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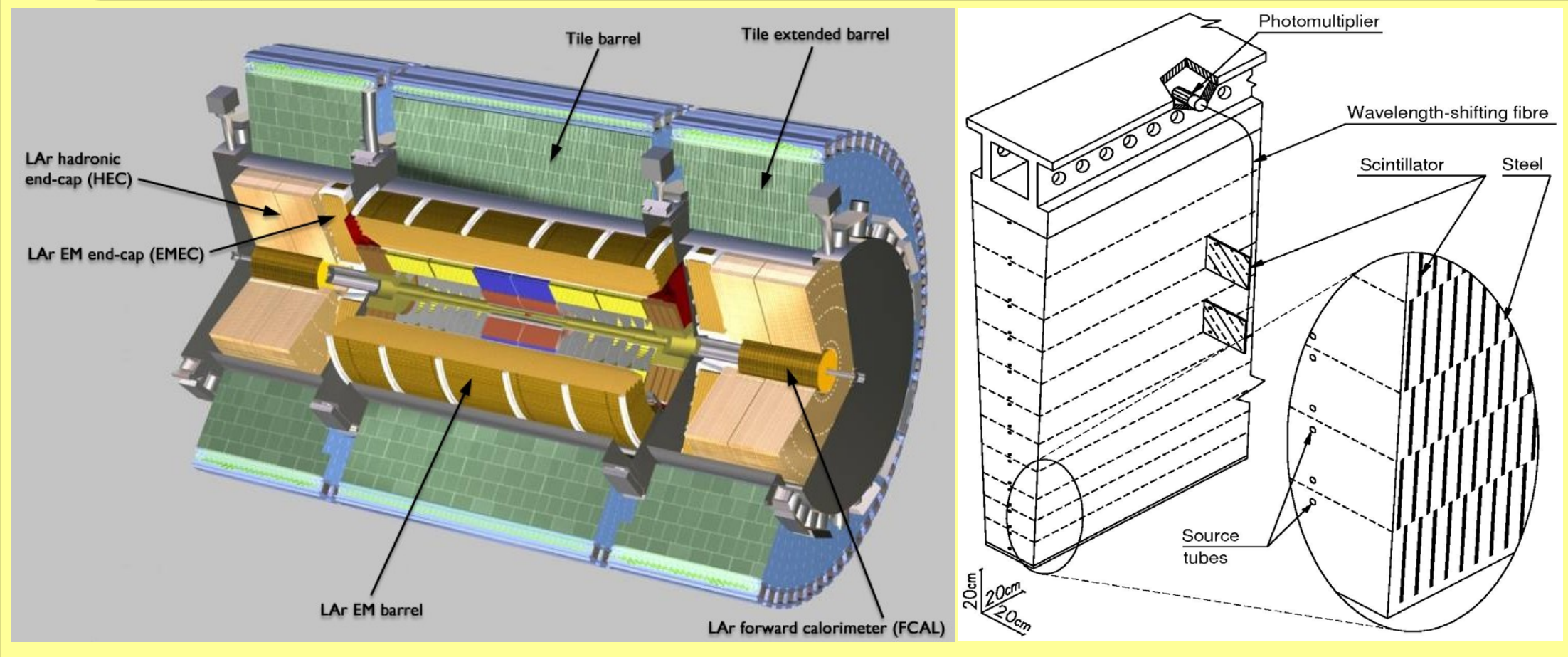
# Simulation and validation of the ATLAS Tile Calorimeter response

The International Conference on Instrumentation for Colliding Beam Physics (INSTR 2014), February 24 - March 1, 2014, Novosibirsk, Russia

## The ATLAS Tile Calorimeter



### Module layout

- *Each barrel is divided in 64 modules in φ*
- *Module consists of alternating layers of steel absorber and scintillating tiles*
- *Cell granularity is Δη x Δφ = 0.1 x 0.1 (0.2 x 0.1 in outermost radial sample - D)*
- *The granularity corresponds to trigger towers of calorimeters*
- *Each cell is read by two photomultiplier tubes (PMTs) from either side of the cell (except for some special cells) via wavelength shifting fibers.*

### Overview of the Tile Calorimeter of the ATLAS detector

- *Total length is 12 m, diameter - 8.5 m*
- *There are 3 cylindrical sections - Long Barrel and two Extended Barrels, over 5000 cells, 2 PMTs per cell*
- *Total thickness of TileCal is 7.4 $\lambda_{int}$ at η=0*
- *Three radial samplings A, BC, D correspond to 1.5, 4.1, 1.8 $\lambda_{int}$ in Long Barrel and 1.5, 2.6, 3.3 $\lambda_{int}$ in Extended Barrel*
- *TileCal cover the pseudo-rapidity region |η| < 1.7*
- *Design resolution of TileCal for jets is: $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ (E in GeV)*

- *The cell energy is the sum of the energy measured in the two channels. The double readout reduces the dependence on the light attenuation in the scintillator and improves the response uniformity.*
- *The readout electronics (including the PMTs) is housed at the outer radius of the calorimeter (in Girder).*

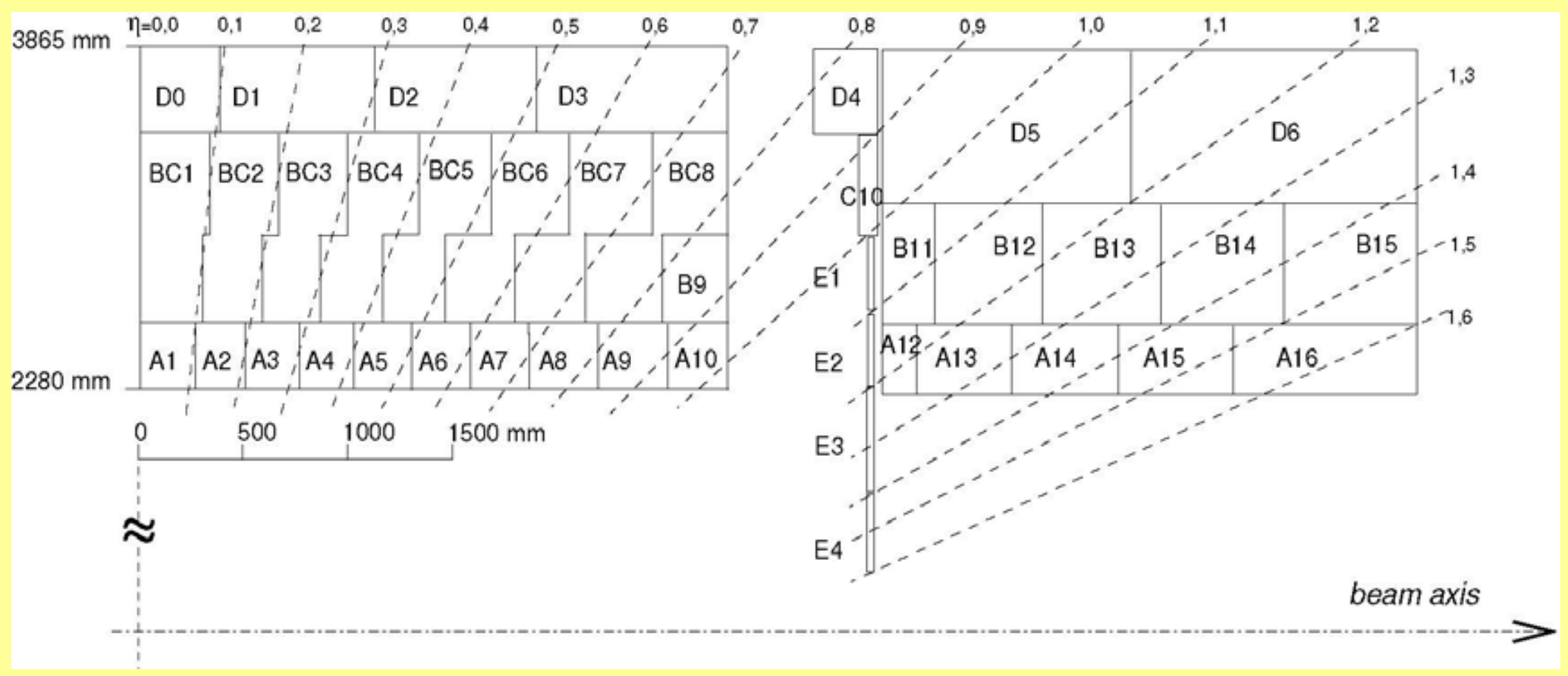
## Simulation of the ATLAS Tile Calorimeter

### Ordinary Geant4 simulation

*The passage of the particle through the ATLAS detector in the Geant4 simulation is characterized by hits. Each hit is defined by the energy deposition, time and its position. We have information only from the sensitive material of the detector in the real experiment. The sensitive part of the TileCal is scintillator and therefore Birk saturation law is applied to every Geant4 hit before adding this hit energy to total energy. When the simulation is finished (hits are collected and stored), the next step that follows is the digitization.*

### Geant4 simulation for cosmic muons

*Simulation of cosmic muons is slightly different from simulation of pp collisions. In particular, internal time of Geant4 hits in the calorimeter can be arbitrary value - not few nanoseconds, but hundreds of nanoseconds (time to go from the earth surface to the detector in the pit) and special precautions have to be made in order to collect and to reconstruct those hits properly.*



### TileCal segmentation over Cells

- *The η, φ and radial segmentation defines the three dimensional cells in TileCal.*
- *Half of the central (Long) Barrel (on the left) and Extended Barrel (right) are on the Figure.*
- *Geometry is not completely symmetric, there are cells with special shape, asymmetric inactive material etc.*
- *All currently known geometric details are carefully described in the MC geometry model.*

## TileCal simulations with calibration hits

### TileCal simulations with calibration hits

*Calibration hits allow us to record not only energy deposited in the scintillator, but also in the non-sensitive parts of the TileCal detector. Energy in the event is divided in electromagnetic, non-electromagnetic, invisible and escaped components. By definition the sampling calorimeter consists of Active and Inactive Materials, but material of support saddle, girder and extra iron structures at outer radius of the calorimeter, readout electronics inside the girder, cables, and other services called Dead Material. It gives us very useful information for the energy calibration studies:*

- *calibration of each ATLAS sub-detector and verification of its geometry*
- *understanding of full energy balance of specific event types, for example evaluation of "missing visible energy" which can be caused by energy deposits in dead materials, and by leakage, and by energy flow at |η| > 5.0*
- *identification of full energy associated with each jet in multi-jet events*
- *calibration hits were used also in determination of the PMT response as a function of the coordinates of the energy deposition point (U-shape) and the Sampling Fraction determination*

### Simulation of TileCal standalone TestBeam

- *It is possible to simulate TileCal standalone TestBeams (3 barrel modules or 2 barrels and 2 extended barrels) as well as Combined Test Beam of 2004.*
- *Particularly it is useful for the Sampling Fraction calculation.*

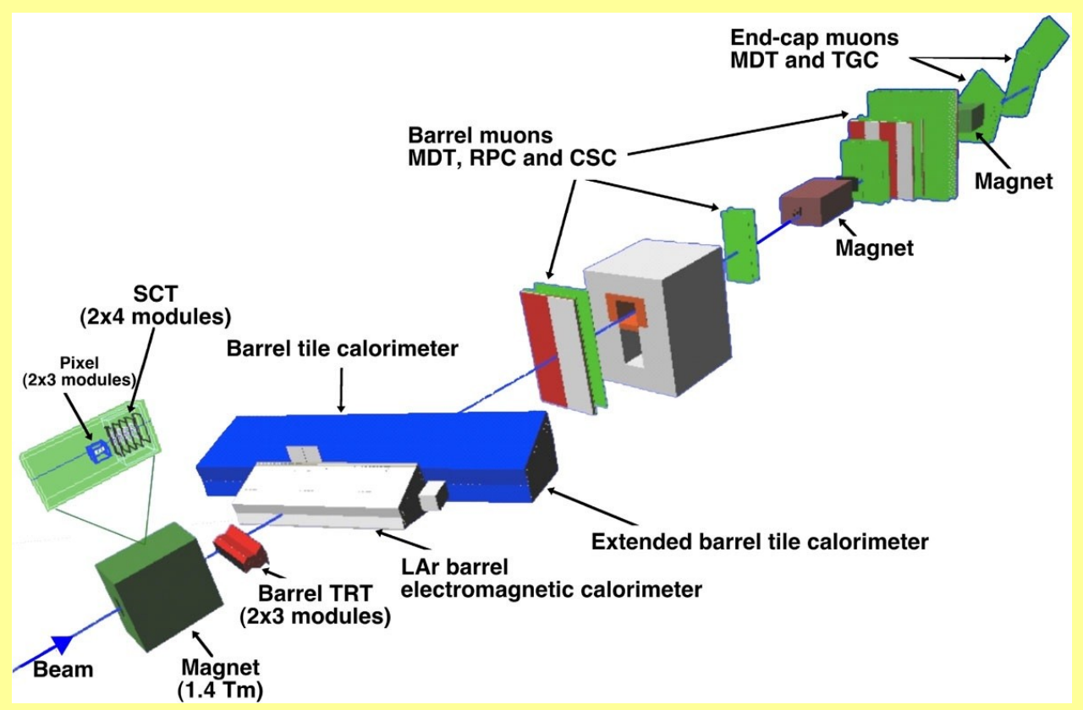
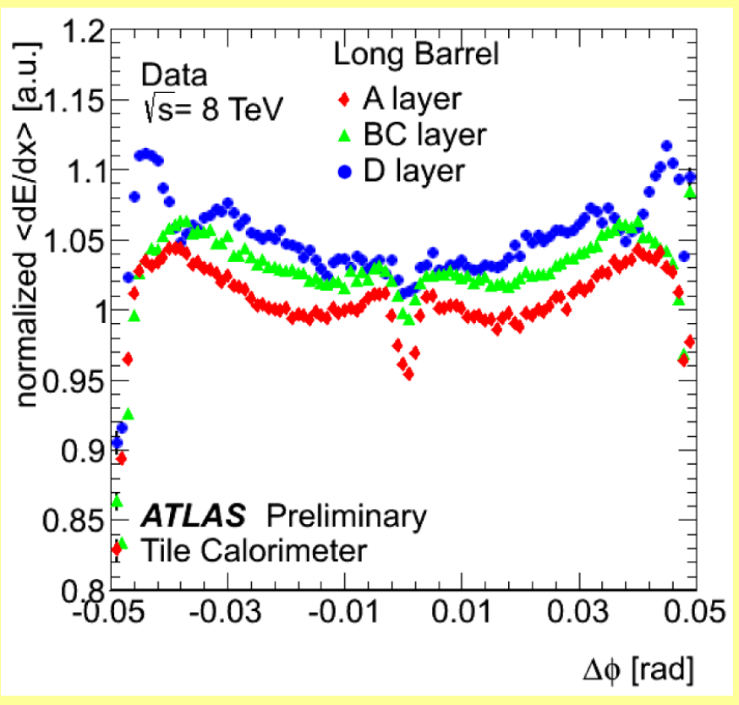
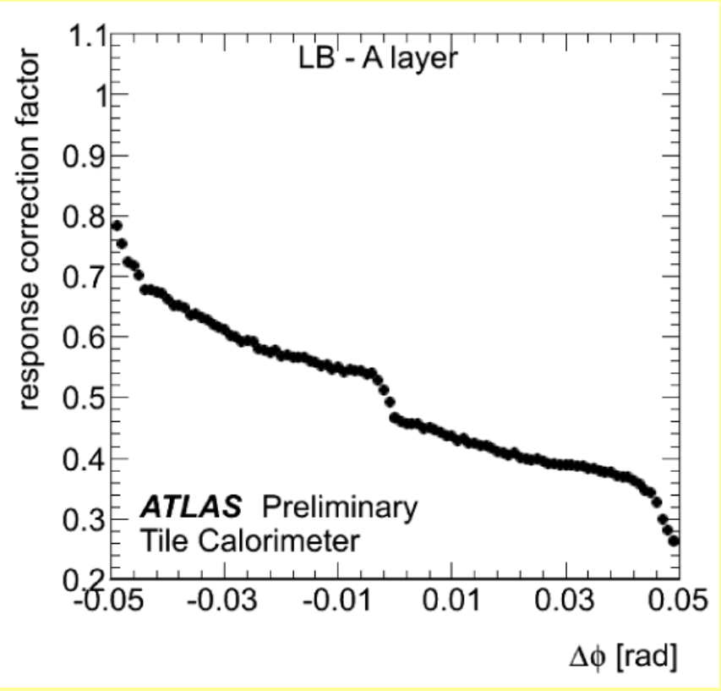


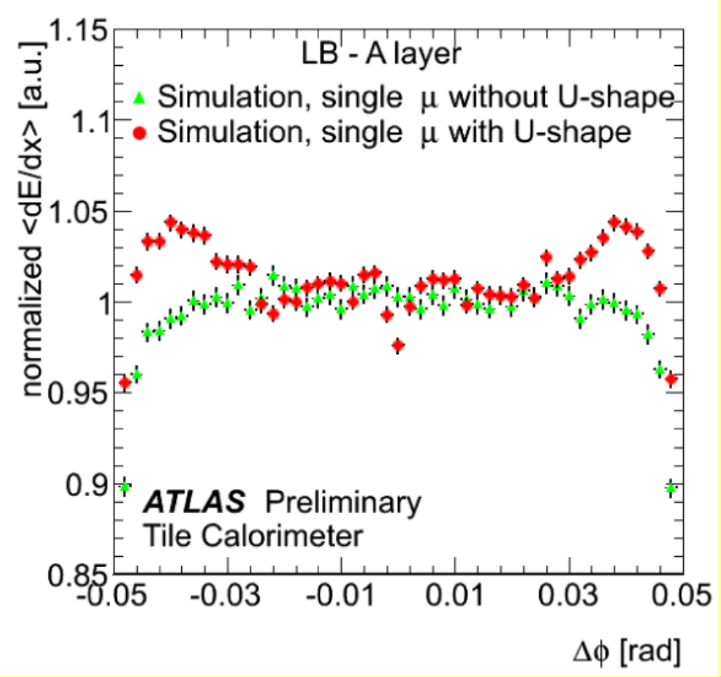
*Figure: The setup scheme of the Combined Test Beam of 2004.*

## Cell response vs. the particle impact point



- *Left: The dependences of the scintillating tiles response on the particle impact point (U-shape) were obtained in measurement of <dE/dx> value of muons produced in leptonic decays of W→μν. Δφ is the azimuthal angle difference between the muon track impact point and the center of the cell.*
- *The profiles were obtained for the cells of the three radial layers of the TileCal Long end Extended Barrels.*
- *The criteria applied to select well reconstructed tracks are: Nmuons=1, $p_T$ >15 GeV, $M_T$ >40 GeV, missing $E_T$ >25 GeV, $p_T$ <1 GeV in cone of ΔR=0.4 around track, $E_{LAr}$ <3 GeV in cone of ΔR=0.4, 20<$p_\mu$<100 GeV, ΔE>60 MeV and Δx>15 cm in the cell.*
- *Right-up: The response correction factors for PMTs were obtained from comparison of response in simulated W→μν and single muon events with collision data at 8 TeV (left). Nonlinear form of the dependence originates from the non-uniformity of light yield over the volume of the scintillating tiles. Look-up tables for each PMT of all barrels and layers were introduced in the ATLAS full simulation in order to reproduce the U-shape.*
- *Right-down: The red (green ) dots distributions were obtained with (without) U-shape in the MC simulation. The difference up to 6% is observed in Long Barrel, A-layer. It can achieve 10% in other layers and barrels. On the contrary, the collision data (left, red) agree very well (within 1%) with MC with U-shape included.*





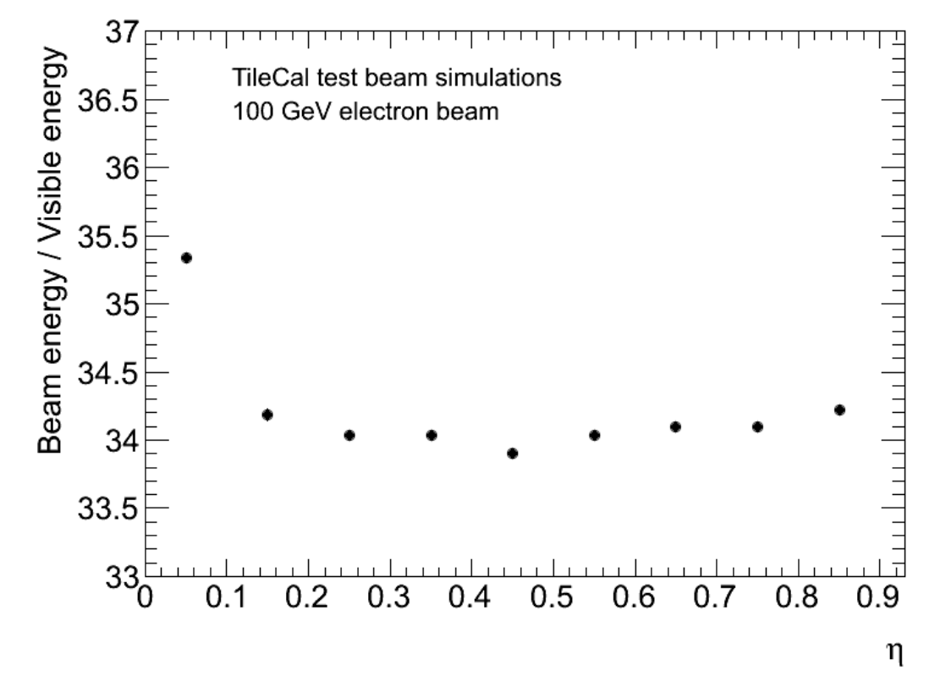
## Sampling Fraction calculation

- *The Sampling Fraction (SF) is the conversion factor between the energy released in the scintillators and the total energy deposited in the TileCal cells*
- *Output from the simulation (hit level) – energy released in the active material $E_{sci}$*
- *Cell energy is calculated as energy in the scintillators multiplied by a constant value 1/SF*
- *If the invisible energy and energy leakage are neglected, the sampling fraction is $E_{beam}/E_{sci}$ = 1/SF*

### Single particle simulation as in TestBeam

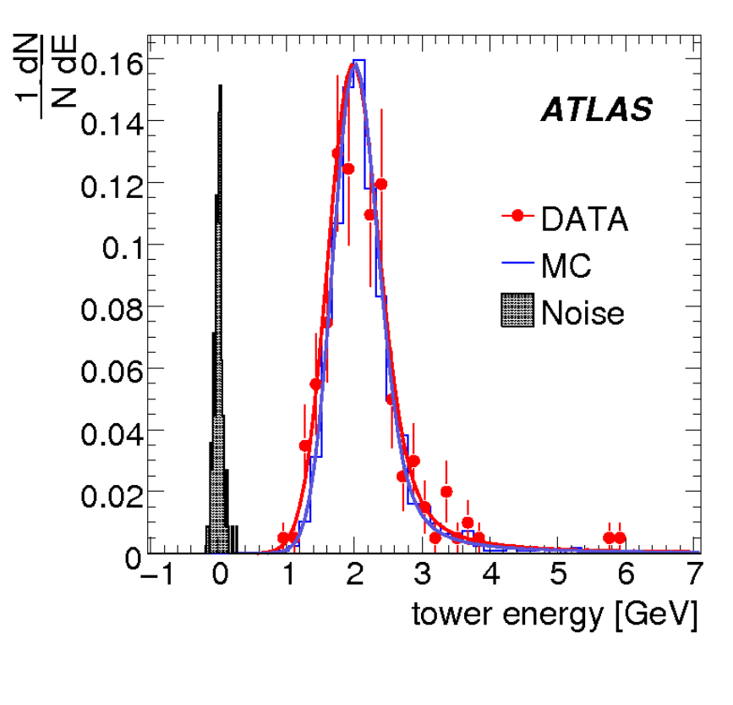
- *Electron beams at 5, 20 and 100 GeV were simulated in eta-projective geometry (0.05<|η|<0.85)*
- *The single electron samples were also simulated at 90 degrees. 1/SF is in the Table below*

| $E_{beam}$ [GeV] | η: 0.25-0.75 | 90 degrees | η & 90° average |
|---|---|---|---|
| 5 | 34.341 ± 0.018 | 33.934 ± 0.019 | 34.14 ± 0.20 |
| 20 | 34.140 ± 0.011 | 33.494 ± 0.009 | 33.82 ± 0.32 |
| 100 | 34.045 ± 0.005 | 33.356 ± 0.004 | 33.70 ±0.34 |

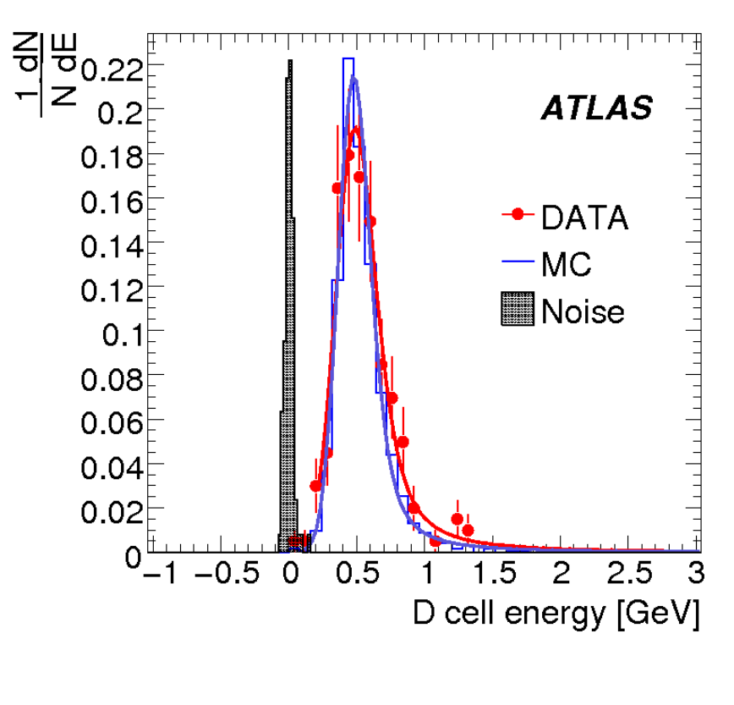


- *The sampling fraction is almost constant in the pseudo-rapidity region between 0.15 and 0.85*
- *The constant 1/SF = 34.0 used in the Monte Carlo simulations is the sampling fraction at η = 0.35*
- *The pseudo-rapidity of 0.35 corresponds to the test beam angle where the electromagnetic scale in TileCal is defined.*
- *The increase of the 1/SF at small η = 0.05 can be qualitatively explained by the periodic scintillator/iron structure of the TileCal. The area in the scintillators touched by the narrow EM shower is smaller at low angles.*
- *Value of 1/SF slightly depends on energy. The maximum of EM shower is shifted to more depth at higher beam energy. Fraction of energy released in iron front plate of the TileCal becomes smaller and fraction of energy released in scintillator increases a bit.*
- *The systematic error of 1/SF obtained in the MC simulation is 0.8%.*

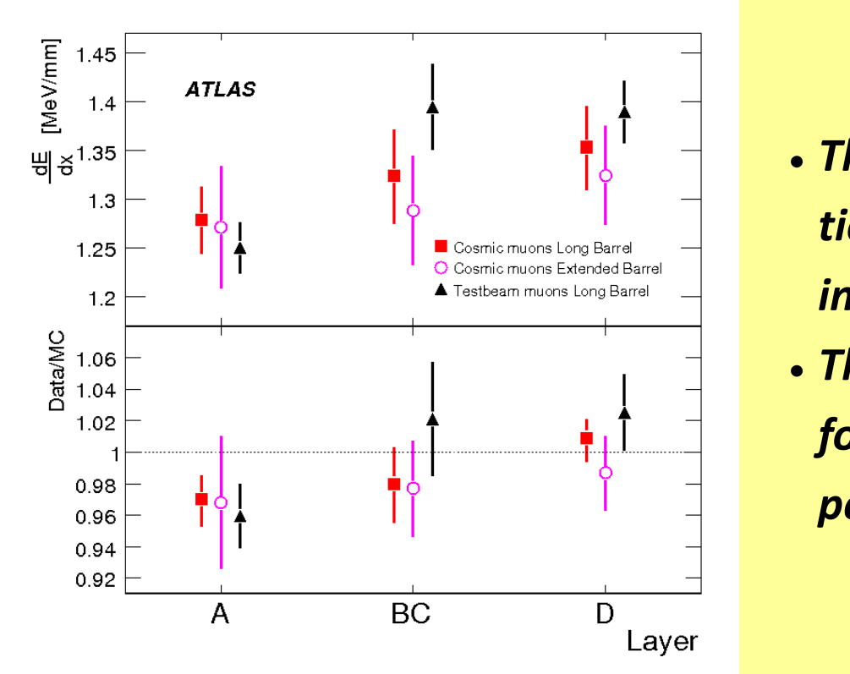
## Validation of EM scale with muons in ATLAS



- *Example of the muon signal and corresponding noise for projective cosmic muons entering the barrel modules at 0.3 < |η| < 0.4.*
- *Top and bottom modules are treated separately.*
- *Left: the total energy summed up over selected cells.*
- *Right: the similar distribution for last radial compartment that can be eventually used to assist in muon identification.*
- *The signal (red) comes from the cosmic muon data sample, the corresponding noise (black) is obtained with the random trigger sample.*

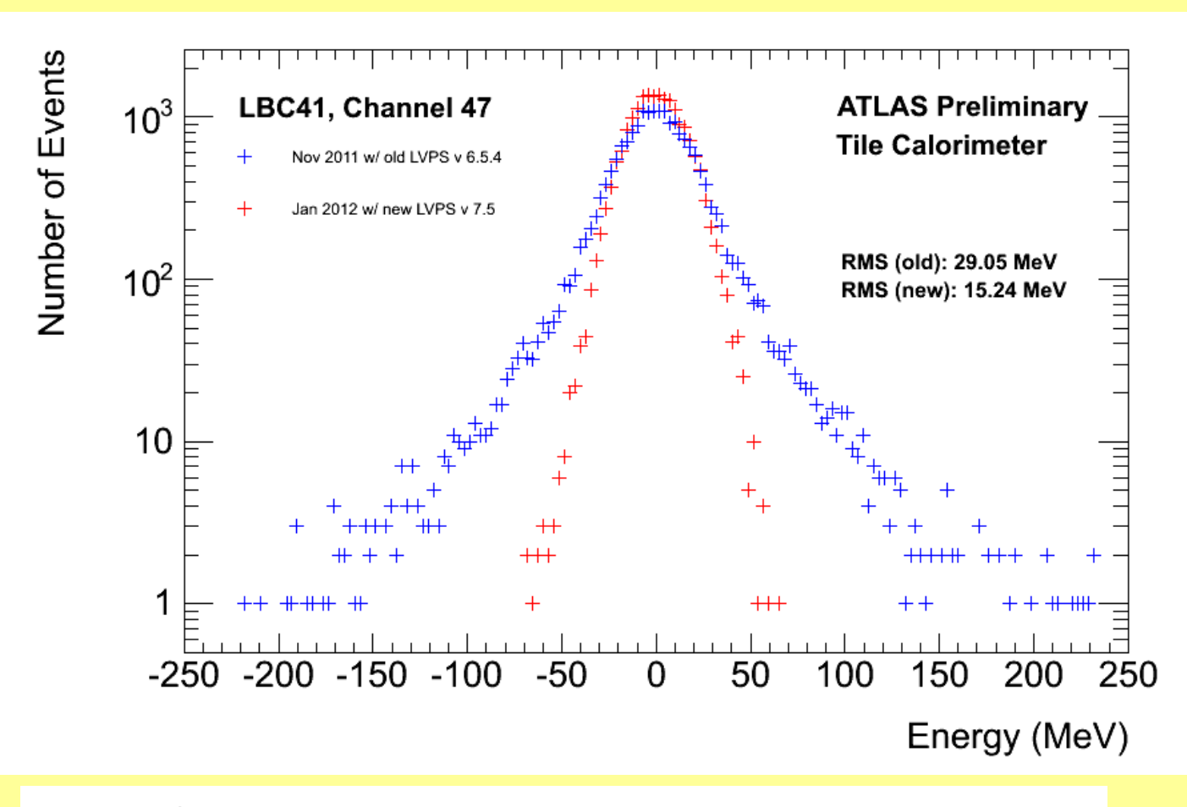


- *The truncated mean of the dE/dx for cosmic and testbeam muons shown per radial compartment and, at the bottom, compared to Monte Carlo.*
- *For the cosmic muon data, the results were obtained for modules at the bottom part of the calorimeter.*

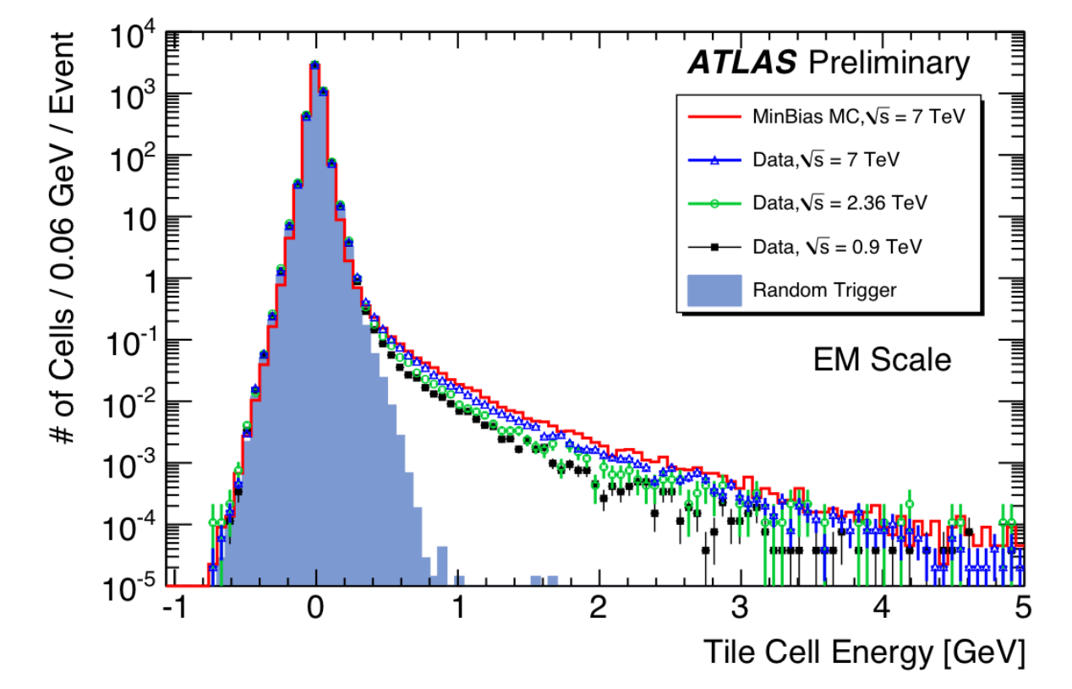


- *The error bars shown combine both statistical and systematic uncertainty summed in quadrature.*
- *The results show that reconstructed dE/dx for MC and data are compatible to a few percent level*

## Electronic Noise

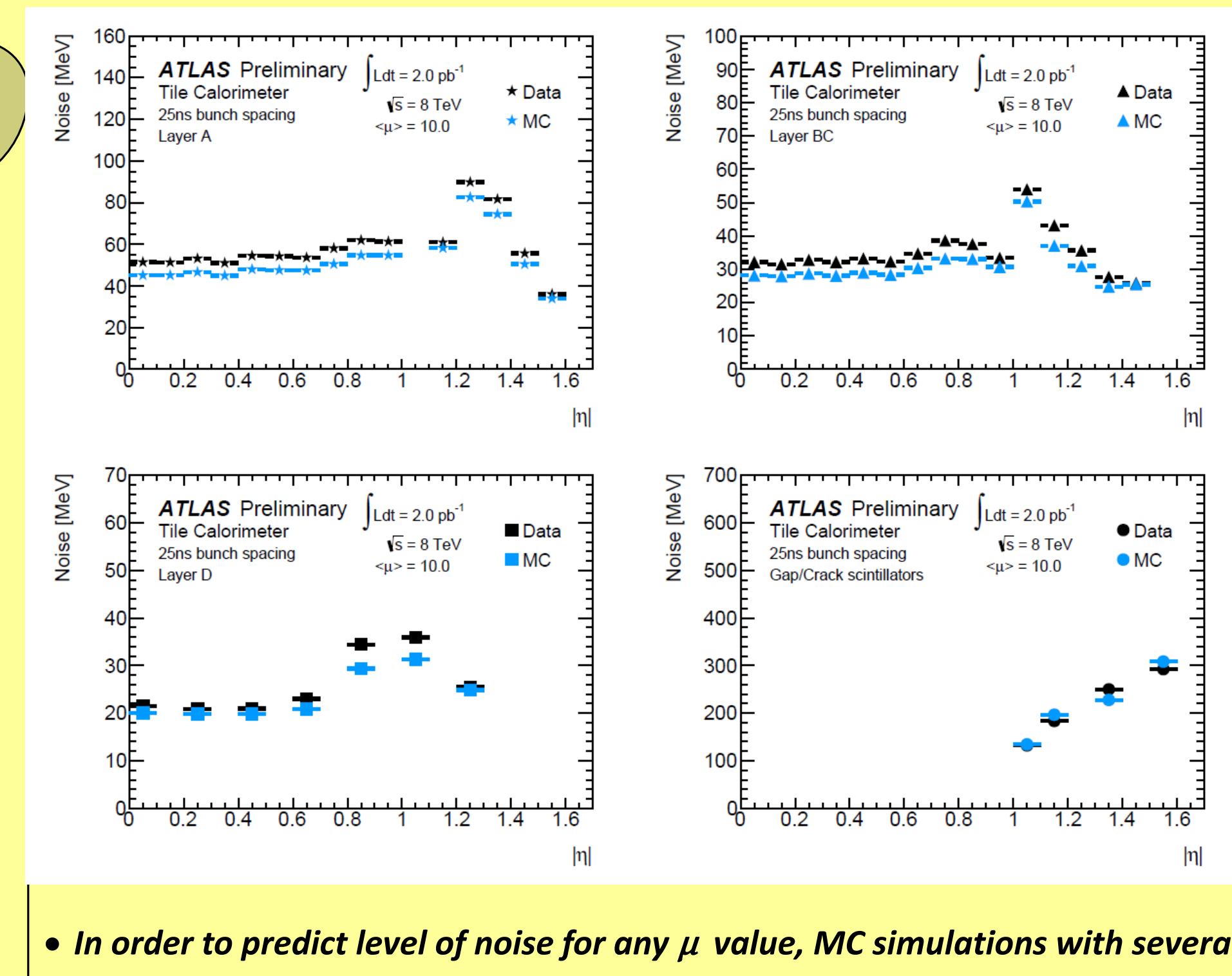


- *Electronic noise in TileCal is not Gaussian. We approximated it with two Gaussians. Mainly, it comes from the Low Voltage Power Supply (LVPS) providing power for front-end electronic.*
- *A comparison between the reconstructed energy in 100k events in two high statistics pedestal runs (run 192130 - 2011 and run 195843 -2012), for module LBC41, channel 47, a previously very noisy channel.*
- *Reconstruction of energy in the events is performed using the Non-iterative Optimal Filtering method. LBC41 had its LVPS changed from version 6.5.4 to version 7.5 in winter 2011-2012. The RMS of the noise distribution for the channel goes down by almost a factor 2 after changing LVPS. Both noise cases are implemented in Monte Carlo.*
- *After the 2013 – 2014 LHC shutdown, all modules will be equipped with new LVPS showing almost perfect Gaussian noise and improved correlated noise too.*



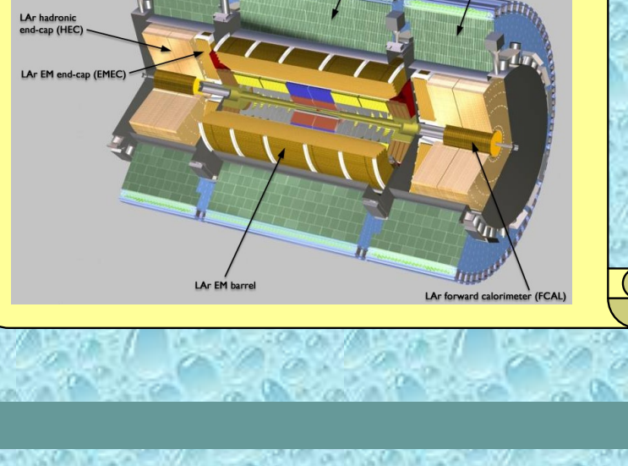
- *Energy of the TileCal cells. The distributions from collision data at 7 TeV, 2.36 TeV, and 0.9 TeV are superimposed with Pythia minimum bias Monte Carlo and randomly triggered events. Each distribution is normalized by the number of events.*
- *Negative side demonstrates good agreement with MC noise description using the Double Gaussian description.*

## Noise with pileup



- *Realistic description of the total noise (Ntot) is mandatory for the jet reconstruction and trigger.*
- *The noise distribution of different Tilecal cells is represented as a function of |η| for zero bias run 216416 of 2012 at a centre-of-mass energy of 8 TeV with a bunch spacing ΔT = 25 ns and an average number of interactions <μ> = 10.0 per bunch crossing.*
- *The Monte Carlo simulation was reweighted to the average number of interactions in data.*
- *The noise was estimated as the standard deviation of the measured cell energy distribution.*
- *The histograms show the results obtained for the cells of different layers of TileCal (A, BC, D, Special Cells).*
- *Overall, noise in the MC simulation agree with the data within ±20%*
- *Pileup is characterized by the average number of minibias collisions μ overlaid to the hard scattering event.*

- *In order to predict level of noise for any μ value, MC simulations with several fixed μ values were performed and total noise in every cell was estimated as $Ntot = \sqrt{ElectronicNoise^2 + PileupNoise^2}$. Where ElectronicNoise doesn't depend on μ and PileupNoise term scales as $\sqrt{\mu}$. The same formula is used In reconstruction.*
- *Pileup noise is estimated as PileupNoise = B x $\sqrt{L}$, where $L$ is luminosity in $10^{33}$ unit, B is Pileup Noise at luminosity = $10^{33}$ $cm^{-2}$ $s^{-1}$.*



JINR

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