The ATLAS Tile Calorimeter experience with 10,000 readout photomultipliers operating since the start of the p-p collisions at LHC

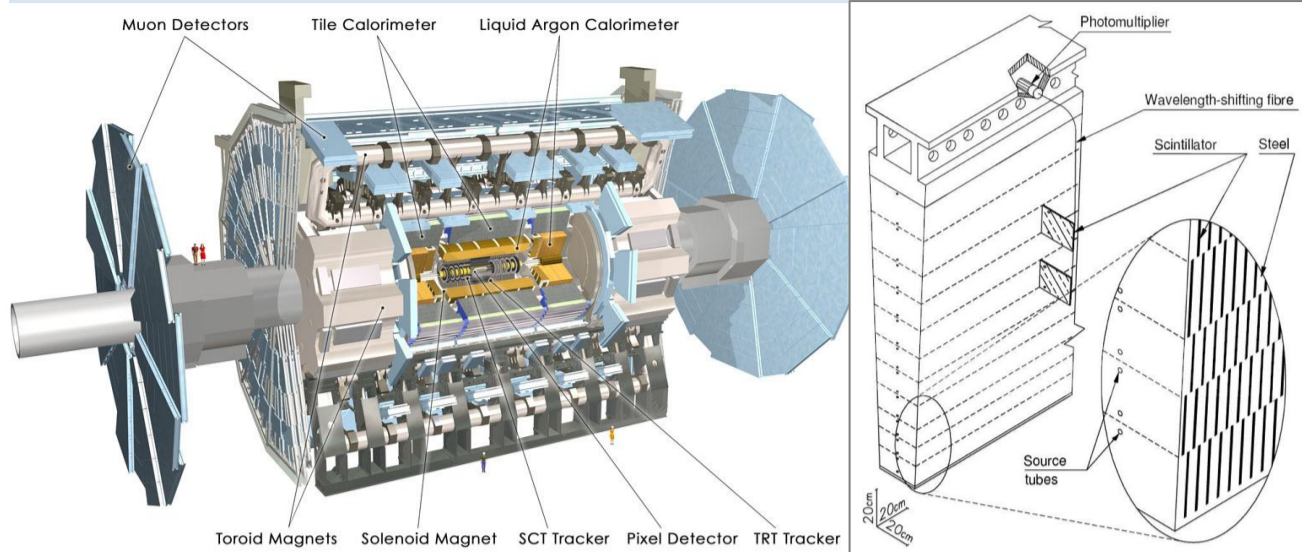## The ATLAS Experiment and the Tile Calorimeter
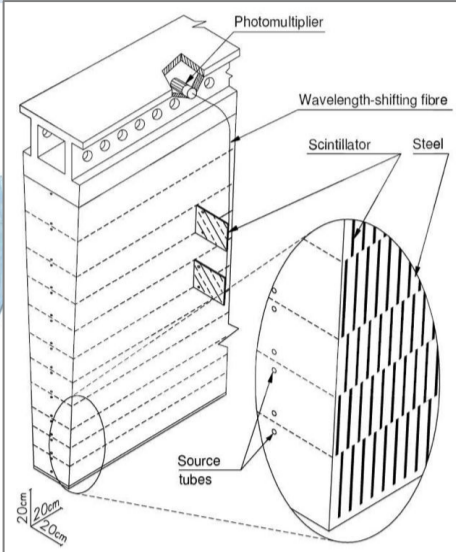

Figure 1. The ATLAS detector

Figure 2. TileCal Module

The Tile Calorimeter is a hadronic calorimeter in the ATLAS detector
- Includes about 10,000 8-stage fine-mesh PhotoMulTipliers (PMTs), a special version of the Hamamatsu model R5900
- Plastic scintillator tiles sample the energy within the detector
- Optical fibers transmit the light from each cell to two PMTs located on the detector
- TileCal is divided into four partitions with 64 modules, each module in the long barrel includes 45 PMTs, and 32 PMTs in the extended barrel
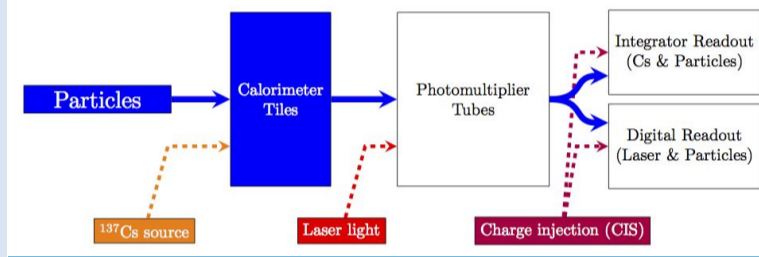
Tile Calorimeter Calibration - ATLAS Detector

Figure 3. Calibration of readout chain

- Three main calibration systems test specific elements of the readout chain: Cesium-137 source, Laser, and Charge Injection System (CIS)
- The systems calculate energy scales and calibration constants to convert readouts in GeV units of energy:

$$E_{channel} [GeV] = A [ADC] \cdot C_{ADC \to pC} \cdot C_{pC \to GeV} \cdot \varepsilon_{C s} \cdot \varepsilon_{Laser}$$

- Cesium: circulates sources of Cesium-137 around the detector to test the stability and uniformity of the optical response of every scintillator tile
- Laser: sends laser pulses of known intensities into the PMT's photocathodes and collects data in low gain in the absence of collisions
- CIS: injects known charge into readout electronics (including Analog to Digital converters)
- Minimum bias system monitors full readout chain for scintillator irradiation studies
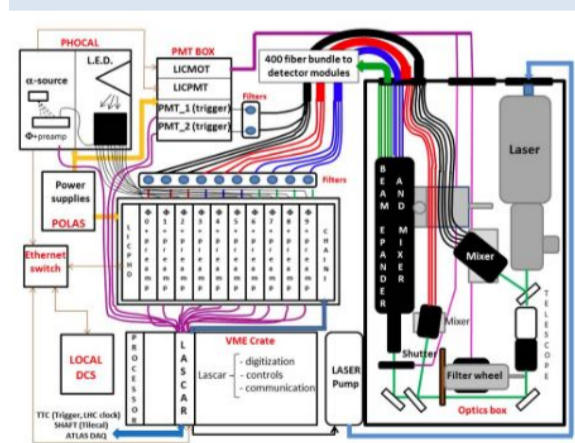
Laser Calibration System - ATLAS Detector

Figure 4. The full Laser II System

Goals:
- System keeps calibrated all detector channels between subsequent calibrations with the Cesium system
- Laser II system aims to reduce contribution of the calibration uncertainty below the irreducible systematics in the determination of the Jet Energy Resolution and Jet Energy Scale

Stability, Figure 5:
- The stability of the Laser II system was determined by responses collected over the course of three months for diodes that were placed at different readout steps of the system
- Groups of three or four diodes were used to monitor the laser intensity, light transmitted after the filter wheel, and light at the exit of the final beam expander

	Short term stability (1 month, between two Cs scans)				Long term stability (4 month observation)			
	RMS		maximum		RMS		maximum	
	LG	HG	LG	HG	LG	HG	LG	HG
Laser monitors (%)	0.3	0.3	0.5	0.5	0.5	0.5	1.5	1.5
Filter monitors (%)	0.3	1.0	1.0	5.0	0.5	1.5	2.0	6.0
Expander monitors (%)	0.3	0.5	1.0	1.5	0.5	1.0	2.0	3.0
Overall (%)	0.3	0.5	1.0	2.0	0.5	1.0	2.5	4.0

Figure 5. Short and long term stability of the Laser system, October 2014.

Laser Test Bench

Test bench at the Pisa-INFN labs
- Measures PMT absolute gain and the absolute and normalized response with stable laser pulses (80 ps, wavelength 437 nm)
- PMTs used were removed from TileCal detector in February 2017
- PMTs were reading out different cell type (A,BC, D, E) having integrated 1 to 5 C during Run I and Run 2
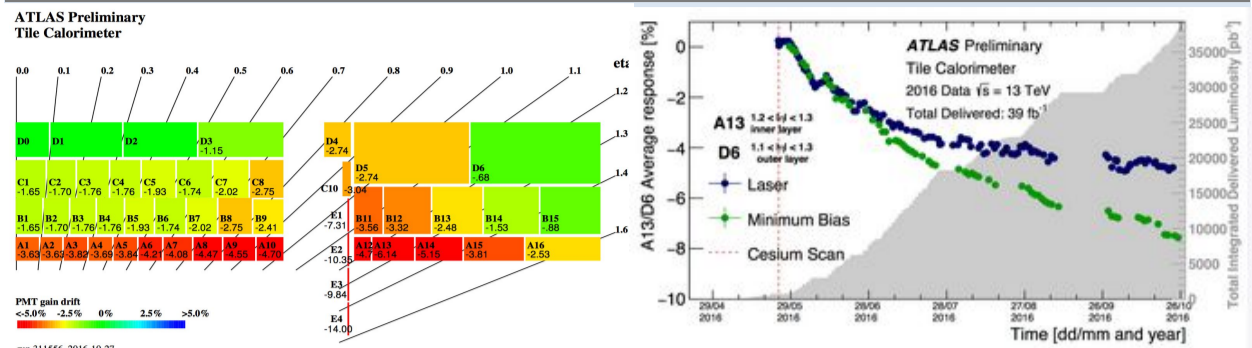
PMT Response Loss - ATLAS Detector

Figure 6. The mean response variation of 10,000 PMT's computed cell-by-cell

Figure 7. Evolution of Down-drift of A13 cells during data-taking in 2016

- The response variation relative to the first day of observation of each PMT is found using the laser system
- For each cell, the response variation is defined as the mean of the gaussian fitting to the response variation distribution of the channel associated with the cell
- Observed down-drift mostly affects cells of the inner radius (A13 cells and cells in the E4 region), which are cells with higher current
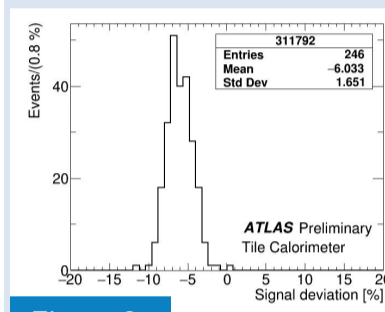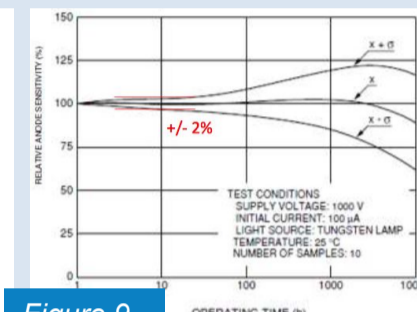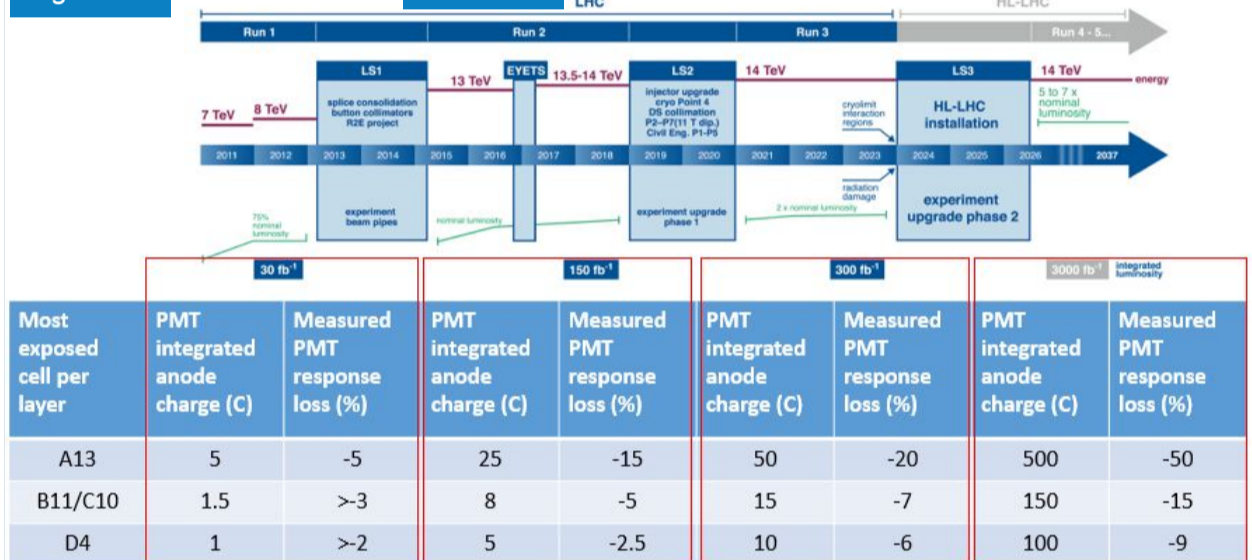

Figure 8

Figure 9

The response variation distribution of A13 cells (figure 8) and Hamamatsu's response over operating time (figure 9) are consistent

Most exposed cell per layer	PMT integrated anode charge (C)	Measured PMT response loss (%)	PMT integrated anode charge (C)	Measured PMT response loss (%)	PMT integrated anode charge (C)	Measured PMT response loss (%)	PMT integrated anode charge (C)	Measured PMT response loss (%)
A13	5	-5	25	-15	50	-20	500	-50
B11/C10	1.5	>-3	8	-5	15	-7	150	-15
D4	1	>-2	5	-2.5	10	-6	100	-9

- Time evolution PMT response indicates an exponential decay both for measurements of on-detector sample and test bench
- Assuming that the PMT response degrades exponentially and estimating the decay constant from the available measurement at the end of Run 1 and after 20 and 35 fb^{-1} in Run 2, it is possible to estimate response loss
- At the end of the HL-LHC era, more exposed PMTs will have lost 50% of their response
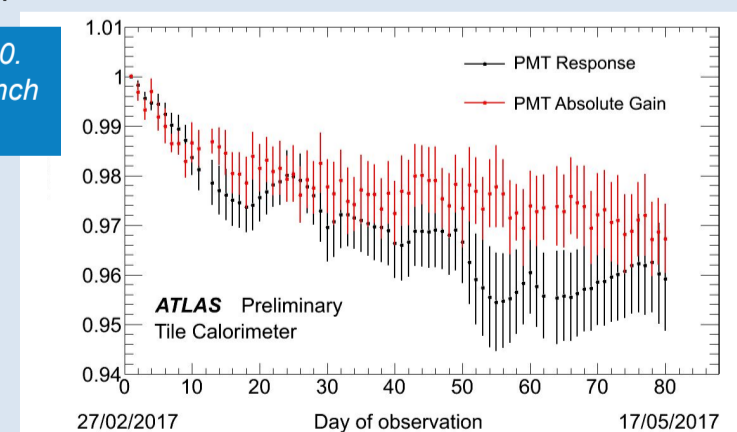
PMT Response and Absolute Gain

- Two methods were developed to measure the laser coherence constant "𝜘" in the formula to statistically measure the absolute gain G_i of a PMT_i

$$(1)\quad G_i = \frac{1}{e*f} * \frac{Var(q_i)}{<q_i>} - \frac{1}{e}k < q_i > \qquad \kappa = \frac{Cov(q_i, q_j)}{<q_i><q_j>} \qquad (2)\quad \kappa = \frac{\frac{var(q_n)}{<q_n>} - \frac{var(q_m)}{<q_m>}}{<q_n> - <q_m>}$$

- Covariance method (1) was chosen over energy scan method (2) to calculate 𝜘 and study gain stability of 9 PMTs in the Test Bench
- Method implemented for PMTs in A13 cells in the ATLAS detector

Figure 10. Test Bench stability

- The difference between PMT response and absolute gain is evident in both the ATLAS detector and test bench
- Difference can include several effects like cathode Q.E. loss, PMT window transparency degradation, and systematic effects (ex. aging of fibers)

Conclusions

- Test bench sees a measurable correlation between signal down-drift and absolute gain down-drift for irradiated PMTs from TileCal
- Thanks to improved sensitivity of the covariance method we are now able to see difference between drifts of absolute gain and of PMT response

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