Detector And Performance Tools for Photons on ATLAS

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On behalf of the ATLAS Collaboration

Workshop on Photon Physics and Simulation at Hadron Colliders
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Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

ATLAS EXPERIMENT

Outline – Run 2, Run 3 and Beyond

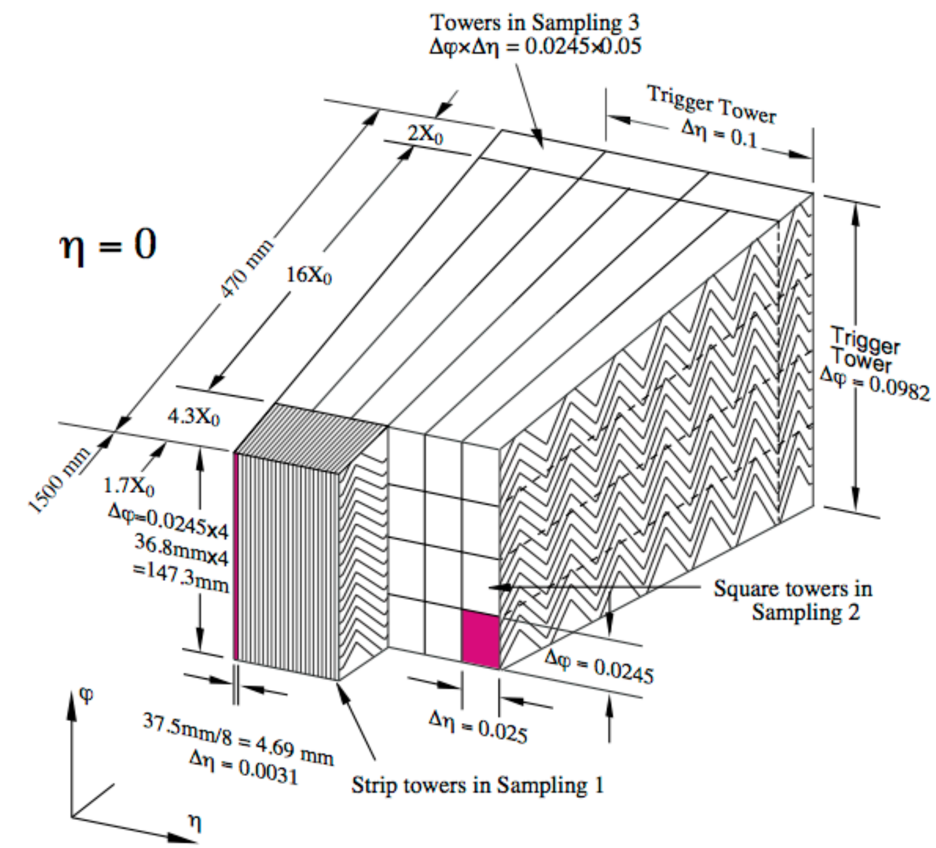
The latest and greatest of ATLAS tools

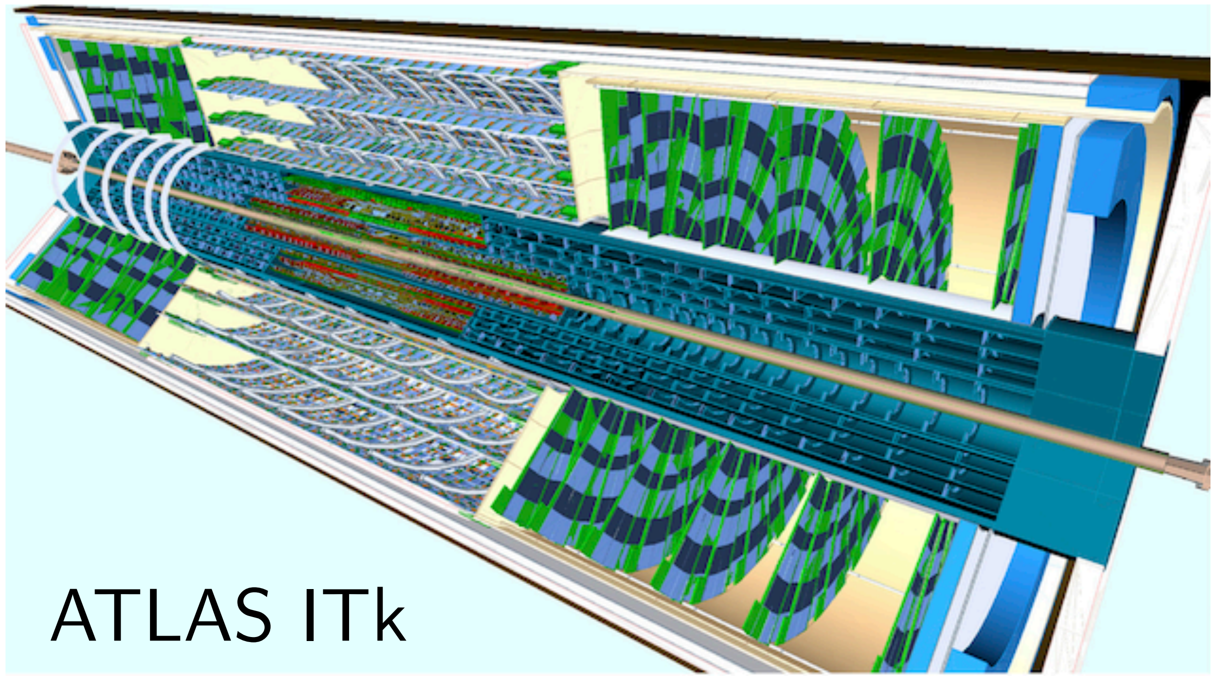
- Reconstruction
- Identification and Isolation
- Efficiency Measurements
- Calibration

- Thoughts on Direct vs Fragmentation Production

- Perspectives and challenges for Run 3 and the HL-LHC

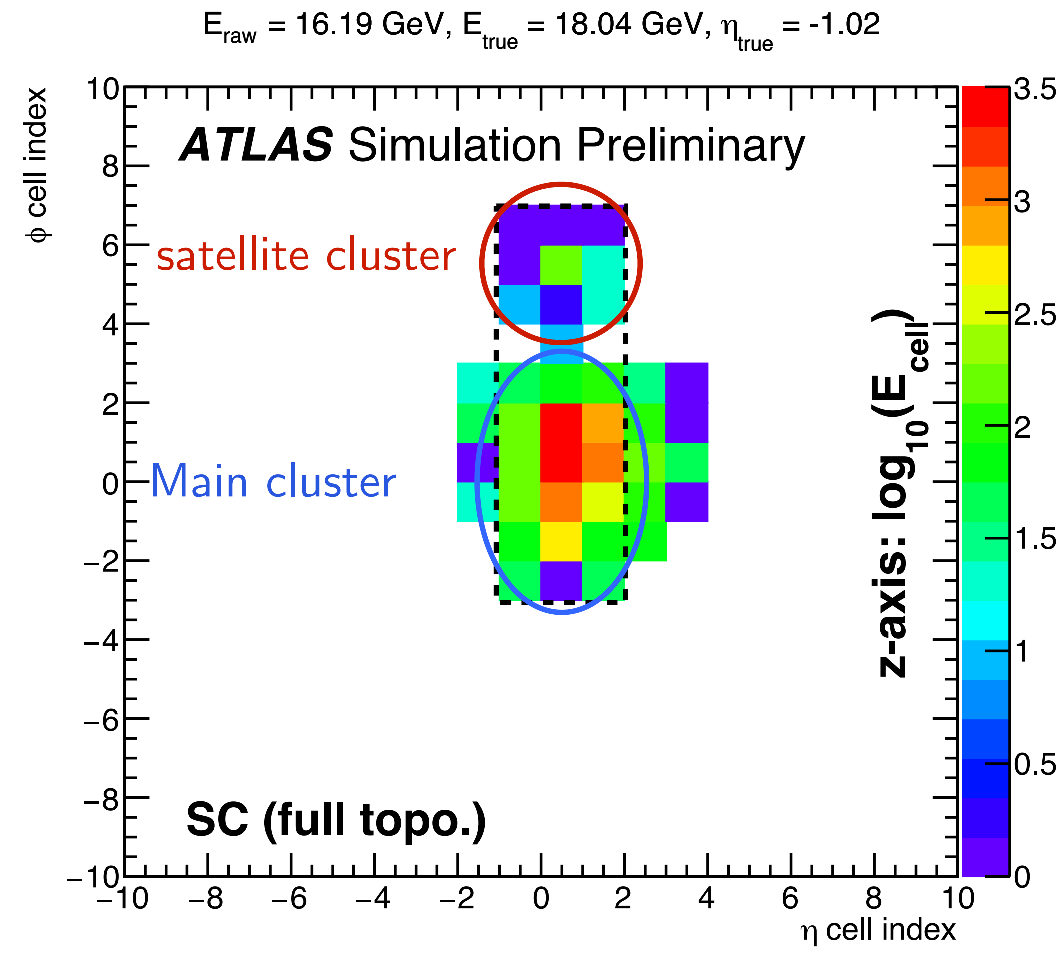
The ATLAS Liquid Argon Calorimeter

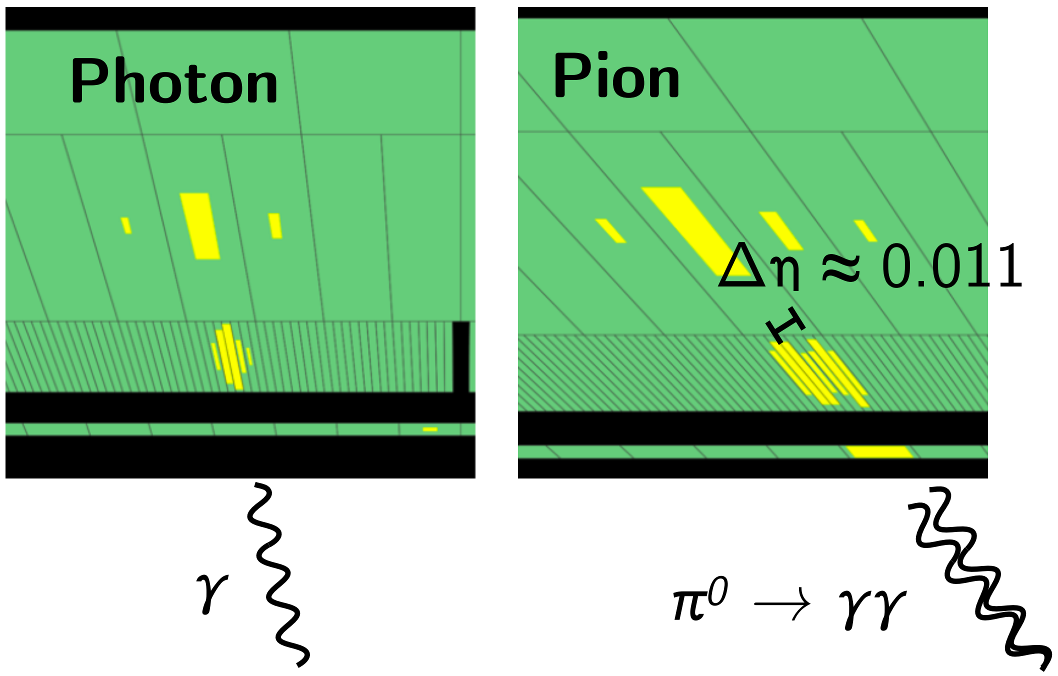


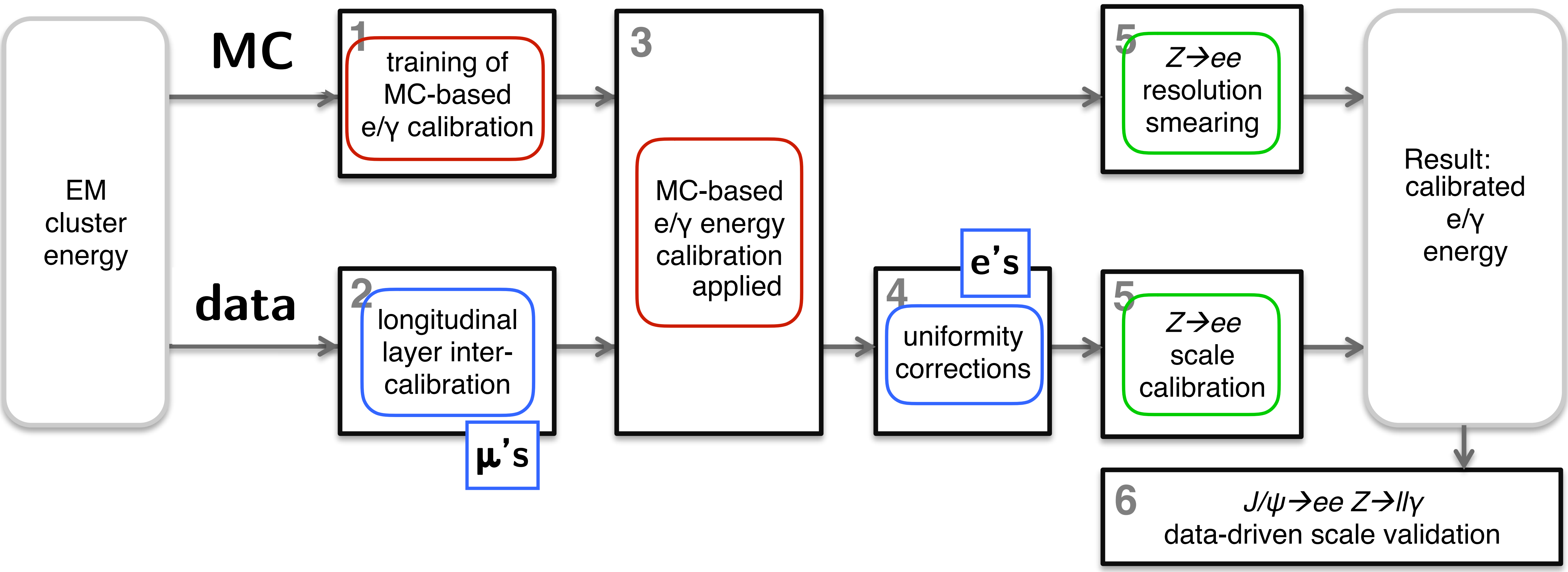


Main Steps of ATLAS Photon Identification

- **"Superclusters" built from EM deposits:**
  - Cells formed into topological clusters (as opposed to a cell window of fixed-area)
  - Logic to collect as much energy as possible
- **Disambiguation between photons and electrons**
  - And between converted and unconverted photons
- **Identification (against mostly jets):**
  - *Jets with $\pi^0 \to \gamma\gamma$ are a primary concern*
  - Finely segmented strip layer in the LAr calorimeter







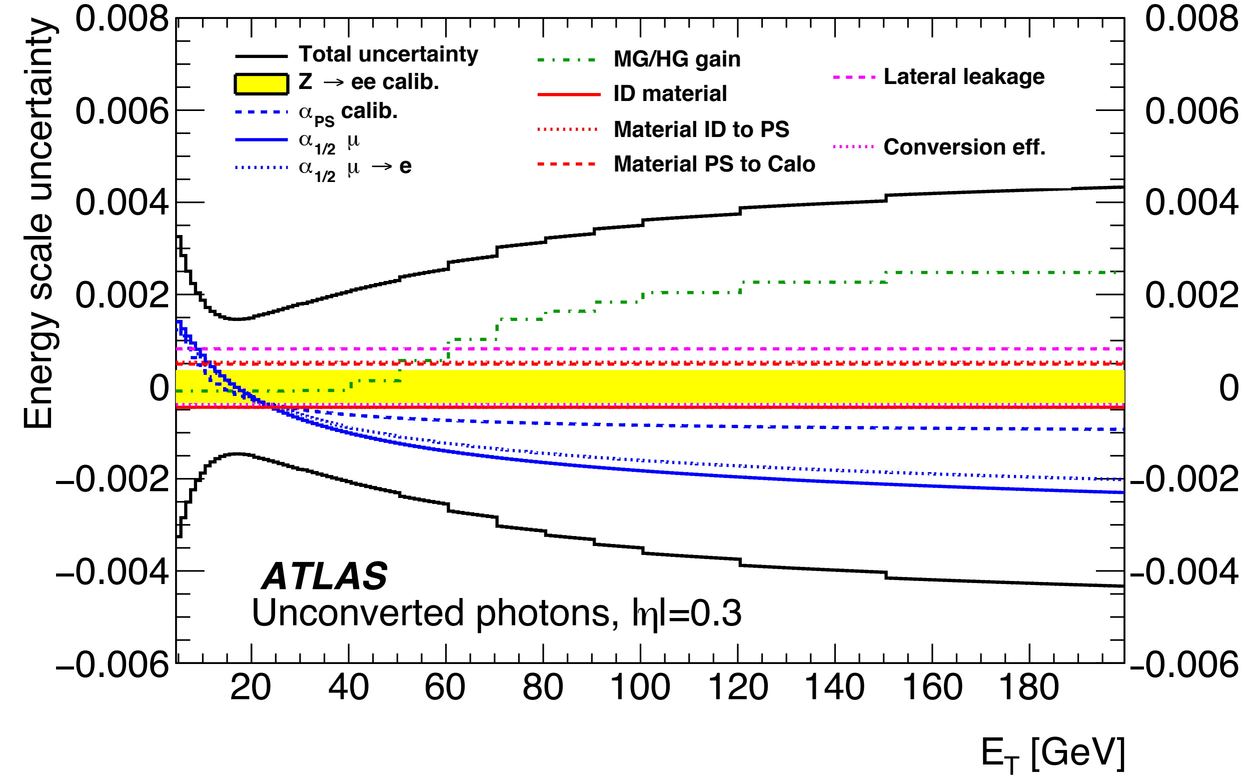
- Several data-driven corrections to correct for energy scale variations in different layers, non-uniformity of local detector regions
- MC-based MVA calibration, different calibration for electrons, converted photons, unconverted photons
  $\rightarrow$ ***require well-understood simulation!***
- $Z \rightarrow ee$ used for scale calibration, MC resolution smearing
- Most corrections are derived using electrons (or muons), extrapolated to photon case with uncertainties
- $Z \rightarrow \ell\ell\gamma$ used for photon validation

Requires a detailed understanding of our detector and its response to e's and γ's

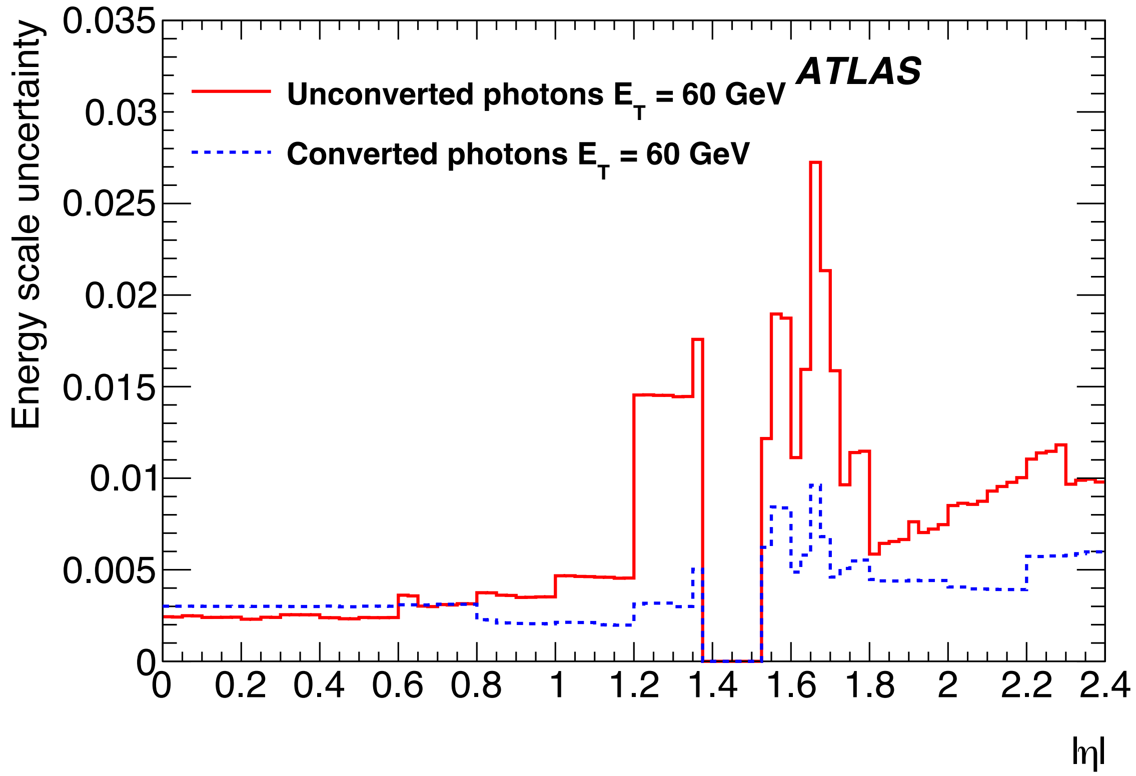
Calibration – Energy Scale Uncertainties

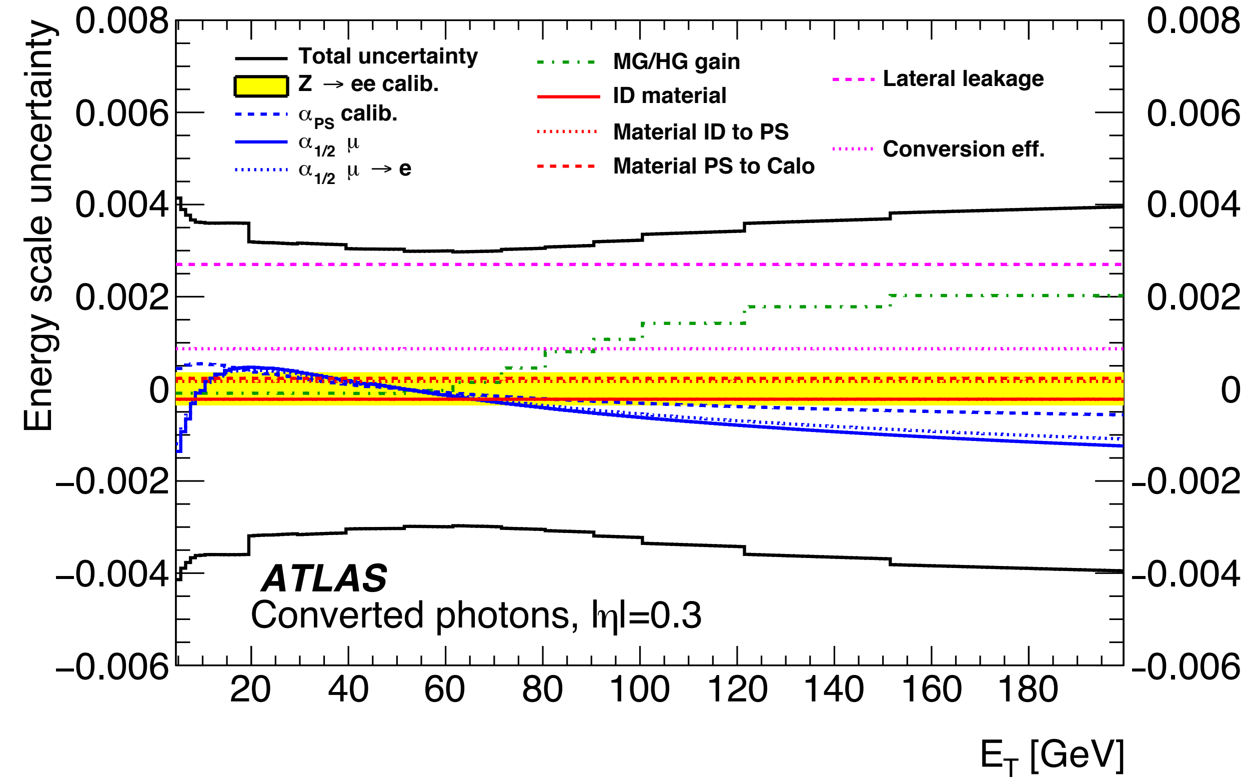
JINST 14 (2019) P03017

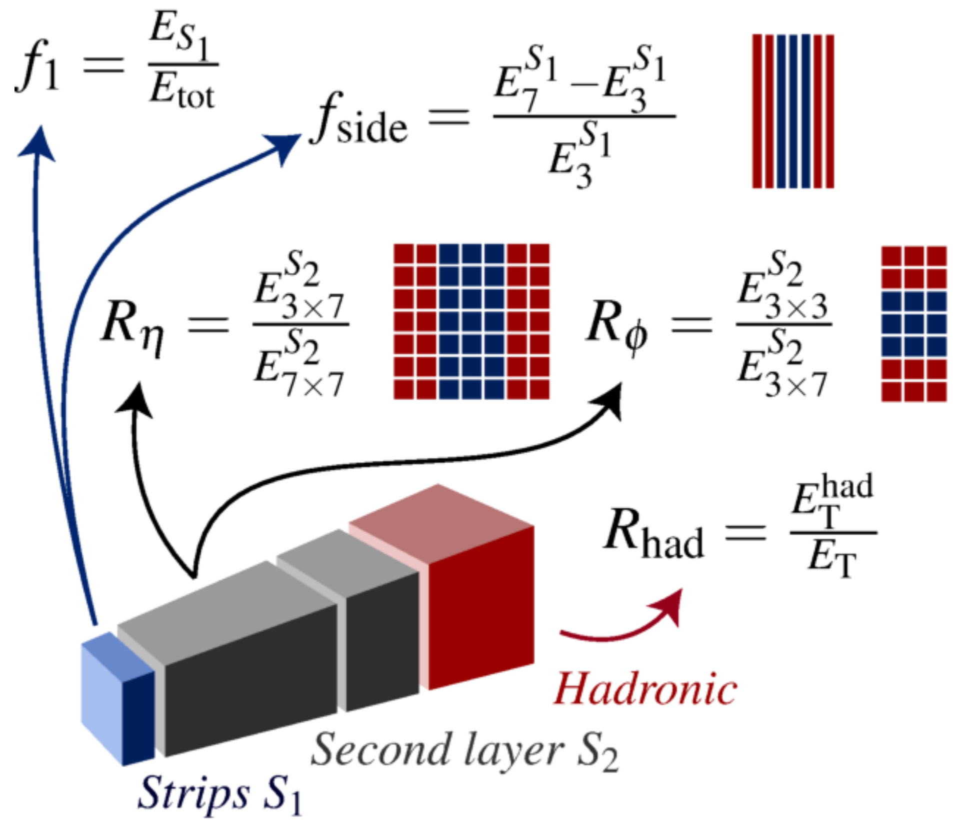
- Uncertainties for converted and unconverted photons **typically 0.2-0.5%**
- Largest effects:
  - LAr response linearity ("MG/HG gain")
  - e-γ differences in the the modeling of lateral shower shapes (lateral leakage)
  - LAr Layer intercalibration
- Reliance on $Z \rightarrow ee$ means that we extrapolate scale uncertainties to high E_T



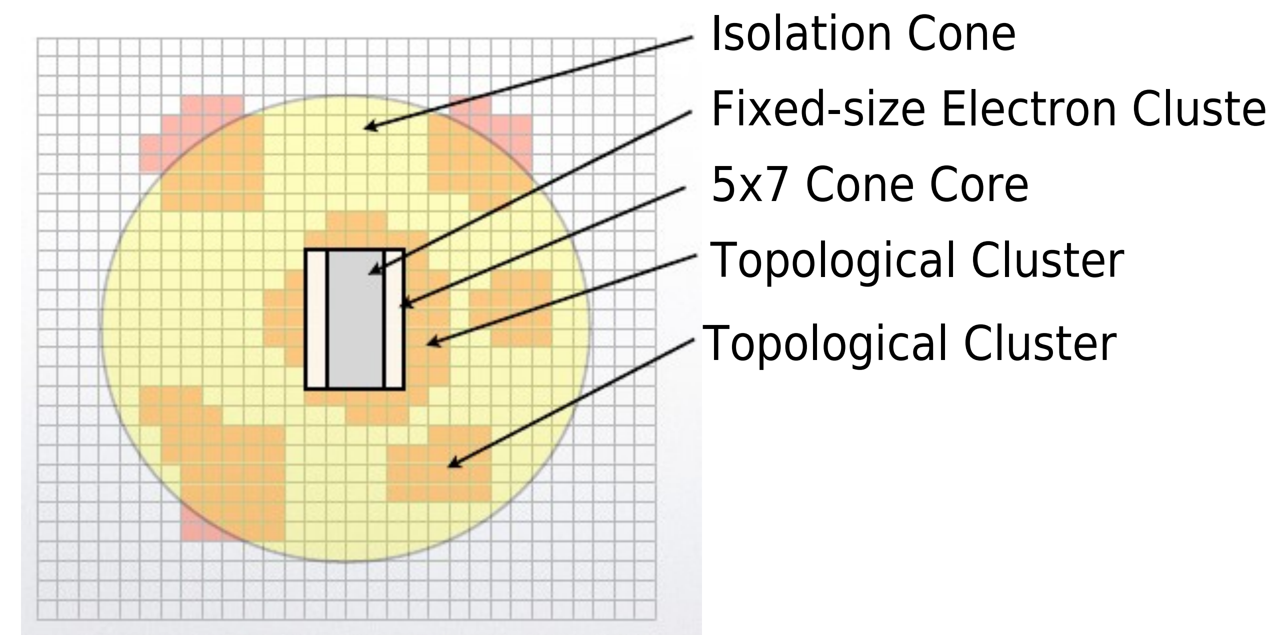
Energy scale uncertainty vs |η|



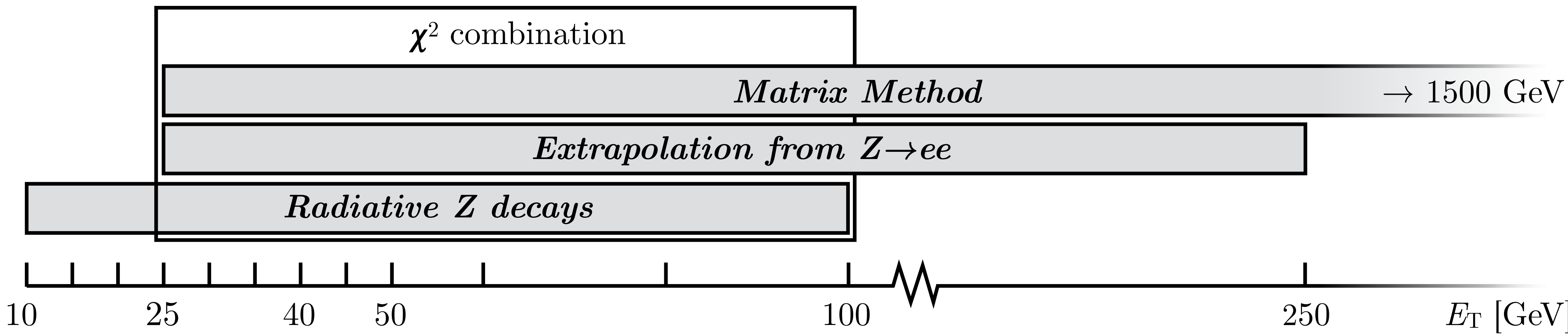




Calorimeter Isolation (using topological clusters)



- **Identification variables**: detailed energy ratios in the 7×7 core
  - hadronic calorimeter energy / EM calorimeter energy
  - Ratios of energy windows in φ and η, consistent with a narrow EM deposit
  - Narrow strip layer variables
  - Use these variables in a **cut-based identification method**
- **Track isolation**: relative momentum of tracks ($p_T > 1$ GeV) in a cone around the photon
- **Topological calorimeter isolation**: sum of energy of topological clusters in an isolation cone (excluding the core)

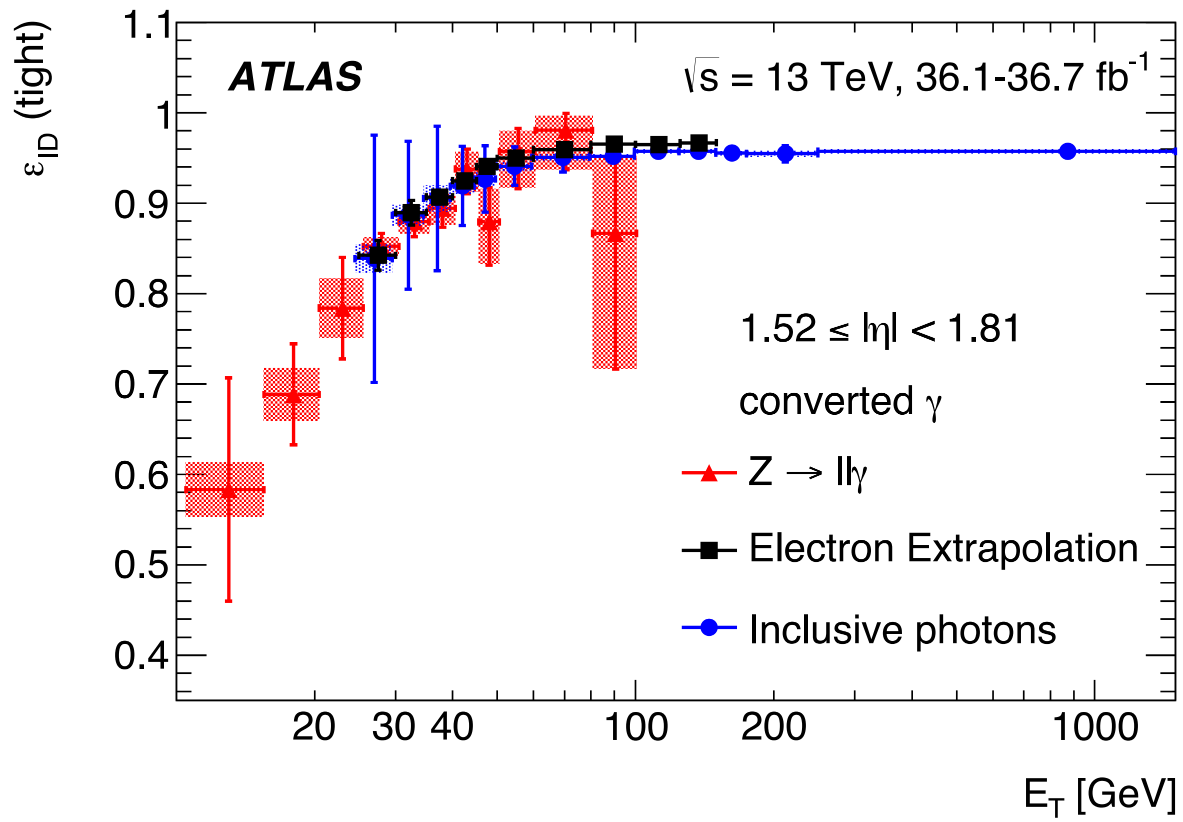


- Measure efficiencies and data-MC corrections for **Isolated Photons*****

Standard Candles for studying photons:

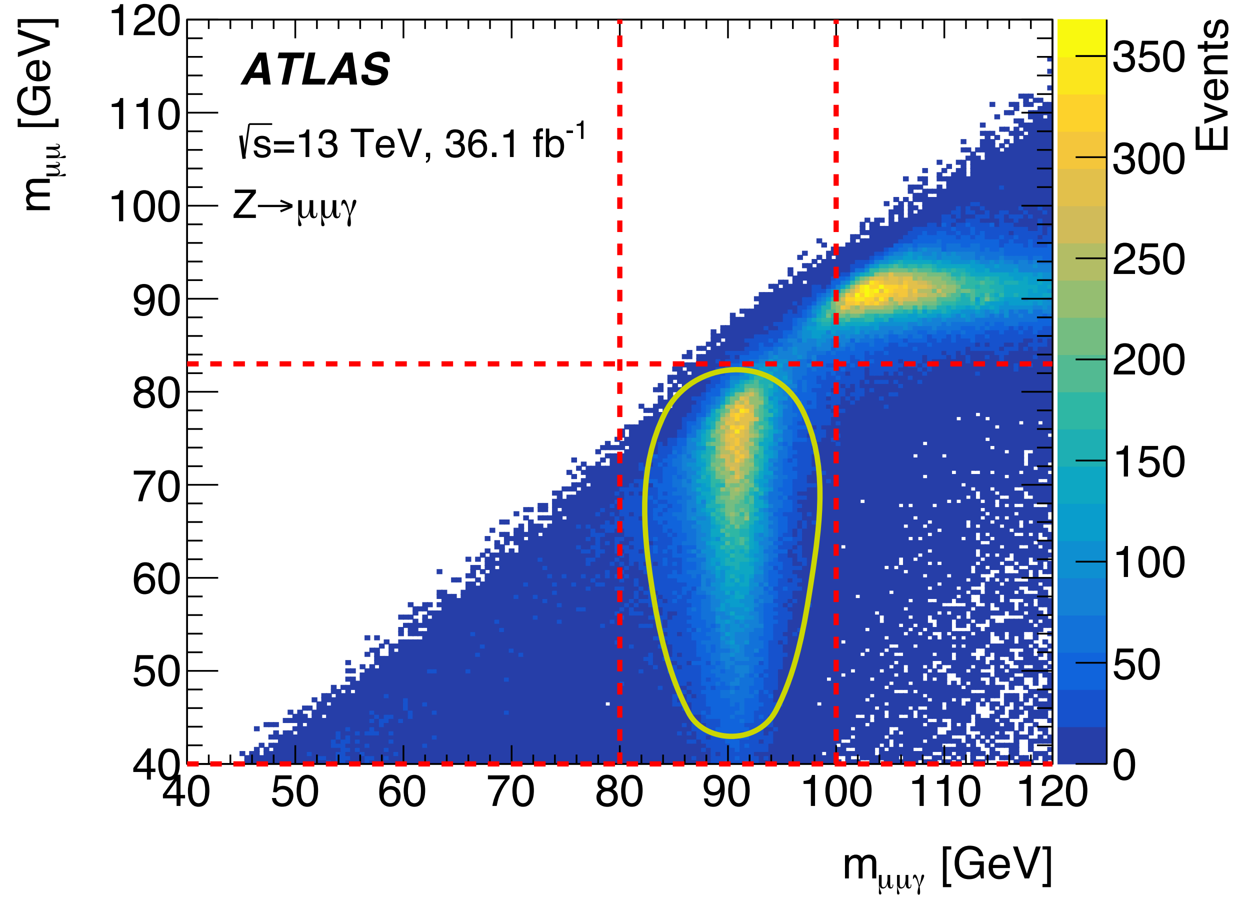
- Photons from ***Radiative-Z (FSR) decay***
- ***Extrapolate efficiencies from electrons in Z→ee*** decays using known differences between e and γ shower shapes
- ***Matrix Method*** to measure γ efficiency by finding γ and jet purities in regions of different track isolation
- Measurements combined in overlap region

Identification Efficiencies



Up to ~percent level accuracy

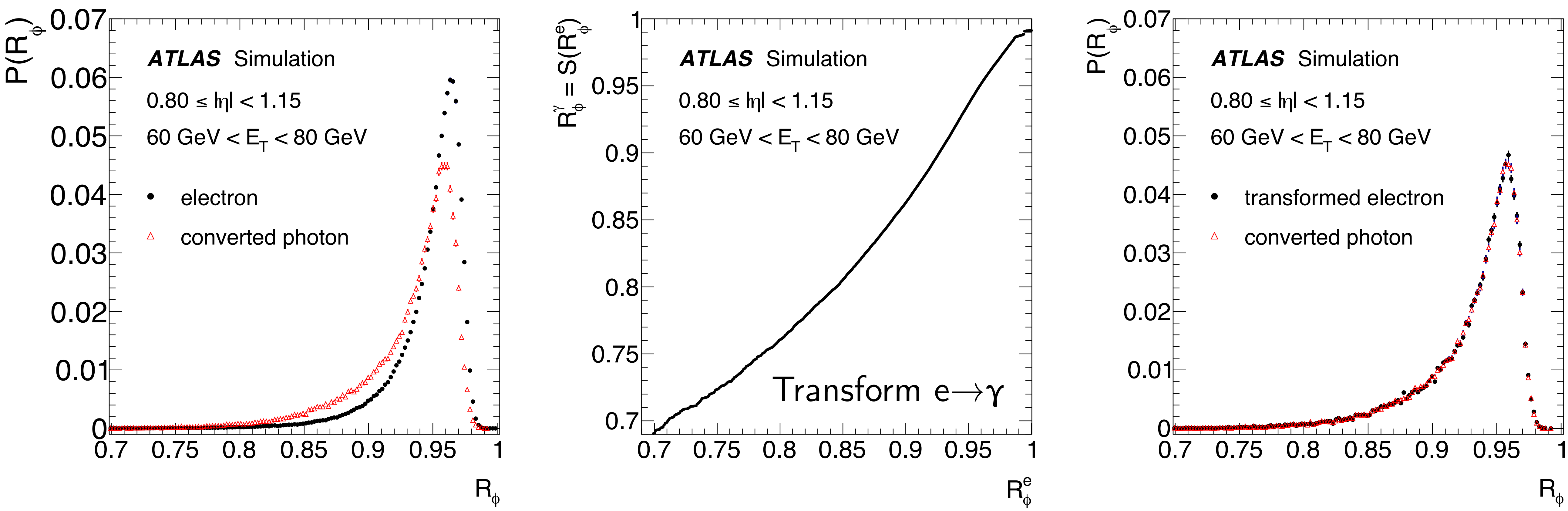
Efficiencies: Radiative-Z Decays



Radiative-Z Efficiency Method:

- Select Z→ee events with an FSR photon:
  - Dilepton mass less than *Z* mass
  - 3-body mass equal to the *Z*-mass
- Very clean, unbiased sample of photons – **easy to measure MVA photons**
- However, statistically the sample reaches only $p_T < 80$ GeV

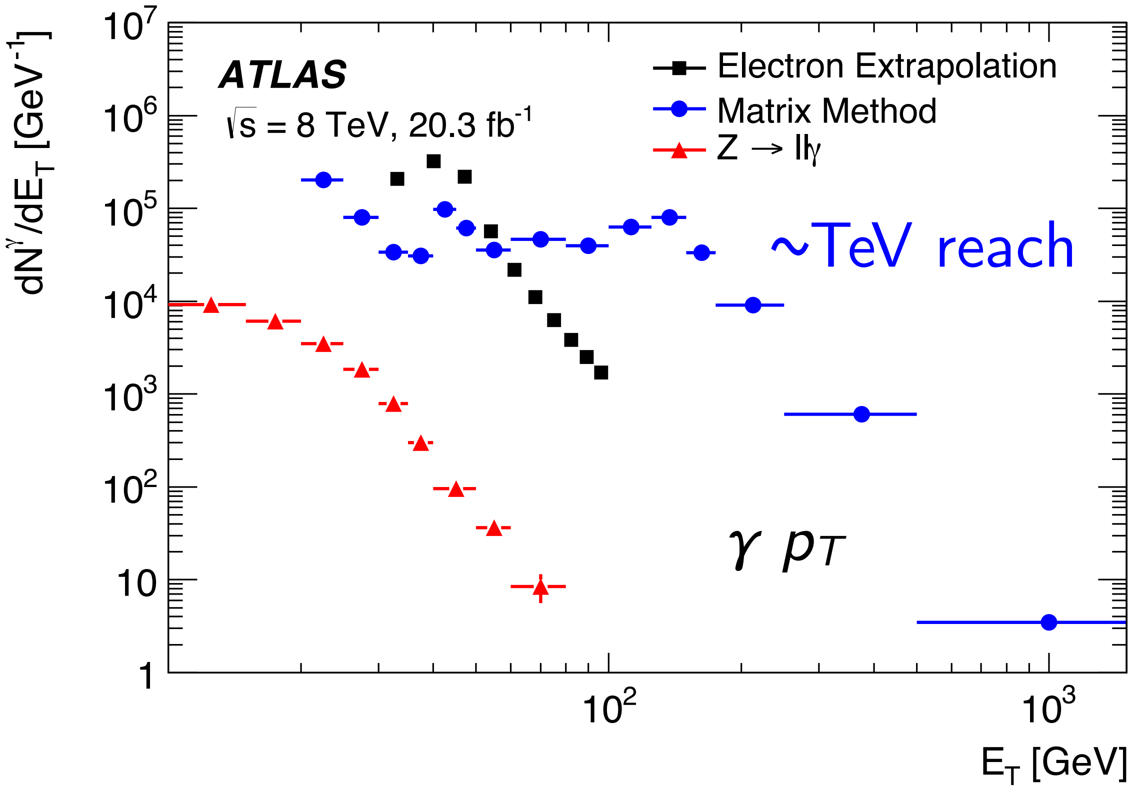
Efficiencies: Electron Extrapolation Method

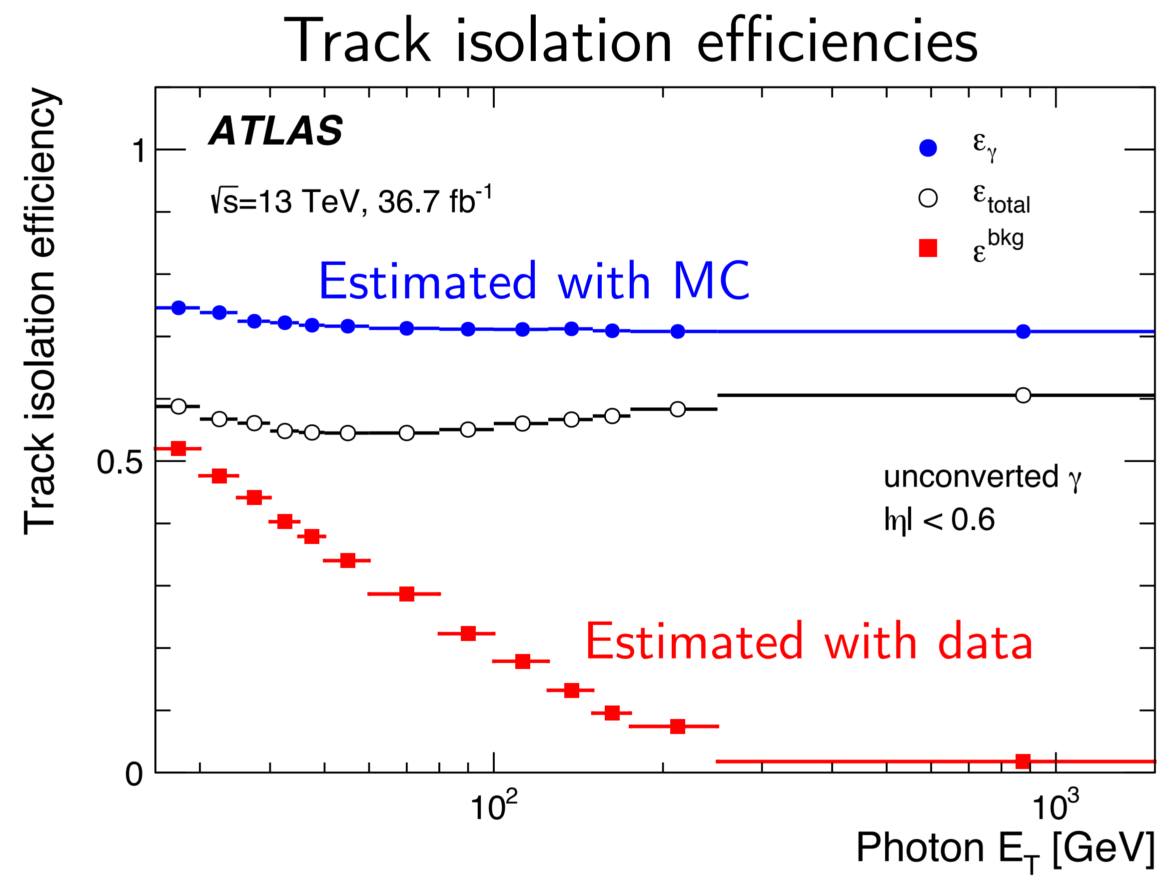


Electron Extrapolation Method:

- Efficiency method used for photons with $25 < E_T < 250$ GeV
- Draws on the similarity between photon and electron shower shapes
- Residual differences are corrected using a MC-based Smirnov transformation
- Data efficiency measurement uses Z→ee events

Relies on e − γ differences that are well-predicted by MC
Difficulty using this measurement to measure MVA photons





Matrix Method:

- Efficiency method used for photons with 25 GeV < E_T < ~TeV
- Collect single-photon production events with prescaled triggers
- Count events that pass/fail identification, pass/fail isolation; perform a **matrix inversion**
- **Models photon track isolation efficiencies using simulation**
- Relies on a collection of **variables uncorrelated with track isolation**

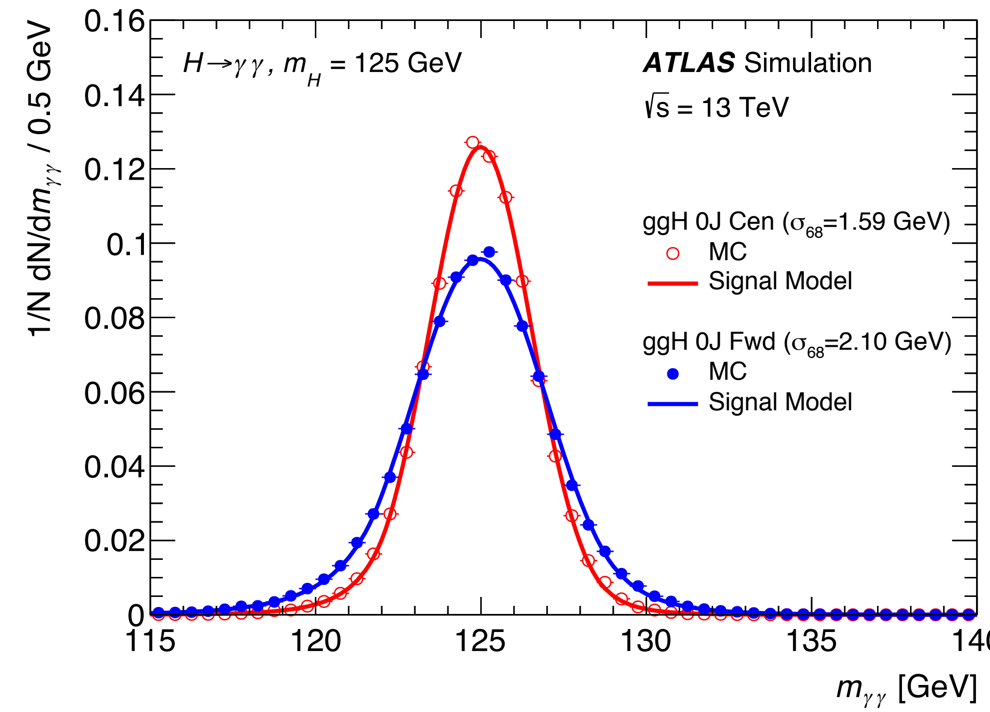
Strong reliance on correlation properties between ID and isolation; Difficulty using this measurement to measure MVA photons

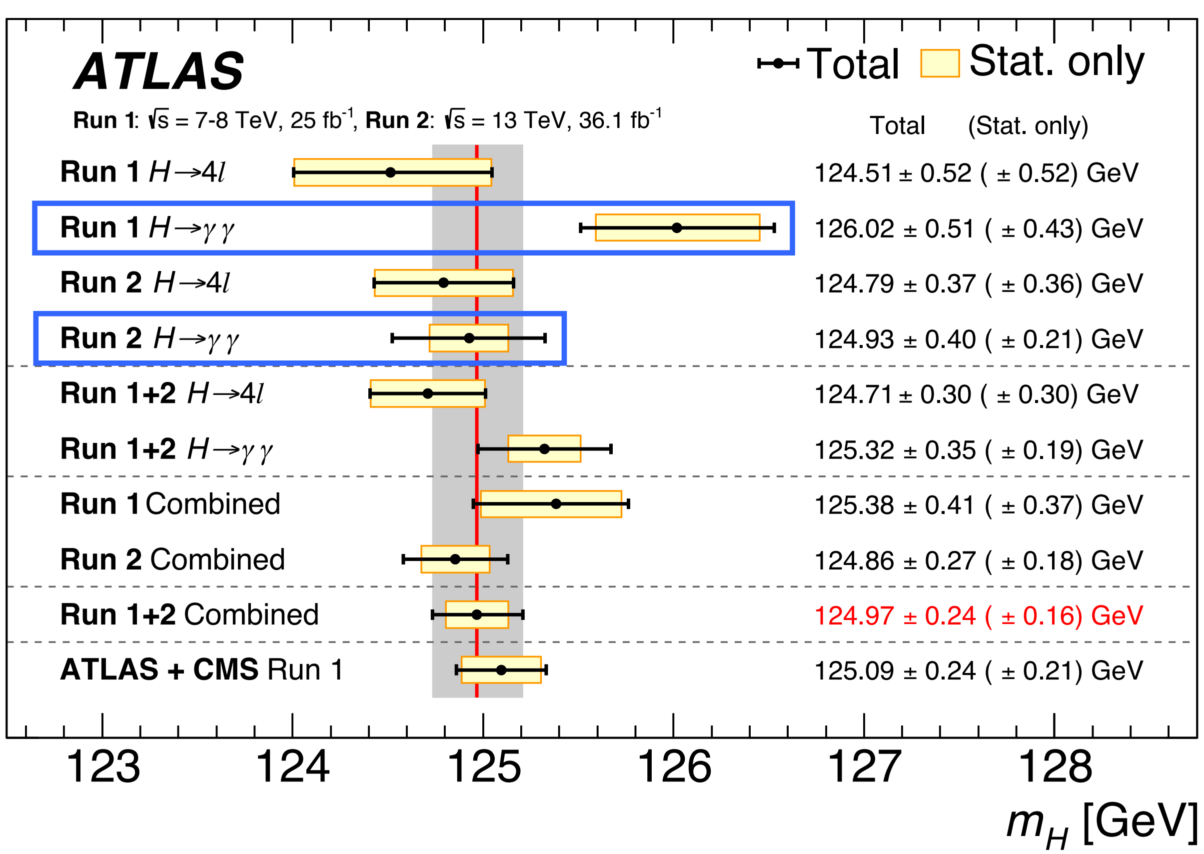
Calibration – Impact on $H\to\gamma\gamma$ Mass Meas.

Phys. Lett. B 784 (2018) 345

- $H\to\gamma\gamma$ mass measurement is on par with $H\to 4\ell$ measurement, but systematics are larger
- Dominated by calibration uncertainties:
  - LAr response linearity
  - Material effects
  - Layer intercalibration

Best/worst photon resolution categories

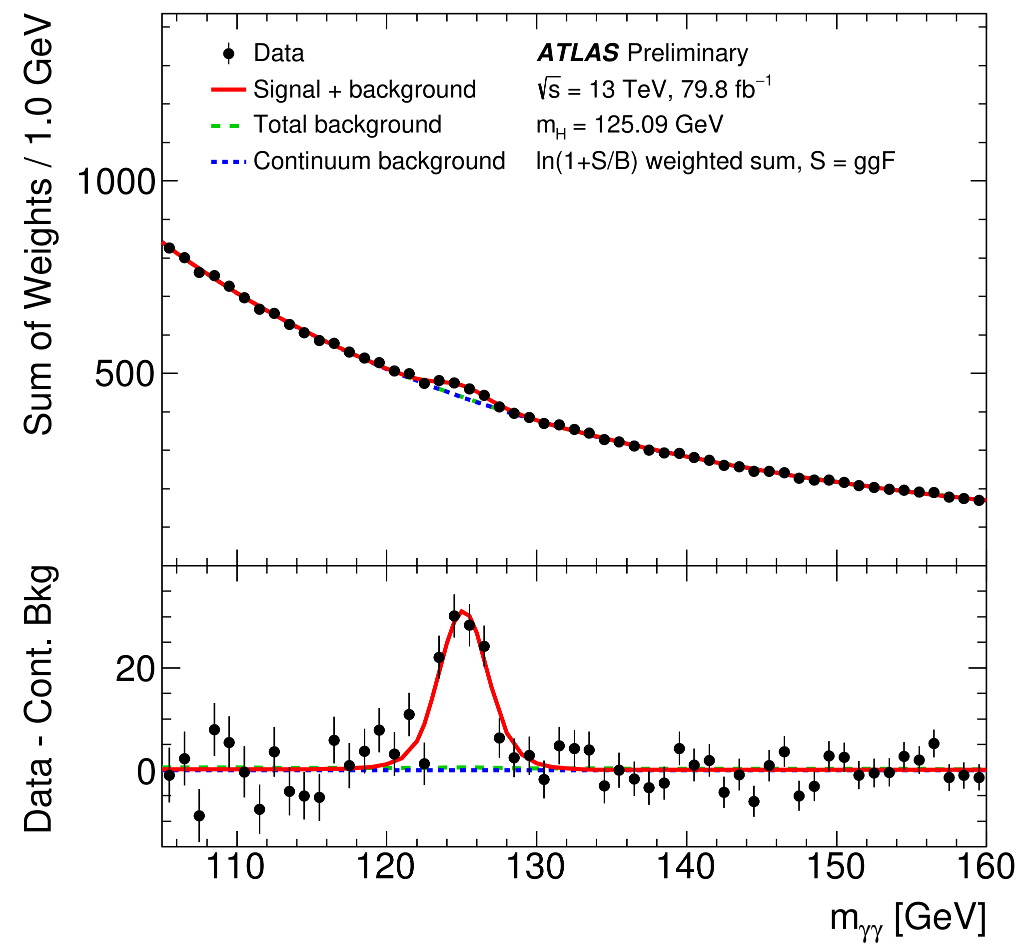




Source	Systematic uncertainty on m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z\to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H\to\gamma\gamma$ background modelling	20
$H\to\gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

Impact on $H\to\gamma\gamma$ Cross Section Measurement

- The $H\to\gamma\gamma$ cross section measurement remains statistically limited (80 fb^{-1}), but systematic uncertainties are not negligible



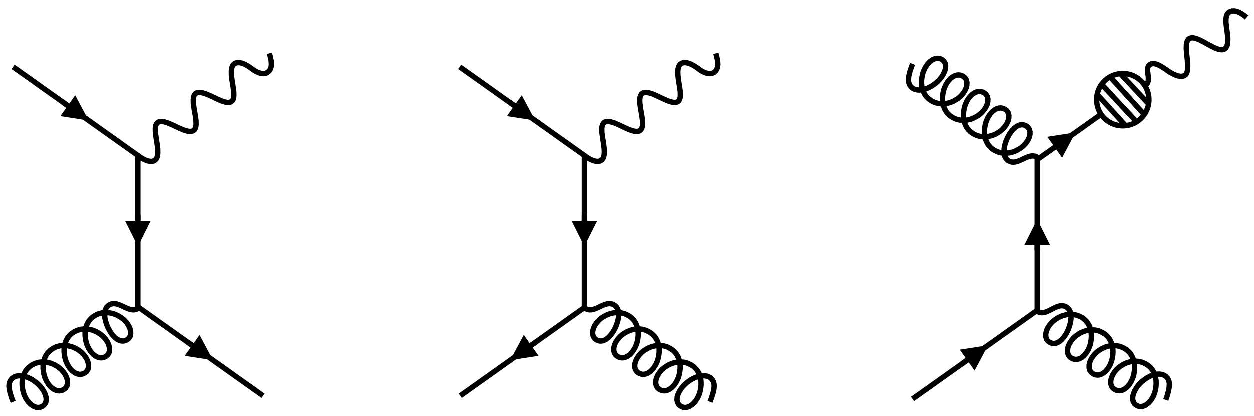
Systematic Uncertainties in $H\to\gamma\gamma$ (80 fb^{-1})

Source	Uncertainty (%)
Fit (stat.)	10
Fit (syst.)	8.3
Photon energy scale & resolution	4.0
Background modeling (spurious signal)	7.3
Correction factor	5.2
Photon isolation efficiency	4.6
Pileup	1.9
Photon ID efficiency	1.3
Trigger efficiency	0.7
Dalitz Decays	0.4
Theoretical modeling	$^{+0.3}_{-0.4}$
Diphoton vertex selection	0.1
Photon energy scale & resolution	0.1
Luminosity	2.0
Total	14

- Moderate energy scale and resolution uncertainties
- Photon ID efficiency measurement is sub-dominant
- Photon isolation efficiency uncertainties have since been reduced

The Fragmentation Component

Leading-order photon production diagrams:

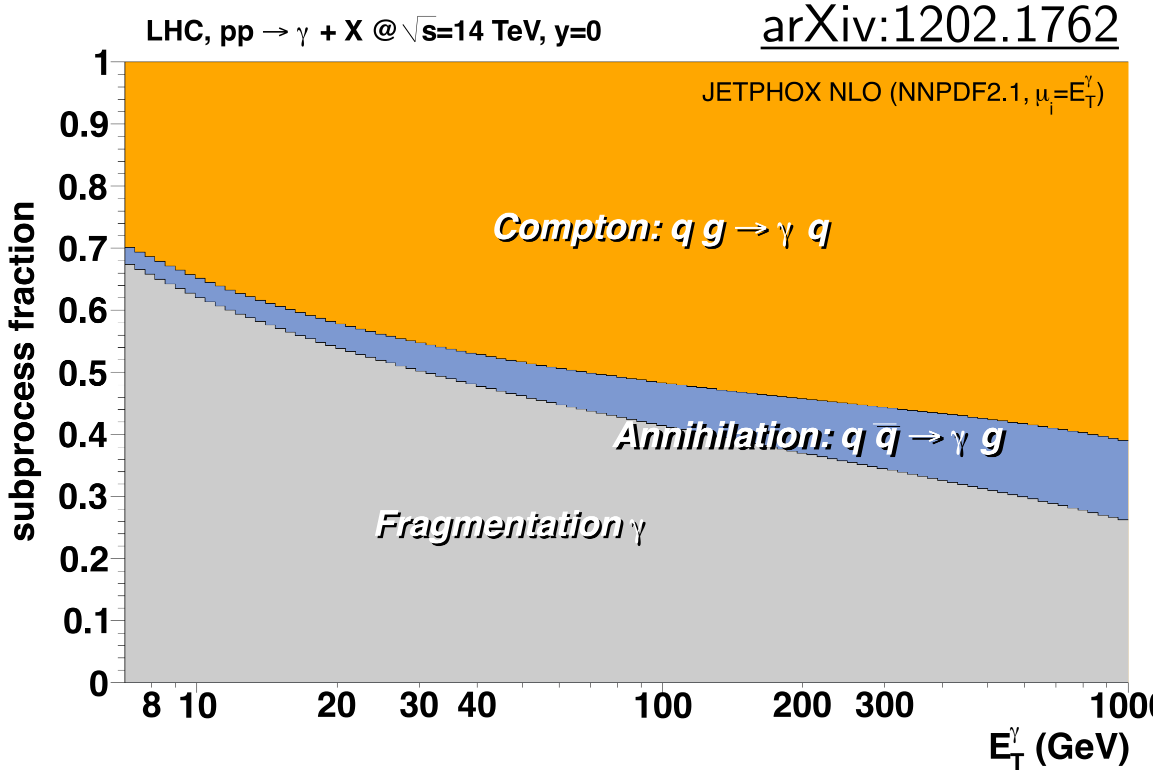


QCD Compton scattering

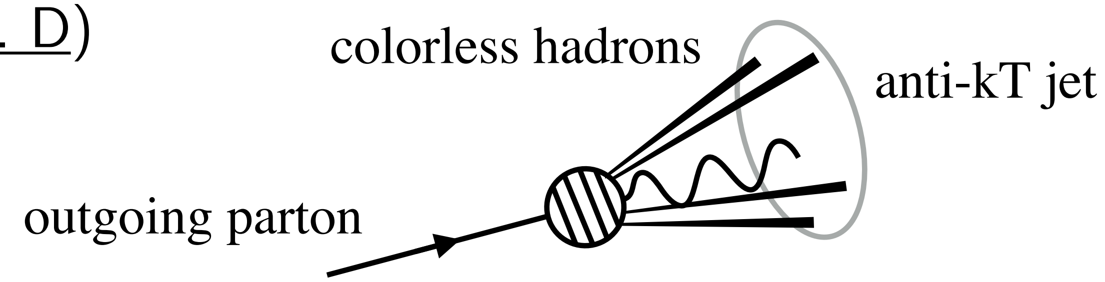
$q\bar{q}$ annihilation

Fragmentation

arXiv:1202.1762



- We measure efficiencies of ***isolated* photons...**
- But the single-photon process (used for Matrix Method) contains non-isolated fragmentation photons
  - **Moderate uncertainties** tied to this **largely unconstrained** component
  - See also the **impact in Standard Model photon production measurements**
- Better understanding of fragmentation component (theory and experiment) will lead to better measurements overall
- E.g. measurement of **photon production inside jets** (proposed by Kaufmann Mukherjee, Vogelsang, Phys. Rev. D)
- **See also theory isolation talks in this conference**

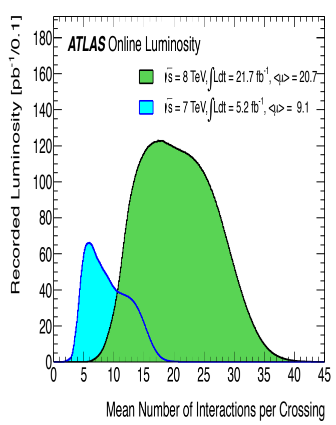


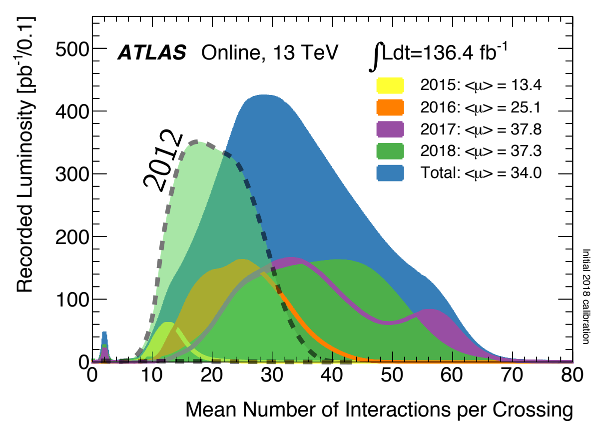
Run 3 and the HL-LHC

ATLAS Challenges in Run 3 and Beyond

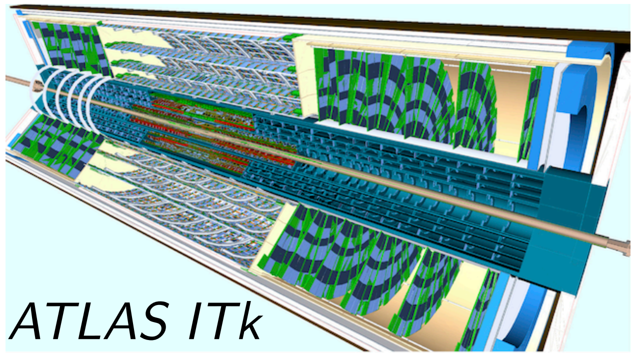
LHC | **HC-LHC**

Run 1	LS1	Run 2	Phase-1 upgrades	Run 3	Phase-2 upgrades	Run 4, 5...
7 TeV, 8 TeV		13 TeV		14 TeV		14 TeV
25 fb^{-1}		150 fb^{-1}		~220 fb^{-1}		3,000 fb^{-1}
2011-12		*2015-18*		*2021-23*		*2026+*

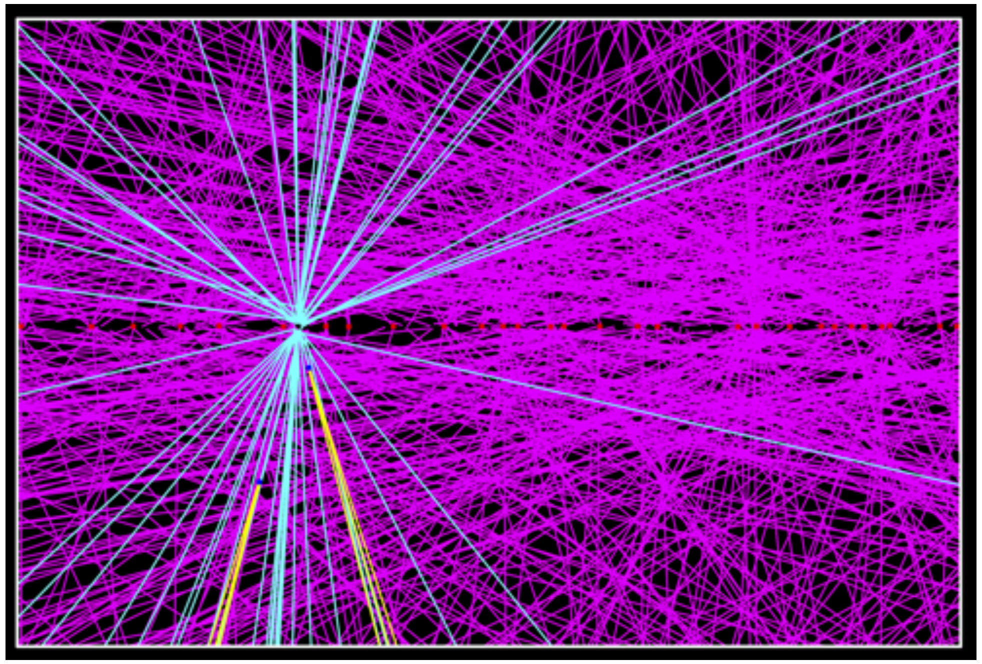




Run-3 pileup:
Leveling at
<μ>=65

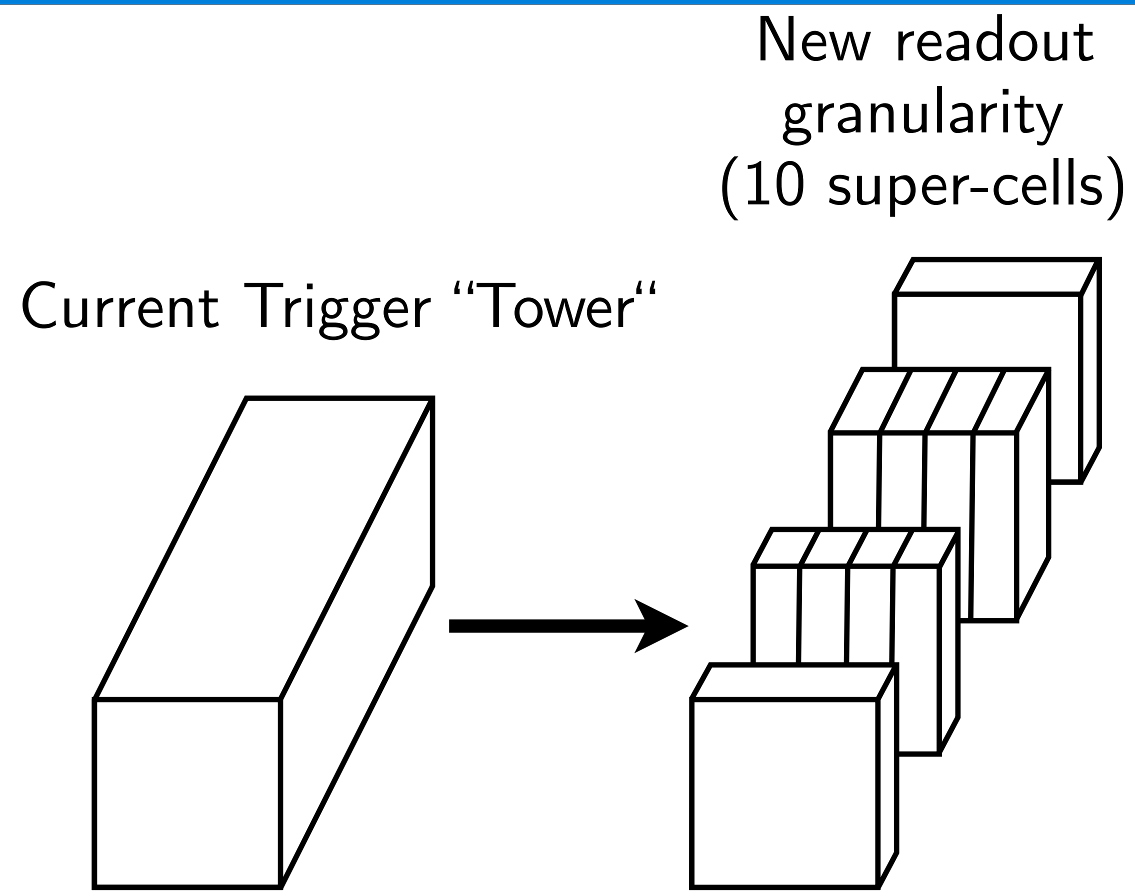


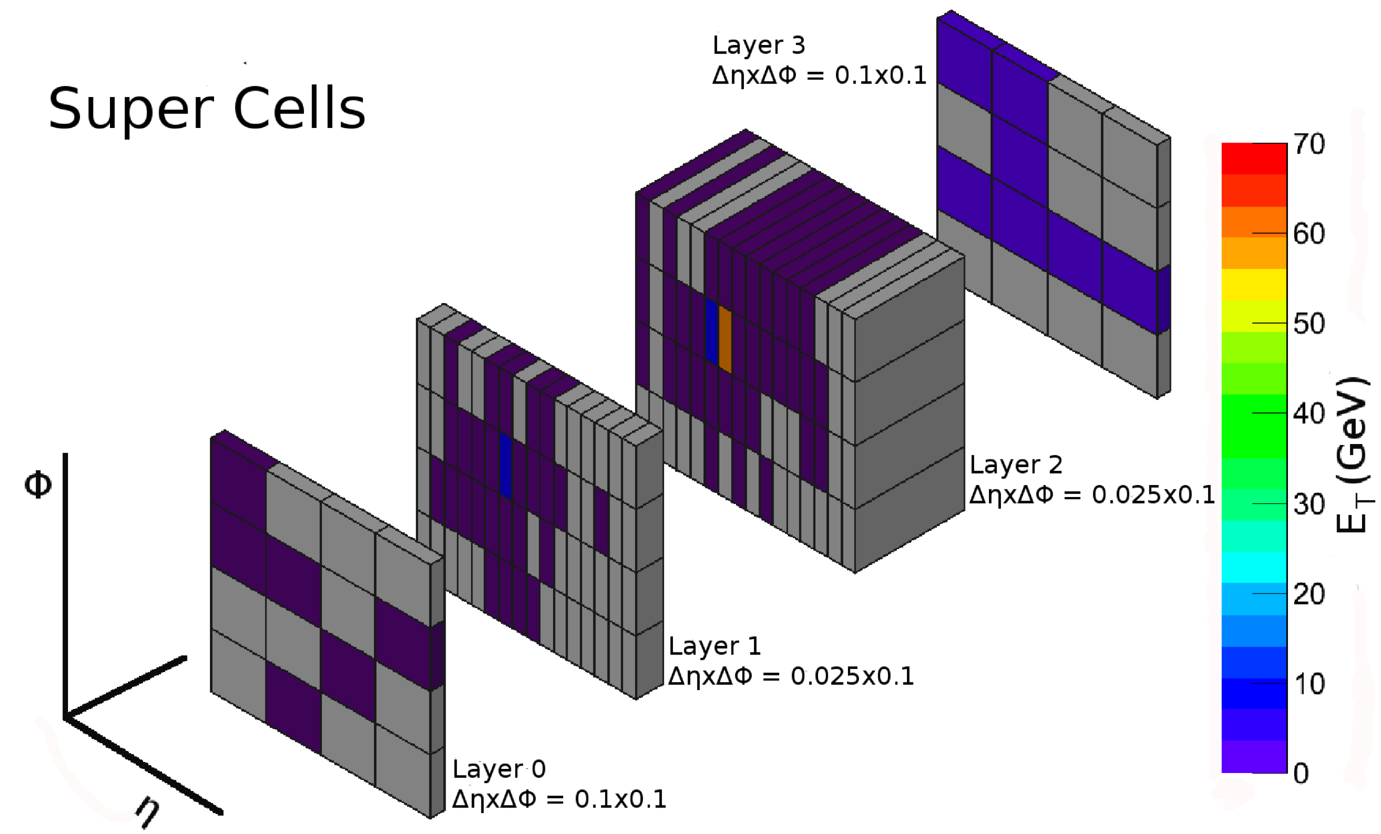
HL-LHC ttbar event at ⟨μ⟩=200



- Pile-up effects
- Trigger Challenges
- HL-LHC and the New Detector

Trigger Upgrades in Run 3 – Super Cells



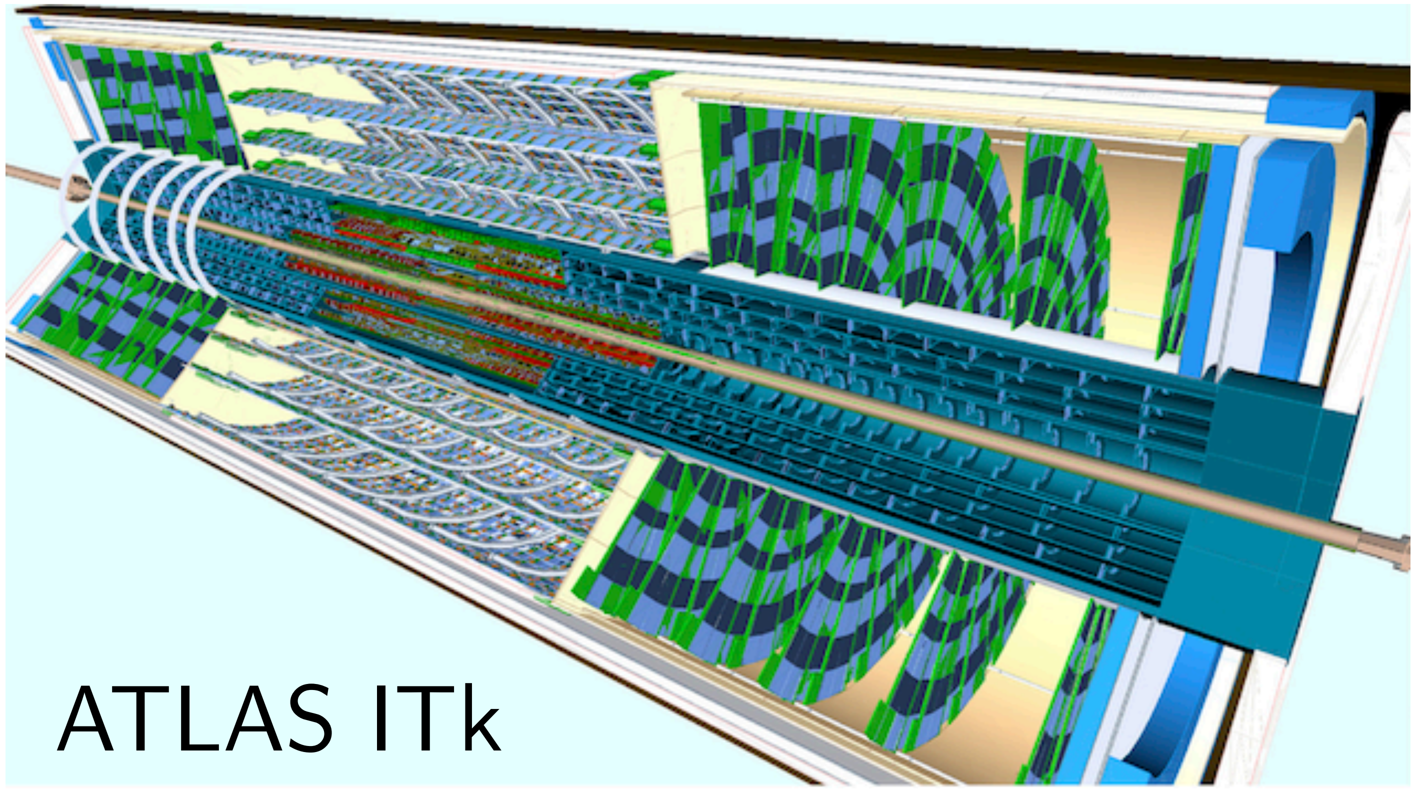


- **Level-1 Trigger in the beginning in Run 3 (Phase I upgrade):**
  - Higher-granularity trigger information allows **"shower shape" information at the level-1 trigger**
  - Upgraded trigger processor electronics (Feature EXtractors, or FEX)
  - Reduced jet fakes, better energy resolution
  - Target: keep the L1 trigger rates at ~100 kHz
- **Overall trigger challenges remain:**
  - Lowest unprescaled single-photon trigger threshold: $p_T = 120$ GeV
  - **Diphoton trigger thresholds (35 GeV, 25 GeV) must remain low for effective study of the Higgs**

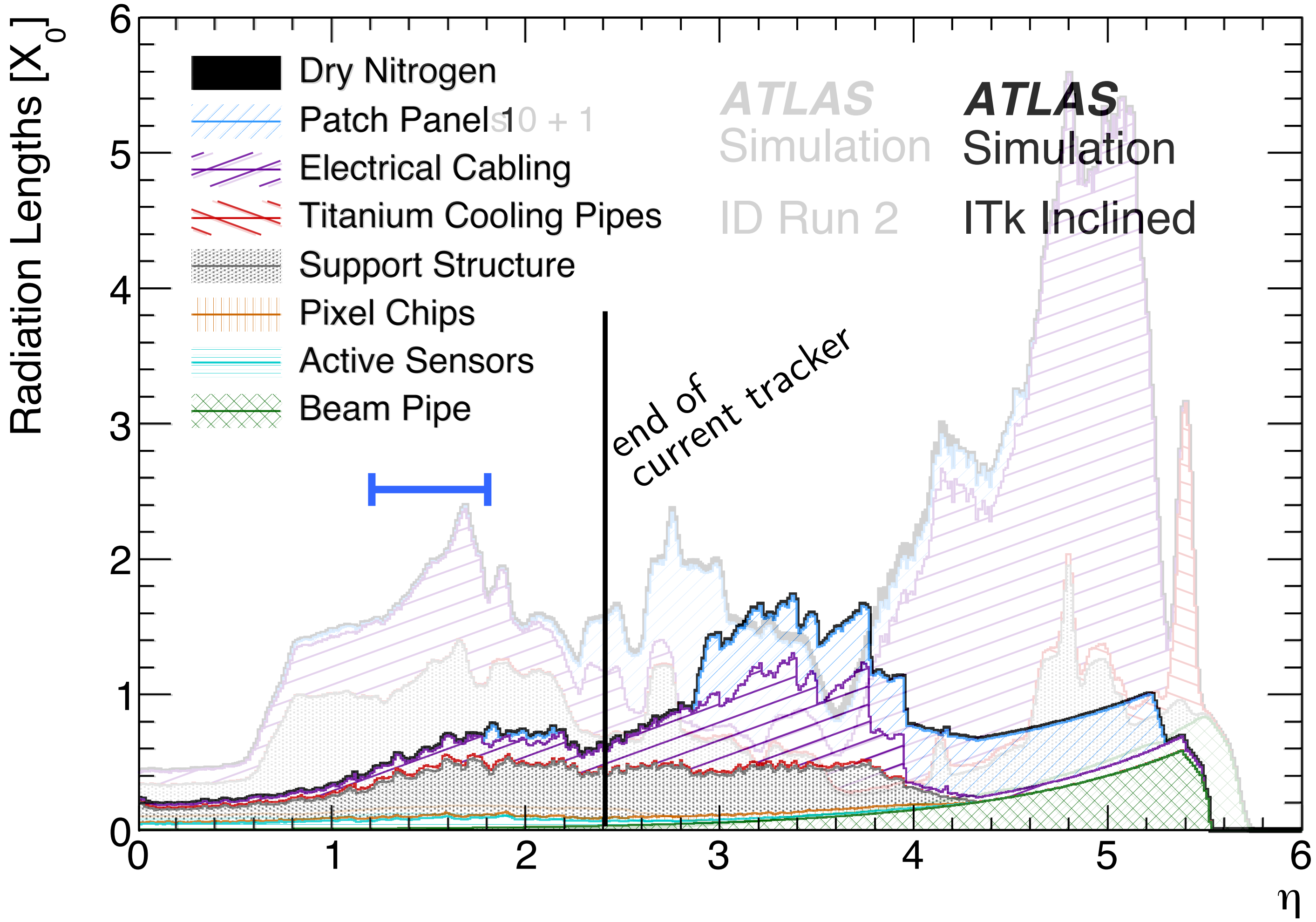
- Electronics upgrades for the LAr Calorimeter
- Replacing the current inner detector (Pixels, Strips, TRT) with an all-silicon **Inner Tracker (ITk)**
  - Tracking coverage out to $|\eta|<4.0$ (was 2.7)
- HGTD (High-granularity timing detector) to help with high-rapidity region ($2.4 < |\eta| < 4.0$)
  - Critical component for high-η jets
  - **Is there a market for high-η ATLAS photons?**

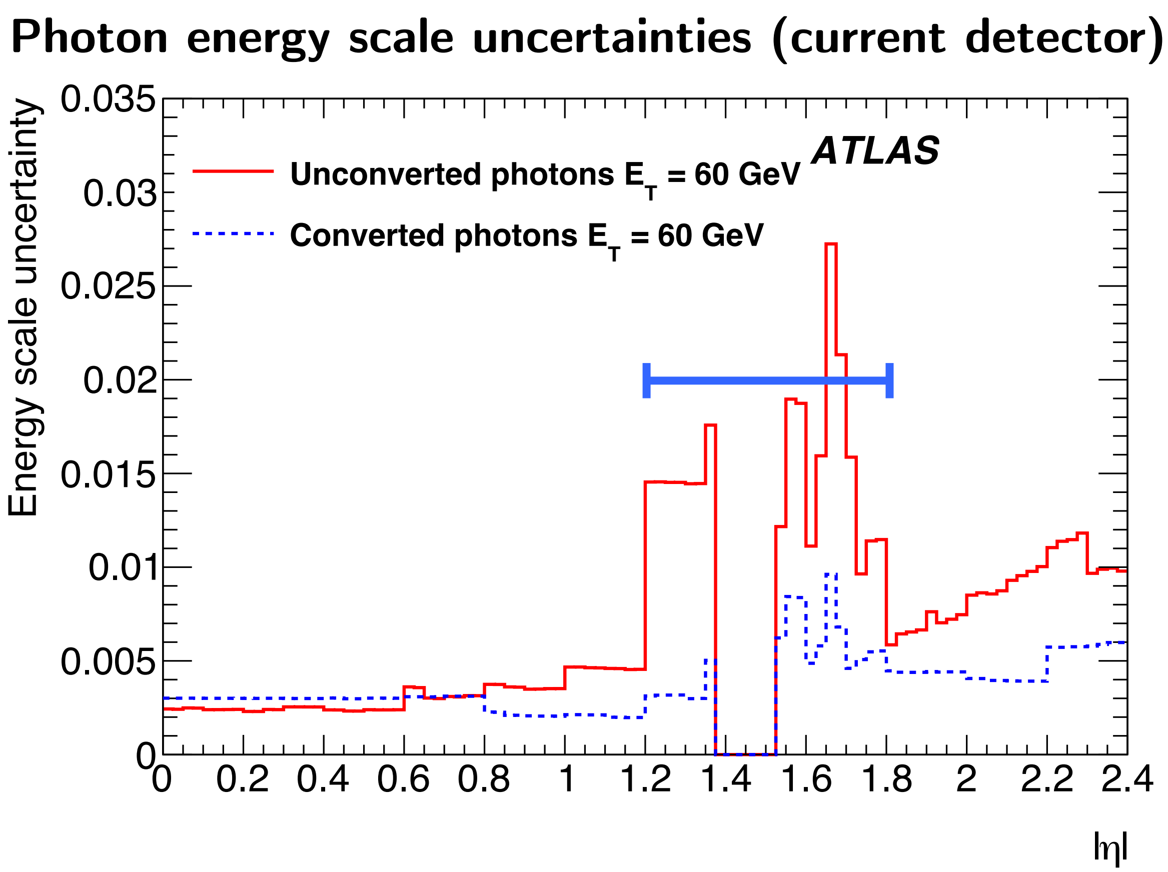
Benefits:

- Better Tracking
- Less material



The ATLAS ITk: A closer look



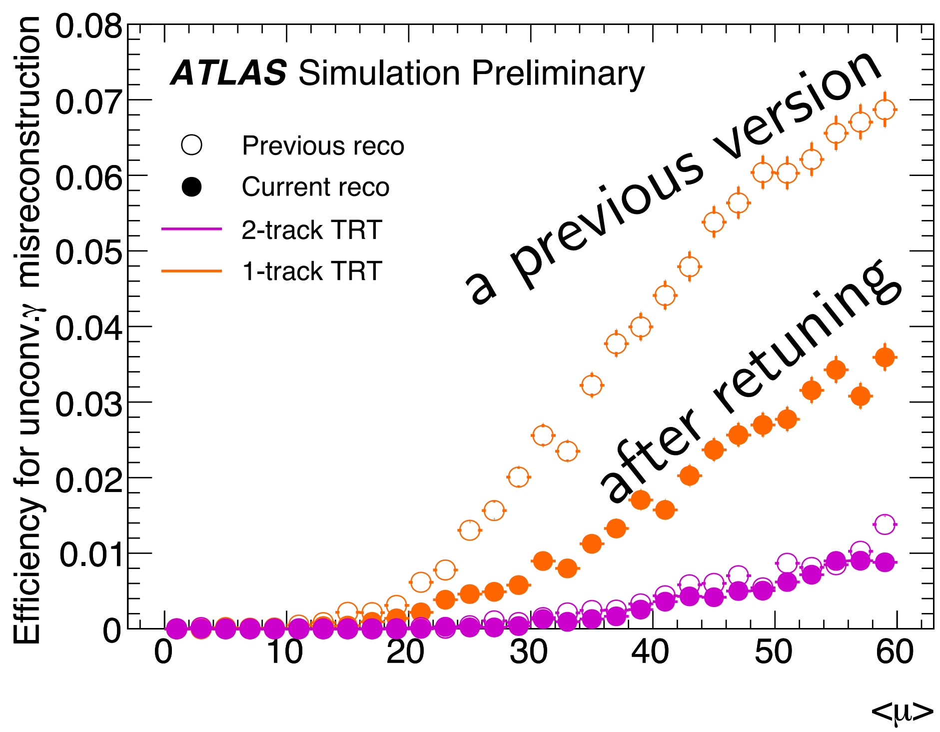


- **Entirely new detector**
  - Many aspects of the **reconstruction must be reworked for new geometry**
- Significantly less material in ~all detector regions
  - Fewer photons convert in the ID
  - **Better energy resolution**
  - **Potentially cleaner shower shapes** (for identification)
  - **Smaller energy scale uncertainties** due to material (see blue bar)

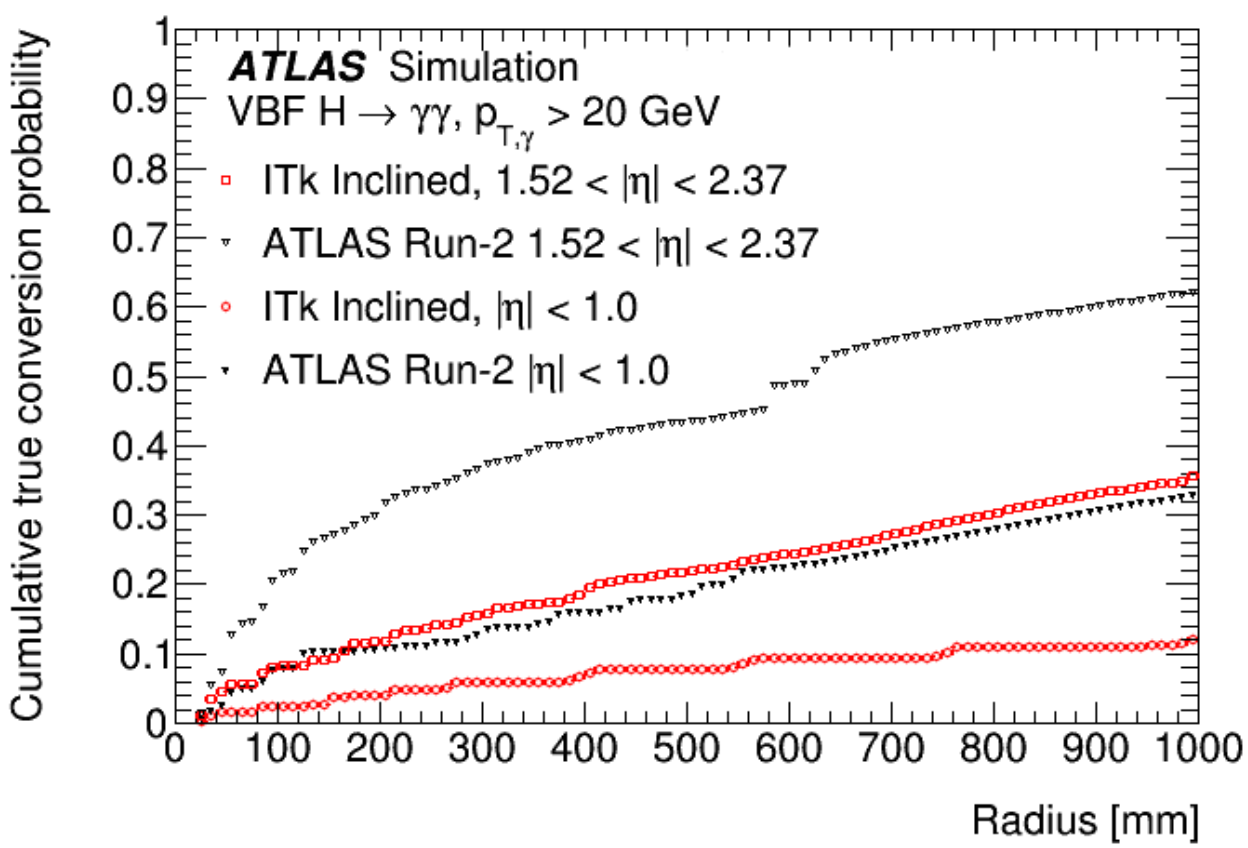
New challenges, opportunities!

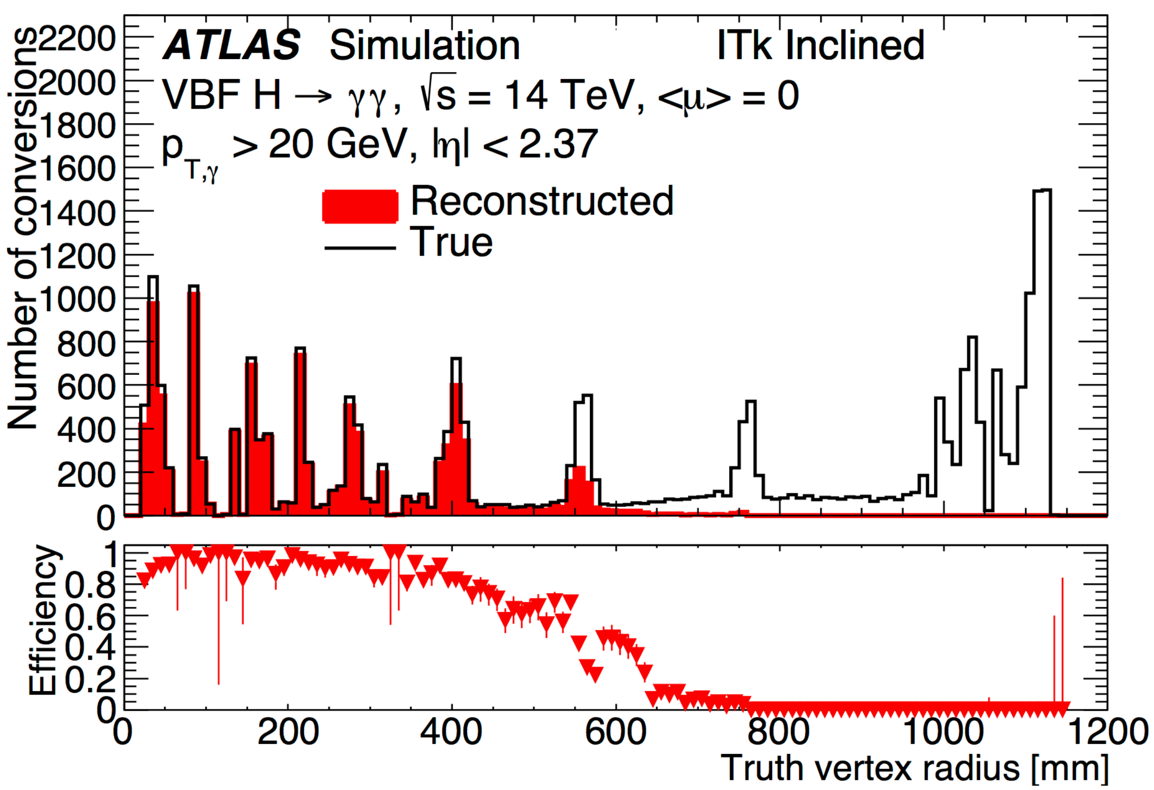
Reconstruction Changes moving toward the ITk

- Reconstruction: We must continually **revisit (tighten) our selection criteria** to reduce fake photons, or converted γ misclassified as unconverted
- We must cope with a **TRT with fewer Xenon modules** (more effective) and more Argon (less effective) due to gas leaks
- **ITk**: **Number of converted photons reduced by a factor of 2** in the ITk (compared to the Run 2 detector); **no TRT**

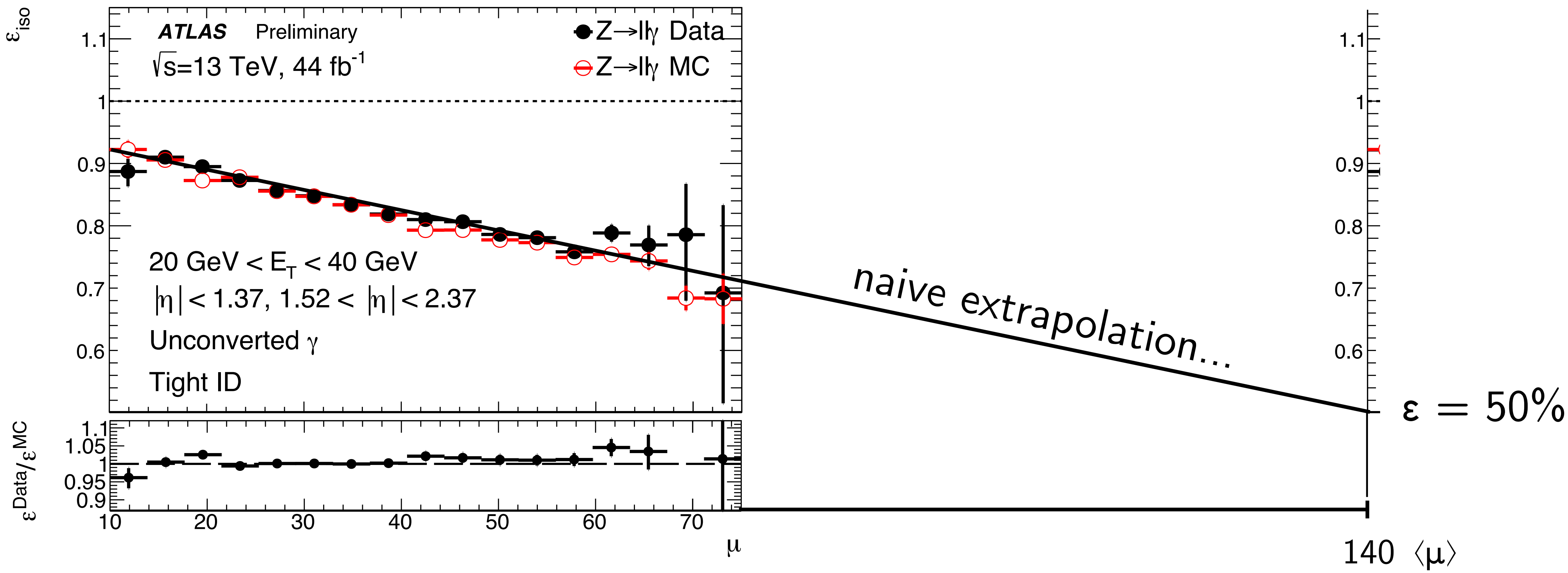


Unconverted γ's misclassified as converted (Run 2)





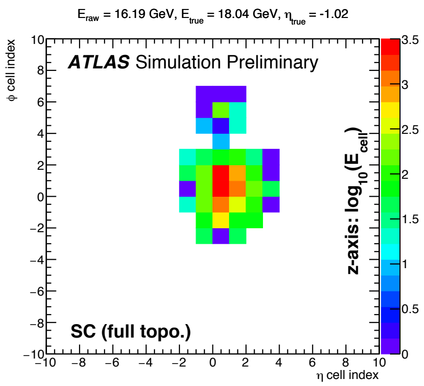
Isolation and the Challenge of Pileup

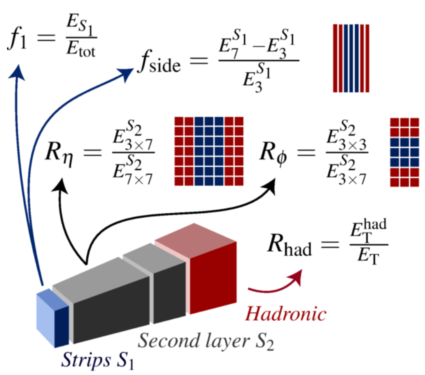


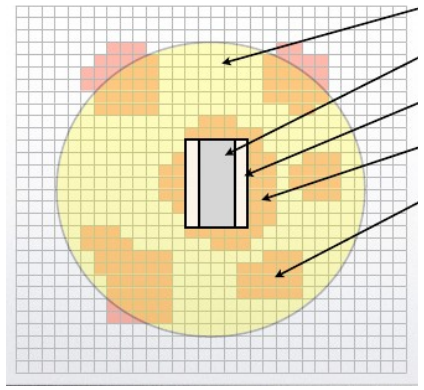
Efficiency of FixedCutLoose isolation, including both track and calorimeter isolation

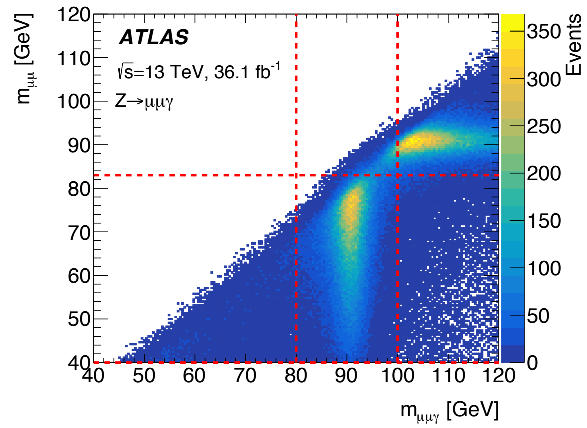
- Improving **isolation efficiency** as a function of pileup will be one of the main challenges of Run 3 and beyond
- **Identification** also quite challenging in high-pileup environments
- Lots of work on pileup suppression is in the pipeline
- **Message to theorists**: disentangling pileup and hard-scatter "truth" isolation is very non-trivial at the detector level (and will become more difficult!)

Conclusions

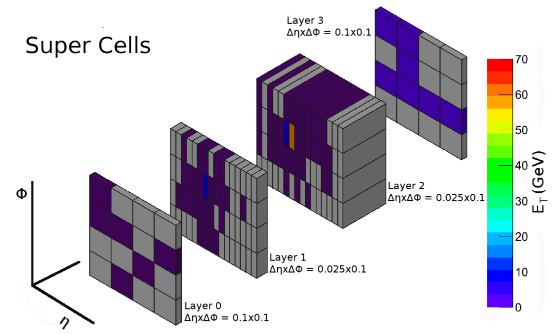




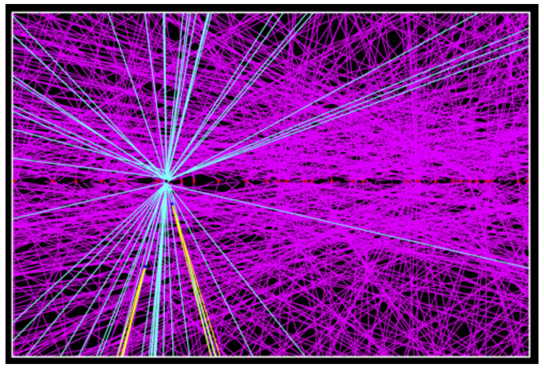


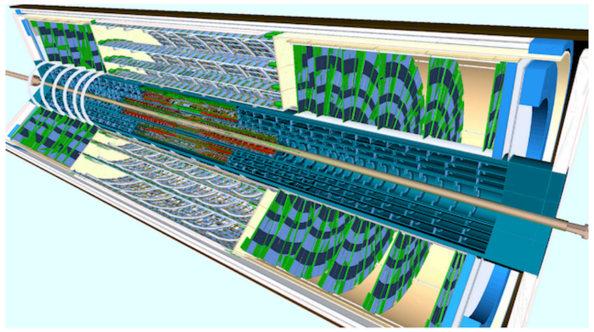


- Summary of ATLAS tools for studying photons:
  - Reconstruction
  - Calibration
  - Identification
  - Isolation
  - Efficiency Measurements



- Upcoming challenges and Opportunities:
  - Pileup
  - Level-1 Trigger Updates (Run 3)
  - The ITk for the HL-LHC

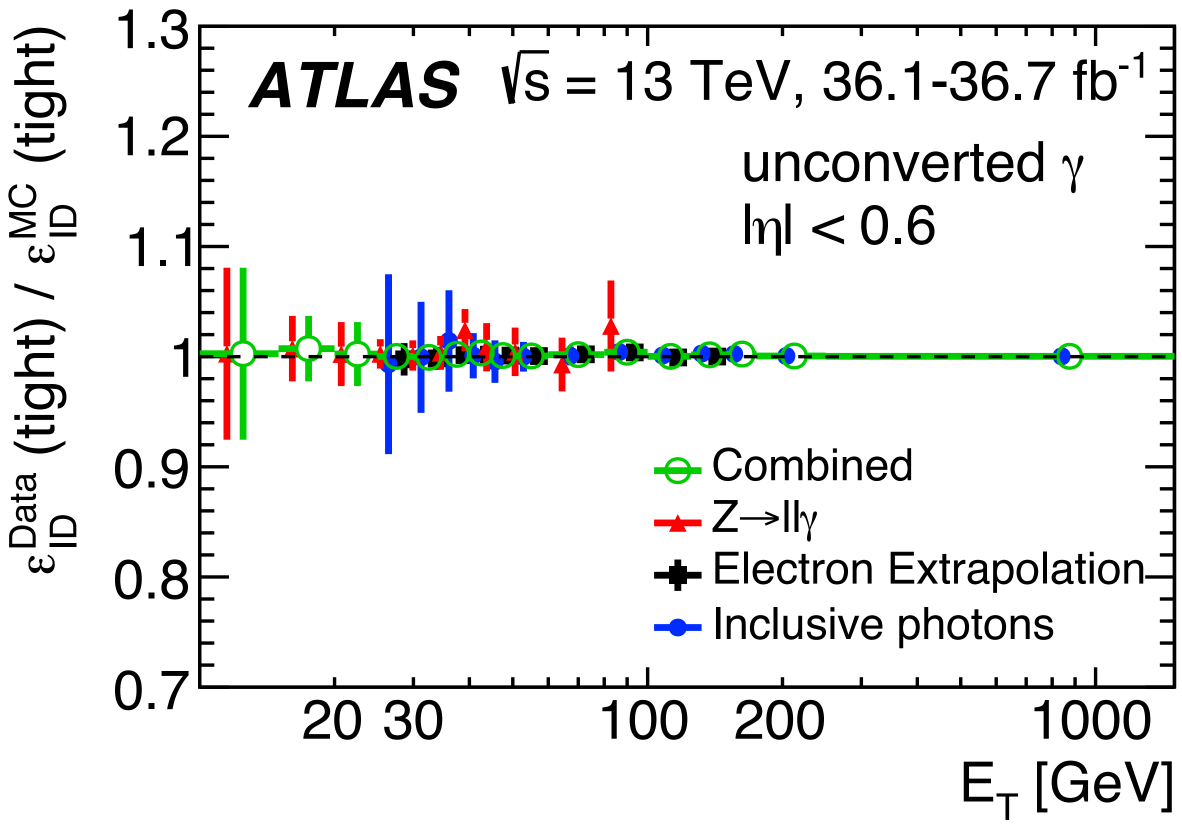


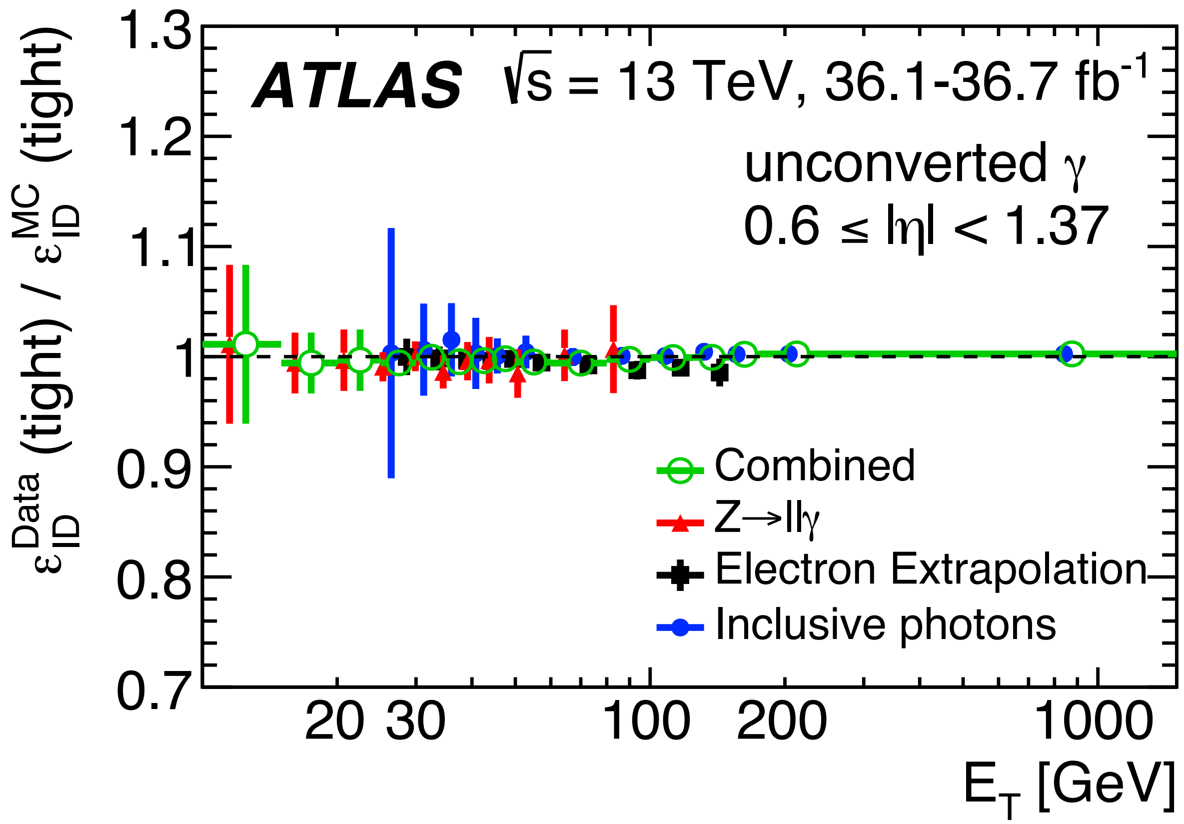


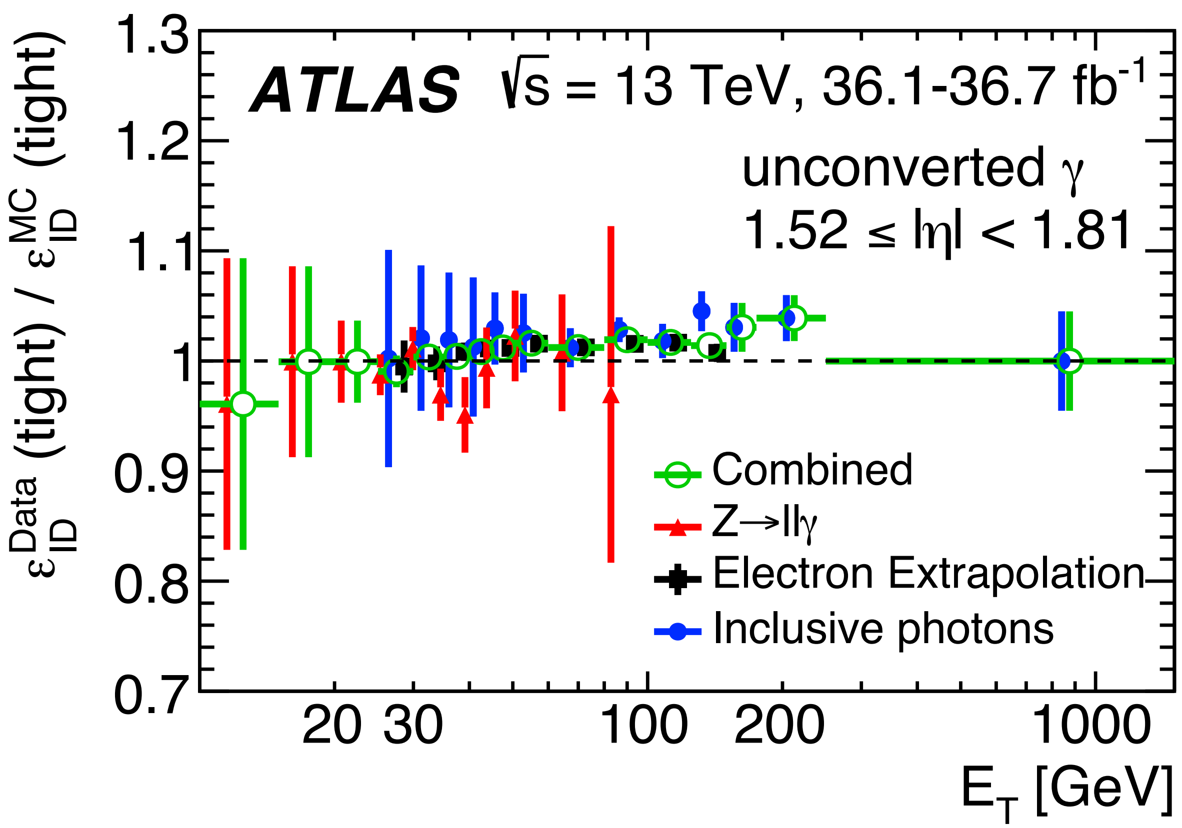
Ready to meet the challenges of Run 3 and Beyond!

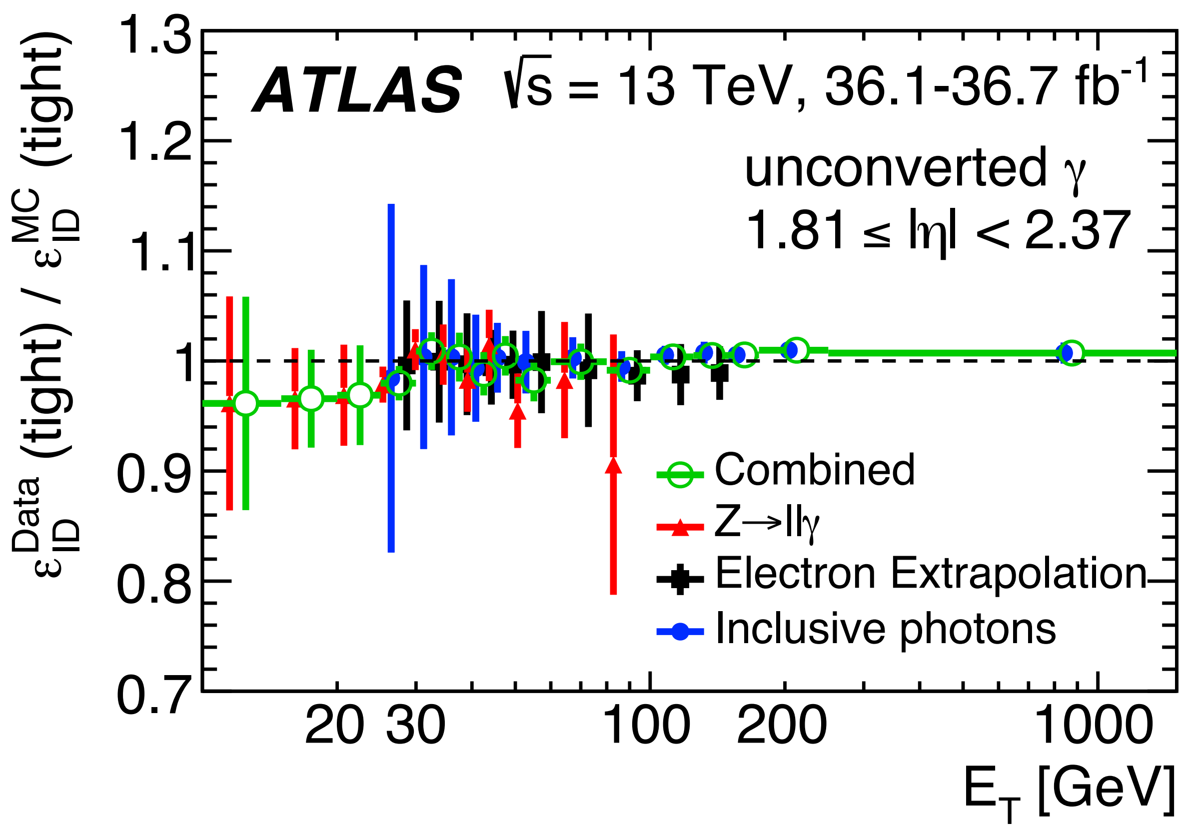
BACKUP

Photon Scale factors and Uncertainties (36 fb^{-1})

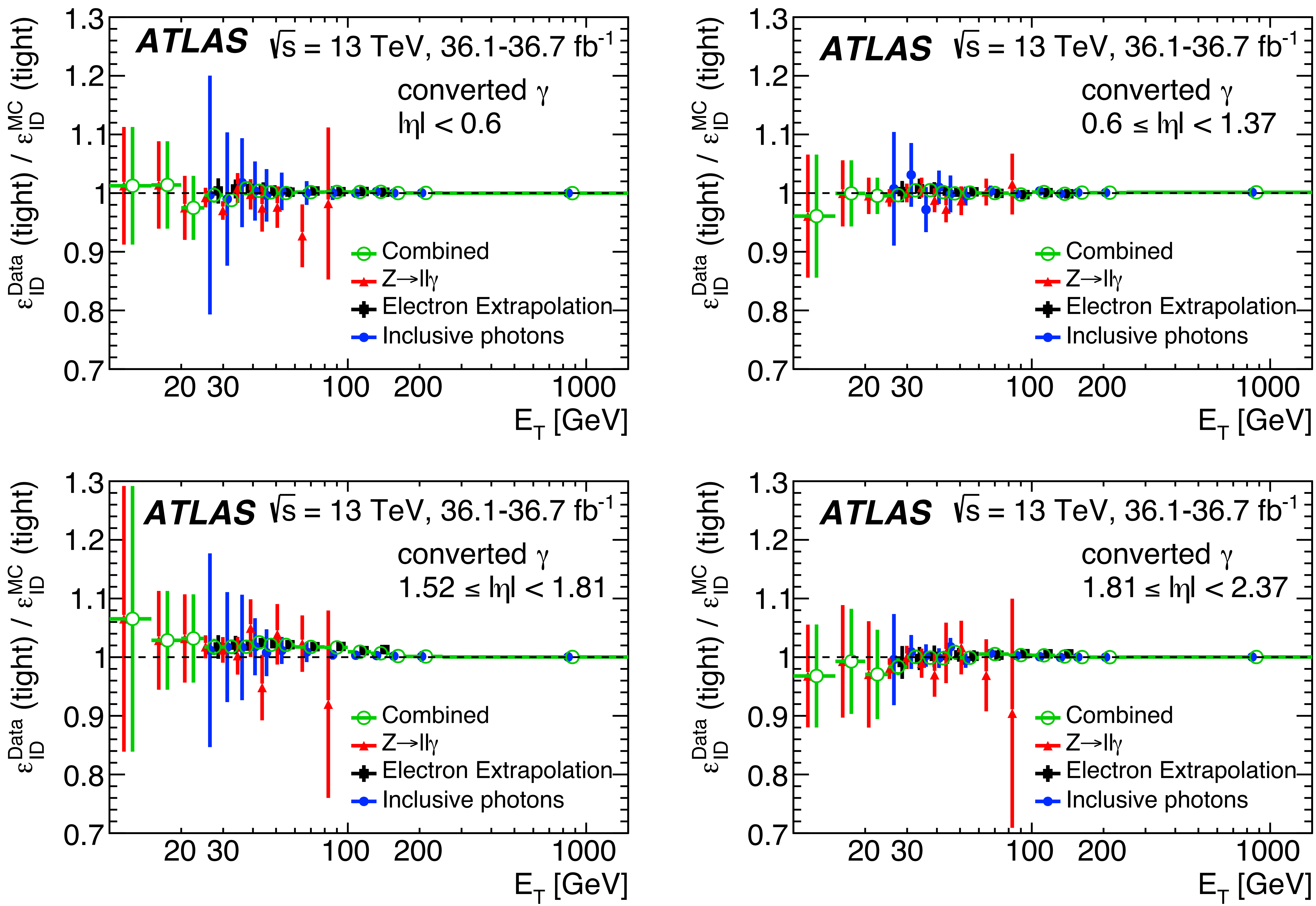




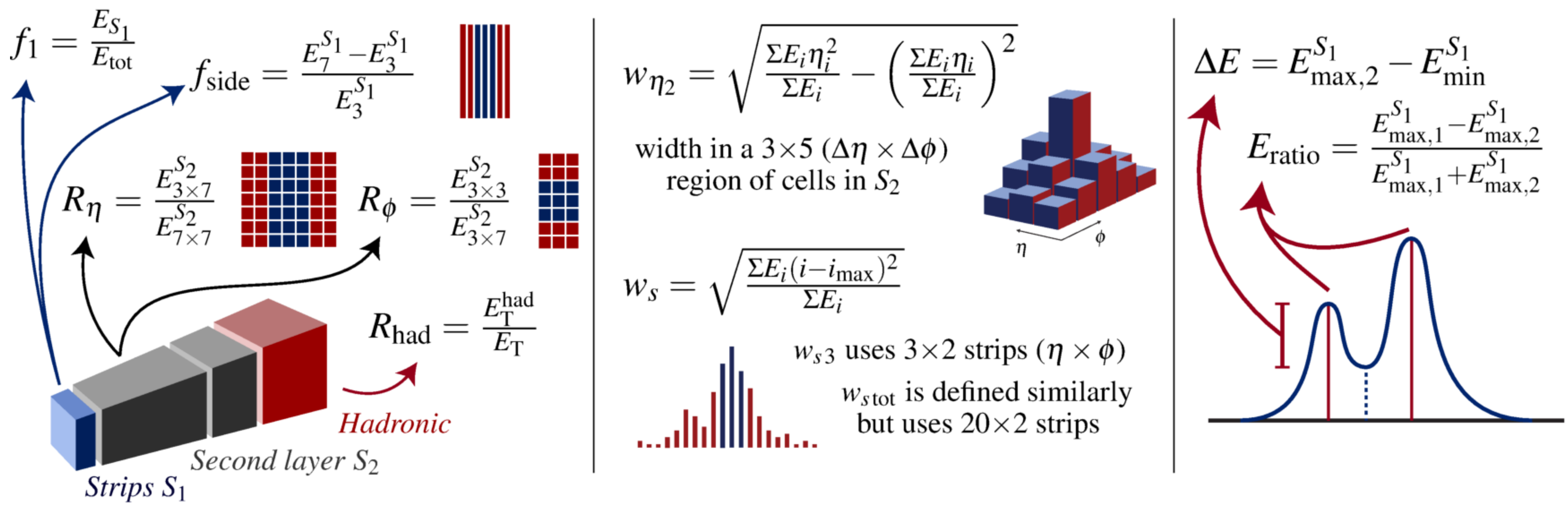




Photon Scale factors and Uncertainties (36 fb^{-1})

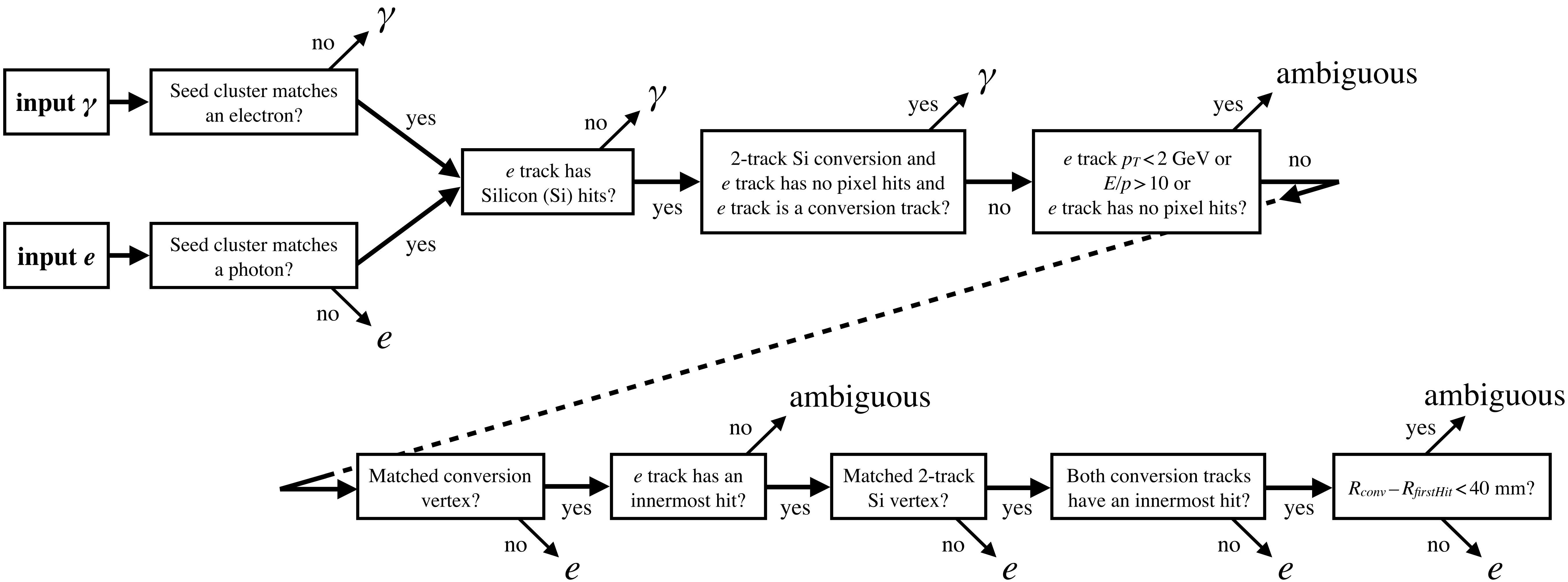


Photon Identification variables

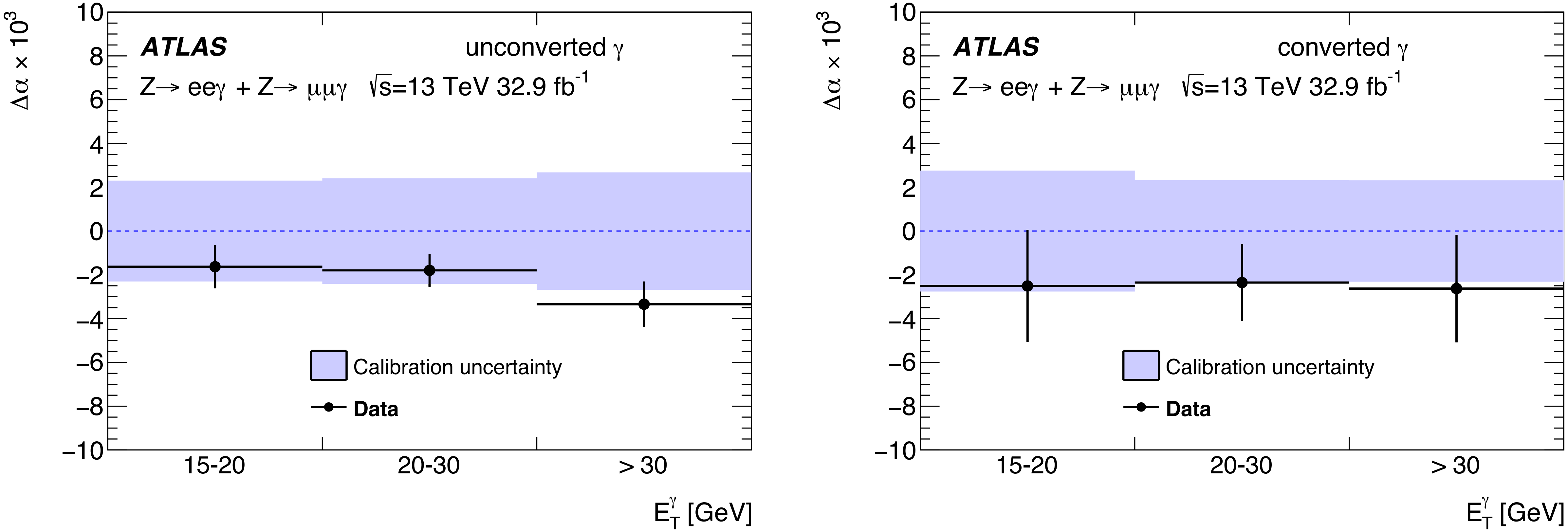


- Shower shape information: energy ratios, widths, etc.

Details of the ATLAS $e - \gamma$ disambiguation

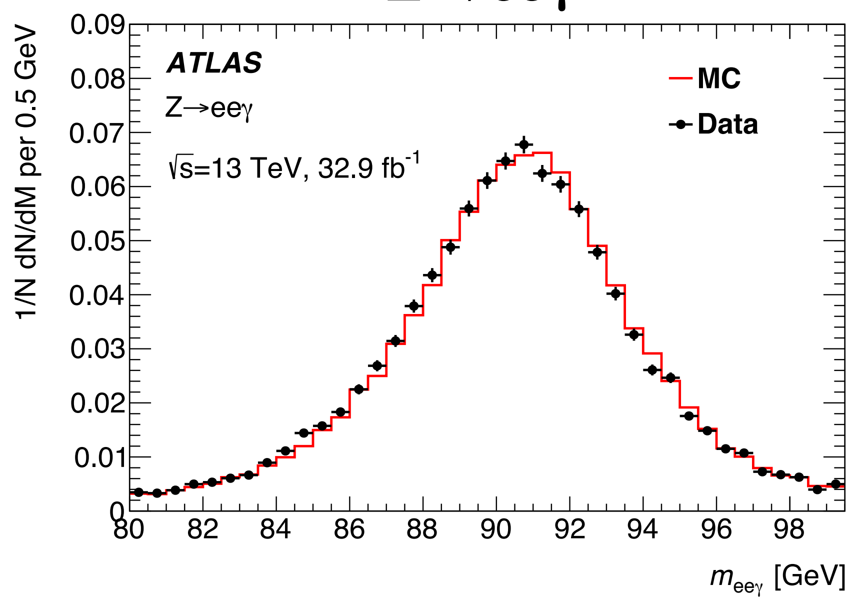


Photon Calibration cross-checks using Z→$\ell\ell\gamma$

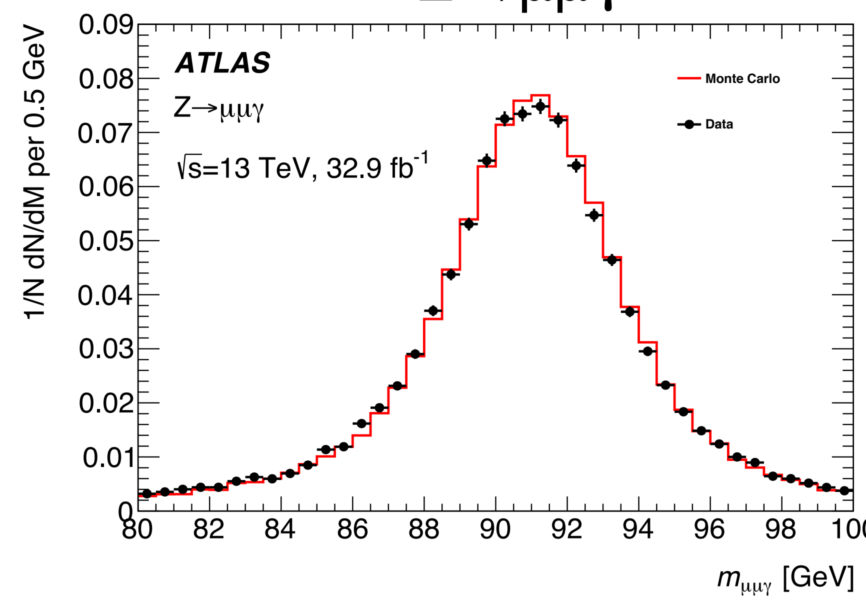


- Residual energy scale parameter $\Delta\alpha$ comparing the full energy calibration uncertainty (band) versus the measured data

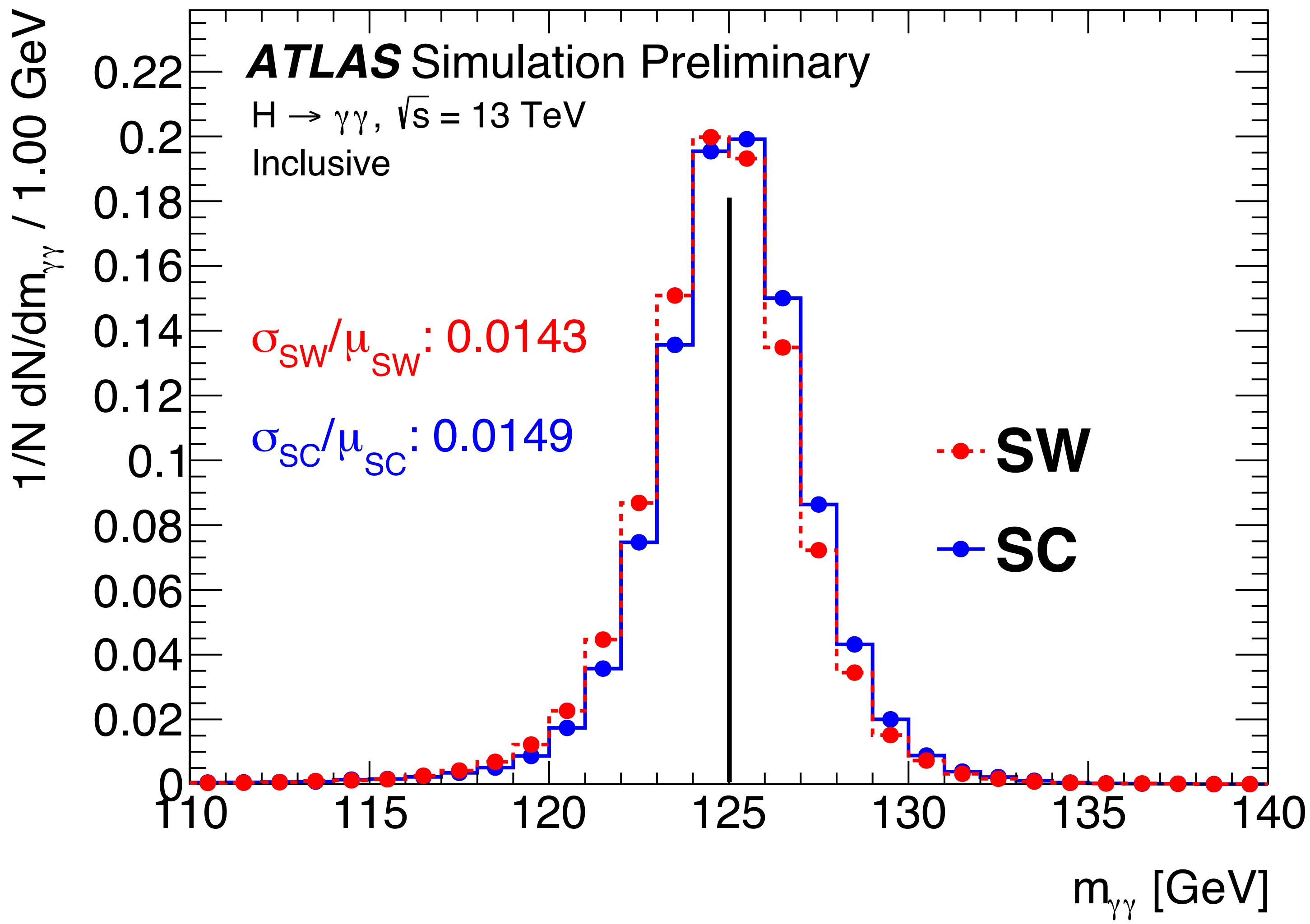
Z→eeγ



Z→μμγ



Impact of superclusters on energy resolution



- Sliding window (SW) versus supercluster (SC) reconstructed invariant mass distributions ($H \to \gamma\gamma$ simulation)