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

- $Z' \rightarrow e e$ 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
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.
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 Symmetry Breaking → Higgs
  - New heavy gauge bosons

<table>
<thead>
<tr>
<th>Processus</th>
<th>Tevatron 1987 (0.07pb⁻¹)</th>
<th>Tevatron 2009 (8fb⁻¹)</th>
<th>LHC (1fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z’ 1TeV</td>
<td>&lt;&lt; 1 evt</td>
<td>&lt; 10 evts</td>
<td>&gt;1000 evts</td>
</tr>
</tbody>
</table>

→ 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

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

- PS $\approx$ energy loss
- S1 $0.003 \times 0.1$ $\approx$ position measurements
- S2 $0.025 \times 0.025$ $\approx$ main energy deposits
- S3 $0.05 \times 0.025$ $\approx$ longitudinal leakage

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
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 \((X_0, Z_0)\)

\(~50\%\) of triggered events have « tile track »
Signal reconstruction at cell level

The above formula describes the LAr electronic calibration chain (from the signal ADC to the raw energy in the cell). Note that this version of the formula uses the general \( M_{\text{ramps}} \)-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:

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

- 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!!
- Asynchronous arrival time: Determine the good timing windows!!

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)
  ➔ Developed 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 measured
Clusters map & first *in situ* tests

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

\( (\eta_{\text{tile}}, \phi_{\text{tile}}) \)

\( (\eta_{\text{LAr}}, \phi_{\text{LAr}}) \)

Compare with cluster position

\[ \Delta \eta = \eta_{\text{tile}} - \eta_{\text{LAr}} \]

\[ \Delta \phi = \phi_{\text{tile}} - \phi_{\text{LAr}} \]

\[ |\Delta \eta| \times |\Delta \phi| < 0.11 \times 0.11 : \text{Purity of } \sim 100\% \]

\[ \text{No tile criteria : Purity of } \sim 90\% \]
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 \( (X_{0\text{LAr}}, Z_{0\text{LAr}}) \)
Compare to tile track position \( (X_0, Z_0) \)

\[ \sigma \approx 6\text{cm} \]

- Can use safely the tile track for projectivity selection
- Projectivity cut applied : 30cm x 30 cm
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

No new S2 dead cells in the available region

Not enough statistics for the other layers

Number of clusters per S2 EM Barrel cells
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 ($\mu$, $\pi$ ....)
Energy deposits in EM Calorimeter

Accumulated energy ($E_{\text{cell}} > 5\sigma$) 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 ($E_{\text{cell}} > 5\sigma$) as a function of $\eta$

- Structure and geometry of all layers is clearly visible
- None obvious problem
Influence of matter

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

Accumulated energy ($E_{\text{cell}} > 5\sigma$) as a function of azimuthal angle
Dead cells search

- Energy deposits over the whole EM calo (cosmics : ~6%)
- Over the 100 available events, count the number of times a cell has a deposited energy $E > 5$ times the noise

No new dead cells
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%
- 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 an experimental physicist (on collider), a Z’ is a 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
  - $\eta$ 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

EM and hadronic showers in the calorimeter are different.
QCD background rejection (2)

- 3 simple cuts, based on EM calo only, $\eta$ independant:

  $\rightarrow f3 <0.04$, >85% of energy in a 3x3 cluster, width in S1< 2.5

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Our 3 cuts</td>
<td>96.4%</td>
<td>71.0</td>
<td>51.8</td>
<td>29.2</td>
</tr>
<tr>
<td>ATLAS Standard</td>
<td>91.2%</td>
<td>29.8</td>
<td>35.4</td>
<td>39.6</td>
</tr>
</tbody>
</table>

$\rightarrow$ Better efficiency with the 3 cut than with ATLAS standard (End-caps)

$\rightarrow$ Important for a discovery because the search is signal limited

$\rightarrow$ 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:
  - $\gamma + \text{jets}$: complete simulation $\sim 100$ times $\lt$ QCD
  - $\gamma\gamma$ et $W + \gamma$ are negligible

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

- 1 pb$^{-1}$ $S \sim 17\sigma$
- 100 pb$^{-1}$ $S \sim 7.4\sigma$
- 290 signal events
- 18 signal events

PS Mangeard

IPMU – March 18th 2009
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

\[MG: Medium \text{ Gain} \]
\[LG: Low \text{ Gain} \]

- For 1 TeV Z’, ATLAS is not affected by saturation
- Extrapol.: 5% of S1 and S2 (|\eta|<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.

\[ E = \lambda (a + w_0 E_0 + E_1 + E_2 + w_3 E_3) \]

where \( \lambda, a, w_0, w_3 \) are \( \eta \)-dependant

- 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.

The resonance mass is underestimated by ~5%

No significance loss with the simple reconstruction

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

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

\(S\sim 7.4\sigma\)

\(S\sim 7.4\sigma\)
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?

$$S \sim 7.4\sigma$$

$$S \sim 7.2\sigma$$

⇒ Even in the realistic case (2%), significance not affected
Uncertainties

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

- 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

![Graph showing signal strength for different conditions.

- L=100 pb⁻¹
- 1 TeV Z' → ee
- Simple E rec. 2% const. term
- Simple E rec.
- Nominal
- EM Calo. +had.
- All ATLAS Detector

For 14 TeV:
- 14 TeV (18)
- 10 TeV (9)

For 10 TeV:
- (8)
What is a Z’?

- If a resonance is discovered…
- What is a Z’ for a theorist?
  - The production mechanism induces a neutral particle, 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 symmetry group extended from SM
  - Spin 2: KK excitation from a graviton in a Randall-Sundrum model

\( \Rightarrow \) Spin determination is crucial to highlight the situation
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
   - $Z' \rightarrow ee$ discovery potential in early data is little affected by non-nominal performances (ATL-PHYS-INT-2008-020)
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)

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

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 : $\Delta R<0.1$

Normalized distributions

<table>
<thead>
<tr>
<th>Cuts</th>
<th>ID Eff.</th>
<th>J4 Rejection</th>
<th>J5 Rejection</th>
<th>J6 Rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>f3 &lt; 0.04</td>
<td>99.1%</td>
<td>1.9</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

$\rightarrow\ 50\%\ \text{of}\ \text{QCD\ background\ is\ eliminated}$
QCD background rejection (2)

Lateral development in EM Calo

Main energy deposits in S2

Ratio $\frac{E(3x3)}{E(ZxZ)}$

Fine granularity in S1

EM shower width in S1

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

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<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$f3 &lt; 0.04$ (1)</td>
<td>99.1%</td>
<td>1.9</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$(1) + S2 &gt;0.85$ (2)</td>
<td>98.3%</td>
<td>30.6</td>
<td>18.5</td>
<td>8.6</td>
</tr>
<tr>
<td>$(1) + (2) + S1&lt;2.5$ (3)</td>
<td>96.4%</td>
<td>71.0</td>
<td>51.8</td>
<td>29.2</td>
</tr>
</tbody>
</table>

$\rightarrow$ Rejection is significantly increased by these simple cuts
**Signal extraction with ATLAS**

1 TeV $Z'$

- **With Had. Calorimeter**
  - $S \sim 10.5\sigma$

- **With Had. Calorimeter and tracker**
  - $S \sim 10.2\sigma$

- Increases significance from $7.4\sigma$ to $10.5\sigma$

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

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