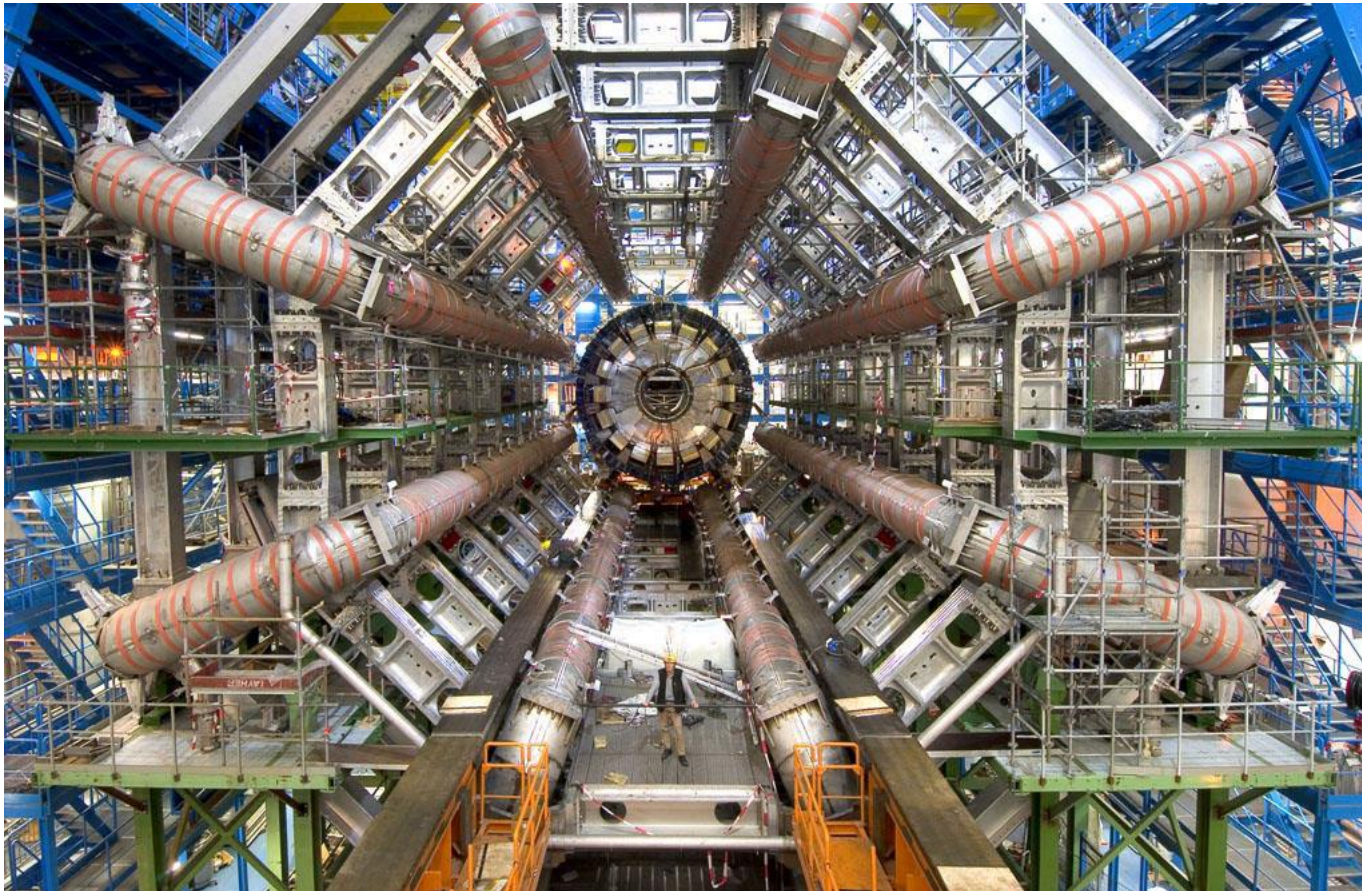


The ATLAS Tile Hadronic Calorimeter Production, calibration and performance

Alexander Solodkov, NRC KI IHEP, Protvino
on behalf of the ATLAS TileCal Community



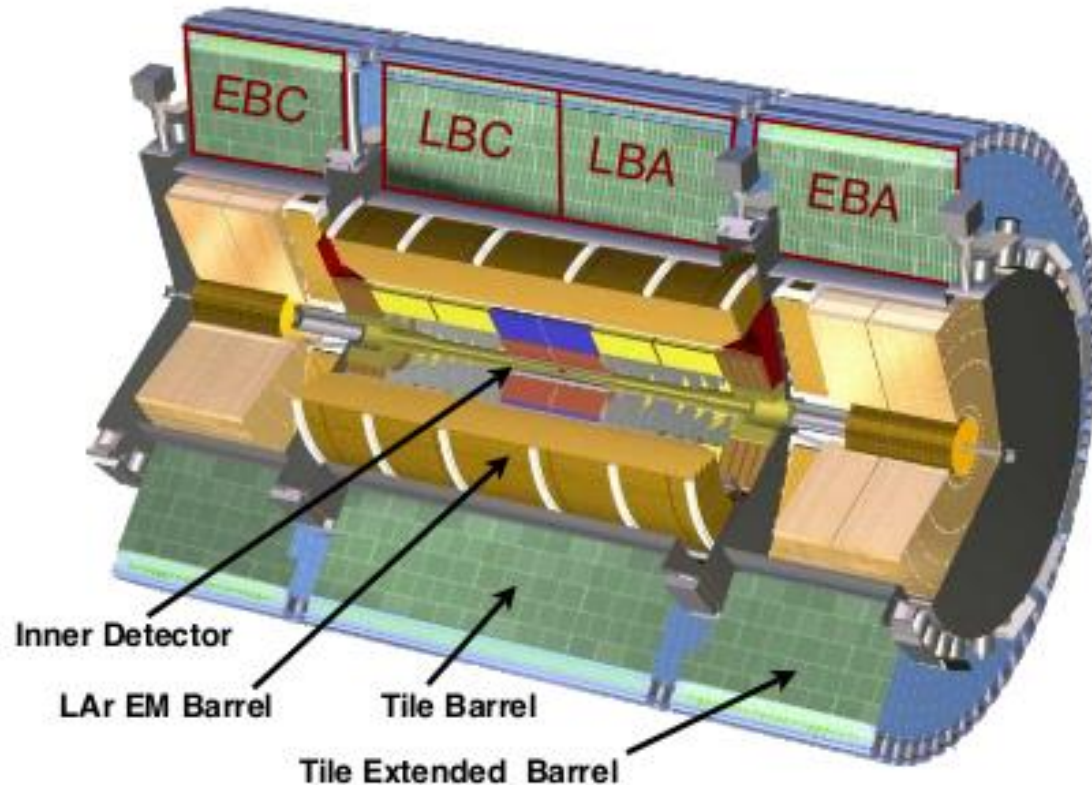
LHC Days in Belarus 2018 Workshop
February 2018, Minsk, Belarus

ATLAS TileCal : 25 Institutes, ~200 people



- Argonne National Laboratory, Argonne, Illinois, USA
- University of Texas at Arlington, Arlington, Texas, USA
- Comenius University, Bratislava, Slovakia
- Institut de Fisica d'Altes Energies, Universitat Autònoma de Barcelona, Barcelona, Spain
- National Institute for Physics and Nuclear Engineering, Bucharest, Rumania
- University of Chicago, Chicago, Illinois, USA
- LPC and Universite Blaise Pascal / CNRS-IN2P3, Clermont-Ferrand, France
- JINR, Dubna, Russia
- Michigan State University, East Lansing, Michigan, USA
- CERN, Geneva, Switzerland
- Kirchhoff-Institut für Physik, Heidelberg Universität, Deutschland
- LIP Lisbon, FCUL Univ. of Lisbon, LIP and FCTUC Univ. of Coimbra, Univ. Católica Figueira da Foz, Portugal
- Institute of Physics, National Academy of Science, Minsk, Belarus
- National Center for Particle and High Energy physics BSU, Minsk, Belarus
- Pisa University and INFN, Pisa, Italy
- Charles University, Prague, Czech Republic
- Academy of Science, Prague, Czech Republic
- Institute for High Energy Physics, Protvino, Russia
- COPPE/EE/UFRJ, Rio de Janeiro, Brazil
- Stockholm University, Stockholm, Sweden
- Tbilisi State University, Tbilisi, Georgia
- University of Illinois, Urbana-Champaign, Illinois, USA
- IFIC, Centro Mixto Universidad de Valencia-CSIC, E46100 Burjassot, Valencia, Spain
- University of the Witwatersrand, Johannesburg, South Africa
- Yerevan Physics Institute, Yerevan, Armenia

Tile Calorimeter – central hadronic calorimeter in ATLAS



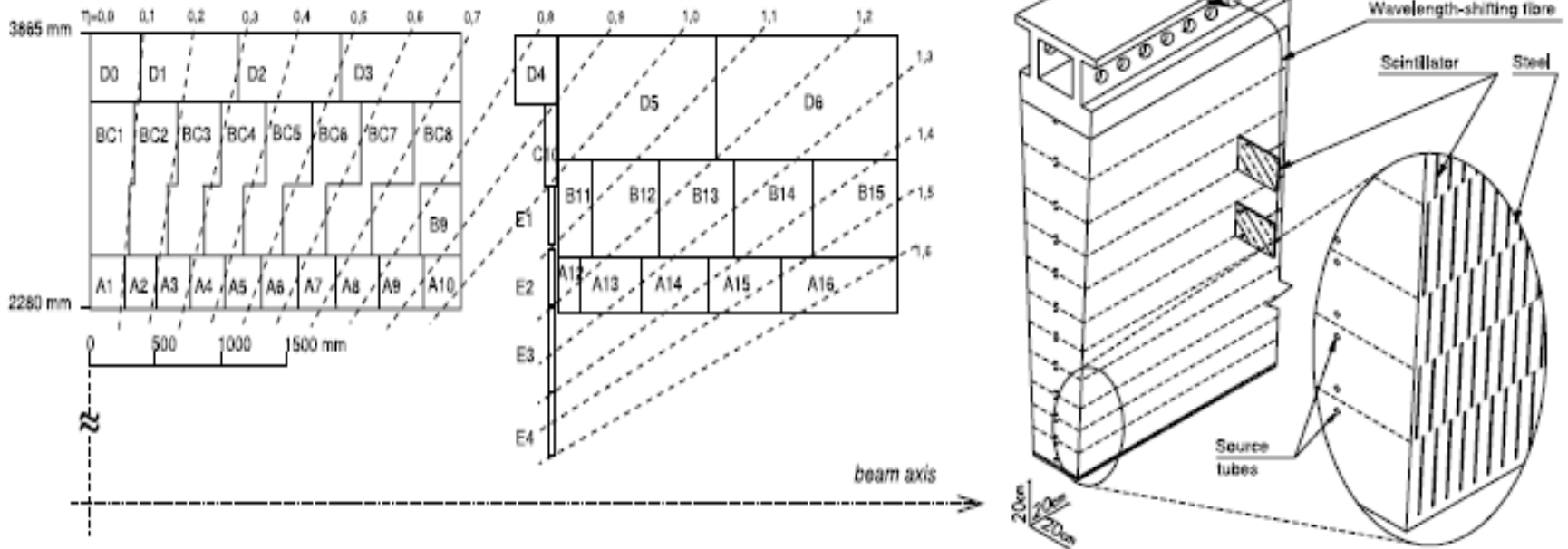
Dimensions

- Diameter: 8.5 m
- Length = 12 m
- Weight: 2900 T

Principle of TileCal:
Measure light produced by charged particles in plastic scintillators (tiles)

- Hadronic sampling calorimeter: iron/scintillator $\sim 5:1$
- 3 cylinders with coverage: $|\eta| < 1.0$ in barrel, $0.8 < |\eta| < 1.7$ in extended barrel
 - 64 independent modules in every cylinder
 - thickness along radius - 7.4λ (1.54 m instrumented part)
- Aim for jet energy resolution: $\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 3\%$

TileCal readout



- Every scintillating tile in 11 rows is read out by 2 wavelength shifting fibers
- Fibers go along both sides of every module to outer radius and are grouped together into pseudo-projective geometry cells in 3 layers
- Granularity $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in first two and 0.2×0.1 in outermost layer
 - number of tiles in one normal cell varies from 16 to 300
- 5182 cells, 9852 channels in total (double readout for normal cells, single readout for special cells E1-E4)
- Readout is organized in four partitions
 - barrel is split in two partitions called LBA for $\eta > 0$, LBC for $\eta < 0$
 - two extended barrels called EBA and EBC

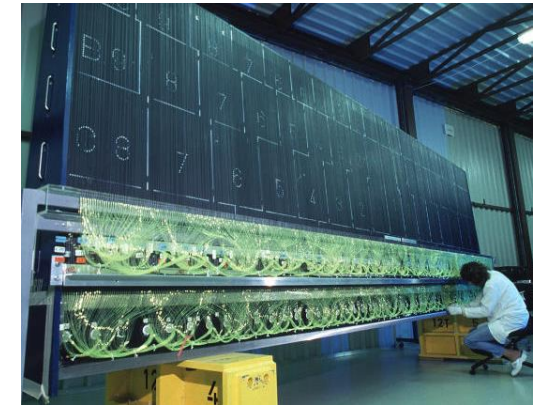
A bit of history....



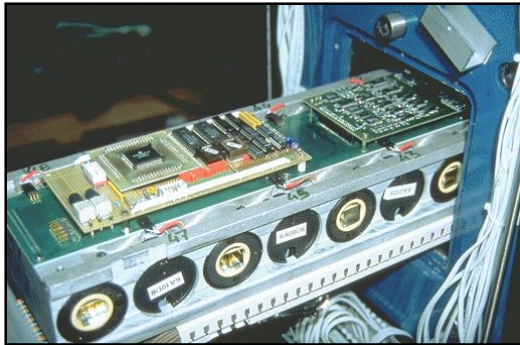
1993-1995 R&D



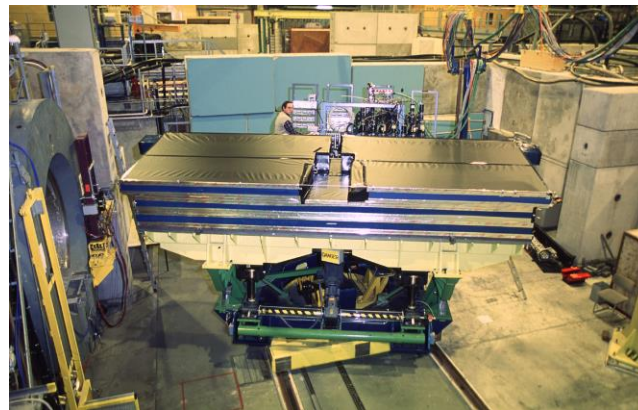
1996-2002 Mechanics and optics construction



1999-2002 Instrumentation



1999-2004: Electronics construction



2001-2004: Calibration at the testbeam



2004-2006: Installation

Since 2006 - commissioning using cosmic muons and calibration triggers
Since 2009 - continuous operation in pp collisions

TileCal assembly

Mechanics assembly



Iron cutting



Submodule stacking



Girder

- 1.5 m height master plates and 10-20 cm height spacers are glued in sub-modules (about 30cm thickness)

- 18 sub-modules are welded to 6m girder to make one barrel module



Module assembly

Scintillating tiles production



Granulated polystyrene



Mixing components



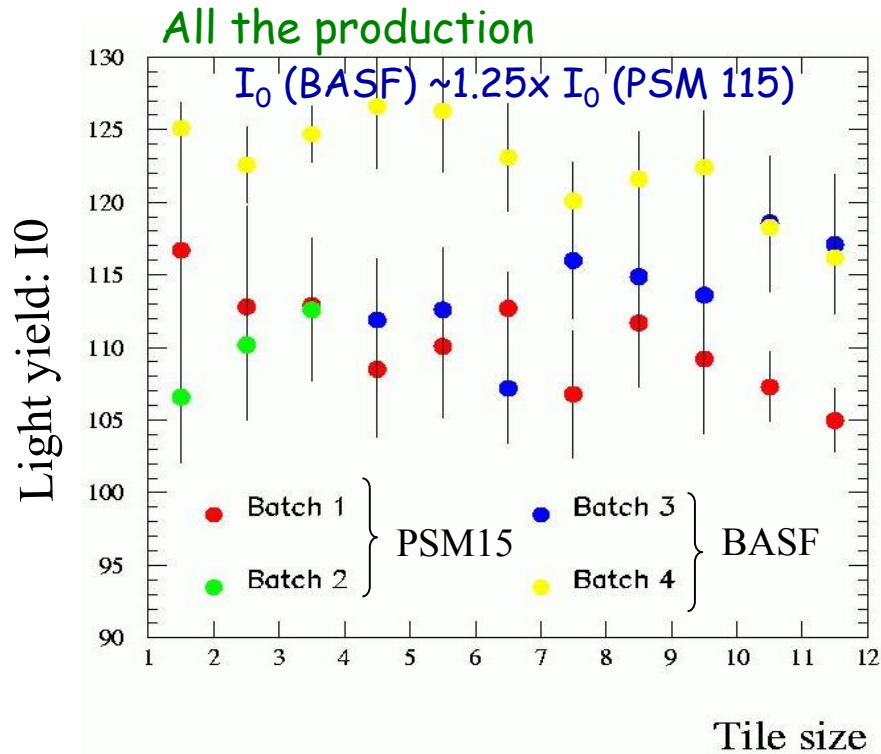
Pressing of tiles



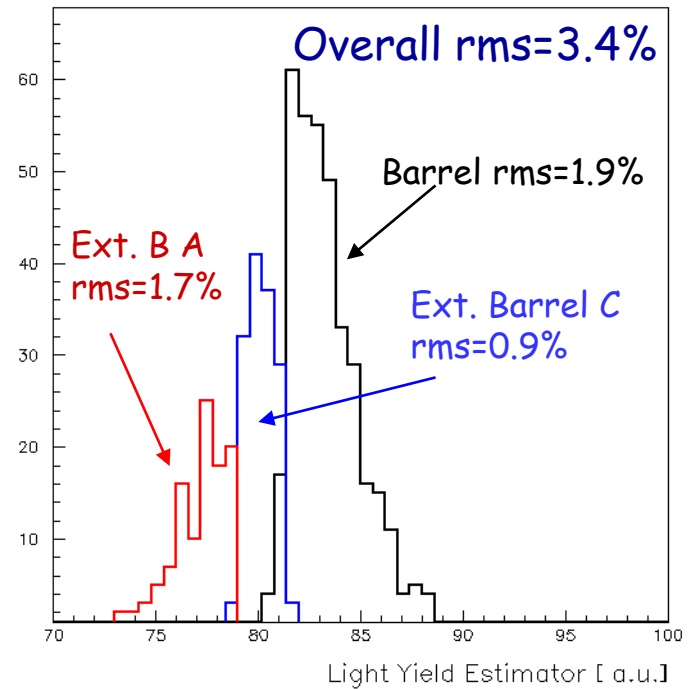
Tiles finished

- 465000 tiles ; 80 tons
- Done by injection molding (2min/tile)
- 3 mm thick tiles in 11 sizes
- Polystyrene + PTP (1.5 %) + POPOP (0.4 %).
- Peak of light emission at 420 nm.
- 40 cm attenuation length.
- ~70 photoelectrons/GeV

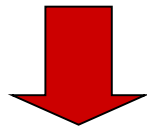
Tile fluctuations



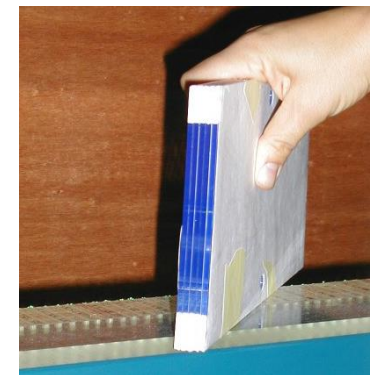
Sorting Batch 4, tile 10



To keep Tile fluctuations inside modules $\ll 5\%$



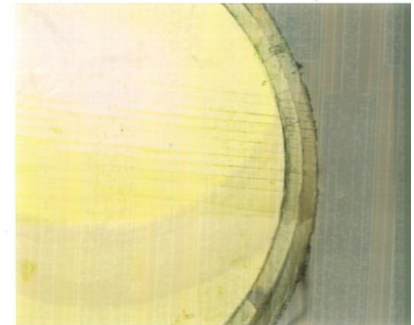
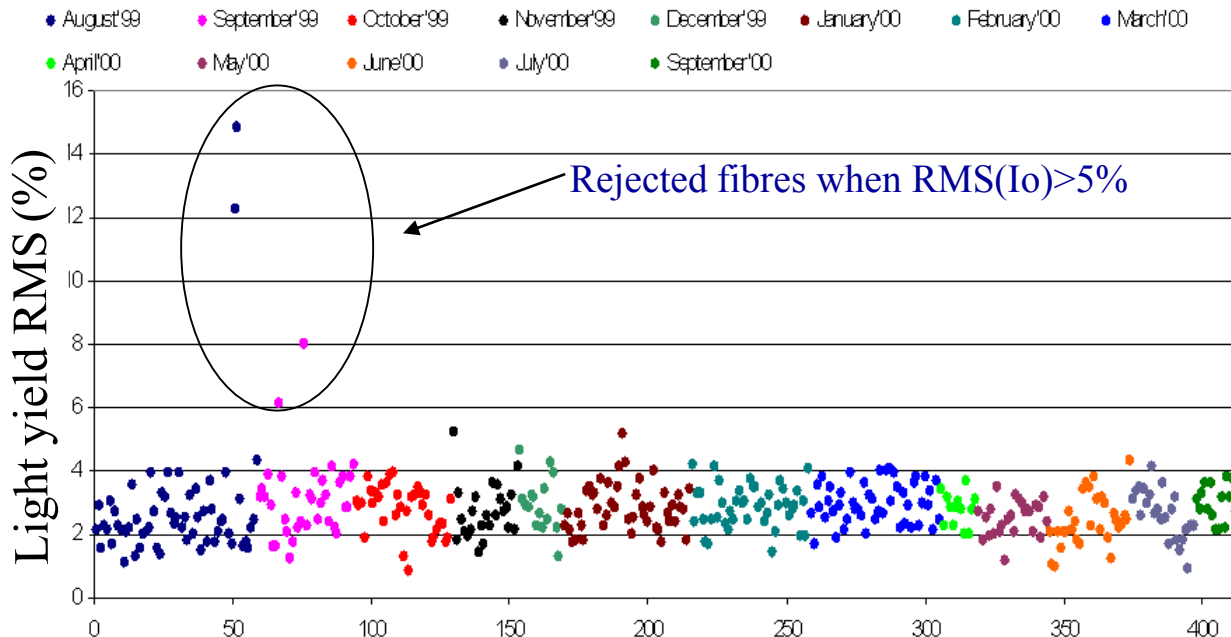
- Tile sorting inside each batch
- Tile masking of BASF tiles when need to mix PSM and BASF polystyrene tiles in a cell



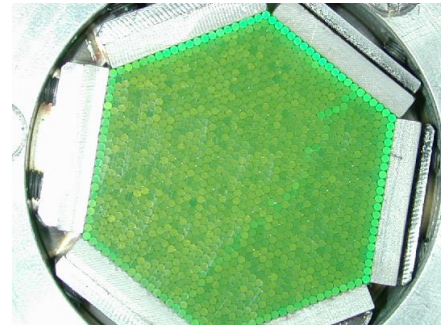
Tile masking

The WLS fibres

- Kurary Y11 s-type double cladding
- 1100 km in total
- Light peak at 495 nm ; $L_{att} \sim 2.9\text{m}$
- Aluminized at one end ($R \sim 78\%$)
- 2.5% of the fibres are measured in the Lab.
- I_0 and L_{att} fluctuations $\sim 3\%$



Double clad. fibre



Fibre bundle polished



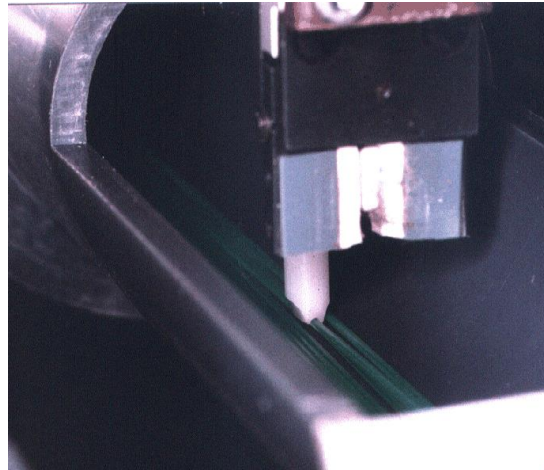
Fibres being aluminized

A robot inserts the fibres in the plastic profiles

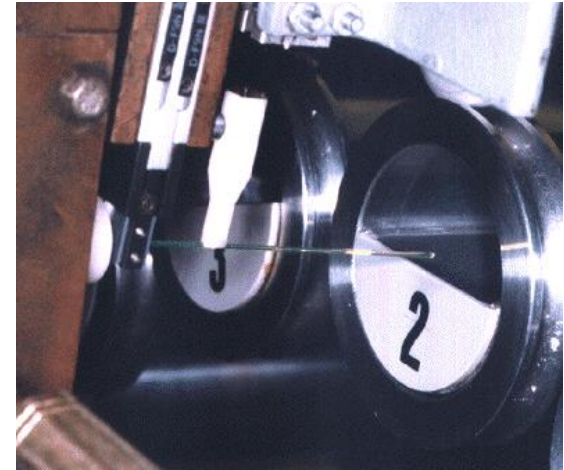


Robot

- Profiles have 3-4 fibres inside to provide cell longitudinal segmentation
- Robot makes ~ 1 profile /2 minutes



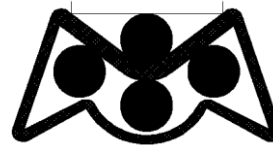
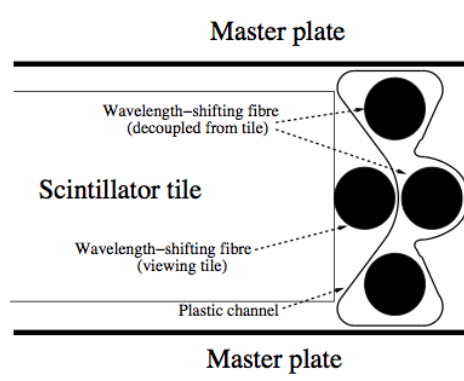
Fibre selected



Insertion in the profile



Profile with 4 fibres inside



Various steps of the TileCal instrumentation



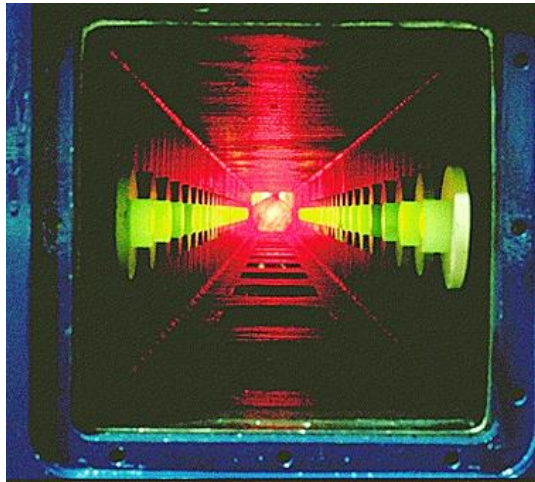
Insert tiles



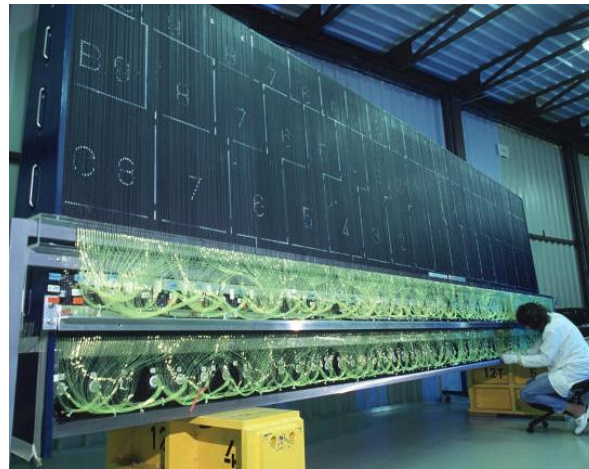
Insert profiles with fibres



Fibre routing



Cut-polish fibre bundles

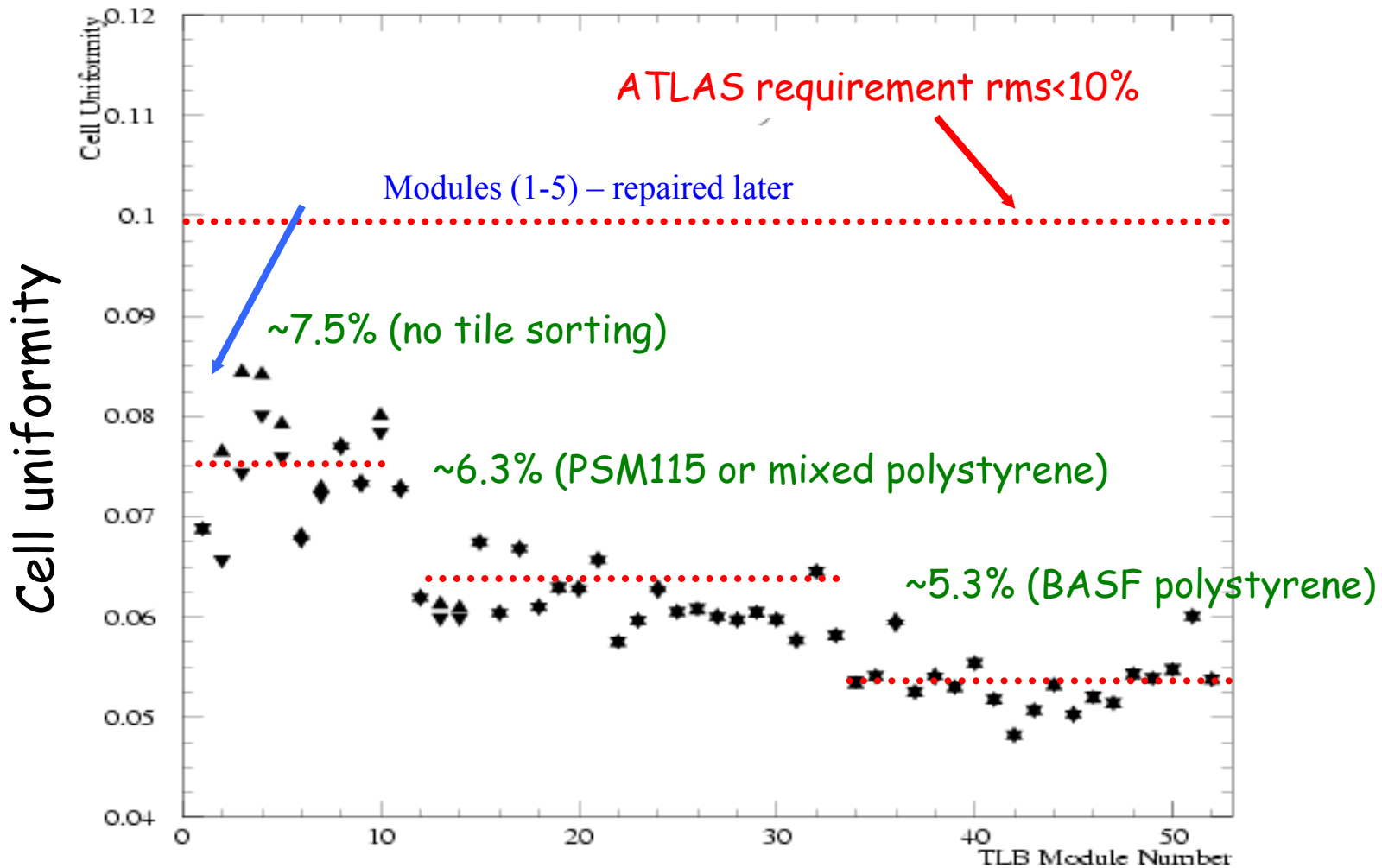


1 barrel



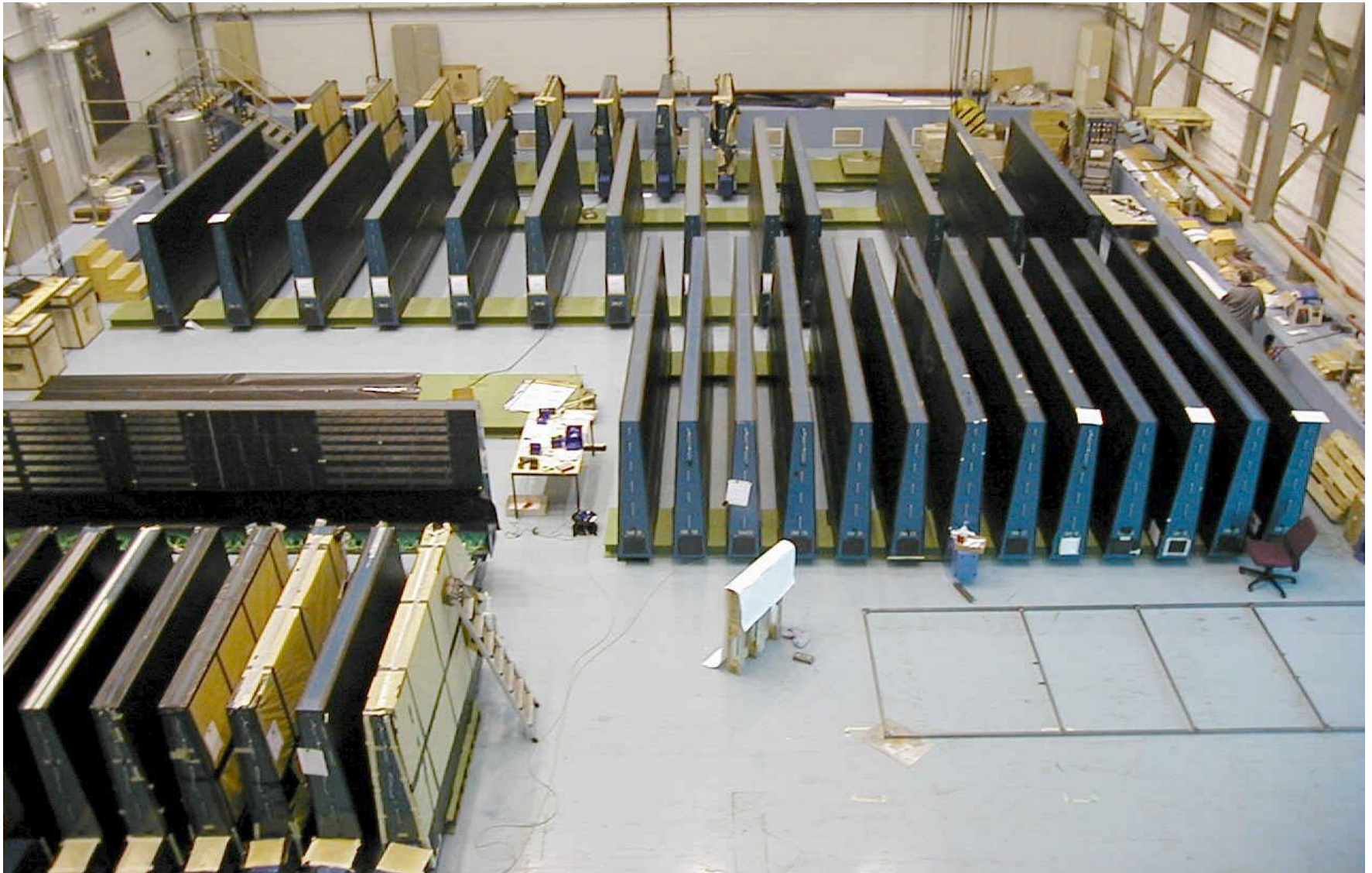
1 Extended barrel

Tile Calorimeter uniformity

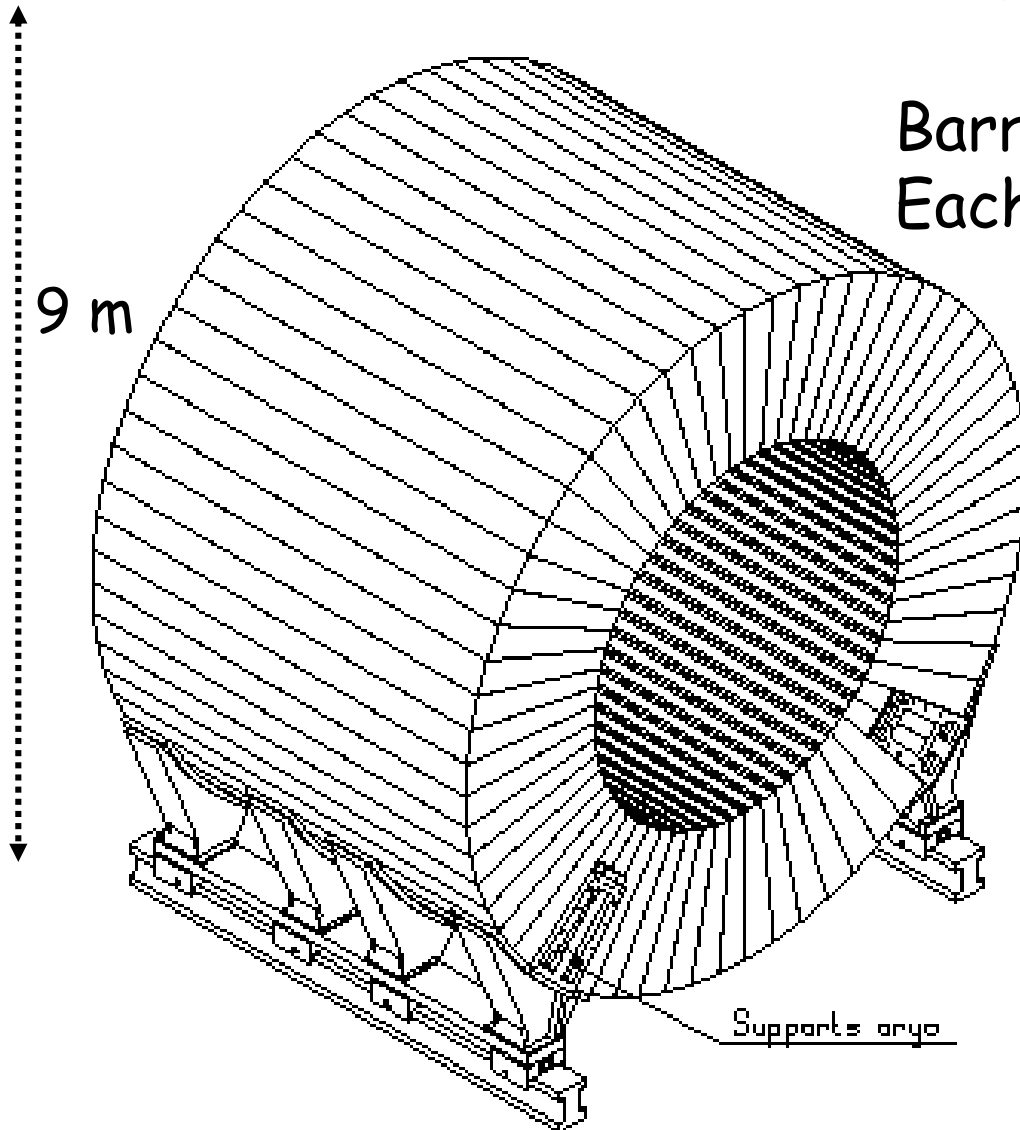


Cesium Calibration system was used to check quality of instrumentation
The cell uniformity is 5-8% for the barrel and Ext. Barrel.

TileCal modules at CERN in storage room



TileCal pre-assembly on the surface

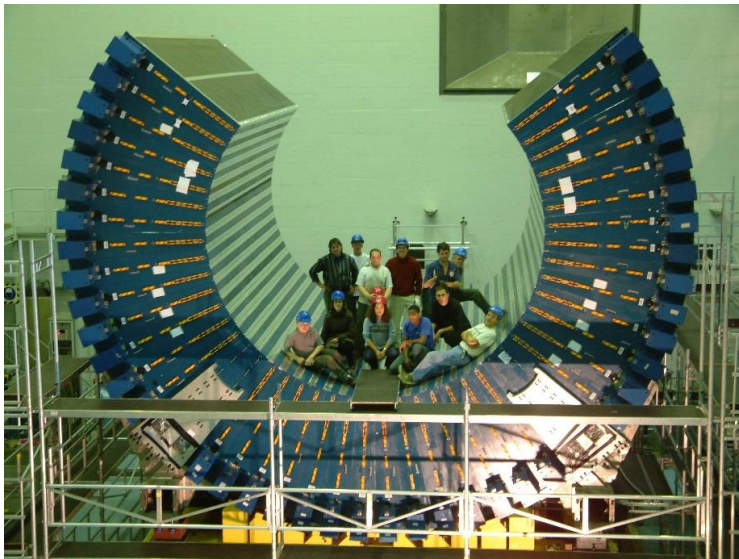
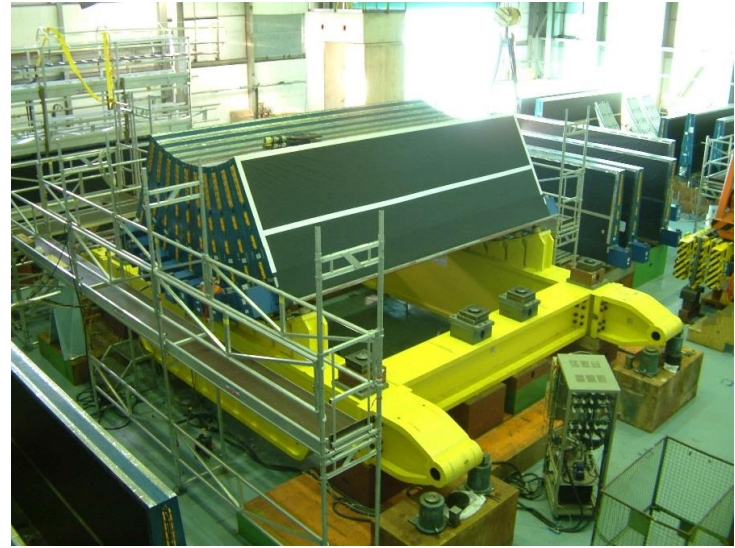


Barrel = 1300tons

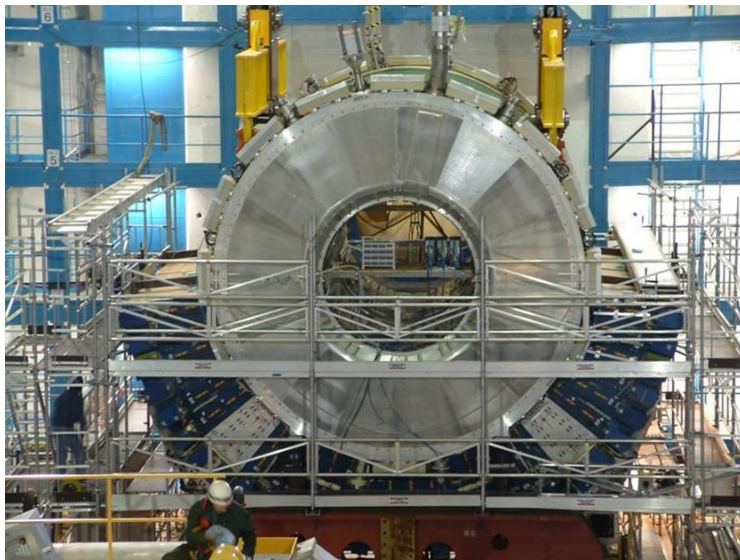
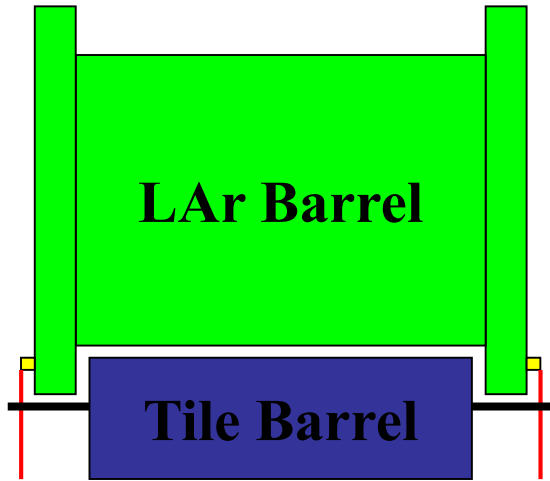
Each Ext. Barrel =700 tons

- Started in summer 2002 with Extended barrel C, then Barrel in 2003 and finally Extended barrel A
- ~6 months to mount-dismount each cylinder
- Installation of Barrel in ATLAS pit started in summer 2004

TileCal pre-assembly on the surface



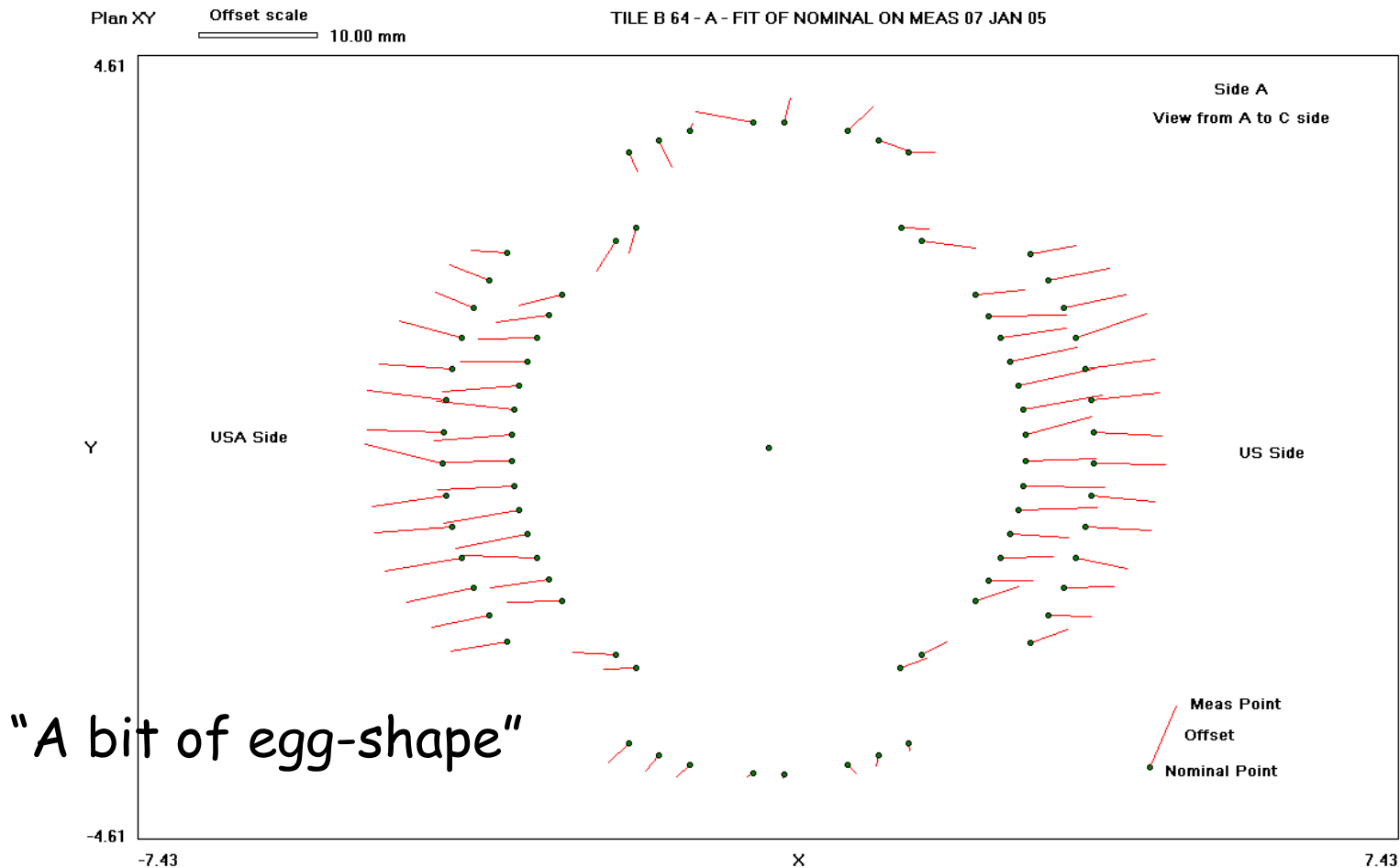
TileCal assembly in the pit



TileCal survey measurements in the pit

Tile Barrel Axis

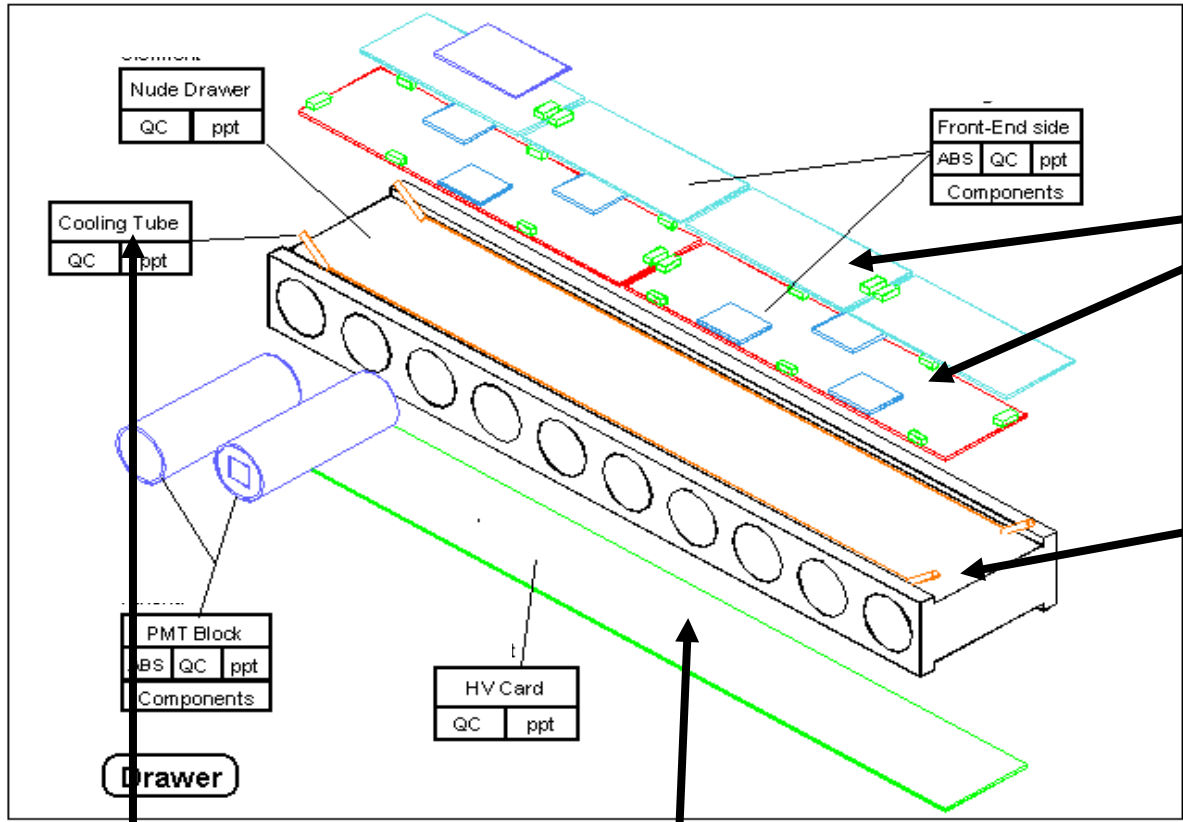
07 Jan 2005 - Side A - Front view A to C



Max deviation from nominal about 8 mm - *within the envelope*

TileCal electronics

TileCal electronics



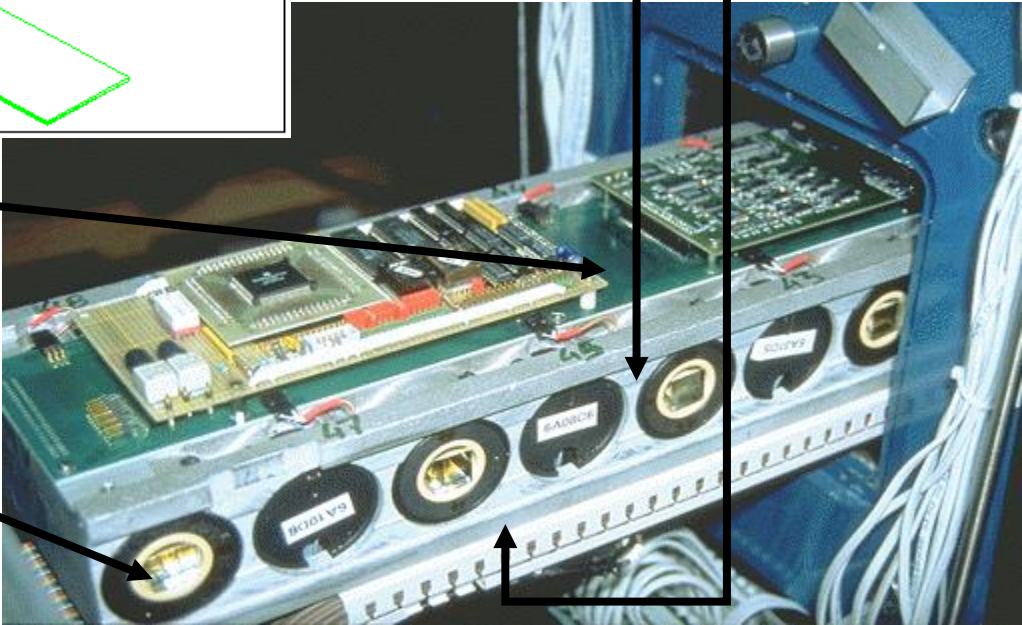
Readout electronics

1.5 m long
~ 50 kg

Drawer mechanics

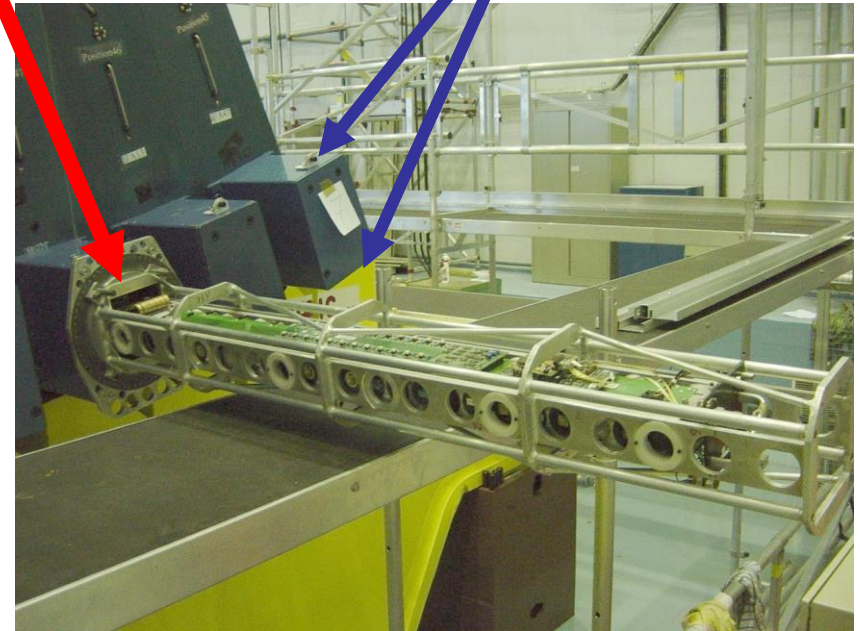
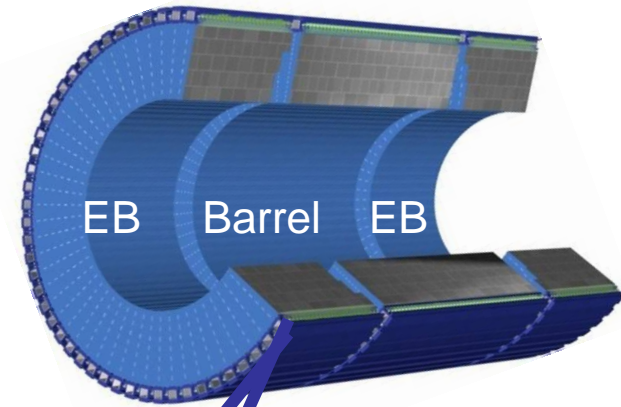
HV distributor

PMT blocks



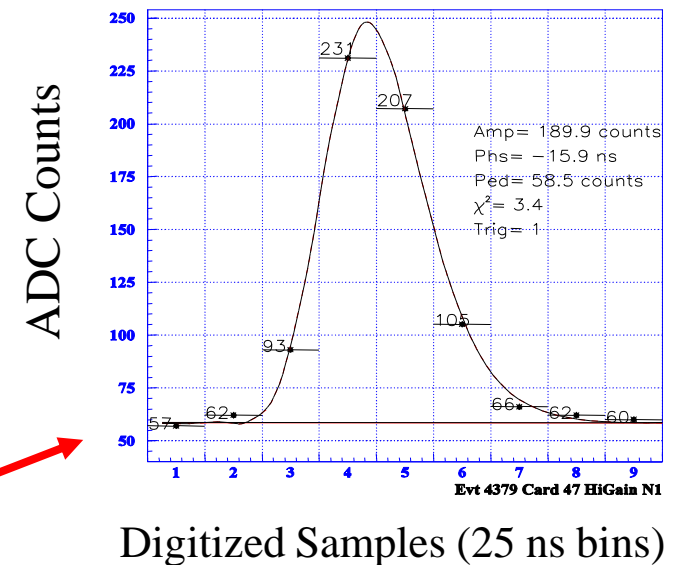
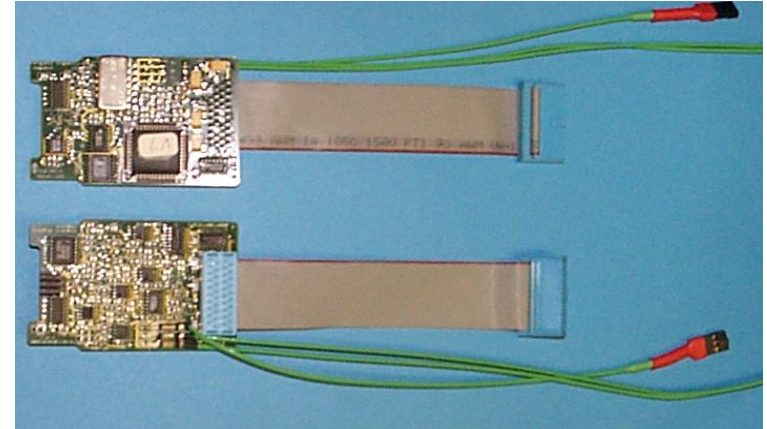
TileCal Front-End Electronics

- Process ~10000 PMT signals
- Electronics located in 256 "drawers"
 - Each 3 m long, 50 kg
 - 45 PMT's/drawer in Central Barrel
 - 32 PMT's/drawer in Ext. Barrel
- Effective 16 bit dynamic range
 - Up to 1.5 - 2 TeV in a single cell
 - Down to 30 MeV per cell
 - Must see muons @ 300 MeV/cell for inter-calibration
 - Non-linearity < 2%
- Special Level 1 trigger cards - 10 bit dynamic range

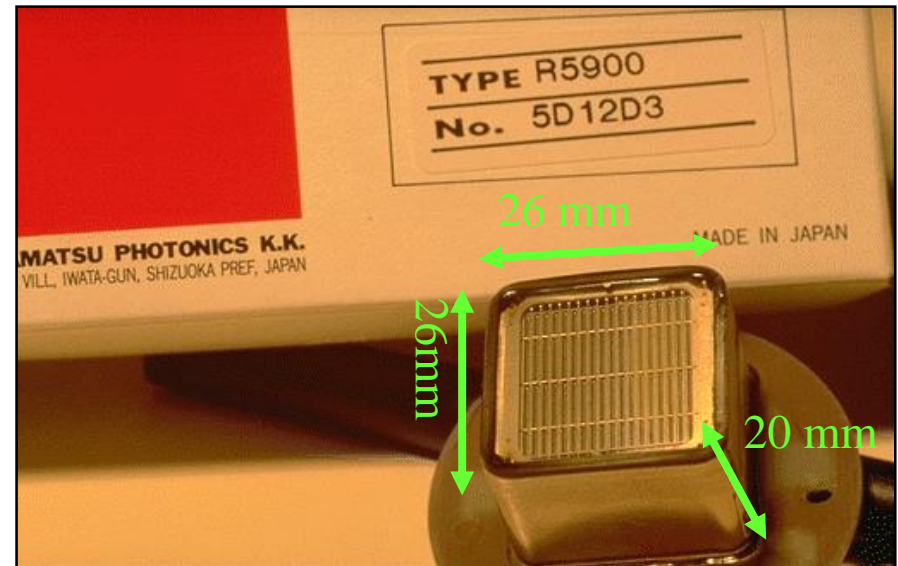
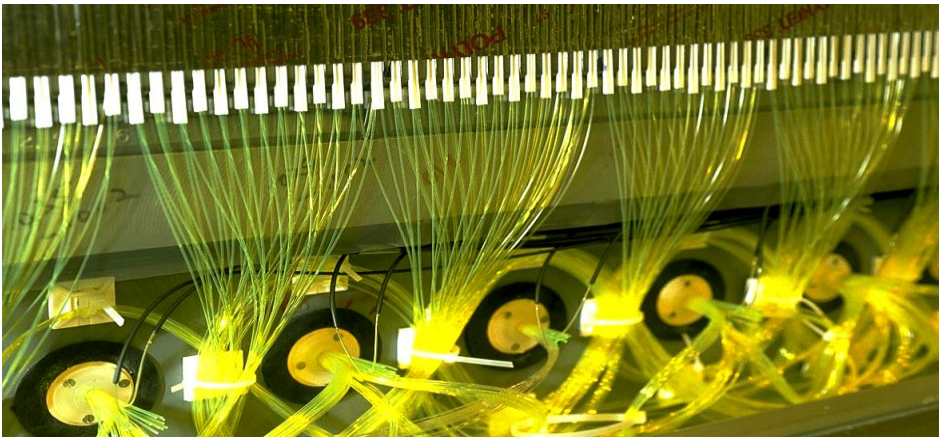


One Front-End Channel: 3-in-1 card

- 3-in-1 card: plugged into anode of each PMT (1 channel = 1 PMT)
- Shaping of PMT signal to digitizers
 - Typically 7 samples digitized
- Bi-gain output (gain ratio 1:64 for dual 10-bit ADC's)
 - high gain (0 - 10 GeV)
 - low gain (10 - 750 GeV)
- Integrator for ^{137}Cs source calibration and monitoring minimum bias current ($\tau \sim 10$ ms)
- Charge injection (CIS) for electronics calibration
 - Example of digitized 3-in-1 pulse shape from 1 channel responding to CIS



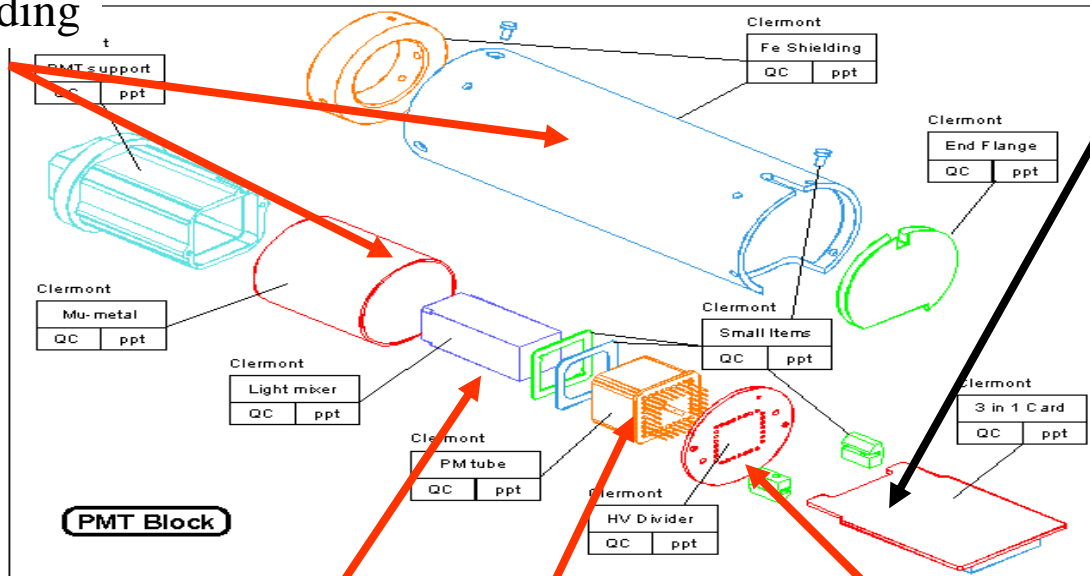
PMT



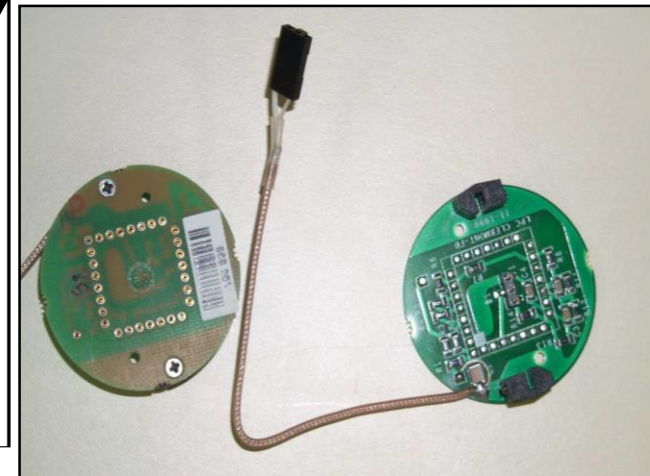
- Hamamatsu R5900
- Produced specially for TileCal
- Photocathode $18 \times 18 \text{ mm}^2$ (bialkali)
- 300 to 650 nm, max @ 420nm
- 8 dynodes
- Dark current $\sim 100 \text{ pA} @ 680 \text{ V}$
- $\tau_{\uparrow} 1.4 \text{ ns}$, width 3.4ns, $\tau_{\downarrow} 3.3 \text{ ns}$ (RMS 0.3ns)
- Small sensitivity to B & T (0.25%/°C)
- Nominal gain 10^5 , gain change @700V: $\sim 1\% / 1 \text{ V}$ ($G = a(HV)^\beta$; $\beta \sim 7$)
- Tile+PMT: ~ 70 photoelectrons/GeV

Front end electronics: PMT block

Shielding

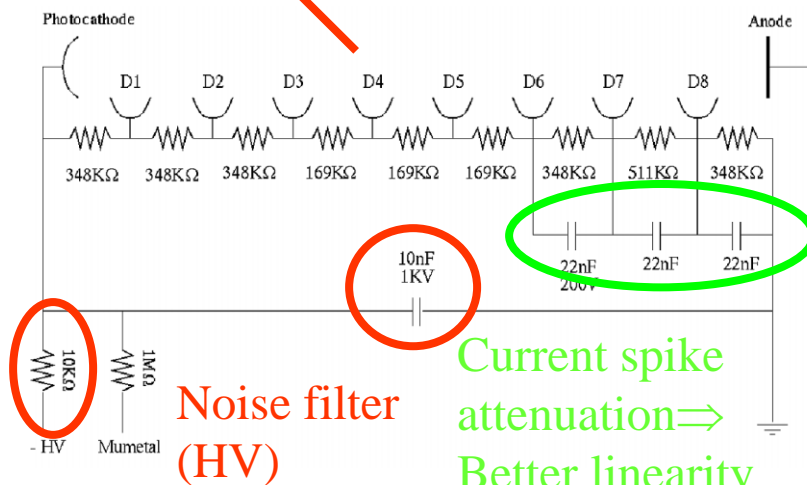


Charge injection
Amplification, shaping
Integration (Cs, min. Bias)



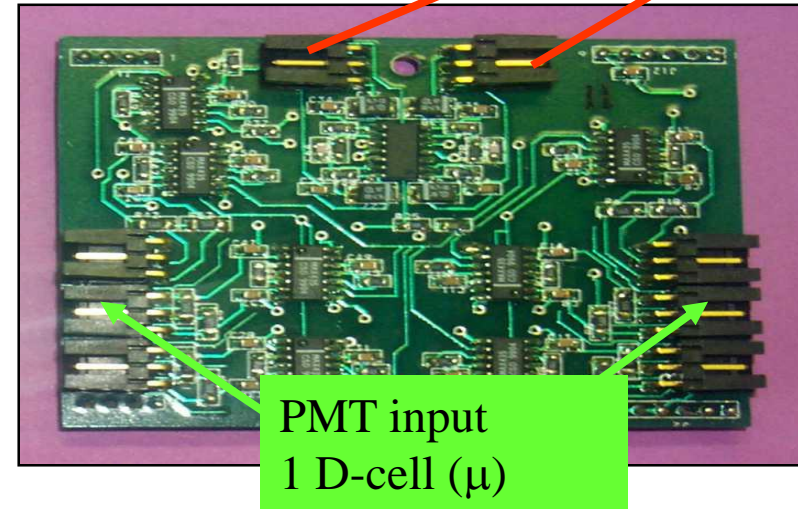
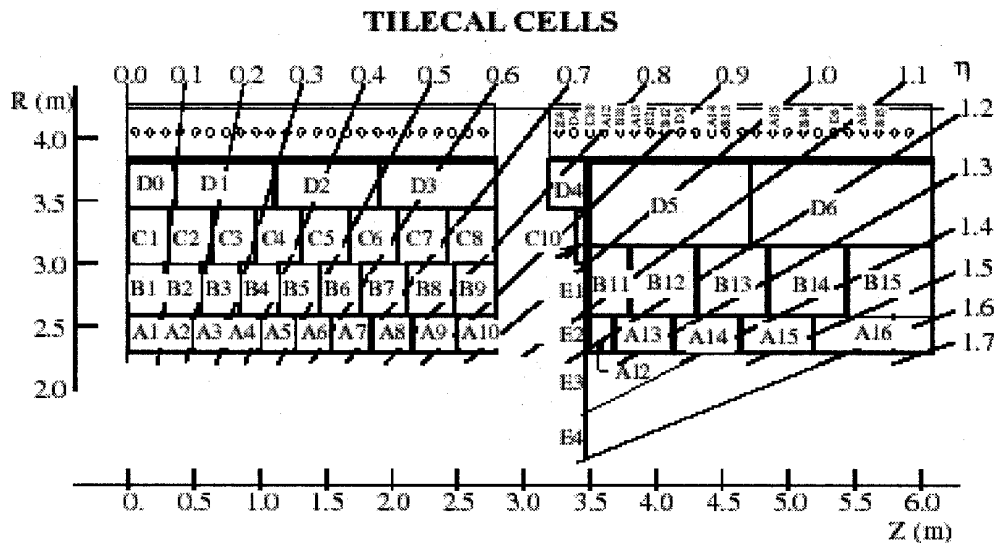
Light mixer

PMT



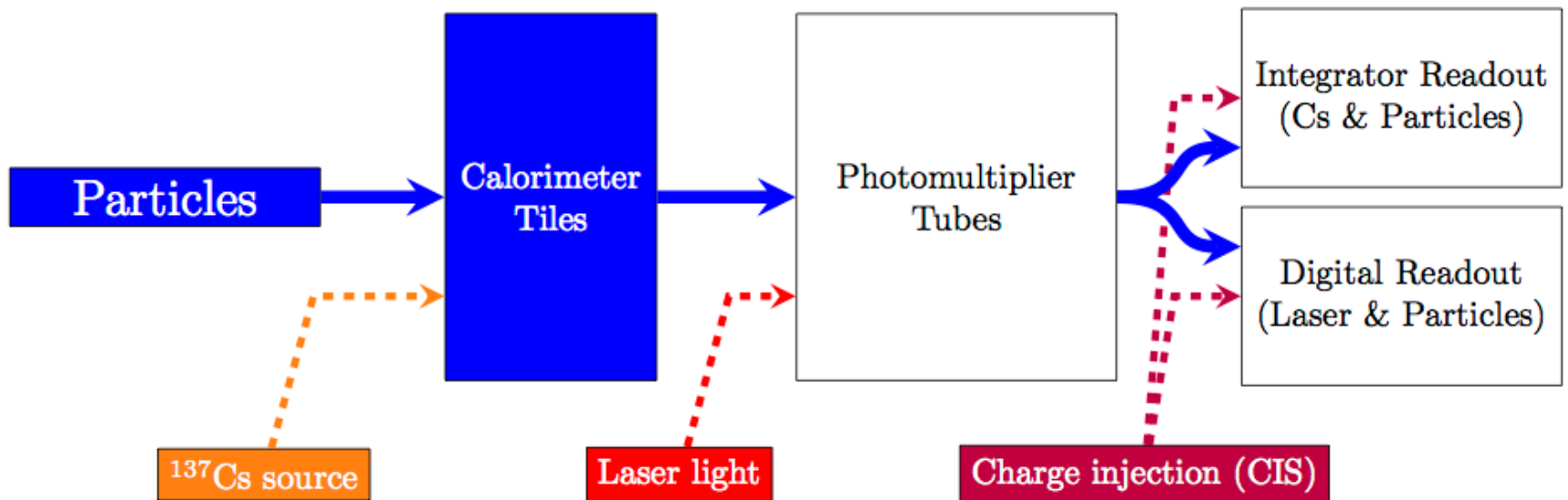
Front end electronics : L1 trigger

Analog LVL1
Hadron μ



- TileCal provides input to L1 Calo trigger as analog sum of signals from several PMTs
- 1 Hadron Trigger output = 1 tower of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
 - Usually 5 PMTs per tower, e.g. cell A1 + cell BC1 + half of cell D0
- 1 Muon Trigger output = 1 cell from D-layer or even 1 PMT of D-cell
 - Was not used in RUN I
 - Output from Ext. Barrel is being validated in RUN II to suppress high fake muons rate in L1 Muon trigger

TileCal Calibration

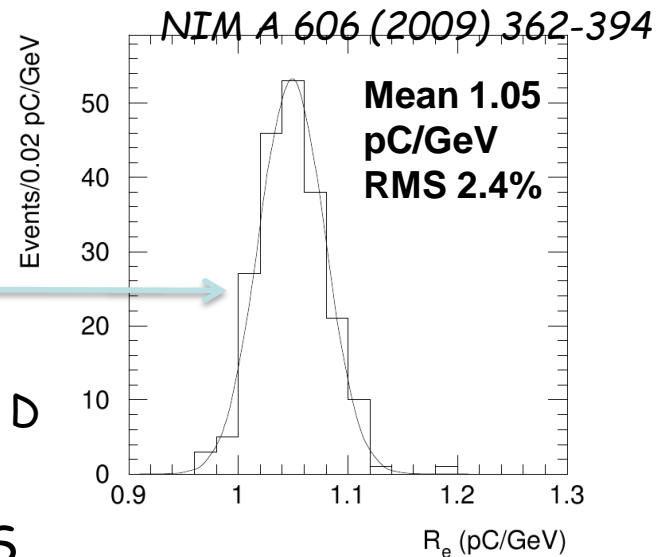


Energy calibration

- To convert amplitude expressed in ADC counts to final energy deposited in a cell the following formula is applied:

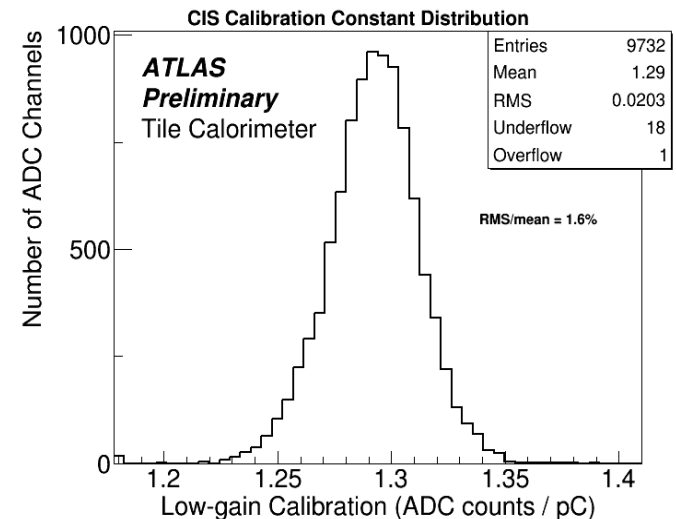
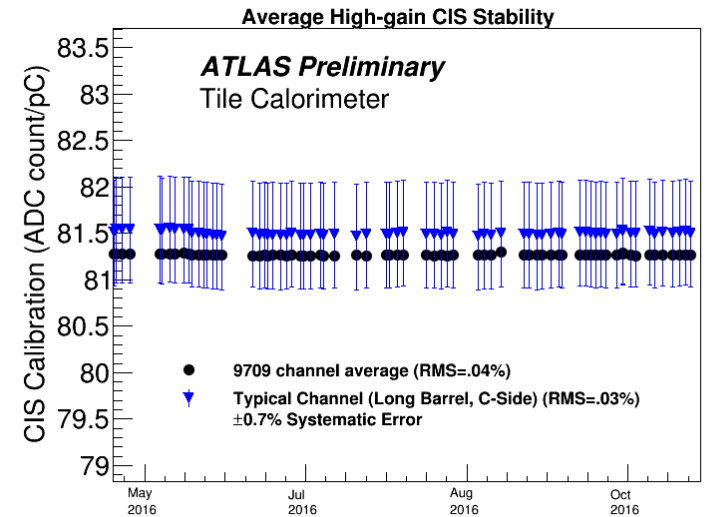
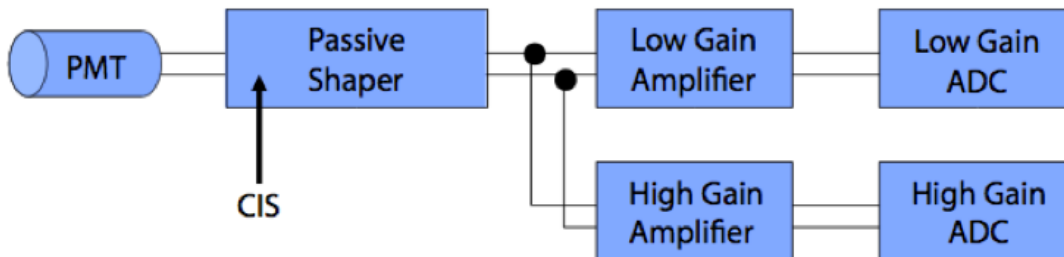
$$\text{Energy [GeV]} = \text{Amplitude [ADC]} \times C_{\text{ADC} \rightarrow \text{pC}} \times C_{\text{Cs}} \times C_{\text{laser}} \times C_{\text{pC} \rightarrow \text{GeV}}$$

- $C_{\text{ADC} \rightarrow \text{pC}}$ is provided by Charge Injection System which monitors stability of electronic chain (weekly calibration runs)
- C_{Cs} is provided by Cesium Calibration System which monitors stability of all optic components - tiles, fibres, PMTs (monthly in RUN I, very rare in RUN II)
- C_{laser} is provided by Laser Calibration System which monitors continuously stability of PMTs (standalone calibration runs and laser calibration events in empty bunches during physics runs)
- $C_{\text{pC} \rightarrow \text{GeV}}$ conversion factor was measured in 2001-2003 when 11% of all TileCal modules were brought to the testbeam at the SPS
- Electrons with $E=20\text{-}180\text{ GeV}$ and 20° incident beam angle were used to establish EM scale in layer A
 - Muons at 90° used to transfer scale to layers BC and D
- Cesium system was used to transfer pC/GeV scale from testbeam measurements to ATLAS



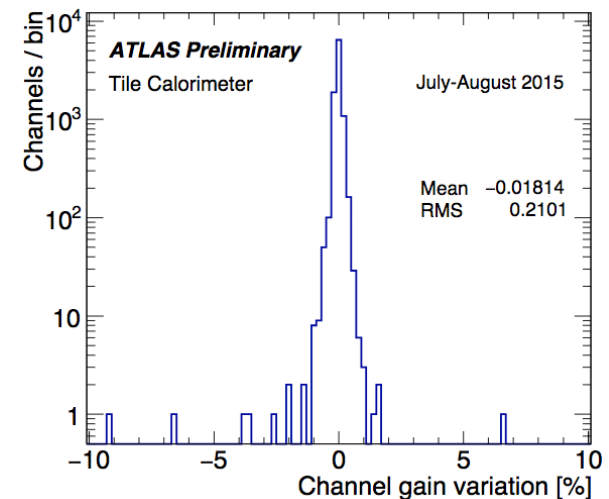
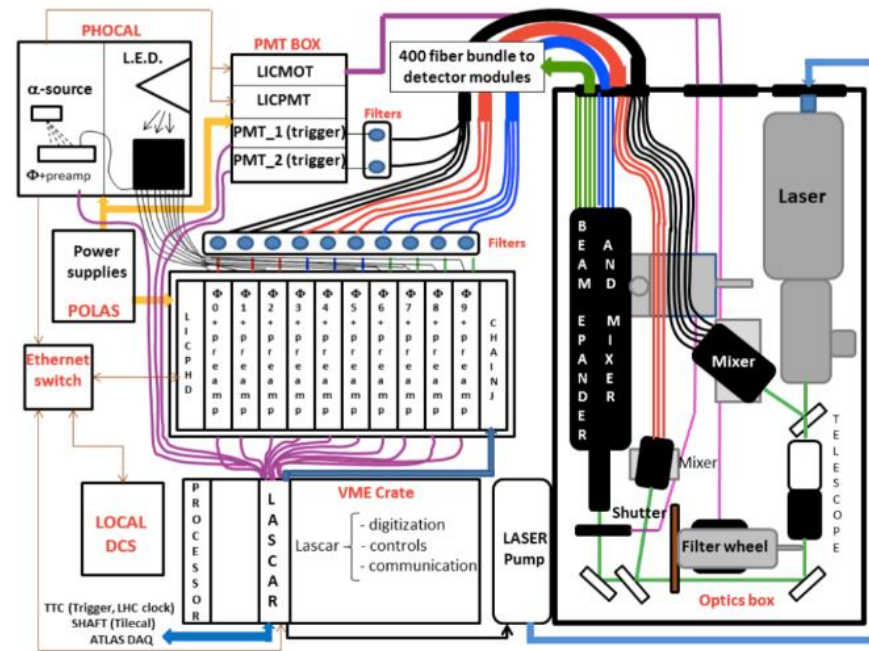
Charge Injection System

- Charge Injection System (CIS) injects a signal of known charge and measures the electronic response
- Calibration checks full ADC range: 2 gains for each PMT
- CIS calibration is taken twice a week
- Aim is to measure the pC/ADC conversion factor and correct for non-linearities in low-gain
- CIS systematic uncertainty $\sim 0.7\%$.
- The stability of the calibration factors is at the level of 0.03-0.04% (for both gains).
- Less than 1% of TileCal channels exhibit large fluctuations.



Laser System

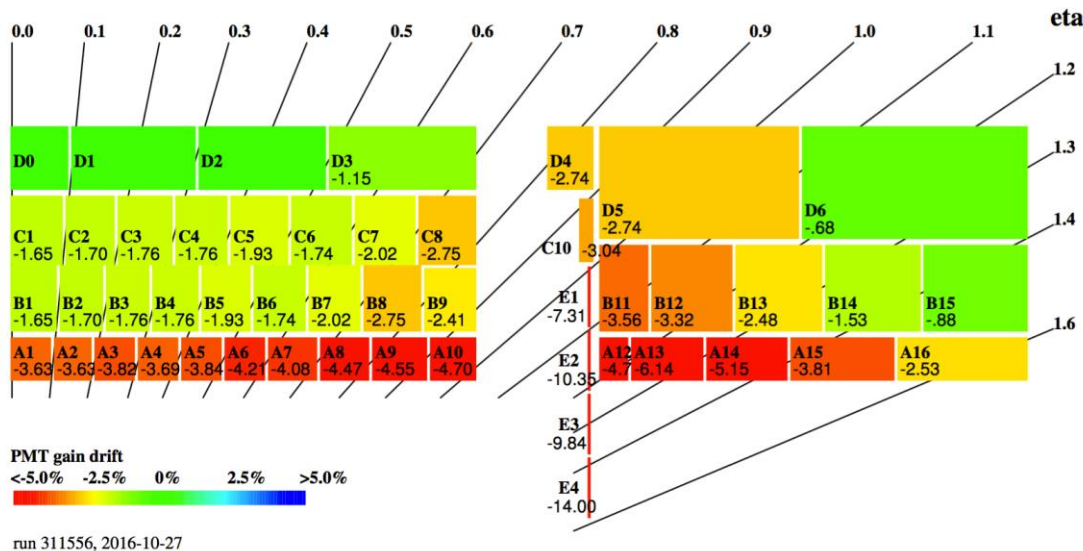
- Send controlled amount of light to the PMT with a wavelength of 532 nm (close to the one of physical signals)
- Dedicated LASER calibration runs are taken twice a week
- LASER pulses are also sent to TileCal during empty bunch crossings (1-2Hz frequency), mostly to control position of the peak (i.e. timing)
- Laser system measures the drift seen in PMTs w.r.t the last Cesium scan
- During the LHC Long Shutdown between Run I and Run II a new Laser II system was developed
 - Upgraded optics box and control electronics
 - Improved laser light estimation (more photodiodes).
 - Improved precision on the gain variation measurement: better than 0.5%



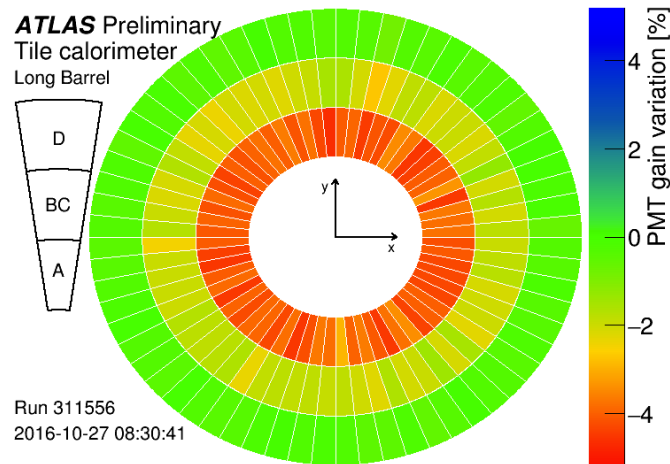
Laser Calibration

- Map of the PMT response variation during pp runs of 2016

ATLAS Preliminary
Tile Calorimeter



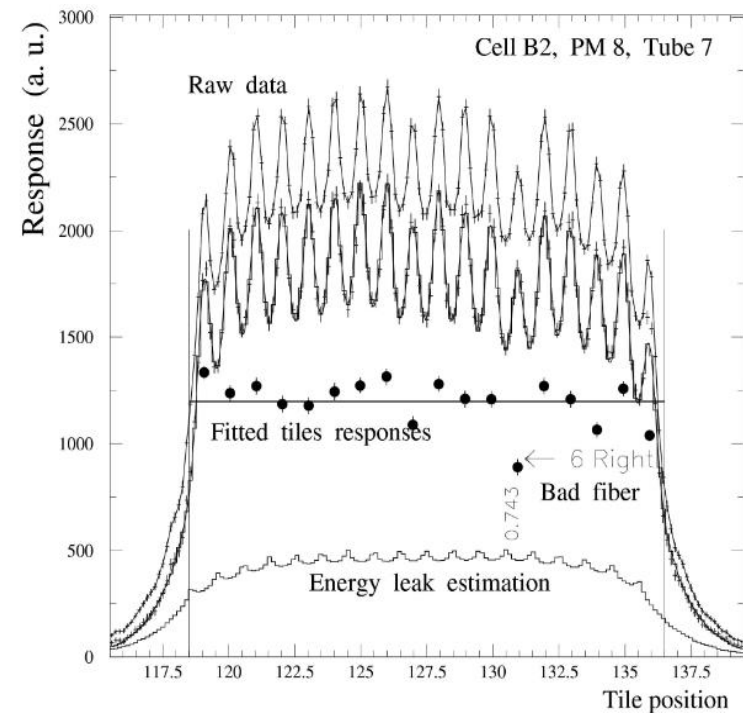
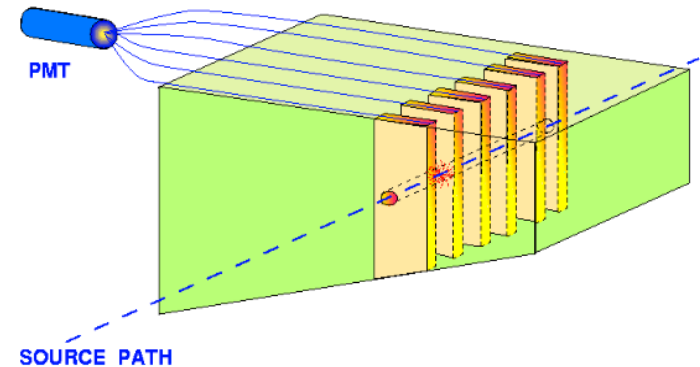
ATLAS Preliminary
Tile calorimeter
Long Barrel



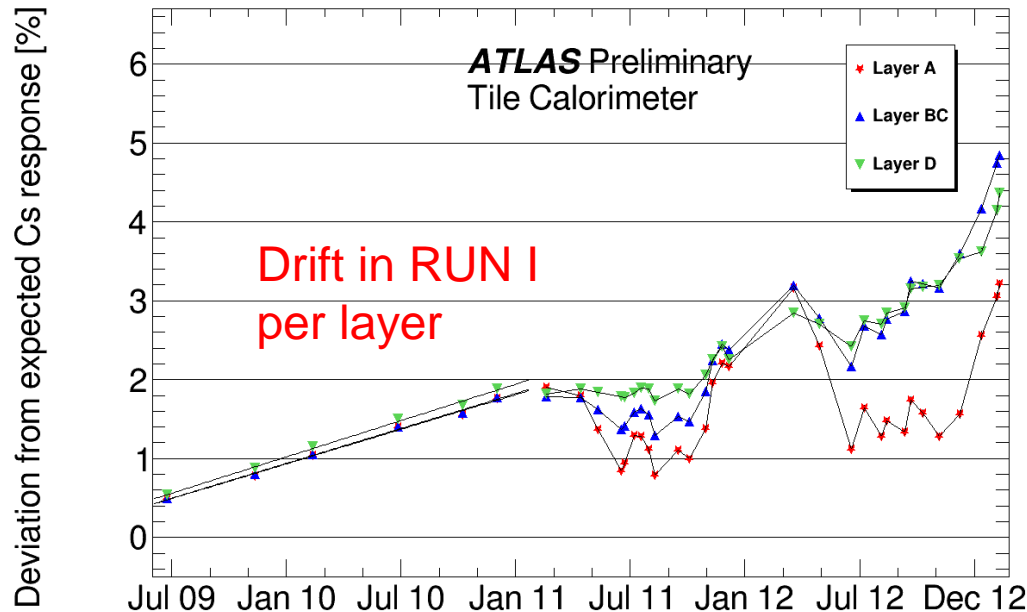
- Precision on gain variation measurement $\sim 0.5\%$.
- Cross check problems (e.g. unstable HV or bad CIS).
- Updates to calibration constants are done as often as weekly, to track changes in PMT responses.
- The maximal drift is observed in E and A cells which are the cells with highest energy deposits

Cesium System

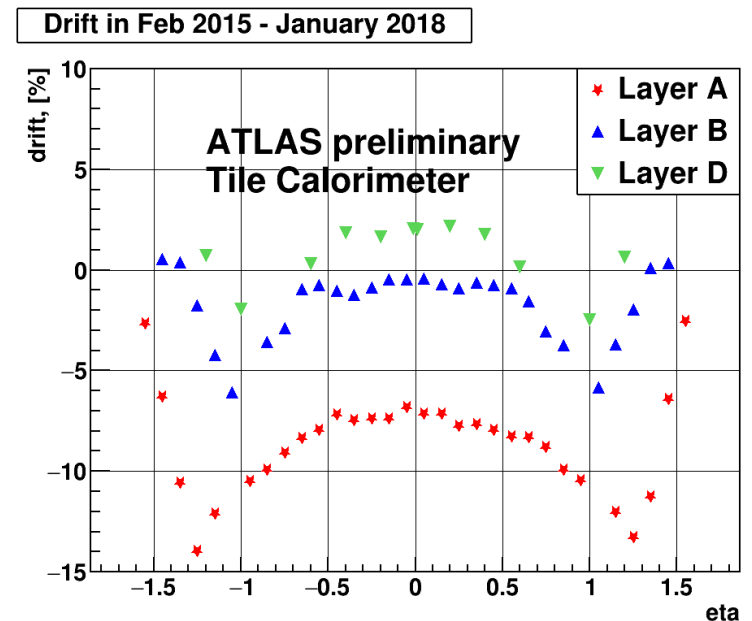
- A moveable radioactive ^{137}Cs source passes through the calorimeter body
- Hydraulic system is used to move 3 different capsules in 3 partitions
- The source emits γ -rays with well-known energy (662 keV)
- Electronic read-out is not the same as for physics, treated by an integrator circuit
- System used to check the quality of the optical component response, to equalize the response of all read-out cells and to monitor the cell electromagnetic scale in time
- Frequency of scans in RUN I was about once per month
- Recently it was decreased to 2-3 scans per year due to more strict safety requirements (no scans when detector is closed)



Cesium calibration



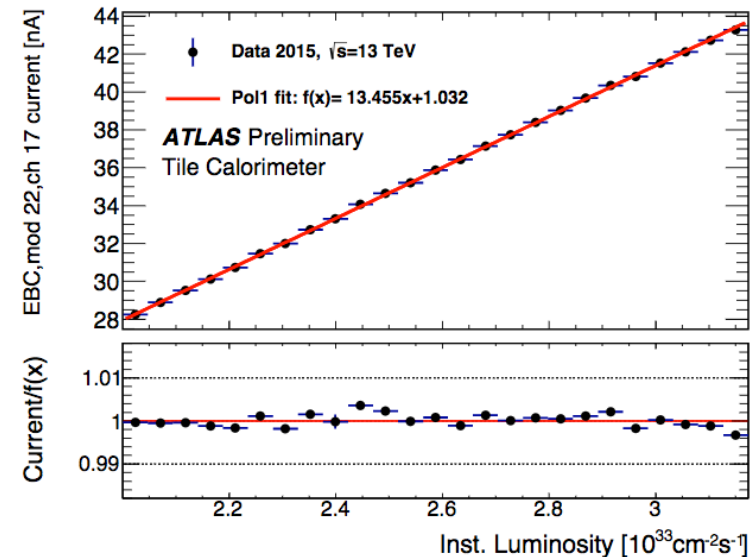
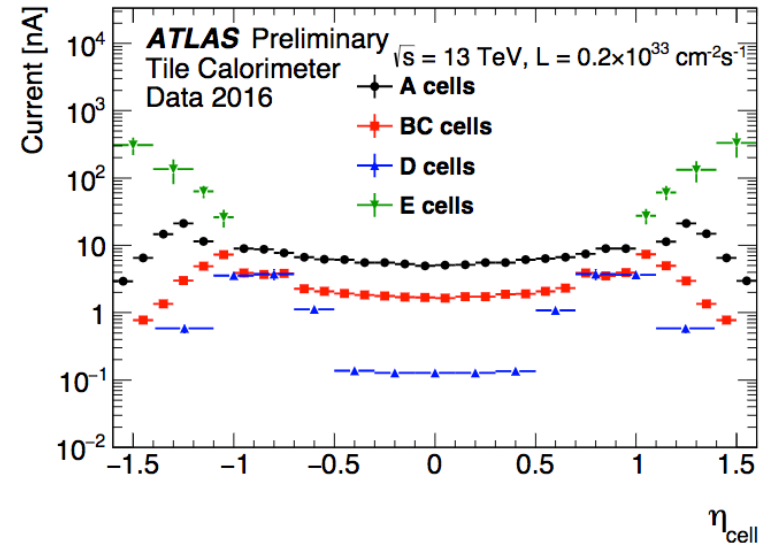
Total drift in RUN II In different cells



- Precision of Cesium calibration 0.3%-0.5% for most of the cells
- Cesium system was used to transfer EM scale from testbeam to ATLAS
- Since 2001-2004 testbeams and up to start of data taking permanent up-drift of about 0.8%/year was observed
- In RUN I (in 2011-2012) PMTs were drifting down during collisions, but recovered fast when beam was off
- In RUN II PMTs of innermost layer A (and partially layer B) do not recover completely, max down-drift in cell A13 - about 5%/year

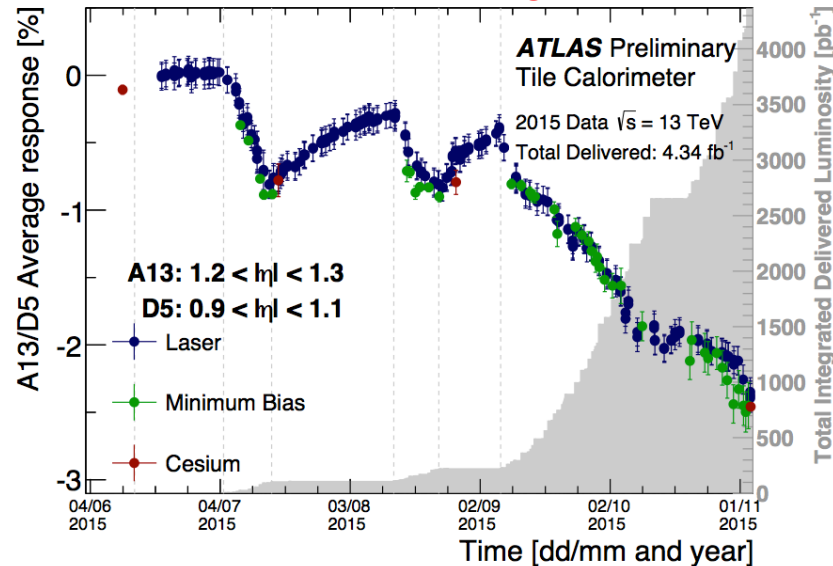
Minimum Bias System

- High energy proton-proton collisions are dominated by soft parton interactions (MB events).
- The integrator readout measures integrated PMT signals over a large time (~ 10 ms).
- As the Cesium system, the MB system monitors the full optical chain.
- As of 2016 it is used to calibrate calorimeter in the absence of Cesium scans
- Measured currents are linearly dependent on the instantaneous luminosity.
- The system can then be used to monitor the instantaneous luminosity.
 - ... or to provide an independent measurement given an initial calibration (luminosity coefficient computed from a single run).

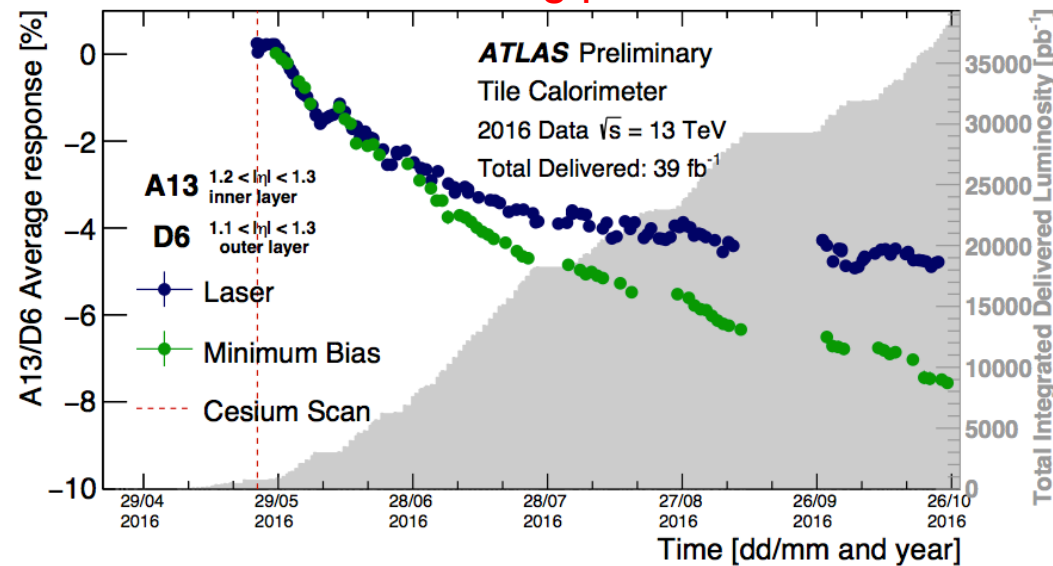


Combined use of calibration systems

2015 data taking period



2016 data taking period

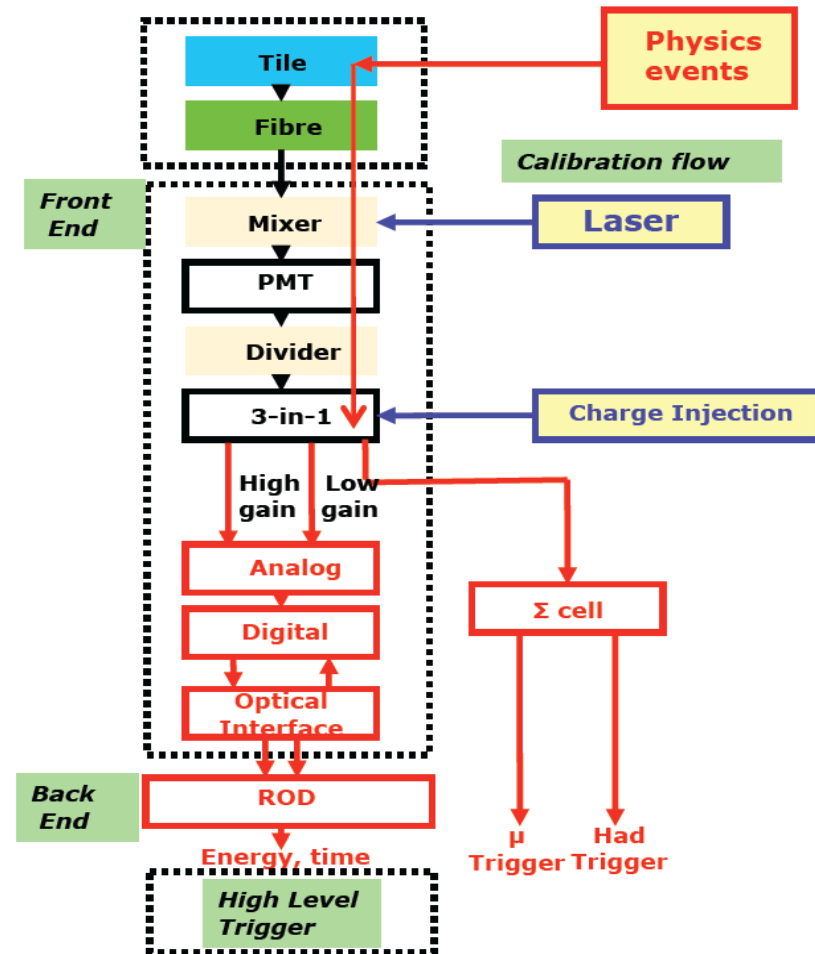


- Combination of the various TileCal calibration systems is used to identify the sources of drifts
- In 2015 the 3 systems show a similar behavior in most exposed cells: drifts attributed mostly to a variation of PMT response
- In 2016 a systematic difference is observed between Laser and Minimum Bias: difference attributed to scintillator irradiations
 - Extra calibration from Minimum Bias applied on some channels (in A-layer and E-layer)

TileCal physics performance

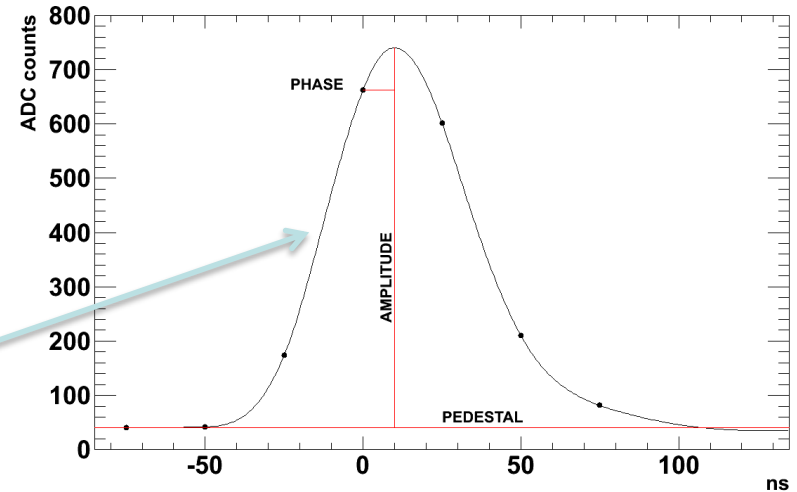
Signal propagation

- Signal collected from tiles to PMTs through WLS fibers
- PMT output signal is shaped with a passive shaping circuit and amplified separately in High and Low Gain branches (in proportion 64:1)
- HG and LG signals are sampled at the LHC bunch-crossing frequency (40 MHz) and digitized using 10-bit ADCs
- A gain switch sends HG or LG to the Read Out Driver Boards (RODs) outside the experimental hall
- Signal properties (amplitude, time, quality) for each channel are reconstructed on-line inside the ROD, sent to High Level Trigger and stored on disk
- For signals above $\sim 70\text{MeV}$ all raw data received from front-end are transmitted and recorded for more precise offline reconstruction
- In special Zero-Biased trigger events absolutely all raw data are kept



Optimal filtering algorithm

- Online and offline signal reconstruction is done using Optimal Filtering Algorithm
 - Aim to reconstruct peak value from 7 consecutive measurements of the signal
 - Online - 16bit integer arithmetic
 - Offline - floating point arithmetic, possibly non-linear corrections
- OF weights are defined by:
 - Pulse shape (reference shape from testbeam pions is used)
 - Noise Autocorrelation Matrix (measured in pedestal calibration runs)
 - Expected signal phase (stored in conditions DB for every channel)
- For cosmics data-taking during commissioning an iterative algorithm was used to select different weights event-by-event according to the non-fixed arrival time of pulses.
- During LHC operation the arrival time of pulses is synchronized with the LHC clock (Bunch Crossing) which is used for pulse digitization.



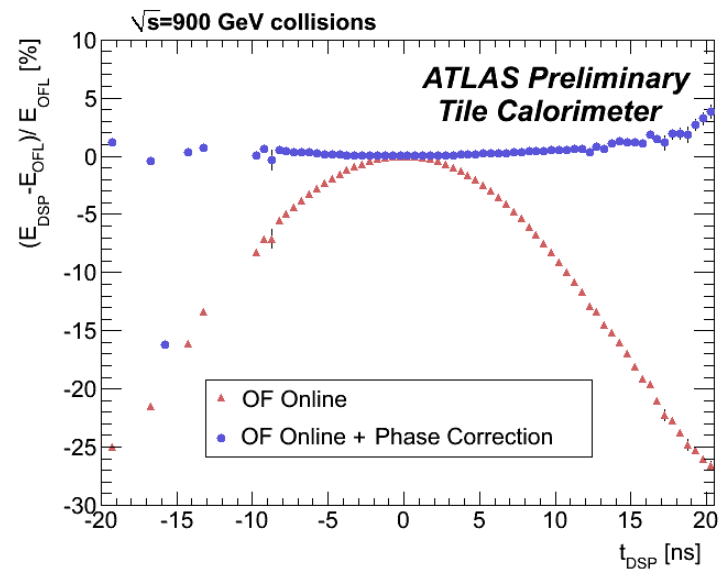
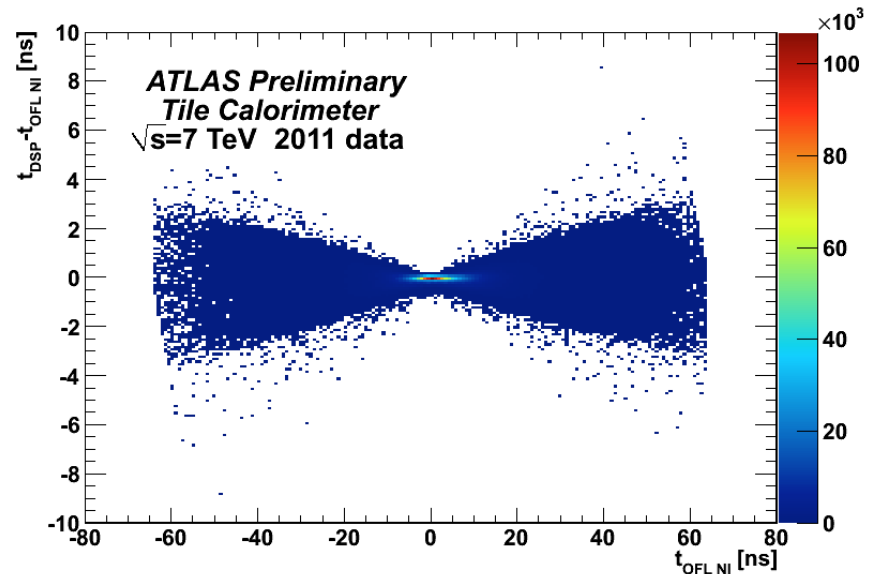
$$A = \sum_{i=0}^n a_i S_i$$

$$\tau = \frac{1}{A} \sum_{i=0}^n b_i S_i$$

$$QF = \sum_{i=0}^n (S_i - (A g_i + A \tau g'_i + p))^2$$

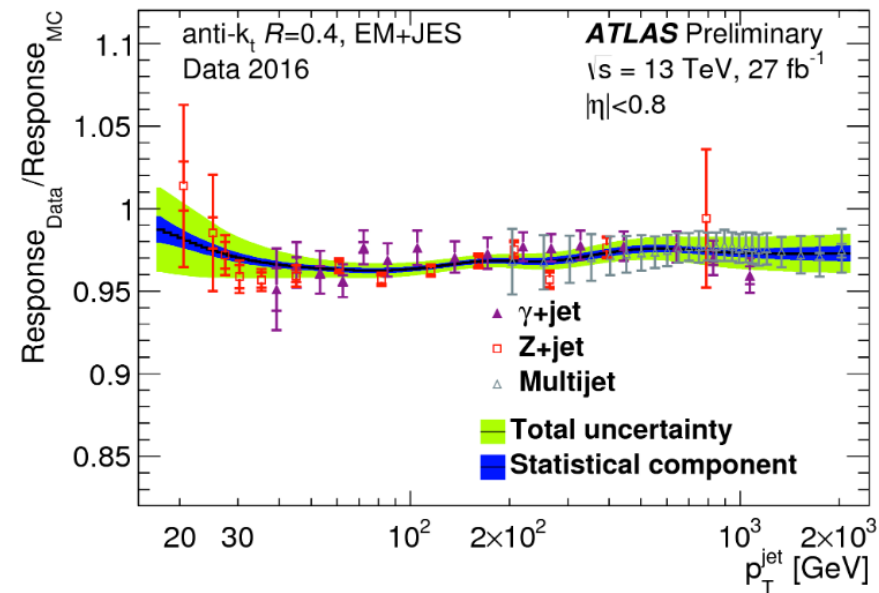
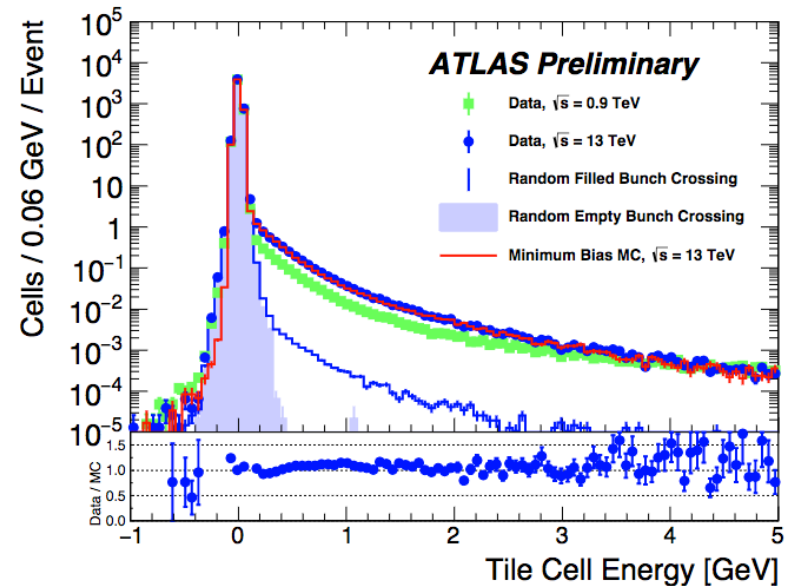
Performance of online reconstruction

- Expected difference between online and offline Optimal Filter is due to:
 - Fixed point arithmetic vs floating.
 - Look-up-Table used in the DSP for amplitude division
- Difference in reconstructed time is negligible for signals above 1GeV; for small signals it's below 1 ns for signals within $[-12.5, 12.5]$ ns (1BC)
- In case time of the signal deviates significantly from expected one, the amplitude reconstructed by non-iterative algorithm is underestimated
- This error can be corrected on-the-fly by applying "parabolic correction"; the residual error is below 1% for signal within $[-12.5, 12.5]$ ns



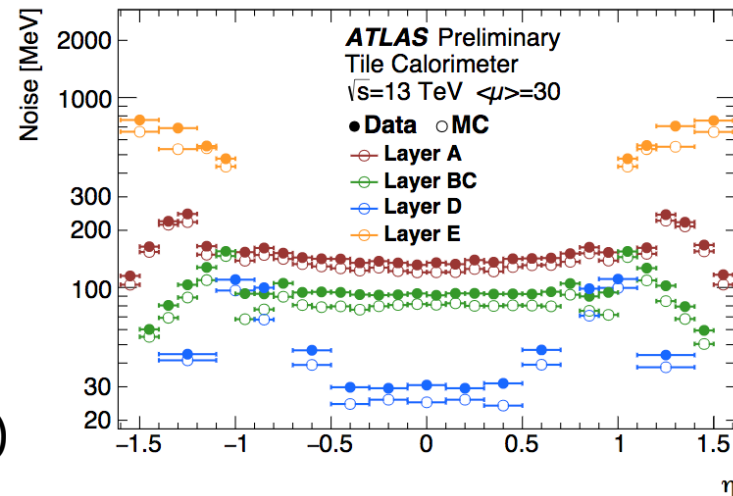
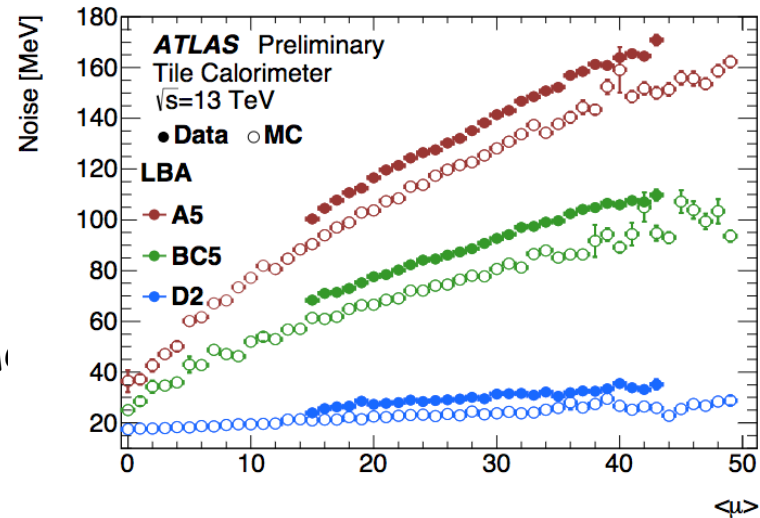
Jet performance

- A good description of the cell energy distribution and of the noise in the calorimeter is crucial for the building of topoclusters which are used e.g. for jet and missing transverse momentum reconstruction.
- Good agreement in Tile cell energy distribution.
 - To ensure exactly one interaction has occurred per bunch crossing, only events having a single reconstructed primary vertex are selected
- Consistent overall jet energy scale
- Jet energy resolution is below 10% at $p_T > 100 \text{ GeV}$
- Constant term is within expected 3%

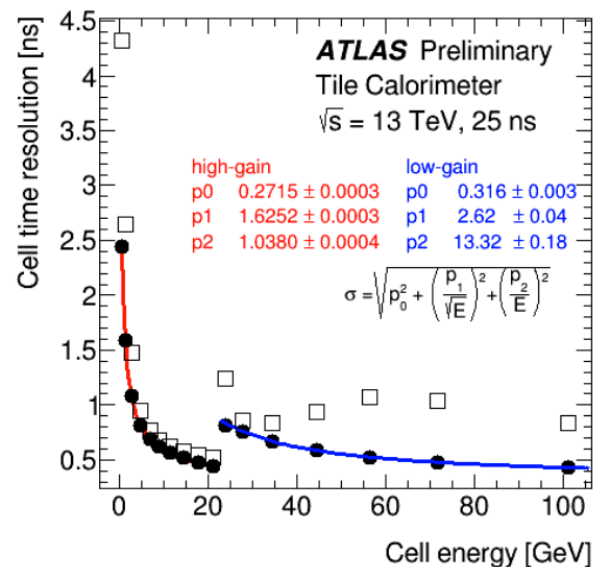
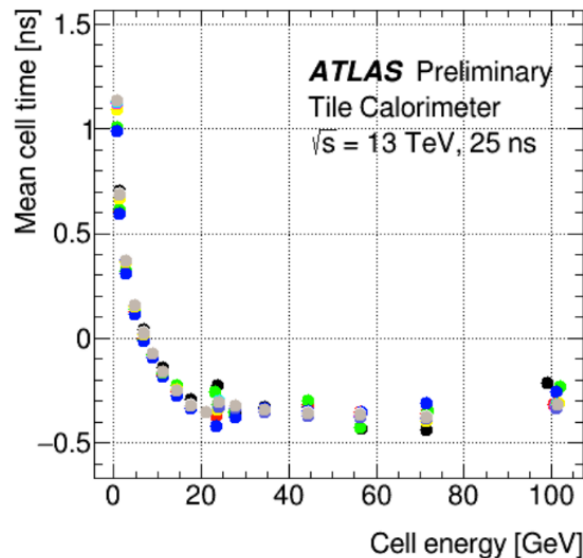
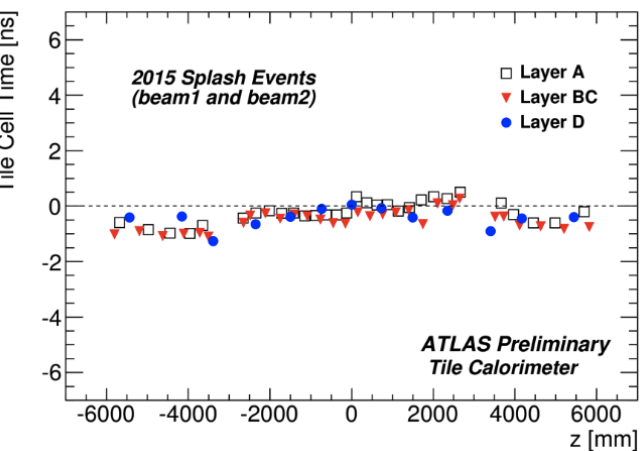


Noise description

- The total noise per cell in the calorimeter comes from two sources:
 - Electronic noise - measured in dedicated runs with no signal in the detector.
 - Pile-up contribution - originates from multiple interactions occurring at the same bunch crossing or from the minimum bias events from previous/following bunch crossings
- Electronics noise stays at the level below 30 MeV for most of the cells. Noise is measured regularly in calibration runs.
 - New power supplies (fLVPS), installed in the long shutdown (2014), have better performance and more Gaussian noise
- Pileup noise is increasing with pile-up as $\sqrt{\mu}$
- The largest noise values are in the regions with the highest exposure (E-cells, A-cells)

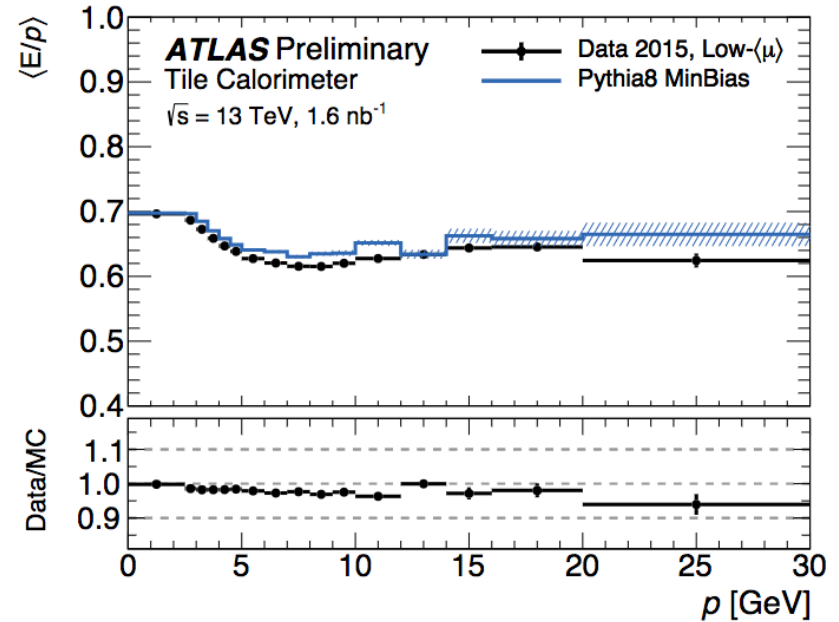
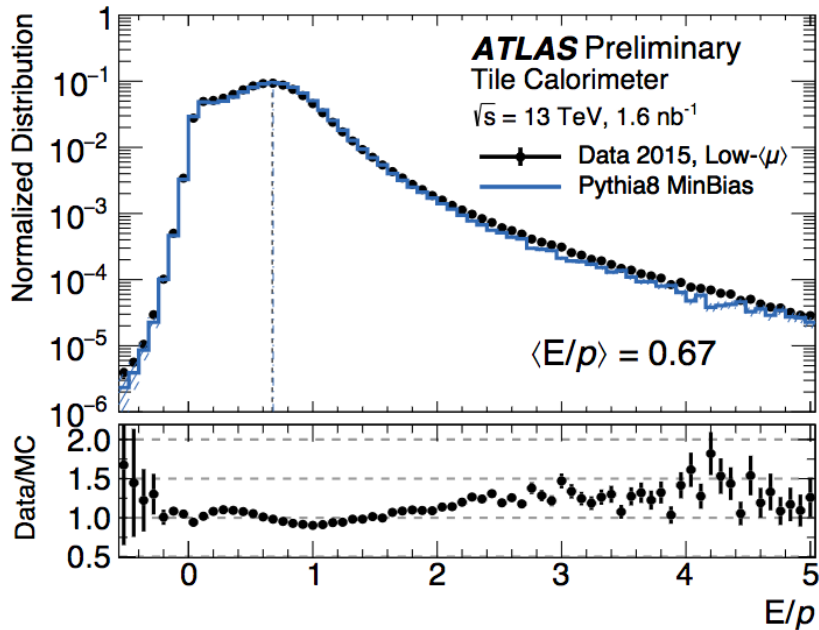


Time calibration



- A precise time calibration is important for the cell energy reconstruction.
 - Phase in each channel is tuned to have reconstructed time close to zero for particles travelling from the interaction point at the speed of light
- Initially set with splash events, tuned later with muons and jets.
 - Cells associated to jets are used for the timing studies in physics data to minimize the effect of the pile-up contamination in the sample.
 - The mean cell time decreases with deposited energy due to neutrons/slow hadronic components of the hadronic shower.
 - Resolution is better than 1 ns for $E_{\text{cell}} > 4 \text{ GeV}$.
- Monitored during physics data taking with laser and corrected if necessary

Single particle response

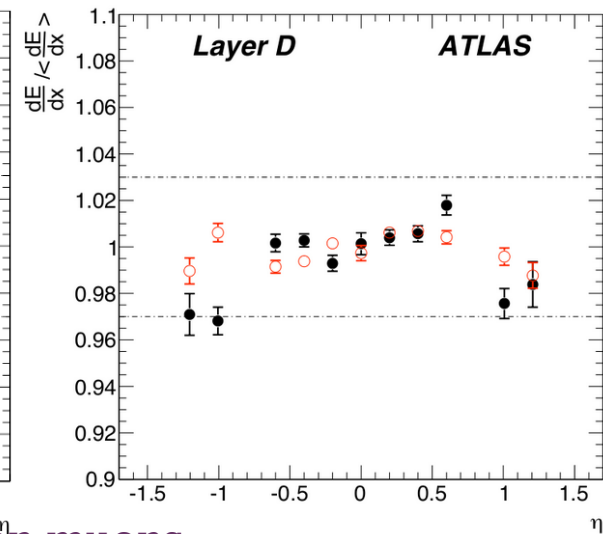
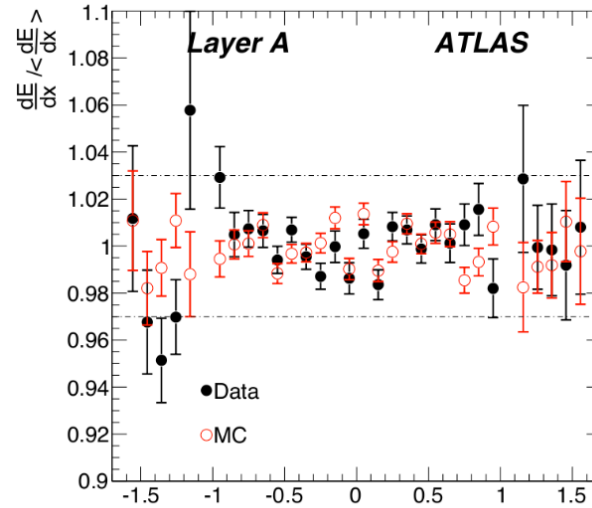


- An important Tile Calorimeter characteristic is the mean of energy to track momentum ratio ($\langle E/p \rangle$) for isolated charged hadrons in minimum bias events.
 - Used to evaluate calorimeter uniformity and linearity during data taking
- Expect $\langle E/p \rangle < 1$ due to the sampling non-compensating calorimeter
- Data and simulation agree, showing linearity and uniformity in detector response
- dE/dx of minimum ionizing muons (near noise threshold) show data/MC agreement within 3%

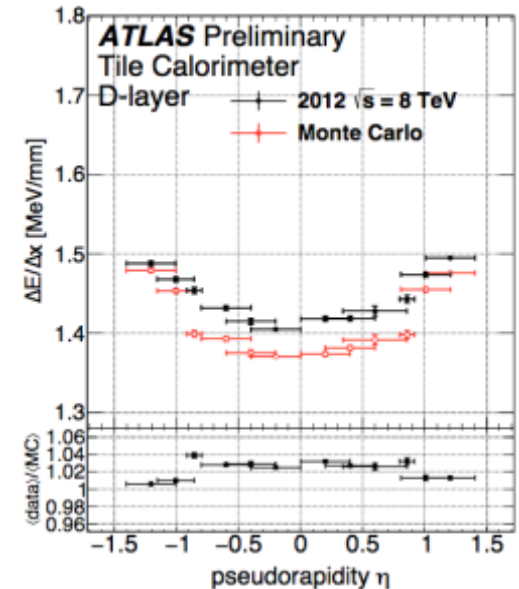
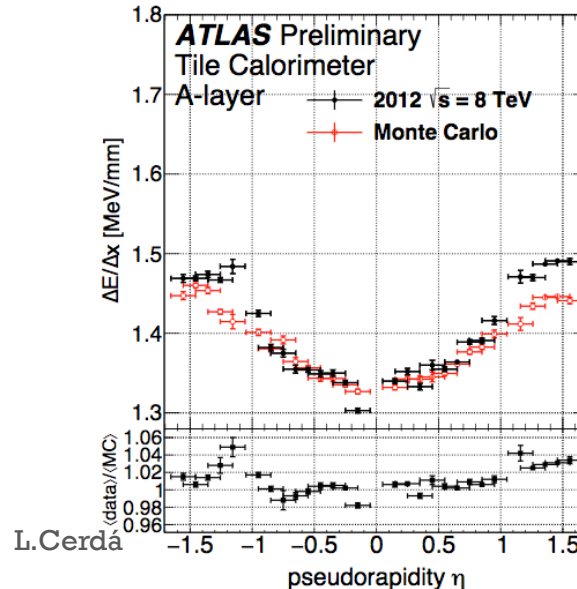
Muons

Cosmic muons

- Muons from cosmic rays, beam halo and collisions are used to check the cells inter-calibration and the electromagnetic energy scale
- 1% / 3% response non-uniformity in η in Long / Extended Barrel with cosmic muons
- A good energy response uniformity in all calorimeter layers
- The data/MC agreement is within 3-4%

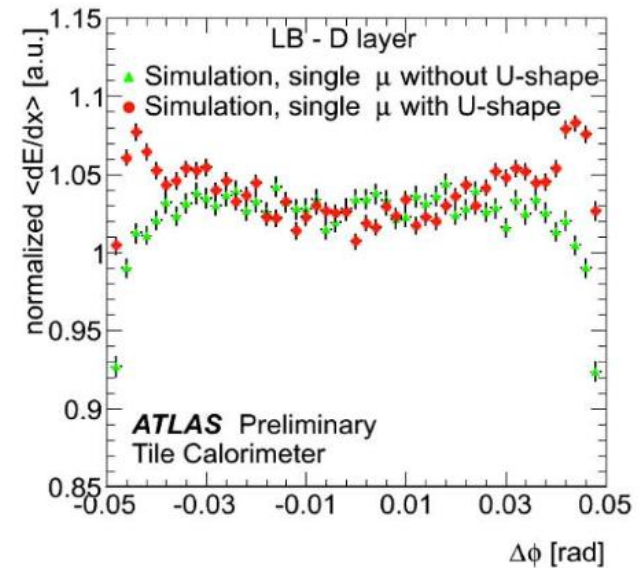
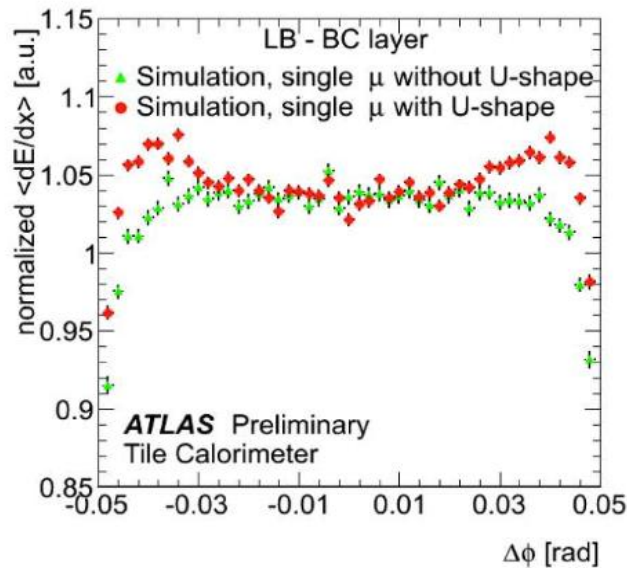
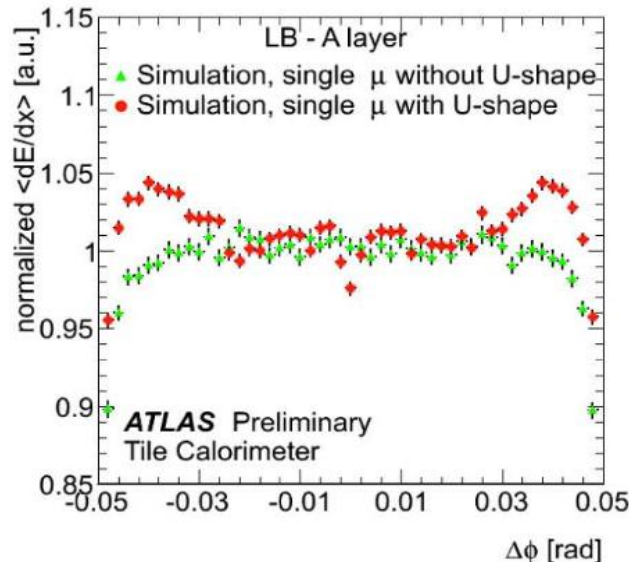
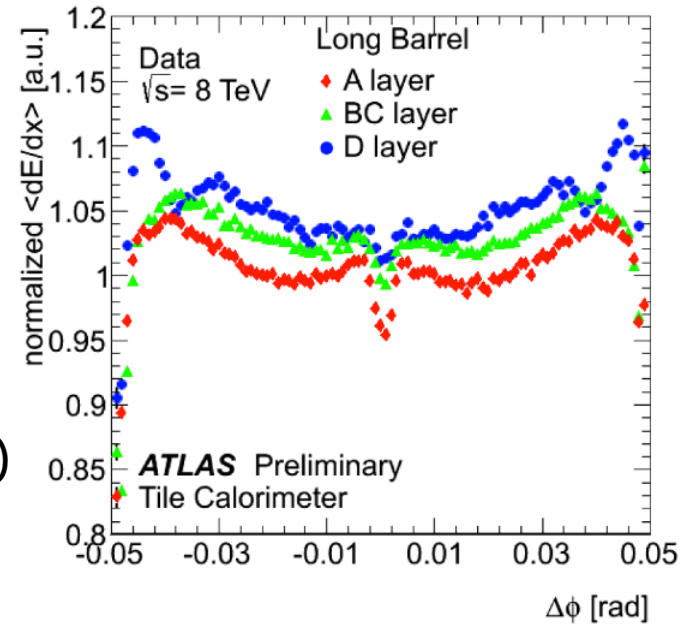


Collision muons

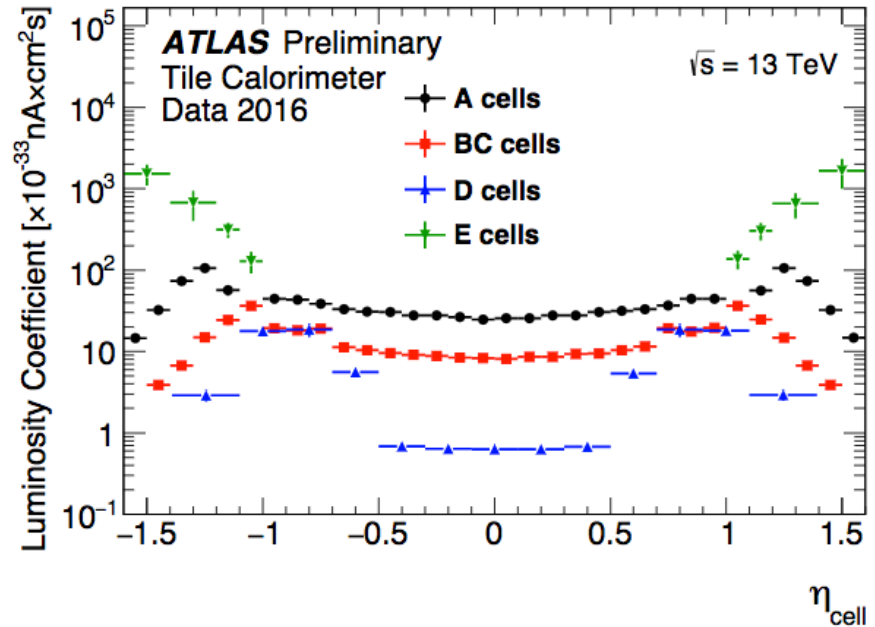
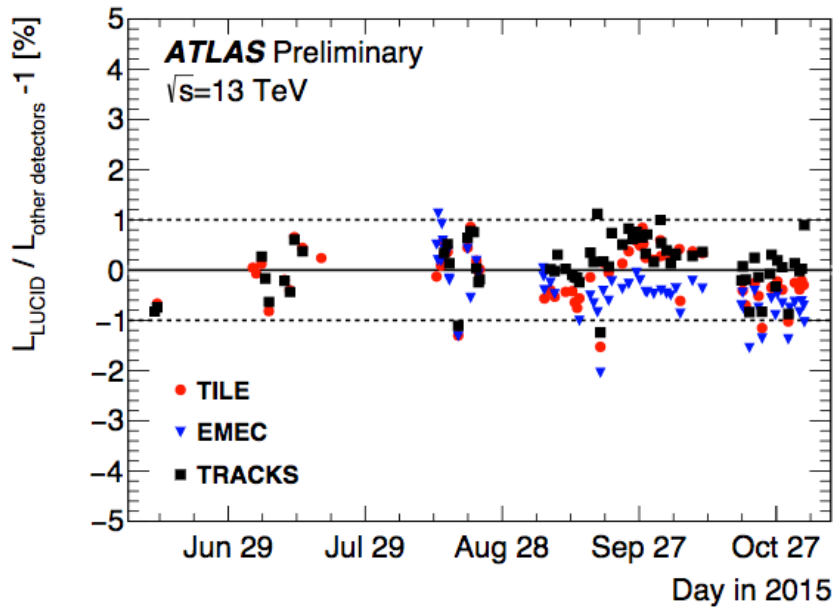


U-shape

- The response of the PMTs is not flat in the azimuthal angle difference between the energy deposition point and the center of the cell ($\Delta\phi$)
 - It shows a dependence called as U-shape
- The dependence of the response on $\Delta\phi$ was measured using $W \rightarrow \mu\nu$ events in the 2012 data
 - A steep dip at the center of the cell ($\Delta\phi = 0$) corresponds to the position of the holes for Cesium pipes in the scintillating tiles
- The light propagation in the MC simulations has been improved by introducing the U-shape



Luminosity measurements

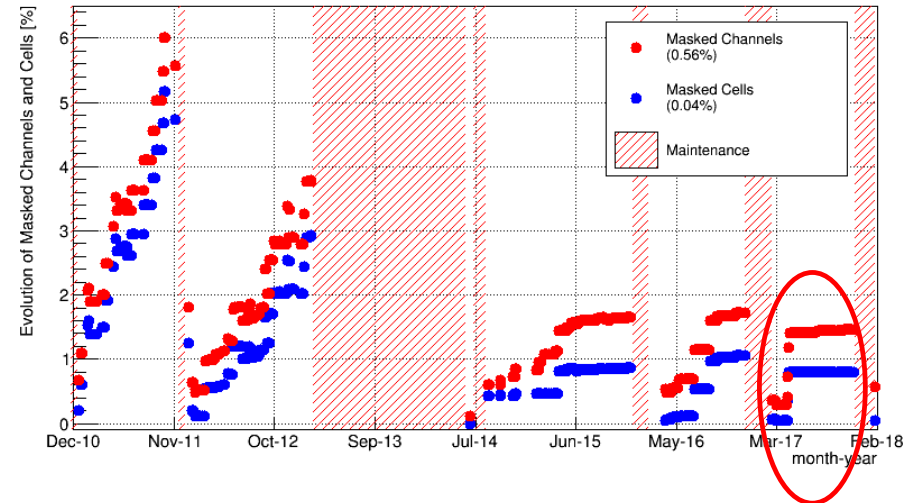


- Tile Calorimeter contributes to the ATLAS luminosity measurement
 - Calibration transfer from low to high luminosity conditions
 - Long term luminosity monitoring
- Dedicated readout of the anode currents in every channel
 - Fully decoupled from trigger
 - Intrinsically independent from pile-up

2017 data taking

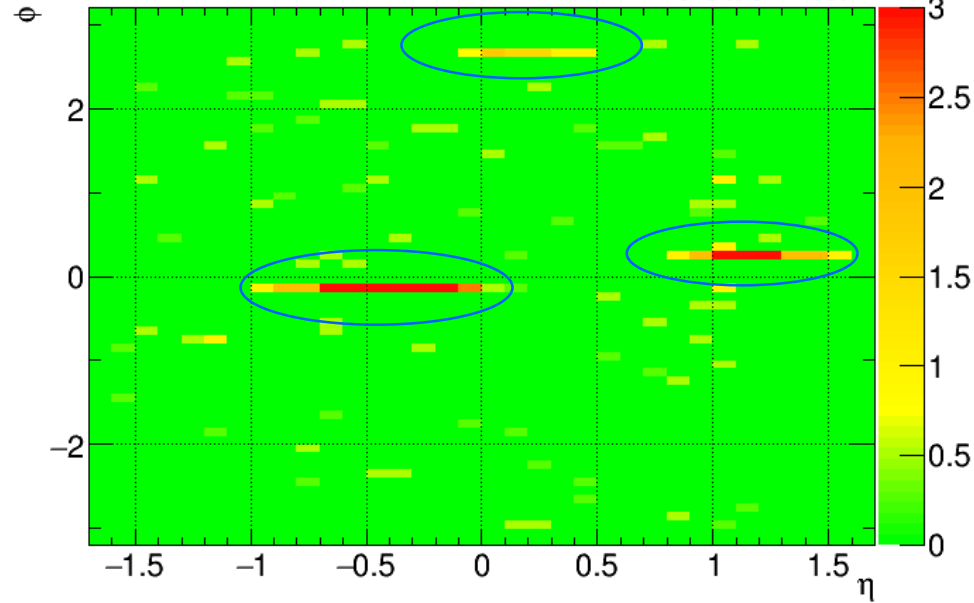
- Not 100% of the 5182 cells of TileCal can be used for physics
 - Failed on-detector electronics can be replaced only during shutdowns
- Non-working channels are masked
 - If one channel in a cell is masked - energy in this cell is estimated using working channel (redundancy!)
- At the end of 2017 0.79% of cells (1.46% of channels) were masked
 - LBC63, EBA03 and $\frac{1}{4}$ of LBA28
- η vs ϕ map of TileCal is showing the number of masked cells per tower (1 tower = 3 cells)
 - All red strips correspond to whole module (or half-module in barrel) being off
- All dead modules were repaired during shutdown
 - Only 2 dead cells remain

Evolution of Masked Channels and Cells: 2018-02-14



ATLAS Preliminary Tile Calorimeter

Amount of Tile Masked Cells 2017-12-05 ATLAS Preliminary Tile Calorimeter



Summary

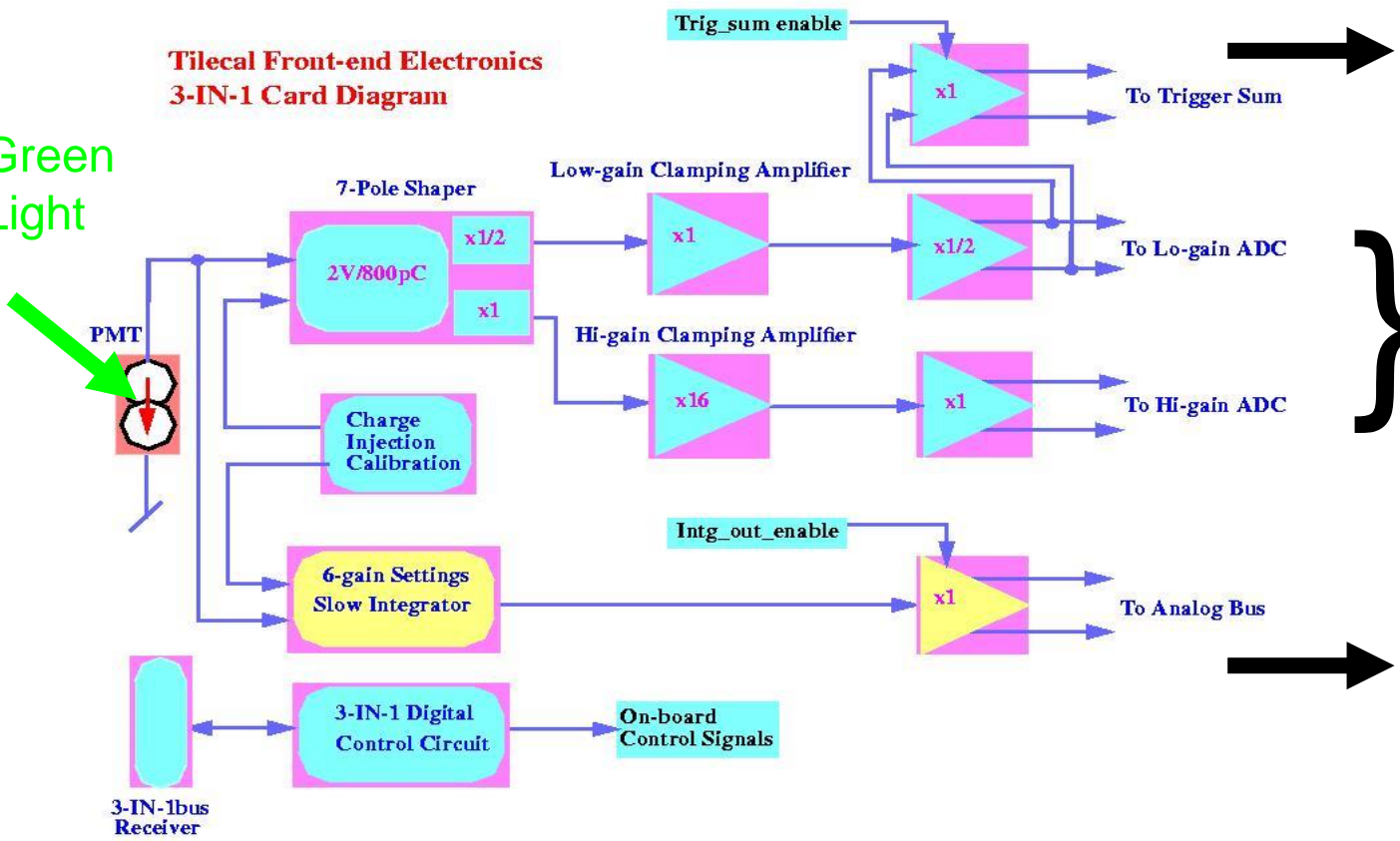
- TileCal provides important information for reconstruction of hadrons, jets, hadronic decays of tau leptons and missing transverse energy.
- Multiple systems are used to calibrate and monitor the response of the TileCal cells.
- These calibration systems allowed to achieve great performance of the calorimeter during the LHC Run I and Run II.
- Stability of absolute energy scale is better than 1%.
- EM scale has been transferred from testbeam measurements and validated with cosmic and collision muons
- Performance of online signal reconstruction is compatible with offline reconstruction
- Time synchronization between cells is well below 1 ns and has been verified with collisions and splash events
- Amount of dead channels is decreasing every year, TileCal as whole is working better with time thanks to efforts of many experts involved

Backup

3-in-1 Card Schematic

Tilecal Front-end Electronics
3-IN-1 Card Diagram

Green
Light



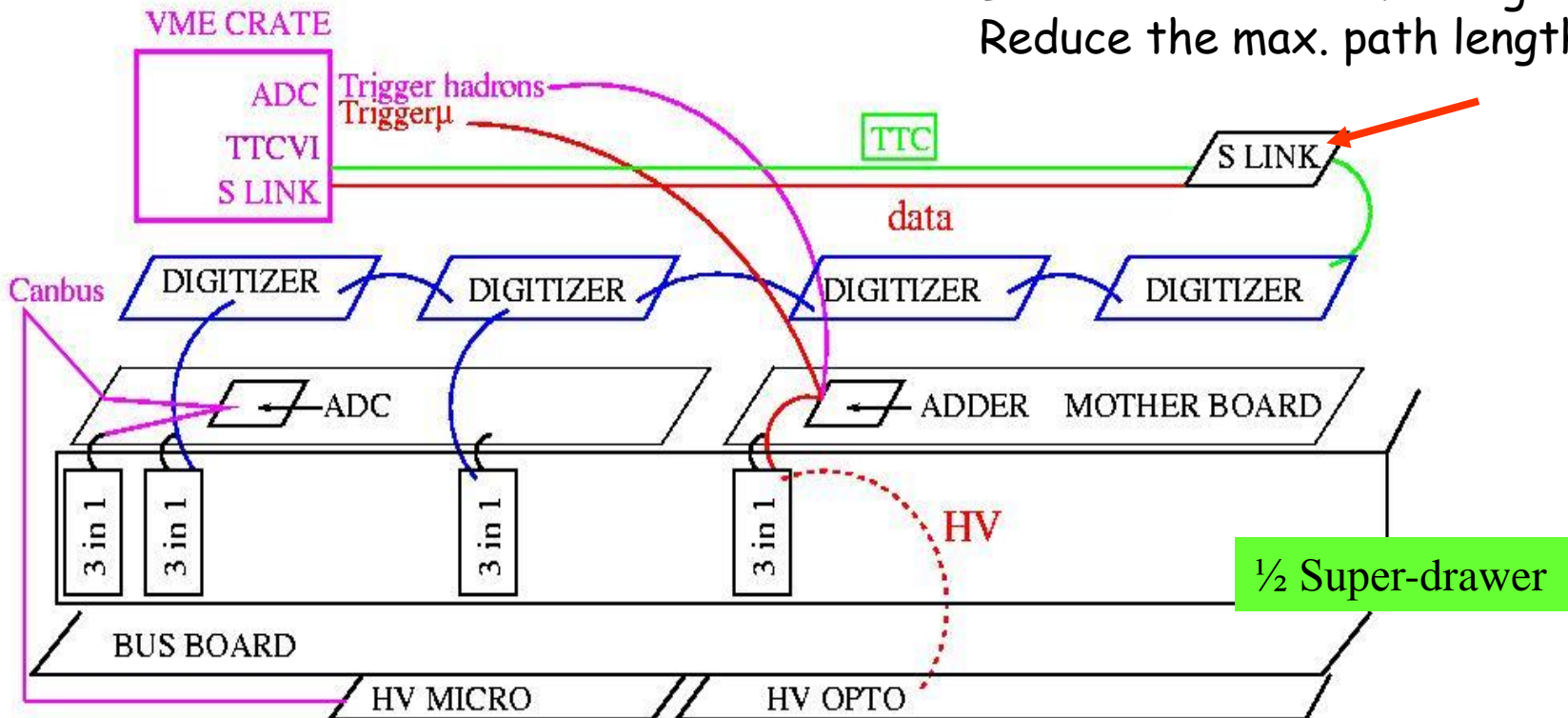
To Analogue
Trigger Sums
For Lvl1 trigger

To Digitizers
e.g. CIS calib

To ADC for
Cs calibration
and min bias
Monitoring
12 bits ADC
Cs current $\sim 50\text{nA}$
 $\sigma(I) \sim 2.5\%$

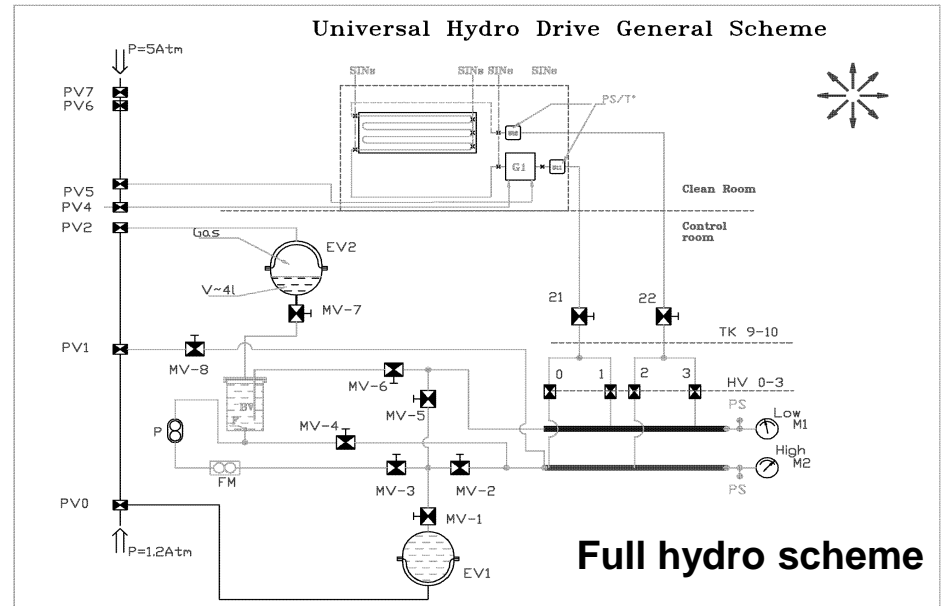
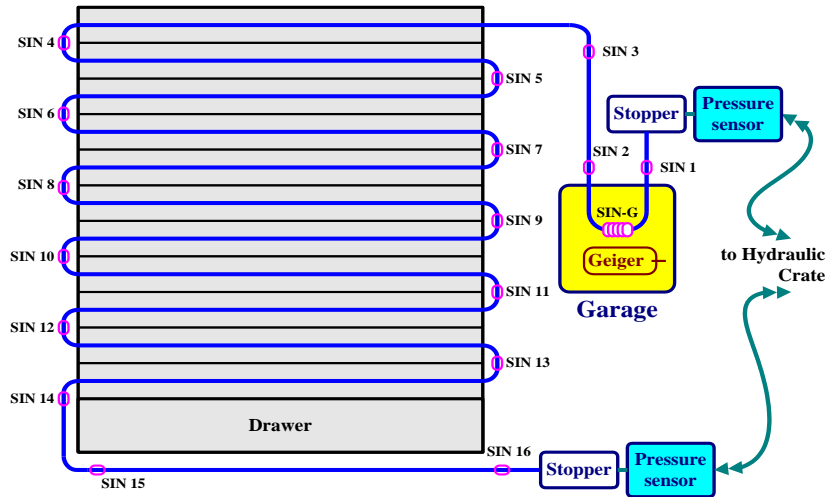
Front end electronics schematic

Better radiation shielding
Reduce the max. path length



Cesium system hydraulic scheme

Single module at the testbeam

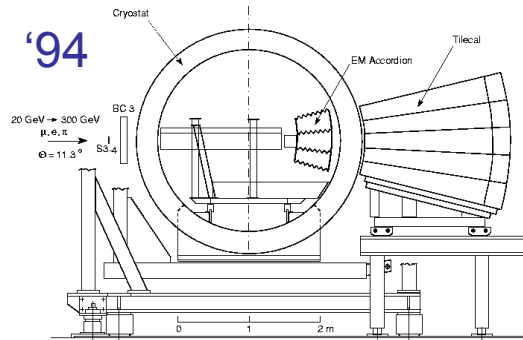


Full hydro scheme

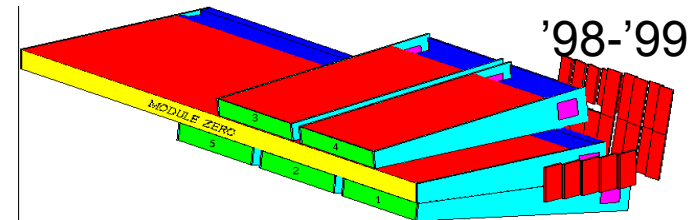
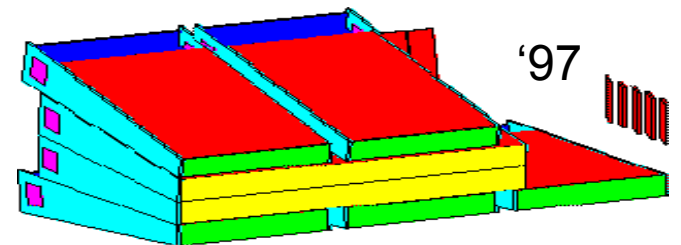
- Source is transported by water flowing inside calibration tubes
- There are three independent systems for ATLAS (barrel + 2 extended barrels)
- Total time to run the source through barrel cylinder is 5 hours
- Cesium runs are taken only few times per year in ATLAS
- System is drained and capsule stored in garage during normal data taking
- 2 Methods for calculation of Cs response

Test Beams History of the TileCal.

- '93 first prototype
- '94 combined with LAR prototypes
- '95 five 1m prototypes
- '96 Barrel Mod0 full size prototype combined with LAR and standalone



- '97 Ext.Barrel M0 full size prototype
- '98 Barrel Mod0 reinstrumented
- '99 Barrel Mod0



- '00 one production Barrel and two ExtB modules.
- '01-'03 two Barrel and two ExtB production modules with final electronics, **start of calibration**
- '04 **ATLAS** Combined test beam, 3 barrel and 3 ExtB
- '15 **Start of Upgrade testbeam program**
- test of new electronics for HL-LHC

