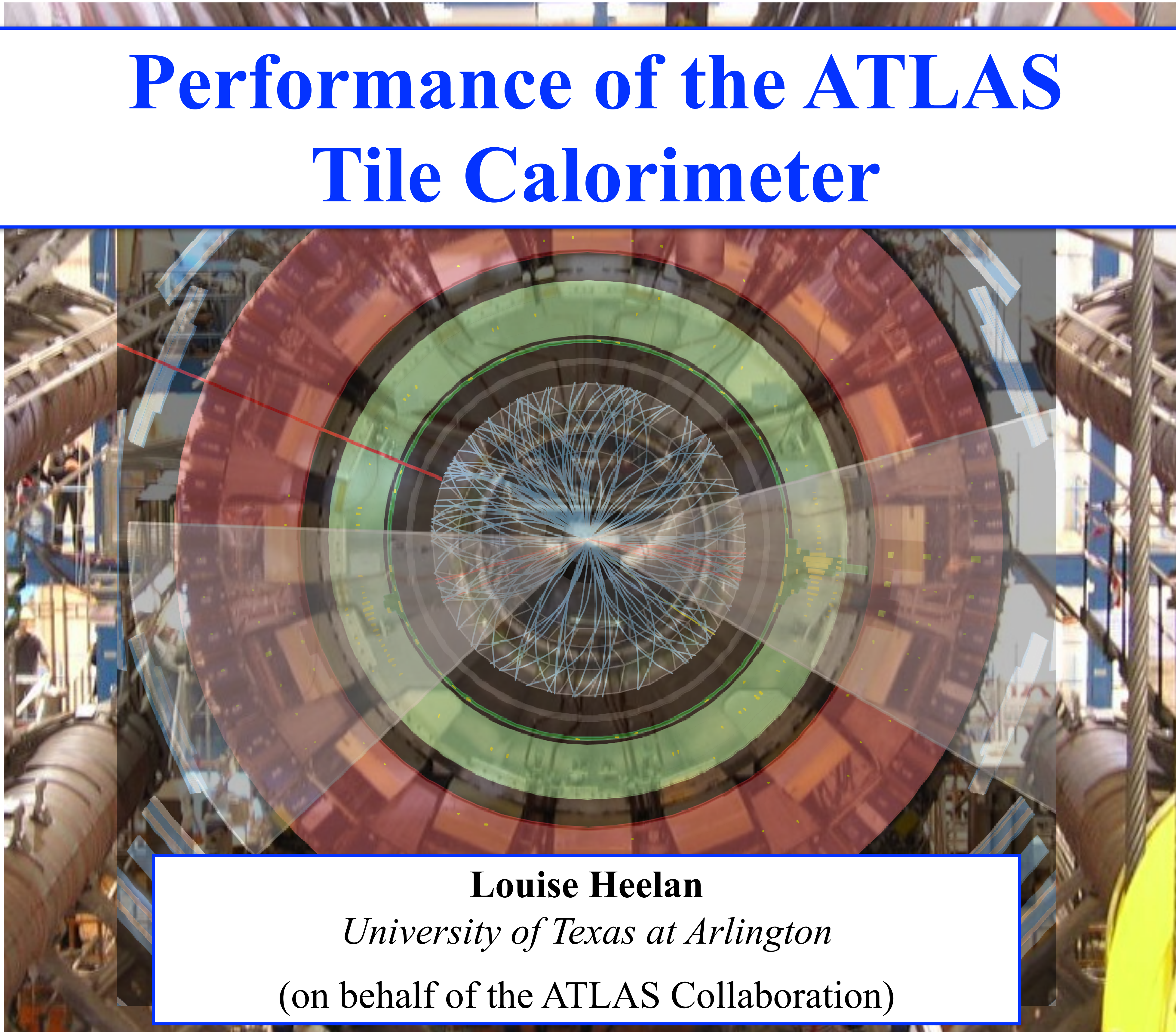
Performance of the ATLAS Tile Calorimeter



Louise Heelan
University of Texas at Arlington
(on behalf of the ATLAS Collaboration)

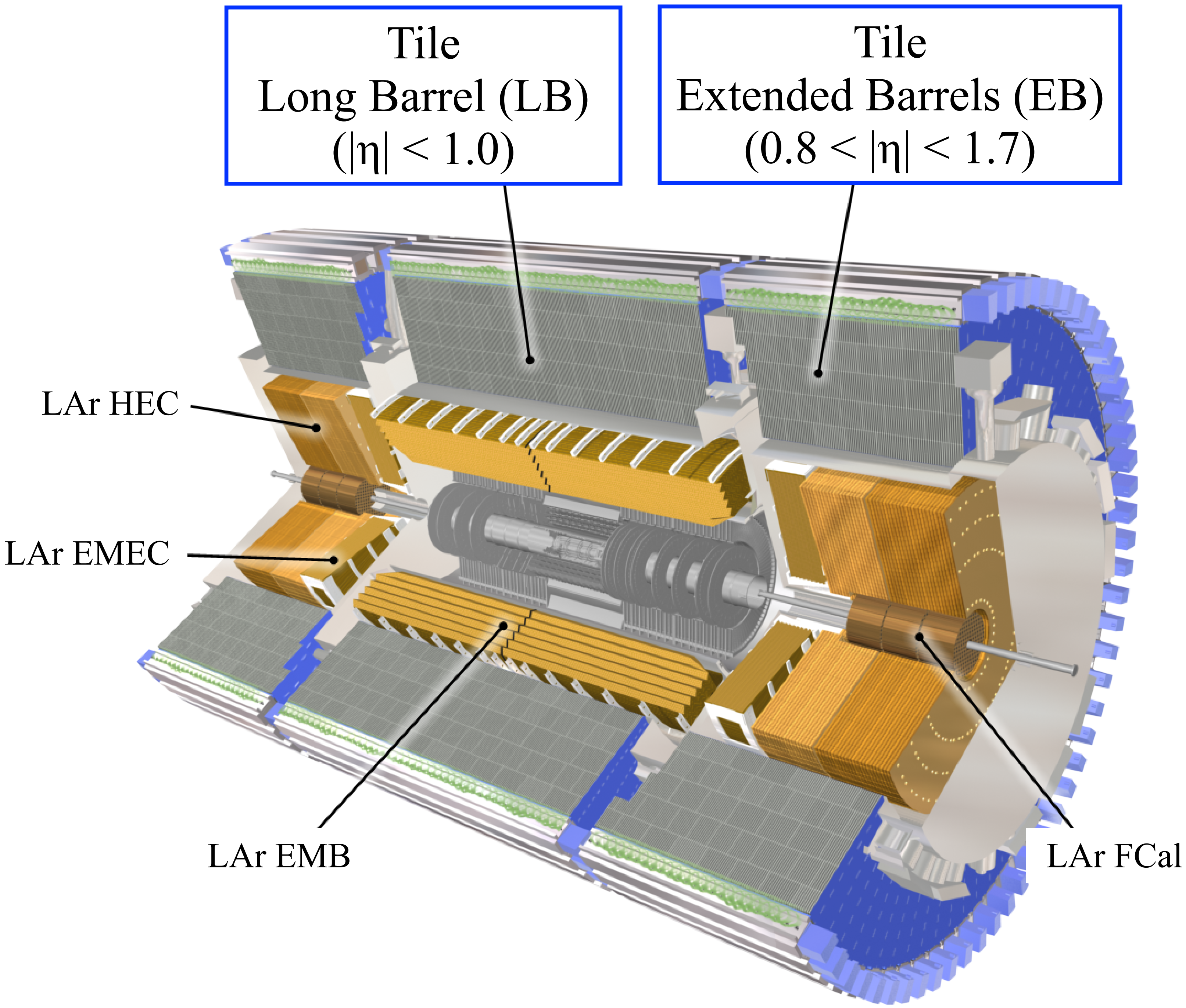
Kruger2014: Discovery Physics at the LHC
December 1-6, 2014

Outline

- Tile calorimeter in ATLAS
- Signal reconstruction
- Calibration techniques
- Detector during Run 1
- Activities during shutdown 2013-2015
- Summary and outlook

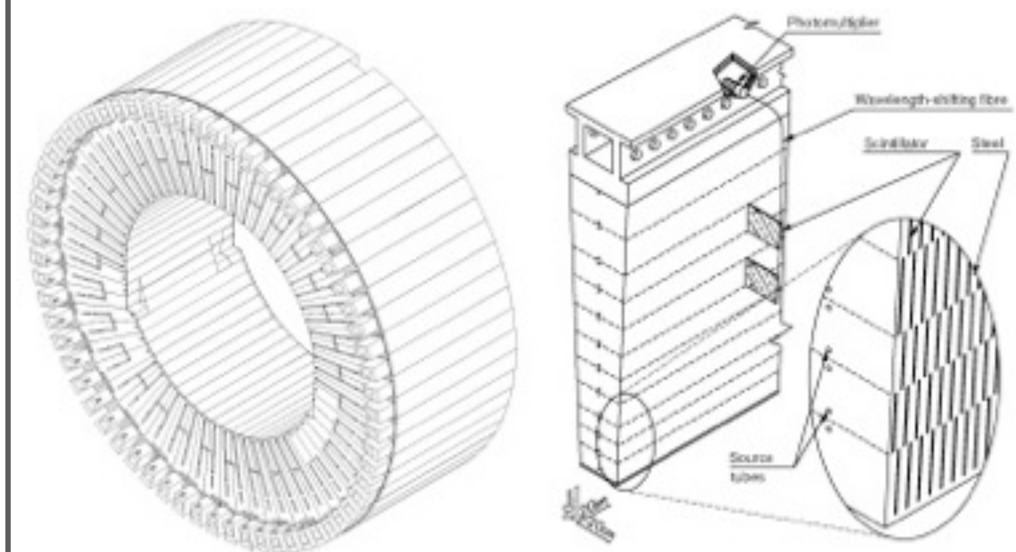
Tile calorimeter in ATLAS
"TileCal"

- hadronic barrel calorimeter used for jet, lepton, and E_T^{miss} reconstruction
- rectangular tiles of plastic scintillator alternating with steel absorber plates



Granularity:

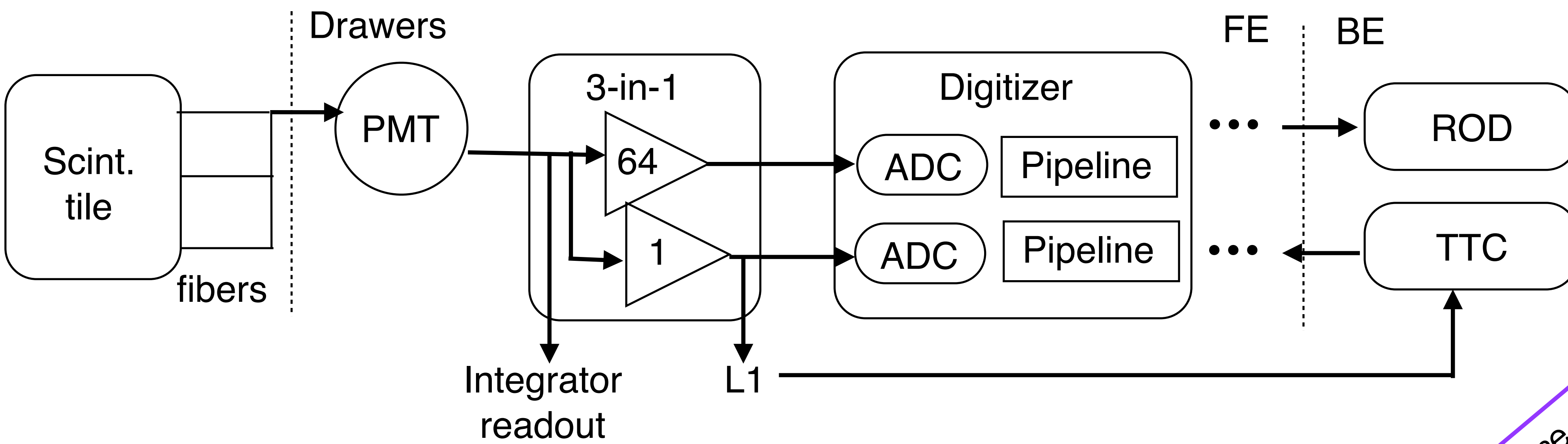
- 64 wedge-shaped modules $\Delta\varphi=0.1$
- three radial layers



Performance goals:

- energy resolution for jets: $\sigma/E = 50\%/\sqrt{E} \oplus 3\%$
- linear within 2% (4 TeV jets)
- hermetic coverage for E_T^{miss} reconstruction

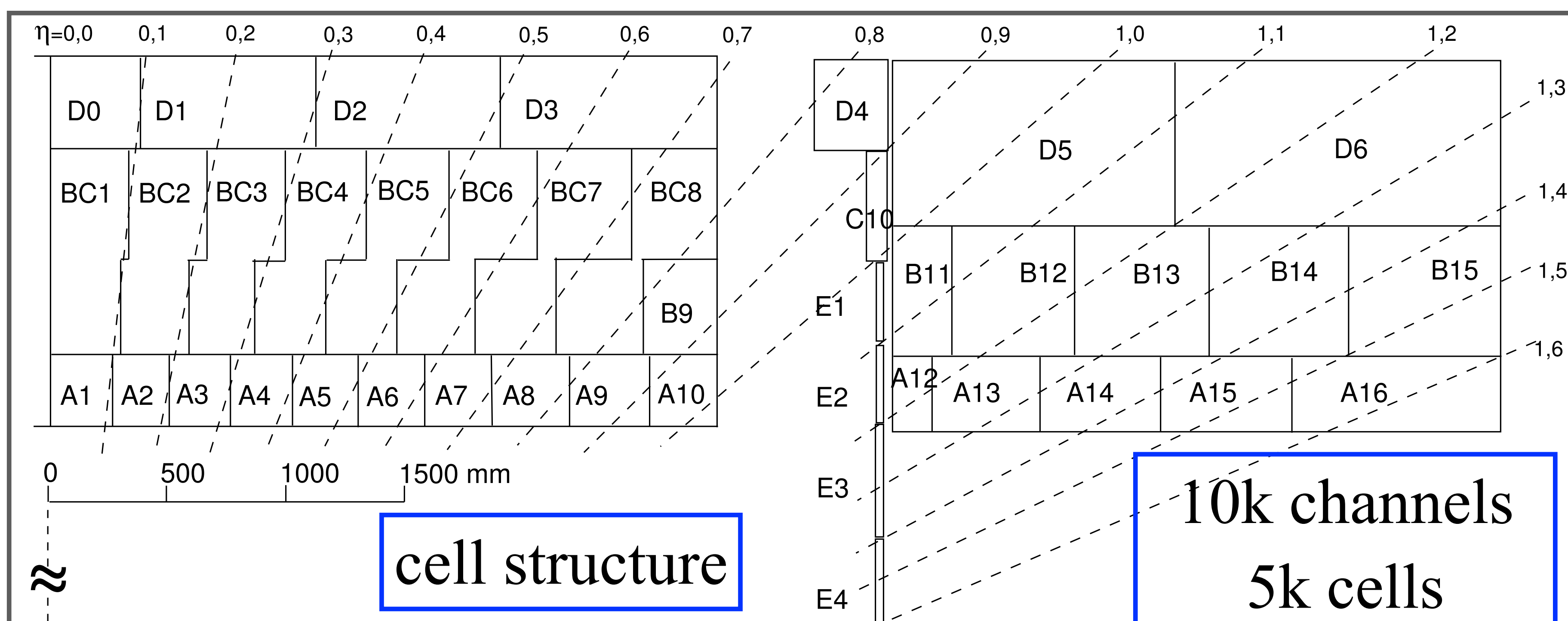
Readout structure



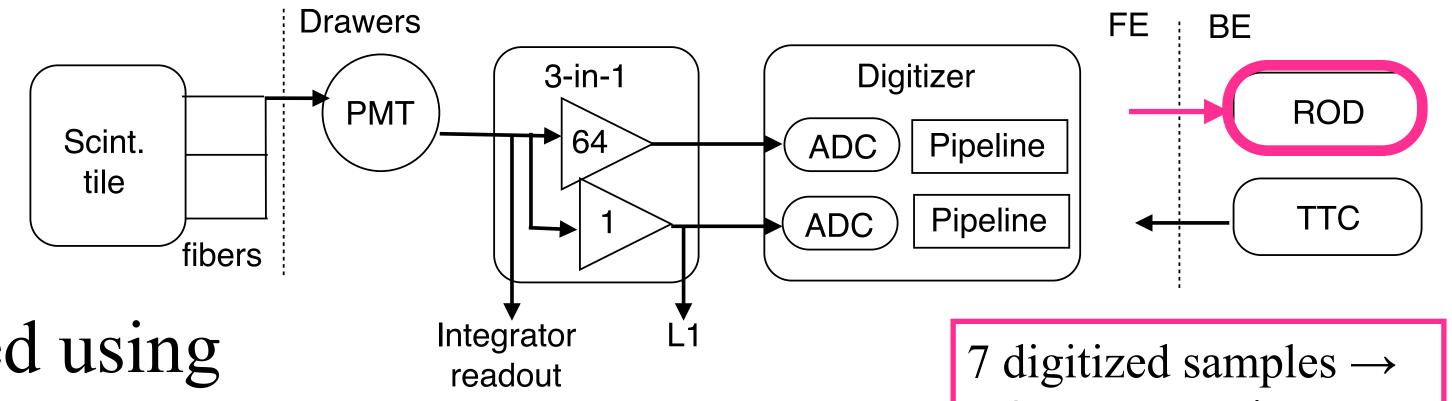
More about TileCal electronics in **Robert Reed**'s talk

- signals from several tiles collected by wavelength shifting fibers sent to PMTs
- PMTs with front end electronics in mechanical drawers (outer radius of module)
- the signal of each PMT is read by one electronic channel
- PMT analog signal -> 3-in-1 for shaping+amplification (bi-gain 1:64), integrator readout, and analog signal to L1 trigger

- dynamic range of PMT: ~10 MeV to 800 GeV
- digitizer samples pulse every 25 ns
- two channels (collecting light from either side of tile) → readout one cell



Signal reconstruction

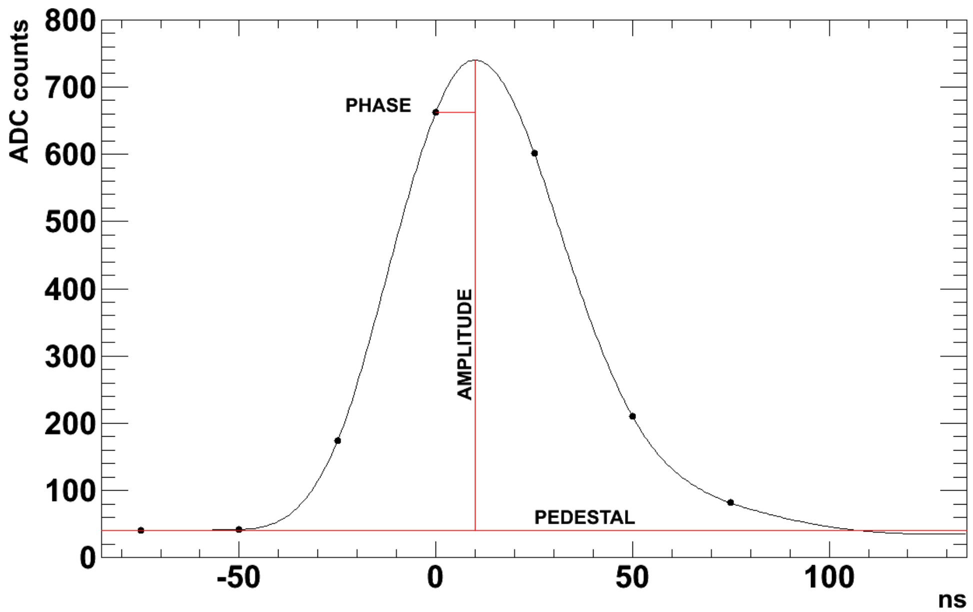


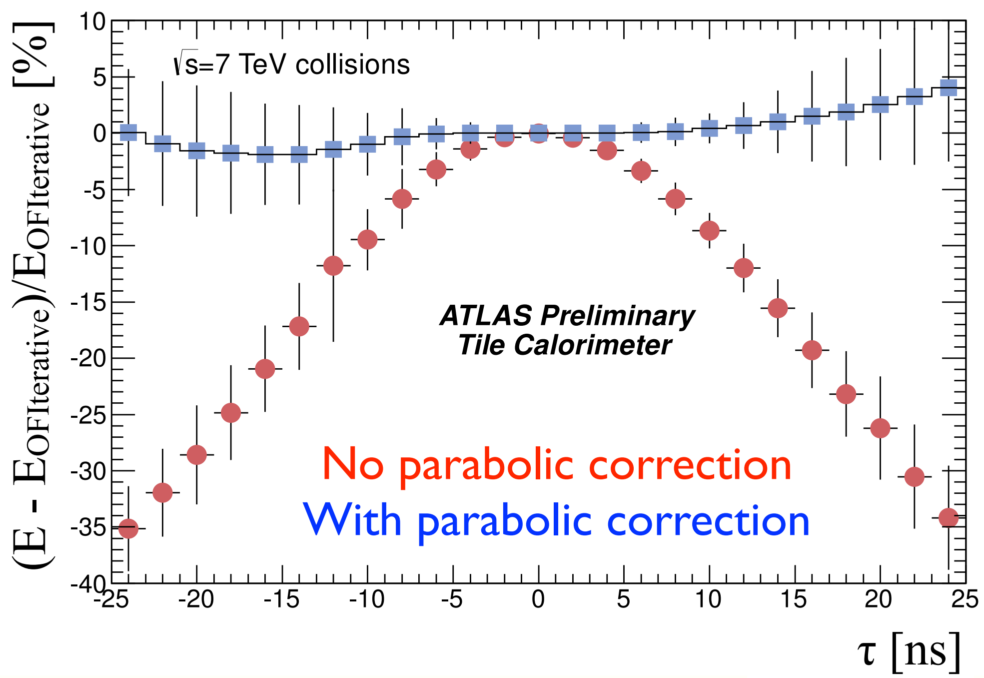
7 digitized samples → ROD energy+time reco

- channel time and energy reconstructed using Optimal Filtering (OF) algorithm:

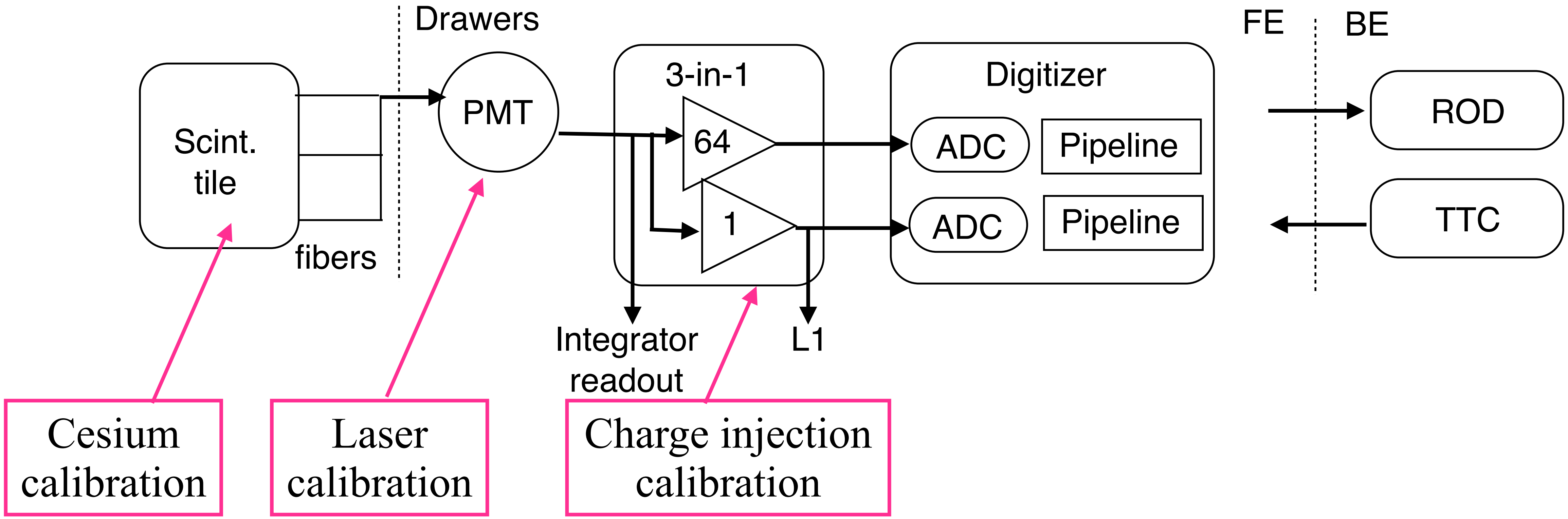
$$A = \sum_{i=1}^{n=7} a_i S_i \;, \qquad A\tau = \sum_{i=1}^{n=7} b_i S_i$$

- weights (a_i, b_i) derived using known pulse shape and sample noise autocorrelation matrix
- energy proportional to A
- τ is time phase (time difference between reconstructed pulse height and expected maximum at central sample)
- OF weights based on expected phase
- for $\tau \neq 0$ reconstructed energy underestimated by a known function → application of parabolic correction to energy
- within ±10 ns energy difference <1%





Energy calibration ADC→GeV

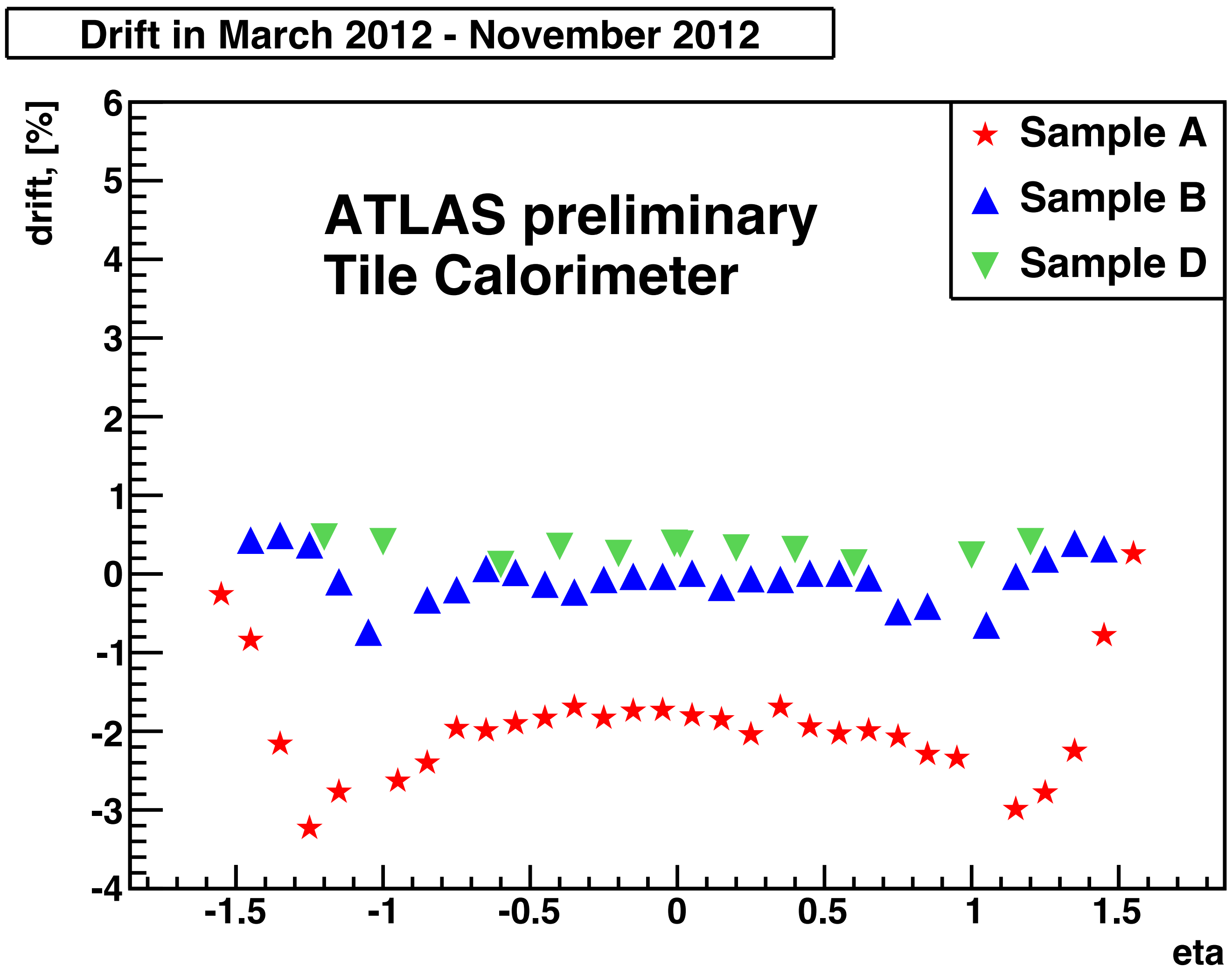


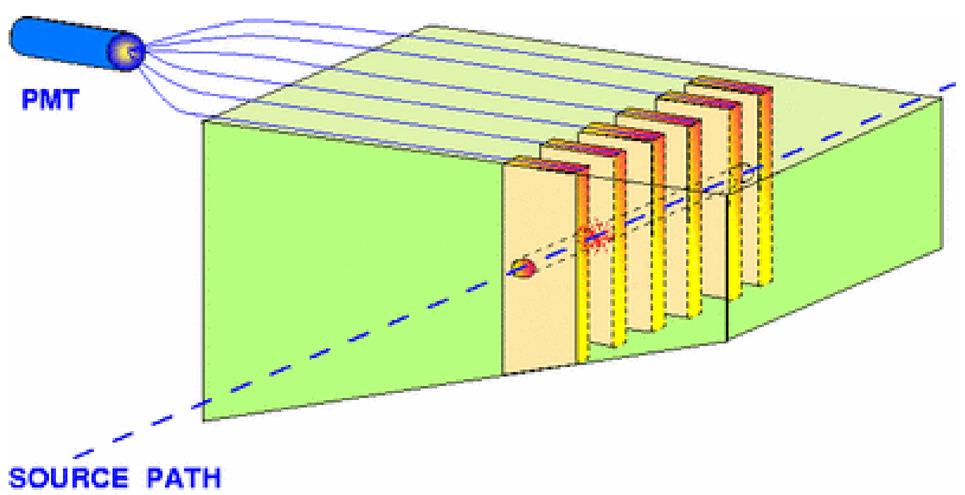
$$E_{\text{channel}} = A \cdot C_{\text{ADC}\rightarrow\text{pC,CIS}} \cdot C_{\text{pC}\rightarrow\text{GeV,TB}} \cdot C_{\text{Cs}} \cdot C_{\text{laser}}$$

- 11% modules exposed to test beam of electrons and muons used to set overall electromagnetic scale (pC→GeV) and inter-calibrate different layers (A, BC, D)
- Cesium: calibration of scintillator tiles and PMTs (read out by integrator circuit)
- Laser: calibration of PMTs and readout electronics
- Charge injection system (CIS): injection of known charge into front end electronics, calibration of readout electronics (ADC→pC)

Cesium calibration system

- ^{137}Cs used to calibrate scintillator tiles by emitting 0.662 MeV photons:
  - three moveable Cs sources located in closed circuit system
  - sources moved through every tile by hydraulic system
- maintain global conversion (test beam)
- apply calibration corrections for residual cell differences (cell inter-calibration)
- calibrations ~1/month, precision of ~0.3%

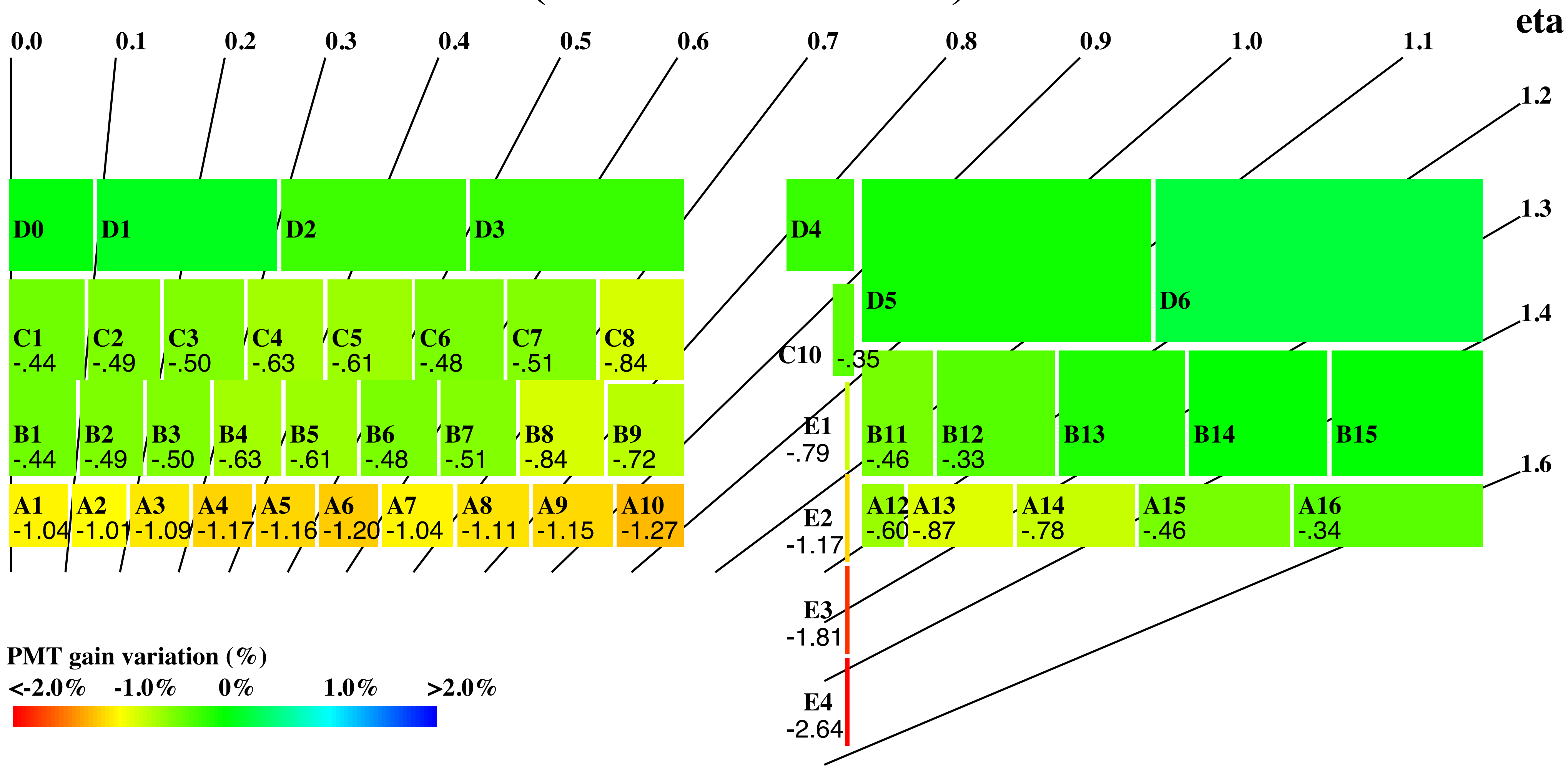




TileCal very stable, maximum loss was ~3.5% from the inner layer (A13 cell, |η| ~1.3):

Laser calibration system

- laser light pulse sent to PMTs
- monitor and measure individual PMT gain variation between Cs scans
- monitor time of individual channels
- laser calibration runs 2/week, and laser pulses sent during empty bunch crossings
- precision <0.5% over one month (between Cs scans)

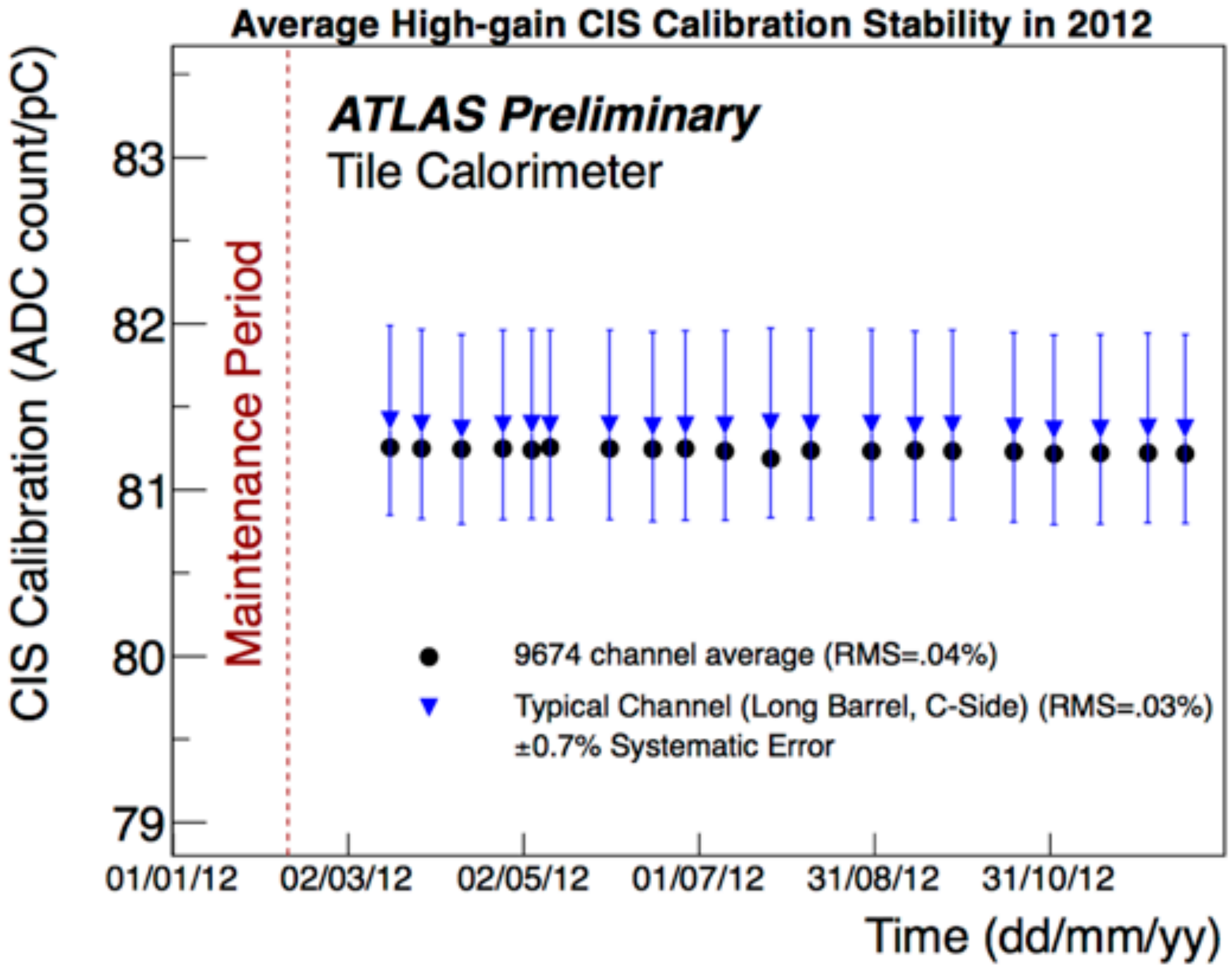


- above shows response variation April-May 2012
- maximum drift in E and A cells → highest energy deposits

Charge injection calibration system

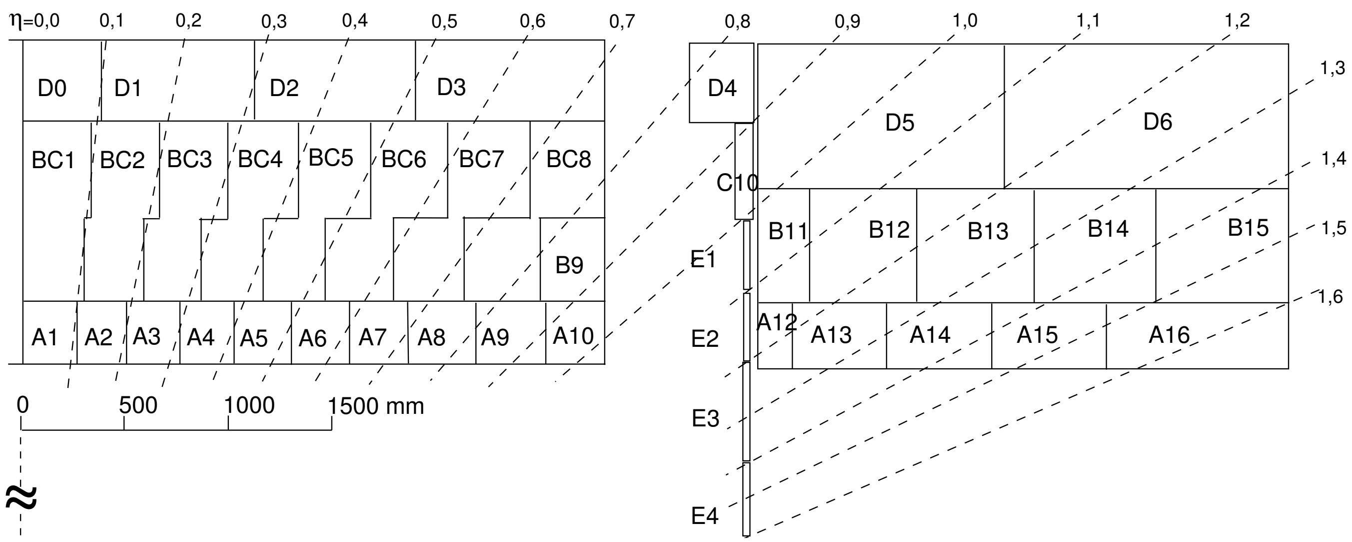
- inject known charge into 3-in-1 cards to measure electronics response (pC→ADC)
- done for both high gain and low gain
- correct for non-linearities
- calibration taken 2/week

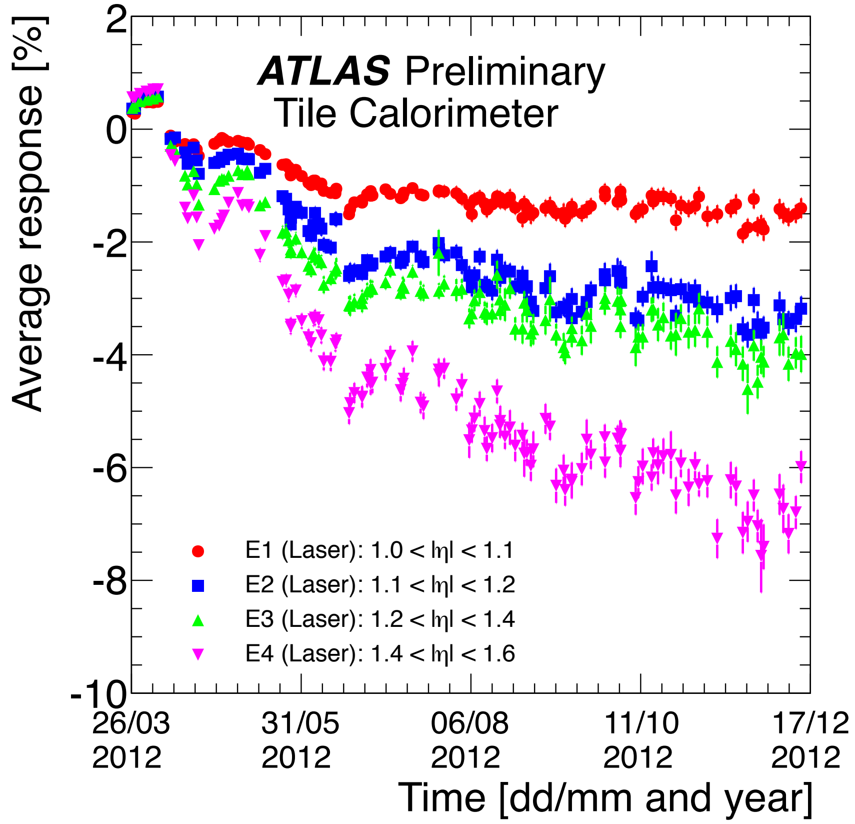
High gain charge injection system calibration constants with time for all channels, and one typical channel → very stable

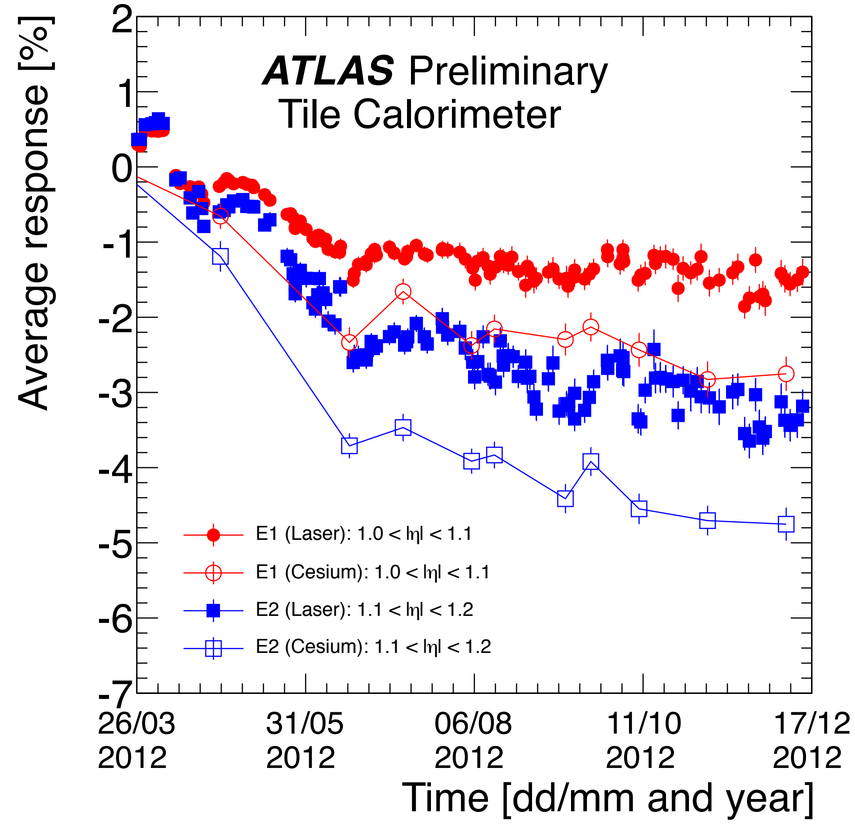


Intermediate TileCal: gap/crack region

- ITC fill gap between LB and EB
- E1, E2: gap scintillators
- E3, E4: crack scintillators (no Cs)
- E-cells exposed to most radiation





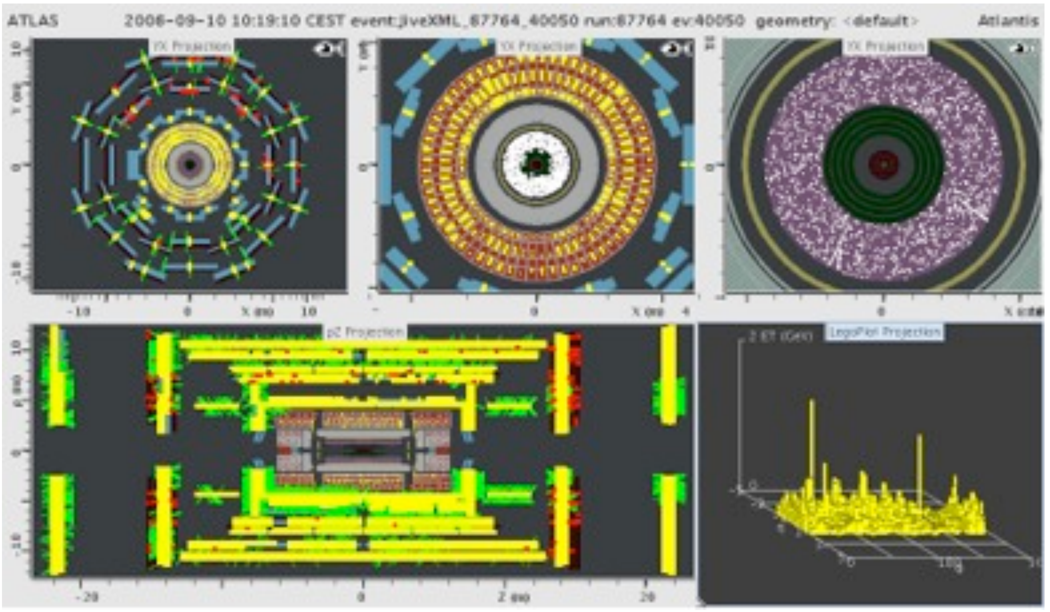


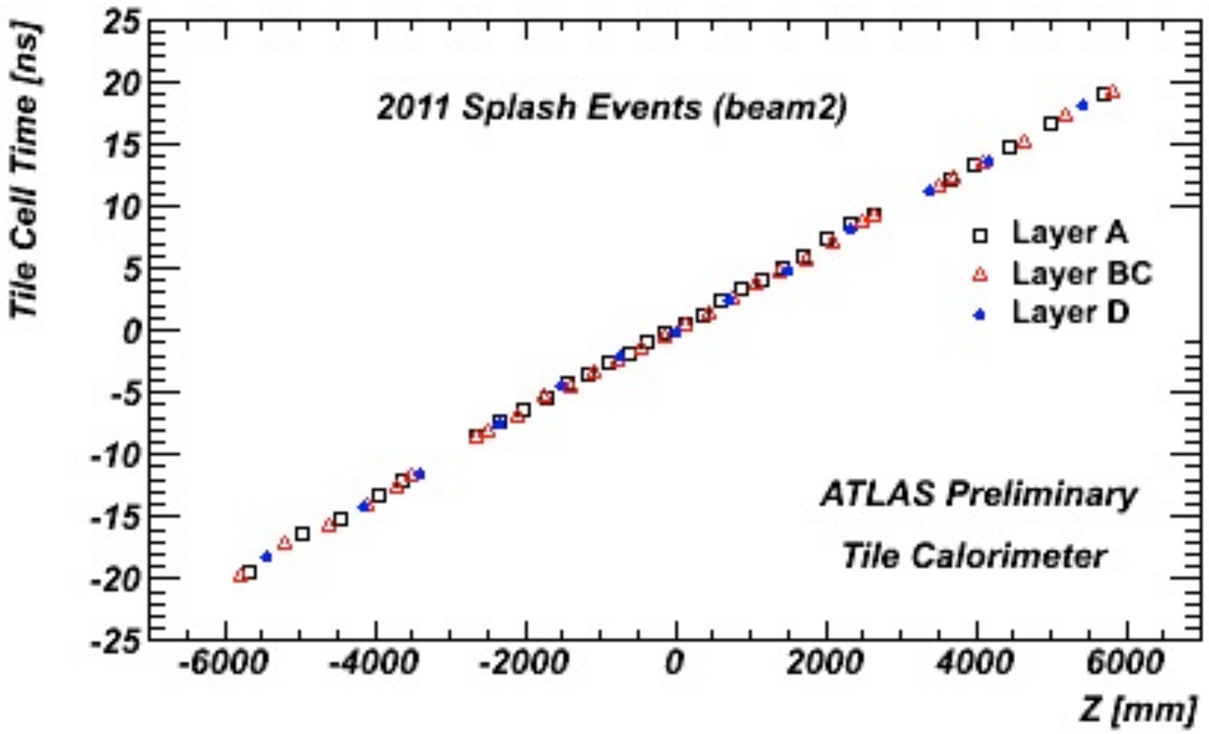
- E4 most irradiated, average response variation of -8% over 2012
- E1, E2 look at response change seen by laser and Cesium system: 50% scintillator irradiation, 50% due to PMT gain change

More about plans for gap scintillators in **Harshna Jivan**'s talk

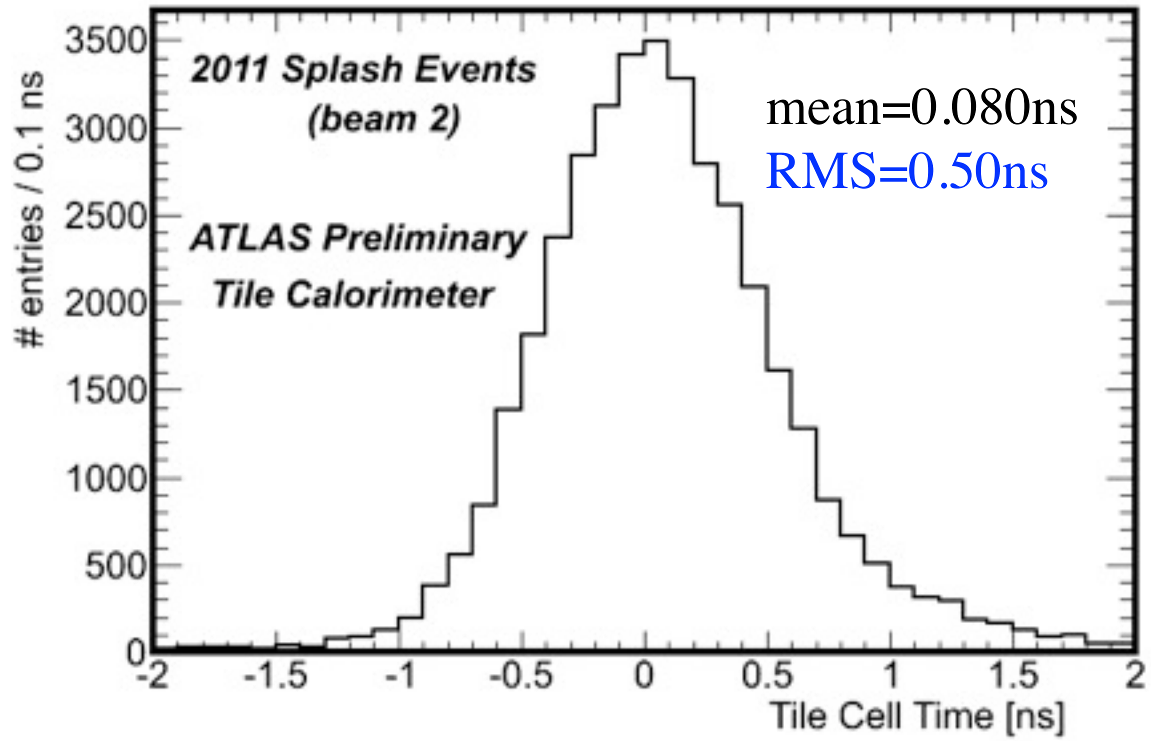
Time inter-calibration

- initial channel time set using laser and single beam events
- single beam "splashes": LHC proton beam hit upstream collimator → many high energy particles produced depositing large signals in all channels





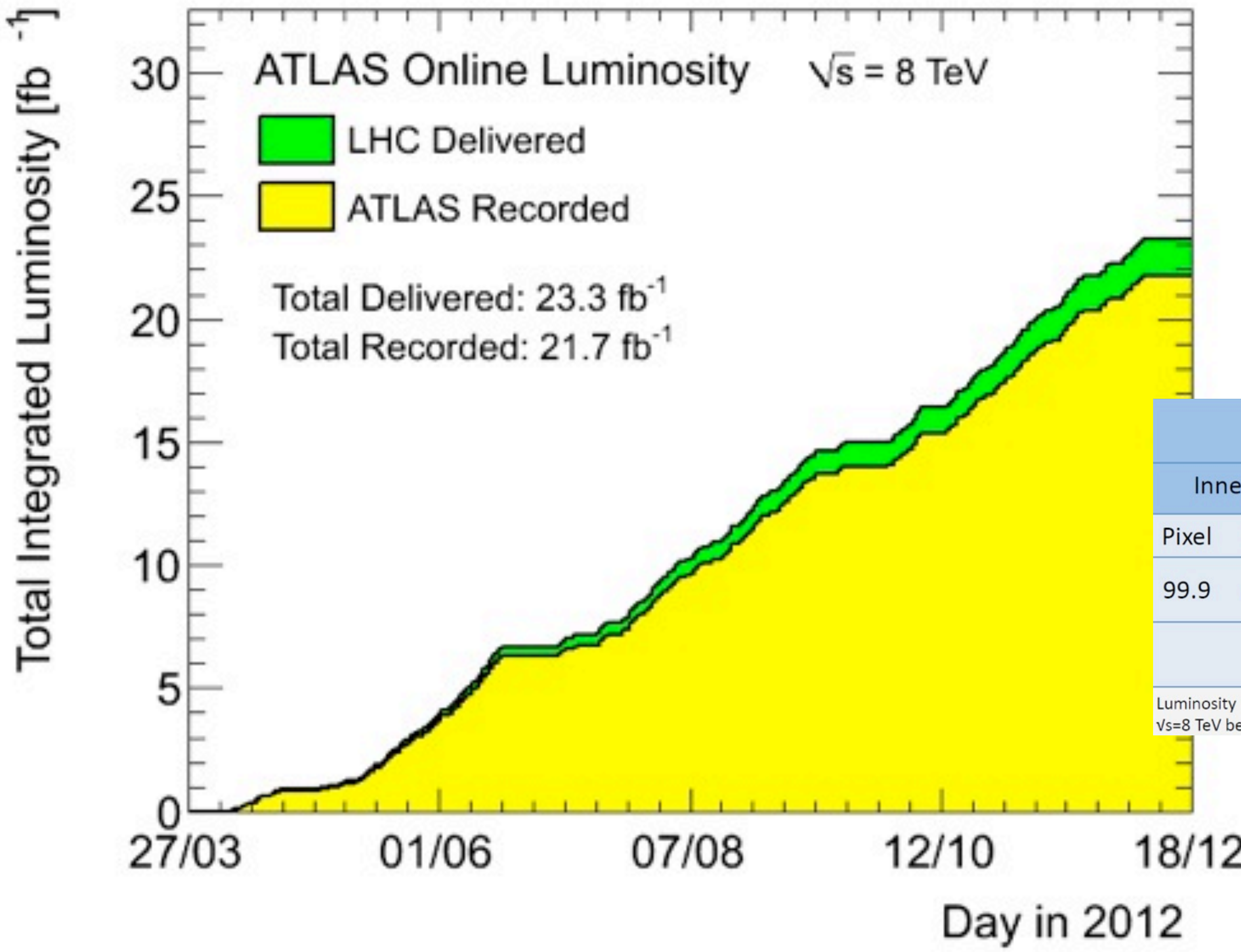
- average cell time vs cell z for three layers
- slope matches particle time of flight



- cell time distribution after particle time of flight correction

Performance study with collision jets (7TeV, 50ns): ~0.5 ns at 20 GeV.

TileCal during Run 1: Operation



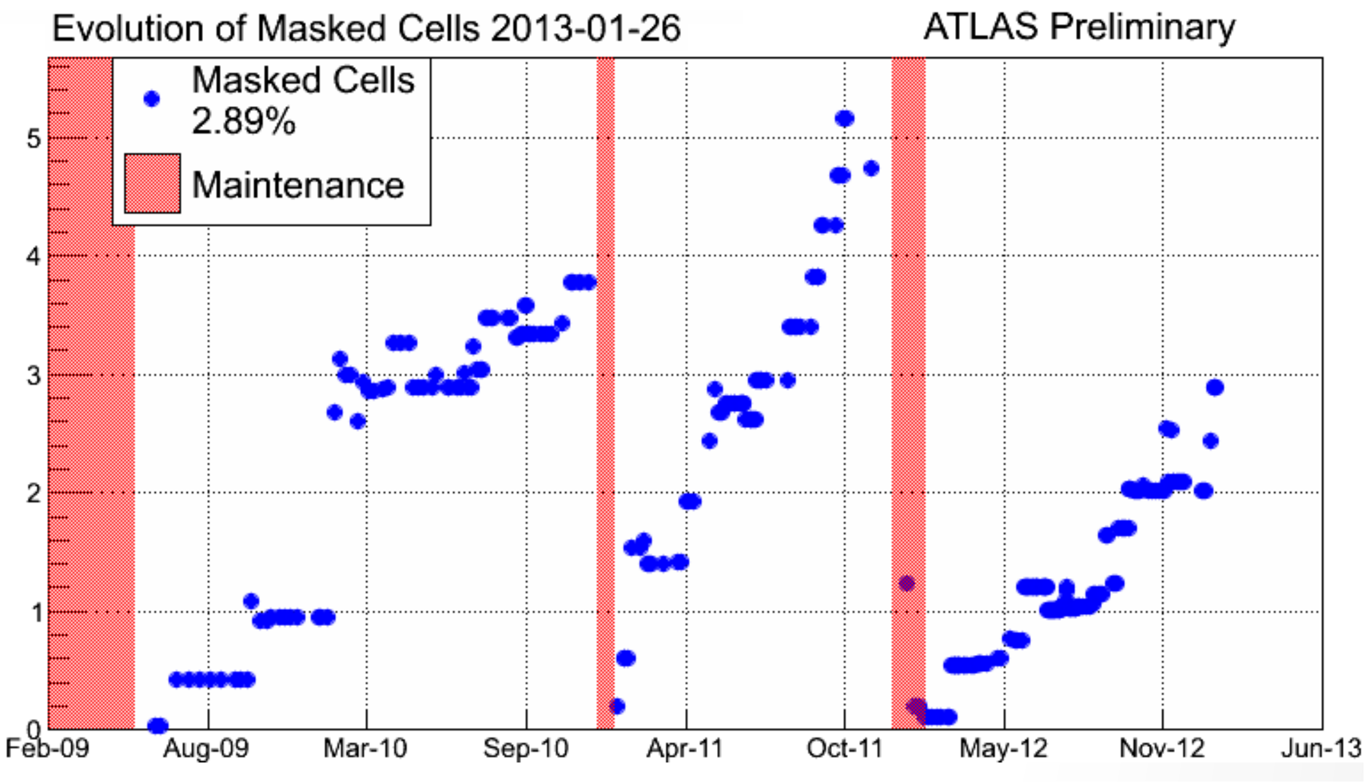
ATLAS p-p run: April-December 2012

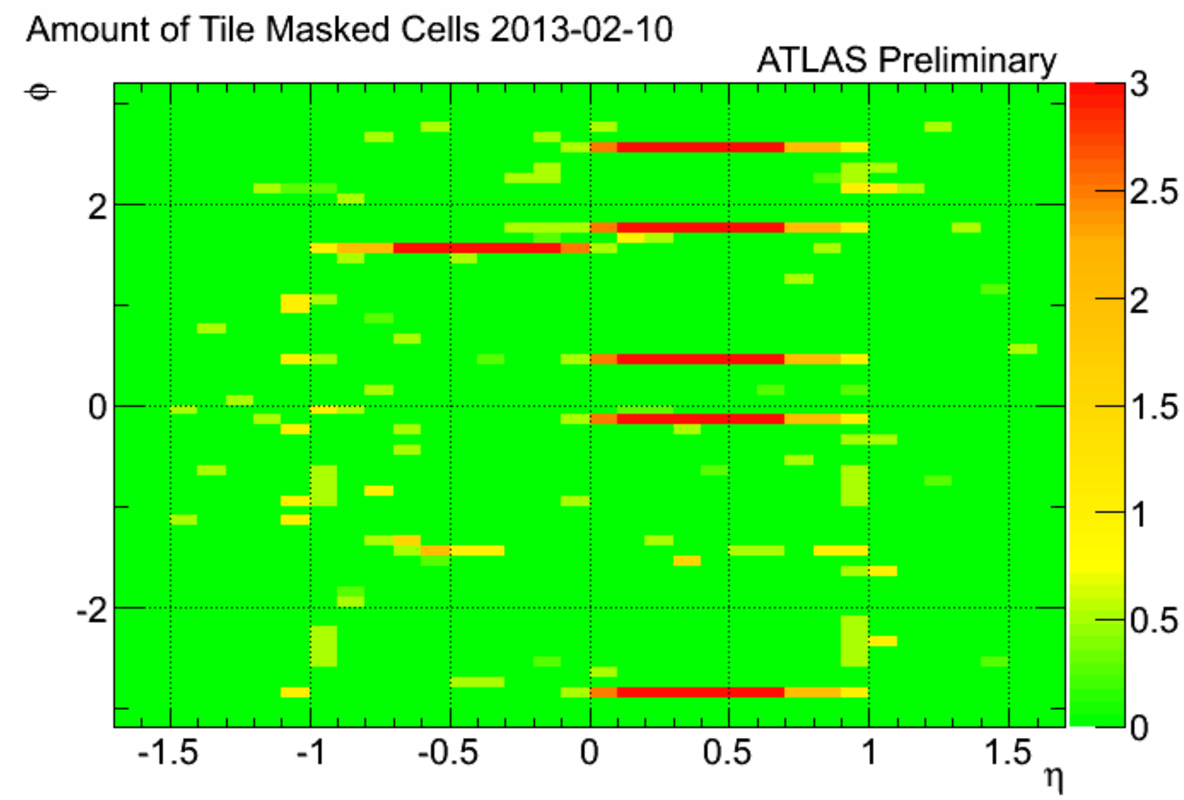
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.5%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at $\sqrt{s}$=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb^{-1} of recorded data.

- Tile DQ efficiency for p-p collisions: 2012 was 99.6% (2011: 99.2%, 2010: 100%)
- efficiency loss due to (four or more consecutive modules off):
  - Read-Out Link (ROL) disabling (not reading data from four modules) → improved (June 2012) when automatic recovery implemented
  - loss from channel time problems after restart (recovered/corrected in data reprocessing)
  - power trips/cuts affecting 200V PS (four consecutive modules off)

TileCal during Run 1: Faulty cells

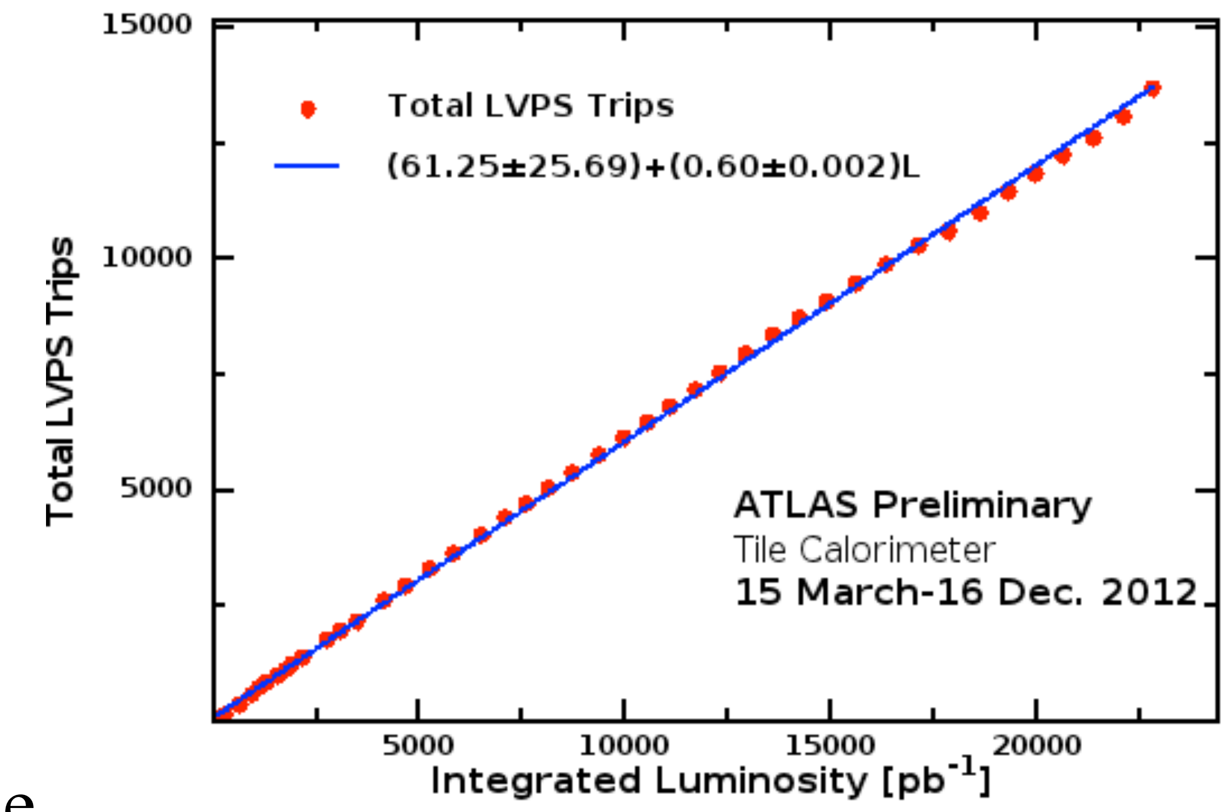


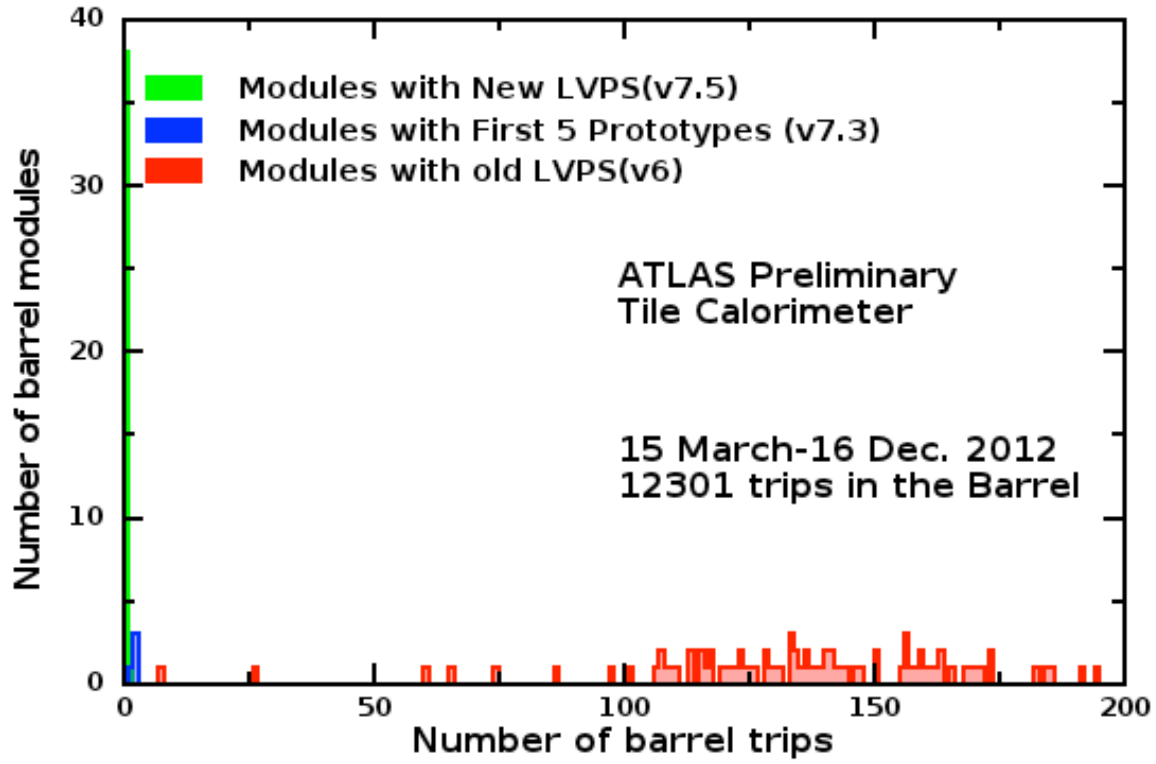


- most dead modules due to failures of low voltage power supplies (LVPS)
  - 2011: lost 1 LVPS/month
  - 2012: lost 0.5 LVPS/month
- maintenance periods allowed replacement of LVPS and/or repair of faulty readout cells
- at end of Run 1 six modules off (LVPS problems) → accounts for most of 2.9% faulty cells
- faulty cell energy interpolated from neighboring cells

TileCal during Run 1: LVPS

- problematic low voltage power supplies (LVPS):
  - LVPS failures (turning module off)
  - frequent trips of LVPS correlated with integrated luminosity →
- automatic recovery of LVPS implemented during physics runs
- energy interpolated from neighboring module
- during 2011-2012 shutdown 40 new LVPS installed
- 2012: total 14k LVPS trips, only one in new LVPS version

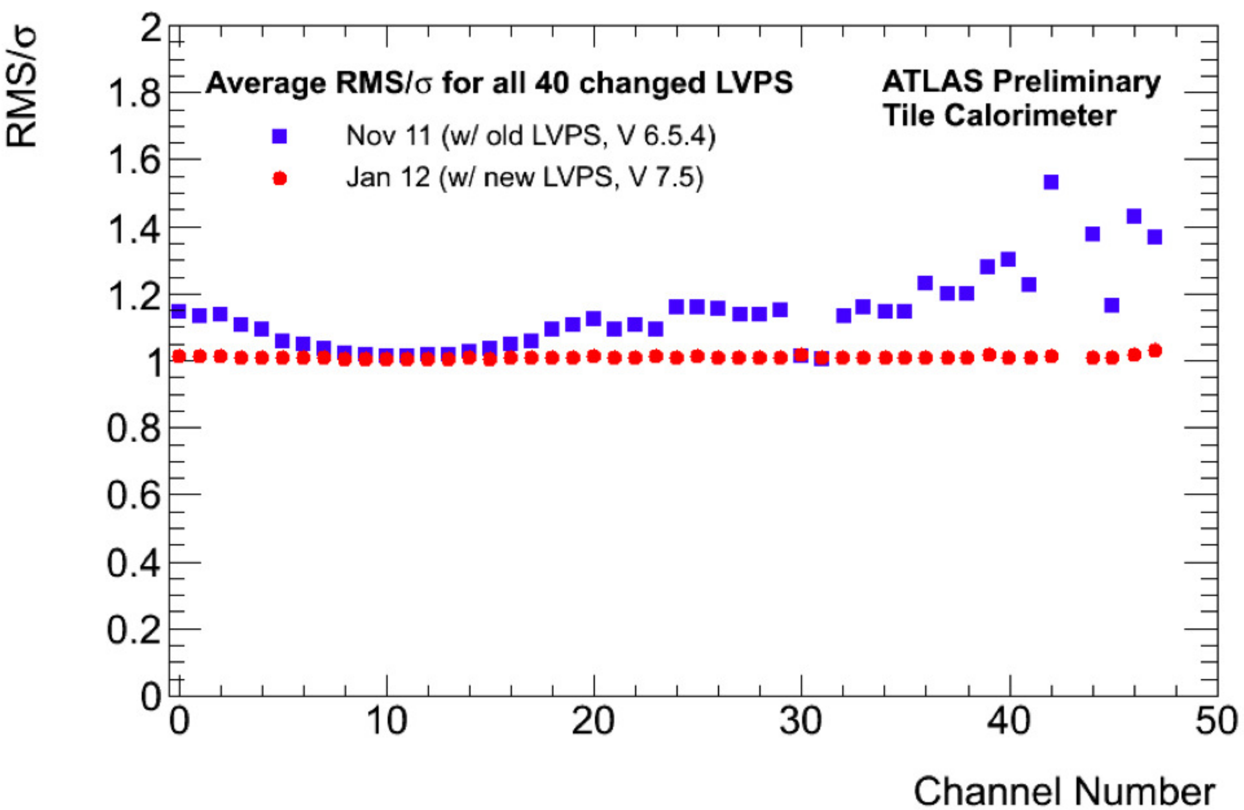




TileCal during Run 1: LVPS & electronic noise

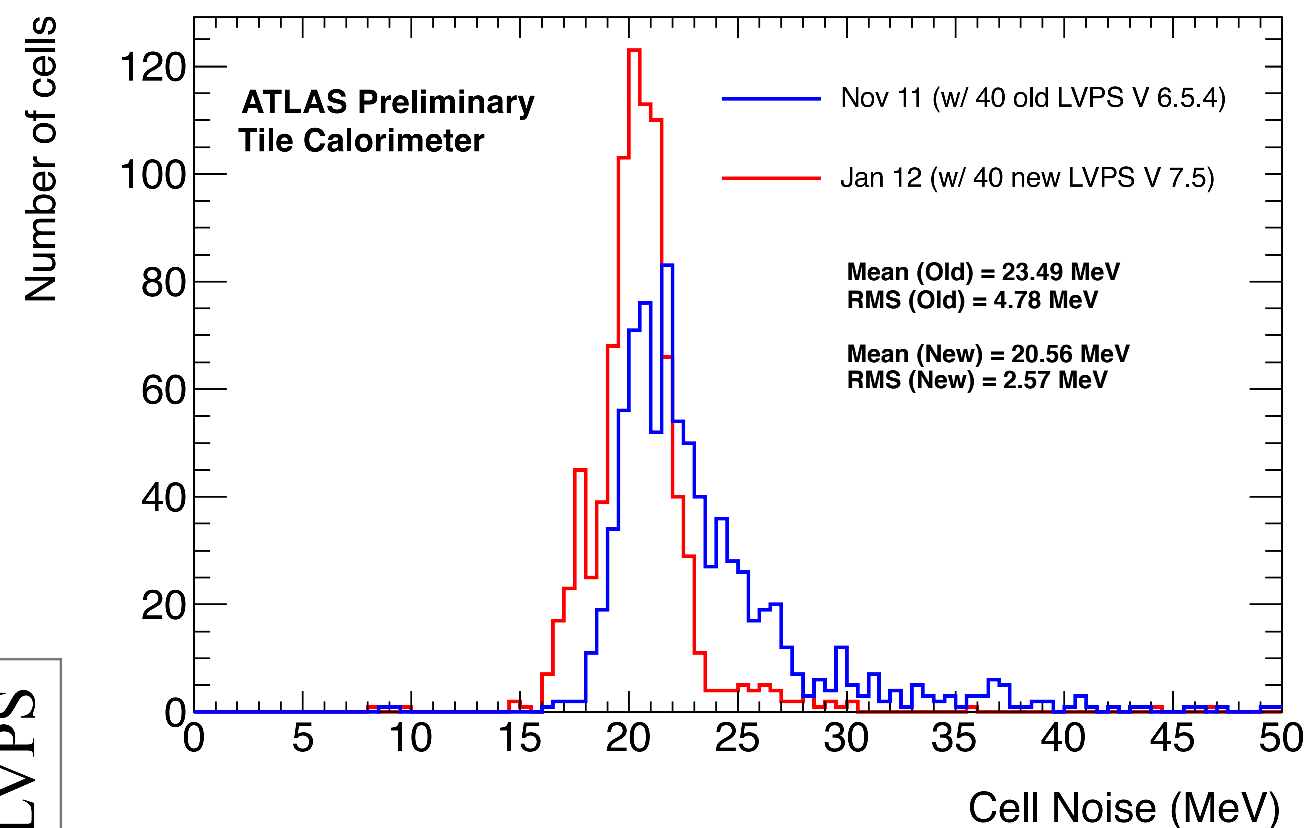
- can evaluate electronic noise using dedicated pedestal runs (both gains)
- Run 1: cell electronic noise best described by double Gaussian
- electronic noise with new LVPS lower and more Gaussian

Comparison of Gaussian shape of electronic noise vs channel for 40 LVPS before/after replacement:



LVPS

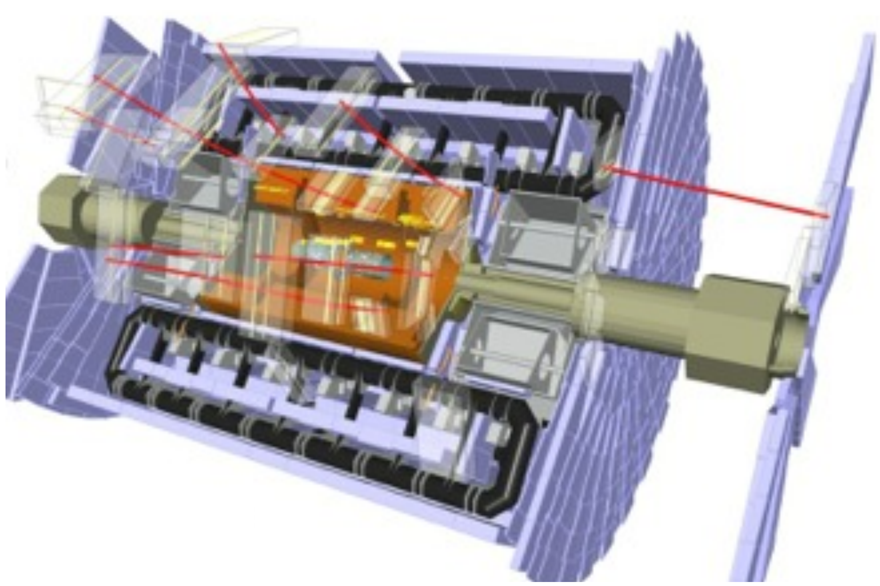
Comparison of cell noise for 40 LVPS before/after replacement:



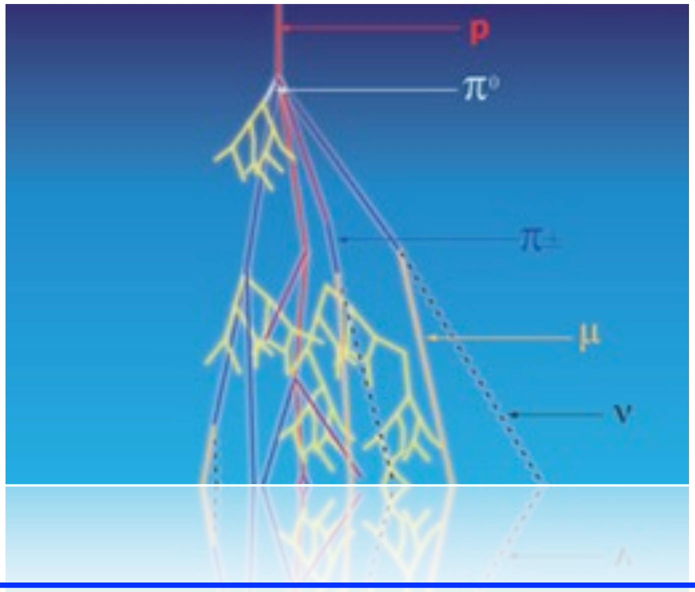
Performance with single muons

- use single isolated muons to study the performance of the detector
- energy deposited by muons in scintillator proportional to path length (*dE/dl*) → validate electromagnetic scale energy calibration:
  - between cells
  - between layers
  - over time
  - by comparing with Monte Carlo simulations
- sources of isolated muons:

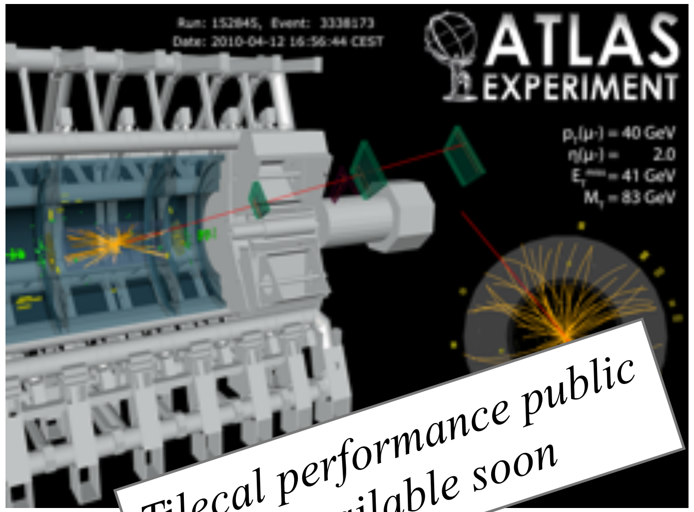
Muons from single beam scraping/ halo events:



Muons from cosmic ray sources:

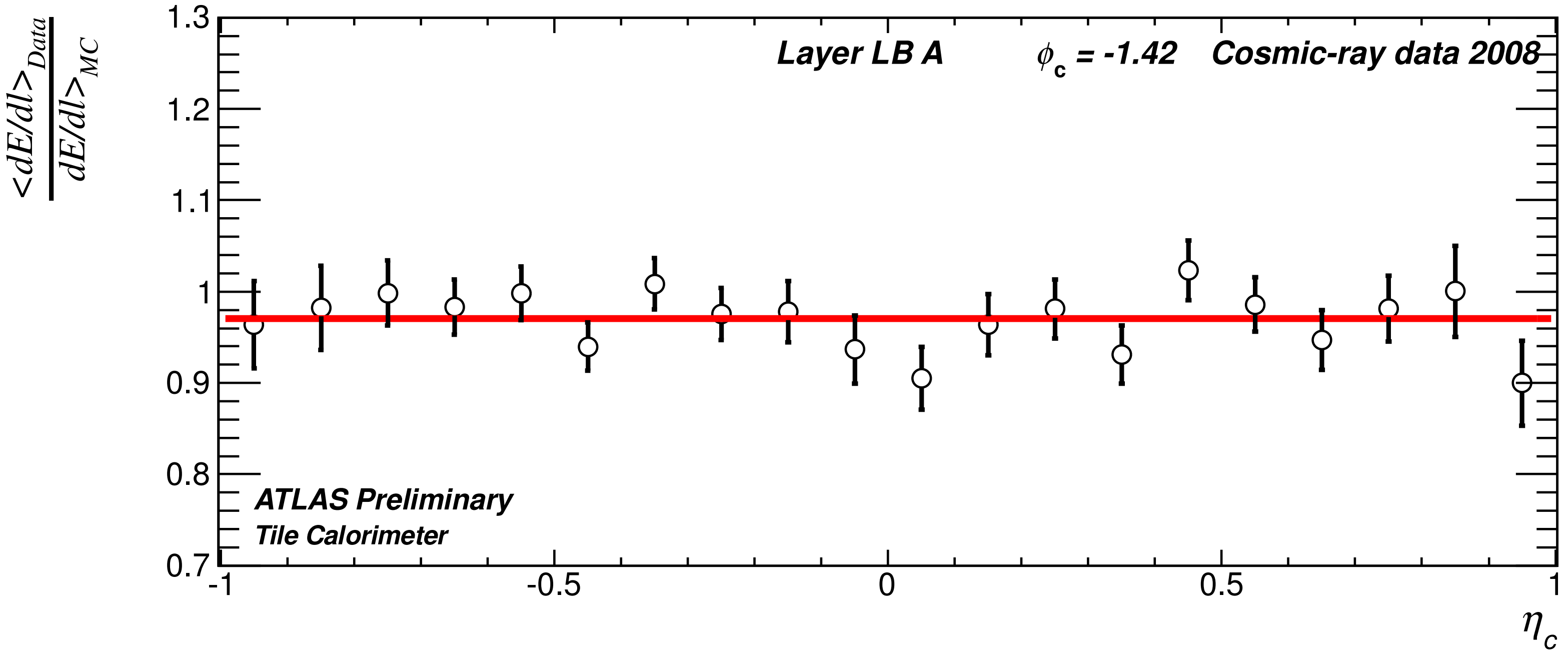


Muons from physics collisions (W→μν):



Tilecal performance public results available soon

Performance with single muons



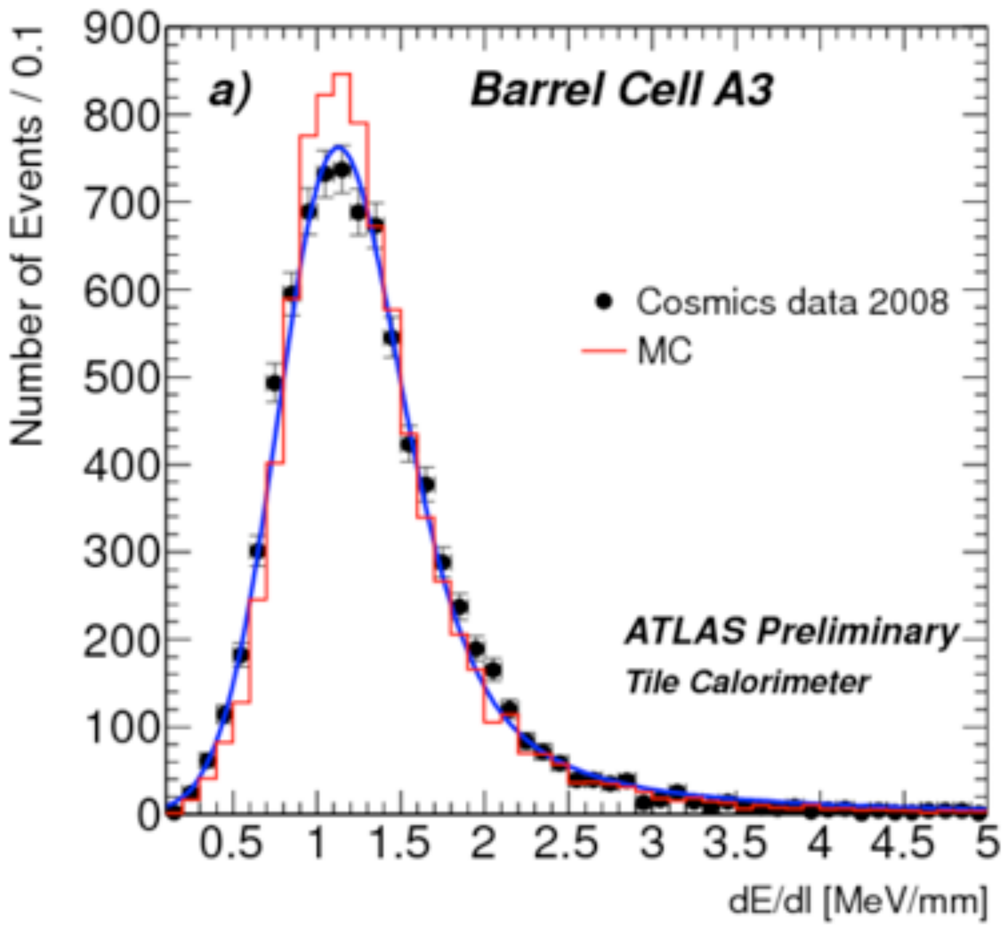


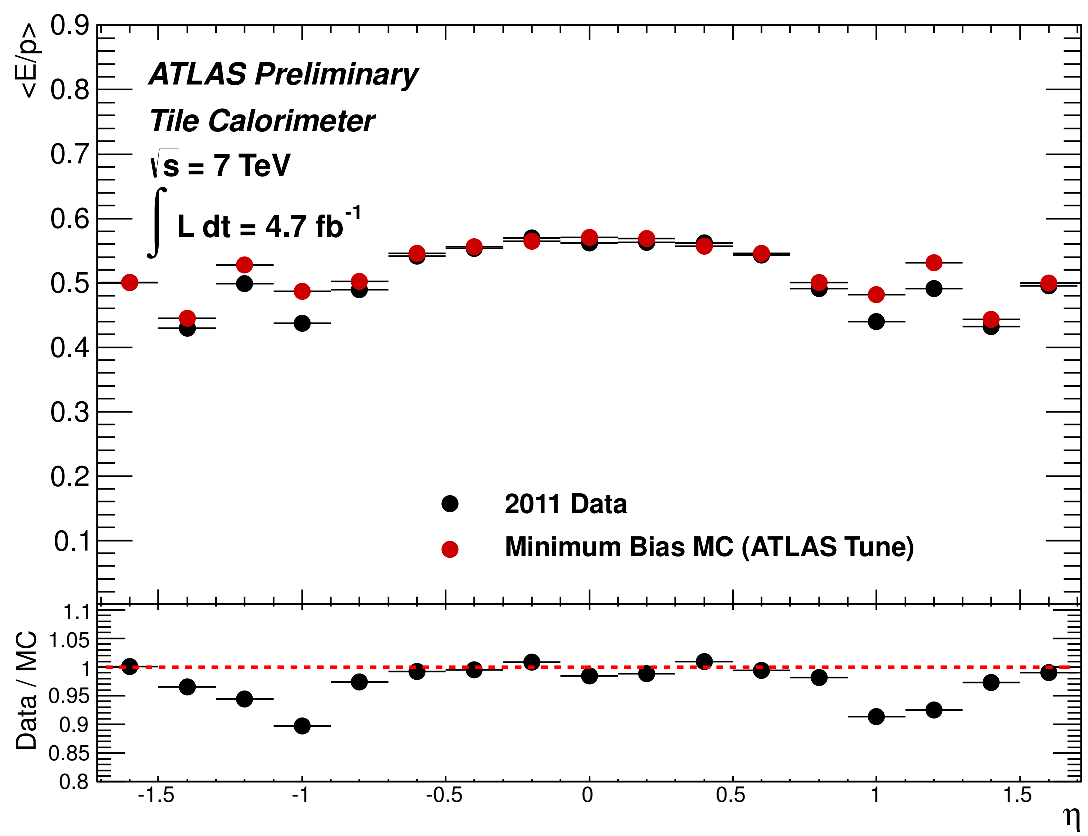
Table shows *dE/dl* [MeV/mm] for cosmic μ analysis.

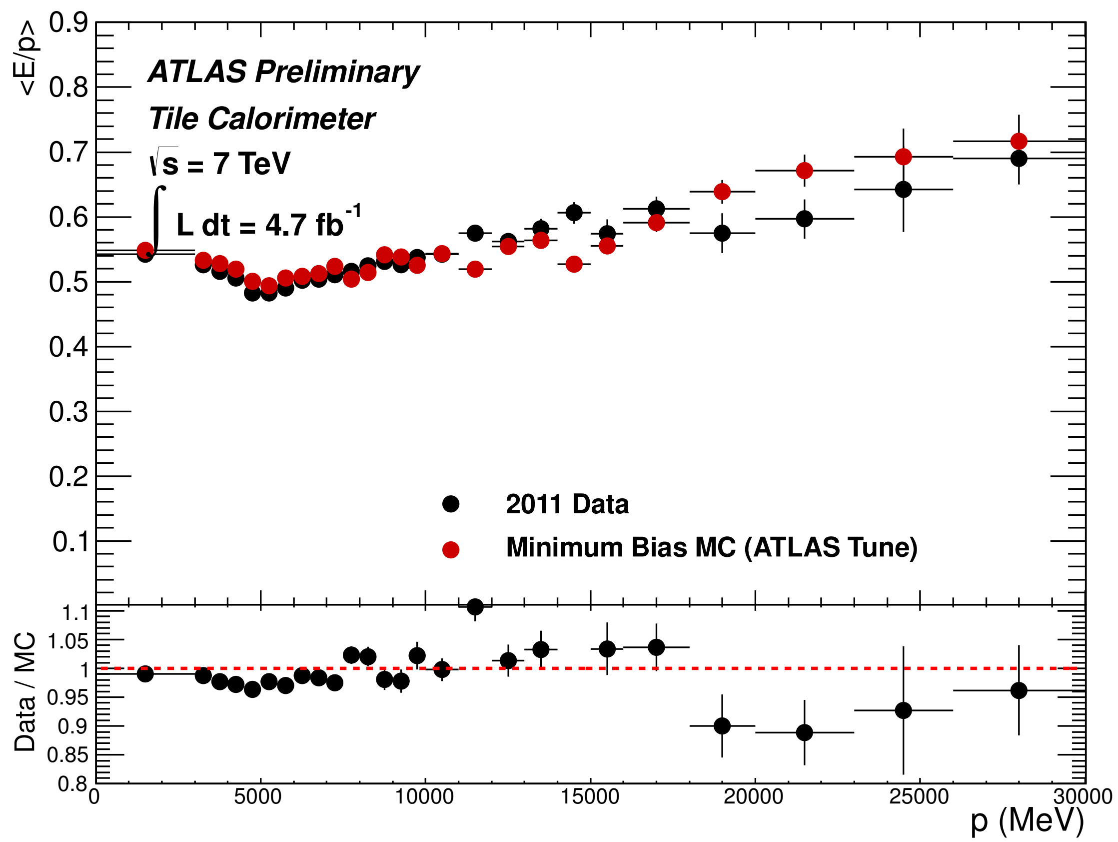
Radial layer	A	BC	D
LB, Data/MC	0.97±0.02	0.98±0.02	1.01±0.01
EB, Data/MC	0.97±0.04	0.98±0.03	0.99±0.02

- average non-uniformity of cell response ±2%.
- data/MC response expected to be 1.0 if perfect data EM scale calibration
- leads to uncertainty of energy scale calibration of 3%
- stable responses obtained across three periods (not shown)
- results consistent with muons from beam scraping, collisions muon results to be released soon

Performance with hadrons

- study isolated charged particles that shower in TileCal
- measure momentum (*p*) from inner detector, and compare with energy of shower in calorimeter (*E*) from clustering around track projection → response given by *E*/*p*



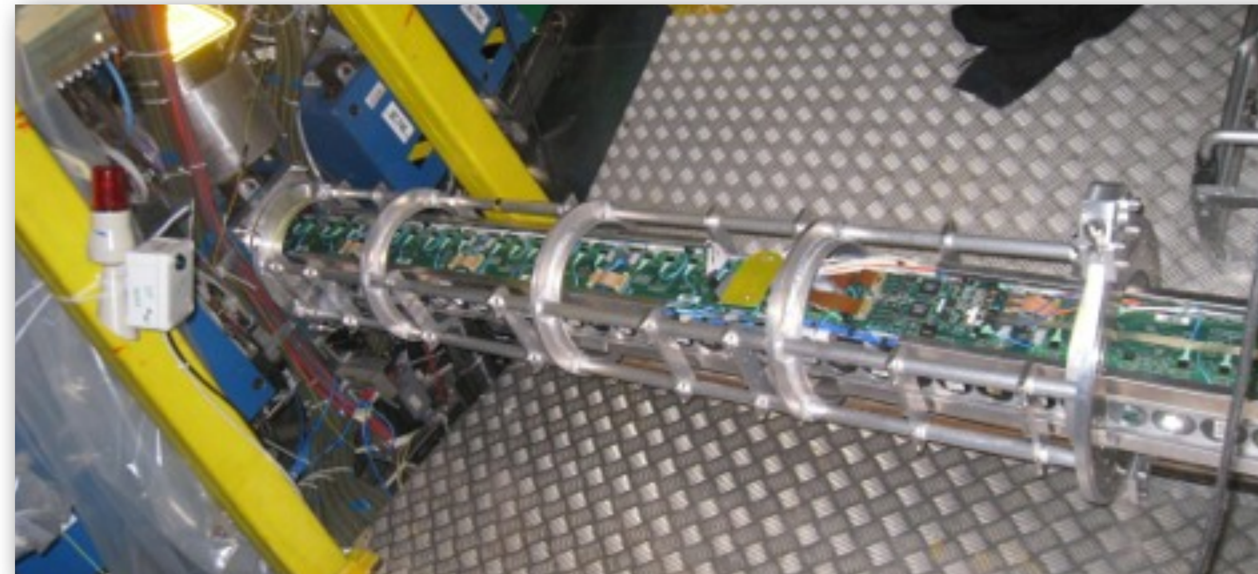


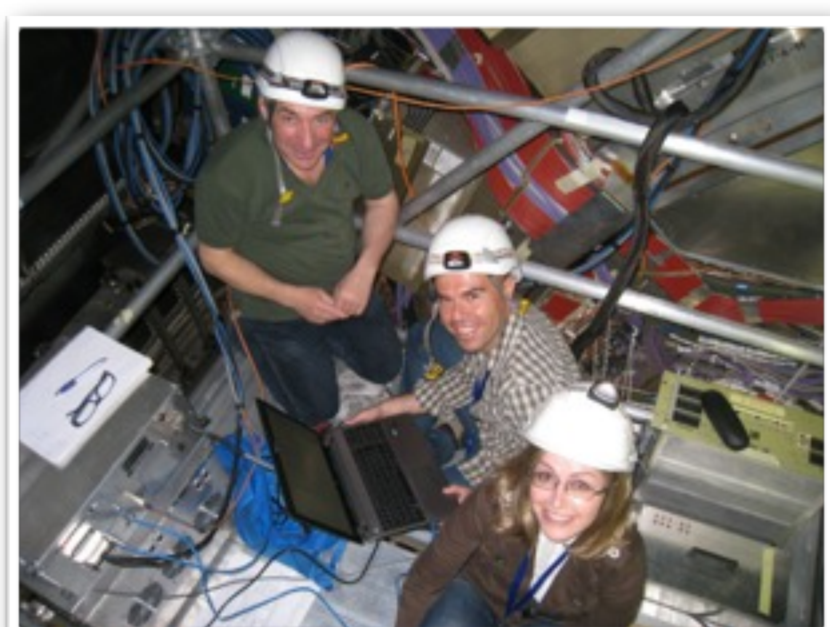
- data and MC agree within 3%
  - except at LB and EB transition regions 0.8<|η|<1.1, deviation up to 10%
  - as a function of *p* agreement deviates around 15 GeV → transition region for gain readout in electronics, and also region poorly described by Geant4 physics list (nuclear fragmentation)

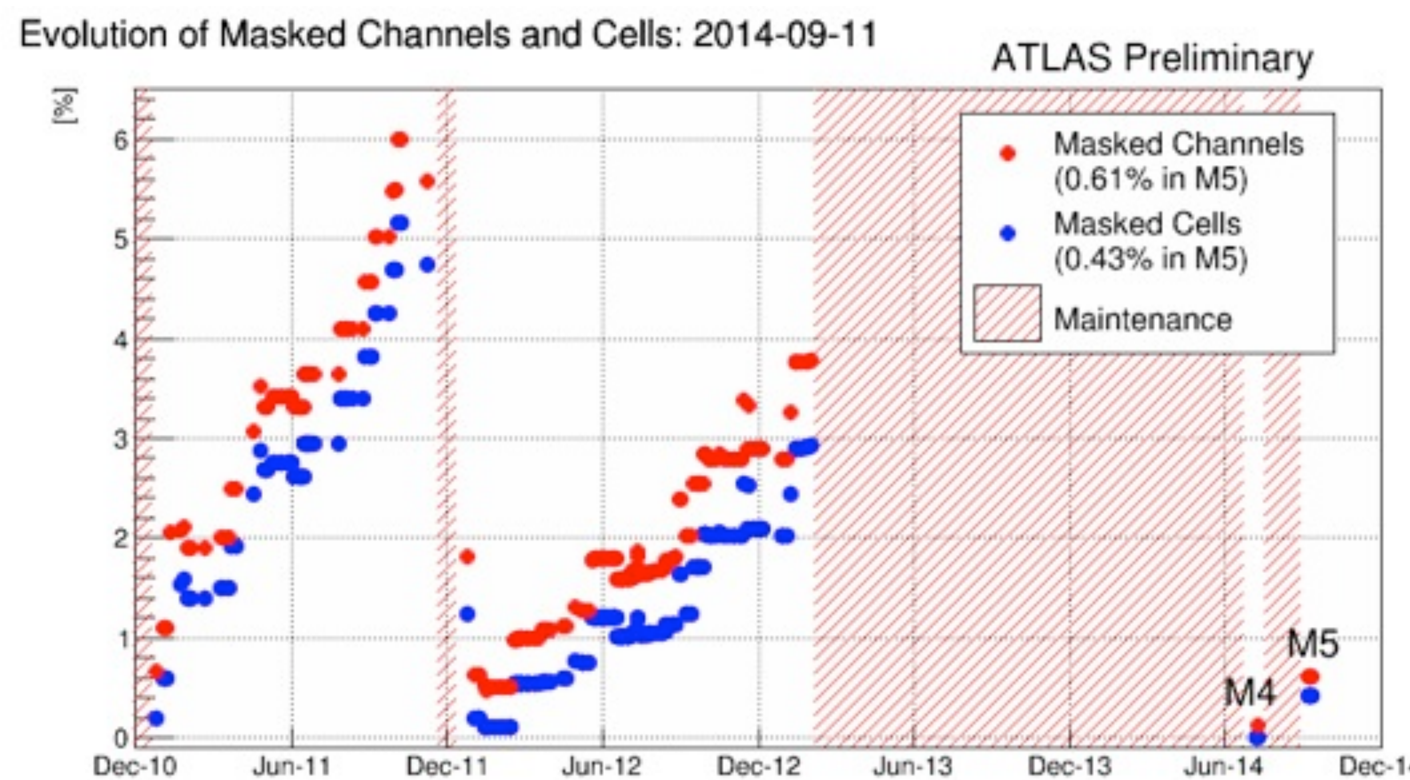
Activities during shutdown 2013-2015

Front end electronics

- several teams worked in parallel to open, consolidate, inspect, and repair front-end electronics in all 256 modules
- module sign-off procedure:
  - using mobile test-bench to test electronics at the front end (MobiDICK)
  - using the detector verification system (DVS) to test full readout of single module
  - run full calibration (pedestal, charge injection, laser system) 3x per week





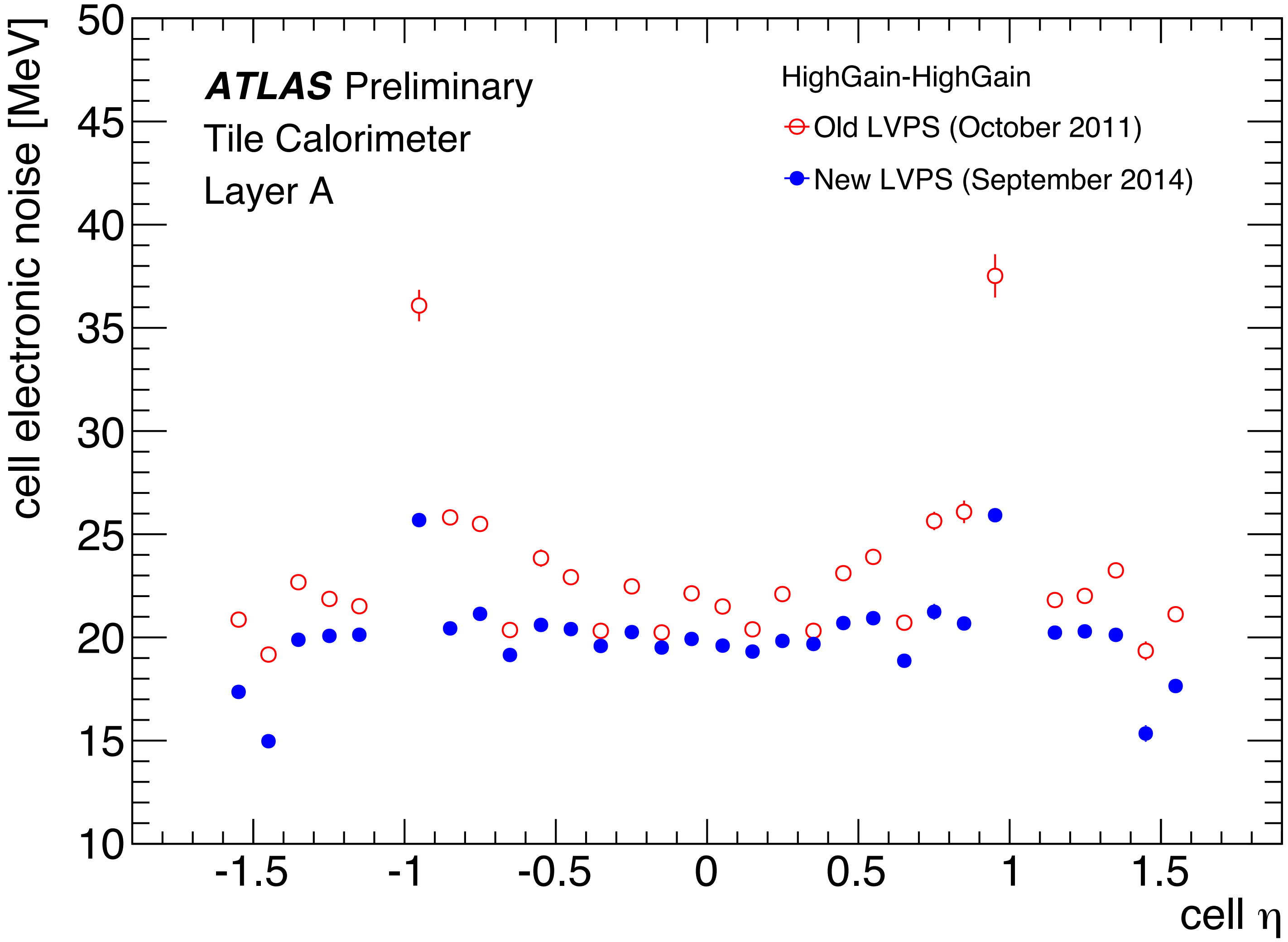


one module currently off

Activities during shutdown 2013-2015

Low Voltage Power Supplies

- replaced all LVPS by newer versions → replacement complete!
- new LVPS expect:
  - number of LVPS trips significantly reduced
  - less corrupted data that resulted from LVPS trips
  - improved noise: lower electronic noise and more Gaussian

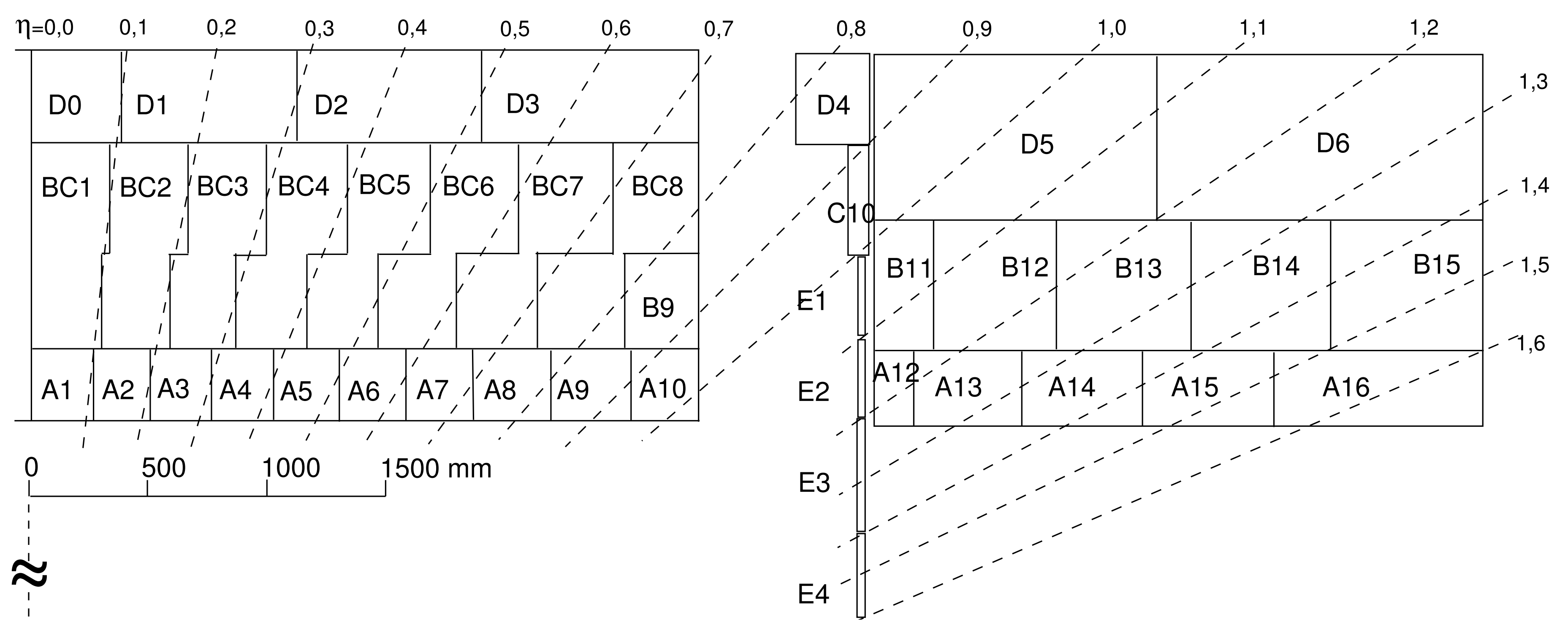


- October 2011 (old LVPS) and September 2014 after the LS1 maintenance campaign (new LVPS)
- shown layer A, average over ϕ
- significant reduction of the electronic noise with new LVPS

Activities during shutdown 2013-2015

Other

- updated of Cesium system mechanical structure
- updated the laser system to improve the light mixing to avoid non-uniformities in light distribution → more precision constants
- modified front-end electronics for E1-E4 cells to improve calibration constants
- installed previously missing 8 (of 64) E3 and 8 (of 64) E4 counters per EB absent in Run 1 (due to MBTS readout)
- will use TileCal D-layer with muon trigger system coincidence to reduce muon trigger fake rate



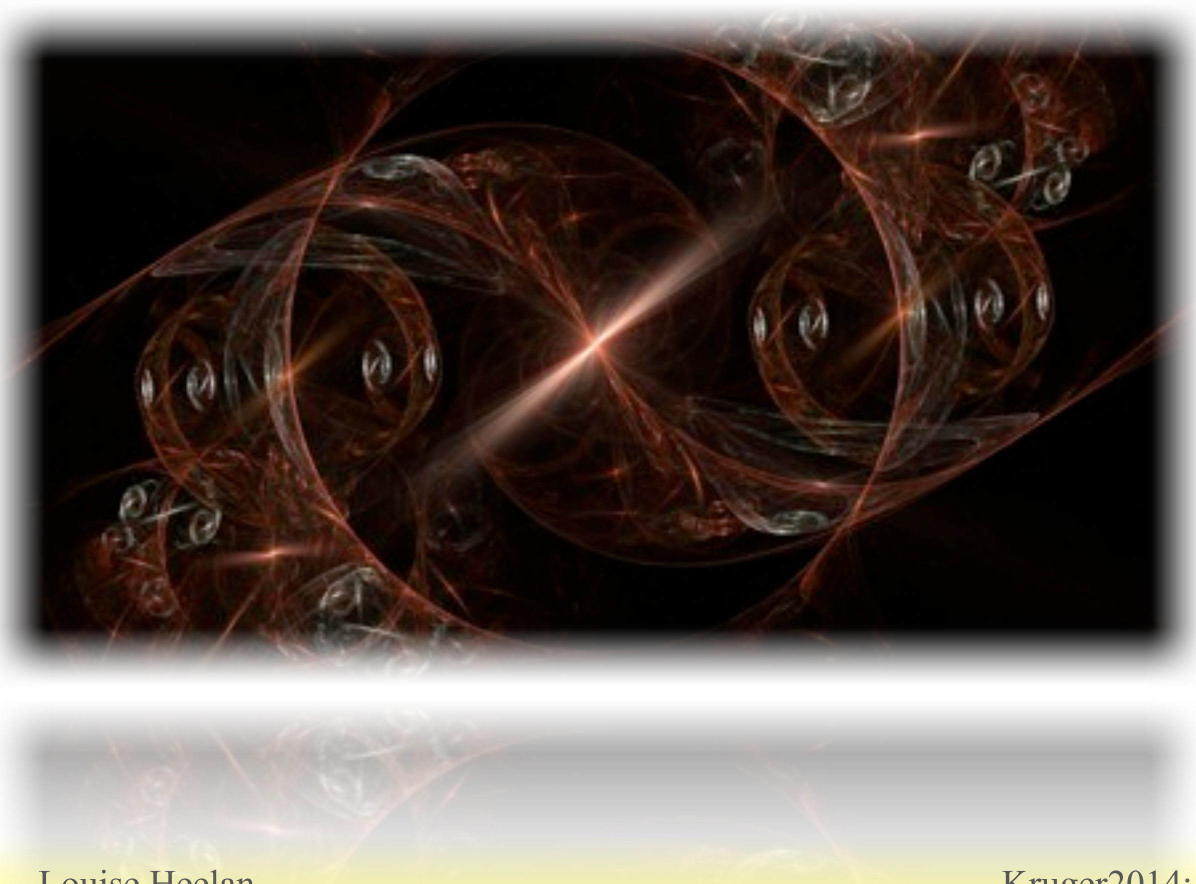
Summary and outlook

- Tile calorimeter performed very well in LHC Run 1 (data quality efficiency 99.6%)
- overall electromagnetic scale of calorimeter known to within 3%, time resolution <1 ns, good agreement between data and MC for minimum bias data, single muons and single hadrons
- "Run 1 Tile Calorimeter Performance" paper in preparation, to include these results +:
  - collision muon results
  - high pt jets
  - single hadrons (*E*/*p* analysis) from 2012 pp collisions
- during the LHC long shutdown (2013-2015) even with no collision data the TileCal community has been quite active in upgrading many components of the system
- Run 2 outlook looks promising, and aim to improve the energy resolution of the system

Precision of calibration → energy resolution (ex. jets)
EM scale calibration → energy scale of objects (ex. EM jets)
correct modeling in MC → many searches use MC for background estimation

To make a *discovery* ATLAS will need to make the best use of its resources.

The ATLAS Tile calorimeter is essential for identification and precision measurements of new physics at the LHC.



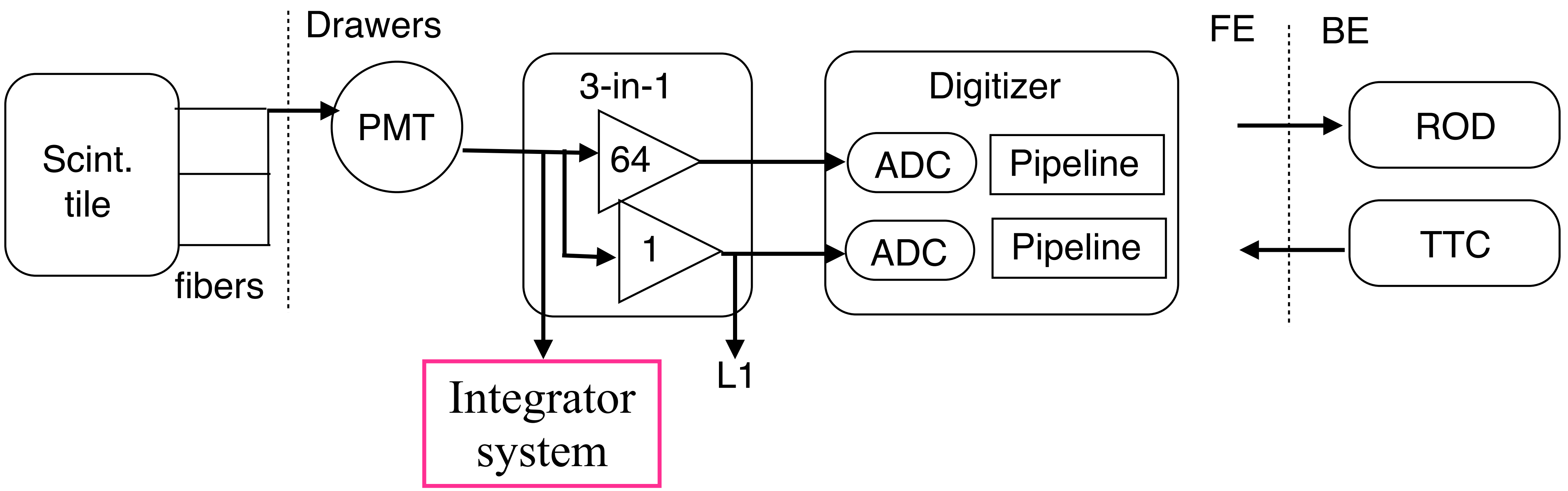
Extra slides

Integrator system

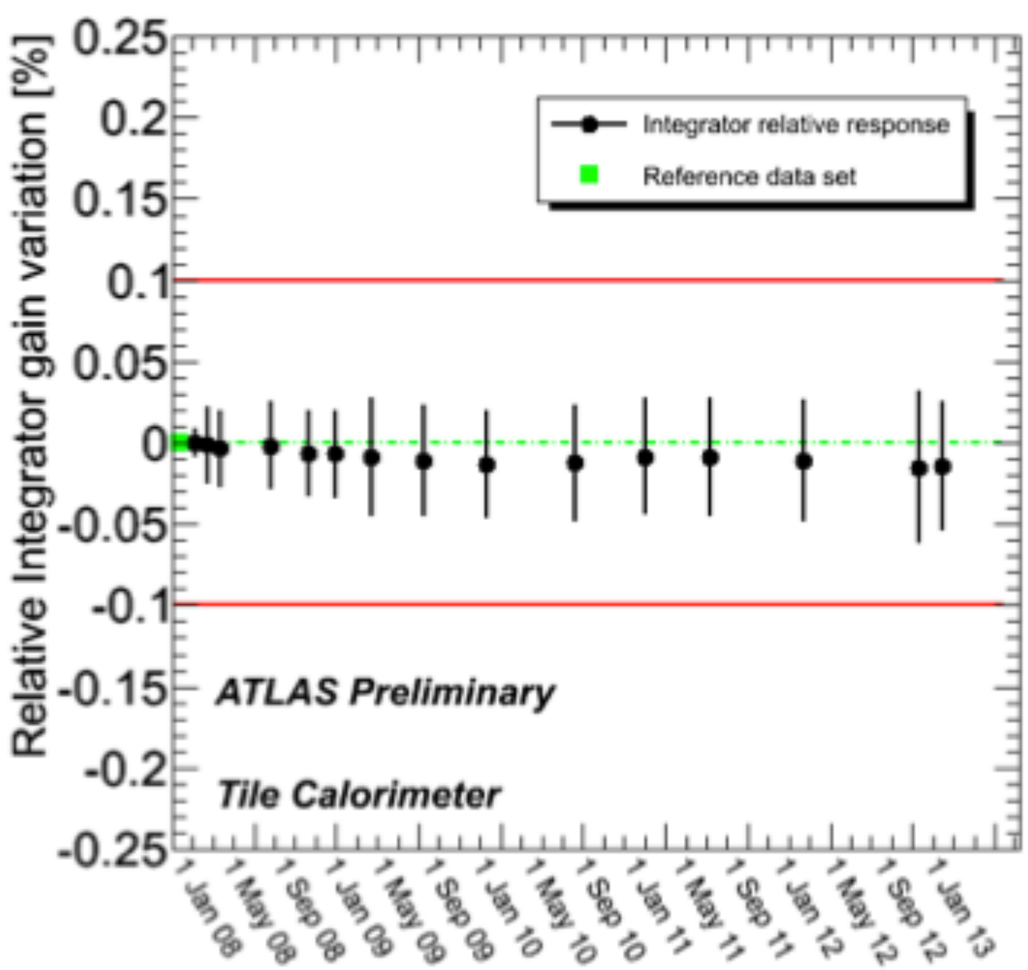
LHC instantaneous luminosity monitor

Performance in the presence of pileup

Integrator system

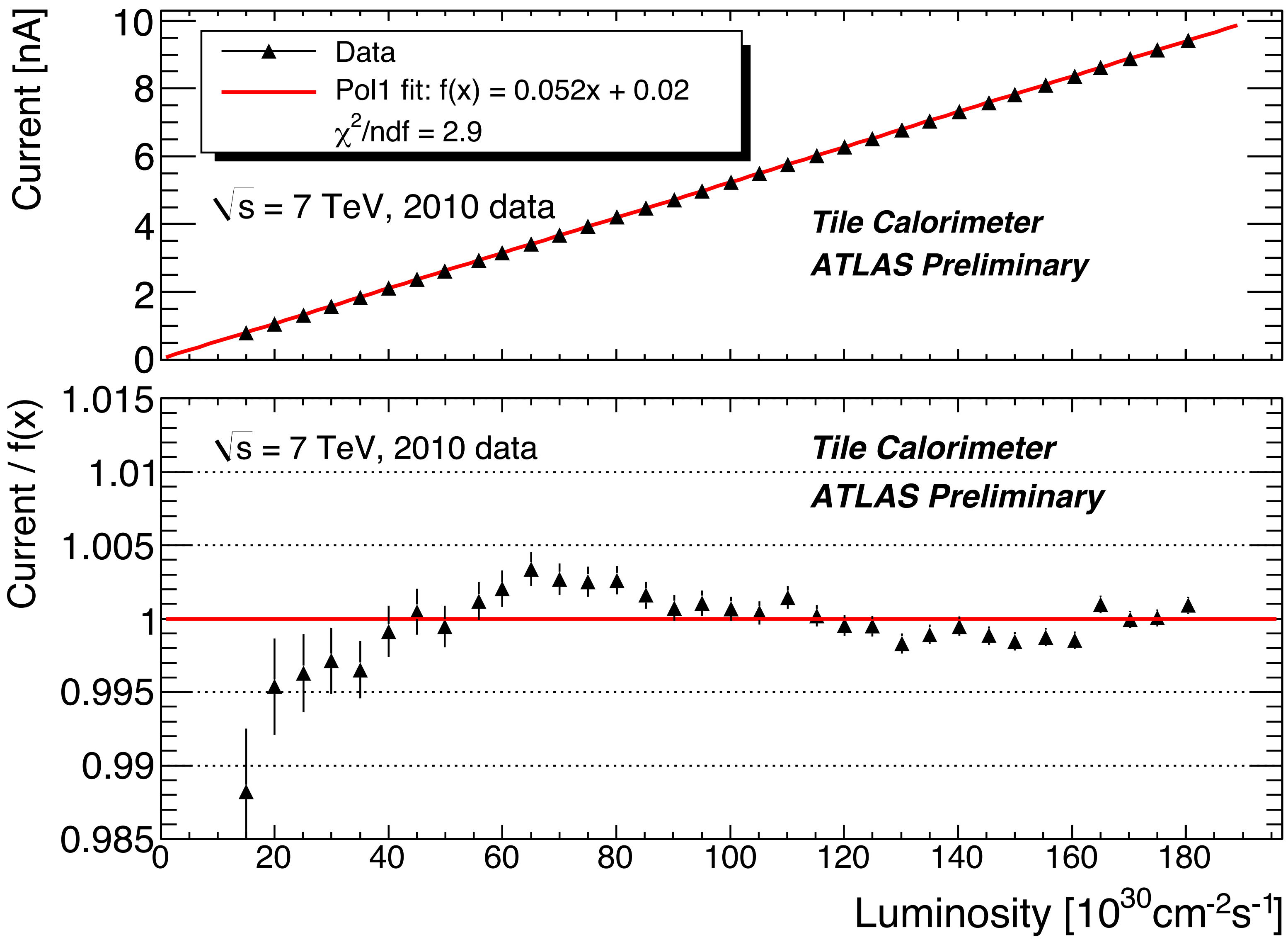


- integrator system slow readout of PMT current (~10ms)
- used in physics to measure minimum bias events and instantaneous LHC luminosity in ATLAS
- used in Cesium scans to measure response
- average stability better than 0.01%



LHC instantaneous luminosity monitor

- using the integrator system slow readout of PMT current can monitor minimum bias activity, and hence LHC instantaneous luminosity



- average PMT anode current for A13 cell as a function of instantaneous luminosity
- errors oare the quadratic sum of the statistical and systematic errors
- red lines are linear fit of data points

Performance in the presence of pileup

- noise distribution in different TileCal cells (8 TeV, 50 ns, <μ>=15.7)
- noise = electronic + pileup (additional *pp* collisions in same or neighboring bunch crossing)

- highest pileup in layer A, and Gap/ Crack (E-cells)
- MC shape agrees well → important for topological clustering algorithm (significance of cell energy to noise)