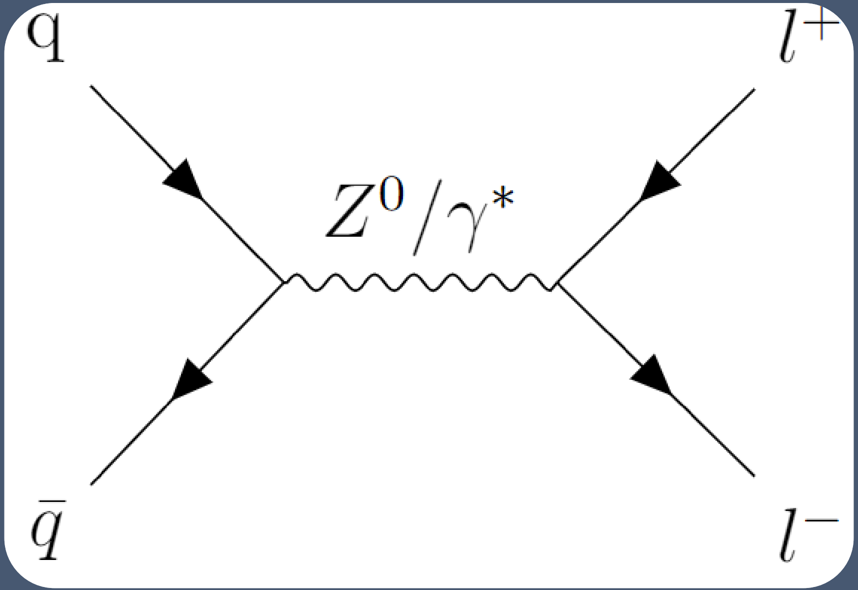
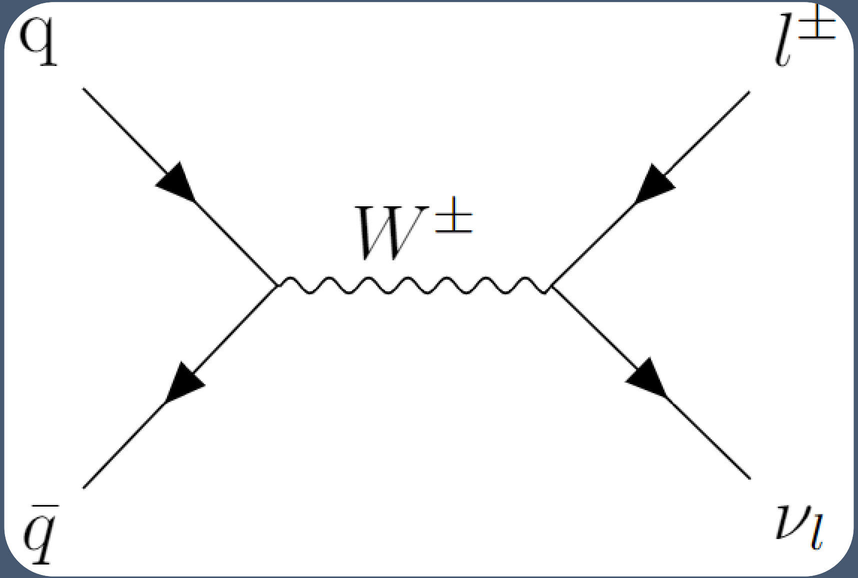




COUNTING OF Z BOSONS & ELECTRON ENERGY CALIBRATION FOR W MASS

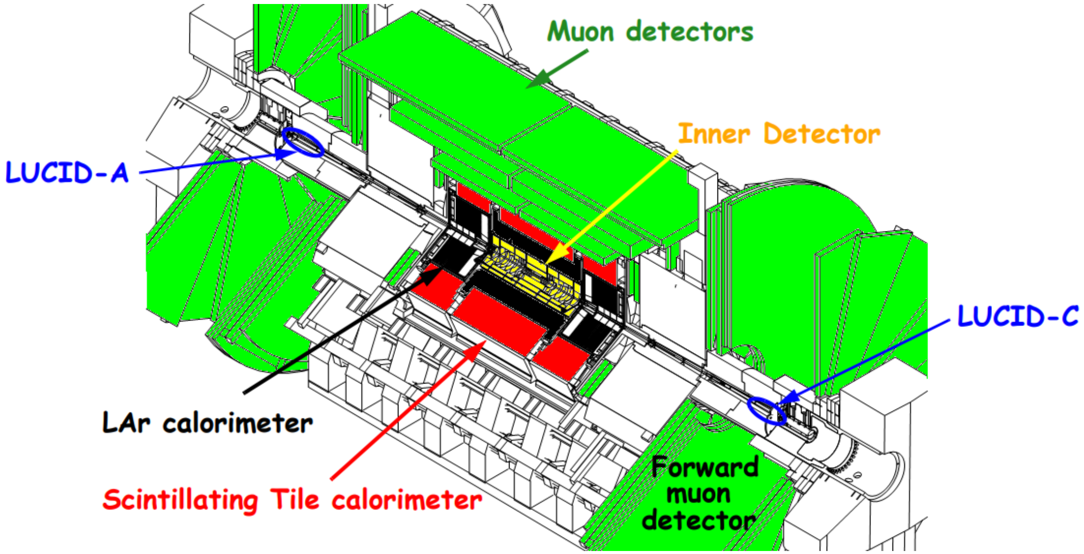
Joshua Newell

Supervisors: *Prof. Uta Klein, Dr Jan Kretzschmar, Dr Ludovica Aperio Bella*

ATLAS EXPERIMENT
UNIVERSITY OF LIVERPOOL
DESY.

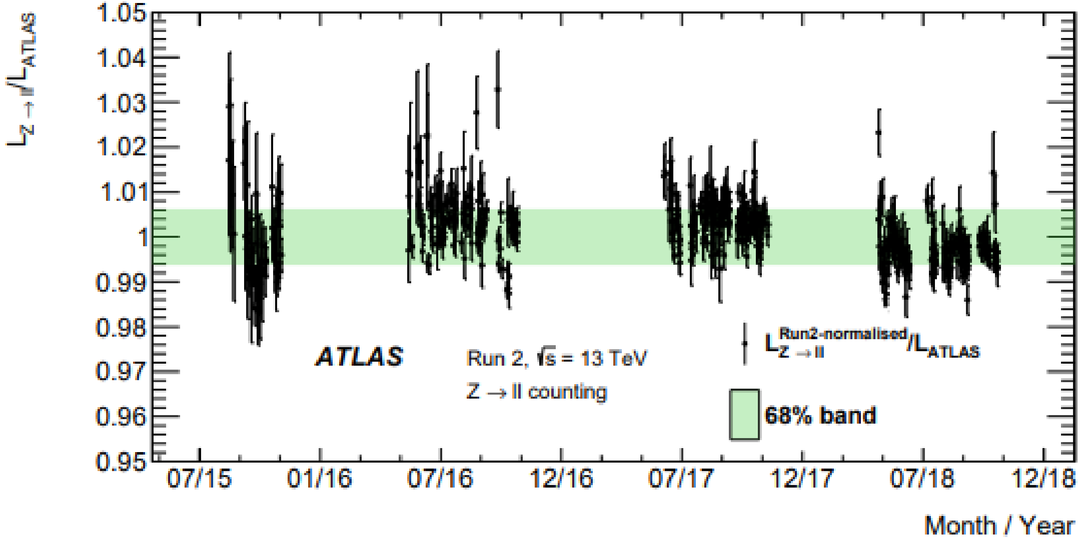
Luminosity at the ATLAS Detector

- ATLAS uses LUCID-2 Cherenkov radiation detector
- Luminosity is one of the dominant uncertainties in high precision cross-section measurements



[1] V. Hedberg. The LUCID-2 Luminometer. Int. J. Mod. Phys. Conf. Ser., 46:1860076, 2018.

- Run 2 – 13 TeV ATLAS achieved best ever luminosity uncertainty for a hadron collider – 0.8% [2]
- Independent methodology of Z-counting validated the dominant time-dependent systematics – 0.6%



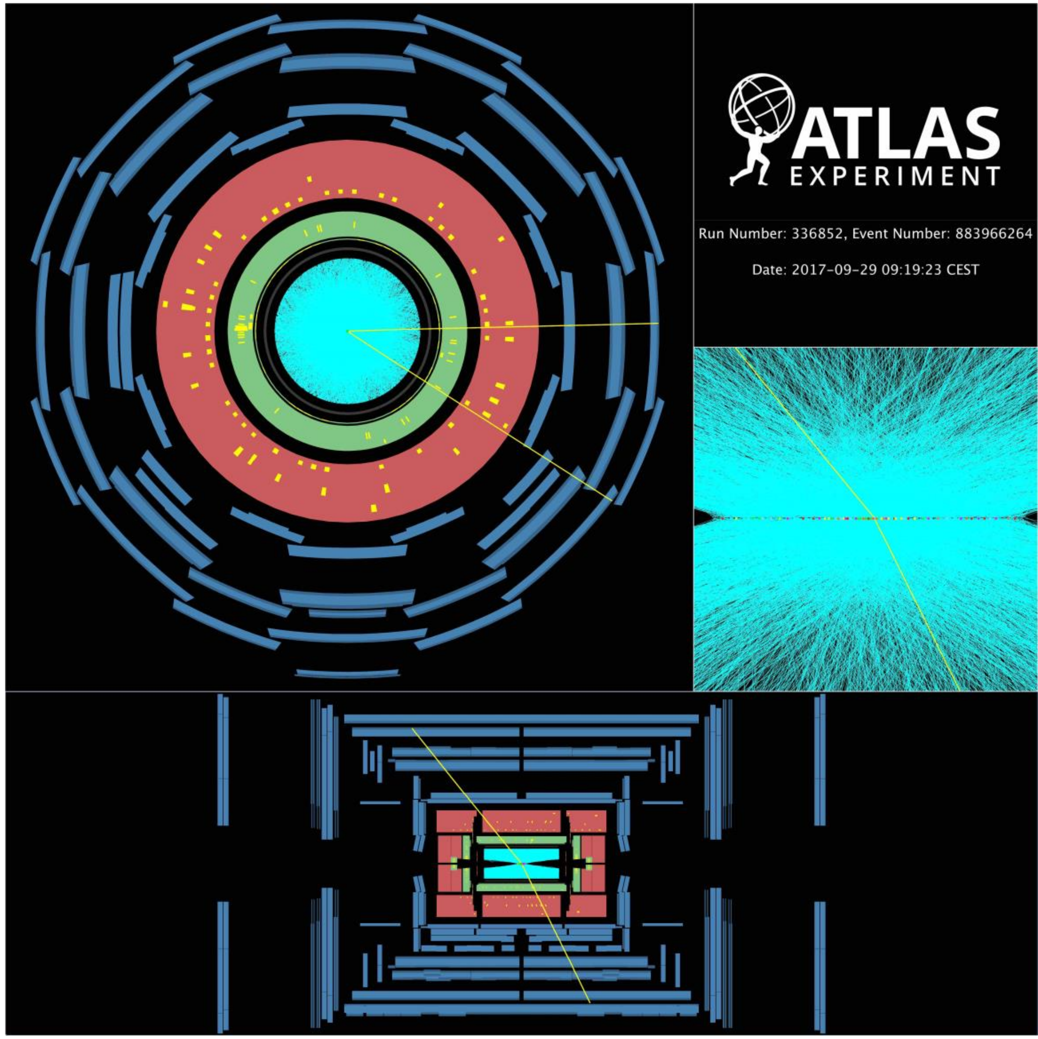
[2] Luminosity determination in pp collisions at √s = 13 TeV using the ATLAS detector at the LHC. 12 2022.

Z–Counting Overview

- Use the decays of Z bosons to electrons or muons to determine proton-proton interaction rate (c.f. Run 2 ATLAS lumi paper [1])

$$\mathcal{L}_Z = \frac{N_Z}{\sigma_Z}$$

- Z boson production cross section is known to high precision
- Good theoretical understanding of Z production and decay
- Experimentally clean signature in electron and muon channels (even at high pileup)

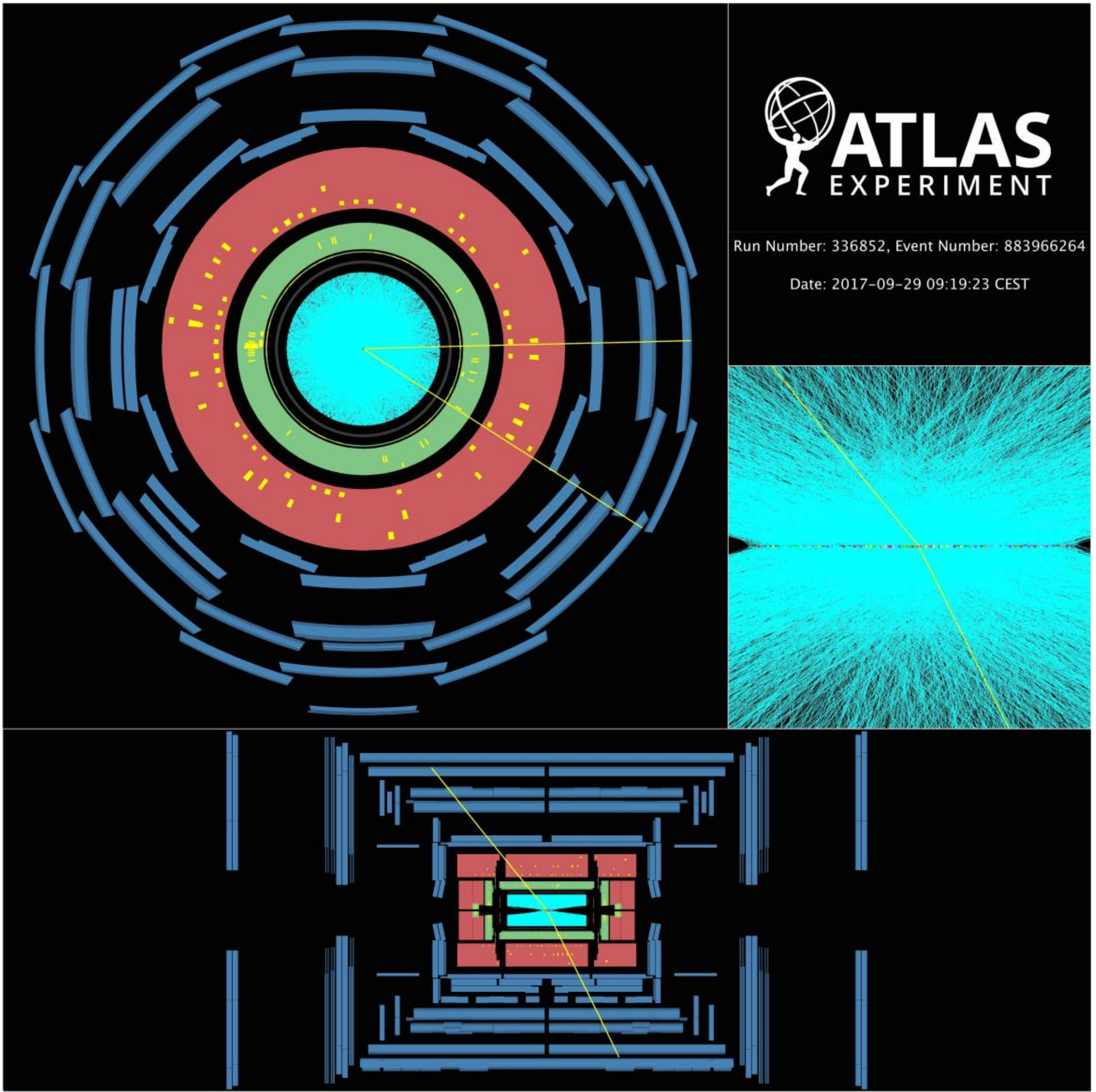


- Event display showing a $Z \to \mu^+\mu^-$ event (yellow tracks) alongside 65 other reconstructed vertices

[1] Luminosity determination in pp collisions at √s = 13 TeV using the ATLAS detector at the LHC. Eur. Phys. J. C 83 (2023) 982

Z-Counting – Event Selection

Pseudorapidity	$0 < \|\eta\| < 2.4$
Transverse Momentum	$p_T > 27$ GeV
Invariant Mass	$66 < m_{ll} < 116$ GeV



Identification criteria are used to ensure the candidate particles are electrons/muons

Monte Carlo correction factors and data-driven efficiencies are then applied

$$\mathcal{L}_Z(\Delta t) = \frac{N_{Z\rightarrow l^+l^-}(\Delta t) \times (1 - f_{bkg})}{F^{\mathrm{MC}}(\mu) \times A^{\mathrm{MC}} \times \epsilon^{T\&P}_{Z\rightarrow l^+l^-}(\Delta t) \times \sigma_{theory} \times \Delta t}$$

Z-Counting – Data-Driven Efficiency

$$\varepsilon^{T\&P}_{Z\to l^+l^-} = \left(1-(1-\varepsilon_{\text{trig, }1l})^2\right)\times(\varepsilon_{\text{reco, }1l})^2$$

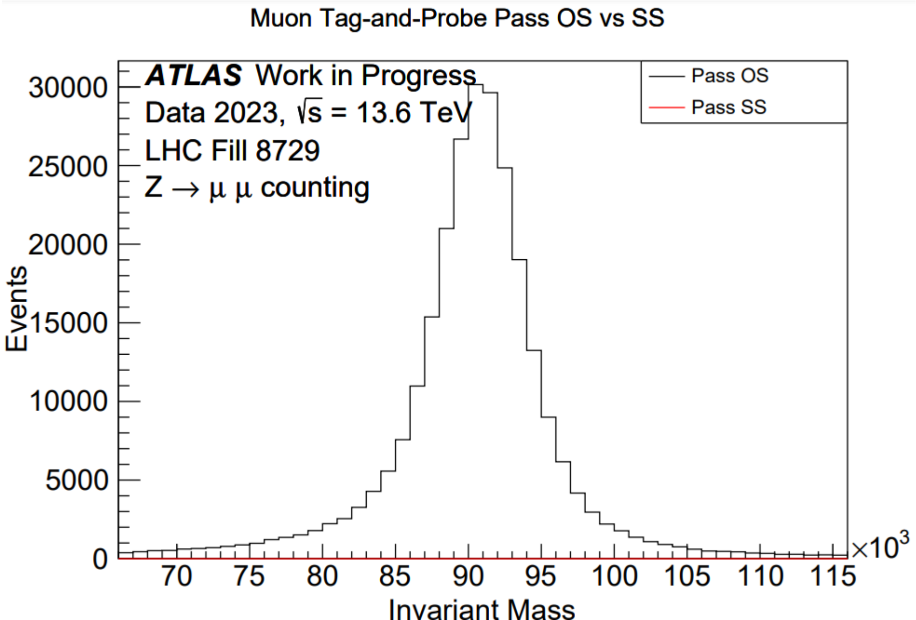
$$\varepsilon_{\text{trig,1l}} = \frac{1}{\frac{N_1}{2N_2}+1}$$

- Data-driven efficiency uses a combination of single-lepton reconstruction and trigger efficiencies to provide a full time and pileup-dependent, event-level efficiency

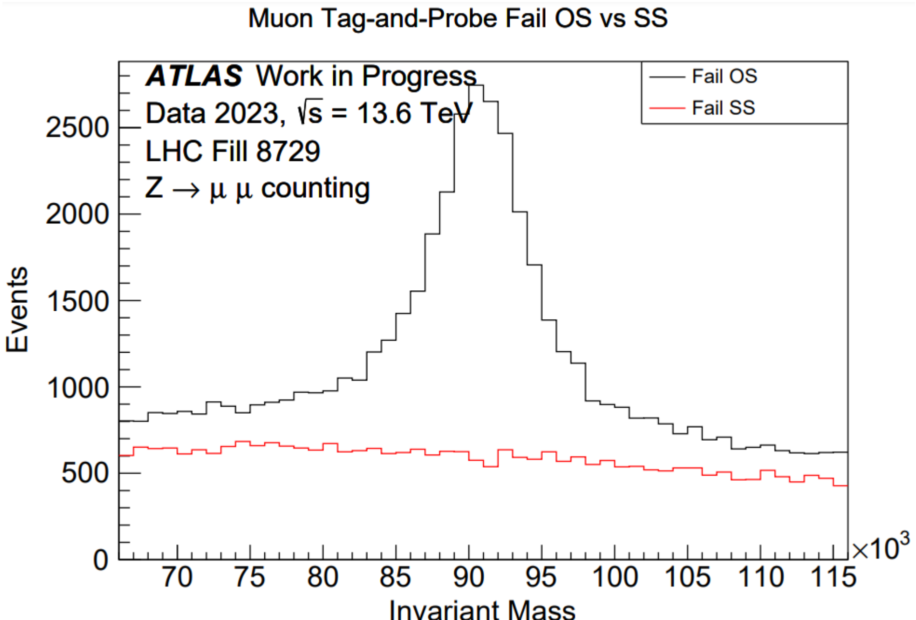
Reconstruction Efficiency Uses Tag-and-Probe Method:

$$\varepsilon^{\mu}_{\text{reco},1l} = \frac{N^{\text{os}}_{\text{pass}} - N^{\text{ss}}_{\text{pass}}}{N^{\text{os}}_{\text{tot}} - N^{\text{ss}}_{\text{tot}}}$$

- Tag-and-Probe Passed Pairs:

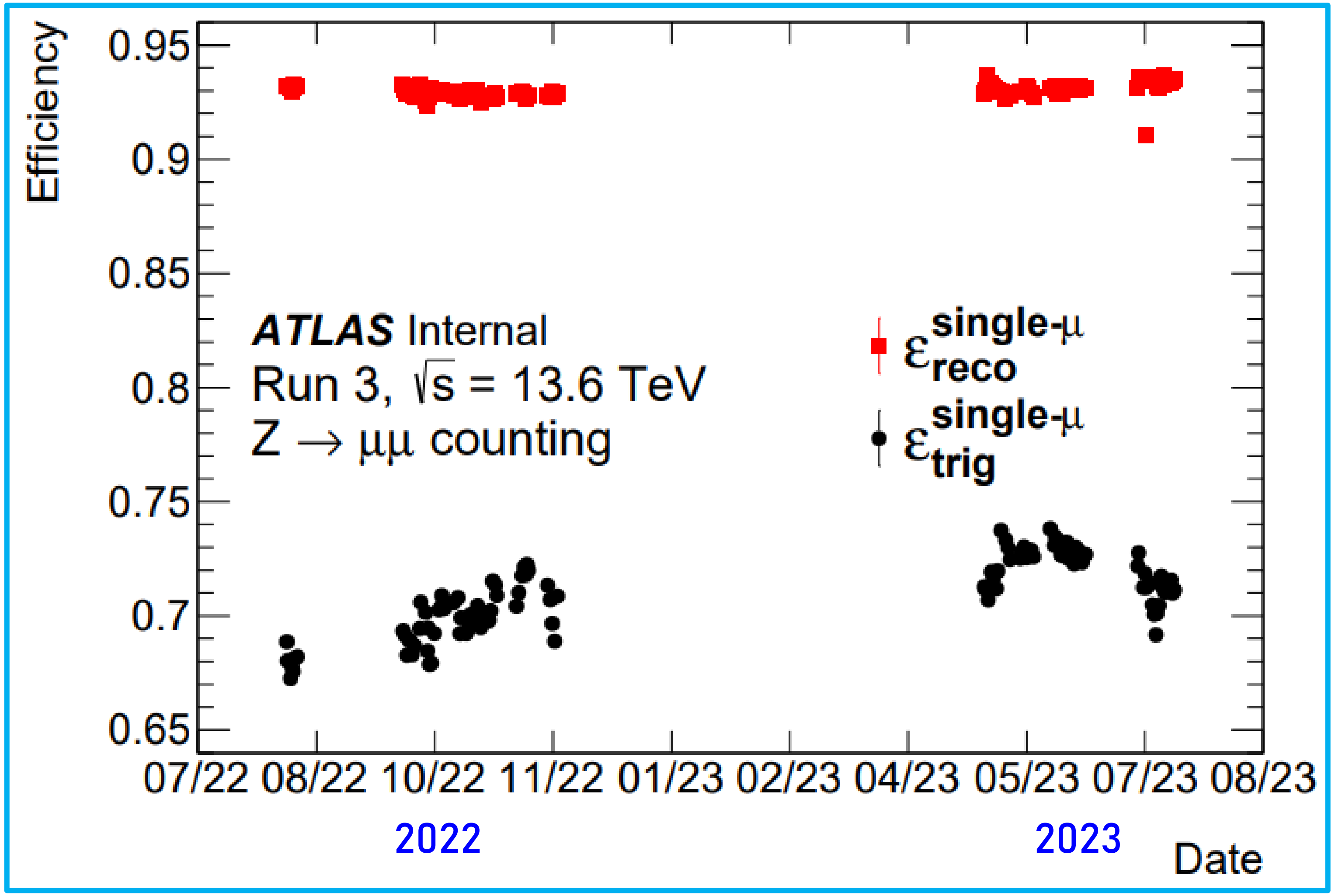


- Tag-and-Probe Failed Pairs :



Z-Counting – Data-Driven Efficiency

$$\varepsilon^{T\&P}_{Z\rightarrow l^+l^-} = \left(1 - (1 - \varepsilon_{\text{trig, }1l})^2\right) \times (\varepsilon_{\text{reco, }1l})^2$$



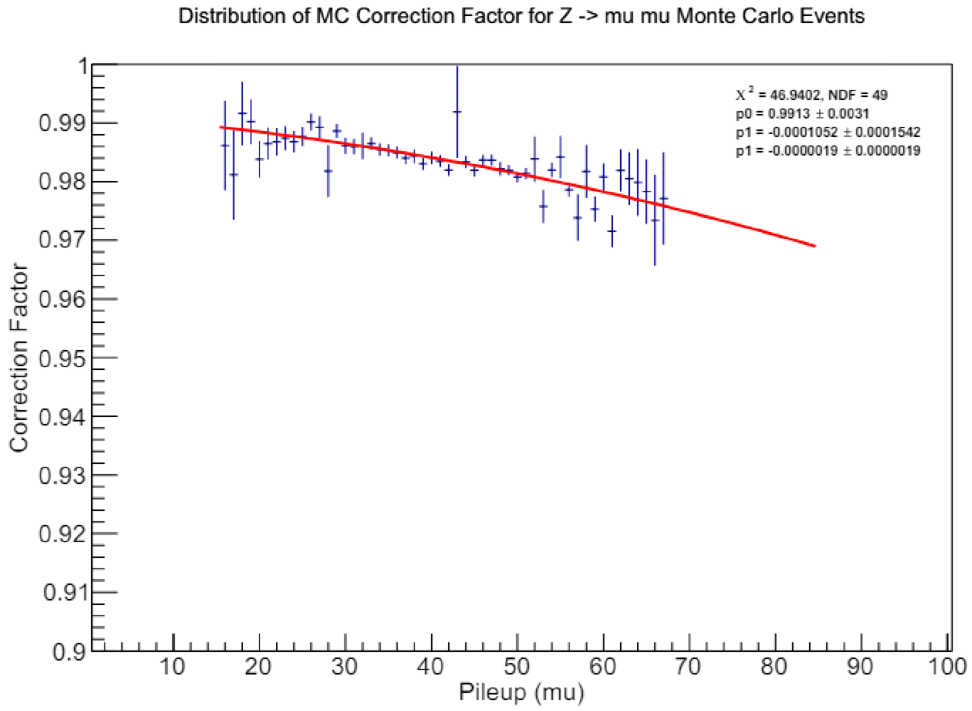
- Single-lepton reconstruction and trigger efficiencies are monitored on a short time basis (~ every 60s)
- Must be monitored in-situ due to small changes through time

Z-Counting – Monte Carlo Correction Factor

$$\mathcal{L}_Z(\Delta t) = \frac{N_{Z\to l^+l^-}(\Delta t) \times (1 - f_{bkg})}{F^{\mathrm{MC}}(\mu) \times A^{\mathrm{MC}} \times \epsilon^{T\&P}_{Z\to l^+l^-}(\Delta t) \times \sigma_{theory} \times \Delta t}$$

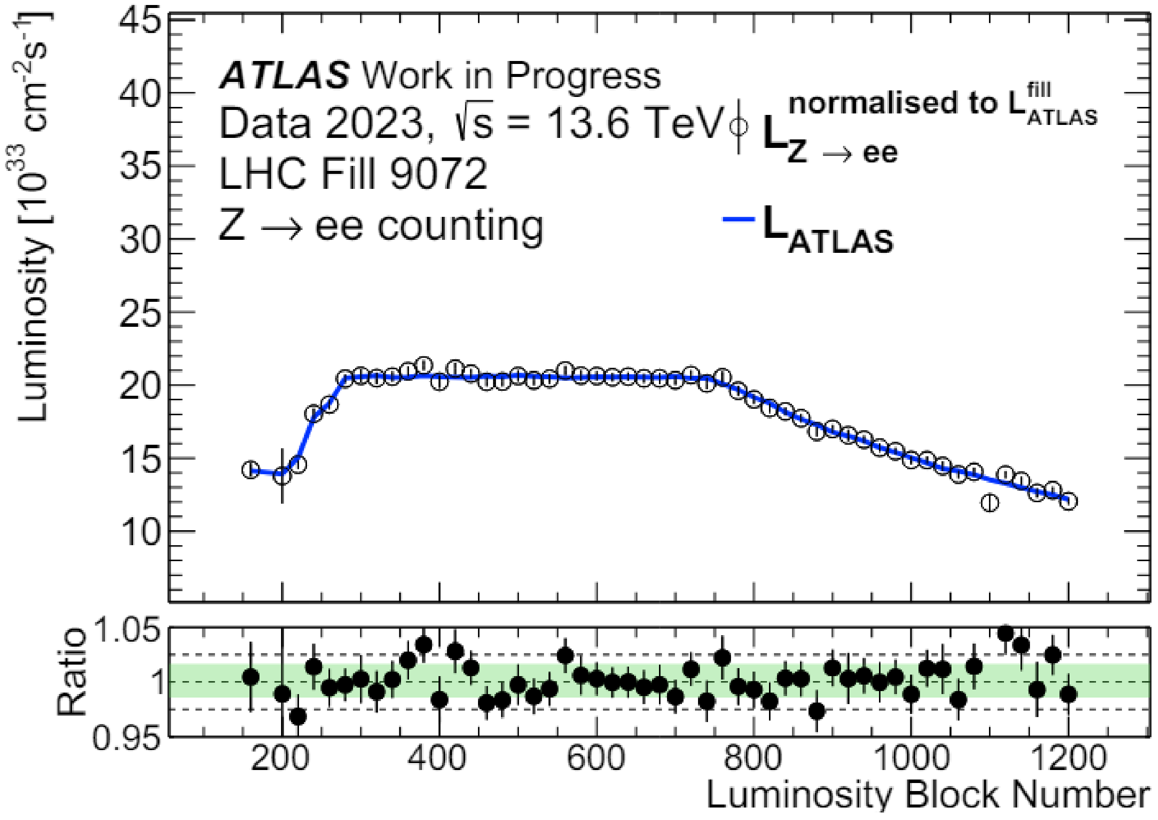
- Simulated ~150 million $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ events
- Event-level efficiency - calculated using the same method
- Fiducial acceptance – ratio of events detected within the fiducial region to the true number generated

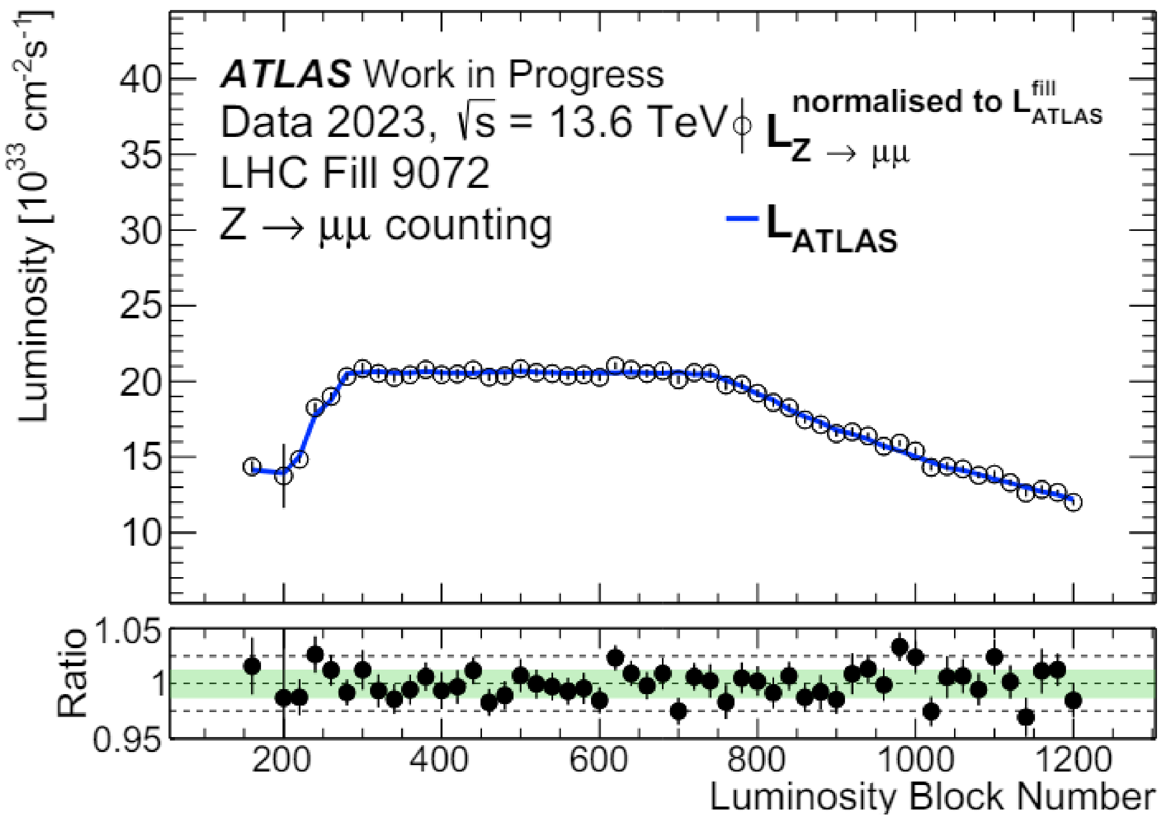
$$F^{\mathrm{MC}} = \frac{N^{\mathrm{reco,fiducial,MC}}_{Z\to l^+l^-}(\mu)}{N^{\mathrm{generated,MC}}_{Z\to l^+l^-}(\mu) \times A^{\mathrm{MC}}} \times \frac{1}{\varepsilon^{T\&P,MC}_{Z\to l^+l^-}(\mu)}$$



Z-Counting – Luminosity Measurements (example Fill)

- Luminosity measurements taken every luminosity block (~60 seconds)
- Points shown are weighted averages of groups of 20 LBs - used for display purposes only

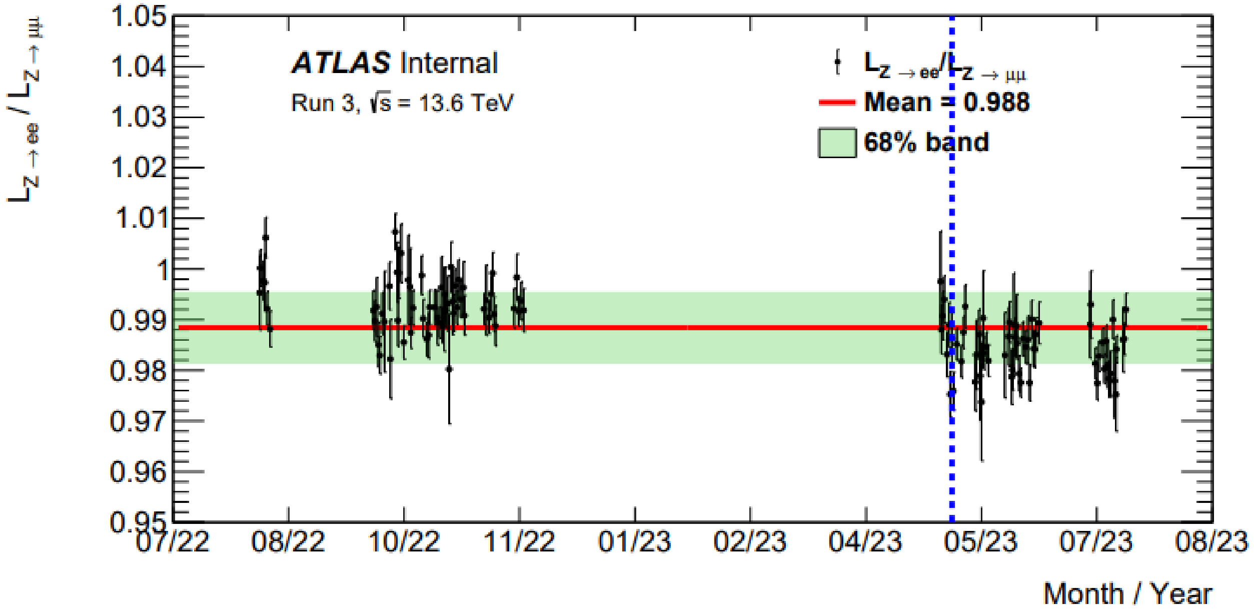




Z-Counting – Luminosity Measurements (Full Run 3)

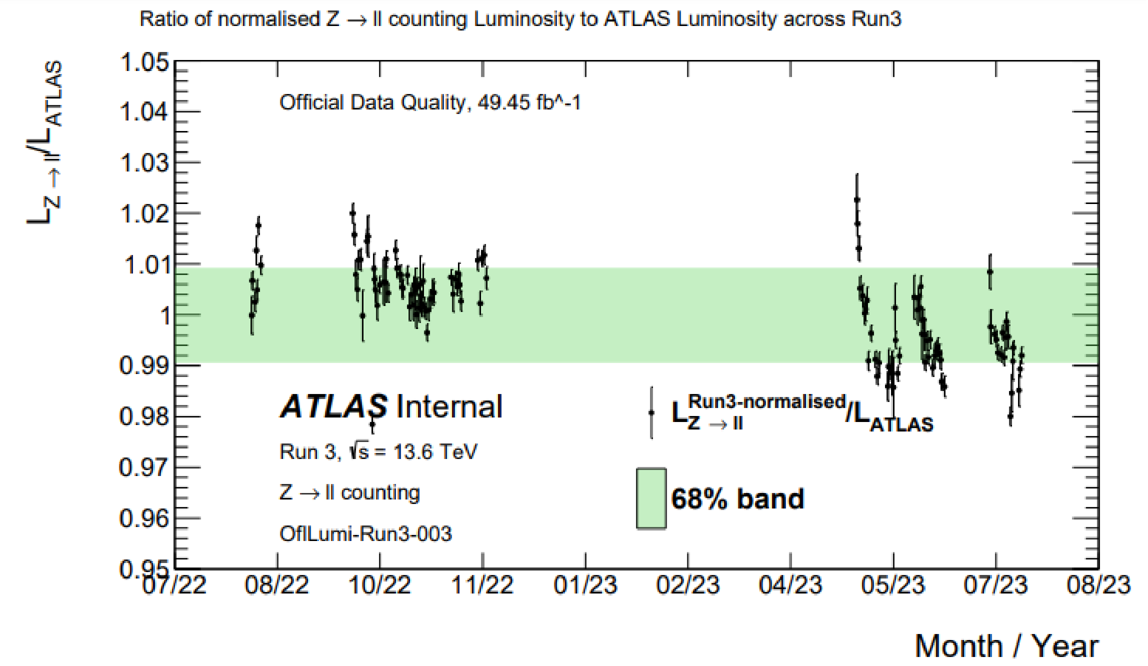
$\mathcal{L}_{e^+e^-}/\mathcal{L}_{\mu^+\mu^-}$ Ratio

- Provides a powerful cross-check for the individual methodologies of each channel (since efficiencies and acceptances are determined in different ways)



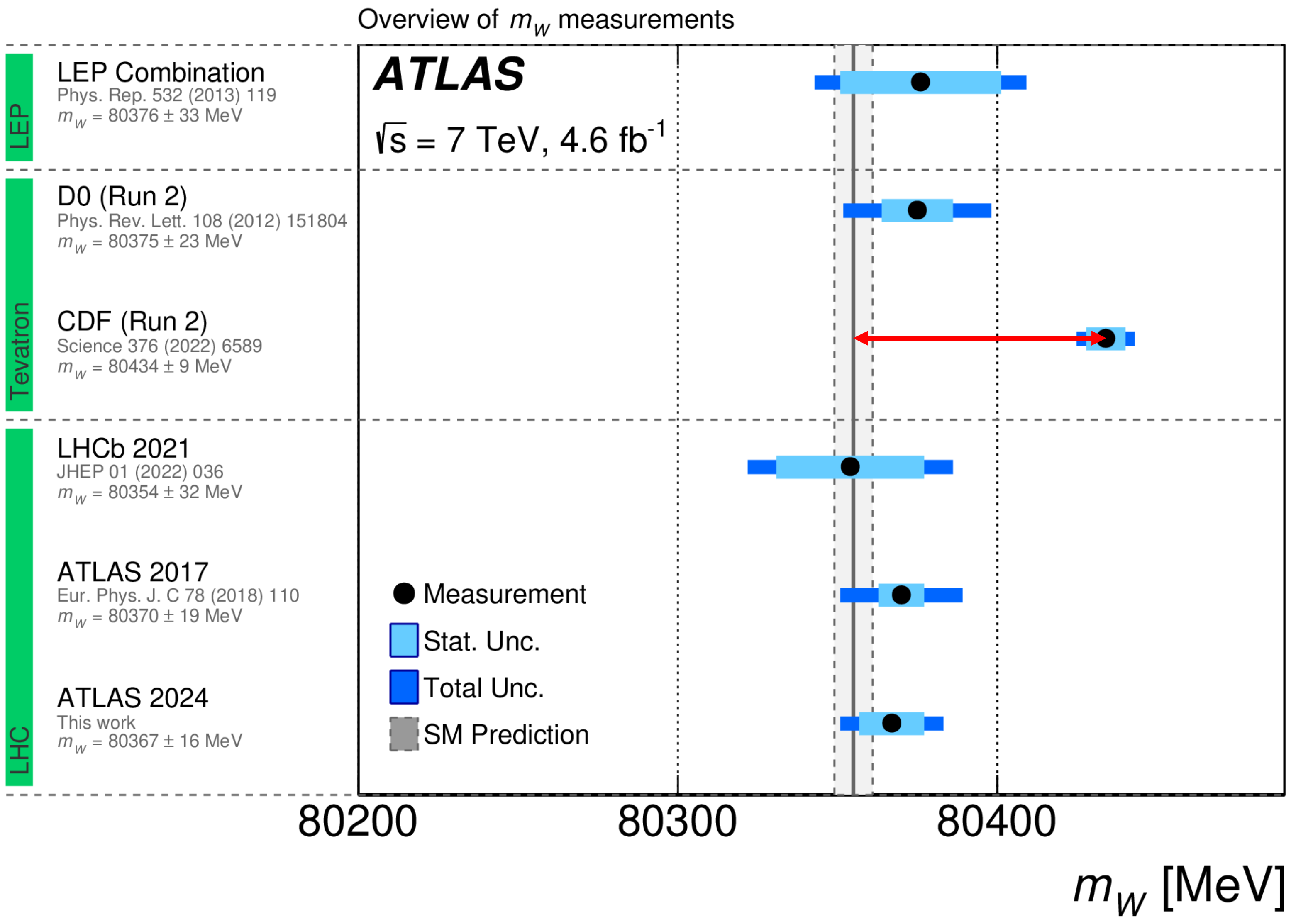
$\mathcal{L}_{l^+l^-}/\mathcal{L}_{ATLAS}$ Ratio

- Gives a direct comparison of Z-counting luminosity to ATLAS preferred luminosity



- $\mathcal{L}_{e^+e^-}/\mathcal{L}_{\mu^+\mu^-}$ ratio close to 1 – methodologies are under control at 1% level
- $\mathcal{L}_{l^+l^-}/\mathcal{L}_{ATLAS}$ ratio shows a spread of <1% across 2022/23 – comparable to Run 2 yearly calibration uncertainty

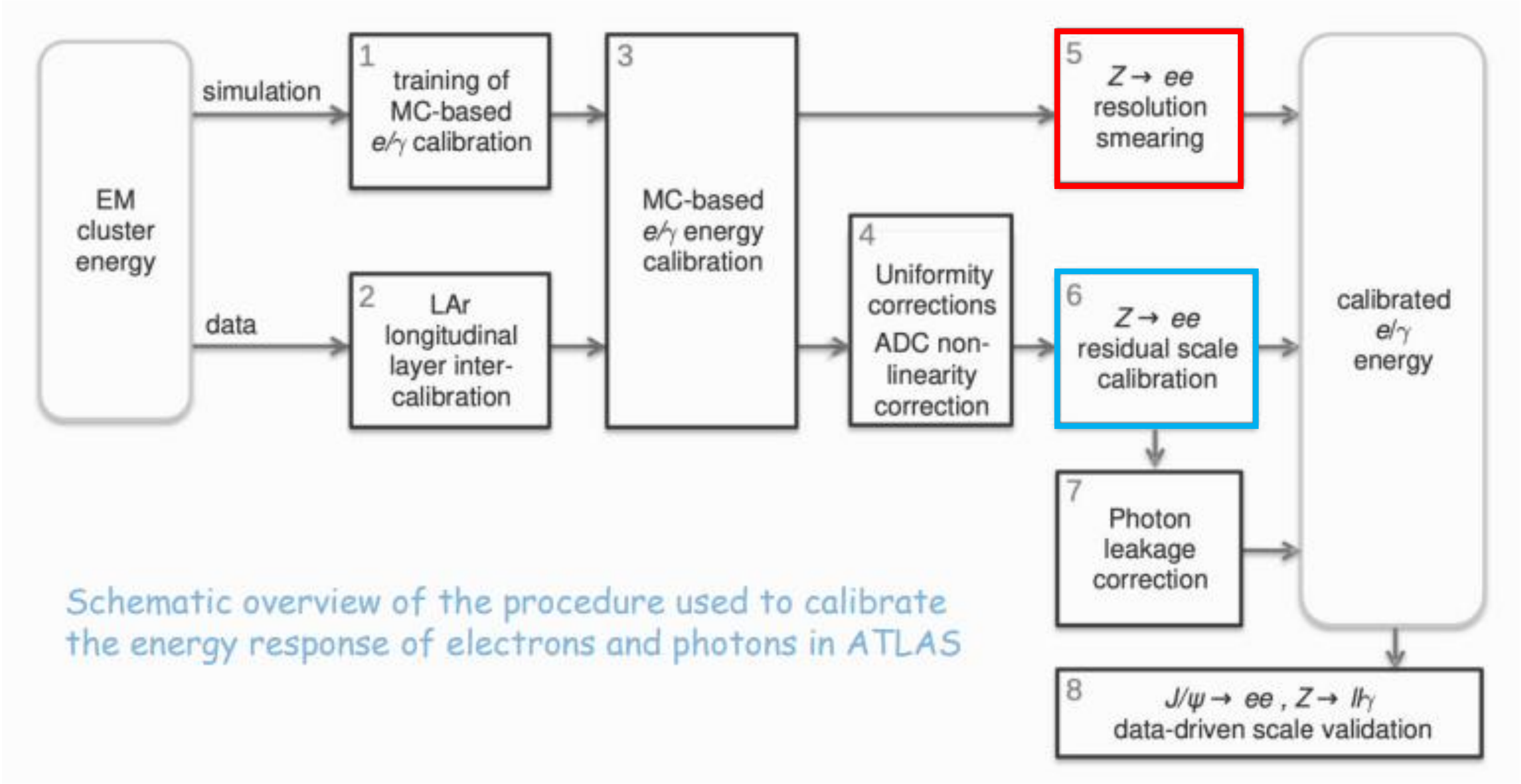
W Mass – Main Thesis Project



- My work so far: Electron energy calibration – precise m_W measurement requires calibration of EM calorimeter response

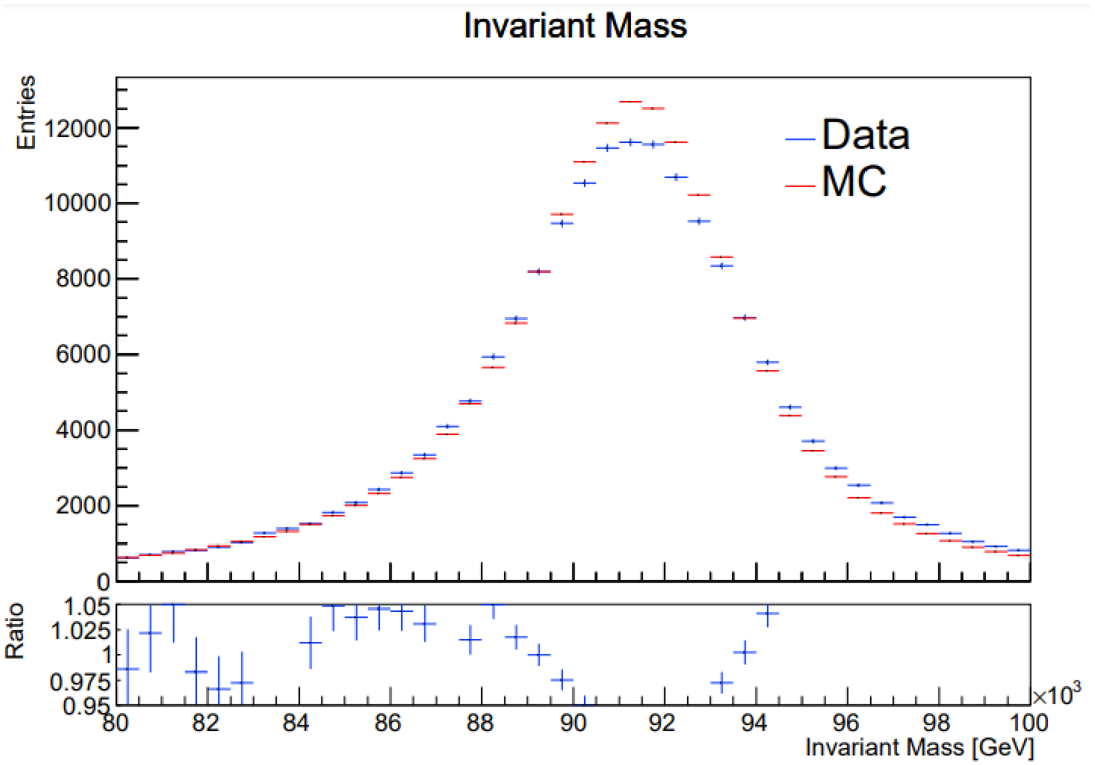
- Using special low-pileup (μ < 2) runs from Run 2 at 5 and 13 TeV – aiming for similar ($\delta m_W \sim$ 15 MeV) uncertainty

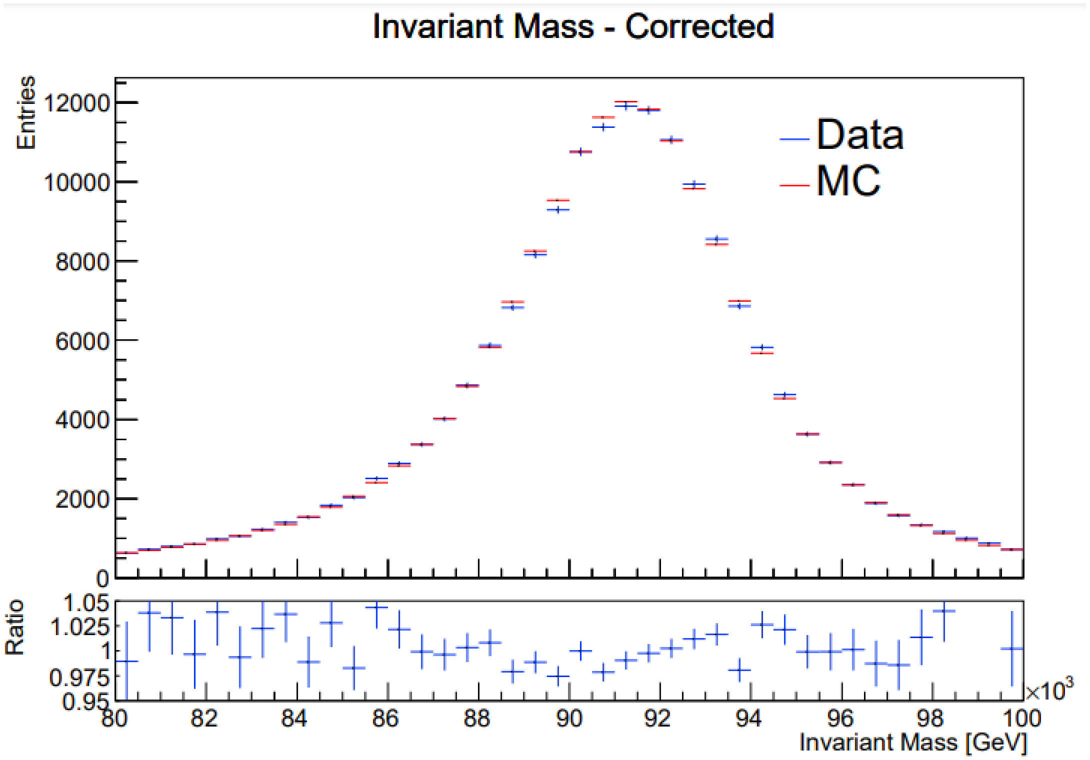
Electron Calibration



- Calibration is performed using low pileup Z mass resonance data at 5 and 13 TeV:
  - Gaussian Smearing, c (constant term): $$\left(\frac{\sigma(E)}{E}\right)^{data} = \left(\frac{\sigma(E)}{E}\right)^{MC} \oplus C(\eta^{calo})$$
  - Energy Shift, α (scale factor): $$E^{data} = E^{MC}\left(1 + \alpha(\eta^{calo})\right)$$

Electron Calibration





- Invariant mass distribution of Z $\rightarrow e^+e^-$ events before and after calibration
- Application of calibration coefficients brings data and MC lineshapes inline with each other
- Systematic uncertainties extracted from electron calibration results – consistent with total m_W target precision

Conclusion

Z–counting:

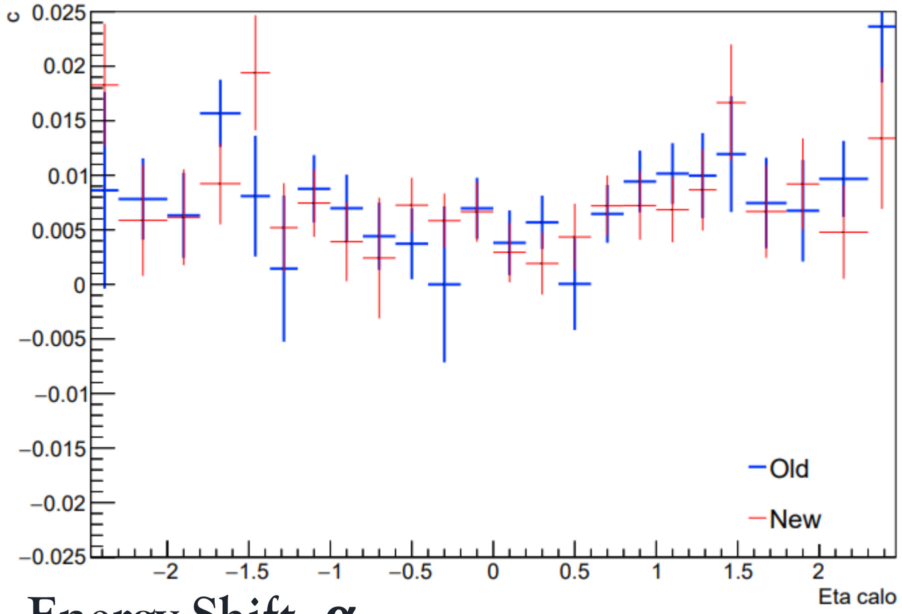
- Transferred methodology from Run 2 (13 TeV) to new ATLAS data at 13.6 TeV – full 2022 and 2023 datasets processed and analysed
- ATLAS author – continuing to work with luminosity team through 2024 data–taking

W Mass – Main thesis project:

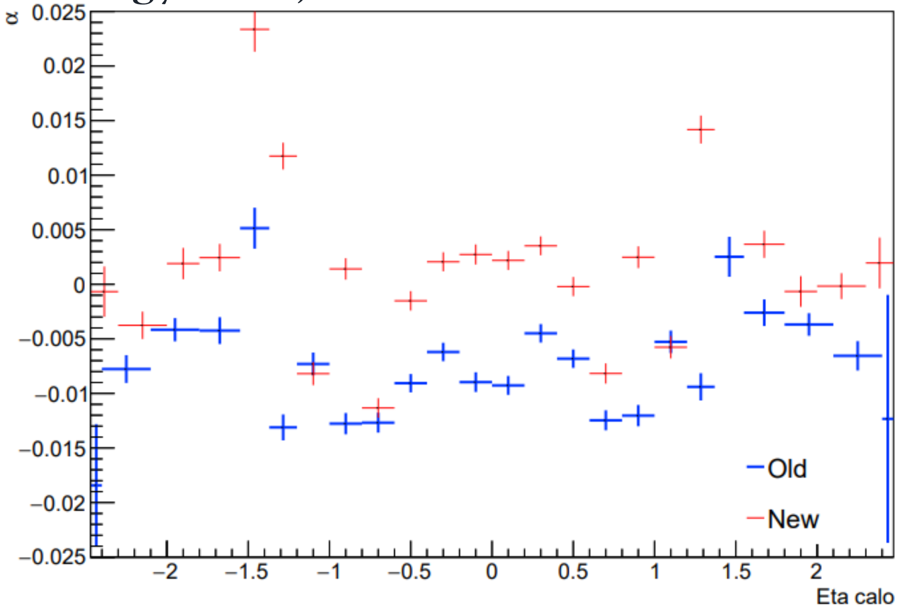
- Finished 1st W mass task: electron calibration for electromagnetic calorimeter response using low–mu dataset at 5 and 13 TeV – systematic uncertainties successfully extracted
- Further work will focus on reducing dominant systematic uncertainties resulting from W boson production modelling and knowledge of proton structure
- Currently working at DESY, Hamburg for 2 years

Backup – Electron Energy Calibration Coefficients

Gaussian Smearing: c



Energy Shift, α



- Calibration results (α and c) as a function of psuedorapidity
- Global upward shift in α is expected due to new E1/E2 correction (same effect is seen at high mu)
- Both results compared to previous results using old model

Backup – Electron Energy Systematics