The new ATLAS Fast Calorimeter Simulation

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On behalf of the ATLAS Collaboration

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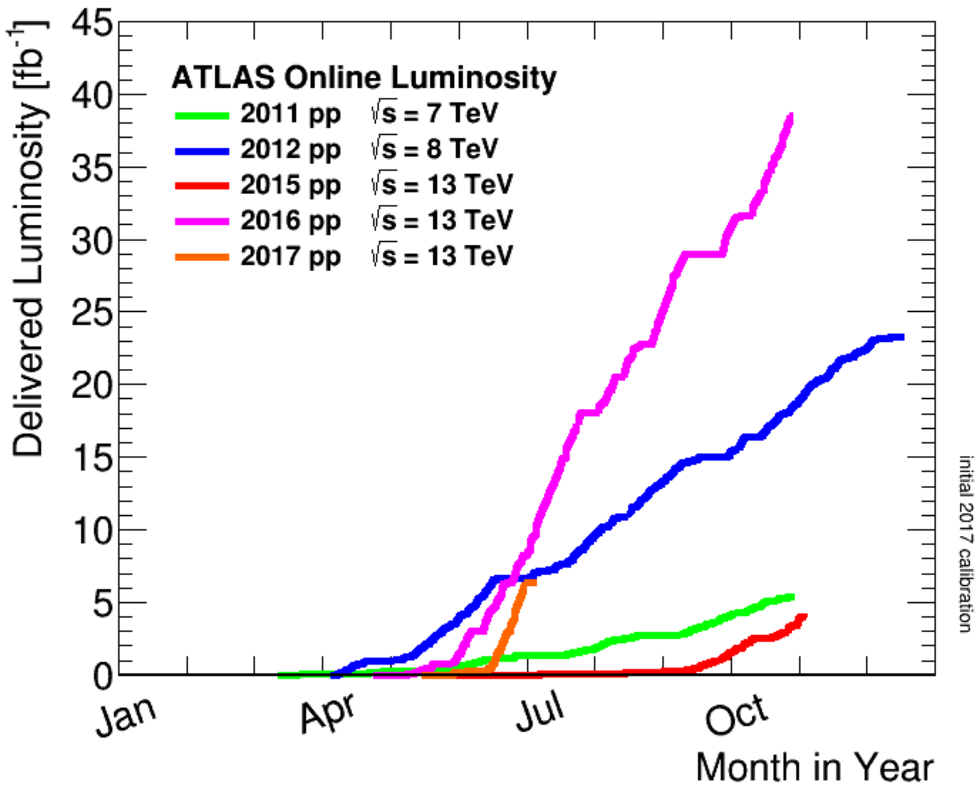
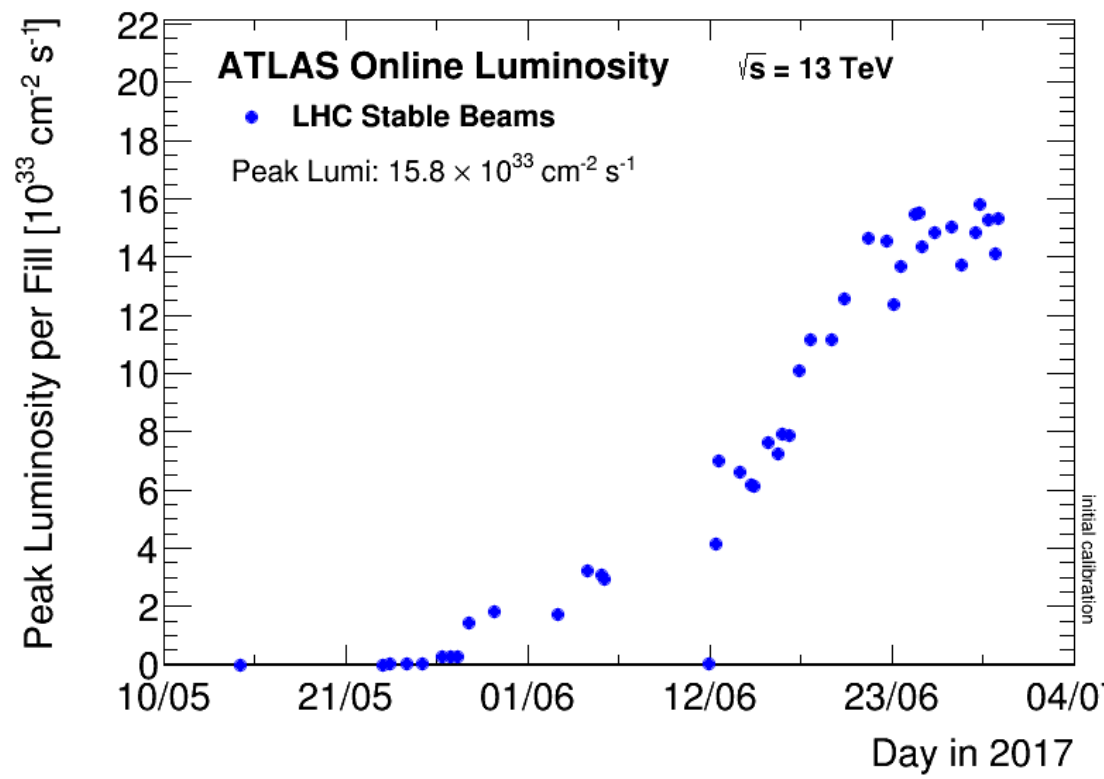
Energy frontier: The Large Hadron Collider

Tremendous performance by the LHC: exploring the high energy frontier at 13TeV

Delivered ~50 fb^{-1} of integrated luminosity at 13 TeV since 2015

Large pile-up interactions $\langle\mu\rangle = 45$ at $10^{34}\ cm^{-2}s^{-1}$ (in 2017)

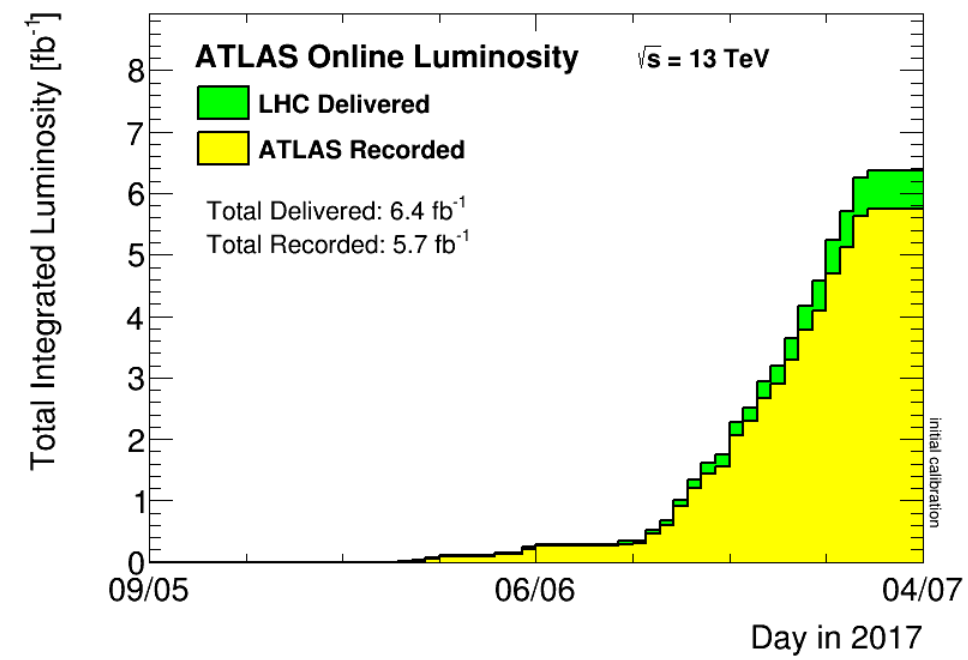




At the designed energy LHC will deliver even higher integrated luminosity and larger pile-up interactions

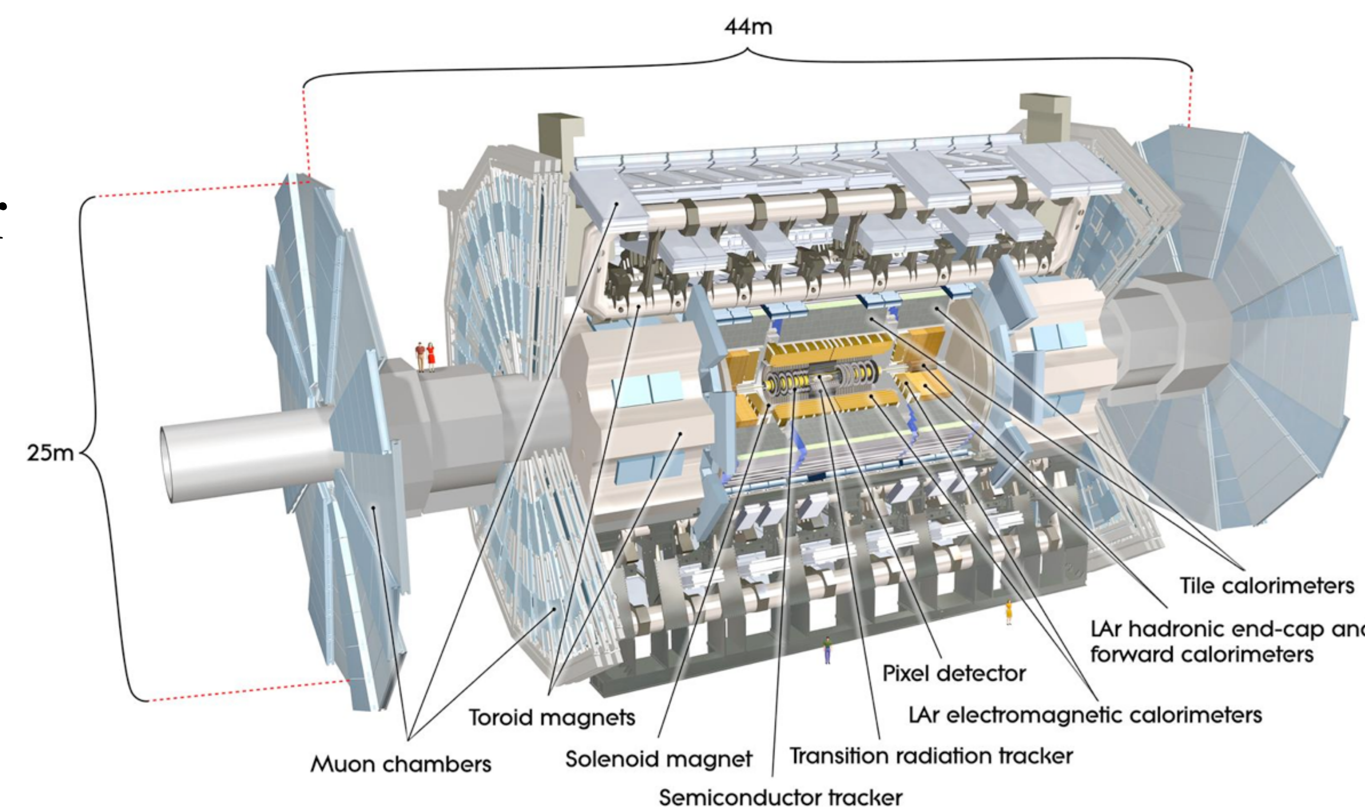
Discovery machine: The ATLAS detector

Outstanding performance in recording delivered luminosity by the LHC



General purpose detector designed for discovery of physics beyond the Standard Model

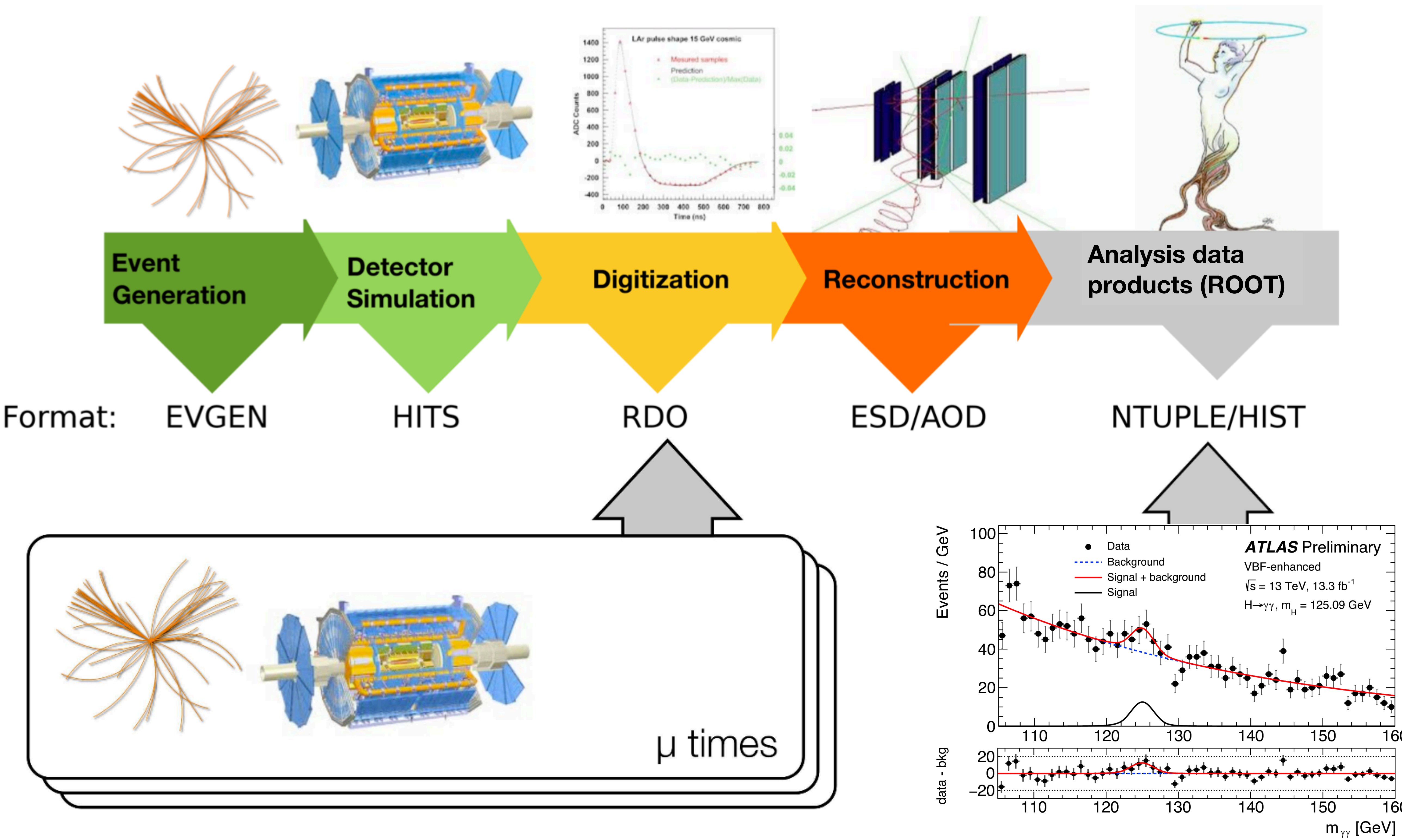
Silicon and transition radiation for charge particle tracking, Calorimeter for energy measurement



Successful physics program depends on large number of Monte Carlo simulated events

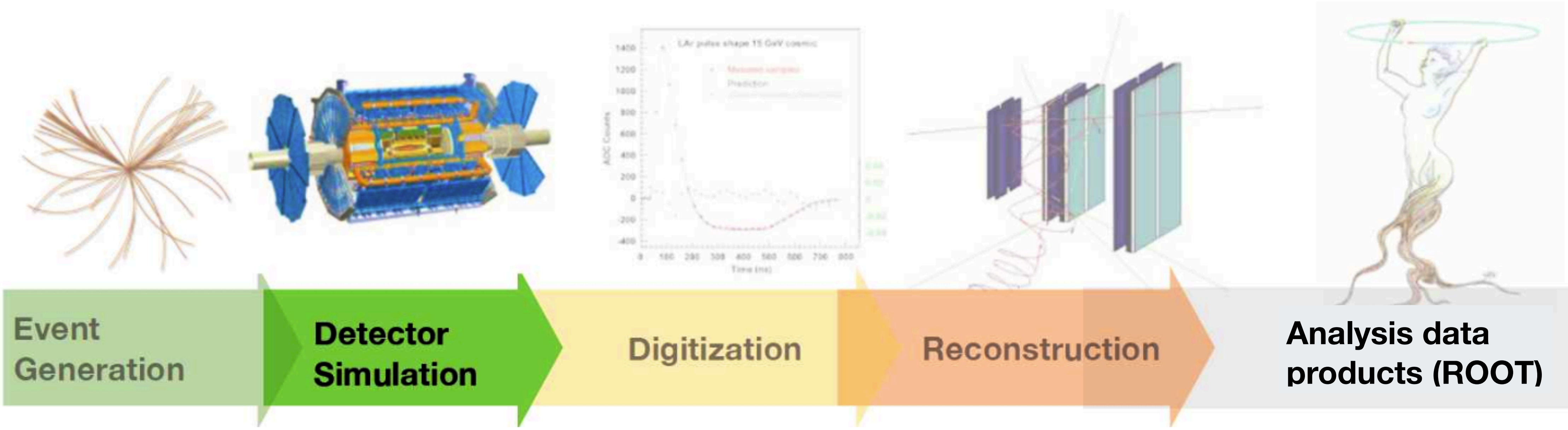
Large collision data events require even larger number of simulated events for physics analysis

ATLAS Monte Carlo Production Chain



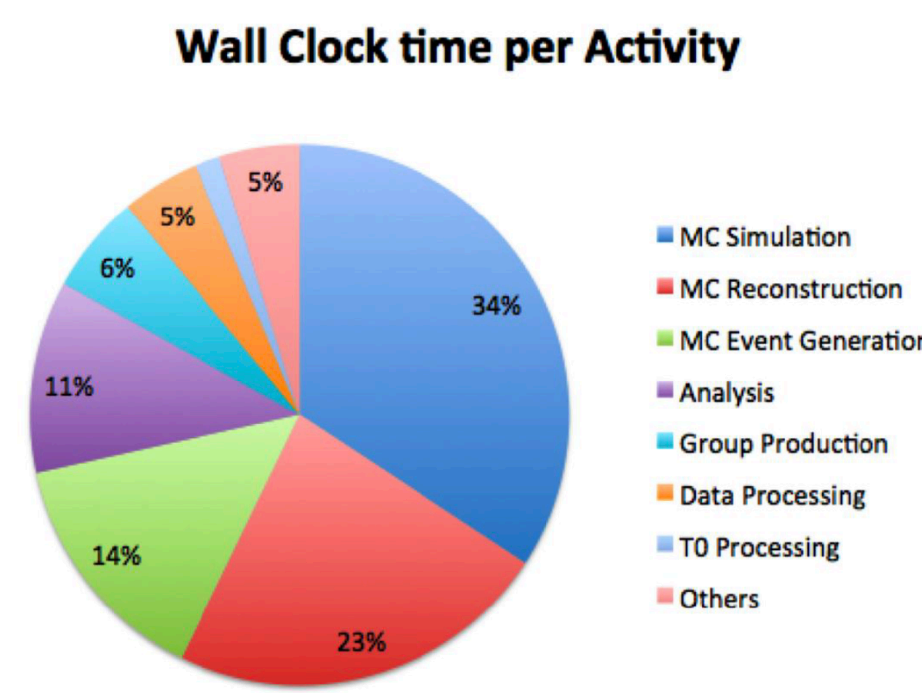
Simulated events undergo the same conditions as reconstructed collision events

ATLAS Standard Simulation: Geant4



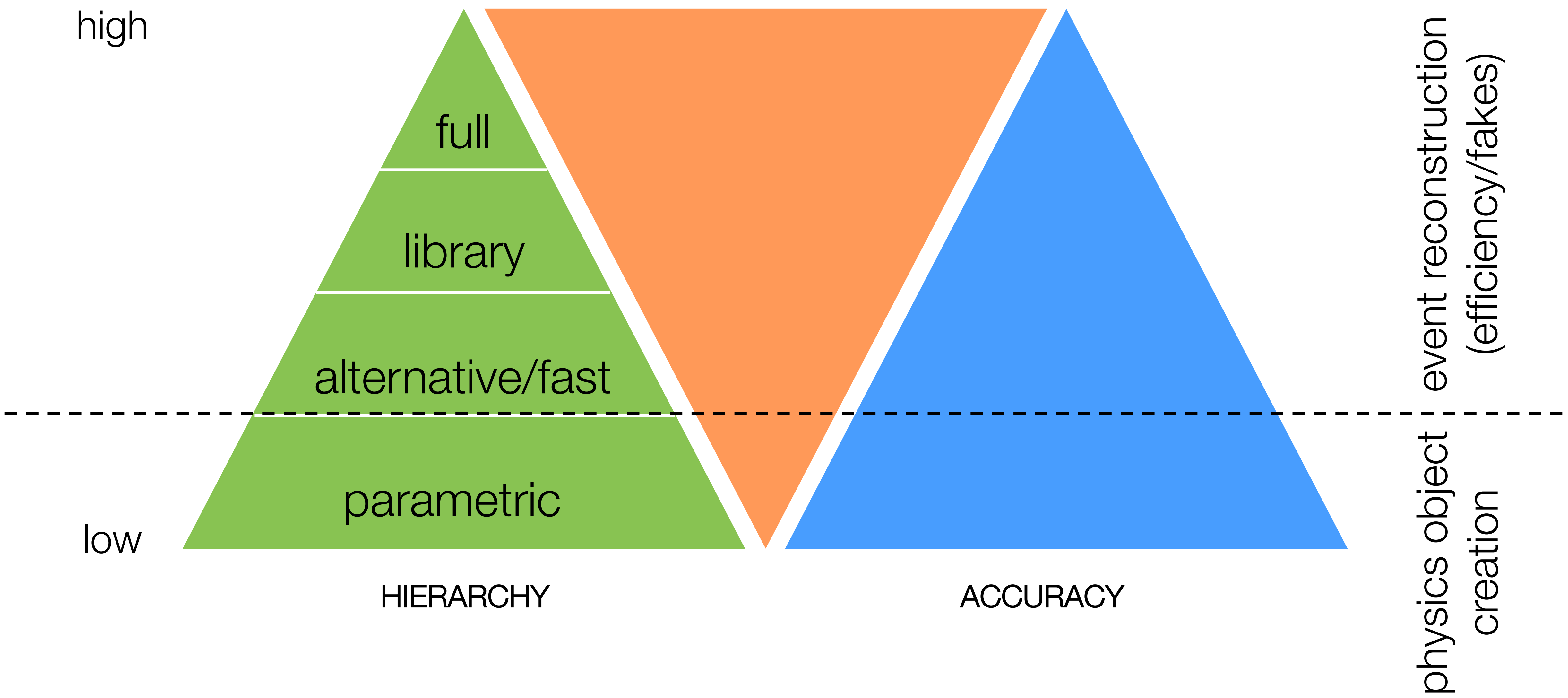
- Geant4 is the standard ATLAS simulator
- Full description of the detector and most precise
- Large CPU and disk space requirement
- Calorimeter simulation accounts for ~90% of total time
- Higher luminosity/pile-up requires larger MC production

Grid usage 2016:



Fast simulation is essential with increasing luminosity!

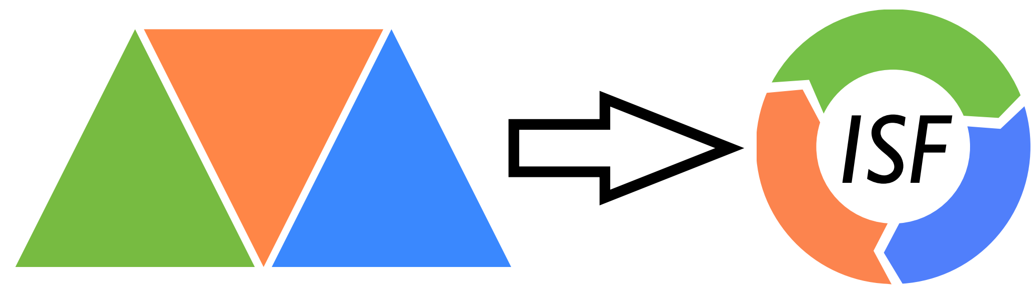
The simulation hierarchy

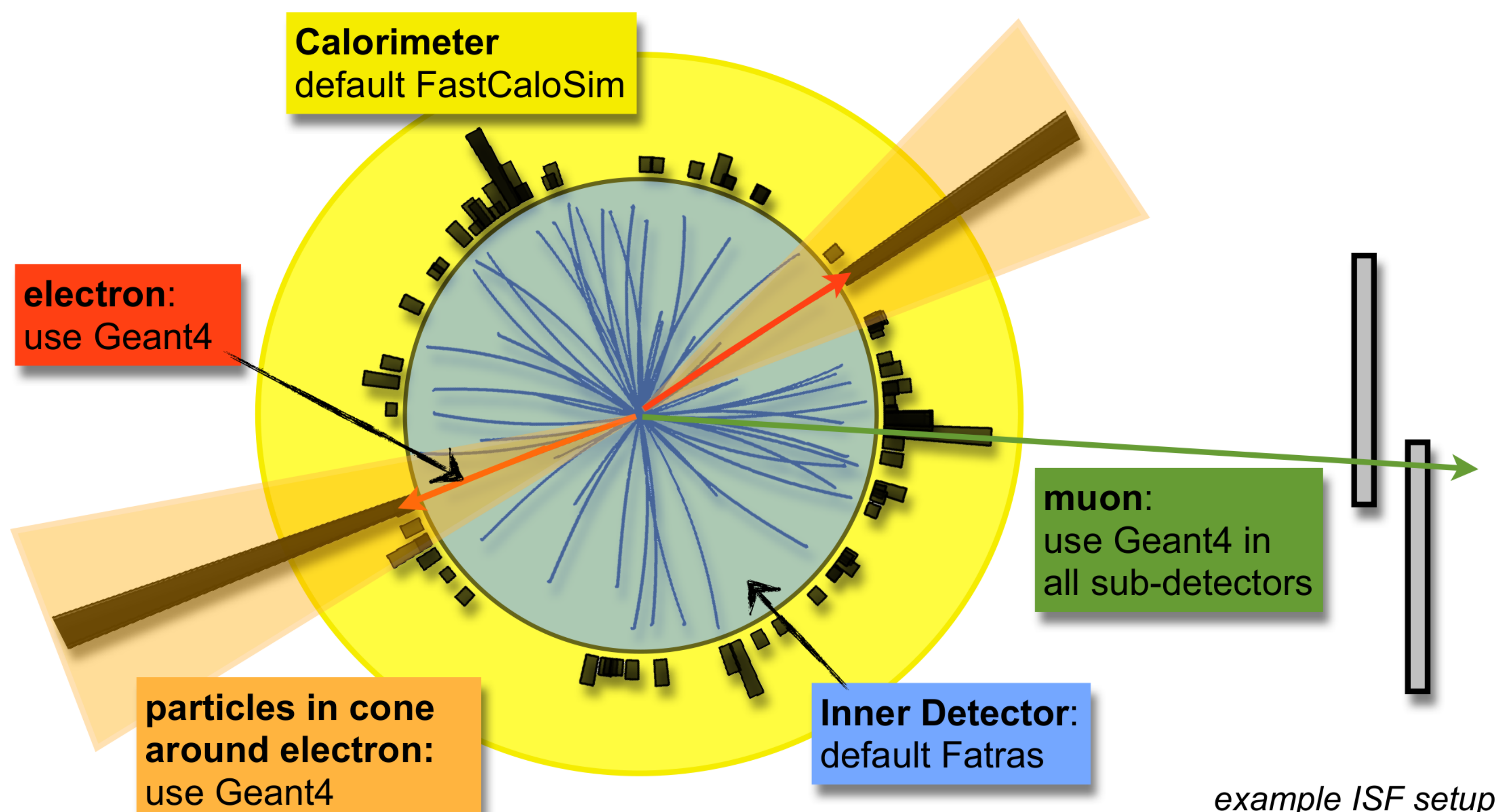


A trade-off between accuracy and speed

ISF - Integrated Simulation Framework

- Combines different simulation approaches in ATLAS into one framework
  - ➡ Output format is always the same independent of simulation chosen
  - ➡ Configuration is done at one central place and standardized
  - ➡ Fast and full simulation setup can be mixed and used alongside
- Compatible with multithreading and multiprocessing

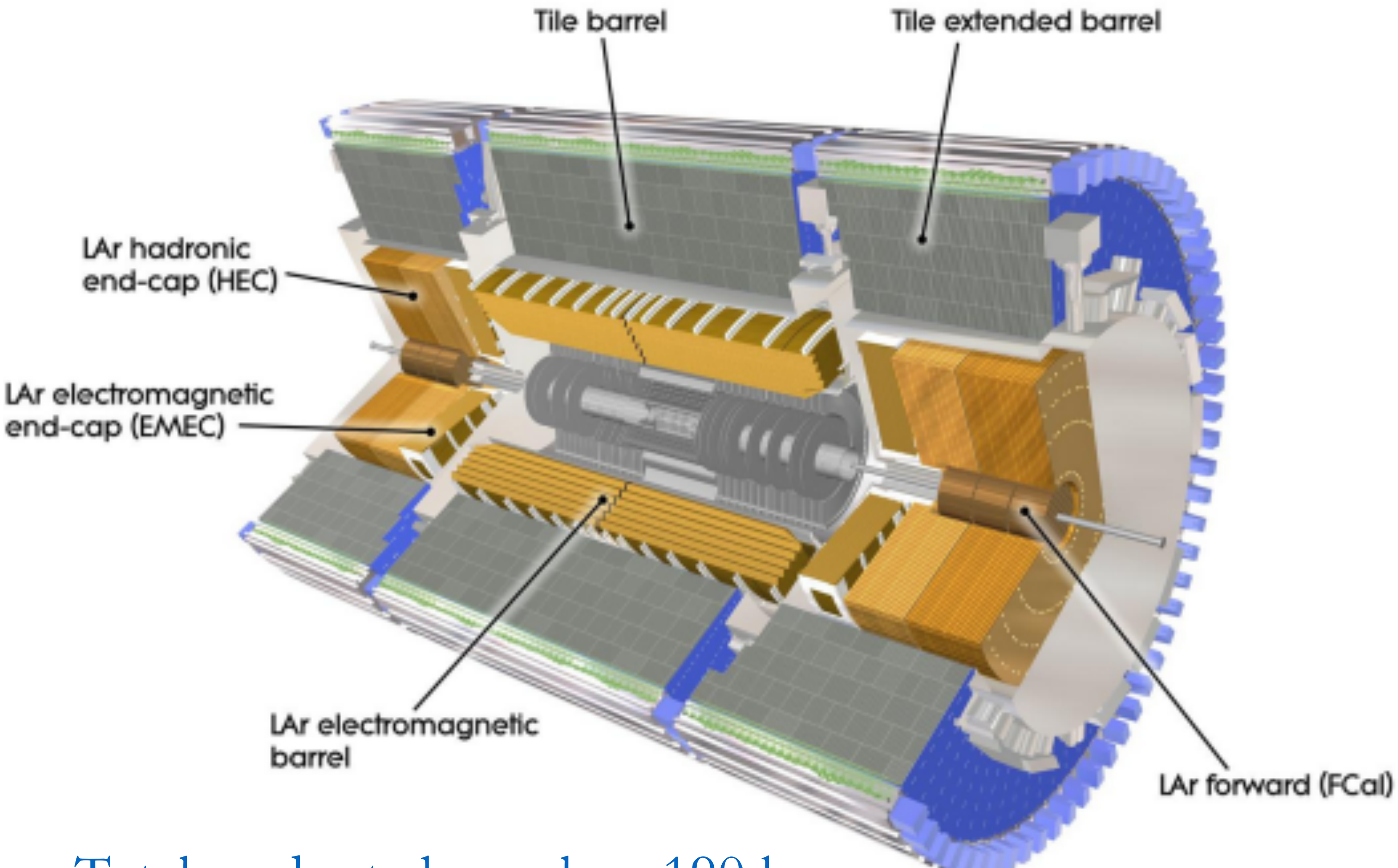


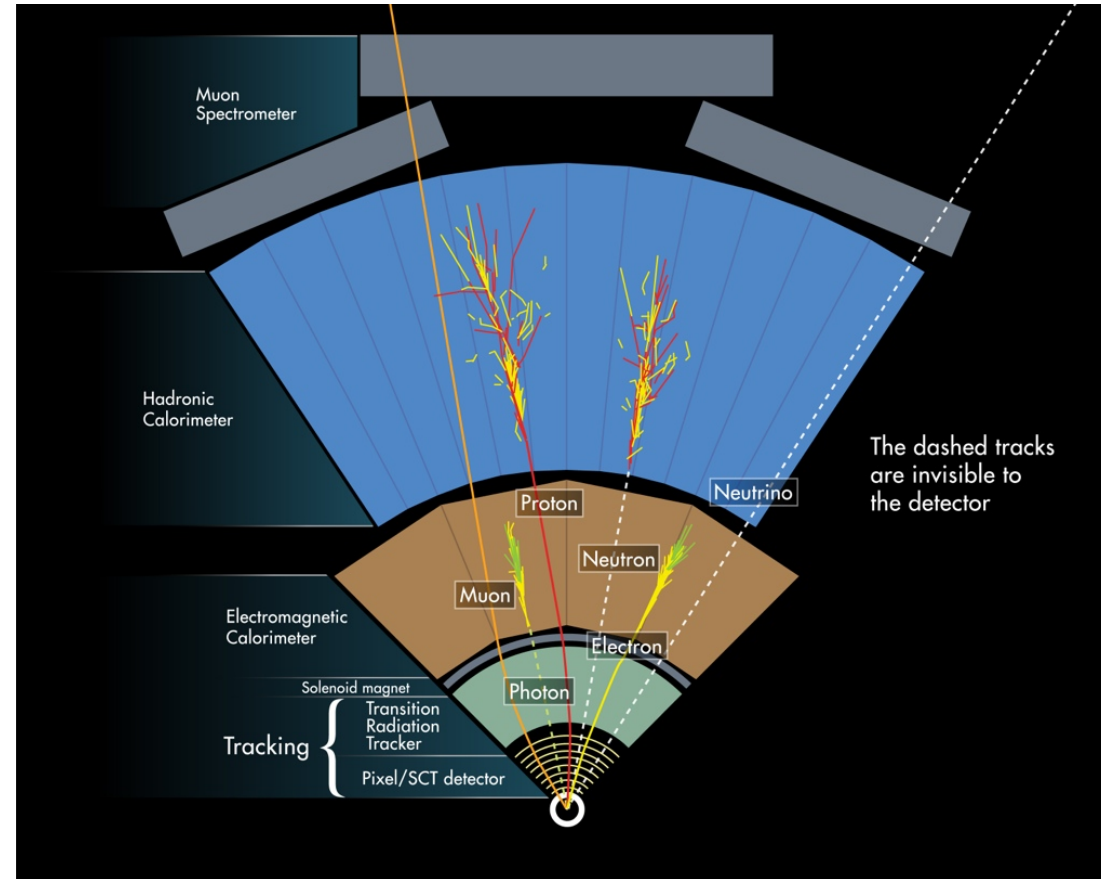


Calorimeter fast simulation can be combined with full simulation of Inner Detector/Muon Systems based on physics requirements

The ATLAS Calorimeter

Sampling calorimeter covering |η| < 4.9





Total readout channels: ~190 k

System	EM Barrel	EM EC	Hadronic EC	FCAL	Tile
#Channels	110k	64k	5.6k	3.5k	9.8k

Electromagnetic (EM) Cal:

- Liquid Argon (active)
- Pb/Cu/Tungsten (absorber)

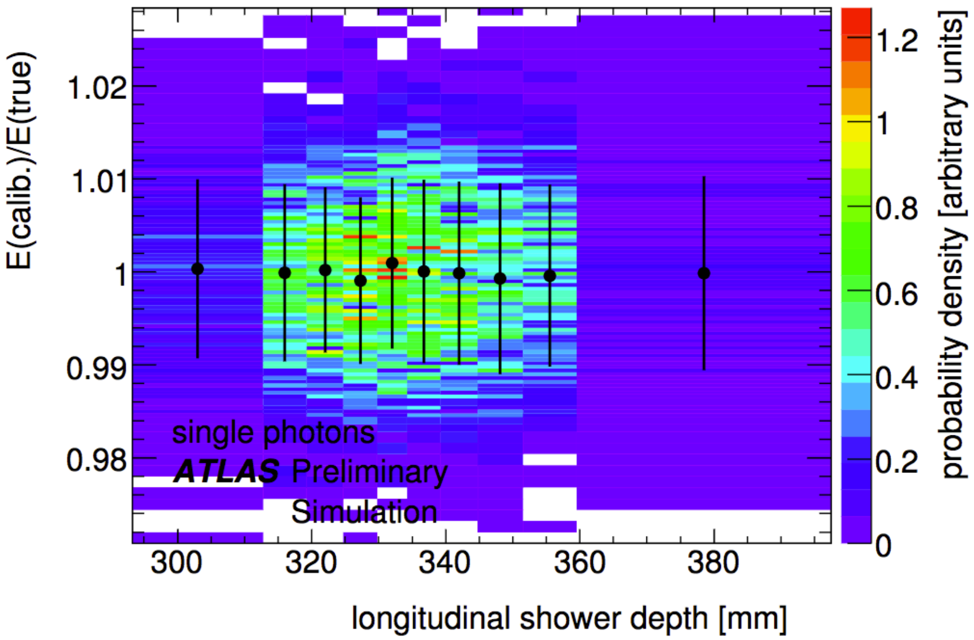
Hadronic/Tile Cal:

- Scintillating tiles (active)
- Steel (absorber)

Crucial for electrons, photons, jets and missing energy reconstruction

Current ATLAS Fast Calorimeter Simulation (FastCaloSim)

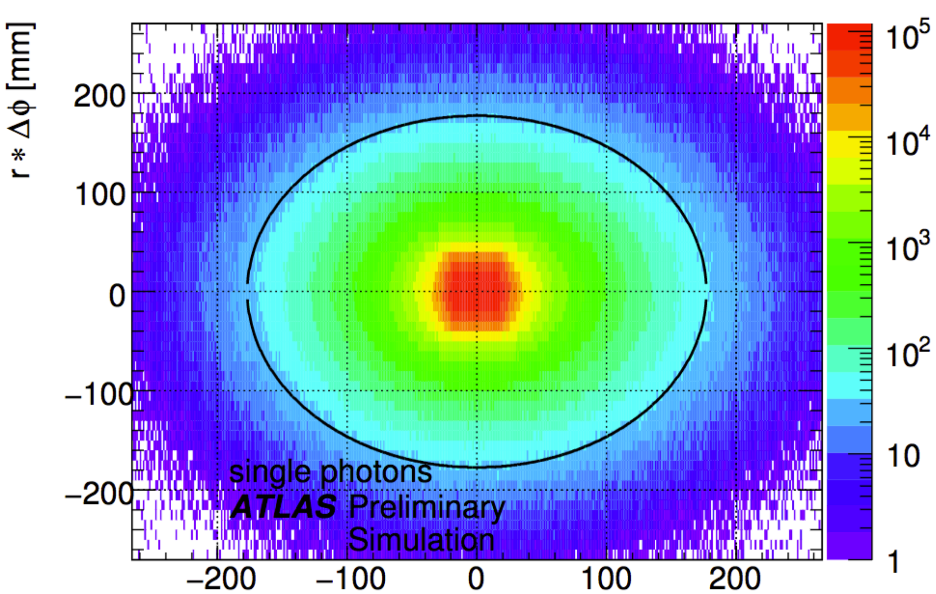
Current FastCaloSim: Parametrization



Parametrized Calorimeter response in E-η grid

Geant4 simulated single particles:
e, γ (EM interaction) and $\pi^{\pm}$(hadronic interaction)

Parametrization split into longitudinal and lateral shower development



Lateral energy distribution

Detailed parametrization of the energy as a function of longitudinal shower depth.

Average lateral shower parametrization obtained from a fit to the Geant4 lateral shower shape

Uses simplified geometry for hit to cell assignment

Calorimeter response modeled with detailed longitudinal and average lateral shower parametrization

Current FastCaloSim: Performance

ATLFASTII = current FastCaloSim for calorimeters + Geant4 for inner detector and muon systems

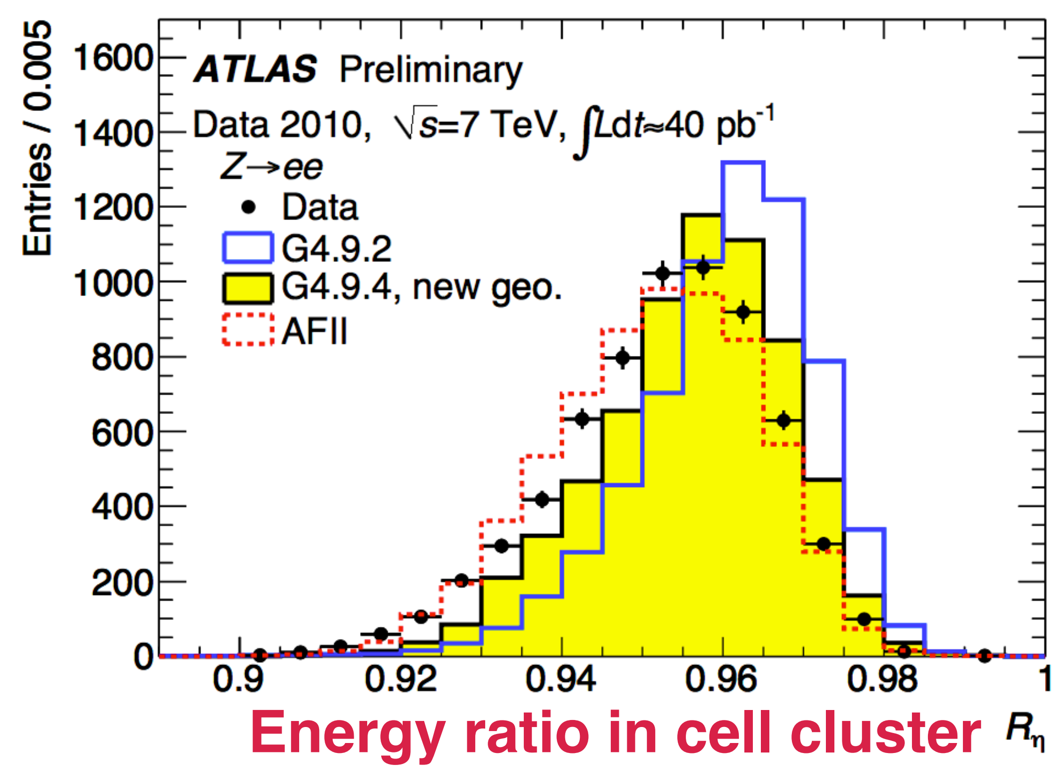
Widely used in ATLAS: e.g. SUSY signal samples for searches, ttbar samples systematic uncertainty studies

ATLFASTII ~20x faster than Geant4

Simulation time per event in seconds

Sample	Full G4 Sim	Atlfast-II
Minimum Bias	551.	31.2
$t\bar{t}$	1990	101.
Jets	2640	93.6
Photon and jets	2850	71.4
$W^{\pm} \to e^{\pm}\nu_e$	1150	57.0
$W^{\pm} \to \mu^{\pm}\nu_{\mu}$	1030	55.1

* based on studies performed in 2010, current Geant4 has better performance



Energy ratio in cell cluster

Good average of shower descriptions, poor modeling of substructure variables

New ATLAS Fast Calorimeter Simulation

New FastCaloSim: FastCaloSimV2

Goals:

Describe the physics variables better than ATLFASTII, esp. substructure variables

Decrease the time required to simulate each event

Optimize I/O and memory consumption

Developments:

Single particle (γ, e, $\pi^{\pm}$) samples on a fine E-η grid produced with current ATLAS geometry in Geant4

New energy (longitudinal) and shower shape (lateral) parametrization

Reduce the amount of information to a compact form

Use multivariate analysis (TMVA) regression to approximate histograms

Add lateral shower fluctuations

Assignment of hits to cells overcoming simplified geometry drawback

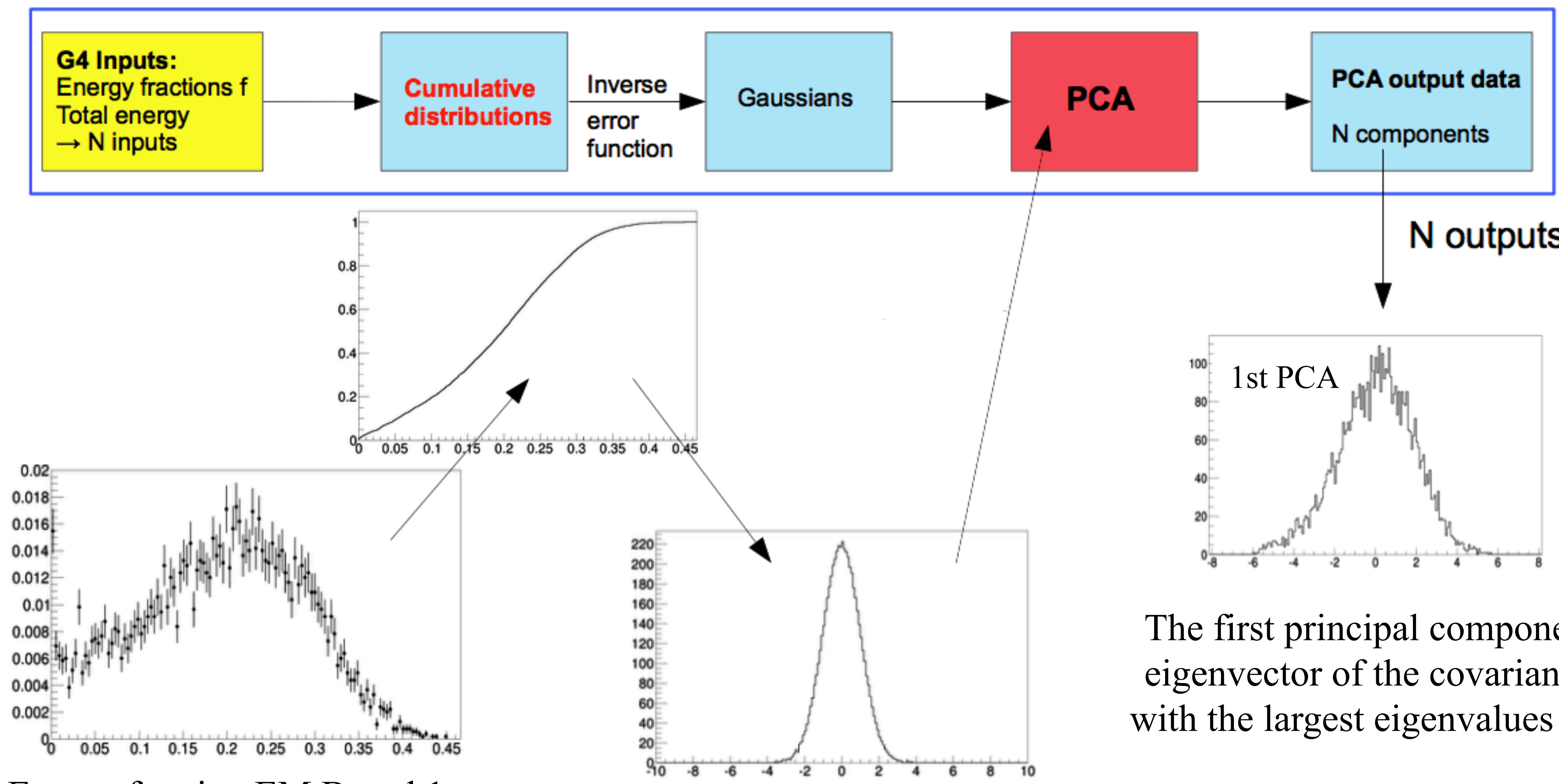
Use exact Forward Calorimeter geometry

FastCaloSimV2 must improve over* ATLFASTII *in describing physics processes

Longitudinal Shower Parametrization

Goal: Model the total energy and energy fraction in each layer
Difficulty: Energy deposits each layer are correlated
Solution: Transform the correlated energy deposits into linearly uncorrelated ones through Principal Component Analysis (PCA)

1st PCA chain:



The first principal component is that eigenvector of the covariance matrix with the largest eigenvalues (variance)

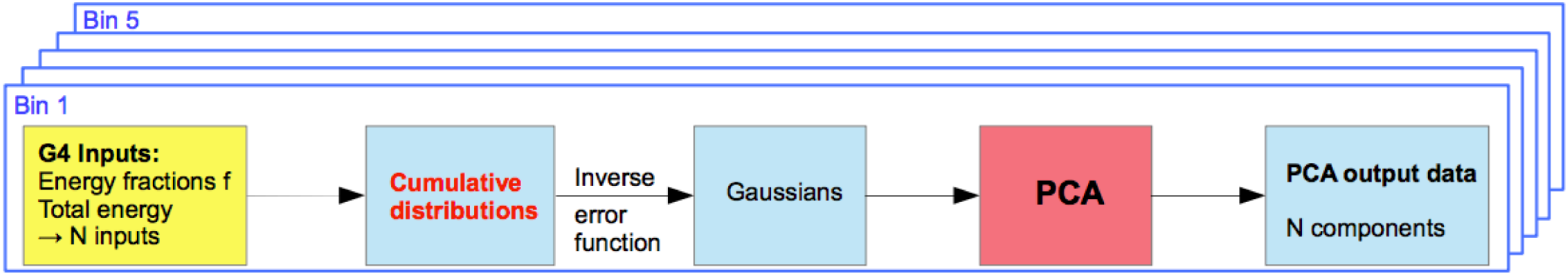
Energy fraction EM Barrel 1

Longitudinal Shower Parametrization

Use the 1st PCA to divide the input events (in different bins of PCA) into categories corresponding to different types of showers

↓

Use a 2nd PCA to further decouple the correlation for each type of shower (i.e. in each PCA bin)



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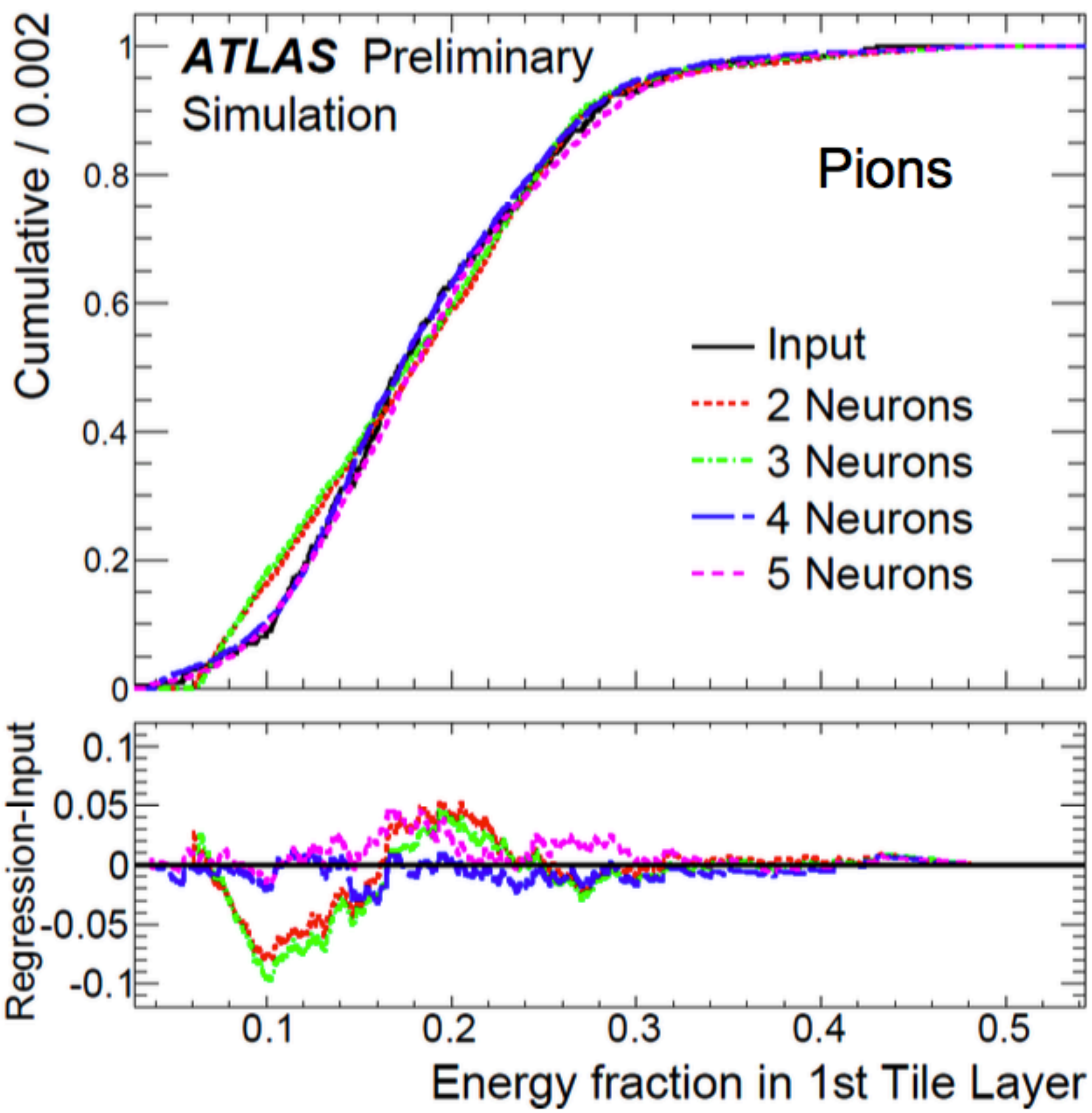
N linearly uncorrelated gaussian distributions

Cumulative distributions, PCA matrices, mean and RMS of the Gaussians are stored for parametrization

Longitudinal Shower Parametrization

Goal: Memory optimization
Difficulty: Large memory consumption by the cumulative distributions
Solution: Multivariate regression to approximate the functional form



Multi Layer Perceptron (MLP) used for regression

Number of weights needs to be saved scales with the number of neurons

No of weights = $1 + n + (2n)$
n = no. of neurons

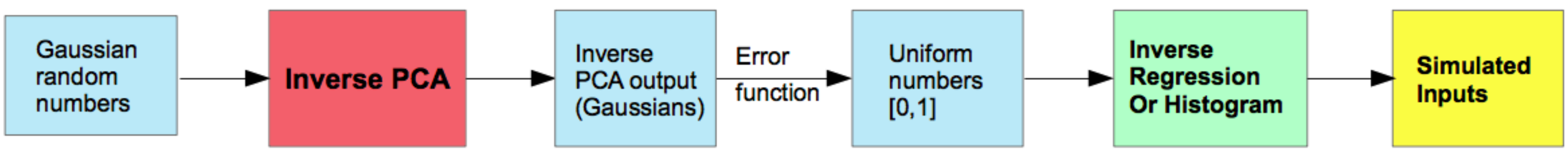
Iterative procedure to achieve good agreement and optimized number of neurons

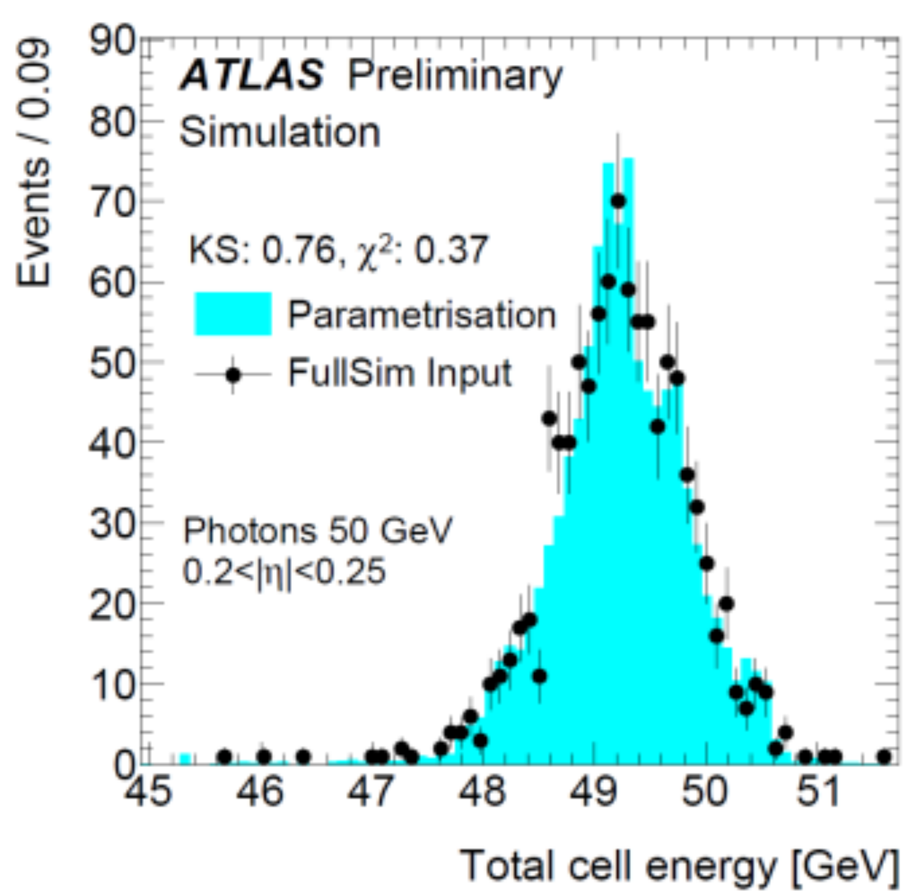
Only weights from multilayer perceptron are stored!

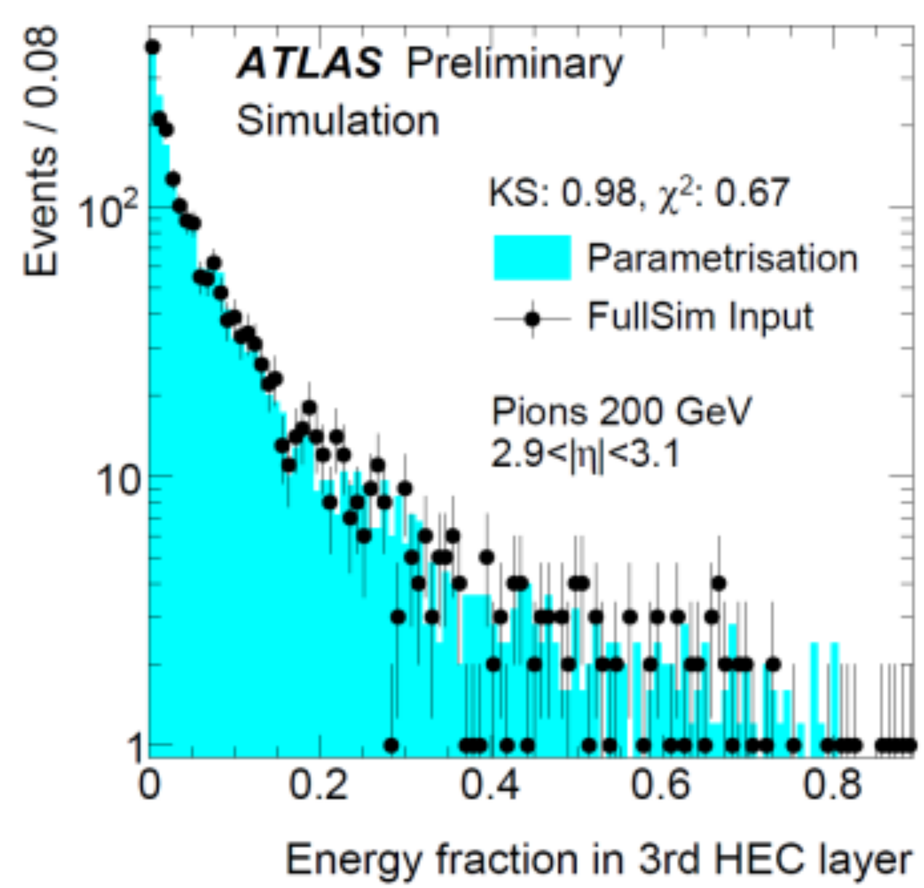
Longitudinal Shower Simulation

Randomly determine the PCA bin: each bin has the same probably by construction

Perform inverse PCA analysis in each PCA bin







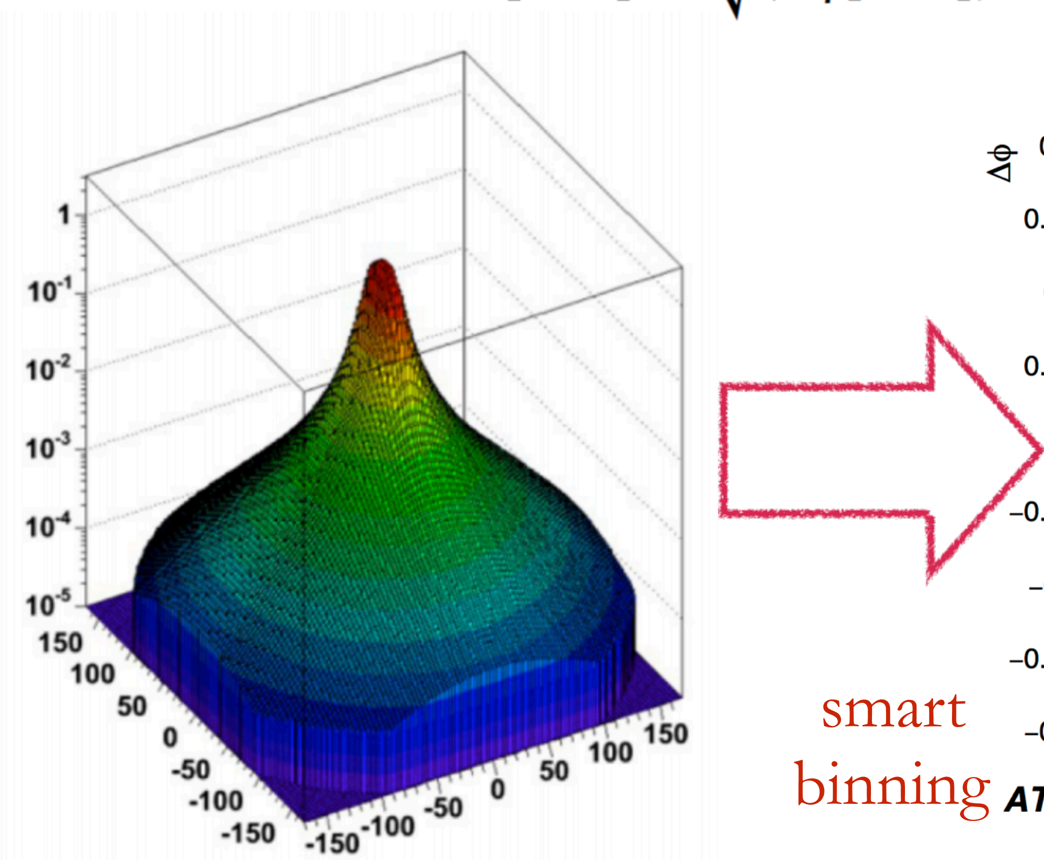
Good agreement between Geant4 and energy parametrization!

Lateral Shower Parametrization

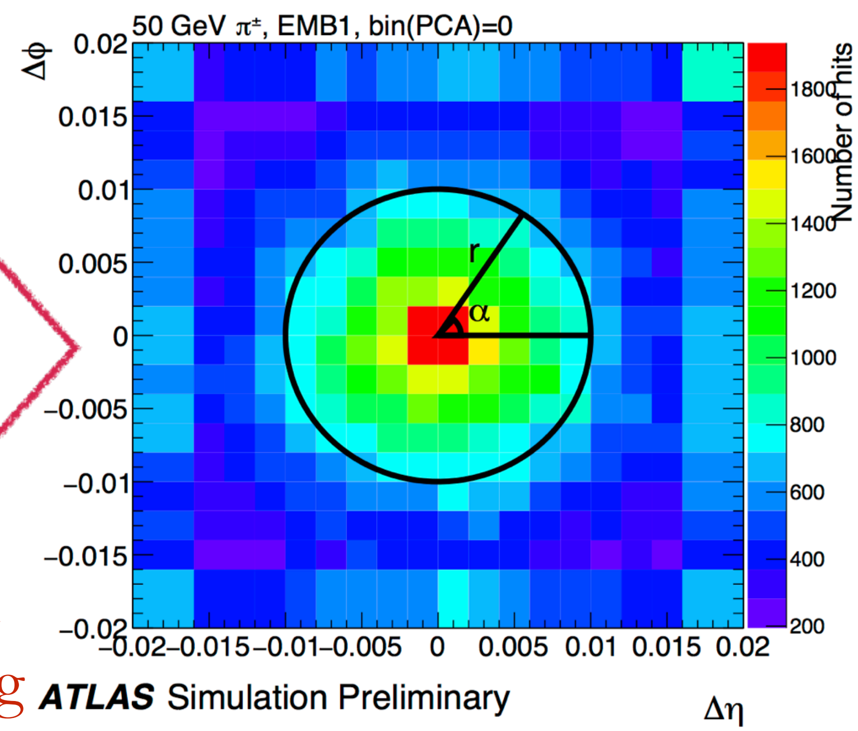
Derive shower shape parametrization for each shower type i.e. each PCA bin

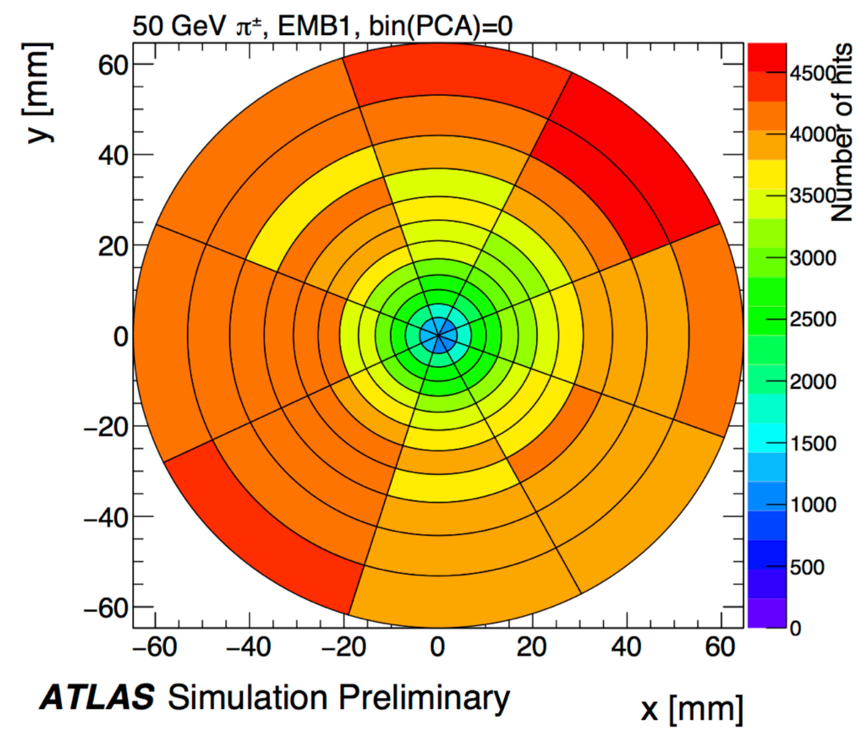
Utilize the symmetric shower topology around the center to refine the shower geometry: radial distance (r) and angle (α)

$$r[\text{mm}] = \sqrt{(\delta\eta[\text{mm}])^2 + (\delta\phi[\text{mm}])^2} \qquad \alpha = \arctan(\delta\phi[\text{mm}], \delta\eta[\text{mm}])$$



smart binning





Binning defined iteratively in (α,r) using mm units to match the calorimeter quantities

Save the parametrized shower shape in a 2D histogram

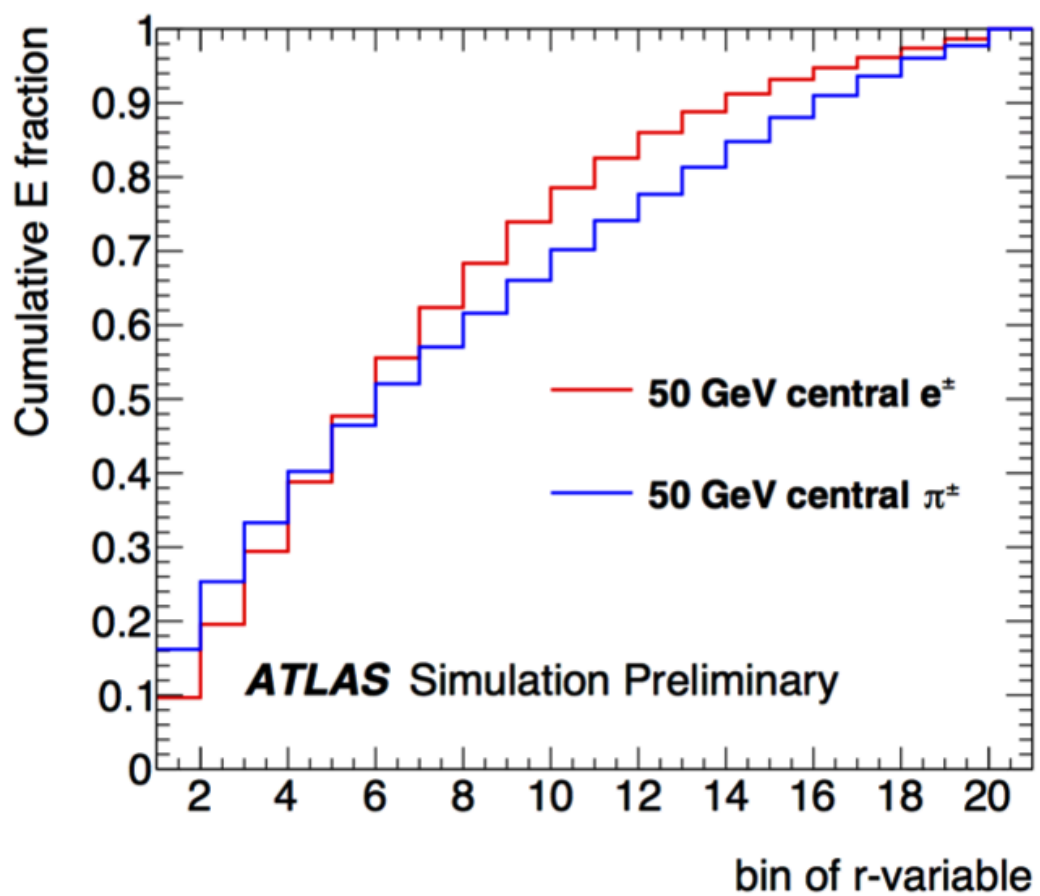
FastCaloSimV2

Lateral Shower Regression

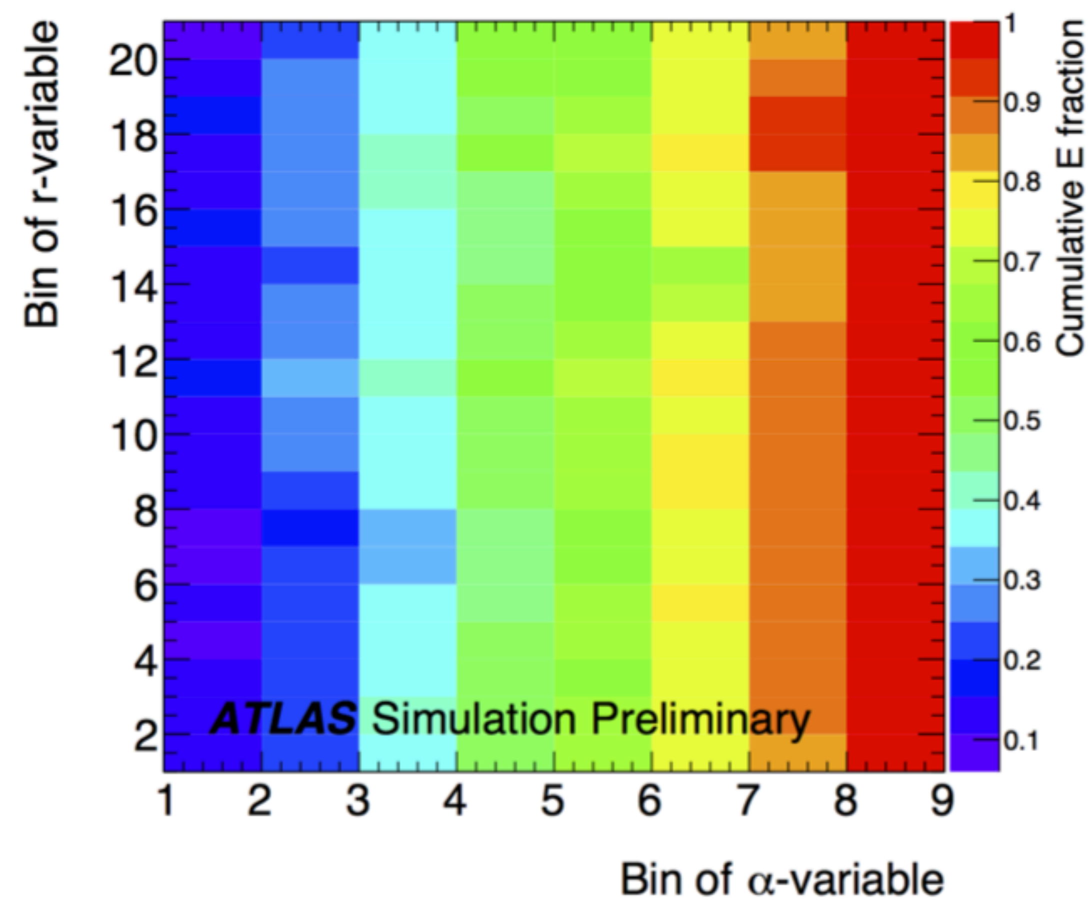
Goal: Optimize memory and I/O consumption

Solution: Get hit co-ordinates (α,r) from probability densities, without saving or reproducing the entire energy distribution

P(r) calculated using the cumulative hit energy in bins or r, averaged for all α:



P(α) calculated using the cumulative hit energy in bins or α, for each r bin:



Train the MLP with P(α) , P(r) as input variables and α, r as target variables

Shape regression is under development: Coming soon!

Lateral Shower Simulation

Randomly sample hit position from the 2D histograms

Number of hits sampled in each layer for a given energy

Determine the number of hits such that the statistical fluctuation corresponds to the stochastic term of energy resolution of each layer:

$$\frac{\Delta E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta \oplus \frac{\gamma}{E}$$

The position of each hit in global coordinates is calculated using a numeric solution

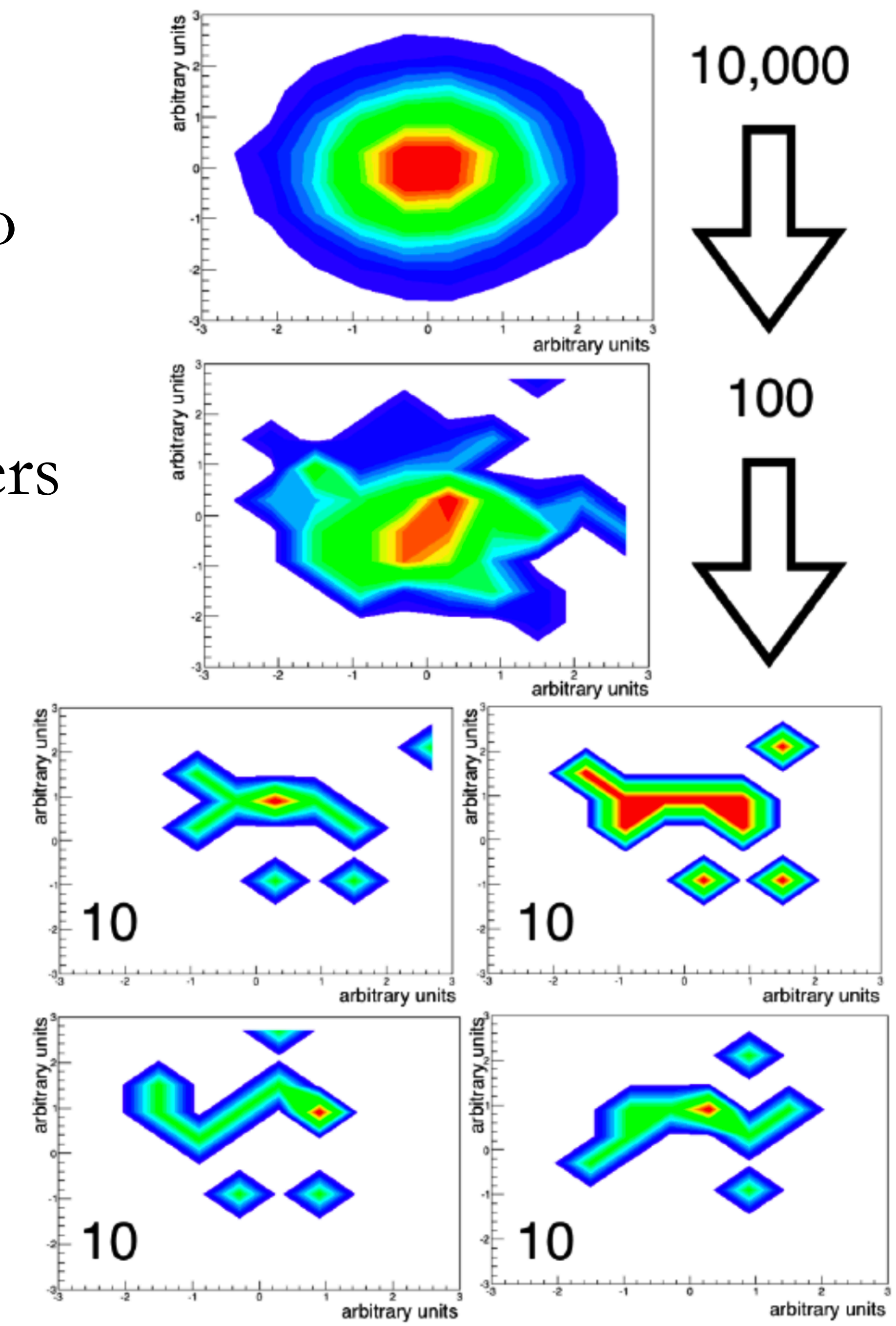
Sufficient to describe fluctuations is electromagnetic showers

Lateral Shower Fluctuation

Hadronic shower characterized by multi particle production and particle emission

Complex and irregular shower formation compared to electromagnetic processing

Results into different number of reconstructed clusters i.e. large fluctuations



Mimic hadronic shower complexity/fluctuation:

Sample fewer hits for each shower

Split one pion shower into two pion showers (probability of splitting derived from Geant4)

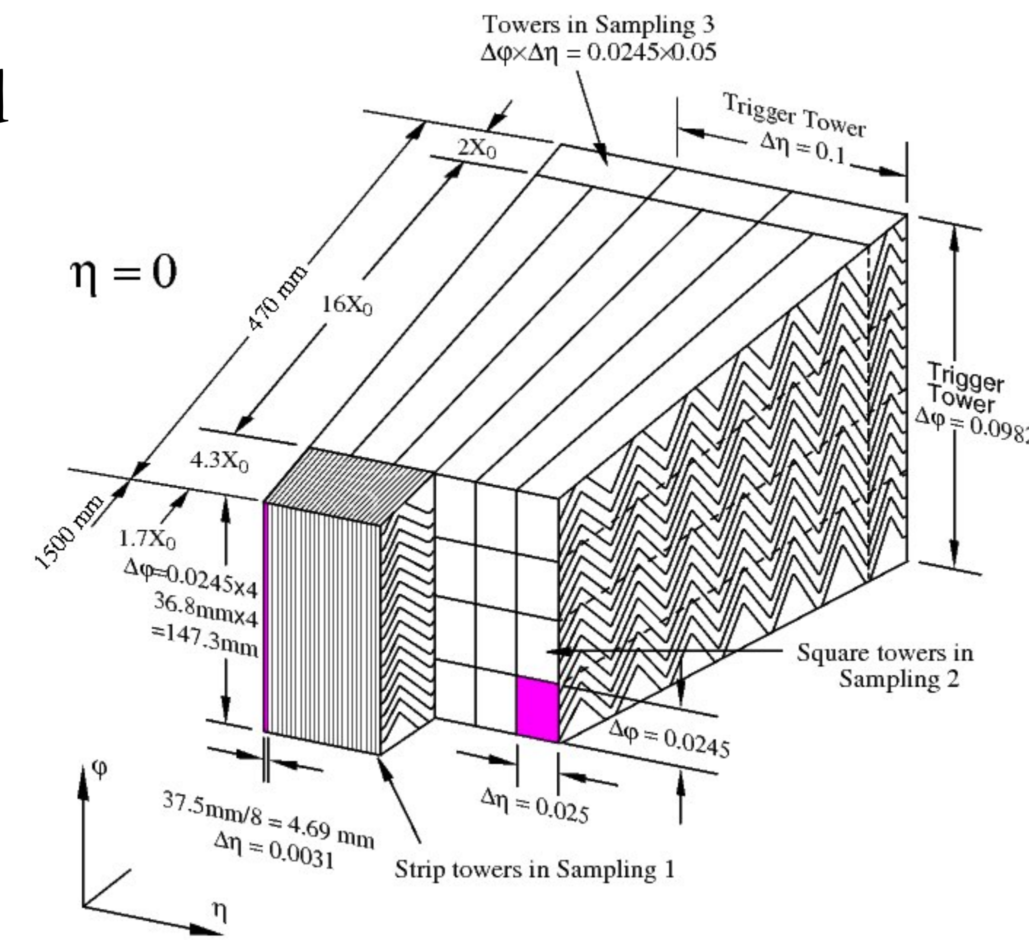
Introduce fluctuation with fewer hits and pion splitting

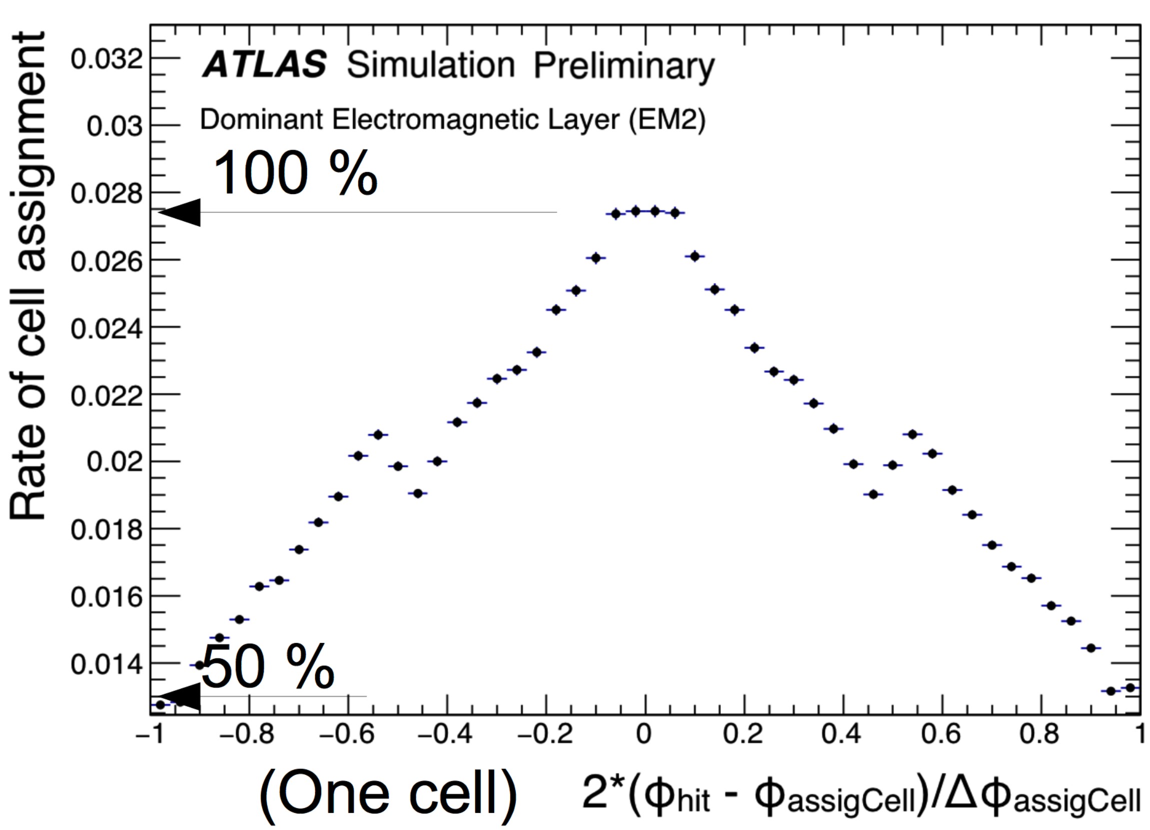
Hit to Cell Assignment: Correct for simplified Geometry

Simulated hits assigned to cells assuming a simplified cuboid geometry

In reality, the calorimeter has a accordion geometry

Results in incorrect hit to cell assignment



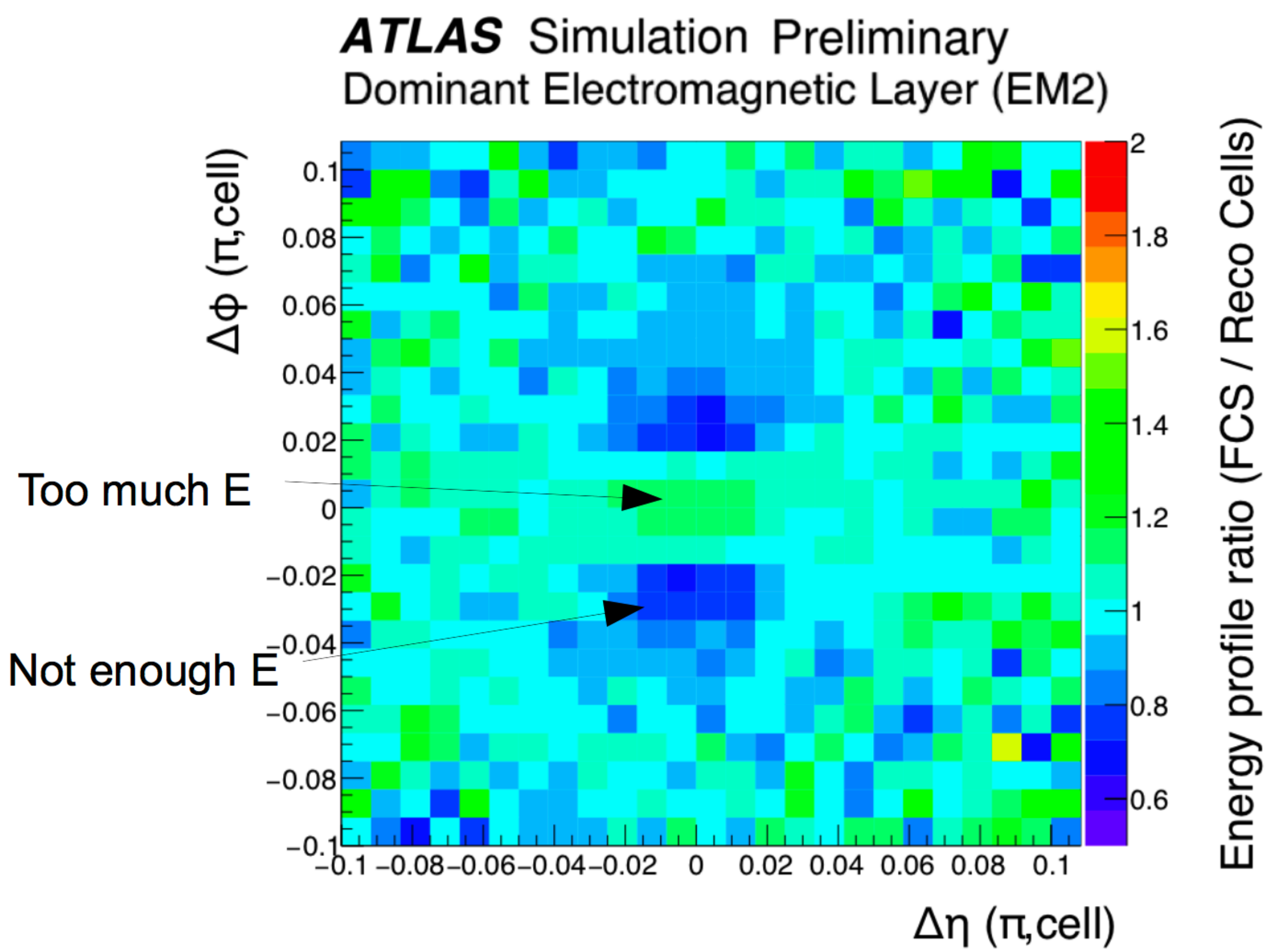


Define a function to describe the probability that a hit belongs to a neighboring cell

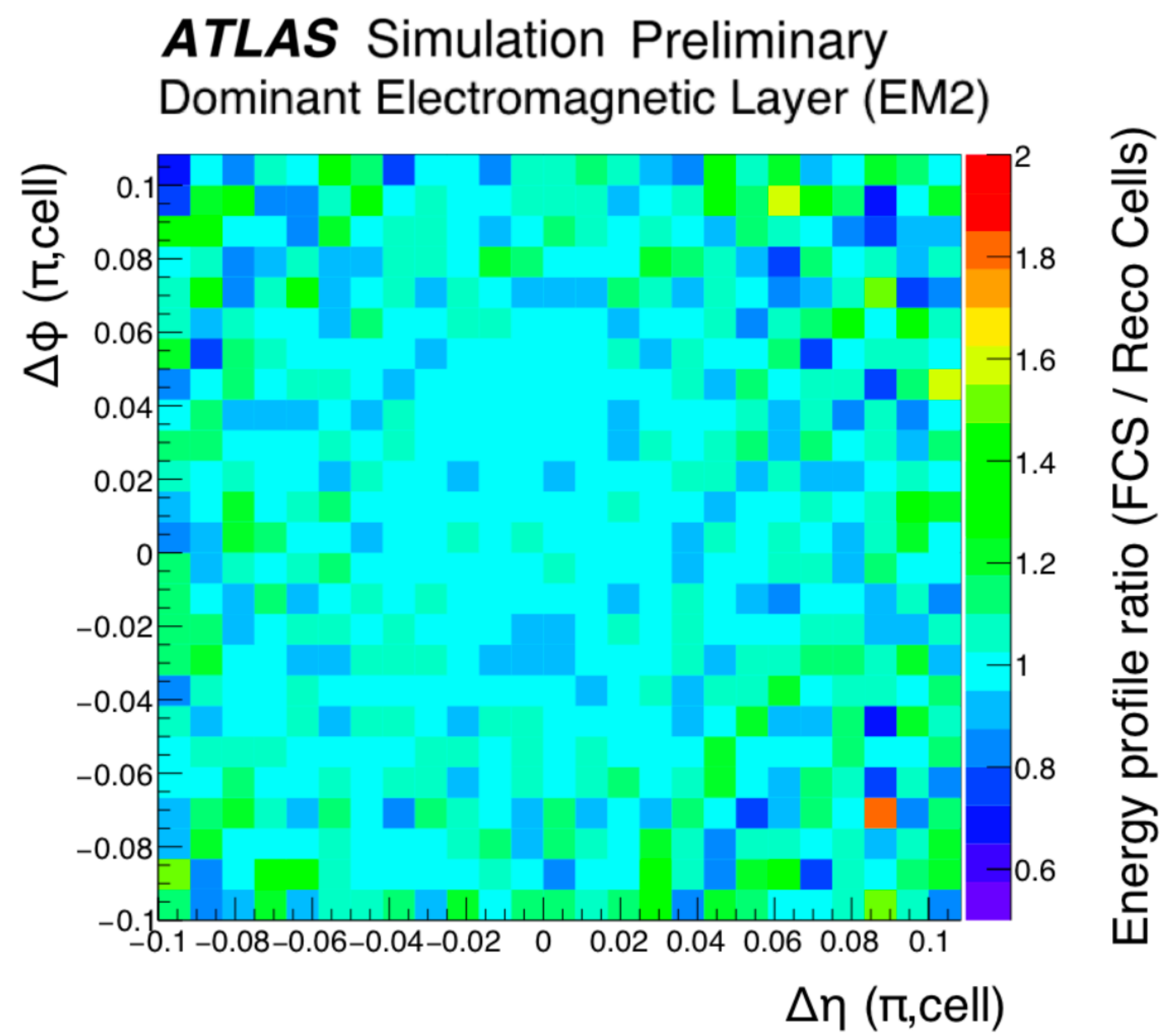
Correct for simplified geometry with a hit displacement function

Hit to Cell Assignment: Correct for simplified Geometry

w/o hit displacement



w/ hit displacement



Reco cell: Geant4 cell
FCS cell: assigned cell

Good agreement with Geant4 cell assignment!

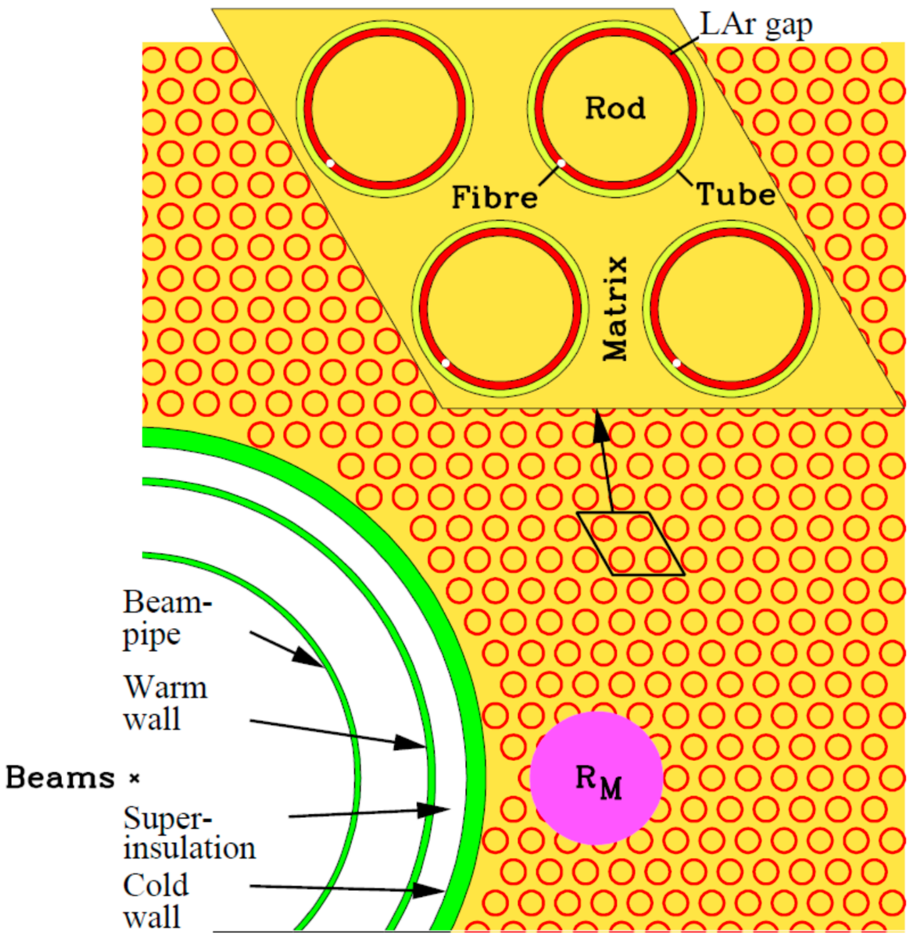
Forward Calorimeter Geometry

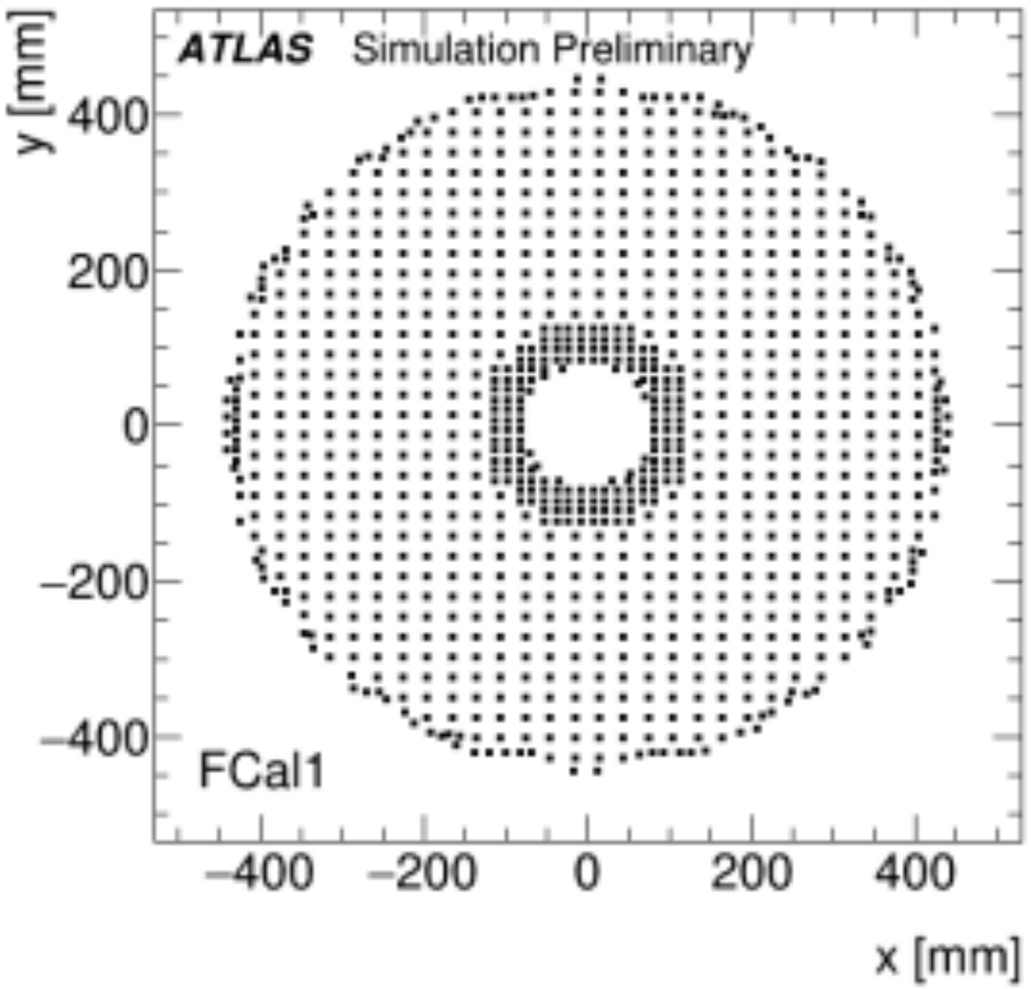
Cylindrical anodes are arranged in a rhombus-like formation for the forward calorimeters (FCal)

Significantly different geometry compared to cuboid barrel layers

Correct geometry is implemented in the FastCaloSimV2

FCAL End View





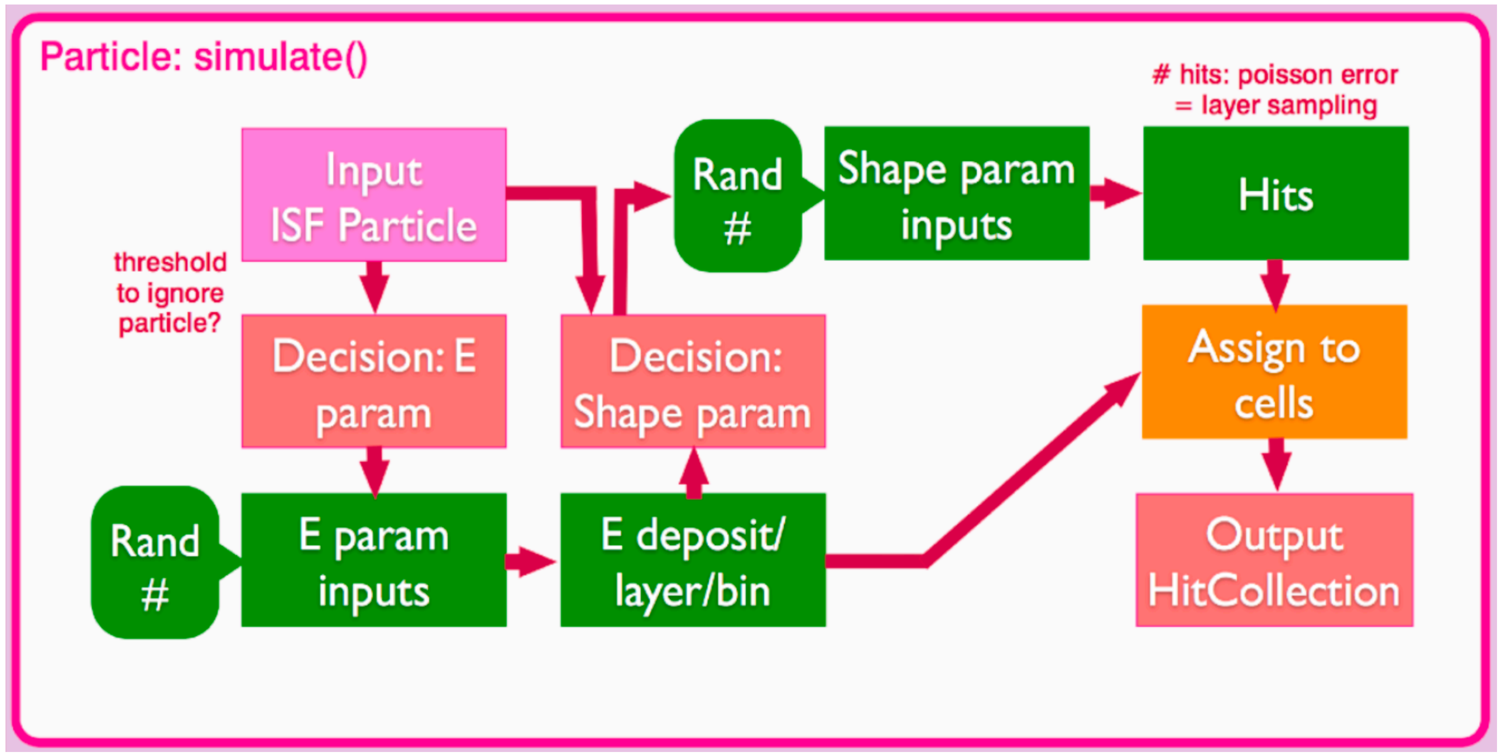
Dedicated parametrization for* FCals *are foreseen

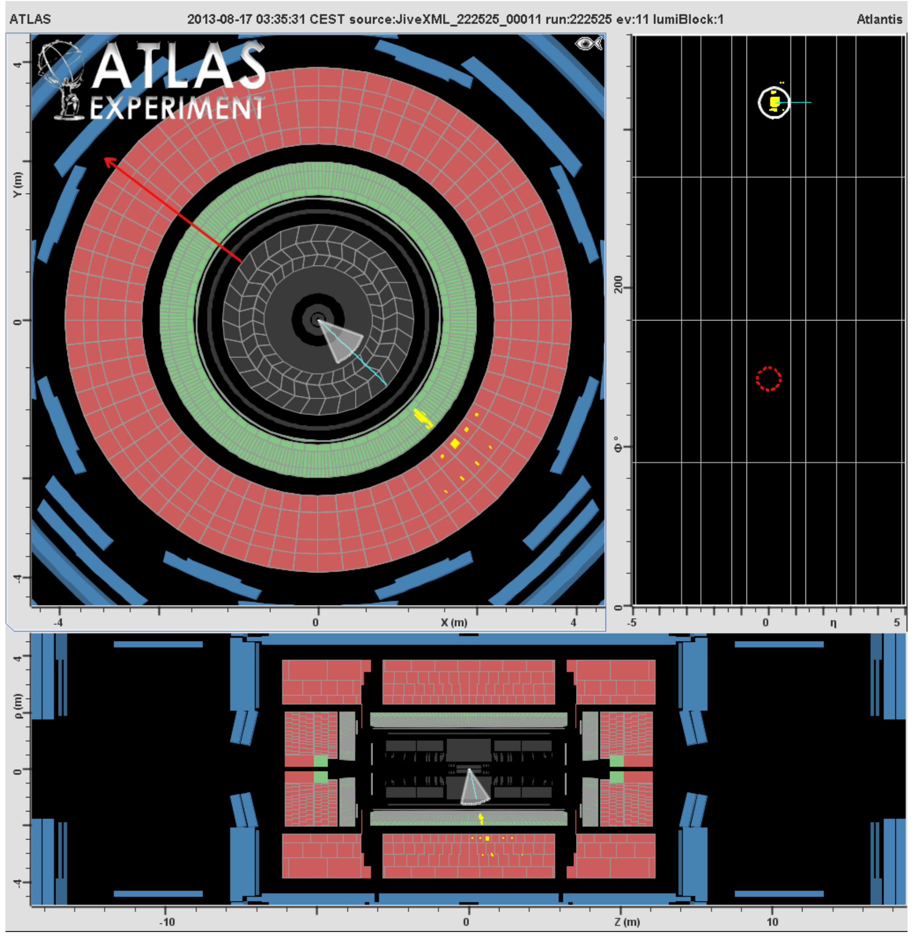
Prototype: Putting it all together!

FastCaloSimV2 is part of the Integrated Software Framework (ISF)

Only the ATLAS Calorimeter is simulated with fast simulation, inner detector and muon systems are simulated with Geant4

Integrated in the ATLAS software development and production releases





Utilizes the entire Monte Carlo production chain to produce reconstructed single particle events for validation

Validation: How well does it perform?

Current validation performed with single particle events

Study shower shape variables for electromagnetic showers and cluster variables for hadronic showers

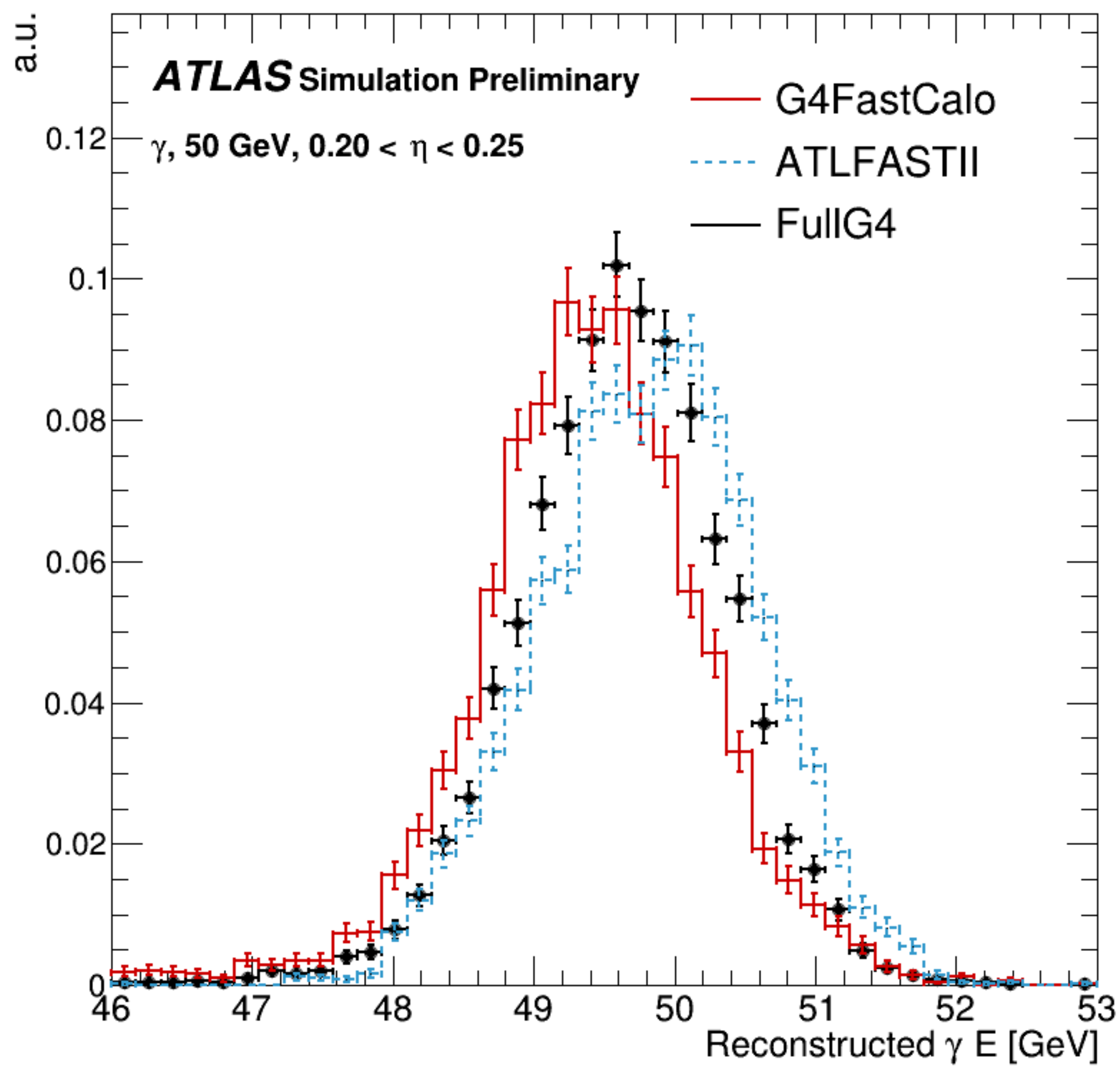
Compare the distributions with the ATLFASTII and Full Geant4 simulated distributions

G4FastCalo = FastCaloSimV2 for calorimeter + Geant4 for ID/muon
ATLFASTII = FastCaloSim for calorimeter + Geant4 for ID/muon
Full Geant4 = Geant4 for calorimeter, ID and muon

ATLFASTII ***events are tuned to data!***
G4FastCalo ***events are not yet tuned***

Performance in electromagnetic shower

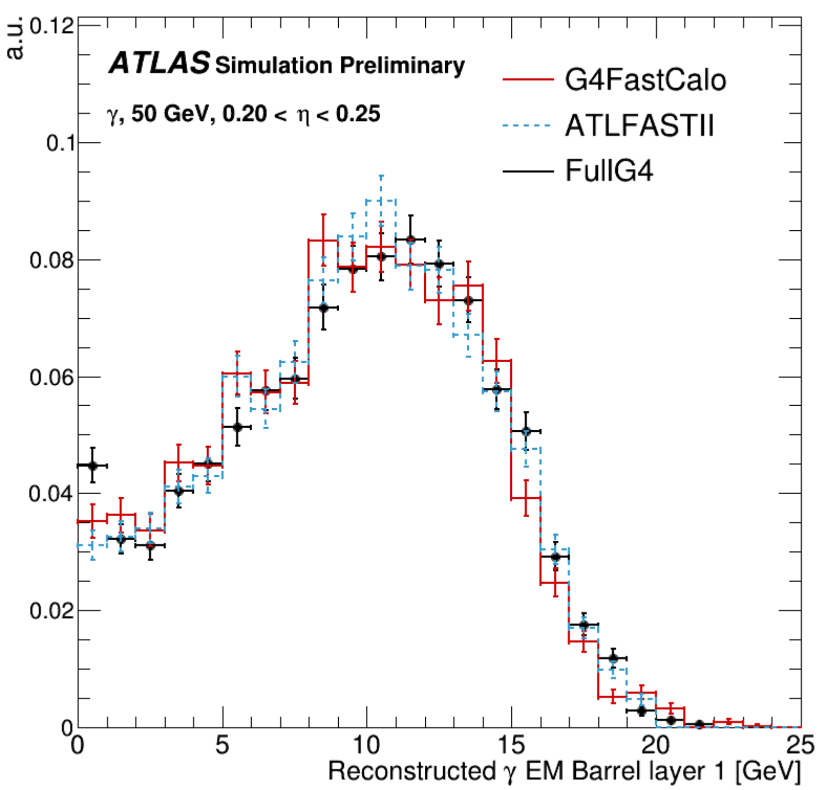
Reconstructed photon energy

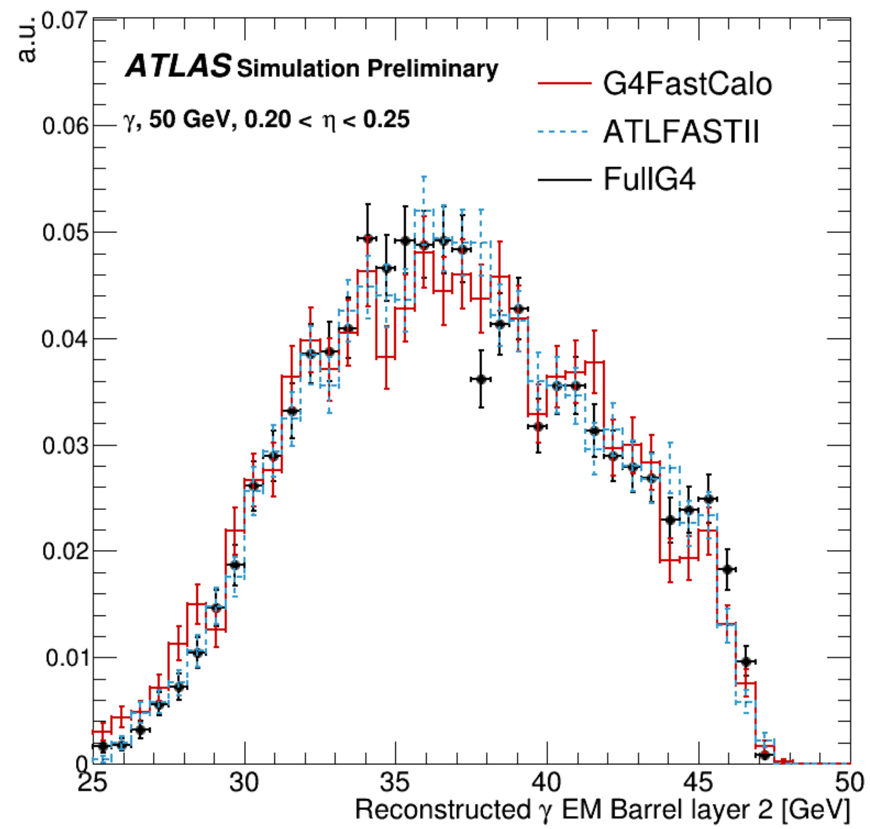


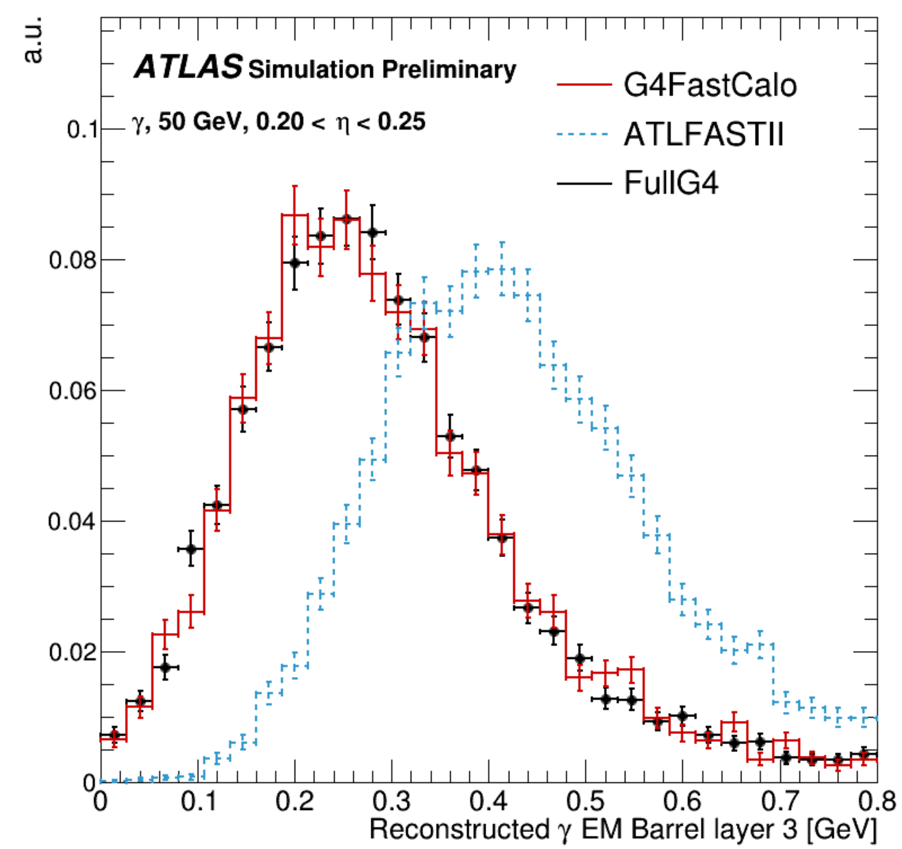
Mean value closer to Geant4 compared to AF2

Reconstructed photon energy in each layer

Energy fraction in each electro magnetic (EM) barrel layer





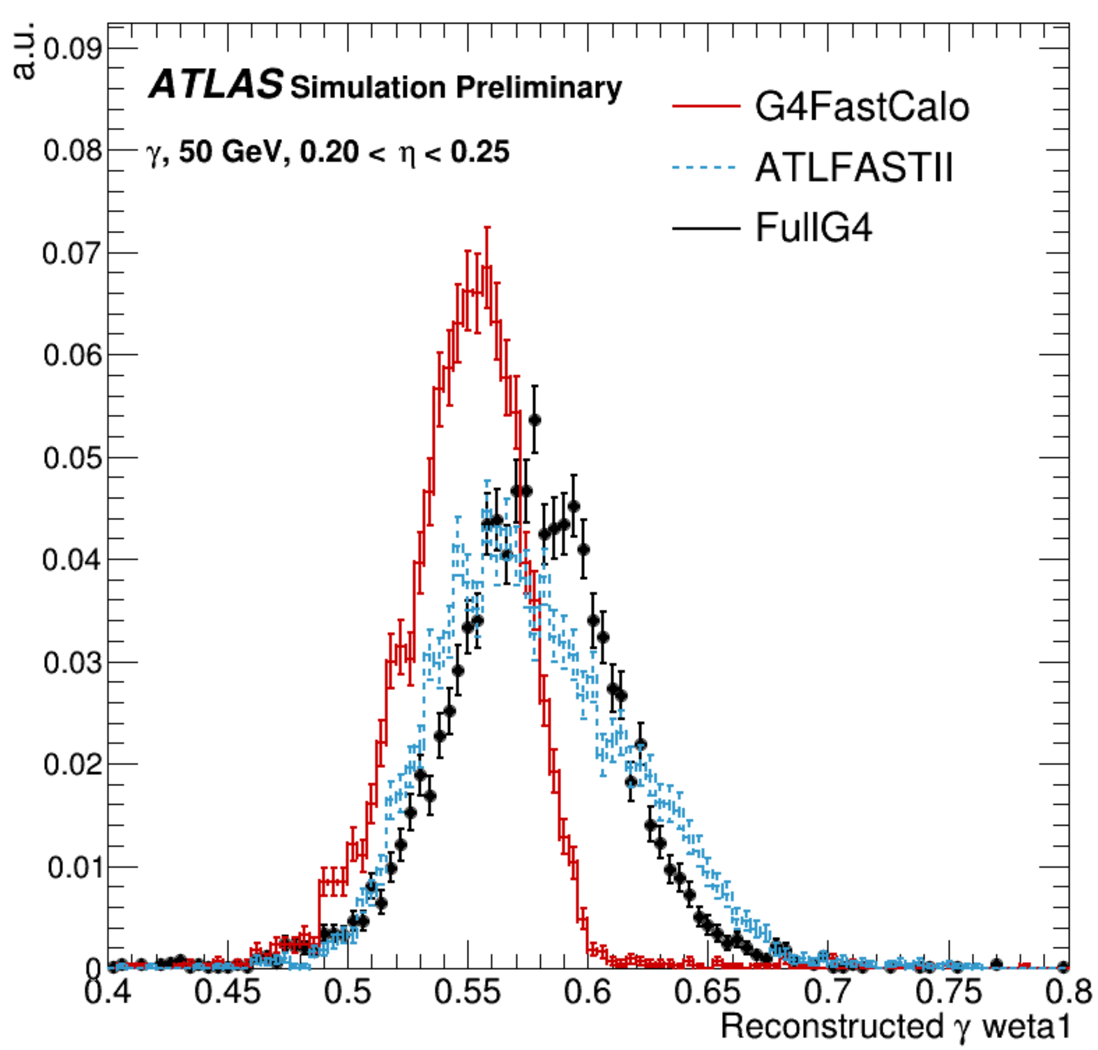


Significant improvement in layer 3 compared to AF2

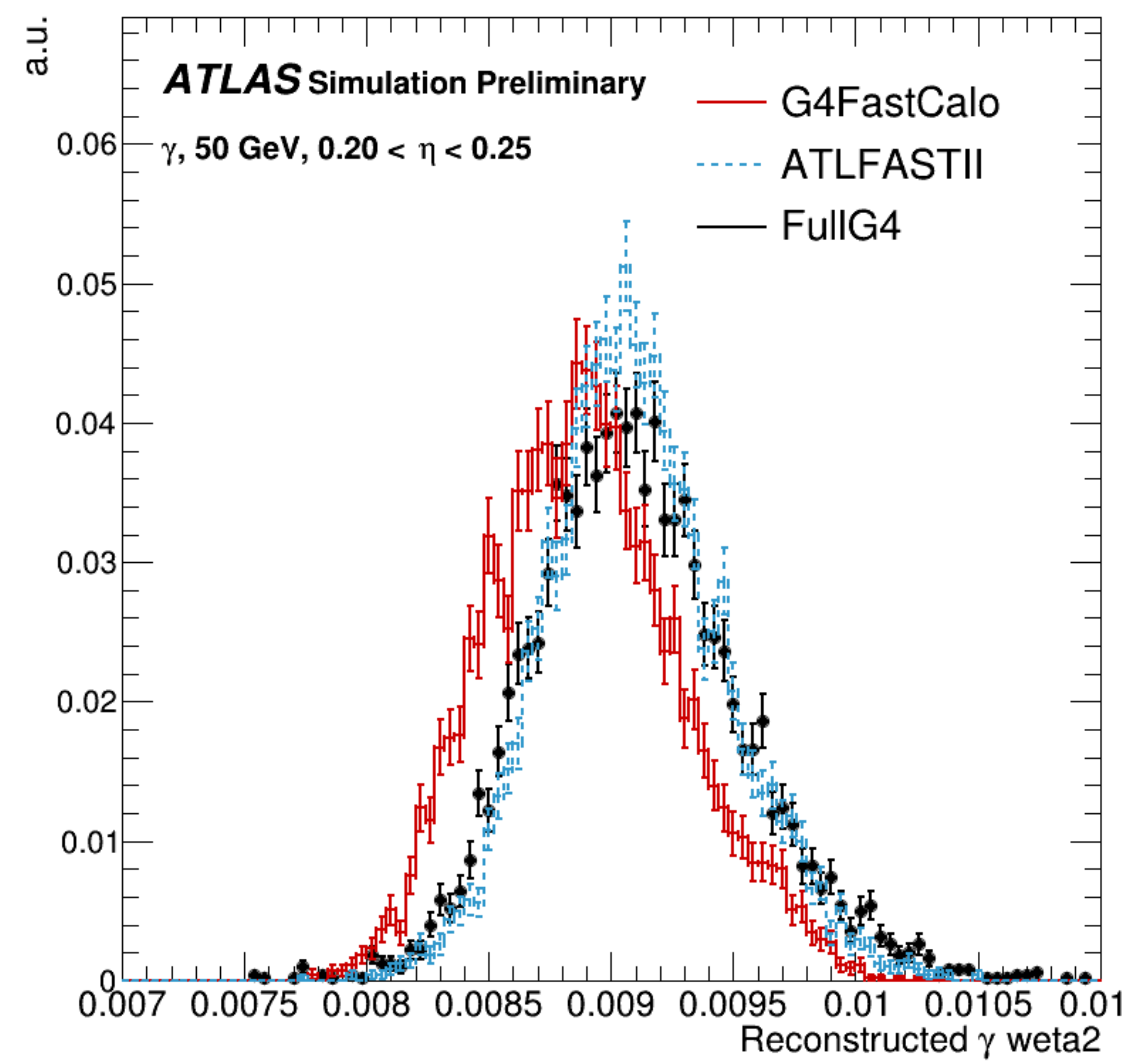
FastCaloSimV2

Photon shower shape

Shower width using +/- 3 strips around the one with the maximal energy deposit



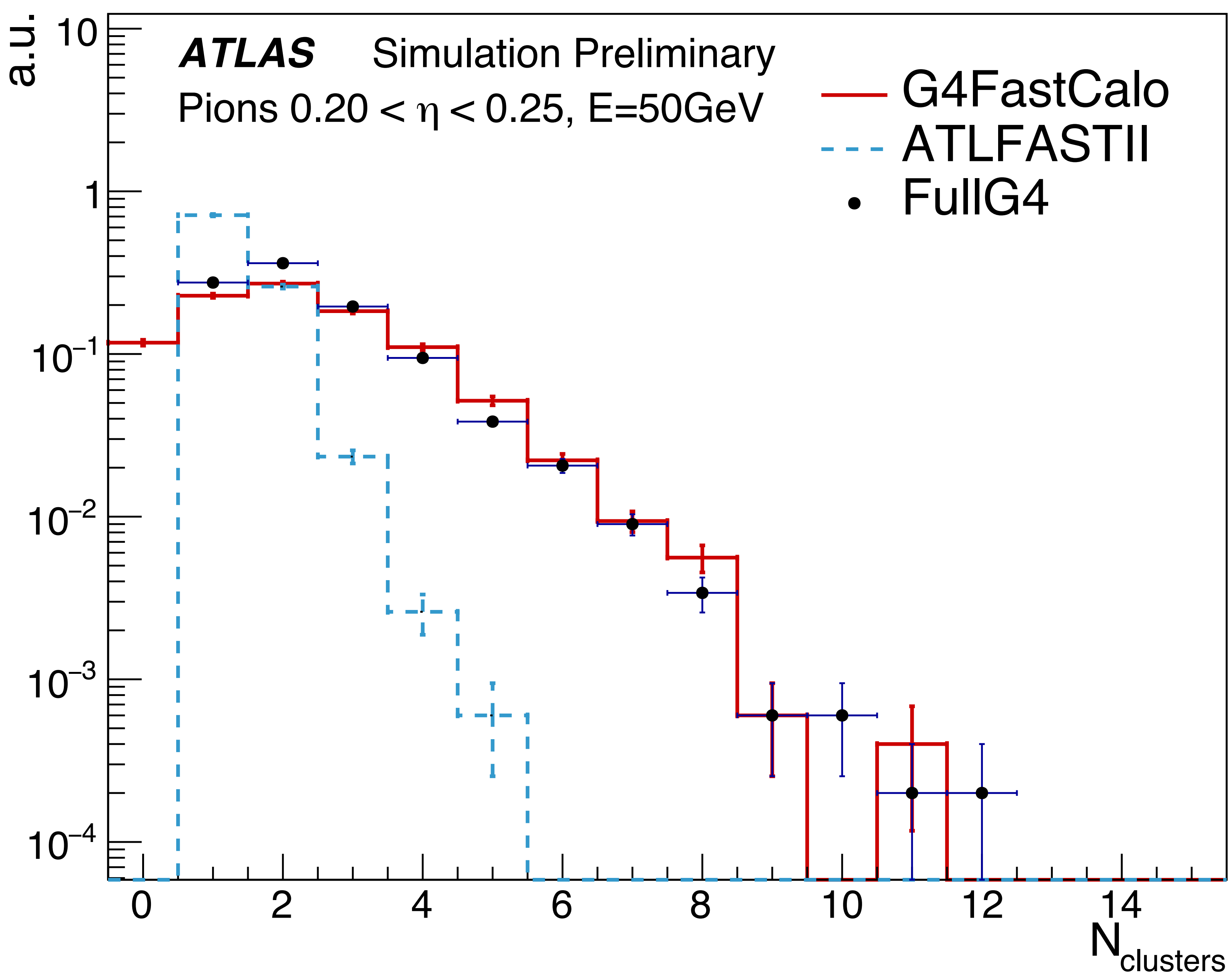
Lateral shower width calculated using 3x5 cells window



Requires tuning and further optimization for some variables

Performance in hadronic shower

Number of Calorimeter Clusters

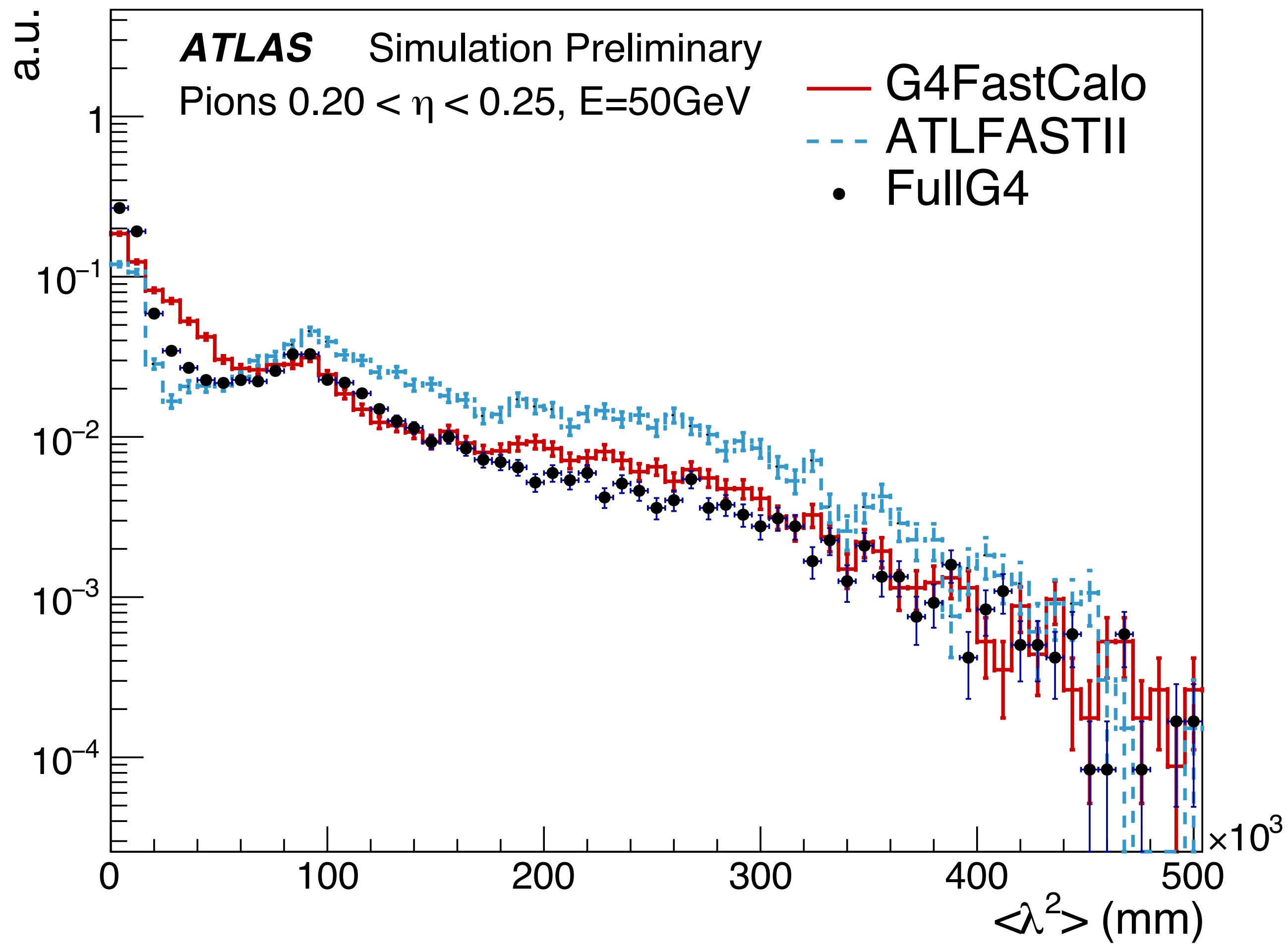


Significant improvement compared to AF2 with a caveat that a fraction of events are reconstructed without any cluster

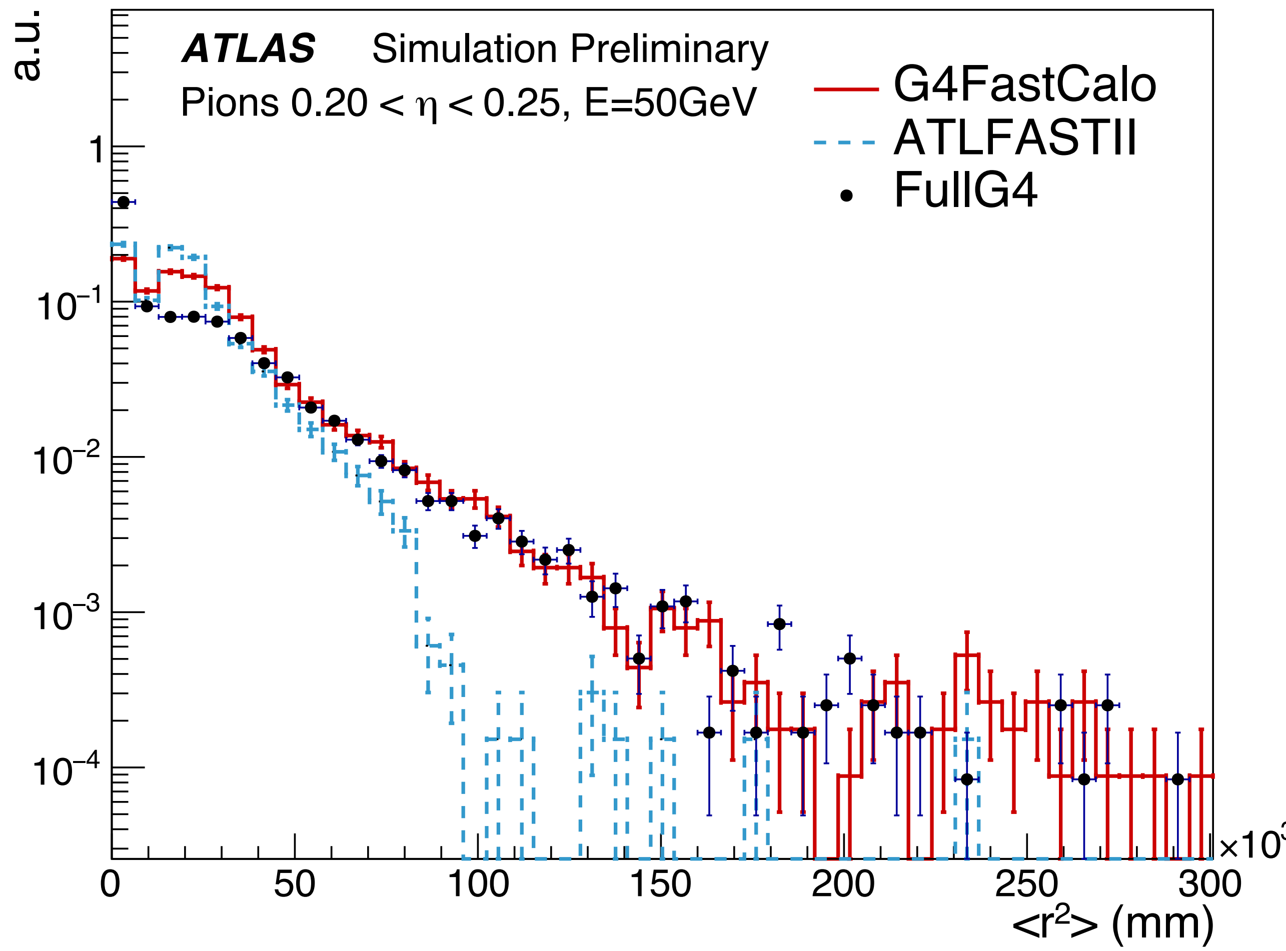
FastCaloSimV2

Cluster moments

Describe inner structure of a cluster $$< x^n >= \frac{\sum_{E_i>0} E_i x_i^n}{\sum_{E_i>0} E_i}$$



λ distance from the shower center along shower axis

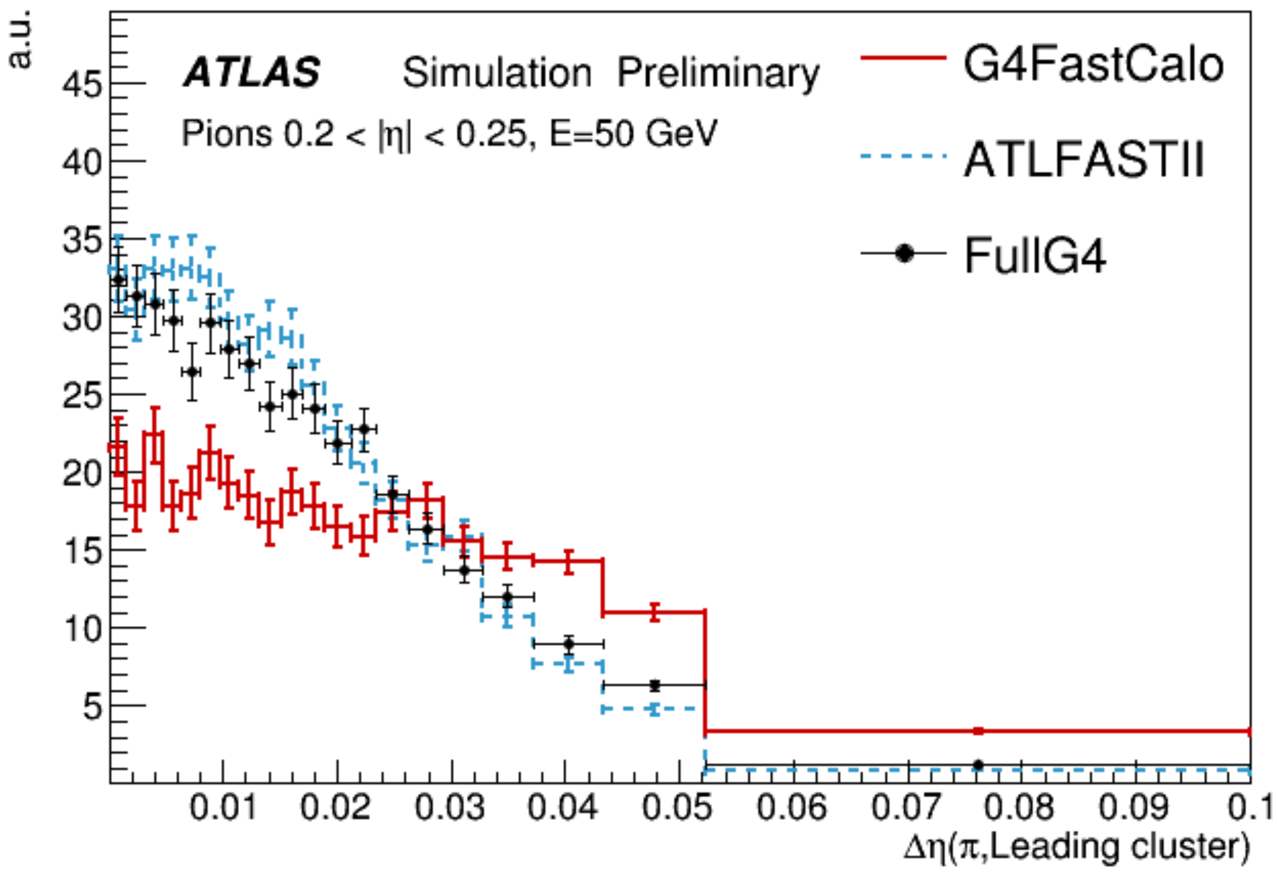


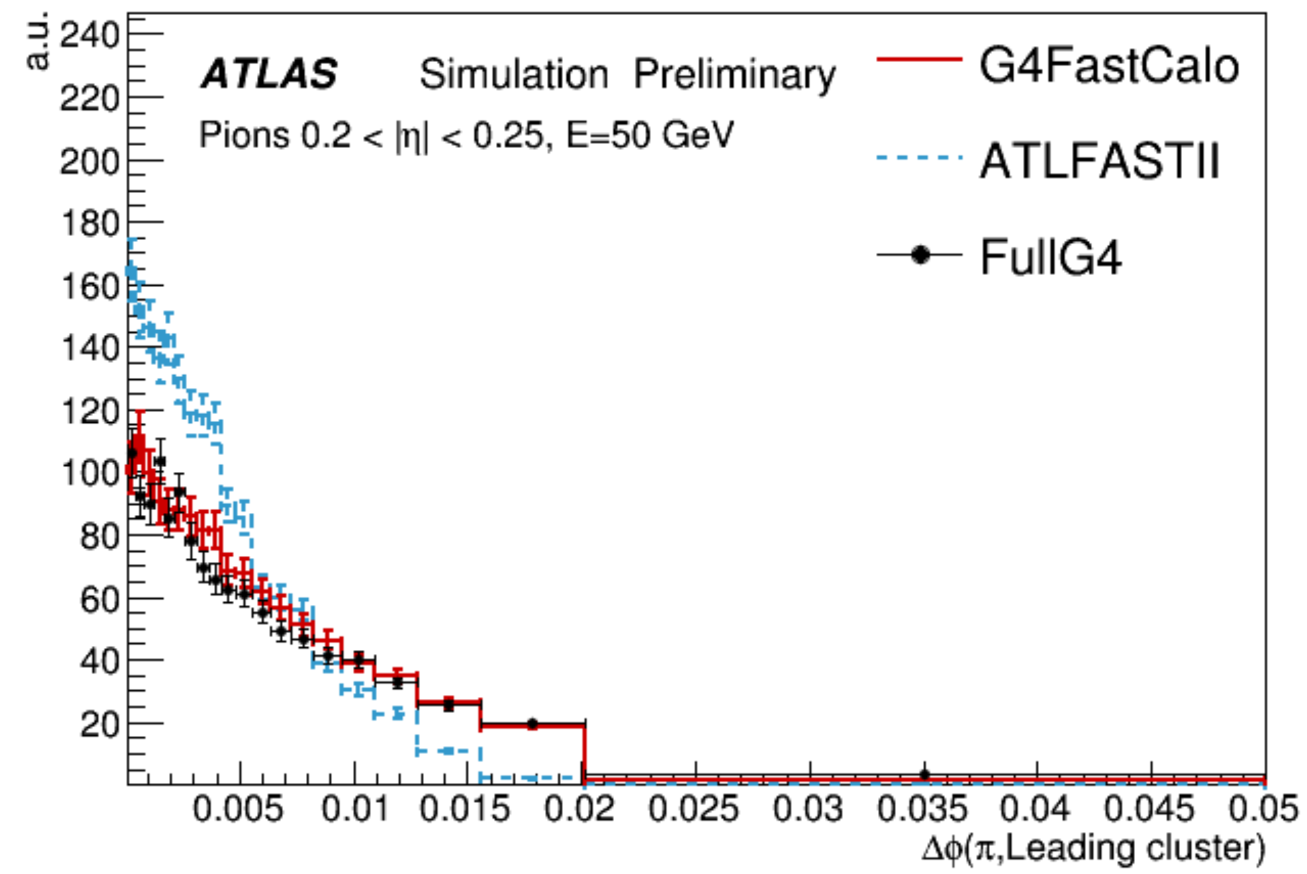
r perpendicular distance of the cell from the shower axis

Agreement with Geant4 can be improved at low values

Leading Cluster Variables

Cluster with the largest energy deposit is the leading cluster





Significant mismodeling for Δη distribution whereas excellent agreement for Δφ distribution

Summary and Outlook

- Fast simulation essential for ATLAS physics program at 14 TeV and at HL-LHC
- Current fast calorimeter simulation does not describe collision data adequately to be used in precision measurements
- New fast calorimeter simulation has been developed and the first prototype is integrated in the ATLAS software release
- FastCaloSimV2 shows good agreement with Geant4 and in some cases outperforms the current FastCaloSim out of the box
- Current version only tested for a certain energy and rapidity region. Parametrization and validation needs to be performed for other (E,η) points
- With complete (E,η) parametrization, physics processes would be simulated for validation and tuning to collision data

Stay tuned!