# In situ commissioning of the ATLAS electromagnetic calorimeter and early $Z' \to ee$ discovery potential

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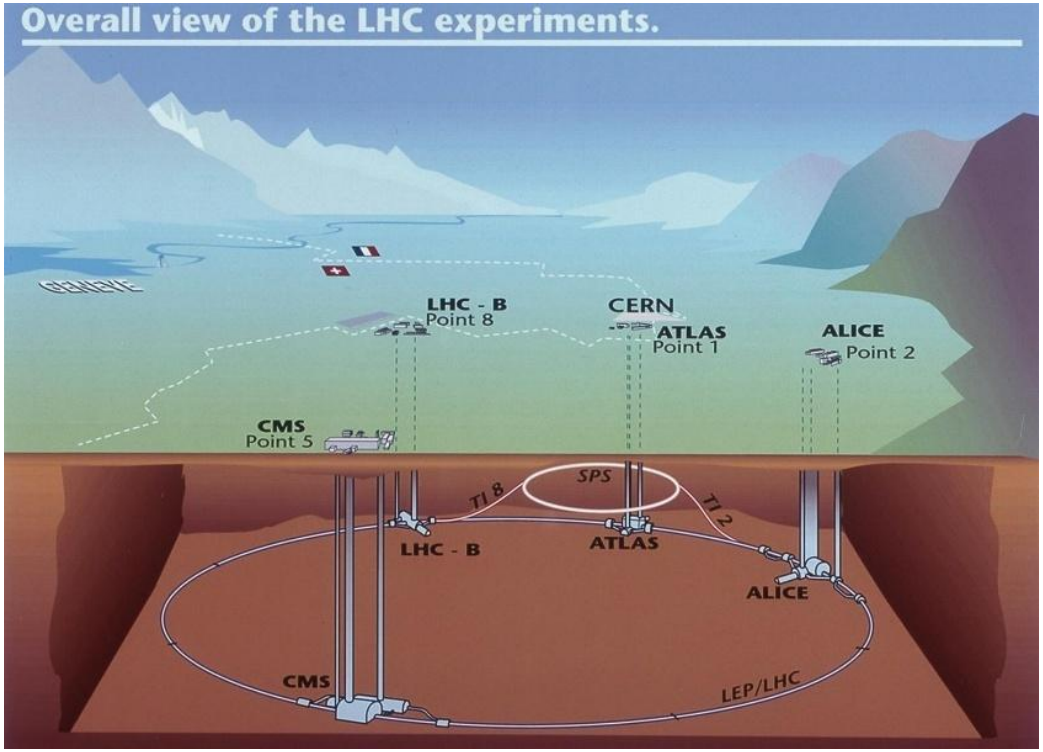
# OUTLINE

- The collider LHC, the detector ATLAS, its EM Calorimeter
- In situ commissioning of the ATLAS EM Calorimeter
    - Cosmic muons analysis
    - First LHC single beam data
- Z'→ee discovery potential in early data (with realistic detector)

# LHC

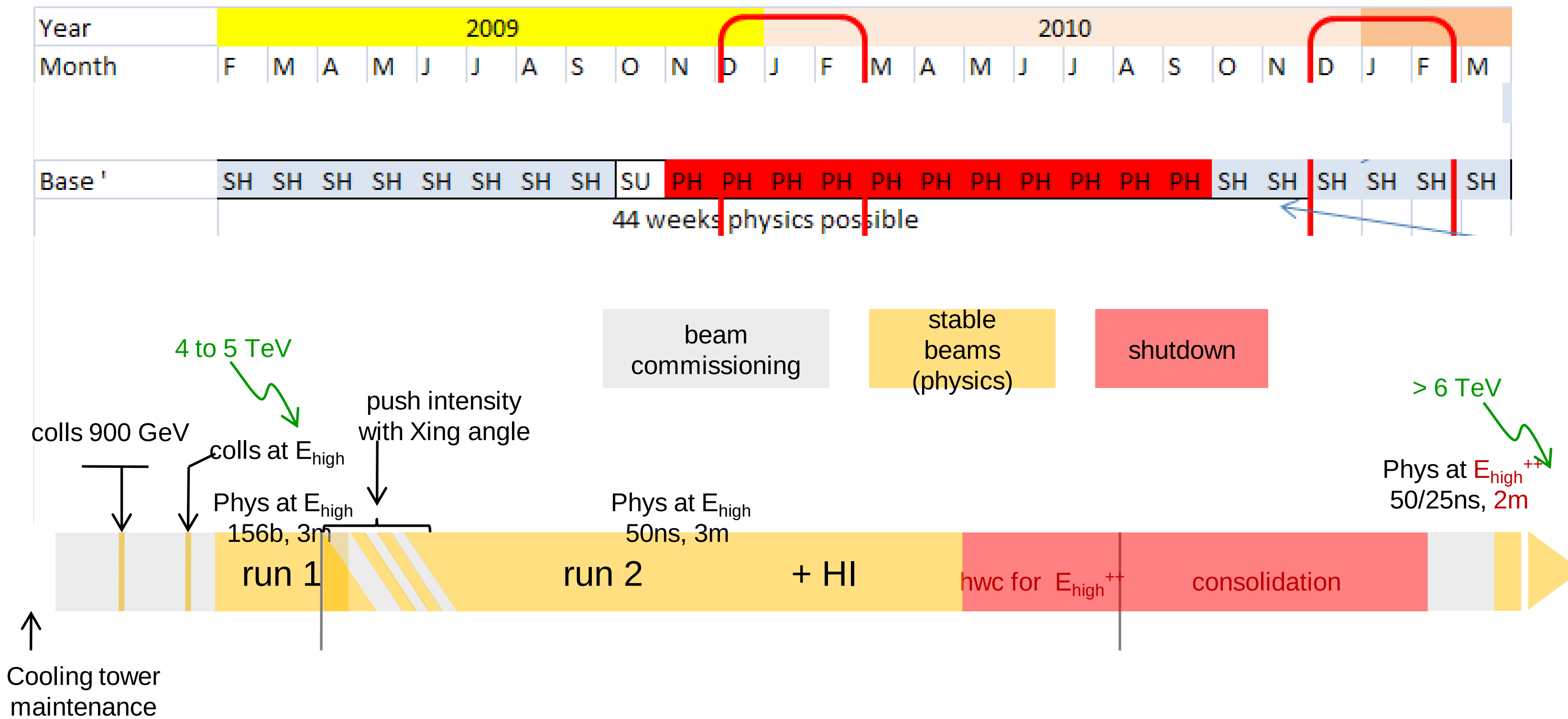
- LHC : Large Hadron Collider, pp collisions at 14 TeV (10 TeV)
- Located at CERN, ring of 27 km
- 4 interaction points for 4 experiments : ALICE, ATLAS, CMS, LHCb

- Start-up the Sept. 10th 2008
- Stopped the Sept. 19th 2008



# LHC new schedule

CERN DG: …foresee first beams in the LHC at the end of Sept. this year, with collisions in late October. A short technical stop over Christmas. Then run through to autumn next year, ..possibility of lead ion collisions in 2010.




T. Virdee, TIPP09

# New physics at LHC

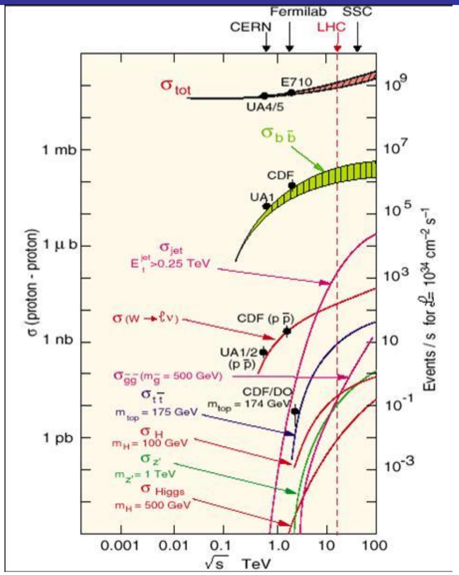
- pp collision at 14 (10) TeV in the center of mass
  - New phase space available
  - New physics may be visible
- Examples :
  - Understand the Electroweak Symetry Breaking

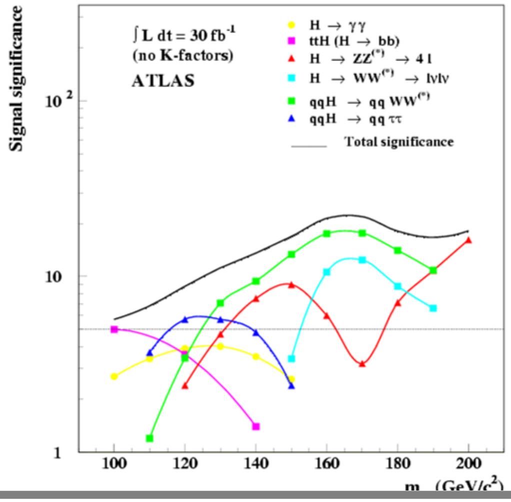
    → Higgs
  - New heavy gauge bosons

| Processus | Tevatron 1987 (0.07pb$^{-1}$) | Tevatron 2009 (8fb$^{-1}$) | LHC (1fb$^{-1}$) |
|---|---|---|---|
| Z' 1TeV | << 1 evt | < 10 evts | >1000 evts |

→ **Possible discoveries soon after the start-up**

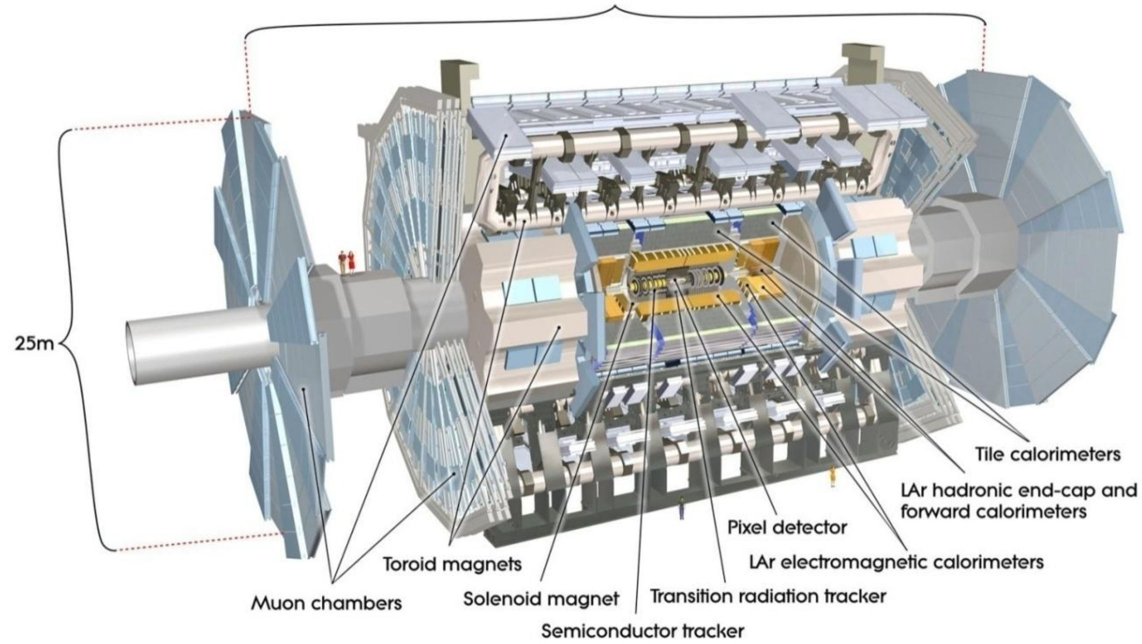
→ **Detector must be understood**

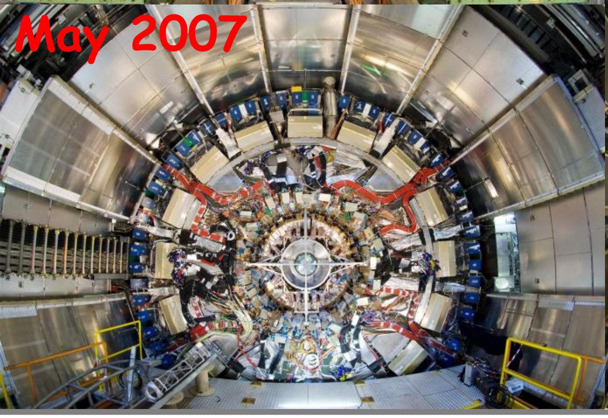


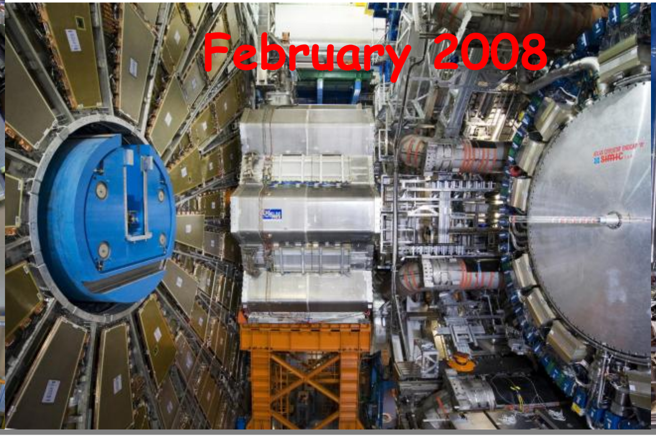



# The ATLAS detector



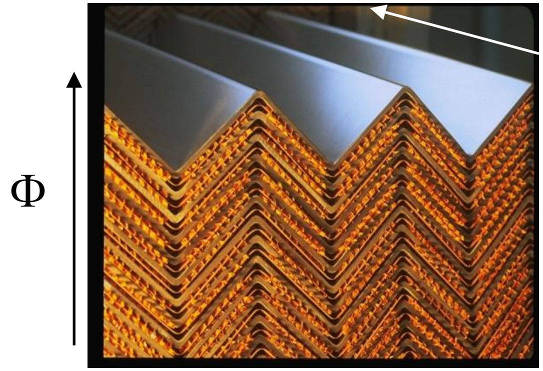


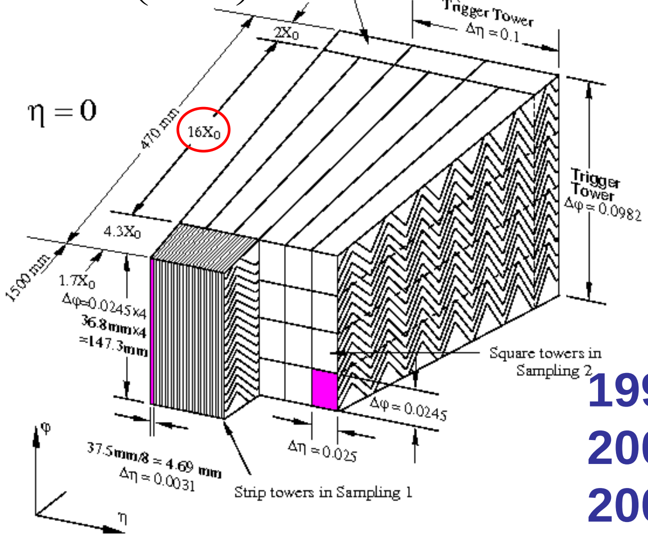




# The ATLAS EM Calorimeter

- Sampling Calorimeter Pb / Liquid Argon (90K)
- Accordeon geometry
  - Almost perfect azimuthal hermeticity
- Fine granularity thanks to longitudinal and transverse segmentation: ~175 000 channels




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




Large pseudo-rapidity coverage $|\eta|<3.2$

- **PS** ➔ energy loss
- **S1 0.003×0.1** ➔ position measurements
- **S2 0.025×0.025** ➔ main energy deposits
- **S3 0.05×0.025** ➔ longitudinal leakage

**1999-2002+2004 : Beam Tests**
**2001-2004 : Construction**
**2004-2008 : Installation and commissioning in the cavern**

# Why using cosmic muons?

- The only physics signals available in the cavern before LHC beam
- Continuity of the commissioning after beam tests
  - Operate *in situ* the detector as a whole system
  - Check *in situ* the physics channels
  - Improve the signal reconstruction
  - Performances test ($\eta$ uniformity, timing …)
- First cosmic data taken in 2006
  - No tracker
  - No muon chambers
  - Few calorimeter modules available : small statistic
  - Very low signal (~300 MeV)

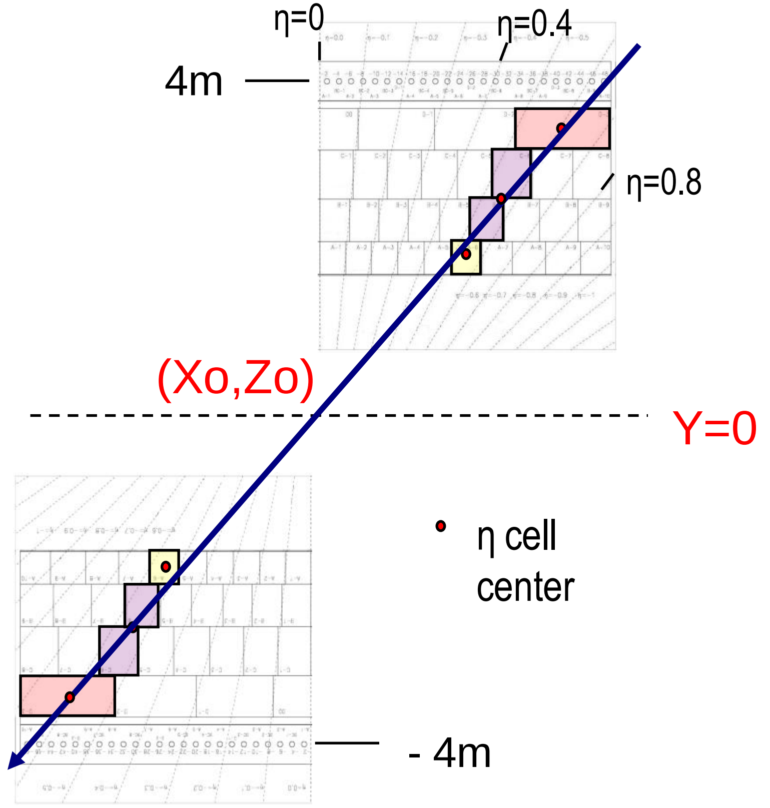
Dedicated trigger using the hadronic calorimeter

# Track reconstruction

No available trackers

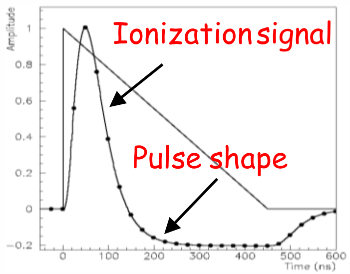
➔ Dedicated algorithm using hadronic calorimeter information

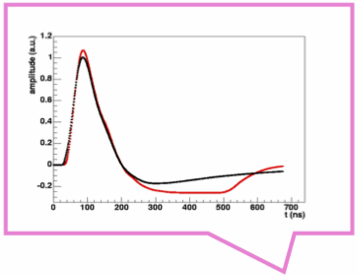
- Cell energy threshold : 100 MeV
- TileCells in top AND bottom: long lever arm
- Fit track that minimizes sum of orthogonal distances to cells weighted by energy density
- Track crosses horizontal plane at (Xo,Zo)




~50% of triggered events have « tile track »

# Signal reconstruction at cell level



ADC to DAC (Ramps)

Pulse Samples

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

Calculation of maximum amplitude

Cell energy

Sampling fraction

Calibration board

Optimal Filtering Coefficients

Pedestals

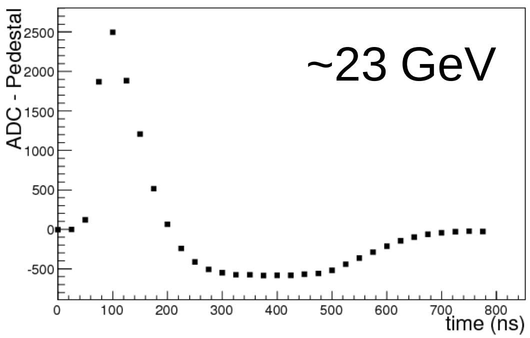
The above formula describe the LAr electronic calibration chain (from the signal ADC samples to the raw energy in the cell. Note that this version of the formula uses the general $M_{ramps}$-order polynomial fit of the ramps. Actually we just use a linear fit (electronic is very linear, and additionally we only want to apply a linear gain in the DSP in order to be able to undo it offline, and apply a more refined calibration). In this case, the formula is simply:

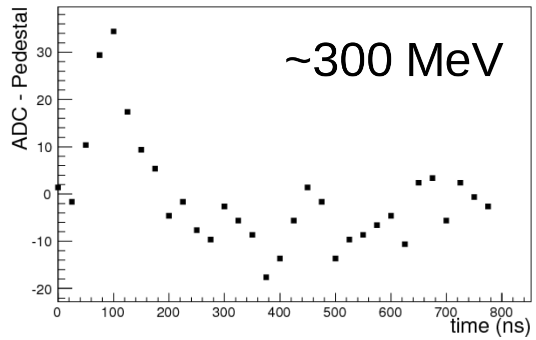
$$E_{\mathrm{cell}} = F_{\mu\mathrm{A}\to\mathrm{MeV}} \cdot F_{DAC\to\mu\mathrm{A}} \cdot \frac{1}{\frac{\mathrm{M_{phys}}}{\mathrm{M_{cali}}}} \cdot R \left[ \sum_{j=1}^{N_{\mathrm{samples}}} a_j \left( s_j - p \right) \right]$$

- Need good prediction of physics pulse shapes
- Need good timing

# Muon signal reconstruction in EM Calo

- Cosmic muons : Low signal (300 MeV) : Reduced noise is crucial !!
- Asynchrone arrival time : Determine the good timing windows !!

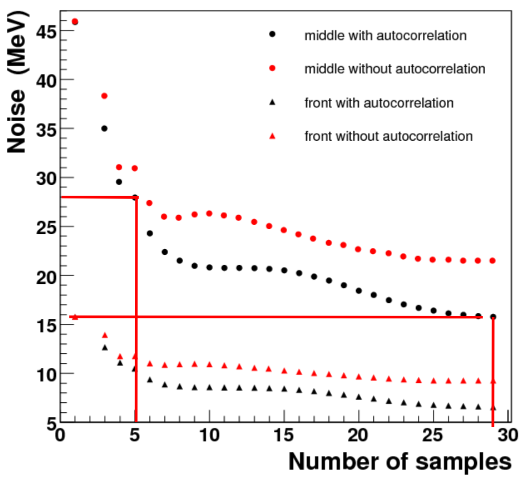



Maximal amplitude $A_{max} = \sum_{k=1}^{N_s} a_k S_k$

$$A_{max}\Delta t = \sum_{k=1}^{N_s} b_k S_k$$

Timing : $t_{prediction} - t_{real}$




➔ Can decrease the noise contribution by a factor 1.8 (2.9) from 5 (1) samples (1s) to 29 samples reconstruction

➔ Energy underestimated by ~3%

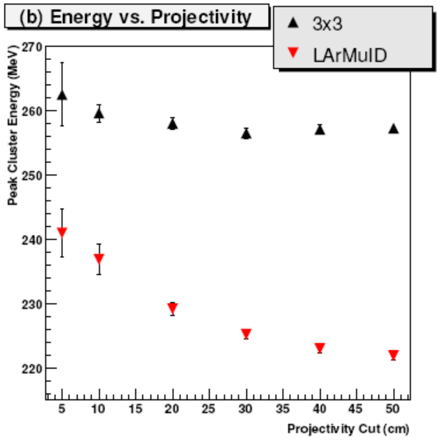
# Cluster algorithms

- Projective muon : 2 cells clusters adjacent in phi
- Cosmic muons are not projective : What kind of cluster algorithm ??

✓ LArMuID : topo. cluster of S2 cells (Seed > 100 MeV>5σ, Neig. > 50 MeV>3σ)

➔ Developped to tag muons in collision data

➔ Underestimate the energy (Missed energy)




✓ 3x3 : Fixed size cluster of S2 cells (Seed >100MeV)

➔ Do not suffer of noise (29s reconstruction)

➔ Small dependence to projectivity (~1-2%)

➔ Suitable choice for the non-uniformity study

➔ Underestimate the energy by 1%

✓ 1X3 : Fixed size cluster of S2 cells (Seed >100MeV + Projectivity cuts)

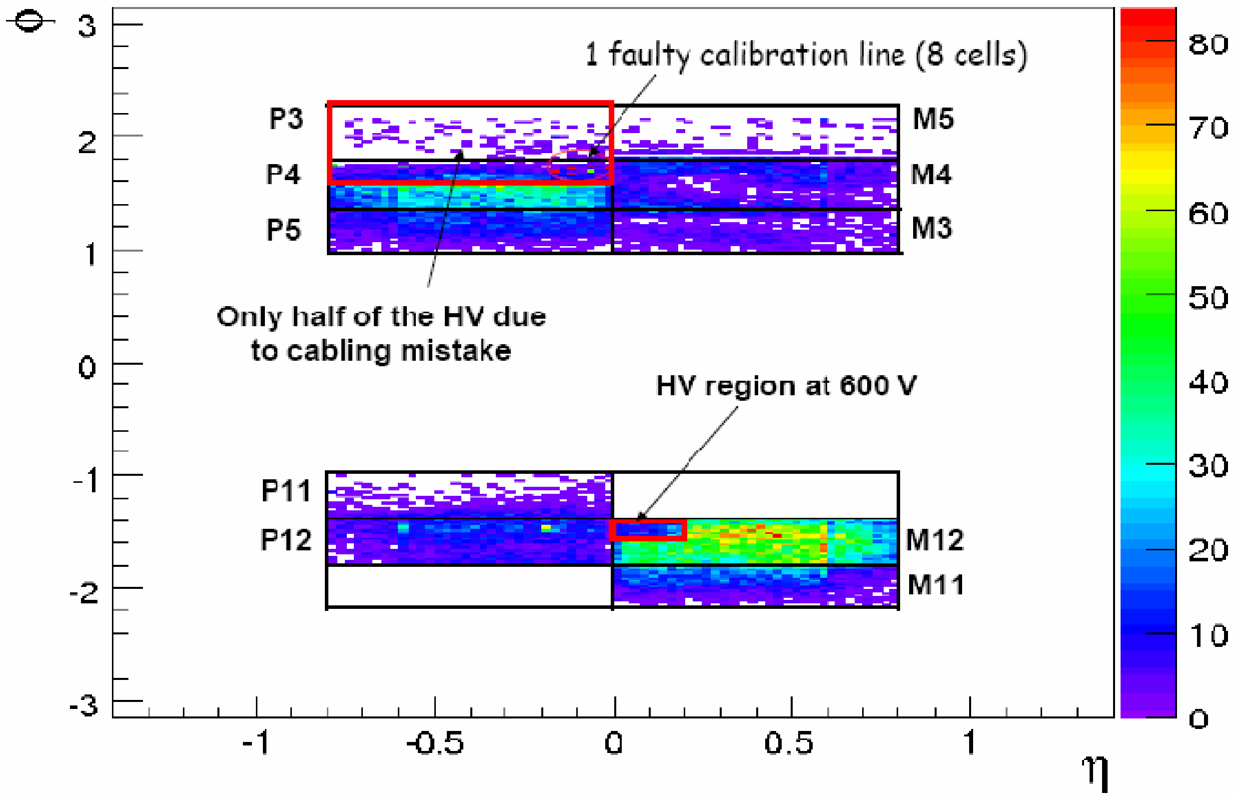
➔ Reduce available statistics

➔ Less sensitive to noise

➔ ~98% of energy is mesured

# Clusters map & first *in situ* tests

Number of clusters per S2 EM Barrel cells




➔ First opportunity to commission *in situ* the calorimeter

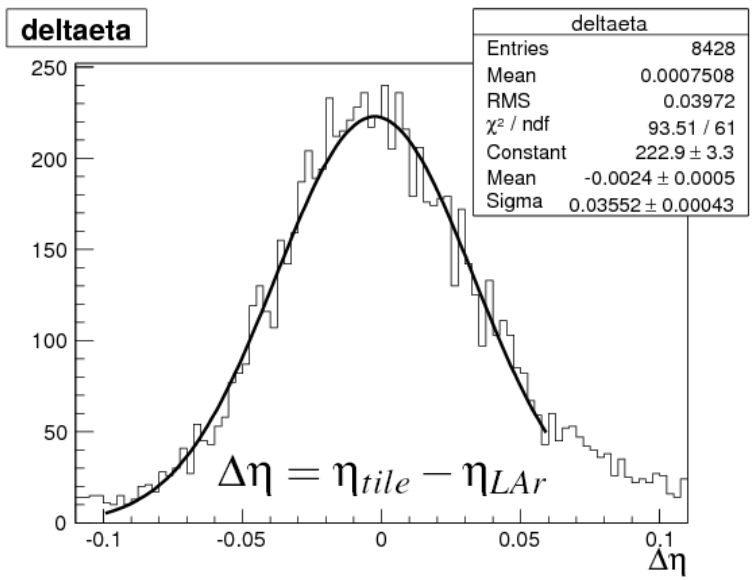
➔ Few problems have been identified and fixed

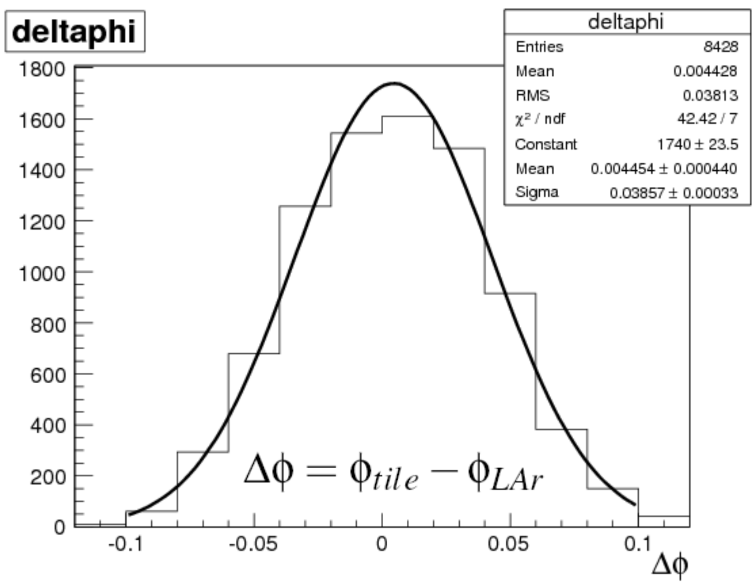
# Tile Track/EM cluster matching

All EM clusters are not necessarily due to muons

Extrapolate the track to S2 $(\eta_{tile}, \phi_{tile})$

Compare with cluster position $(\eta_{LAr}, \phi_{LAr})$




➔ $|\Delta\eta| \times |\Delta\phi| < 0.11 \times 0.11$ : Purity of ~ 100%

➔ No tile criteria : Purity of ~ 90%

# Muons projectivity

To check the energy response uniformity

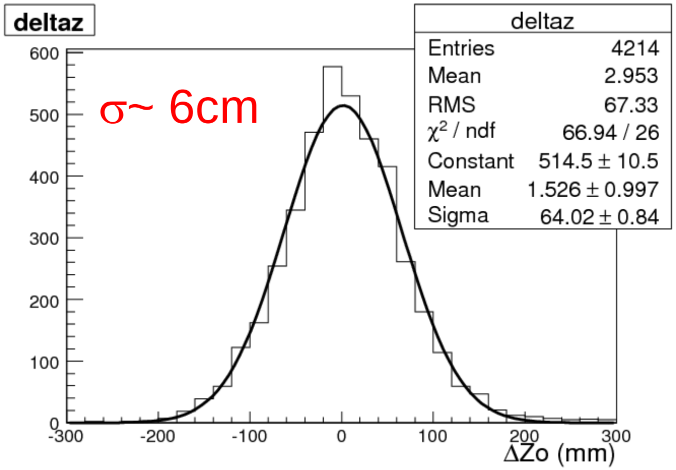
➔ Need to know how well projective the muons are

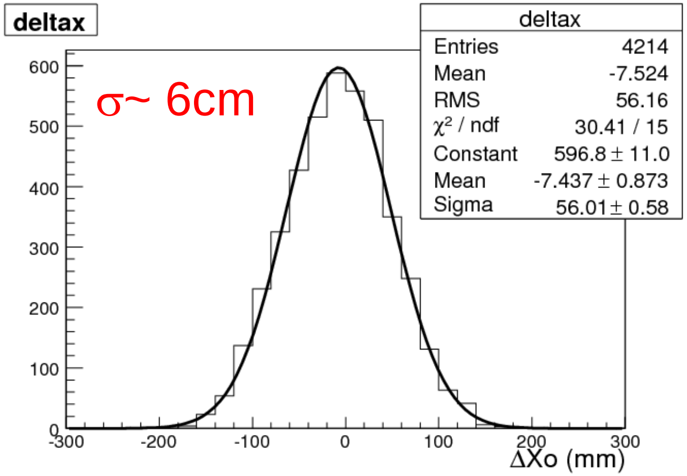
➔ Can we use again the tile information?

Events with 2 EM clusters one in top and one in bottom

Extrapolate a LAr track to plan Y=0 $(X_{0LAr}, Z_{0LAr})$

Compare to tile track position $(X_0, Z_0)$



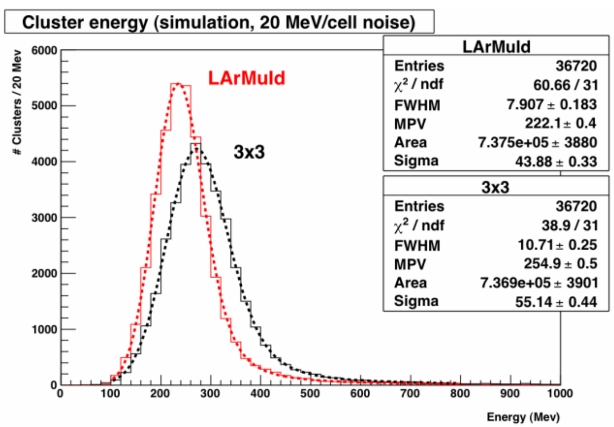

➔ Can use safely the tile track for projectivity selection

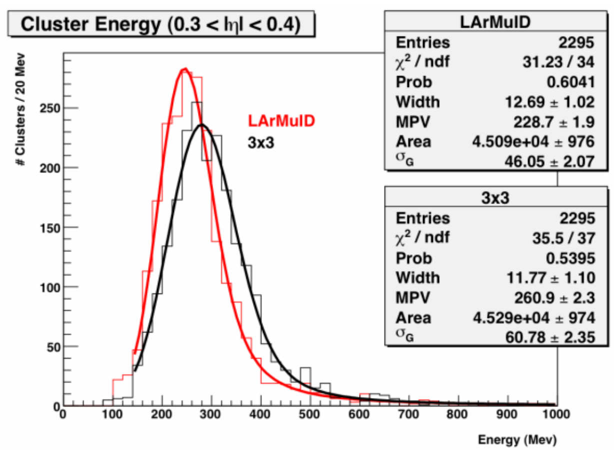
➔ Projectivity cut applied : 30cm x 30 cm

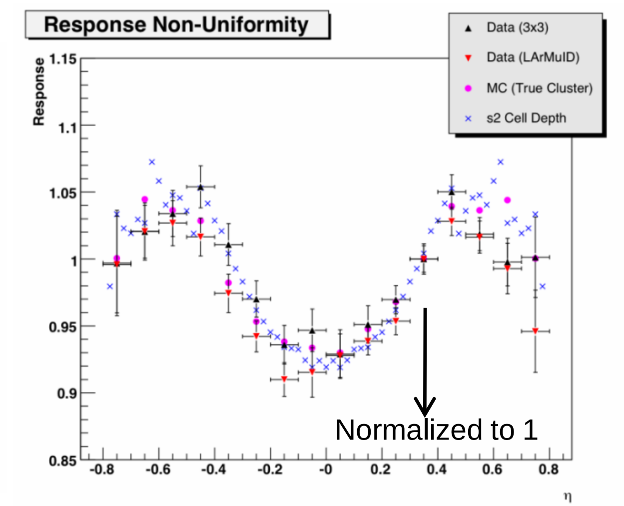
# Energy Response in EM Calo

A first *in situ* check of the performance of the EM Calo has been performed with the first cosmic data taken in 2006 and March 2007 (~120k events).

**Cluster energy distributions have been fit with a Landau convoluted with a Gaussian**




➔ Systematic uncertainties on energy scale of ~5%

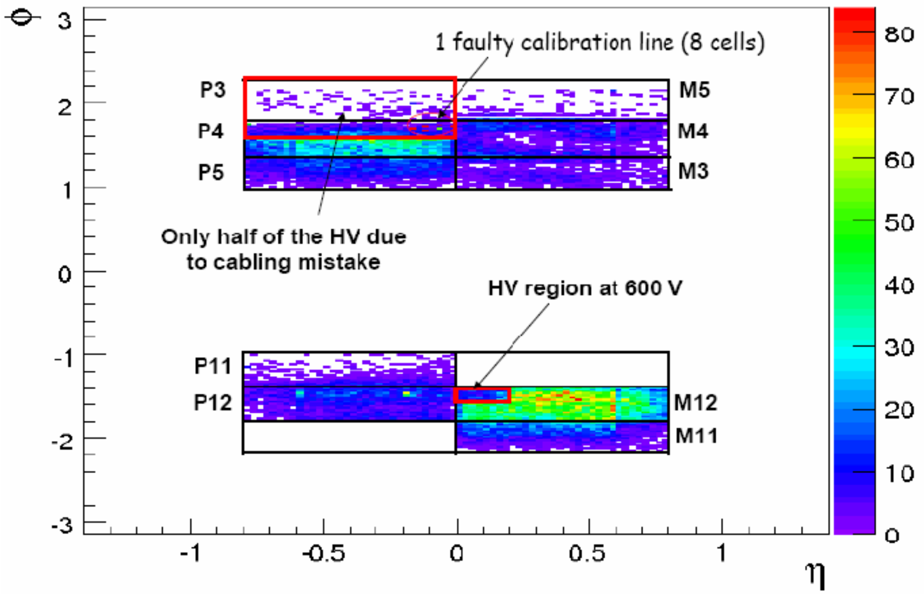
➔ Uniformity agrees with simulation within < 2%

➔ A similar study is currently performed with the new statistics (~2M events)

# Search of new dead cells

- Search of new dead channels:
  - From calibration pulse injection : expected <0.02%
  - Search only on 6% of the calorimeter coverage

Number of clusters per S2 EM Barrel cells

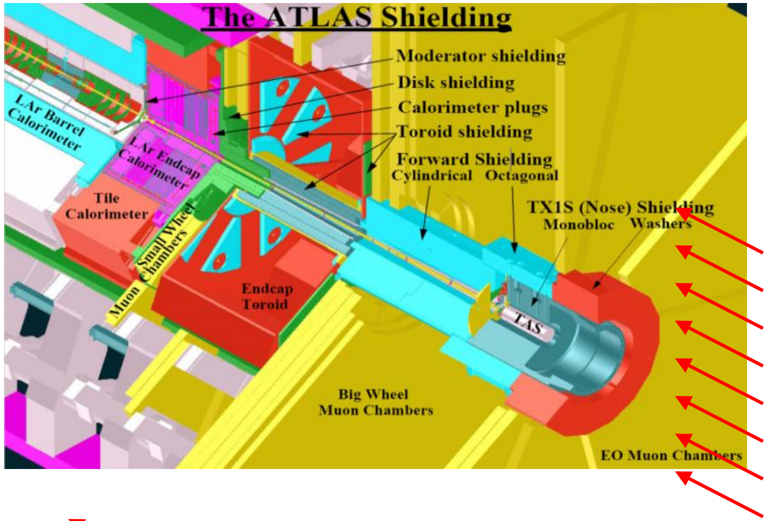



➔ No new S2 dead cells in the available region

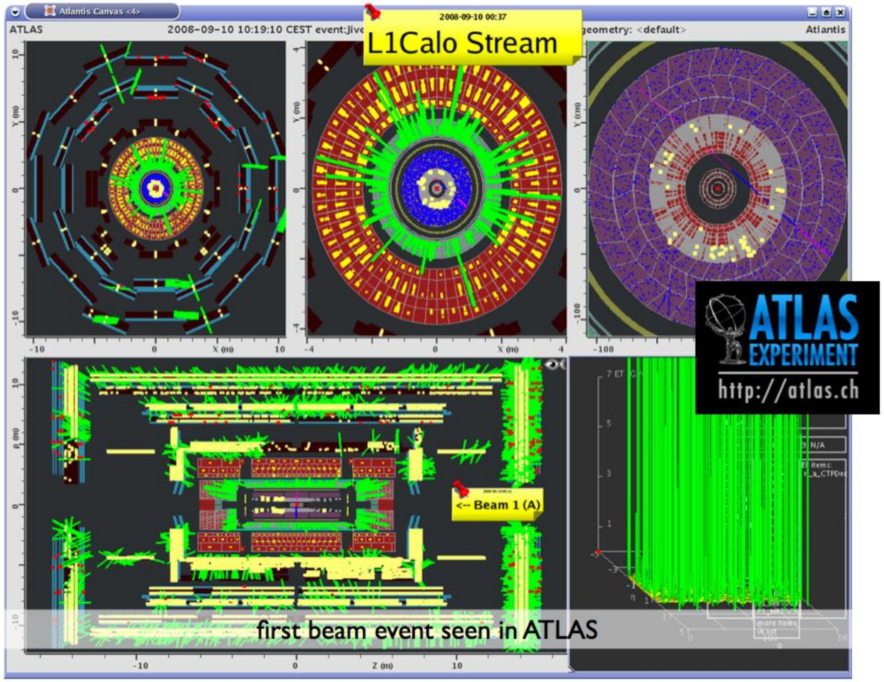
➔ Not enough statistics for the other layers

# Single Beam runs

- During the first week of LHC operation in September 2008
  - ➢ Several single beam runs with splash events from beams 1 & 2
  - ➢ Due to the collimator position (140 m in front of the ATLAS interaction point) a specific energy flow occurs in calorimeter

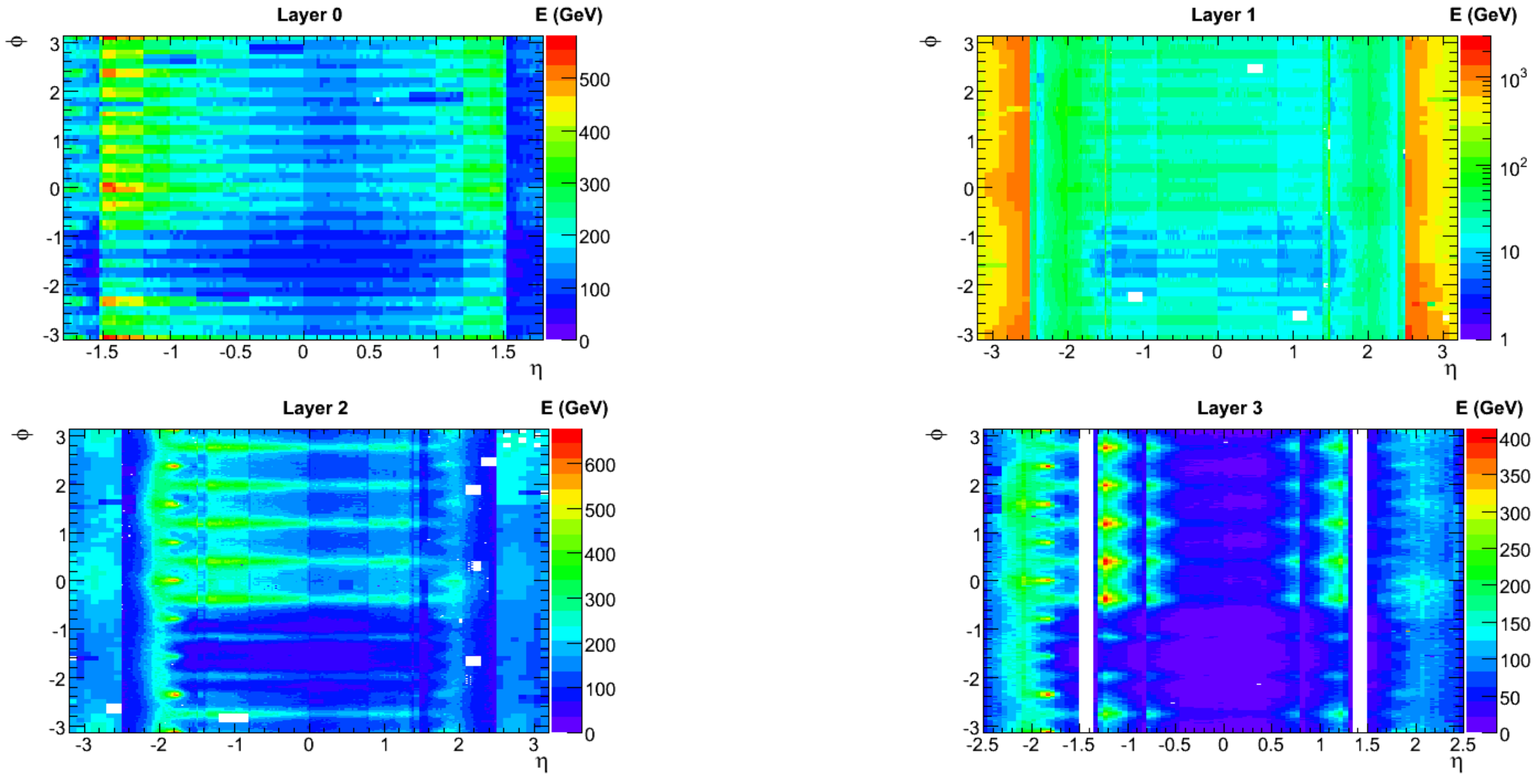



Particles flow (μ, π ....)



# Energy deposits in EM Calorimeter

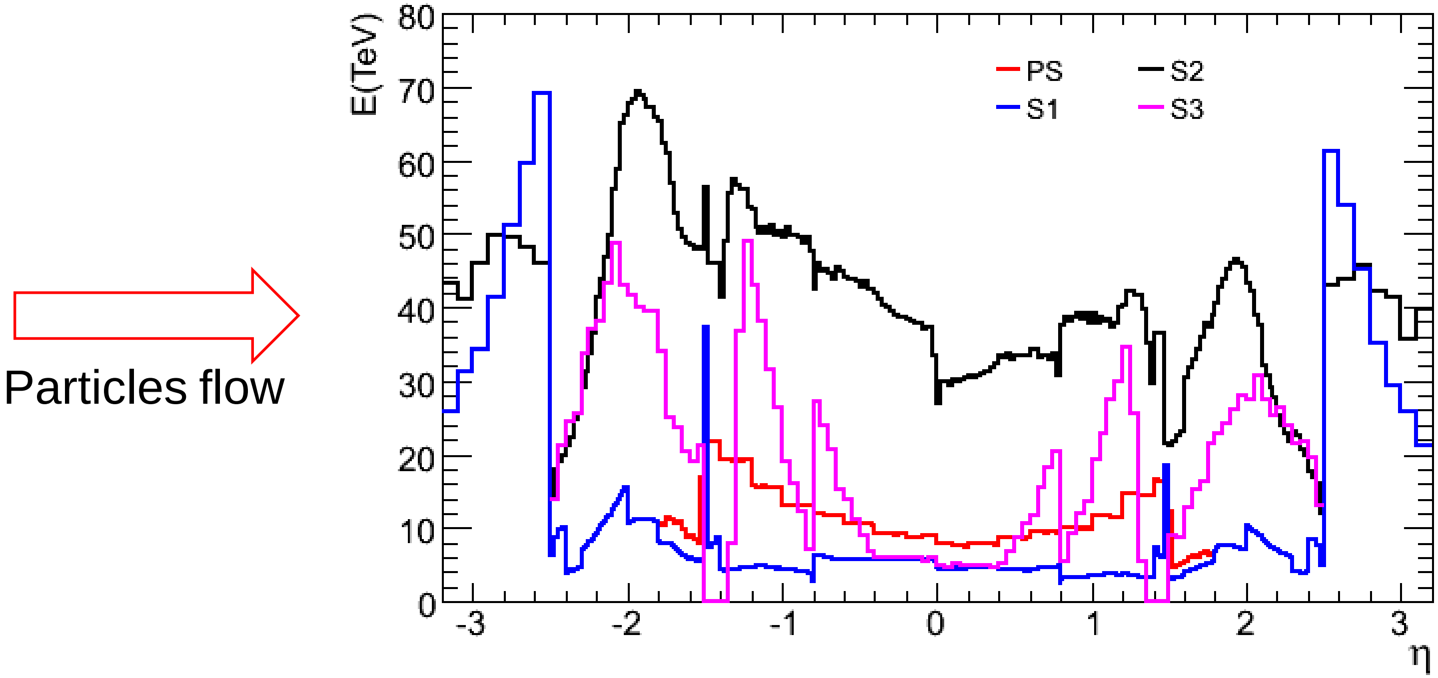
Accumulated energy (Ecell > 5$\sigma$) over 100 single beam events




- ➔ Deposited energy > 100 TeV per event
- ➔ Energy flow over the whole EM calorimeter in the four layers
- ➔ Several structure are observed

# Scanned geometry

Accumulated energy (Ecell > 5$\sigma$) as a function of $\eta$

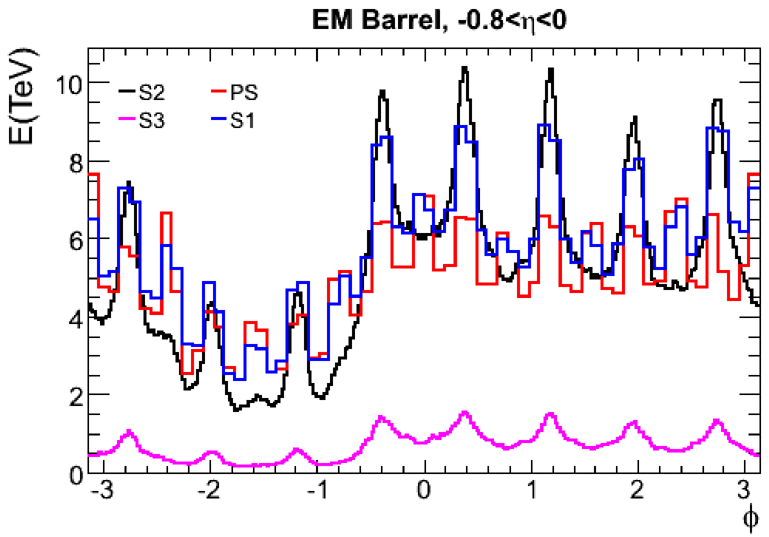


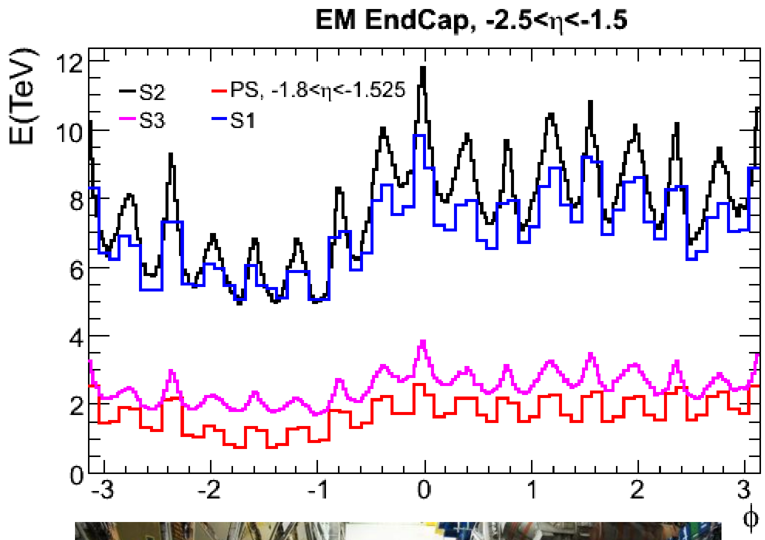

➔ Structure and geometry of all layers is clearly visible

➔ None obvious problem

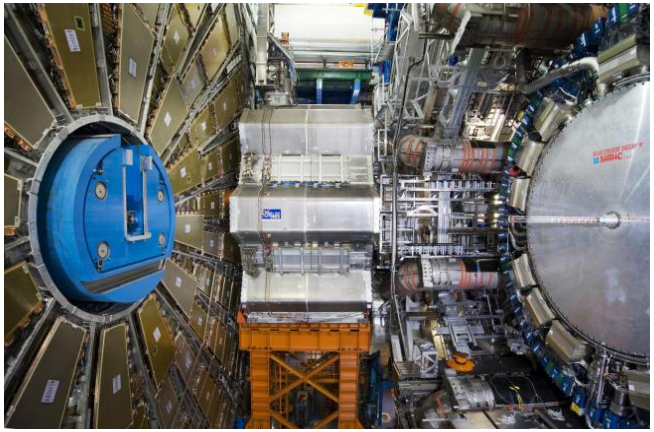
# Influence of matter

Accumulated energy (Ecell > 5σ) as a function of azimuthal angle



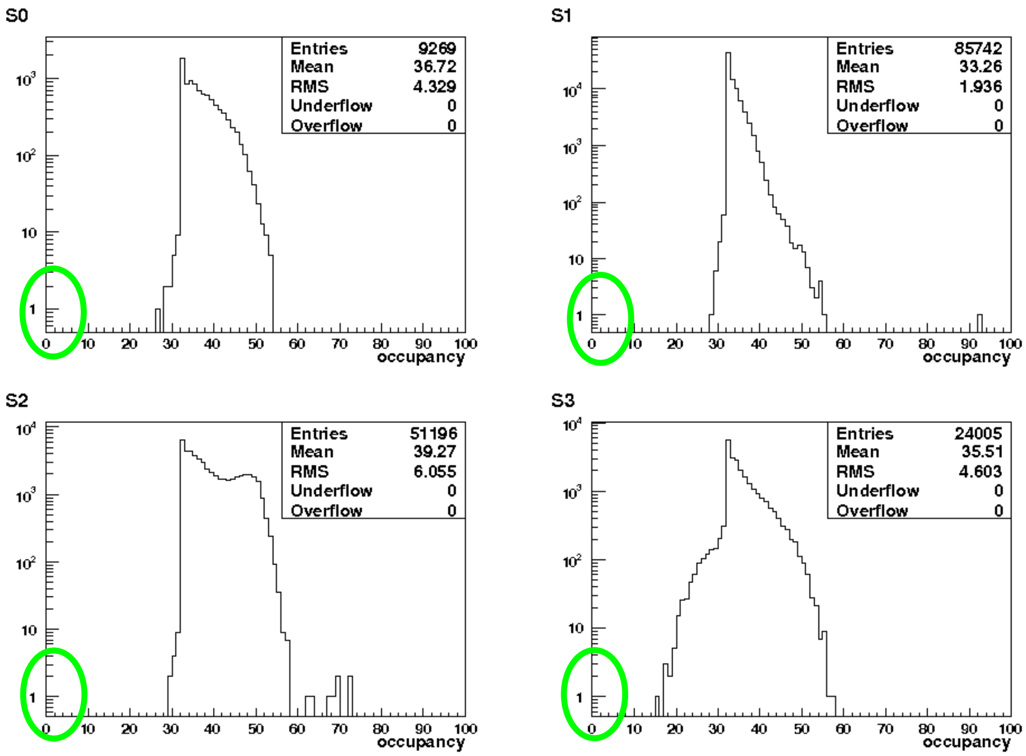




The amount of matter between the collimator and ATLAS induces a specific particles flow trough the detector and b.c. a specific energy flow in the calorimeter



# Dead cells search

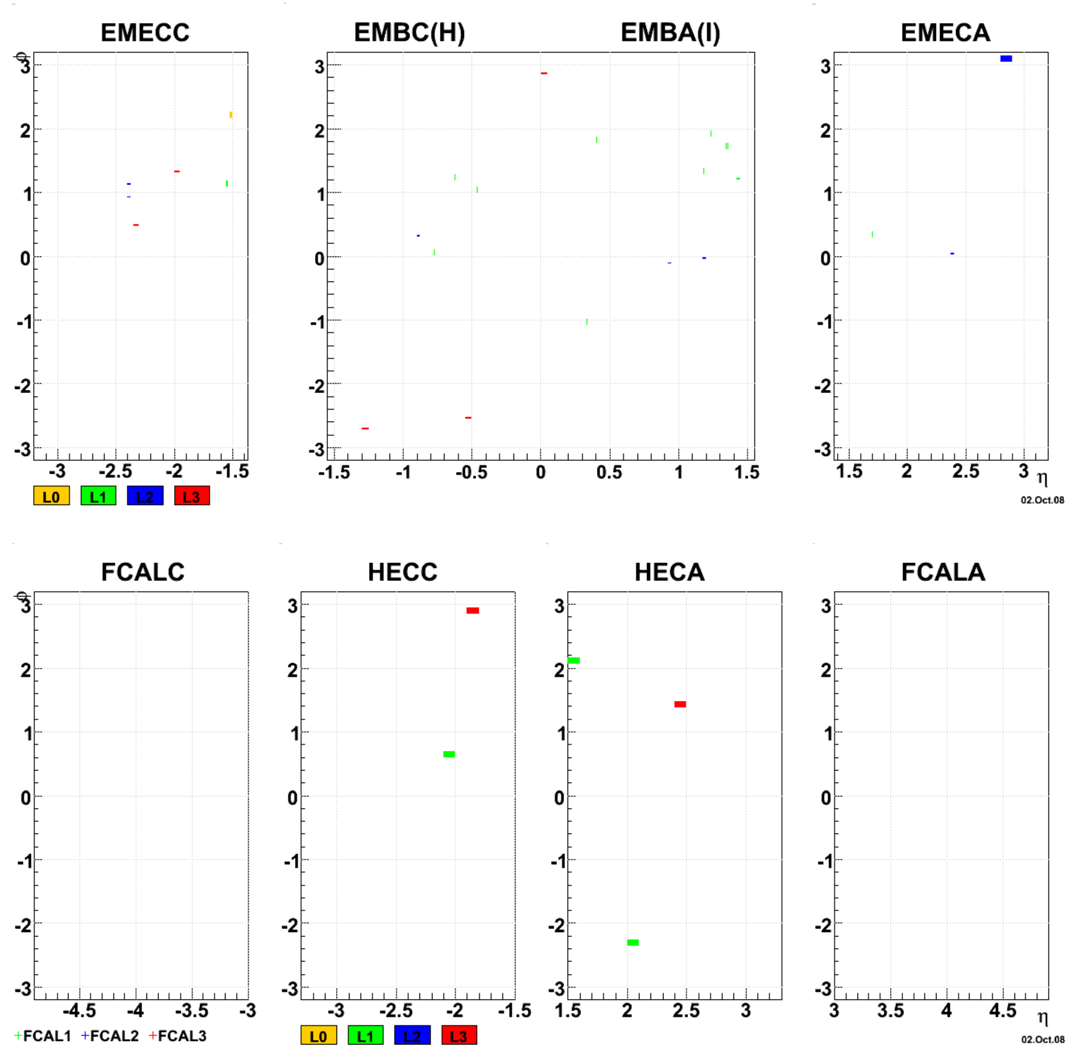
- Energy deposits over the whole EM calo (cosmics : ~6%)
- Over the100 available events, count the number of times a cell has a deposited energy E> 5 times the noise




No new dead cells

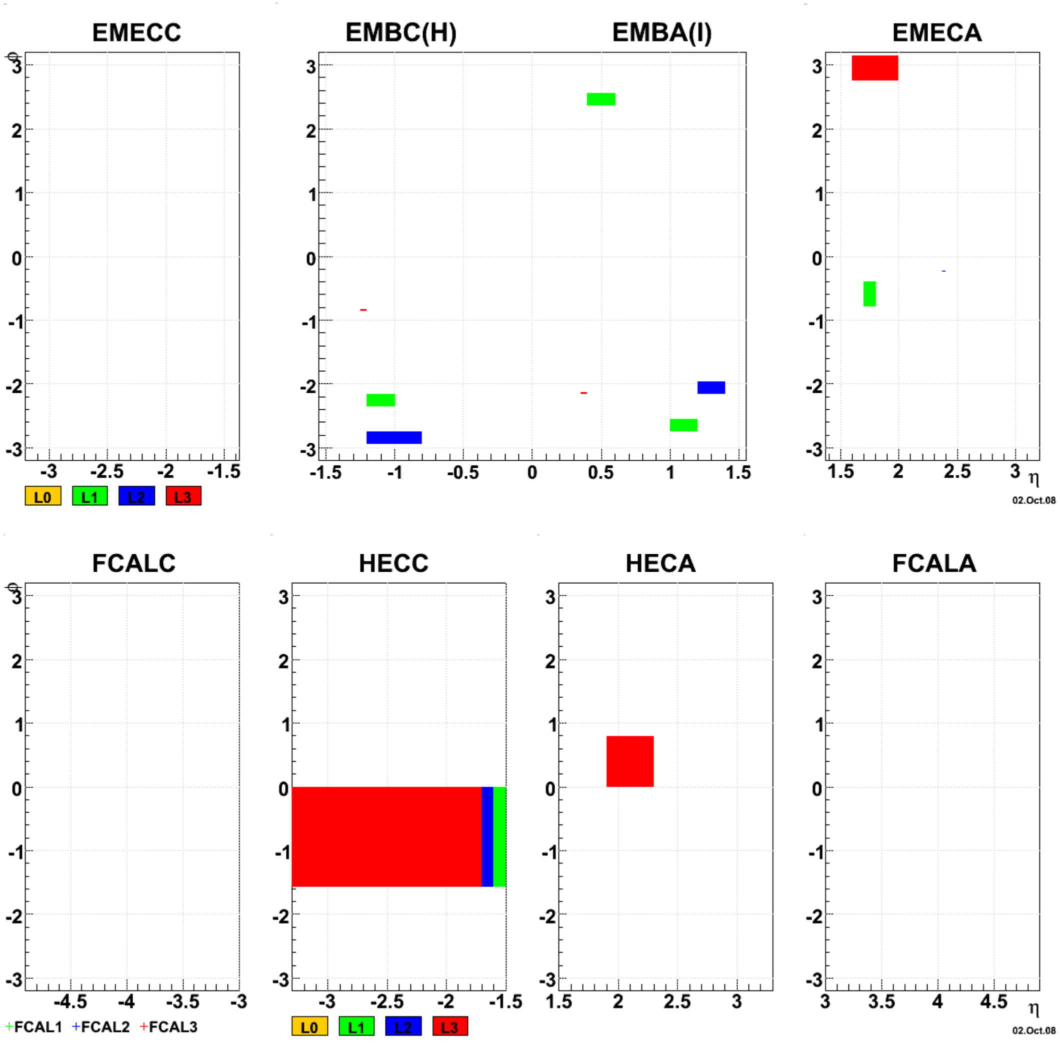
# LAr Dead Channels in 2008

- Channels that can not be read out from the detector
- The problem is expected to be located inside the detector
- No repair foreseen
- Dead channels < 0.02 %
- No High Voltage dead zone
- ~ 6% need Correction > 1%

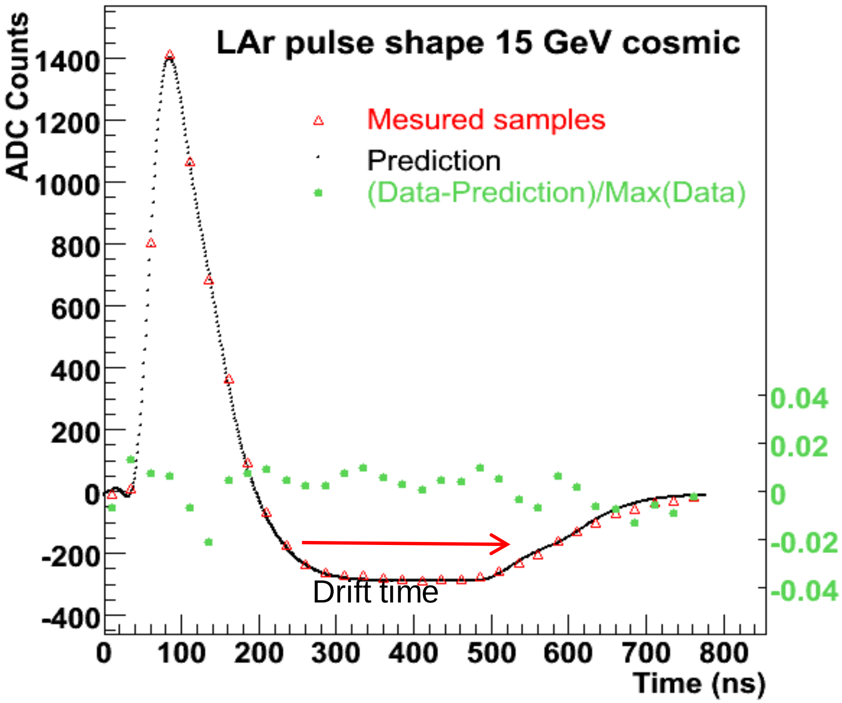


# LAr Dead Readout Channels in 2008

- channels for which the electronics readout is currently not functioning
- To be fixed in shutdown
- Dead readout channels < 0.95%

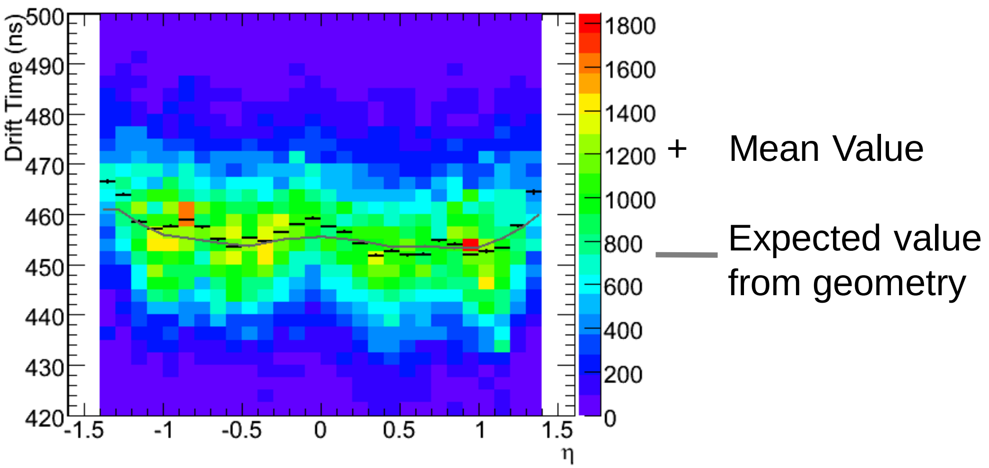


# Pulse Shapes : EM Calo




The rising at the end of the pulse is sensitive to a shift of the electrode with respect to its nominal central positioning

Need 32 samples recorded data




➔ Physics pulses are well predicted

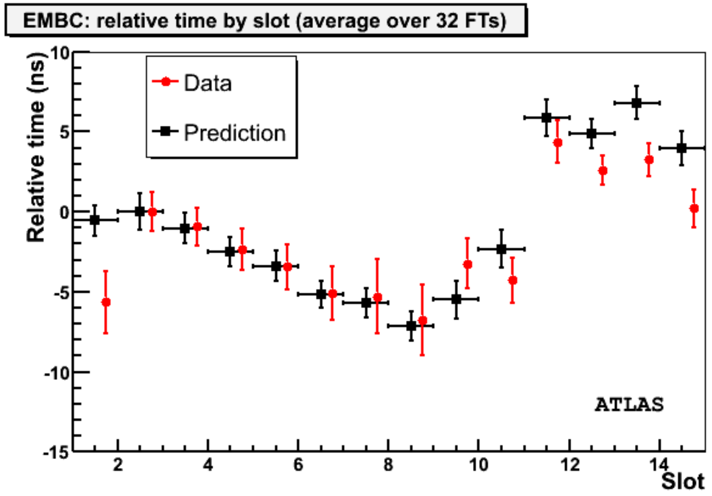
➔ Residuals ~1-2%

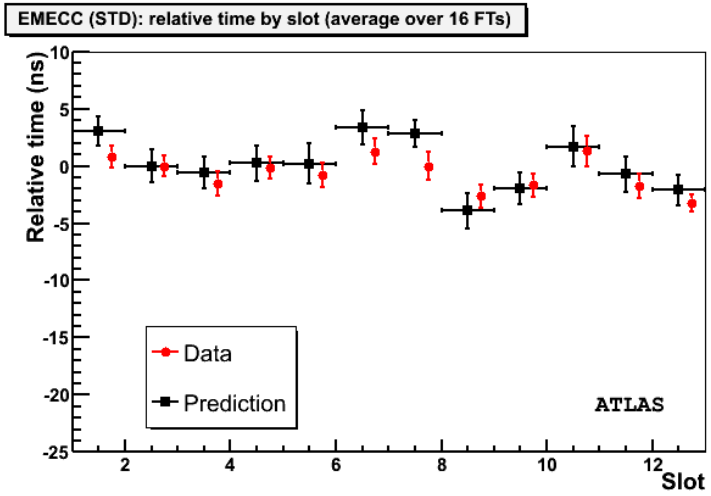
➔ The contribution of the gap variation to the barrel calorimeter response uniformity is not larger than 0.3%

# Timing study in EM Calo

The difference between the physics timing and the calibration timing was extracted per cell and per type of FEB from single beam events

Data: the time is first computed straightforwardly using the OFC iteration and then a time-of-flight correction is applied to get an "equivalent-to-collisions" time.
Prediction : the time is computed from the calibration pulse and the readout path.




→ The agreement between the measurement of the time and the prediction using calibration pulses is at the level of 2 ns except for the presampler

# To a Z' Discovery ?

- LHC is a machine with a fast discovery potential
- The understanding of first collision data is crucial
- All the commissioning work performed with cosmics and single LHC beam data is necessary to an optimal use of data

- To a experimental physicist (on collider) , a Z' is an resonance, heavier than the SM Z one, observed in the Drell-Yan $pp \rightarrow l^+l^- + X$ with $l=\mu,e,\tau$
- I focused my study on the discovery potential of a $Z' \rightarrow e^+e^-$ using only the EM calorimeter

# A realistic approach

## 1. Can we use the EM calo only?

→ Keeping a maximum electron identification efficiency

→ Rejecting background :

- Without hadronic calo : Jets rejection?
- Without tracker : No $\gamma$ rejection

## 2. The non nominal EM calo performances

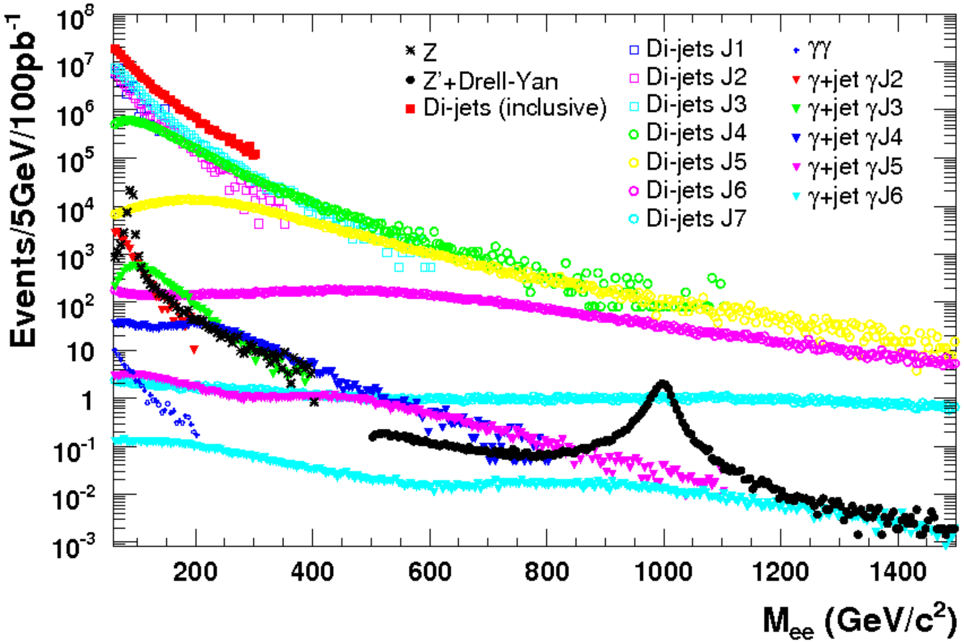
→ What impact on the energy reconstruction ?

→ The constant term may be degraded wrt measurements realized during the beam tests.

→ Effects linked the trigger system ?

# Signal and Backgrounds

Simulation from the last ATLAS data challenge (14 TeV)



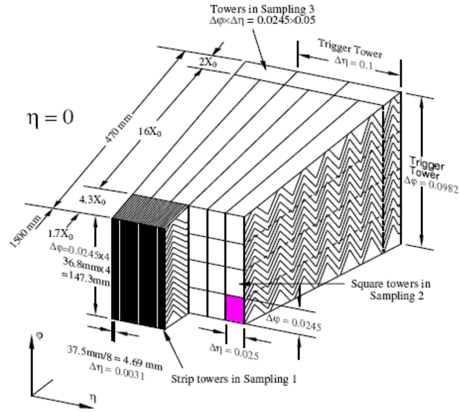

→ 3 orders of magnitude between signal and QCD background

**Challenges :**

Can we reject it by a factor 1000 with the EM calo only?

Can we do it keeping a good efficiency? (signal limited search)

# Electron Identification




- **Simple and robust cuts :**
  - Based on the EM Calo only
  - η independant cuts
  - Similar as for the Z extraction
- **Take advantage of EM decay specificities :**
  - Longitudinally : energy fractions in S1, S2, S3
  - Laterally : energy distribution for different sizes of cluster in S1, S2, S3

➔ Uncalibrated energy of clusters was available

- I tested several sizes in the three layers

# QCD background rejection (1)

**EM and hadronic showers in the calorimeter are different**

Longitudinal development :

**Energy fraction in S3**

Lateral development :

Main energy deposit in S2

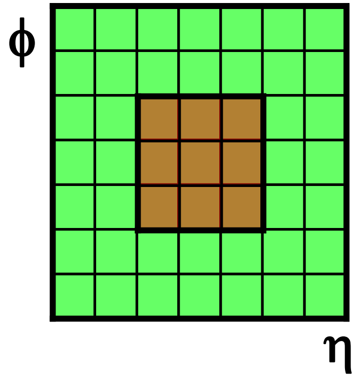
**Ratio E(3x3)/E(7x7)**

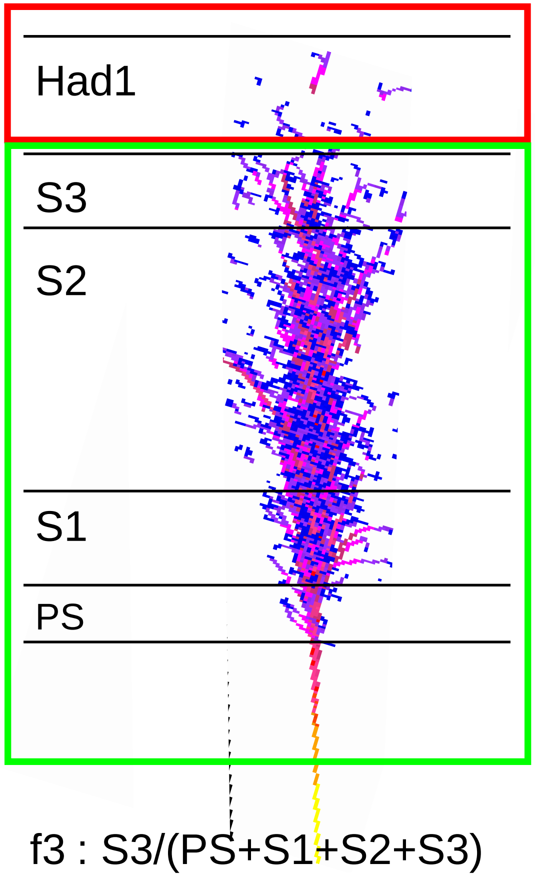
Fine granularity in S1

**Width of EM shower in S1**

Had. Calo

EM Calo



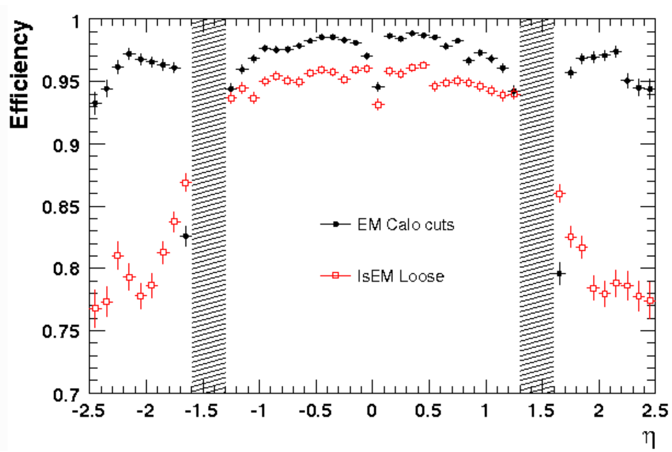



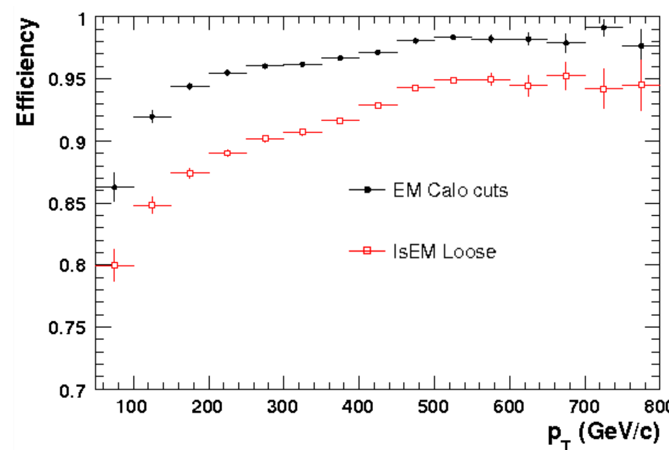

f3 : S3/(PS+S1+S2+S3)

# QCD background rejection(2)

- 3 simple cuts, based on EM calo only, η independant :
  - → f3 <0.04, >85% of energy in a 3x3 cluster, width in S1< 2.5

| Cuts | Ident. Eff. | J4 Rej. | J5 Rej. | J6 Rej. |
|---|---|---|---|---|
| Our 3 cuts | **96.4%** | **71.0** | **51.8** | **29.2** |
| ATLAS Standard | **91.2%** | **29.8** | **35.4** | **39.6** |




→ Better efficiency with the 3 cut than with ATLAS standard (End-caps)

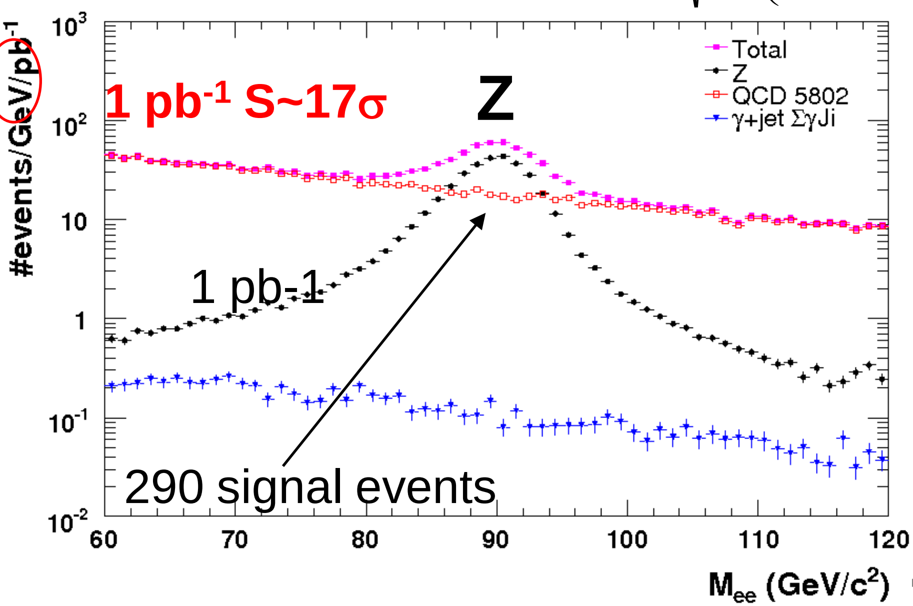
→ Important for a discovery because the search is signal limited

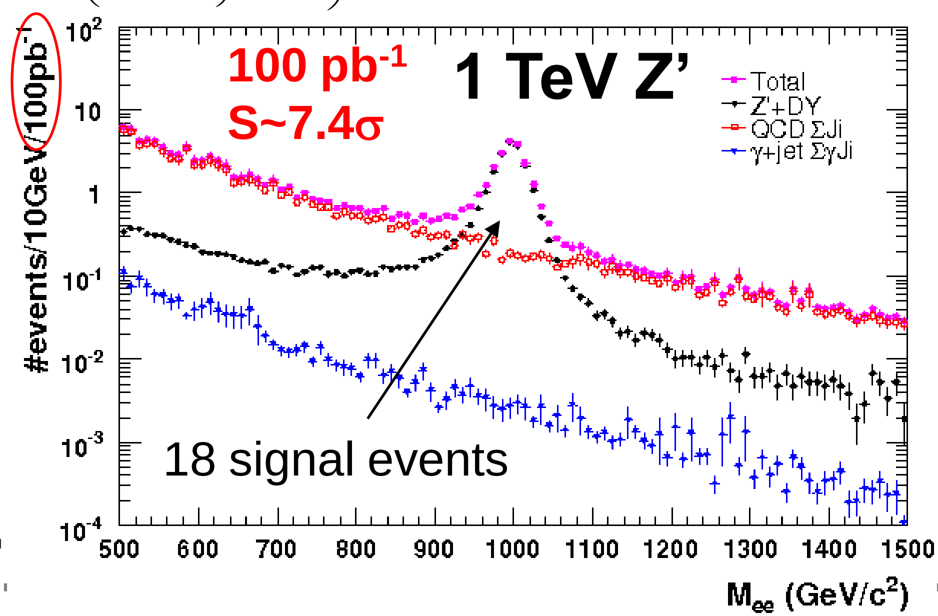
→ Similar cuts as for the Z extraction from the first data

# Signal extraction with the EM calo

- Up to now, only the EM calo is used
- Photons are not rejected:
  - γ+jets : complete simulation ~100 times < QCD
  - γγ et W+γ are negligible

Significance : $S = \sqrt{2\times\left(\left(Sig+B\right)\times\ln\left(1+\frac{Sig}{B}\right)-Sig\right)}$



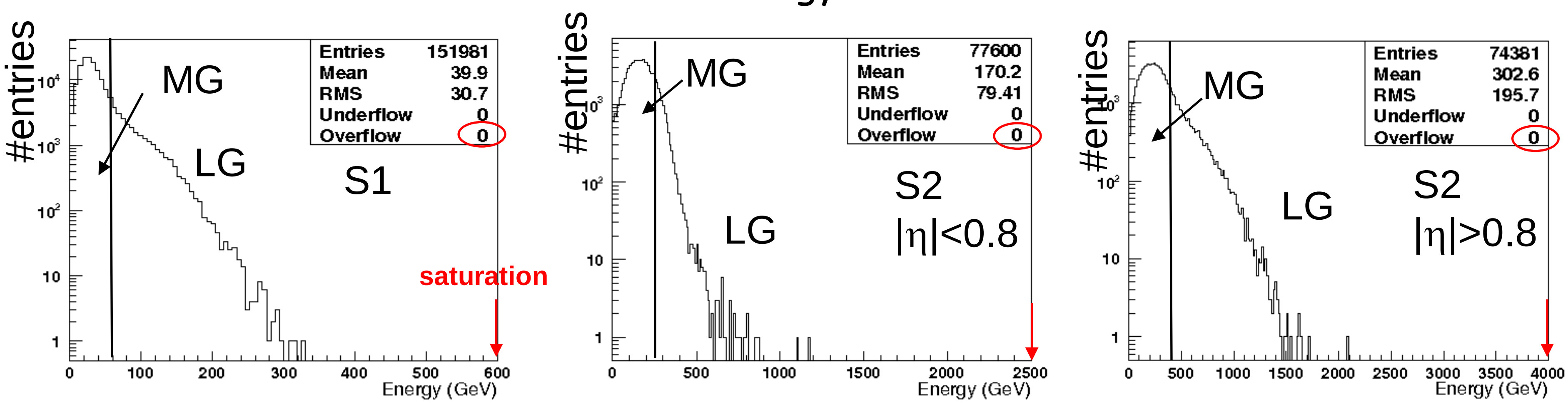



# Saturation

- EM calorimeter has been designed to be able to see a Z'
- 3 electronic gains allow an energy reconstruction with a large dynamic range : from few tens of MeV to few TeV electrons

MG : Medium Gain
LG : Low Gain

Maximum energy cell in cluster




→ For 1 TeV Z', ATLAS is not affected by saturation

→ Extrapol. : 5% of S1 and S2 (|η|<0.8) cells will saturate for a 6 TeV Z'

# Energy reconstruction

- The calibrated energy reconstruction sums the weighted energies of clusters in the PS and the 3 layers.

$$E = \lambda\left(a + w_0 E_0 + E_1 + E_2 + w_3 E_3\right)$$

Link to material in front of the calo

Link to longitudinal leakage

where $\lambda, a, w_0, w_3$ are η-dependant

$\lambda, a, w_0, w_3$ are determined from MC

- At the beginning of data taking, MC may (will) not fit correctly data. Let's reconstruct energy naively !

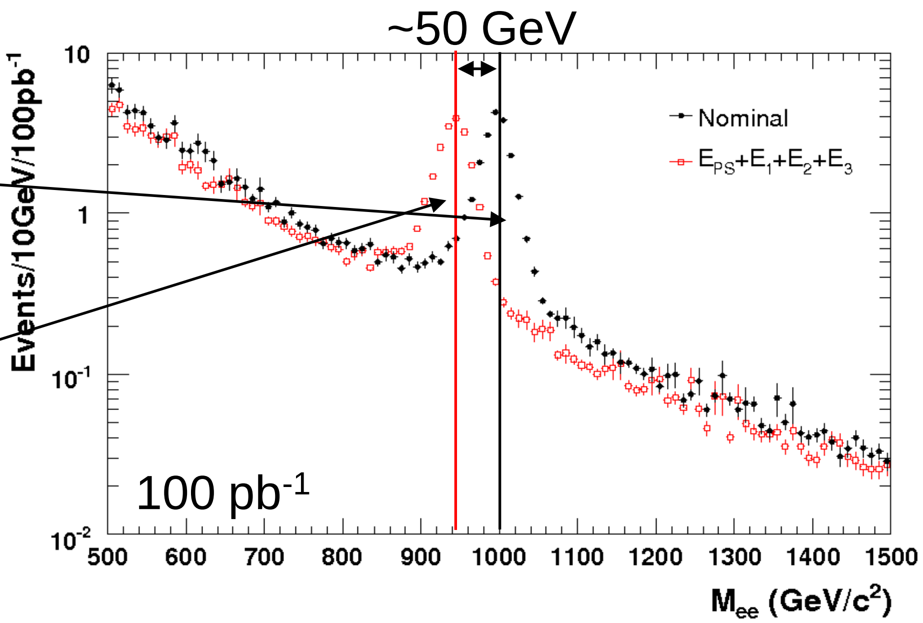
$$E = (E_0 +) E_1 + E_2 + E_3$$

# Impact of calibration

- Inv. Mass spectra after the 3 cuts electron identification
- In black, optimized reconstructed energy with MC coefficients
- In red, energy reconstruction via the simple sum of cluster energies.

~18 signal events in [$\mu$-3$\sigma$,$\mu$+3$\sigma$]

~18 signal events in [$\mu$-3$\sigma$,$\mu$+3$\sigma$]




**S~7.4$\sigma$**

**S~7.4$\sigma$**

➔The resonance mass is underestimated by ~5%

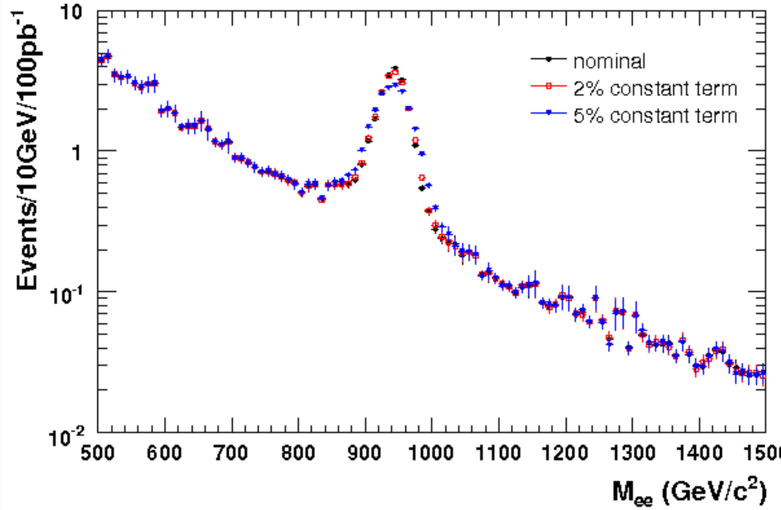
➔ No significance loss with the simple reconstruction

# Constant term effects

- The constant term dominates the energy resolution at high energy

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

- Has been carefully measured <1% in standalone beam test for few modules (15%)
- But at start-up, all modules, in situ, with matter in front of it …effects?




**S~7.4σ**

**S~7.2σ**

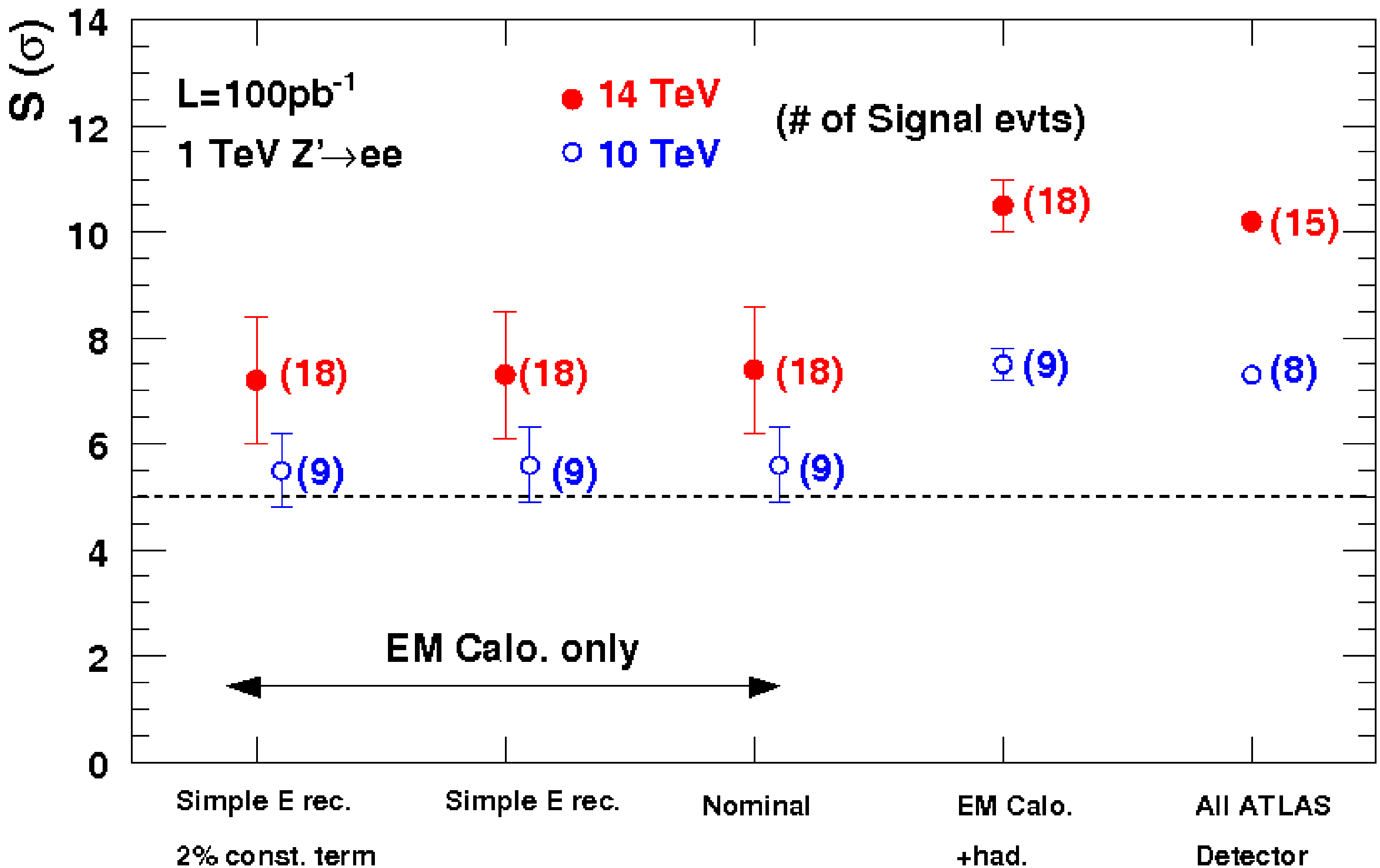
**➔ Even in the realistic case (2%), significance not affected**

# Uncertainties

- QCD background level :
  - Assume a factor 2 of uncertainties
  - Uncertainty on the significance ~ $\pm 1.2\sigma$

- Normalize the cross sections from 14 TeV to 10 TeV
  - Conservative choice of 50% for the Z' signal
  - From 67% for QCD J0 to 20% for QCD J7
  - Significance decreases from $7.4\sigma$ to $5.6\sigma$

# Summary



S (σ)
14
12
10
8
6
4
2
0
L=100pb-1
1 TeV Z'→ee
14 TeV
10 TeV
(# of Signal evts)
(18)
(18)
(18)
(18)
(15)
(9)
(9)
(9)
(9)
(8)
EM Calo. only
Simple E rec.
2% const. term
Simple E rec.
Nominal
EM Calo.
+had.
All ATLAS
Detector

# What is a Z'?

- If a resonance is discovered…
- What is a Z' for a theorist ?
  - The production mechanism induces a neutral particule, without color and which is its own antiparticle.
  - Spin 0 : $\tilde{\nu}$ in some SUSY model with violated R-Parity
  - Spin 1 :
    - Kaluza-Klein (KK) excitation from a SM gauge boson in extradimension models
    - Gauge boson from symetry group extended from SM
  - Spin 2 : KK excitation from a graviton in a Randall-Sundrum model

➔ **Spin determination is crucial to highligth the situation**

# CONCLUSION

Since several years a large effort of in situ commissioning has been undertaken by the ATLAS Collaboration thanks to cosmic muons and single beam data

1. The EM Calorimeter has been highly commissionned
   - Cosmic muons analysis (ATL-LARG-PUB-2007-013)
   - Single LHC beam data analysis

→ EM calorimeter (as ATLAS) is ready for physic & pp collision data

2. New physics may be seen soon after the pp collision start-up
   - Z'→ee discovery potential in early data is little affected by non-nominal performances (ATL-PHYS-INT-2008-020)

# SPARE

# Simulated data

→ Working at 14 TeV

→$Z_\chi$' of 1 TeV + Drell-Yan in same sample

→ ~96k events of $Z_\chi$' AND DY (extract ~79k $Z_\chi$' from fit)

| | CSC Sample | $P_t$ range (GeV) | $\sigma$ (nb) | # of events | Luminosity ($pb^{-1}$) |
|---|---|---|---|---|---|
| Signal | 5605 | $M_{ee}$>500 | $376.5\ 10^{-6}$ | 79k | 208500 |
| dijets J3 | 5012 | 70-140 | 588 | 1101k | 1.87 |
| dijets J4 | 5013 | 140-280 | 308 | 383k | 1.24 |
| dijets J5 | 5014 | 280-560 | 12.5 | 332k | 26.4 |
| dijets J6 | 5015 | 560-1120 | 0.36 | 328k | 777.8 |
| dijets J7 | 5016 | 1120-2240 | $5.71\ 10^{-3}$ | 155k | 27132 |

Samples generated with Pythia

Simu version : 12.0.6; reco version : **13.0.3** ; Geometry : CSC-01-02-00

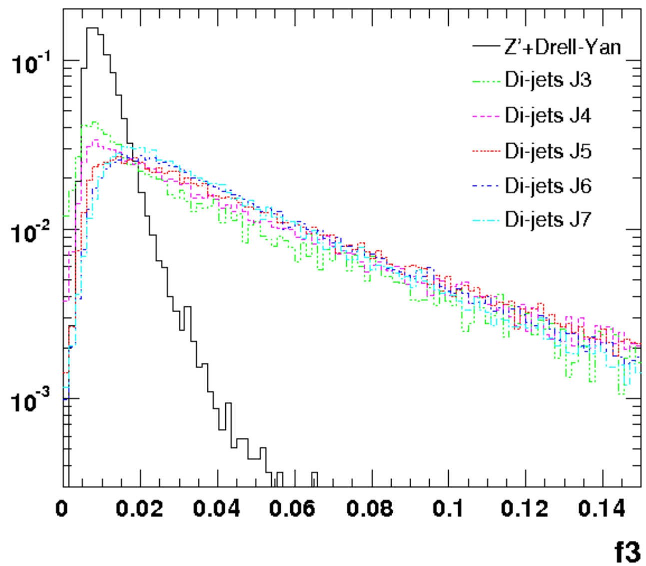
# QCD background rejection (1)

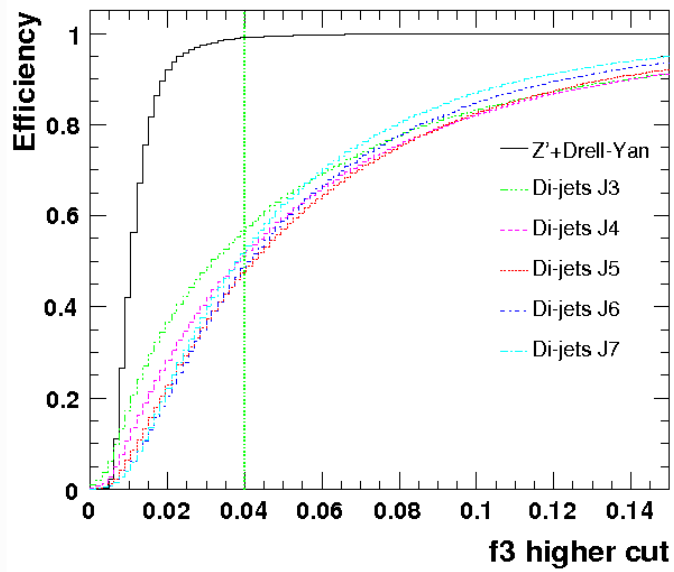
Longitudinal development in EM Calo

Kinematic cuts + Signal/Truth : $\Delta R<0.1$

**ENERGY FRACTION IN S3**

Normalized distributions




| Cuts | ID Eff. | J4 Rejection | J5 Rejection | J6 Rejection |
|---|---|---|---|---|
| f3 < 0.04 | 99.1% | 1.9 | 2.0 | 2.0 |

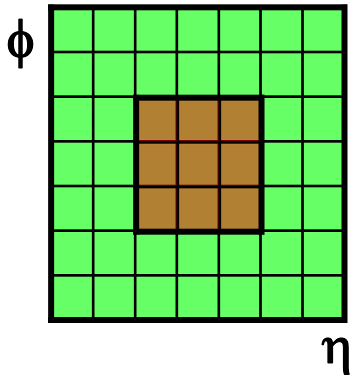
**→ 50% of QCD background is eliminated**

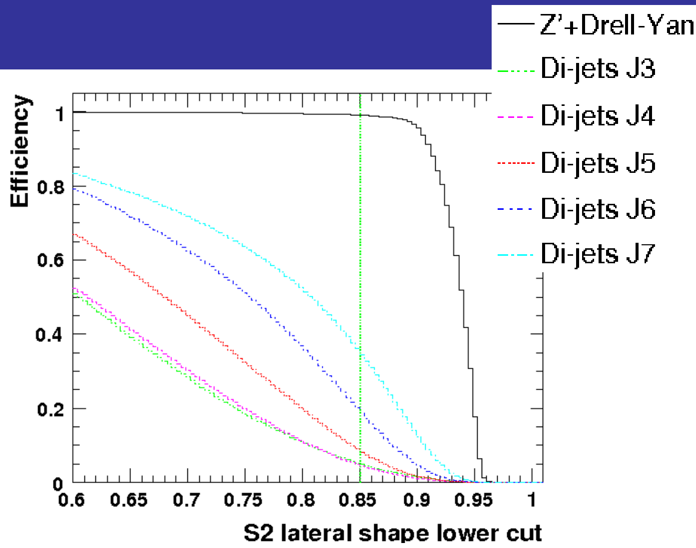
# QCD background rejection (2)

Lateral development in EM Calo

Main energy deposits in S2

**Ratio E(3x3)/E(ZxZ)**

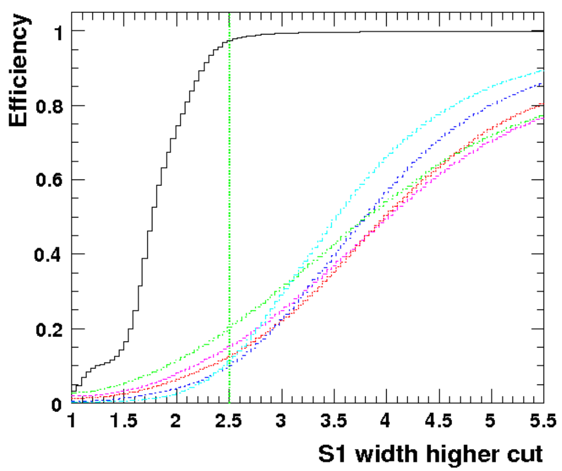



Fine granularity in S1

**EM shower width in S1**

$$w_{tot} = \sqrt{\sum_{i=1}^{40} E_i \times \left(i - i_{\max}\right) / \sum_{i=1}^{40} E_i}$$



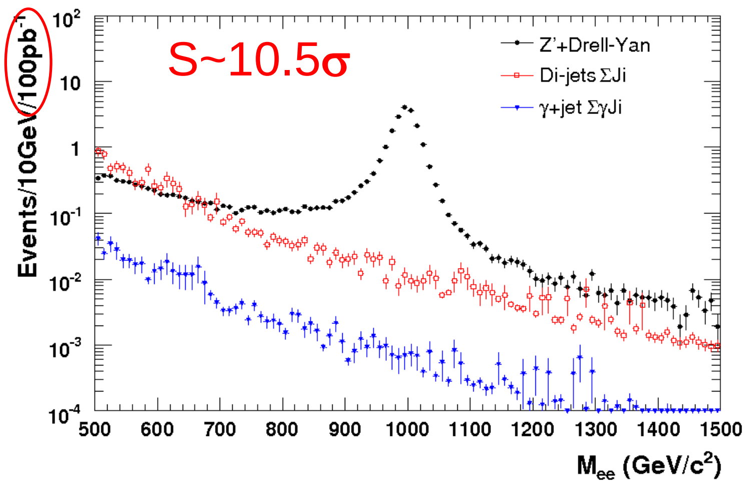

| Cuts | ID Eff. | J4 rej. | J5 rej. | J6 rej. |
|---|---|---|---|---|
| f3 < 0.04 (1) | 99.1% | 1.9 | 2.0 | 2.0 |
| (1) + S2 >0.85 (2) | 98.3% | 30.6 | 18.5 | 8.6 |
| (1) + (2) + S1<2.5 (3) | 96.4% | 71.0 | 51.8 | 29.2 |

➔ Rejection is significantly increased by these simpl cuts

# Signal extraction with ATLAS

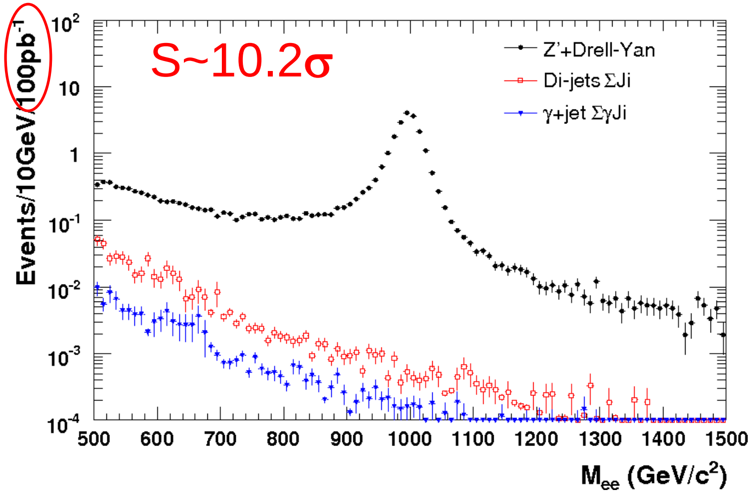
**1 TeV Z'**

With Had. Calorimeter




➔ Increases significance from 7.4σ to 10.5σ

With Had. Calorimeter and tracker




➔ Tracker allow to distinguish di-photon from di-electron resonances

# Remarks

- Our method using the EM Calo only works also for di-photon resonances