Simulation of Electrons and Photons in ATLAS

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for the ATLAS Collaboration

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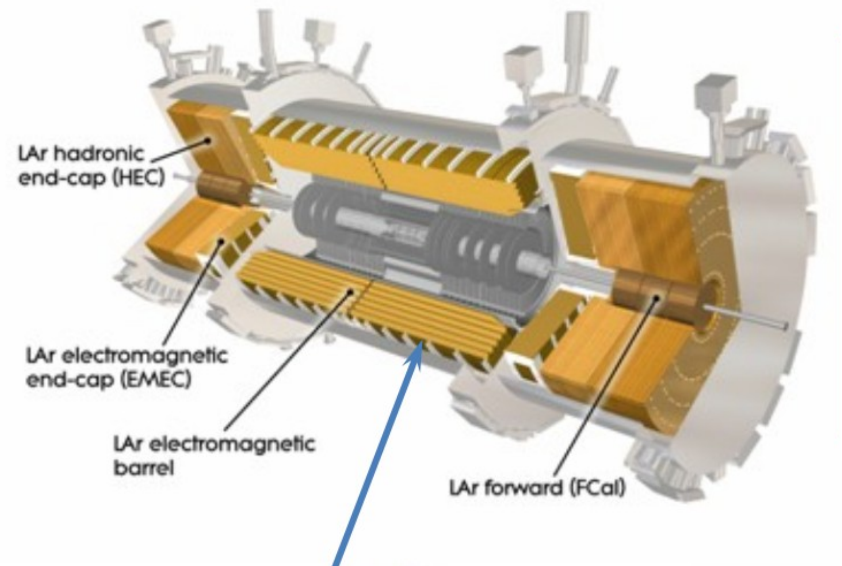
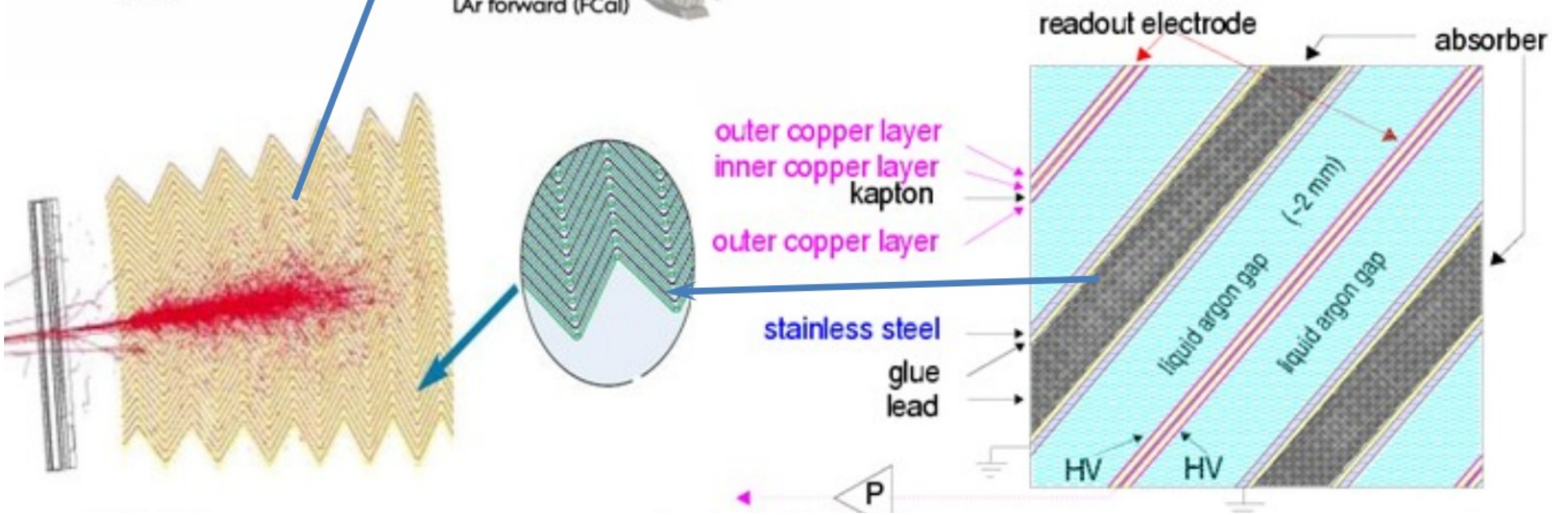
Outline

- Brief reminder about the ATLAS EM Calorimeter and its simulation
- Simulation of particle detection performance. Correction procedures
- Efficiencies, energy response and resolution
- Lateral and longitudinal shower development
- Summary

ATLAS and the EM calorimeter

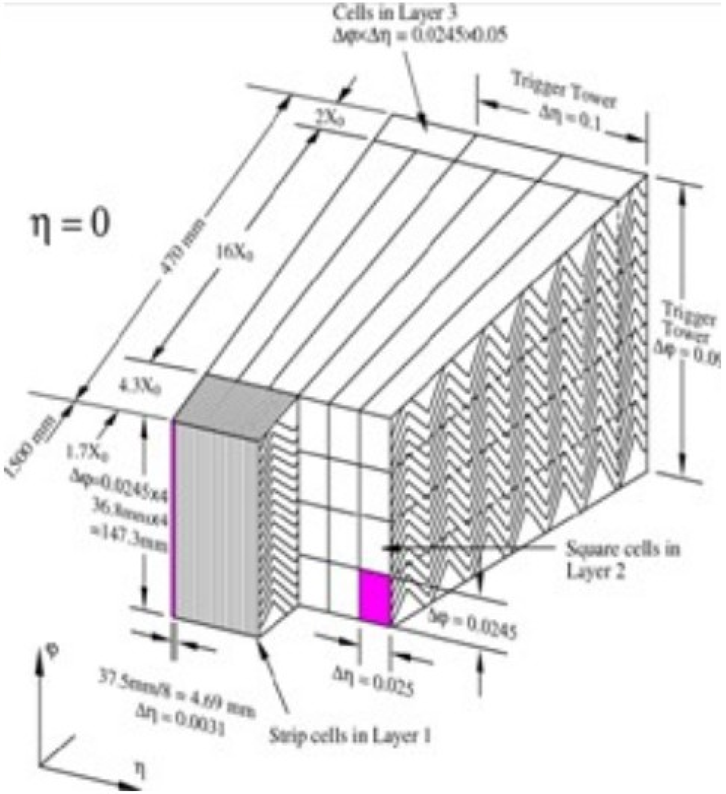


- Pb-LAr sampling calorimeter with accordion geometry and high transverse and longitudinal granularity
- Sampling fraction ~15-20% ;
  intrinsic energy resolution ~ 10-12%/√E
- 3 cryostats (one barrel including solenoid; two endcaps)
- Tracking (Silicon pixels/strips, TRT) in front of the calorimeter
- Typically 2-3 X0 before the active part of the calorimeter

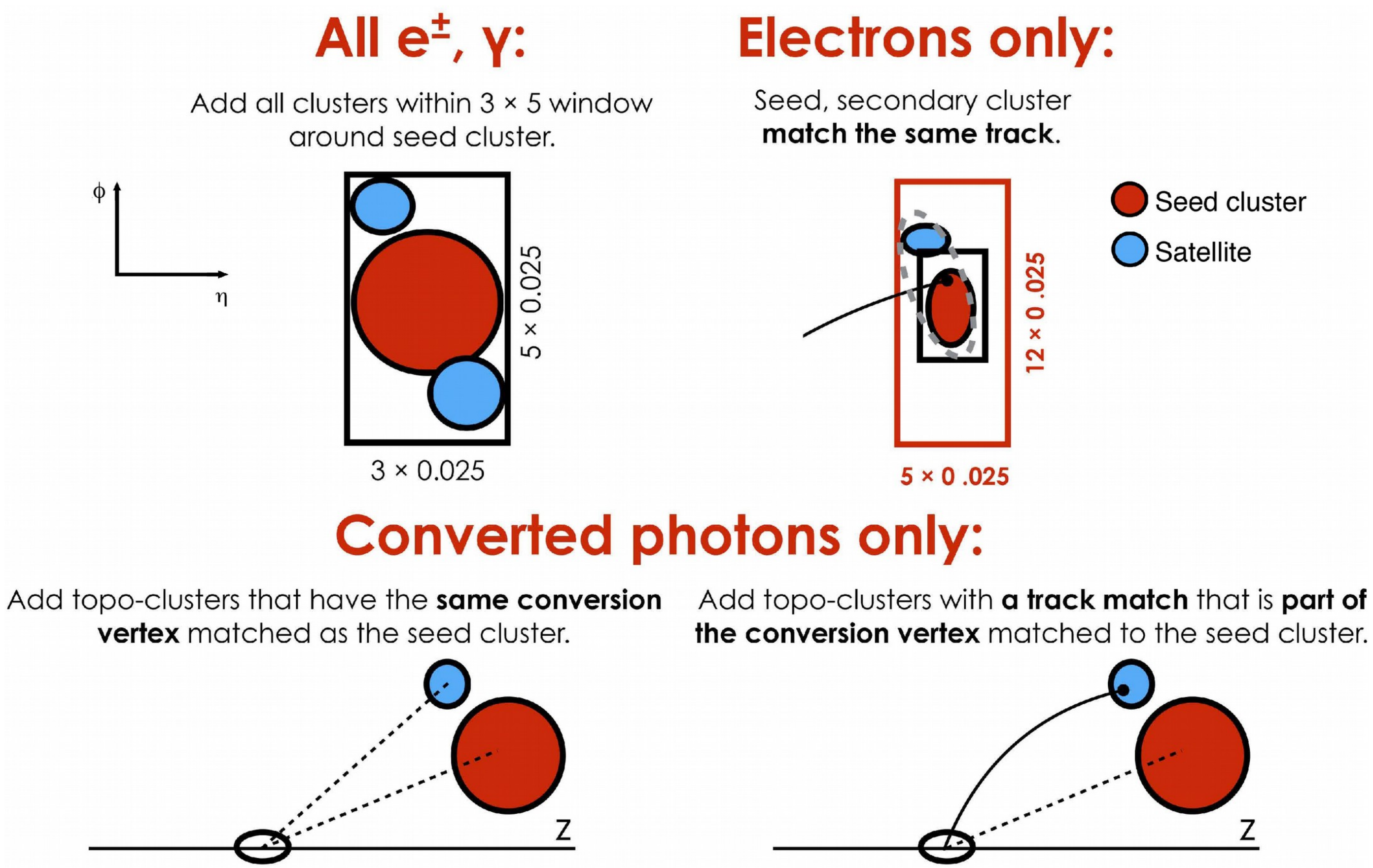


ATLAS and the EM calorimeter

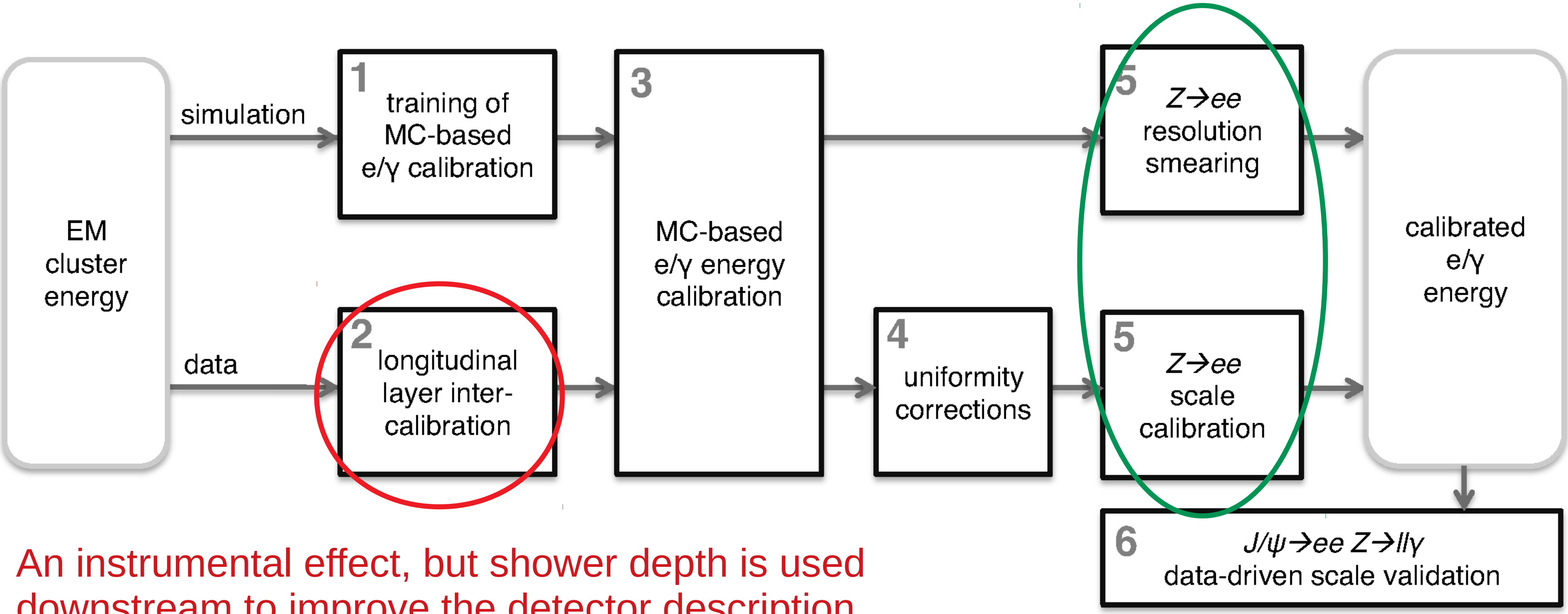
- EM (EMB+EMEC)
  - Pre-sampler: Recover energy deposited before Calo
    - $|\eta|<1.8$, 0.025*0.1
  - Strips: Fine η granularity ensure good gamma/pi separation
    - $|\eta|<3.2$, typical 0.003*0.1
  - Middle: Most EM energies deposited
    - $|\eta|<3.2$, typical 0.025*0.025
  - Back: Recover e/g longitudinal energy leakage
    - $|\eta|<2.5$, 0.05*0.025
- HEC
  - Four layers: $1.5<|\eta|<2.5$, 0.1*0.1; $2.5<|\eta|<3.2$, 0.2*0.2
- FCAL
  - Three layers, $3.1<|\eta|<4.9$, Non projective



Electron and Photon Reconstruction



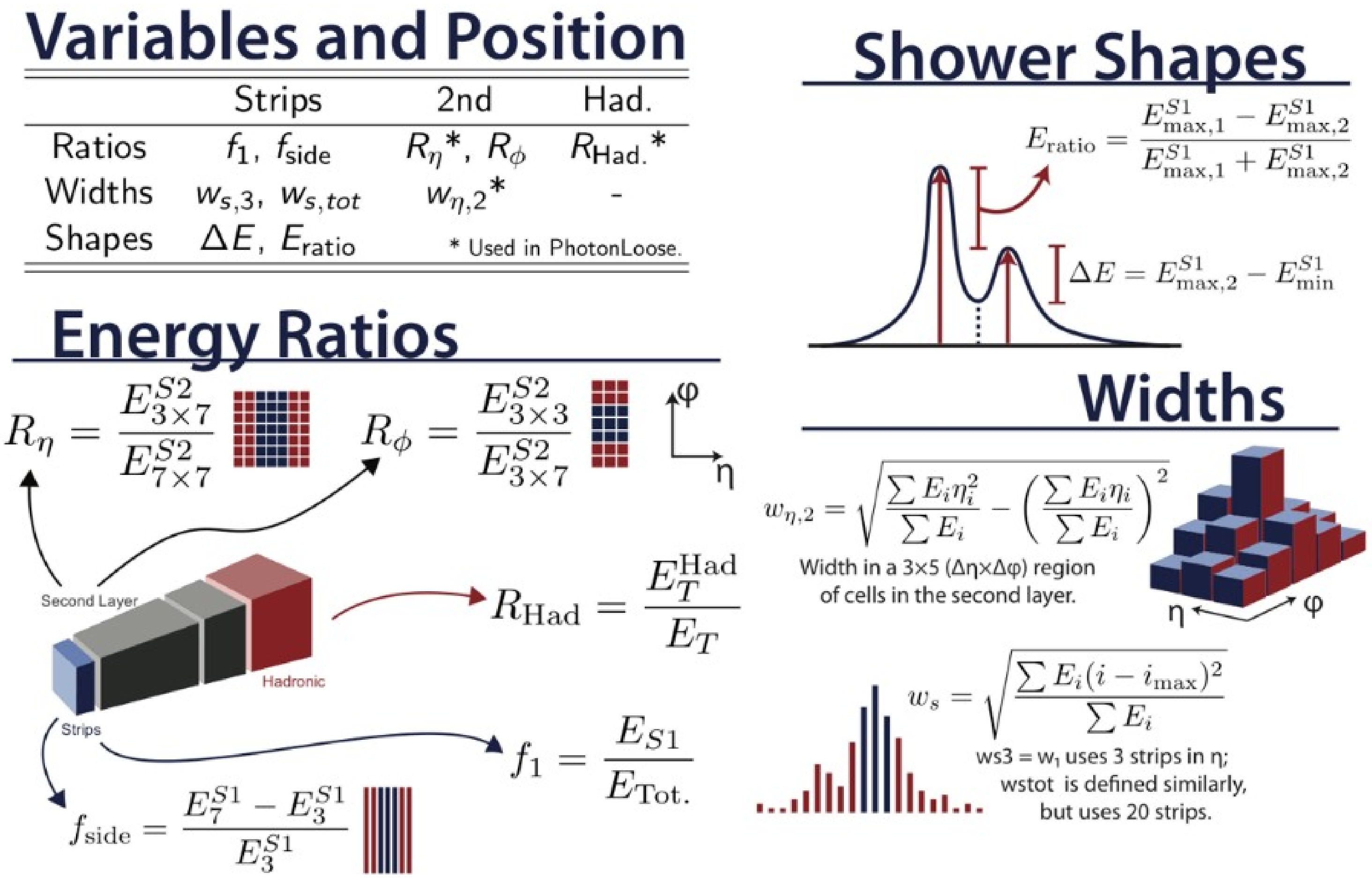
Calibration flow



An instrumental effect, but shower depth is used downstream to improve the detector description

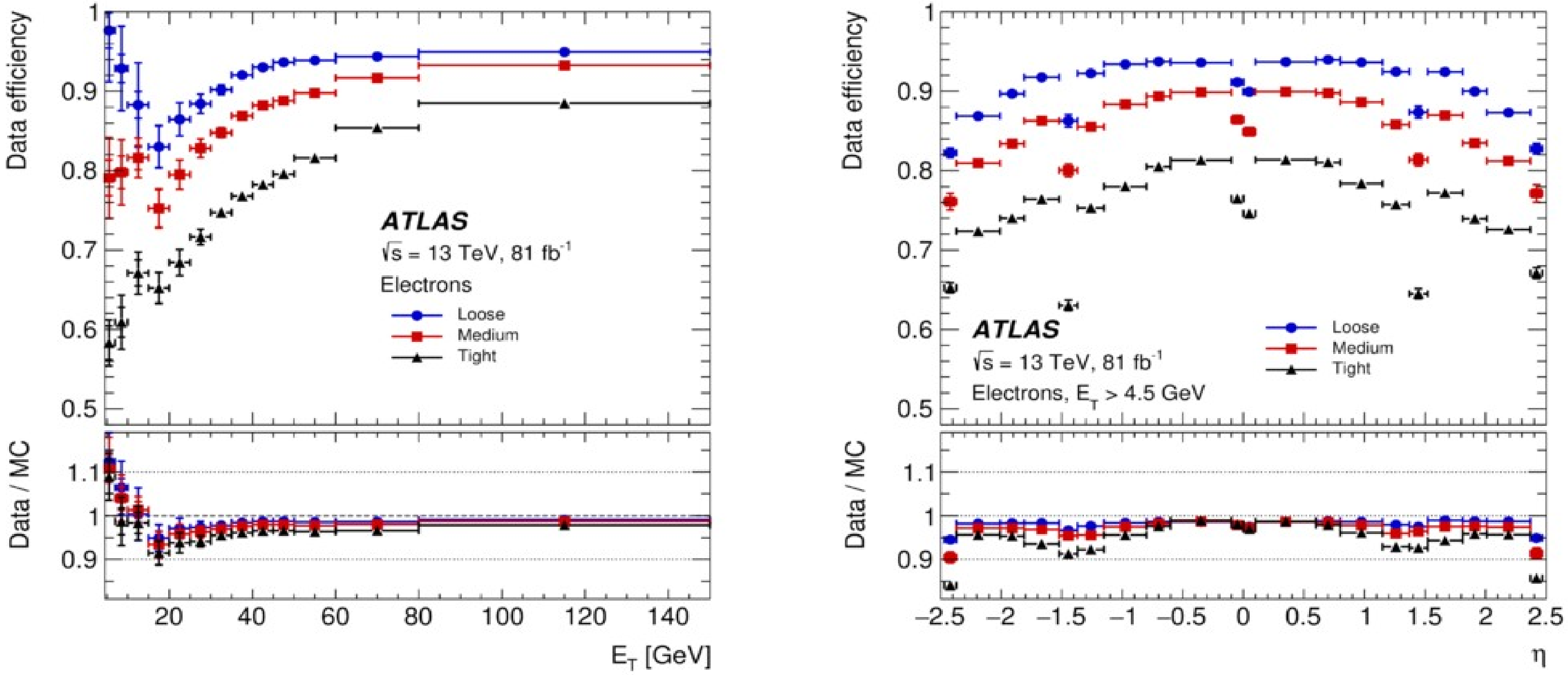
Absorbs instrumental as well as simulation imperfections

Particle identification



Particle detection performance & corrections

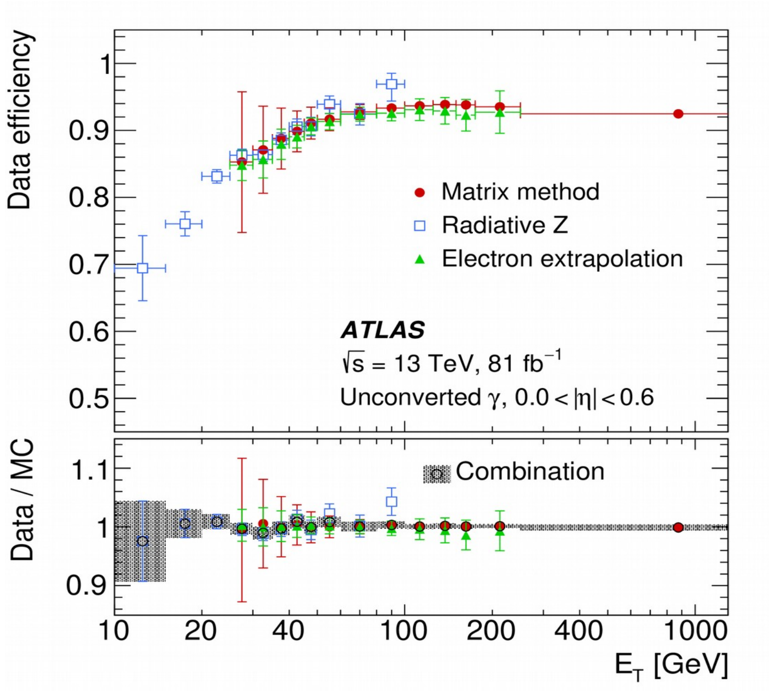
- Efficiencies : electrons

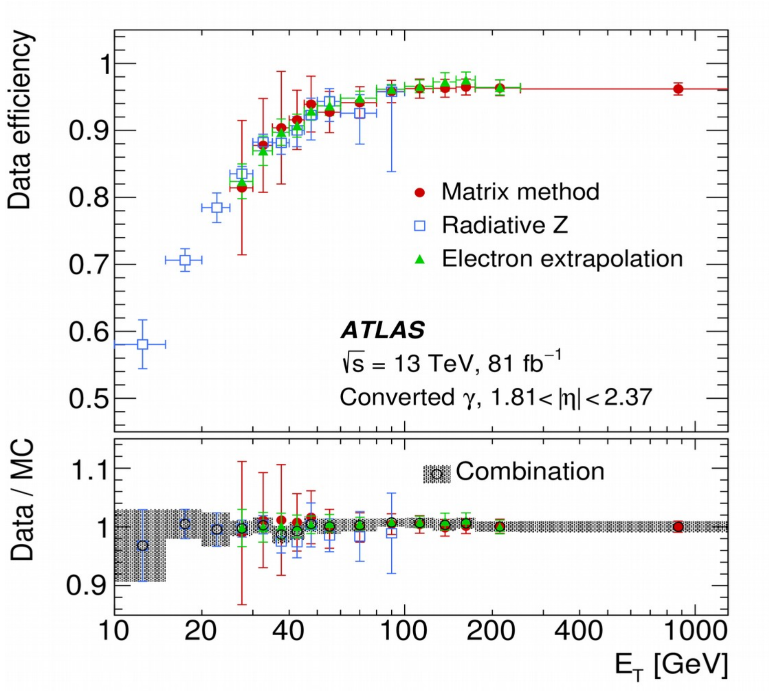


Data/MC agreement at the ~5% level, depending on E_T and identification requirement.
The main reason is mis-modeling of the shower distributions used for the identification

Particle detection performance & corrections

- Efficiencies : photons

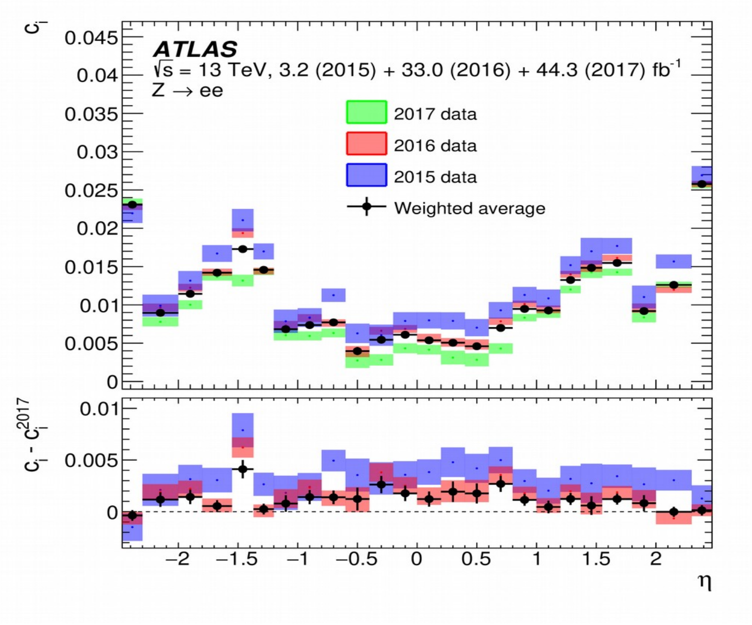


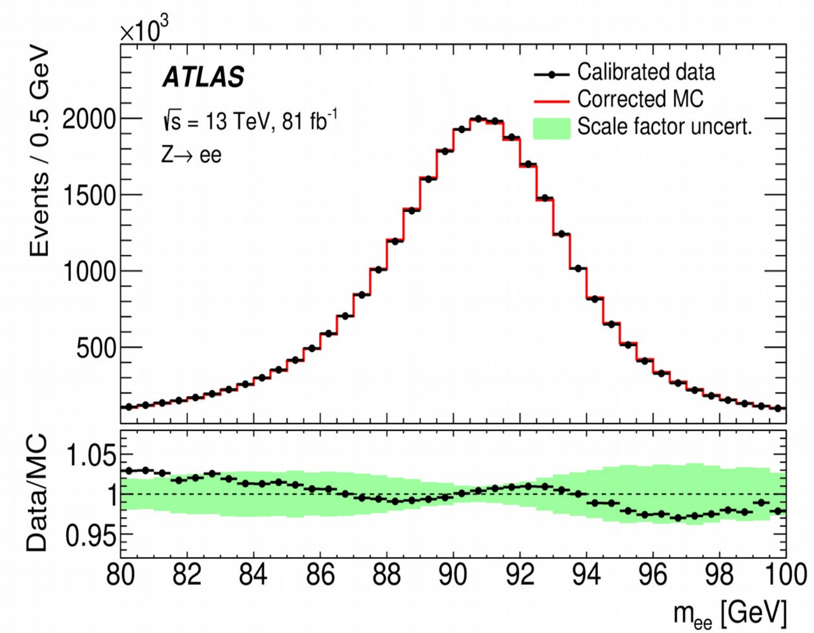


For photons, the shower distributions have been corrected “by hand”, leading to a better modelling of the efficiency. See later

Particle detection performance & corrections

- Energy resolution and energy tails

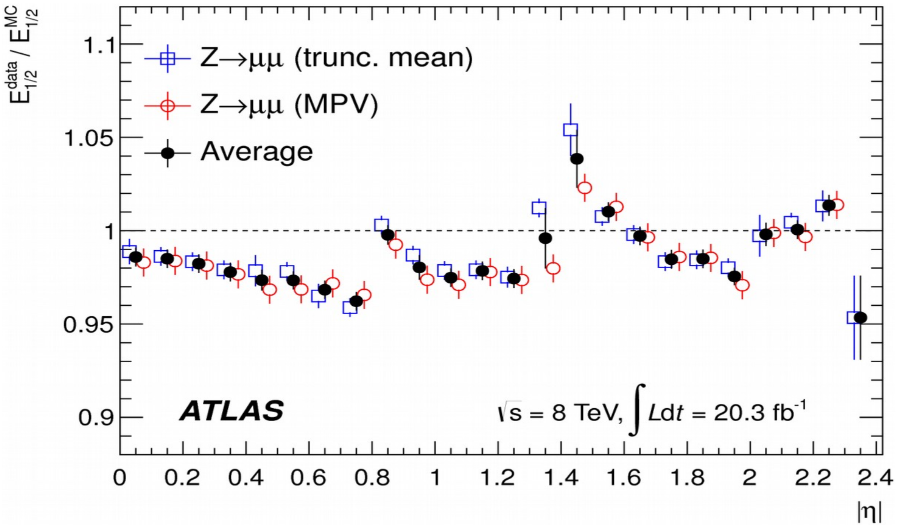




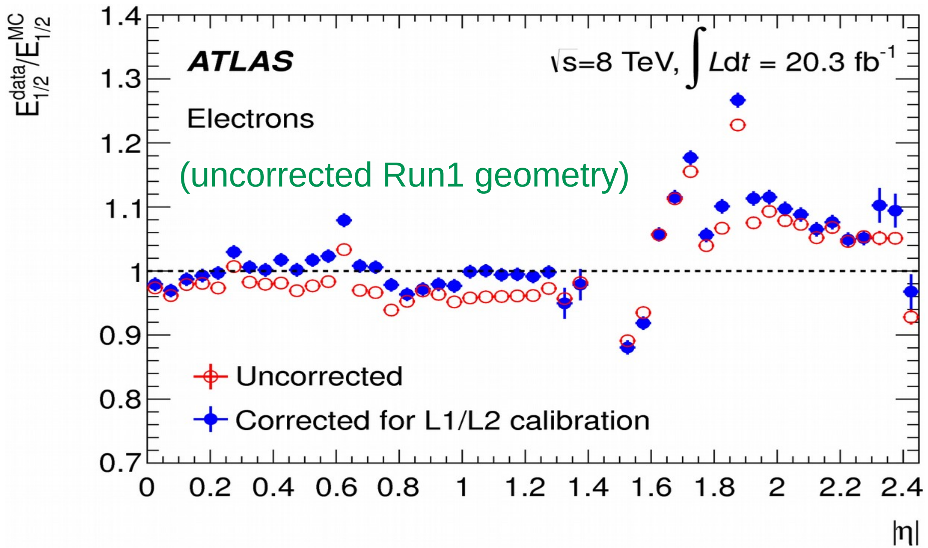
- Size of (gaussian) resolution corrections ~0.5–1.5%, depending on |η|. After corrections, the shape of the Z resonance agrees within 2-3%.
- Characteristic modulation around the peak indicates residual mis-modelling of tails; reasonable passive material variations do not seem to explain this effect.

Particle detection performance & corrections

- Passive material in front of the EM calorimeter



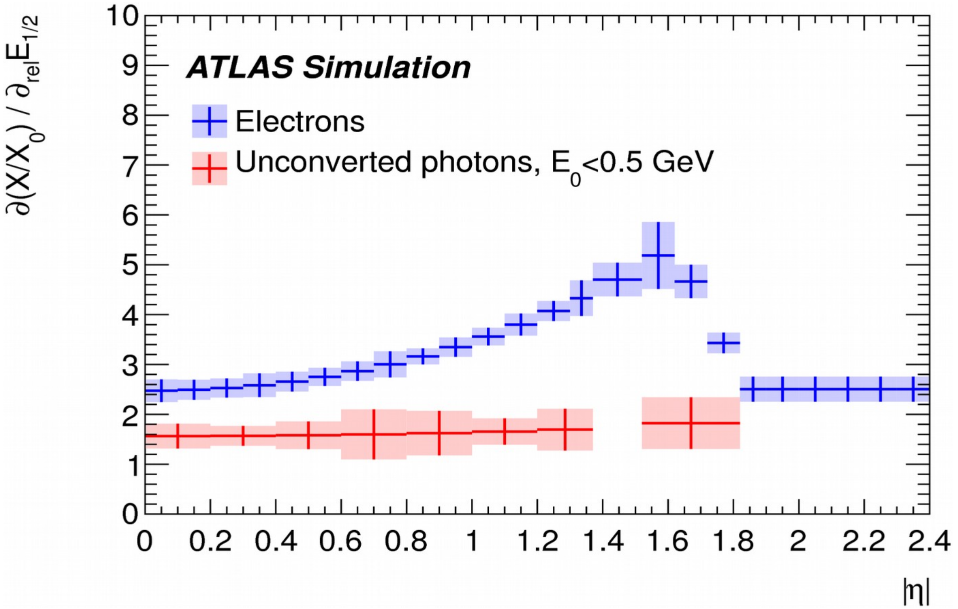
Intercalibration of layer response using muons (insensitive to material)



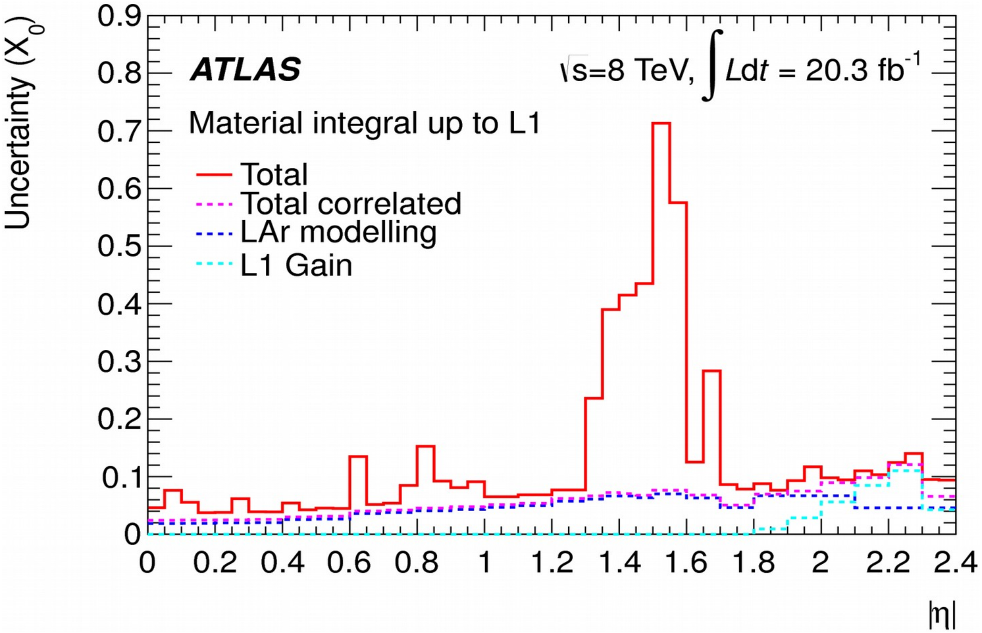
Measure E1/E2 with electrons; interpret in terms of upstream material
More material
→earlier showers
→larger E1/E2

Particle detection performance & corrections

- Passive material in front of the EM calorimeter



Sensitivity of E1/E2 to material variations



Final material measurement uncertainty

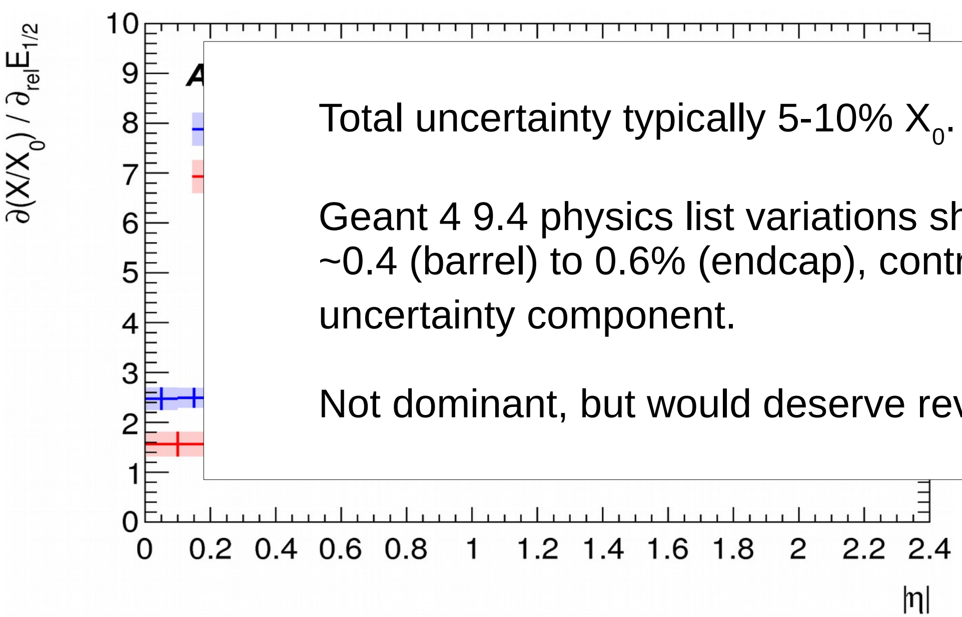
Particle detection performance & corrections

- Passive material in front of the EM calorimeter

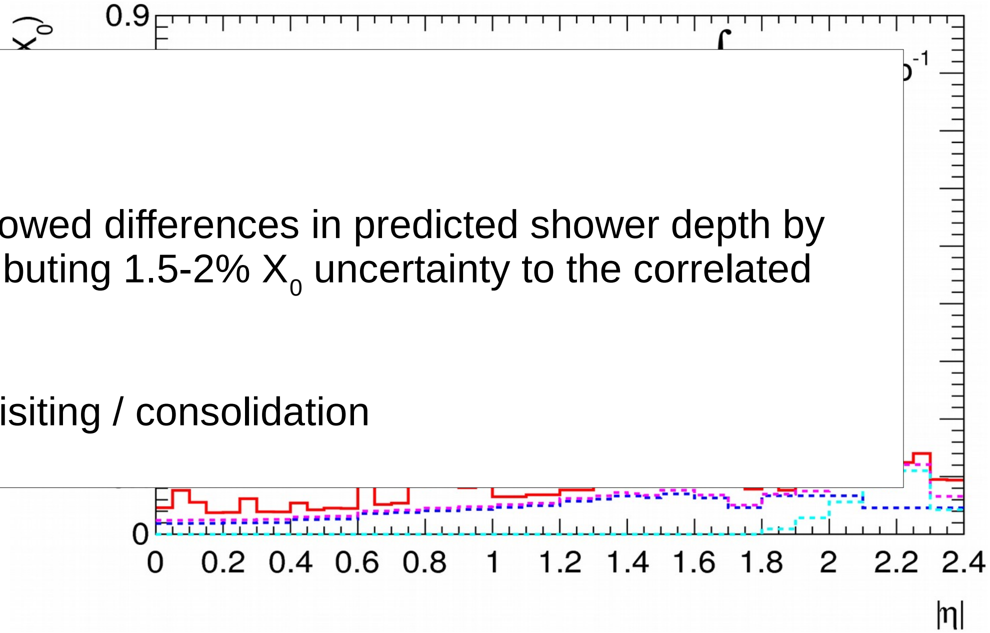
Total uncertainty typically 5-10% X_0.

Geant 4 9.4 physics list variations showed differences in predicted shower depth by ~0.4 (barrel) to 0.6% (endcap), contributing 1.5-2% X_0 uncertainty to the correlated uncertainty component.

Not dominant, but would deserve revisiting / consolidation



Sensitivity of E1/E2 to material variations



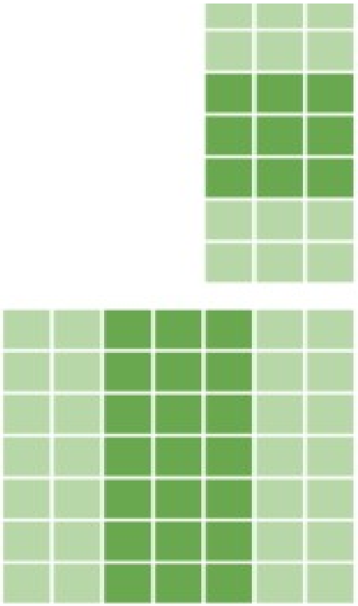
Final material measurement uncertainty

Lateral shower shapes (reminder)

- R_η, R_ϕ

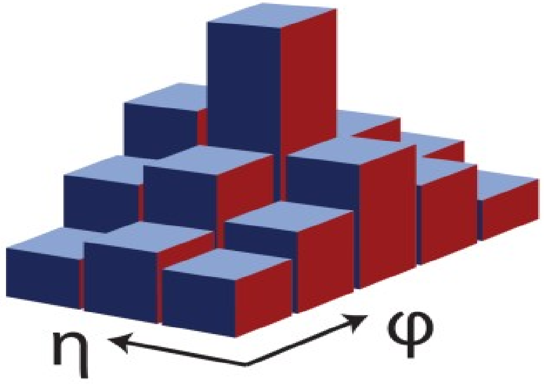
$$R_\phi = E_{3x3}/E_{3x7}$$

$$R_\eta = E_{3x7}/E_{7x7}$$



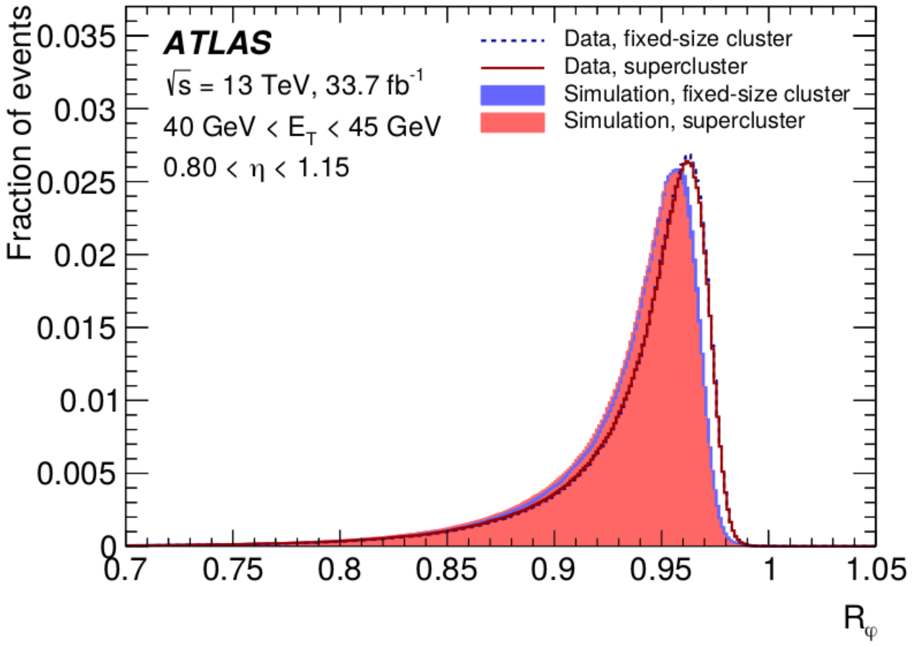
- $W_{\eta,i}$: shower “RMS” in layer *i*

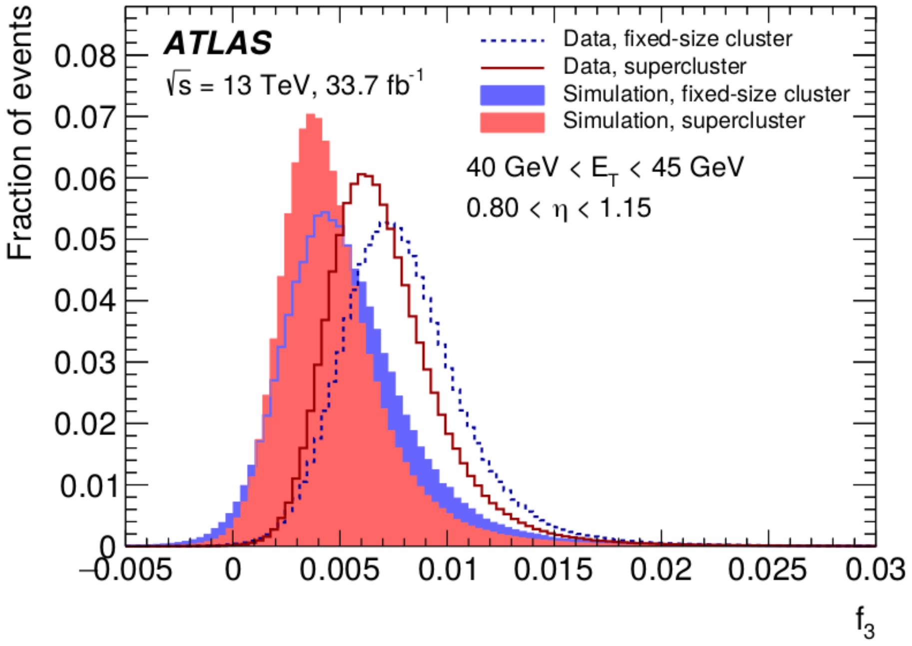
$$W_{\eta 2} = \sqrt{\sum (E_i\eta_i^2) - (\sum (E_i\eta_i)/\sum (E_i))^2}$$



Lateral shower shapes

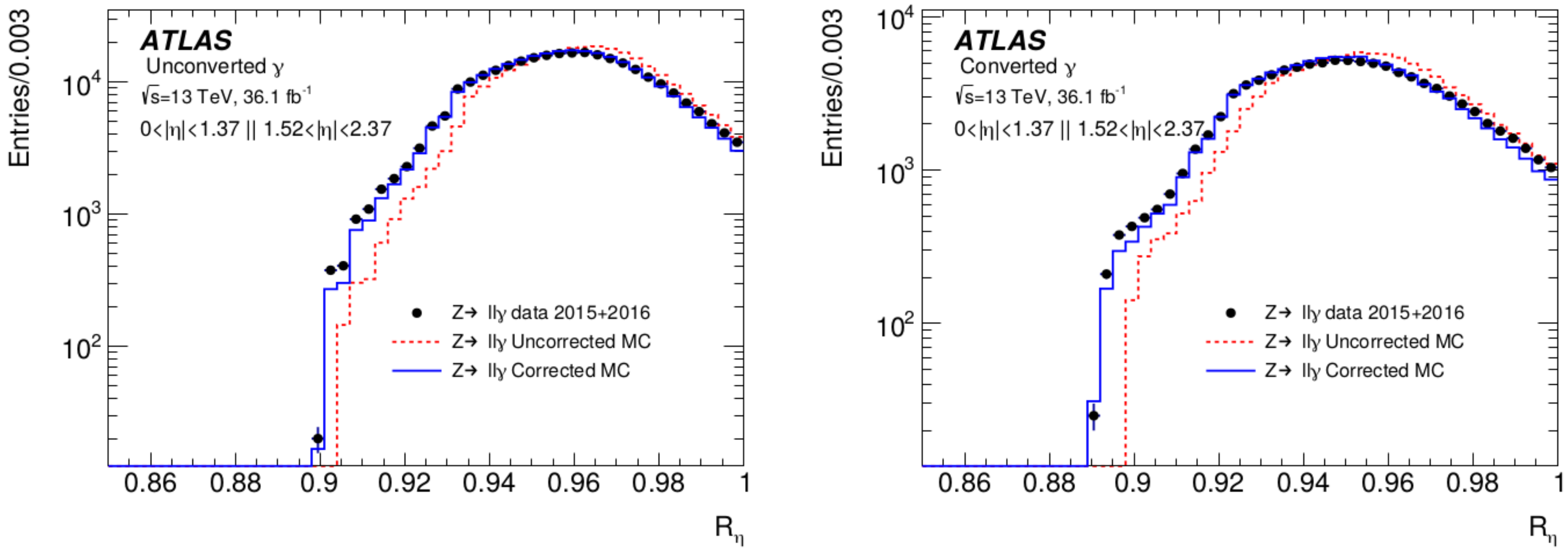
- Recent data/MC comparisons
  - data/MC differences and impact of new clustering (electrons)
    - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EGAM-2018-01/





Lateral shower shapes

- Recent data/MC comparisons
  - Illustration of data/MC corrections for photons (shifting / stretching the initial MC distributions, to reach agreement with data)
    - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2017-02/

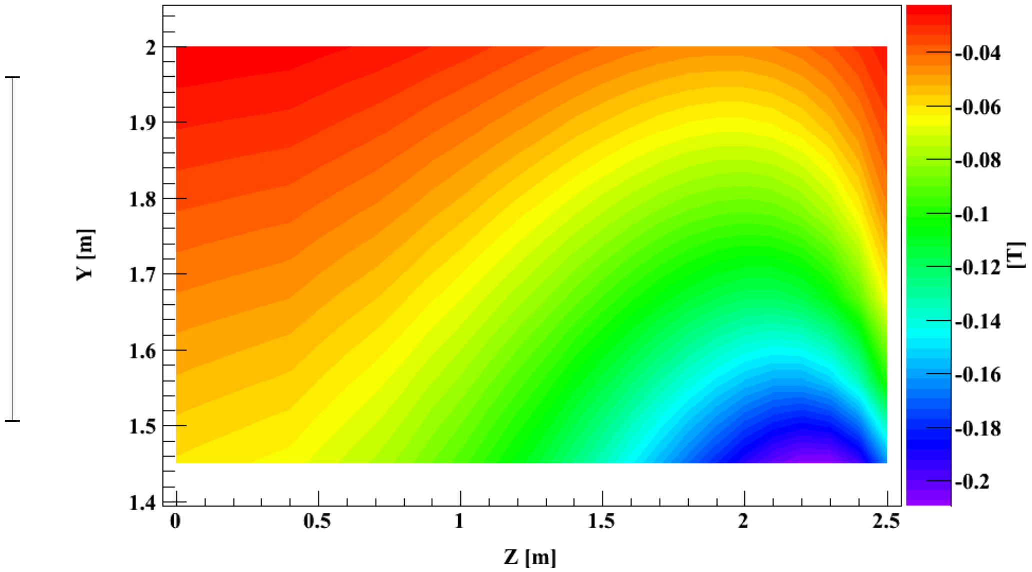


Lateral shower shapes

- Checks performed
  - A remnant B-field persists in the EM calorimeter, located outside the solenoid. The Bz component potentially affects lateral shower shapes as secondaries can spiral along the field lines, widening the showers.

    This effect is simulated, and switching this field off showed no significant effect on the shower shape variables in the low field regions of the calorimeter.

LAr calorimeter
Inner & outer radius



Bz typically -0.05 to -0.15 T

(~5% of nominal field at detector centre)

Lateral shower shapes

- Checks performed (continued)
  - Cross-talk
    - Nominal = best understanding
    - Variations : $\times 2$ in L1; $\times 2$ in L2; cross talk OFF

  → some effect on $w_{\eta 1,2}$, but not commensurate with the difference between data and MC
  - Switching Birk’s law ON/OFF

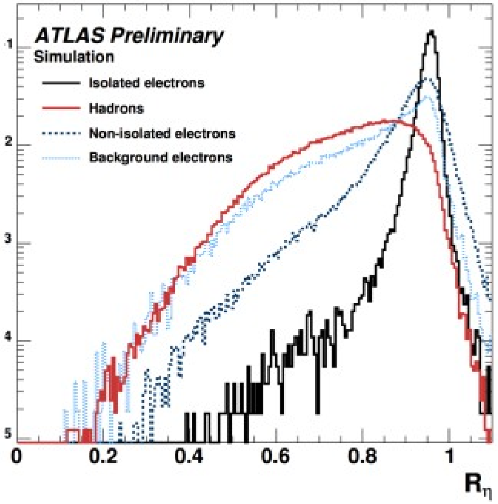
  → no effect

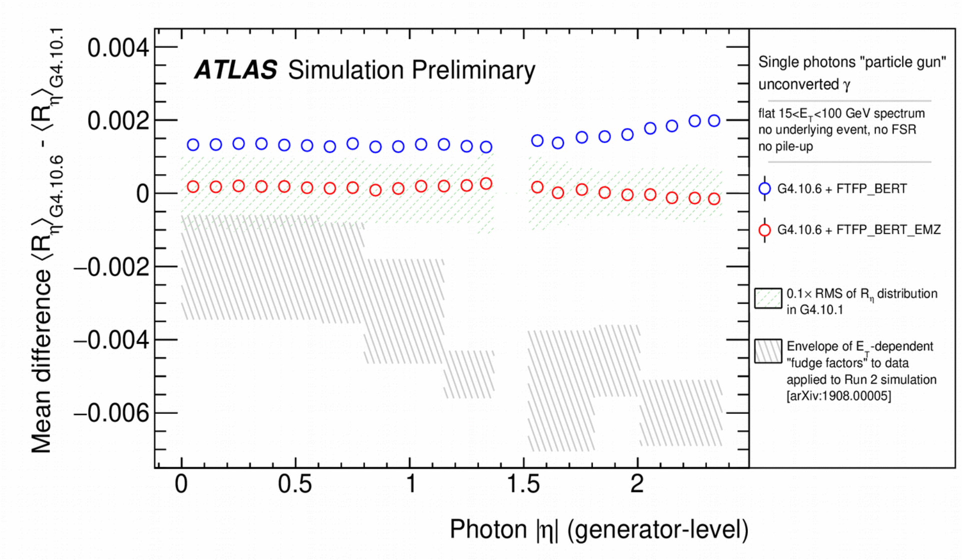
Lateral shower shapes

- Tests of recent Geant4 versions
  - Geant4 10.1 (used for Run2 simulation) vs 10.6

    software optimizations; improved EM physics : multiple scattering, new model for photon conversions, rare processes (eg 3-photon annihilation), …
  - Within 10.6, study effect of EMZ option (slowest & best)
    - NB : observed change or sampling fraction by 1.5%, as expected by Geant4 experts
- Impact on shower shapes :
  - Reference : Geant4 10.1 FTFP_BERT
  - Variations :
    - fudge-factors for 10.1 (representing the discrepancy between 10.1 simulation and data)
    - 10.6 FTFP_BERT and FTFP_BERT_EMZ
- Single photons; $15 < E_T < 100$ GeV ; $0 < |\eta| < 2.5$; no pile-up, no FSR, ...

R_η, R_ϕ



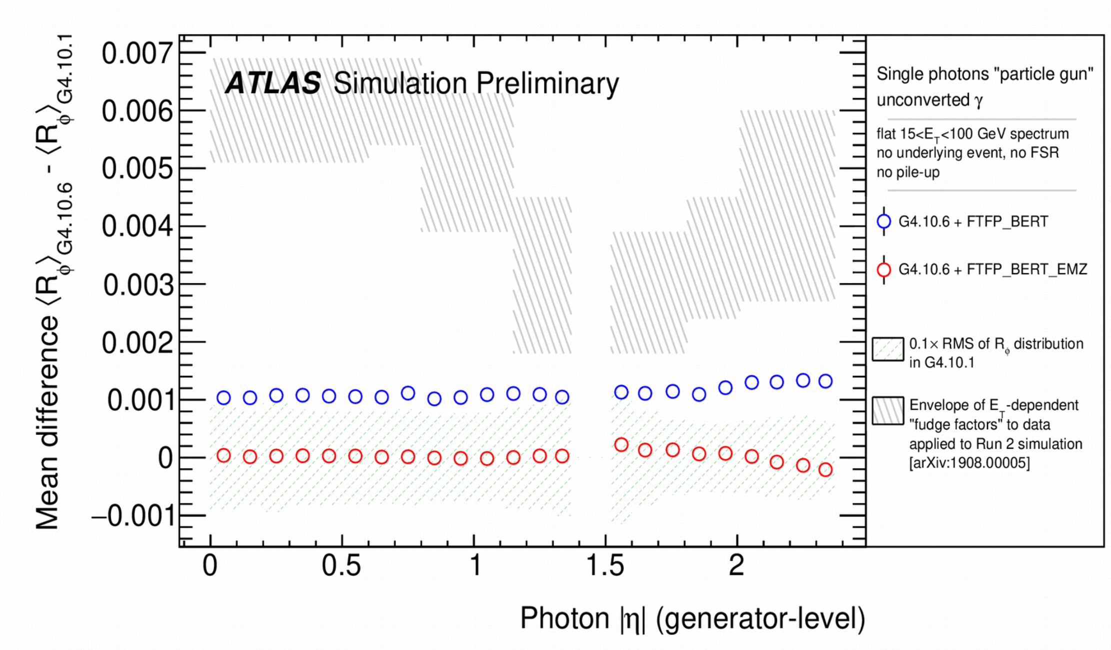


narrower

wider

G4 10.1 → 10.6 gives narrower showers; in 10.6; EMZ reproduces 10.1.

R_η, R_ϕ

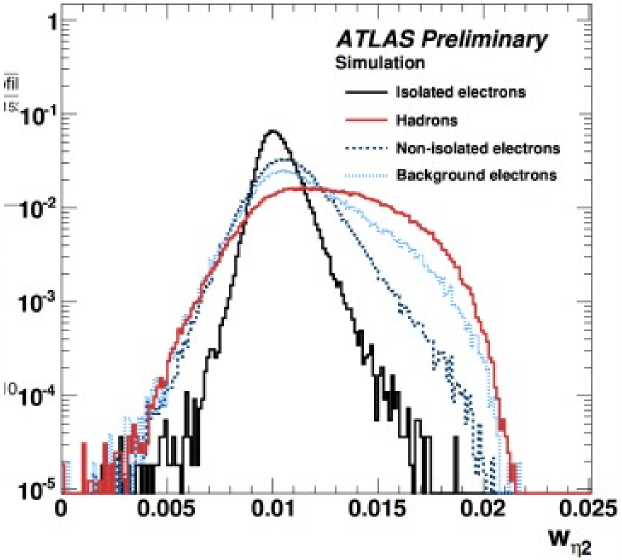


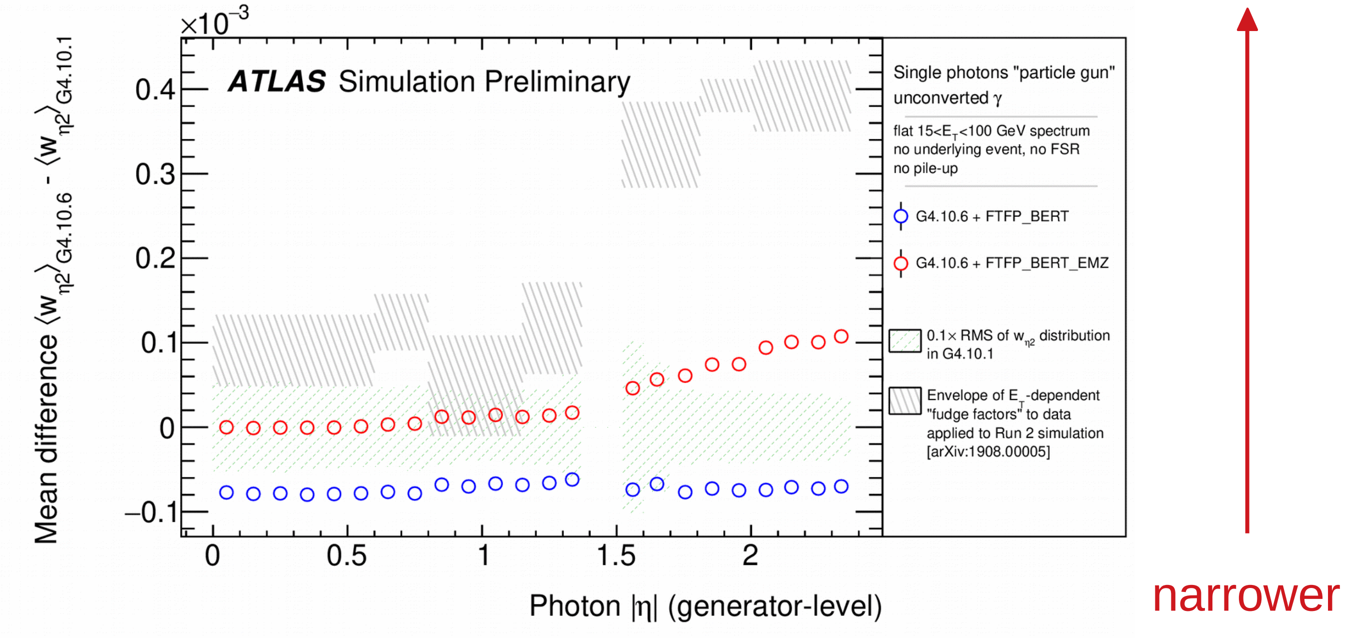
narrower

wider

G4 10.1 → 10.6 gives narrower showers; in 10.6; EMZ reproduces 10.1.

$w_{\eta 2}$

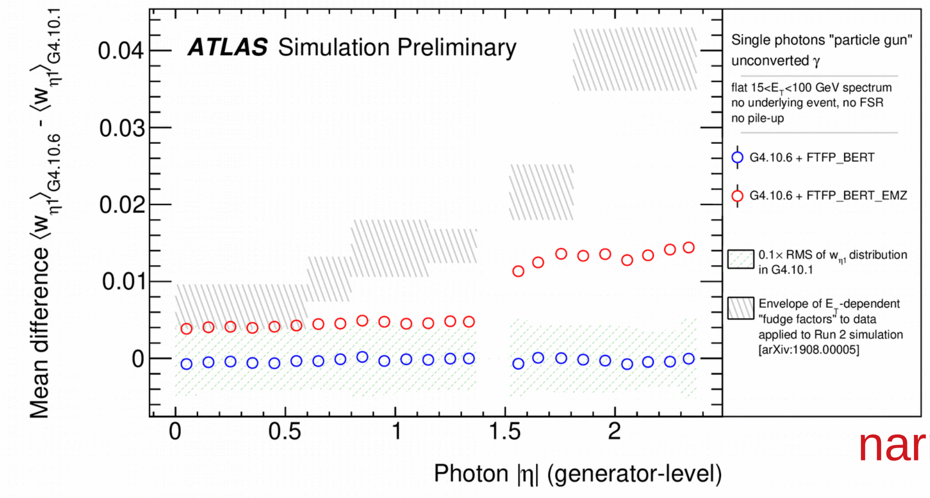


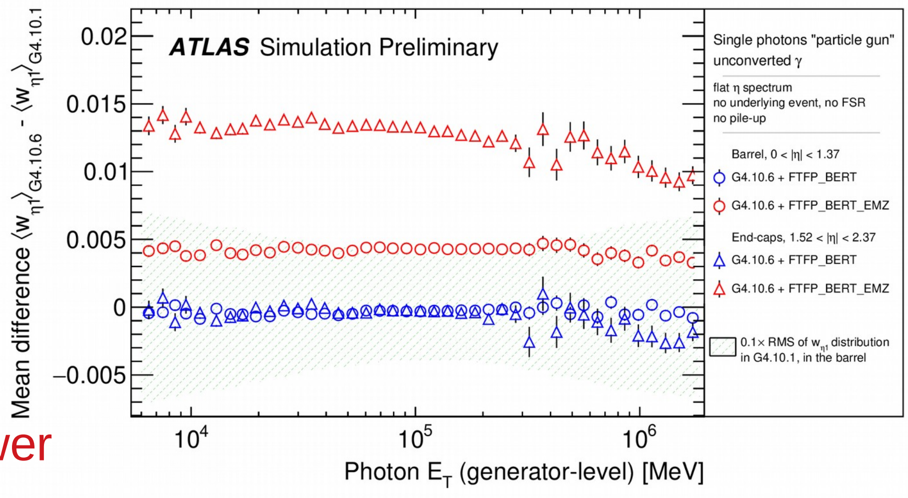


Very correlated to R_η in layer 2; similar behaviour and discrepancies

$w_{\eta 1}$

wider





narrower

Similar behaviour in Layer1. Discrepancy mostly independent of E_T

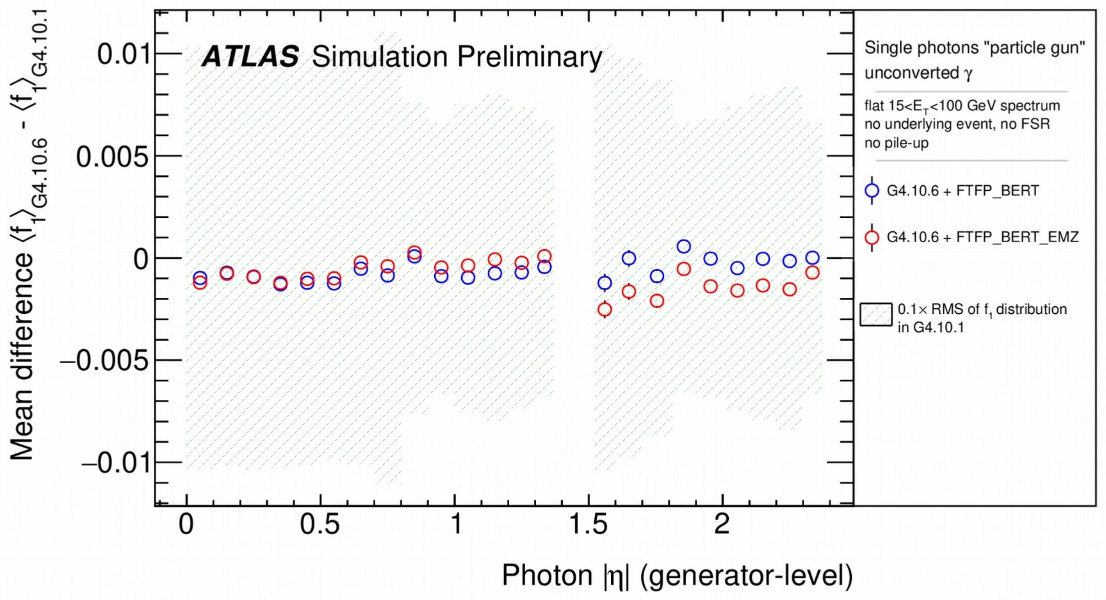
Comments

- G4 10.1 → 10.6 gives narrower showers; in 10.6; EMZ reproduces 10.1.
  For R_η, showers are wider in data; for R_ϕ, data are narrower.

- Polar and azimuthal shower shapes constitute two partly separate poblems:
  - η goes along absorbers & electrodes → sensitive to cross talk; stable under passive material variations
  - ϕ goes across absorbers → insensitive to cross talk but feels upstream passive material
  - both probe the same intrinsic lateral shower development

→ the opposite behaviour for R_η and R_ϕ points probably at least two competing effects

f1



- Stable to 0.1 – 0.2 % : good!
- Relevant for the measurement and interpretation of E1/E2
- An accurate prediction is critical as we don’t have means to measure the “intrinsic” accuracy of longitudinal shower development, except returning to (very) old testbeam data

Summary

- First-principles simulation of ATLAS EM physics is accurate at the level of one to a few percent. Corrections used to reach permille precision are mostly effective in nature
- The determination of upstream passive material relies on a precise simulation of the longitudinal development of EM showers, given amount of passive material. The corresponding uncertainty limits the achievable precision to ~1.5-2% X_0 (not a dominant uncertainty component this far)
- Tails in energy response so far not understood
  - explanation due to passive material disfavoured.
  - Intrinsic to the calorimeter? Losses related to mis-modeled lateral or longitudinal shower fluctuations?
- The mis-modeling of lateral shower distributions is a common underlying cause to many observed discrepancies, and is still an open question
  - Checks of detector description, cross-talk, data-taking conditions did not reveal obvious culprits.
  - Updates in the Geant4 physics do not yield significant improvements in the predictions.