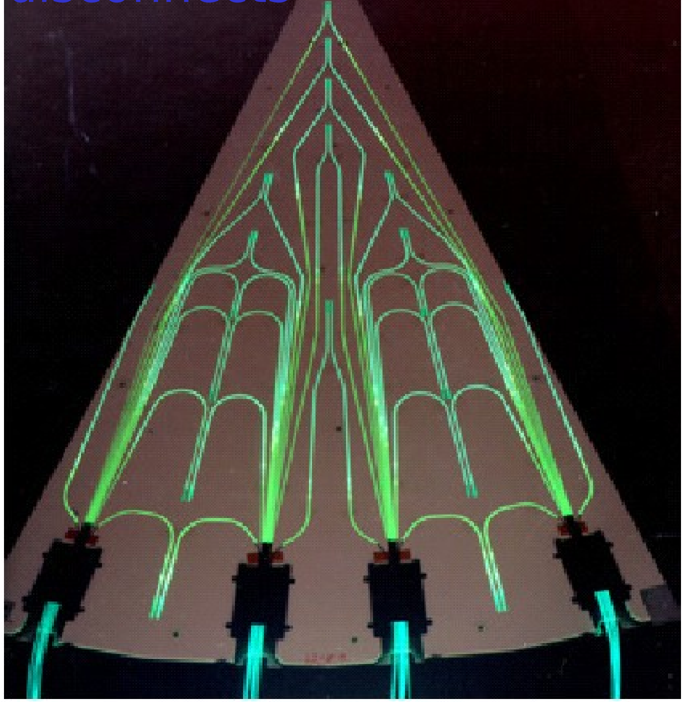


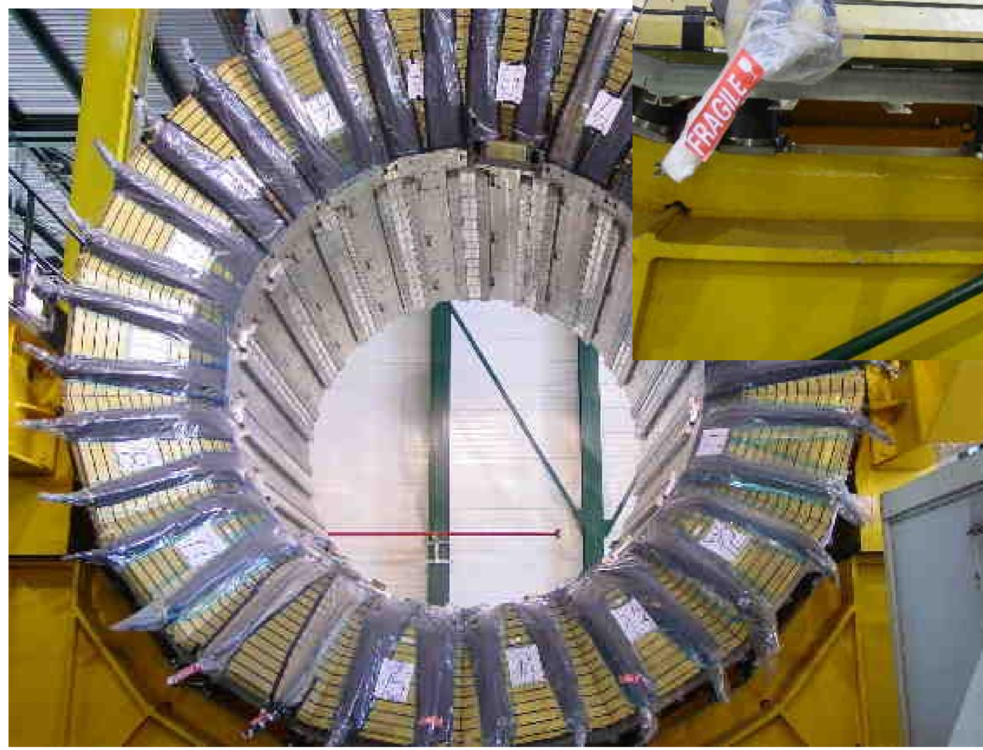
CMS HCAL

WLS fibres
Embedded in
plastic scint.
plates



Routing of
clear fibres to
optical
disconnects





CMS HCAL

Central Region (|η|<3) :

projective geometry

granularity $\Delta\eta \times \Delta\phi = 0.0875 \times 0.0875$

١٩ Scintillator 4 mm thick with WLS fibre readout,Interleave with 50mm plates of brass

٢٠ **no longitudinal sampling**

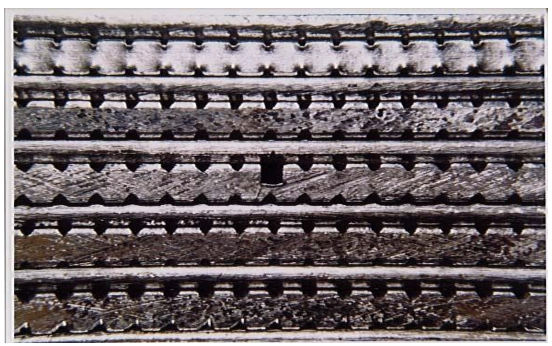
٢١ **e/h ~ 1.4**

$$\boxed{\frac{\sigma(E)}{E} \propto \frac{(120\%)}{\sqrt{E}} \oplus 5\%}$$

ÉCOLE DE PHYSIQUE
LES HOUCHES
XXVII

CMS: Verv Forward Calorimeter

Fibres insertion
in HF wedges



Forward Region (3<|η|<5): Fe/Quartz Fibre, Cerenkov light

A lot was not covered

Alignment issues (mainly : tracker and muon system)
Magnets system
Luminosity measurements

Electronics
- *Front end and related radiation hardness issues*
- *Readout Electronics / Buffering*

Trigger
- *What is in/out of the triggers*
- *Filtering (from 40 Mhz to 100 Hz)*

DAQ
- *Event building*
- *Data flow*

Jets , Events Reconstruction, Simulations (Hadronic Models)
- *See D.Froidevaux Lecture*