Calorimeters :
key detectors for LHC physics

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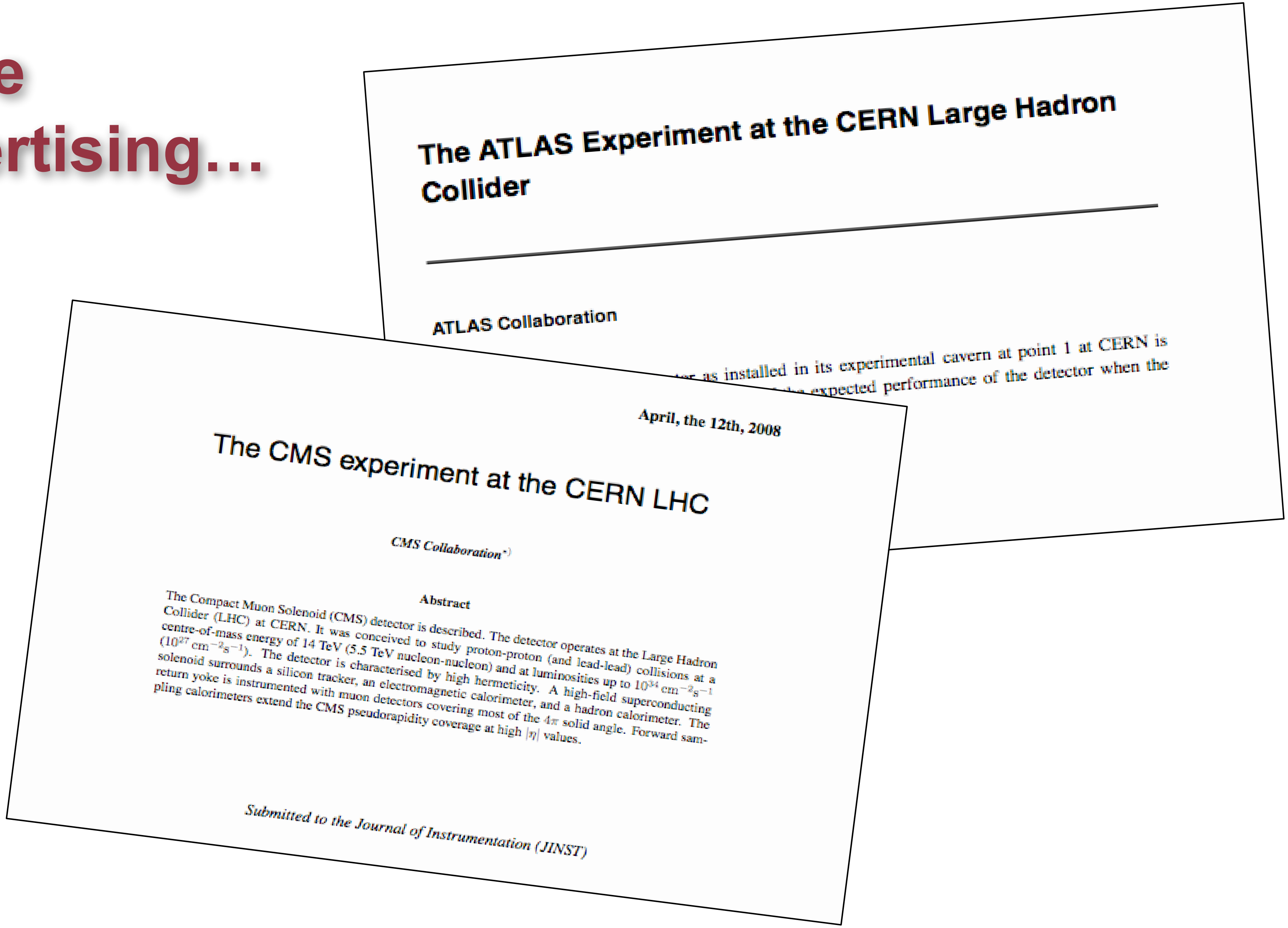
20 years of LHC calorimetry…

- Calorimetry at LHC seen from the privileged observatory of CALOR conference series
- LHC detectors are almost installed and running!
- Millions of cosmics collected, collisions expected soon…
- Next CALOR conference hopefully focused on collected data (or detector improvements) rather than philosophy…
- Final detectors descriptions available soon

some advertising…



The ATLAS Experiment at the CERN Large Hadron Collider

ATLAS Collaboration

as installed in its experimental cavern at point 1 at CERN is

expected performance of the detector when the

April, the 12th, 2008

The CMS experiment at the CERN LHC

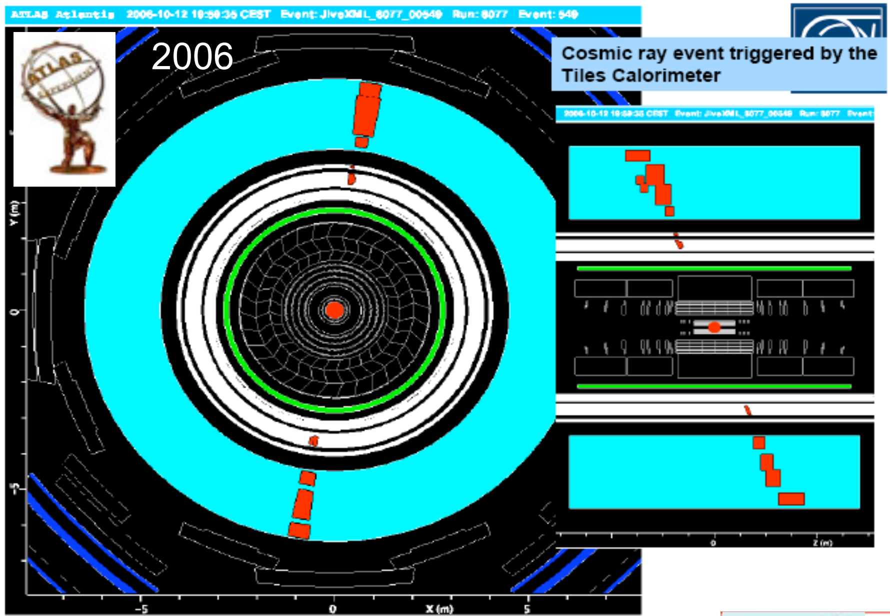
CMS Collaboration *)

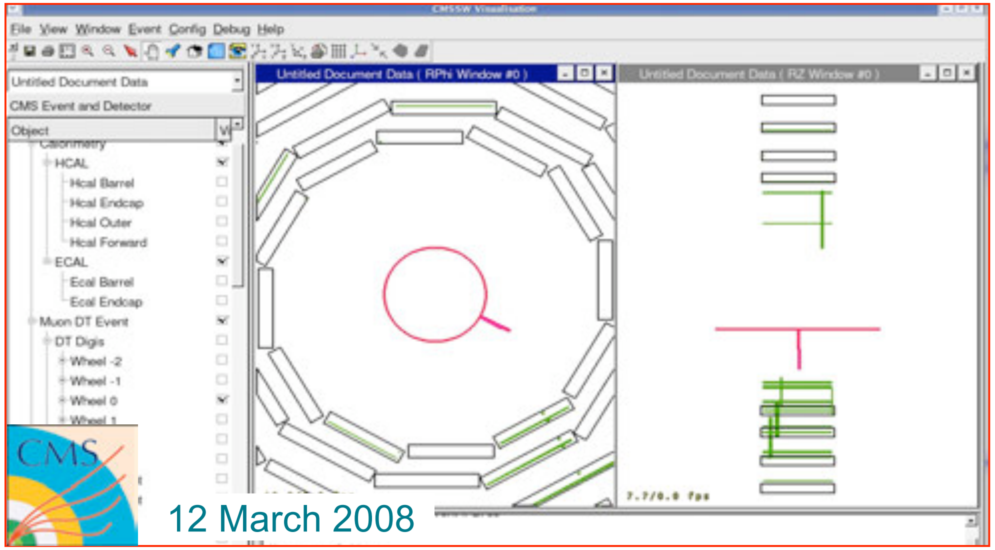
Abstract

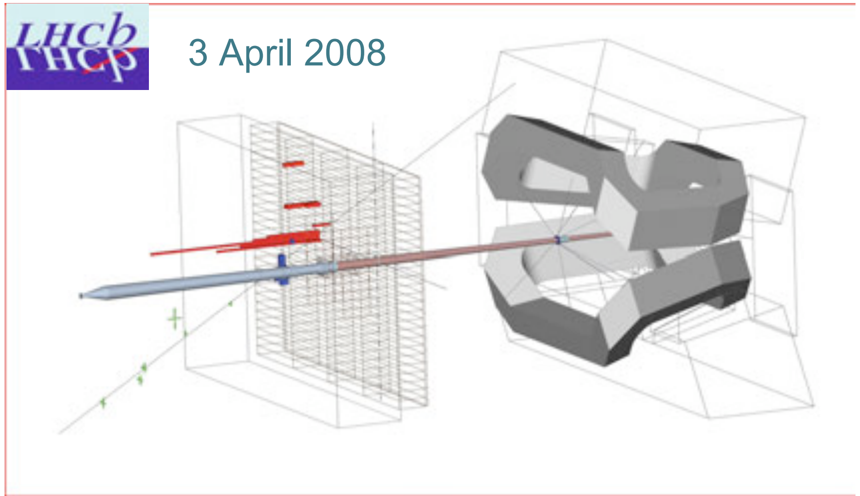
The Compact Muon Solenoid (CMS) detector is described. The detector operates at the Large Hadron Collider (LHC) at CERN. It was conceived to study proton-proton (and lead-lead) collisions at a centre-of-mass energy of 14 TeV (5.5 TeV nucleon-nucleon) and at luminosities up to 10^{34} $cm^{-2}s^{-1}$ (10^{27} $cm^{-2}s^{-1}$). The detector is characterised by high hermeticity. A high-field superconducting solenoid surrounds a silicon tracker, an electromagnetic calorimeter, and a hadron calorimeter. The return yoke is instrumented with muon detectors covering most of the 4π solid angle. Forward sampling calorimeters extend the CMS pseudorapidity coverage at high $|\eta|$ values.

Submitted to the Journal of Instrumentation (JINST)

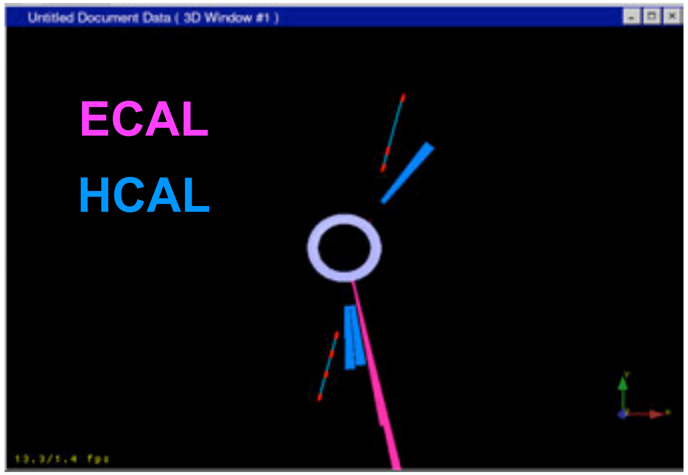
cosmic events in the calorimeters

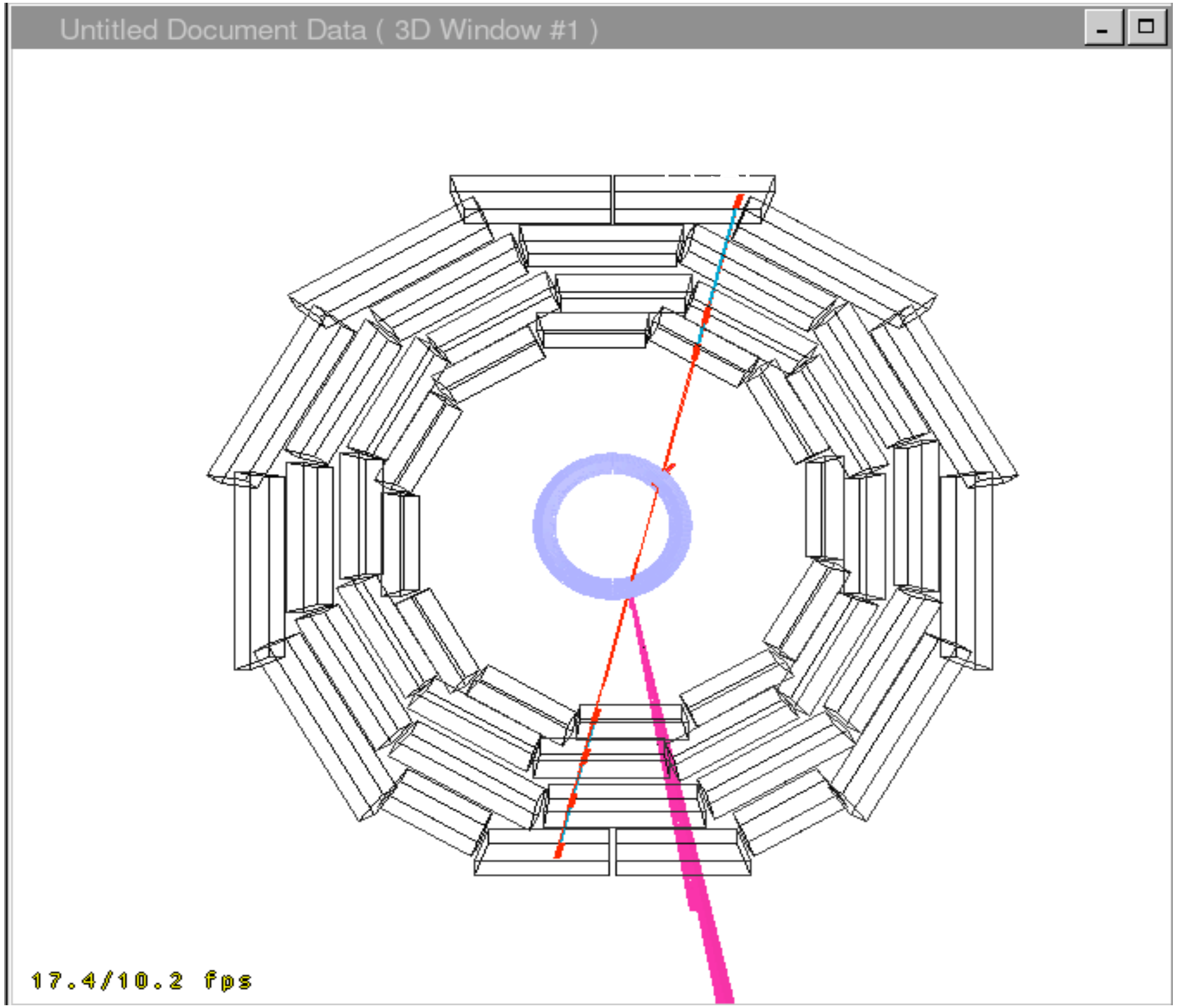






a spectacular muon showering in CMS





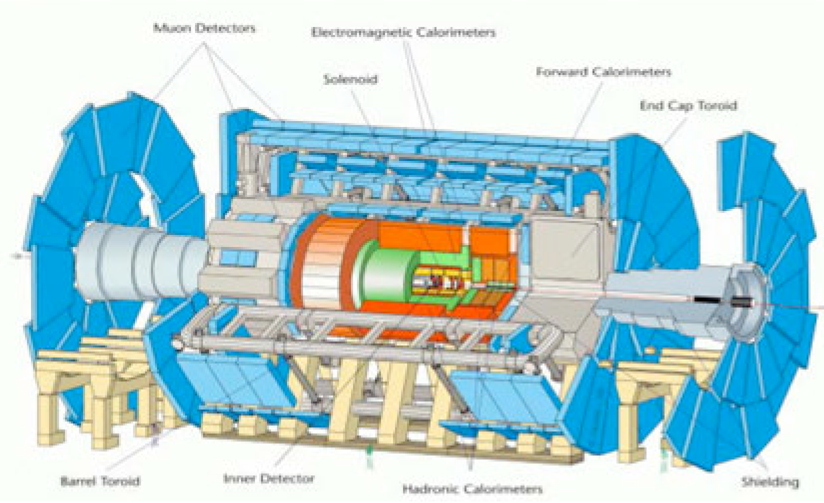
1991 calorimeter requirements

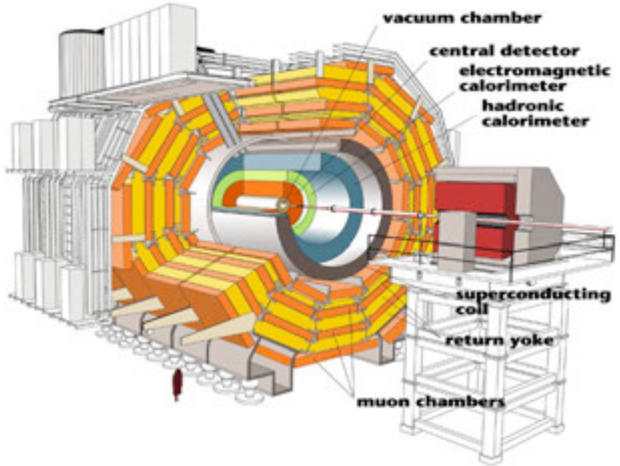
(D. Green, CALOR91 Capri)

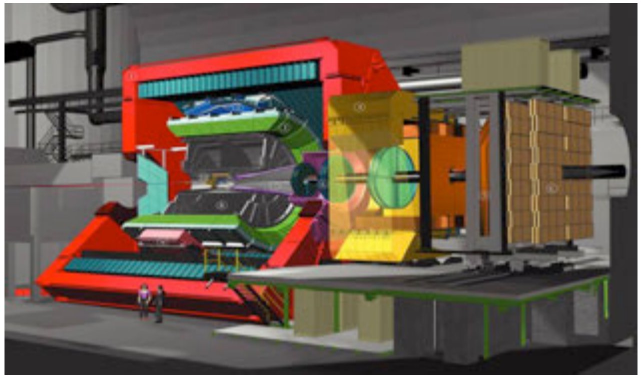
- hermeticity, speed
- P_T triggering
- upstream material ≤ 1 X_0 coil, ≤ 0.1 X_0 tracker
- angular coverage $\eta<3$ em, $\eta<5$ jet
- Hcal depth > 10 λ
- e.m transverse segmentation $\Delta\eta<0.05$
- hadronic transverse segmentation $\Delta\eta<0.05$
- longitudinal segmentation (to fight radiation damage)
- em resolution $< 0.2/\sqrt{E} \oplus 0.01$
- had resolution $< 0.7/\sqrt{E} \oplus 0.03$
- compensation e/h difference <0.3

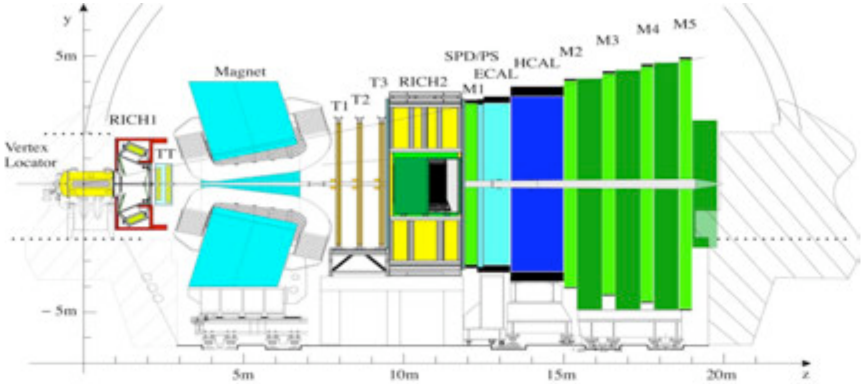
(linearity more important than precision)

Atlas and CMS: pp, general purpose





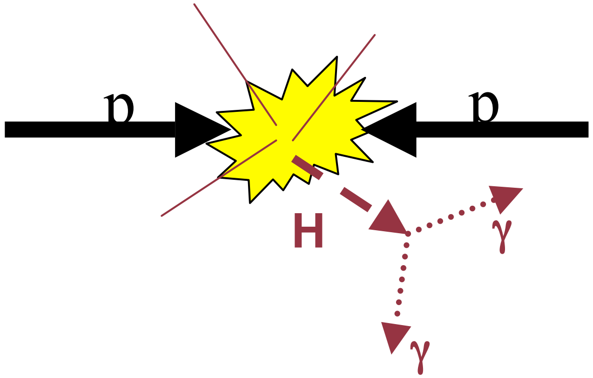




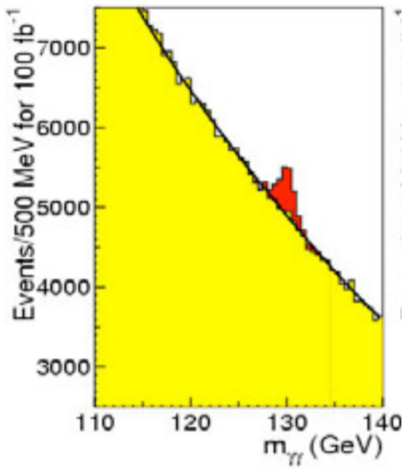
Alice: heavy ions, QG plasma

LHCb: pp, B physics

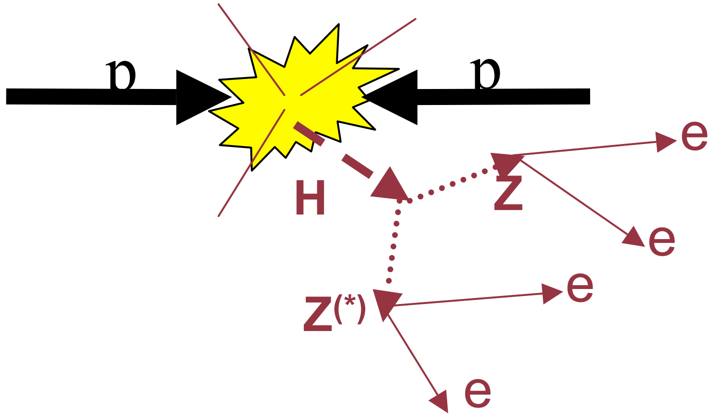
Physics goals of general purpose exp. need precision calorimetry



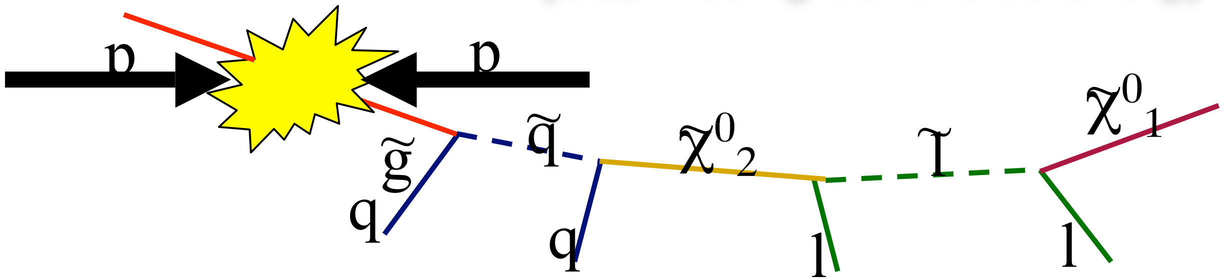
Photons high precision



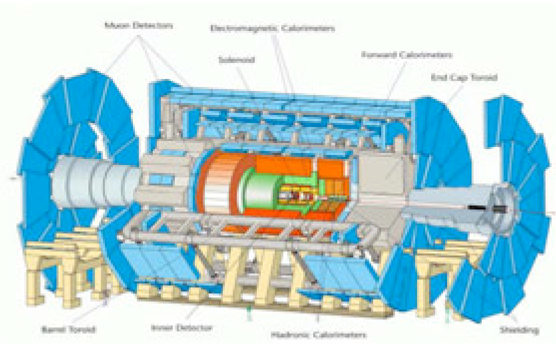
leptons high precision



identify complex decay chains by measuring electrons, jets, missing transverse energy



the two general purpose detectors

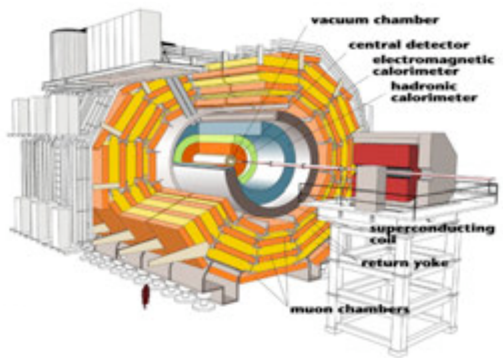


ATLAS main features:

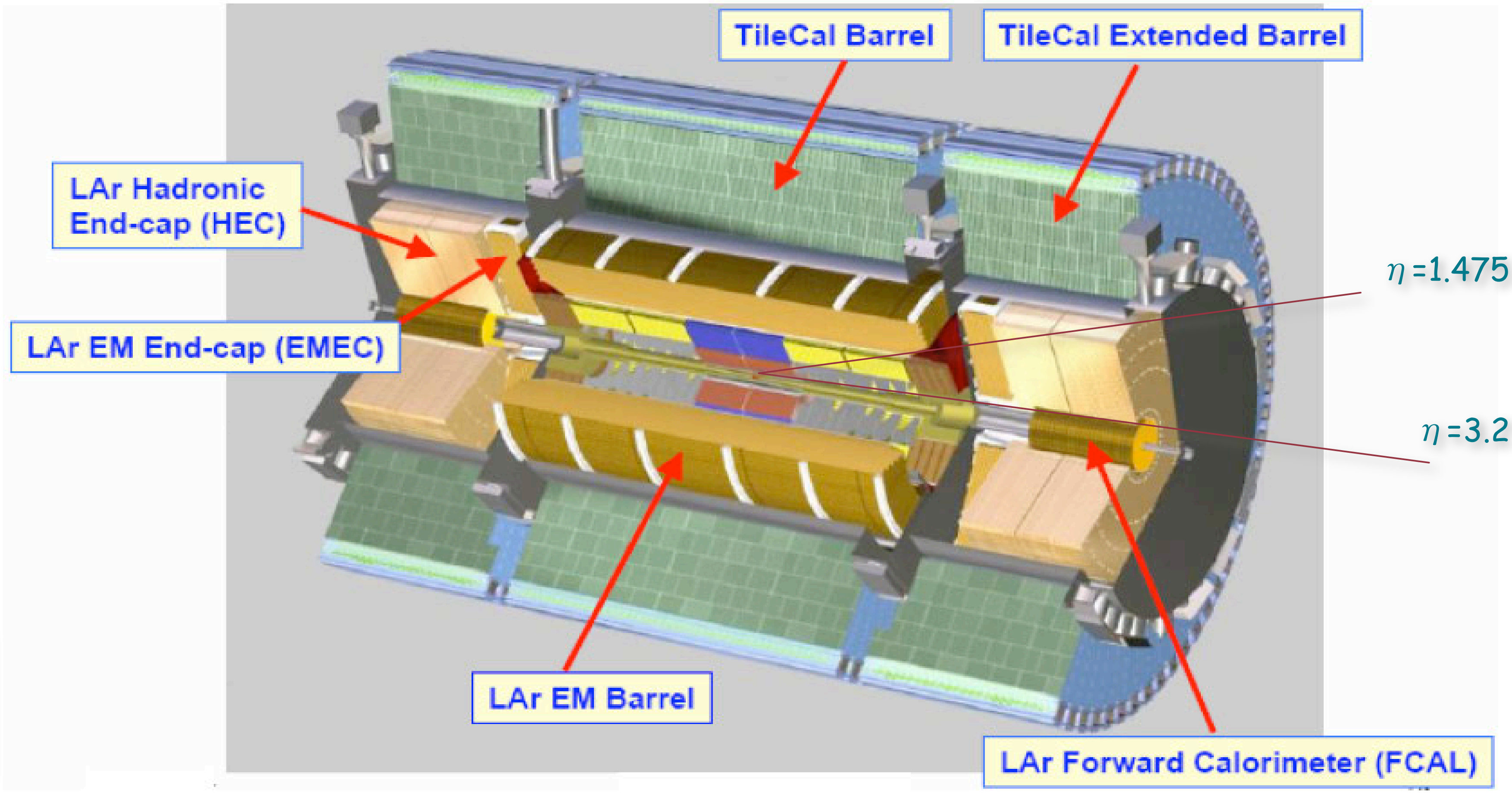
- Air muon spectrometer with three toroidal magnets
- Tracker inserted in a 2T solenoid
- Highly segmented LAr em calorimeter
- Tile or LAr for hadronic activity

CMS main features:

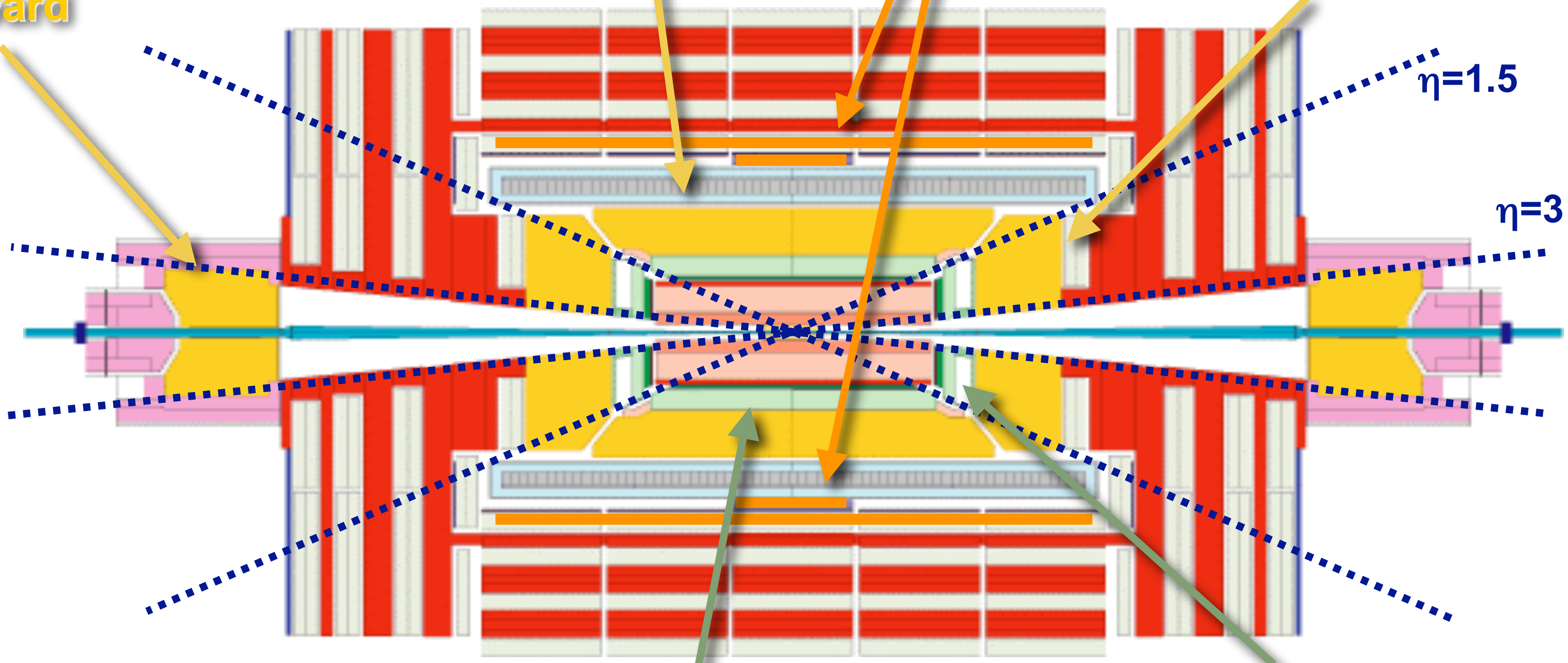
- Compact solenoid (4T) containing the calorimeters and the Si tracker
- Muon chambers embedded in the iron return yoke
- Electromagnetic calorimeter made by homogeneou crystals
- Tile calorimeter for hadronic activity



ATLAS calorimeters



CMS calorimeters



Calorimetric triggers

Calorimeters provide fast and granular signals

- electromagnetic clusters
- jets
- transverse missing energy
- large transverse energy
- isolation

ATLAS Low Lumi trigger example

Signature	L1 rate (Hz)	HLT rate (Hz)	Comments
Minimum bias	Up to 10000	10	Pre-scaled trigger item
e10	5000	21	$b, c \to e, W, Z$, Drell-Yan, $t\bar{t}$
2e5	6500	6	Drell-Yan, J/ψ, Υ, Z
γ20	370	6	Direct photons, γ-jet balance
2γ15	100	< 1	Photon pairs
μ10	360	19	$W, Z, t\bar{t}$
2μ4	70	3	B-physics, Drell-Yan, J/ψ, Υ, Z
$\mu 4 + J/\psi(\mu\mu)$	1800	< 1	B-physics
j120	9	9	QCD and other high-p_T jet final states
4j23	8	5	Multi-jet final states
τ20i + xE30	5000 (see text)	10	$W, t\bar{t}$
τ20i + e10	130	1	$Z \to \tau\tau$
τ20i + μ6	20	3	$Z \to \tau\tau$

Table 64. Subset of items from an illustrative trigger menu at 10^{31} cm^{-2} s^{-1}.

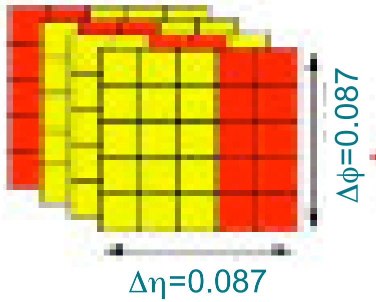
example: CMS L1 regional calo trigger

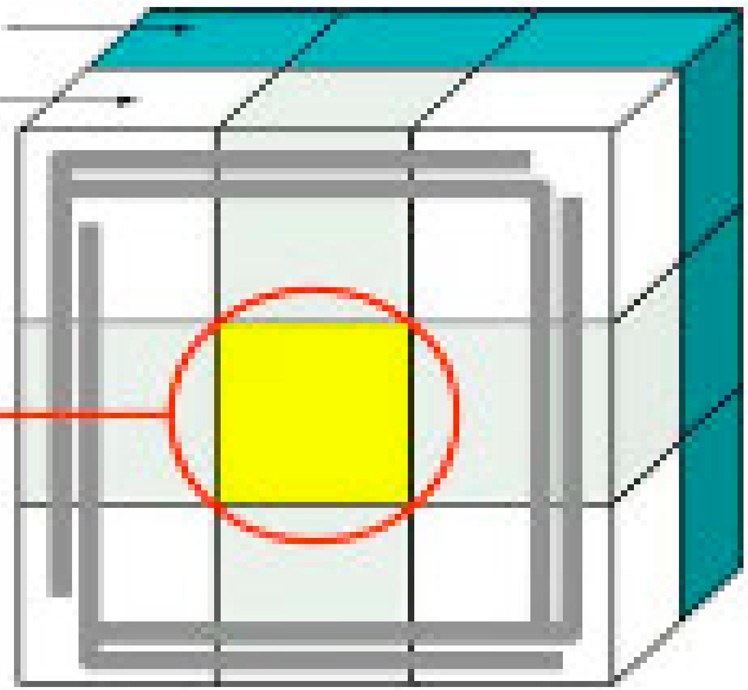
provides isolated e/γ trigger

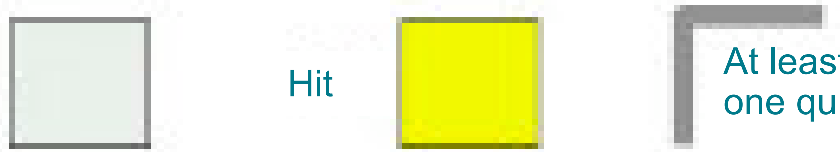
$E_h/E_{em}<5\%$

“fine grain profiles”:

2 x 5 crystal dominos to identify narrow shower profiles







Requirements for e.m. calorimeters

- large acceptance
- good energy and position resolution for high energy em showers up to $|\eta|<2.5$
- fast
- compact
- granular
- radiation tolerant
- large dynamic range (from MIP to TeV)
- linear
- particle identification (e/jet and γ/π^0 separation)

ATLAS LAr-Pb sampling calorimeter

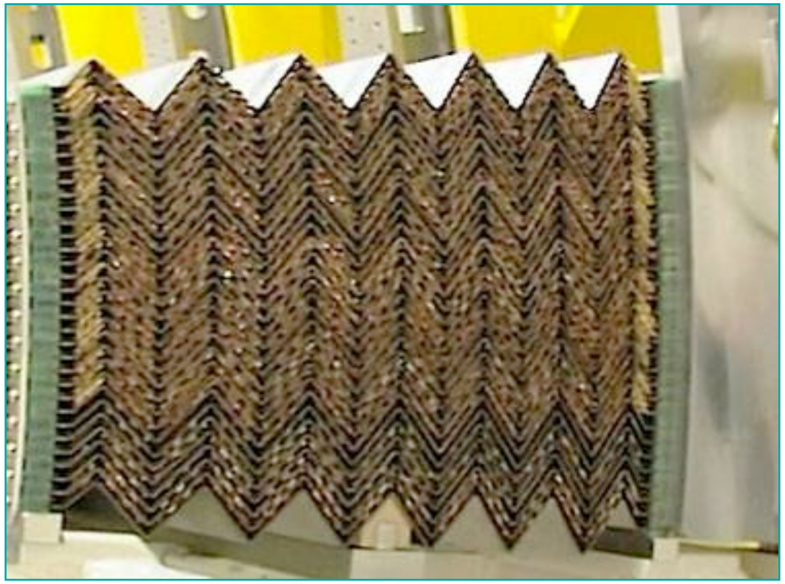
- large acceptance
- good energy and position resolution for high energy em showers up to $|\eta|<2.5$
- fast
- compact
- highly granular (longitudinal and transversal)
- radiation tolerant
- large dynamic range (from MIP to TeV)
- linear
- particle identification (e/jet and γ/π^0 separation)

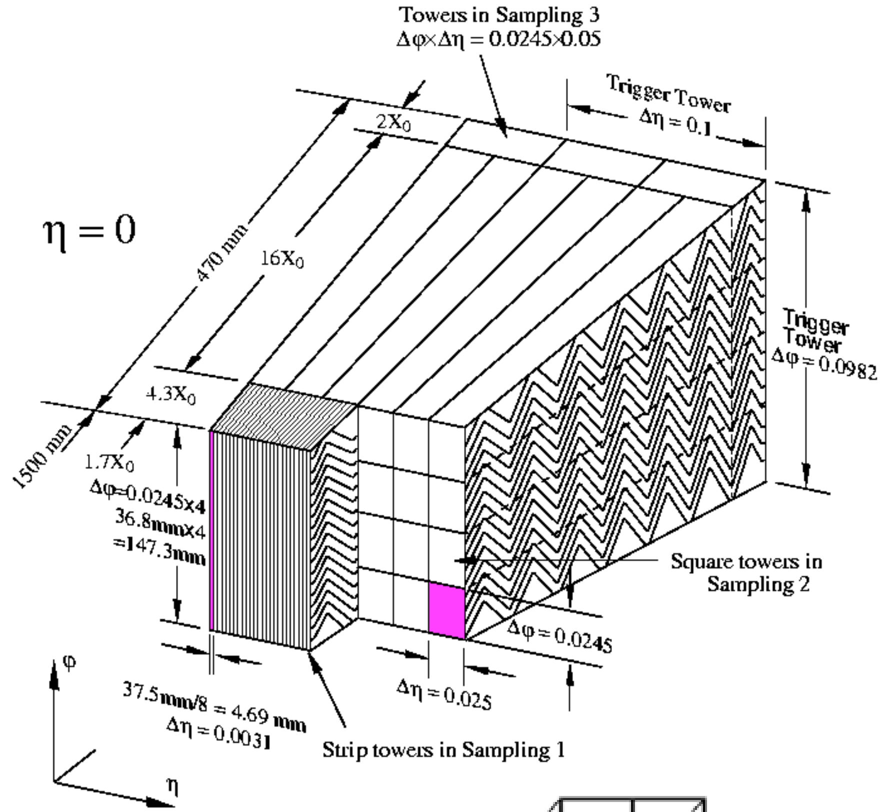
CMS $PbWO_4$ scintillating crystals cal.

- large acceptance
- excellent energy and position resolution for high energy em showers up to $|\eta|<2.5$
- fast
- compact
- granular
- radiation tolerant
- large dynamic range (from MIP to TeV)
- linear
- particle identification (e/jet and γ/π^0 separation)

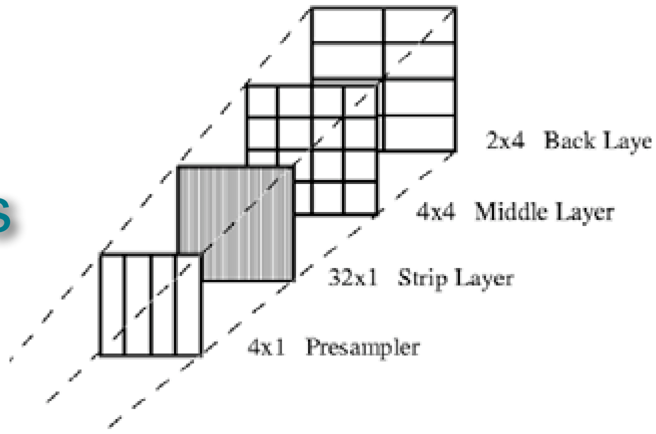
ATLAS Pb/LAr EM

- Length: at least 22 X_0 (47 cm)
- 3 longitudinal layers (+presampler)
- 4 X_0 rejection of π^0 in two photons
- 16 X_0 for shower core
- 2 X_0 evaluation of late showers





170000 channels

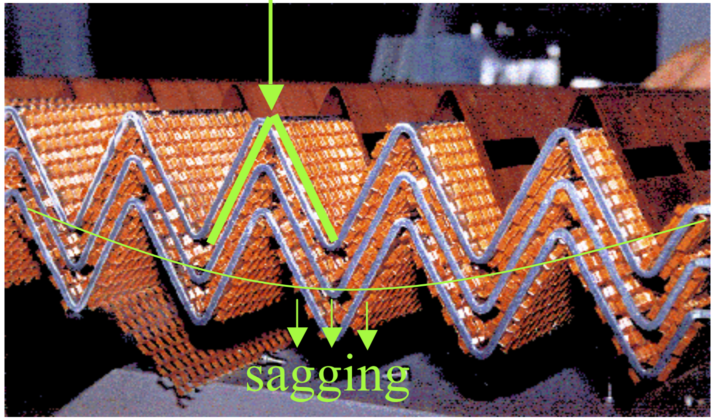


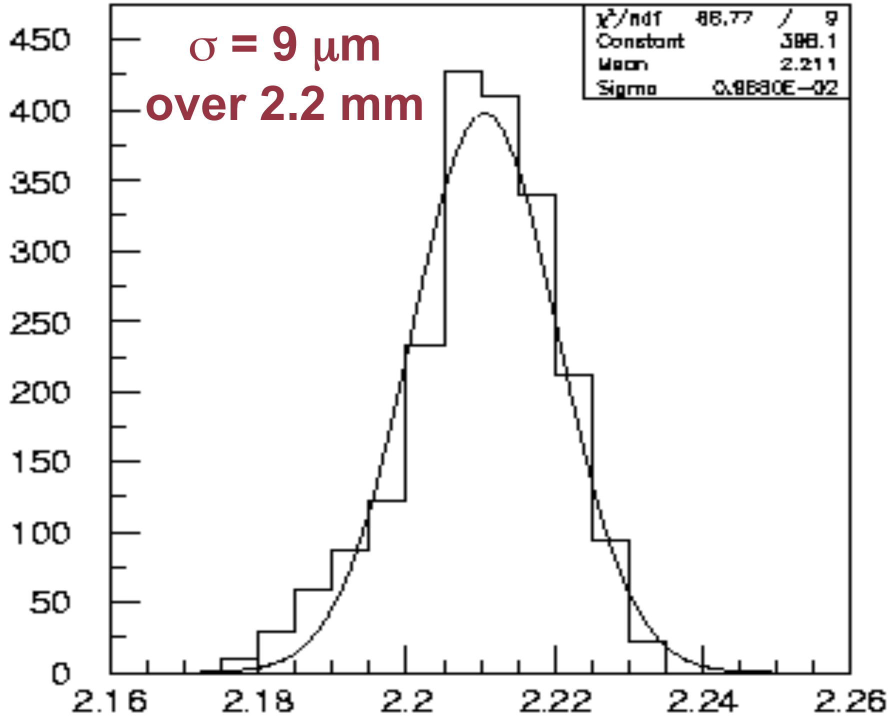
Mechanical non uniformities

1% variation in lead thickness

→ 6 ‰ drop in response

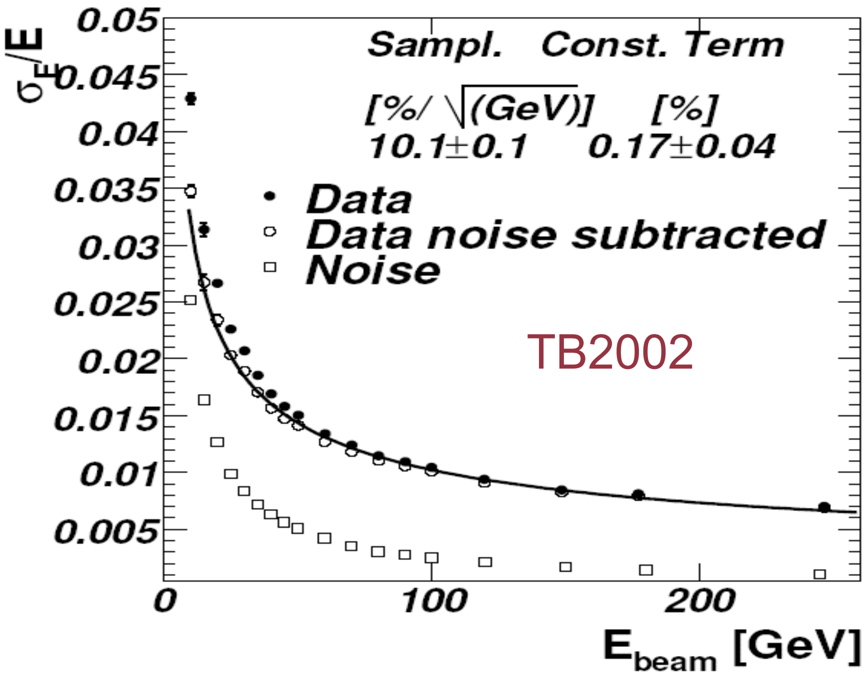
slant angle : 1º/~100º is sensitive





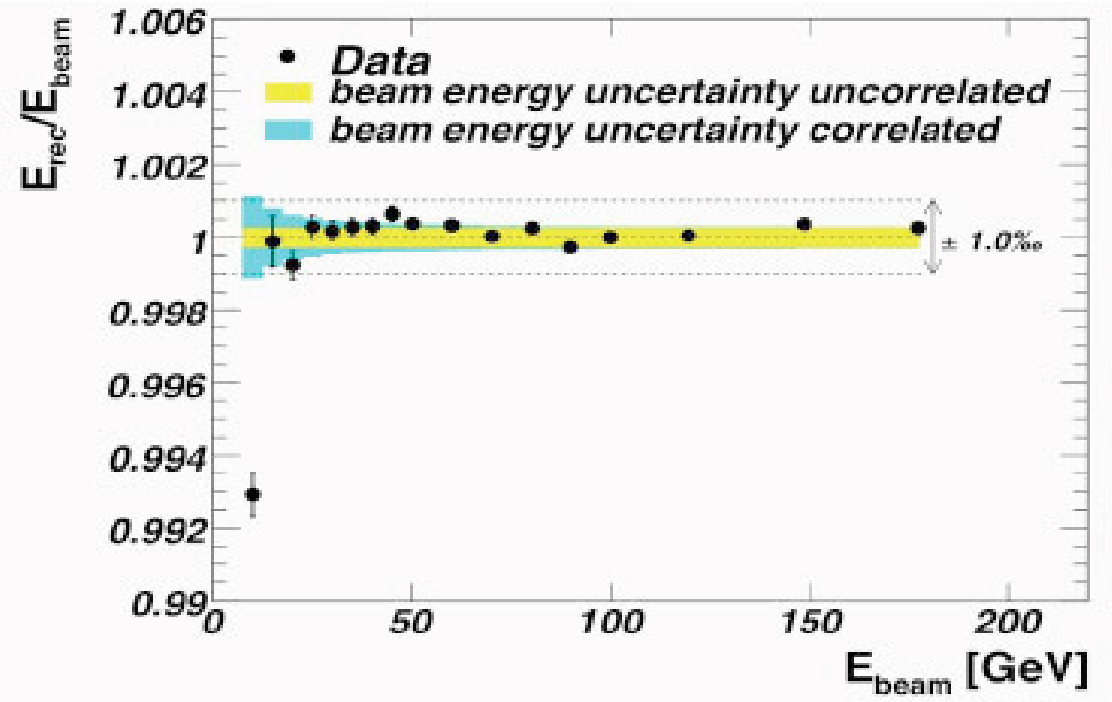
measured absorber thickness

ATLAS EM performance



resolution at η = 0.687

linearity

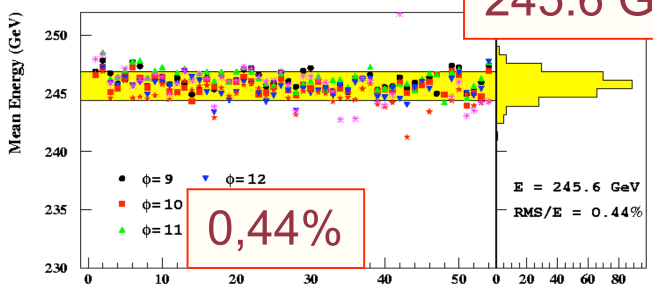


ATLAS EM uniformity

Scan modules with monochromatic electrons

Module P13

245.6 GeV

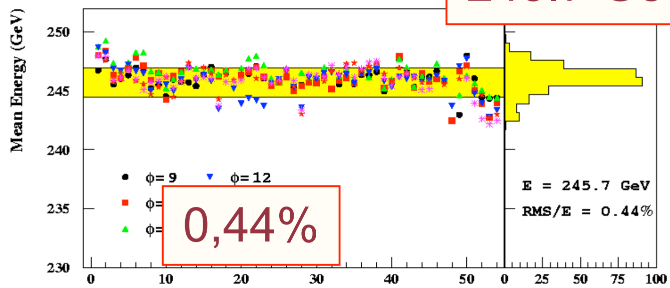


0,44%

η

Module P15

245.7 GeV

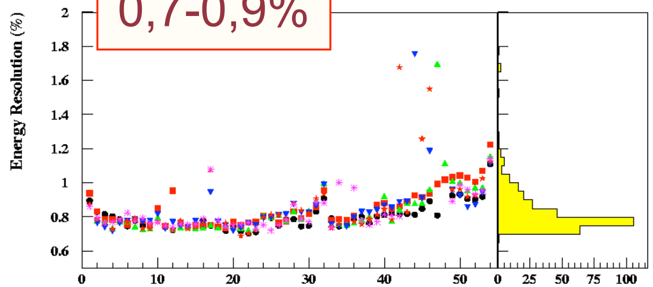


0,44%

η

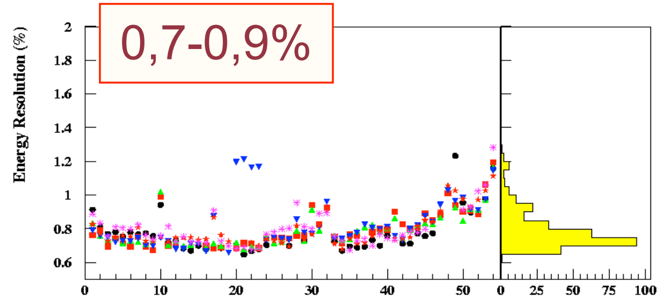
Uniformity

0,7-0,9%



η

0,7-0,9%



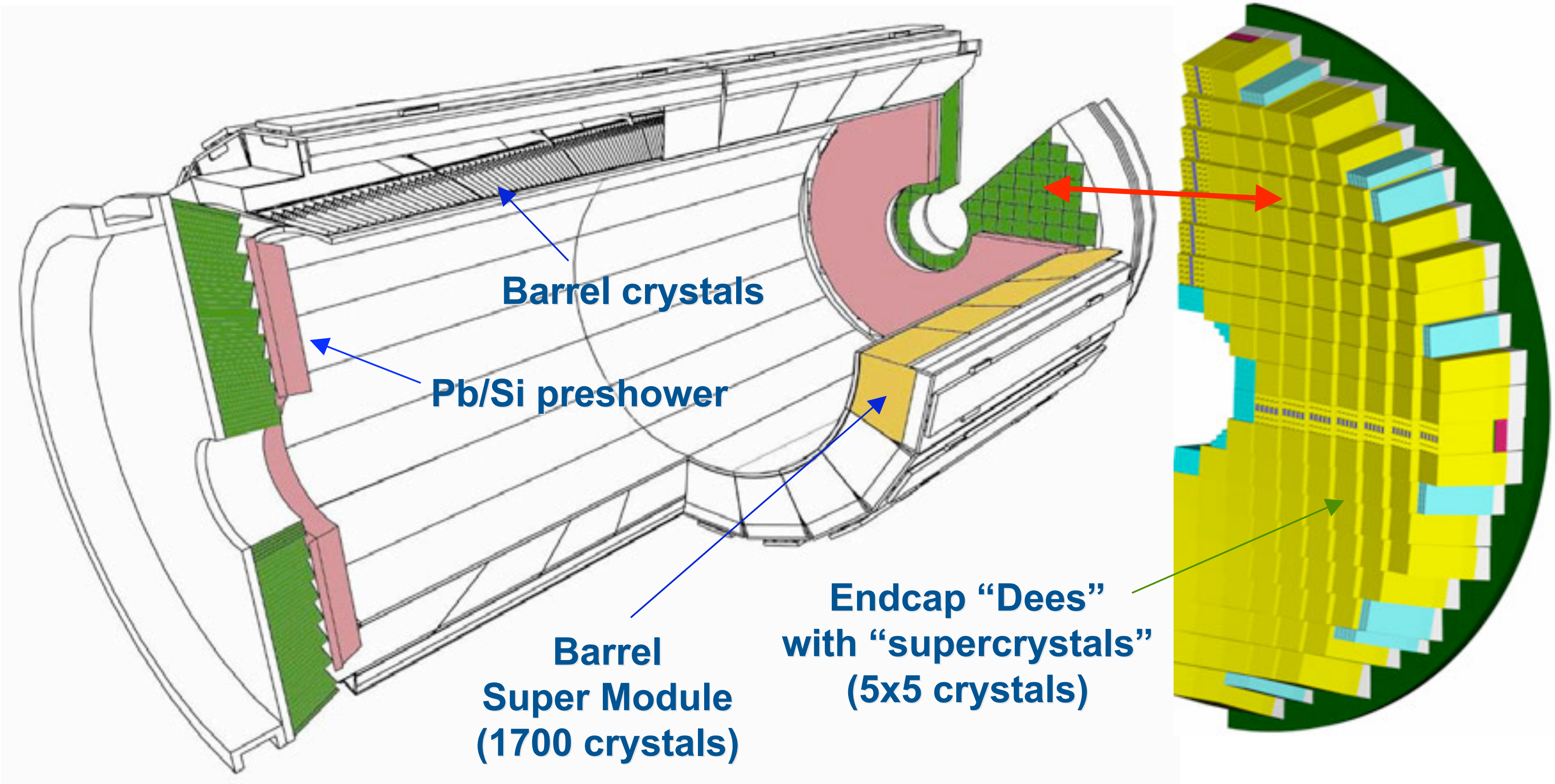
η

Resolution

Global constant term: ~ 0.6 %

The CMS ECAL

$PbWO_4$ crystals



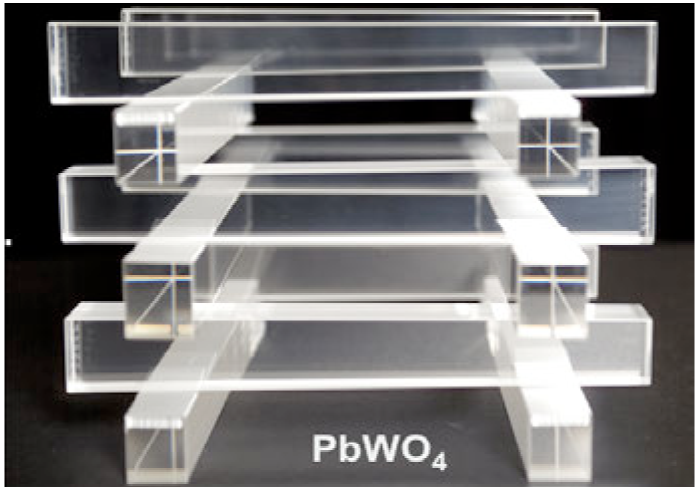
Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23cm³)

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

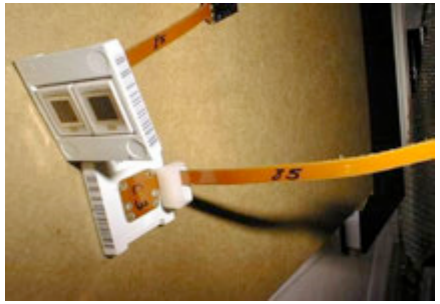
PWO crystals

X_0	0.89	cm
Molière radius	2.2	cm
Light in 25 ns	80%	
LY	100	γ/MeV

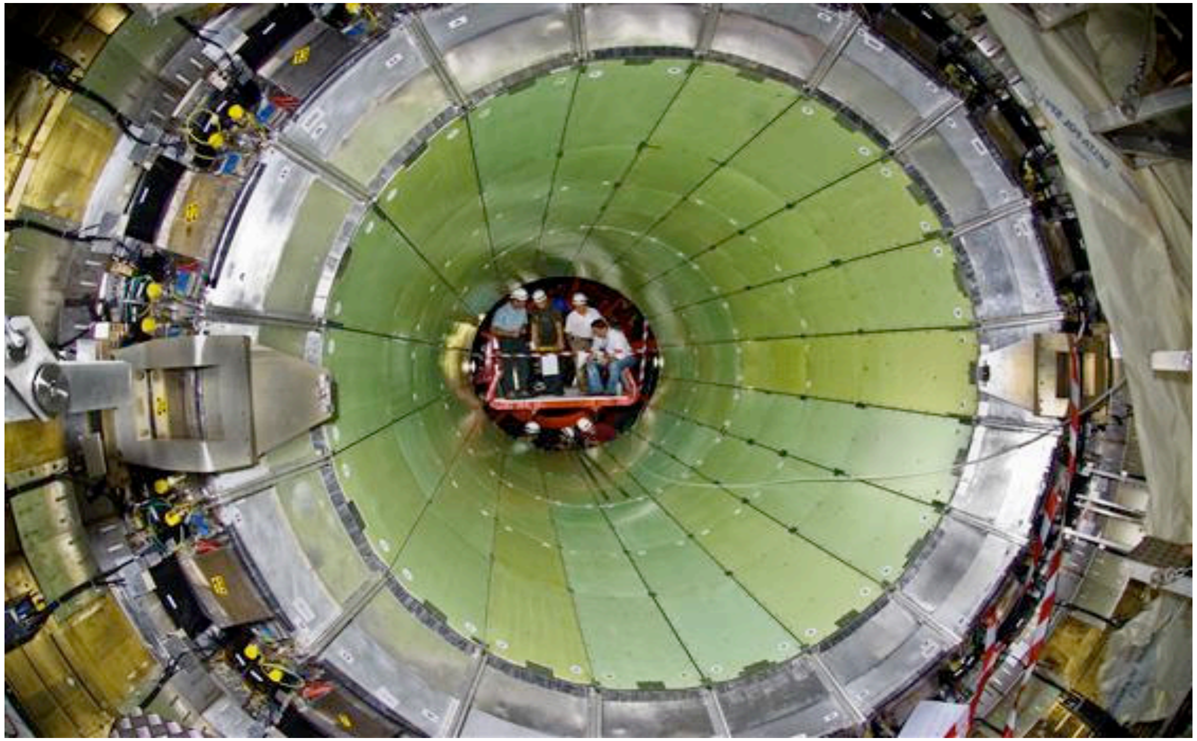
Compact homogeneous calorimeter
$\Delta\eta \times \Delta\phi$ =
0.017 × 0.017
for the barrel



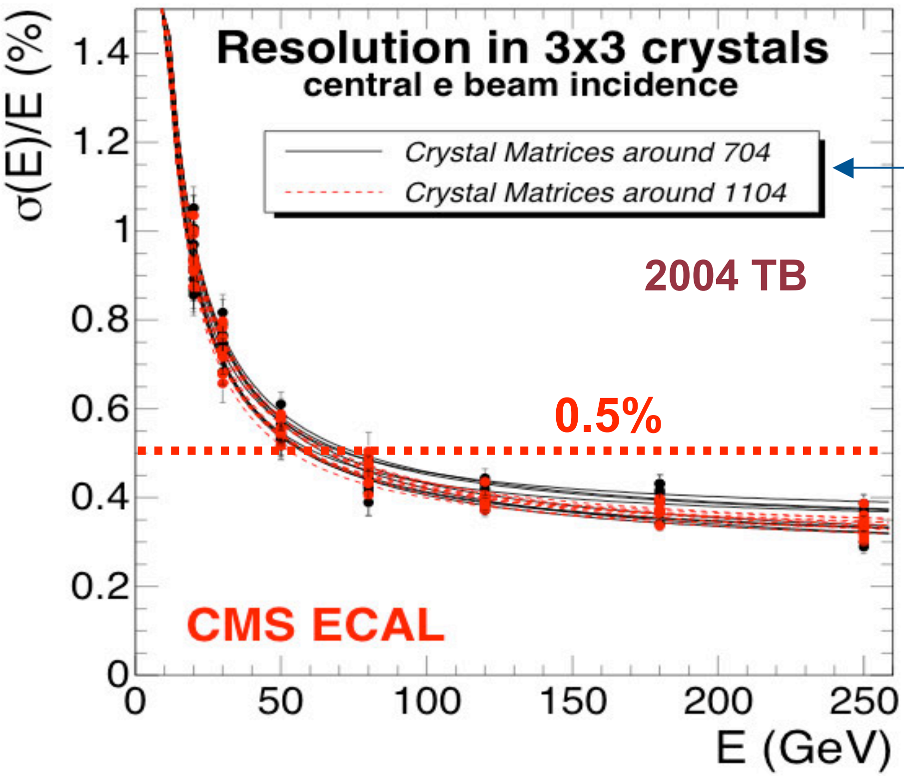
APD



VPT



CMS ECAL test-beam performance



η independent

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

Calibration

convert individual channel response to particle energy for electrons, photons and hadrons

e.g. CMS ECAL:

to be determined

$$E_{e,\gamma} = G \times \mathcal{F} \times \sum_{i}^{\text{Cluster}} c_i \times A_i,$$

- G: absolute energy scale
- $\mathcal{F}$: cluster-algorithm dependent factor (containment, position, particle type, momentum…)
- c_i: inter-calibration constants
- A_i: digitized signals

ATLAS

Start data taking with well pre-calibrated calorimeter (< 1%)

- *Electronic calibration system*
- *Mechanics uniform by construction*

10% tested with beams: Uniformity of response ~0.45%

Long range $Z \rightarrow e\, e$ or $W \rightarrow e\, \nu$ decays

50k $Z \rightarrow e\, e$ ***events (0.1 fb^{-1}) global constant term <0.7%***

CMS

Start-up intercalibration for ECAL:

- Cosmic inter-calibration *all barrel supermodules ≤ 2 %*
- **1/4 of ECAL SMs** testbeam inter-calibration **~ 0.3 %**

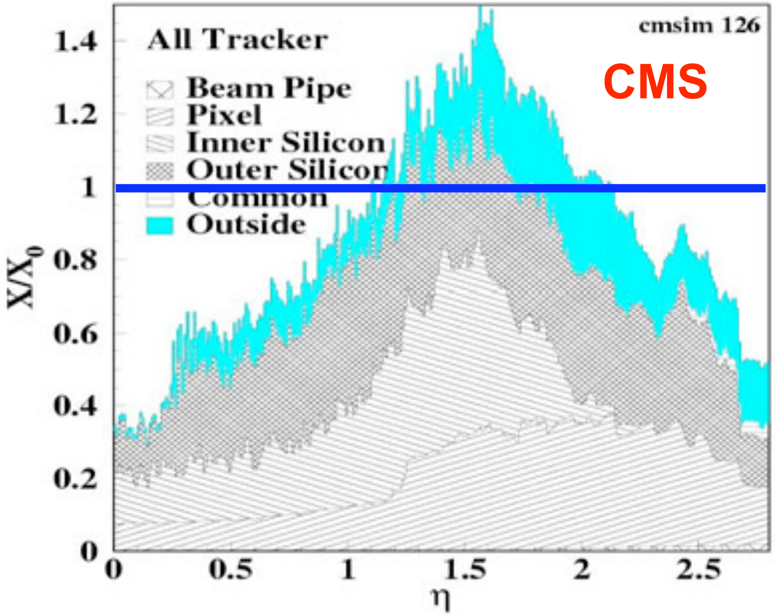
Intercalibration and absolute calibration in situ:

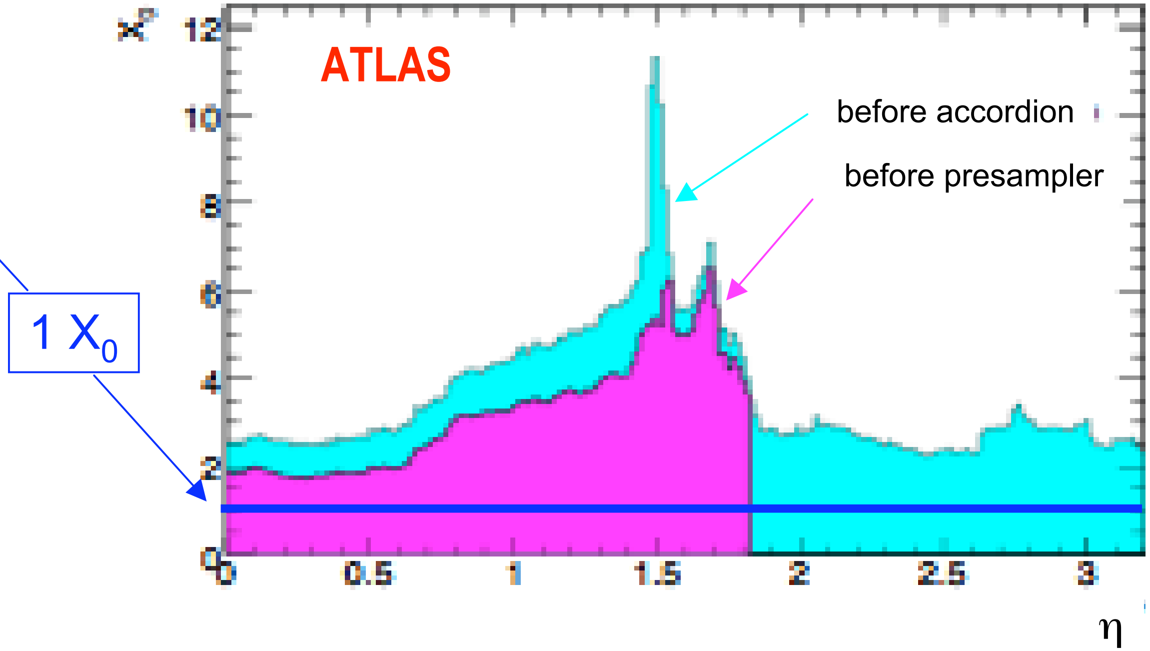
- ϕ-symmetry in min. bias ev. *fast equalisation at 1.5 to 2%*
- $W \rightarrow e\, \nu$ from E/p *inter-calibration*
- $Z \rightarrow e\, e$ invariant mass *absolute calibration*

From W alone intercalibration < 0.5% with 5 fb^{-1}

MC studies show that faster calibration is possible by π^0 mass reconstruction

Material budget in front ef ECALs





Tracker material:

- electrons loose energy via bremsstrahlung
- photons convert

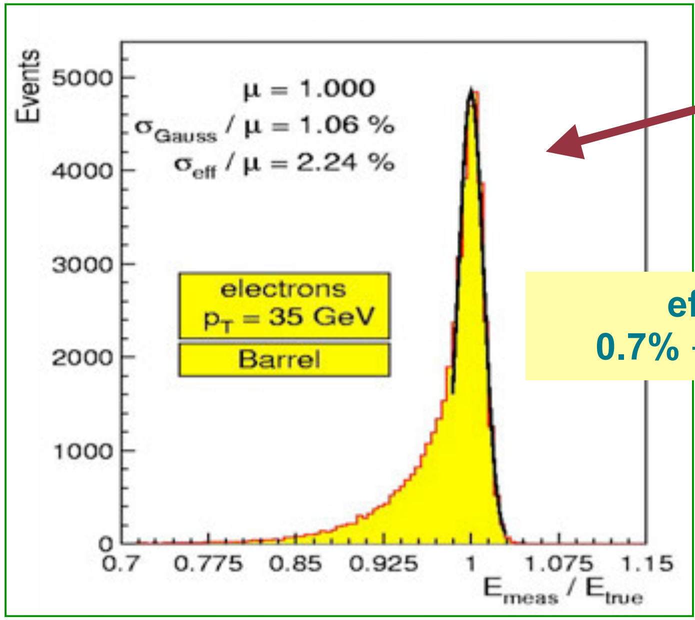
4T (2T) solenoidal B field :

- Electrons bend ⇒ radiated energy spread in φ

Different effects for photons and electrons…

Effects of material in front

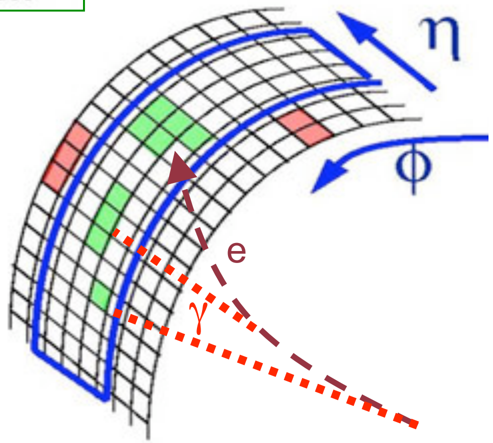
CMS

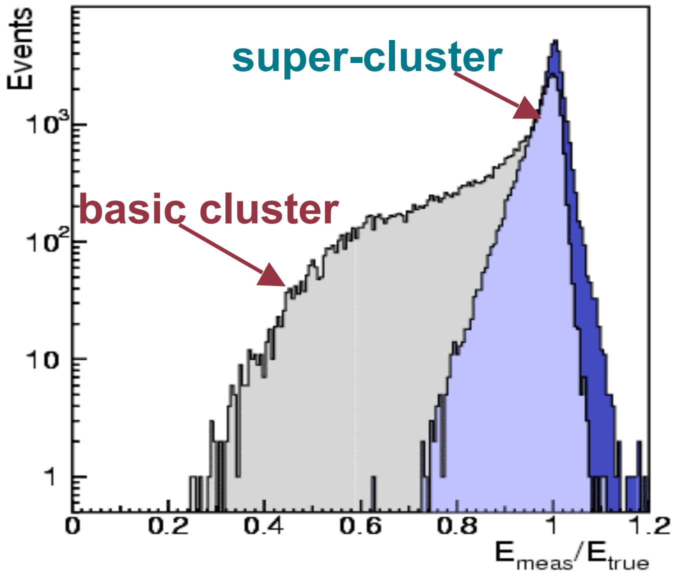


50% electrons undergo not negligible bremsstrahlung

effect on resolution at p_T 35 GeV:
0.7% → 1.06% (gauss) → 2.2 % (effective)

dynamic clustering algorithms (superclusters) can resum photon energies





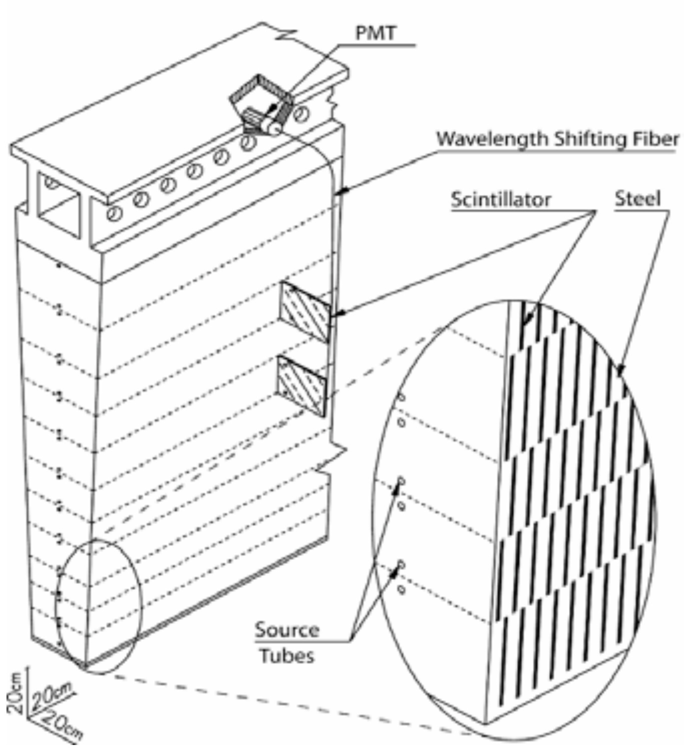
Role of Hadron calorimeters

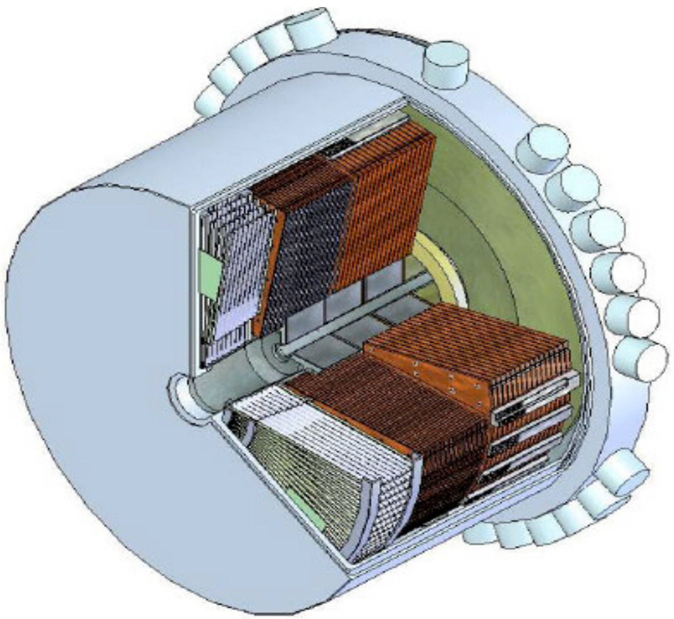
- Physics channels with jets => good energy and position resolution for high E jets (>10 λ for E_{jet}~1TeV)
- Searches => jets measurements, hermeticity, to provide good resolution on E_T missing
- Jets are made of an e.m. component as well, so good combined hadronic + e.m. resolution is required
- Forward calorimeters must
  - tag forward jets (searches of "combined production channels")
  - provide reasonable forward jet energy measurement for missing Et resolution

Structure of ATLAS had. calorimeters

Barrel HCAL (TileCal):

- Iron/Plastic scintillator with tiles perpendicular to beam axis
- Wavelength shifting fibers carry light to PMT
- 10-13 λ, 3 longitudinal samplings
- Covers $|\eta|<1.7$
- $\Delta\eta \times \Delta\varphi = (0.1\text{-}0.2) \times 0.1$

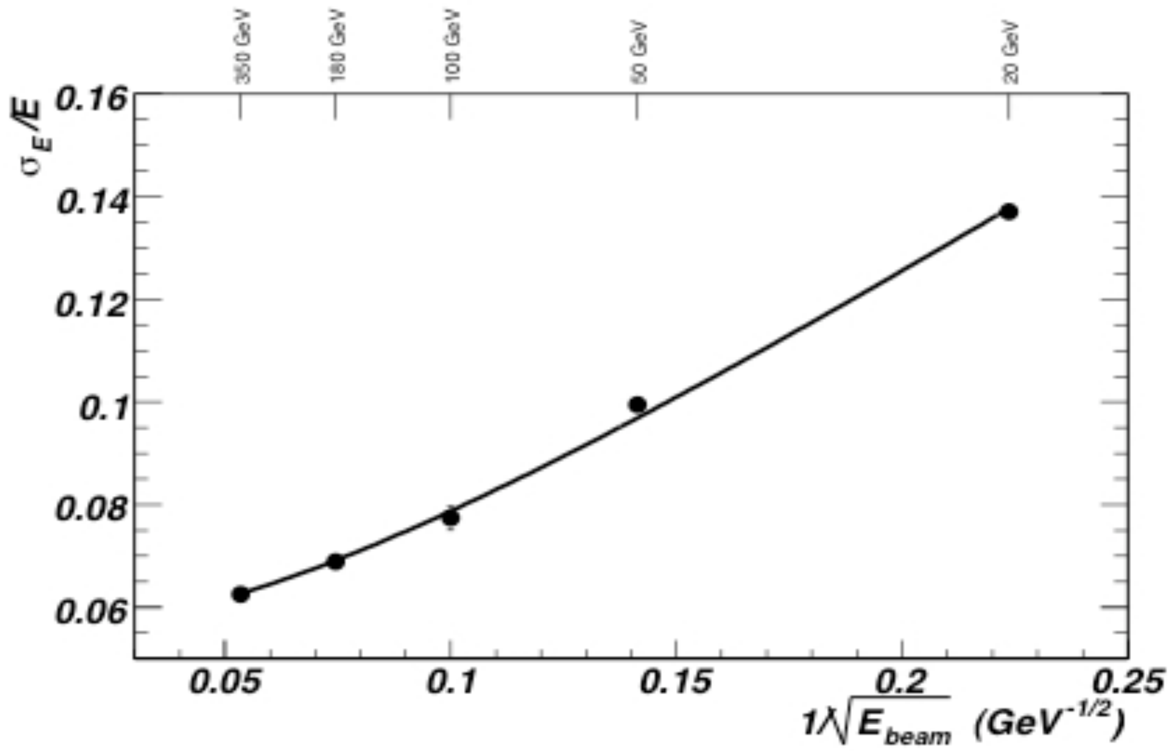




Endcap HCAL (HEC):

- Cu-LAr layers
- 2 wheels per endcap (3 with e.m. part)
- 10-12.5 λ, 4 longitudinal samplings
- $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ and 0.2×0.2 for $|\eta|>2.5$

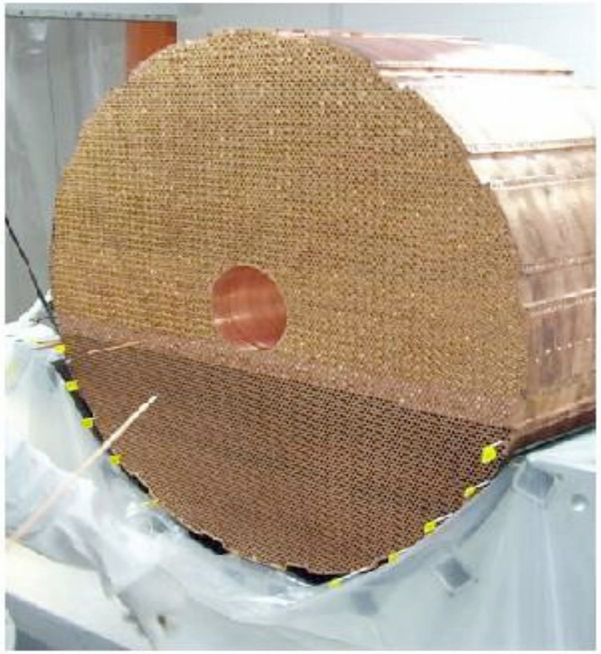
ATLAS Tile calorimeter performance

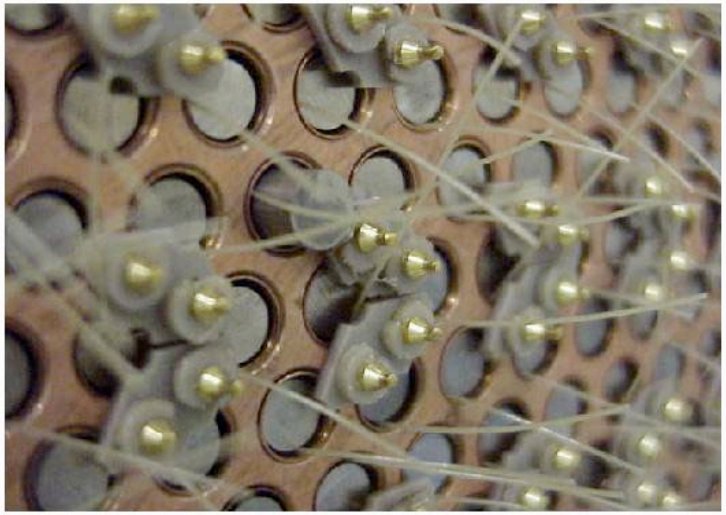


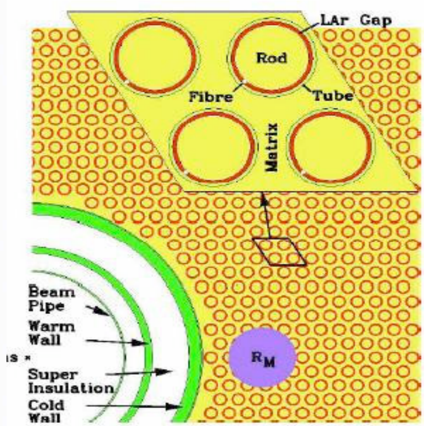
test beam isolated pions
standalone Tile calorimeter at η=0.35

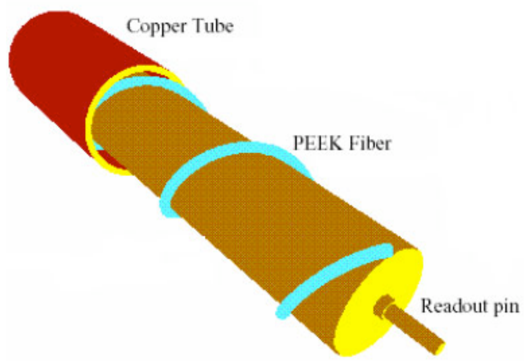
ATLAS forward calorimeter

- tubolar structure, very narrow LAr gaps
- 28 X_0 LAr-Cu: electromagnetic
- 2 x 3.7 λ LAr-W: hadronic
- $3.2<|\eta|<4.9$
- Total number of channels: 2822

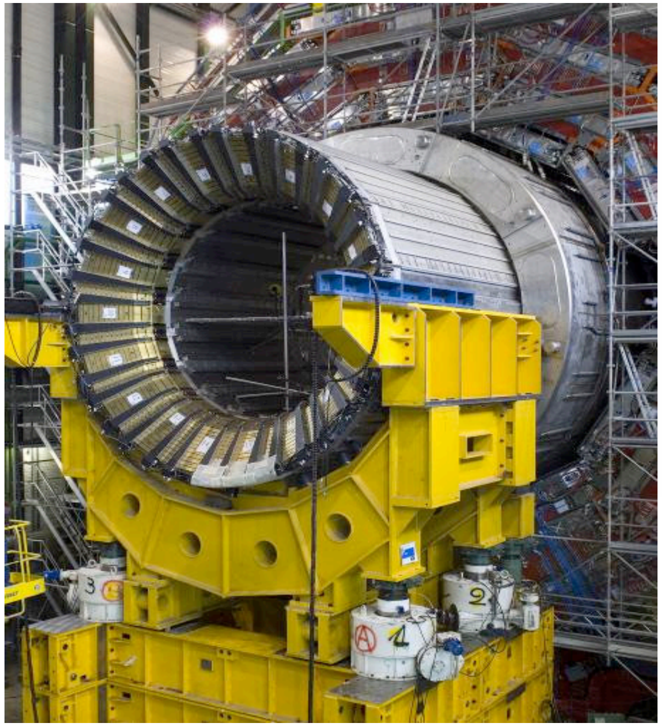


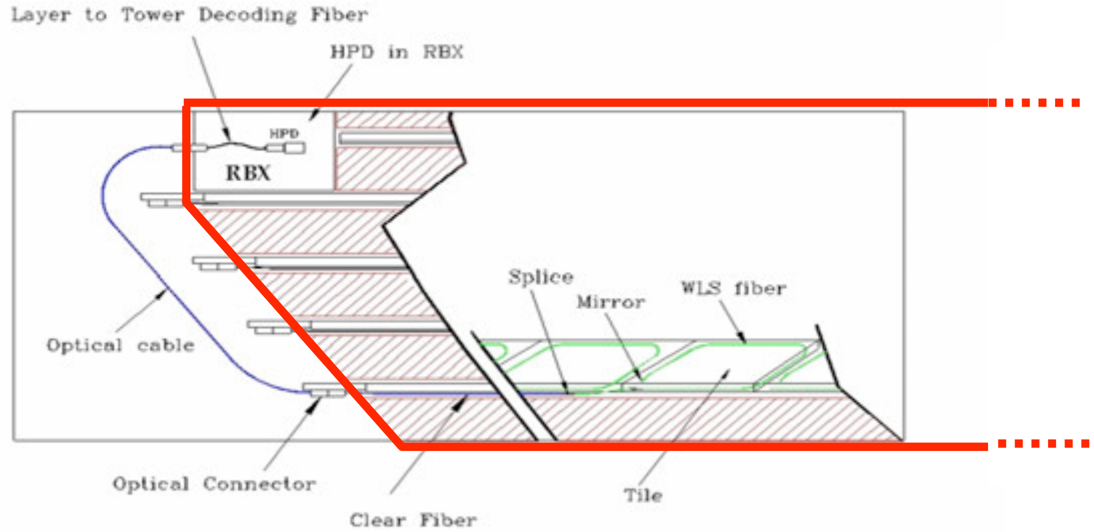






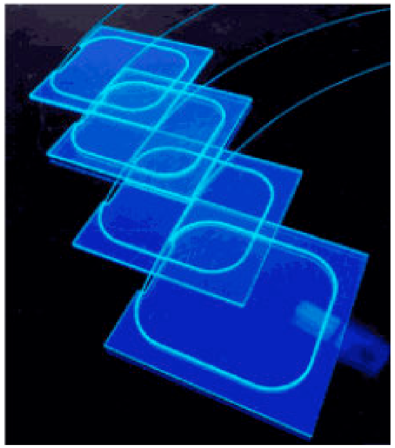
CMS HCAL barrel

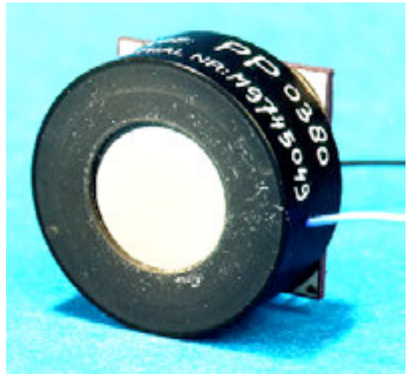




2593 towers

$\Delta\eta \times \Delta\phi = 0.017 \times 0.017$

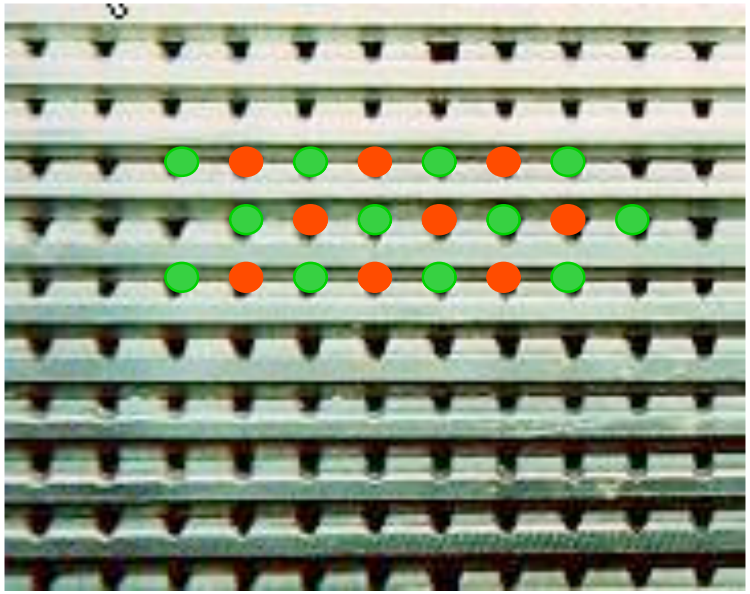


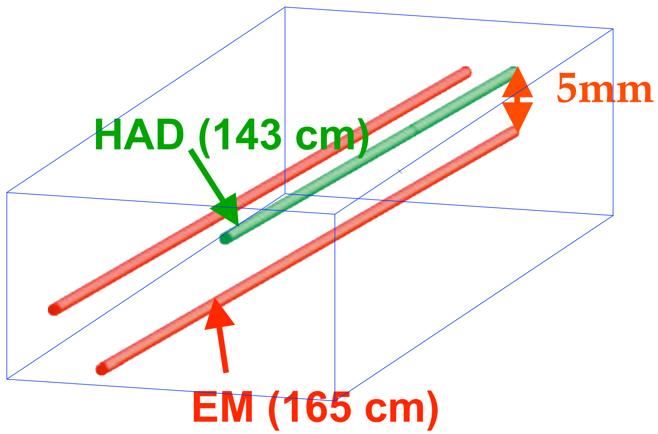


pixel HybridPhotoDiode

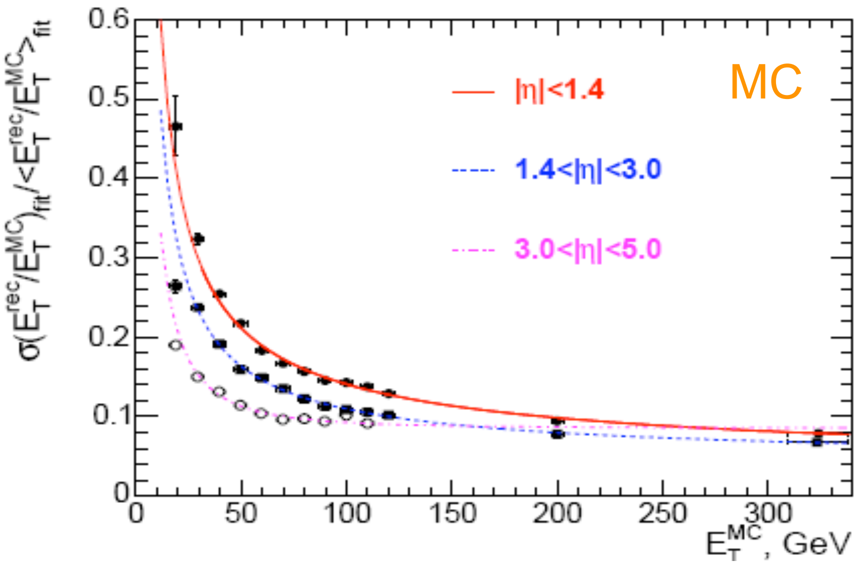
CMS forward calorimeter

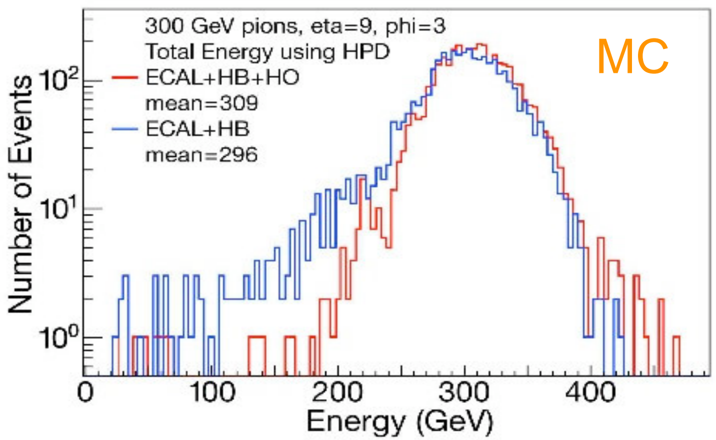
- Iron/Quartz fiber to detect Cerenkov light
- Covers 3<|η|<5
- Total of 1728 towers, 2 x (2 x 432 towers for EM and HAD)
- η x ϕ segmentation (0.175 x 0.175)





CMS HC + EC energy resolution for jets

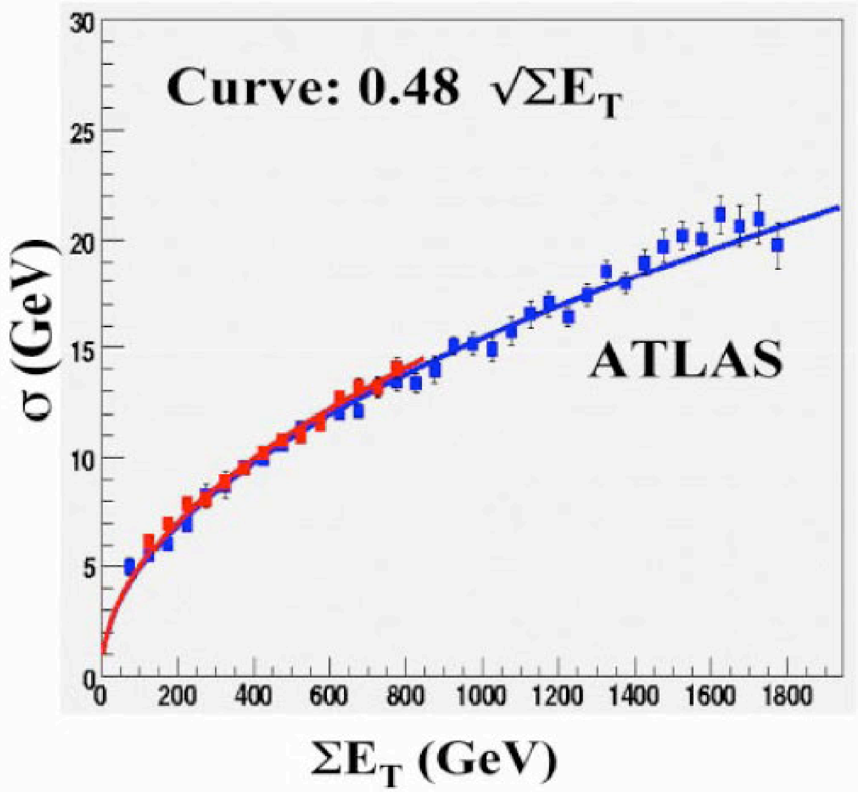


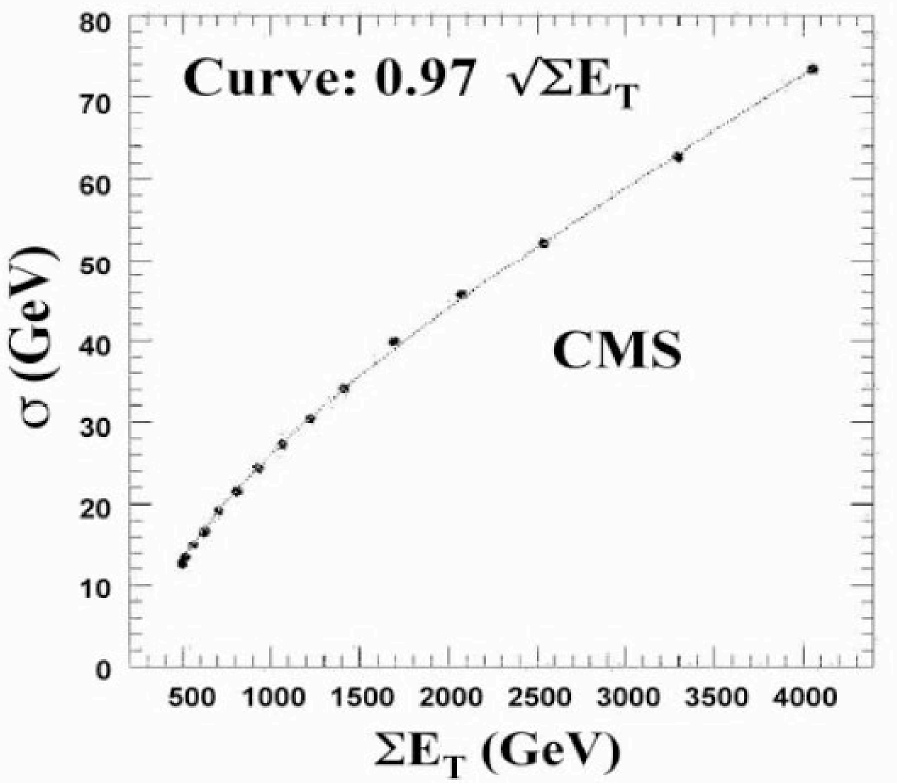


limits on the resolution:

- Non compensation e/h~1.4
  - resolution sensitive to fluctuations in the electromagnetic component
  - non linearity.
  - Improvements can be obtained with particle flow technique
- Limited depth
  - 5% of a 300 GeV pion energy escapes HB
  - tail catcher HO outside the coil improves by 10% the energy resolution for pions of 300 GeV and linearity

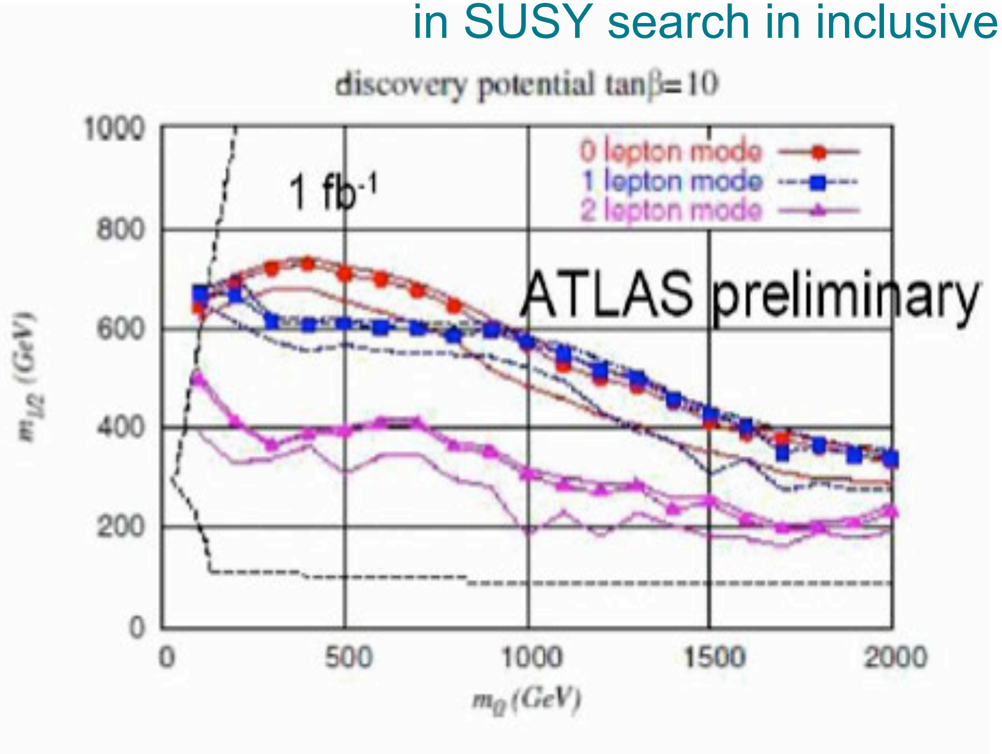
Missing E_T expected performance

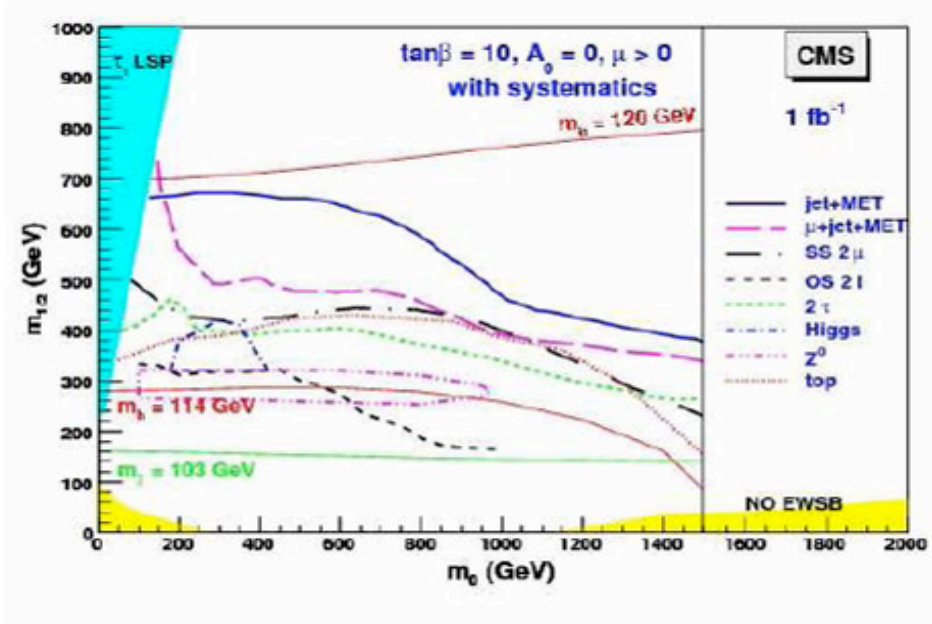




Performance on SUSY searches

Atlas and CMS show similar performance
in SUSY search in inclusive channels with jets and large E_{Tmiss}

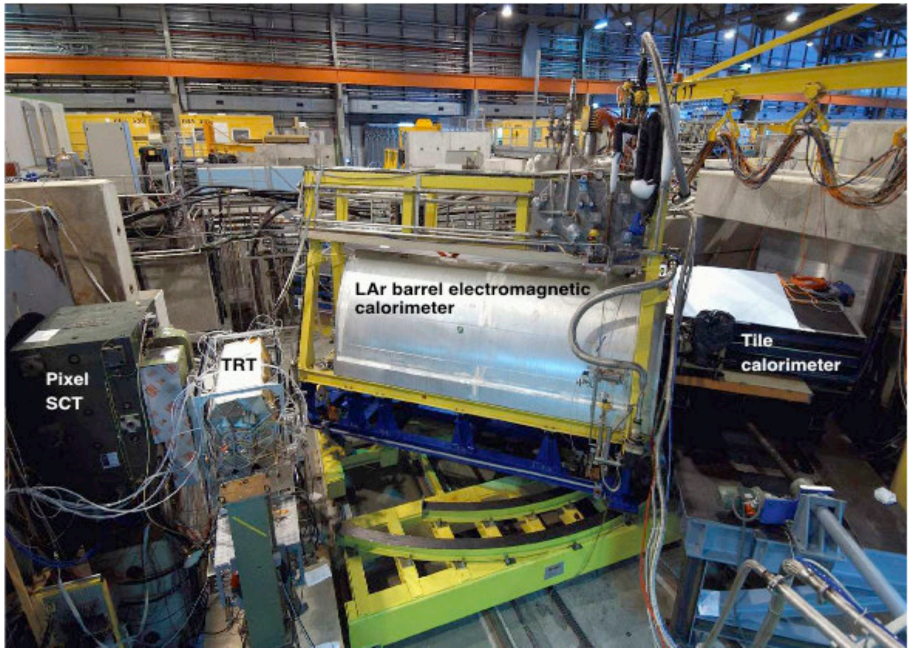


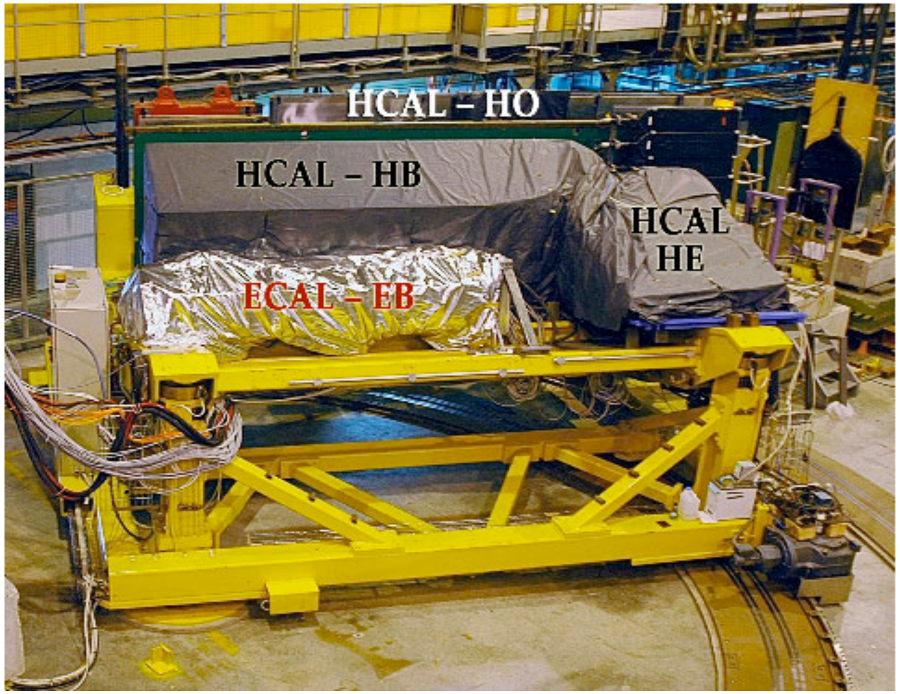


What really counts is the hermeticity of the detector
(and correct Monte Carlo description of non-hermetic zones)
rather than the E_{Tmiss} resolution

Combined beam test set-up

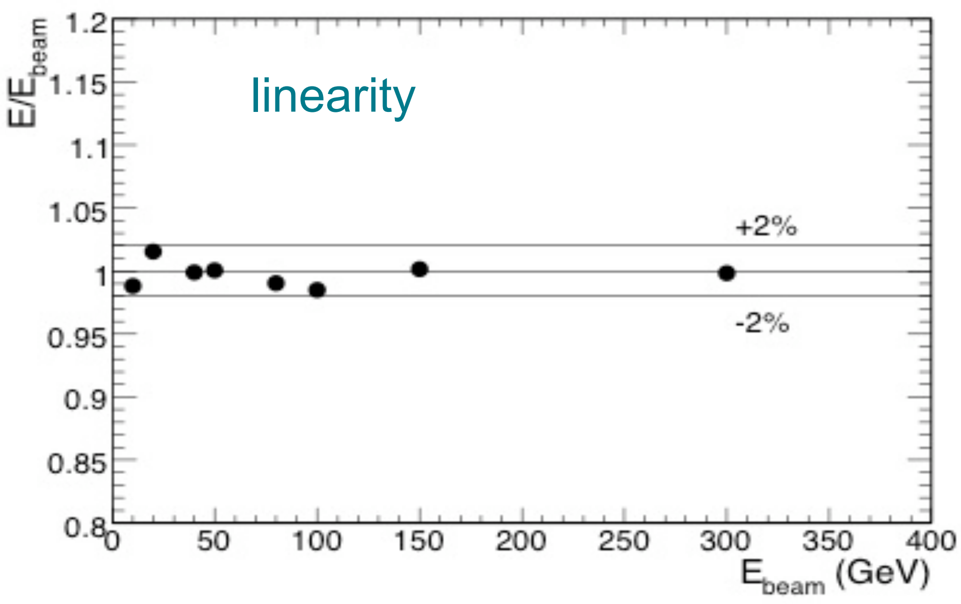
ATLAS

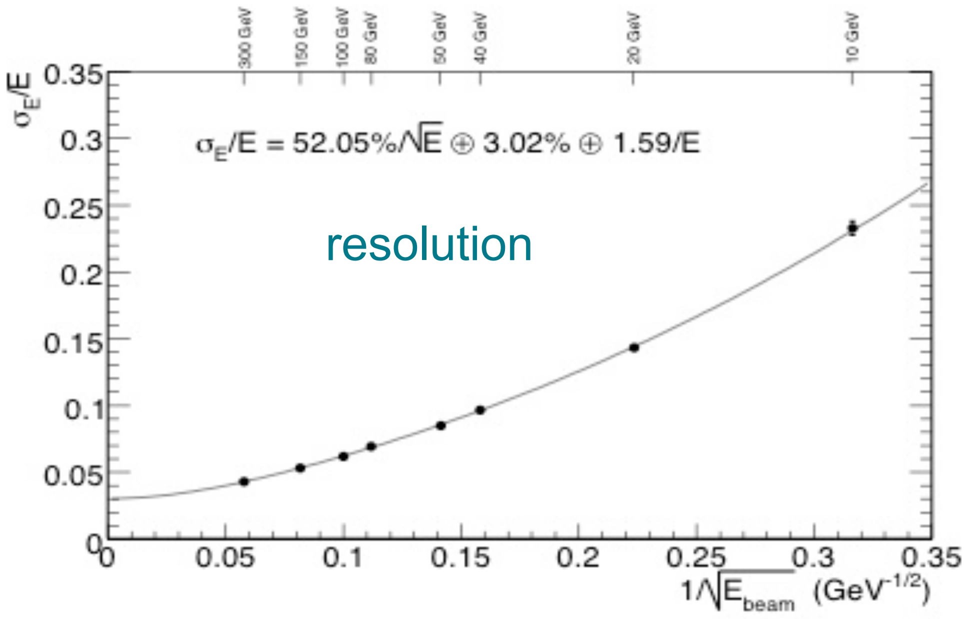




CMS

ATLAS combined LAr + Tile





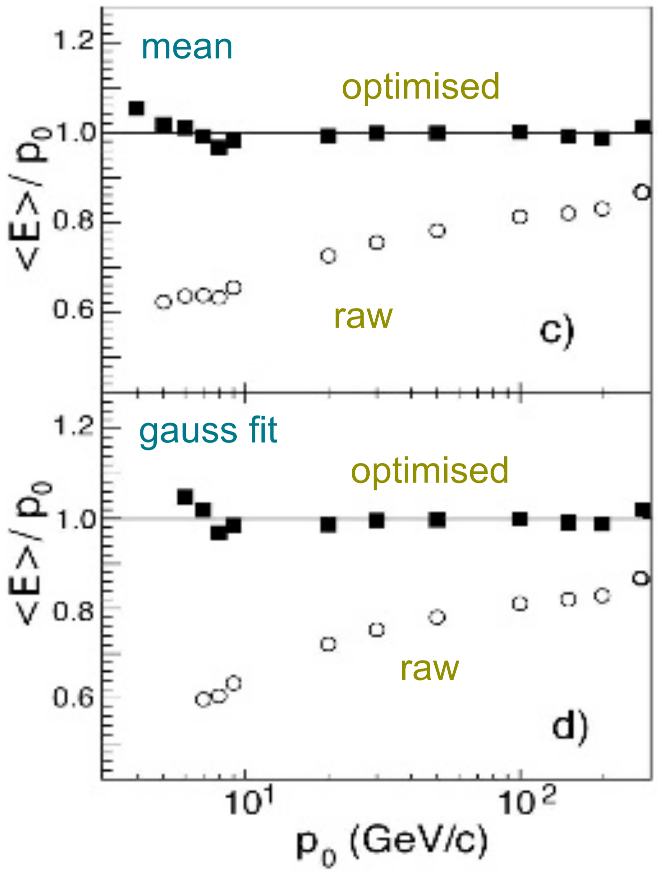
Test-beam results for pions at $\eta = 0.25$

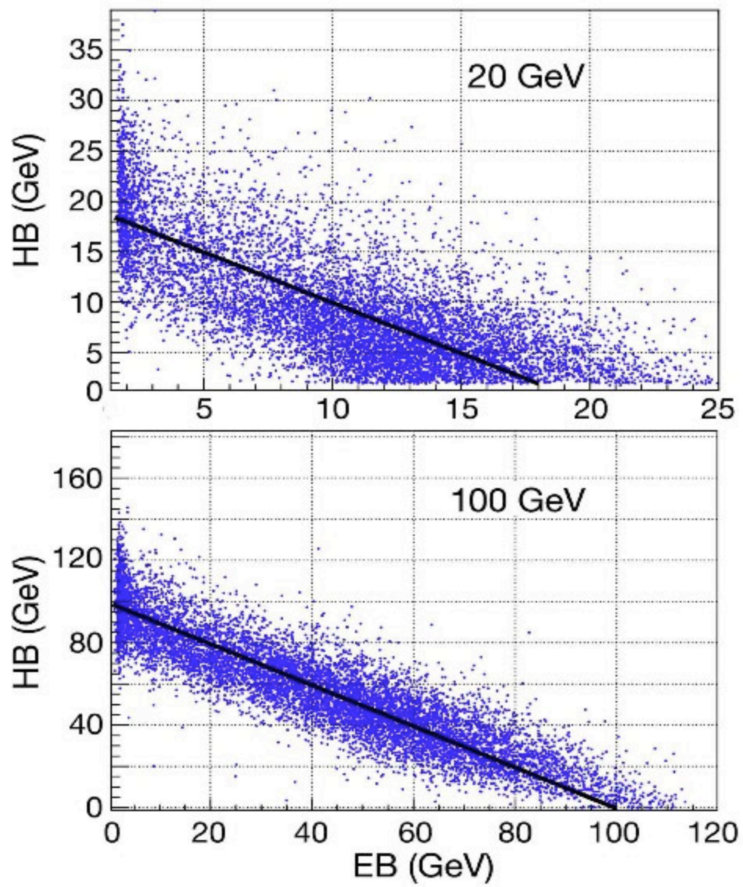
“cell weighting” technique:

a different weight, varying with energy, is assigned to each had. or em. cell

CMS combined EB and HB

"Optimised" energy sum restores linearity (see Yazgan talk)





1991 requirements revisited

- hermiticity, speed
- P_T triggering
- upstream material ≤ 1 X_0 coil, ≤ 0.1 X_0 tracker
- angular coverage $\eta<3$ em, $\eta<5$ jet
- Hcal depth > 10 λ
- e.m transverse segmentation $\Delta\eta<0.05$
- hadronic transverse segmentation $\Delta\eta<0.05$
- longitudinal segmentation (rad. damage)
- em resolution $< 0.2/\sqrt{E} \oplus 0.01$
- had resolution $< 0.7/\sqrt{E} \oplus 0.03$
- compensation $e/h-1<0.3$

(linearity more important than precision)

1991 requirements revisited

	CMS	ATLAS
• hermiticity, speed	👍	👍
• P_T triggering	👍	👍
• upstream material ≤ 1 X_0 coil, ≤ 0.1 X_0 tracker		
• angular coverage η<3 em, η<5 jet	👍	👍
• Hcal depth > 10 λ		☺
• e.m transverse segmentation $\Delta\eta$<0.05	☺	☺
• hadronic transverse segmentation $\Delta\eta$<0.05		
• longitudinal segmentation (rad. damage)	👍	☺
• em resolution < $0.2/\sqrt{E} \oplus 0.01$	☺	👍
• had resolution < $0.7/\sqrt{E} \oplus 0.03$	👍	☺
• compensation e/h-1<0.3		

(linearity more important than precision)

1991 requirements revisited

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1991 requirements revisited

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(linearity more important than precision)

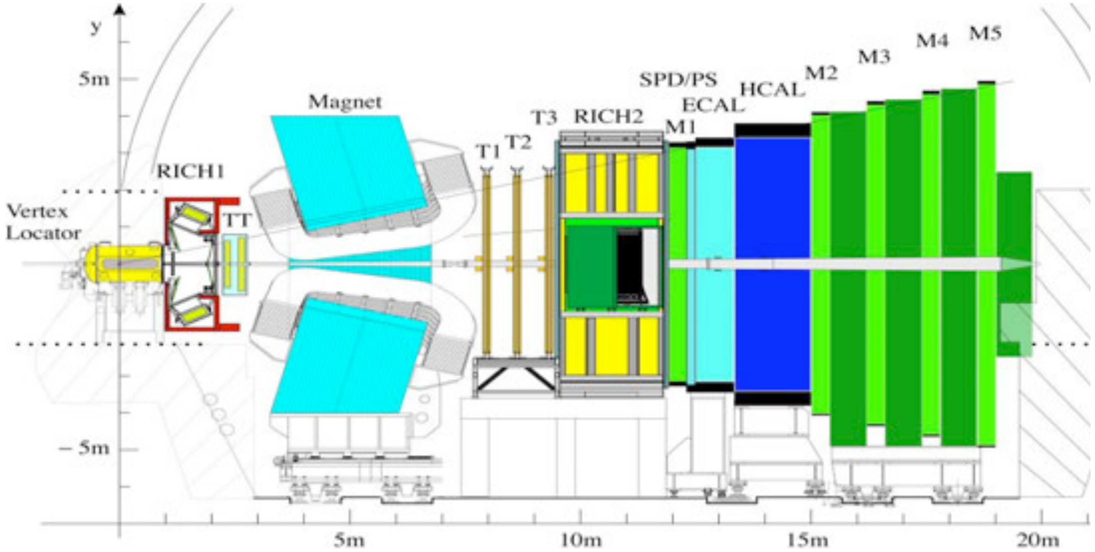
1991 requirements revisited

CMS ATLAS

- hermiticity, speed
- P_T triggering
- upstream material ≤ 1 X_0 coil, ≤ 0.1 X_0 tracker
- angular coverage η<3 em, η<5 jet
- Hcal depth > 10 λ
- e.m transverse segmentation $\Delta\eta$<0.05
- hadronic transverse segmentation $\Delta\eta$<0.05
- longitudinal segmentation (rad. damage)
- em resolution < $0.2/\sqrt{E} \oplus 0.01$
- had resolution < $0.7/\sqrt{E} \oplus 0.03$
- compensation e/h-1<0.3

(linearity more important than precision)

LHCb calorimeters

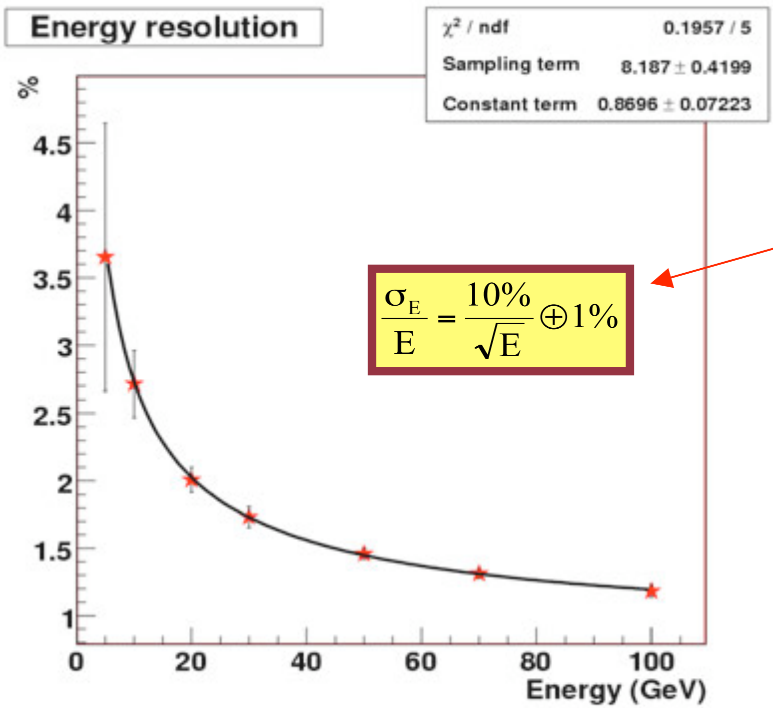


The LHCb experiment uses high production rate of B particles at small angle to study CP-symmetry violation in the neutral B meson systems.
Single arm spectrometer, covering angles from 10-300 mrad

Calorimeters purpose:

- electron/hadron separation for trigger and offline analysis
- measure position and energy for electrons/photons and hadrons

LHCb calorimeters



$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 1\%$$

Scintillating PAD/PS:

Pb/Scint. + MAPMT, 2.5 X0

ECAL:

Pb/Scintillator in Shashlik config.+PMT, 25 X0

HCAL:

Fe(16mm)/Scint.tiles(4mm) 5.6 λ

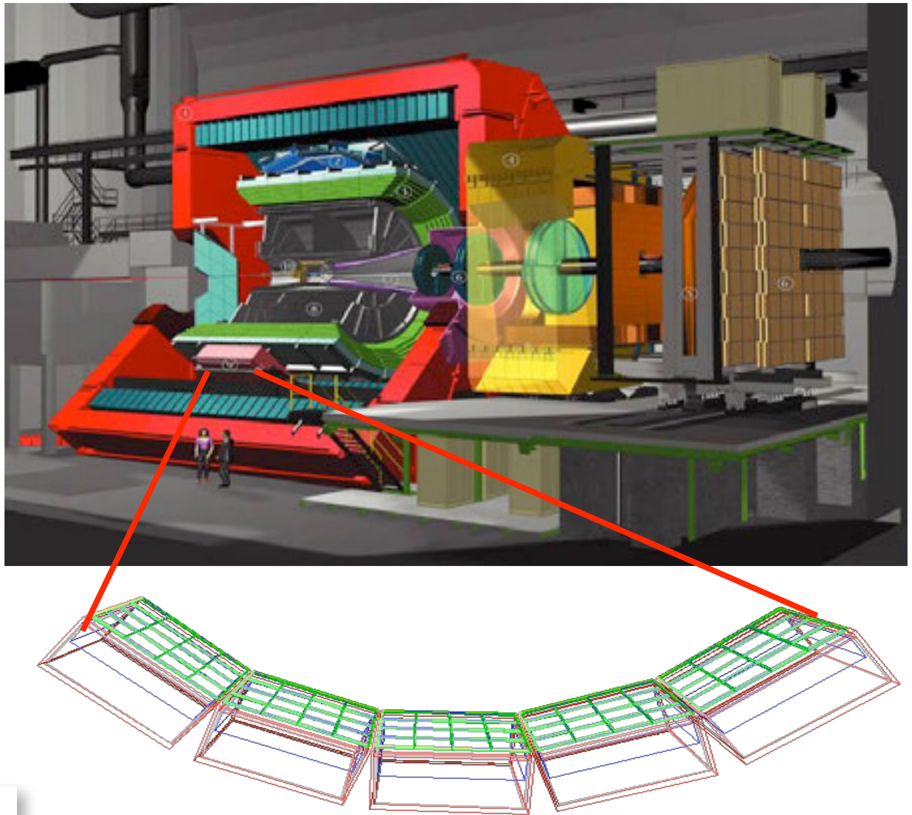
High radiation level at small angle

Trigger on electrons, photons and hadrons:

- ScintPAD signs charged particles
- PS tags e.m. nature
- ECAL E_t
- HCAL E_t

- ECAL calibration by energy flow, electron p/E, π^0 mass reconstruction
- HCAL precalibration by Cs source
- response monitored by LED systems

ALICE detector



Dedicated heavy ion experiment for nucleus-nucleus interactions to study strongly interacting matter at high densities where the formation of quark-gluon plasma is expected. Need to study hadrons, electrons, muons and photons produced in the collisions

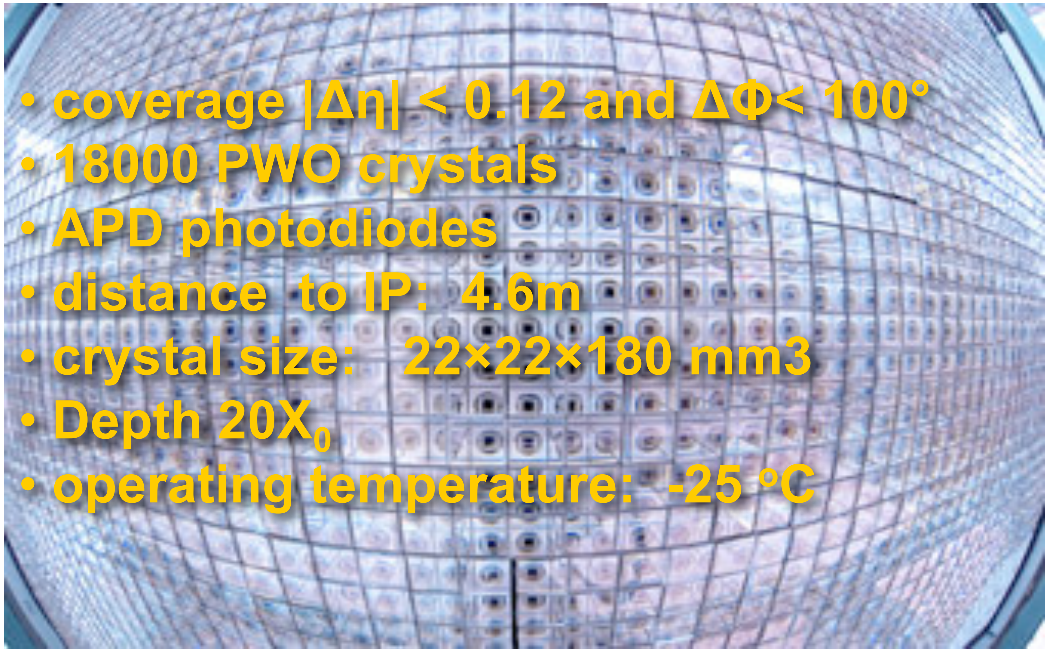
PHOS – photon spectrometer

quark-gluon plasma thermometer: the spectrum of the emitted photons is related to the temperature of the source

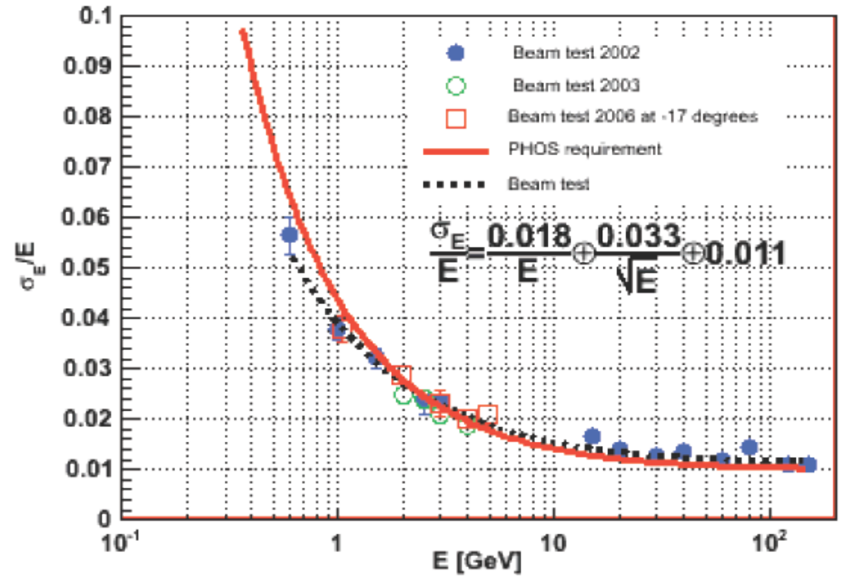
EMCAL approved and funded, ready in 2011

ALICE PHOS

To measure γ, π^0 and η from 0.5 to 100 GeV

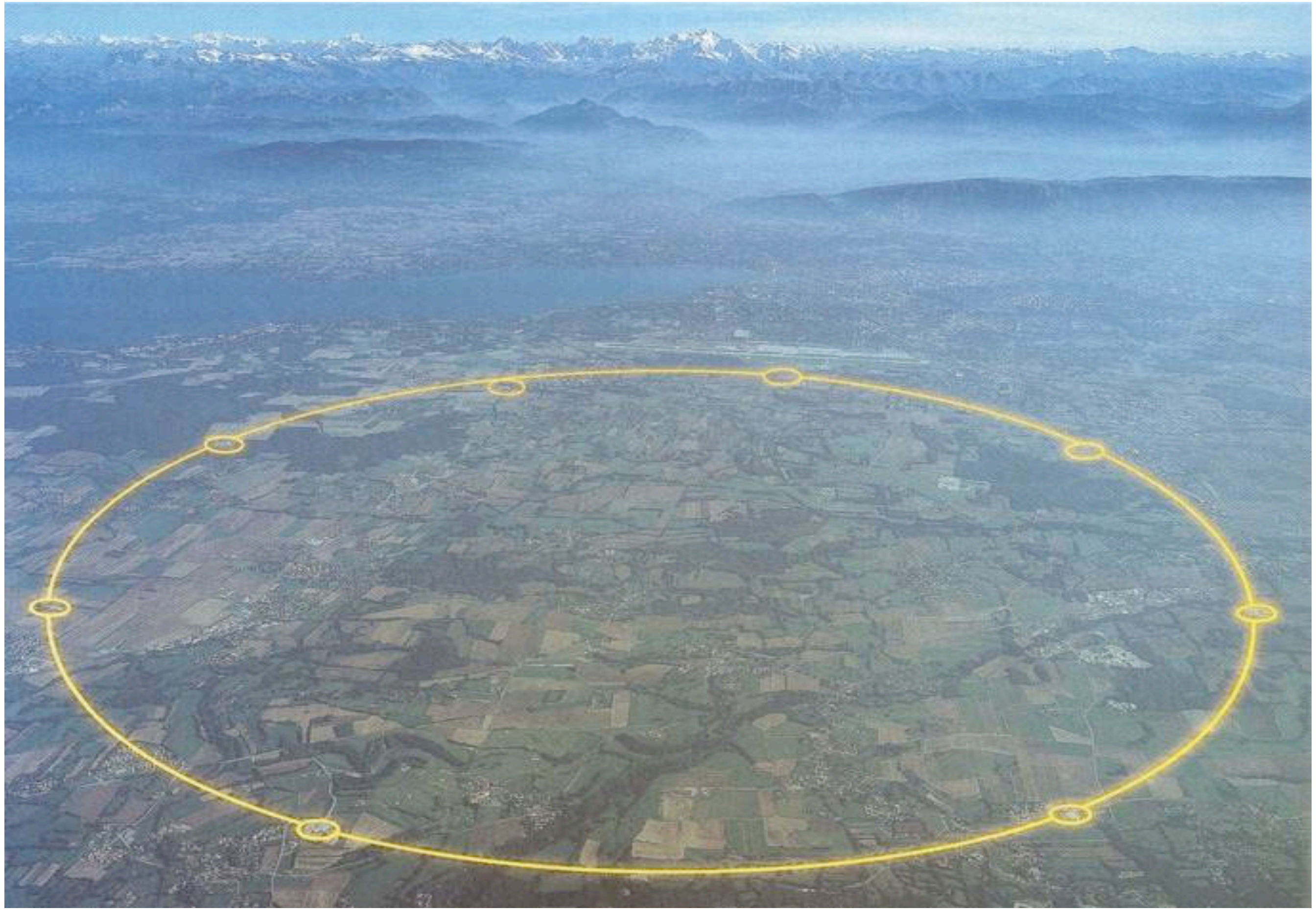


- coverage $|\Delta\eta| < 0.12$ and $\Delta\Phi < 100°$
- 18000 PWO crystals
- APD photodiodes
- distance to IP: 4.6m
- crystal size: 22×22×180 mm3
- Depth $20X_0$
- operating temperature: -25 °C



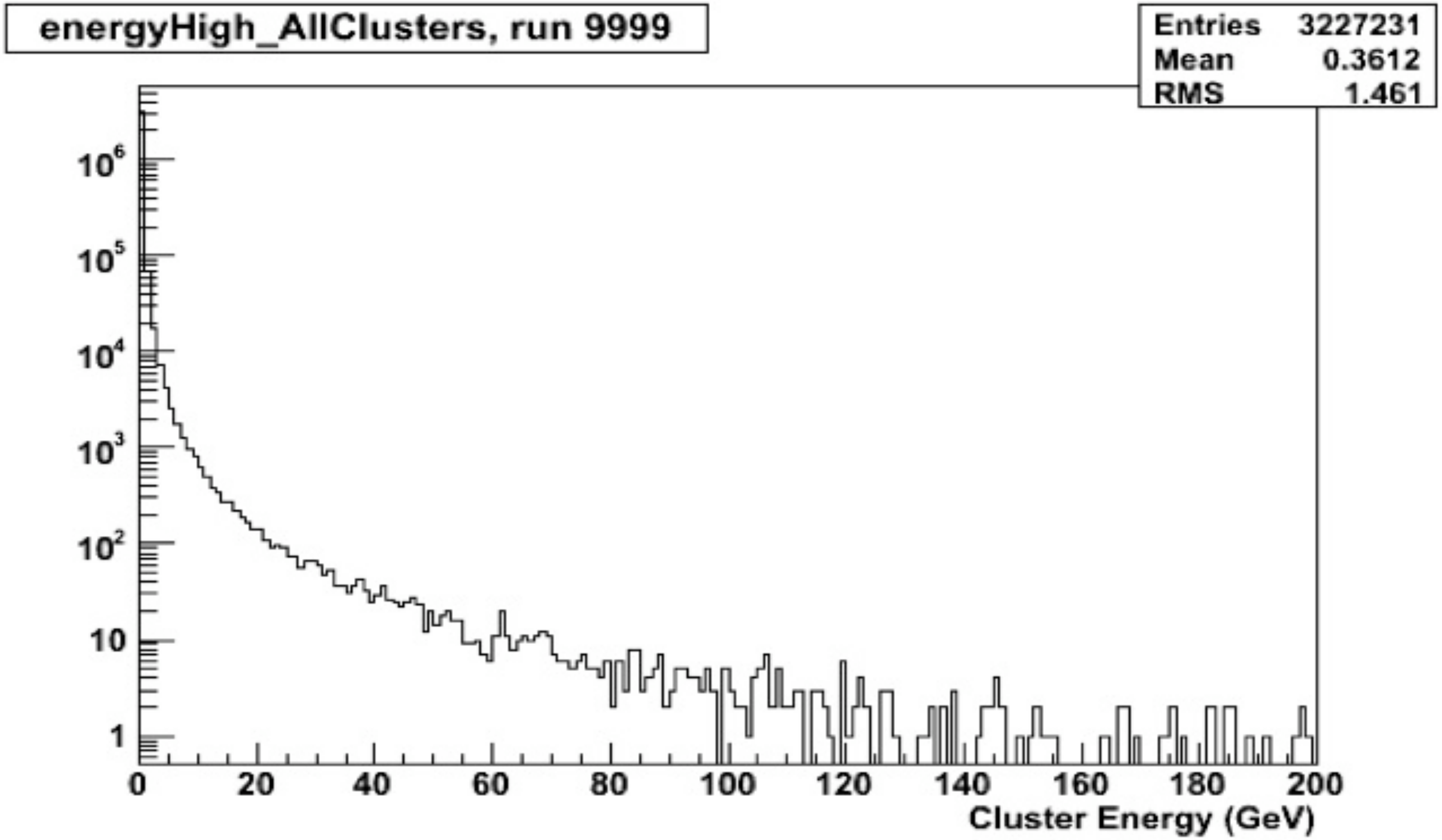
1 module installed
2 more in first long shut down completed in 2010

after 2 decades…
calorimeters are ready and running in the big wheel

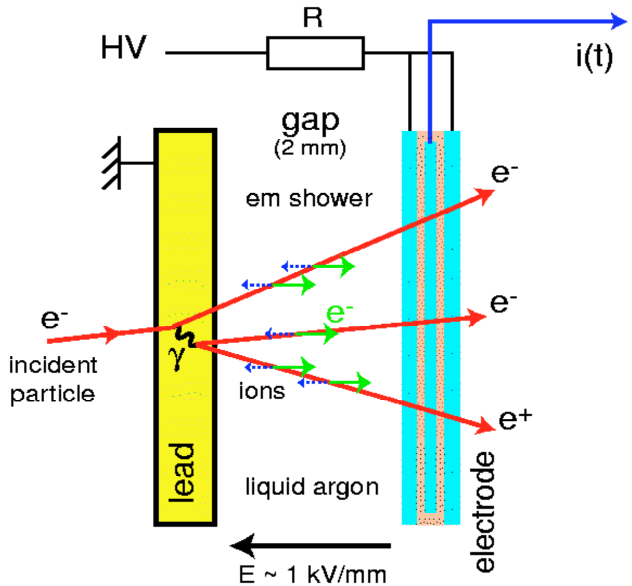


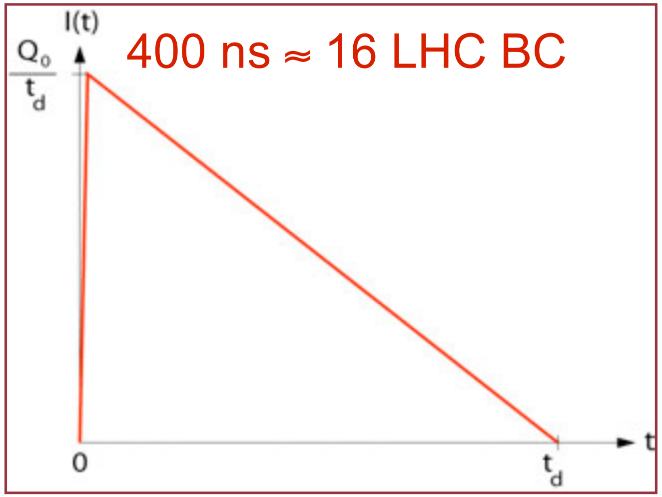
les jeux son faits, rien ne va plus

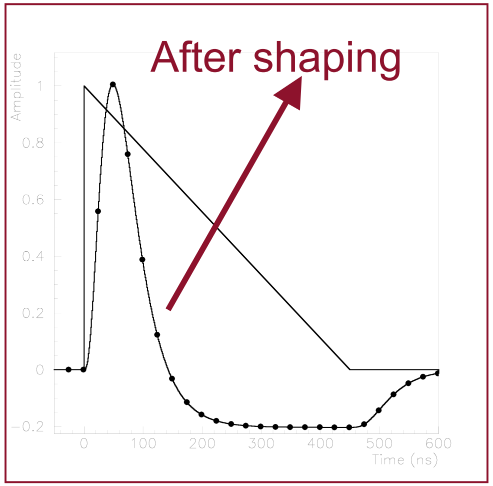
back up slides


energyHigh_AllClusters, run 9999
Entries 3227231
Mean 0.3612
RMS 1.461
1
10
10^2
10^3
10^4
10^5
10^6
0 20 40 60 80 100 120 140 160 180 200
Cluster Energy (GeV)

LAr signal collection







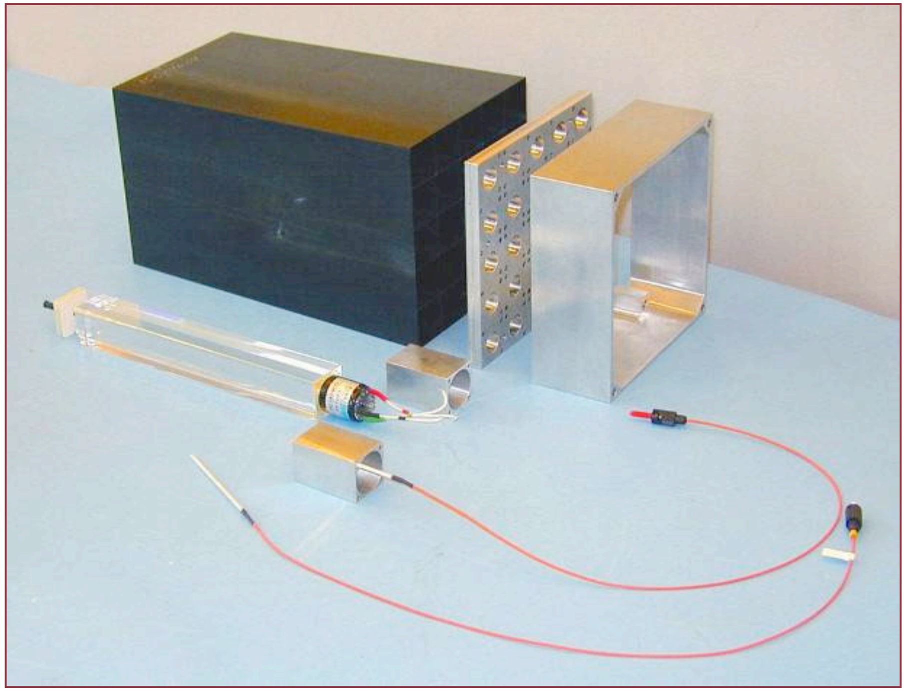
Pulse is shaped and sampled

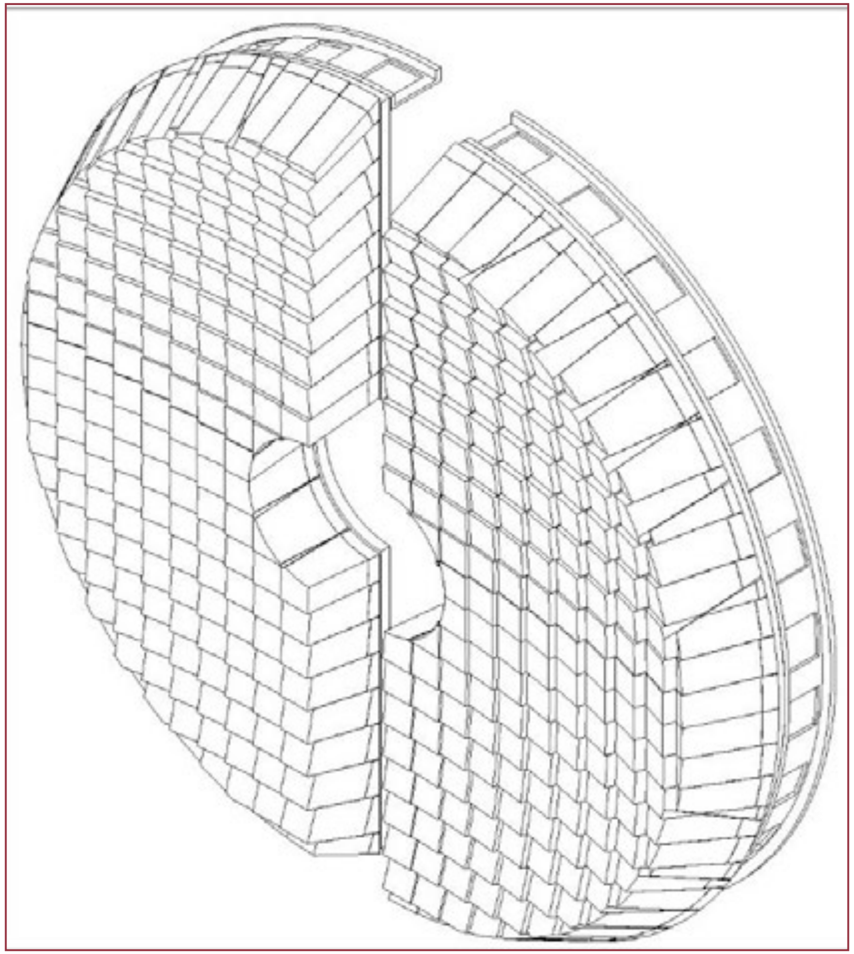
each 25 ns, has 0 time integral

→ mean value of pileup is cancelled (no baseline shift)

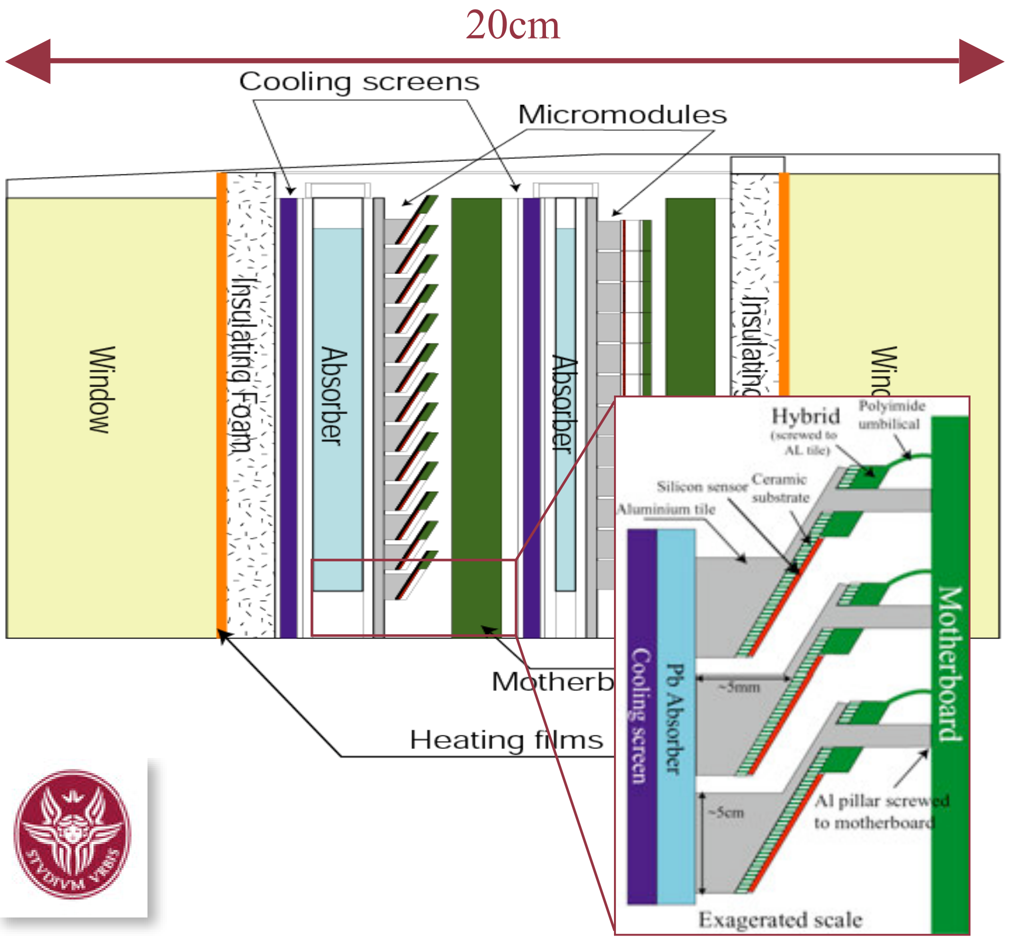
CMS ECAL endcaps

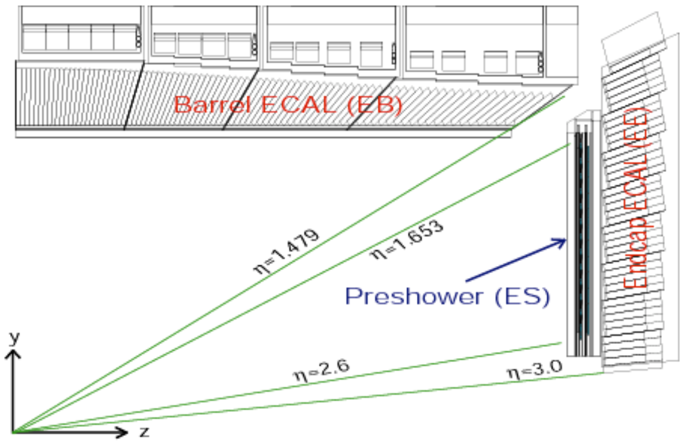
- 'SuperCrystal': carbon-fibre alveola containing
  5x5 tapered crystals + VPTs + HV filter cards
- 156 Supercrystals per Dee
- All crystals have identical dimensions
- All Supercrystals are identical
  (apart from 'partials' at inner/outer perimeter)





CMS **ECAL Preshower**

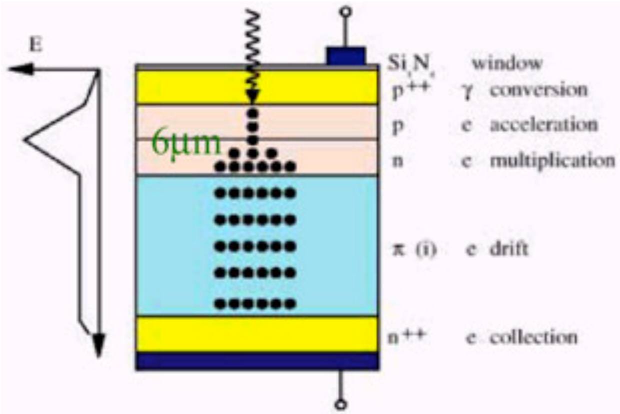


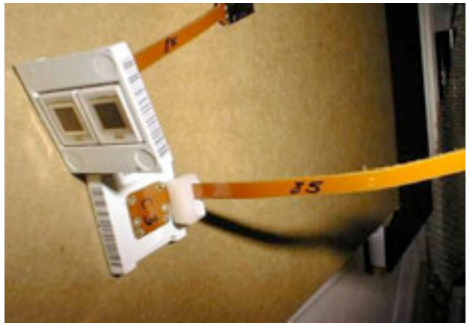


~4300 micromodules

- 2mm-pitch Si sensors

CMS Light sensors





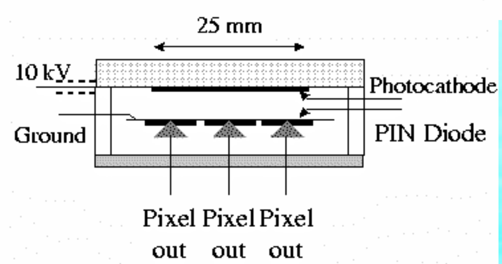
ECAL Endcaps: Vacuum phototriodes (VPT by Research Institute Electron in St. Petersburg)

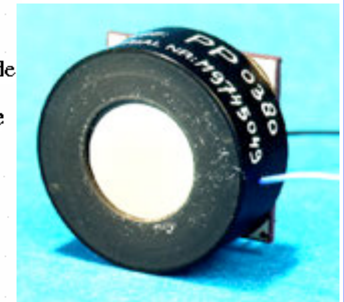
- A VPT is a single-gain-stage photomultiplier tube
- Diameter 25.4 mm
- Quantum eff. ~22 % at 420nm
- Gain at 0 magnetic field ~10
- Rad. tolerance <10% loss after 20 kGy
- Magn. field resp. loss at 4T < 15% w.r.t. 0T

ECAL Barrel: Avalanche Photodiodes (APD, Hamamatsu)

- Characteristics optimized with an extensive R&D Program
- insensitive to B-field as PIN diodes
- Internal gain (M=50 used, M=200 for cosmics calibration)
- good match to Lead Tungstate scintillation spectrum (Q.E. ~ 70%)
- dM/dV = 3%/V and dM/dT = -2.3%/°C :

→T and V stabilization needed

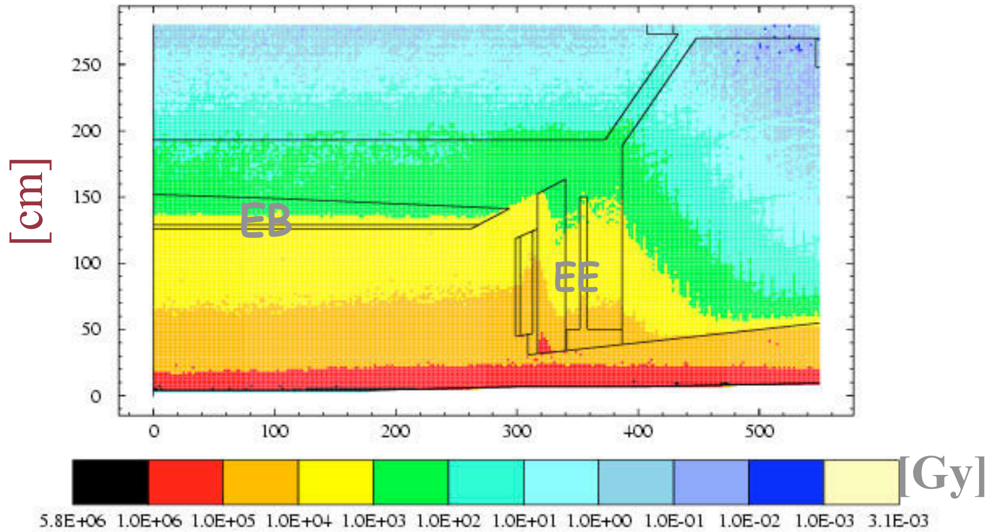


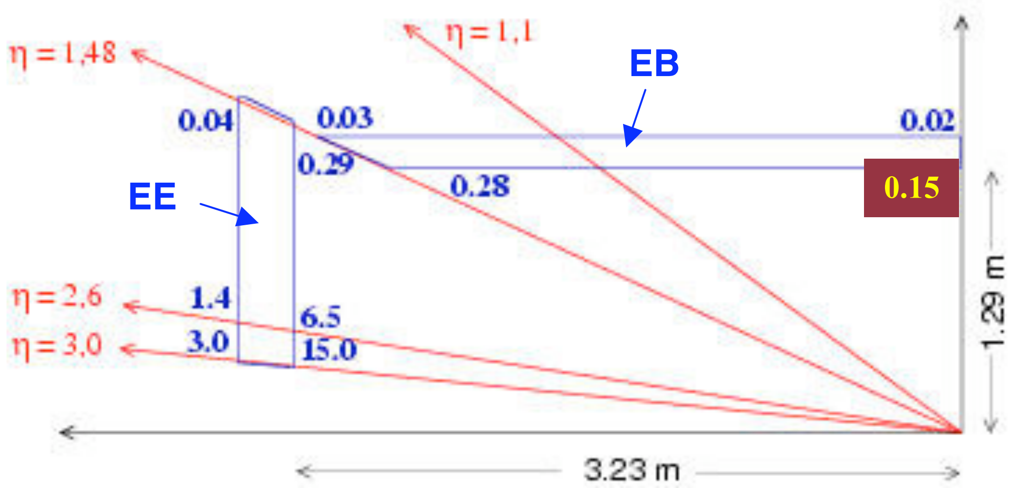


HCAL HPD

Radiation environment in CMS

Total dose after 10 years of running ($5x10^5\ pb^{-1}$)





Dose rates [Gy/h] in ECAL at luminosity $L=10^{34}cm^{-2}s^{-1}$

Total dose in the barrel after 10 years at the LHC is ~$2\text{-}4\cdot10^3$Gy and neutron fluence $2\cdot10^{13}$ n/cm^2

Dose rate at high L in the Barrel is 0.15 – 0.3 Gy/h
in the Endcaps 0.3-15 Gy/h

CMS ECAL: constant term

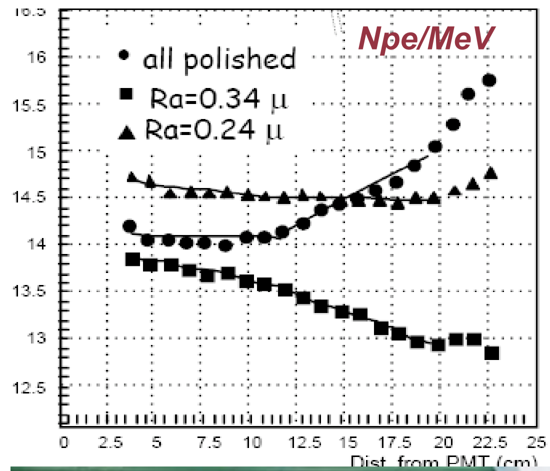
- **Light collection uniformity ~0.3%**

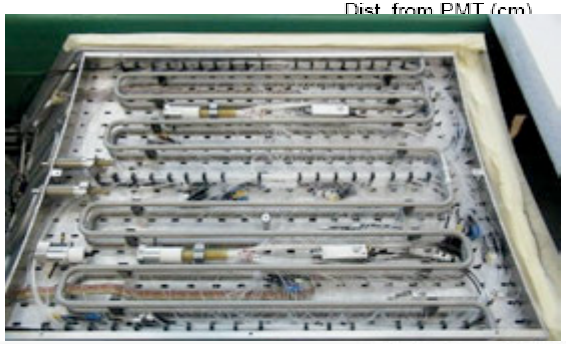
tapered shape of crystals induces the focusing effect in the light collection → can be controlled by de-polishing one lateral face

$|dLY/X_0| < 0.35\%/X_0$ between 3 and 13 X_0

as measured in laboratory using ^{60}Co source

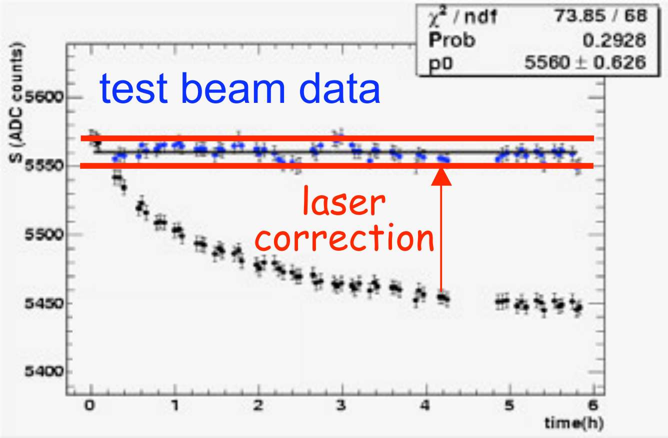
Crystal properties measured for ALL crystals





- **Radiation damage followed by monitoring ~0.2%**

Radiation damage causes transparency deterioration. Scintillating mechanism is not damaged. Changes can be tracked using light injection monitoring system.



- **Temperature and HV ~0.1%**

(talk)

- **Intercalibration with physics signals < 0.5%**

	Atlas		CMS	
Technology	Lead/Lar accordion		PbWO4 scintillating crystals	
	Barrel	**Endcaps**	**Barrel**	**Endcaps**
η coverage	0-1.475	1.4-3.2	0-1.48	1.48-3
channels	110208	63744	61200	14648
Granularity	ΔηxΔΦ		ΔηxΔΦ	
pre-sampler	0.025x0.1	0.025x0.1	-	-
Strips/Si-preshower	0.003x0.1	0.003-0.006x0.1	-	32x32 Si-Strips per 4 crystals
Main sampling	0.025x0.025	0.025x0.025	0.017x0.017	0.018x0.003 to 0.088x0.015
Back	0.05x0.025	0.05x0.025	-	-
Depth				
pre-sampler	10 mm	2x2mm	-	-
Strips/Si-preshower	~4.3 Xo	~4.0 Xo	-	~3 Xo
Main sampling	~16 Xo	~20 Xo	26 Xo	25 Xo
Back	~2 Xo	~2 Xo	-	-
Energy Resolution				
Stochastic Term	10%	10-12%	3%	5.50%
Local constant term	0.20%	0.35%	0.50%	0.50%
Noise per cluster(MeV)	250	250	200	550

ATLAS expected calibrations

	Start-up of LHC	Ultimate goal	Physics goals
Electromagnetic energy uniformity	1–2%	0.5%	$H \to \gamma\gamma$
Electron energy scale	~2%	0.02%	W mass
Hadronic energy uniformity	2–3%	< 1%	E_T^{miss}
Jet energy scale	< 10%	1%	Top-quark mass
Inner-detector alignment	50–100 μm	< 10 μm	b-tagging
Muon-spectrometer alignment	< 200 μm	30 μm	$Z' \to \mu\mu$
Muon momentum scale	~1%	0.02%	W mass

Table 68. Expected calibration and alignment accuracies at the LHC start-up and the ultimate design goals. Examples of physics channels or measurements driving the requirements are indicated in the last column.

Atlas **and** CMS **HCAL comparison**

	ATLAS	CMS
Technology		
Barrel / Ext. Barrel	14 mm iron / 3 mm scint.	50 mm brass / 4 mm scint.
End-caps	25 mm (front) - 50 mm (back) copper / 8.5 mm LAr	80 mm brass / 4 mm scint.
Forward	Copper (front) - Tungsten (back) 0.25 - 0.50 mm LAr	4.4 mm steel / 0.6 mm quartz
# Channels		
Barrel / Ext. Barrel	9852	2592
End-caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta \times \Delta\phi$)		
Barrel / Ext. Barrel	0.1 x 0.1 to 0.2 x 0.1	0.087 x 0.087
End-caps	0.1 x 0.1 to 0.2 x 0.2	0.087 x 0.087 to 0.35 x 0.028
Forward	0.2 x 0.2	0.175 x 0.175
# Longitudinal Samplings		
Barrel / Ext. Barrel	Three	One
End-caps	Four	Two
Forward	Three	Two
Absorption lengths		
Barrel / Ext. Barrel	9.7 - 13.0	5.8 - 10.3 10 - 14 (with Coil / HO)
End-caps	9.7 - 12.5	9.0 - 10.0
Forward	9.5 - 10.5	9.8

H→ γγ : ECAL benchmark

$$m_{\gamma\gamma} = 2\, E_1 E_2 \,(1 - \cos\theta_{\gamma\gamma})$$

$$\frac{\sigma_m}{m} = \frac{1}{2}\left[\left(\frac{\sigma_1}{E_1}\right)^2 + \left(\frac{\sigma_2}{E_2}\right)^2 + \left(\frac{\sigma_\theta}{tg\theta/2}\right)^2 + \right]^{1/2}$$

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

In situ: $\pi^0 \rightarrow \gamma\gamma$ for intercalibration

Method: Constraint *unconveted* photons energies (fixed arrays of crystals) and positions to π^0 mass peak

- Little sensitivity to tracker material
- Useful π^0's $E_T \sim 5$ GeV

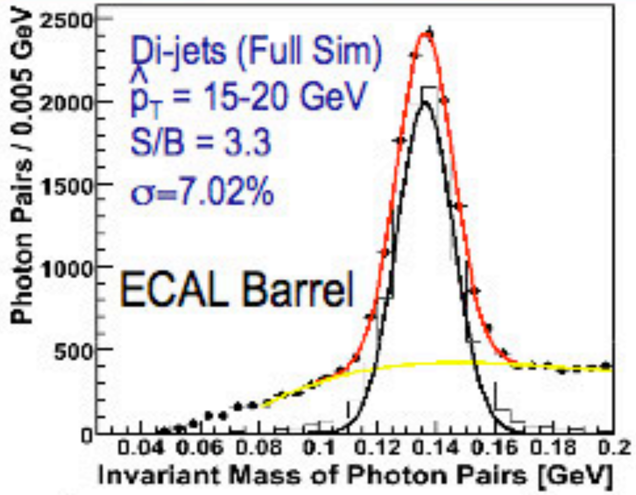
Precision in the Barrel 0.5% with 2000 π^0/crystal → (≈1 day for ≈2 kHz rate)

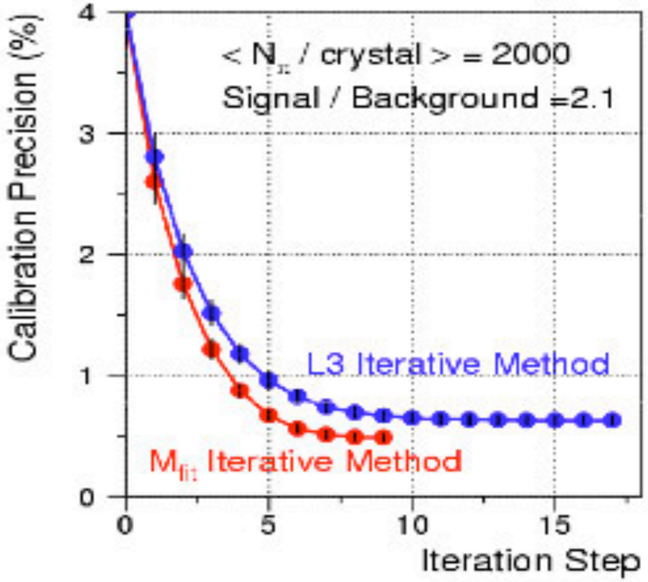
Trigger/Selection: High Level Trigger filter accessing L1 EM-candidates

- Clean π^0 stripping (S/B = 1.5÷3.0) based on shower-shape, π^0 kinematics and isolation
- Efficiency (π^0's/EM L1 objects):
  - 1% (Minimum Bias)
  - 6-10% (QCD evts)

  →O(1 kHz)
- Save only 3x3 crystal arrays around candidates (small bandwidth usage)

Detailed study in the Endcaps ongoing





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