The 2009 Europhysics Conference on High Energy Physics,
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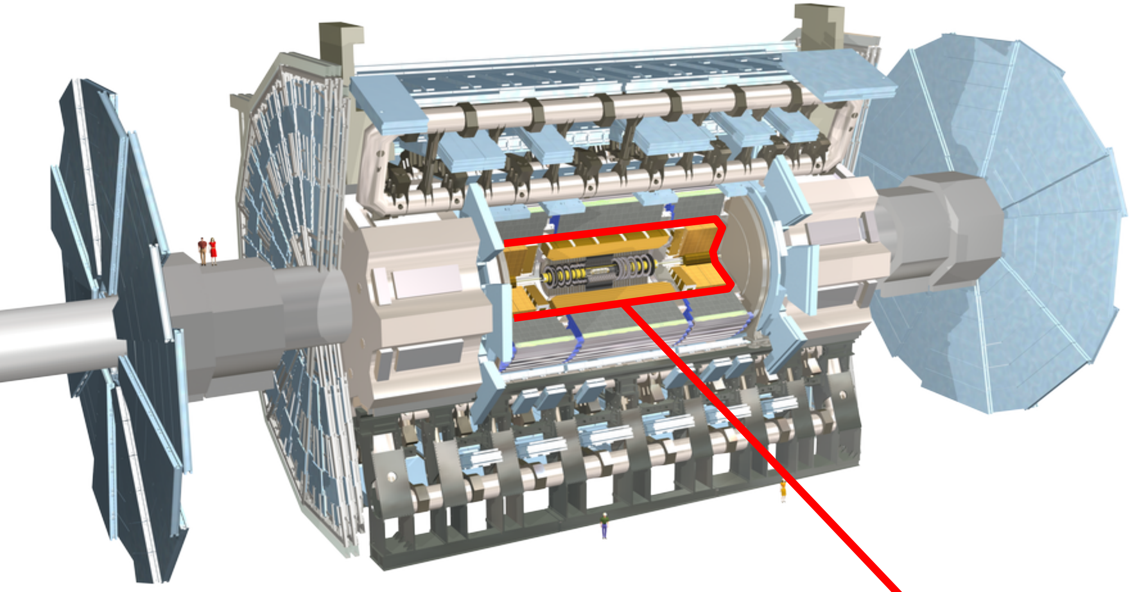
Commissioning of the ATLAS Liquid Argon Calorimeter

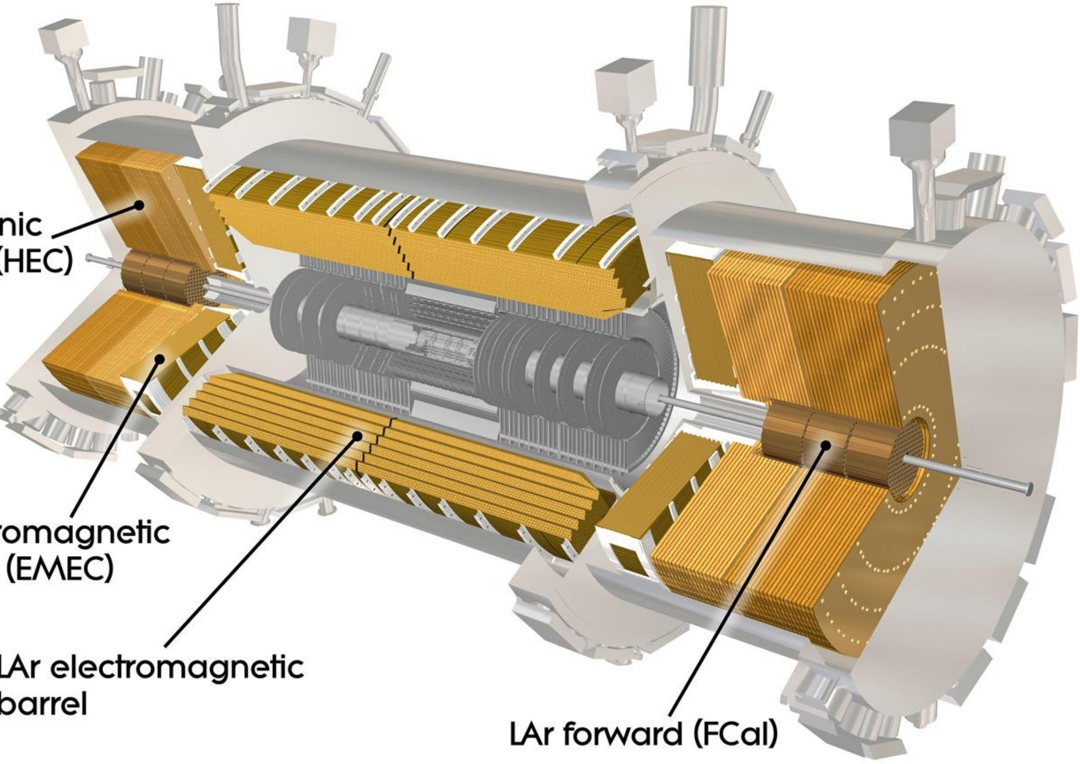
Julien Labbé
(LPSC Grenoble, UJF-CNRS/IN2P3-INPG)
on behalf of the ATLAS LAr Calorimeter group

The Liquid Argon (LAr) Calorimeter of the ATLAS Experiment



- **The ATLAS experiment**
  - general purpose detector at the LHC, at CERN
- **LHC environment**
  - proton-proton collisions ($\sqrt{s}$ = 14 TeV) every 25 ns
  - ~900 M inelastic collisions per second at design luminosity
    - ➲ high interaction rate
    - ➲ high radiation doses

- **Liquid Argon (LAr) Calorimeter**
  - ➲ sampling calorimeter
  - ➲ intrinsically radiation-hard
  - Very good electromagnetic calorimetry
    - ➲ main benchmarks : $H \rightarrow \gamma\gamma$, $Z' \rightarrow ee$
    - ➲ identification and measurement over a large dynamic (50 MeV $\rightarrow$ TeV : 16 bits)
  - Hermetic jet and transverse missing energy calorimetry
    - ➲ Hadronic End-Cap and Forward Calorimeter

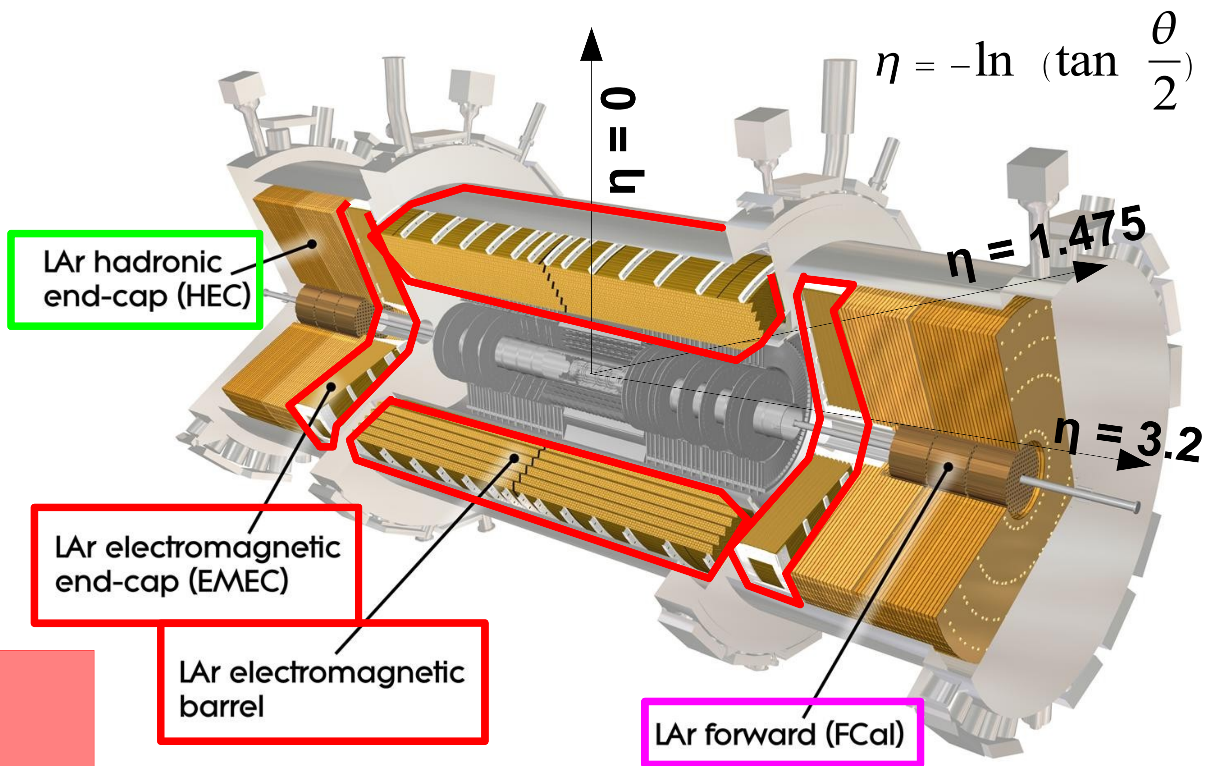


The Electromagnetic Calorimeter

- **Hadronic End-Cap [Cu + LAr]**
  - Flat-plat design
    - ➲ Coverage : 1.5 < |η| < 3.2
  - Resolution :

$$\frac{\Delta E}{E} = \frac{50\,\%}{\sqrt{E(GeV)}} \oplus 3\,\%$$

  - 4 sampling depths
    - ➲ ~ 11 λ in total



- **Electromagnetic Calorimeter [Pb + LAr]**
  - Accordion geometry providing an uniform φ coverage without crack
    - ➲ Barrel + End-cap : |η| < 3.2
  - Resolution :

$$\frac{\Delta E}{E} = \frac{10\,\%}{\sqrt{E(GeV)}} \oplus 0.7\,\%$$

  - 3 sampling depths (|η| < 2.5)
    - ➲ ~ 22-30 X_0 in total
    - ➲ + one presampler (|η| < 1.8)

- **Forward Calorimeter [Cu/W + LAr]**
  - Small LAr gaps between rods and tubes parallel to the beam axis
    - ➲ Coverage : 3.1 < |η| < 4.9
  - Resolution :

$$\frac{\Delta E}{E} = \frac{100\,\%}{\sqrt{E(GeV)}} \oplus 10\,\%$$

  - 3 sampling depths
    - ➲ 1 EM (Cu) / 2 HAD (W)
    - ➲ ~ 11 λ in total

The Hadronic End-Cap Calorimeter

- **Hadronic End-Cap [Cu + LAr]**
  - Flat-plat design
    - ➲ Coverage : 1.5 < |η| < 3.2
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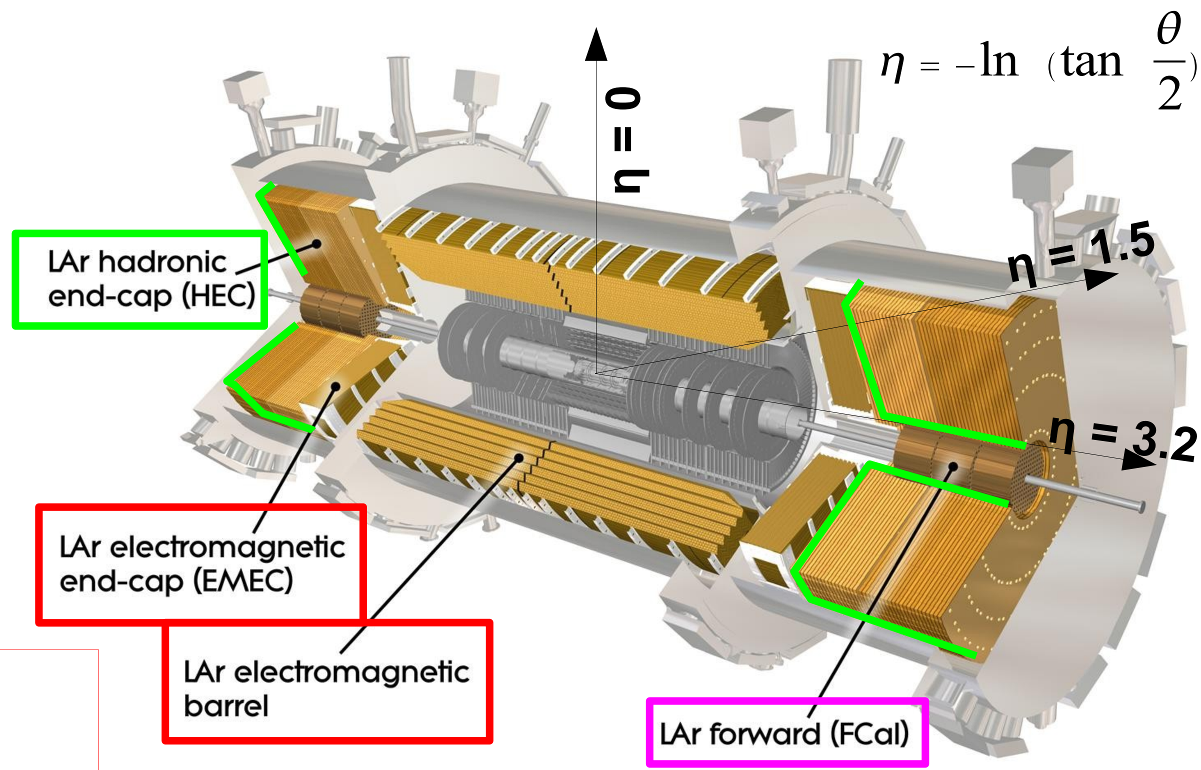

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The Forward Calorimeter

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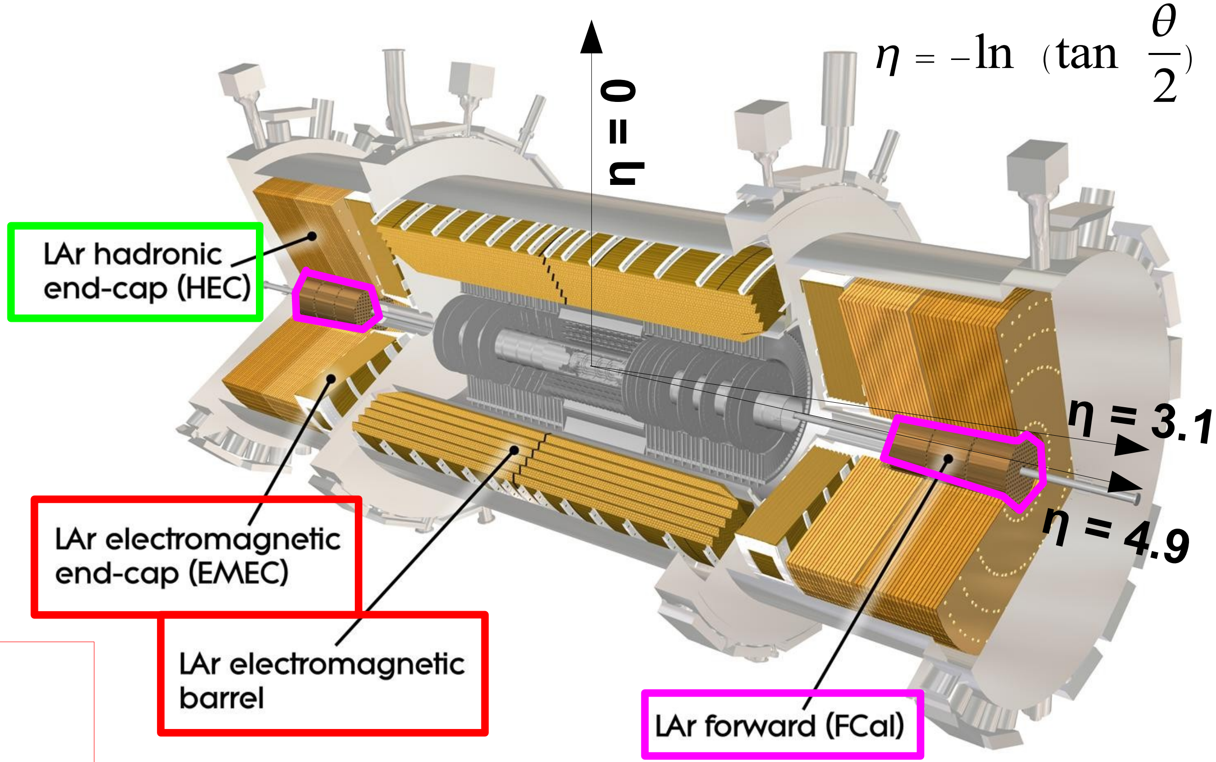
    - ➲ ~ 11 λ in total

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$



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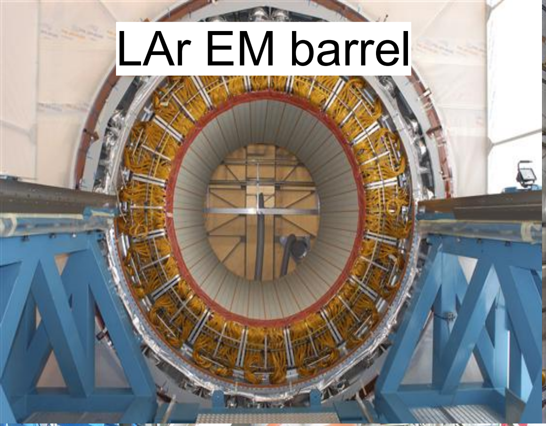
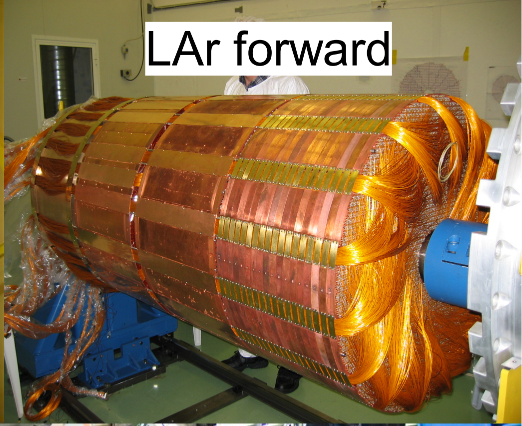
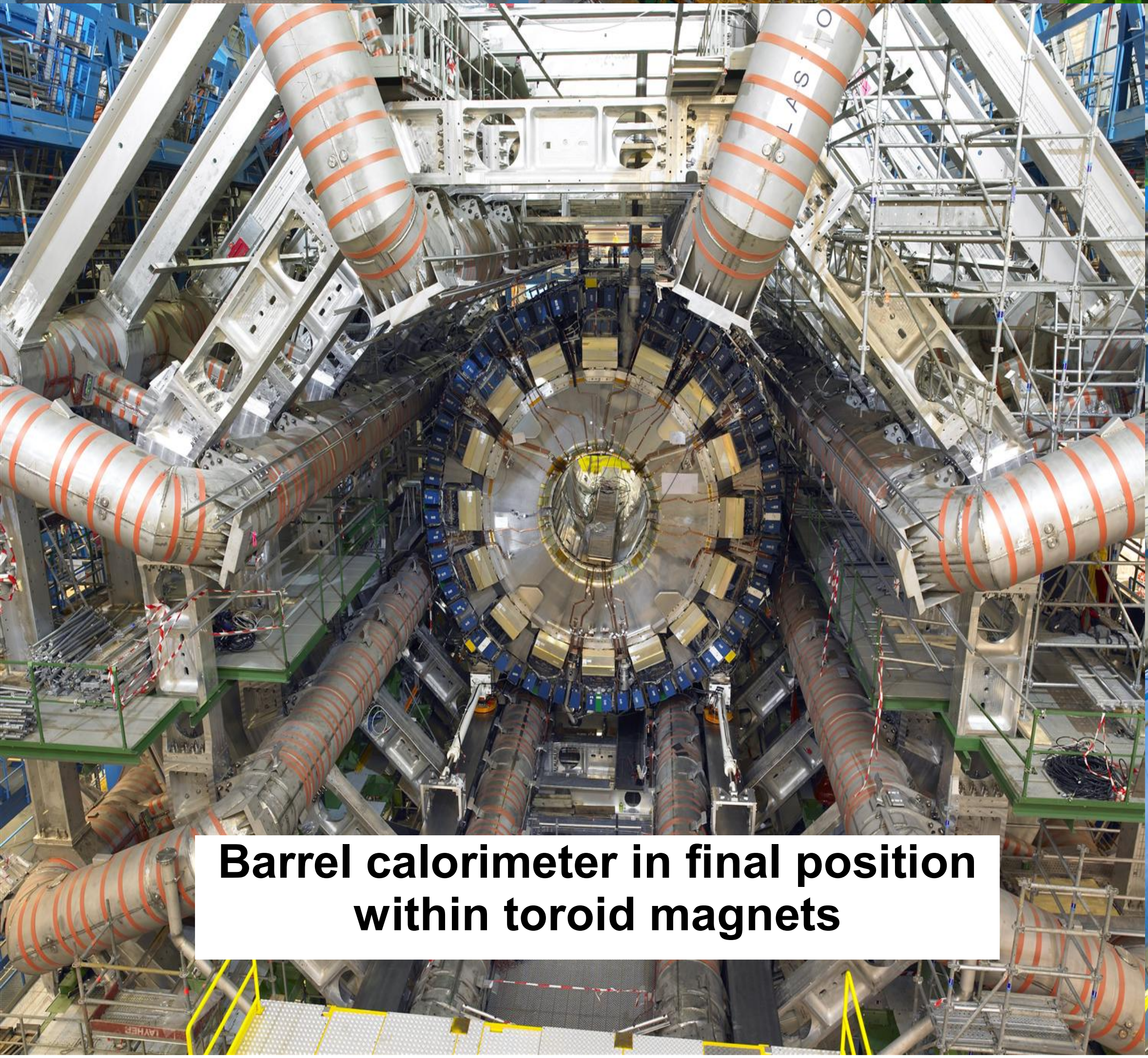
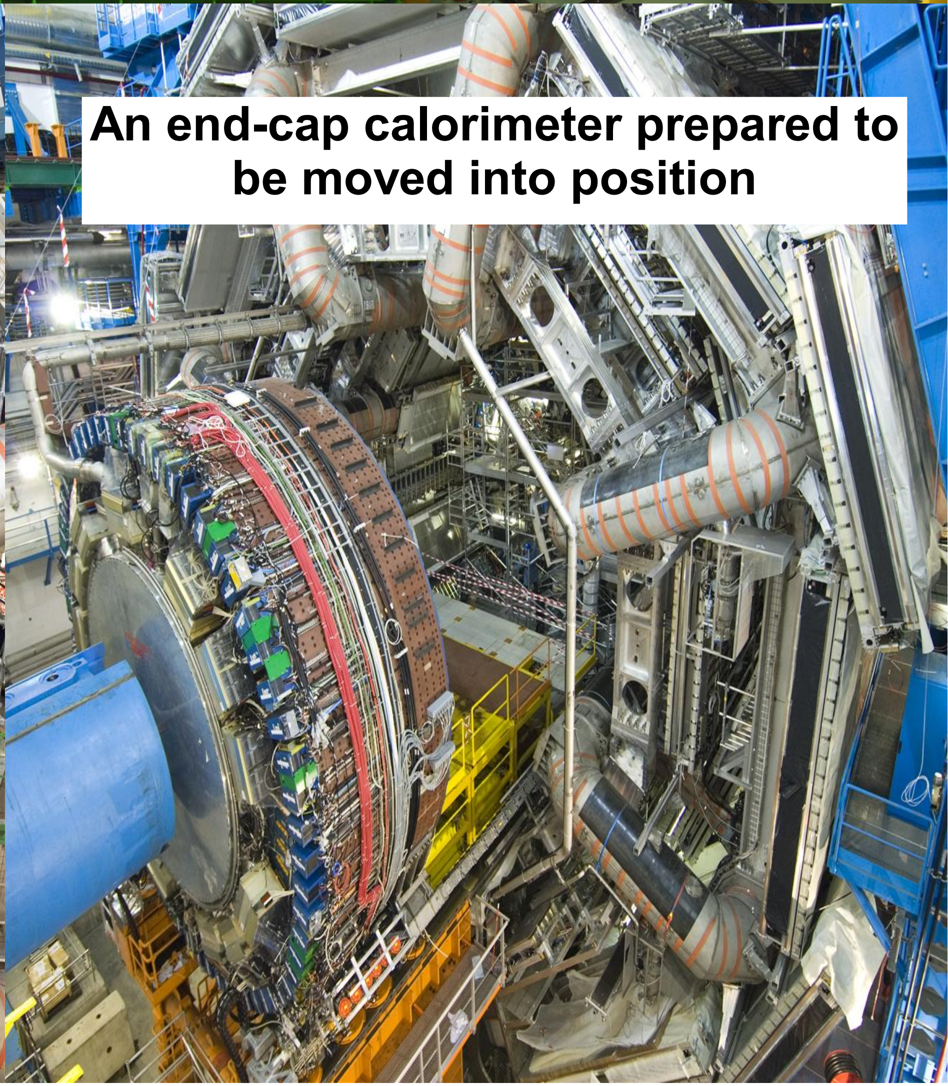

LAr EM barrel


LAr EM end-cap


LAr HAD end-cap

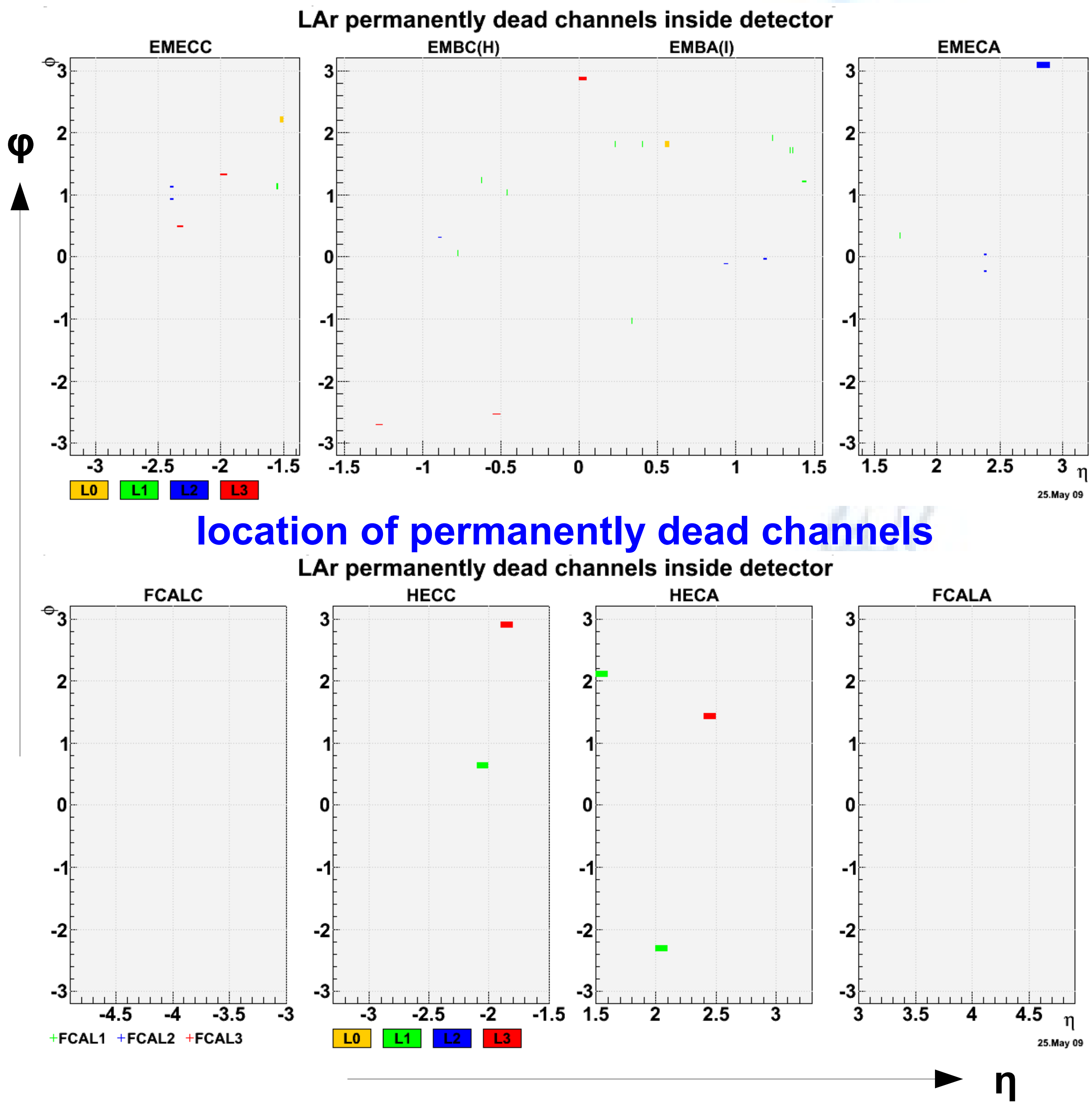

LAr forward


Barrel calorimeter in final position
within toroid magnets


An end-cap calorimeter prepared to
be moved into position

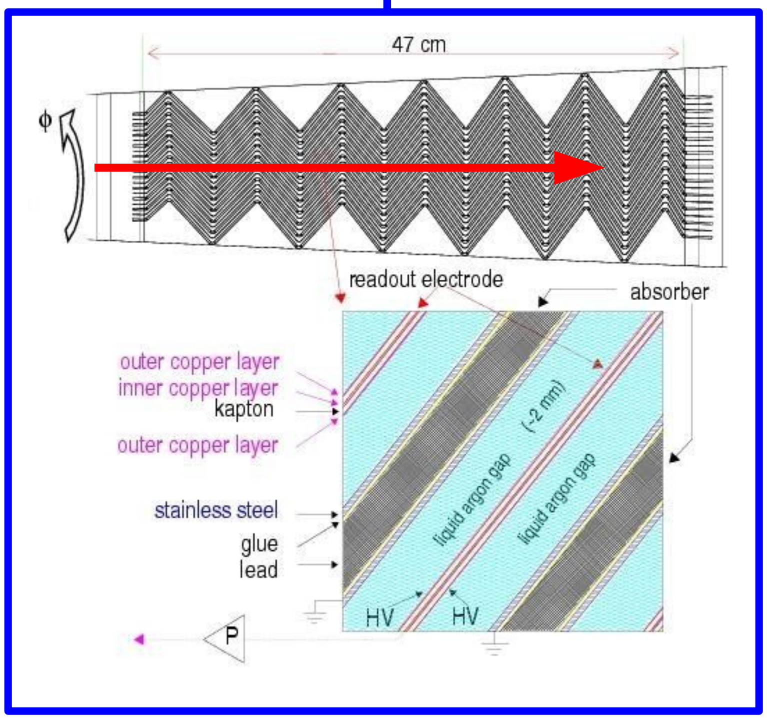
Detector Status as of June 1st 2009

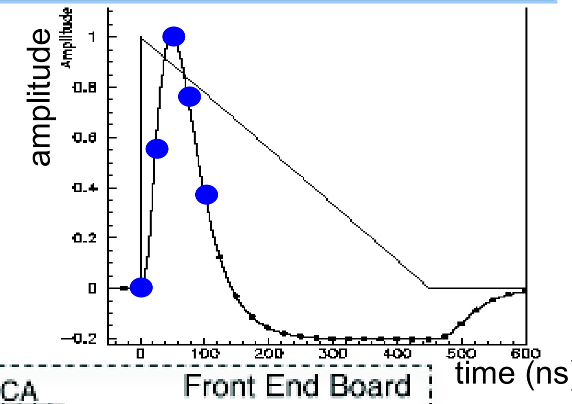
- **~ 182 k channels in total**
- **Only 0.02% are permanently dead**
  - the problem is expected to be located inside the detector
- **~ 0.2% dead readout channels**
  - Origin : optical transmitters between front-end and back-end electronics
  - to be fixed next time the access is available
- **~ 0.4% need special treatment for calibration**
  - limited impact on performances (~2% on pulse height)

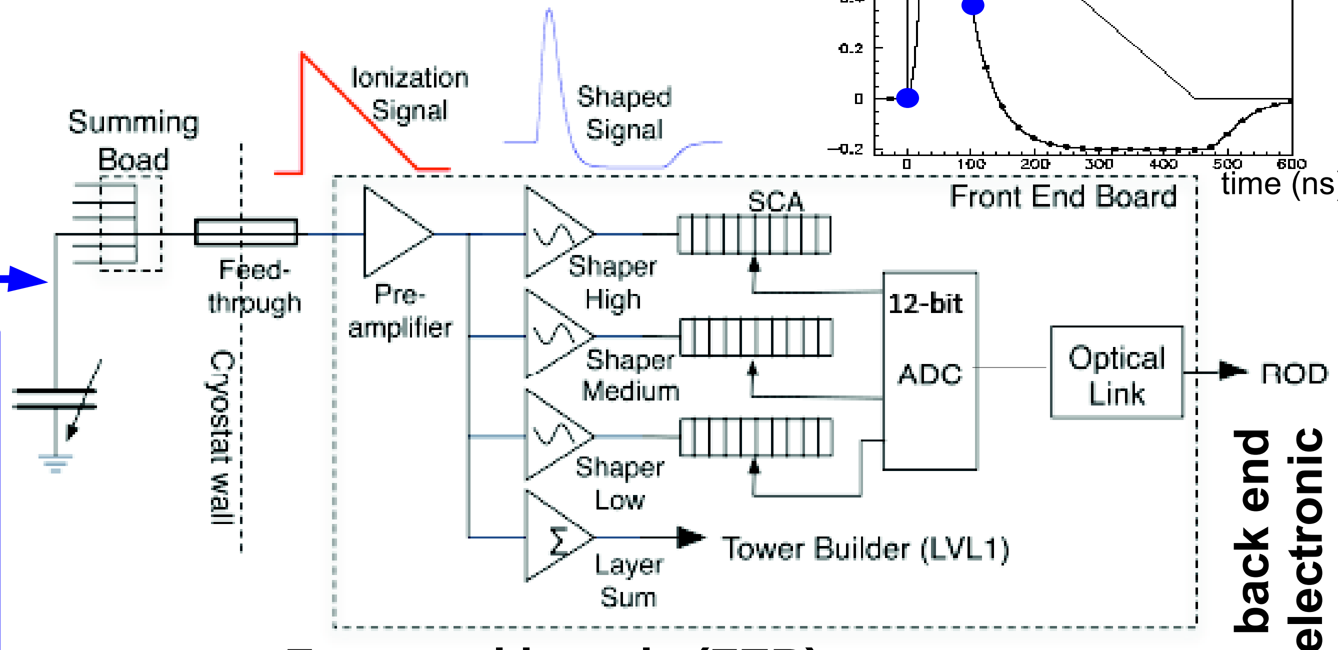


Ionization Current and Signal Processing

- **Calorimeter**
  - Absorber material initiates shower development
  - LAr medium is ionized
  - Electrodes collect ionized electrons through high voltage



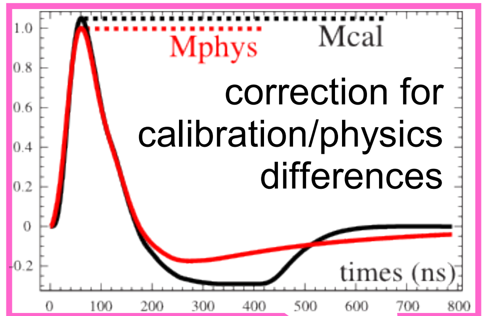




- **Front end boards (FEB) located on detector**
  - amplify and shape
    - ➲ 3 gains, ~1:10:100
  - sample and analog store during L1 trigger latency
  - gain select
  - digitize upon L1 trigger accept
  - transmit samples (usually 5) to back end electronic

Energy Reconstruction

- **Energy is computed in DSP located in back end crates**
  - Each cell is individually calibrated with a charge-injection system



ADC to DAC (Ramps)

Pulse Samples

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

Cell energy

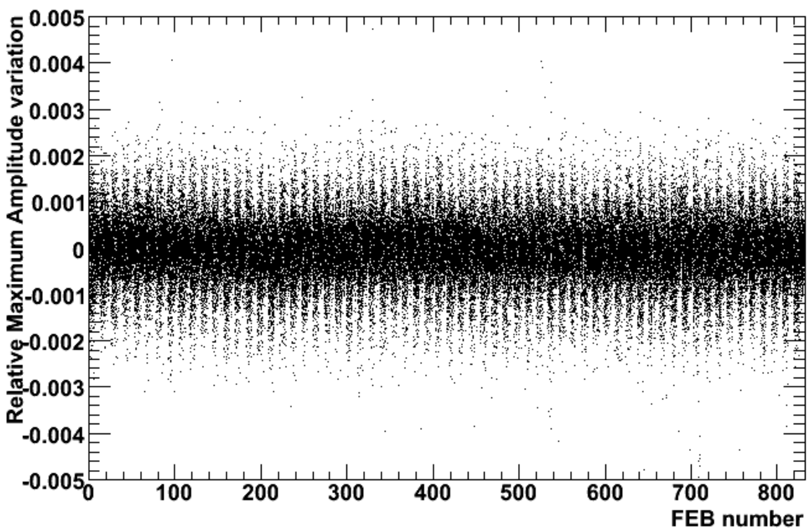
Sampling fraction

Calibration board

Optimal Filtering Coefficients

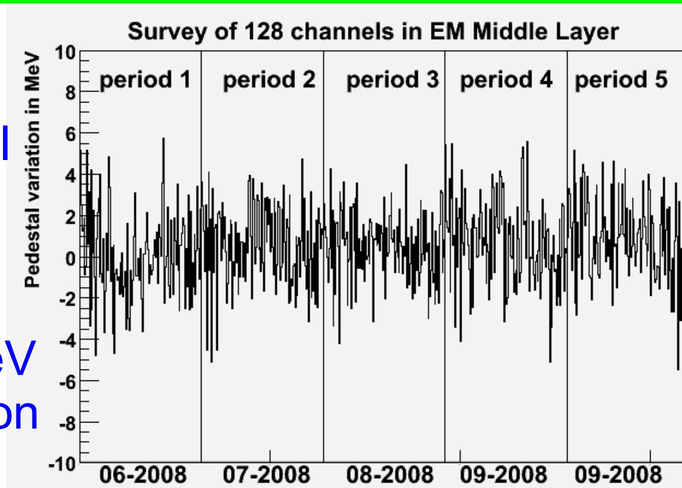
Pedestals

Amplitude variation < 0.1% between different calibration runs (here all barrel channels)



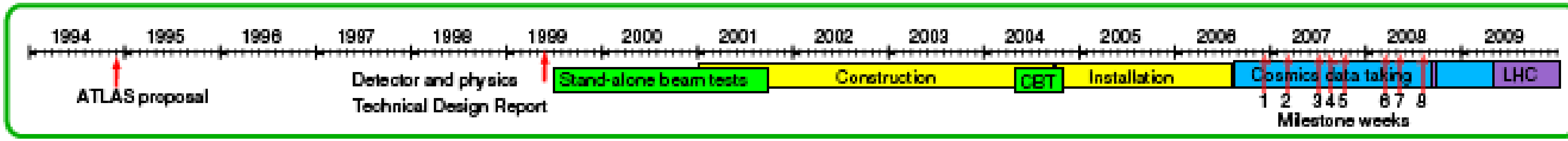
Pedestals are stable over several months

Variations < 1 to 3 MeV depending on sampling

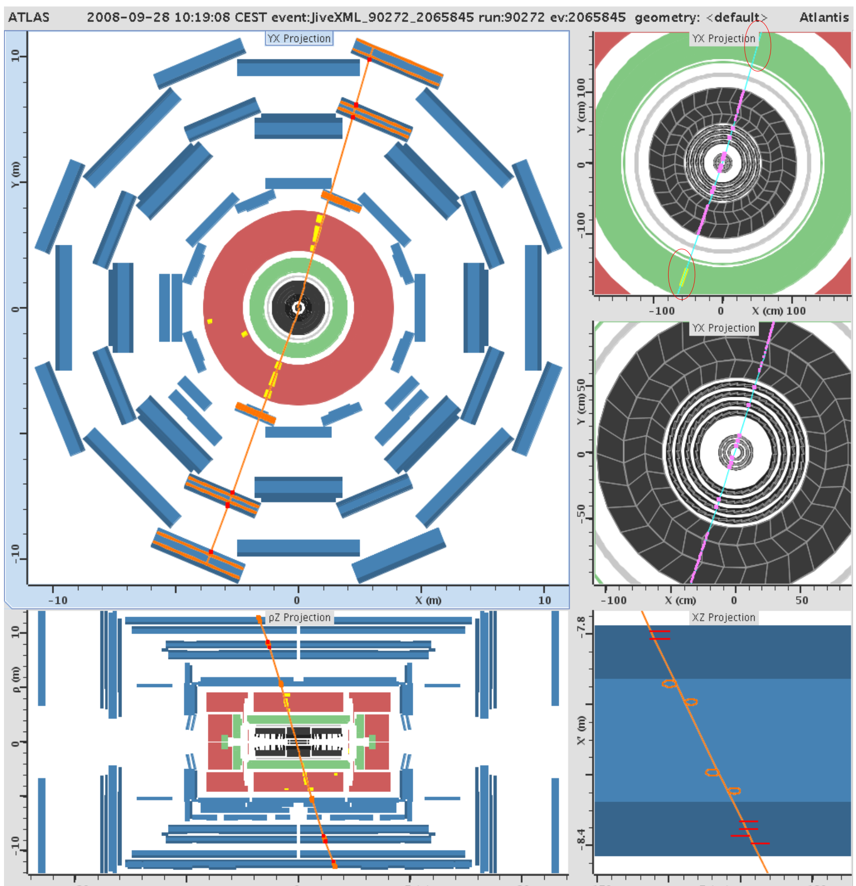


In Situ Commissioning ongoing since 3 years

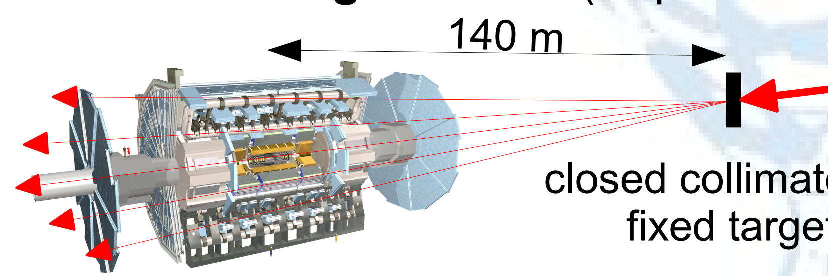
1994 1999 2004 2009



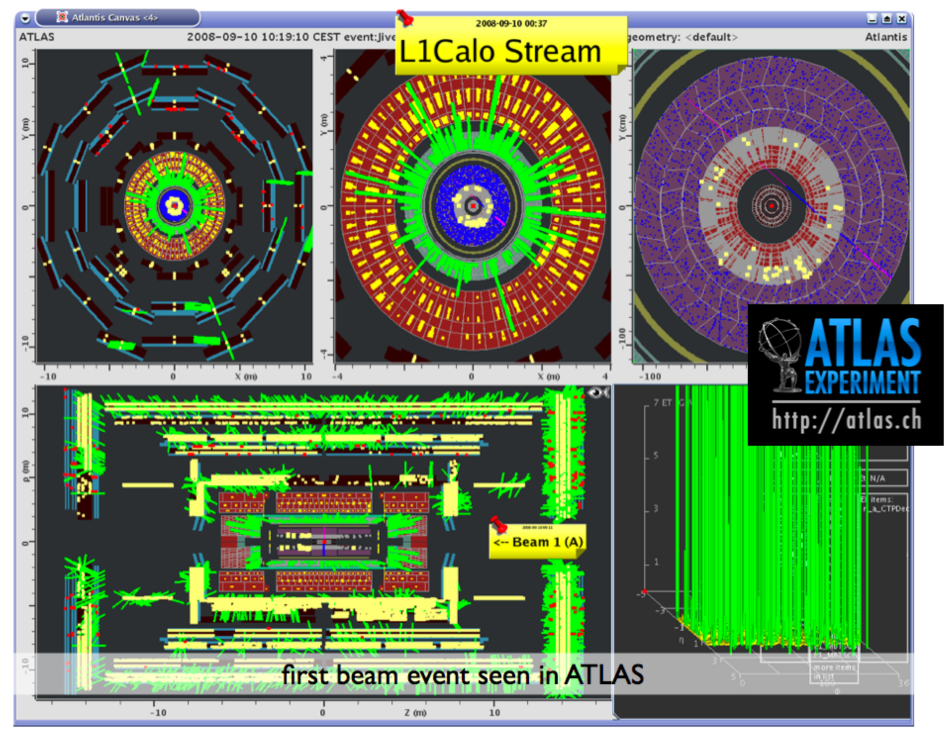
Cosmic muons
Recorded in the LAr calorimeter
since 2006



LHC Single beams (Sept. 2008)

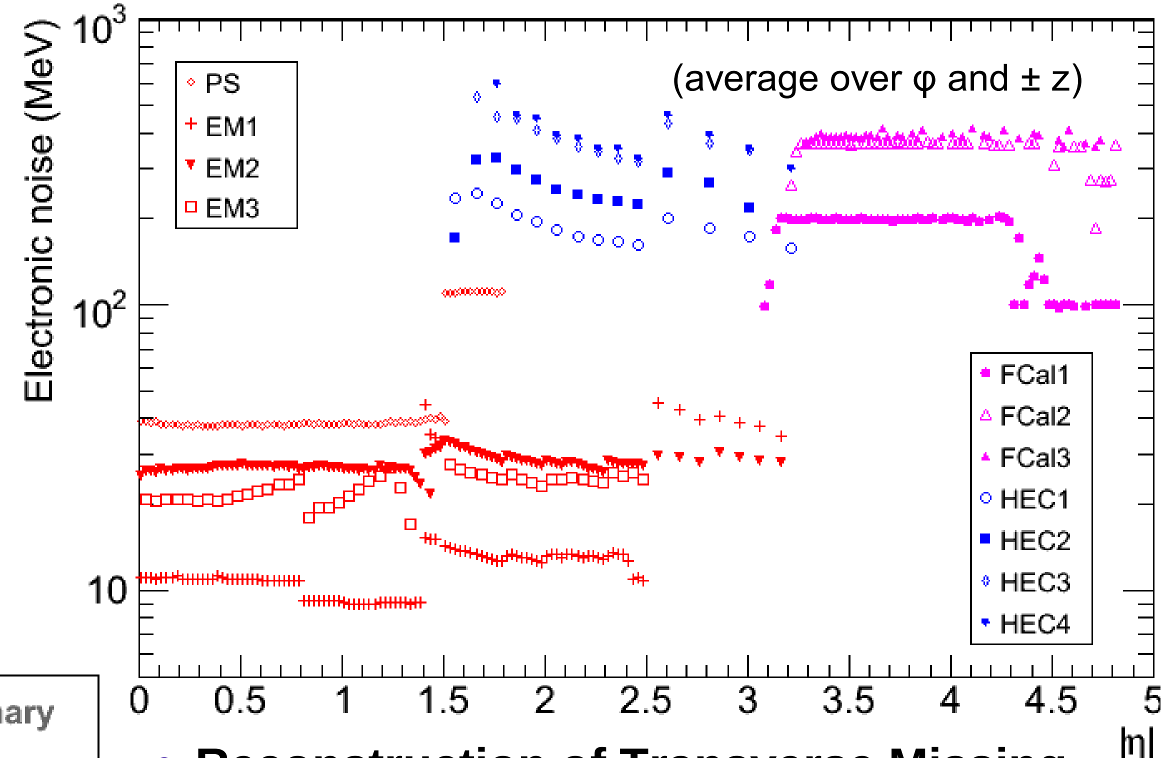


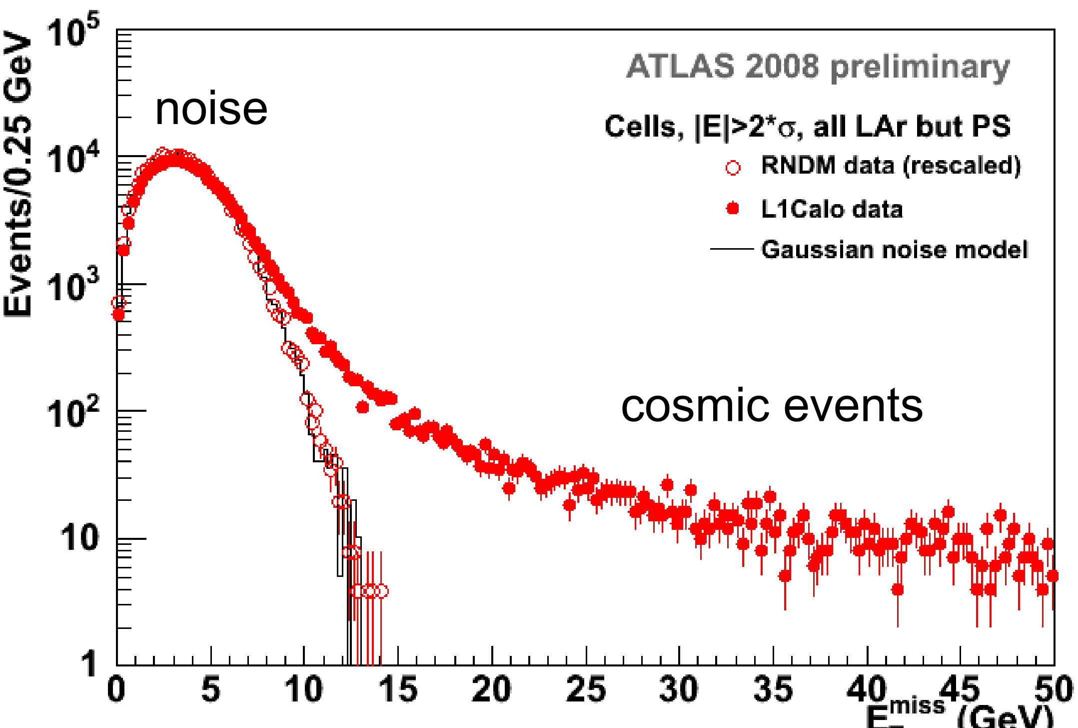
closed collimator as
fixed target



Noise studies

- **Noise**
  - Noise is measured for each cell with random trigger events
    - Main contribution : thermal noise of the FEB preamplifier loaded by the detector capacitance
    - Noise varies with η and detector element
  - Incoherent, as coherent, noise are within design requirements





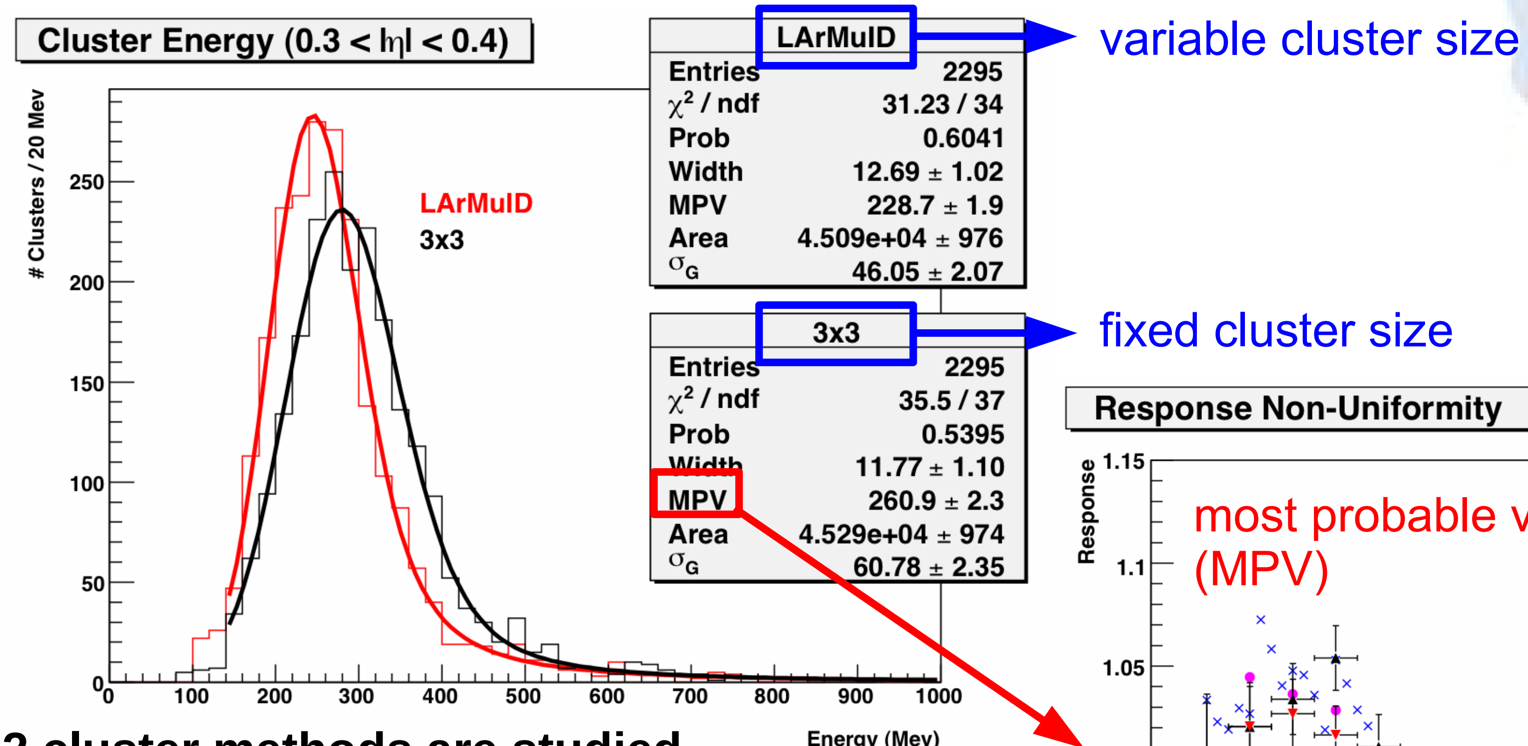
- **Reconstruction of Transverse Missing Energy in LAr**

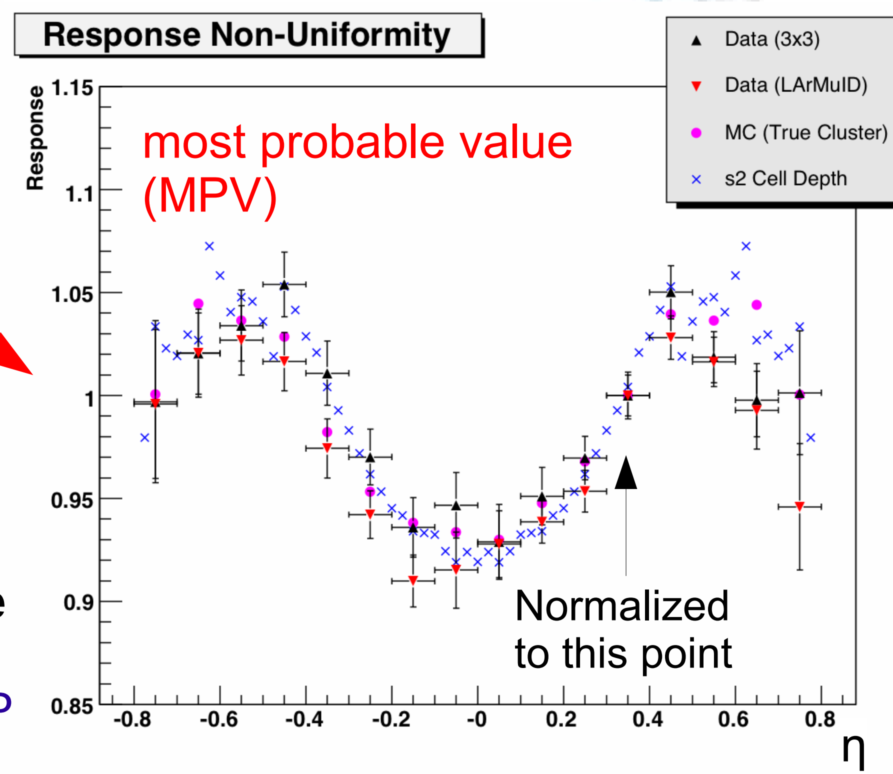
$$E_T^{miss} = \sqrt{\left(\sum E \sin\theta \cos\phi\right)^2 + \left(\sum E \sin\theta \sin\phi\right)^2}$$

  - In random trigger events
    - consistent with incoherent noise prediction
  - In events triggered by L1Calo (calorimeters – not only LAr)
    - Examination of pulse shapes in the tail of the distribution indicate true cosmic events

Response to Minimum Ionizing Muons

- **Muons are minimum ionizing particles (MIP)**
  - Small energy deposition in LAr
  - The energy deposit follows a Laudau distribution
    - ➲ here fit convoluted with gaussian to take into account electronic noise

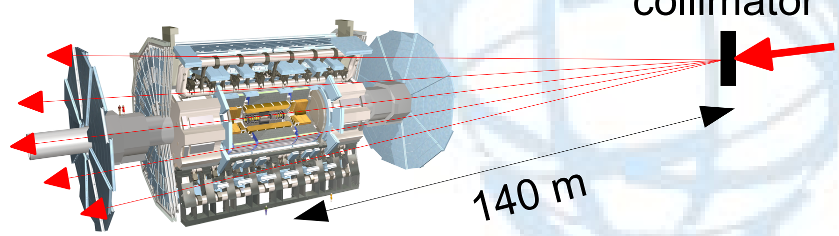




- **2 cluster methods are studied**
  - Fitted Gaussian noise (σ_G) and Landau width for 3x3 consistent with expectation
- **MPV distribution agrees with simulation at the level of 2%**
  - MPV follows the cell depth as expected for MIP

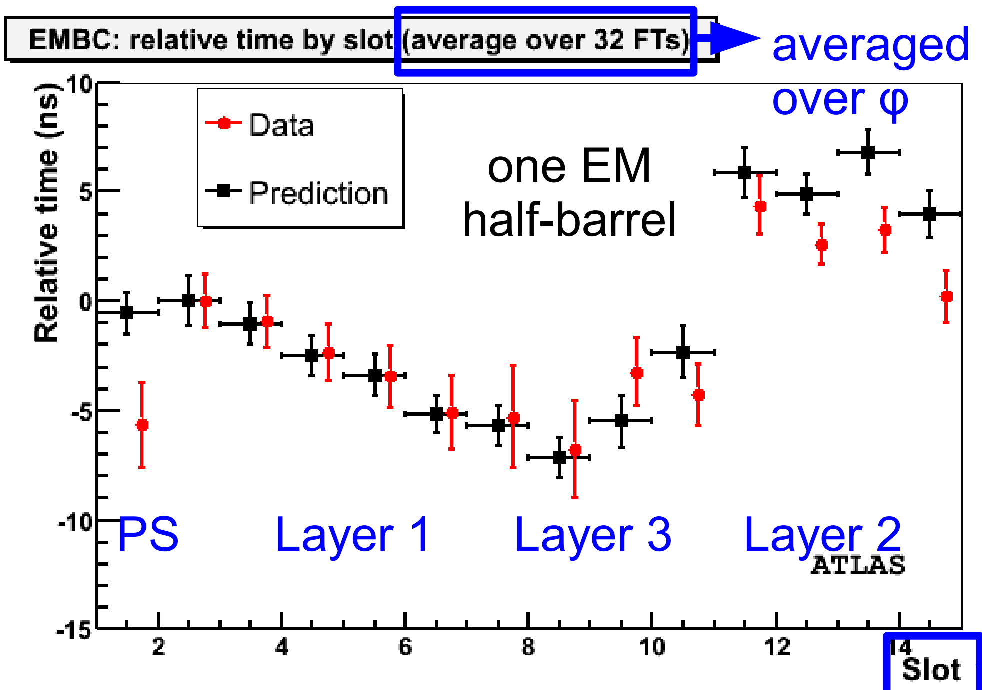
Timing Study

- **From single beam events**
  - Large amount of energy deposited over large portions of LAr
  - High amplitude signals to perform precision timing studies with common reference time

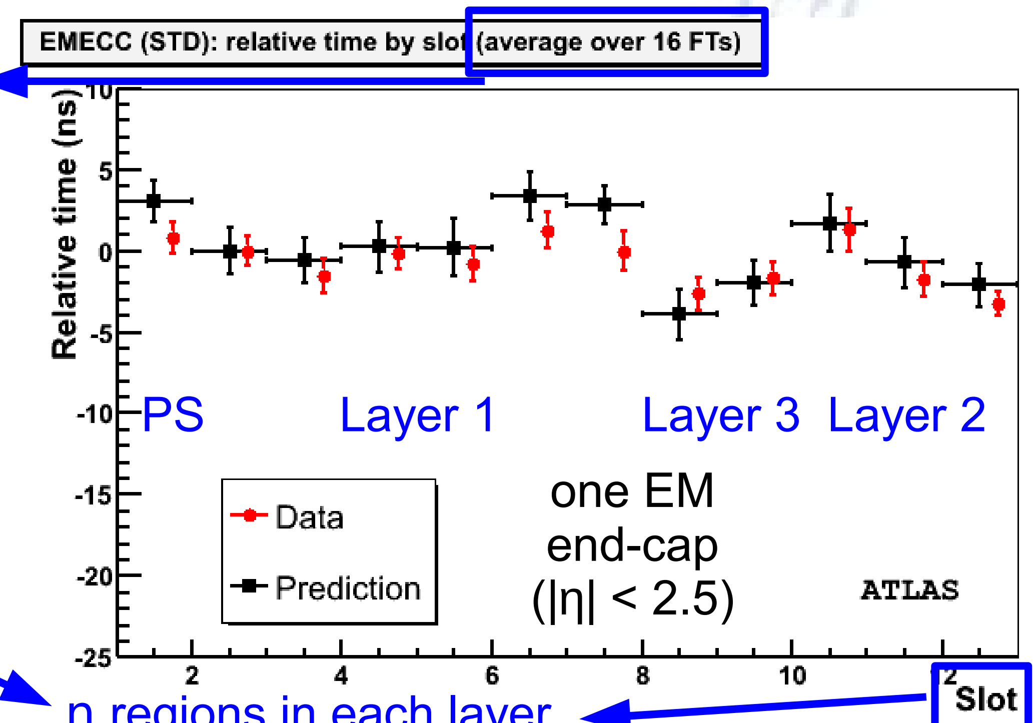


- **Time is computed with optimal filtering**
  - corrected from expected time of flight
  - Prediction from the calibration pulse and readout path

- **Agreement at the level of 2 ns except for the barrel presampler**



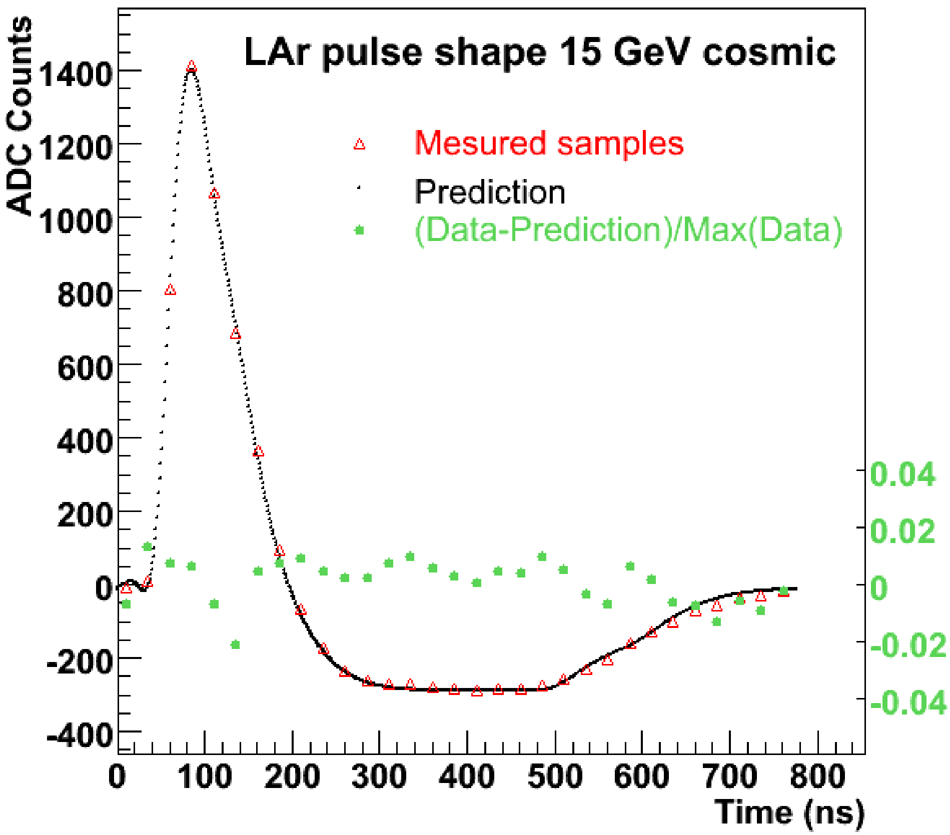
averaged over φ



η regions in each layer

Signal shape

- **High energy depositions are used to validate the signal shape of calorimeter response derived from calibration pulse**
  - 32 samples cosmic pulse is compared with prediction
  - Agreement better than 2 % is observed across the full length of the pulse

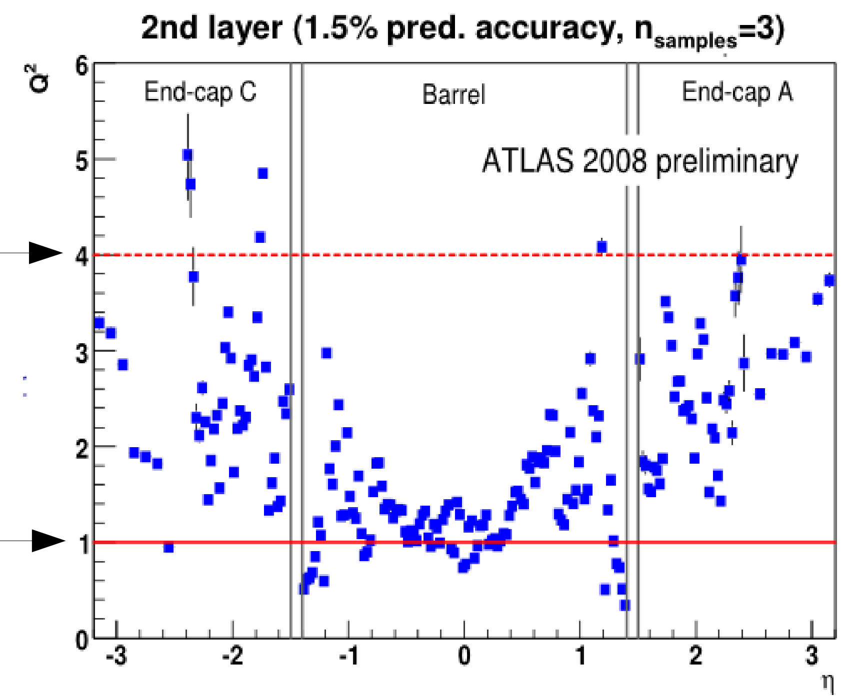


- **Quality estimator Q^2**

$$Q^2 = \frac{1}{nDoF} \sum_{i=1}^{n_{samples}} \frac{(A_i^{data} - A_i^{pred})^2}{\sigma_{noise}^2 + \sigma_{pred}^2}$$

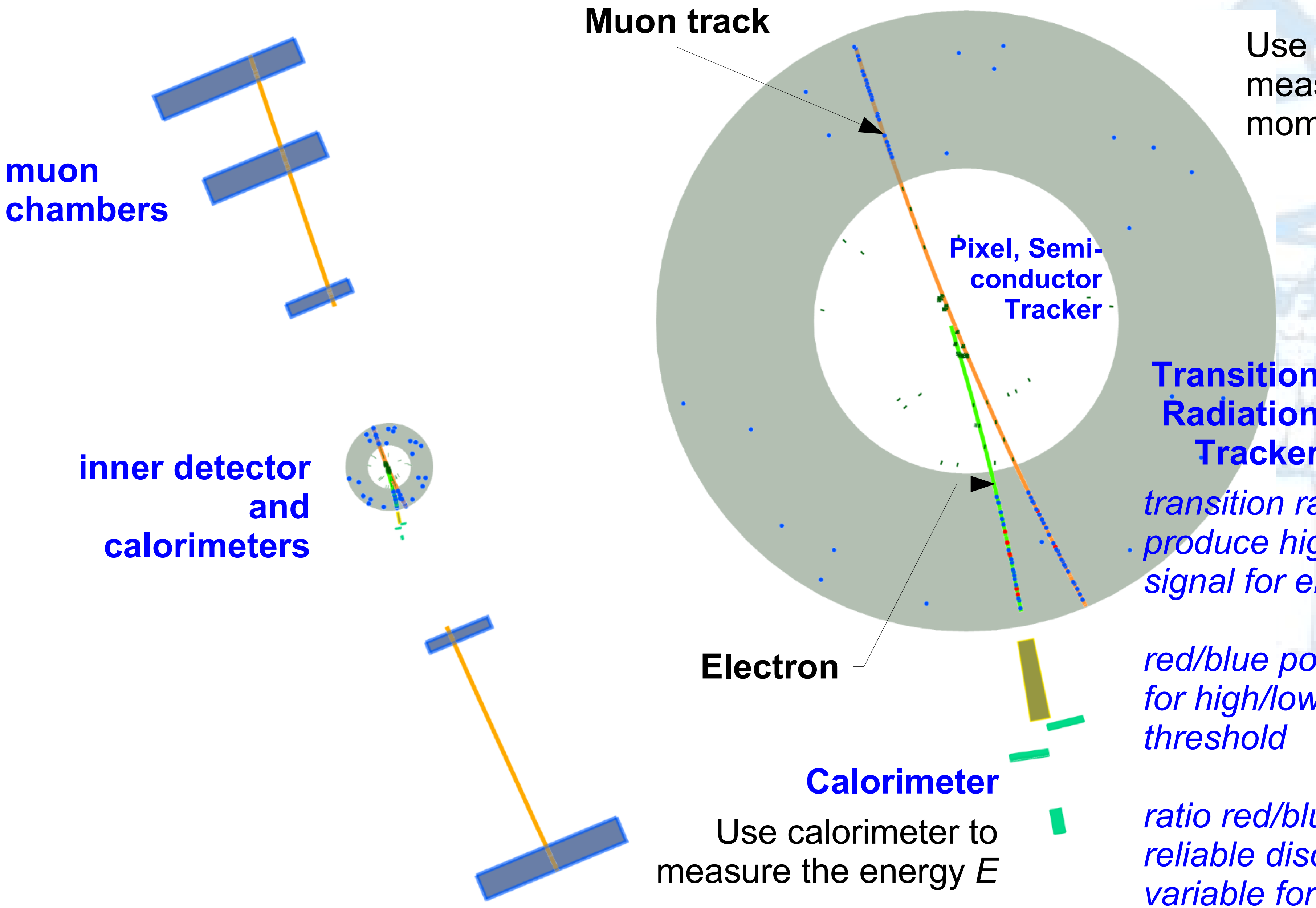
Pulse shape predicted at ~3%

Pulse shape predicted at ~1.5%



Signal reconstruction in control over the full EM calorimeter coverage.

Electrons from Ionisation in Cosmic Muons [1/2]



Use tracker to measure the momentum *p*

Use calorimeter to measure the energy *E*

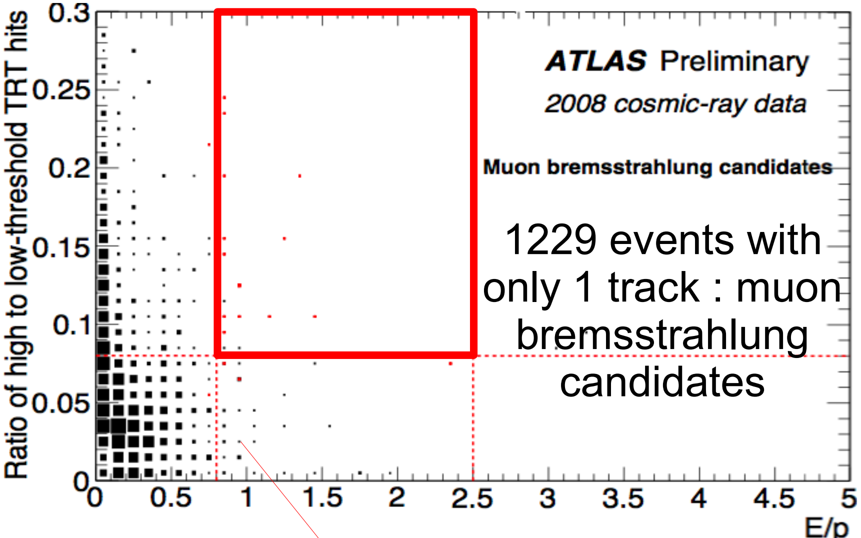
transition radiations produce higher signal for electrons

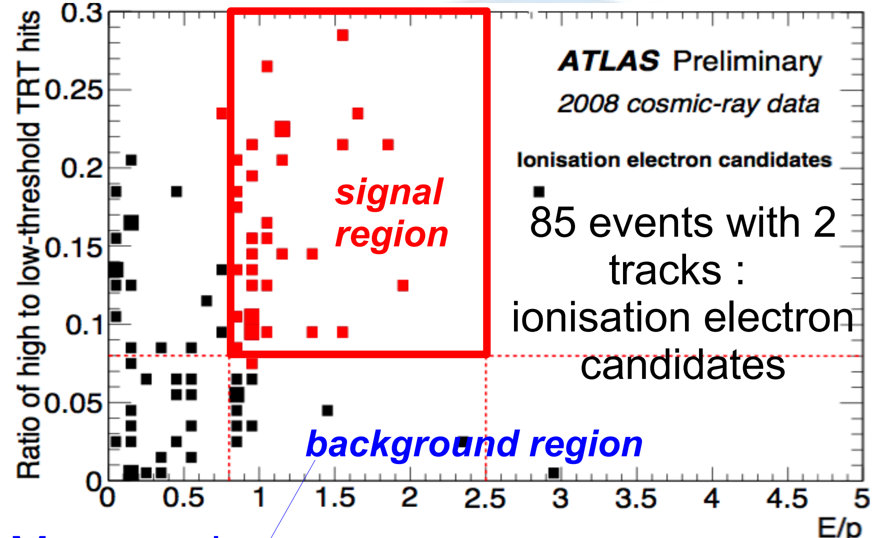
red/blue points are for high/low TRT threshold

ratio red/blue is a reliable discriminant variable for electron identification

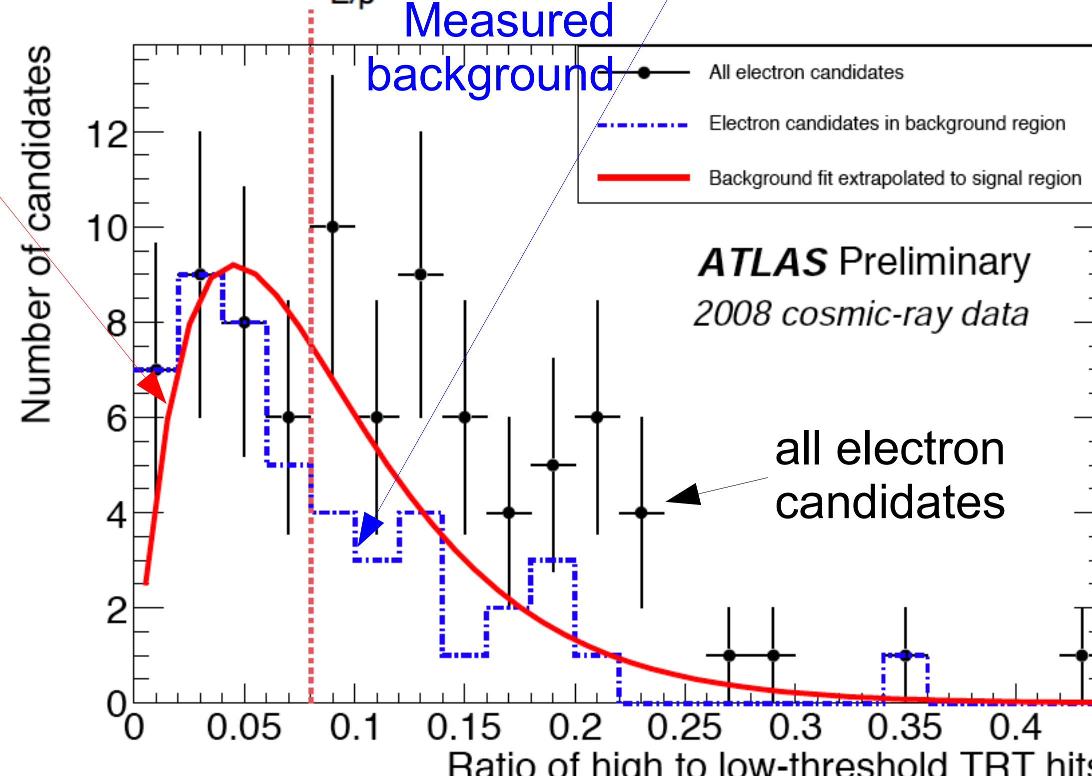
Electrons from Ionisation in Cosmic Muons [2/2]

- **EM cluster (E_T > 3 GeV) + loose (downward) track match + electron like shower shape**
  - 1314 events





Expected background shape from muon bremsstrahlung candidates



First observation of electrons in the ATLAS detector

Conclusion

- **LAr calorimeter is completely installed with the other sub-detectors in the ATLAS cavern**
  - Very few number of dead channels (< 0.02% permanent)
  - Calibration system is exercised regularly
    - ➲ Calibration constants are stable

- **In situ commissioning of the ATLAS LAr calorimeter ongoing since several years with cosmic muons and single beam data**
  - Incoherent and coherent noise of the full calorimeter system is consistent with design requirements
  - MIP energy deposition of cosmic muons has been studied
    - ➲ variations follow the cell depth as expected
  - Relative timing is known at the 2 ns level
  - Pulse shape prediction has been validated with data
  - Electron from ionisation identified in cosmic muons events

The commissioning of the ATLAS LAr calorimeter has shown that the detector, calibration system and signal reconstruction infrastructure are fully ready for the LHC collisions
(scheduled for autumn 2009)

Complements

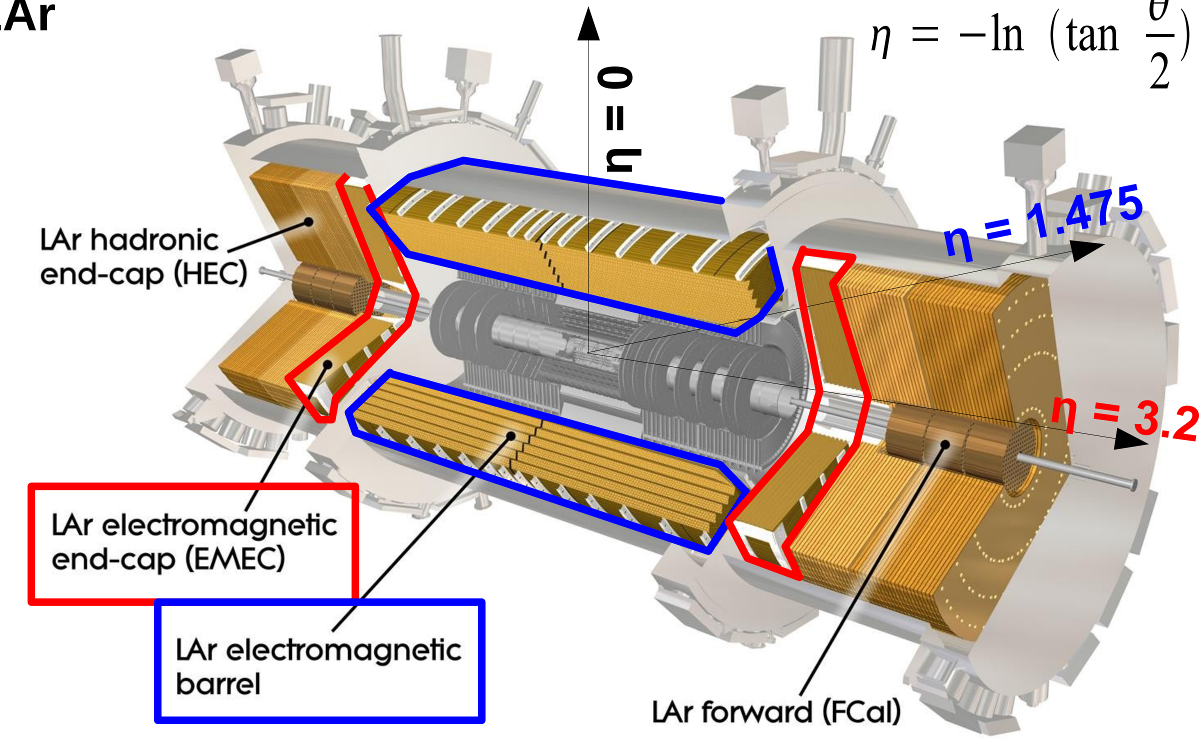
The Electromagnetic Calorimeter

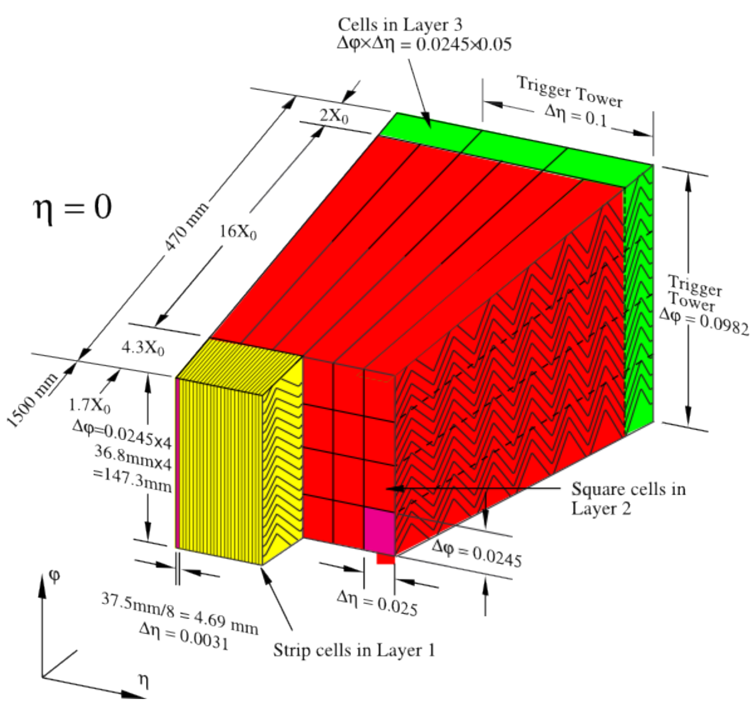
- **Electromagnetic Calorimeter Pb + LAr**
  - Good energy resolution

$$\frac{\Delta E}{E} = \frac{10\,\%}{\sqrt{E(GeV)}} \oplus 0.7\,\%$$

  - Large acceptance
    - Barrel + end-caps : |η| < 3.2
    - Accordion geometry : uniform φ coverage without crack
  - 3 sampling depths (|η| < 2.5)
  - + 1 Presampler (|η| < 1.8)
  - Fine granularity
    - ~ 174 k channels

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$



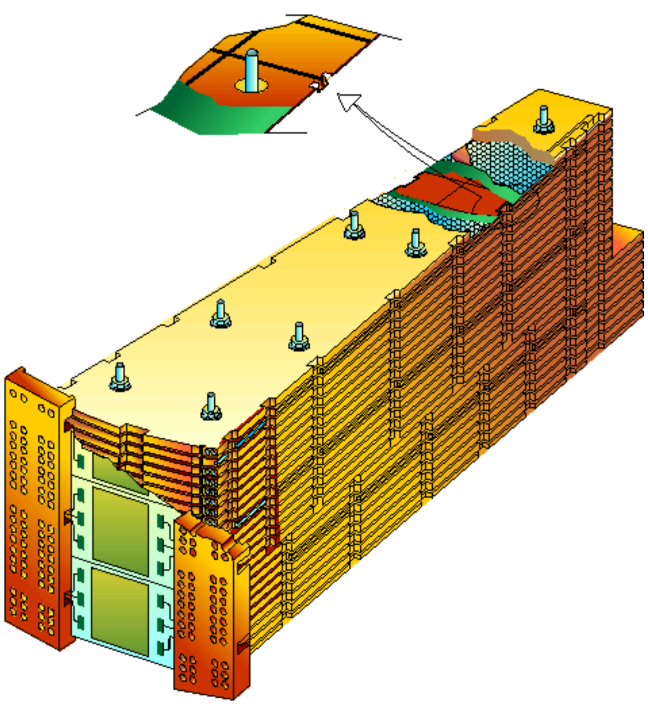


Layer 3 (back) ΔηxΔφ = 0.025 x 0.050	~ 2-12 X_0
Layer 2 (middle) ΔηxΔφ = 0.025 x 0.025	~ 16 X_0
Layer 1 (front) ΔηxΔφ = 0.003 x 0.1	~ 4 X_0

(η < 2.5)

The Hadronic End-Cap and Forward Calorimeters

- **Hadronic End-Cap Cu + LAr**
  - Flat-plat design
  - Coverage : 1.5 < |η| < 3.2
  - Resolution :
    $$\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E(GeV)}} \oplus 3\%$$
  - 4 sampling depths
    - ➲ ~ 11 λ in total
  - 5632 channels in total



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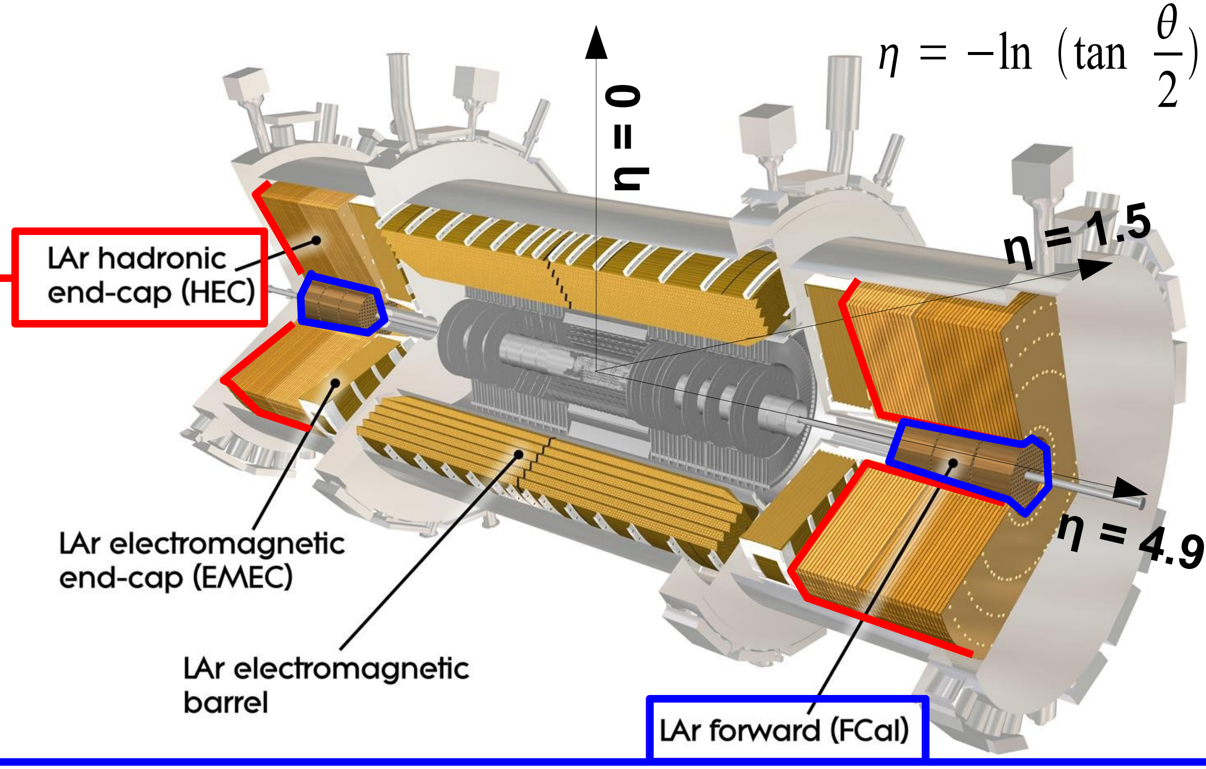
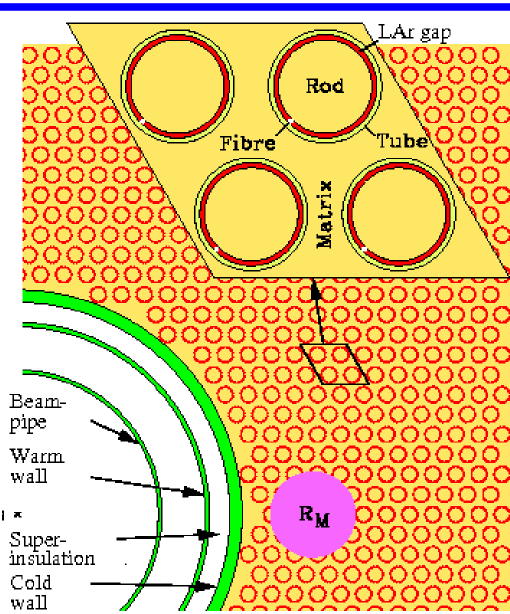




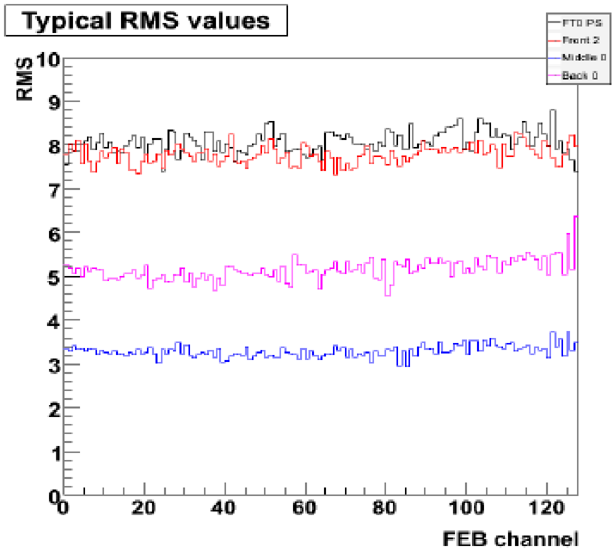
- **Forward Calorimeter Cu/W + LAr**
  - Small liquid argon gaps between concentric rods and tubes parallel to the beam axis
  - Coverage : 3.1 < |η| < 4.9
  - Resolution : $\frac{\Delta E}{E} = \frac{100\%}{\sqrt{E(GeV)}} \oplus 10\%$
  - 3 sampling depths
    - ➲ 1 EM (Cu) / 2 HAD (W)
    - ➲ ~ 11 λ in total
  - 3504 channels in total

Calibration Constants

pedestals and noise

FEB are read with no input signal to obtain:

- Pedestal
- Noise
- Noise autocorrelation (OFC computation)

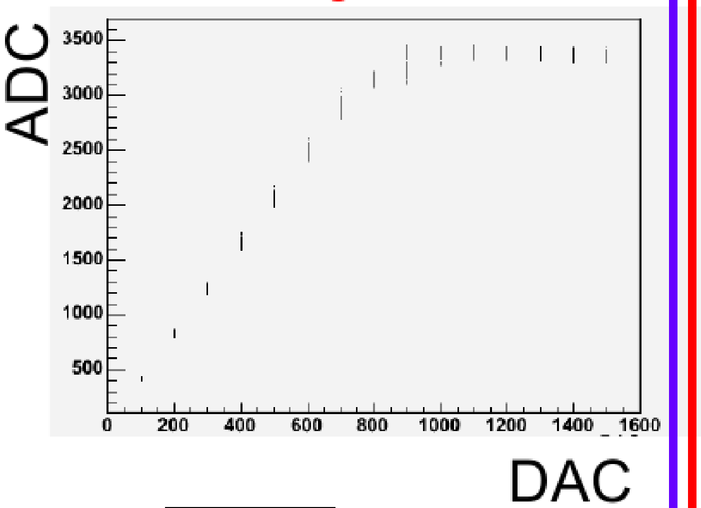


PEDESTAL

ADC → MeV conversion

F = ADC2DAC × DAC2μA × μA2MeV

- Scan input current (DAC)
- Fit DAC vs ADC curve with a first (second) order polynomial, outside of saturation region

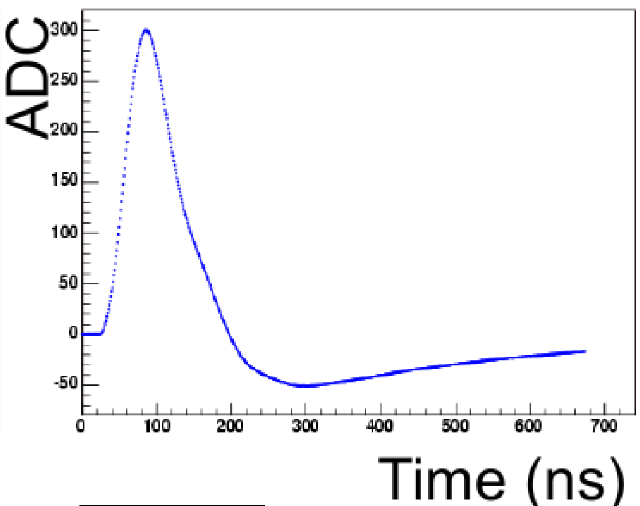


RAMP

response to current pulse

All cells are pulsed with a known current signal:

- A delay between calibration pulses and DAQ is introduced
- The full calibration curve is reconstructed (Δt=1ns)



DELAY

Optimal Filtering Coefficients

$$f(t) = Ag(t-\tau) + n(t) \cong A\{g(t) - \tau g'(t)\} + n(t)$$

$$S_k = A(g_k - \tau g'_k) + n_k$$

$$\langle n_k \rangle = 0$$

$$\langle n_i n_j \rangle = R_{ij}$$

noise autocorrelation function

Choose coefficients for the expressions:

$$U = \sum_{k=1}^{N} a_k S_k \qquad V = \sum_{k=1}^{N} b_k S_k$$

such to minimize σ_U and σ_V with the constraints:

$$\langle U \rangle = A \Rightarrow \sum_{k=1}^{N} a_k g_k = 1 \ , \quad \sum_{k=1}^{N} a_k g'_k = 0$$

$$\langle V \rangle = A\tau \Rightarrow \sum_{k=1}^{N} b_k g_k = 0 \ , \quad \sum_{k=1}^{N} b_k g'_k = -1$$

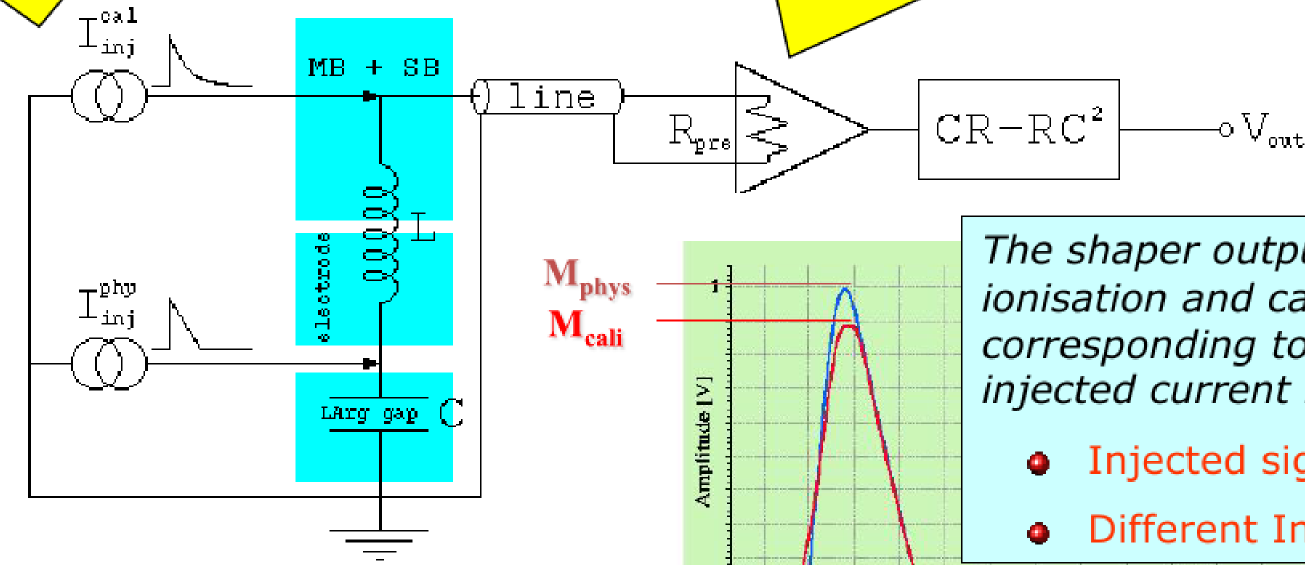
$$\sigma_U^2 = \mathrm{Var}[U] = \sum_{ij} a_i a_j R_{ij}$$

$$\sigma_V^2 = \mathrm{Var}[V] = \sum_{ij} b_i b_j R_{ij}$$

Calibration Scheme

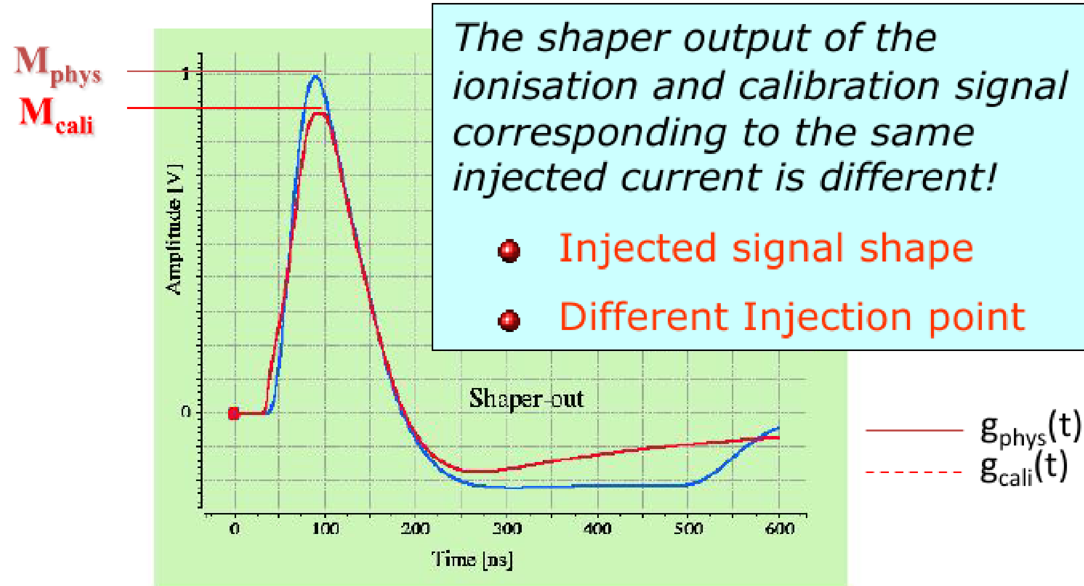
A known exponential current pulse is injected at the MB level…

… and reconstructed through the full readout chain. The actual gain of each readout channel is computed.



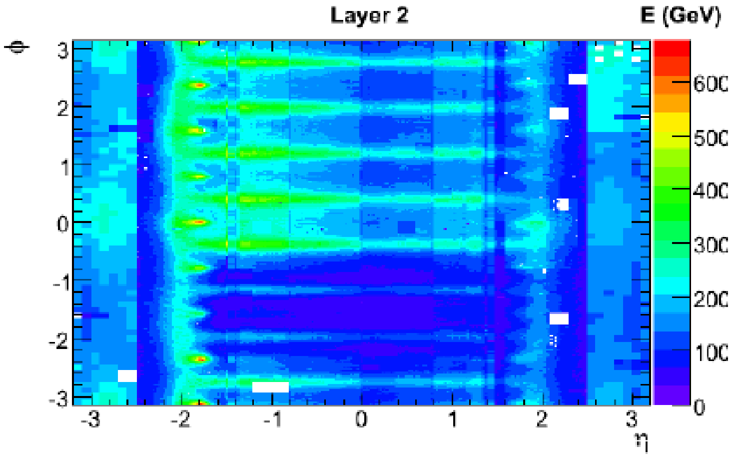
The shaper output of the ionisation and calibration signal corresponding to the same injected current is different!

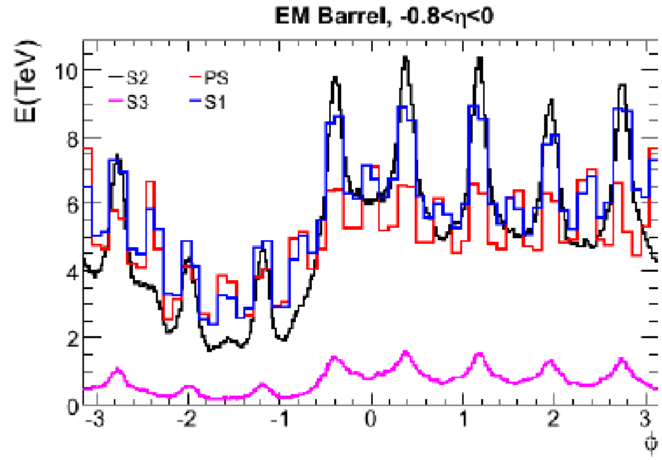
- Injected signal shape
- Different Injection point

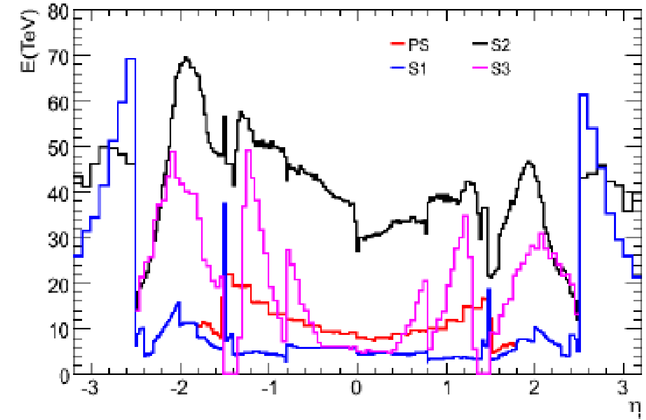


Energy Deposited in LHC "splash" Events

Accumulated energy (Ecell > 5σ) over 100 single beam events



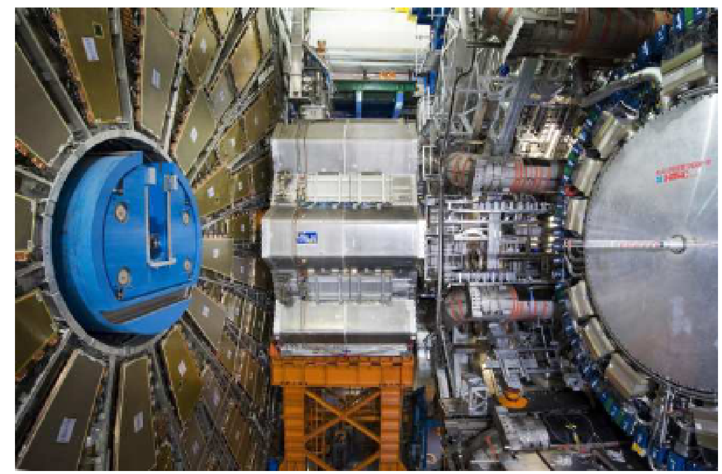




→ Hundreds of TeV deposited

→ Energy flow over the whole EM calorimeter in the four layers

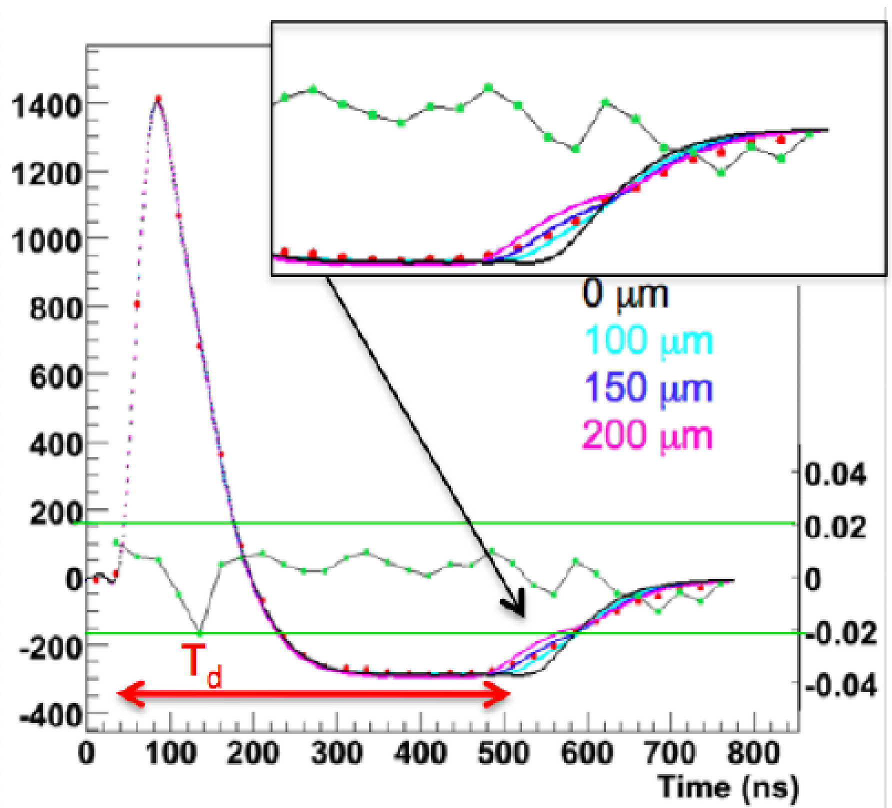
→ Understood η and ϕ structure, top/bottom asymetry

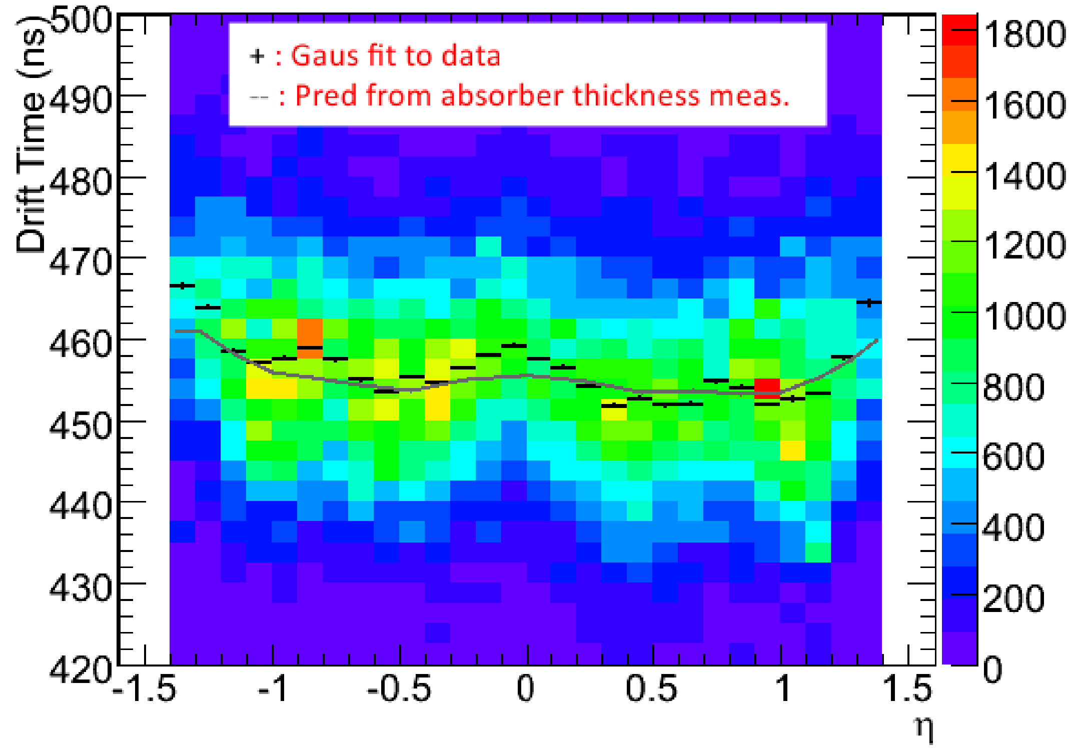


→ Allow signal reconstruction and timing studies over the total coverage

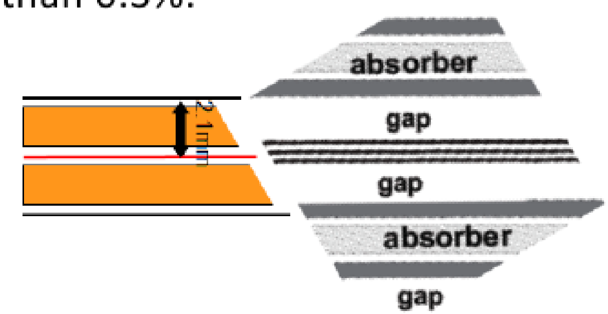
Quality of Physics Pulse Shapes

- The drift time is an important parameter in the physics pulse shape prediction.
- Also sensitive to the purity of the LAr.
- Detailed drift time measurements have been made with ~350k EM barrel cosmic pulses with E > 1 GeV taken in 32 sample read out mode.





- Drift time varies with η as a result of observed ~100 µm shifts of electrode within LAr gap.
- Study has concluded the contribution of the gap variation to the response non–uniformity is not larger than 0.3%.



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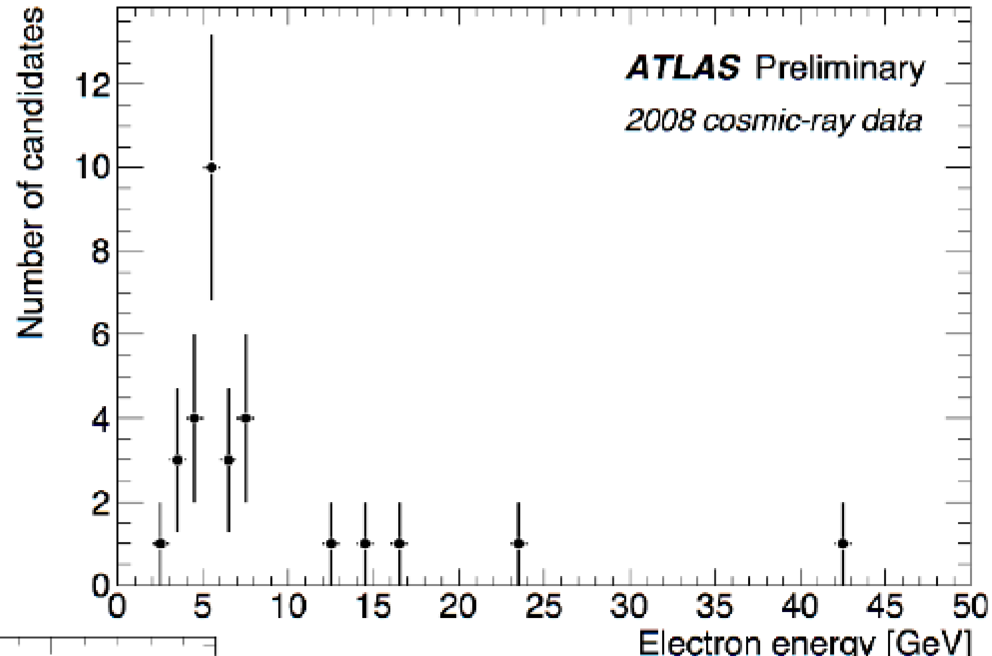
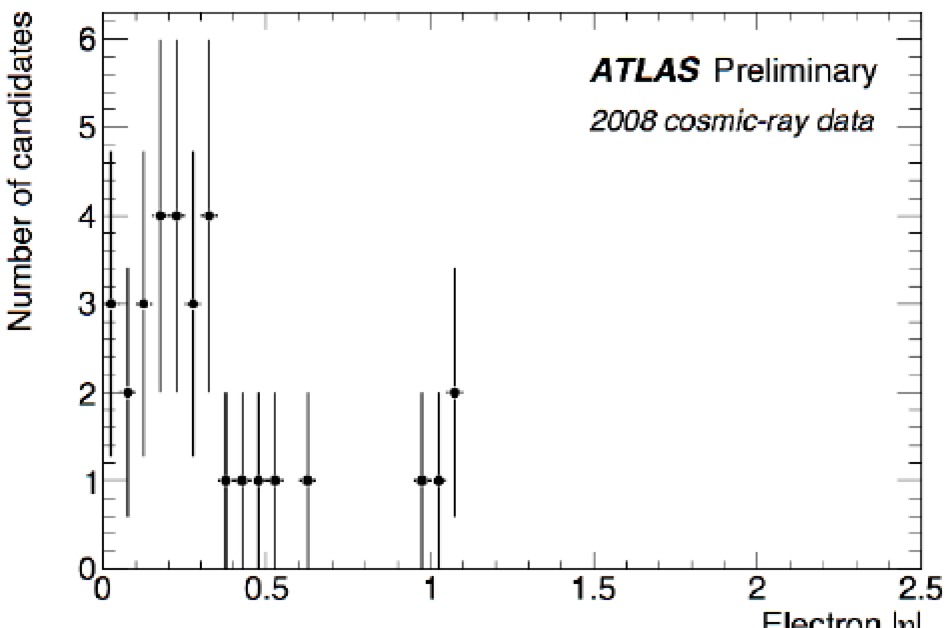
Ionisation Electron Candidates Distributions

Distribution of the energy and pseudo-rapidity measured in the electromagnetic calorimeter for the final 32 ionisation electron candidates.

Note that two candidates have an energy above 50 GeV (and are most likely background).

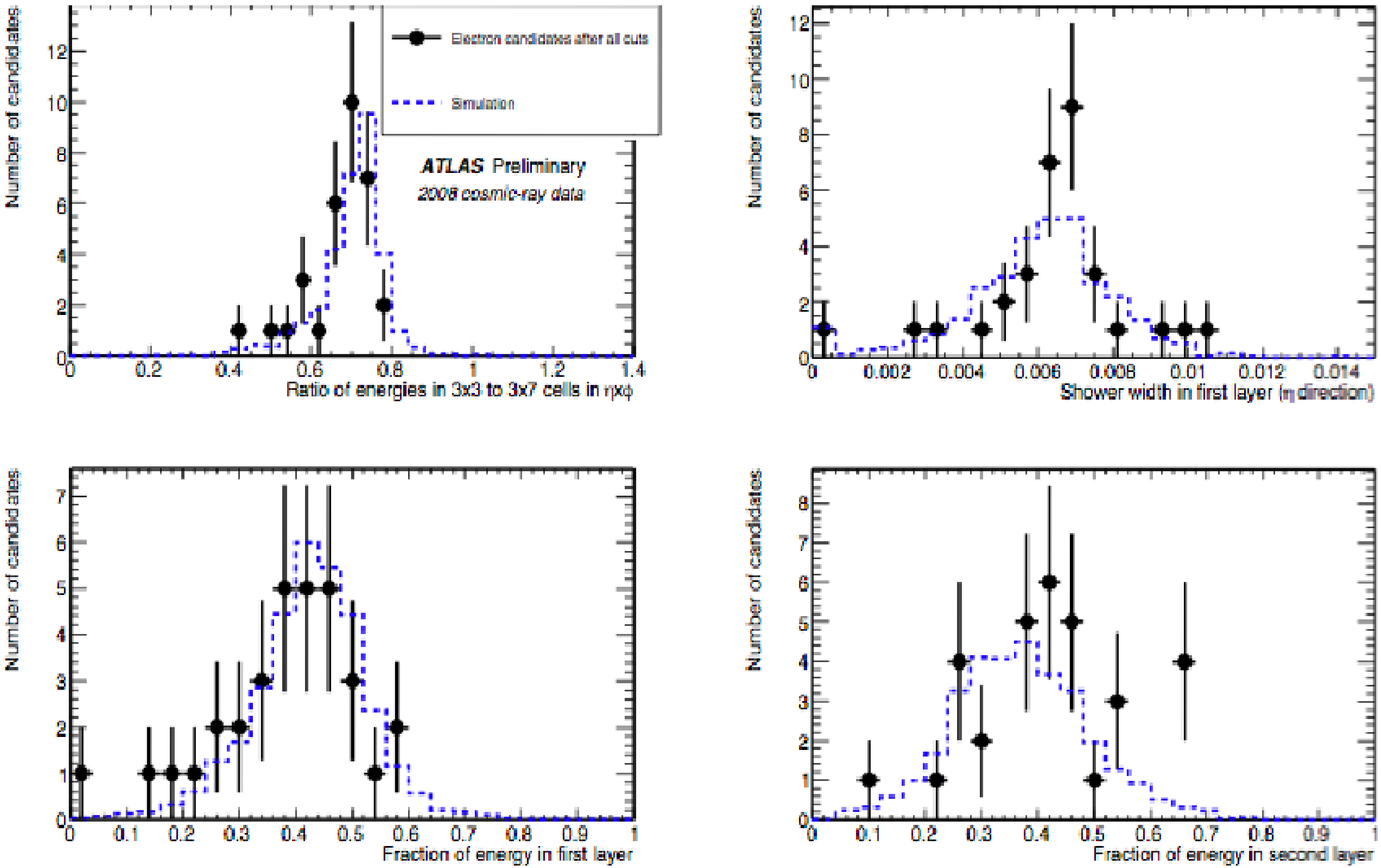




As expected for electrons from ionisation in the inner detector volume, the energy spectrum shows an accumulation at low energies, near the seed threshold of 3 GeV (in transverse energy) used to build the electromagnetic clusters.

Ionisation Electron Candidates Shower Shapes

Comparison of shower shapes between electron candidates and Monte-Carlo simulation of 5 GeV projective electrons



Detector Status as of July 1st 2009 (details)

- **LAr dead readout channels (to be fixed in next shutdown):**
  - EMB: 266 of 109568 (0.243%)
  - EMEC: 129 of 63744 (0.202%)
    - EM tot: 395 of 173312 (0.228%)
  - HEC: 0 of 5632 (0%)
  - FCAL: 0 of 3524 (0%)
    - total: 395 of 182468 (0.216%)

- **LAr permanently dead channels inside detector:**
  - EMB: 18 of 109568 (0.0164%)
  - EMEC: 11 of 63744 (0.0173%)
    - EM tot: 29 of 173312 (0.0167%)
  - HEC: 5 of 5632 (0.0888%)
  - FCAL: 0 of 3524 (0%)
    - total: 34 of 182468 (0.0186%)

- **LAr noisy readout channels (more than 10 sigma above phi average):**
  - EMB: 19 of 109568 (0.0173%)
  - EMEC: 2 of 63744 (0.00314%)
    - EM tot: 21 of 173312 (0.0121%)
  - HEC: 0 of 5632 (0%)
  - FCAL: 1 of 3524 (0.0284%)
    - total: 22 of 182468 (0.0121%)

- **LAr readout channels w/o calibration (constants from phi average of eta neighbours):**
  - EMB: 199 of 109568 (0.182%)
  - EMEC: 350 of 63744 (0.549%)
    - EM tot: 549 of 173312 (0.317%)
  - HEC: 37 of 5632 (0.657%)
  - FCAL: 1 of 3524 (0.0284%)
    - total: 587 of 182468 (0.322%)

- **LAr readout channels with reduced High Voltage**
  (correction factor from 1.01 to 2):
  - EMB: 7075 of 109568 (6.46%)
  - EMEC: 2936 of 63744 (4.61%)
    - EM tot: 10011 of 173312 (5.78%)
  - HEC: 1017 of 5632 (18.1%)
  - FCAL: 55 of 3524 (1.56%)
    - total: 11083 of 182468 (6.07%)