# The fast calorimeter simulation FastCaloSim for the ATLAS detector

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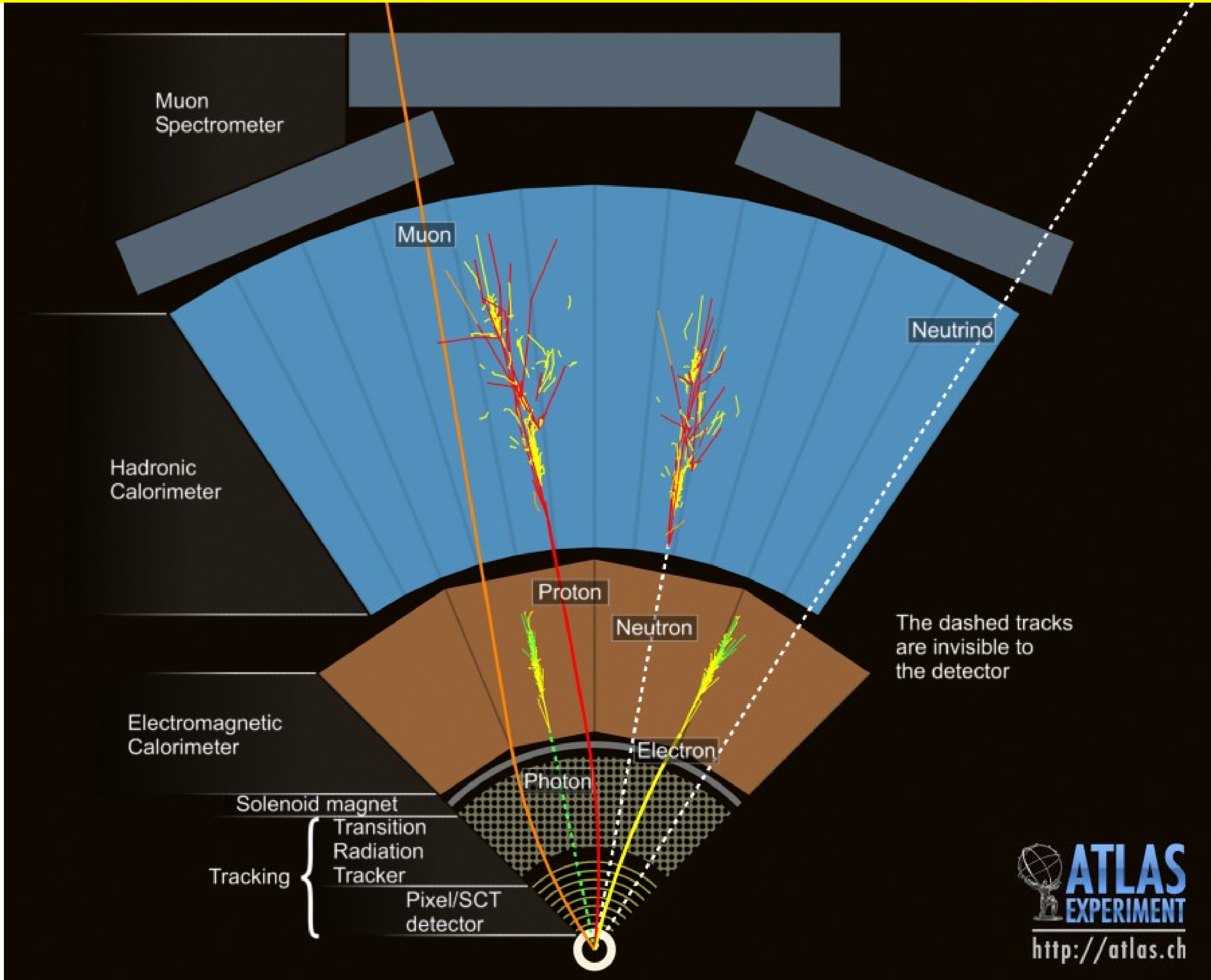
# Complexity of the full simulation

- ATLAS uses Geant 4
- The progress of each particle through the detector is tracked in small steps
- A large number of material interaction processes is simulated
- The shower of secondary particles is simulated down to ~ MeV energies
- Particle energy loss in sensitive detector material is recorded and processed further

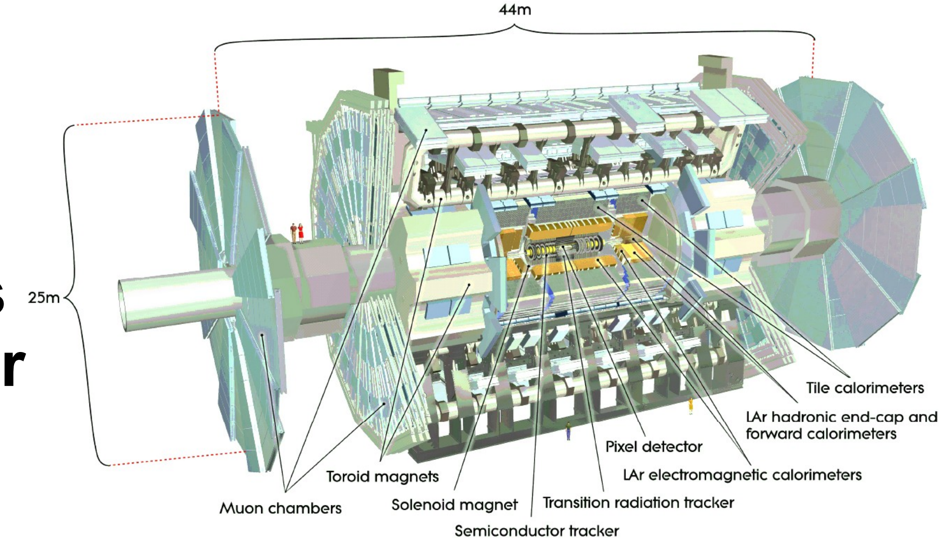



For tt events (~500 part./event)

| QGSP_BERT | Steps | Hits in SD | Sec. above 50 MeV | Sec. above 1 GeV |
|---|---|---|---|---|
| Inner Detector | $2.13 \times 10^6$ | $1.98 \times 10^5$ | 1,450 | 269 |
| Calorimetry | $3.93 \times 10^7$ | $1.36 \times 10^7$ | 40,100 | 2,170 |
| Muon System | $2.69 \times 10^6$ | 1,285 | 8,210 | 385 |
| Total ATLAS | $4.41 \times 10^7$ | $1.38 \times 10^7$ | 49,700 | 2,820 |

# The ATLAS detector geometry

- **The ATLAS detector is big**
- **The ATLAS detector is complicated**
- **Everything needs to be simulated, including cables and support structures**
- **Aim: The simulated and the real detector should be as identical as possible !**



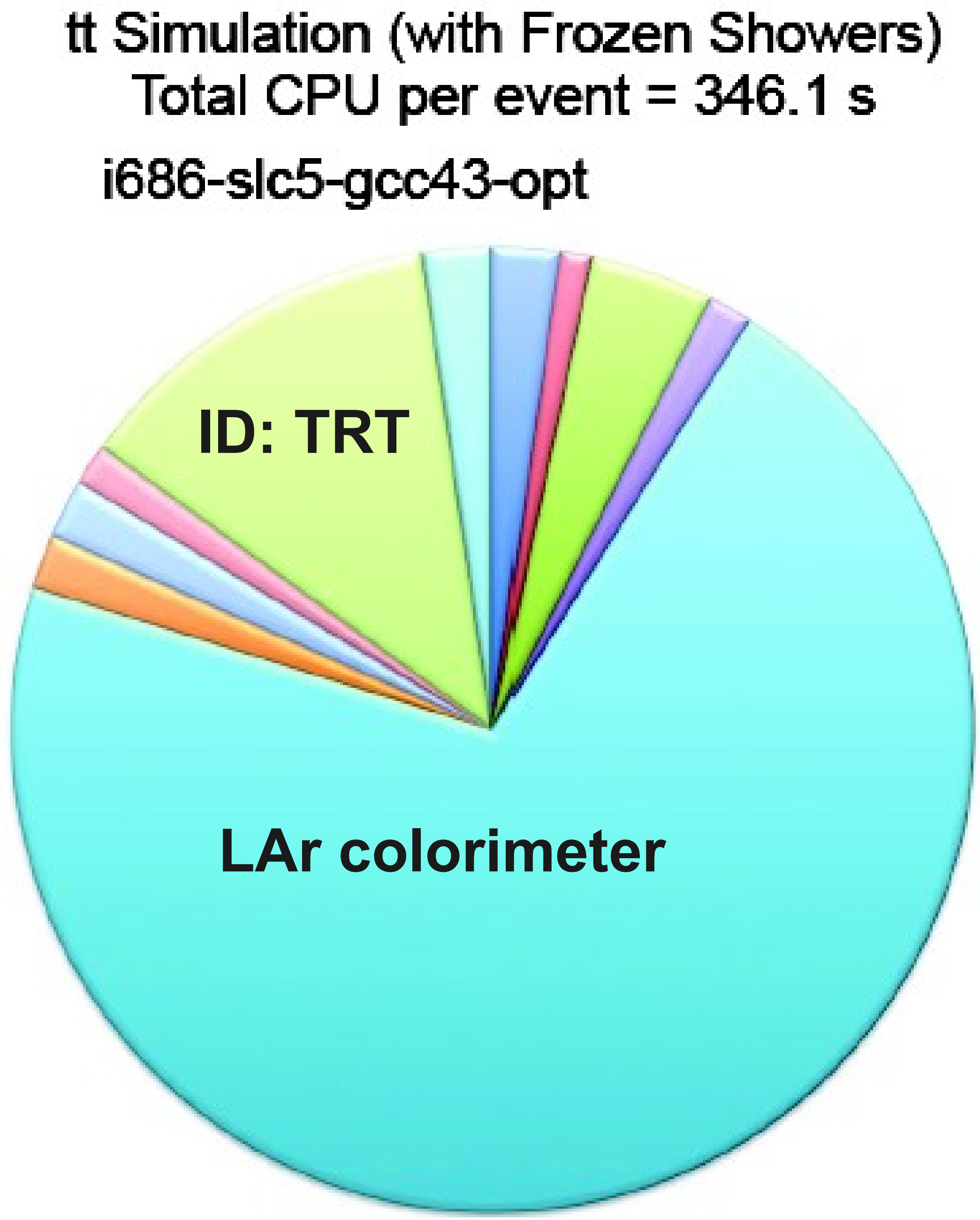

**Number of virtual detector parts**

| **Subsystem** | **Materials** | **Solids** | **Logical Vol.** | **Physical Vol.** | **Total Vol.** |
|---|---|---|---|---|---|
| Beampipe | 43 | 195 | 152 | 514 | 514 |
| BCM | 40 | 131 | 91 | 453 | 453 |
| Pixel | 121 | 7,290 | 8,133 | 8,825 | 16,158 |
| SCT | 130 | 1,297 | 9,403 | 44,156 | 52,414 |
| TRT | 68 | 300 | 357 | 4,034 | 1,756,219 |
| LAr Calorimetry | 68 | 674 | 639 | 106,519 | 506,484 |
| Tile Calorimetry | 8 | 51,694 | 35,227 | 75,745 | 1,050,977 |
| Inner Detector | 243 | 12,501 | 18,440 | 56,838 | 1,824,614 |
| Calorimetry | 73 | 52,366 | 35,864 | 182,262 | 1,557,459 |
| Muon System | 22 | 33,594 | 9,467 | 76,945 | 1,424,768 |
| **ATLAS TOTAL** | $\boxed{327}$ | 98,459 | 63,769 | 316,043 | $\boxed{4,806,839}$ |

# Full simulation speed

- The ATLAS full simulation is very accurate, but unfortunately also rather slow
- Average of ~10min/event
- Frozen showers in the forward calorimeters help, but still ~70% of the time is spend in the calorimeter simulation

- In order to produce billions of MC events, a much faster simulation of the calorimeter is needed
- However, simple smearing of truth is unfortunately not sufficient either



# ATLAS detector simulation flavors

- Full Simulation (Geant 4)
  - All detectors in full simulation; standard ATLAS reconstruction
- Fast Geant 4 Simulation
  - All detectors in full simulation; use of partial parametrization/frozen showers for EM processes within G4; standard ATLAS reconstruction
- **Atlfast-II**
  - **Combination of Geant 4 ID+Muon simulation and FastCaloSim for the calo; standard ATLAS reconstruction**
- Atlfast-IIF (with ISF)
  - All detectors in fast simulation; standard ATLAS reconstruction
- Atlfast-I
  - Combination of simulation and reconstruction in one step, based mostly on generator information and smearing functions

Simulation times in kSI2K seconds

| Sample | Full Sim | Fast G4 Sim | ATLFAST-II | ATLFAST-IIF | ATLFAST-I |
|---|---|---|---|---|---|
| Minimum Bias | 551. | 246. | 31.2 | 2.13 | 0.029 |
| $t\bar{t}$ | 1990 | 757. | 101. | 7.41 | 0.097 |
| Jets | 2640 | 832. | 93.6 | 7.68 | 0.084 |
| Photon and jets | 2850 | 639. | 71.4 | 5.67 | 0.063 |
| $W^{\pm} \rightarrow e^{\pm}\nu_e$ | 1150 | 447. | 57.0 | 4.09 | 0.050 |
| $W^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$ | 1030 | 438. | 55.1 | 4.13 | 0.047 |
| Heavy ion | 56,000 | 21,700 | 3050 | 203 | 5.56 |

# Where is a calorimeter simulation needed

True, isolated electron

True, isolated photon

Can use truth + data efficiency measurements instead of simulation

Electrons and photons with high event activity close by

Need some calorimeter simulation for isolation effects

Jets

Hadronic taus

Need calorimeter simulation for clustering effects and detector response corrections

MET

Jet sub-structure

Jet → electron/photon fakes

Need calorimeter simulation for the understanding of shower shape effects and low energy particle response corrections. Intrinsic calorimeter effects dominate

# Where is a calorimeter simulation needed

True, isolated electron

True, isolated photon

→ Can life without simulation to some degree. Truth smearing works well

Electrons and photons with high event activity close by

Jets

Hadronic taus

MET

→ Need at least a fast calorimeter simulation for any realistic analysis using these objects

Jet sub-structure

Jet → electron/photon fakes

→ Tough to get correct even for full simulation. Don't expect fast simulation to do better

# FastCaloSim requirements

True, isolated electron

True, isolated photon

Electrons and photons with high event activity close by

Jets

Hadronic taus

MET

Jet sub-structure

Jet → electron/photon fakes

Speed! Want to use FastCaloSim in a Hz level event simulation.
For the calorimeter this means:
~ ms per object
~ s per event
→ need a solution tailored to ATLAS

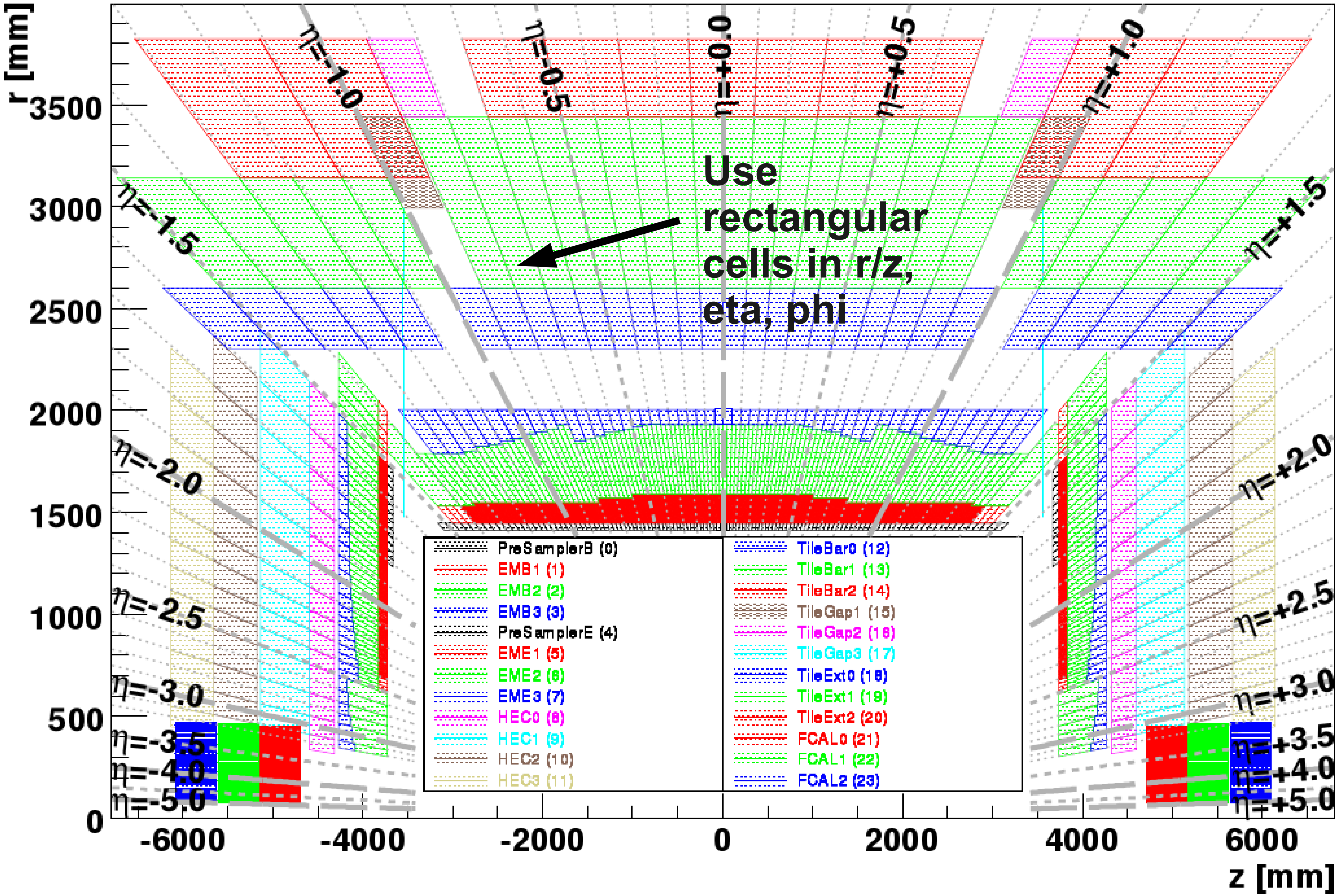
Focus to get these objects as good as possible.
MET most important as it is hardest to apply data-driven ad-hoc corrections to MET

# FastCaloSim

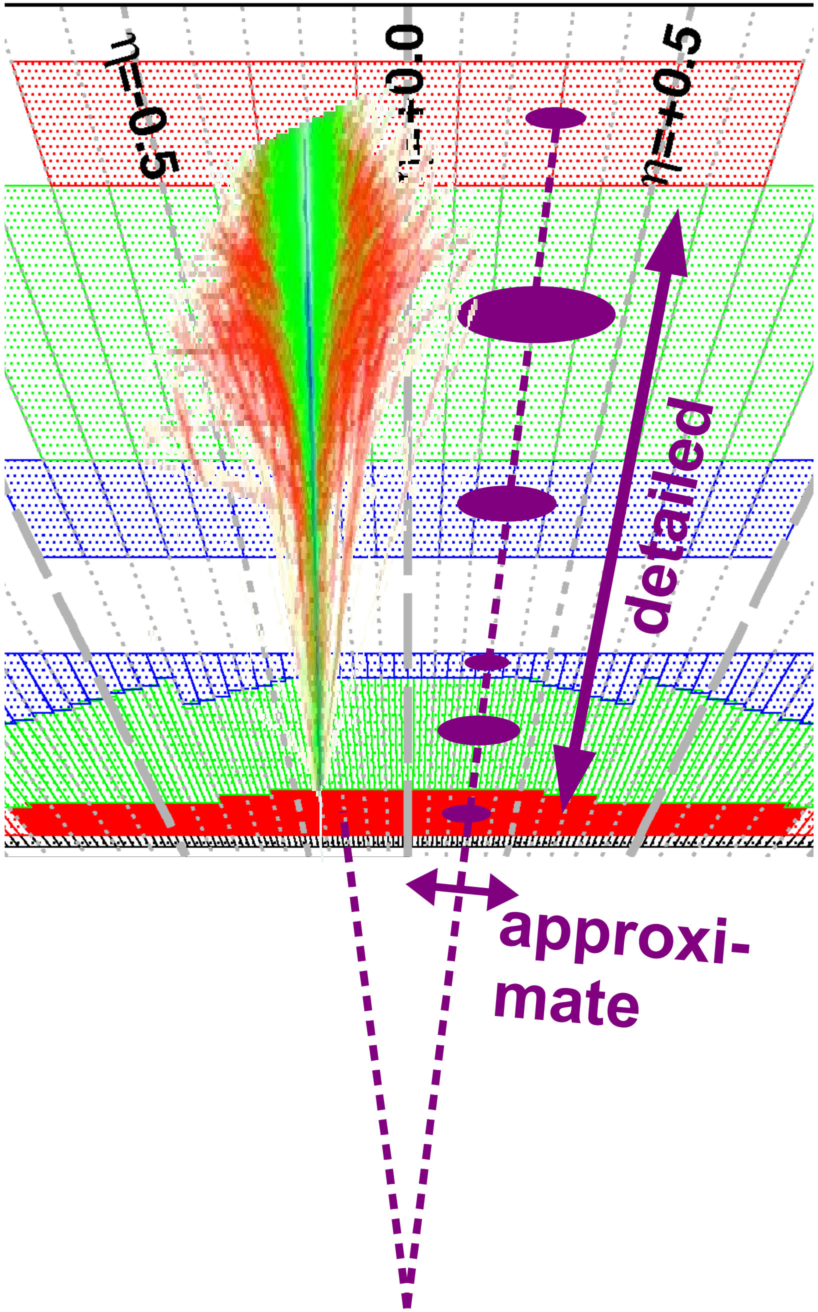
- **Parametrization of the calorimeter response for**
  - photons (used for photons and electrons)
  - charged pions (used for all hadrons)
  - The parametrization is based on the full G4 simulation using a fine E/η grid
- **Simulation of**
  - the total particle energy response
  - energy fractions in the calorimeter layers, including fluctuations and correlations
  - the average lateral particle shape
- **No simulation of**
  - Lateral shower shape fluctuations
  - Particle decays in the calorimeter ($\pi \rightarrow \mu$) and punch through
- **Residual differences**
  - To be reduced by data (or G4 MC) driven corrections applied to the reconstructed objects
  - Can also be be minimized by tuning FastCaloSim to data

- **Uses the same digitization+reconstruction as full simulation**

# Detector geometry in FastCaloSim



# Concept of FastCaloSim




## Full simulation

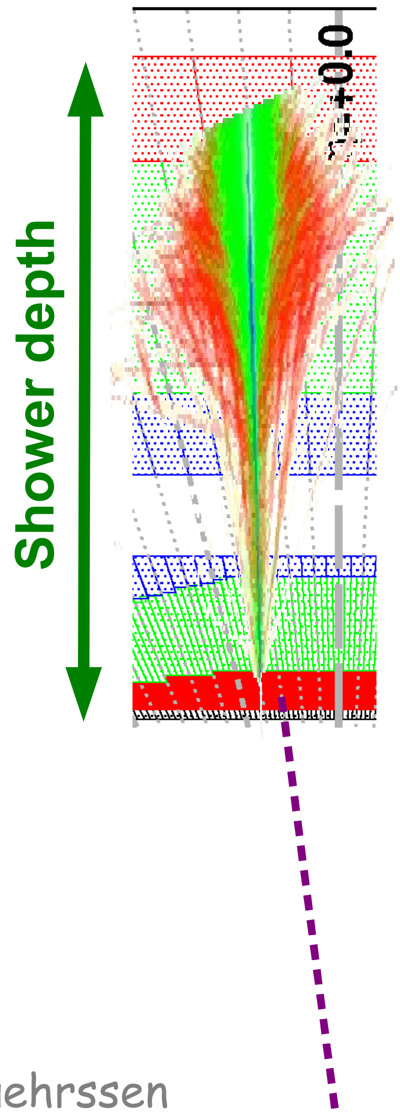
- Detector as built with all complications
- All physics processes for all primary and secondary particles.
- Tracking of shower development through the calorimeter in fine steps

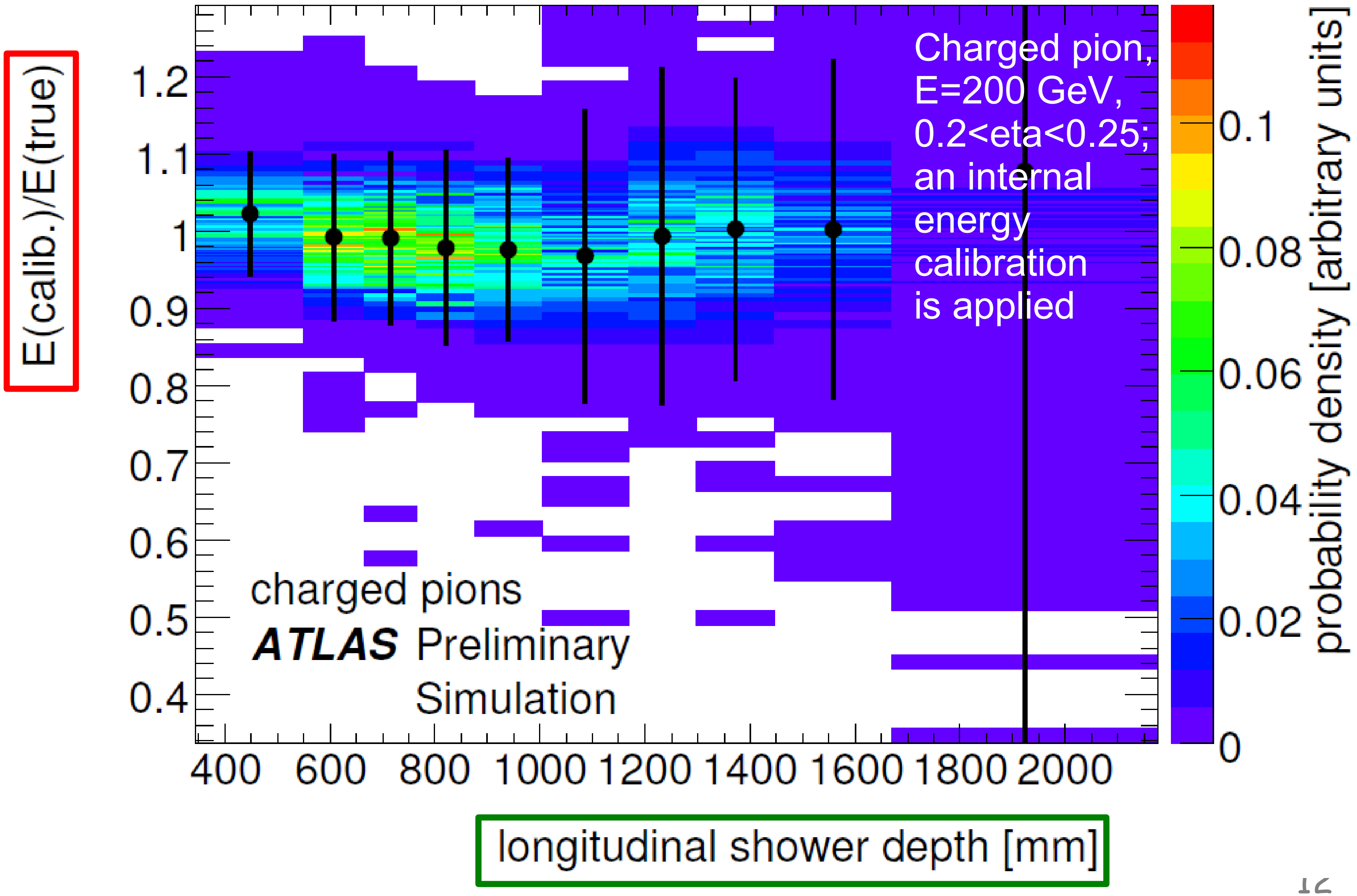
## FastCaloSim

- Simple reconstruction geometry with only ~185000 cells
- Energy and shape parametrization only for photons and charged pions. Parametrization derived from ~30M fully simulated single particle events
- Deposition of the particle energy in each calorimeter layer in one step.

# Particle energy simulation – brute force

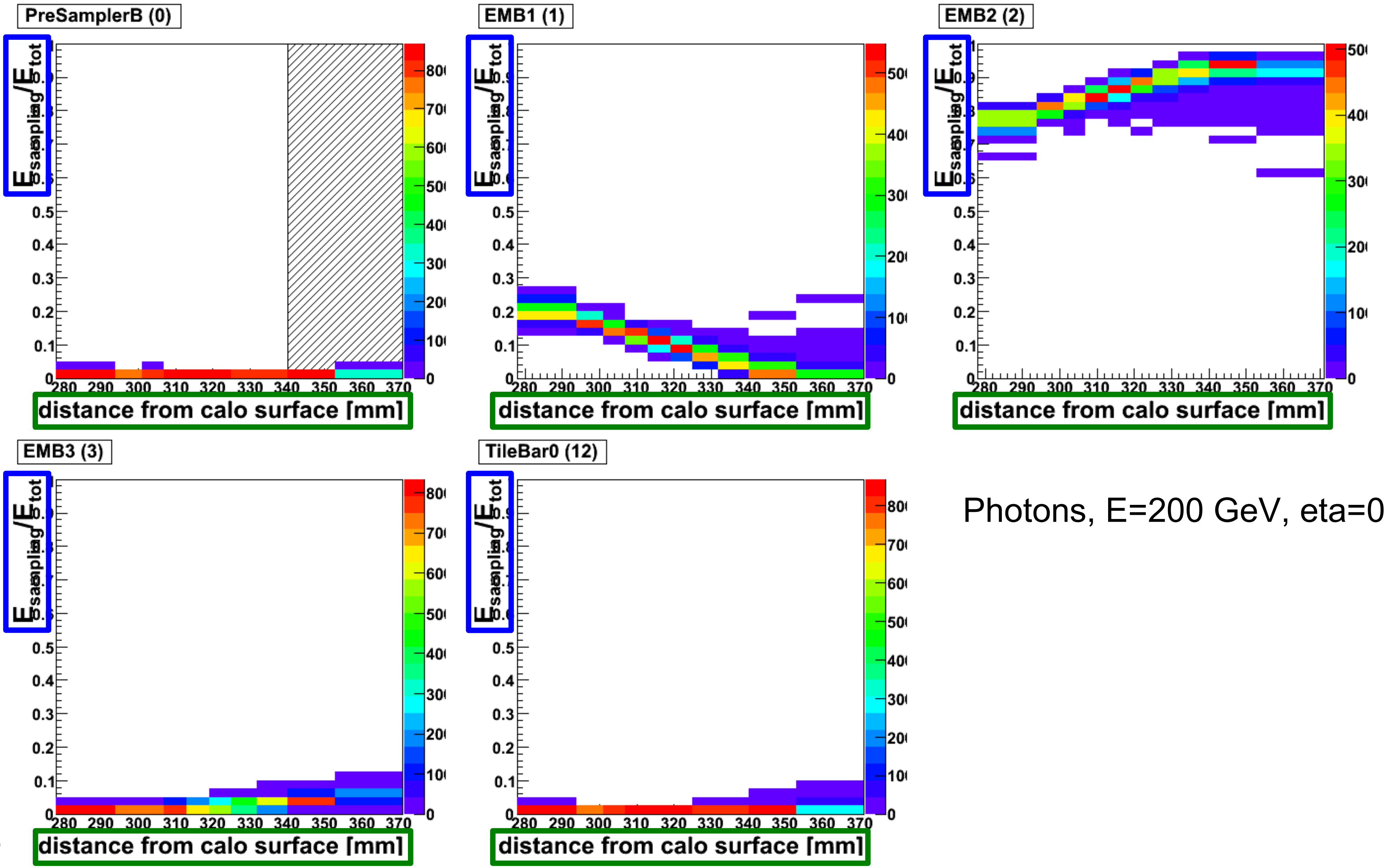
- 1st priority: correct simulation of the total energy
- 2nd priority: correct simulation of the longitudinal shower depth
- Store a 2D histogram of both for a large range of energy and eta points and use these histograms in the simulation



# Particle energy simulation – brute force

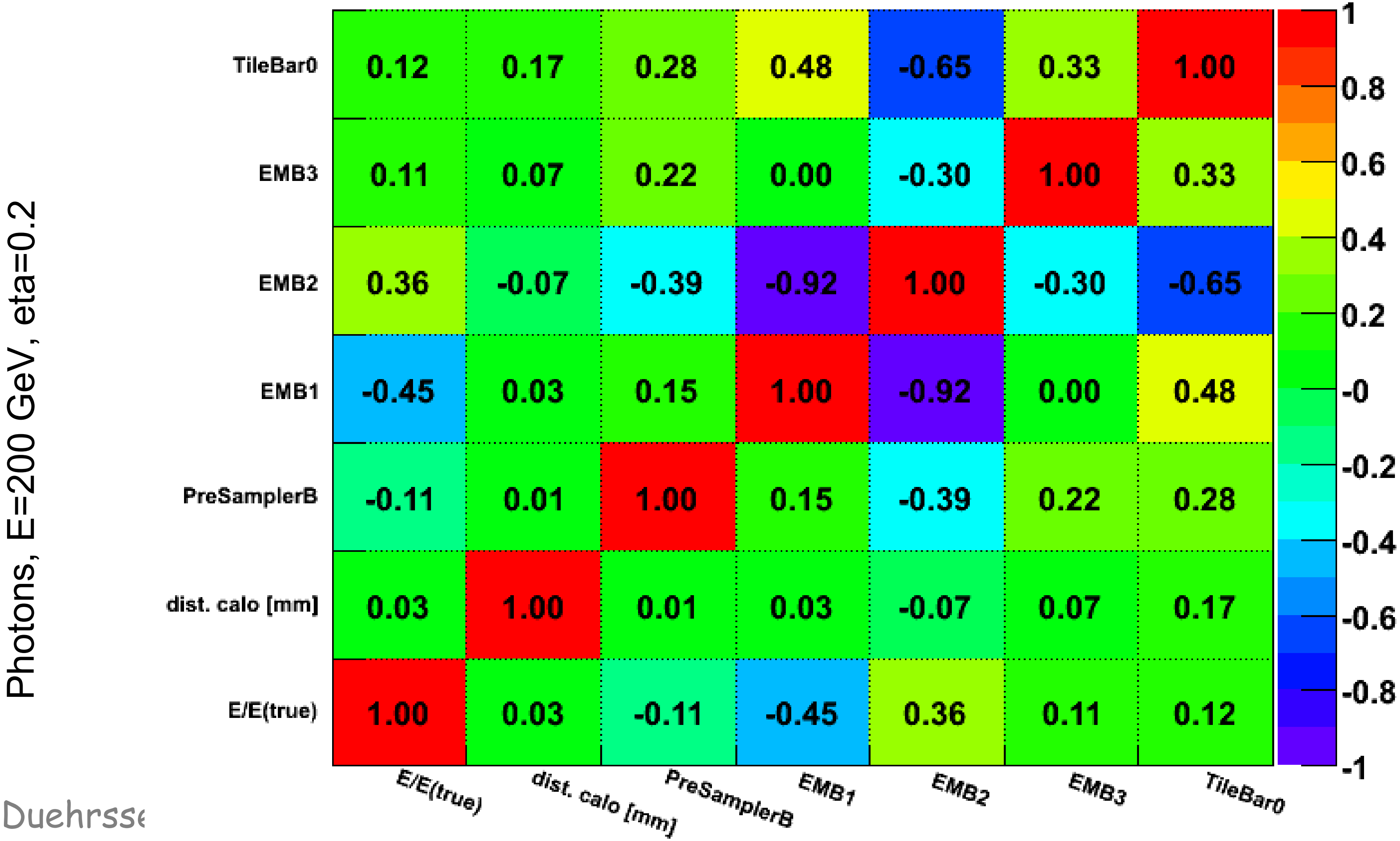
- 3rd priority: correct simulation of the energy fraction in each calorimeter layer as function of the longitudinal shower depth
- Store 2D histograms for the same range of energy and eta points




Photons, E=200 GeV, eta=0.2

# Particle energy simulation – refinement

- 4th priority: correct simulation of the correlation of energy fractions in each calorimeter layer
- Without this correlations, the energy fractions do not add up to 1
- Store correlation matrices of the energy fractions as function of the longitudinal shower depth



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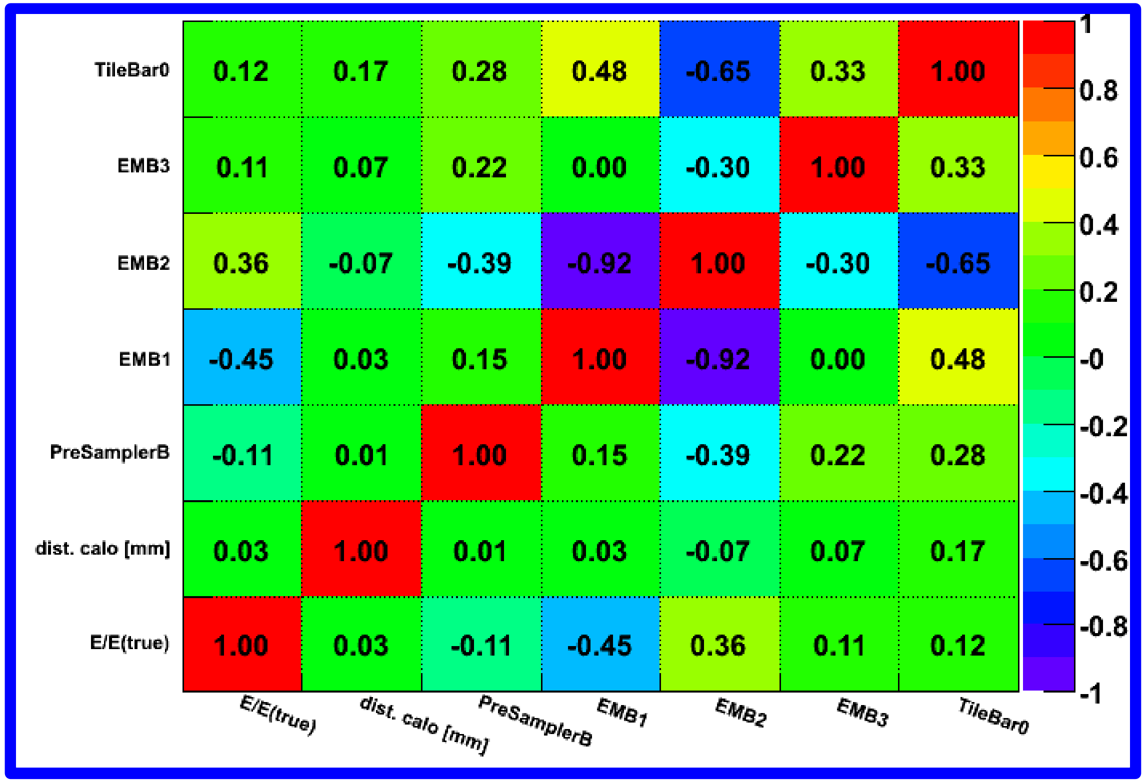
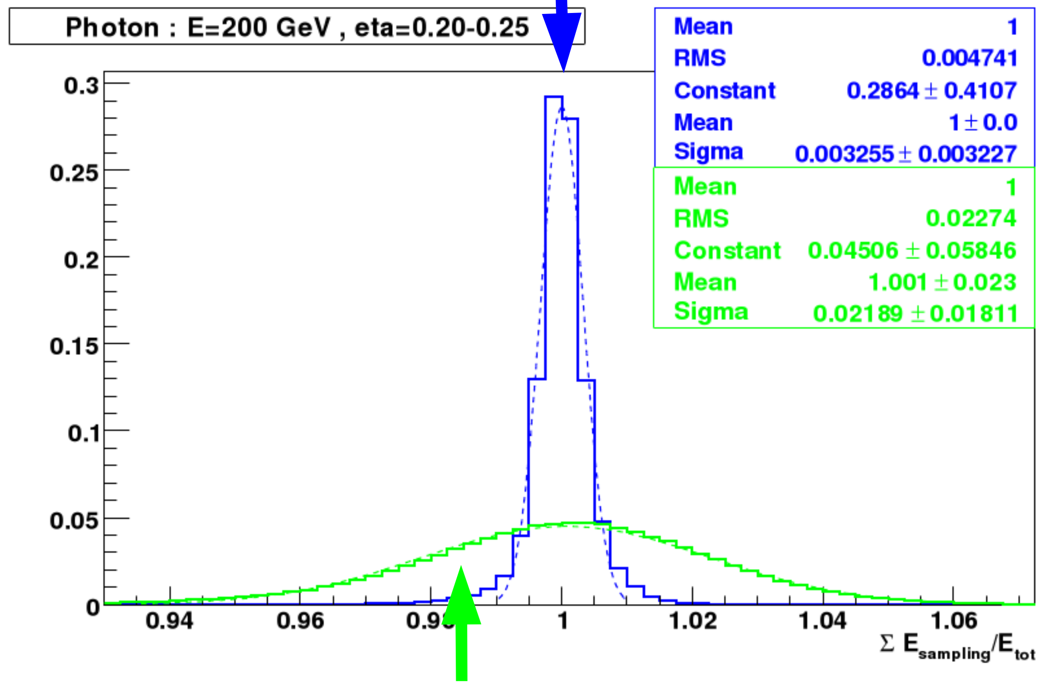


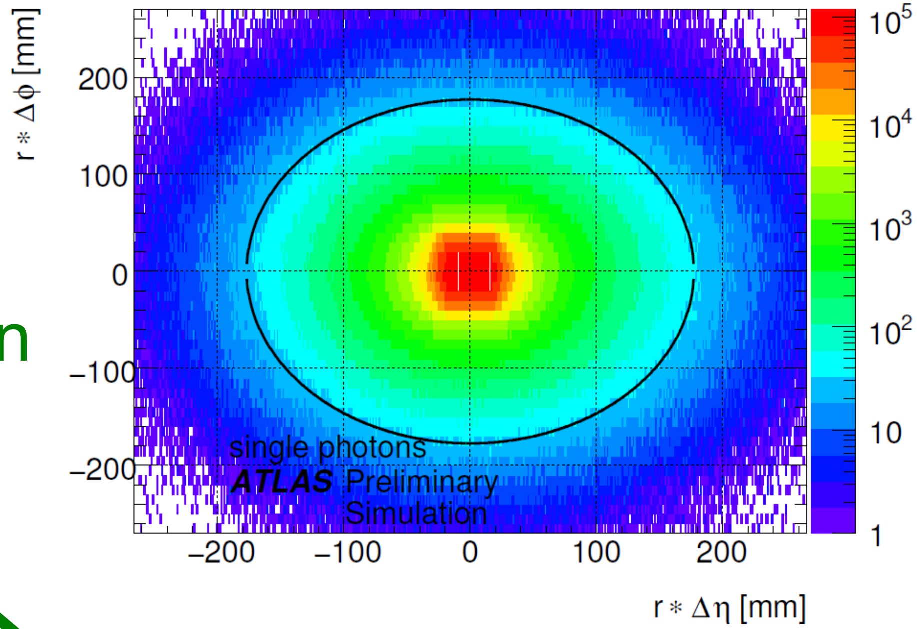

with correlations

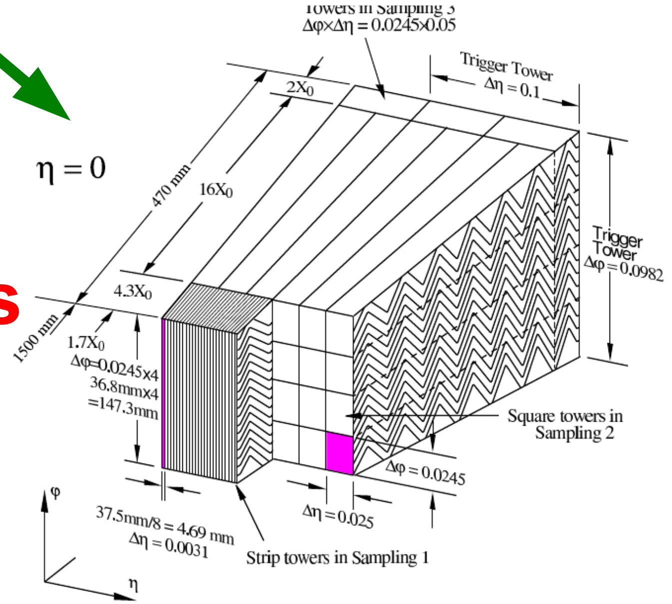



without correlations

# Lateral particle shape simulation

- 5th priority: description of the lateral energy distribution
- The lateral particle shape is described by a fitted average shape function
  - ➔ A shape is fitted for every energy and eta point, every calorimeter layer and ~10 shower depth bins
  - ➔ Uses a radial symmetric shape function
  - ➔ Modified to account for
    - - eta/phi asymmetries
    - - displaced z-Vertex
    - - EM calorimeter accordion shape




- This describes only the average particle shape!
- Works well for electrons and photons
- But no shape fluctuations!
- Especially hadrons (pions) are not well described

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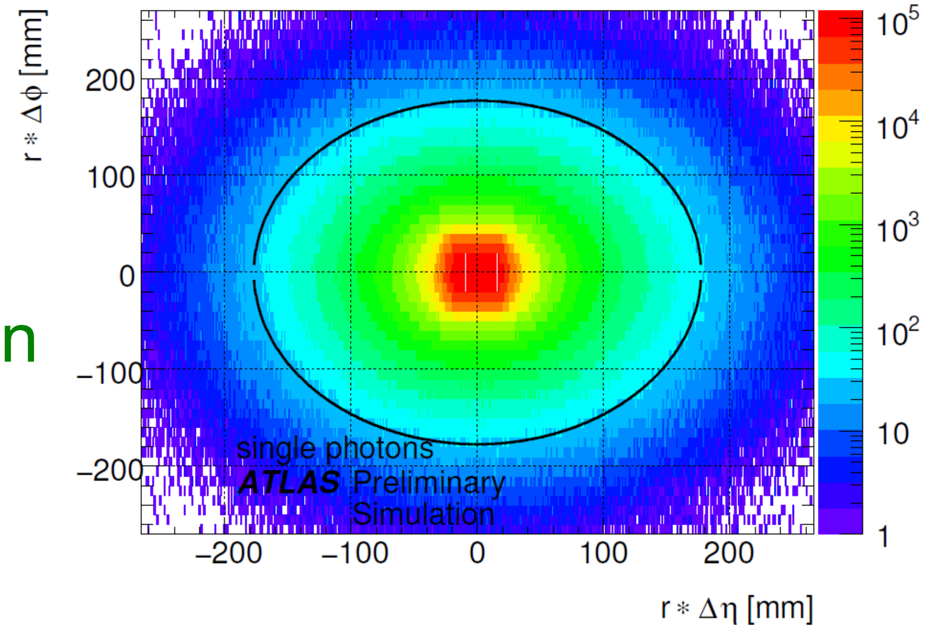


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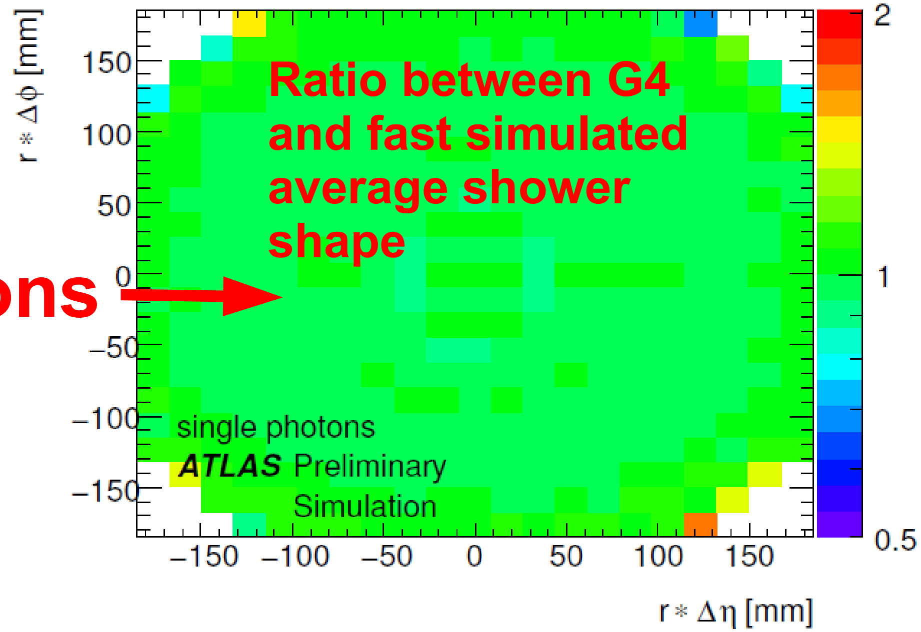


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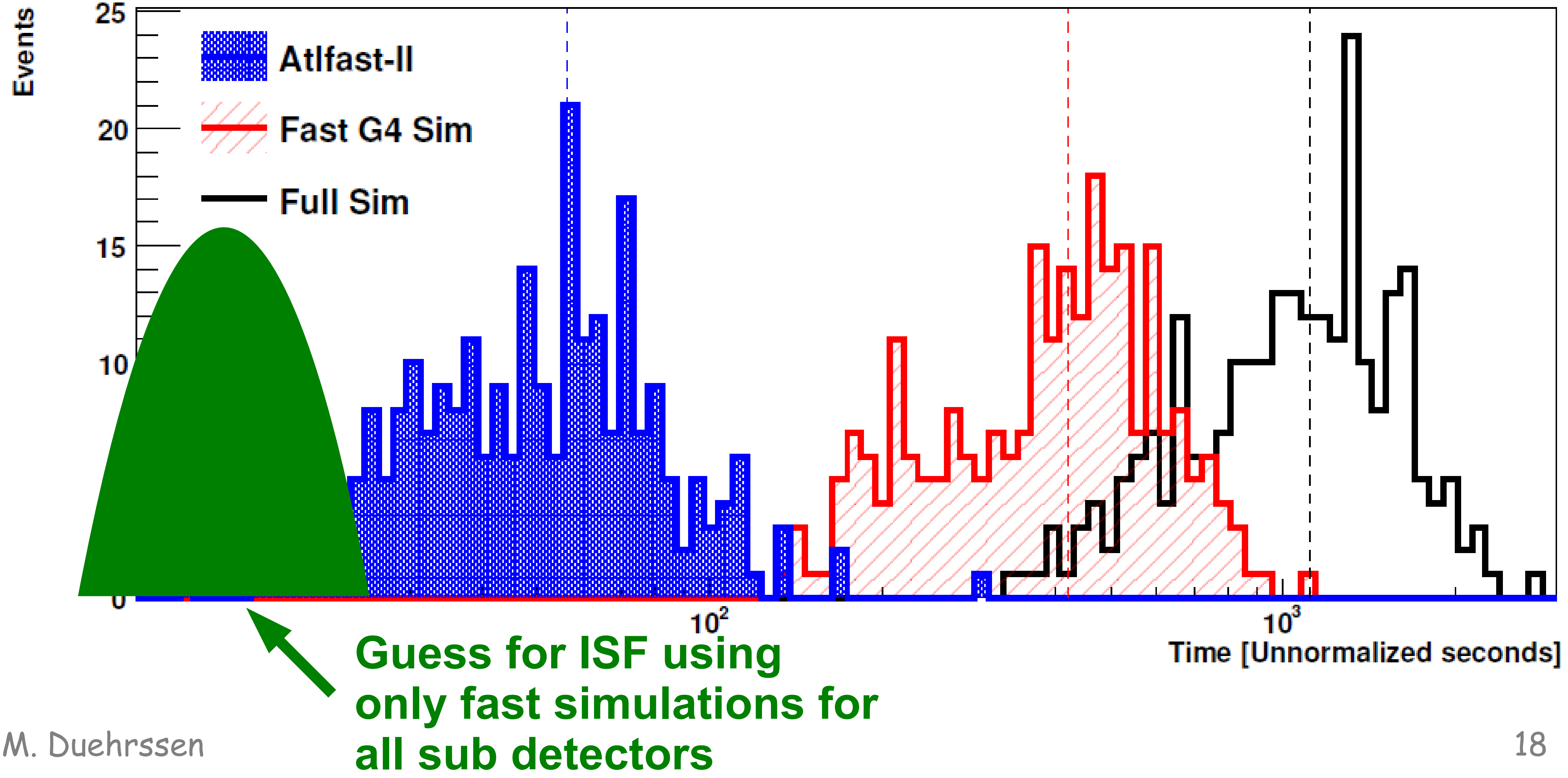
# How well does it work for the speed ?

- **ATLAS uses FastCaloSim within Atlfast-II**
  - Full simulation of the inner detector (dominant CPU consumer)
  - Full simulation of muons in the calorimeter and muon system
  - Fast simulation of all other particles in the calorimeter with FastCaloSim



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- **Speed**
  - >>90% of the time is spent in the ID full simulation
  - FastCaloSim itself more than a factor 100 faster than fullsim for the calo
  - Altogether still a factor 10-20 faster than fullsim for the whole detector
  - With 20-30 pileup events digitization and reconstruction are as slow as fast simulation → so far no *fast* options for these

- **Total simulation budget**
  - About 50% of the current MC budget is covered by Atlfast-II: ~2000M full G4 simulated events + ~2000M Atlfast-II events per year
  - For the future: full G4 simulation will stay at ~2000M events/year fast simulation needed to keep up with data → ISF

# How well does it work for the quality ?

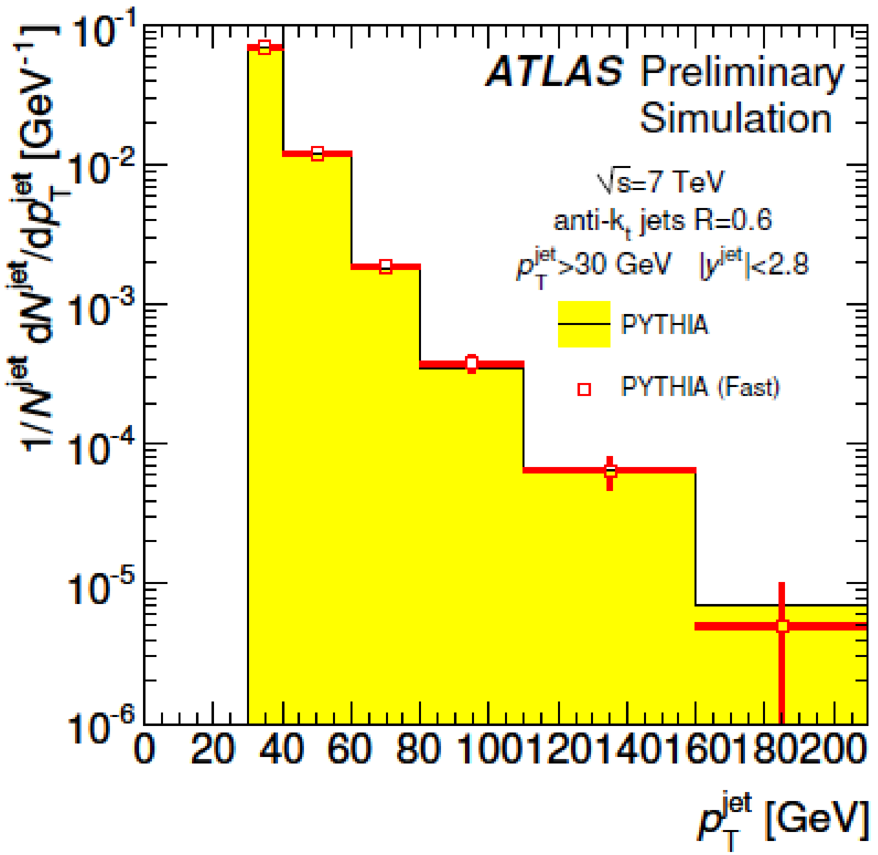
- **To some degree the fact that 50% of the simulation is done with Atlfast-II shows that it is usable for physics analysis**
- **But it also shows that fast simulation is needed already today. Without it there would be 50% less MC !**

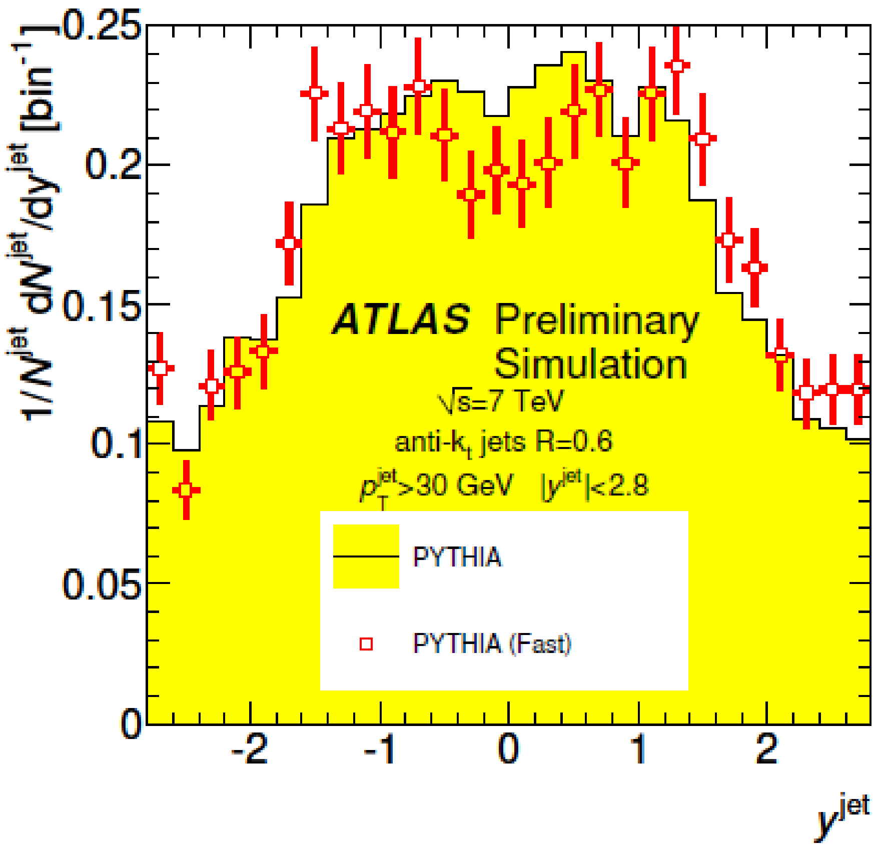
- **Not many MC (and data) comparison plots for Atlfast-II public, but it is used in many analysis for**
  - Signal grids
  - Large backgrounds
  - Systematic samples
  - …
- **In most cases cut flows agree to full sim to within O(%)**

- **Hence only a small collection of material for**
  - Jets and MET
  - Electrons

# Jets

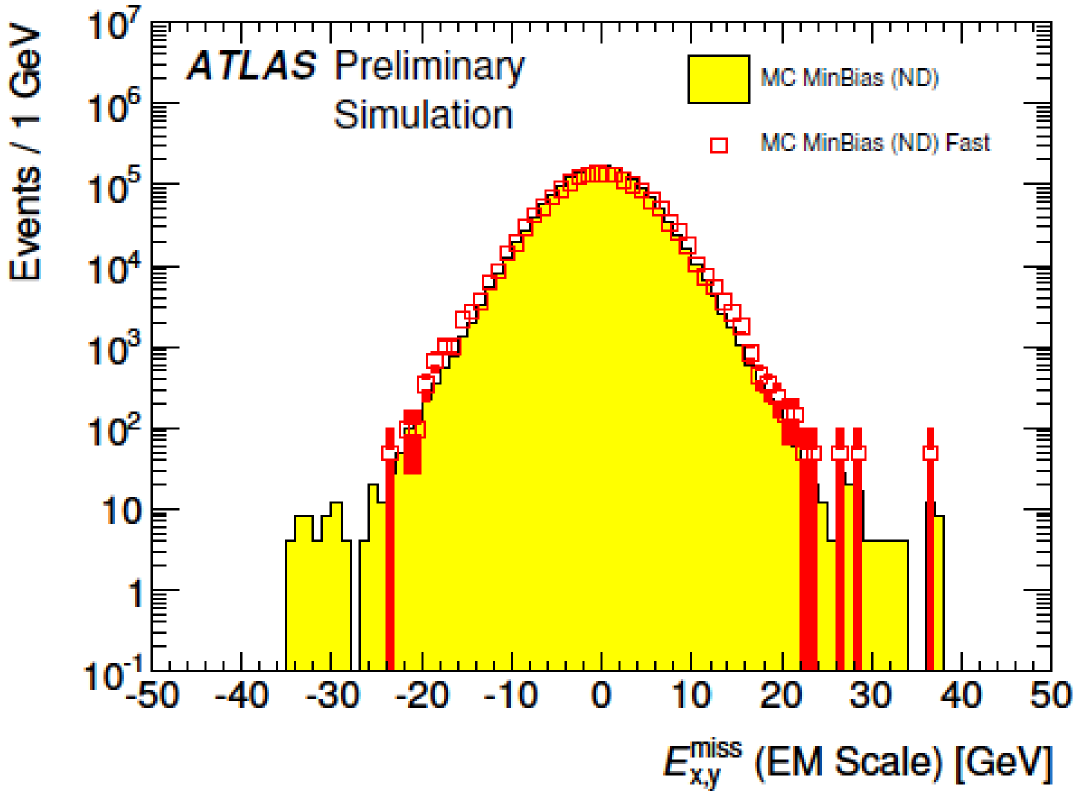
- **Agreement for inclusive jet quantities within a few % of full simulation out of the box**
- **Improved by now by**
  - using dedicated jet calibrations for Atlfast-II
  - having pileup which “smears” full and fast simulation in the same way – removes many small differences!

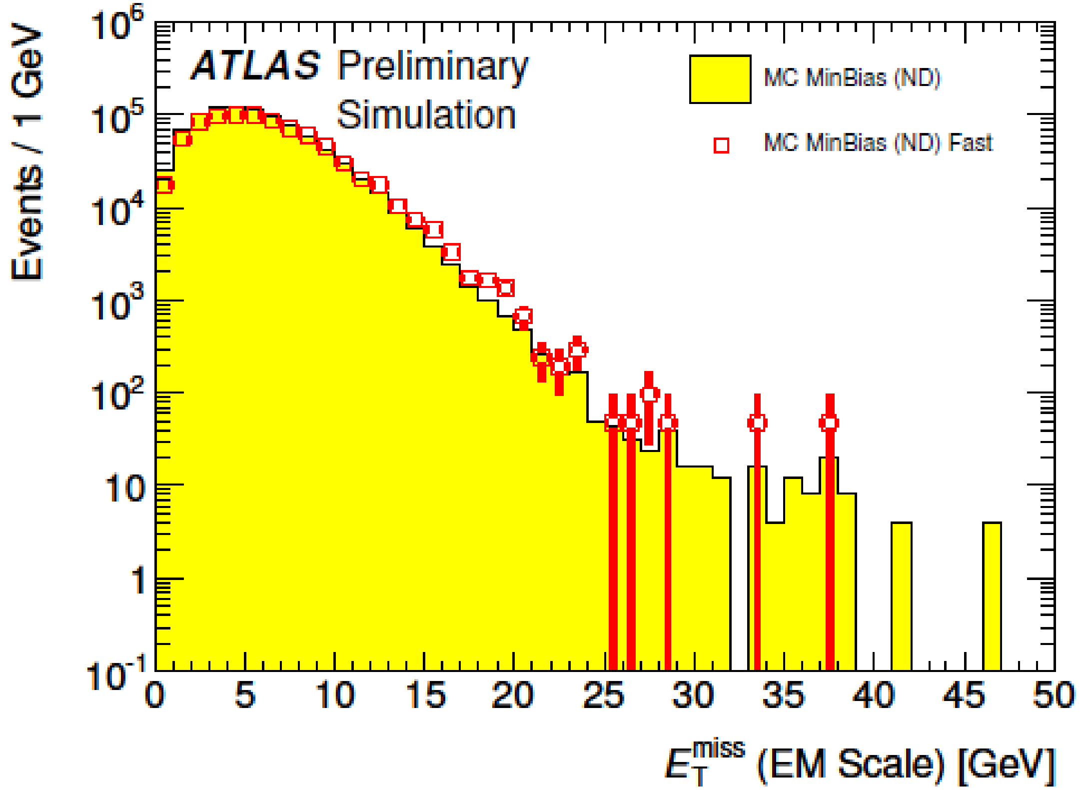


# MET

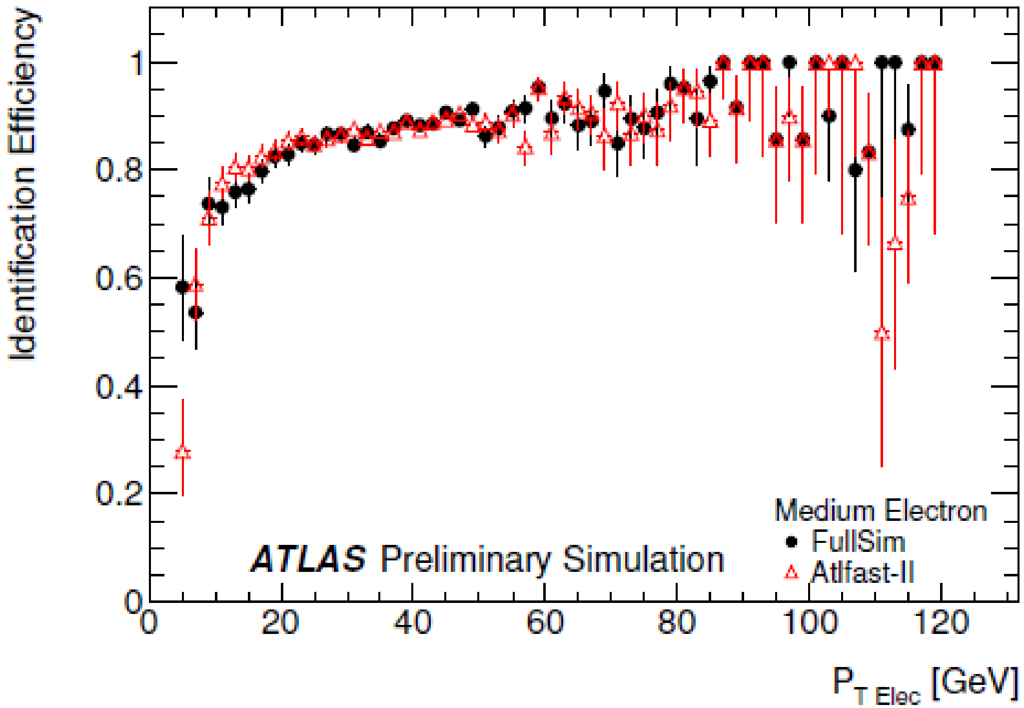
- **Good agreement for the bulk of the distributions, but differences appear in the tails**
- **Improved by now by**
  - using dedicated jet calibrations for Atlfast-II
    → removes most tails
  - Pileup actually dominates MET in 2012
    → including pileup causes MET to be in very good agreement

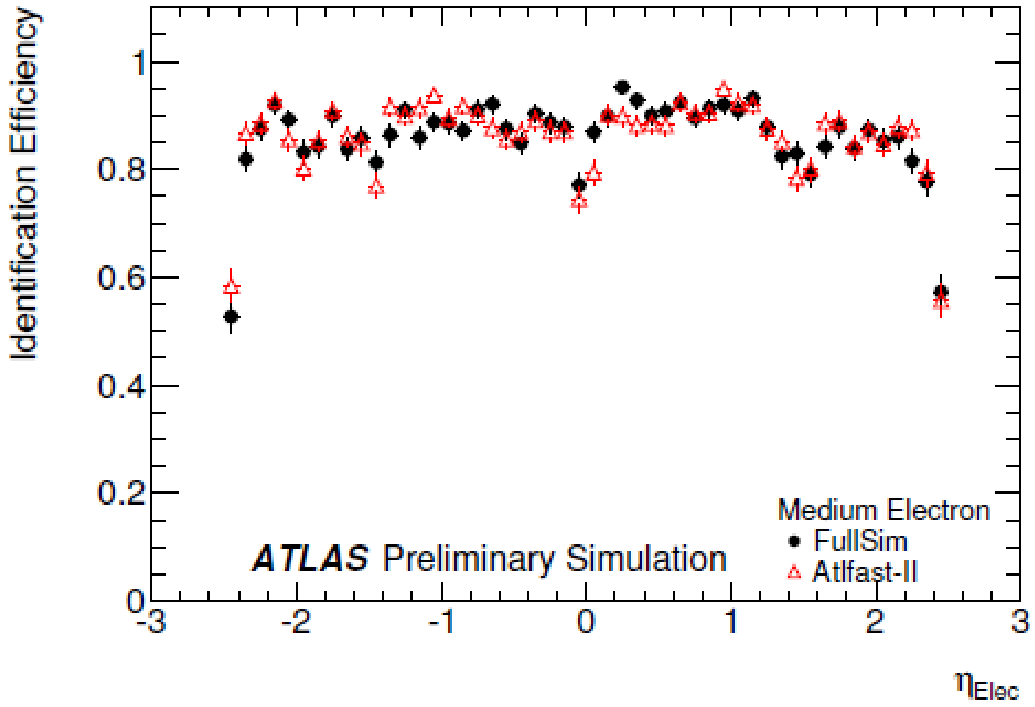


# Electrons

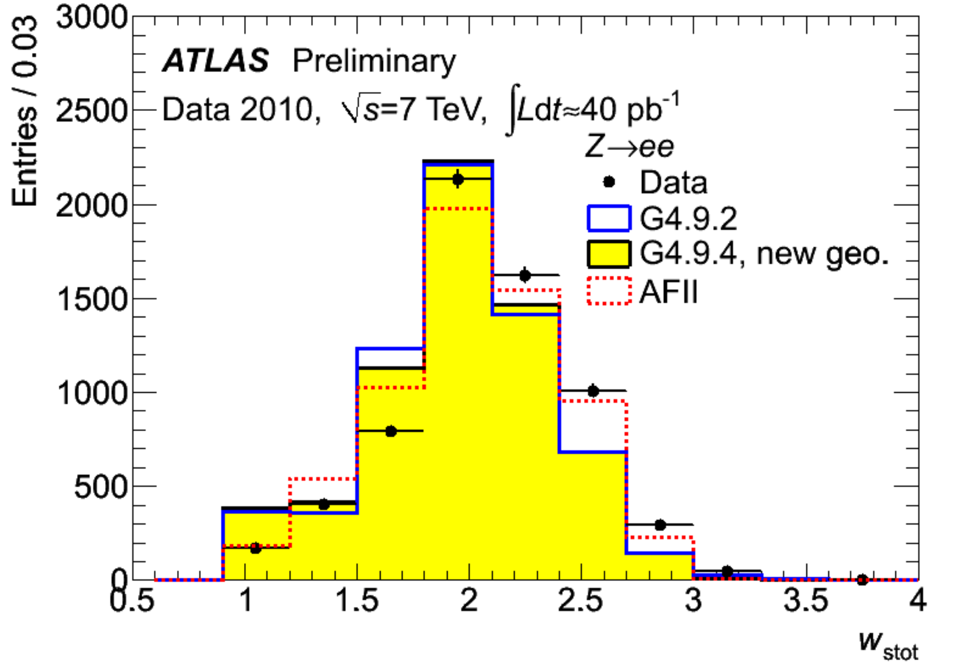
- From the initial requirements simulating isolated electrons well was not mandatory, as a truth based correction is possible
- However, if they are simulated well, it is a big advantage and opens new possibilities!
  - Electrons/photons have very regular shower shapes $\rightarrow$ very well suited for fast simualtions

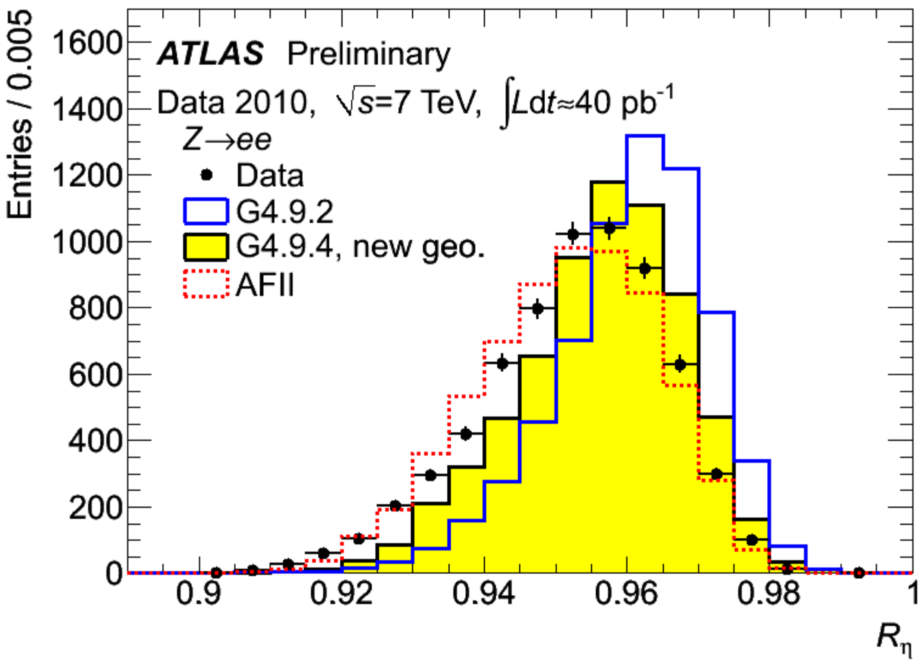


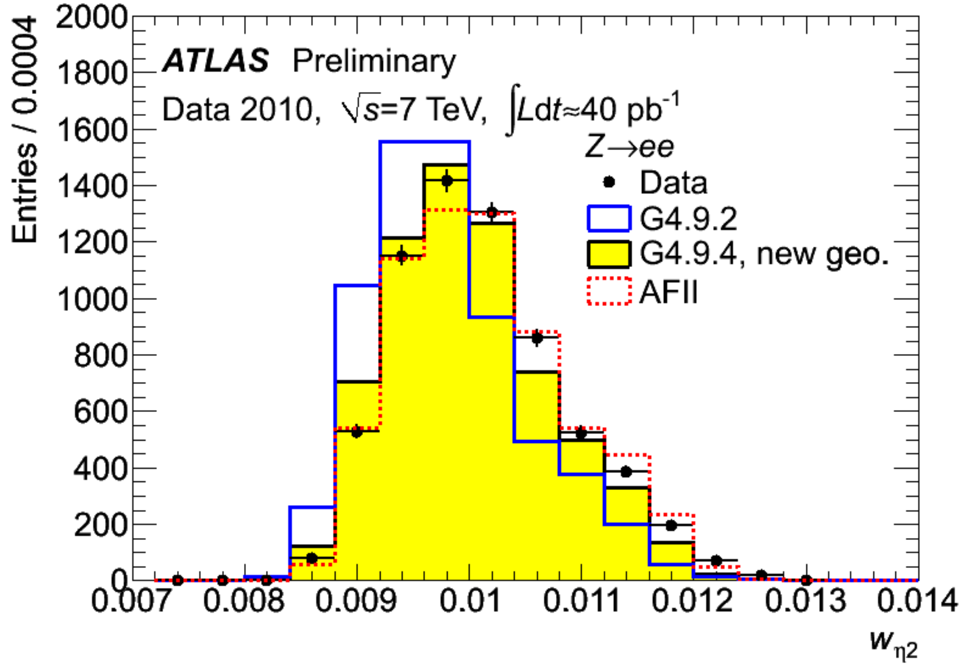



# Electrons

- FastCaloSim was designed from the beginning for some tuning possibility to data
- Tuning to data W/Z events gives big improvements in the description of electrons shower shapes
- In some cases, Atlfast-II describes shapes after tuning better than full simulation



# Where are the problems ?

- **Fake muons**
  - **Currently simply no simulation of $\pi \rightarrow \mu$ decays in the calorimeter**
  - **ISF will include a simulation engine for “fake” muons**

- **Hadron shower shapes**
  - **Biggest shortcoming! The average lateral shower shape is just not a good description**
  - **Difference because of lateral hadron shape is visible in**
    - **cluster properties**
    - **jet→X fake rates**
    - **jet sub-structure**
  - **Improve FastCaloSim for the future to add a fast hadron shape models**

- **Exotic particles in the calorimeter**
  - **Think of R-hadrons, heavy ions with high momentum, …**
  - **Could in principle be added as special parametrization, but lots of work. Full simulation is better suited for such use cases**

# Summary

- **FastCaloSim is developed as fast calorimeter simulation tailored to the ATLAS fast simulation needs**
  - Uses parametrizations to describe the longitudinal and lateral shower development
  - Is fast: CPU time needed is O(s)/event
  - Gives % level agreement to the full simulation
  - Can be tuned to data to improve the agreement

- **Atlfast-II (using FastCaloSim for the calorimeter) is in use for MC production for physics analysis**
  - Offers a factor of 10-20 increase in total simulation speed
  - Used so far to produce ~2B events/year (for 2011 and 2012)

- **Demands will increase in the future**
  - Higher demands on speed → ISF
  - Higher demands on precision → improve FastCaloSim model