Calorimetry

for Hadron Colliders

(mainly LHC)

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A few points

Why build calorimeters ?
- Calorimeters important properties

Electromagnetic processes involved

EM shower developments

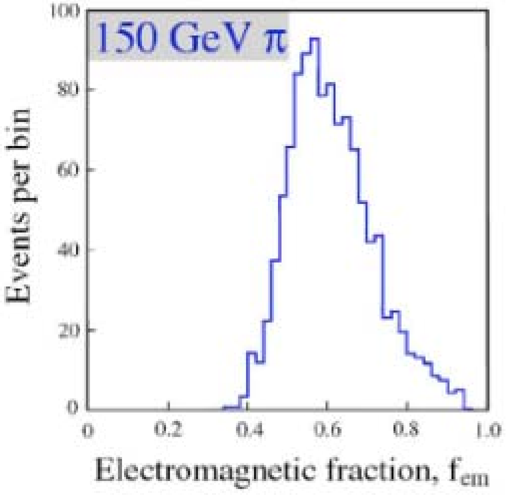
Experimental techniques
- Homogeneous calorimeters
- Sampling calorimeters

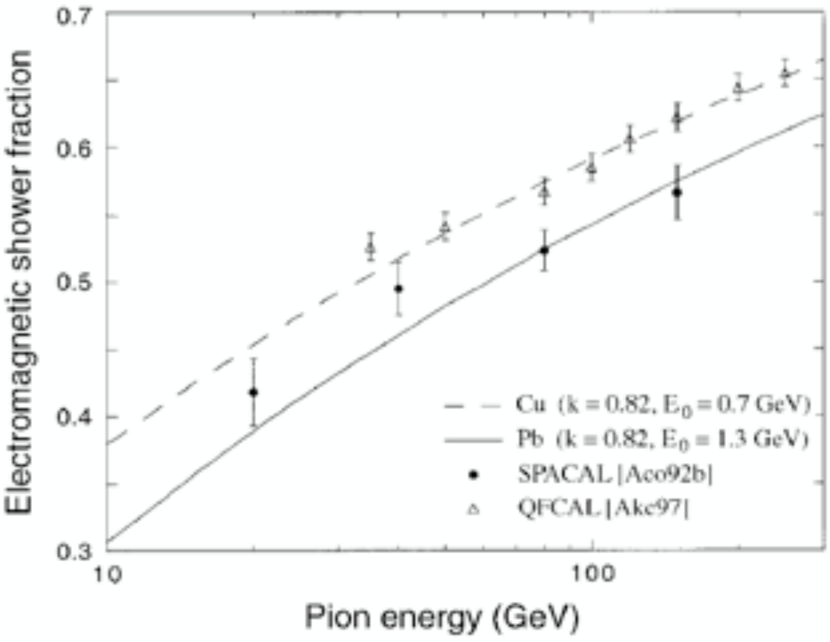
Hadronic Showers

Tevatron and LHC calorimeters
- CDF, D0, CMS, LHCb, ALICE, ATLAS
  - Structure
  - Performance

Calorimeters for Linear Colliders

Hadronic Showers: EM fraction





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

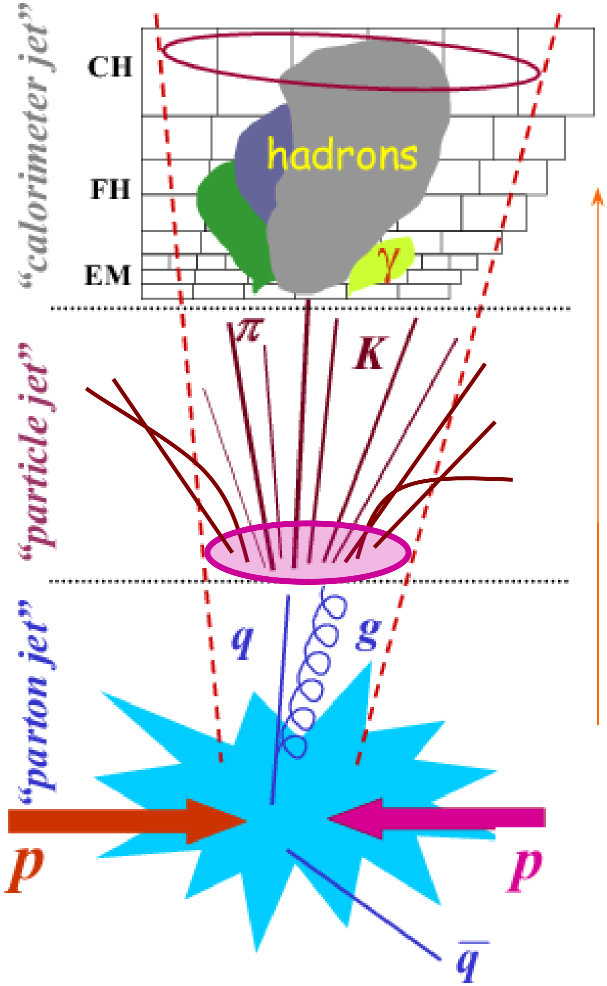
Varies with energy

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

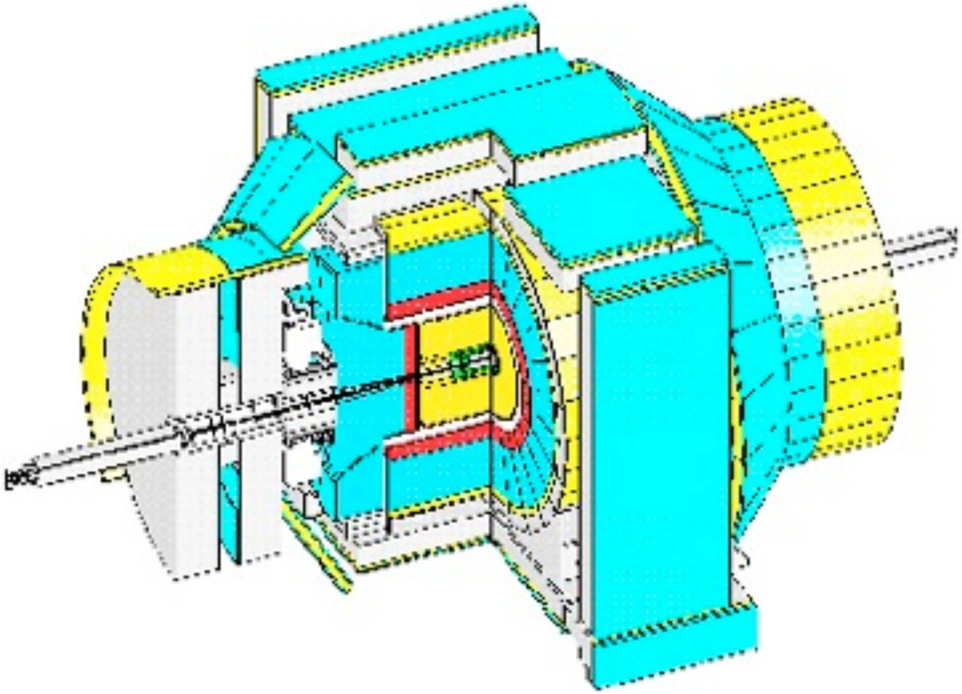
50-100%/√E ⊕ a few %

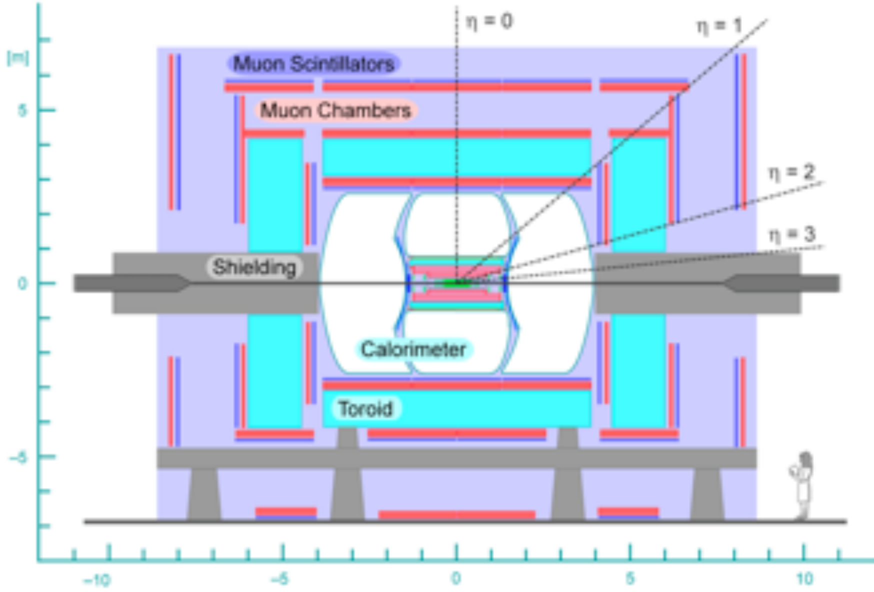
Jets

- 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)

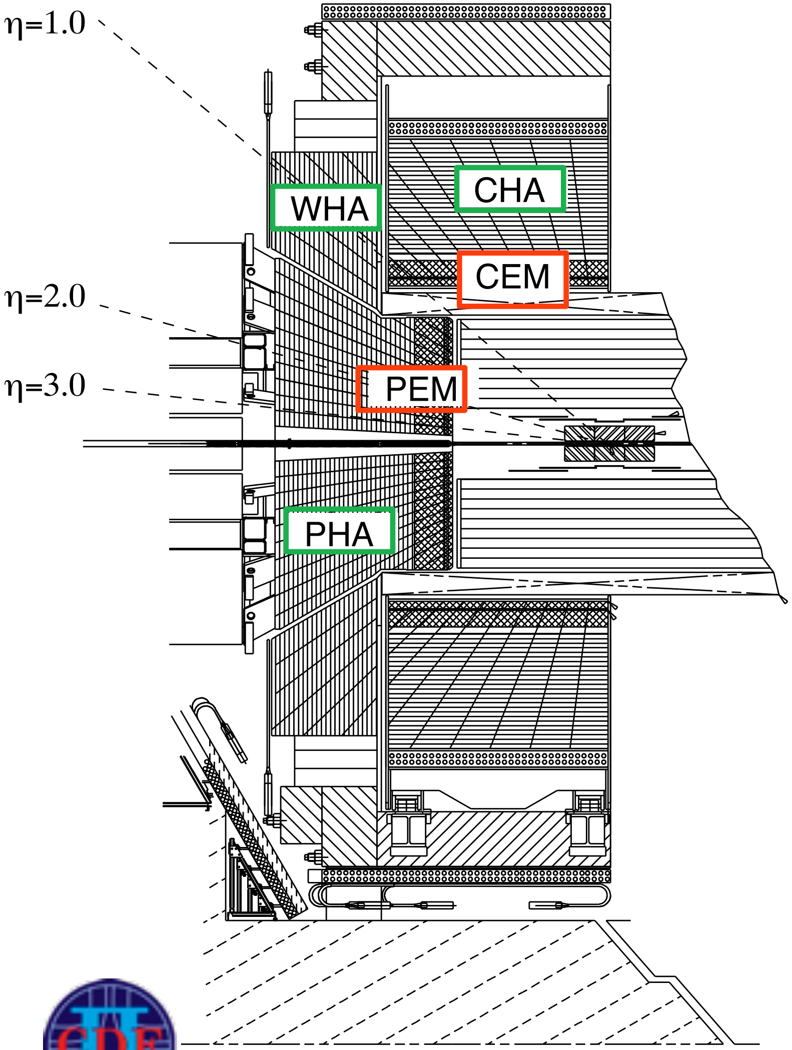


Tevatron: 25 years ago!





Tevatron: 25 years ago



EM Calorimeter: Pb-Scintillator

CEM $|\eta|<1.1$ - 18 X_0

$\Delta\eta \times \Delta\varphi = 0.1 \times 0.26$

$\sigma(E)/E = 13.5\%/\sqrt{E} \oplus 1.5\%$

PEM $1.1<|\eta|<3.6$ - 23.2 X_0

$\Delta\eta \times \Delta\varphi = 0.26 \times 0.26$ & 0.13×0.13

$\sigma(E)/E = 16\%/\sqrt{E} \oplus 1.\%$

HAD Calorimeter: Fe-Scintillator

CHA+WHA $|\eta|<1.1$ - 4.7 λ

$\Delta\eta \times \Delta\varphi = 0.1 \times 0.26$

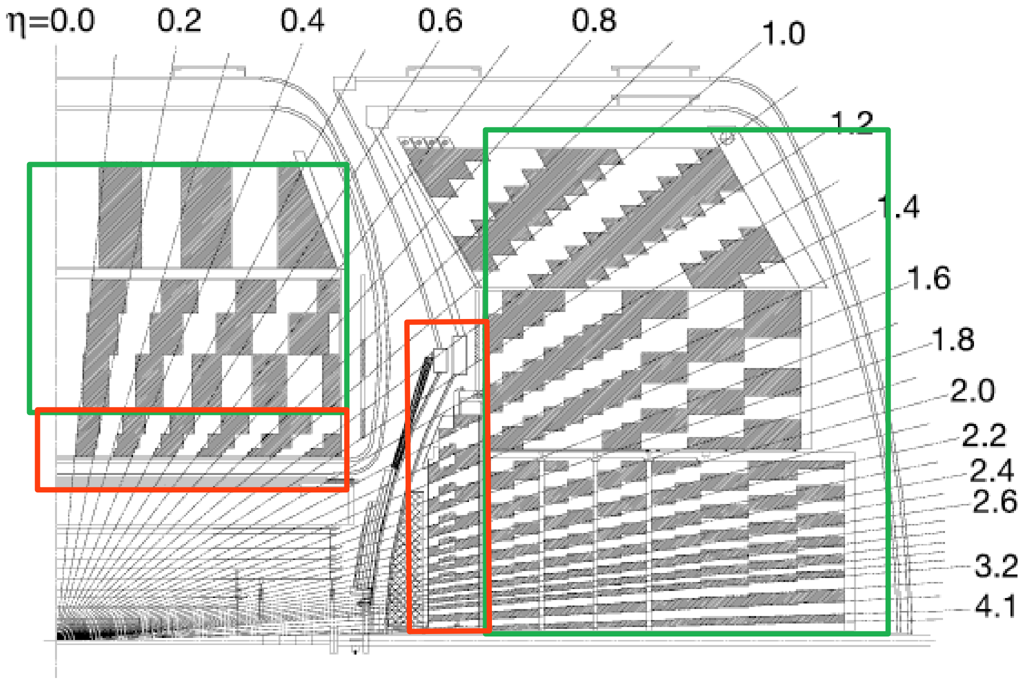
$\sigma(E_T)/E_T = 50\%/\sqrt{E_T} \oplus 3\%$

PHA $1.1<|\eta|<3.6$ - 23.2 X_0

$\Delta\eta \times \Delta\varphi = 0.26 \times 0.26$ & 0.13×0.13

$\sigma(E)/E = 80\%/\sqrt{E} \oplus 5\%$

Tevatron: 25 years ago and still taking data



EM Calorimeter: U/LAr

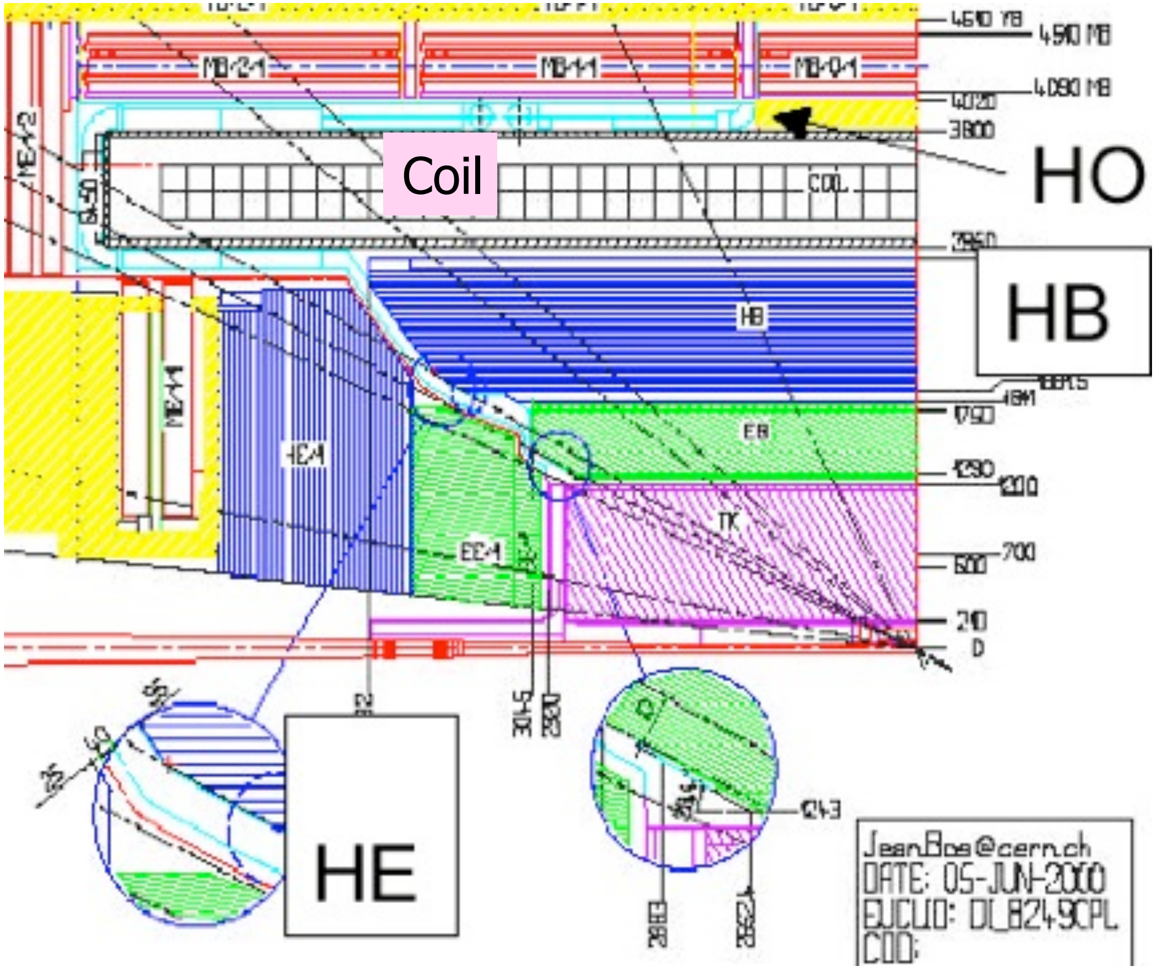
4 layers: ~1.4, 2.0, 6.8, 9.8 X_0
$\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
$\sigma(E)/E = 13.5\%/\sqrt{E} \oplus 1.5\%$

HAD Calorimeter: U-Cu-Fe/LAr

3 layers: ~1.3,1., 0.76 λ
$\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

CMS calorimeter

The CMS calorimeter



The CMS choices

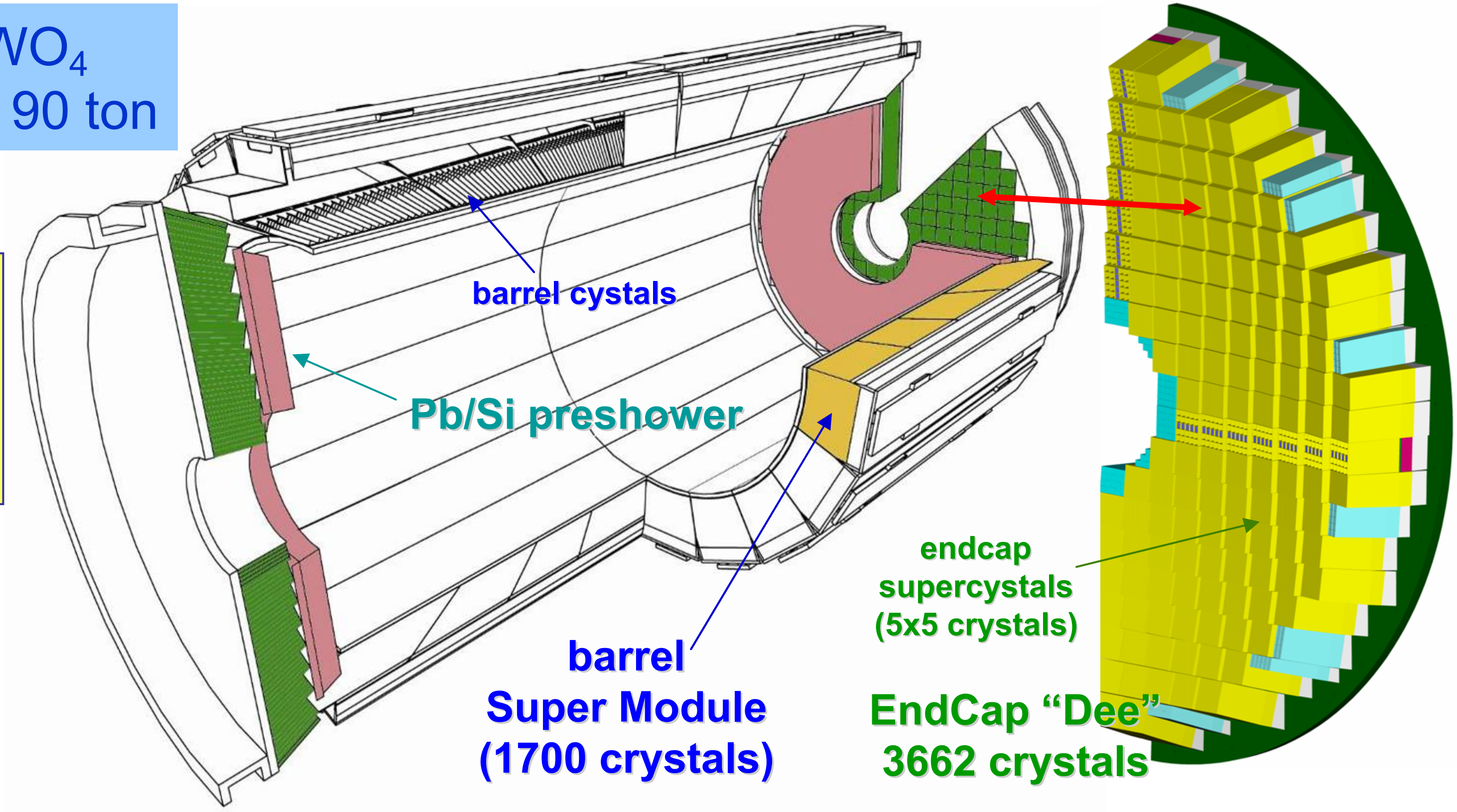
- Solenoidal Magnetic Field: 4T
- Outside the calorimeter
  - “Compact” calorimeter
- Very precise EM calorimeter
  - PbWO crystal (very dense)
- “Thin” HAD calorimeter

ECAL @ CMS

Precision electromagnetic calorimetry: 75848 PWO crystals

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

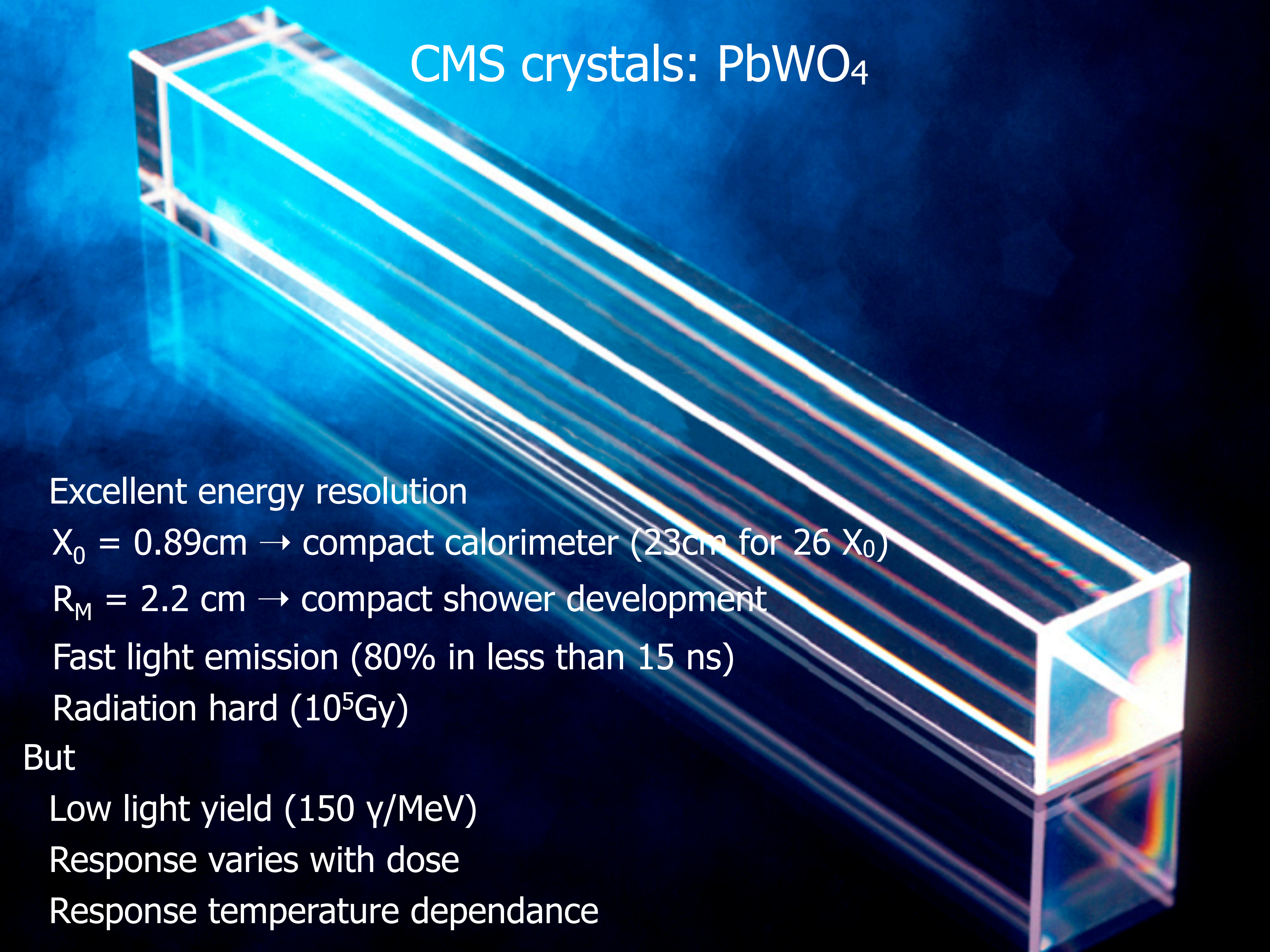
Previous Crystal calorimeters: max $1 m^3$



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

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

CMS crystals: $PbWO_4$



Excellent energy resolution

$X_0 = 0.89$cm → 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)

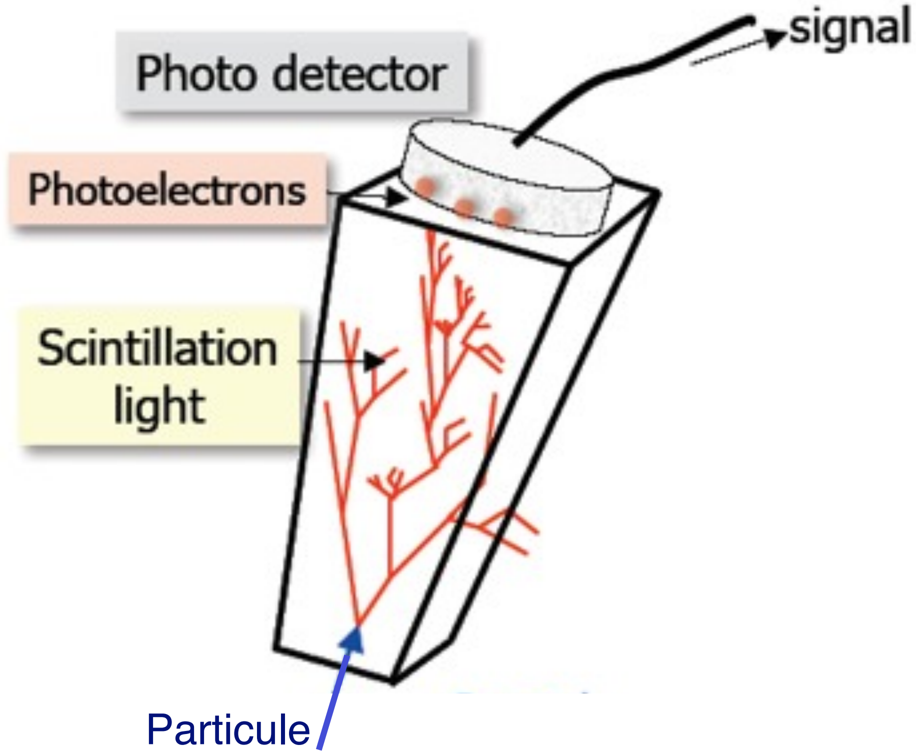
But

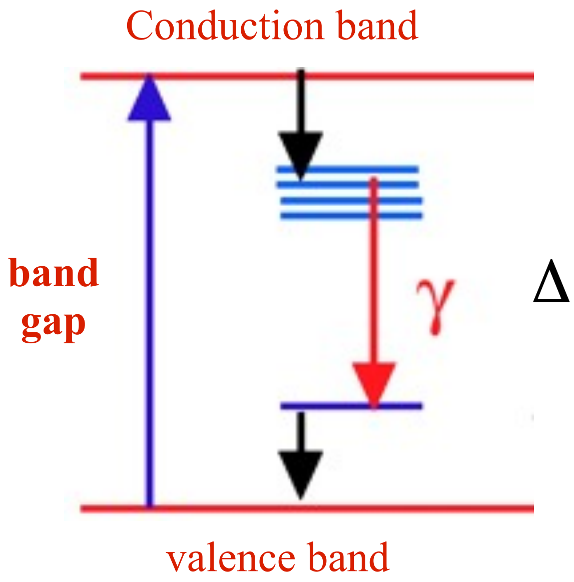
Low light yield (150 γ/MeV)

Response varies with dose

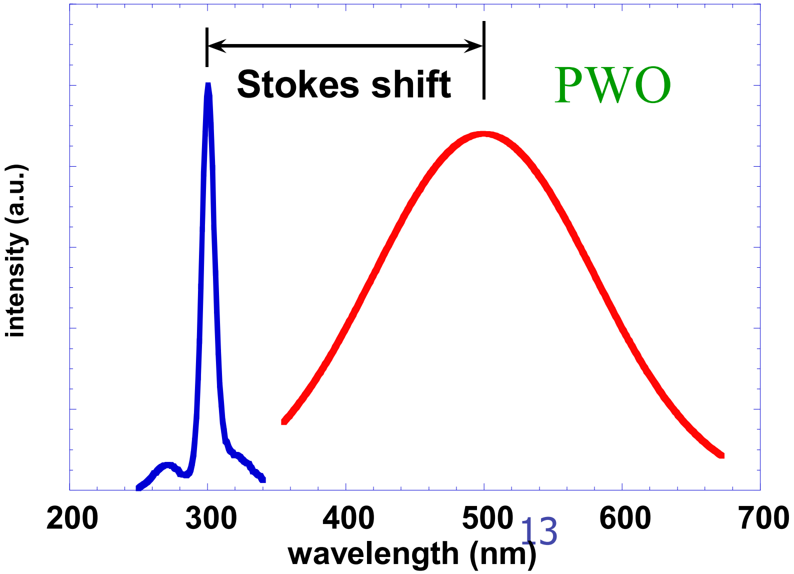
Response temperature dependance

Signal Emission





ΔE, ΔT



Fast light emission: ~80% in 25 ns

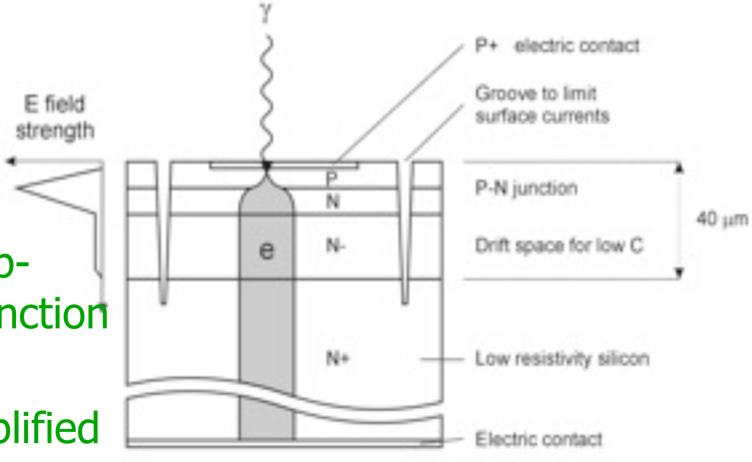
Peak emission ~500 nm (visible region)

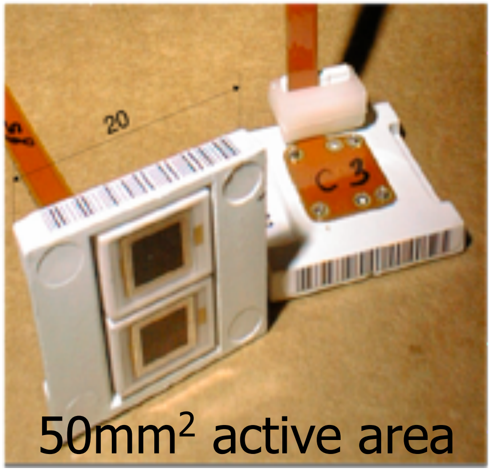
Radiation resistant to very high doses

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

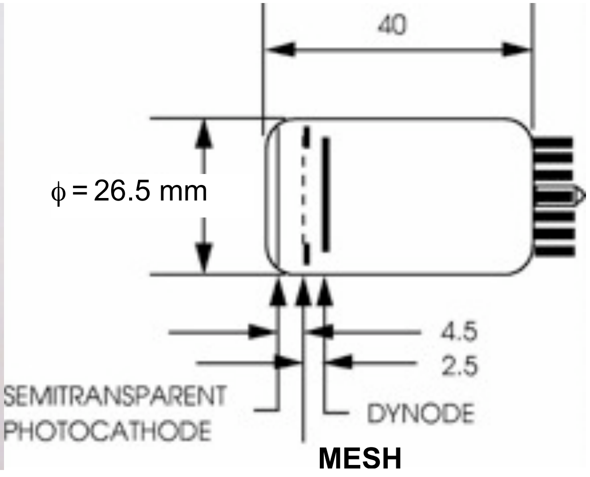




50mm^2 active area

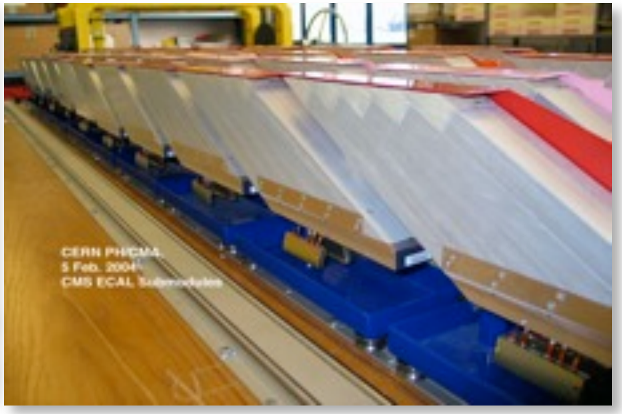
Vacuum Phototriodes: ECAL Endcaps

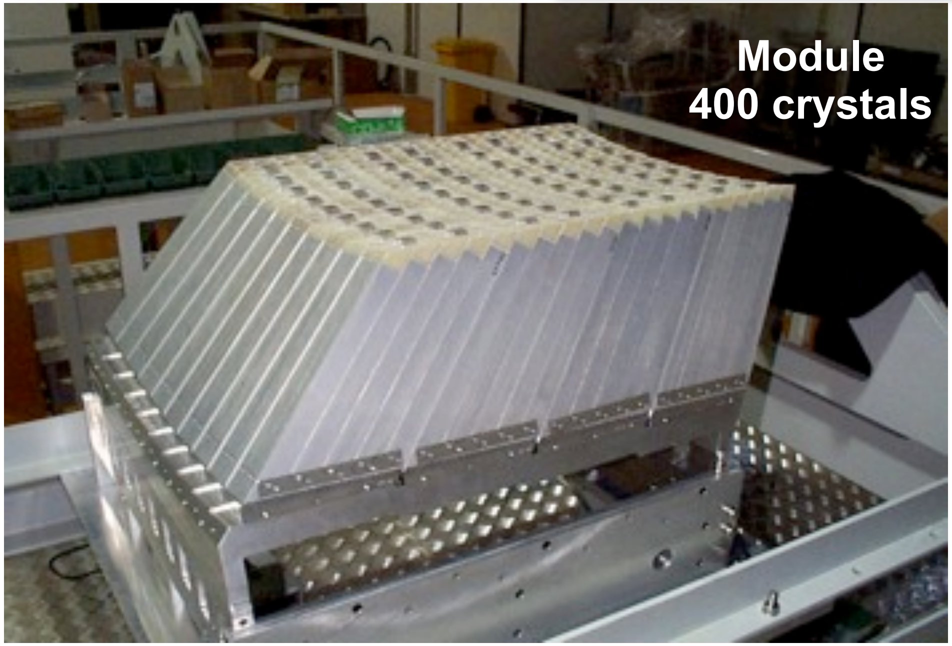
- Single stage PM tube with fine metal grid anode (insensitive to axial magnetic fields)
- Favourable for EC-ECAL
- Q.E. ~20% at 420nm



CMS ECAL Construction

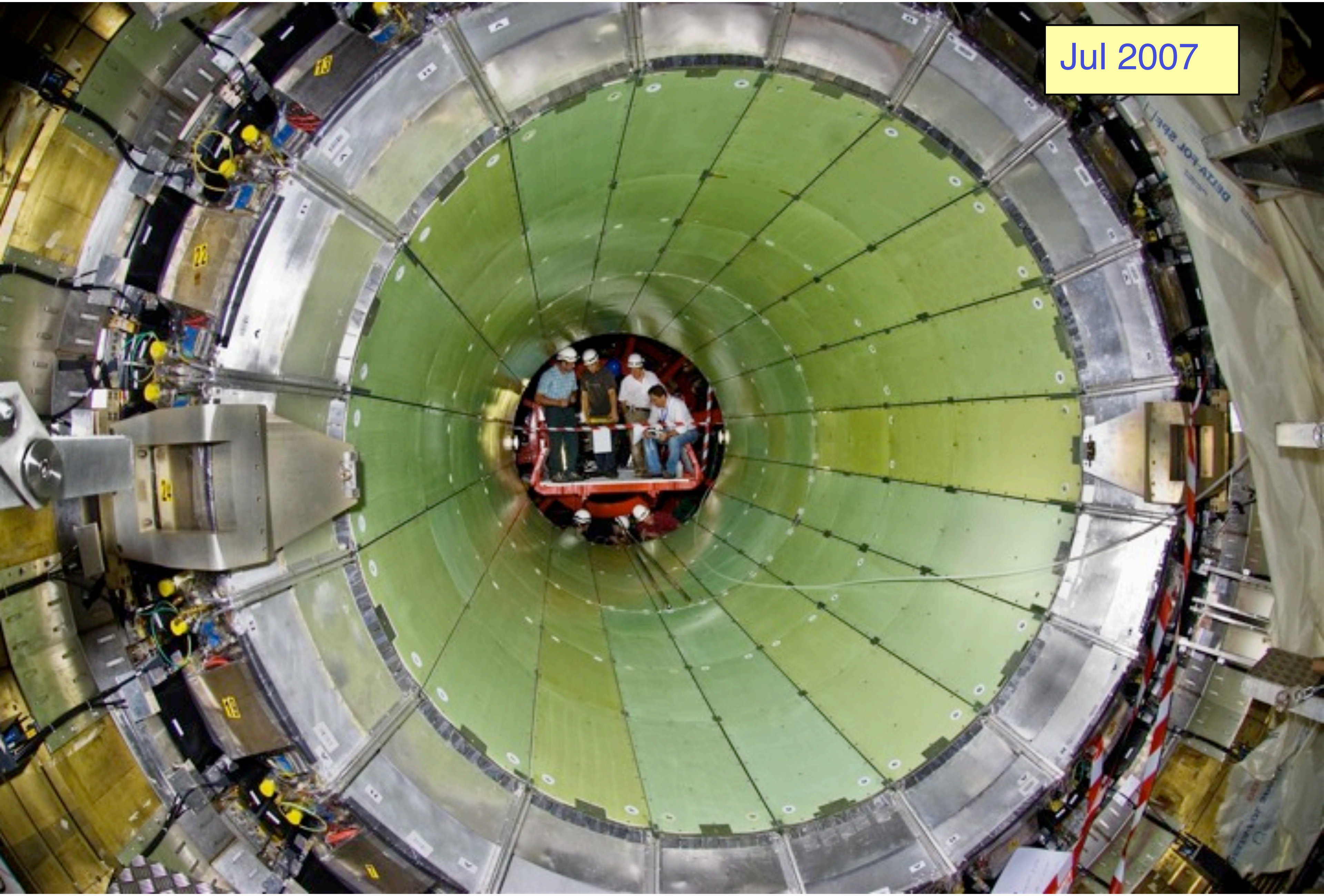

Submodule
2x5 crystals




Module
400 crystals

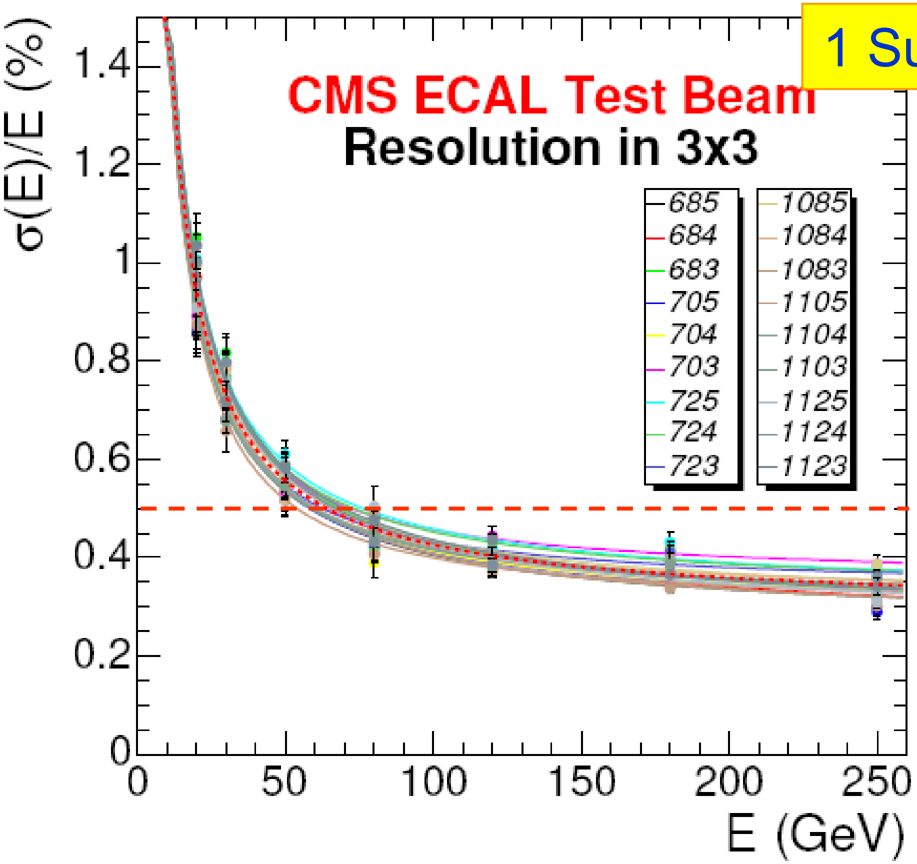

Supermodule
1700 crytsals

Total 36 Supermodules

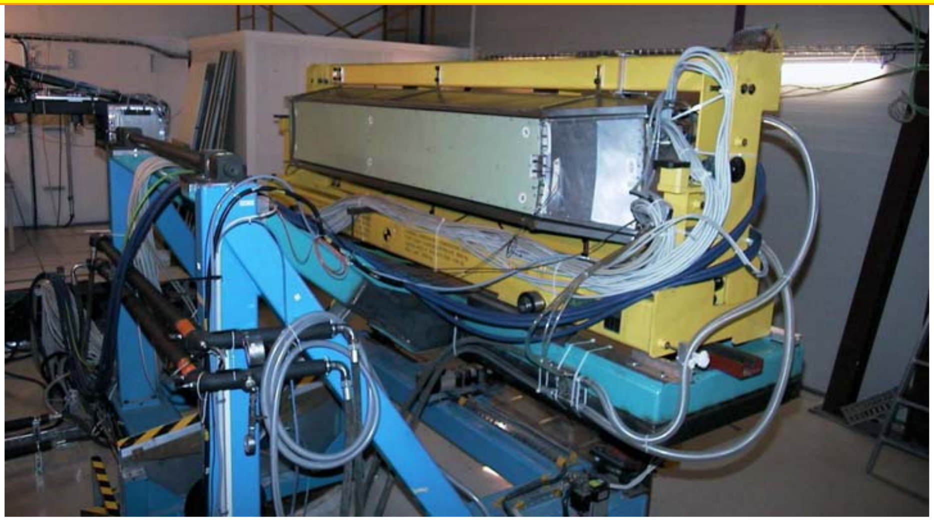


Jul 2007

CMS ECAL: Performance in testbeam



1 Super Module 1700 xl on test beam in 2004



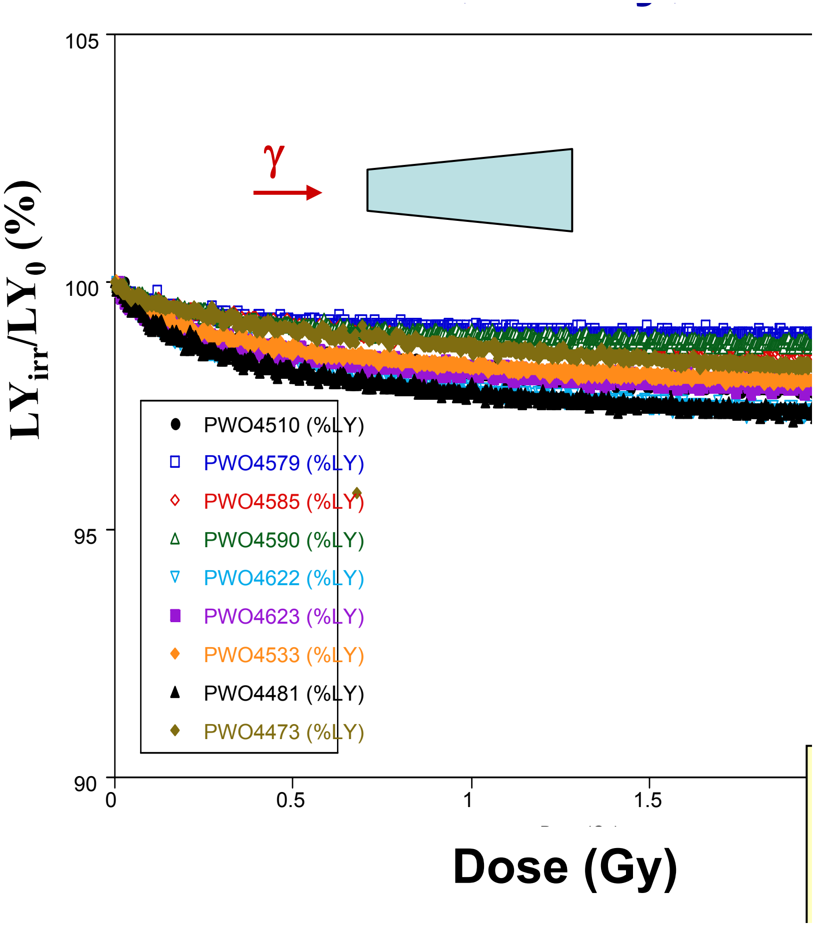
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

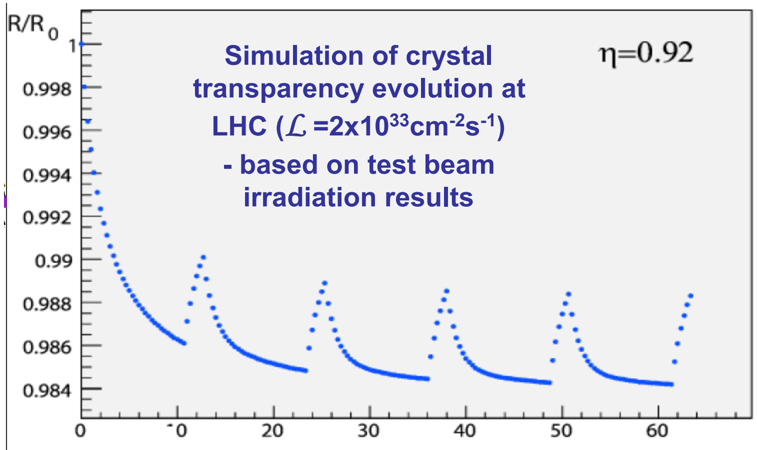
Excellent performance obtained in testbeam

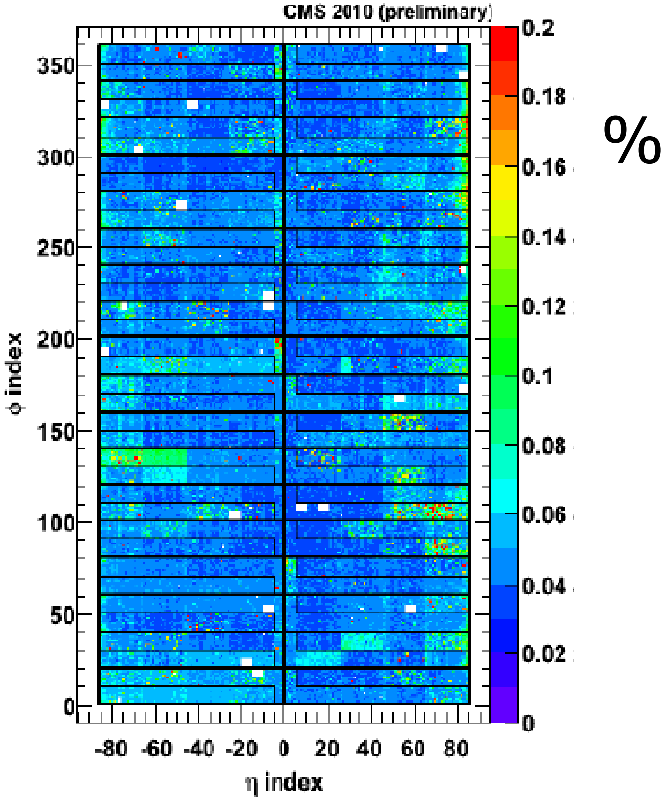
1/4 of barrel modules

How to preserve it at LHC

Sensitive to radiation dose




Simulation of crystal transparency evolution at LHC ($\mathcal{L}$ =2x$10^{33}$$cm^{-2}s^{-1}$) - based on test beam irradiation results



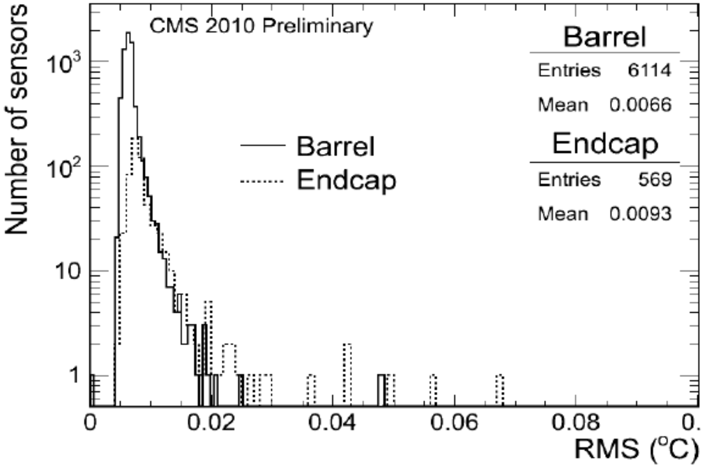
Large effect which needs to be corrected for

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

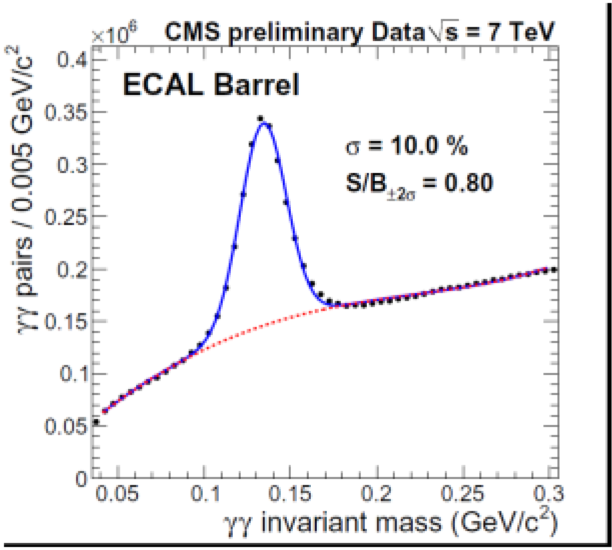
Crystal calibration in CMS

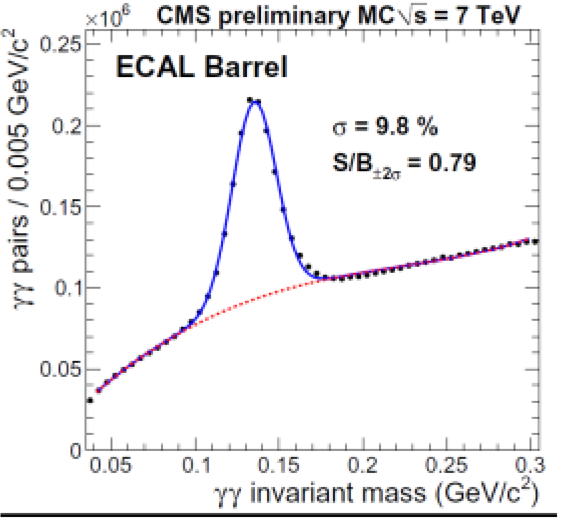
Inter-calibration: several steps

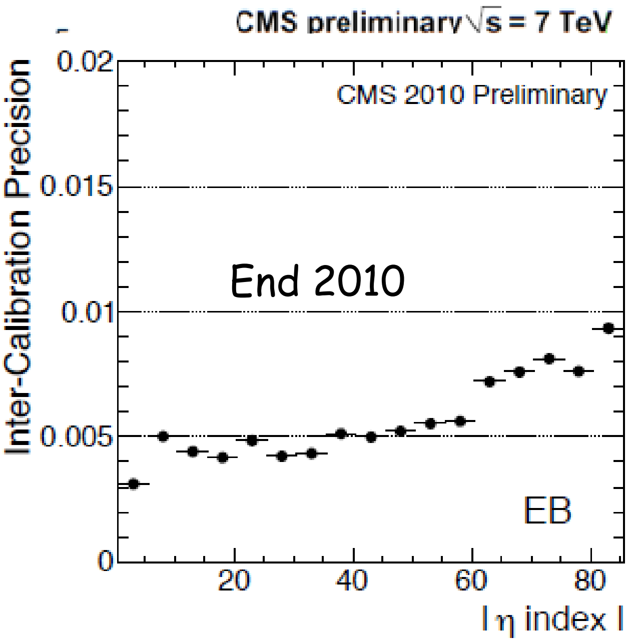
- testbeam (1/4 of barrel ECAL)
- cosmic muons in situ
- Laser pulsing: tracks variations during data taking
- Temperature stability: $\Delta E/E = -2\%/^{0C}$
- Using particles: π^0, η^0



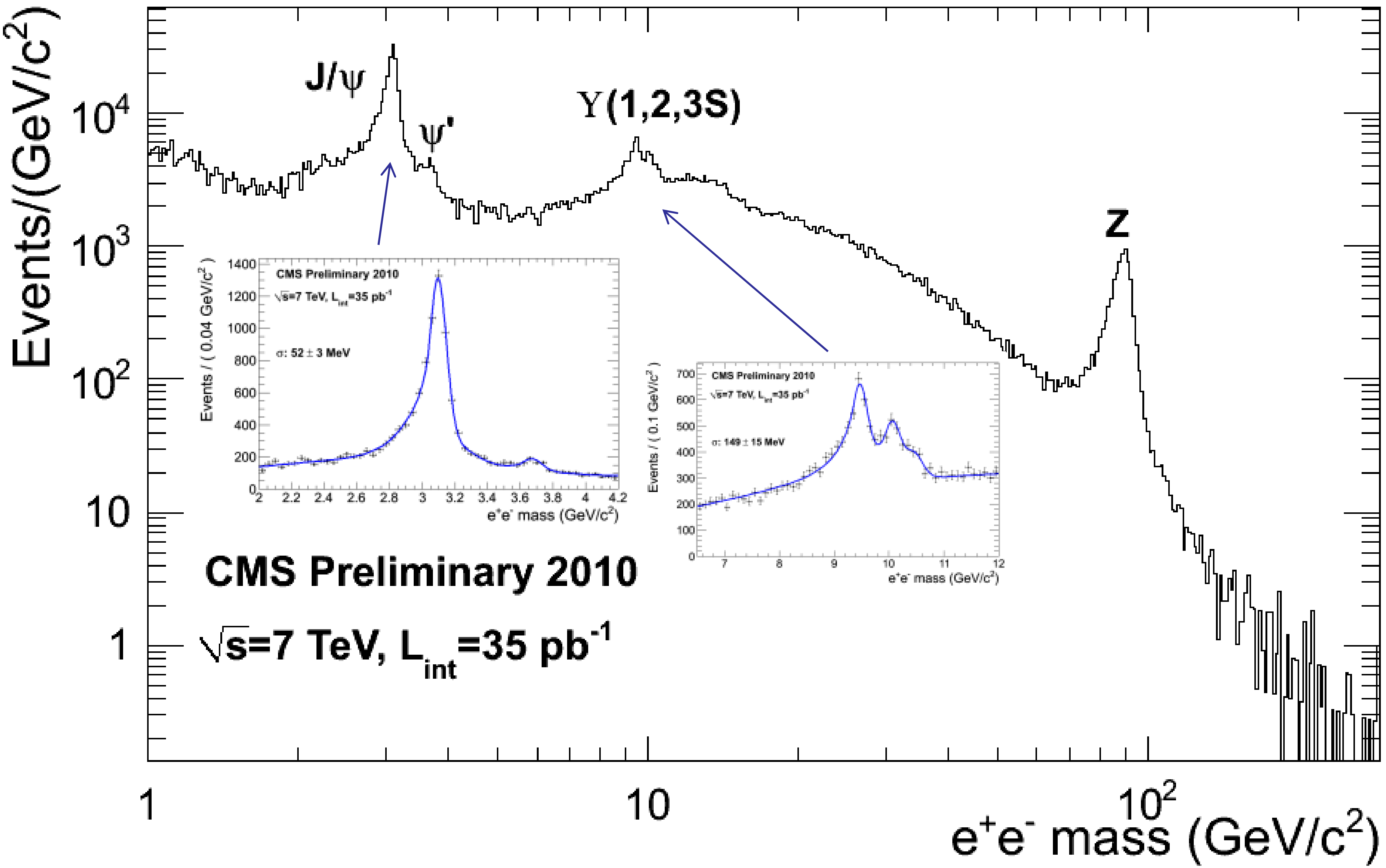
June 2010 - Dec 2010



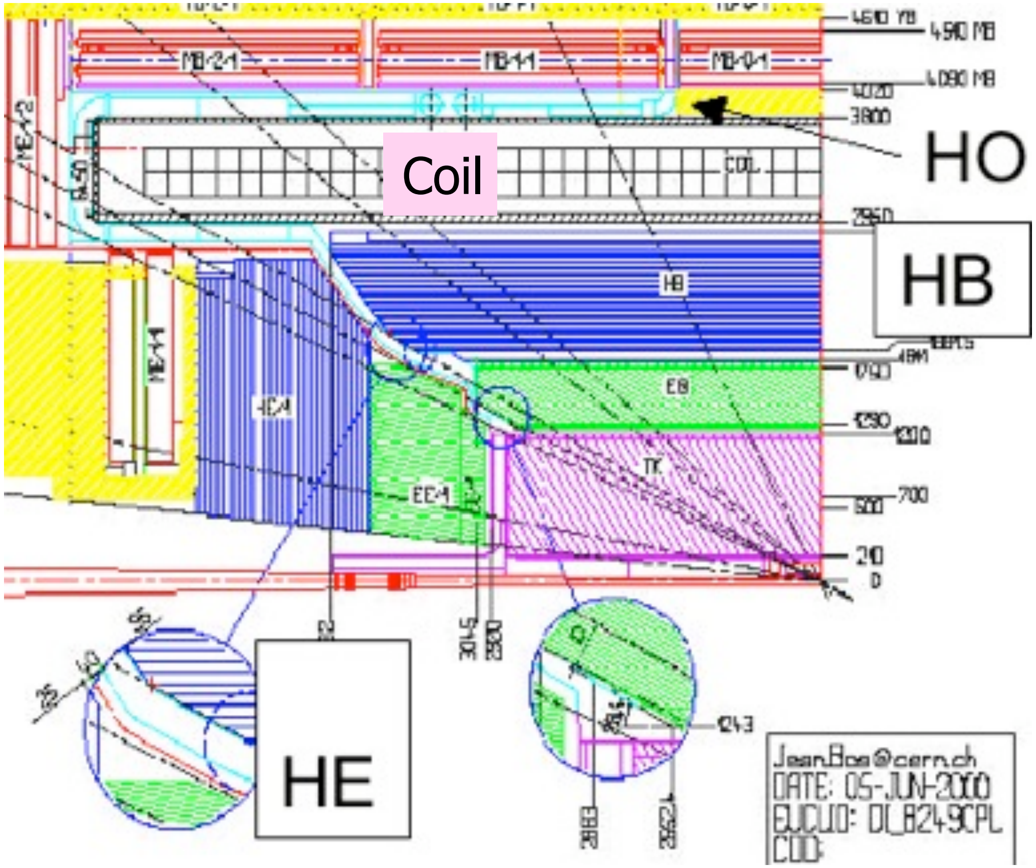




Performance in-situ CMS



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 $2.85 < |\eta| < 5.19$

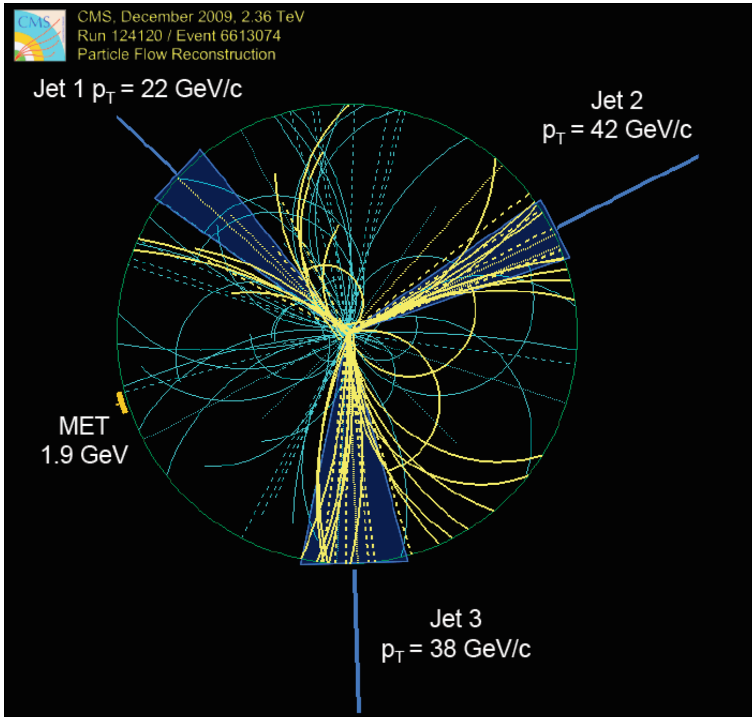
Fe/quartz fibers (radiations)

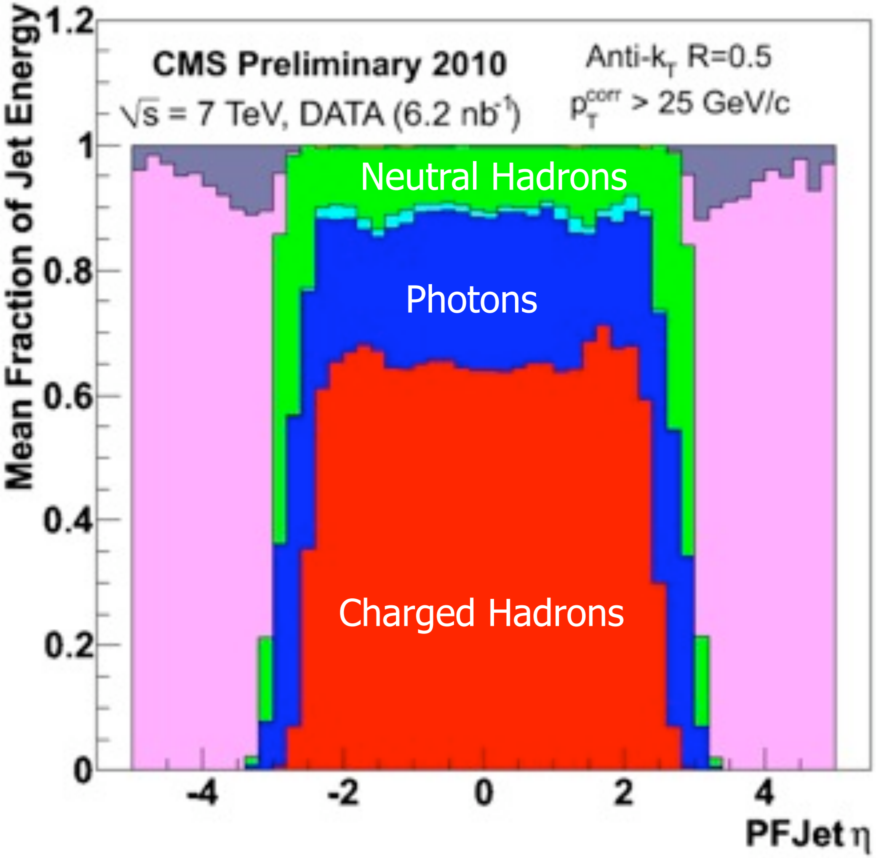
Copper: non magnetic material

CMS Hadronic Response

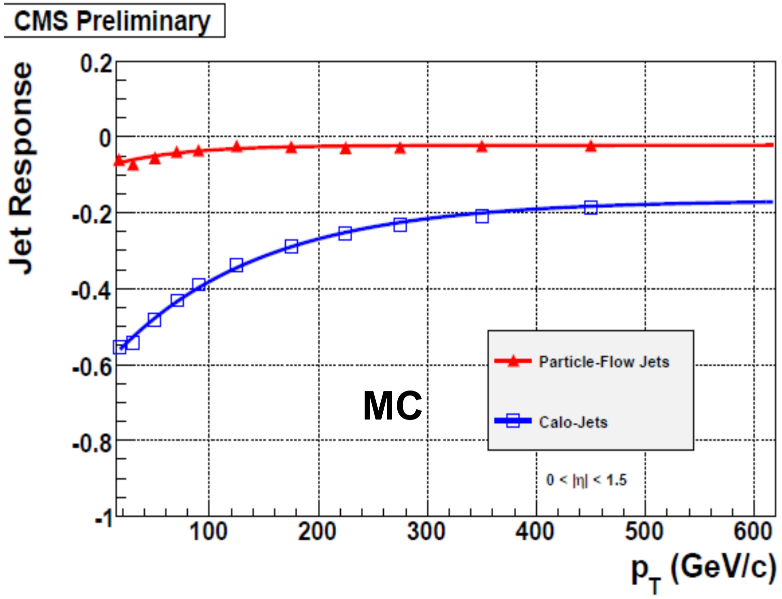
CMS is using a Particle Flow Technic to reconstruct Jets and Missing Transverse Energy

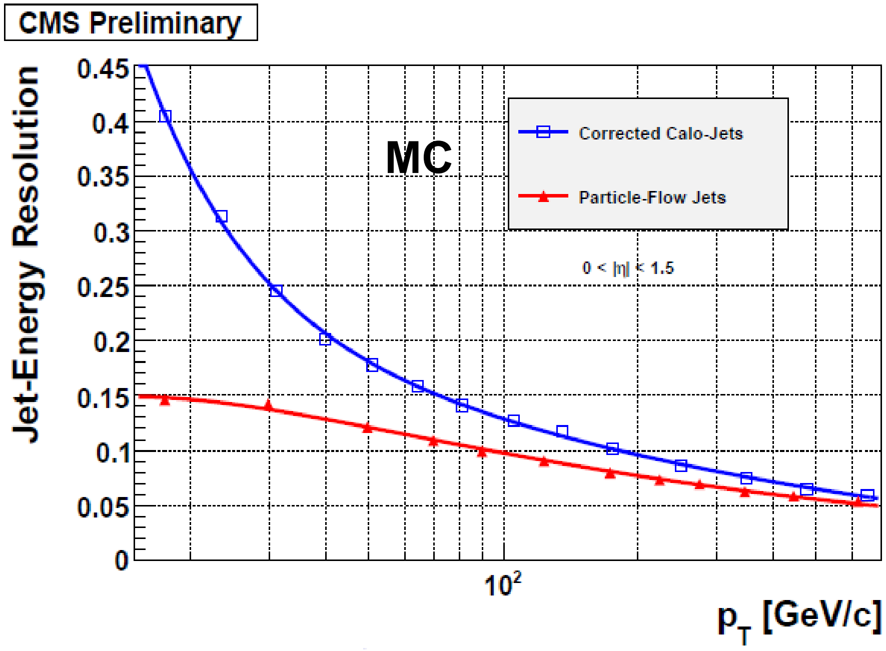
- use the best measurement for each component
  - Tracker for charged hadron
  - ECAL for electrons & photons
  - HCAL for neutral hadrons

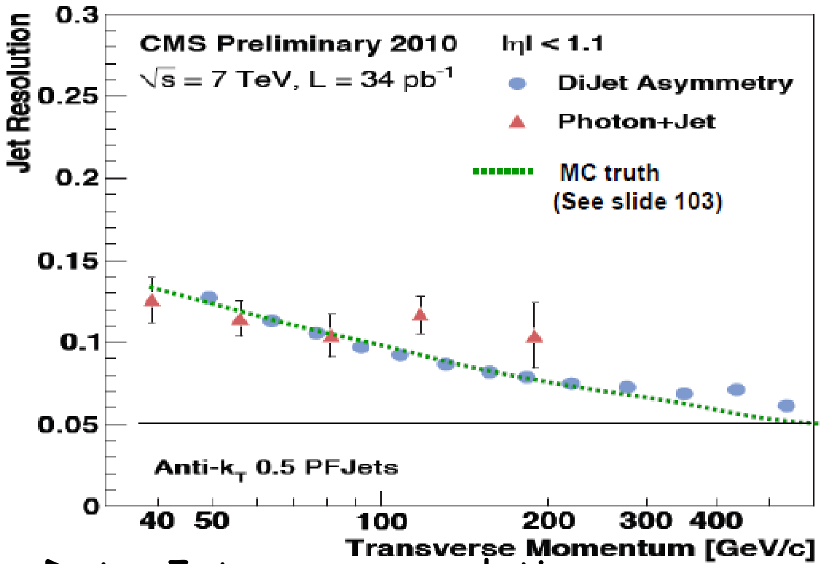




CMS-Particle Flow Jet Reconstruction Performance

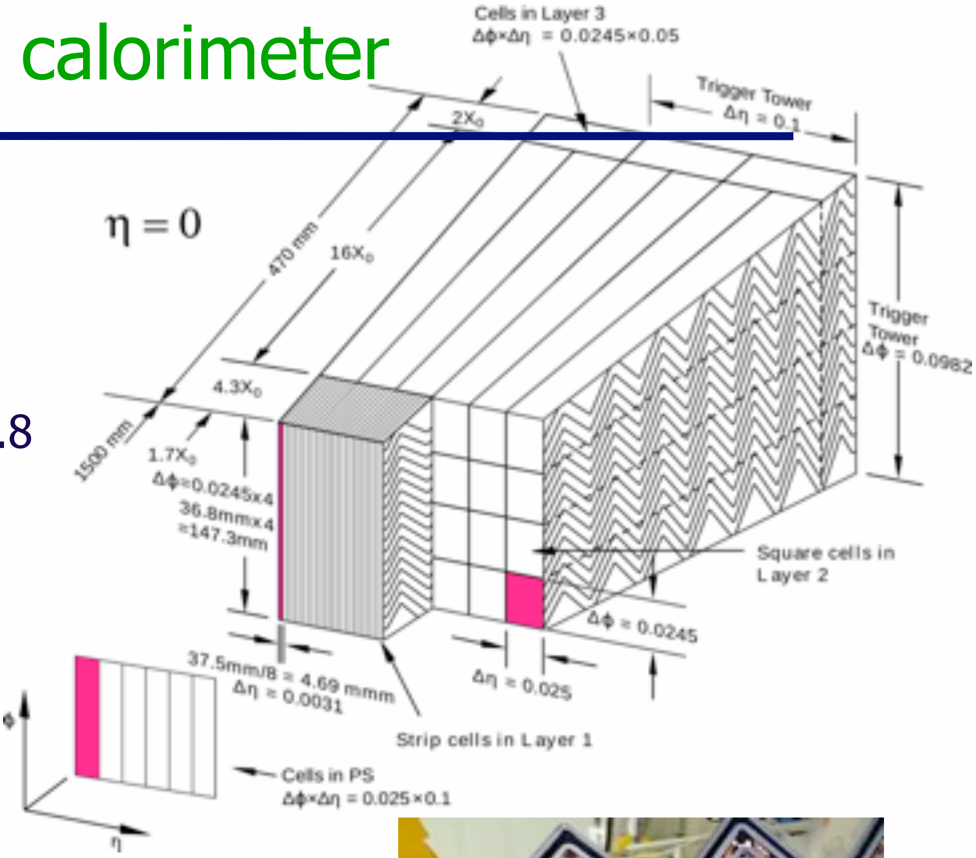






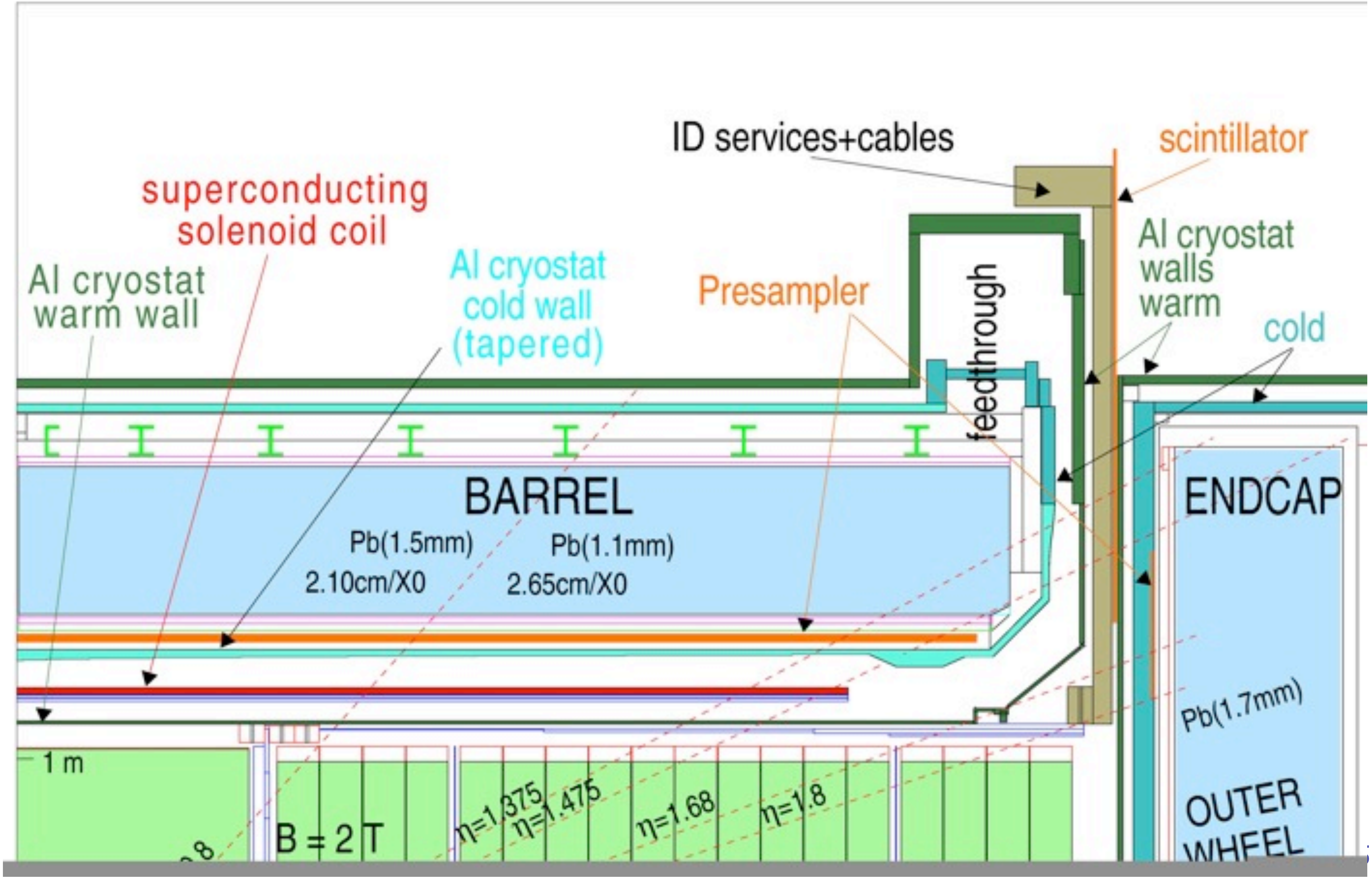
ATLAS calorimeter

ATLAS EM calorimeter

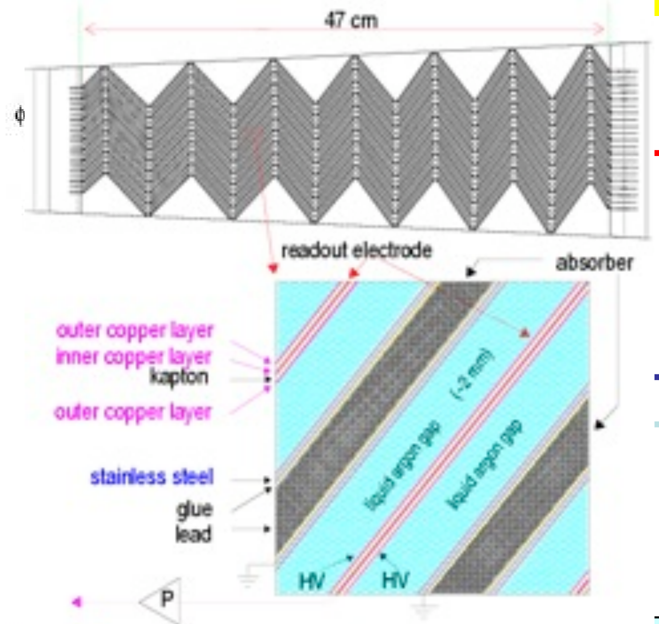


- Accordion Pb/LAr |η|<3.2 ~170k channels
  - Precision measurement |η|<2.5
- 3 layers up to |η|=2.5 + presampler |η|<1.8
- 2 layers 2.5<|η|<3.2
  - Layer 1 (γ/π^0 rej. + angular meas.)
  - Δη.Δφ = 0.003 x 0.1
  - Layer 2 (shower max)
  - Δη.Δφ = 0.025 x 0.0.25
  - Layer 3 (Hadronic leakage)
  - Δη.Δφ = 0.05 x 0.0.025
- Energy Resolution: design for η~0
  - $\Delta E/E \sim 10\%/\sqrt{E} \oplus 150\ \text{MeV}/E \oplus 0.7\%$
- Angular Resolution
  - $50\text{mrad}/\sqrt{E(\text{GeV})}$

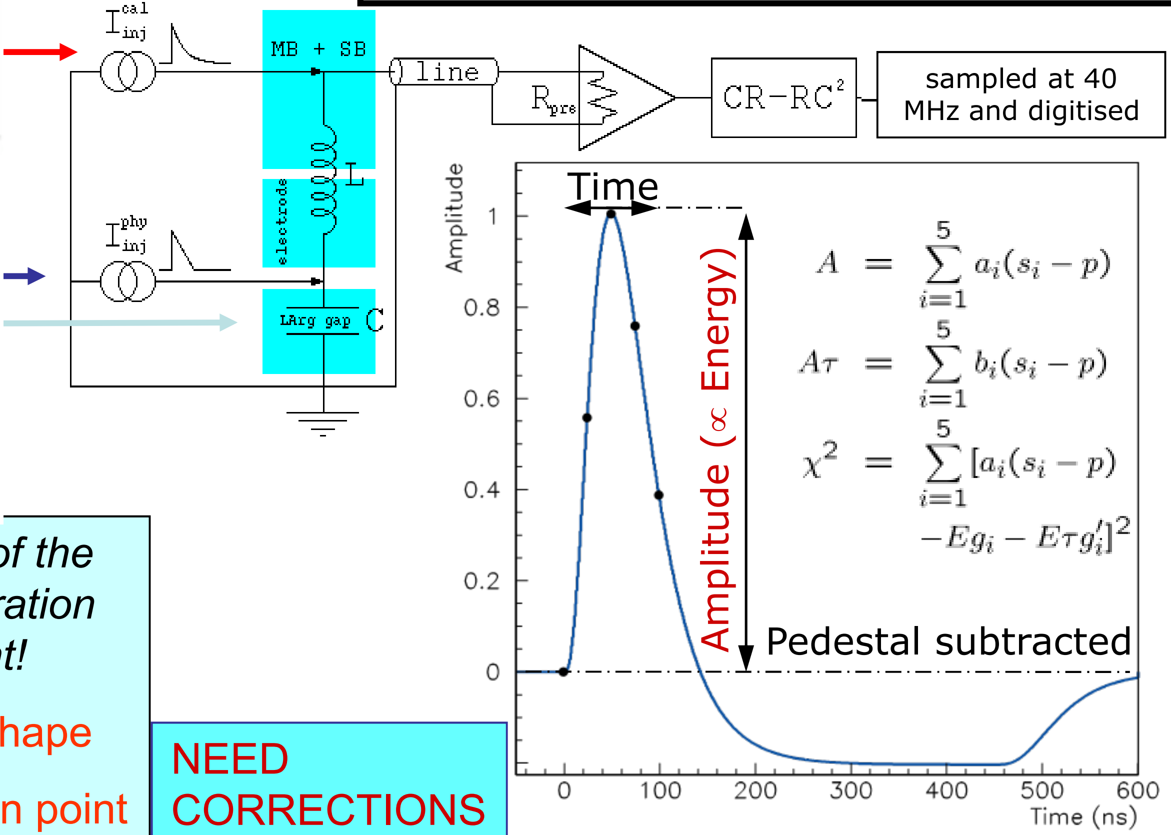
The cryostat structure



Accordion: collecting the signal



The ionization signal is sampled every 25 ns by a 12 bits ADC in 3 gains. 5 samples are recorded at ATLAS.



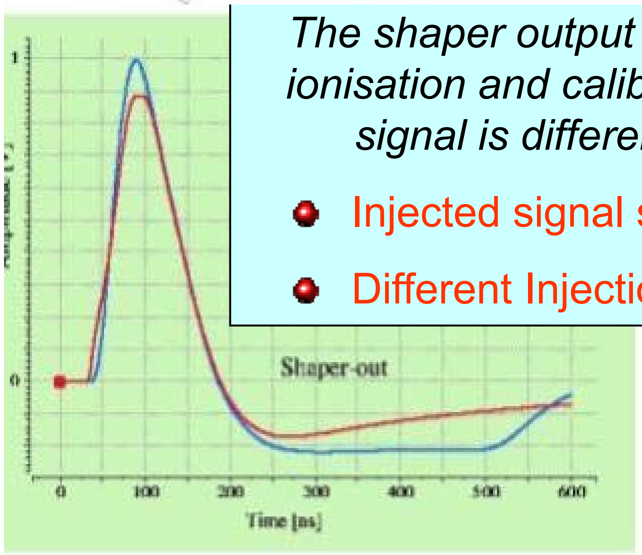
$$A = \sum_{i=1}^{5} a_i(s_i - p)$$

$$A\tau = \sum_{i=1}^{5} b_i(s_i - p)$$

$$\chi^2 = \sum_{i=1}^{5} [a_i(s_i - p) - Eg_i - E\tau g_i']^2$$

The shaper output of the ionisation and calibration signal is different!

- Injected signal shape
- Different Injection point

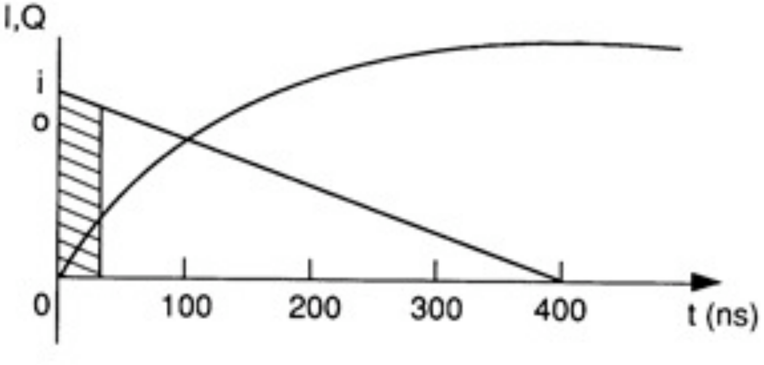


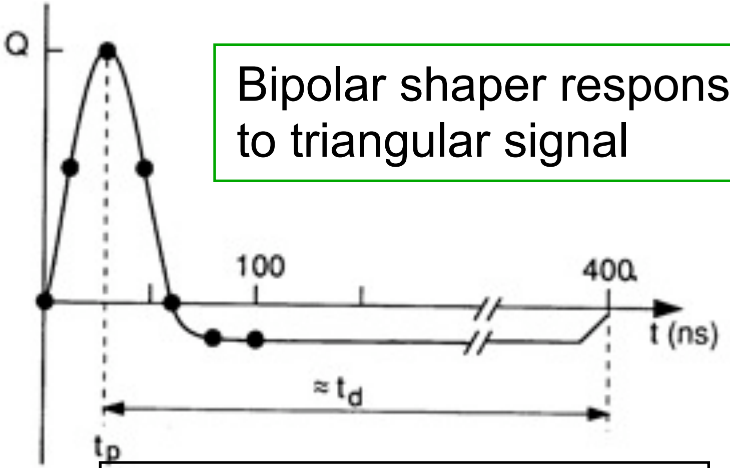
NEED CORRECTIONS

The equalization of the electronic readout. Requires to know the shaping function of each cell at few percent level
→ equalization with an electronic control signal

Obtaining a fast response

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





Bipolar shaper response to triangular signal

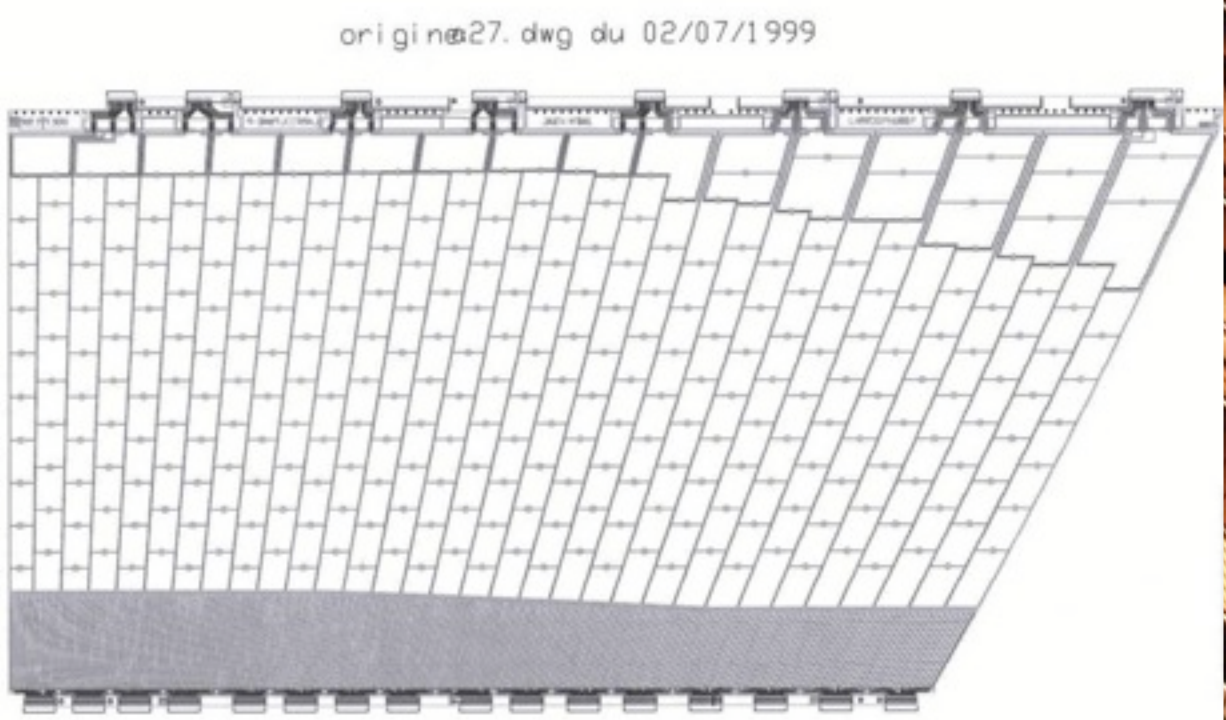
→ detector response time is not t_d but t_p

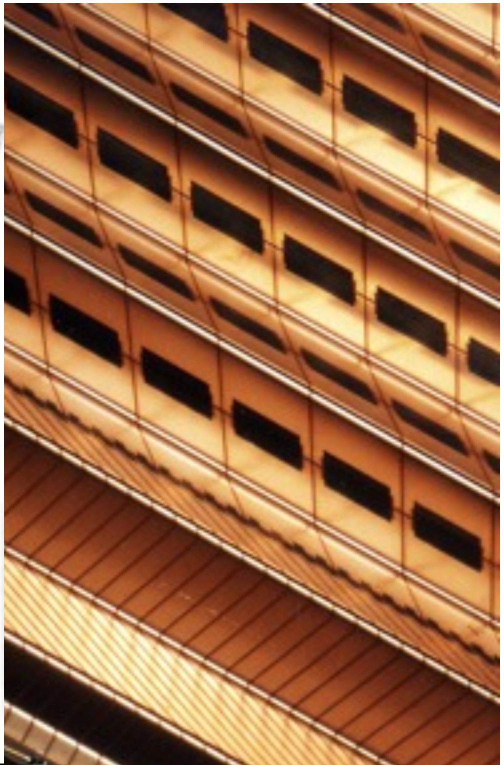
S/N is smaller than in the case $t_p=t_D$

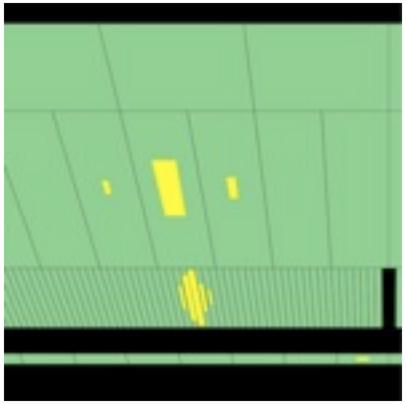
$$S \sim t_p, N \sim \frac{1}{\sqrt{t_p}} \Rightarrow \frac{S}{N} \sim t_p^{3/2}$$

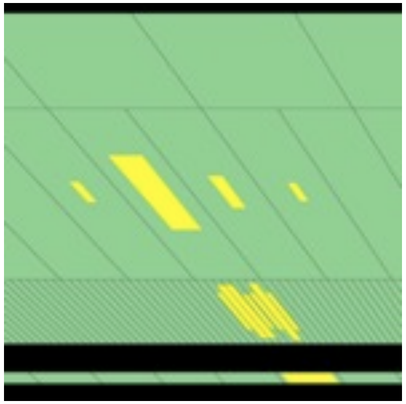
~30 smaller for 40 ns than for 400 ns

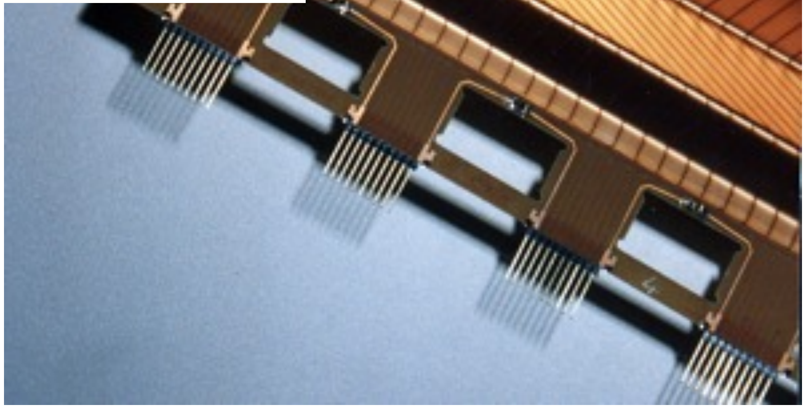
The segmentation



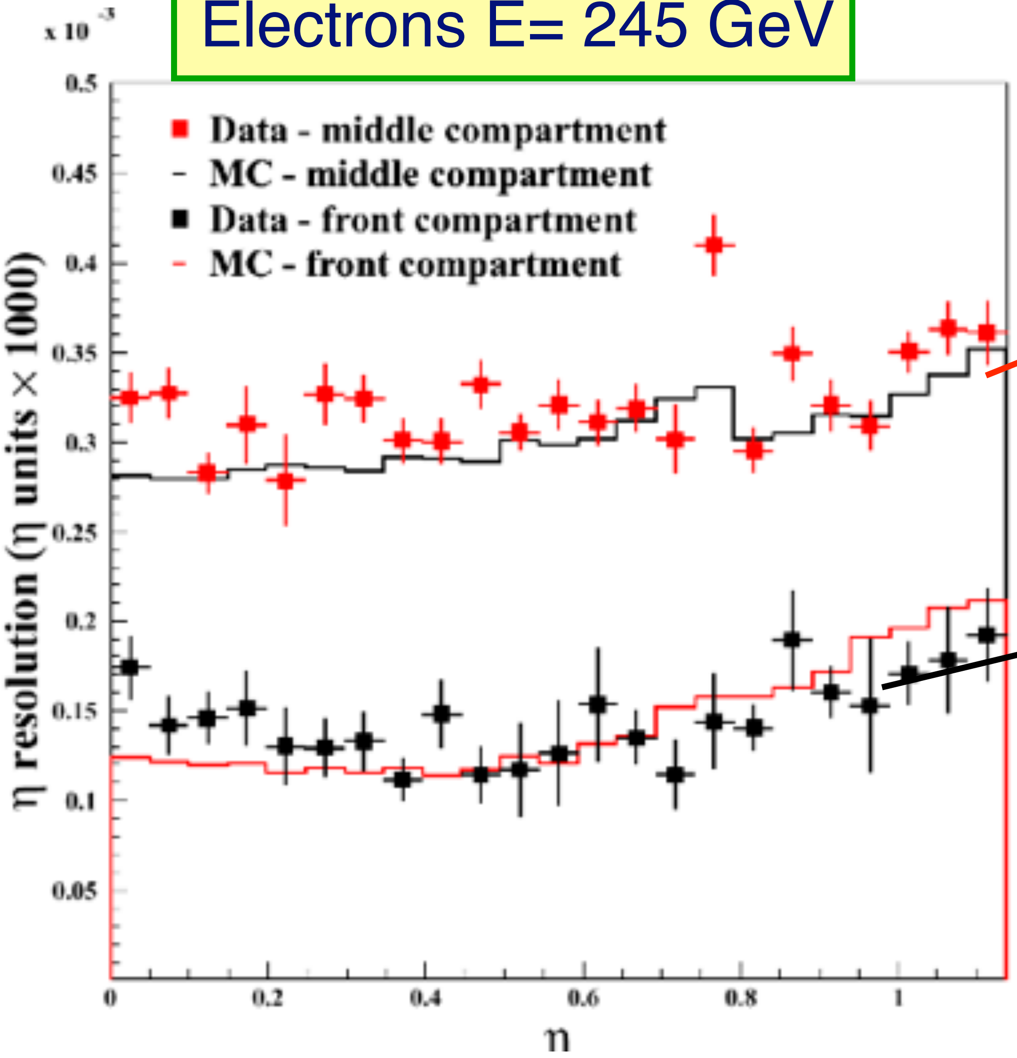


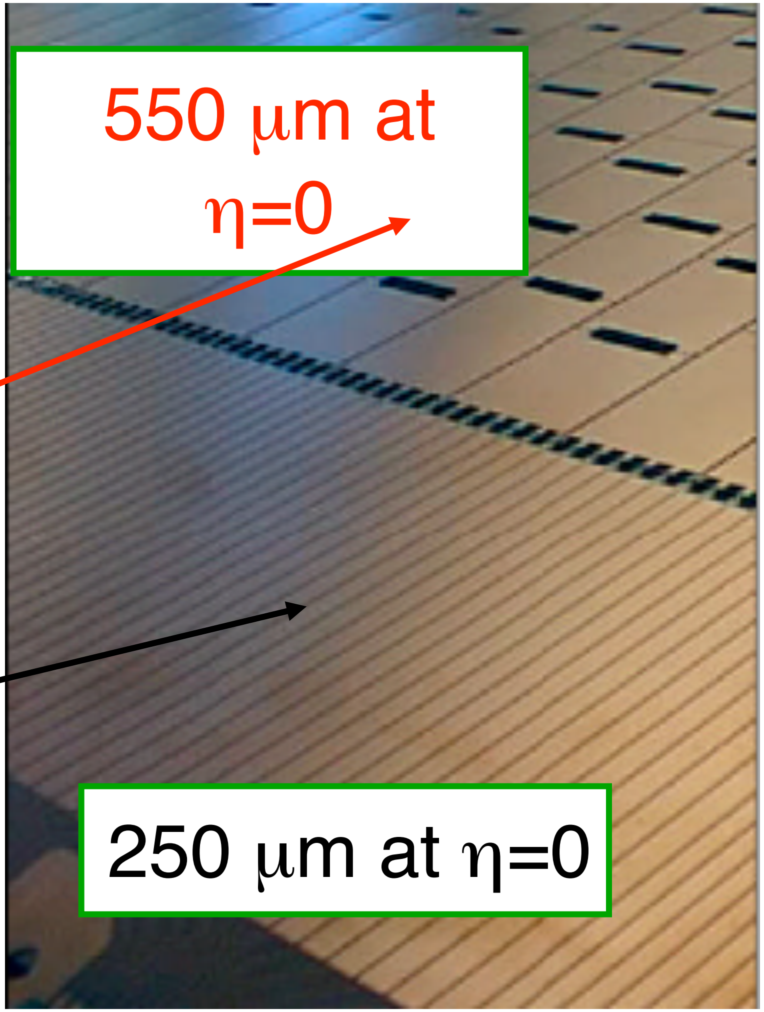






Electrons E= 245 GeV





550 μm at η=0

250 μm at η=0

Energy Resolution CMS vs ATLAS

CMS (PbW0$_4$) / ATLAS (Pb/LAr)			
	10 GeV	100 GeV	1000 GeV
Stochastic (GeV)	0.095 / 0.32	0.3 / 1	0.949 / 3.2
Noise (GeV)	0.3 / 0.3	0.3 / 0.3	0.3 / 0.3
Constant (GeV)	0.05 / 0.07	0.5 / 0.7	5 / 7
σ(E) (GeV)	0.30 / 0.44	0.65 / 1.26	5.1 / 7.7
σ(E)/E (%)	3 / 4.4	0.65 / 1.26	0.51 / 0.77

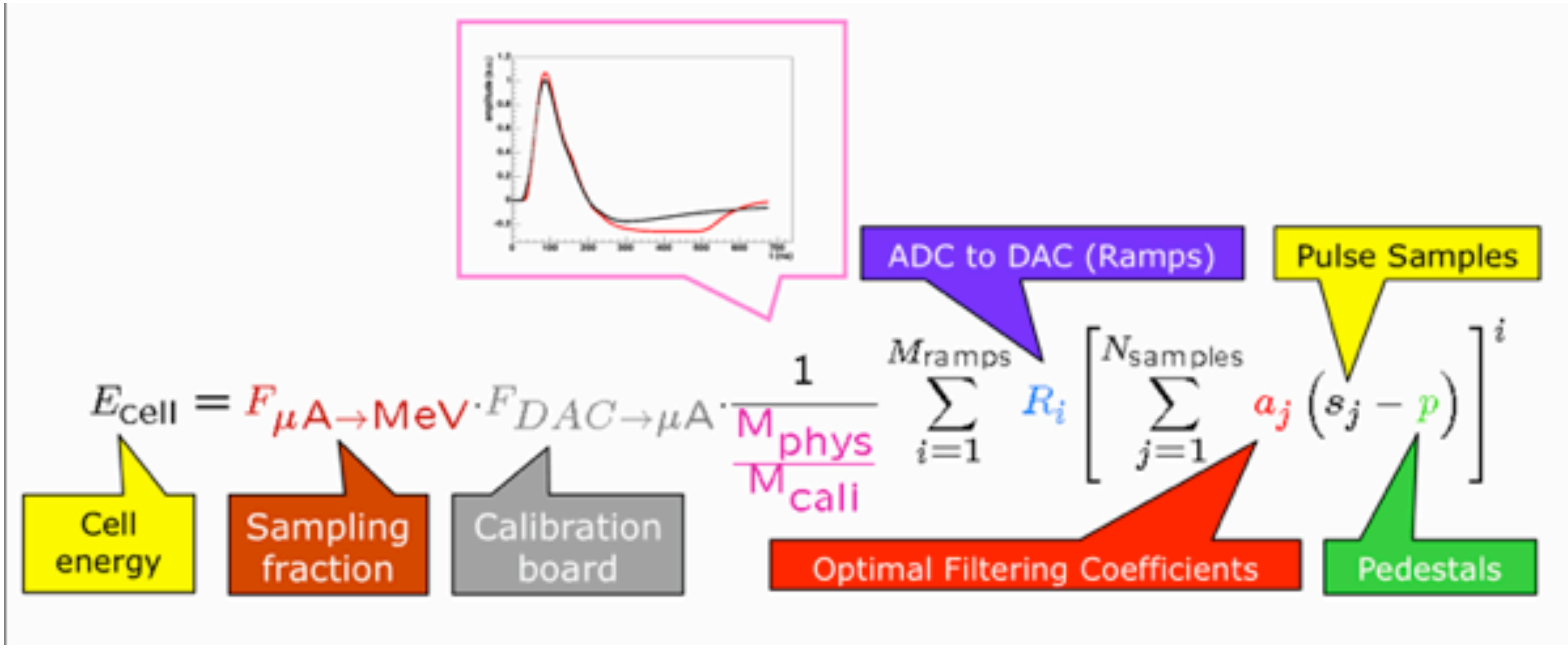
$$\frac{\sigma(E)}{E} = \frac{0.03}{\sqrt{E(GeV)}} \oplus \frac{0.3}{E(GeV)} \oplus 0.005$$

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

ATLAS LAr cell calibration

Cell to cell calibration from electronics calibration system

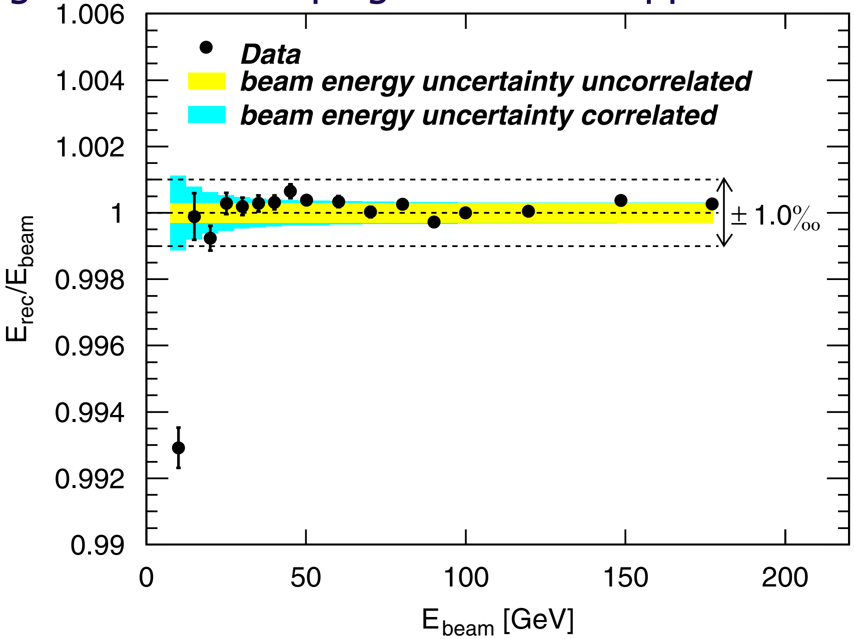
- Inject a know signal amplitude
- Correct for the difference between calibration signal and ionisation signal shapes
- Correct for the sampling fraction
- Apply calibration factor



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

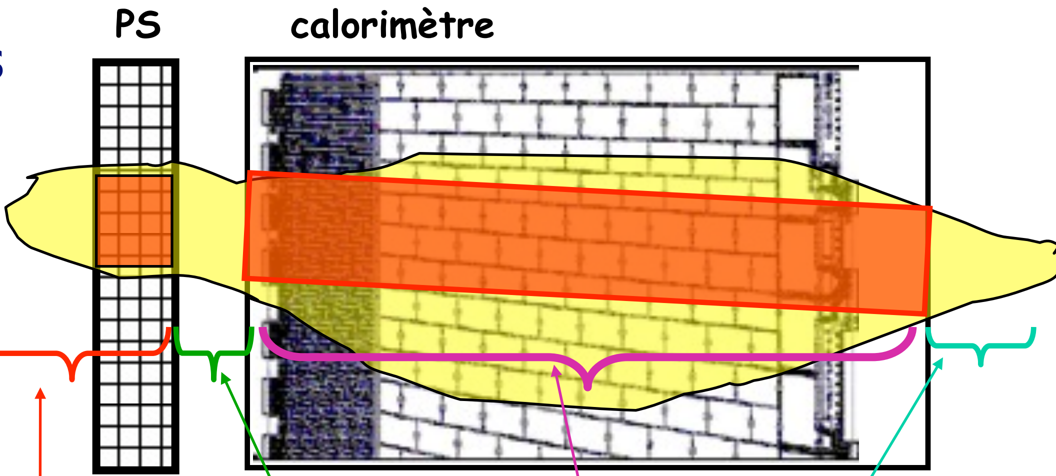
ATLAS cluster correction

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

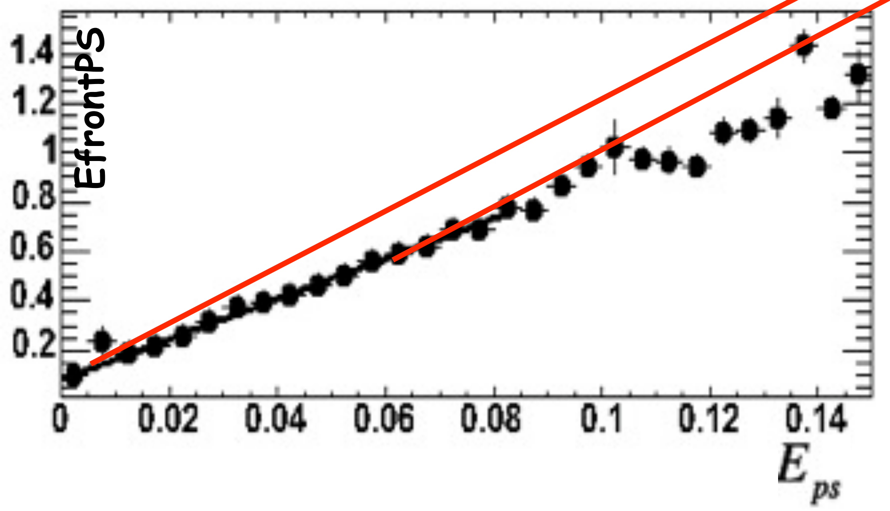


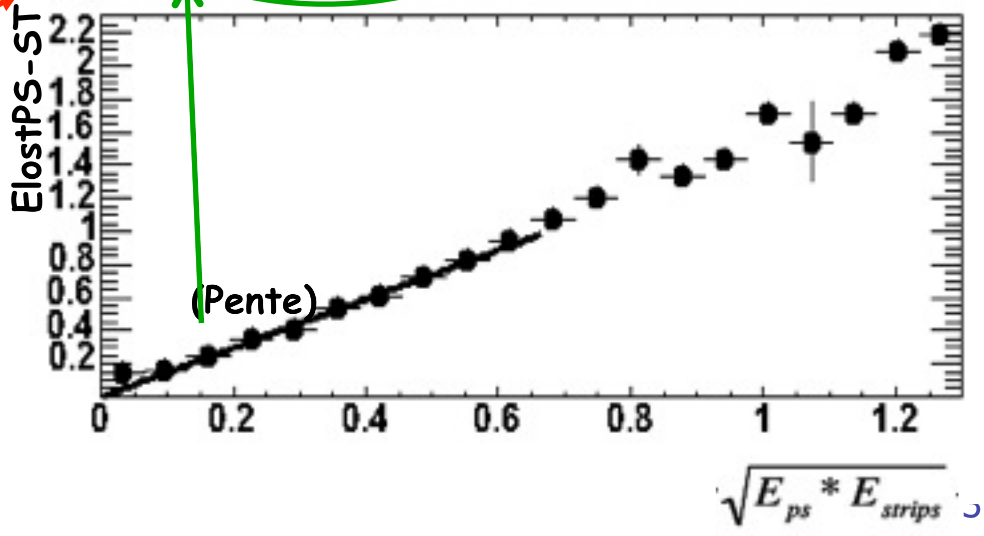
Cluster Energy Reconstruction

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

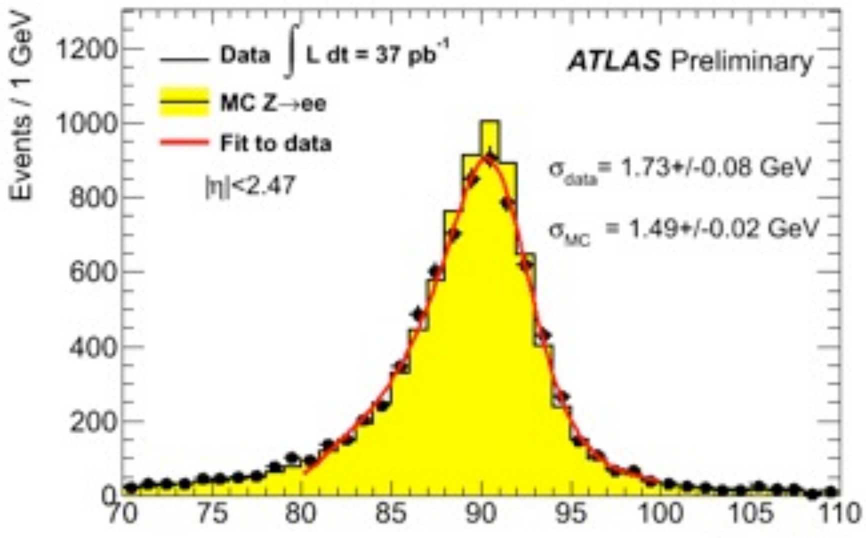


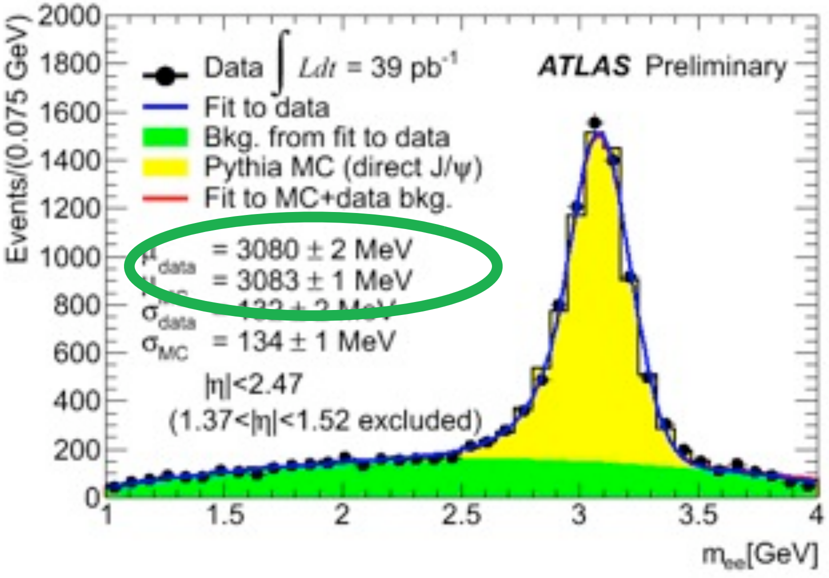
$$E_{rec} = E_{outcluster} + a + bE_{ps} + c\sqrt{E_{ps} * E_{strips}} + Eacc + Eleak$$

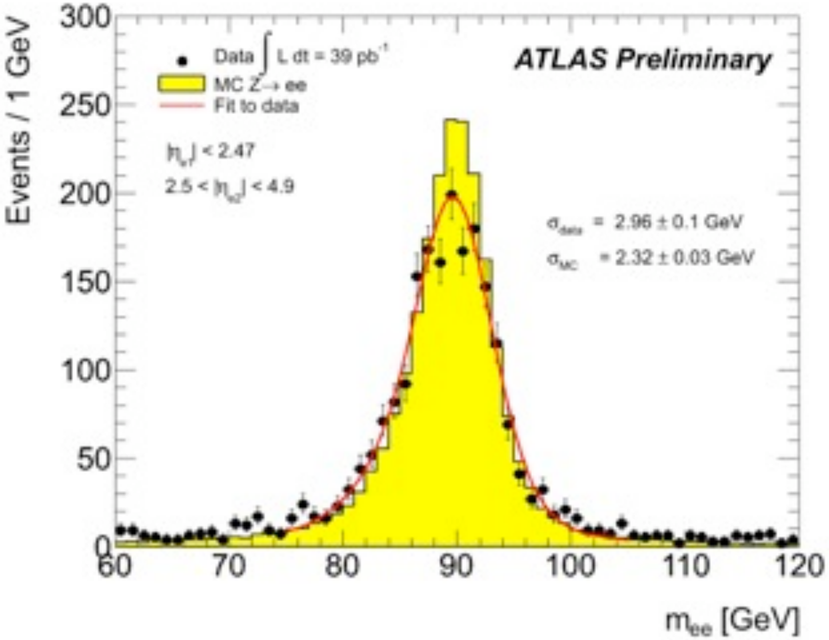




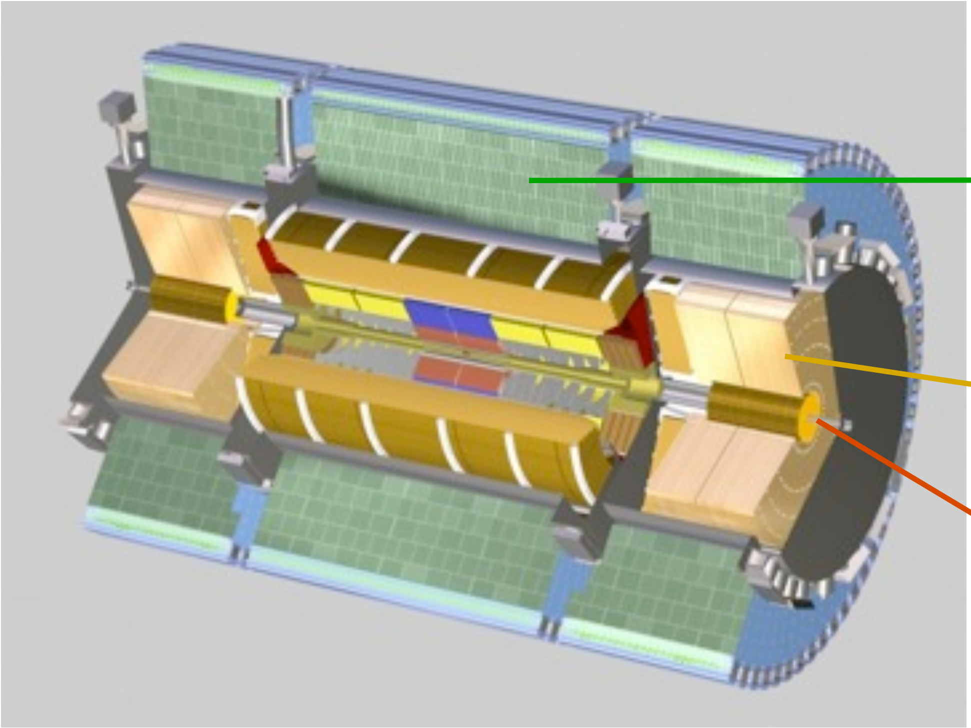
ATLAS Linearity with data







ATLAS Hadronic calorimeters



Tiles Calorimeter $|\eta| < 1.7$

Fe / Scintillator

3 layers in depth

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

4 layers in depth

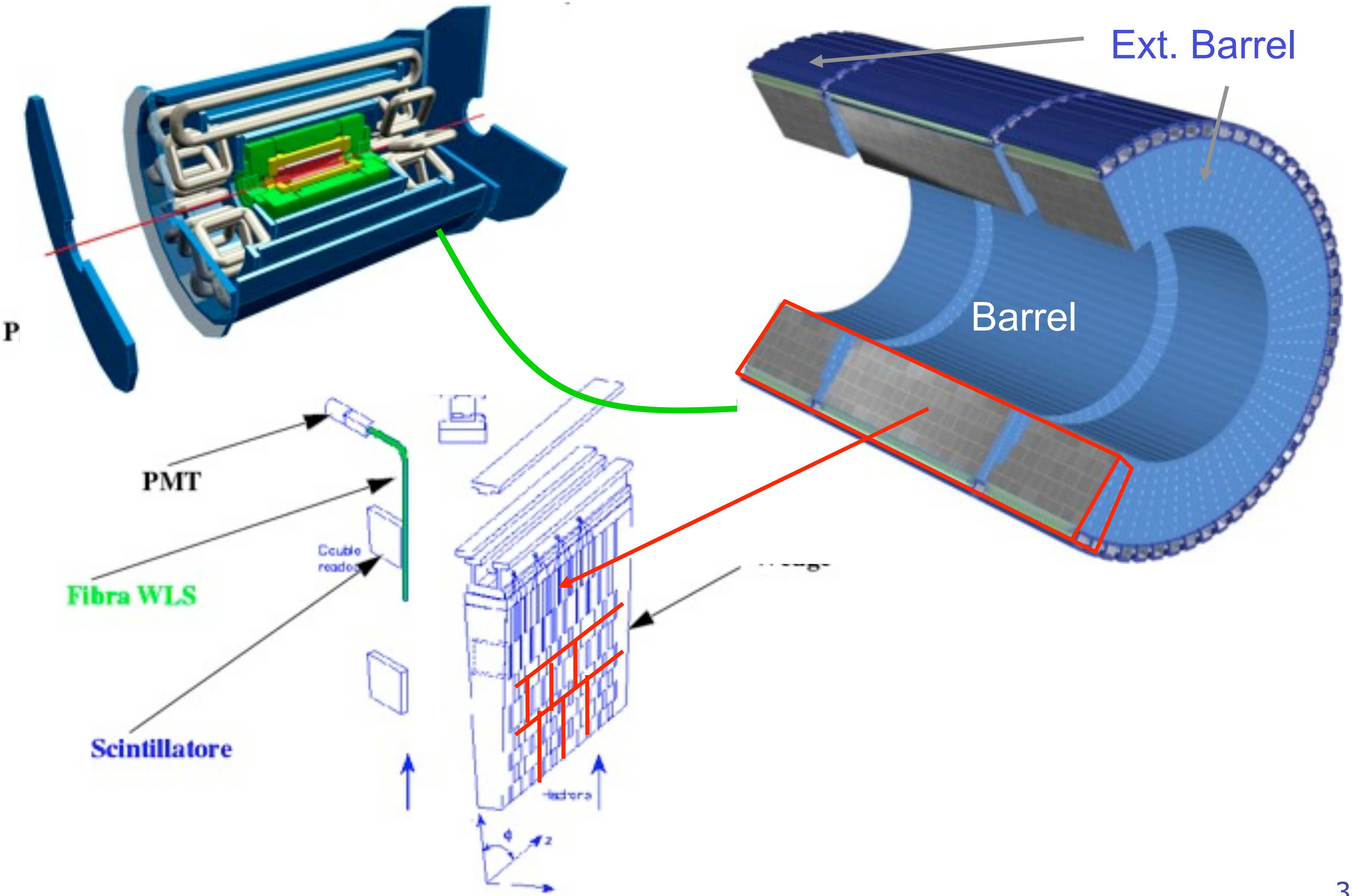
Forward: 1 layer EM, 2 HAD

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

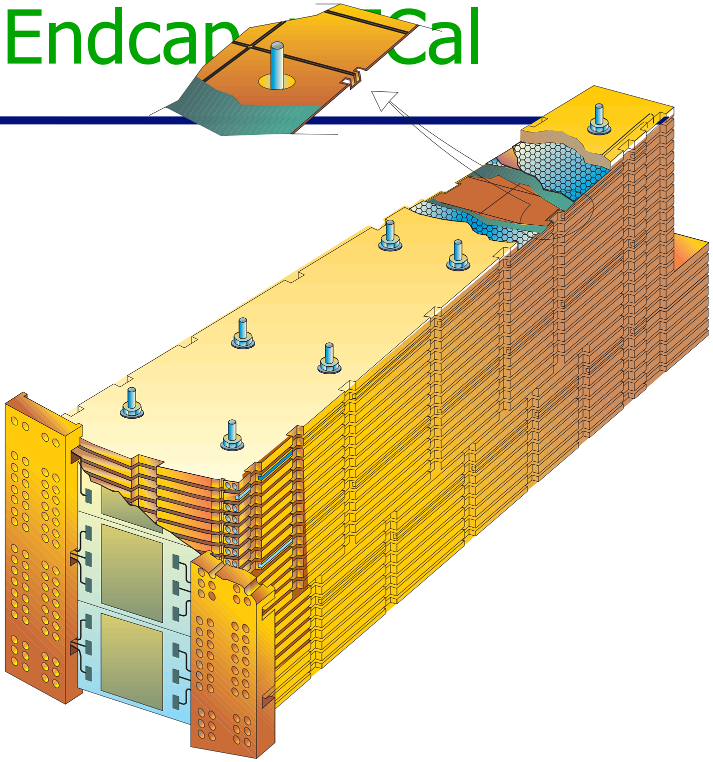
Total thickness: ~ 8 -10 λ

Use of different technics: cope with radiations in forward region

ATLAS Hadronic Tiles calorimeter



ATLAS LAr Hadronic Endcap FCal



HEC Cu/LAr

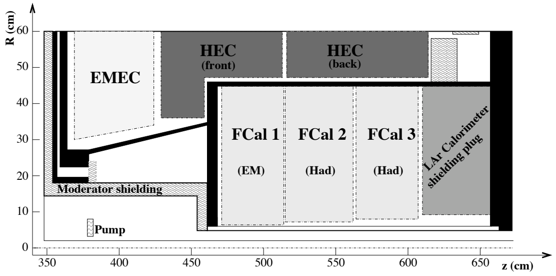
1.5< |η|<3.2 ~5600 channels

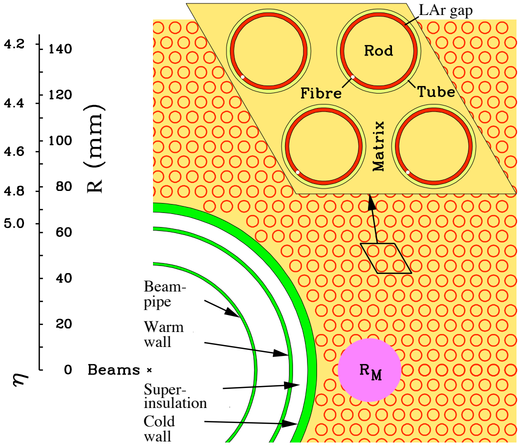
4 layers Δη.Δφ = 0.1 x 0.1 & 0.2x0.2

FCal Cu-W/LAr

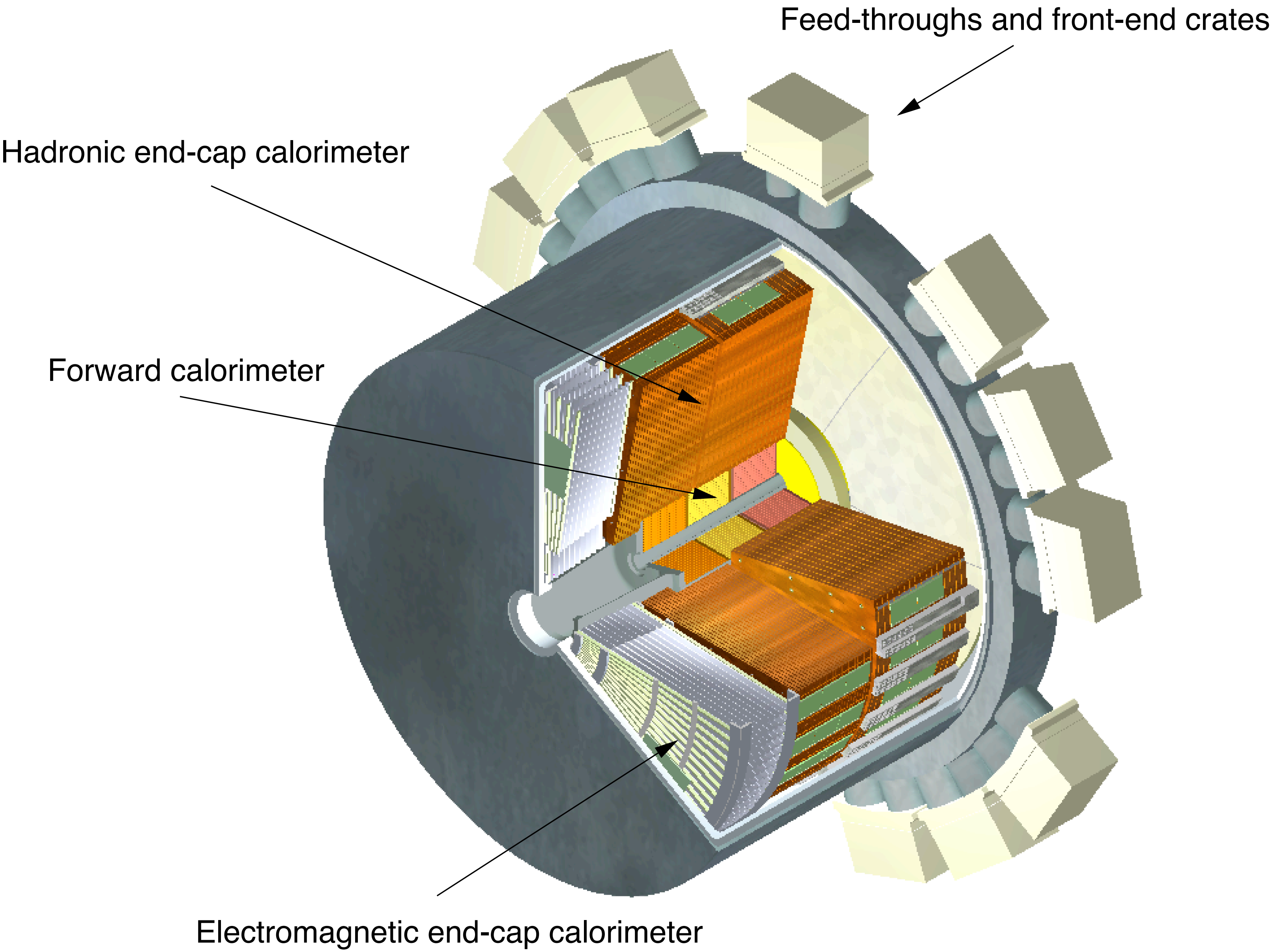
3.1<|η|<4.9 ~3500 channels

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

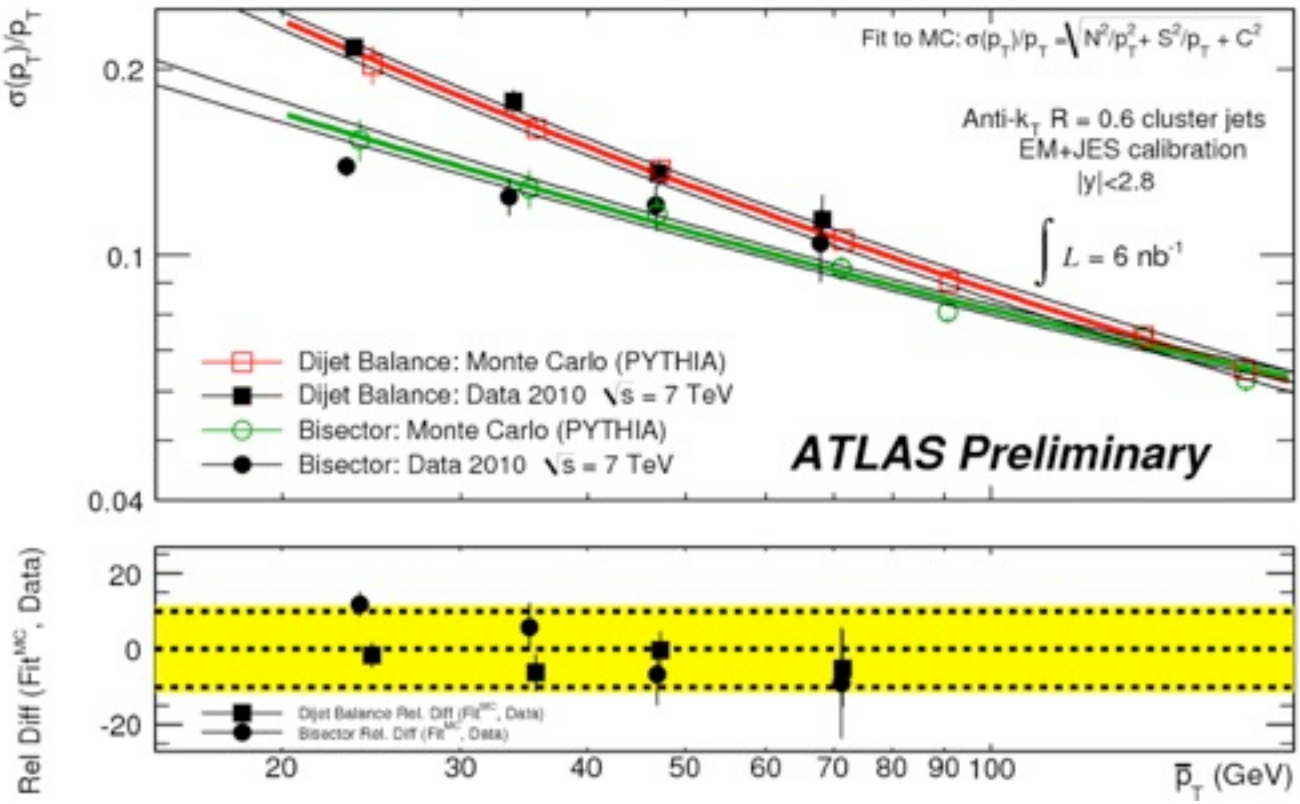




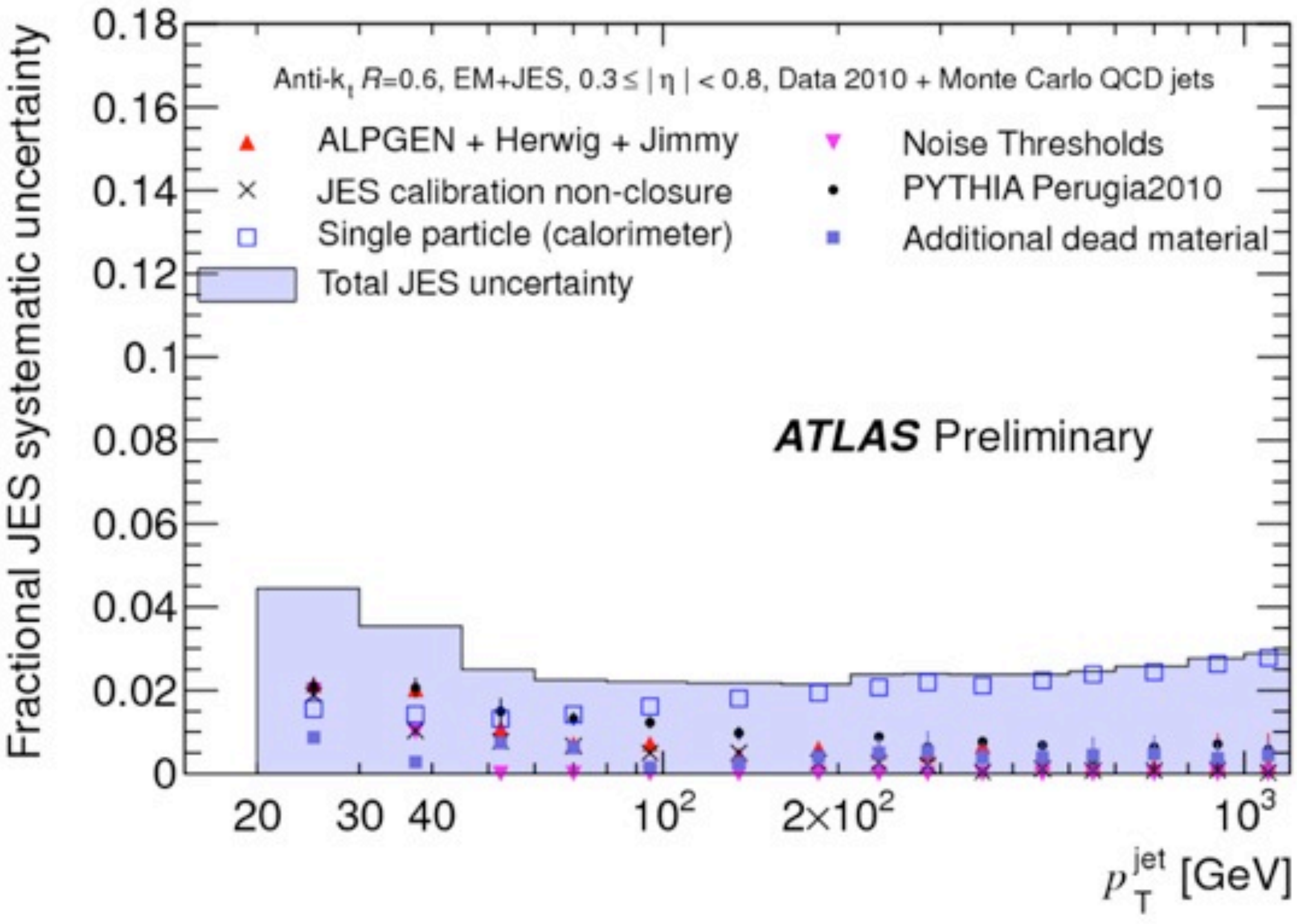
Endcap cryostat view



ATLAS Jets Performance

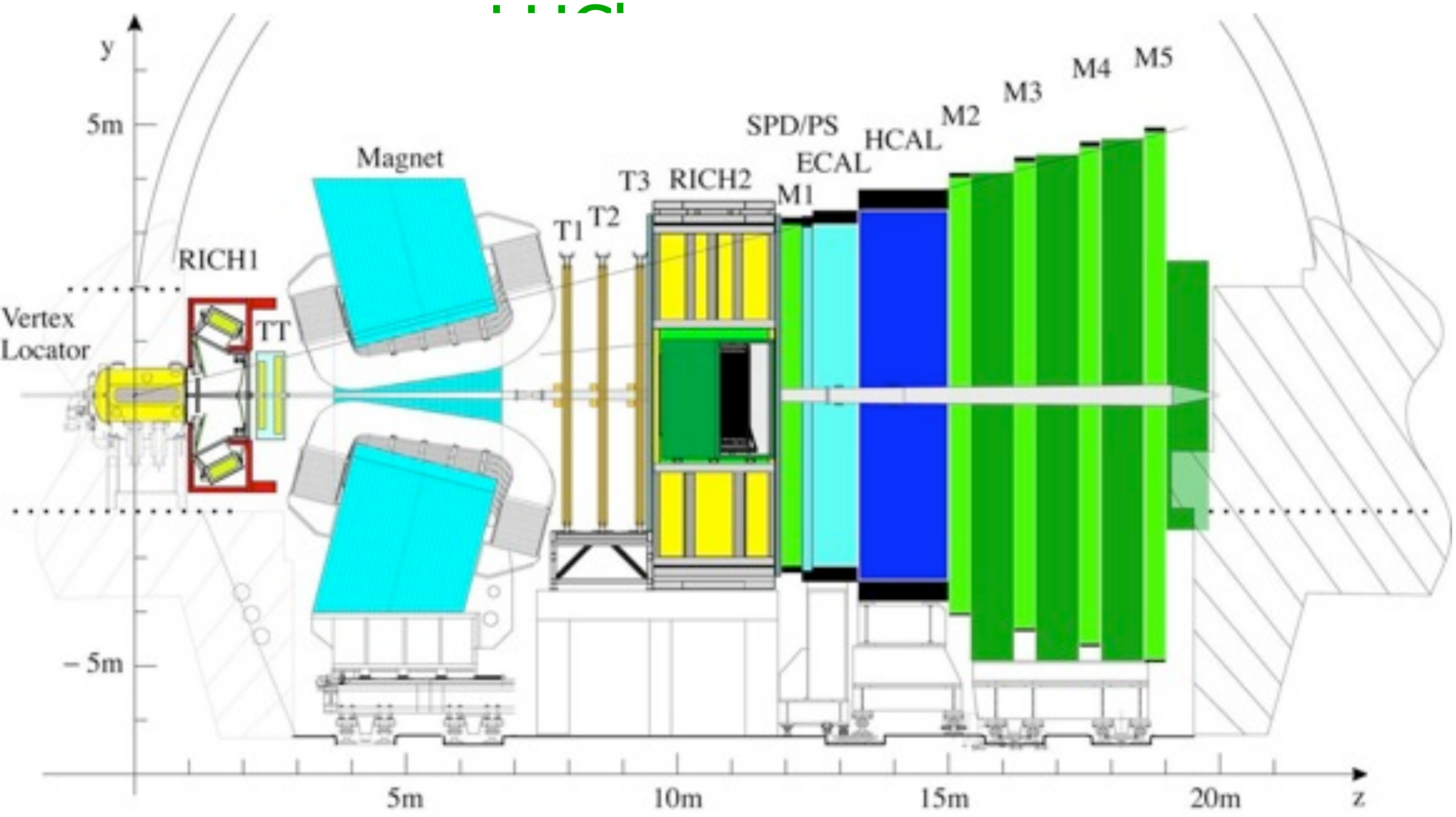


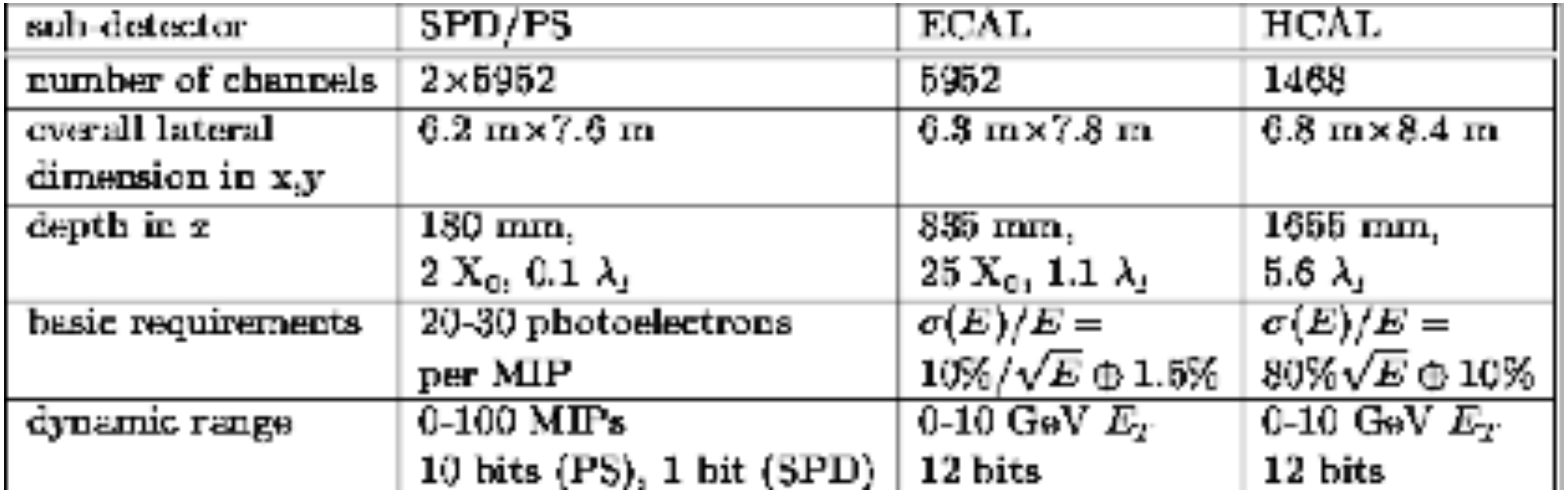
σ(E)/E (50 GeV) ~ 15 %


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

LHCb calorimeter

LHCb





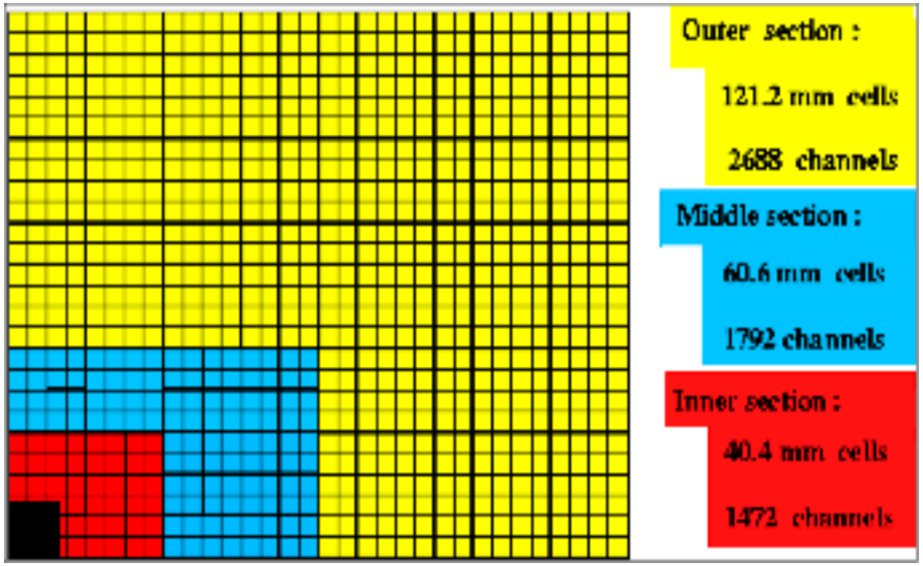
sub detector	SPD/PS	ECAL	HCAL
number of channels	2×5952	5952	1468
overall lateral dimension in x,y	6.2 m×7.6 m	6.3 m×7.8 m	6.8 m×8.4 m
depth in z	180 mm, 2 X_0, 0.1 λ_I	835 mm, 25 X_0, 1.1 λ_I	1655 mm, 5.6 λ_I
basic requirements	20-30 photoelectrons per MIP	$\sigma(E)/E =$ $10\%/\sqrt{E} \oplus 1.5\%$	$\sigma(E)/E =$ $80\%\sqrt{E} \oplus 10\%$
dynamic range	0-100 MIPs 10 bits (PS), 1 bit (SPD)	0-10 GeV E_T 12 bits	0-10 GeV E_T 12 bits

LHCb segmentation

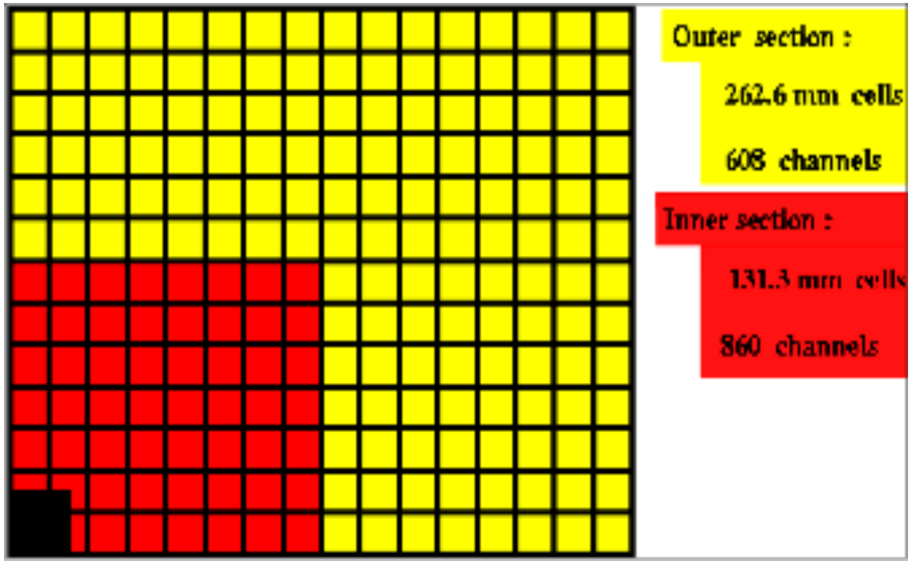
Lateral segmentation

(showing 1/4 of the detectors front face)

ECAL (SPD/PS)

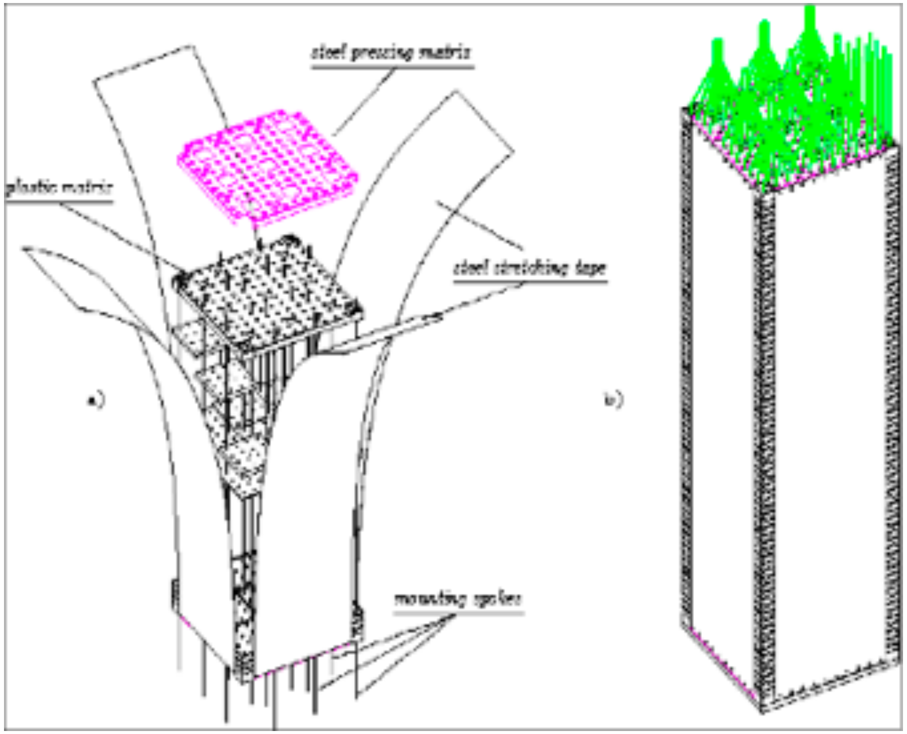


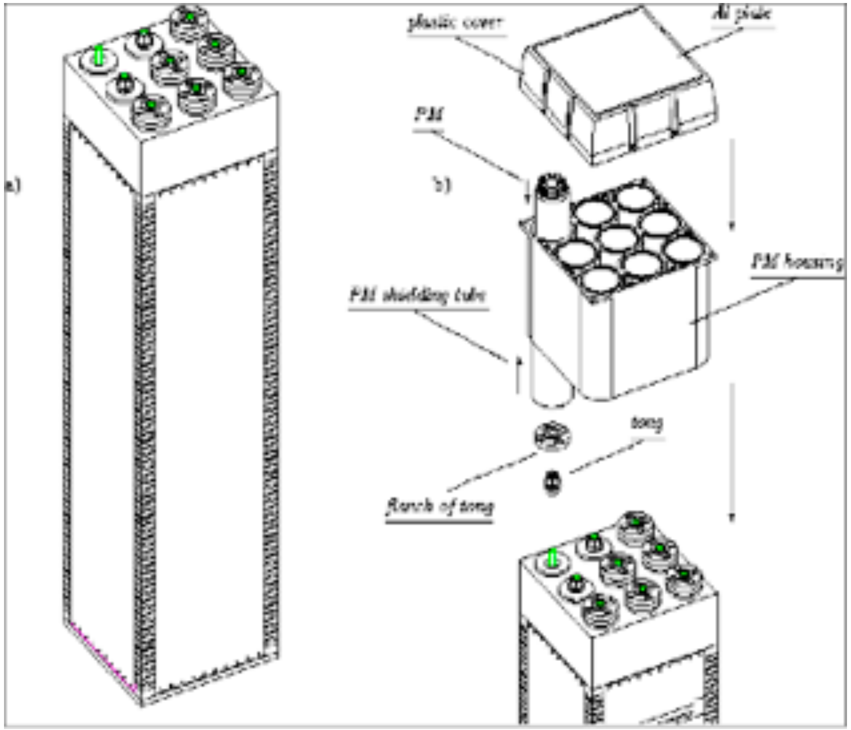
HCAL



Module structure: Pb/Scintillator

Engineering design and assembly of modules:

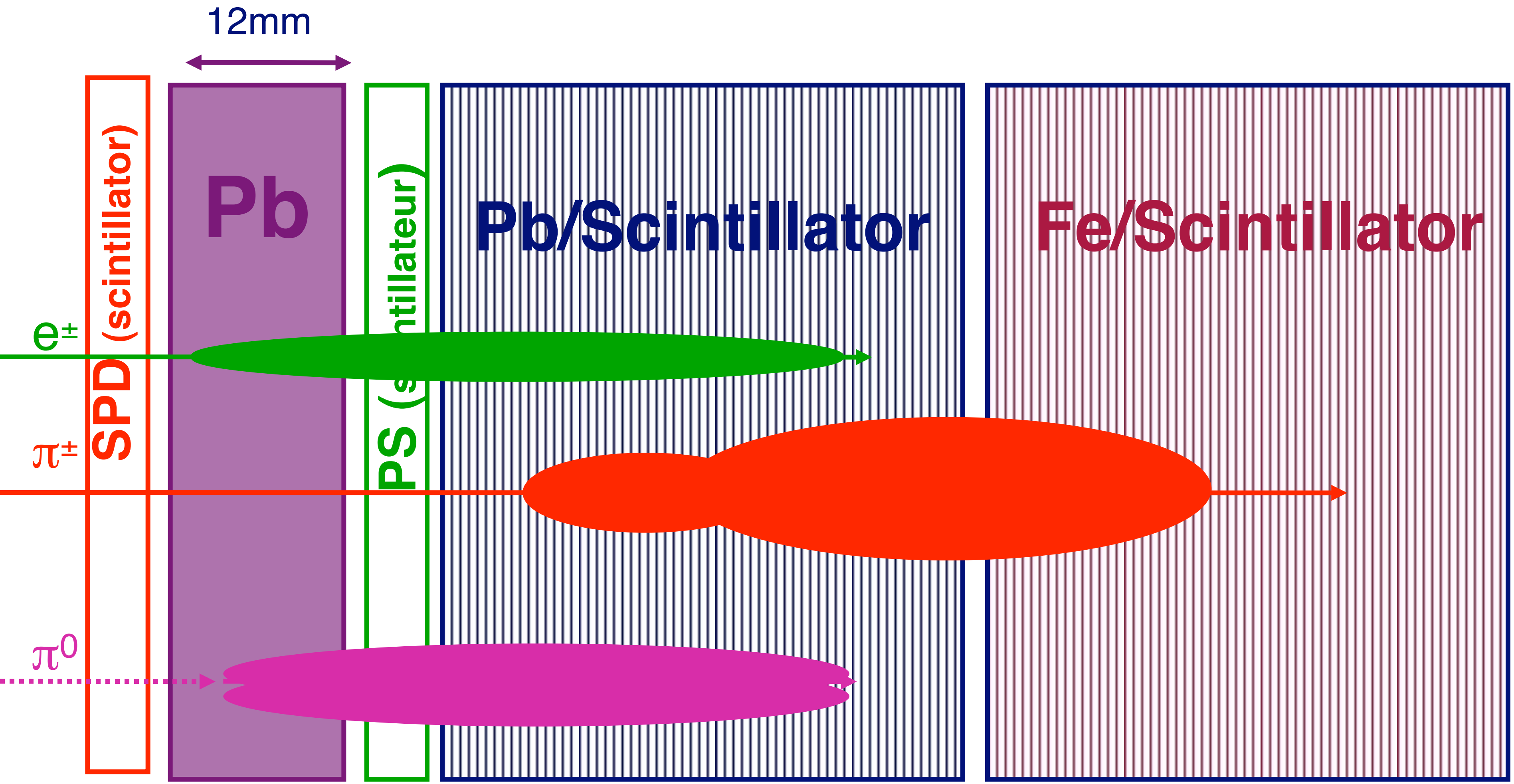




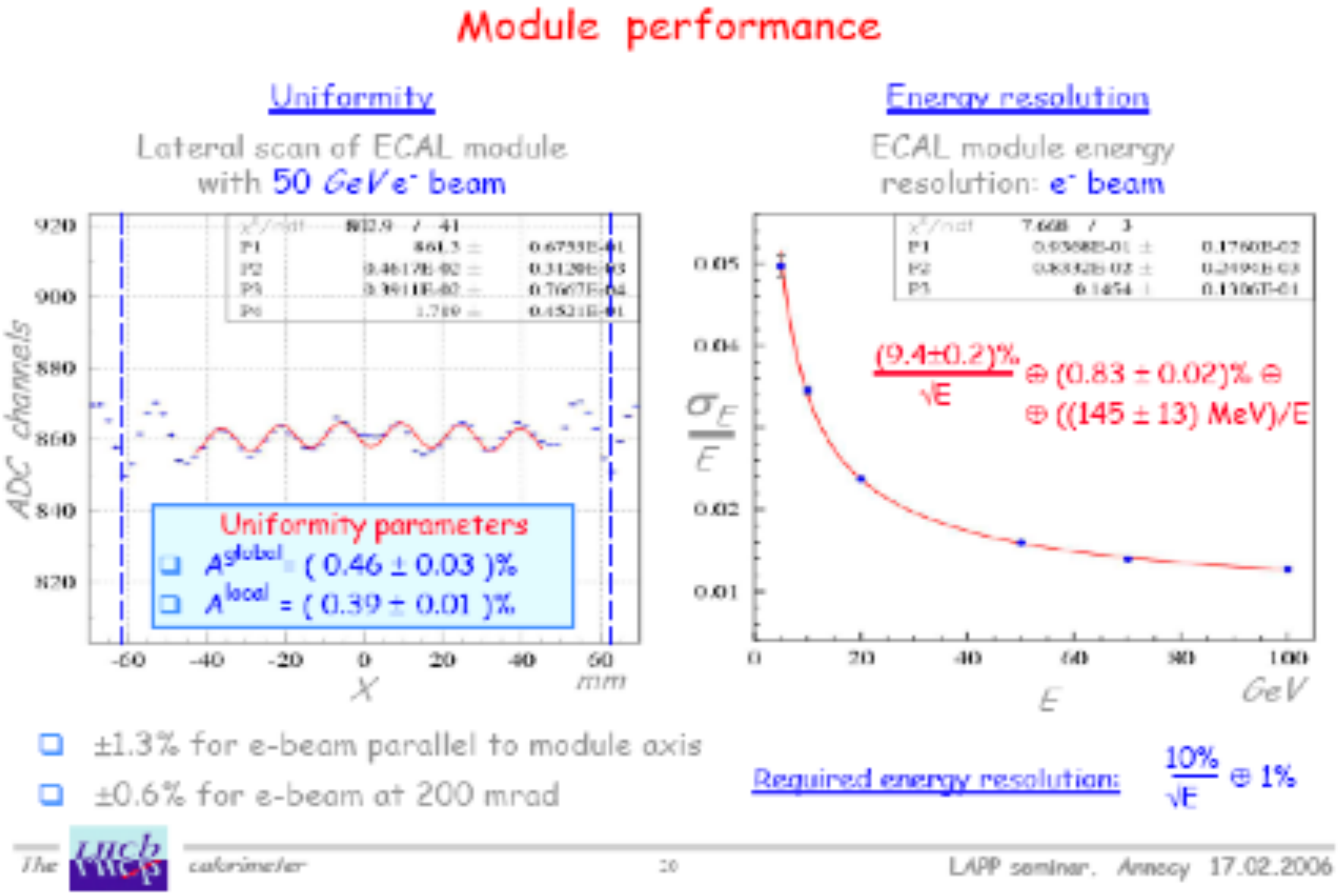
Weight of one module ~28 kg

Assembly of scintillator, lead, fibers and the readout part for inner section modules

Shower identification of triggering



Module performance (testbeam)



Module performance

Uniformity

Lateral scan of ECAL module with 50 $GeV\ e^-$ beam

Uniformity parameters

- ☐ A^{global} = (0.46 ± 0.03)%
- ☐ A^{local} = (0.39 ± 0.01)%

Energy resolution

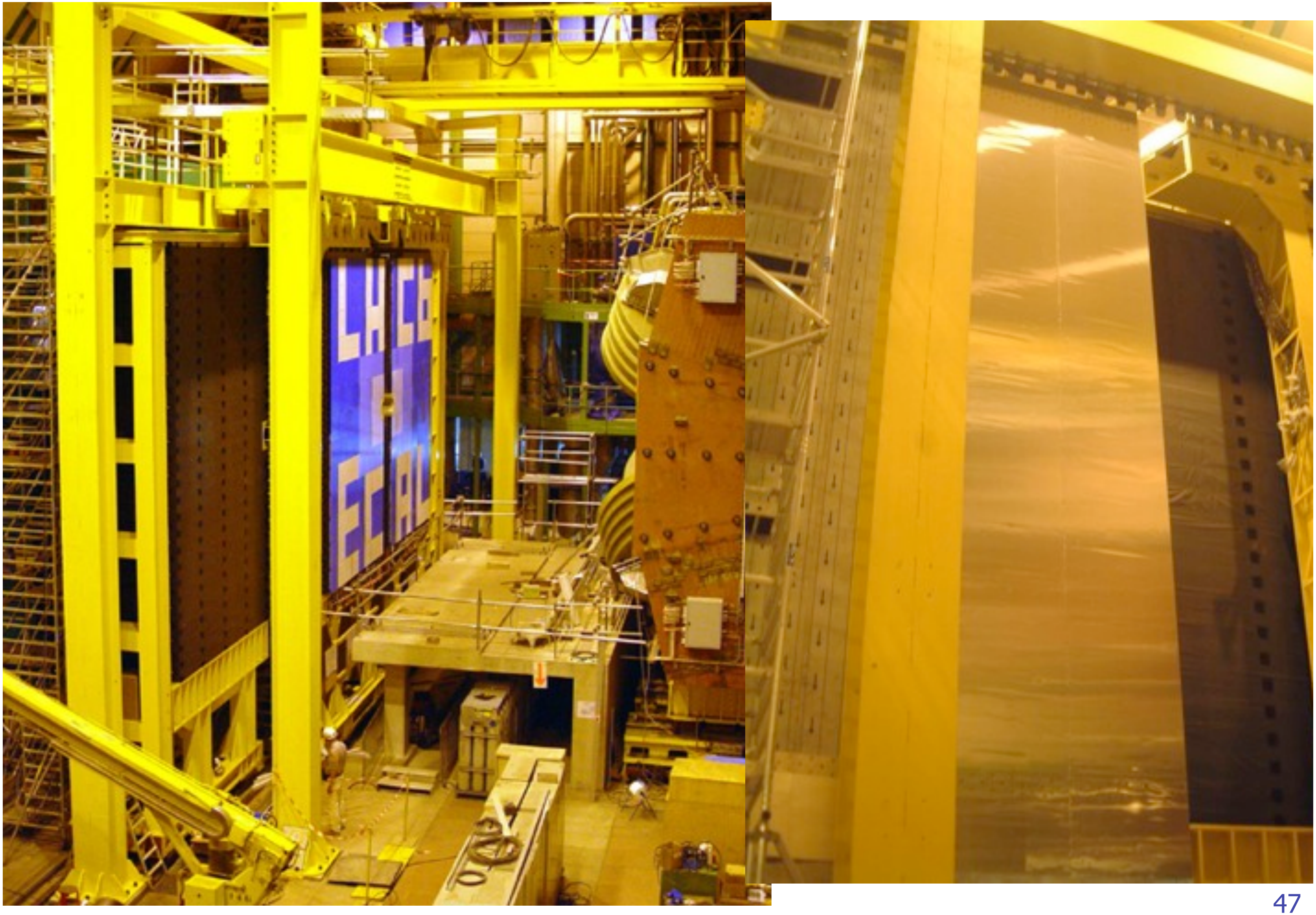
ECAL module energy resolution: e^- beam

$$\frac{(9.4 \pm 0.2)\%}{\sqrt{E}} \oplus (0.83 \pm 0.02)\% \oplus ((145 \pm 13)\ \mathrm{MeV})/E$$

- ☐ ±1.3% for e-beam parallel to module axis
- ☐ ±0.6% for e-beam at 200 mrad

Required energy resolution: $\frac{10\%}{\sqrt{E}} \oplus 1\%$

The LHCb calorimeter 20 LAPP seminar, Annecy 17.02.2006


LHCb
ECAL

ALICE calorimeter

ALICE Detector

Complete since 2008:

ITS, TPC, TOF, HMPID,
FMD, T0, V0, ZDC,
Muon arm, Acorde
PMD , DAQ

Partial installation (2010):

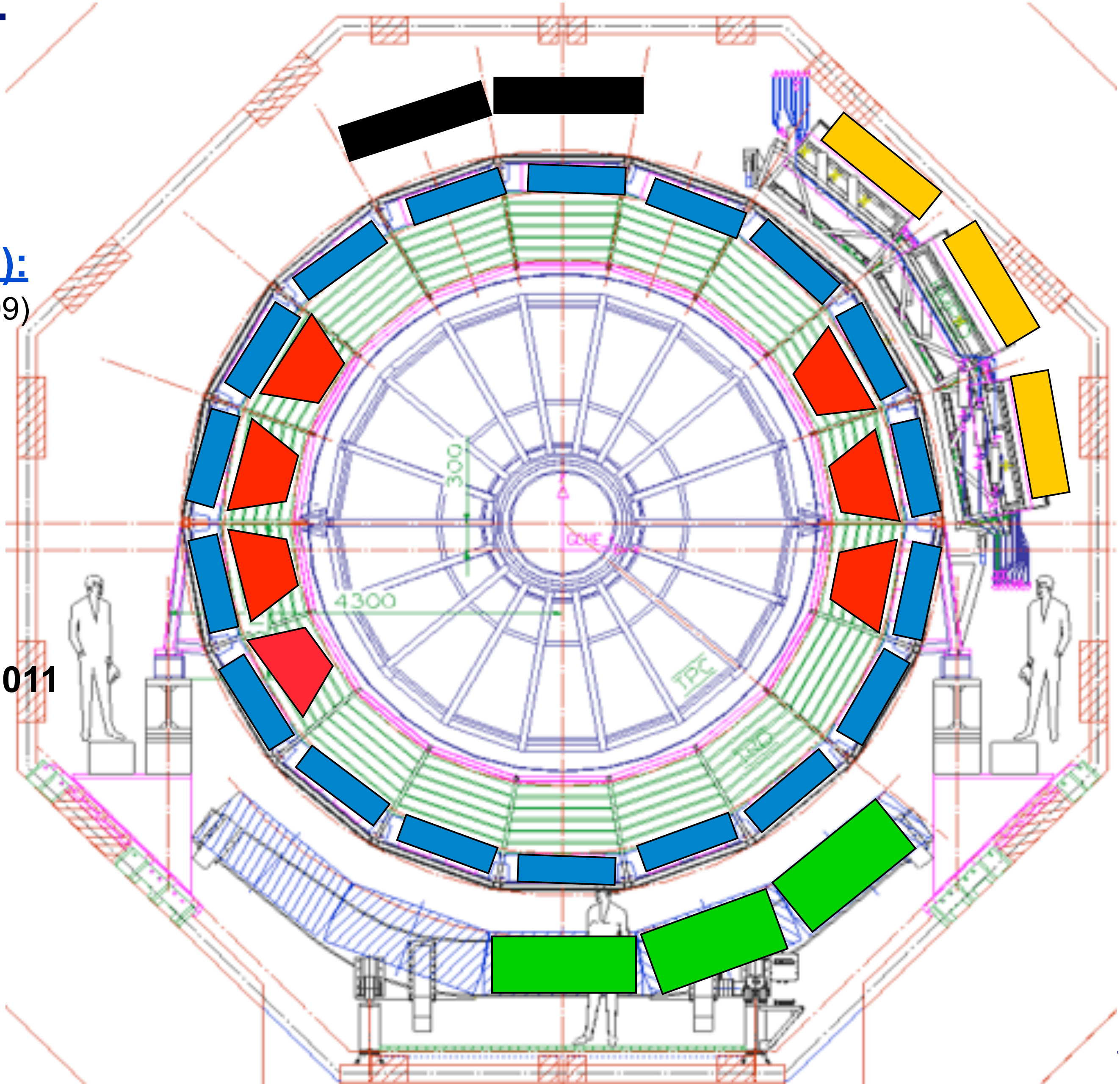
4/10 **EMCAL*** (approved 2009)
7/18 **TRD*** (approved 2002)
3/5 **PHOS** (funding)

~ 60% **HLT** **(High Level Trigger)**

2011

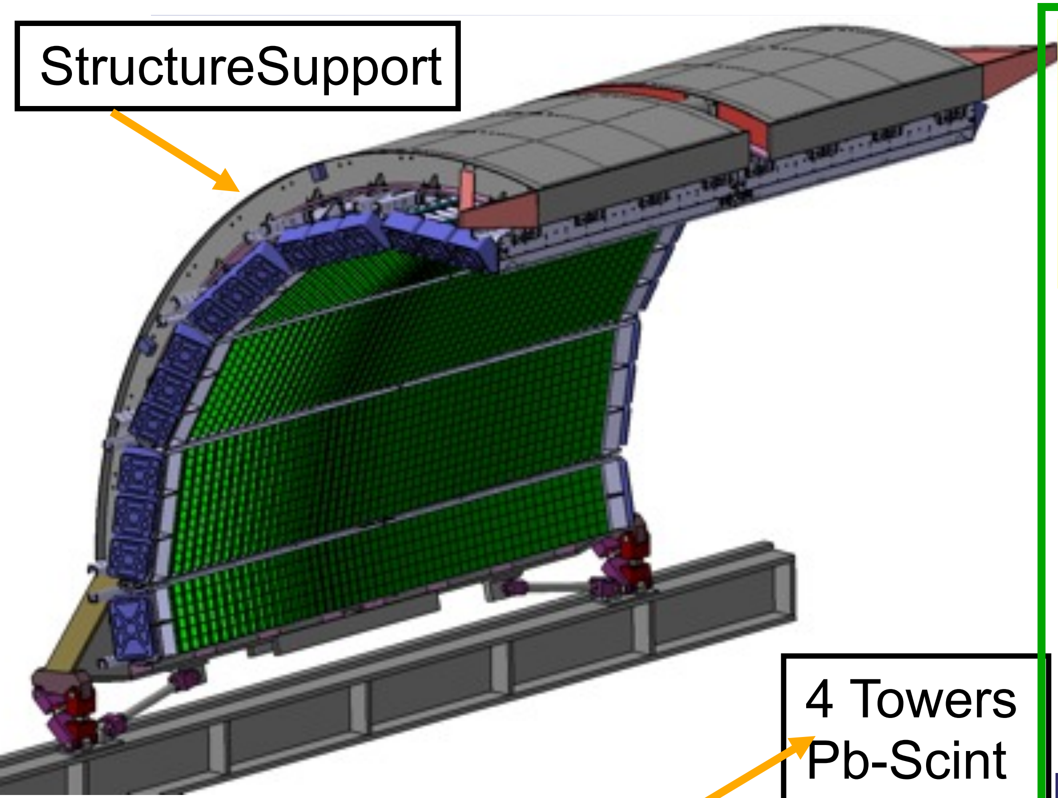
10/10 **EMCAL**
10/18 **TRD**

TRD to be completed end 2011



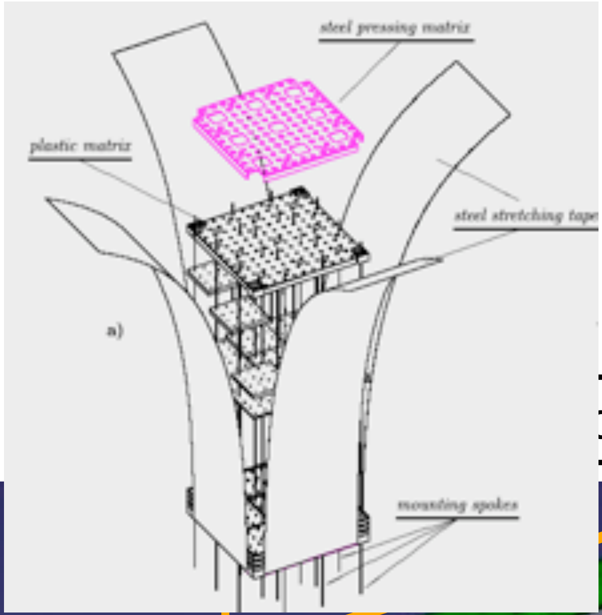
Elements of the ALICE calorimeter

StructureSupport



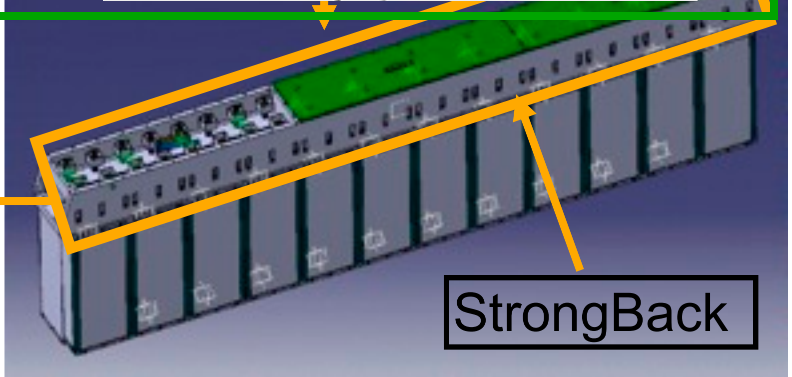
Sampling calorimeter (20 X_0)

- 1 module = 4 towers ($\Delta\eta\Delta\phi \sim 0.014 \times 0.014$)
- 1 towers = 77 layers of 1.76 mm scint./ 1.44 mm Pb



4 Towers
Pb-Scint

12 Modules



dules

StrongBack

Dual readout for hadronic showers DREAM

Intermezzo: DREAM (ongoing R&D)

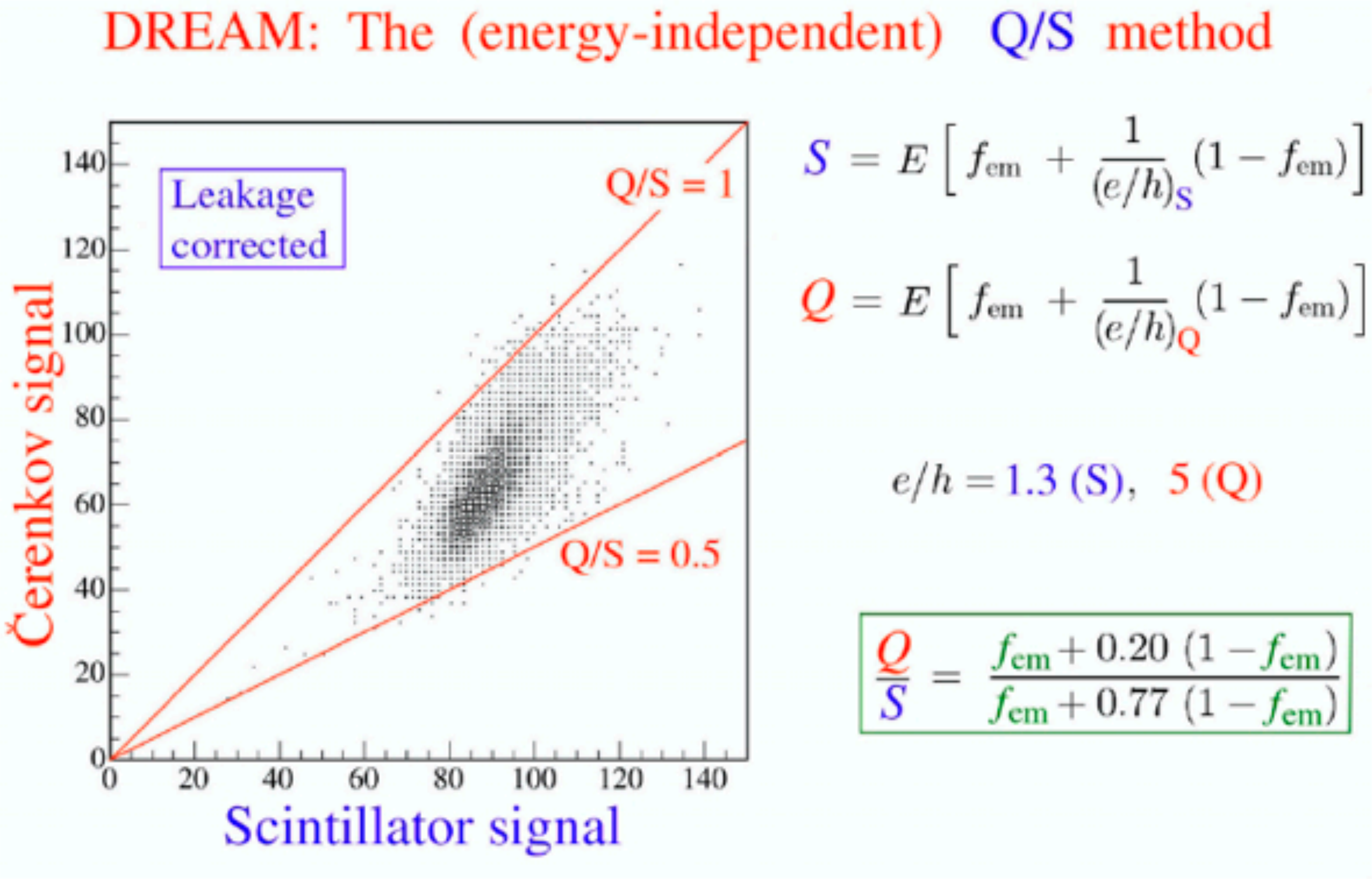
DREAM: Structure

- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

Scintillator sensitive
to visible energy only

Quartz sensitive
to em only
(Cerenkov light)

DREAM: The principle



DREAM: The (energy-independent) Q/S method

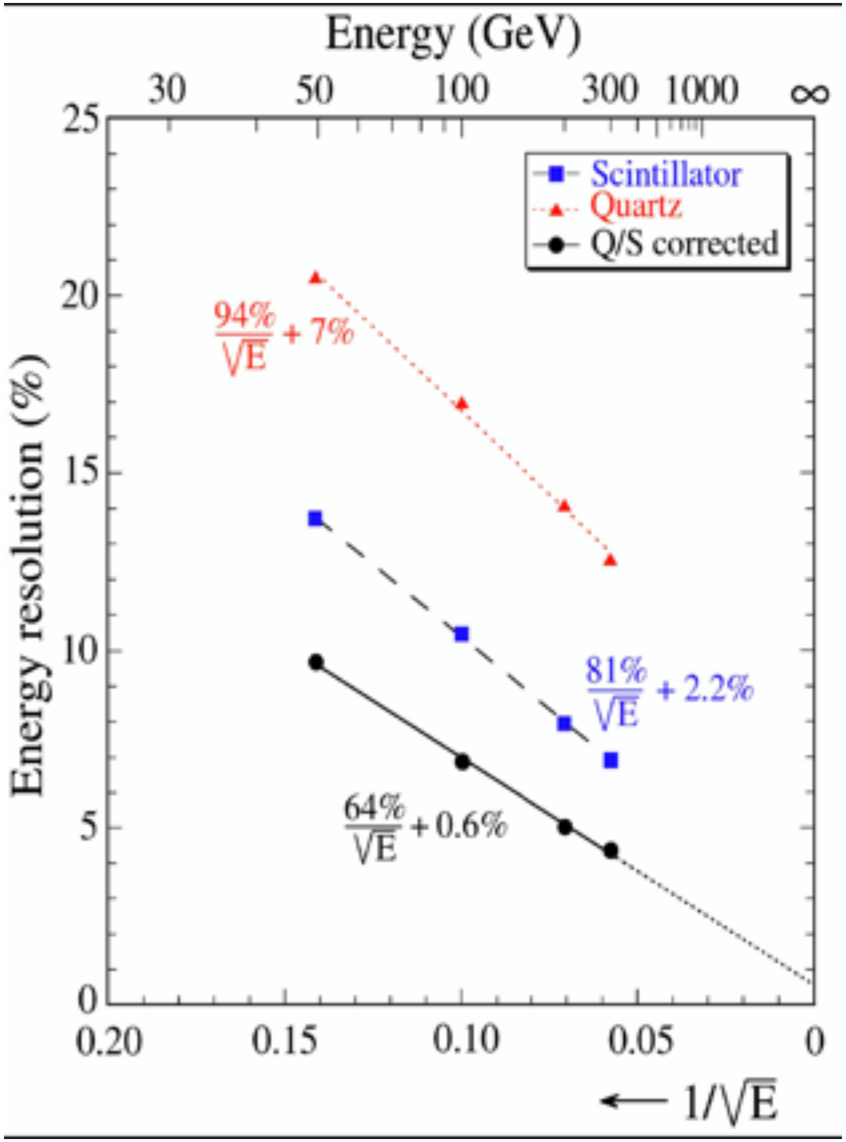
$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

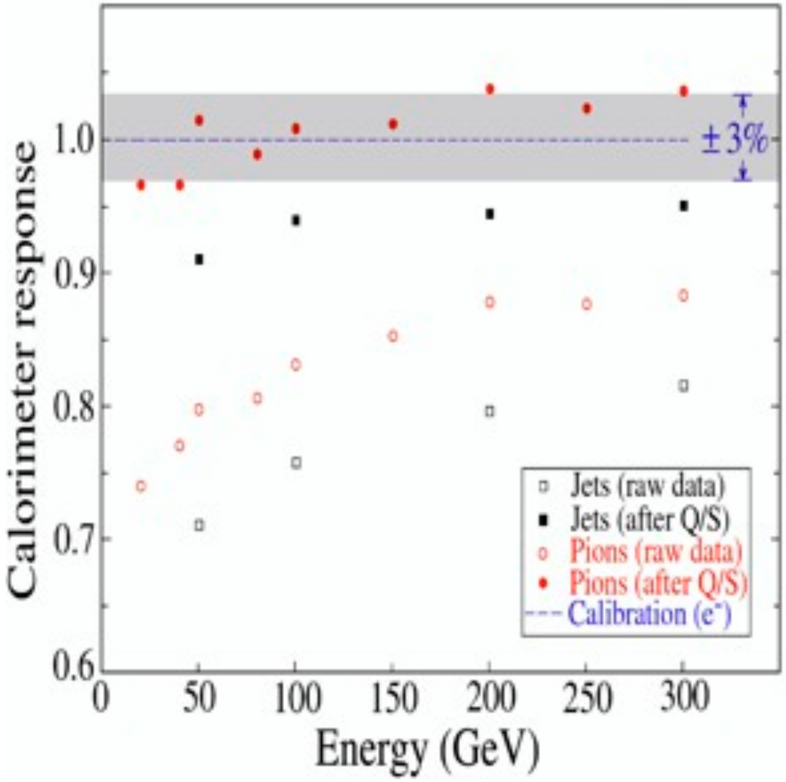
$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

$e/h = 1.3$ (S), 5 (Q)

$$\boxed{\frac{Q}{S} = \frac{f_{em} + 0.20\ (1 - f_{em})}{f_{em} + 0.77\ (1 - f_{em})}}$$

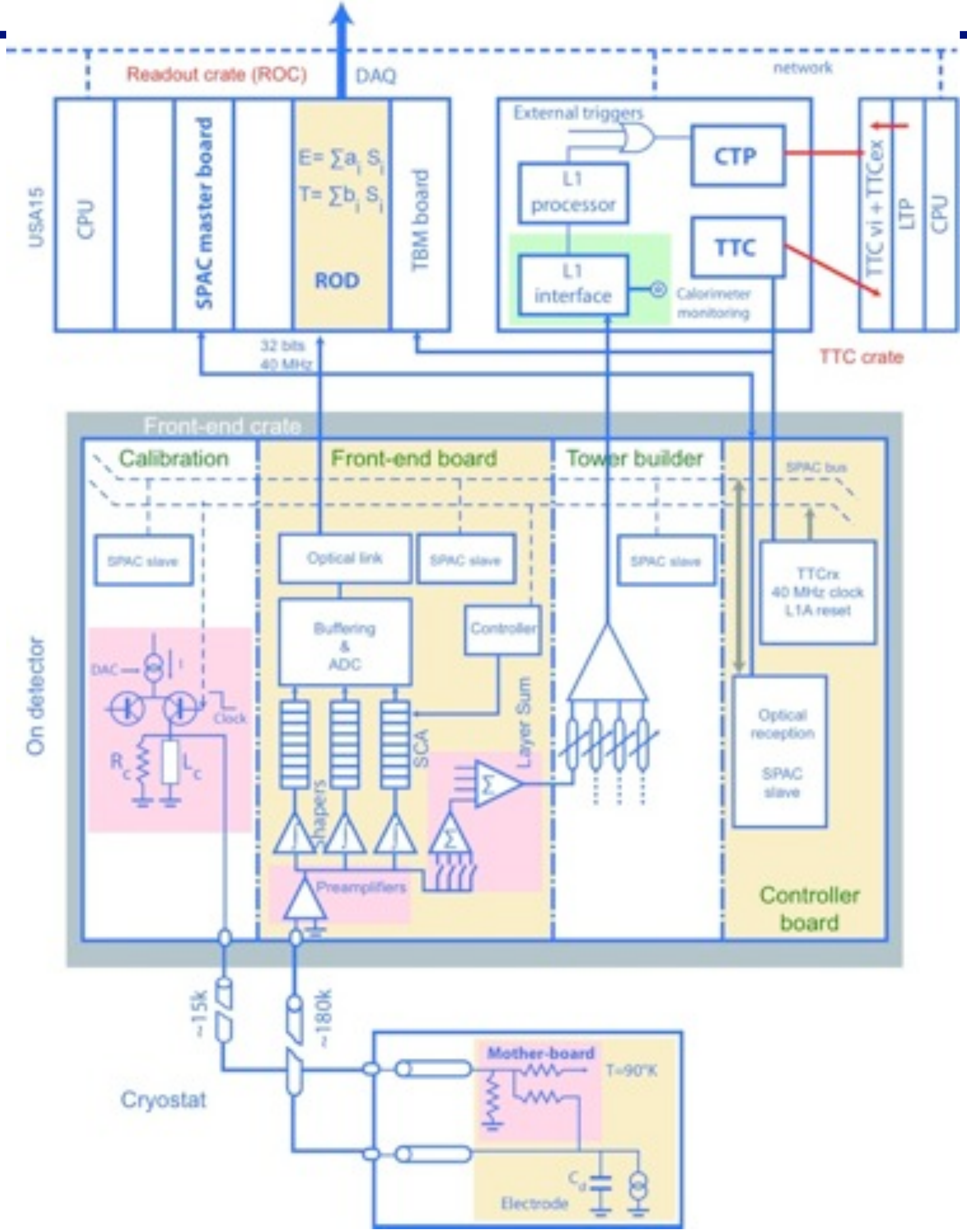
DREAM: some results





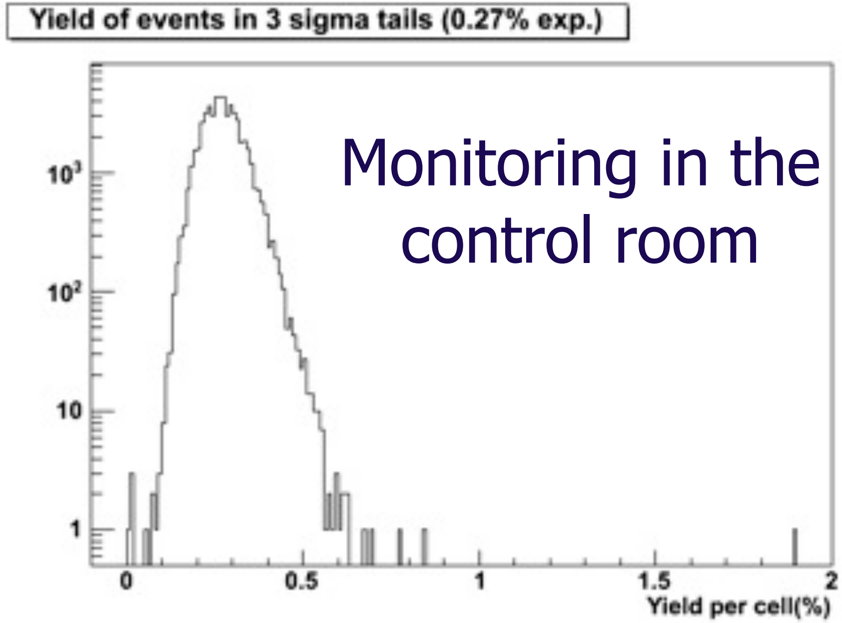
Back to LHC: Taking data

Signal Readout: ATLAS LAr example



In the cavern

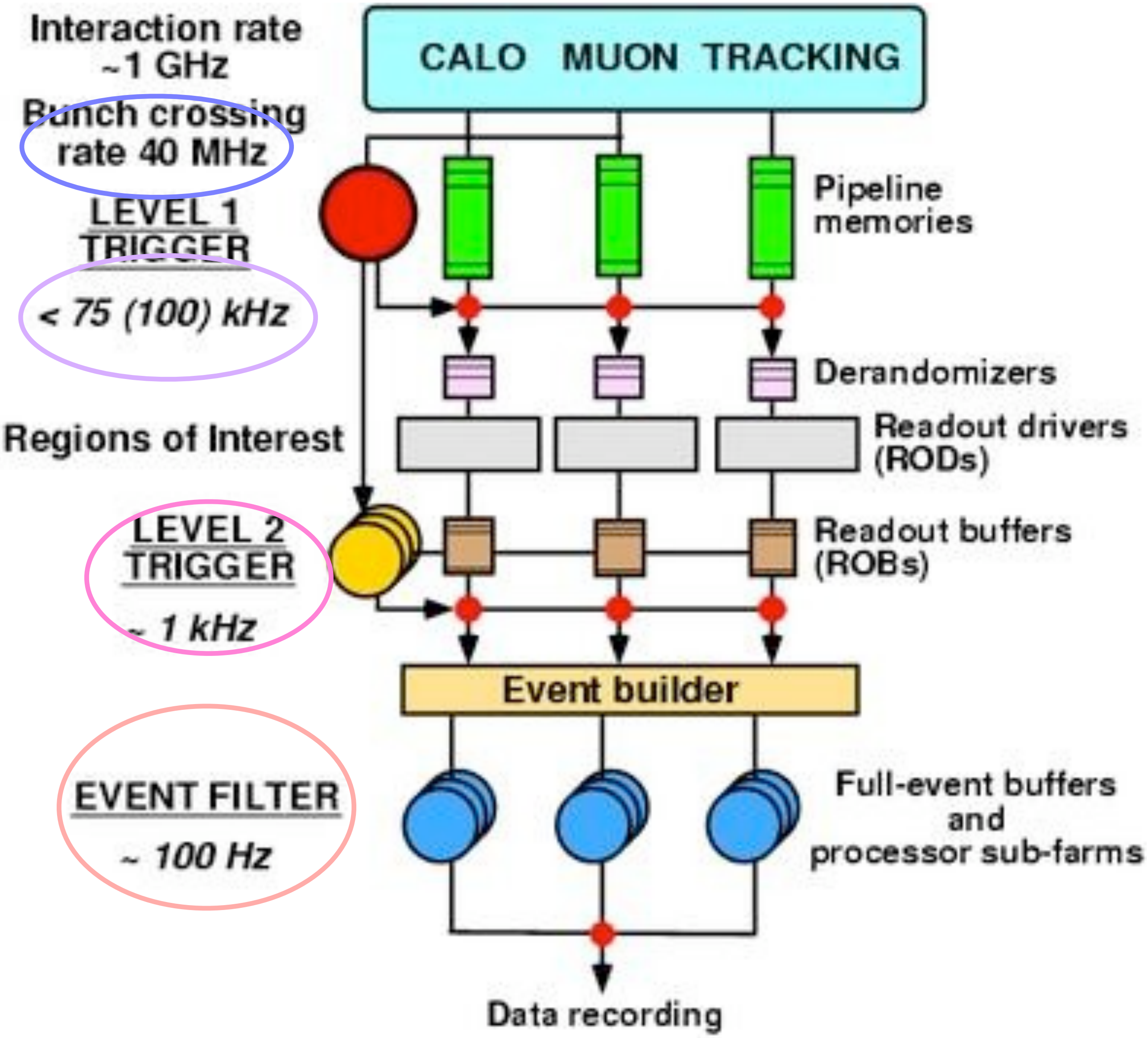
In the counting room



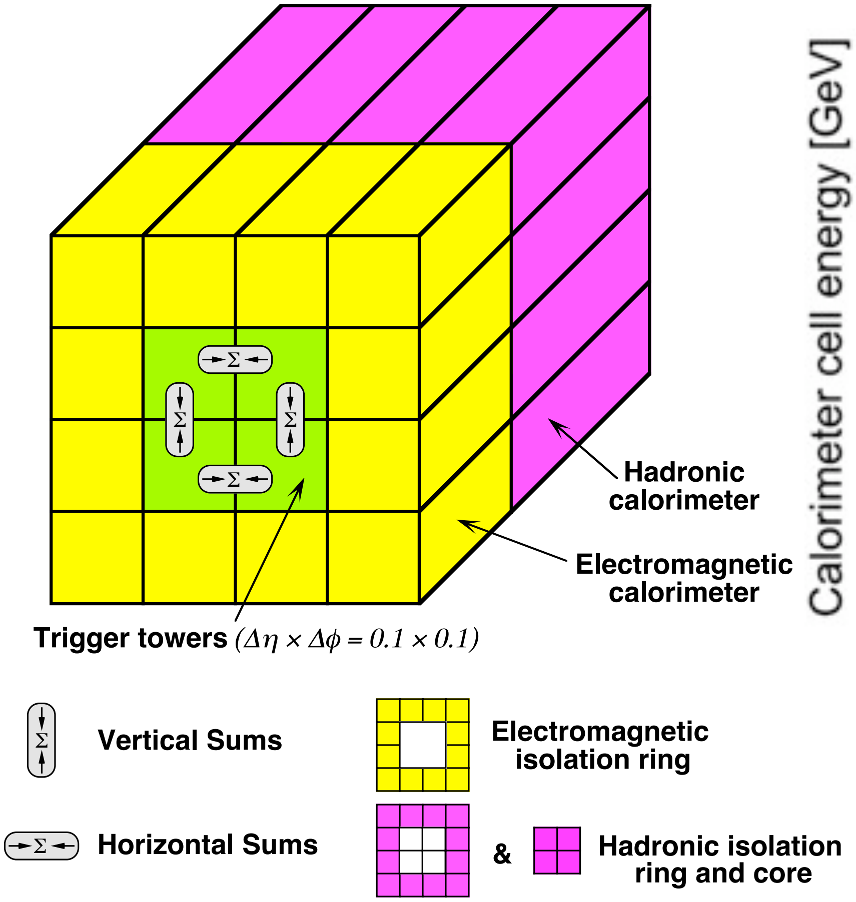
Monitoring in the control room

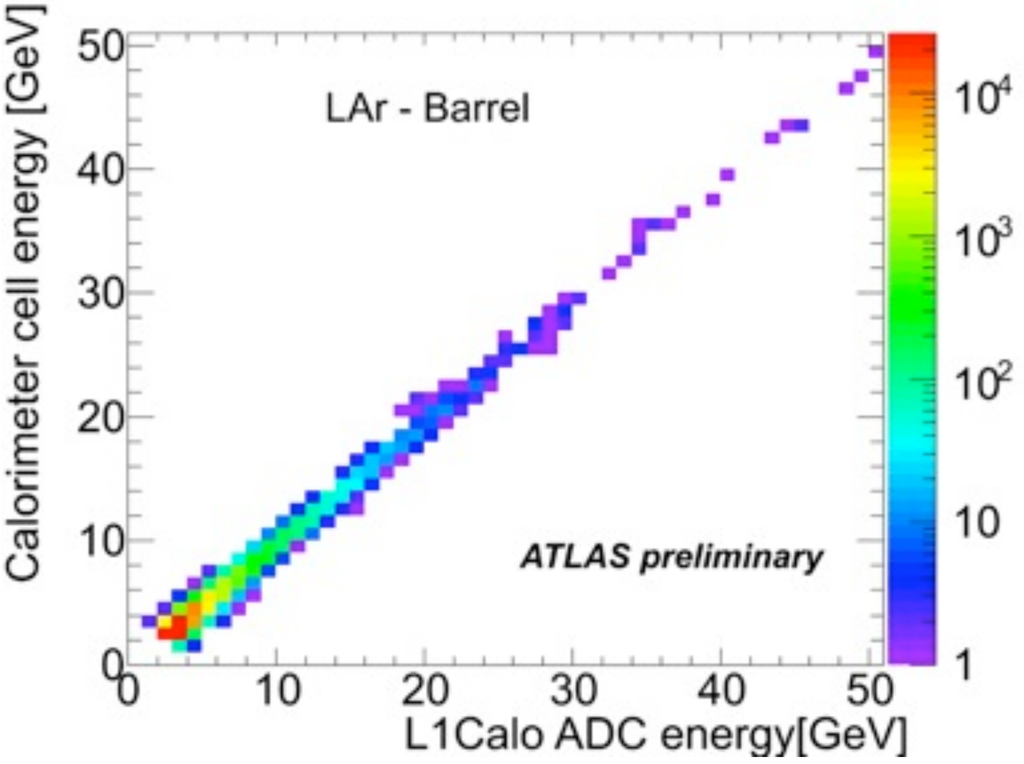
Trigger

ATLAS Trigger chain

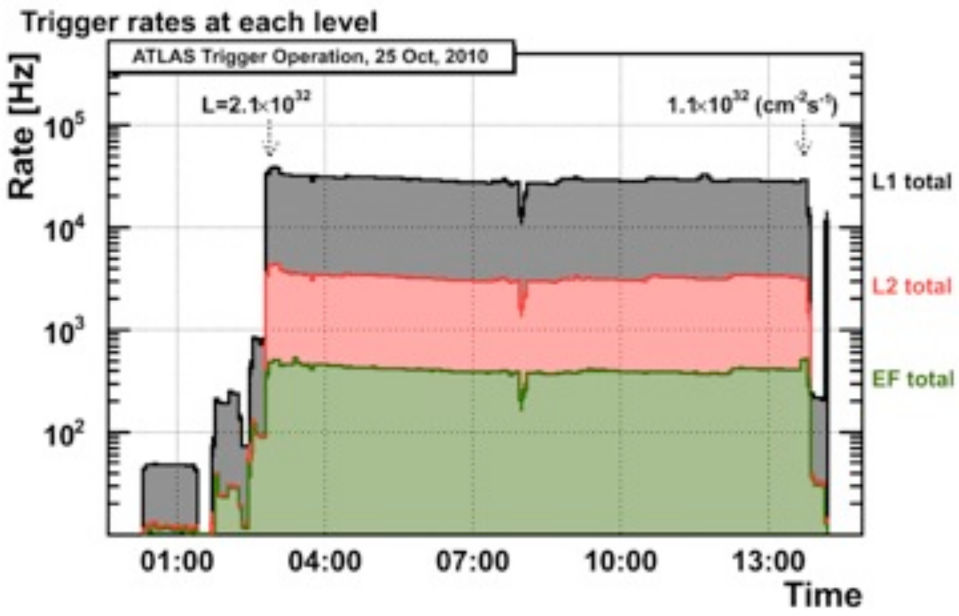


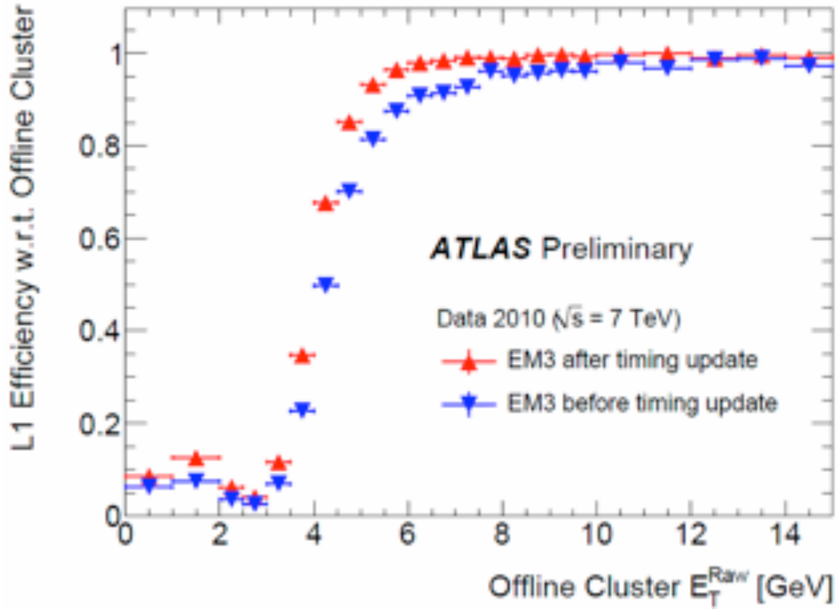
Level 1 calorimeter trigger





Calorimeter Trigger Efficiency

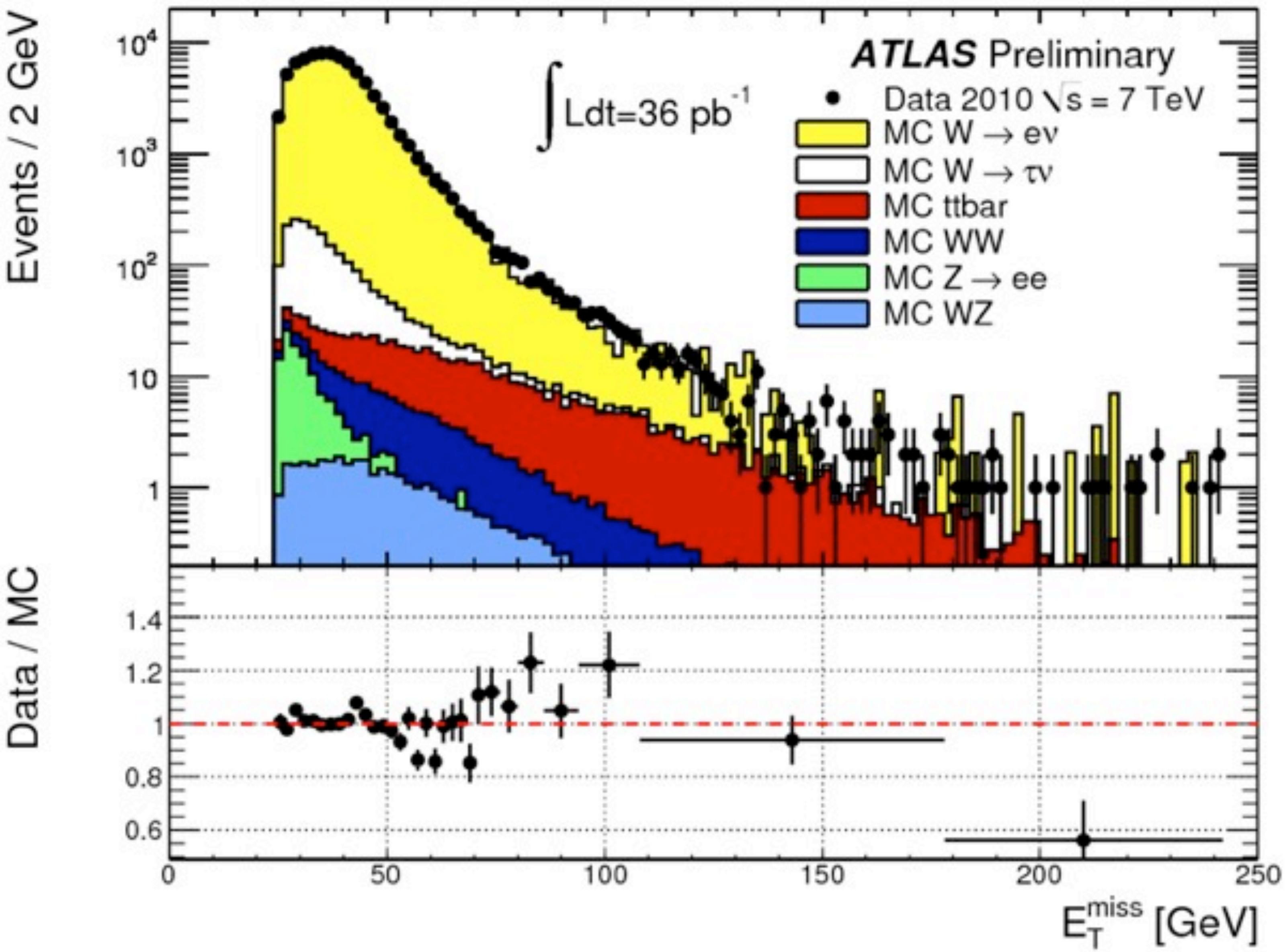




Trigger performance and “menus” are a key element towards physics results

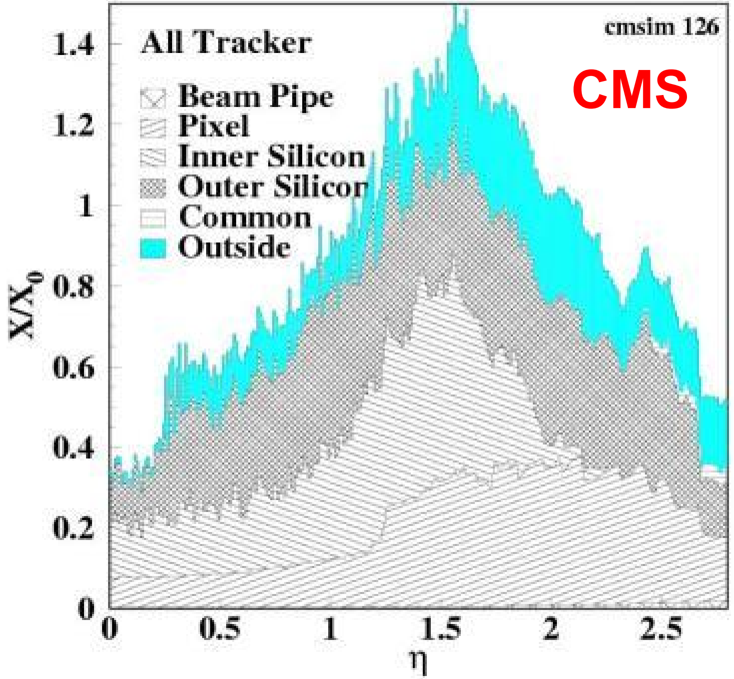
- Balance between the various channels are regularly adjusted vs instantaneous luminosity
- For calorimetry:
  - Get calibrated energy for L1
  - Use “final” energy calibration (à la offline) for HLT

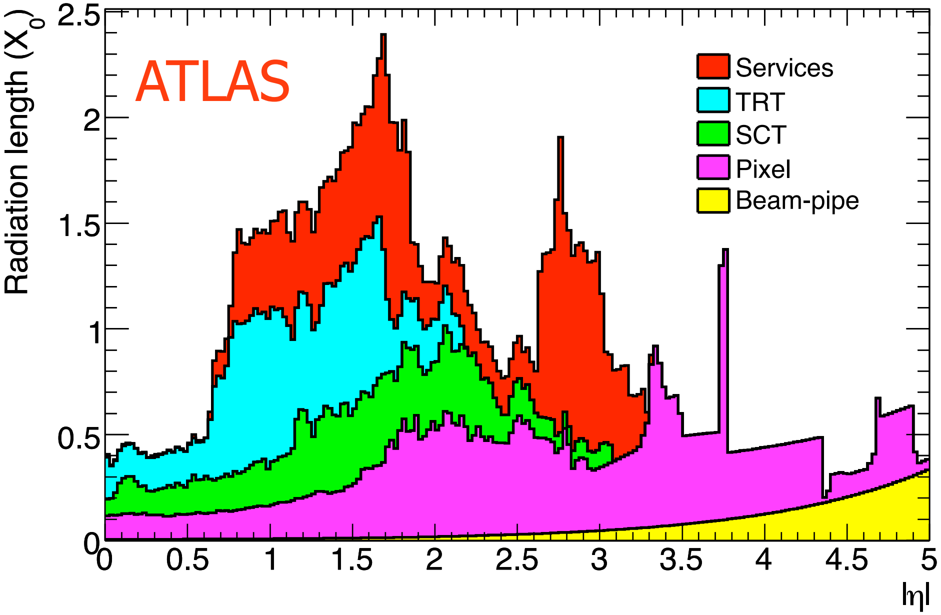
ATLAS E_T^{miss} calibration



Calorimeters: behind the Inner Detector

Material in front of calorimeters



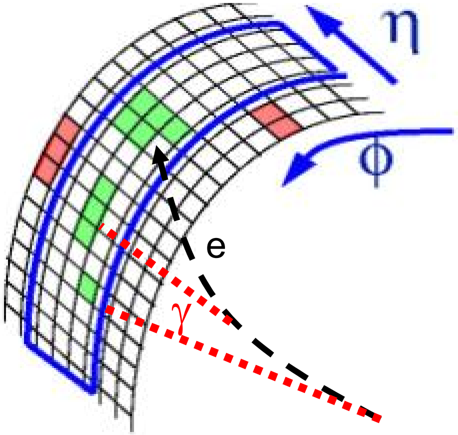


Electron Brem

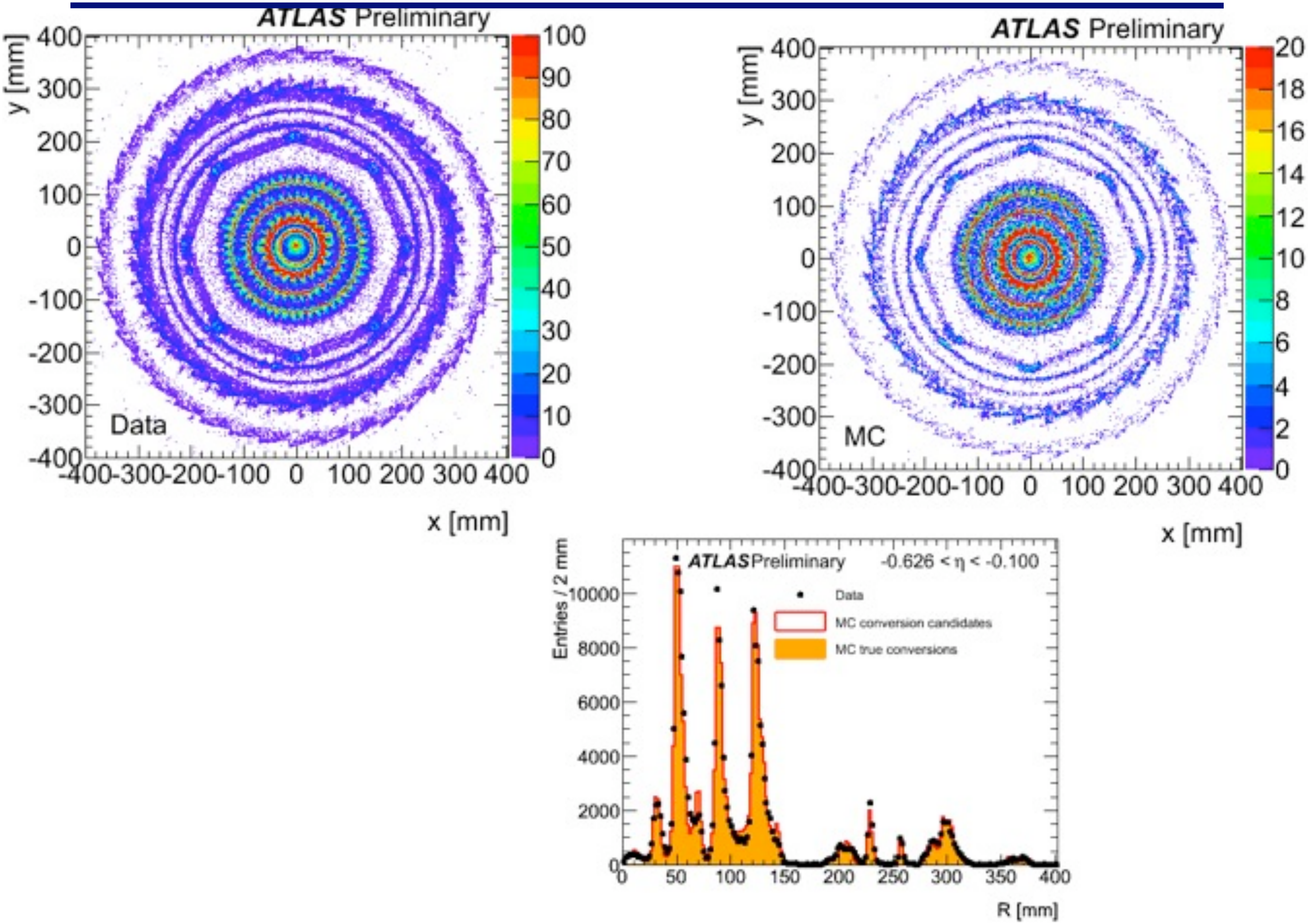
Photon conversions

Proper description of material (ID weighting during construction)

Taken into account for event reconstruction



Understanding material in front of calorimeter



Calorimeters R&D for Linear Colliders

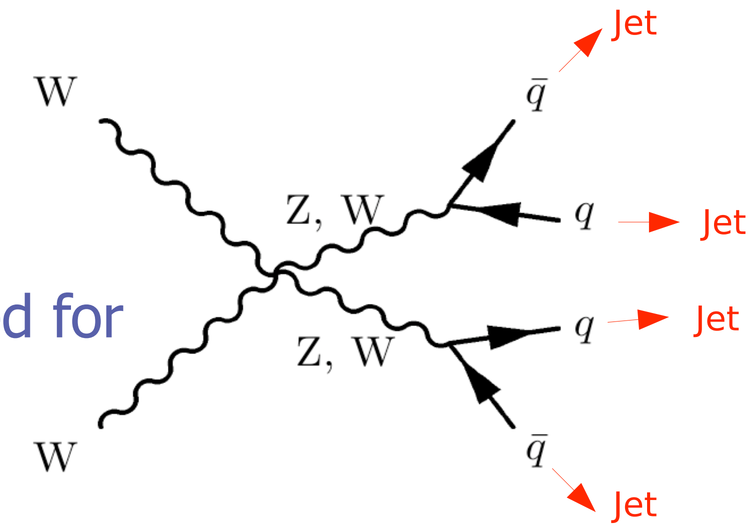
Some ideas for future calorimeters (Linear Colliders)

Boson-Boson scattering

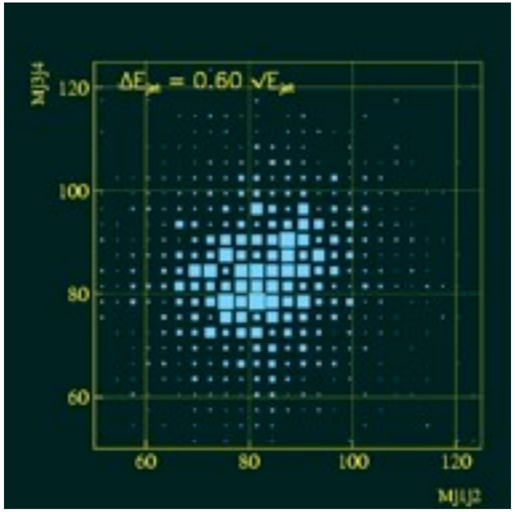
- Hadronic Decay of W & Z

Needs improved energy resolution

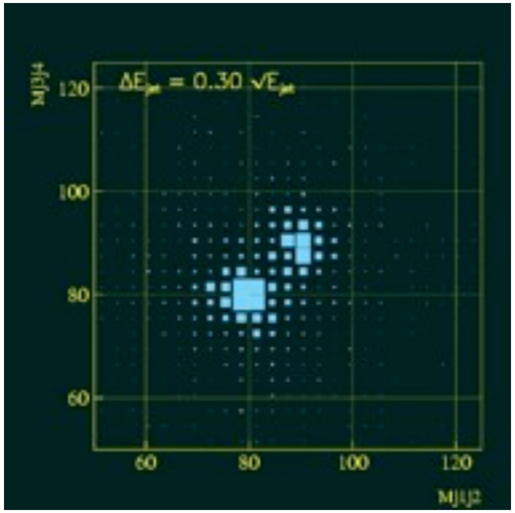
- Higly granular calorimeters optimized for particle flow



$\Delta(M_Z,M_W) \sim 10$ GeV



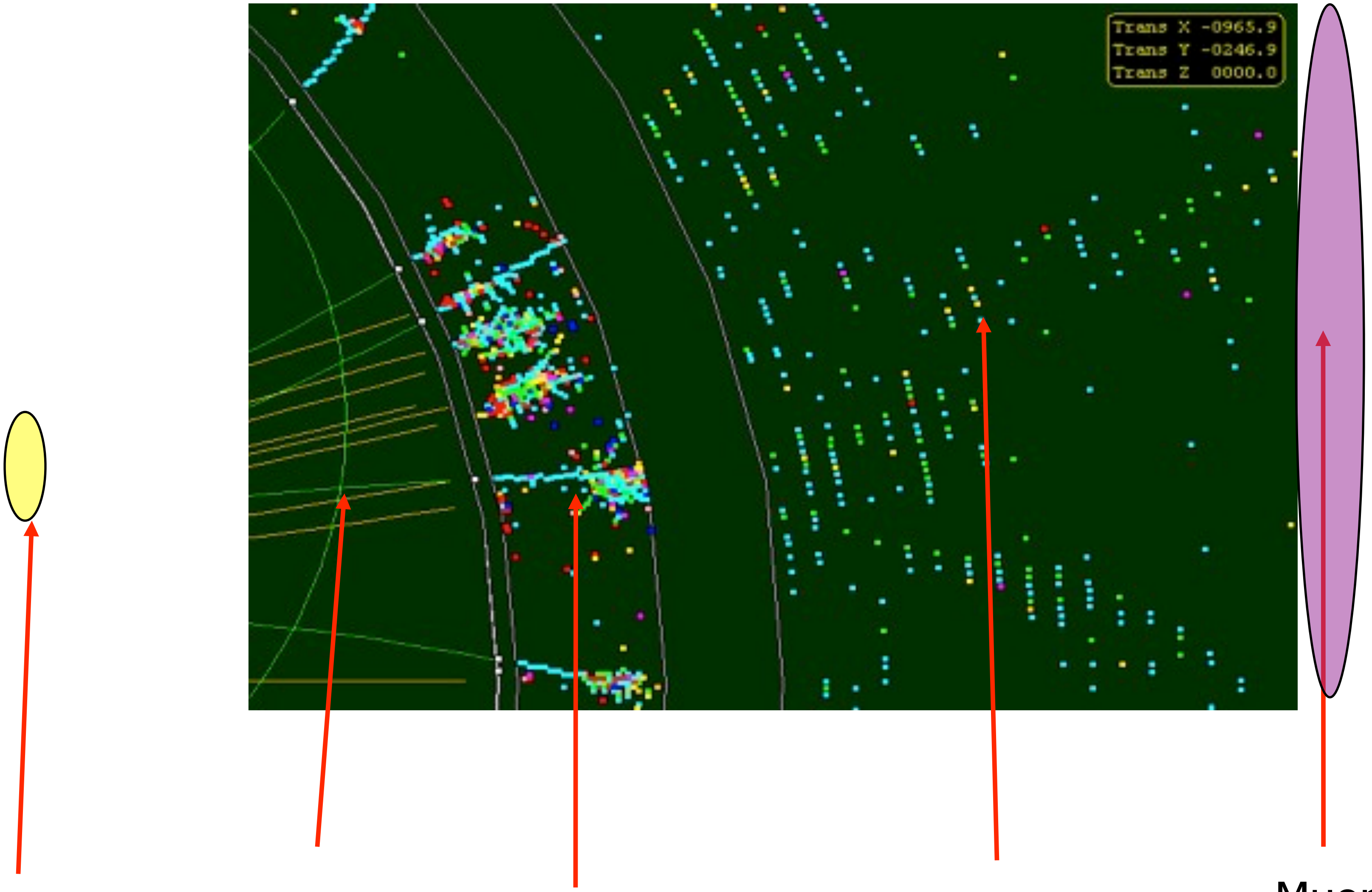
60%/√E



30%/√E

c.f. R. Pöschl for the CALICE collaboration - SPSC January 2011

Calorimeters developed for Linear colliders



VXD
tag b,c
jets

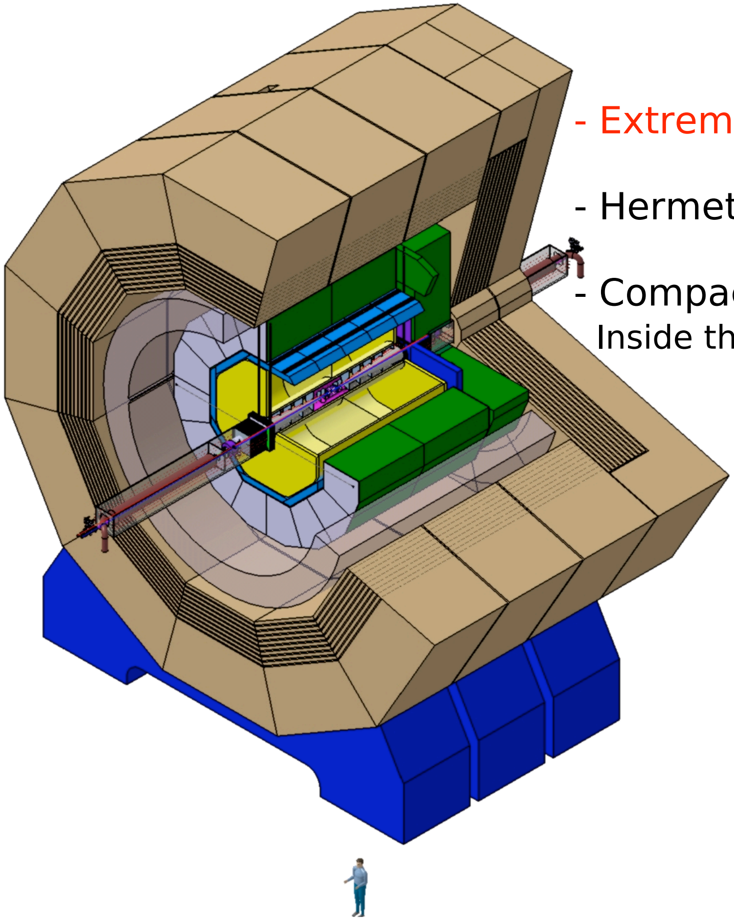
Tracking
system

EM Cal

HAD Cal

Muon
system

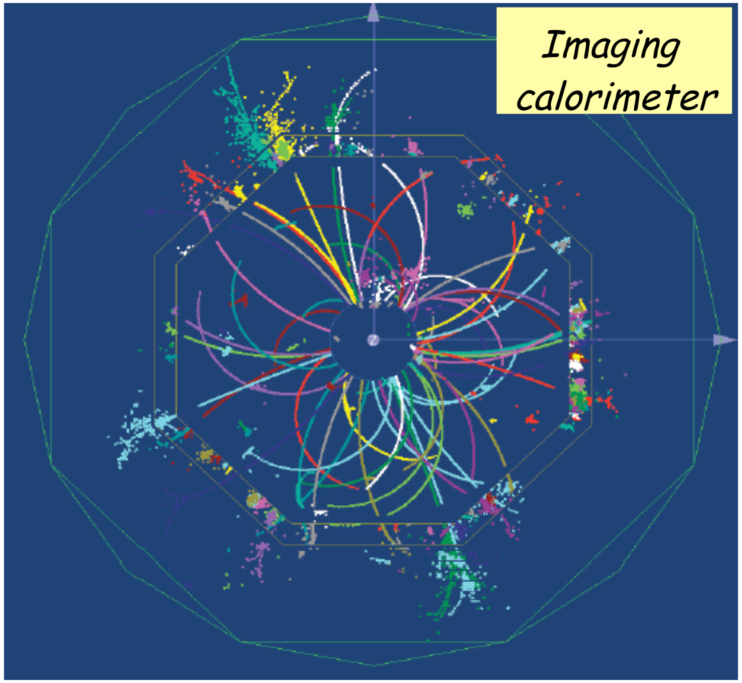
Calorimeter requirements



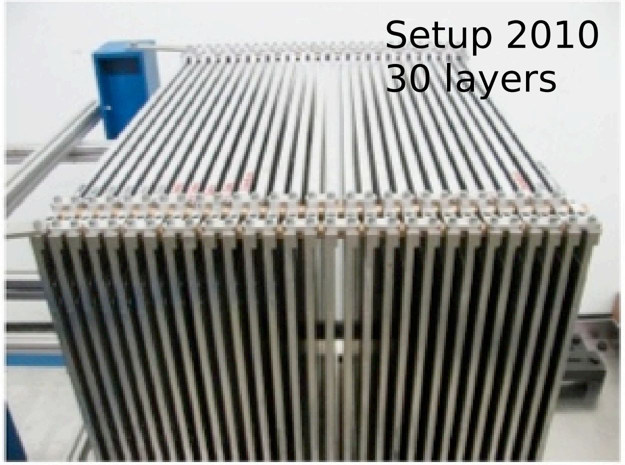
- Extreme high granularity

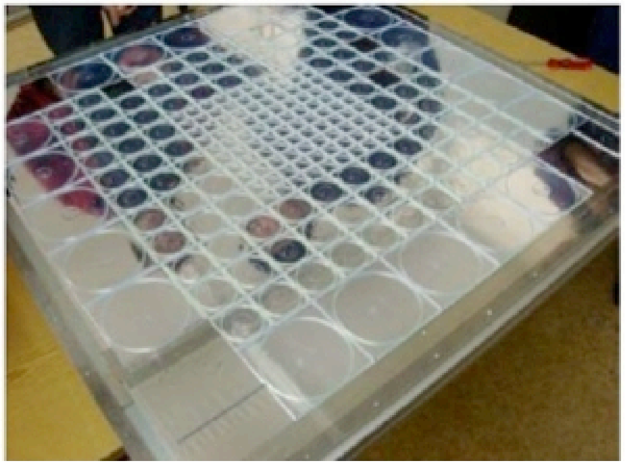
- Hermetic

- Compact
  Inside the coil of the solenoid



Many ongoing testbeams (e.g. CALICE)





Linear Collider Calorimeters Development:

- Fine segmentation (also for HAD)
  - Both longitudinal and lateral
- Self-suporting calorimeter
  - Minimize dead zones
- Semi-digital readout
  - Electronics embedded inside the calorimeter
  - Development of Power Pulsing

Example: DHCAL

Some conclusions

Calorimeters are playing a critical role in the interpretation of events at LHC

- Electron/Photon - Jet - E_T^{miss} reconstruction
- Background rejection $e^{\pm}$/jets - γ/π^0
- Triggering

Detector design & construction have (obviously) a direct impact onto the physics

- Cell segmentation 0.1x0.1 at Tevatron, 0.025(0.003)x0.025 at LHC, semi-digital R/O for Linear Collider
- More and more precise simulation (interaction with matter, detector geometry) allows to understand quickly and very efficiently the detector performance

LHC detectors and calorimeters in particular are performing already very close to designed specifications