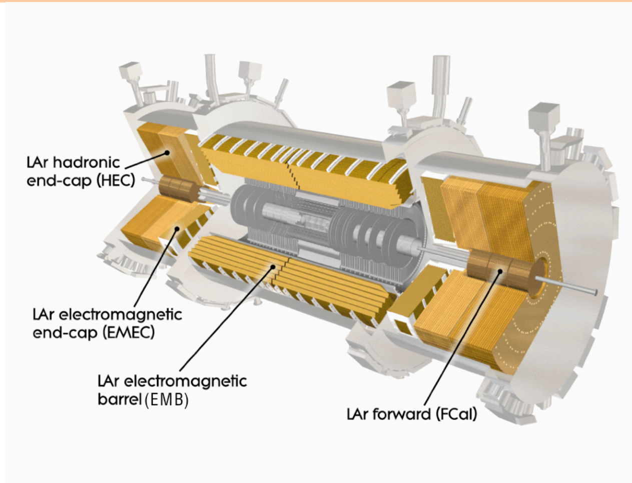
Performance of the ATLAS Liquid Argon Calorimeters in the LHC Run-1 and Run-2



THE UNIVERSITY OF IOWA

ATLAS EXPERIMENT

J. Benitez (The University of Iowa)

on behalf of the ATLAS LAr collaboration

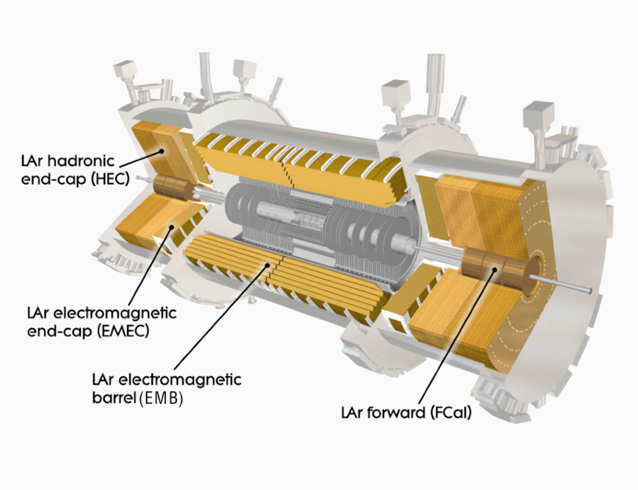
The 17th International Conference on Calorimetry in Particle Physics,

15-20 May 2016

EXCO in Daegu (Republic of Korea)

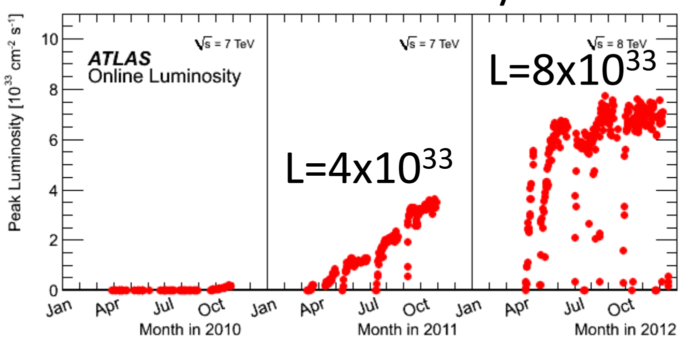
outline

- ✧ Detector Description
- ✧ Operation and Data Quality
- ✧ Calibration
- ✧ Trigger Performance
- ✧ Electron, Photon Performance
- ✧ Forward Jet Performance

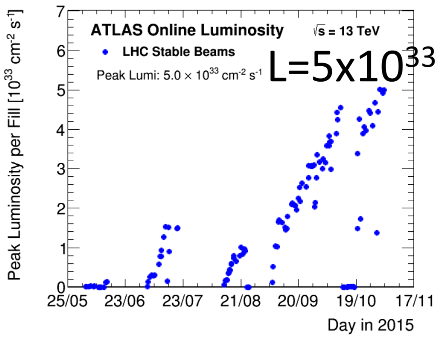


Other talks at this conference:
- *L. March*, "Searches for BSM physics ..."
- *R. Polifka*, "Upgrade ... for the HL-LHC"
- *S. Staerz*, "Electronics Development of Trigger and Readout for Future LHC"

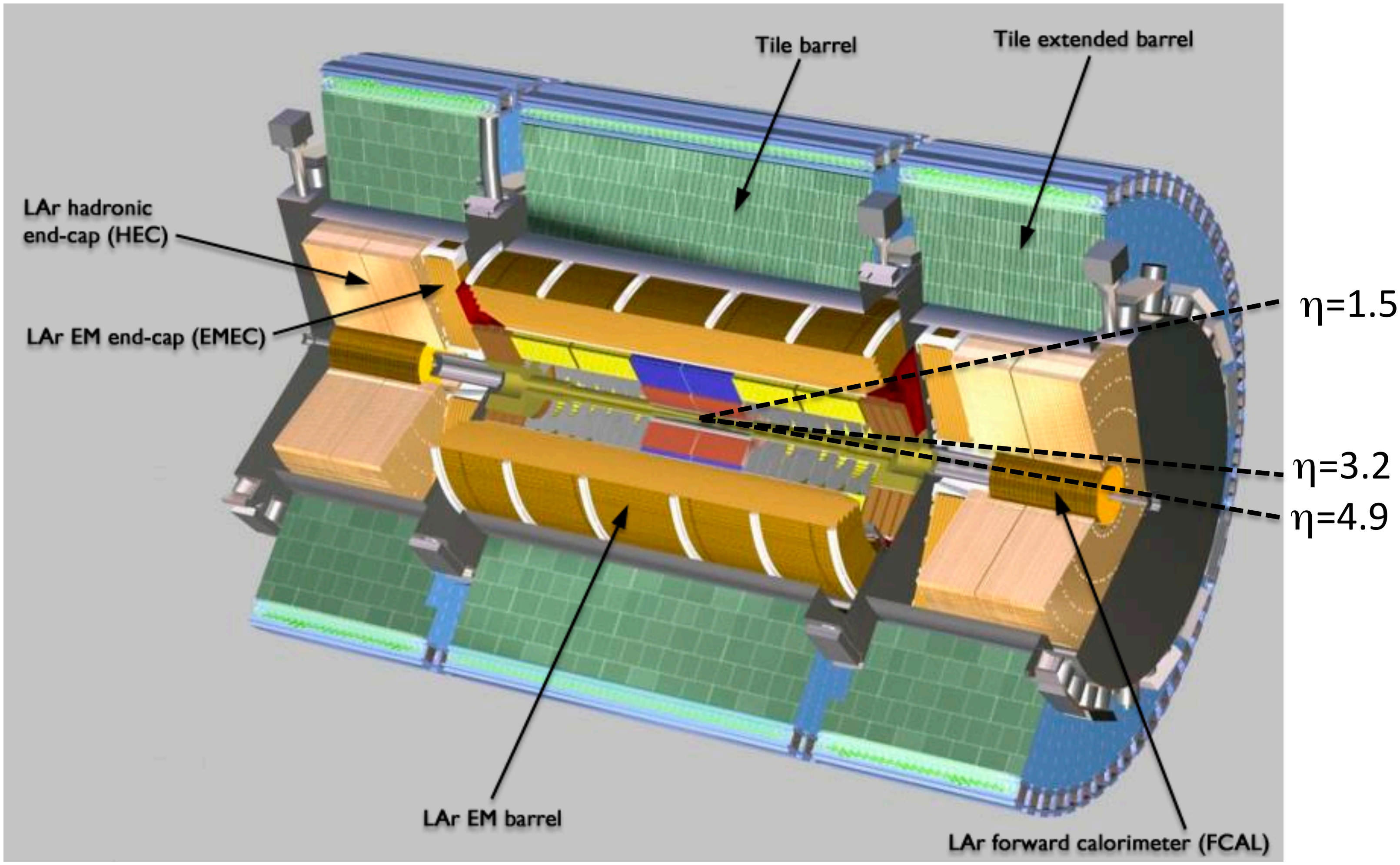
LHC Peak Luminosity Run I



Run II



ATLAS calorimeters



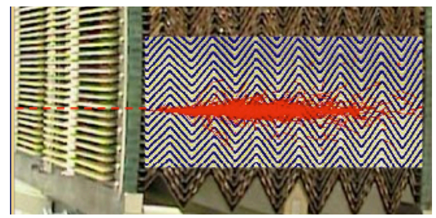
*The calorimeters provide primary Level 1 triggers for ATLAS.

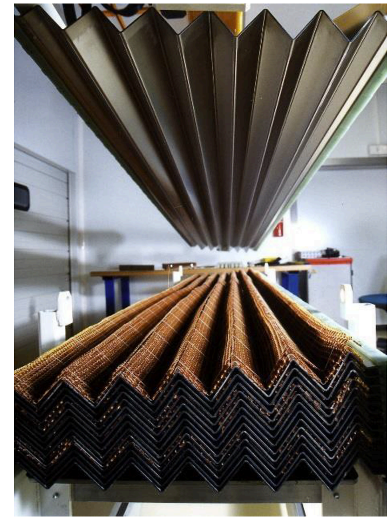
LAr calorimeters

<u>Physics goals:</u>
$H^0 \rightarrow \gamma\gamma$
$H^0 \rightarrow ZZ \rightarrow 4e$
$W' \rightarrow e\nu, Z' \rightarrow ee$
Missing E_T

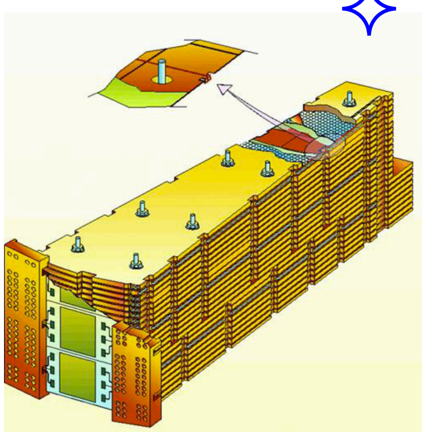
<u>Properties</u>: Radiation hard, stability, uniformity, linearity, speed

- ✧ EM Barrel and Endcap
  - ✧ Accordion shape
  - ✧ **Pb** absorber and **Cu** electrode

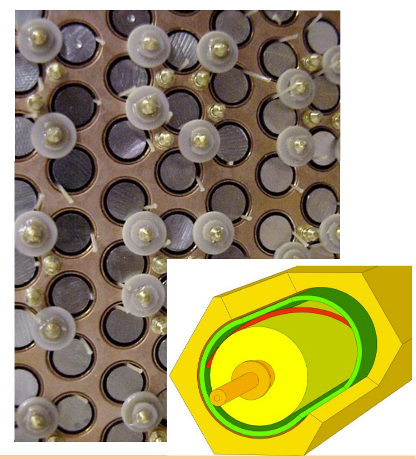




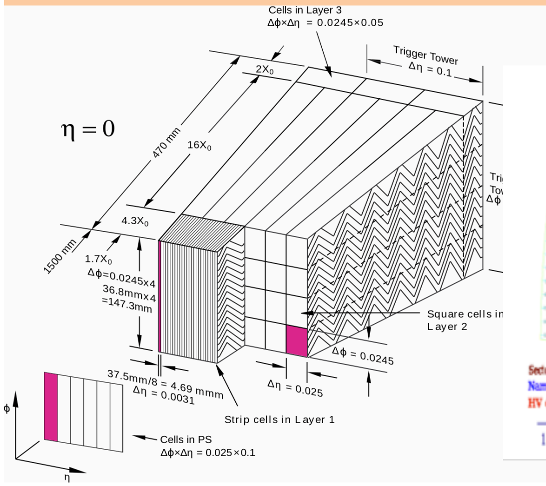
- ✧ Hadronic Endcap (HEC)
  - ✧ Plates
  - ✧ **Cu** absorber and electrode

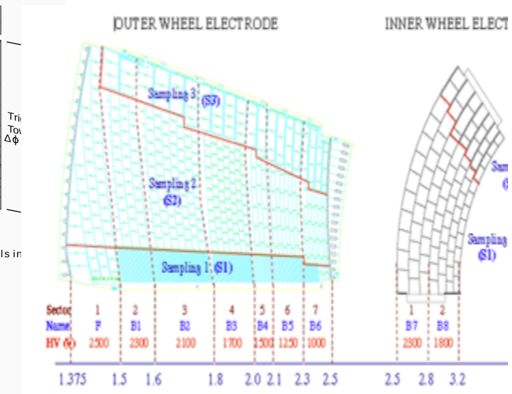


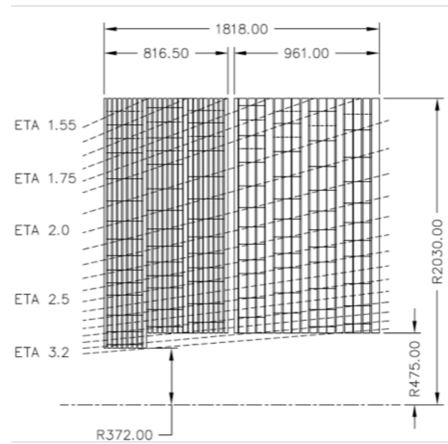
- ✧ Forward calorimeter (FCAL)
  - ✧ Rod matrix
  - ✧ FCAL1 (EM): **Cu**
  - ✧ FCAL 2, 3 (Had.): **W**

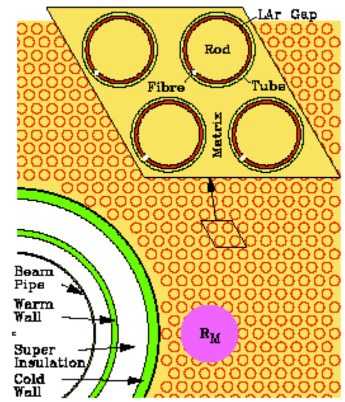


Granularity









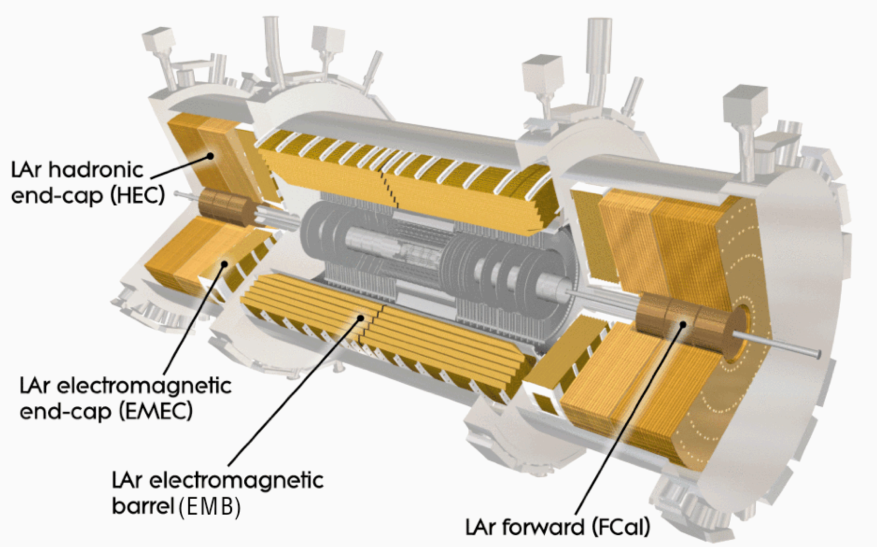
EM Barrel	EM Endcap	HEC	FCAL
✧ $\lvert\eta\rvert<1.475$	✧ $1.375<\lvert\eta\rvert<3.2$	✧ $1.5<\lvert\eta\rvert<3.2$	✧ $3.1<\lvert\eta\rvert<4.9$
✧ 110k cells	✧ 64k cells	✧ 5.6k cells	✧ 3.5k cells

Cell size: **$\Delta\eta=0.025$, $\Delta\phi=0.025$,** **$\Delta\eta=0.1$, $\Delta\phi=0.1$**

- ✧ **3 EM energy samplings**: front, middle, back
- ✧ **pointing capability**: σ_z(vertex) ~0.3 mm combined with tracker
- ✧ Total # of channels ~ 180,000

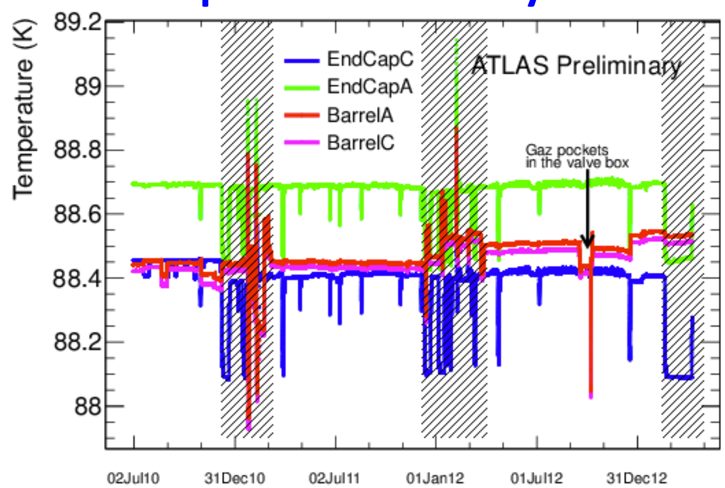
OPERATIONAL STABILITY DURING RUN I AND RUN II

Liquid Argon Temp. & Purity

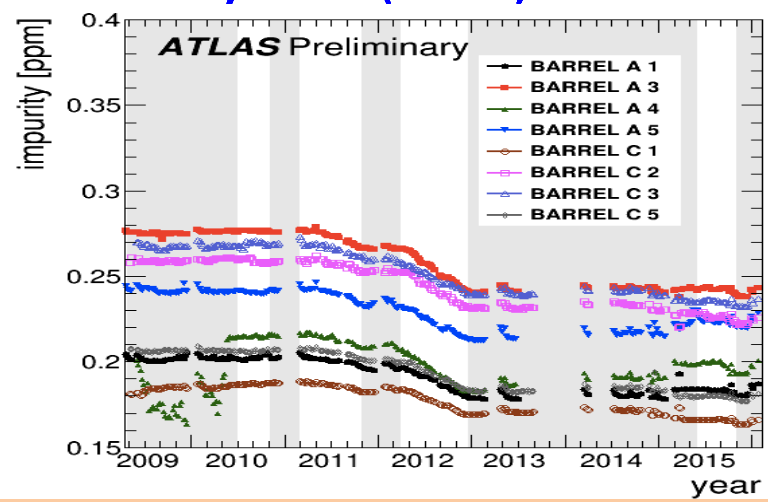


- ✧ Temperature ~ 88 K +/- 0.07 K
  - ✧ Energy response degrades: -2%/K
  - ✧ < 100 mK stability required
- ✧ Liquid Argon impurity < 300 ppb
  - ✧ < 1000 ppb required

Temperature stability 2010-2012



Purity levels (Barrel)



operational channels

✧ More than 99.6% of channels remain operational

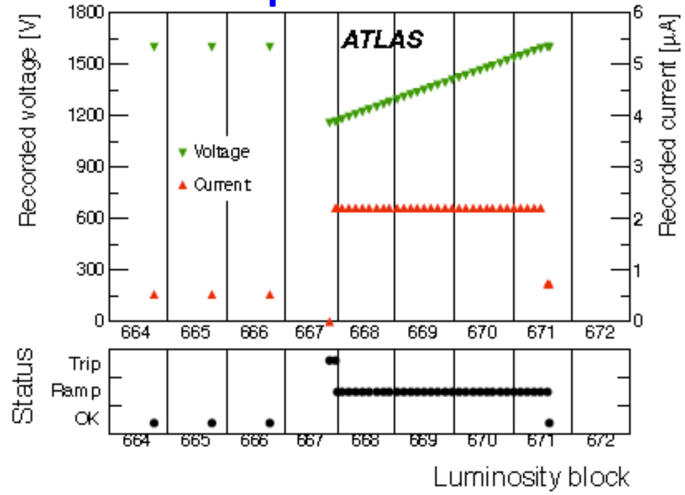
ATLAS Run-1 Detector Status (from Oct. 2012) | Oct. 2015)

Subdetector	Number of Channels	Approximate Operational Fraction	Approximate Operational Fraction
Pixels	80 M	95.0%	98.2%
SCT Silicon Strips	6.3 M	99.3%	98.6%
TRT Transition Radiation Tracker	350 k	97.5%	97.3%
LAr EM Calorimeter	170 k	99.9%	100%
Tile calorimeter	9800	98.3%	99.2%
Hadronic endcap LAr calorimeter	5600	99.6%	99.6%
Forward LAr calorimeter	3500	99.8%	99.8%
LVL1 Calo trigger	7160	100%	100%
LVL1 Muon RPC trigger	370 k	100%	99.75%
LVL1 Muon TGC trigger	320 k	100%	100%
MDT Muon Drift Tubes	350 k	99.7%	99.7%
CSC Cathode Strip Chambers	31 k	96.0%	98.4%
RPC Barrel Muon Chambers	370 k	97.1%	96.6%
TGC Endcap Muon Chambers	320 k	98.2%	99.6%

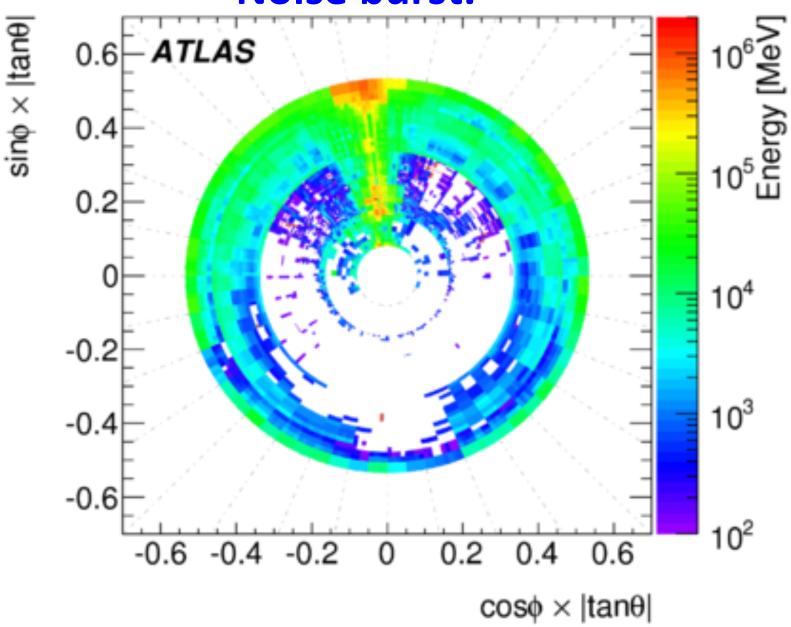
HV Trips and Noise Bursts

- HV trips occur mainly during peak luminosity.
  - lumi-block when trip occurs is vetoed, ok during ramping.
- Noise bursts are coherent energy over a large region of the detector, mainly end-caps.
  - monitored using empty bunch crossings.
  - events within a time window of 200ms in run 1 vetoed.

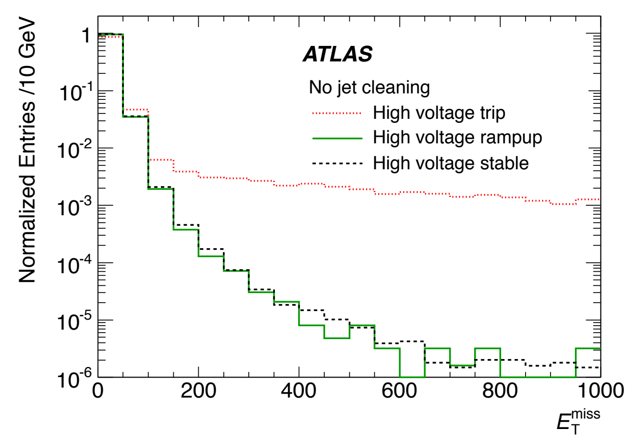
HV Trip



Noise burst.

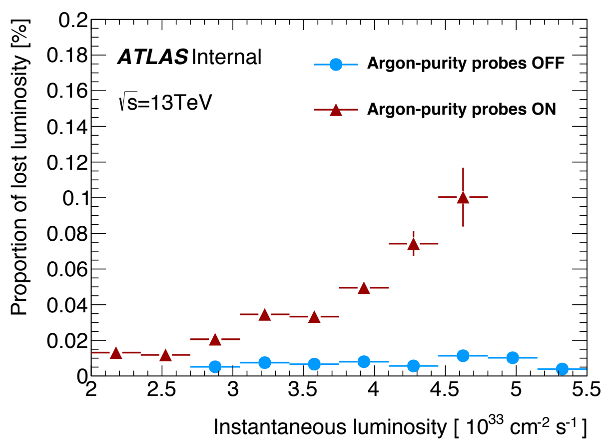


Both problems cause bad energy measurements visible in E_T^{miss}.



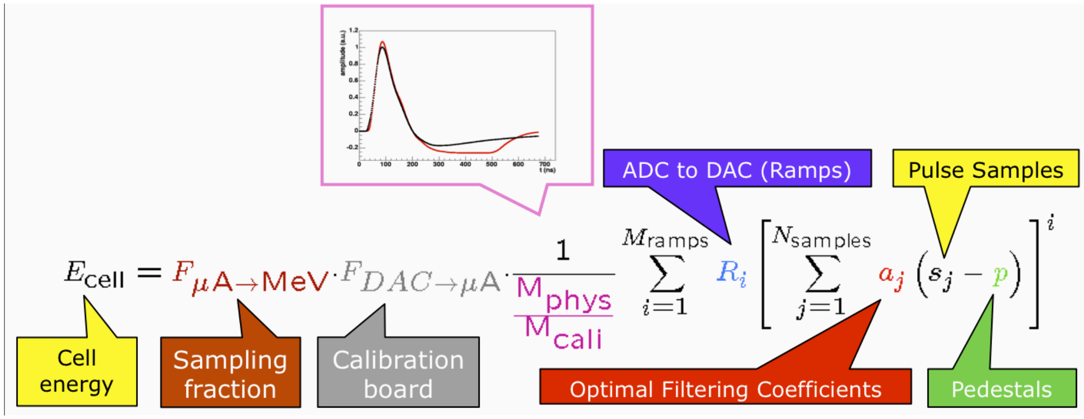
improvements

- HV Trips:
  - During 2011 - 2012 shutdown EMEC HV modules have been replaced by sophisticated ones capable of controlling current spikes.
  - During 2015 - 2016 shutdown HEC HV modules have also been replaced.
- Noise bursts:
  - During 2015 data-taking it has been observed that noise bursts were correlated with the purity monitors (operating with high voltages).
  - Purity monitors now operate only during off-beam periods.

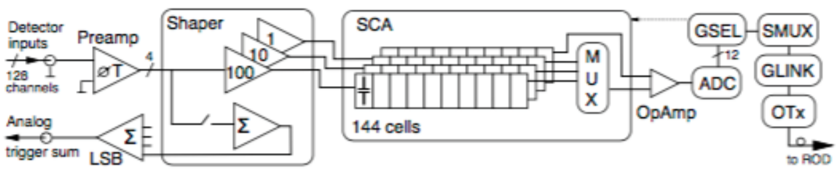


Electronics Stability

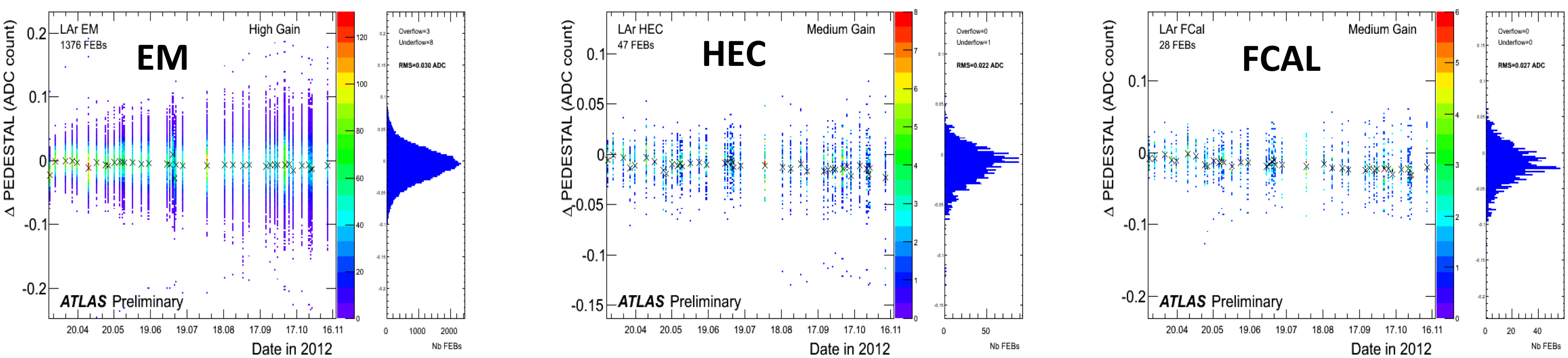
- Cell energy computation involves several calibration constants.
- Constants are monitored on a Daily or Weekly basis



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



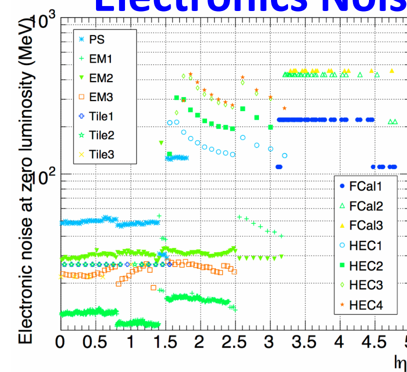
Pedestal stability during a full year (2012):



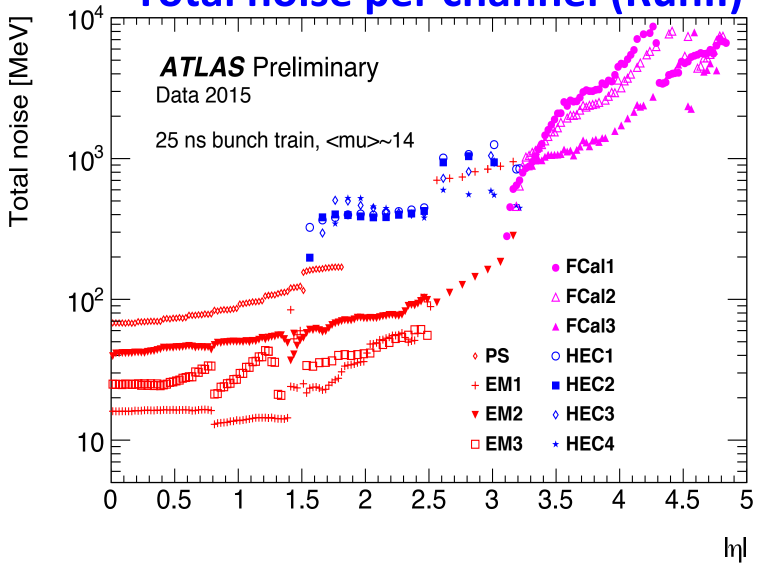
Noise Levels

- ✧ Electronics noise: 10-50 MeV in Barrel depending on layer and < 500 MeV in the forward detectors.
- ✧ Pile-up noise: contributes up to ~8 GeV in the FCAL
- ✧ The total noise is modeled by the event simulation.

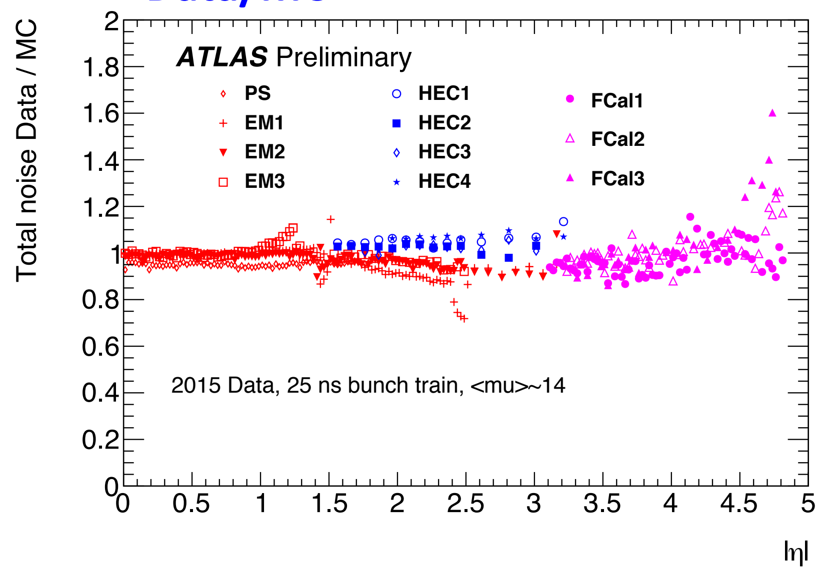
Electronics Noise



Total noise per channel (RunII)

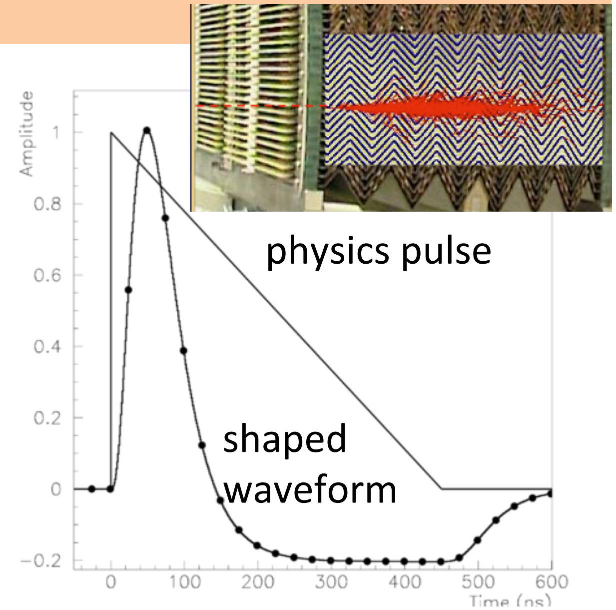


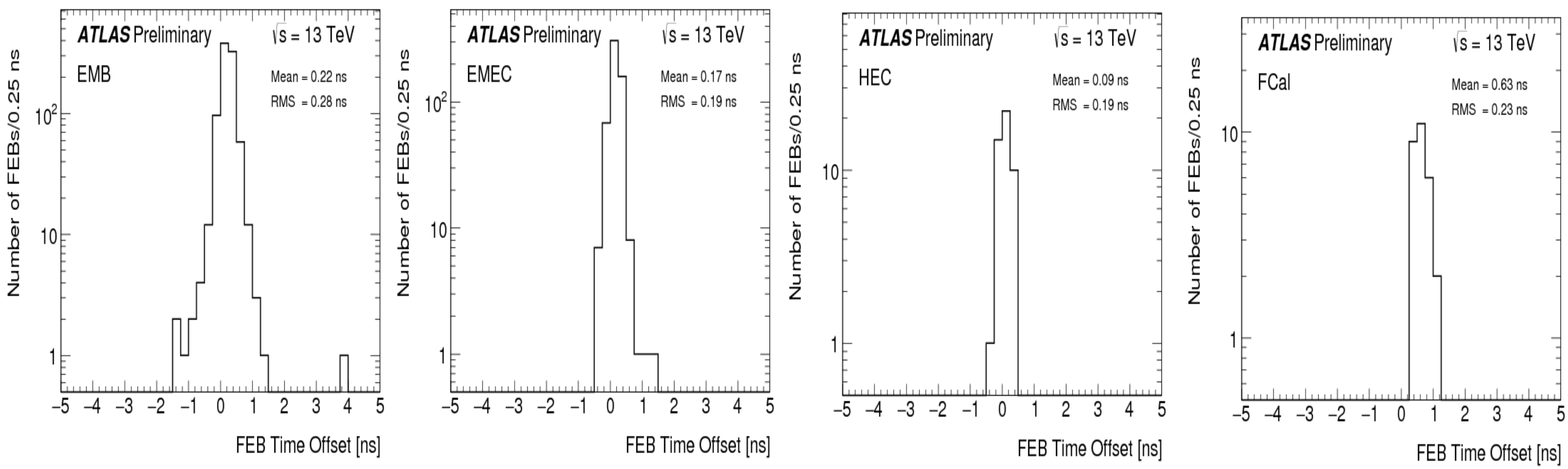
Data/MC



Online Timing Resolution

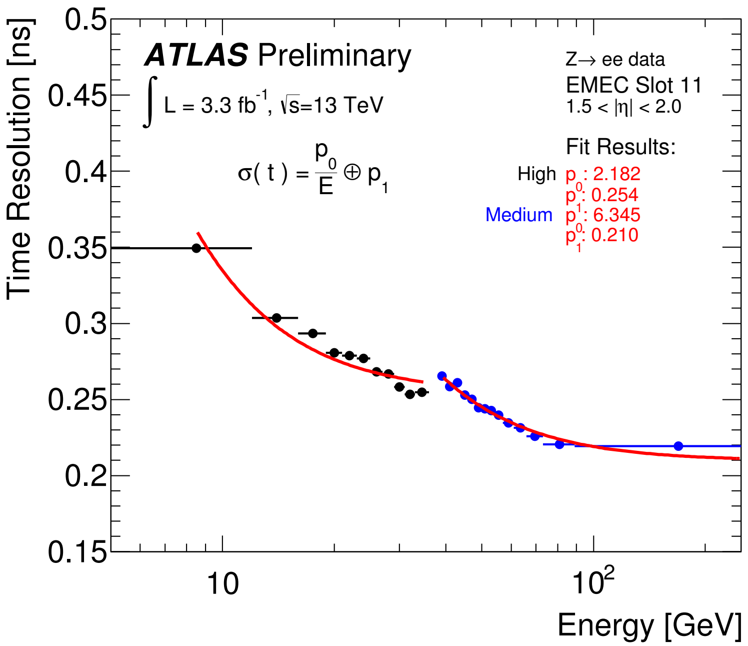
- Used for online data quality monitoring
- Fine adjustments derived for Front-End-Board synchronization using beam-splash events as well as early collision data.
- Resolution is < 1 ns over all boards





Offline Timing Analysis

- Precise timing calibration derived using W→eν and tested in Z→e^+e^-.
- Time measurement used for exotic (long-lived) searches
- Procedure corrects for physics as well as electronics effects per channel.
- Final resolution is ~200 ps for electrons above 10 GeV.



*Values in this plot do not account for beam-spot spread.

Overall Data Quality

Year	Total	Data corruption	Missing condition data	HV trips	Coverage	Noise bursts	Noisy channels
2011	3.20%	0.04%	0.11%	0.96%	0.70%	1.24%	0.15%
2012	0.88%	0.01%	0.02%	0.46%	0.28%	0.06%	0.05%

- Largest source of bad data was HV trips and Noise bursts. Both are now greatly reduced.
- LAr remained with good quality for >99% of Run 2.

ATLAS 2011 p–p run

Inner Tracking			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

ATLAS p-p run: April-December 2012

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5

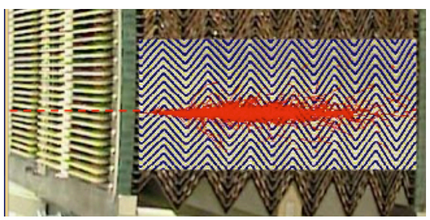
ATLAS pp 25ns run: August-November 2015

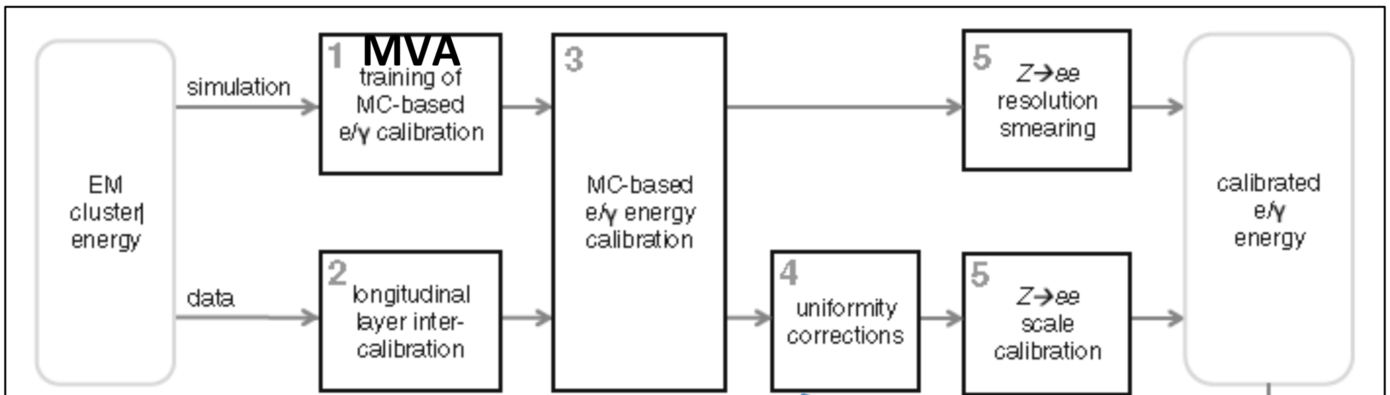
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
93.5	99.4	98.3	99.4	100	100	100	100	100	100	97.8

EM SCALE CALIBRATION

procedure

- The precise energy calibration of clusters is performed from collision data and MC simulations of the detector response to electrons.
- The absolute energy scale is fixed by the Z boson mass



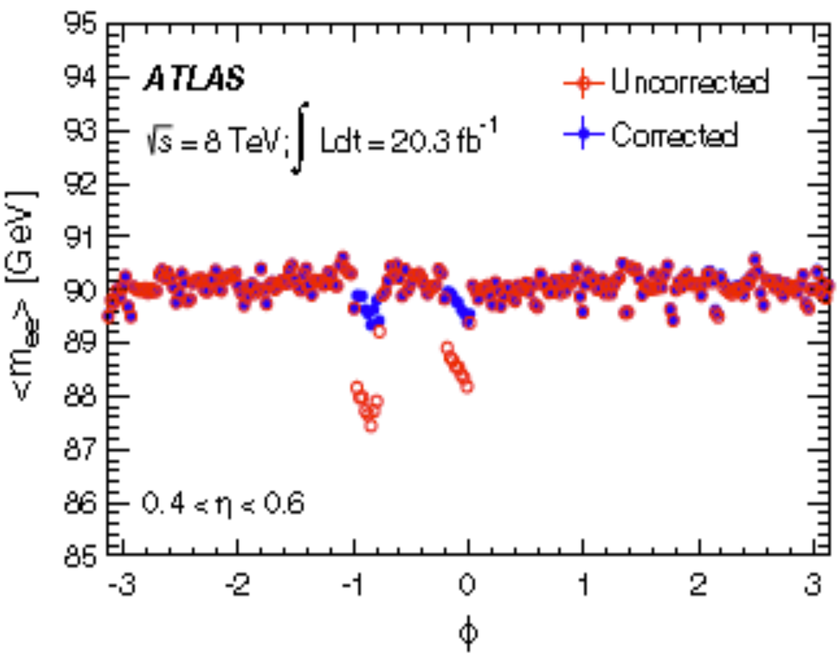


- Data are corrected for
  - residual interlayer differences w.r.t. simulation
  - non-uniformities due High-Voltage and module size variations.

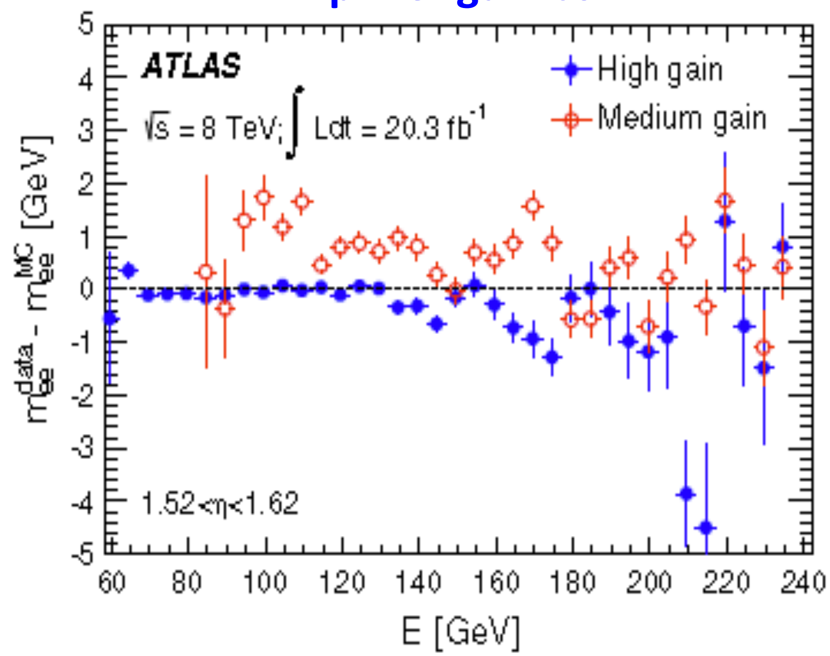
uniformity corrections

- The plots show examples of the effect of the non-uniformity corrections on the energy calibration.
- Regions operating with lower than nominal voltages can generate significant energy offsets.

HV correction

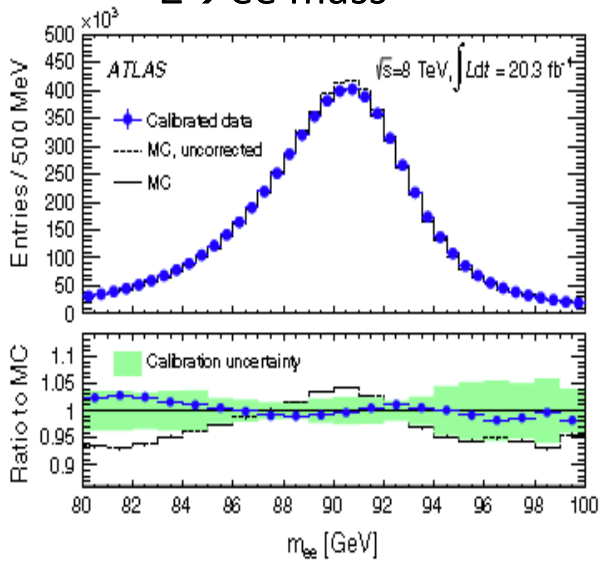


Amplifier gain corr.

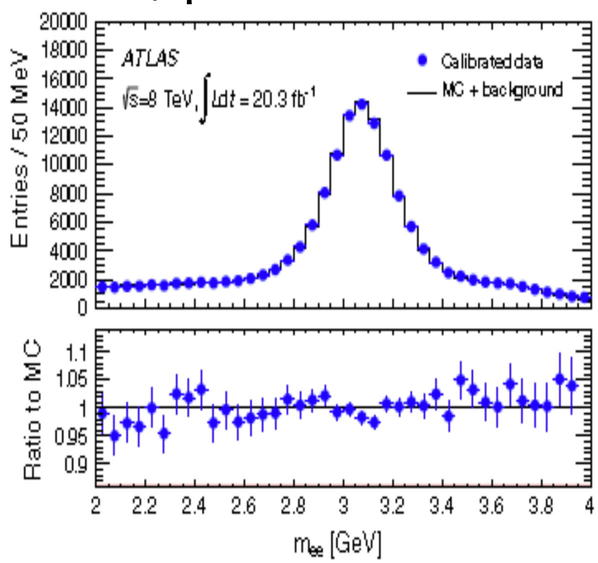


Run I Results and Cross-checks

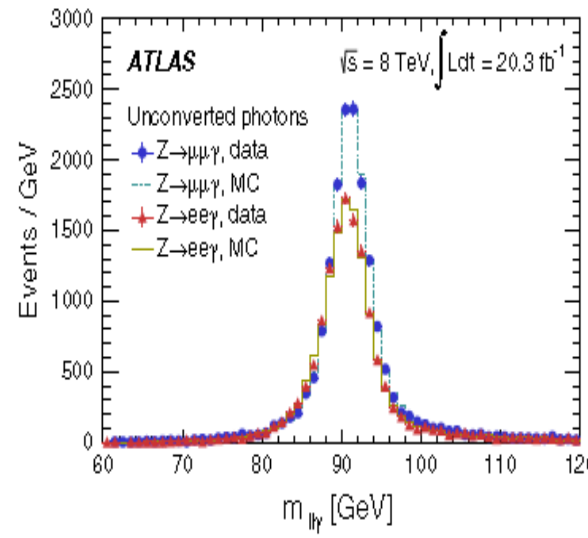
Z→ee mass



J/ψ→ee mass

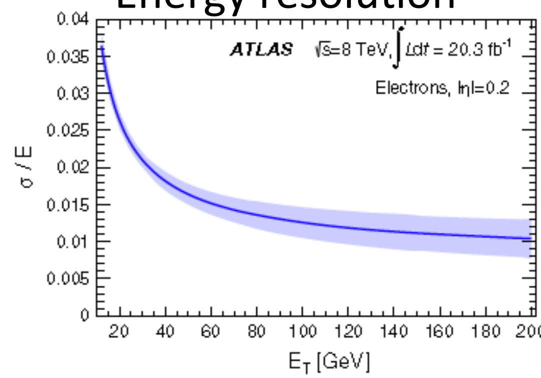


Z→llγ mass

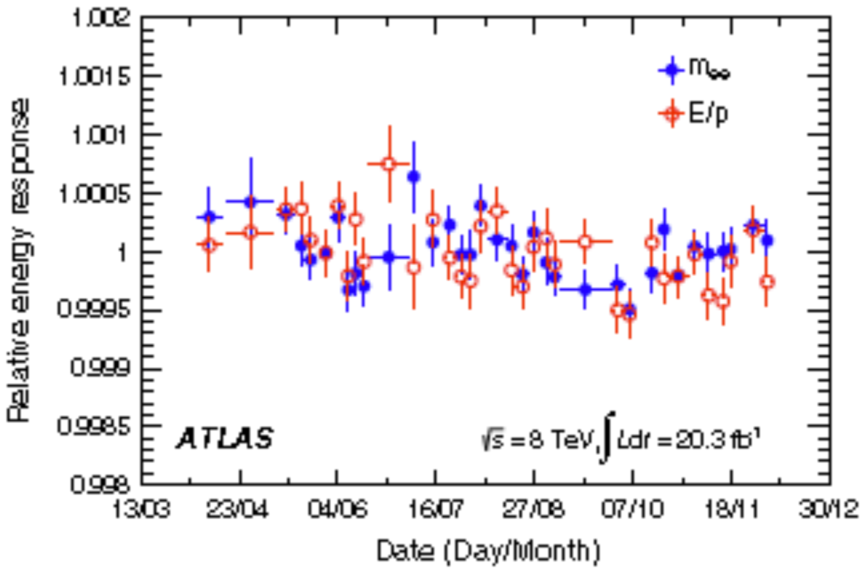


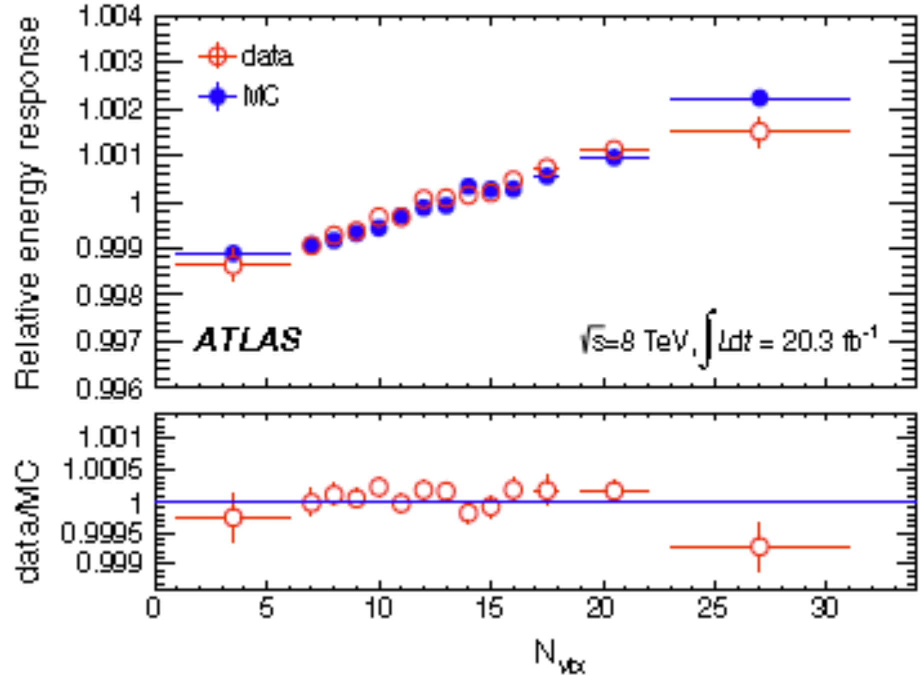
- **Energy scale uncertainty** for electrons(photons) at 40 GeV is
  - < 0.05%(0.3%) for |η|<1.37 or |η| > 1.82,
  - < 0.2%(0.9%) for 1.37<|η|<1.82 .
- **Energy resolution** is ~3% at E_T ~20GeV and improves to ~1% at high E_T.

Energy resolution



Stability

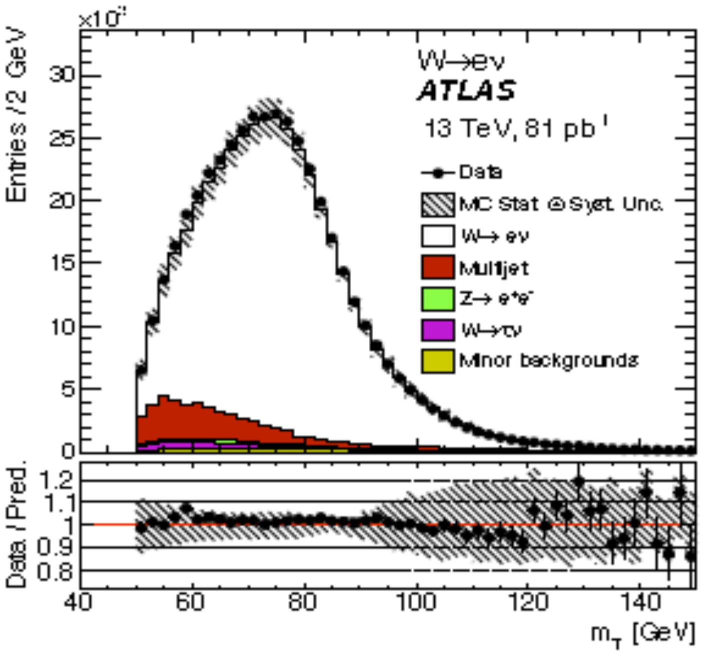


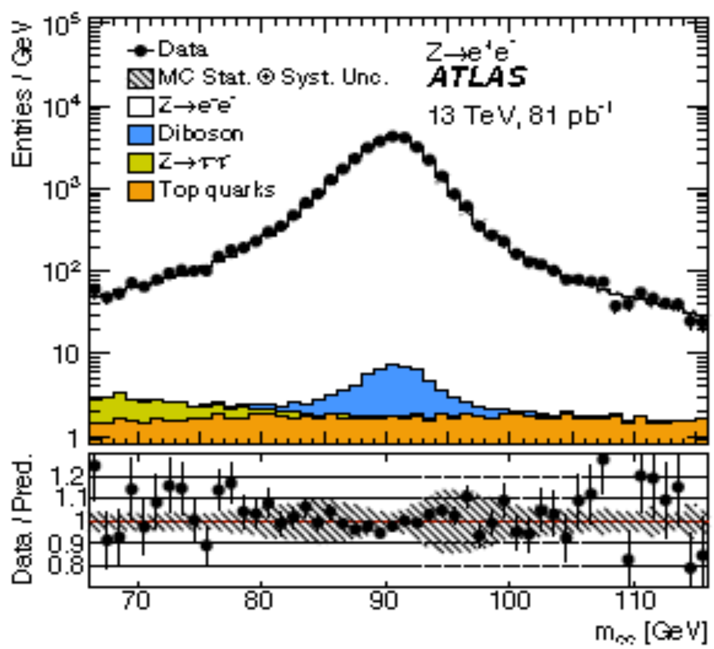


- Stability of the energy calibration was checked for the Run I data over a full year, the variation is < 0.05%.
- Some dependence on the pile-up is observed at the level of <0.3% up to N_{vtx}=30, but is modeled by the simulation.

Run II Performance

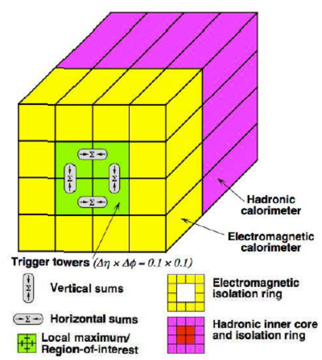
- For Run II the EM calibration has been updated with
  - improved detector geometry
  - data/MC correction factors have been re-derived to account for changes in readout : 4 vs. 5 pulse samples and pile-up with 25 ns bunch spacing.
- Early W, Z measurements show excellent agreement between data and MC.





TRIGGER PERFORMANCE

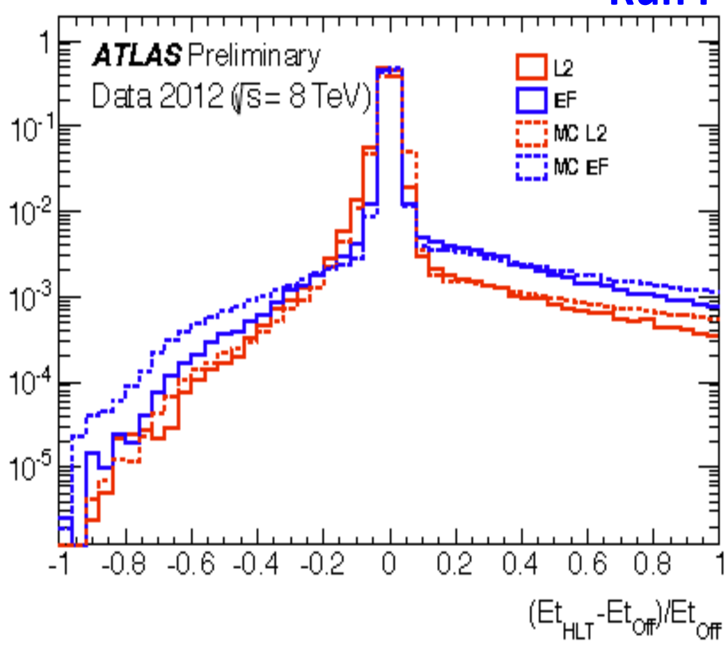
Trigger towers are defined with $\Delta\eta$=0.1,$\Delta\phi$=0.1 granularity



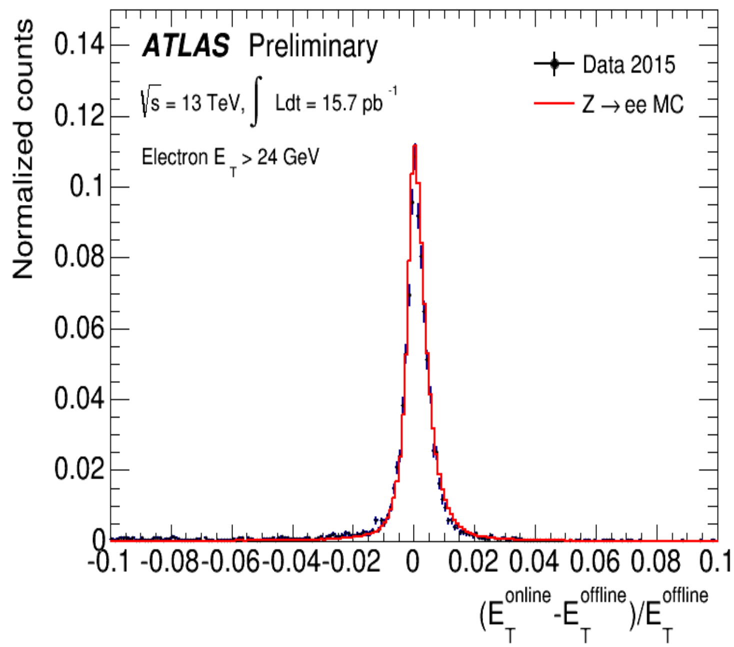
Energy resolution

- Good energy resolution is needed online for efficient triggering of events.
- The difference between online and offline measurements remained at < 1% in Run II

Run I



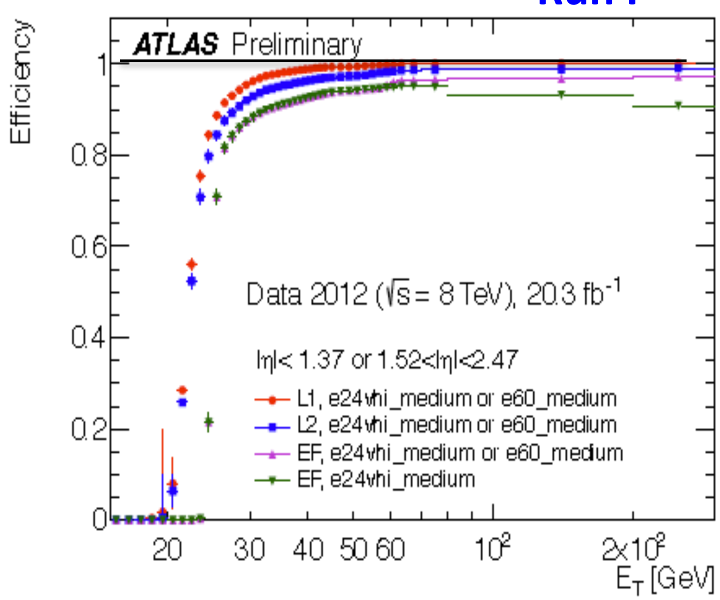
Run II



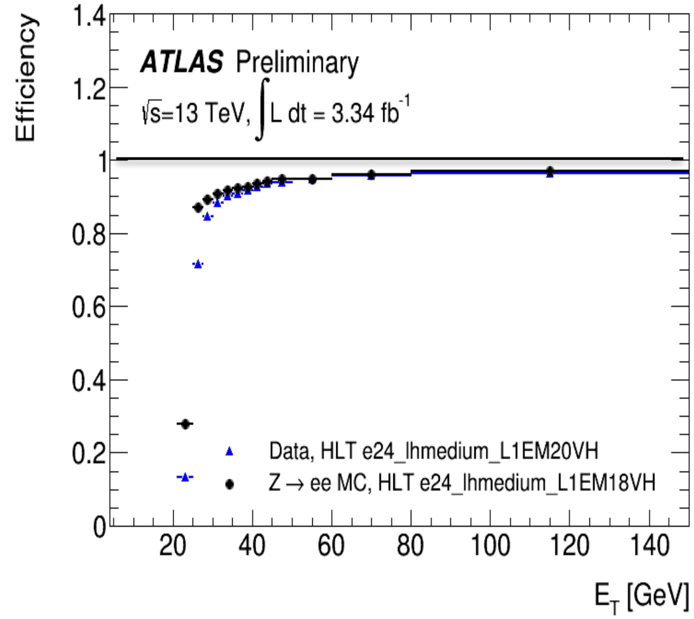
Electron efficiency

- The lowest un-prescaled single electron trigger remained with a threshold of 24 GeV and > 95% efficiency at the plateau.
- For Run II the high-level trigger adopted a Likelihood based identification which improved the turn-on and plateau efficiencies.

Run I



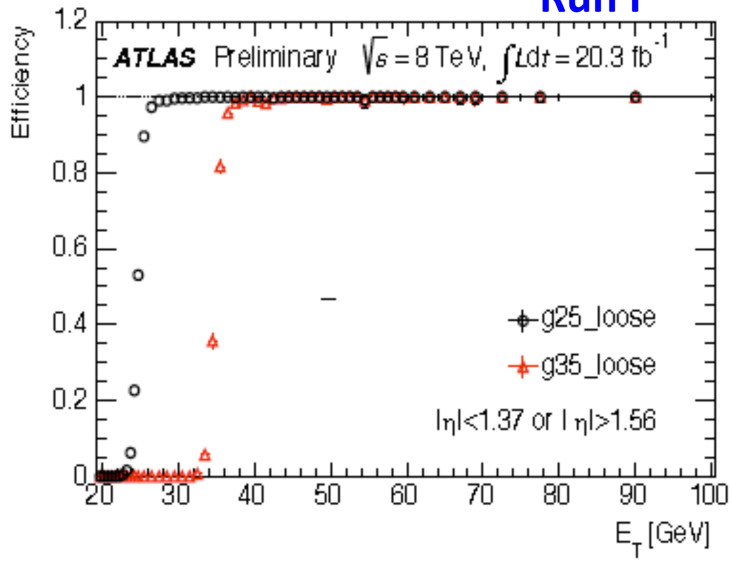
Run II



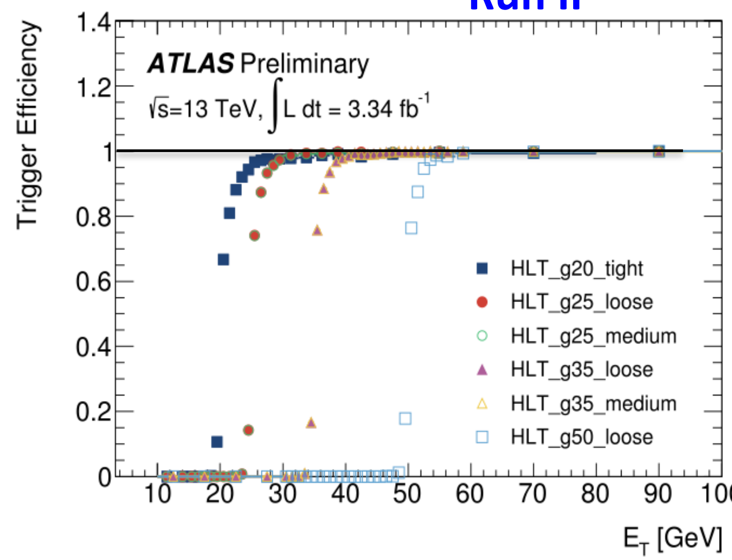
Photon efficiency

- Efficiencies remain ~100% at the plateau.
- The lowest un-prescaled single-photon trigger is g120_loose
- Di-photon searches use triggers requiring two photons with low energy thresholds (g35_loose_g25_loose).

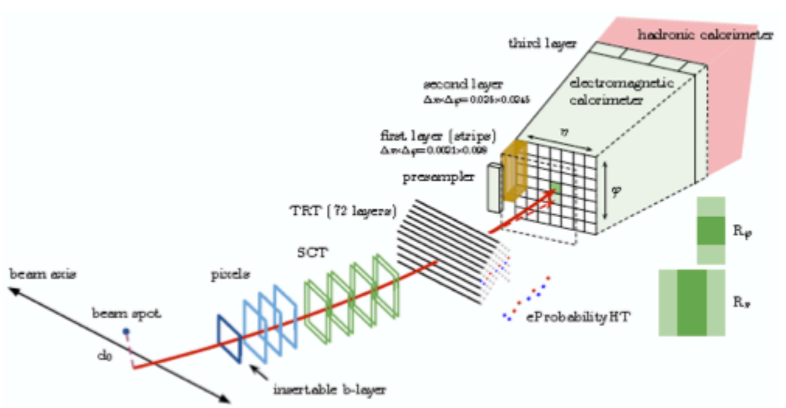
Run I



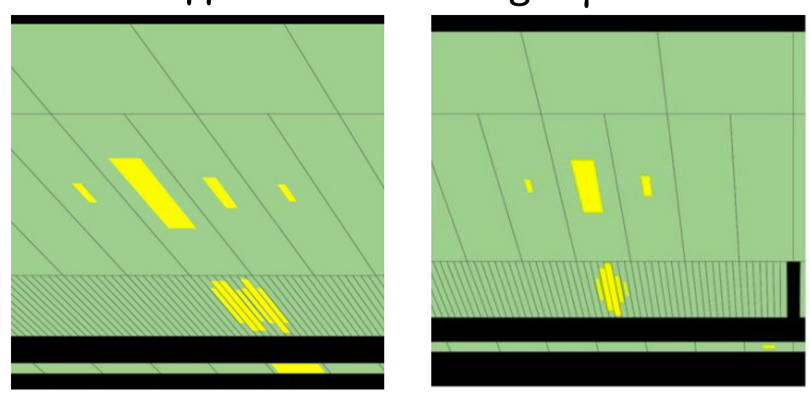
Run II



ELECTRON AND PHOTON IDENTIFICATION



$\pi^0 \rightarrow \gamma\gamma$ single γ



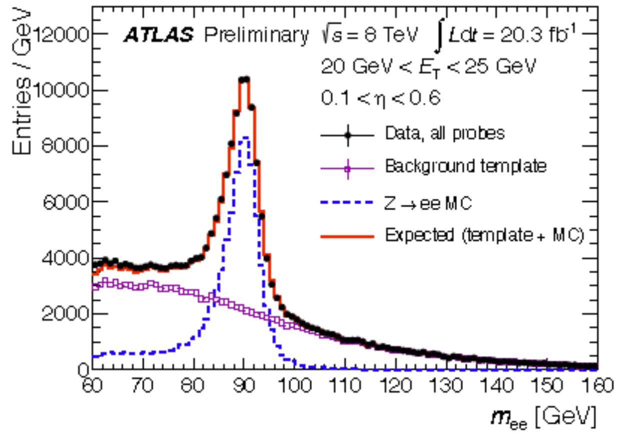
samples

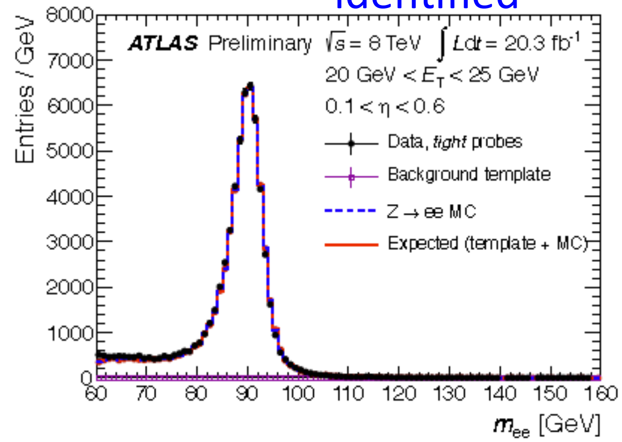
- ✧ Reconstruction and identification efficiency is determined using tag-and-probe methods using $Z \rightarrow e^+e^-$ for high p_T and $J/\psi \rightarrow e^+e^-$ events at low p_T.

without identification

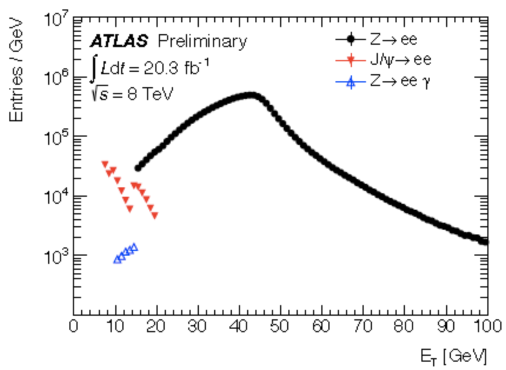
identified

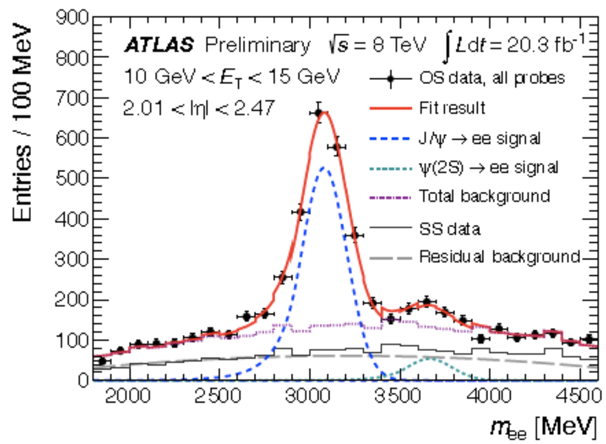
$Z \rightarrow e^+e^-$ events:

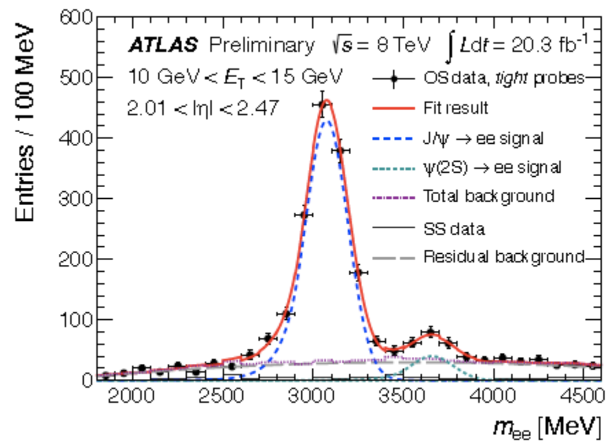




$J/\psi \rightarrow e^+e^-$ events:



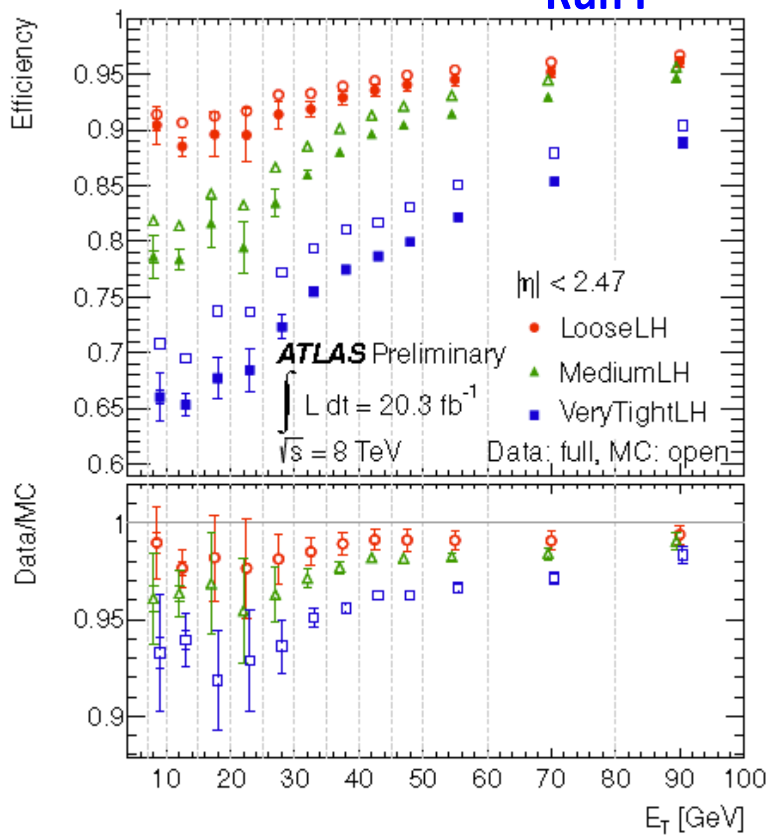




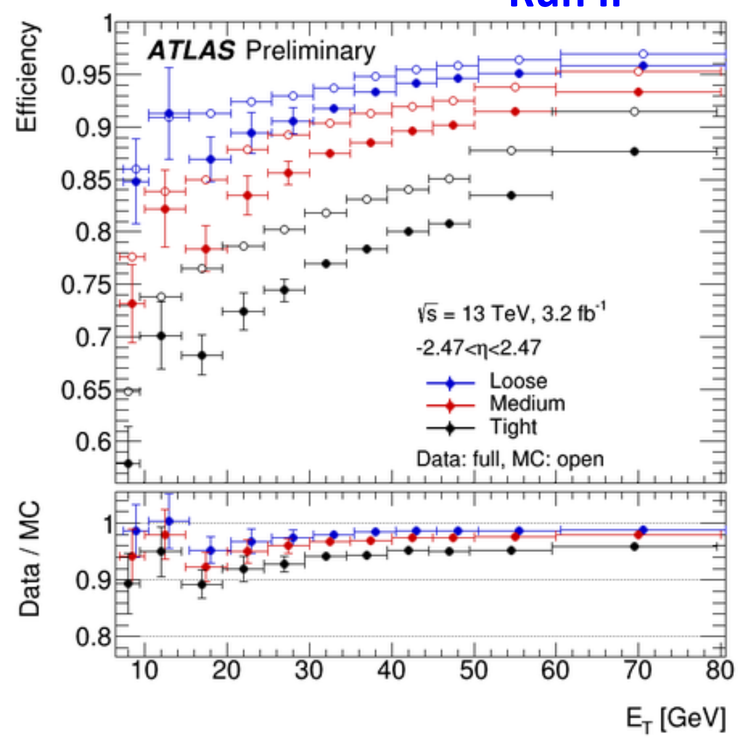
Electron Efficiency

- Efficiencies during Run II remain similar to Run I: > 90% with the loose working point above 20 GeV.
- MC correction factors < 10%

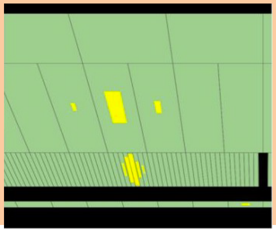
Run I



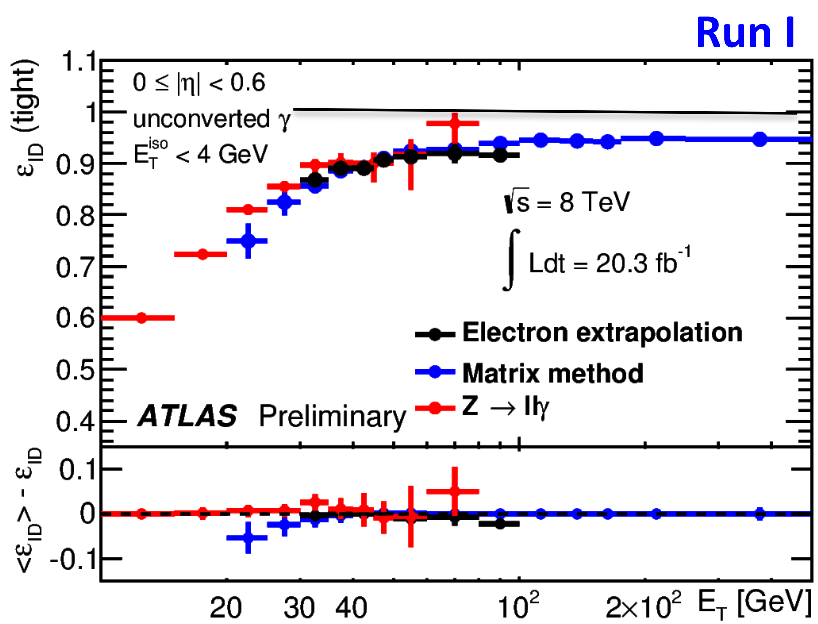
Run II

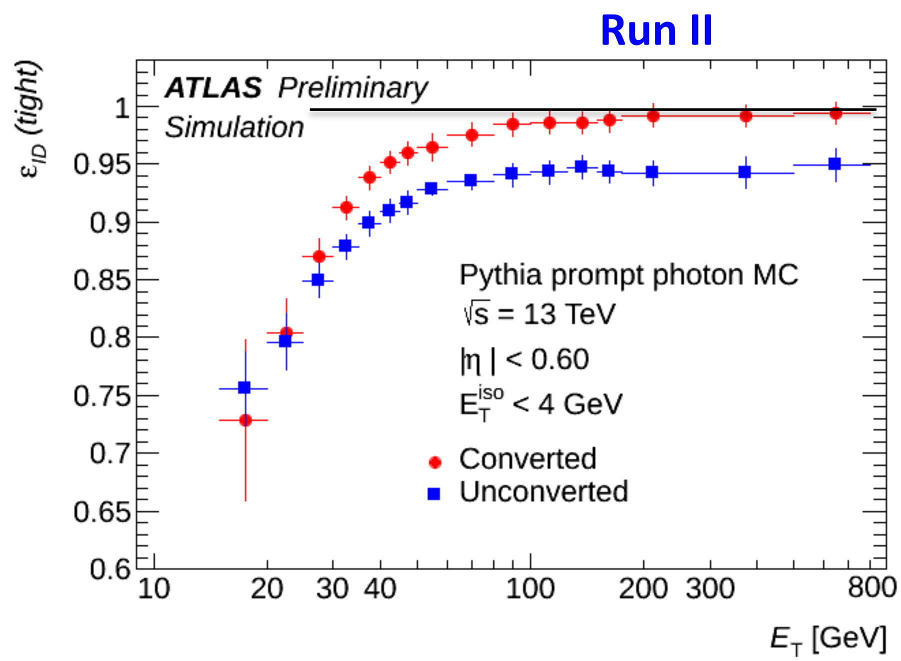


Photon efficiency



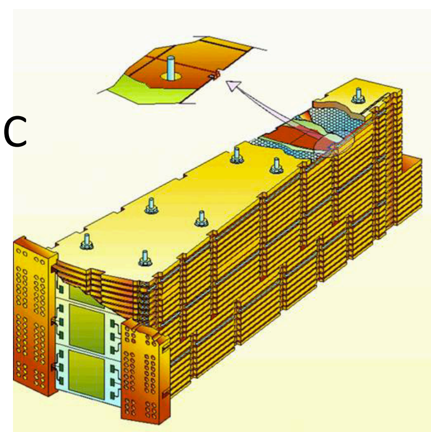
- Photon id efficiency is measured using three methods : 1) clean Z→eeγ, μμγ events, 2) an extrapolation method using Z→ee events, and 3) using a "matrix" method.
- For photons above E_T=40 GeV the efficiency remains at ~95% similar to Run I.

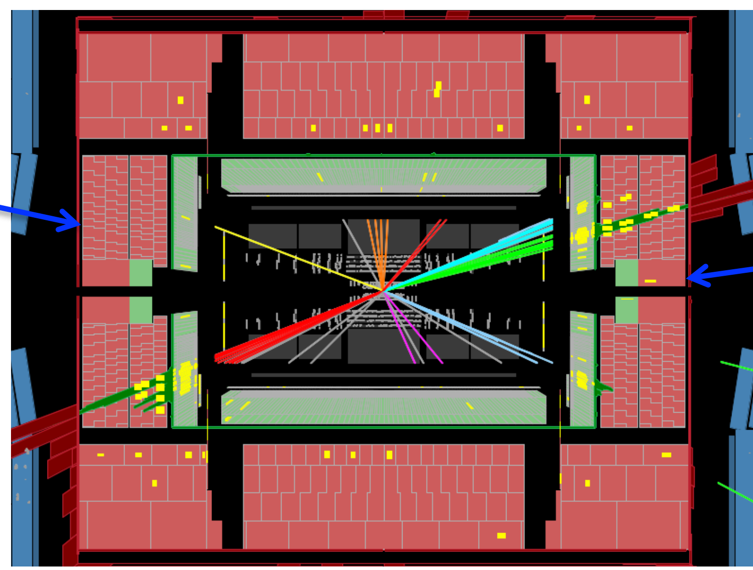




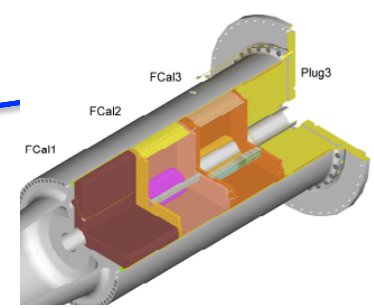
FORWARD DETECTOR PERFORMANCE

HEC





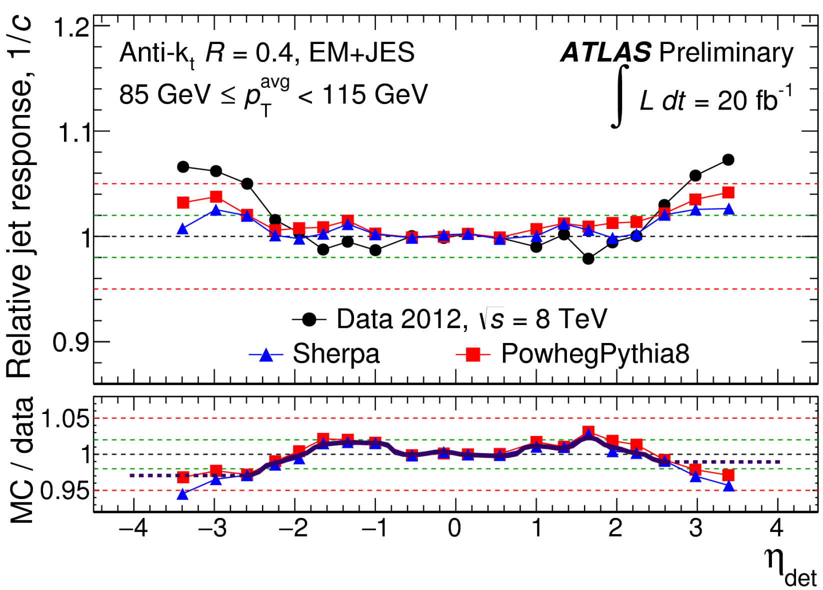
FCAL



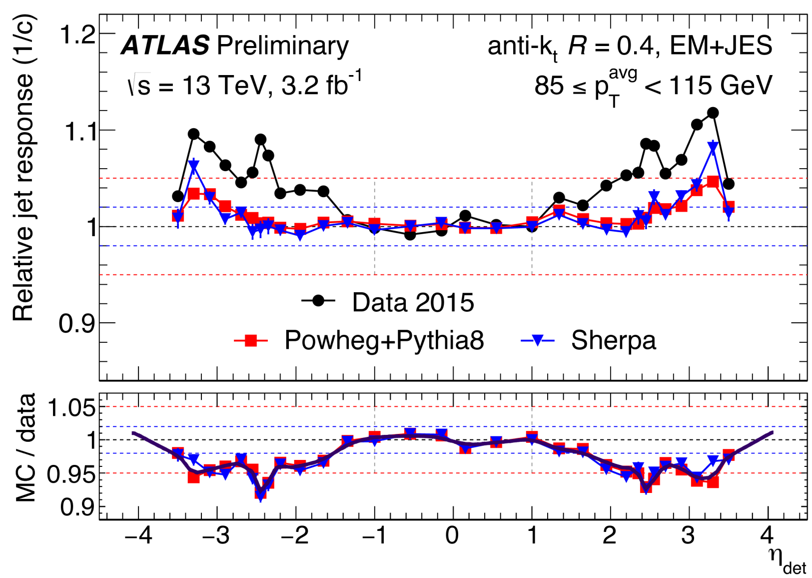
Jet energy response

- Jet energy scale calibration is determined from simulation.
- The energy response of the forward calorimeters is studied for fully calibrated jets using momentum balance in real data events.
- The corrections found from this method are less than 6% in Run I and less than 10% in Run II in the forward region.

Run I

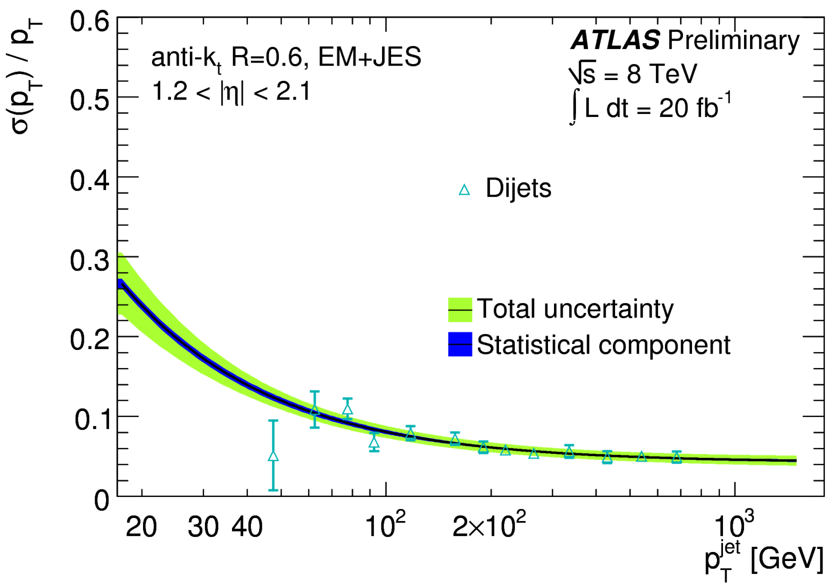


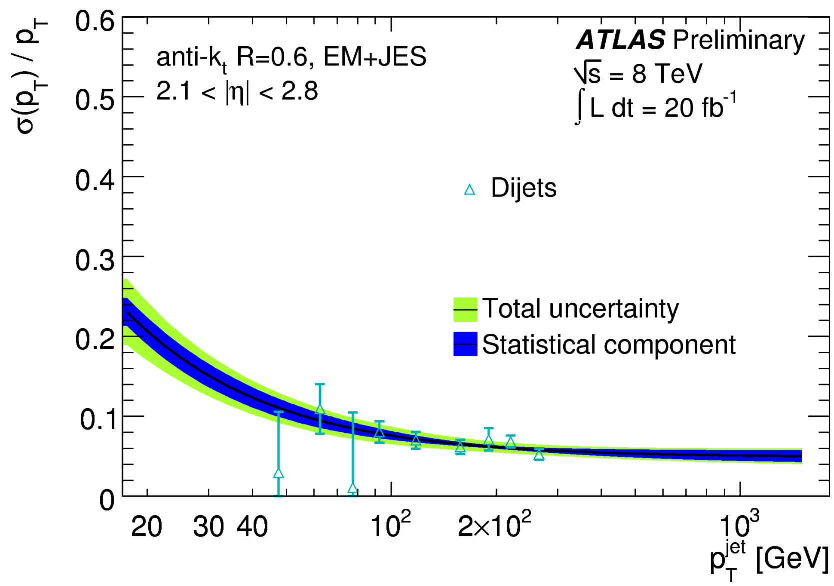
Run II



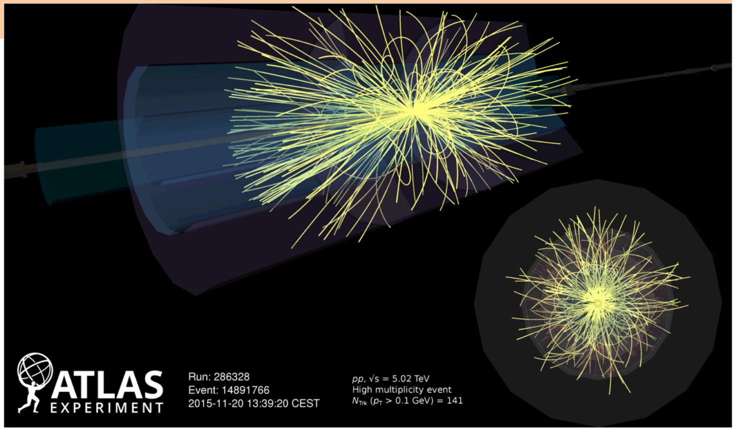
Jet energy resolution

- The plots show the jet energy resolution for two regions covered by the HEC.
- The resolution for jets with p_T=40 GeV is ~10% and improves to ~5% at large p_T.

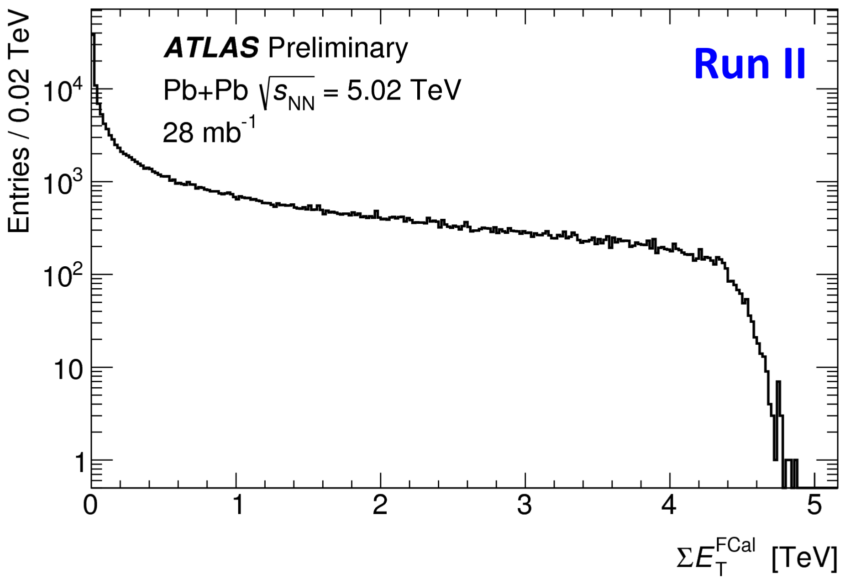


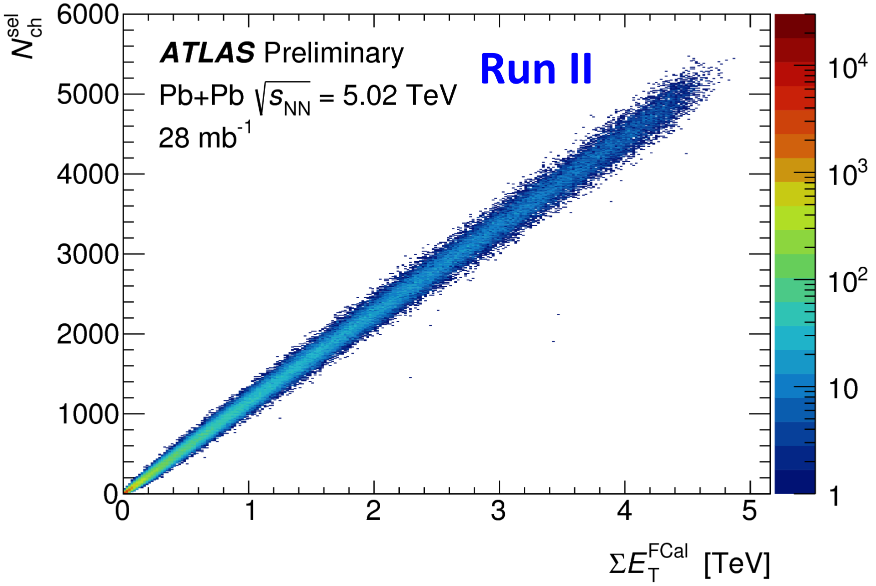


FCAL performance

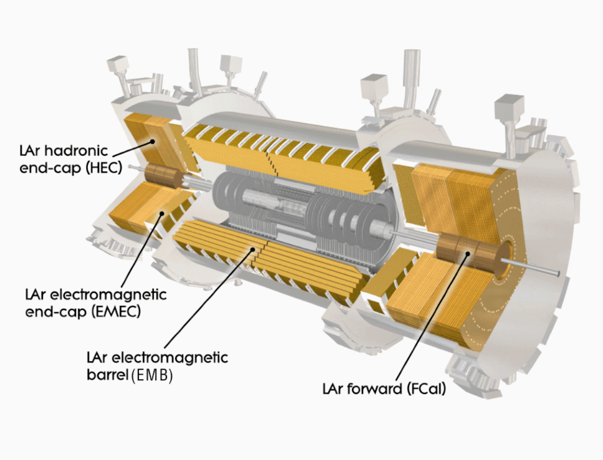


- The performance of the FCAL is best observed from the Heavy Ion data. The total energy sum is used for studies of these high multiplicity events.
- A good correlation is measured between the charged particle multiplicity and the total FCAL energy.





Summary



- The Liquid Argon calorimeters in ATLAS showed excellent performance during the LHC runs I and II.
- The detectors have operated with > 99% data quality.
  - Improvements in the HV system and understanding of the noise have reduced the amount of discarded data.
  - The continuous monitoring of the electronics shows no degradation in the noise levels.
- The calibration of the EM scale shows no degradation over time, pile-up effects are minimal.
- Good online resolution in the energy measurement of EM showers has allowed for triggers to remain with low threshold and high efficiency.
- Electron, photon, and jet performance studies in Run I and Run II show excellent efficiency and good energy response for both the EM and hadronic calorimeters.

ADDITIONAL MATERIAL

abstract

Performance of the ATLAS Liquid Argon Calorimeters in LHC Run-1 and Run-2

The ATLAS detector was designed and built to study proton-proton collisions produced at the LHC at centre-of-mass energies up to 14 TeV and instantaneous luminosities up to 10^{34} cm^{-2} s${^-1}$. Liquid argon (LAr) sampling calorimeters are employed for all electromagnetic calorimetry in the pseudorapidity region $|\eta|<3.2$, and for hadronic calorimetry in the region from $|\eta|=1.5$ to $|\eta|=4.9$.

The calibration and performance of the LAr calorimetry system was established during beam tests, cosmic ray muon measurements and in particular the first three years of pp collision data-taking. During this period, referred to as Run-1, approximately 27~fb^{-1} of data have been collected at the center-of-mass energies of 7 and 8~TeV.

Following a period of detector consolidation during a long shutdown, Run-2 started in 2015 with approximately 3.9~fb^{-1} of data at a center-of-mass energy of 13~TeV recorded in this year.

Results on the LAr calorimeter operation, monitoring and data quality, as well as their performance will be presented, including the calibration and stability of the electromagnetic scale, response uniformity and time resolution. These results demonstrate that the LAr calorimeters perform excellently within their design requirements.

The calorimetry system thus played a crucial role in the Run-1 physics programme, and, in particular, in the discovery of a Higgs boson.