Fast Simulation in ATLAS

Fast Simulation Discussion
HSF Simulation Working Group

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On behalf of the ATLAS Collaboration

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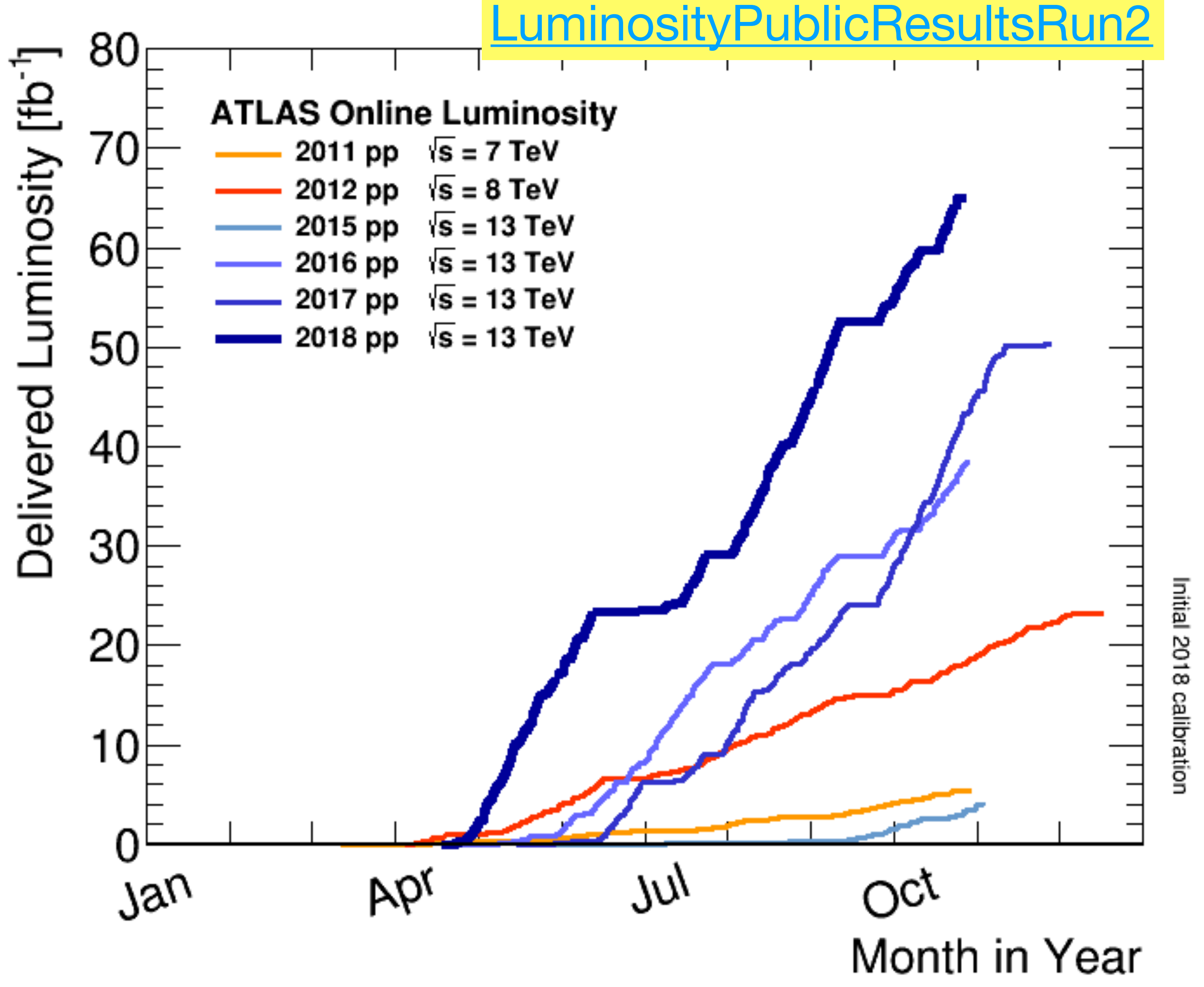
Overview: things we [all] know

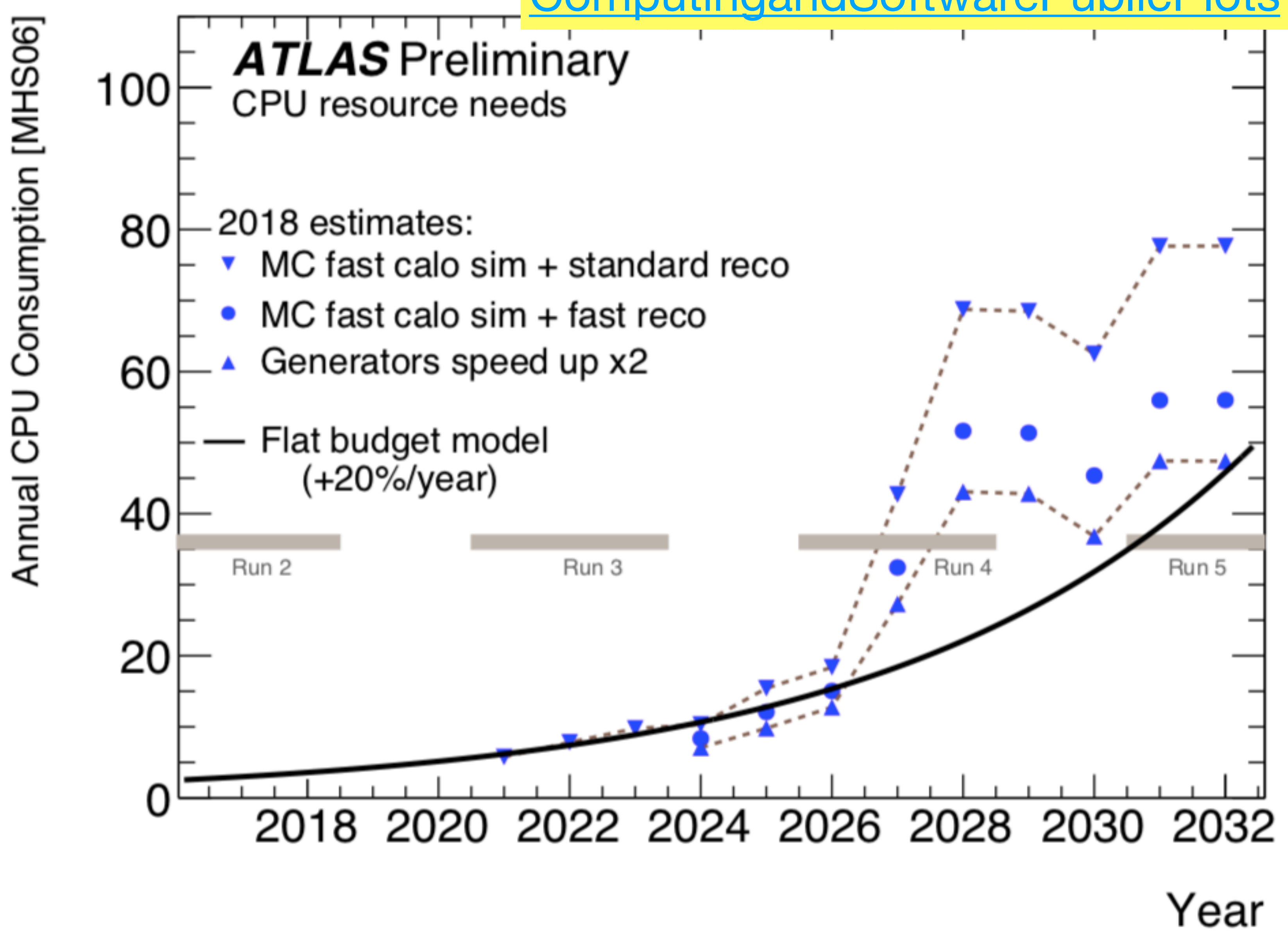
Many physics and performance studies require large datasets of simulated events

- Geant4 is highly CPU-intensive
- Already lacking statistics -- increasing luminosity poses greater challenges

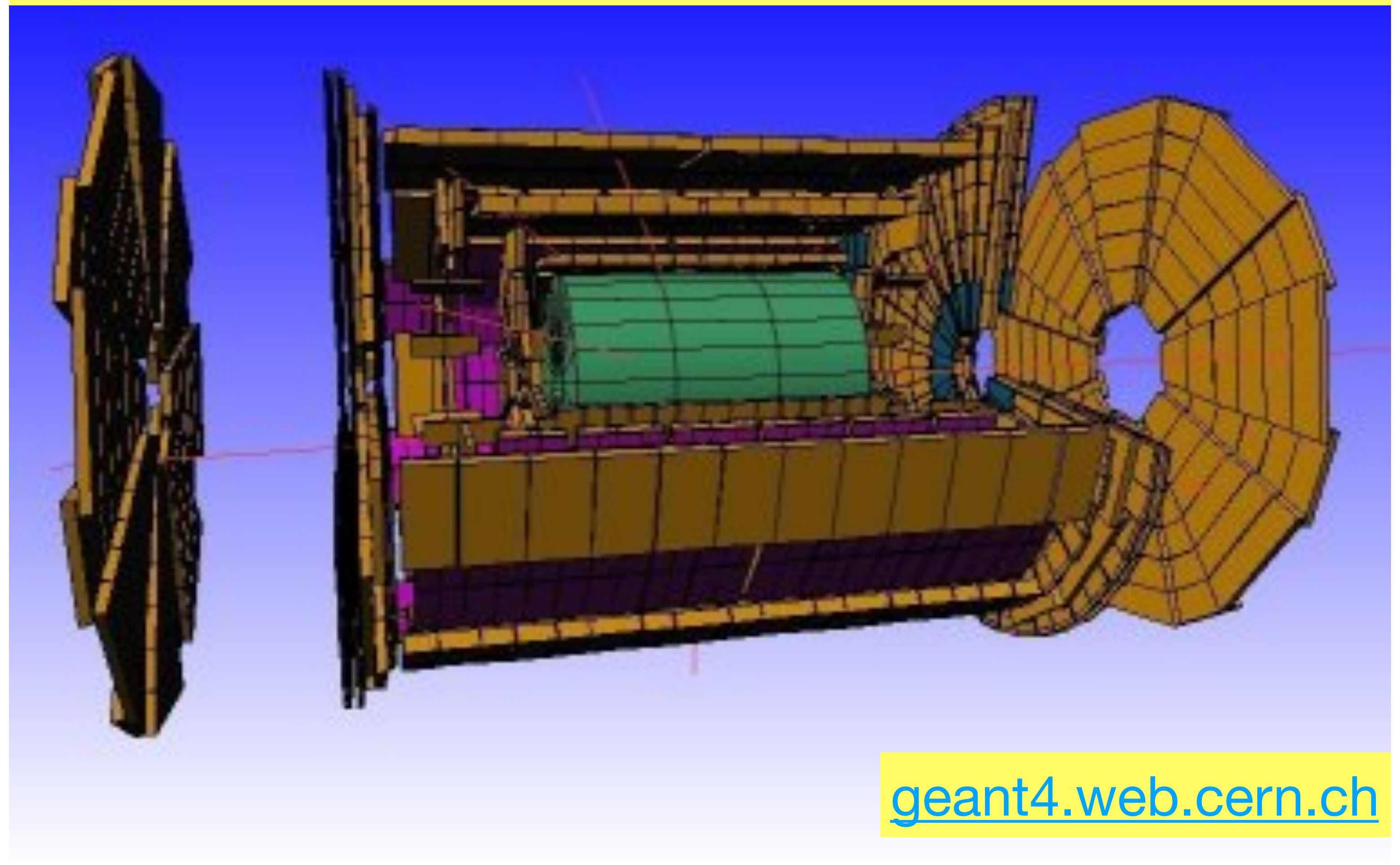
LuminosityPublicResultsRun2



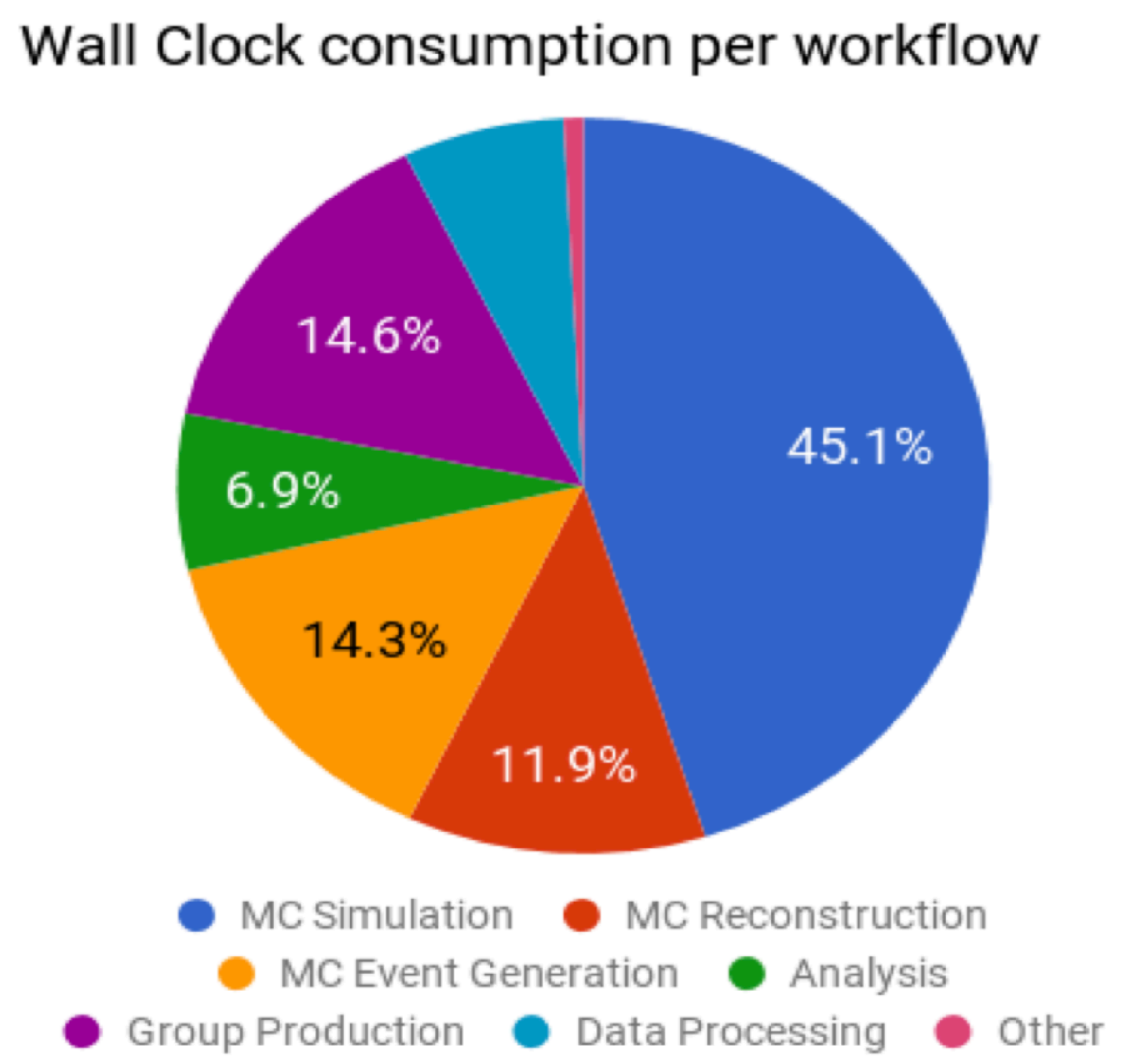
ComputingandSoftwarePublicPlots



Geant4: O(10^7) detailed volumes!



geant4.web.cern.ch



Highly-descriptive detector description not always necessary

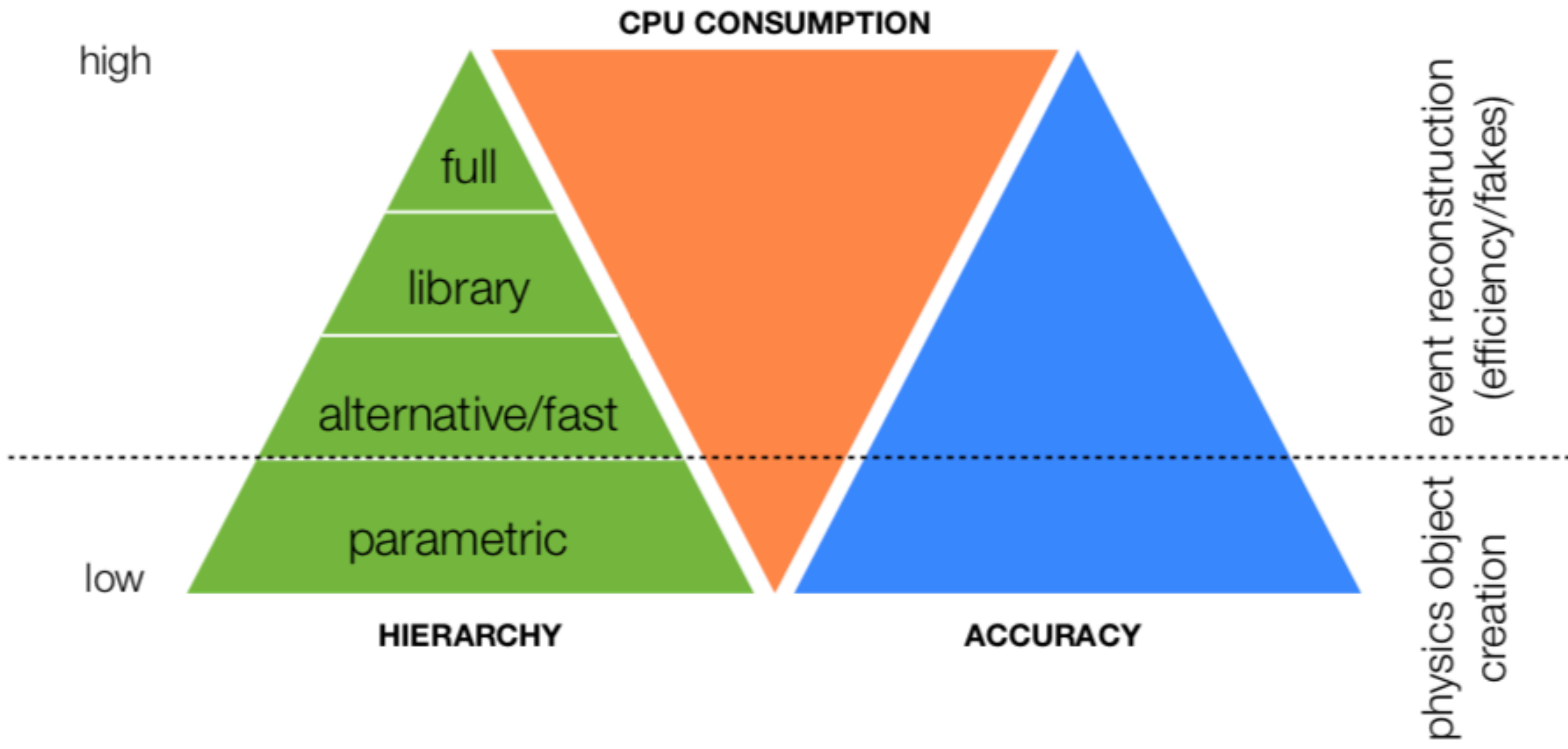
- Signal samples
- Alternative backgrounds for systematics

Overview: what we [all/ATLAS] need

Jansky 2015 J. Phys.: Conf. Ser. 664 072024

Sacrifice level of accuracy and precision for speed

- Fully simulate what is needed, use fast methods otherwise



Compatibility

- Early fast simulation (ATLFAST, i.e. object smearing) in ATLAS was incompatible with digitisation and reconstruction used for real data
- Desirable to have simulated data that can use same digitisation and reconstruction software as real data

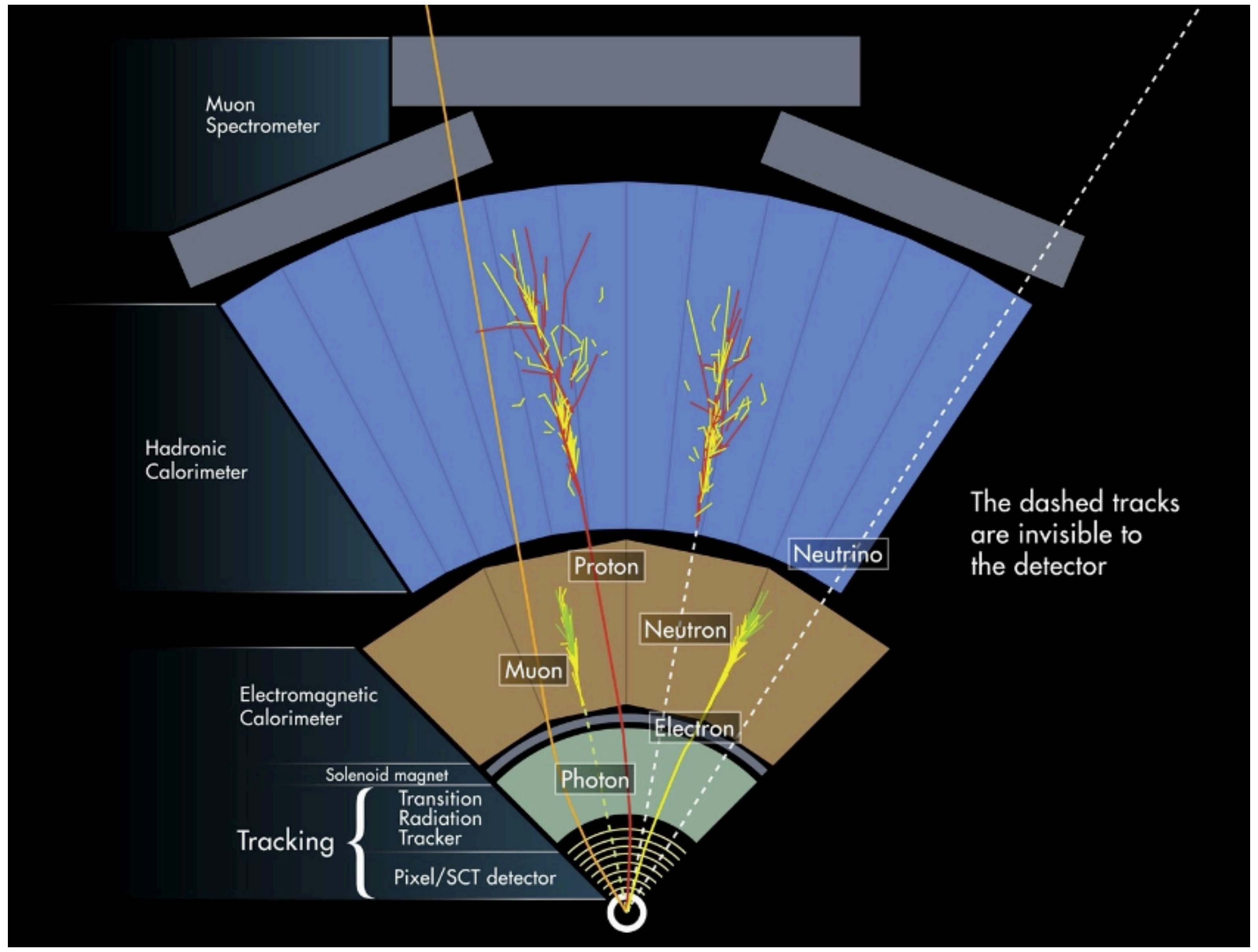
Areas for improving CPU performance

Calorimeter

- Most CPU-intensive (>90% of simulation time): particles are stopped; complicated shower modelling
- First prospect for fast simulation

Inner Detector

- Nearly 10^8 readout channels; complex modelling of readout emulation
- Pattern recognition: combinatorial problem as function of <μ>

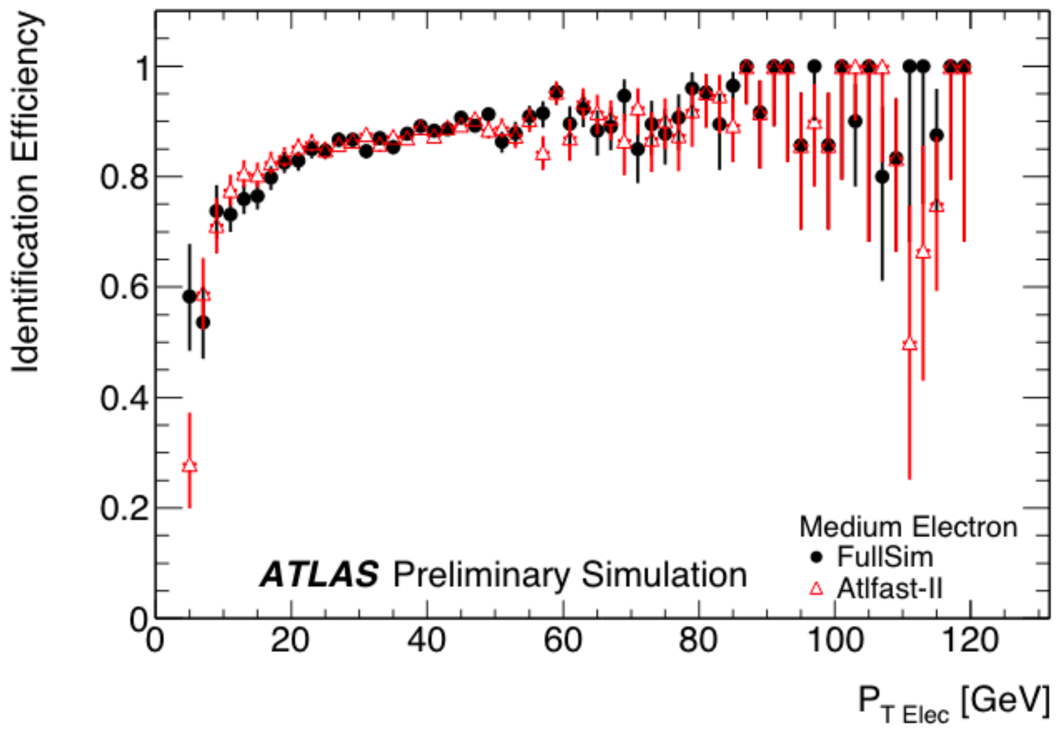


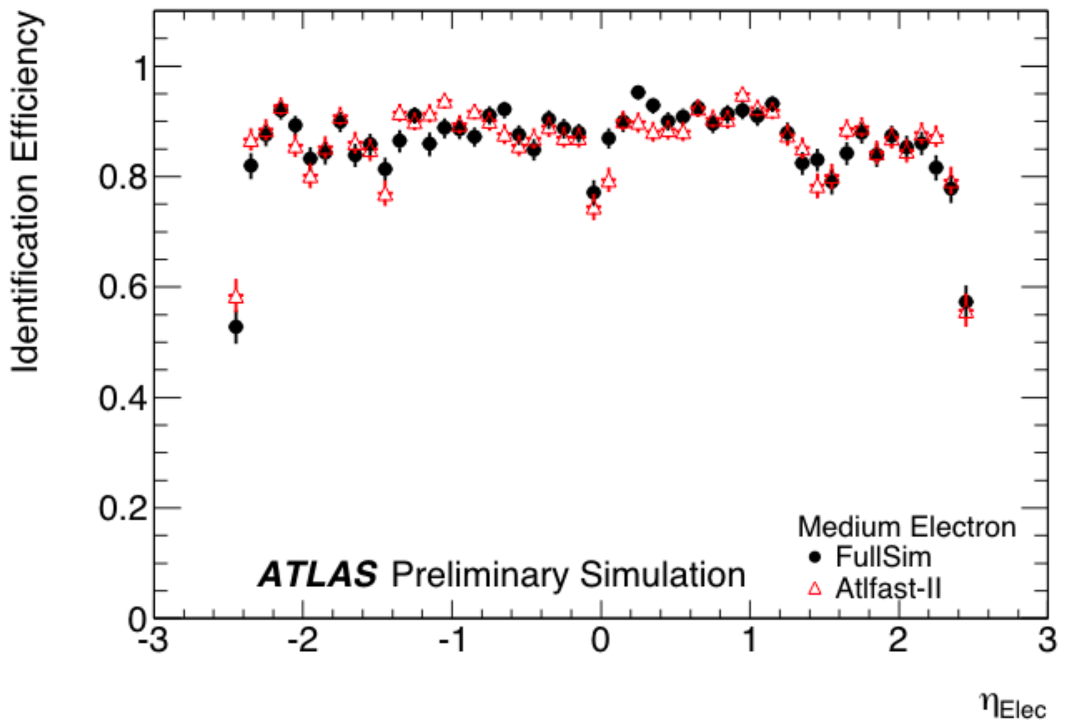
*Fast Calo*rimeter *Sim*ulation (FastCaloSim)

ATL-PHYS-PUB-2010-013

Legacy fast calorimeter simulation (ATLFAST-II)

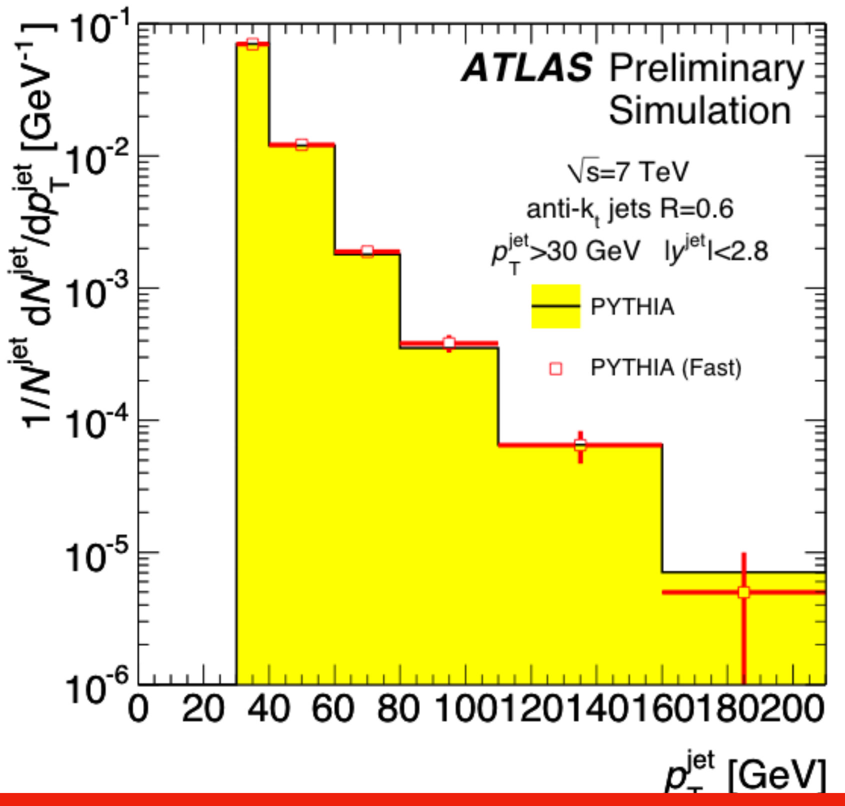
- Simplified "cuboid" geometry
- Reduces CPU by order of magnitude
- Developed nearly a decade ago; still used today for official production

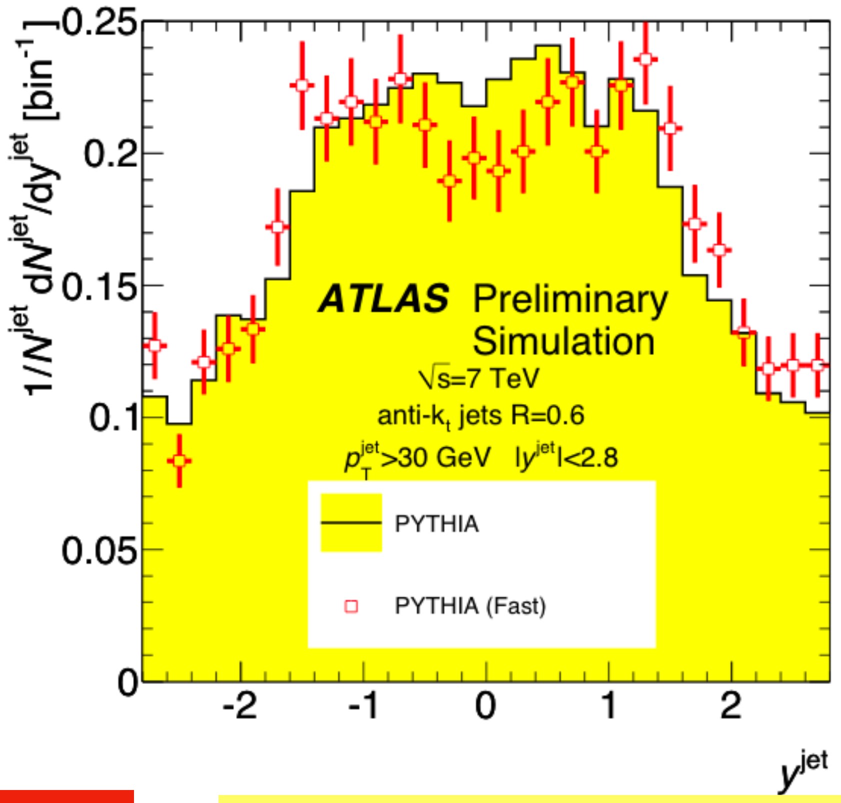


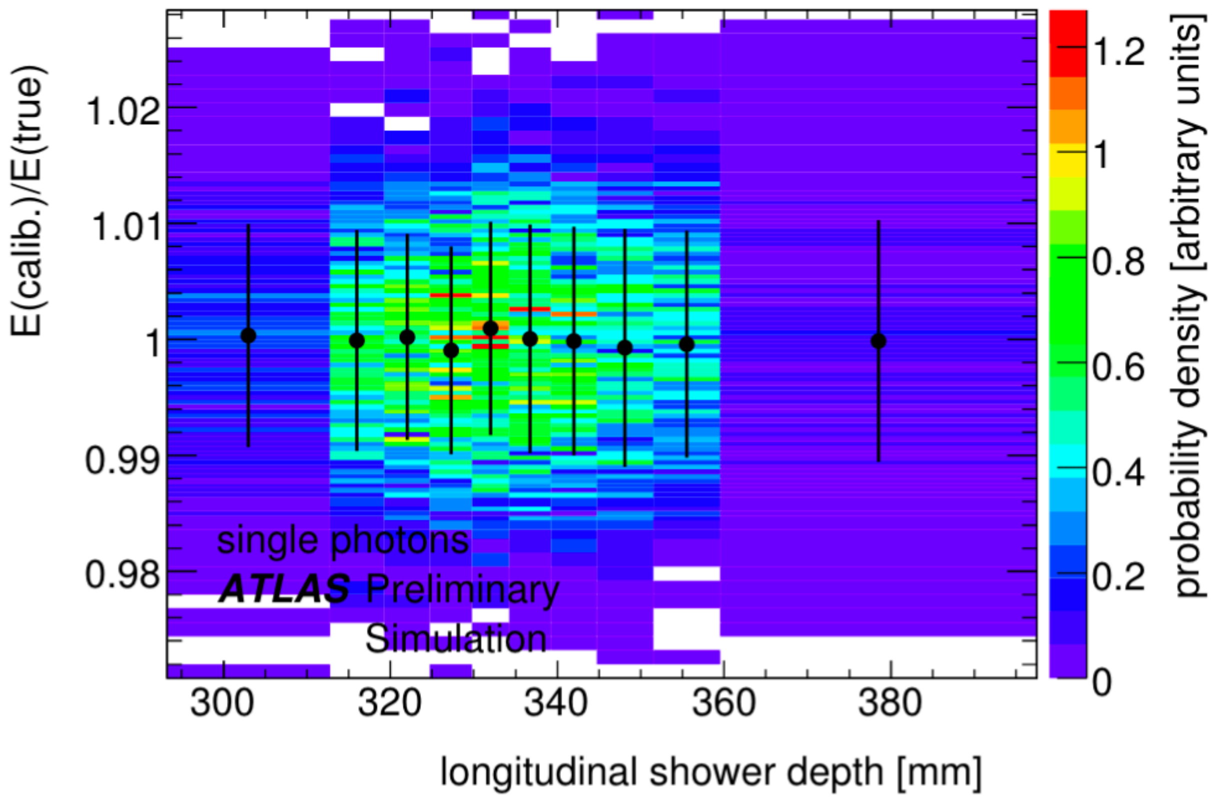


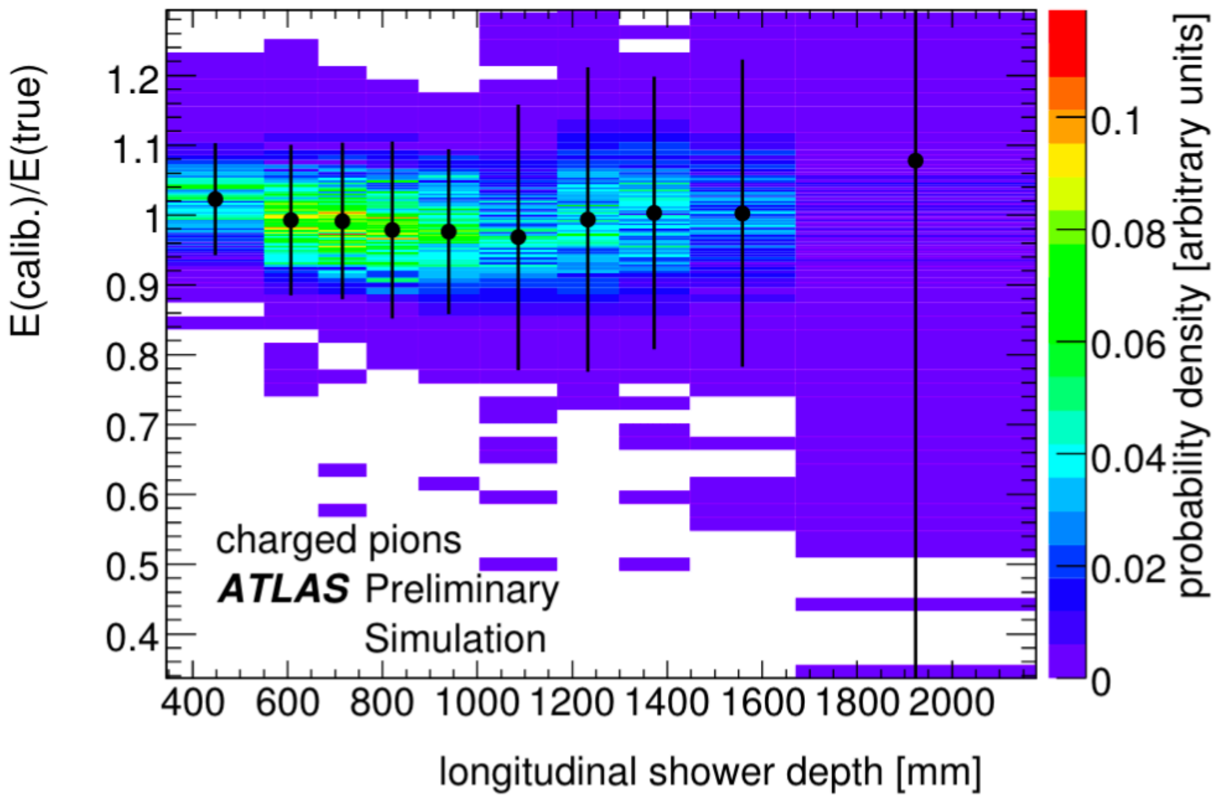
Geant4-based parameterisations

- O(10^6) single-particle events
- 50 MeV < E < 1 TeV (16 points), $|\eta|$ < 4.9 (100 equidistant bins)
- Longitudinal shower properties, fluctuations and correlations
- Average lateral properties and uncorrelated fluctuations



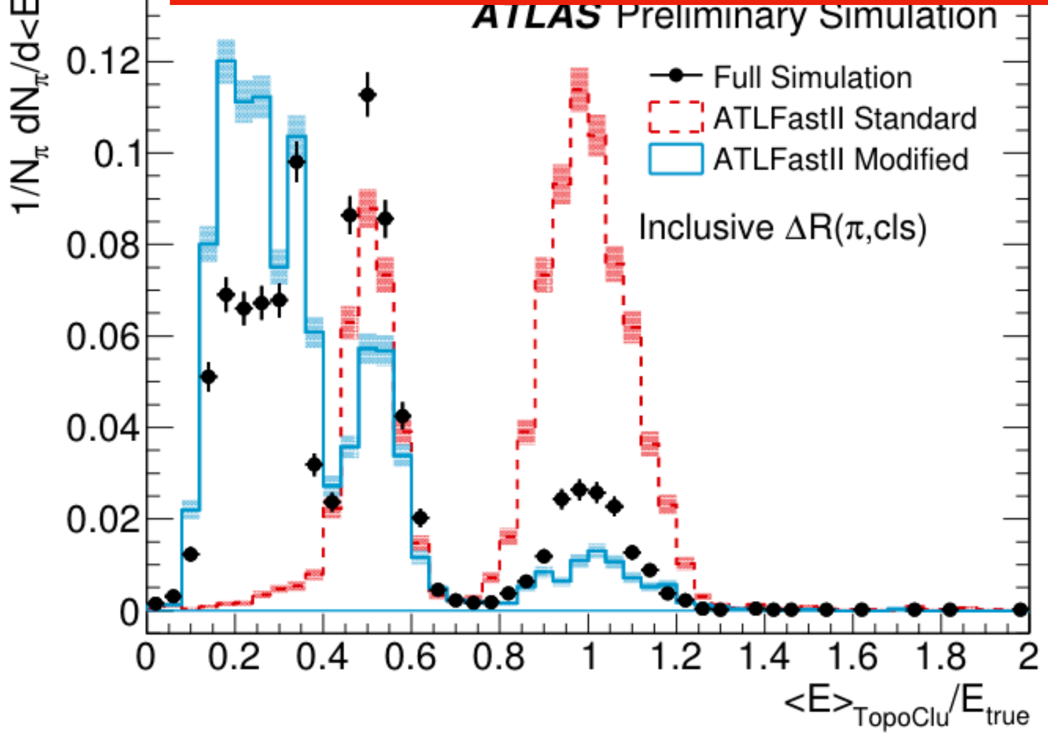


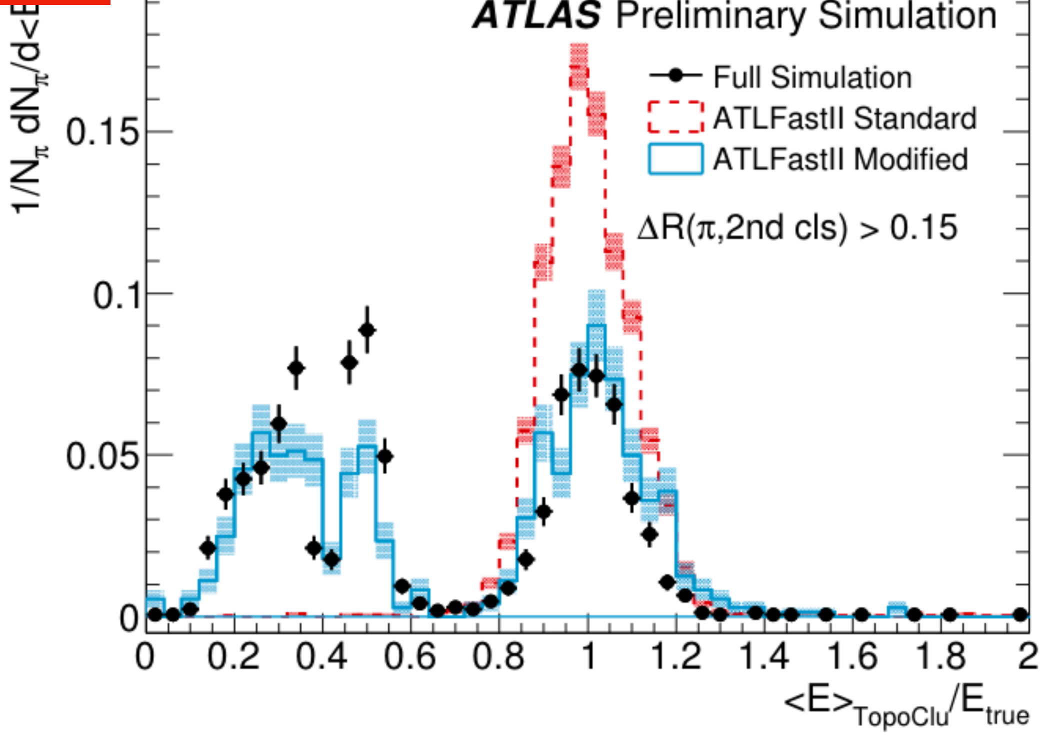




Unable to model jet substructure

ATLAS-SOFT-PUB-2014-001





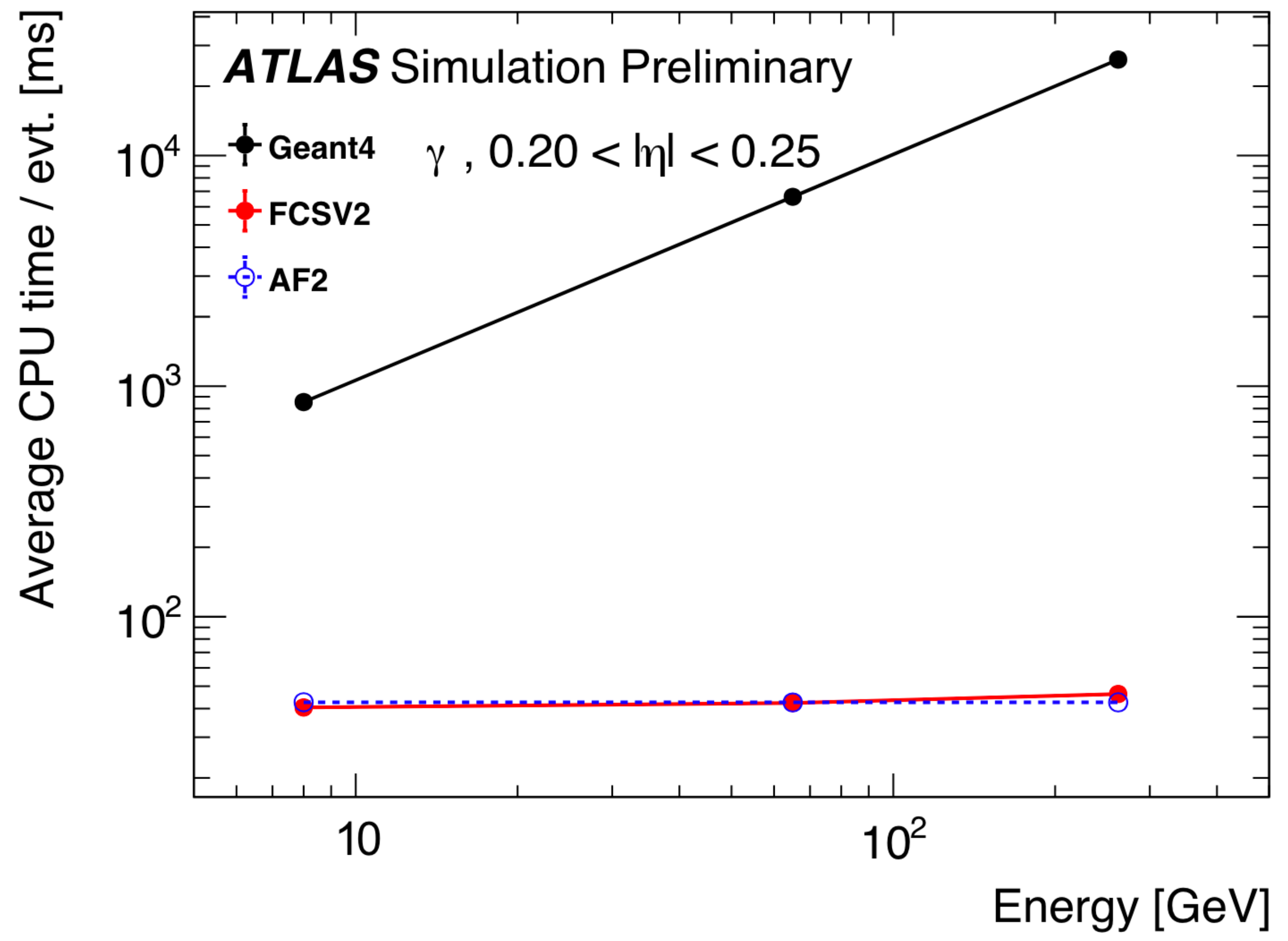
FastCaloSimV2

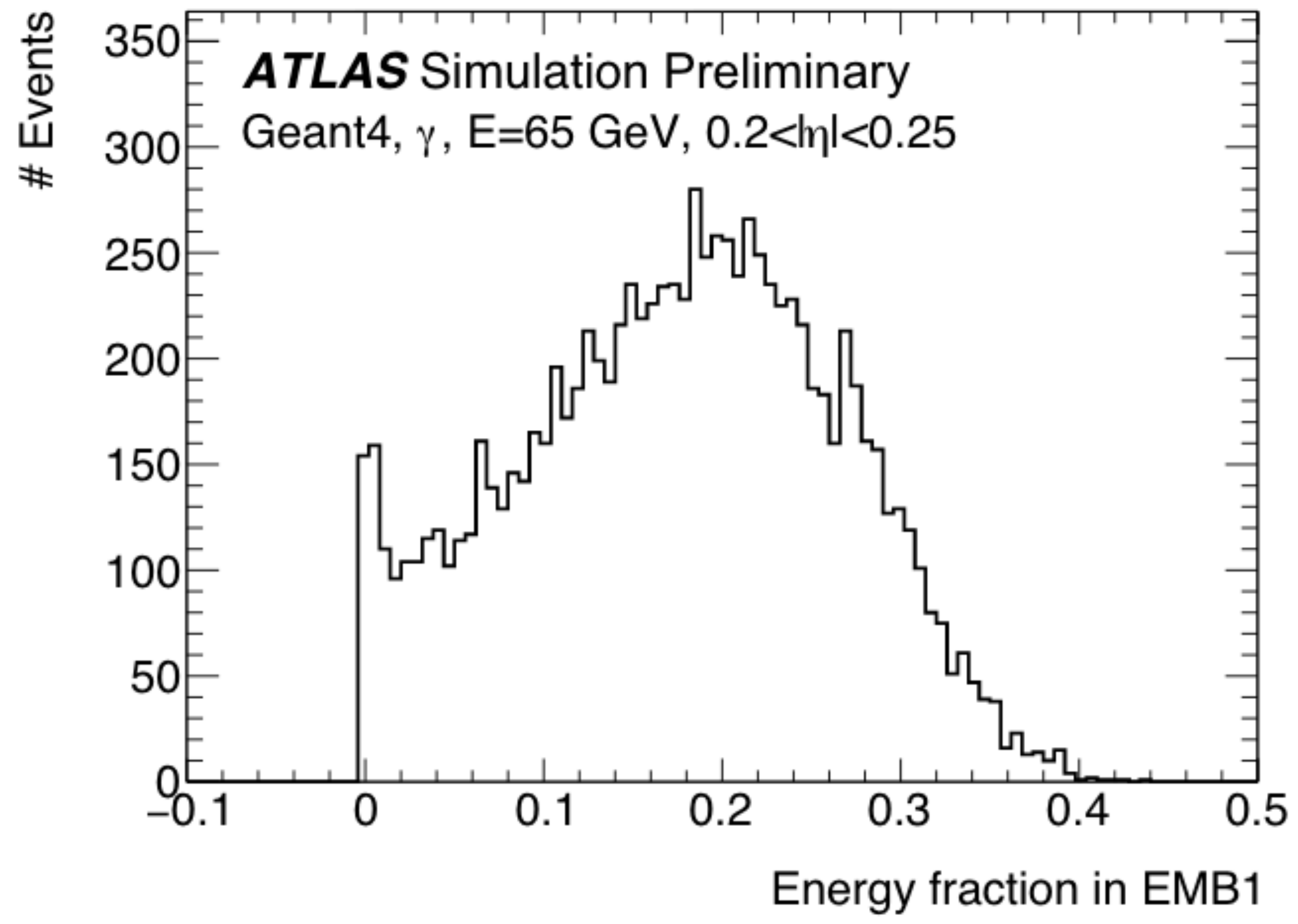
Increased accuracy

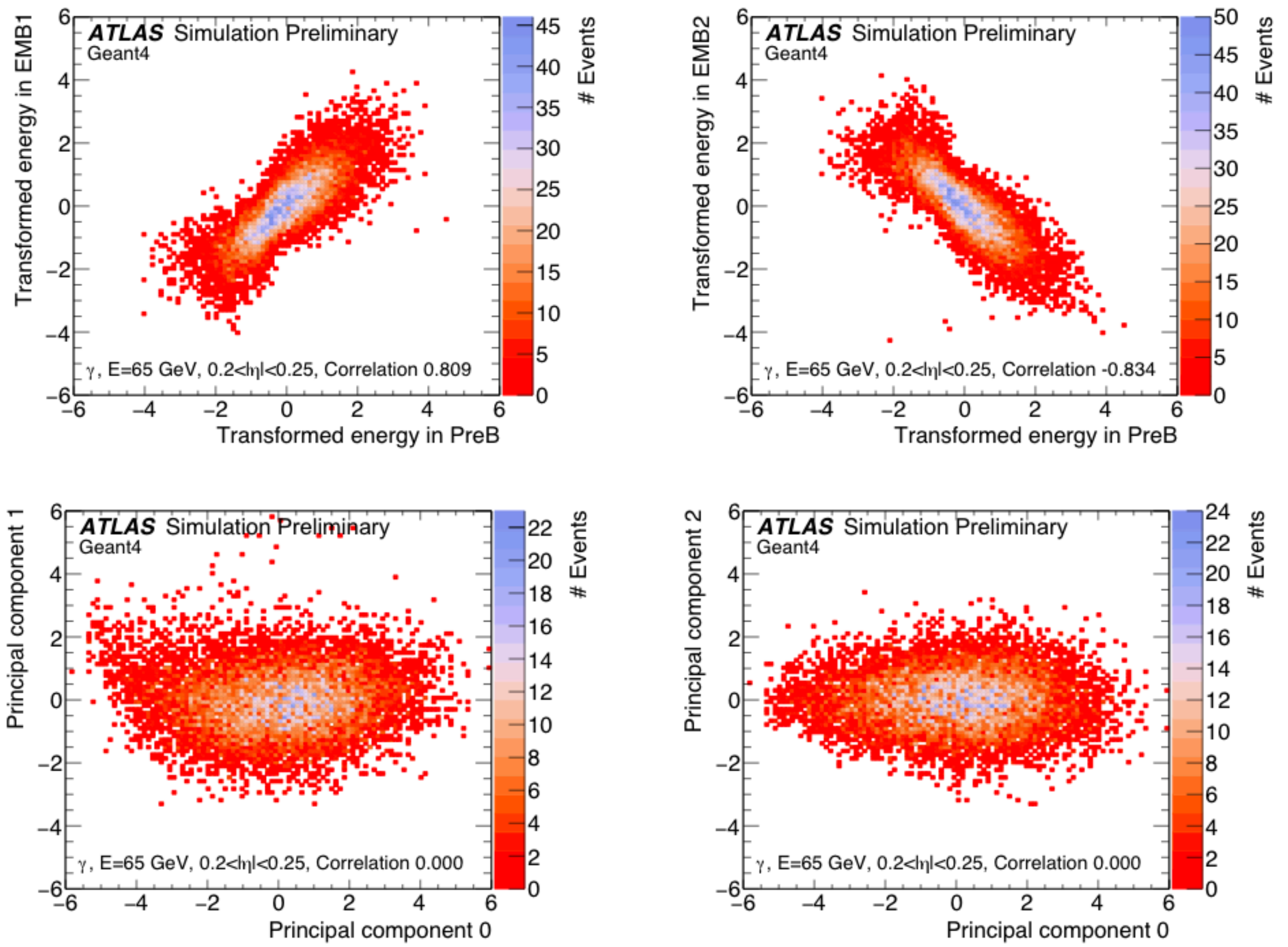
- Improved lateral shower modelling
- Includes forward calorimeter simulation
- Ability to model Lorentz-boosted topologies, *i.e.* jet substructure
- CPU performance similar to FastCaloSim; same simplified geometry

New energy and shower shape parameterisations

- Generate inputs -- total energy (all layers), fractional energy (per layer) -- for Principal Component Analysis (PCA)
    - Store only cumulative energy, second PCA matrices, mean and RMS of Gaussians post-PCA
- Fast simulation reverse order of PCA chain
    - Correlated uniform randoms numbers and cumulative energy distributions are obtained for each layer
- Lateral shower parameterisation derived in each relevant layer for each PCA bin
    - Store parameterisations of (η,ϕ) in 2D histograms





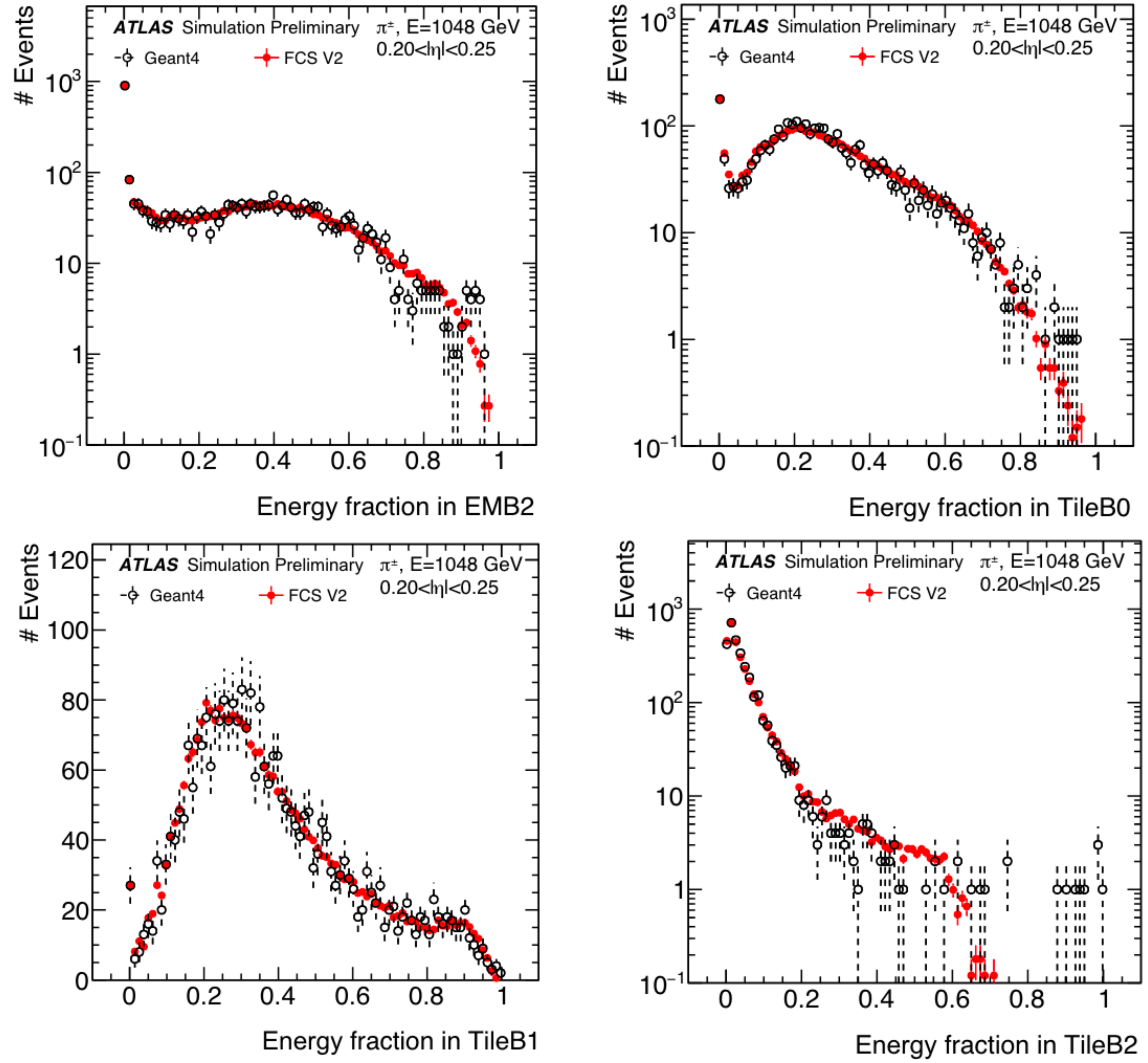


FastCaloSimV2 (*cont'd*)

ATL-SOFT-PUB-2018-002

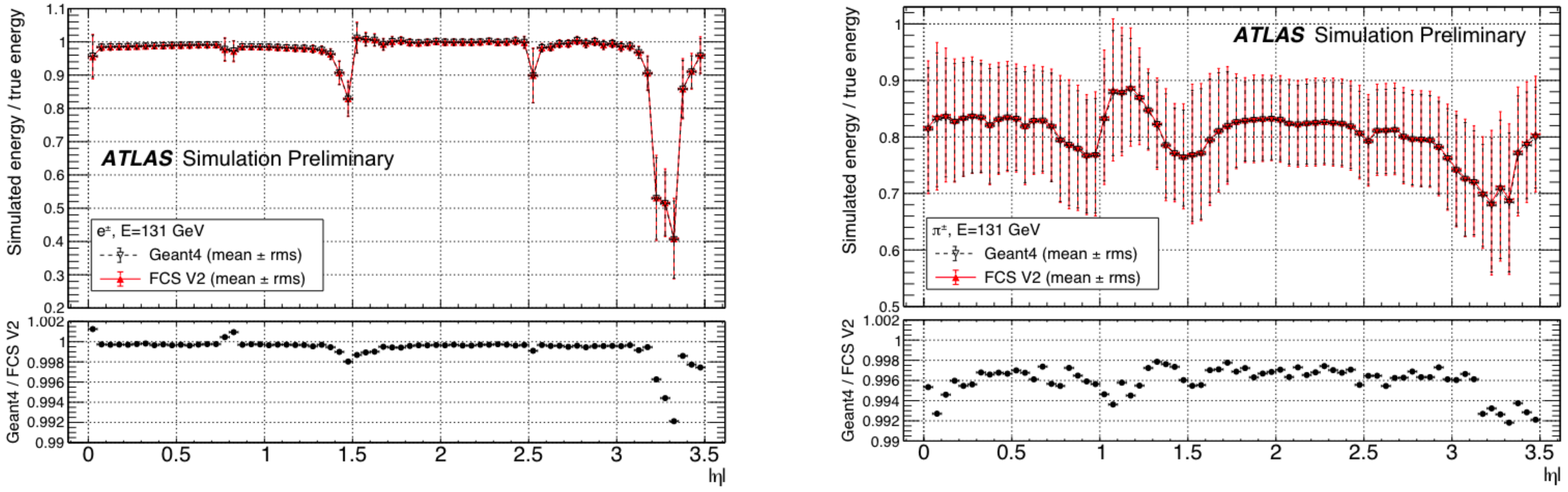
Longitudinal energy parameterisation

- Toy simulation for pions of E = 1 TeV within 0.20 < $|\eta|$ < 0.25



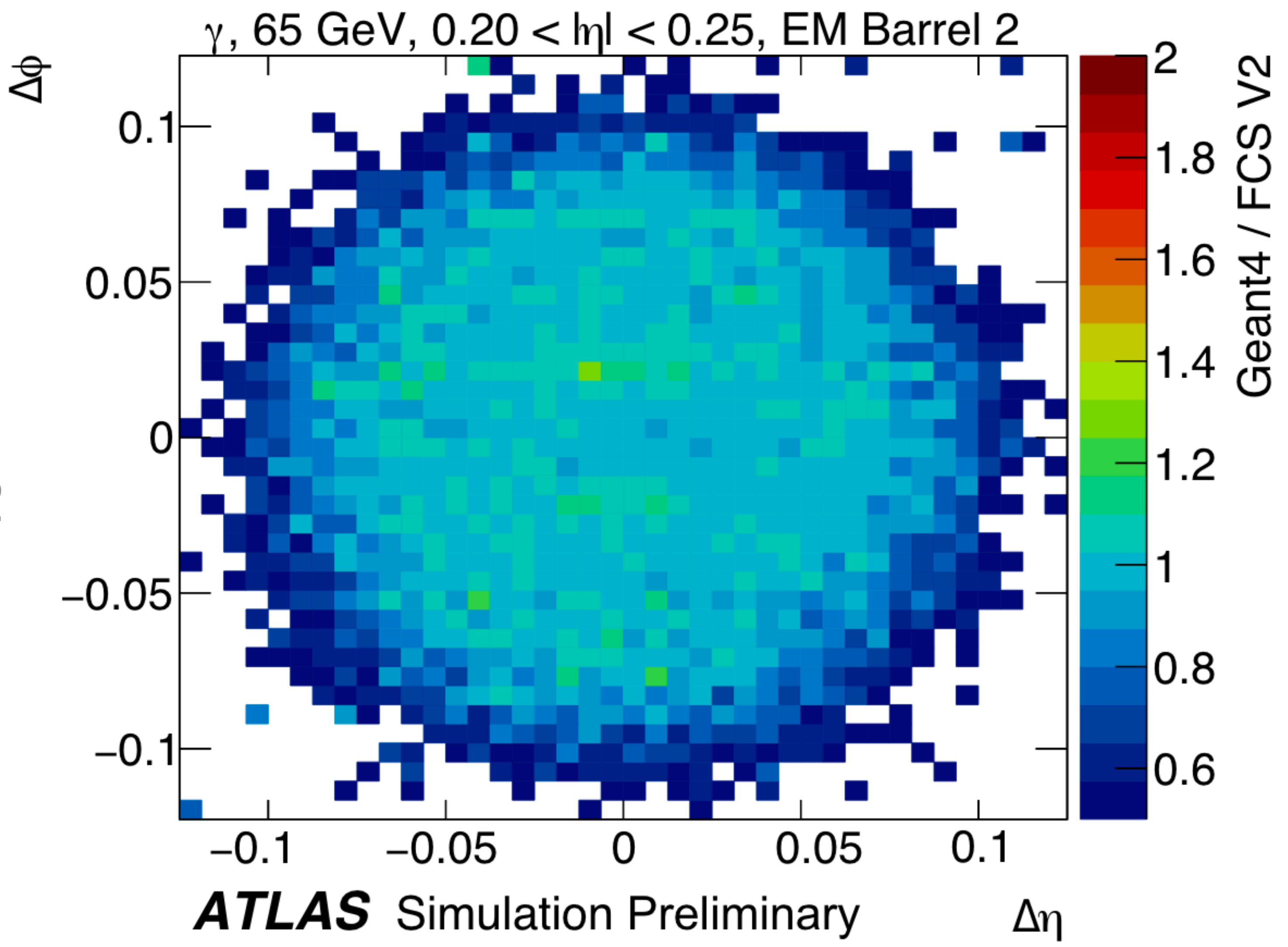
Total energy response

- Electrons (left) and pions (right) of E = 131 GeV within 0 < $|\eta|$ < 3.5



Lateral shower parameterisation

- Photons of E = 65 GeV within 0.20 < $|\eta|$ < 0.25
- Shown is ratio of FastCaloSimV2 and Geant4
- Coordinates calculated w.r.t. position of incident particle on calorimeter layer surface



Fast ATLAS *Track* Simulation (FATRAS)

[ATL-SOFT-PUB-2008-001]

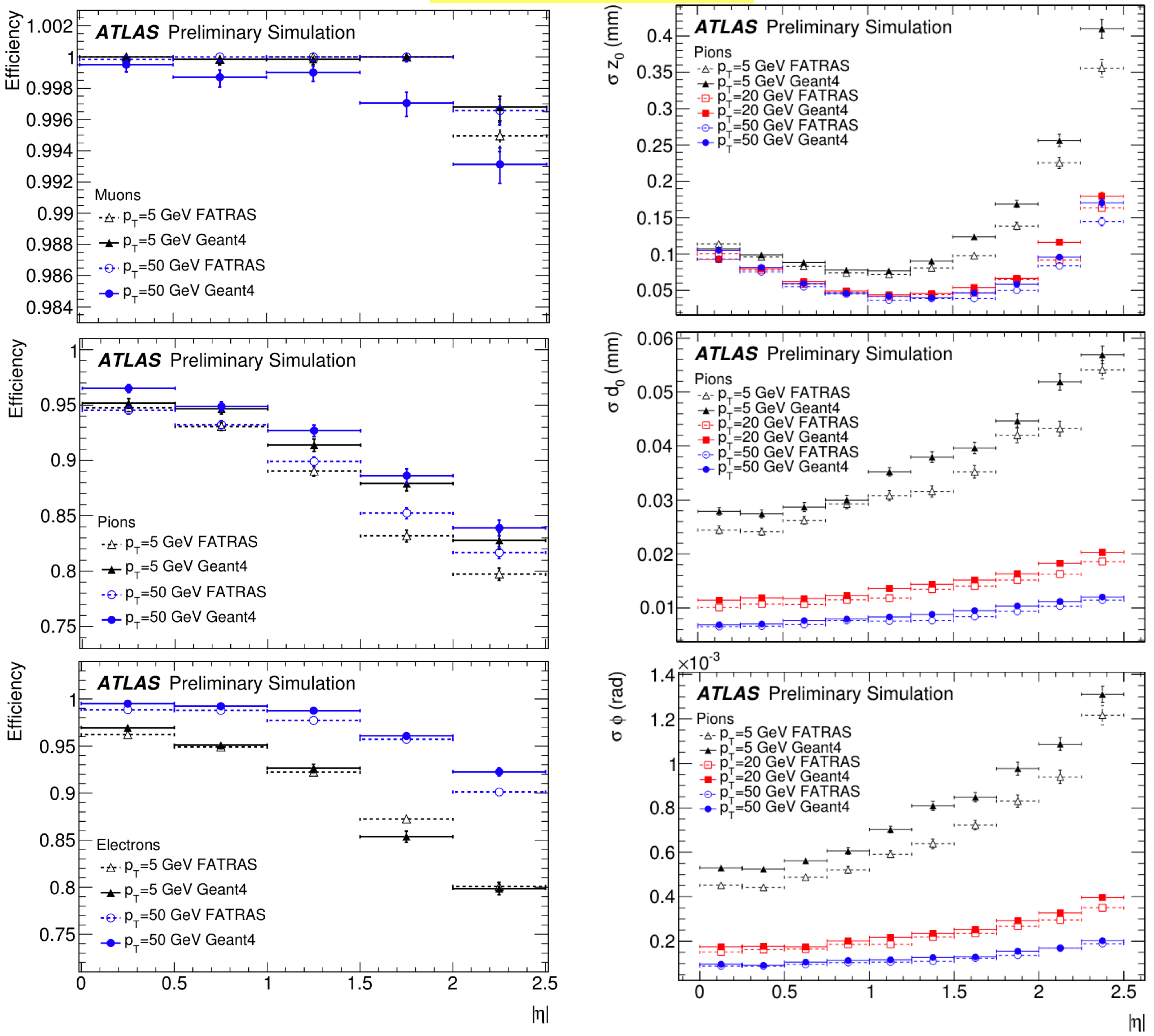
Fast track simulation engine

- Inner Detector and Muon Spectrometer
- Based on simplified `TrackingGeometry`
  - Volumes projected onto thin layers
- Produces full track information, *e.g.* hits on tracks
- Part of ATLFAST-IIF configuration
  - FastCaloSim + FATRAS

Extrapolator [ATLAS-SOFT-PUB-2007-005]

- Transports track parameters (d_0, z_0, ϕ, θ, q/p) through detector
- Material effects applied based on amount of traversed material
- Supports multiple scattering, bremsstrahlung, photon conversion, unstable particle decay (modelled in Geant4)

[ATL-SOFT-PUB-2014-001]



Pile-up Overlay

ATL-SOFT-SLIDE-2017-375

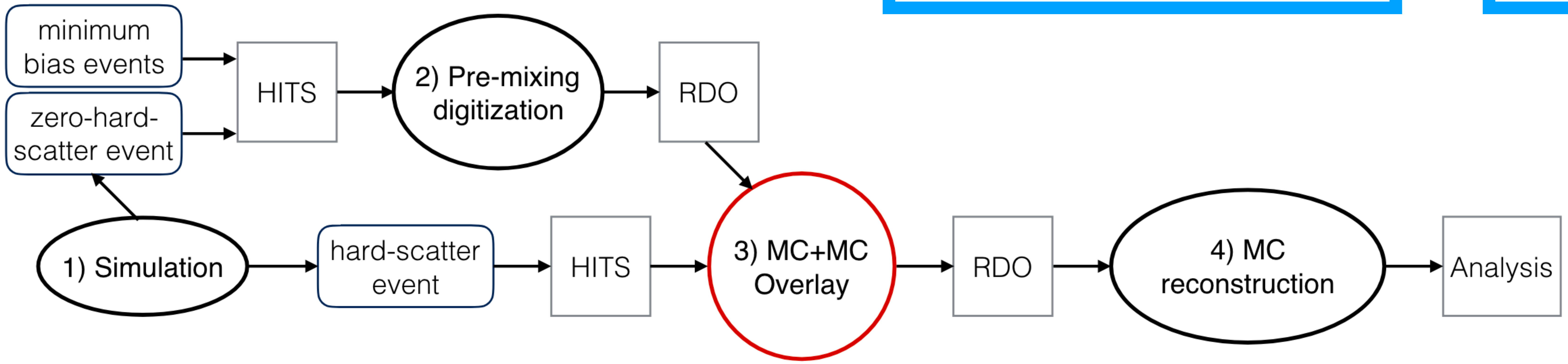
Incorporating pile-up into simulation

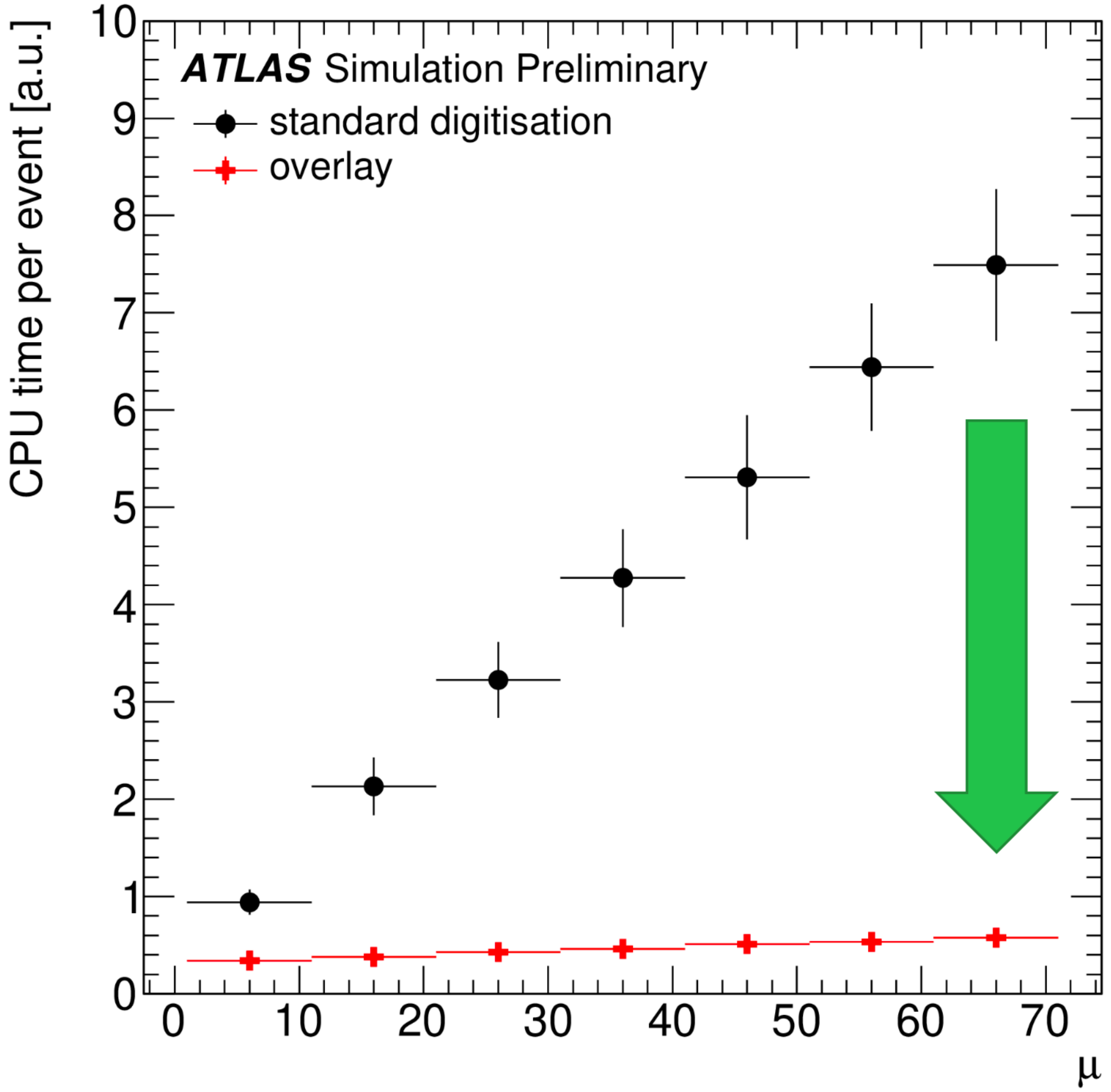
Option 1:
"Pile-up MC" (current default)

Simulate both hard and soft interactions in MC and mix together in proper ratios.

Option 2:
"Pile-up Overlay"

Simulate only hard interaction in MC and overlay a random background event.





Benefits

- CPU requirements substantially decreased
  - Digitise once
  - IO "thrashing" reduced

Drawbacks

- Uniquely labelling pre-mixed events
- Sub-threshold HS+PU lead to above threshold signal would be missed
- 10^9 events ~ 4 PB

Fast Chain: overview

Highly modularised for flexibility

Develop*, *test*, *debug*, *validate* each component *independently

Example production setup

- **Hard-scatter**: Geant4, standard digitisation+reconstruction
- **Pile-up**: FATRAS+FastCaloSim, fast digitisation+reconstruction

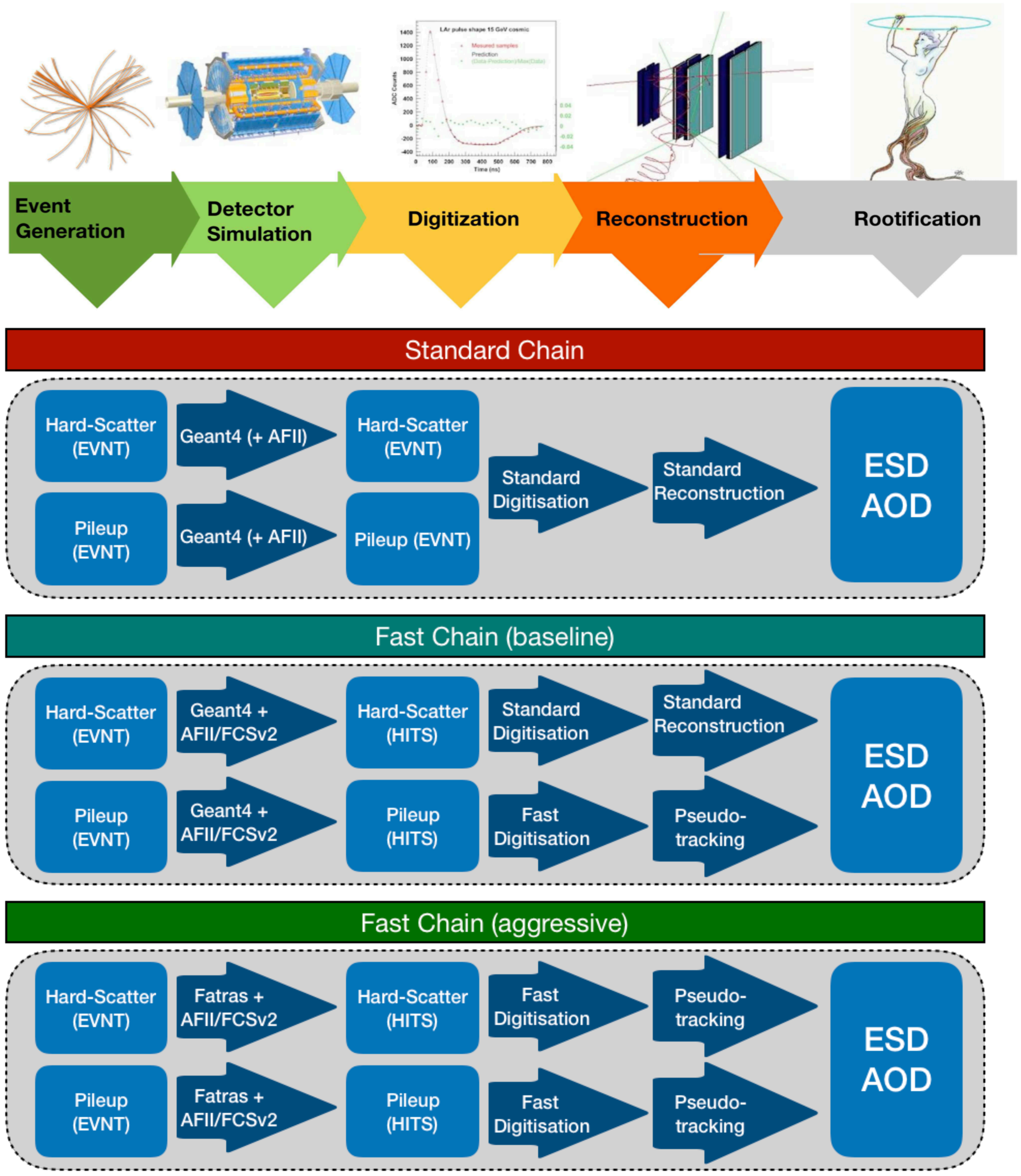
Incorporates all fast methods discussed

- **Inner Detector**: FATRAS
- **Calorimeter**: FastCaloSim

...and then some

- Fast Digitisation
- Fast Reconstruction

One transform to rule them all.



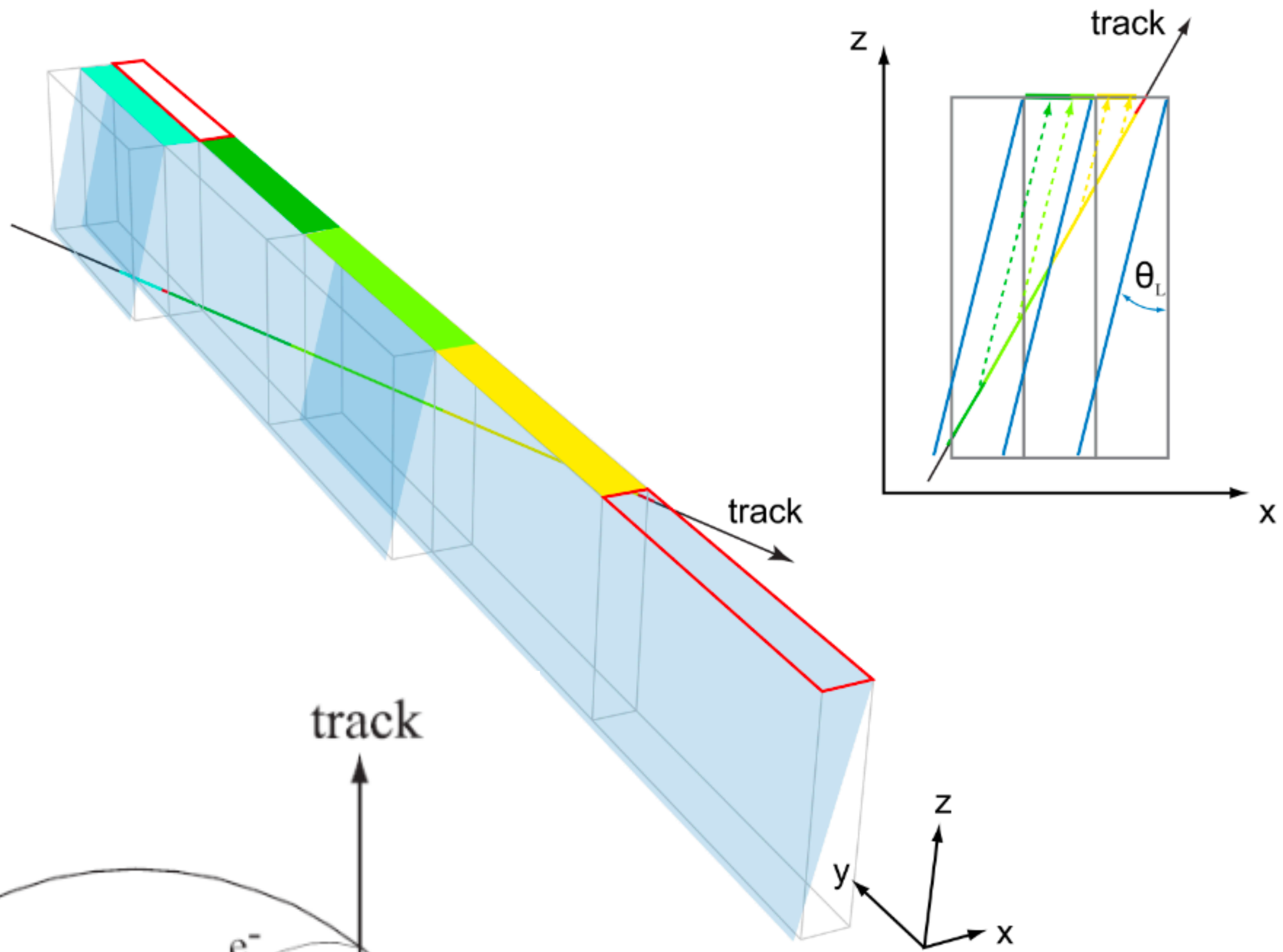
Fast Chain: fast digitisation

Fast Digitisation for Inner Detector

- Most time-consuming (~50%) due to high density of hits
- Implemented for Pixel, SCT, and TRT detectors

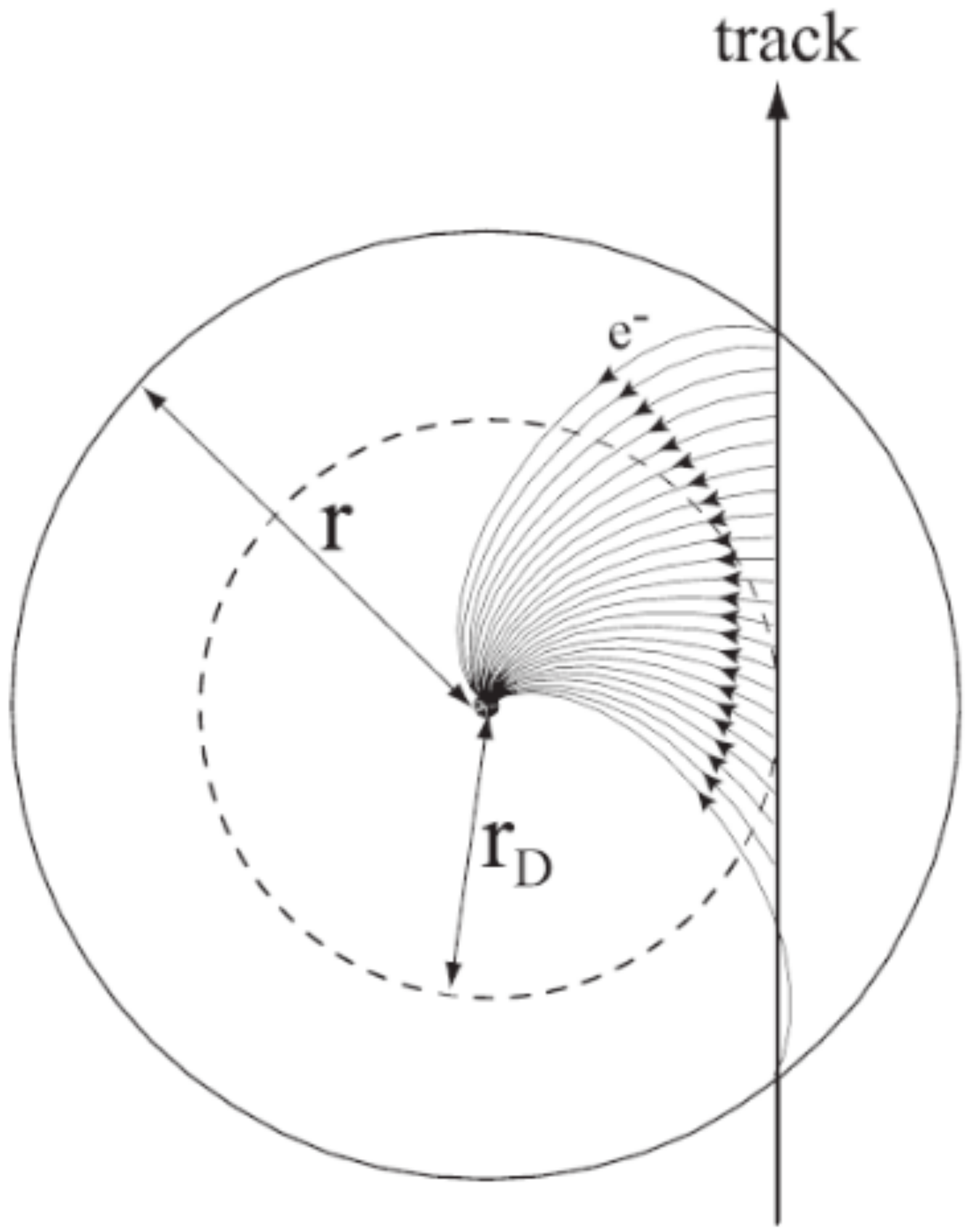
Pixel and SCT

- Estimate charge by projecting simulated track length onto readout surface (for each readout channel)
  - Corrections made for Lorentz angle drift
- Charge and track lengths smeared to account for multiple scattering
- Form clusters directly from track information (no cluster-finding algorithms)



TRT

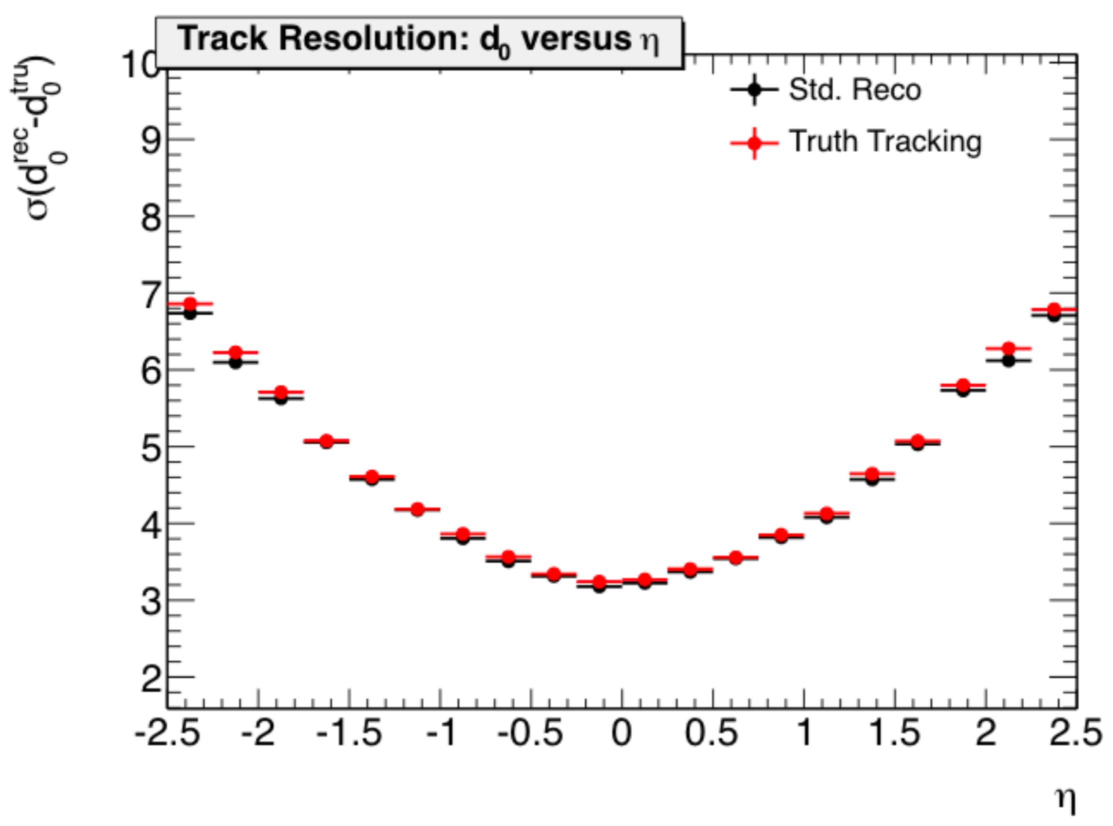
- Emulate response using distance of nearest approach
- Smear for uncertainty estimate
- Transition radiation parameterisation allows for particle ID

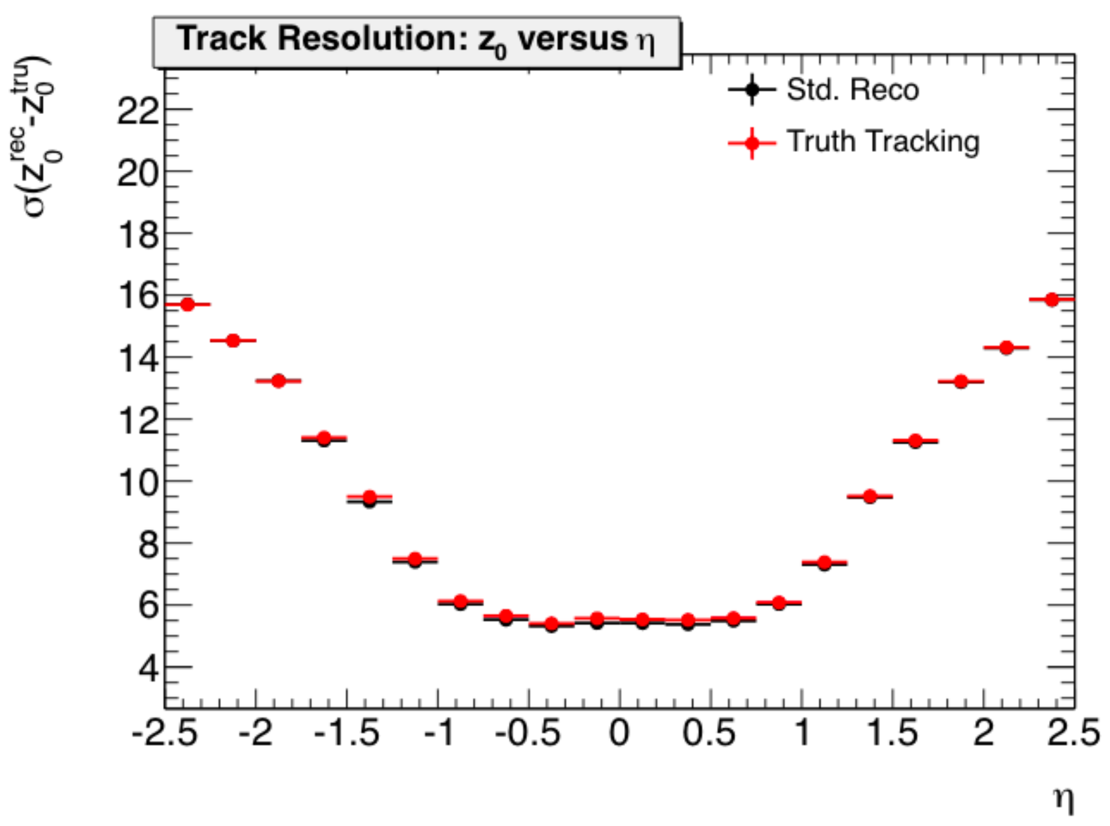


Fast Chain: fast reconstruction

Fast(/truth-assisted(/seeded)) Reconstruction (/Pseudo-tracking)

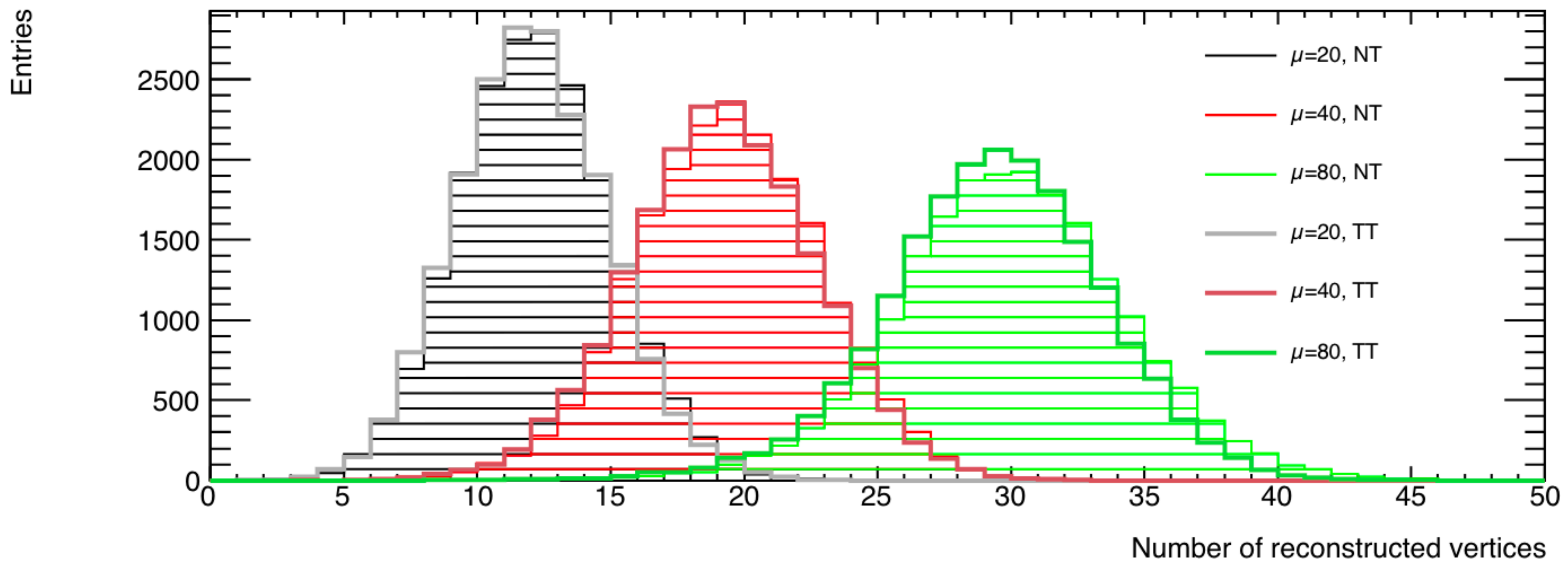
- Build particle trajectories from digitised hits
  - Combinatorial in nature, exponential increase with increasing pile-up
    - Dominated by Inner Detector

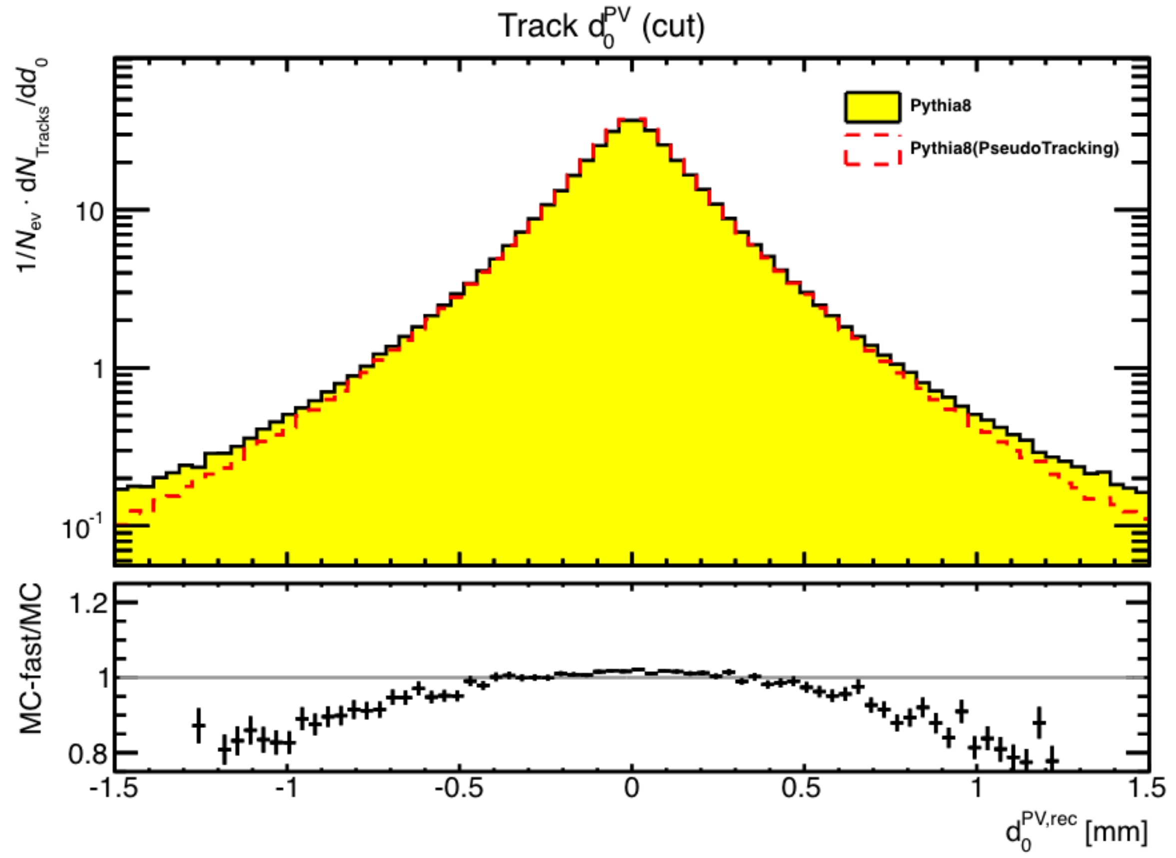


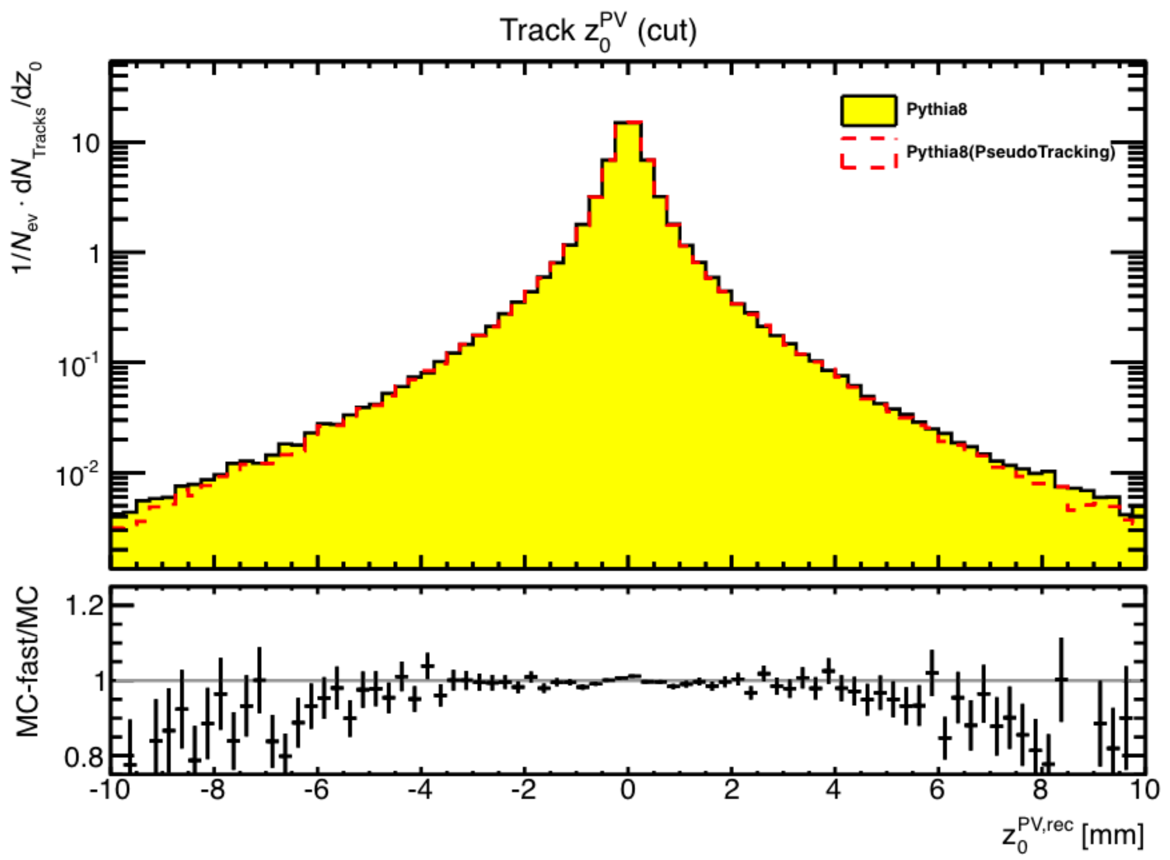


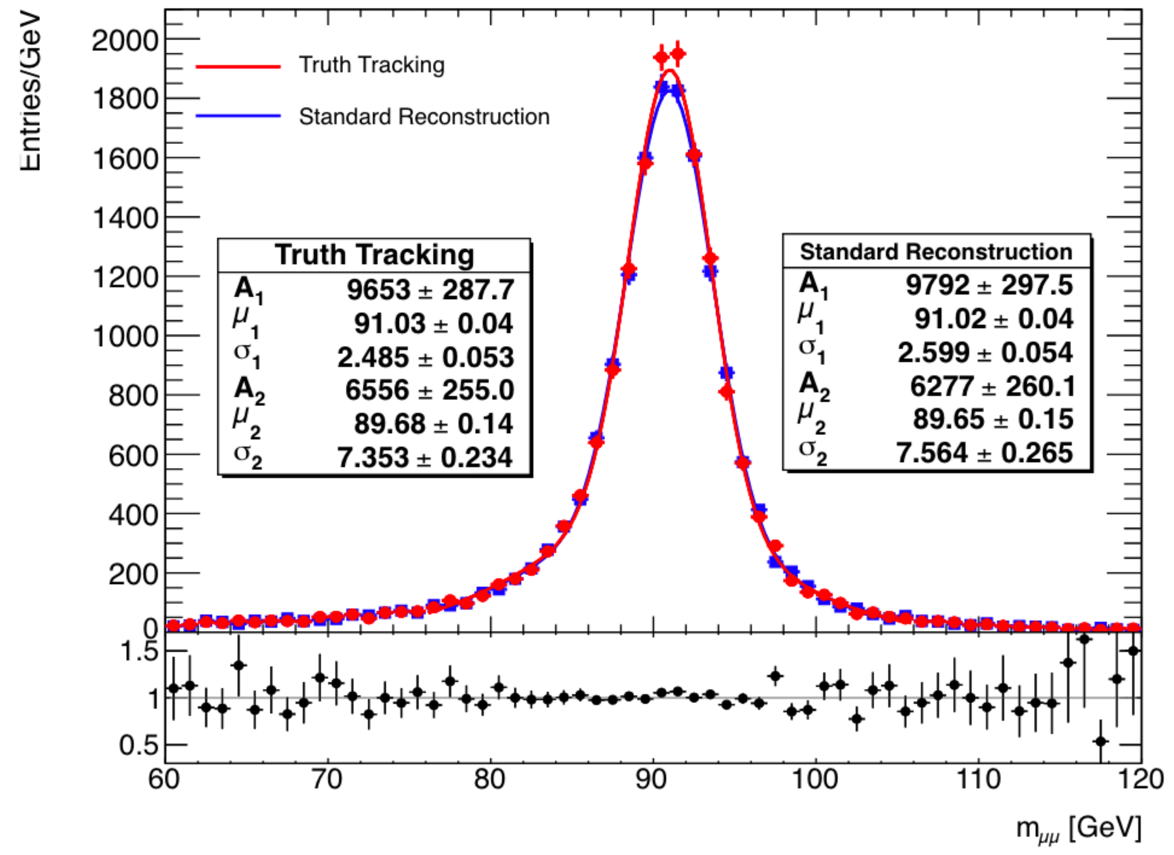
Methodology

- Emulate effect of standard algorithms using MC generator (*i.e.* truth) information
  - Skip time-consuming pattern recognition
- Manipulate hit content and efficiency
  - Apply similar selection on criteria used in standard tracking









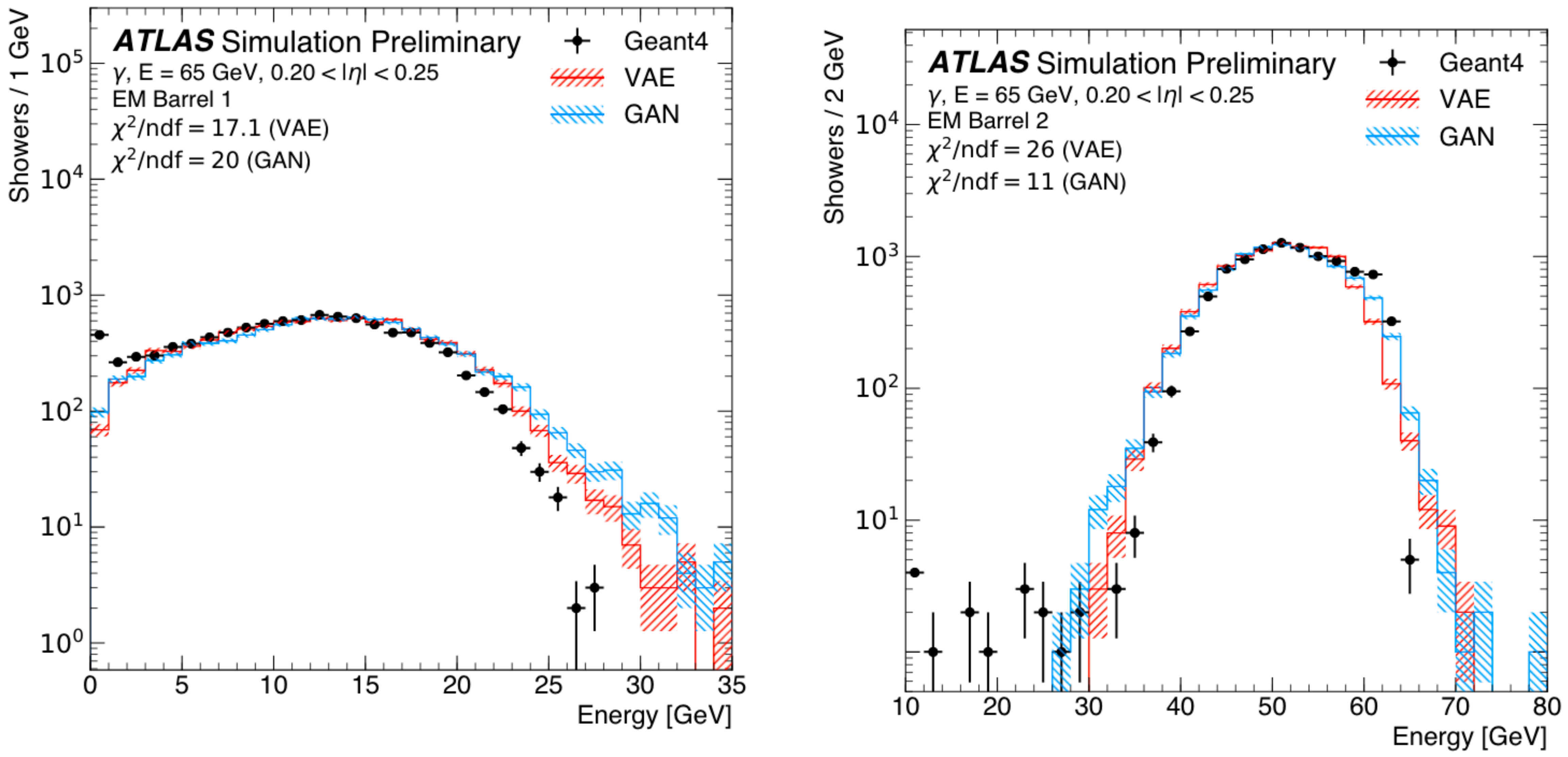
The future of [ATLAS] fast simulation

ATLAS EXPERIMENT

Machine Learning

***DNNCaloSim* (ATLAS-SOFT-SLIDE-2018-464)**

- Variational Auto Encoder (VAE)
  - Unsupervised learning with variational Bayesian method
- Generative Adversarial Network (GAN)
  - Generative network with discriminator network feedback



General Purpose Graphics Processing Units

- Geant4 colleagues/friends already investigating (*Canal et al 2015 J. Phys.: Conf. Ser. 513 052013*)

Algorithm	CPU [ms]	GPU [ms]	CPU/GPU
Classical Runge-Kutta	78.6	1.7	47.4
Cash-Karp	87.9	1.6	55.2
Runge-Kutta-Nystrom	30.9	0.7	46.9

Host	GPU Device	CPU [ms]	GPU [ms]	CPU/GPU
AMD Opteron^{TM} 6136	M2090 [12]	748	37.8	19.8
Intel® Xeon E5-2620	K20M [8]	571	30.4	18.7

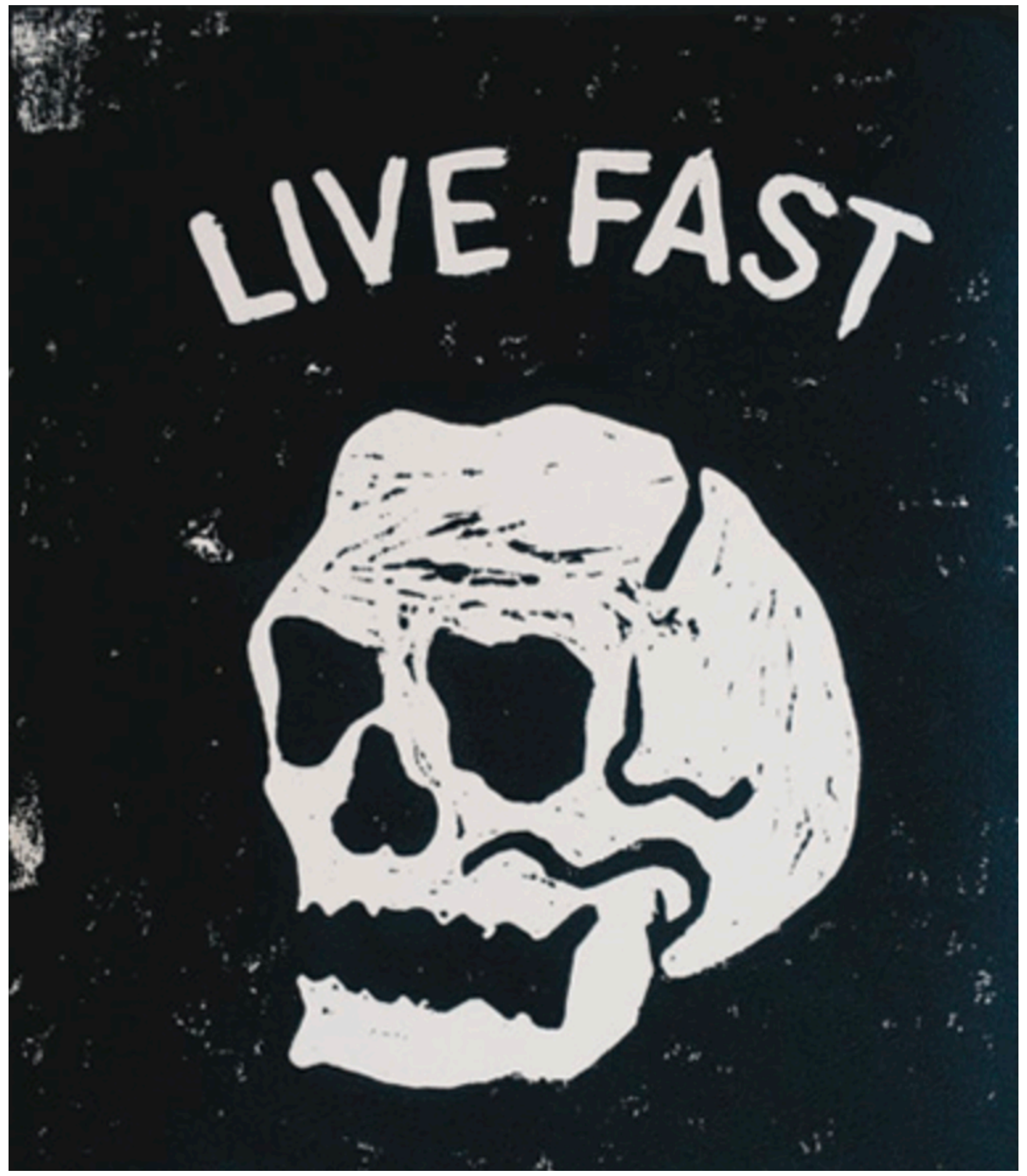
High Performance Computing

- Multi-core/process/thread exploitation, MPI, ...
- Theory unit at CERN :)

Summary

We all know Fast Simulation is a must in HEP

- Ever increasing luminosity, particle flux, pile-up
- Many unique techniques/methodologies have been tried within our experiments
- New ideas are needed: parameterisations and other naïve simplifications will do not suffice, and **it will only get worse!**



MarkRichardsonPrints

Take advantage of new and exciting opportunities

- New avenues need to be explored in HEP simulation
  - Machine learning
    - Only recently (this has been done for years in the analysis realm!)
  - Multi-processing/threading/parallelisation, utilising HPC and GPUs
    - Current ATLAS codebase (*i.e.* Athena) and ROOT not thread-safe
    - ATLAS making good progress to correct this

Usually studies are burdened by lack of human-power.

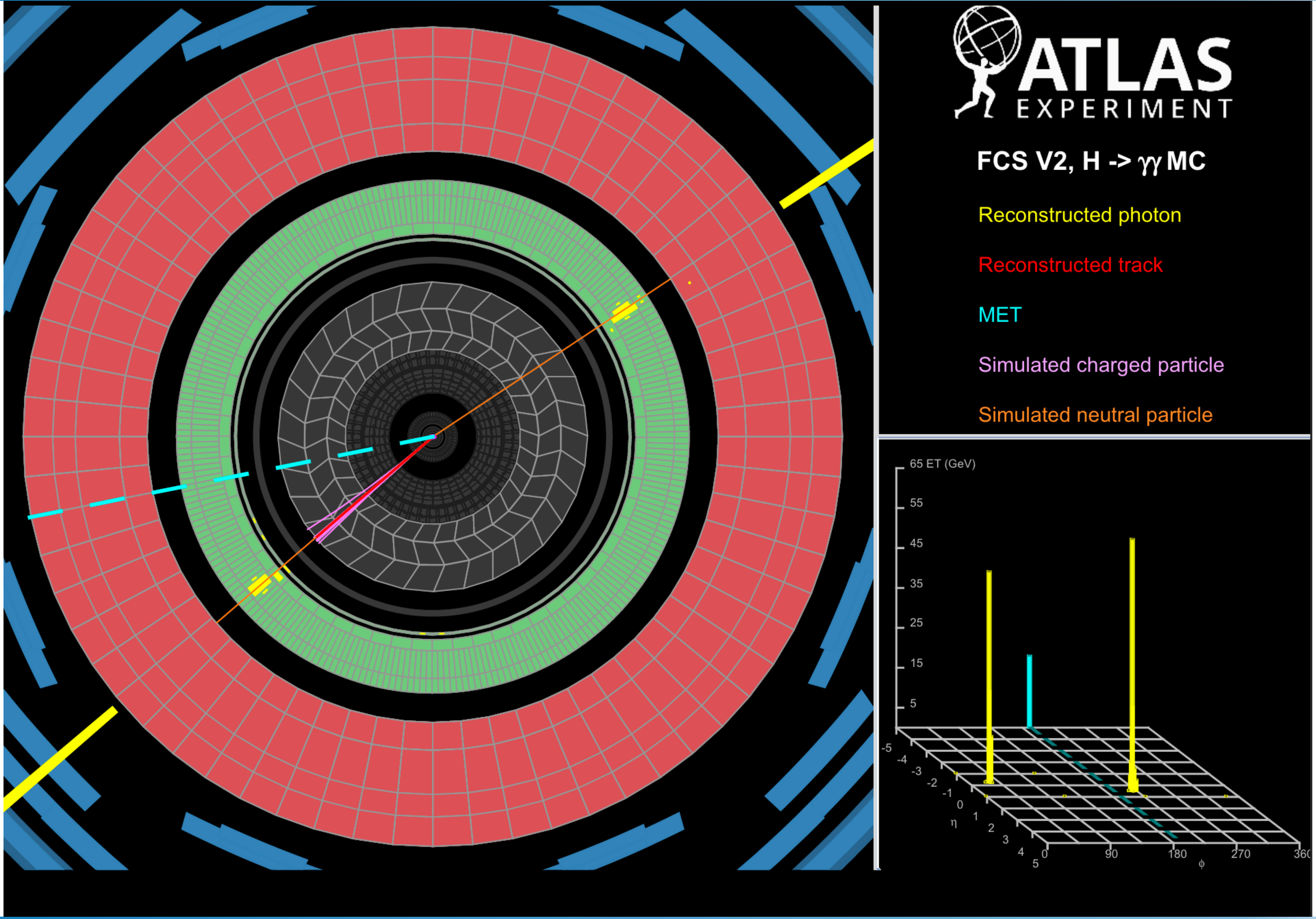
We need to bring a larger focus to HEP software and computing!

Backup

(The joke: Calvin Pickard is/was a "backup" goalie.)

Event display of a H -> γγ event (FCSv2)

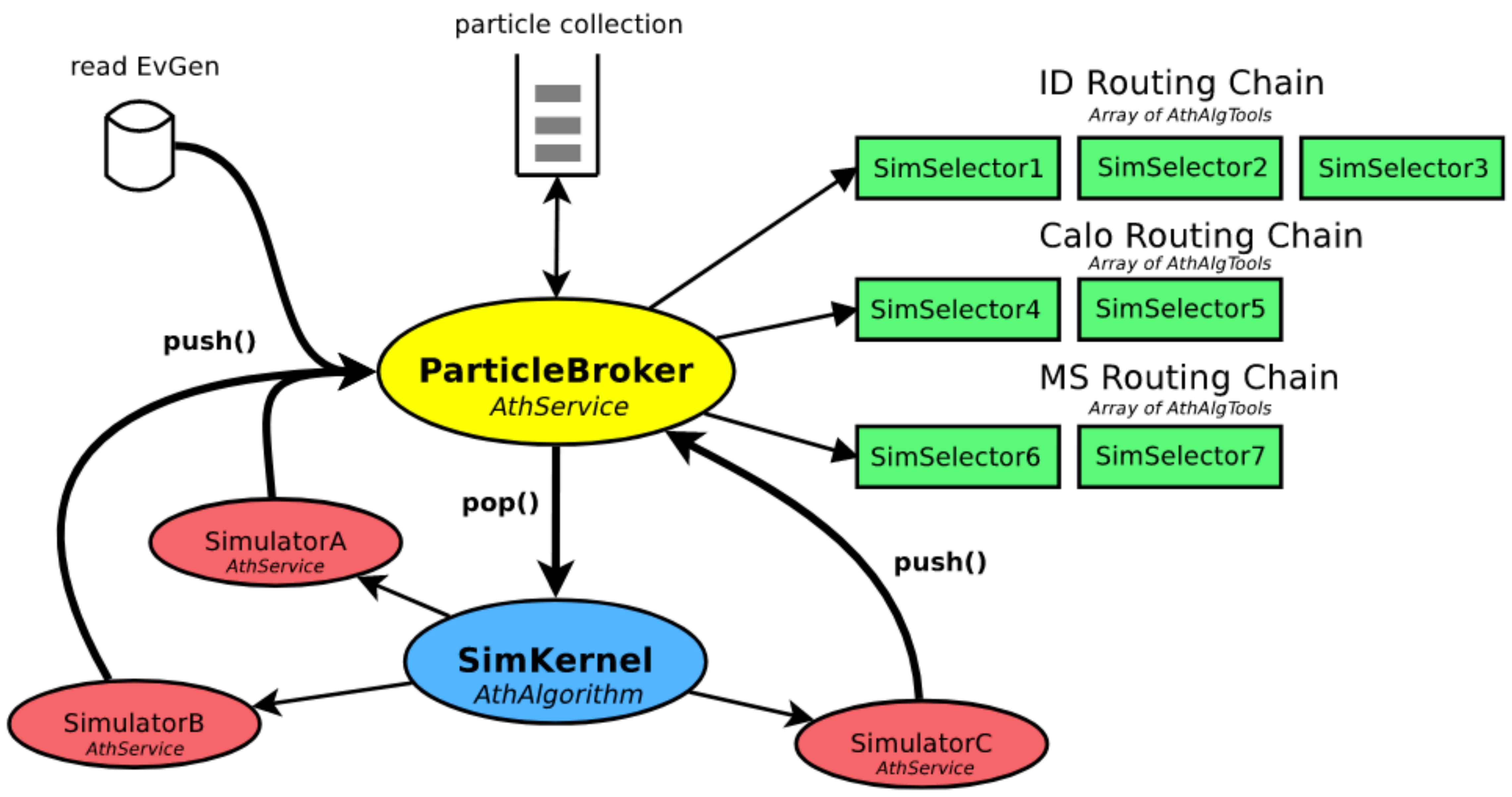
ATL-SOFT-PUB-2018-002

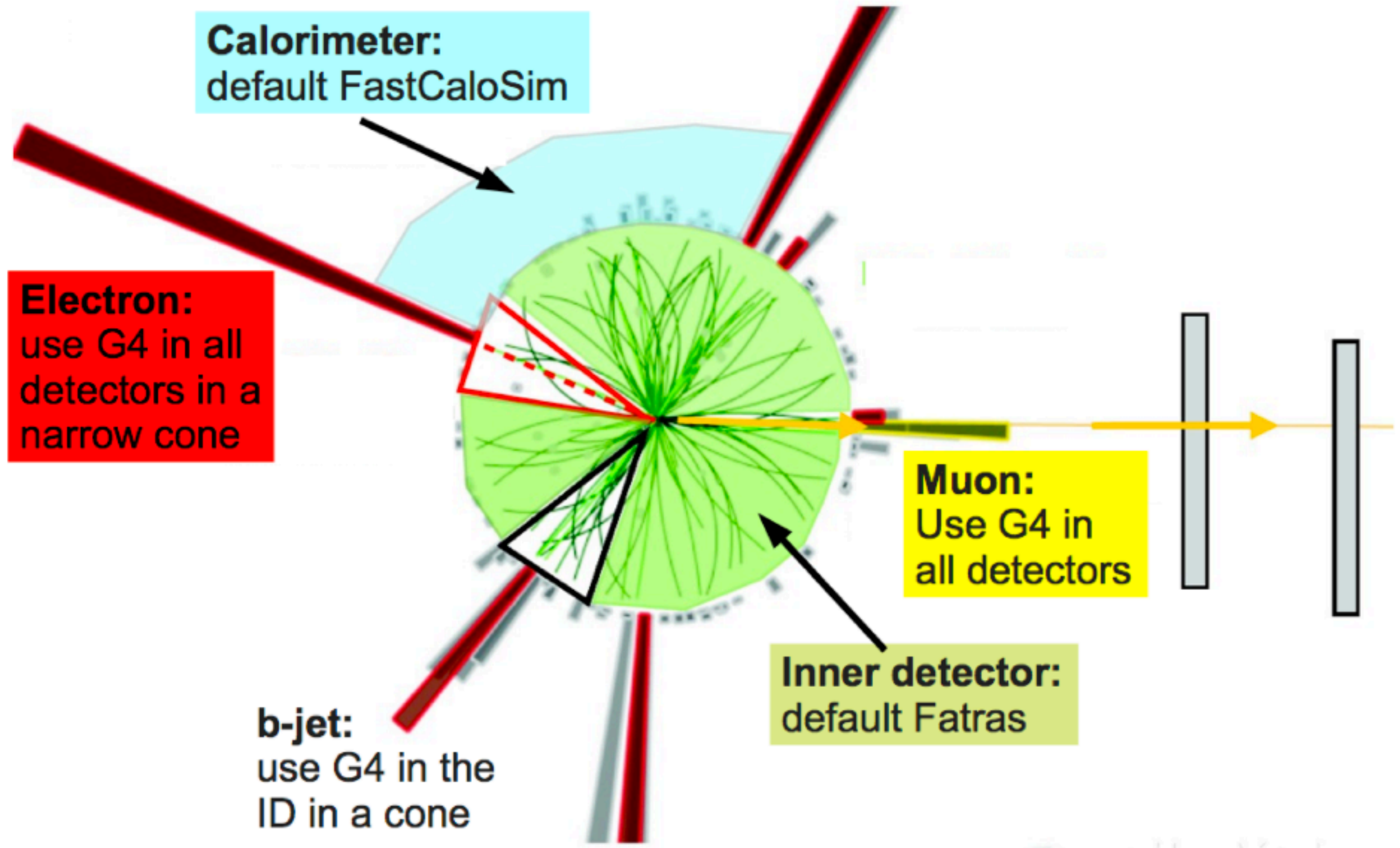


*I*ntegrated *S*imulation *F*ramework (ISF)

A different simulator for each particle type

- Combined Geant4 and fast simulation within same event
- Finely tailorable based on physics analysis needs
  - Fully simulated particles of interest, fast simulate all others
  - Fast simulate within dR cone around particle of interest
  - Partial event simulation





Example: Higgs to two photons

- Simulate only particles in cones around photons