中国科学院高能物理研究所
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Novel photon energy calibration method and Higgs mass measurement

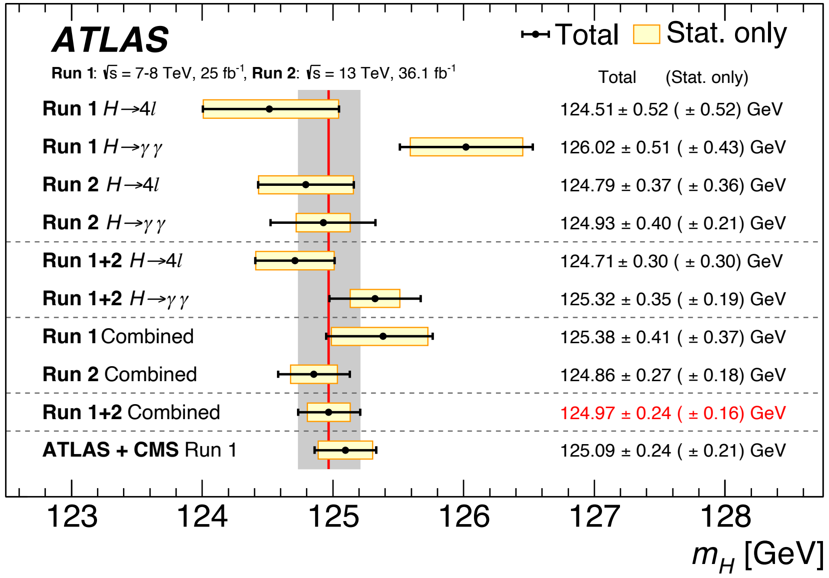
Mingxu He @ CLHCP 2023

IHEP, CAS

Phys. Lett. B 784 (2018) 345

Introduction

Run 1 + partial Run 2 Higgs mass measurement

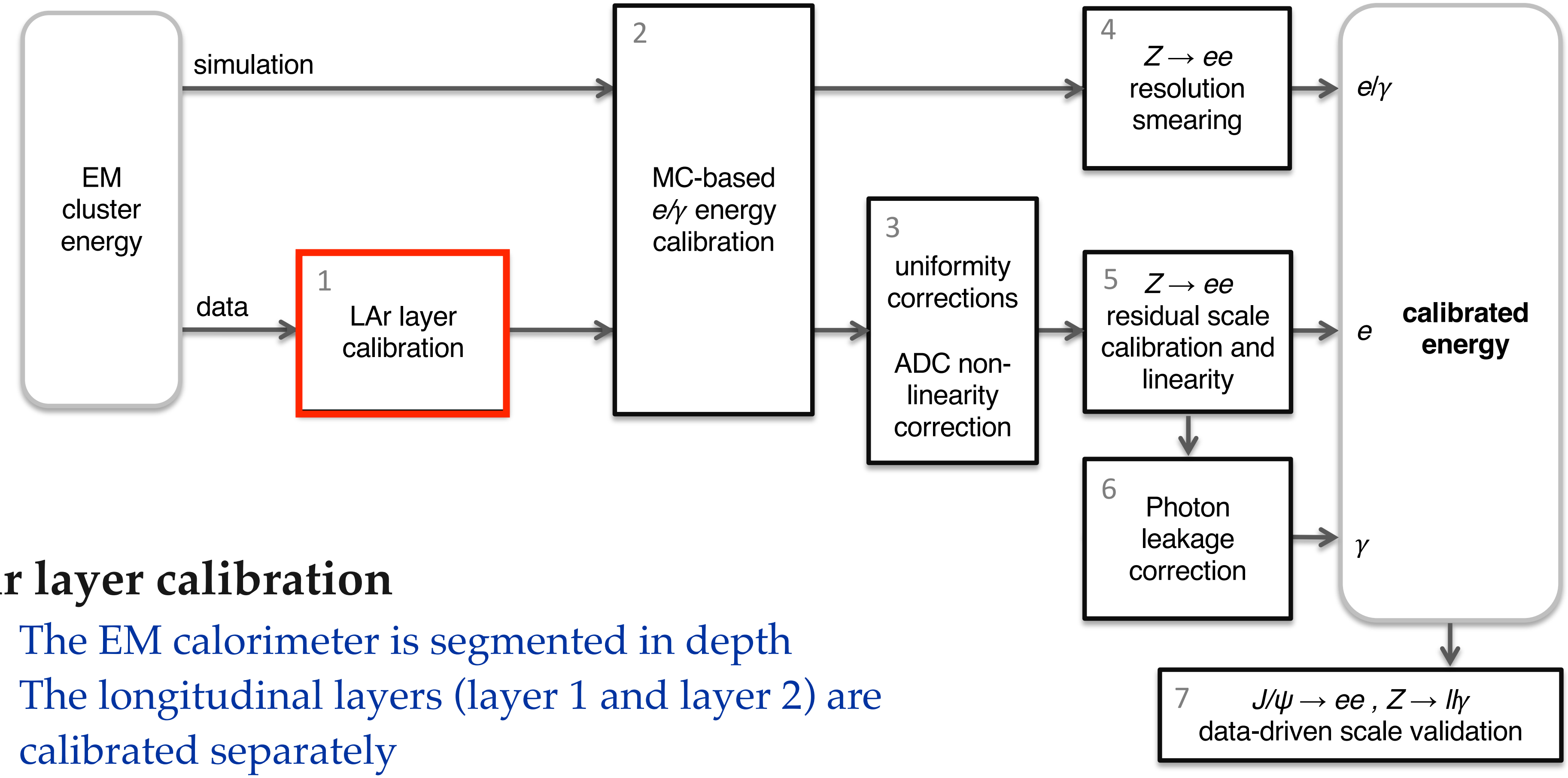


- ◉ **Optimal energy reconstruction and calibration of the electromagnetic calorimeter**
  - necessary for all analyses involving electrons and photons
  - **especially for precise measurements of the masses and properties of the Higgs, W and Z bosons**
- ◉ **In the last round Higgs mass measurement:**
  - Partial Run 2, $H \rightarrow \gamma\gamma$ channel only
  - Systematic uncertainties **(±0.34)** became larger than statistical uncertainty **(±0.21)**
- ◉ **Vital to increase the precision of e/γ energy calibration**

Systematic uncertainties in $H \rightarrow \gamma\gamma$ channel

Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
EM calorimeter cell non-linearity	±180
EM calorimeter layer calibration	±170
Non-ID material	±120
ID material	±110
Lateral shower shape	±110
$Z \rightarrow ee$ calibration	±80
Conversion reconstruction	±50
Background model	±50
Selection of the diphoton production vertex	±40
Resolution	±20
Signal model	±20

Overview of the e/γ energy calibration

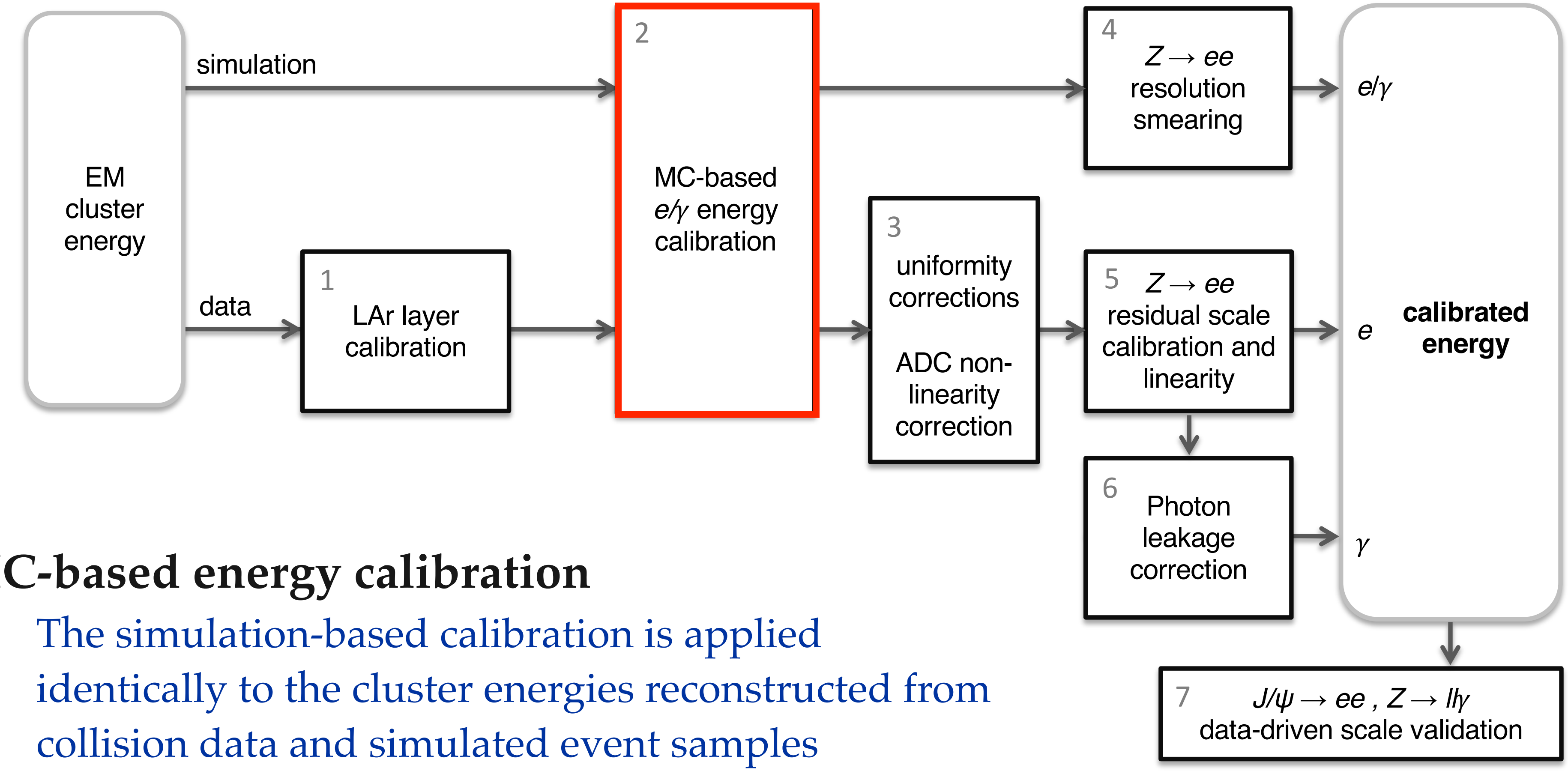


LAr layer calibration

The EM calorimeter is segmented in depth

The longitudinal layers (layer 1 and layer 2) are calibrated separately

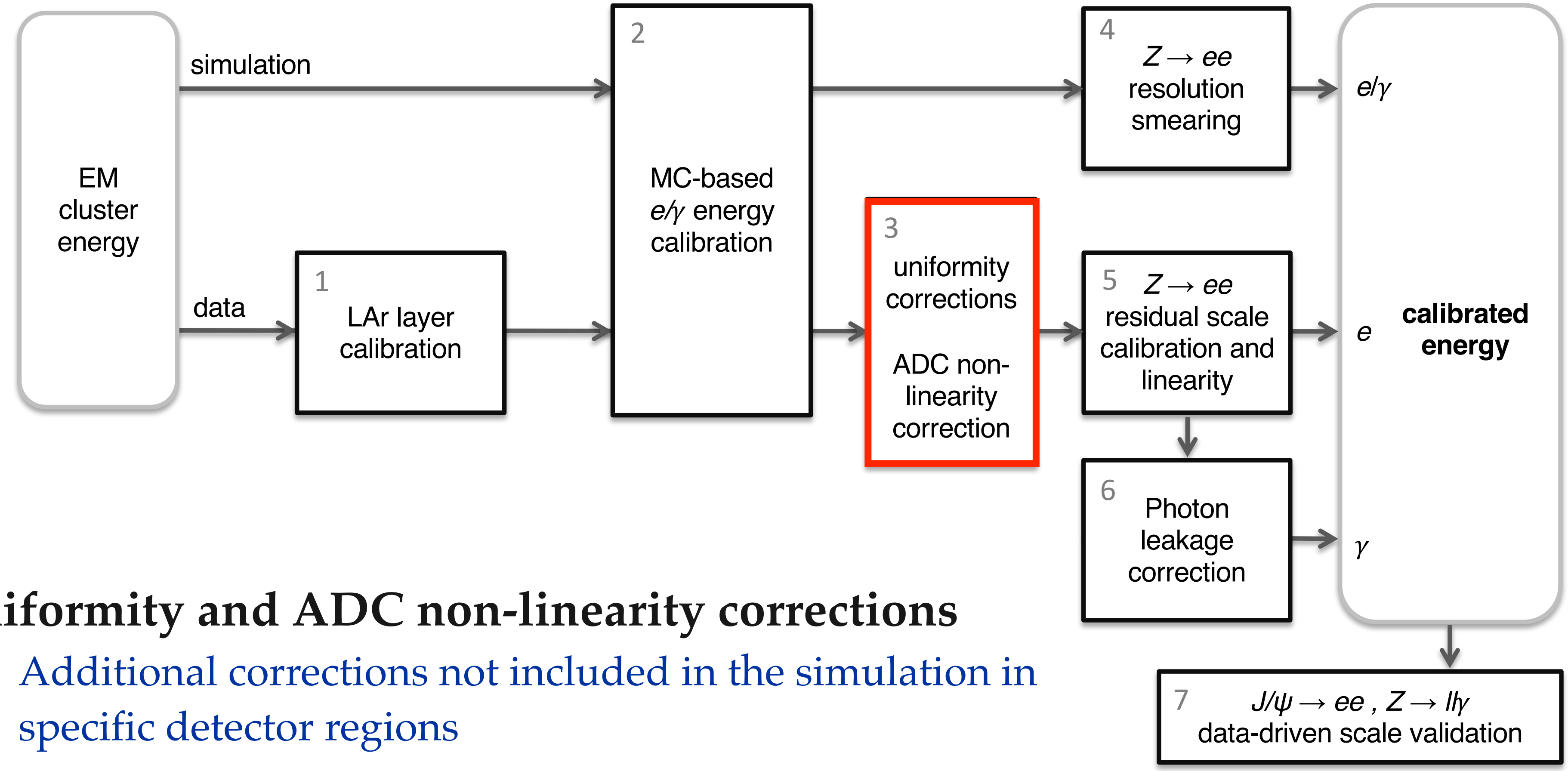
Overview of the e/γ energy calibration



MC-based energy calibration

The simulation-based calibration is applied identically to the cluster energies reconstructed from collision data and simulated event samples

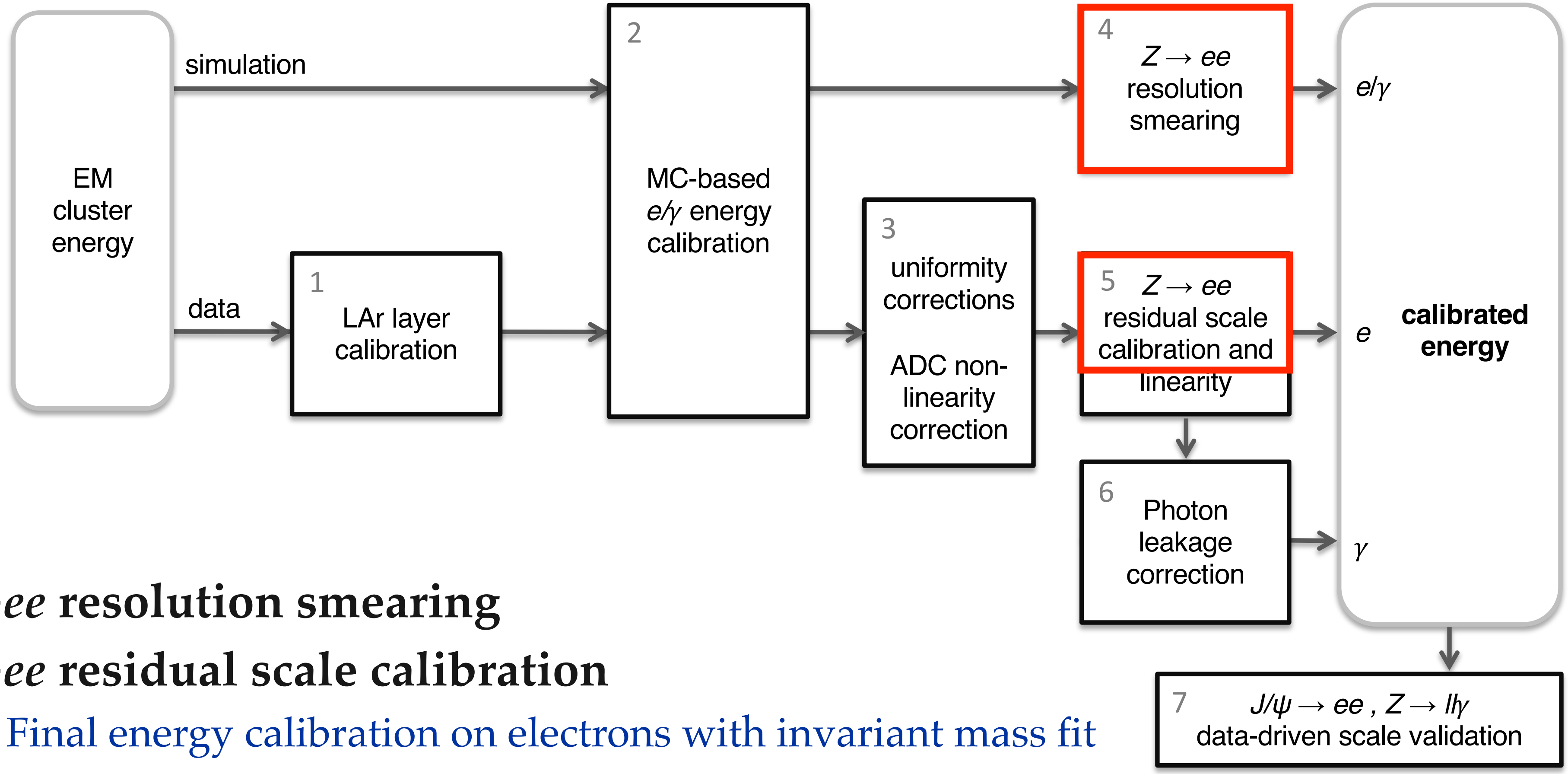
Overview of the e/γ energy calibration



Uniformity and ADC non-linearity corrections

Additional corrections not included in the simulation in specific detector regions

Overview of the e/γ energy calibration

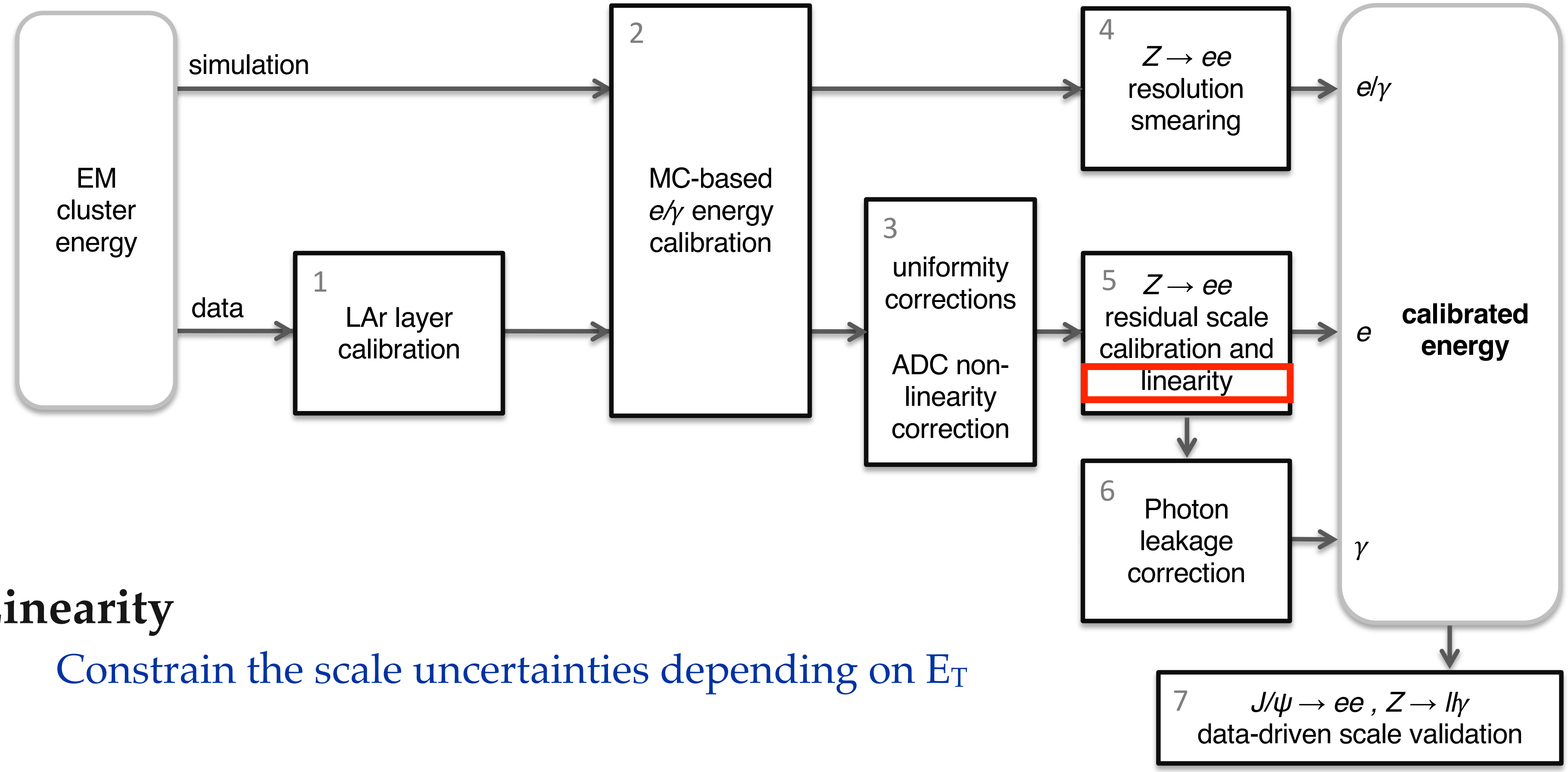


$Z \to ee$ resolution smearing

$Z \to ee$ residual scale calibration

Final energy calibration on electrons with invariant mass fit

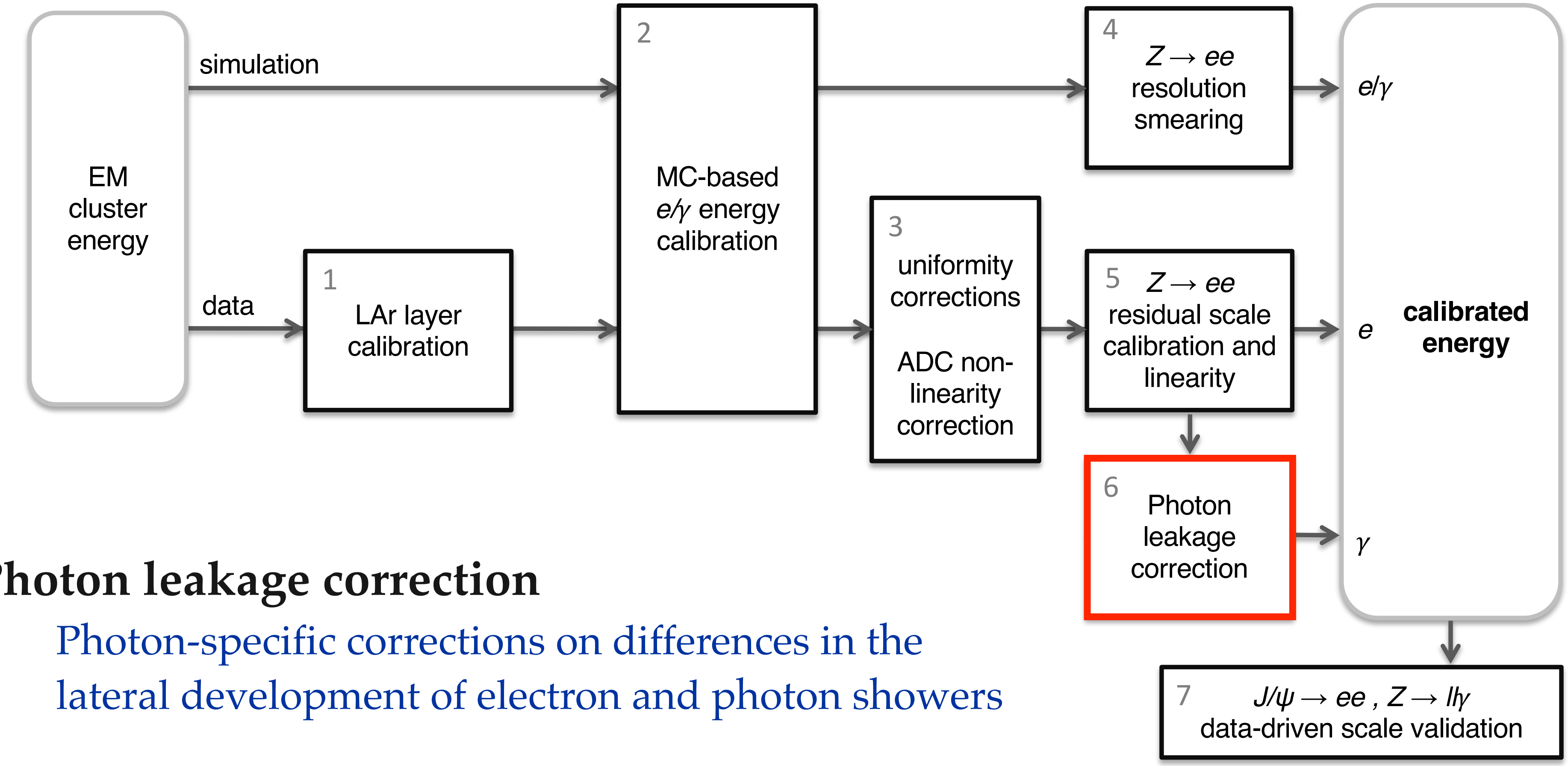
Overview of the e/γ energy calibration



Linearity

Constrain the scale uncertainties depending on E_T

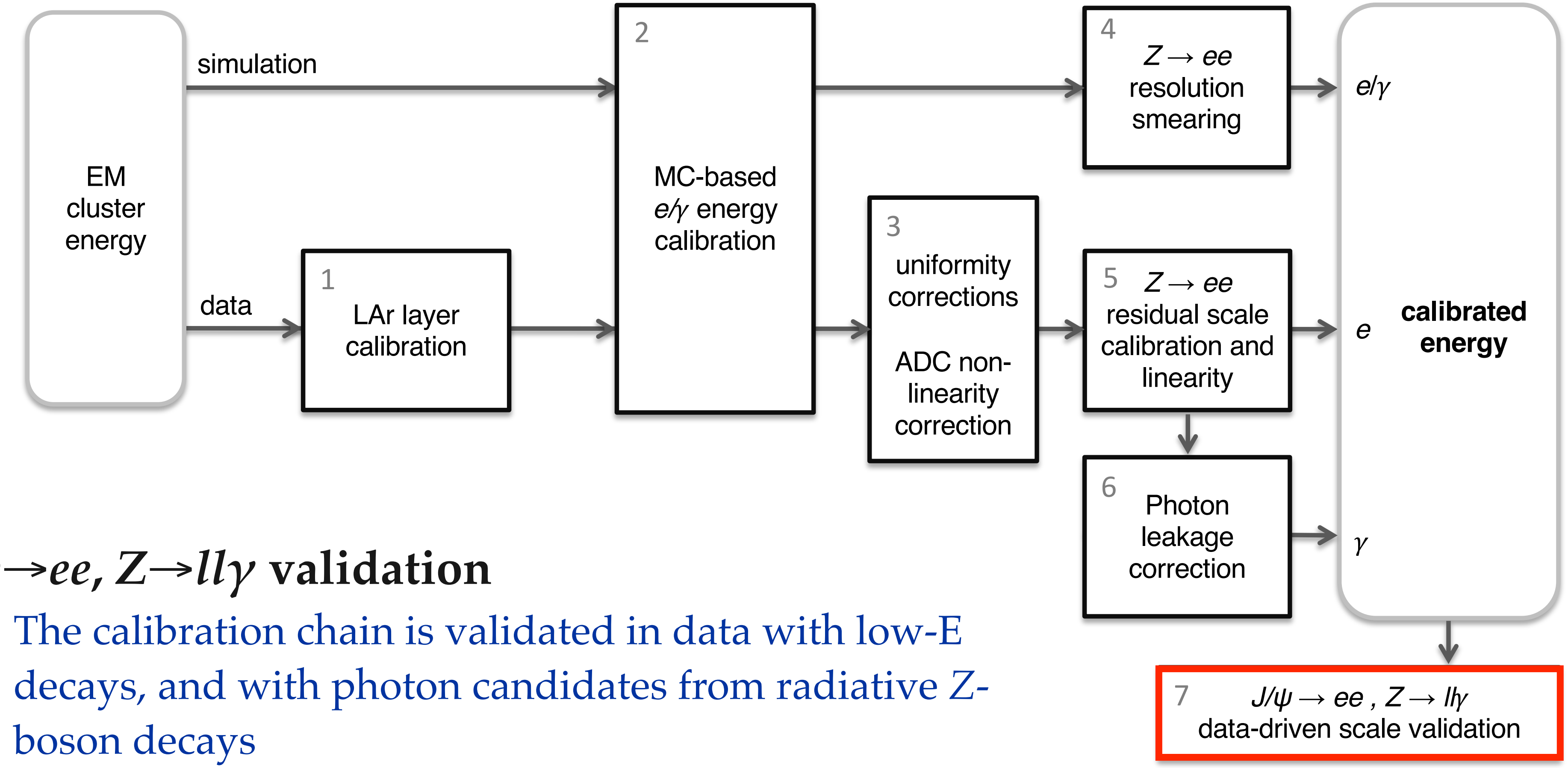
Overview of the e/γ energy calibration



Photon leakage correction

Photon-specific corrections on differences in the lateral development of electron and photon showers

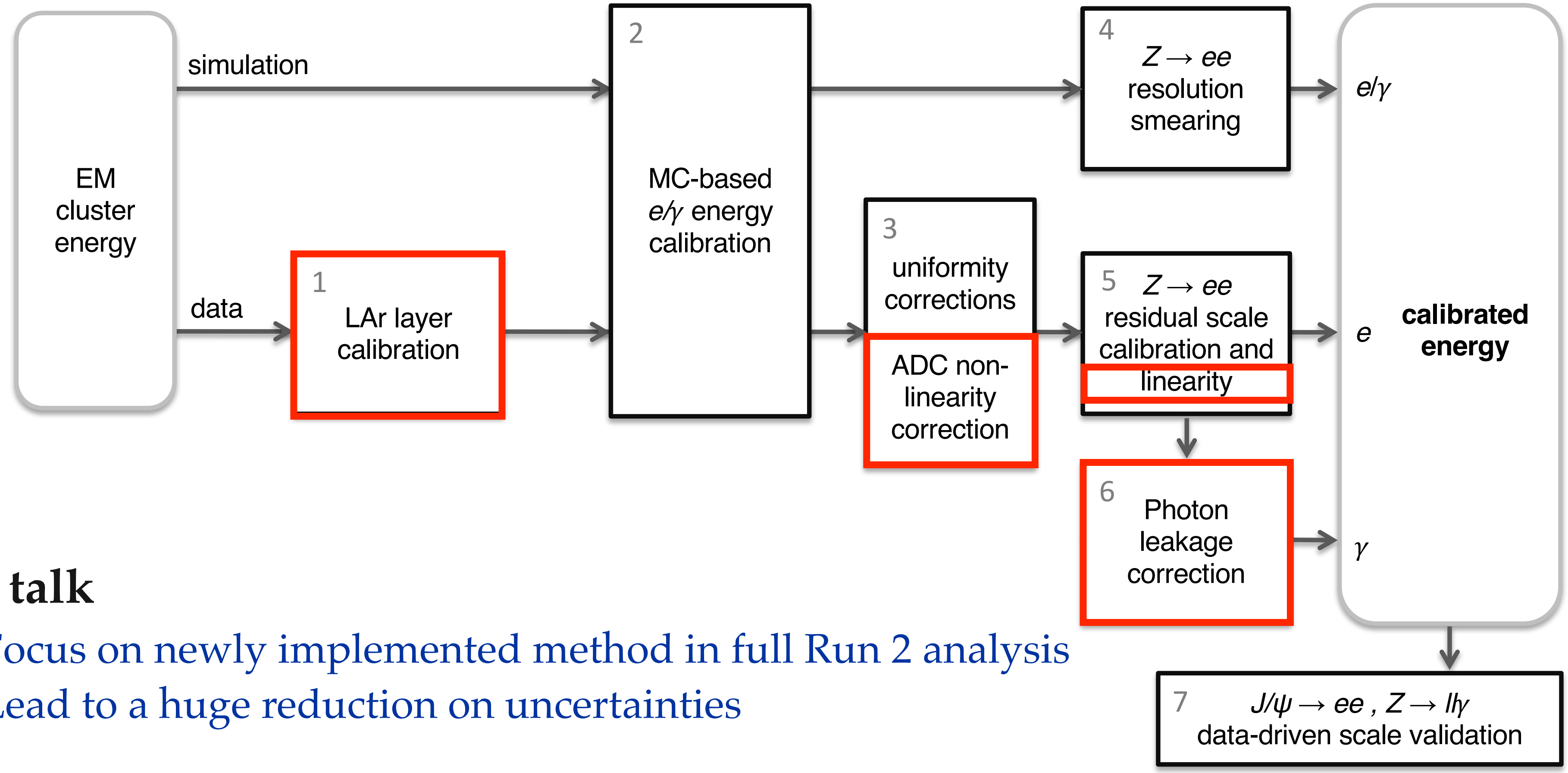
Overview of the e/γ energy calibration



$J/\psi \to ee$, $Z \to ll\gamma$ validation

The calibration chain is validated in data with low-E decays, and with photon candidates from radiative Z-boson decays

Overview of the e/γ energy calibration



This talk

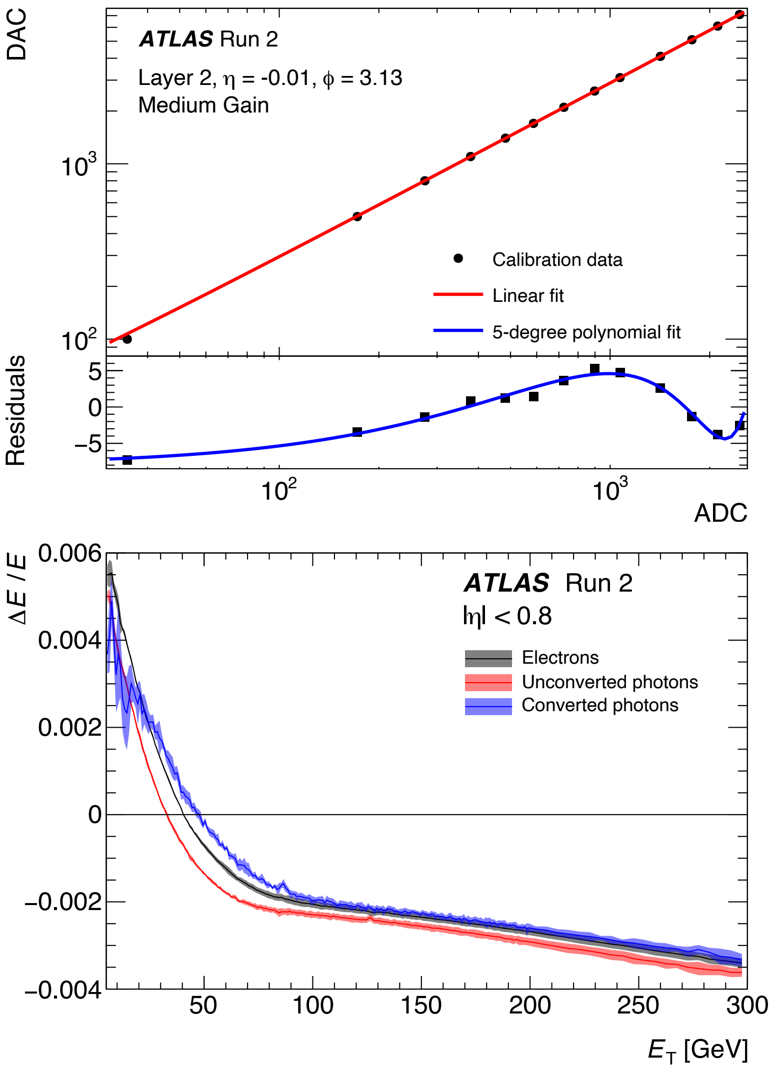
Focus on newly implemented method in full Run 2 analysis

Lead to a huge reduction on uncertainties

ADC correction

arXiv:2309.05471

- The energy reconstruction in a LAr calorimeter cell
  - linear conversion from ADC counts to current
  - an additional factor converting current into energy
- In practice, the energy response of each cell is determined during dedicated electronics calibration runs
  - Non-zero residuals: caused by intrinsic non-linear behavior of the electronics
- A non-linearity ADC correction is implemented for the first time
  - separately for each cell of the calorimeter
  - built to not modify the cluster energies of electrons for final in-situ scale
- Cluster energies are increased by about 0.4% at low E_T, and decreased by about 0.2% at high E_T

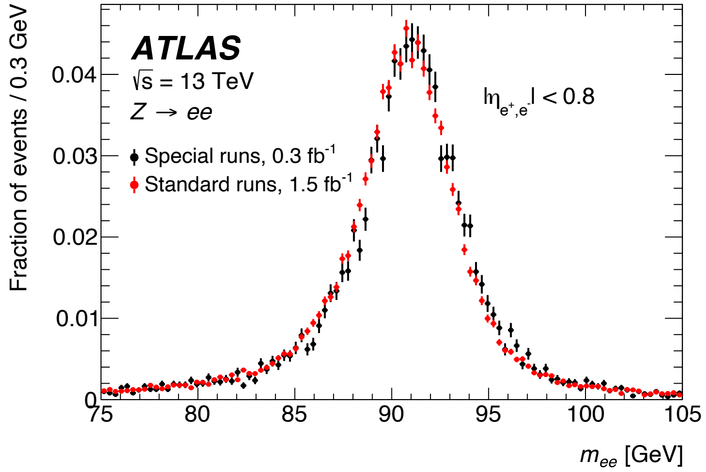


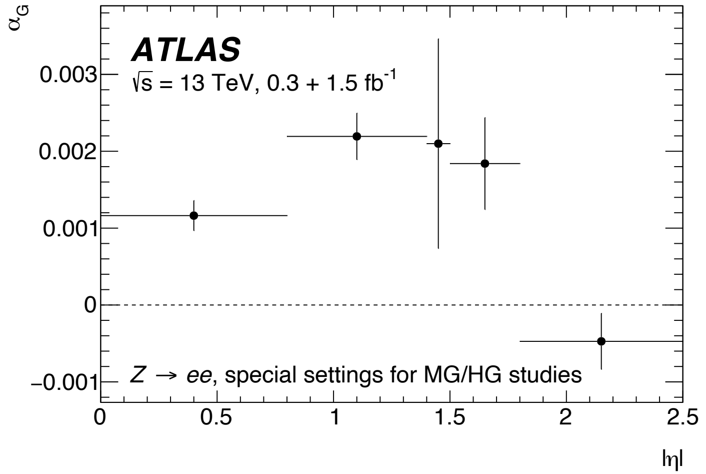
Energy response in high and medium gain

arXiv:2309.05471

- **Non-linearities in the ADC-to-current conversion affect comparisons of the energy response in different readout gains**
  - Standard configuration: high gain (HG) readout is the majority in $Z \rightarrow ee$ decays
    - ➡ The transition to medium gain (MG) for a cell energy of about 25 GeV, for 2nd layer
- **Use standard runs and special runs (lower threshold to MG)**
- **The energy response difference between HG and MG**
  - $$\frac{\Delta E}{E} = \alpha_G \cdot \frac{1}{\delta_Z} \cdot \delta_G^{e,\gamma}$$
  - α_G: difference of total energy between two runs from fit
- **ΔE/E: a systematic uncertainty in the energy measurement**
  - typically 0.1% in barrel, 0.4%in endcap

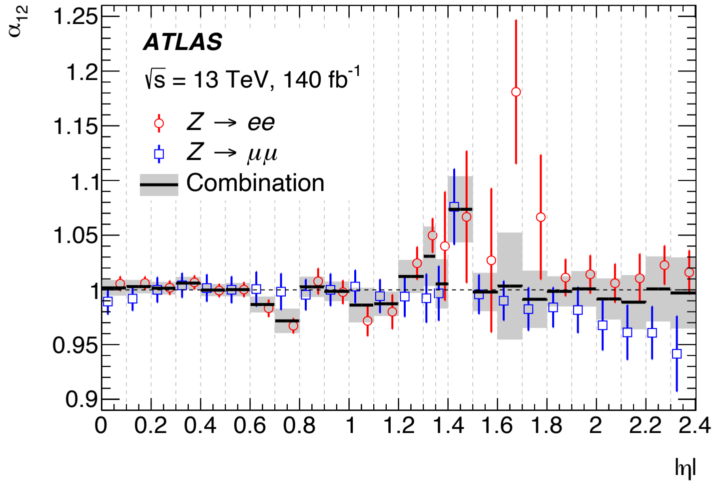
- For a given change in the energy recorded in MG
  - δ_Z: fractional change in energy for electrons between two runs
  - $\delta_G^{e,\gamma}$: the fractional change in total energy for electron/photon

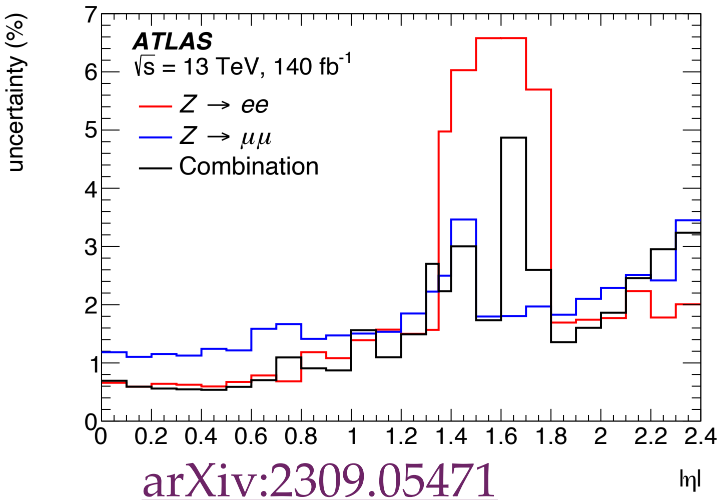




Intercalibration of the first and second calorimeter layers

- **The intercalibration of the first and second calorimeter layers**
  - paramount in controlling the linearity of the electron and photon responses
- **In the previous calibration**
  - Intercalibration is preformed with muons
  - Electron probes were used only as a cross-check
- **In full Run 2 calibration: combine the electron-based and muon-based measurements**
  - Better constrain the layer intercalibration
  - The uncertainty reduced by a factor of ~1.8 in the first half of the barrel

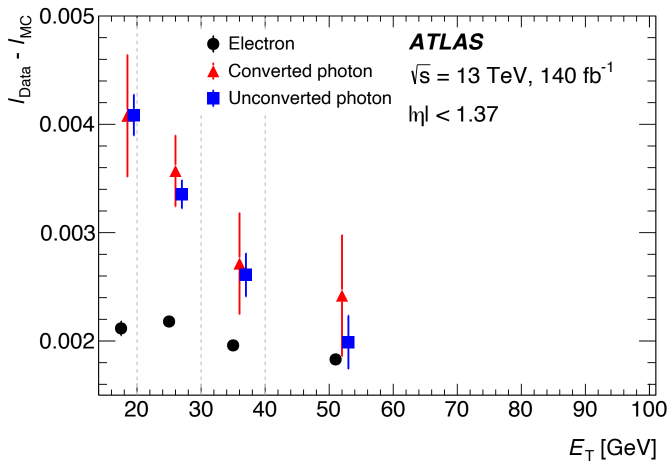


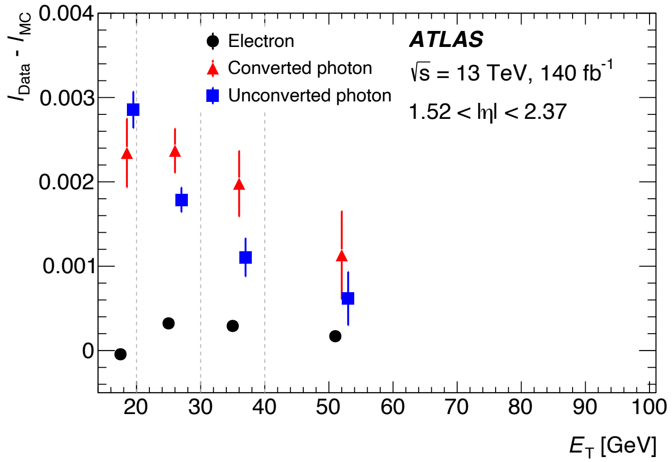


arXiv:2309.05471

Photon-specific calibration

- **Electrons and photons deposit energy outside of the cluster used in the reconstruction: 1~6%**
  - The global energy scale correction is performed based on electrons
    - ➡ absorbs any potential discrepancy on lateral leakage modeling for electrons
- **Lateral energy leakage in the calorimeter outside the area of the cluster is specifically estimated for electrons and photons**
  - **In the previous calibration, the leakage difference between e/γ was a systematic uncertainty**
- **The statistical power of the Run 2 data allows an correction depending on η and E**
  - Decrease the corresponding calibration uncertainty by a factor of ~2





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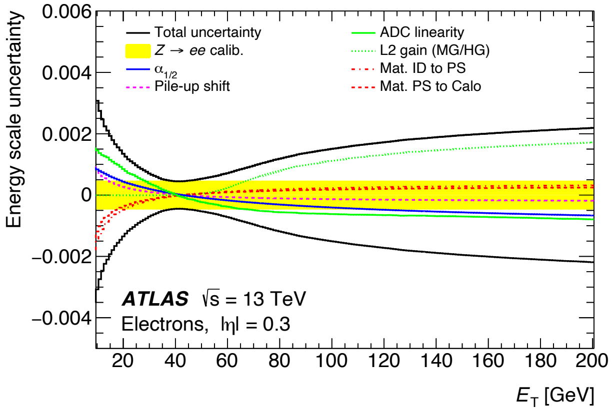
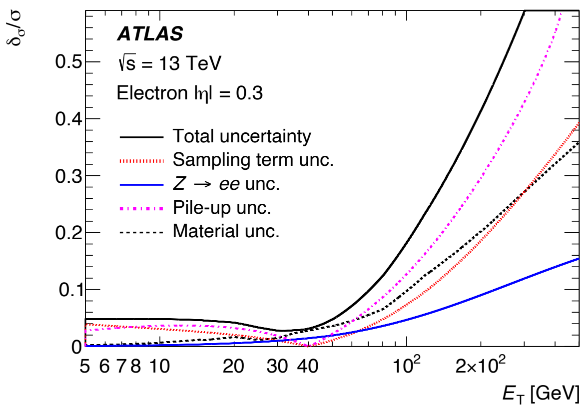
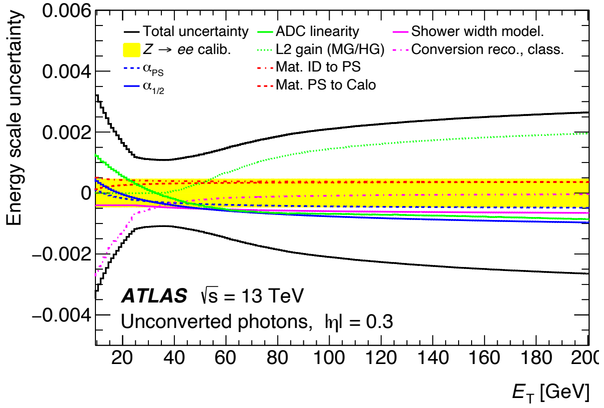
Energy linearity and constraints on the calibration uncertainties

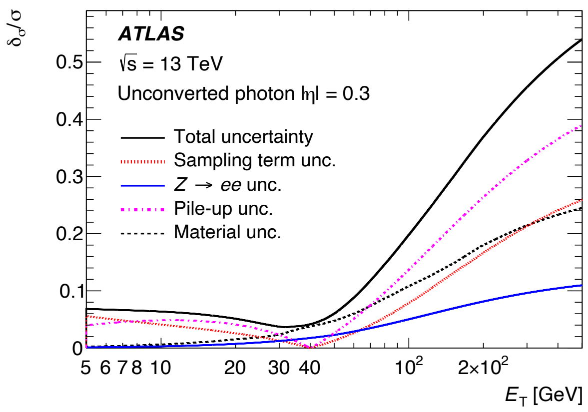
- **The complete systematic uncertainty model**
  - 64 and 67 independent uncertainty variations for the electron and photon energy scales
  - In the previous calibration, **no correlation** is considered among all the uncertainties
- **New idea to further constrain the energy scale systematic uncertainties**
  - Measure the residual dependency of the in-situ scale versus E_T (linearity)

arXiv:2309.05471



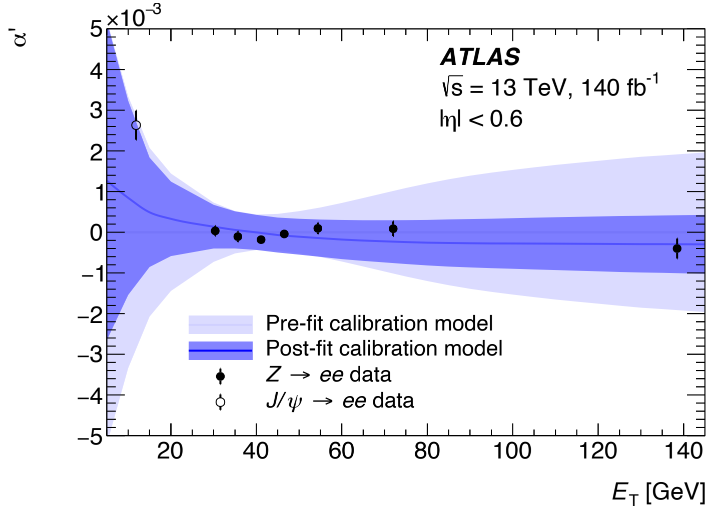




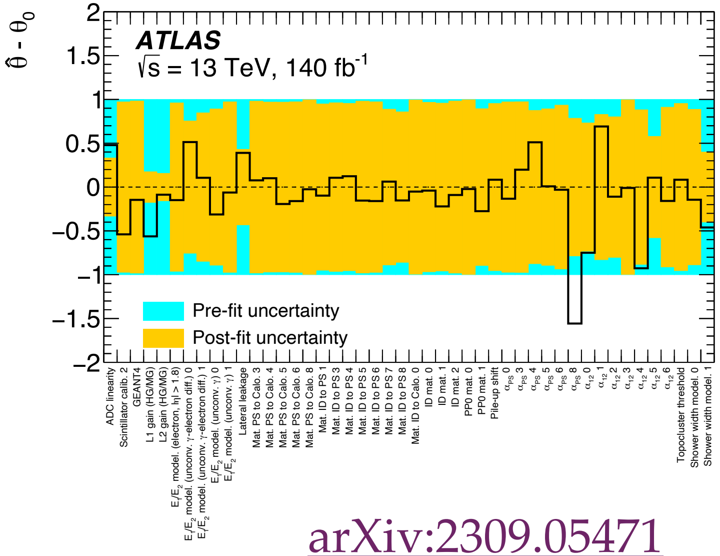


Energy linearity and constraints on the calibration uncertainties

- **Measure the residual dependency of the in-situ scale versus E_T**
  - $E^{\text{data,corr}} = E^{\text{data}}/[(1+\alpha_i)(1+\alpha'_j)]$
  - α_i — in-situ scale, α'_j — **energy dependence** of the energy scale
    - ➡ Vary α' to get best agreement between the $Z \to ee$ invariant mass distributions in data and simulation



- **Each uncertainty can be calculated from the minimization on**
  - $$\chi^2 = \sum_{j_1,j_2} [\alpha'_{j_1} - \alpha'_{mod,j_1}(\theta)] C^{-1}_{j_1,j_2} [\alpha'_{j_2} - \alpha'_{mod,j_2}(\theta)] + \sum_k \theta_k^2$$
    - ➡ α'_{mod} is total effect of all systematic variations
    - ➡ θ is the impact of each source, C is the covariance matrix



- **With few exceptions, the measured values of α'_j are well within the initial calibration uncertainties**

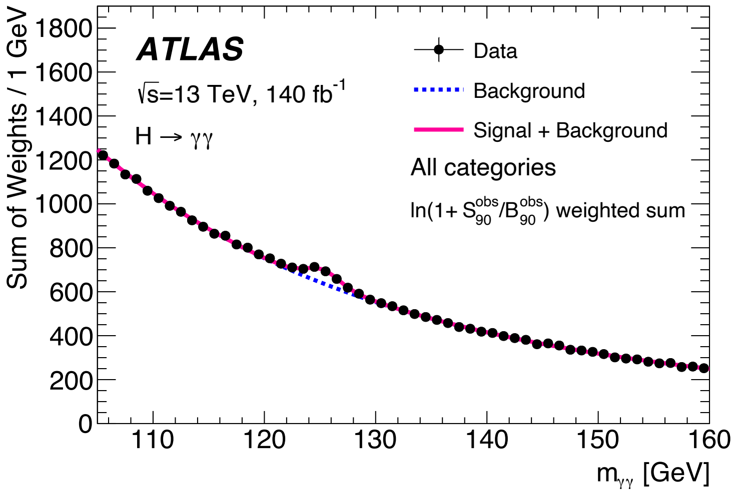
arXiv:2309.05471

Higgs mass measurement with di-photon decay mode

arXiv:2308.07216

- **A measurement of the mass of the Higgs boson in $H \to \gamma\gamma$ decay channels is performed with Run 2 data**
  - Events are classified into 14 mutually exclusive categories
    - ➡ according to photon properties: conversion status, η_{S_2} and $p_{Tt}^{\gamma\gamma}$
- **The E_T-dependence of the energy scale correction**
  - Linearity fit to constrain the systematic uncertainties
    - ➡ **reducing the corresponding uncertainty by a factor of four**
  - Propagated to the mass measurement
    - ➡ multivariate Gaussian constraint term with covariance from linearity fit
- **Higgs mass: 125.17 ± 0.14 (± 0.11 stat., ± 0.09 syst.) GeV**

Source	Impact [MeV]
Photon energy scale	83
$Z \to e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^{\pm} \to \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

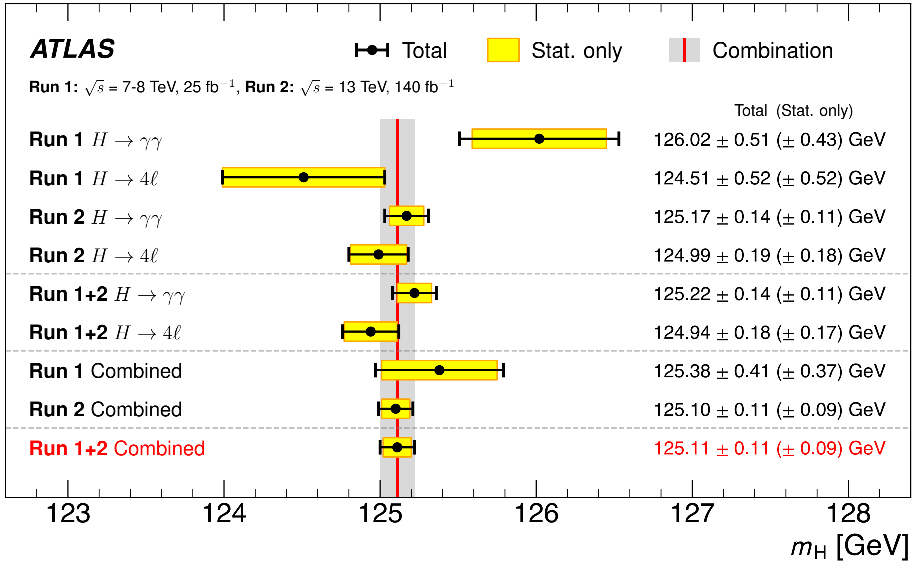


Higgs mass measurement

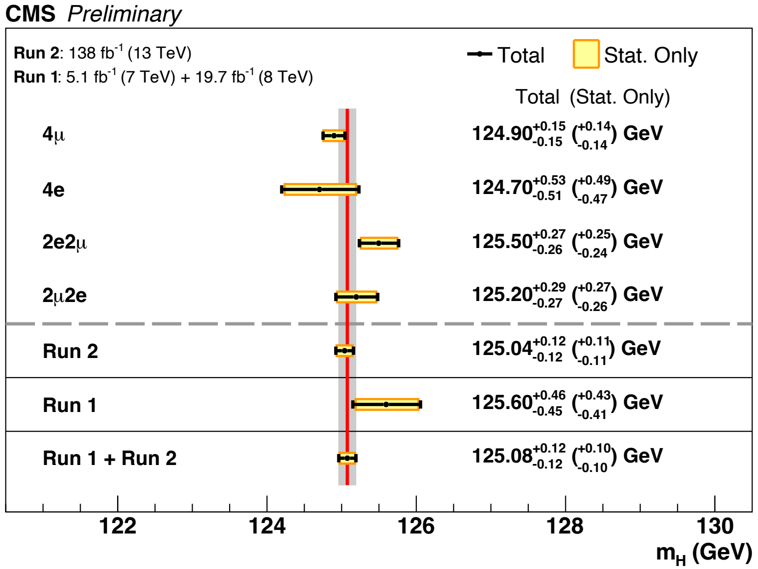
- **Combining Run 1 + Run 2, $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4l$ channels**
  - 125.11±0.11 (±0.09 stat., ±0.07 syst.) GeV
  - Most precise Higgs mass measurement so far!

For detailed information:
Yangfan's talk

Latest ATLAS Higgs mass results: arXiv:2308.04775



Latest CMS Higgs mass: CMS-PAS-HIG-21-019



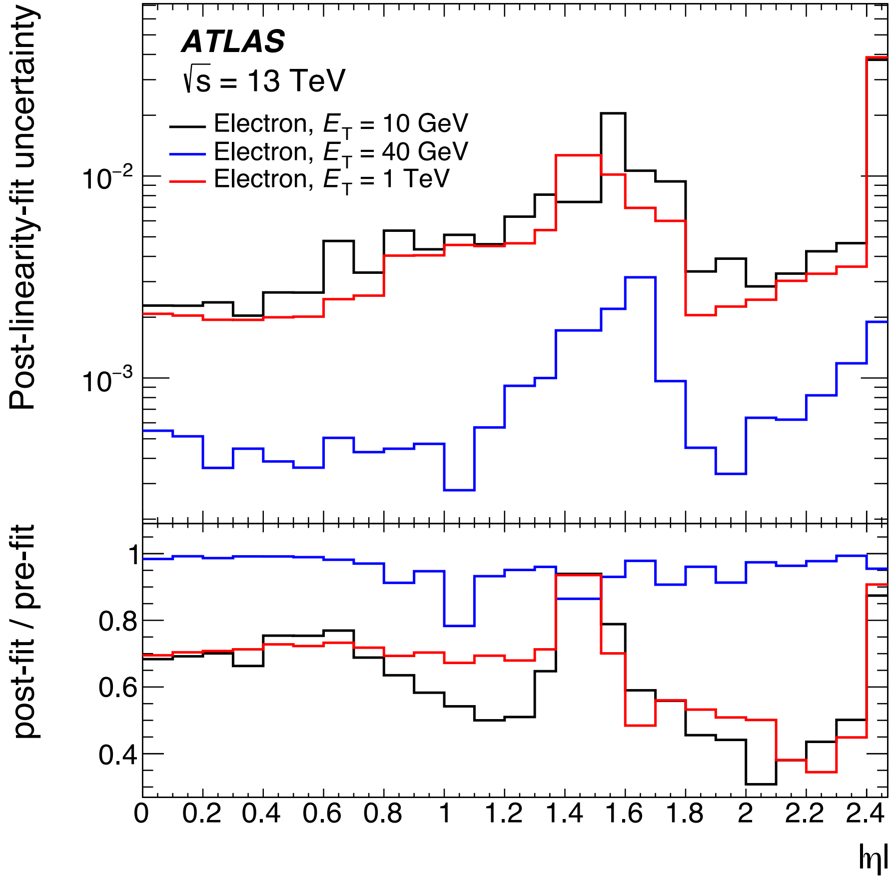
Summary

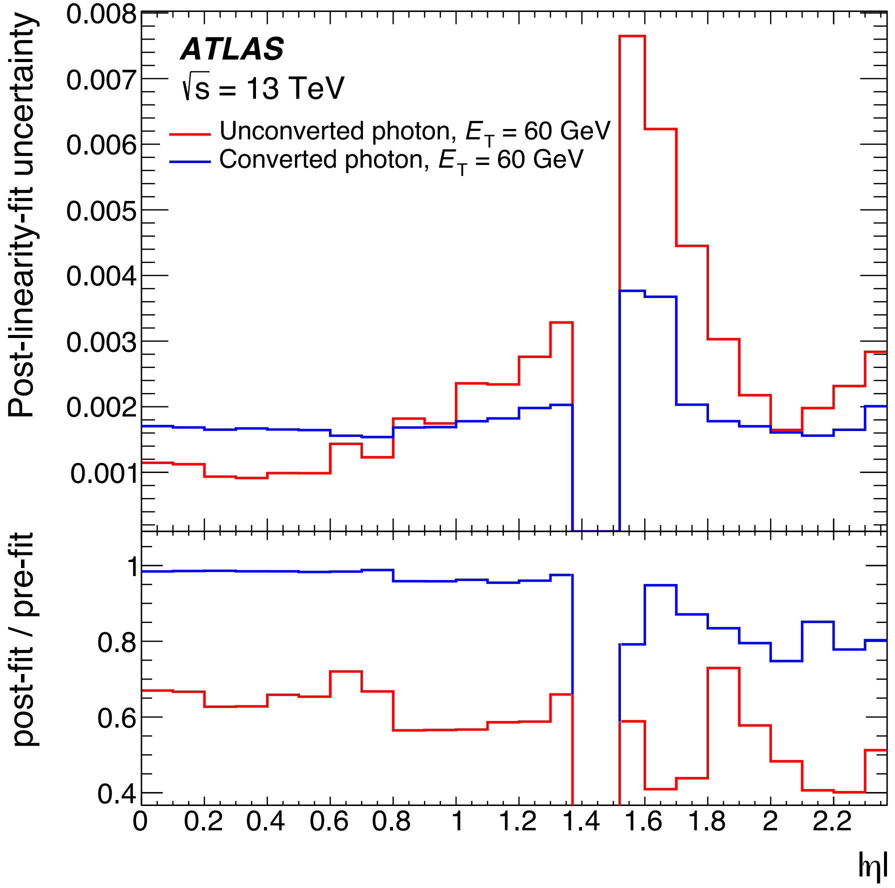
- **The energy calibration is extracted for electrons and photons reconstructed in 140 fb^{-1} of 13 TeV proton–proton collision data recorded by ATLAS during Run 2 of the LHC**
- **New methods are introduced to reduce the impact of major uncertainties**
  - The overall calibration uncertainty is reduced by a factor of 2–3
- **With the new calibration, the precision of Higgs mass measurement is greatly improved using di-photon decay mode**

Thank you for listening!

Backup

Total relative systematic uncertainty in the energy scale

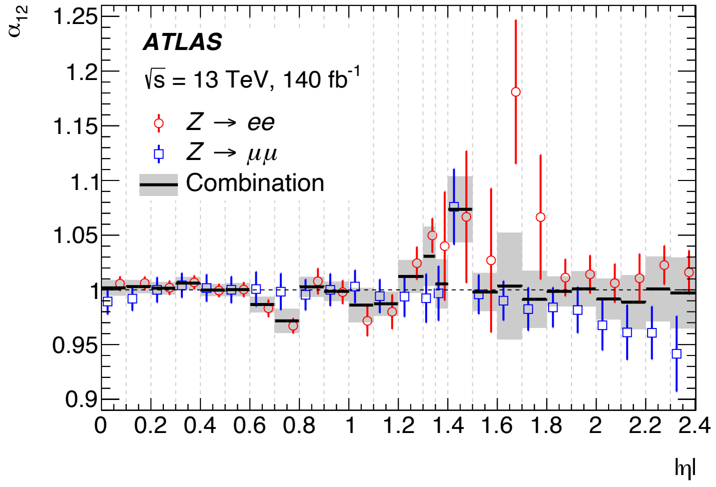




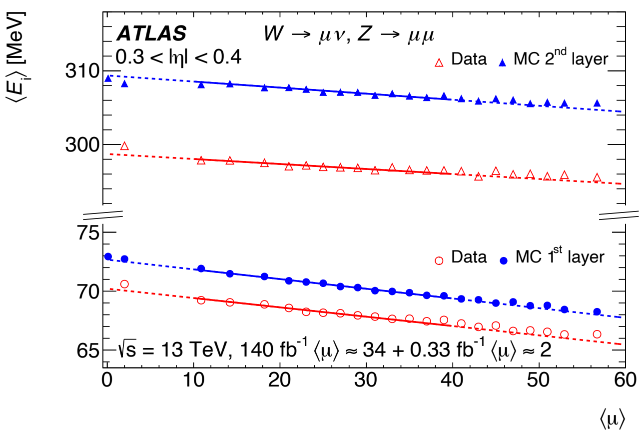
Intercalibration of the first and second calorimeter layers

arXiv:2309.05471

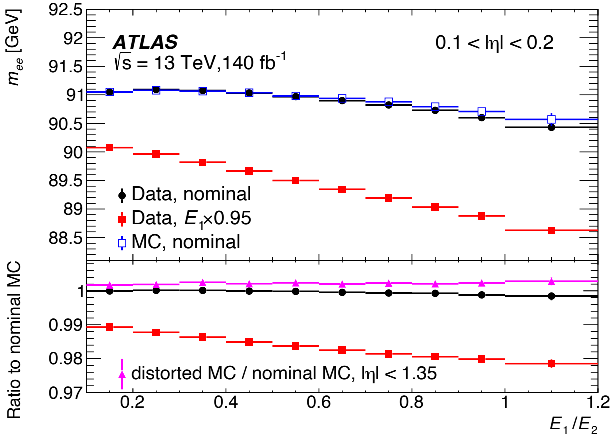
- **Intercalibration using muons**
  - Measure $\langle E_i \rangle$ in intervals of $\langle \mu \rangle$, extrapolate to 0 and extract the final α_{12}
- **Intercalibration using electrons**
  - Calibrate the ratio of estimators (E/p or m_{ee}) in data and the simulation to be constant
    - ➡ Rescaling E_1 in data by adjusting α_{12}
- **The combination of muon and electron measurements**
  - The uncertainty reduced by a factor of ~1.8 in the first half of the barrel

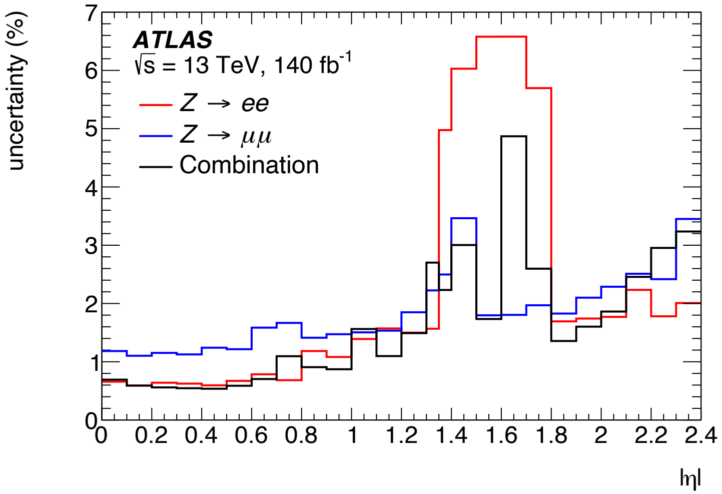


$\langle E_i \rangle$ measurement using muons



Calibrate the estimator using electrons

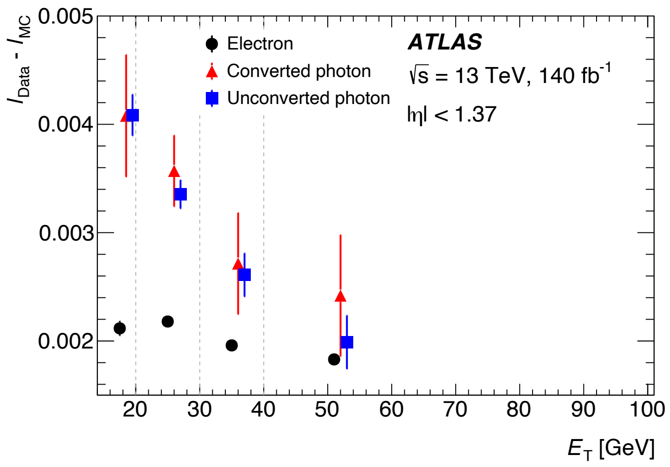


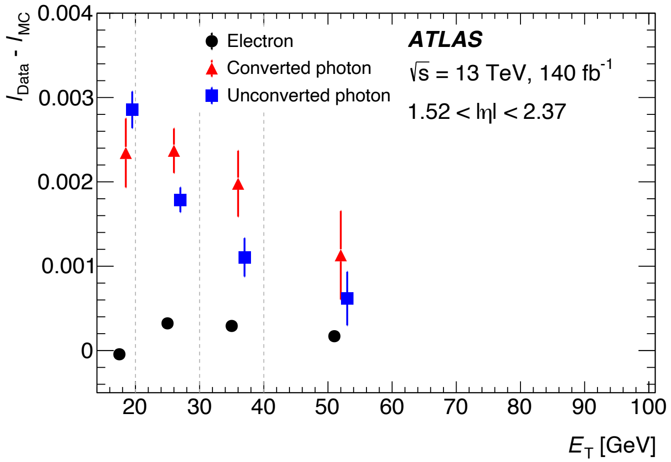


Photon lateral energy leakage calibration

- **The lateral energy leakage:** $l = E^{L2}_{7\times11}/E^{L2}_{nom} - 1$
  - E^{L2}_{nom}: the energy collected in the second-layer cells belonging to the supercluster
  - $E^{L2}_{7\times11}$: the energy deposited in second-layer cells in a larger rectangular window of size 7×11 in $\eta \times \phi$ around it
- **The double difference is used to corrected the photon energy scale**
  - $\alpha_l = (l_e - l_\gamma)^{data} - (l_e - l_\gamma)^{MC}$
- **Decrease the corresponding calibration uncertainty by a factor of about two**

The systematic uncertainty of the calibration is estimated from the reconstruction and classification of photon conversions





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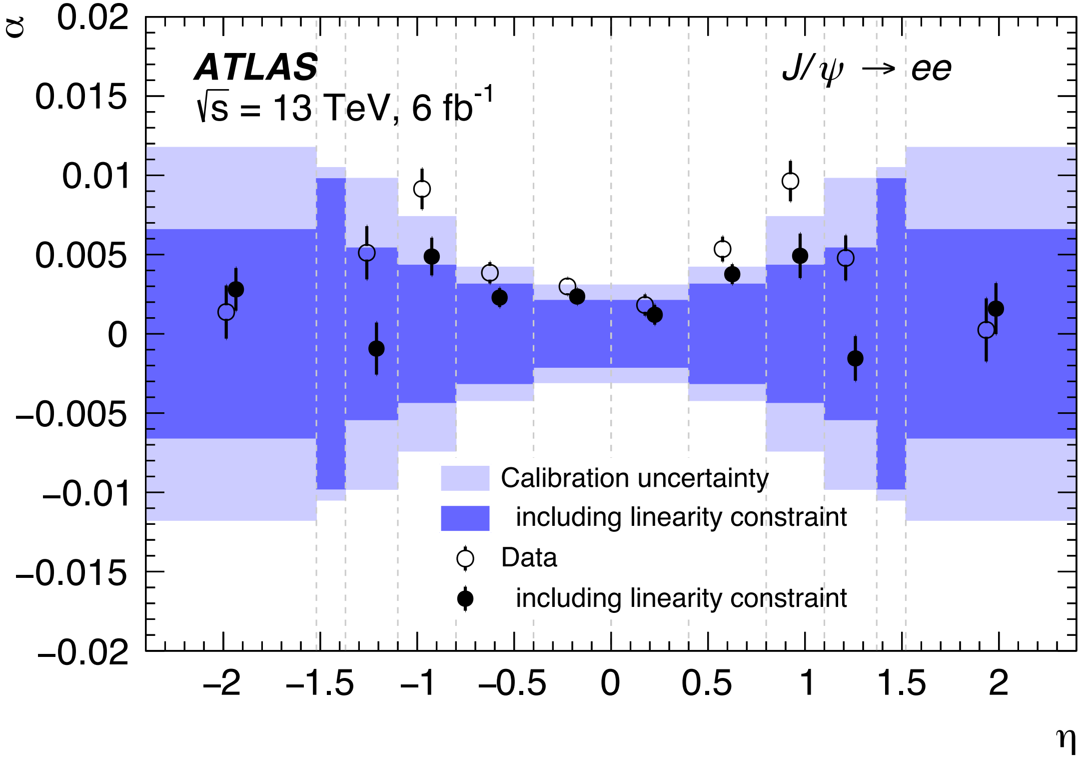
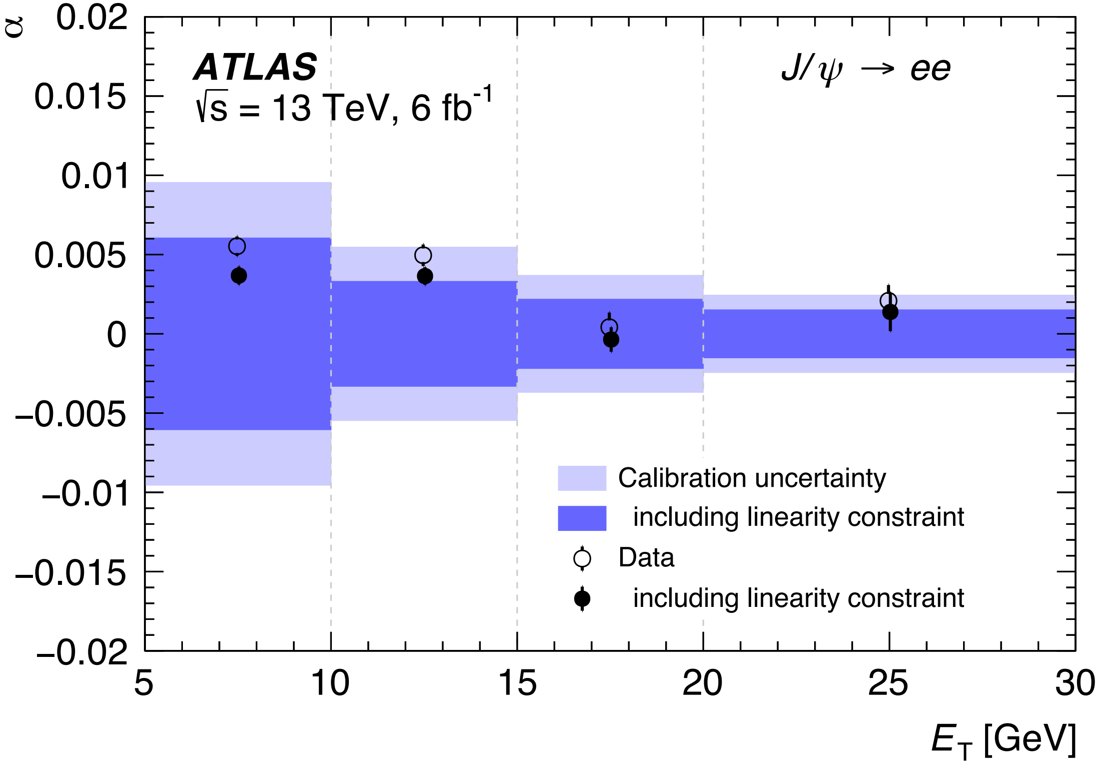
Calibration cross-checks with $J/\psi \to ee$





Calibration cross-checks with $Z \rightarrow ll\gamma$