Counting of Z Bosons
and
Electron Energy Calibration for W Mass

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Introduction – Z-counting overview

- Use the decays of Z bosons to electrons or muons to determine luminosity: $\mathcal{L}_Z = \frac{N_Z}{\sigma_Z}$

  Monte Carlo correction factors and data-driven efficiencies are applied

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

- Used to cross-check ATLAS preferred luminosity measurement: independent confirmation of dominant time-dependence of systematic uncertainty for Run 2 [1]

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

Pileup-dependent Monte Carlo Correction Factor:

- Accounts for non-closure between data-driven reconstruction and trigger efficiencies and the true Z-event level efficiency given by Monte Carlo simulation – dependent on number of simultaneous pp collisions (pileup)

Time-dependent Z-event-level Efficiency (10 – 60s “Luminosity Blocks”):

- Broken down into single-lepton reconstruction (tag-and-probe) and trigger efficiencies

Updates:

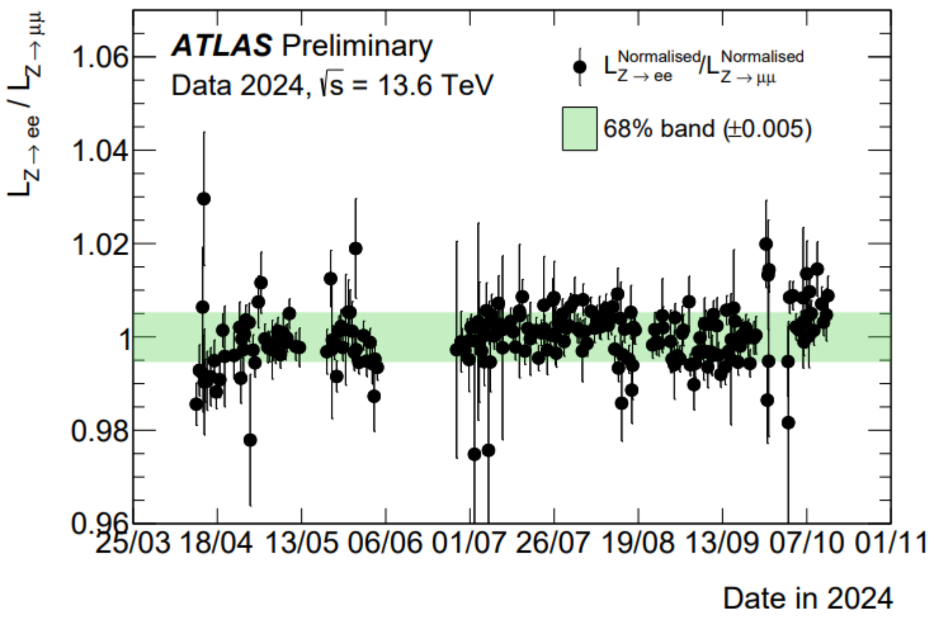
- Z-counting framework running within ~1 week of data-taking – updated and ready for 2025 data-taking (started recently)
- Selected plots from 2024 results made public for the Lumi Days workshop
- New: Updated Monte Carlo correction factors processed for all Run 3 data-taking periods so far (2022-24) – unique running conditions each year require new simulation samples

NEW – Public Z Counting Luminosity Plots 2024

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

Provides a powerful cross-check for the individual methodologies of each channel

Normalised to 1 for display purposes

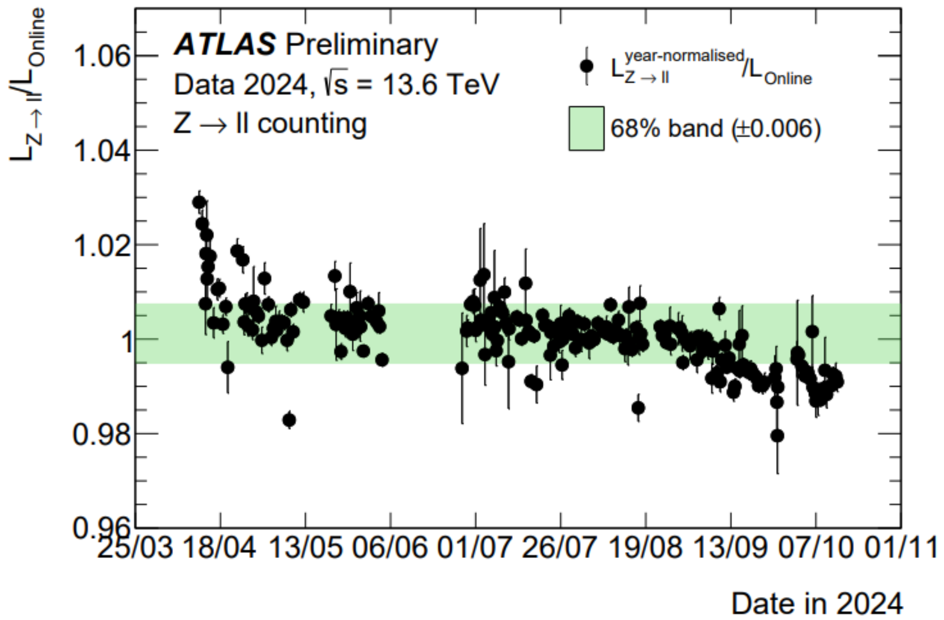


Time dependence shows good stability with new correction factors across 2024 data-taking period (0.5% spread)

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

Gives a direct comparison of Z-counting luminosity to ATLAS Online (not fully calibrated) luminosity.

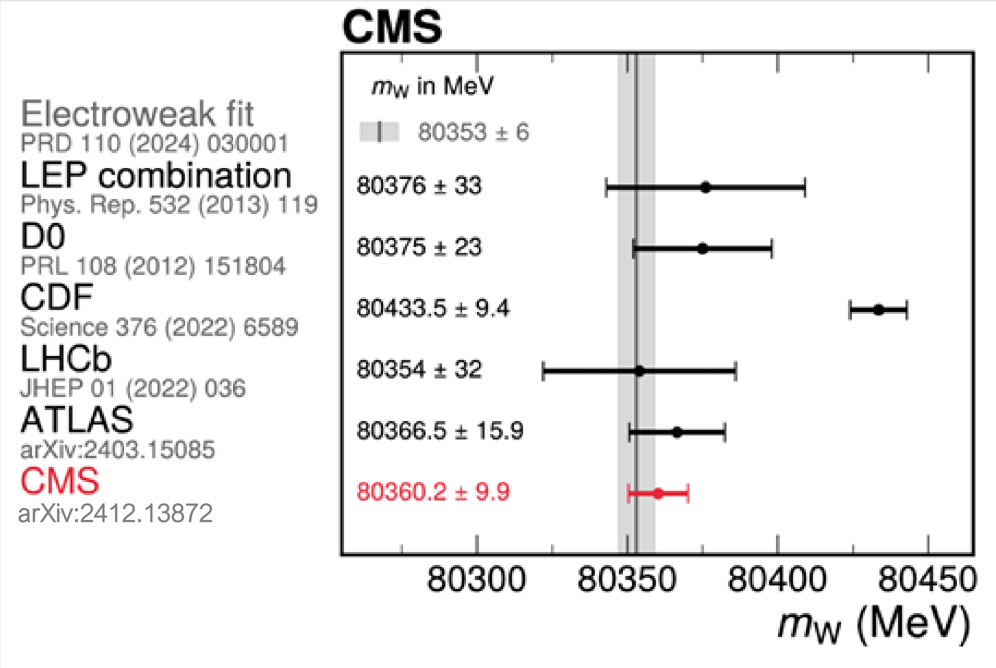
Able to get Z-counting results before full ATLAS Lumi calibration (Van der Meer scan) is complete



Shows good stability with new correction factors across full 2024 data-taking period (0.6% spread)

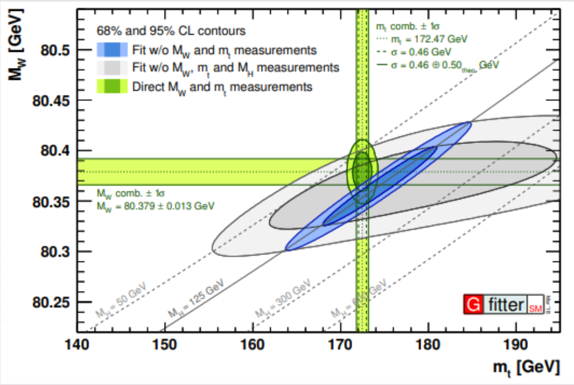
Introduction – Electron Calibration for mW

- **Main PhD analysis** – W boson mass measurement using special dataset with dedicated running conditions with few simultaneous pp collisions (low-pileup: μ ~ 2) at 5 and 13 TeV
- Low-pileup trades lower luminosity/statistics for greater systematic precision



Vladimir Chekhovsky et al. High-precision measurement of the W boson mass with the CMS experiment at the LHC. 12 2024.

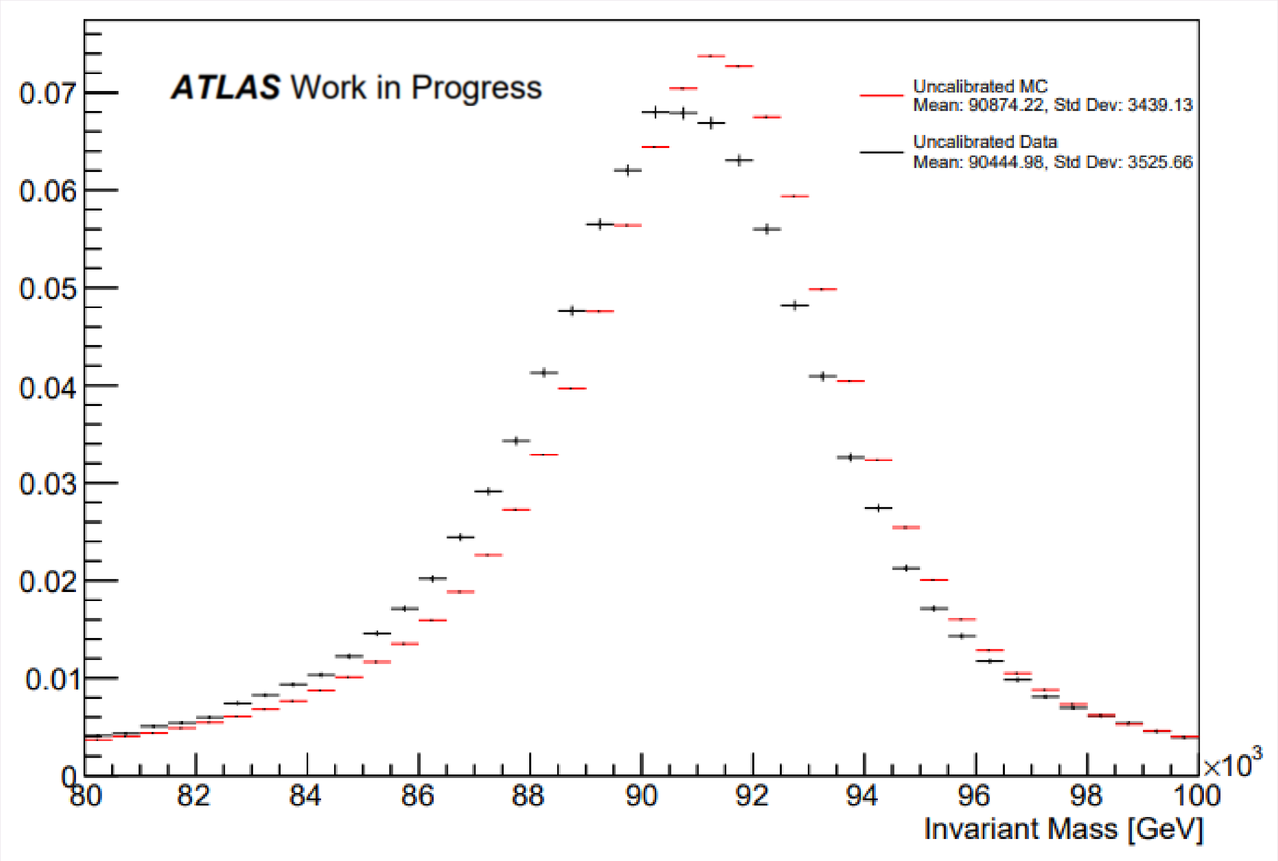
- W mass is vital to understanding the SM due to its interrelation to other fundamental SM parameters. Large number of W bosons plus very precise theoretical prediction allows probing of new physics on 1/10000 level



- W boson events detected through leptonic final state: $pp \to W \to \ell\nu$ due to clean experimental signature – need to account for undetected mass from neutrino using hadronic recoil
- ATLAS can measure electrons and muons (CMS only measures muons) at the same time with similar precision – electrons are more challenging to calibrate at the needed precision
- Electron energy calibration is one of the dominant sources of uncertainties for mW – main component of which comes as a result of data/MC discrepancy

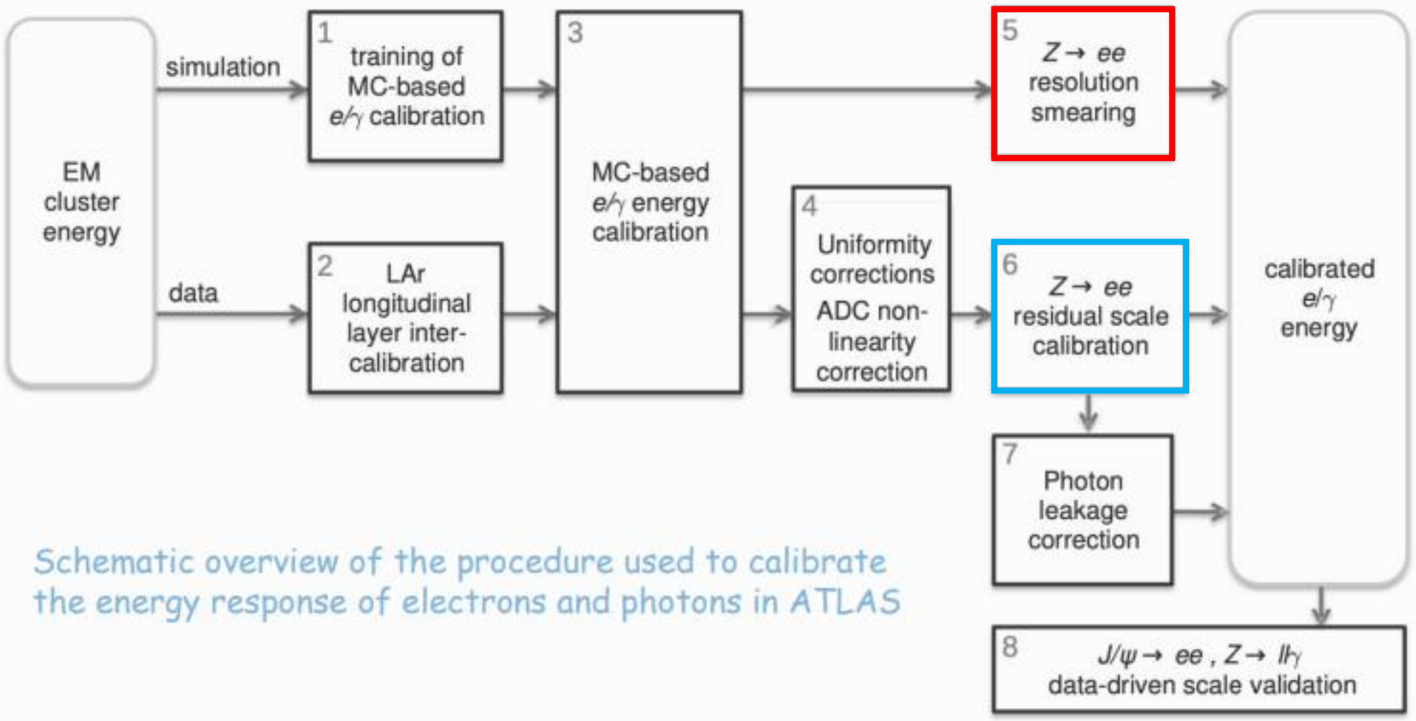
Electron Energy Calibration:
Data - MC agreement: 13 TeV low-mu data (before final calibration)

- In-situ electron energy calibration is performed using low pileup Z → ee mass peak data at 5 and 13 TeV
- Data and MC clearly not in agreement before final calibration process takes place



In-situ Electron Calibration Overview

- Electron calibration procedure uses several steps to bring EM calorimeter response in data and MC in agreement
- Steps 5 & 6 make up In-situ electron calibration – extract energy shift and resolution smearing terms



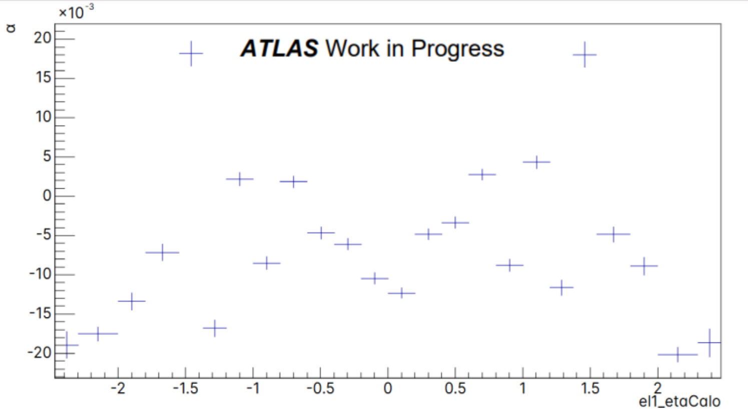
Schematic overview of the procedure used to calibrate the energy response of electrons and photons in ATLAS

In-situ Electron Energy Calibration:
Data - MC agreement: 13 TeV low-mu data (after calibration)

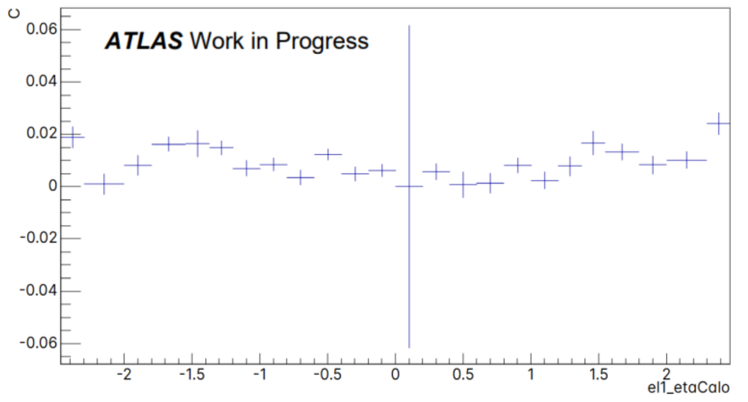
- Uncalibrated MC and data is put through in-situ calibration framework and energy shift and resolution smearing values (left) are extracted and applied
- Data and MC lineshapes brought in agreement with each other (below)

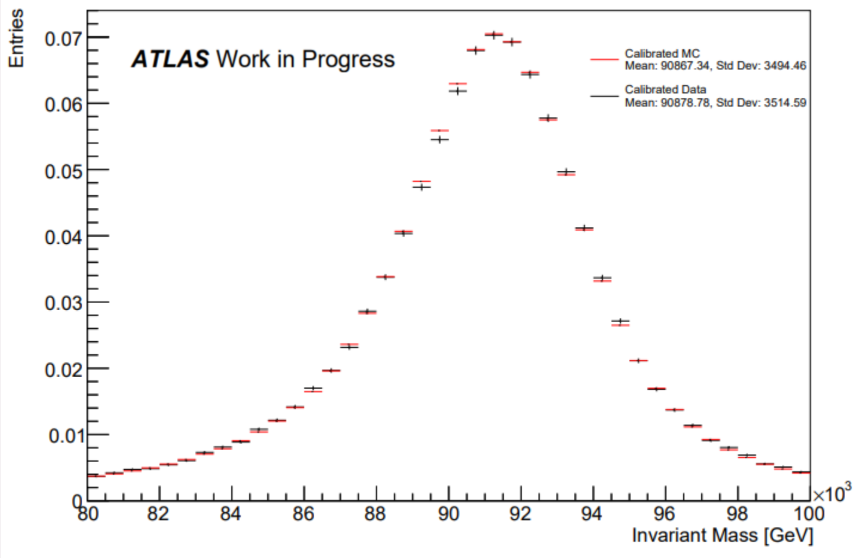
- Systematics for precision of Z peak to determine energy calibration extracted: vary different parameters and take the difference in the shifts of the Z peak mean (below)

Energy Shift:



Gaussian (Resolution) Smearing:





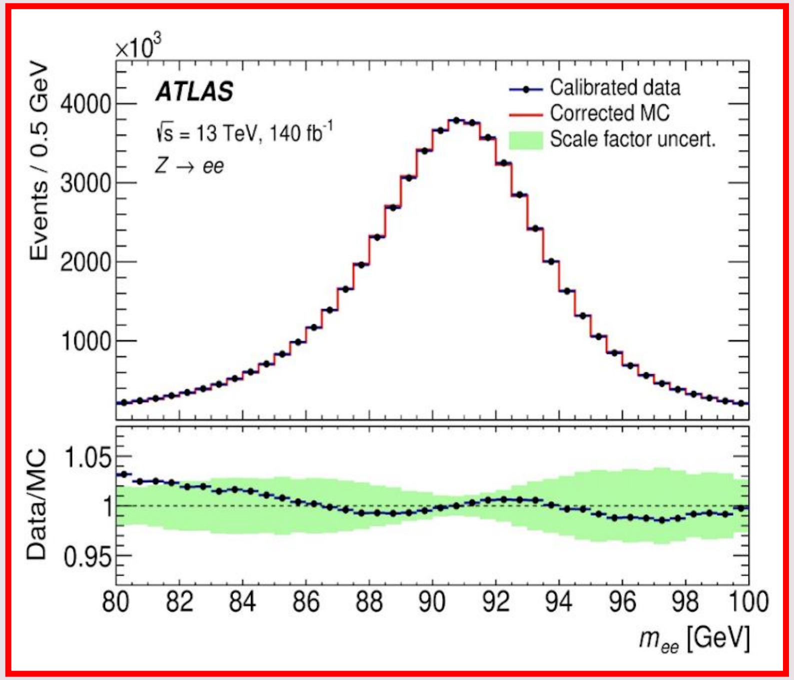
Source	Z Peak - Mean (MeV)	Z Peak - σ (MeV)
Nominal	90878.78	3514.59
Mass Window	90769.63	3512.17
Bremsstrahlung	90937.48	3451.17
Isolation	90868.13	3525.89
Tight ID	90938.02	3448.19

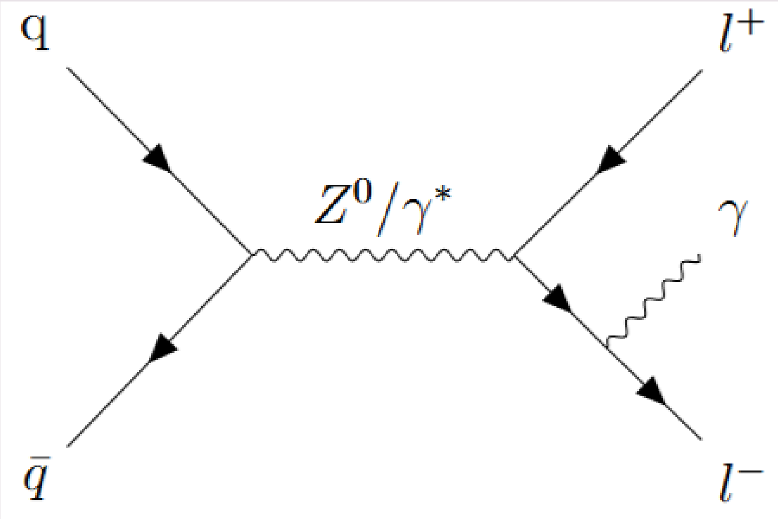
Motivation for QED FSR Studies

•Z → ee data show an excess of tails in invariant mass distributions, since Run1. This generates energy scale systematics – specifically in the mass window variation – that limit the overall calibration precision.

Using Run 2 high-pileup dataset – require high precision due to low stats in invariant mass tails

Having excluded more obvious causes, e.g. effects of material in front of the calorimeter in data, now investigating potential effects of QED FSR - modelled in simulation but not included in MVA training (used in step 3 of calibration)

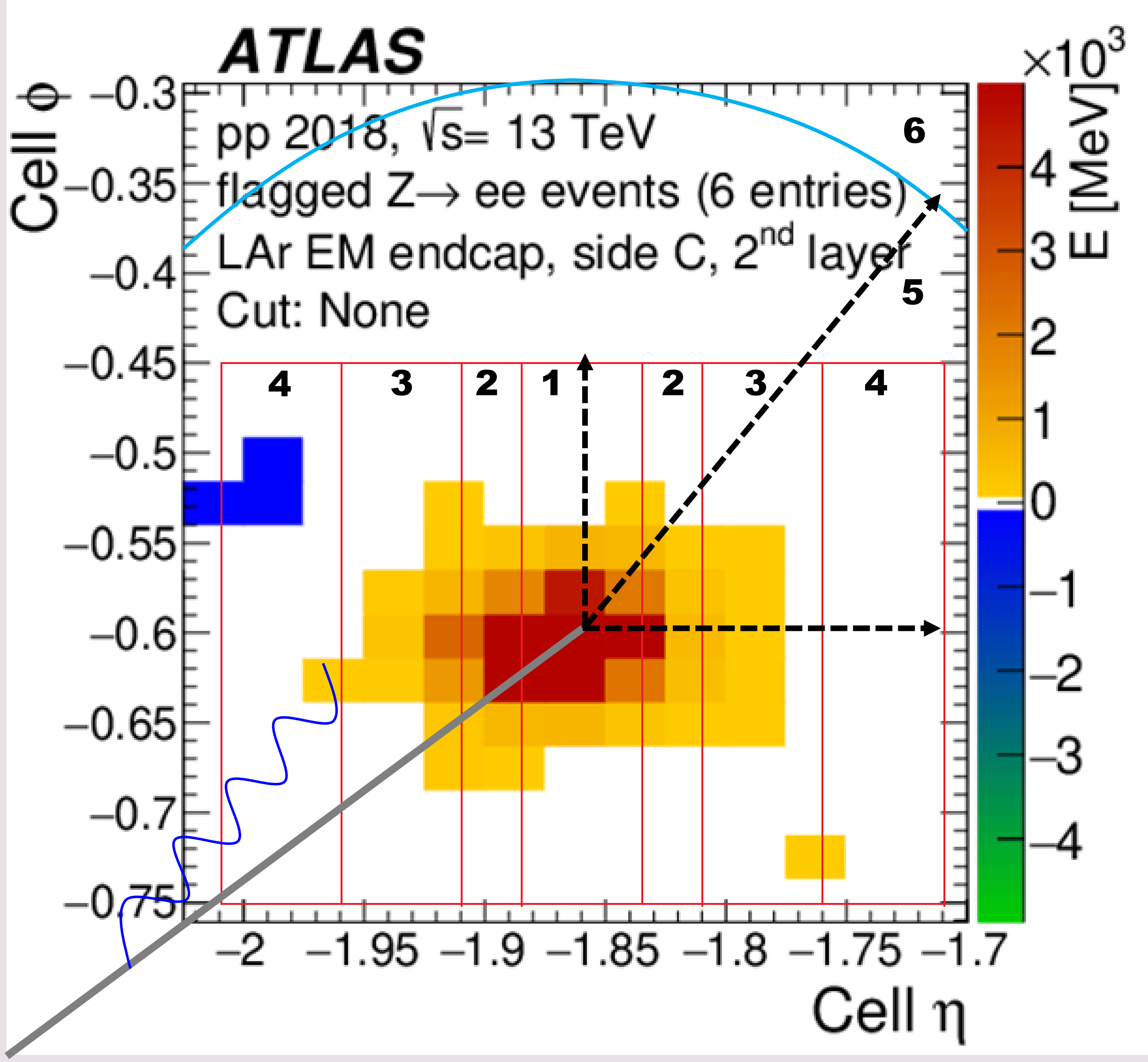




Categorising events based on QED FSR

Events are categorised to probe various kinematic configurations to see how they affect the data/MC discrepancies

Categorisation based on total FSR photon energy in regions of angular separation between FSR photons and matched electrons (see diagram)



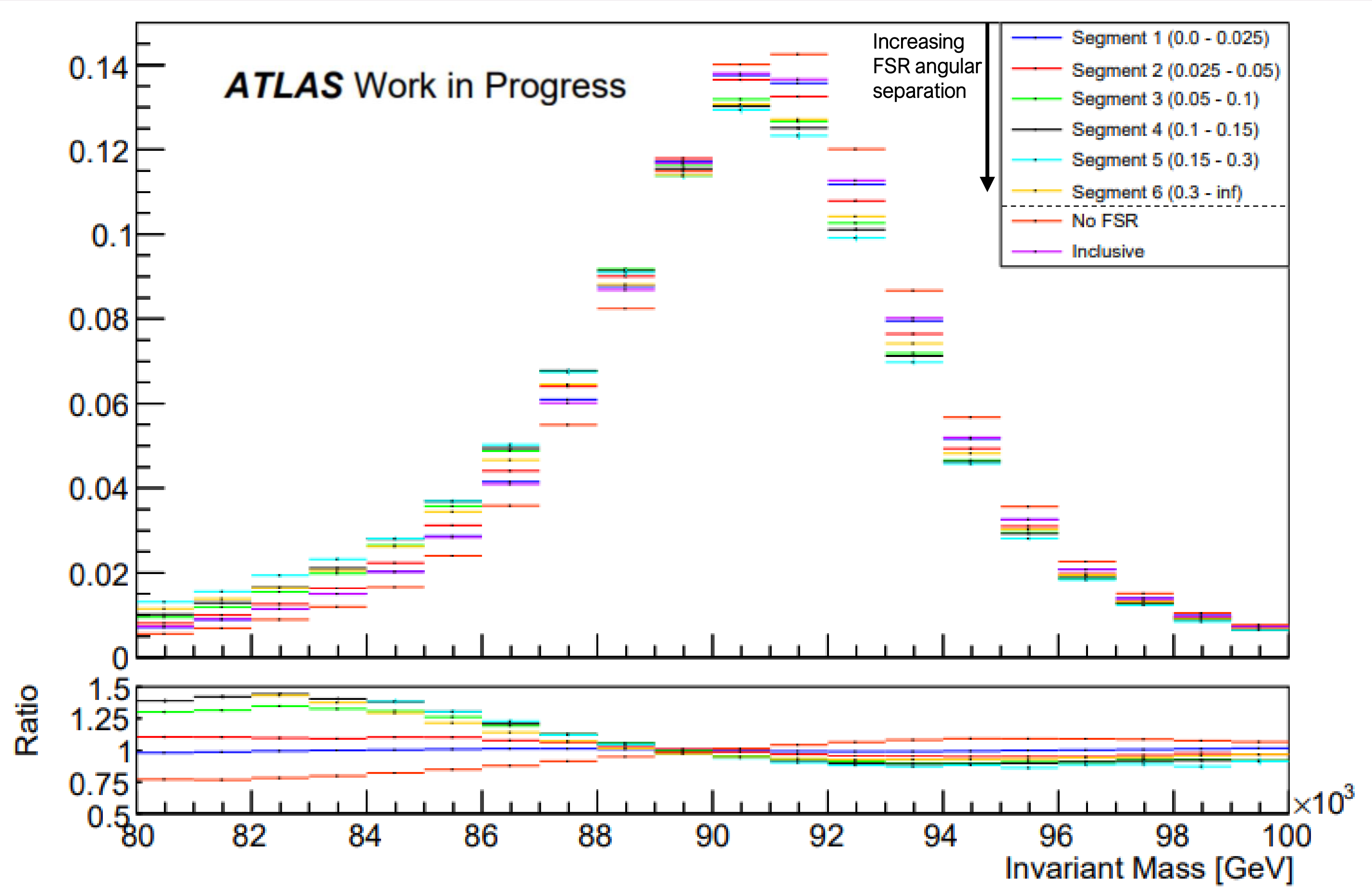
Invariant Mass

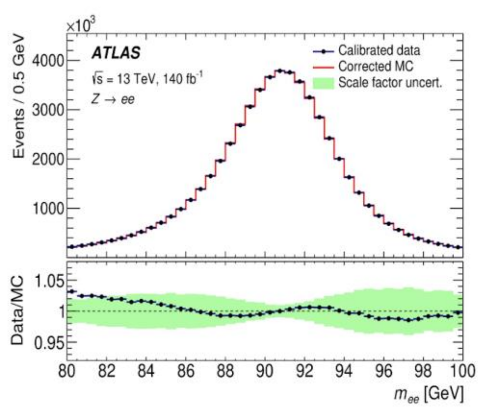
Studying invariant mass distributions in each category shows the effects of QED FSR

Lineshape is more distorted (with respect to inclusive) when QED FSR is further from electron

Events with FSR in segment 1 (closest to electron) shows best agreement to inclusive – expected as this is within the cluster in which electrons are selected

Resulting categorised distributions can be calibrated against the inclusive MC sample to see if tails are removed – currently working on final results





Conclusion and Outlook

Z Counting Luminosity Measurement:

- Z-counting framework running well – 2022–24 data processed with updated Monte Carlo correction factors
- Preliminary Z-counting 2024 results made public and shown at Lumi Days workshop

W Mass: In-situ Electron Energy Calibration:

- In-situ electron energy calibration framework running well - results and systematics extracted and presented regularly at ATLAS W Mass workshops
- FSR studies: Investigating effects of QED FSR on $Z \rightarrow ee$ invariant mass lineshape - currently working on final results

- Coming to the end of 2 years at DESY, Hamburg – returning to Liverpool in mid/late September and will soon start writing my thesis

Backup

Overview

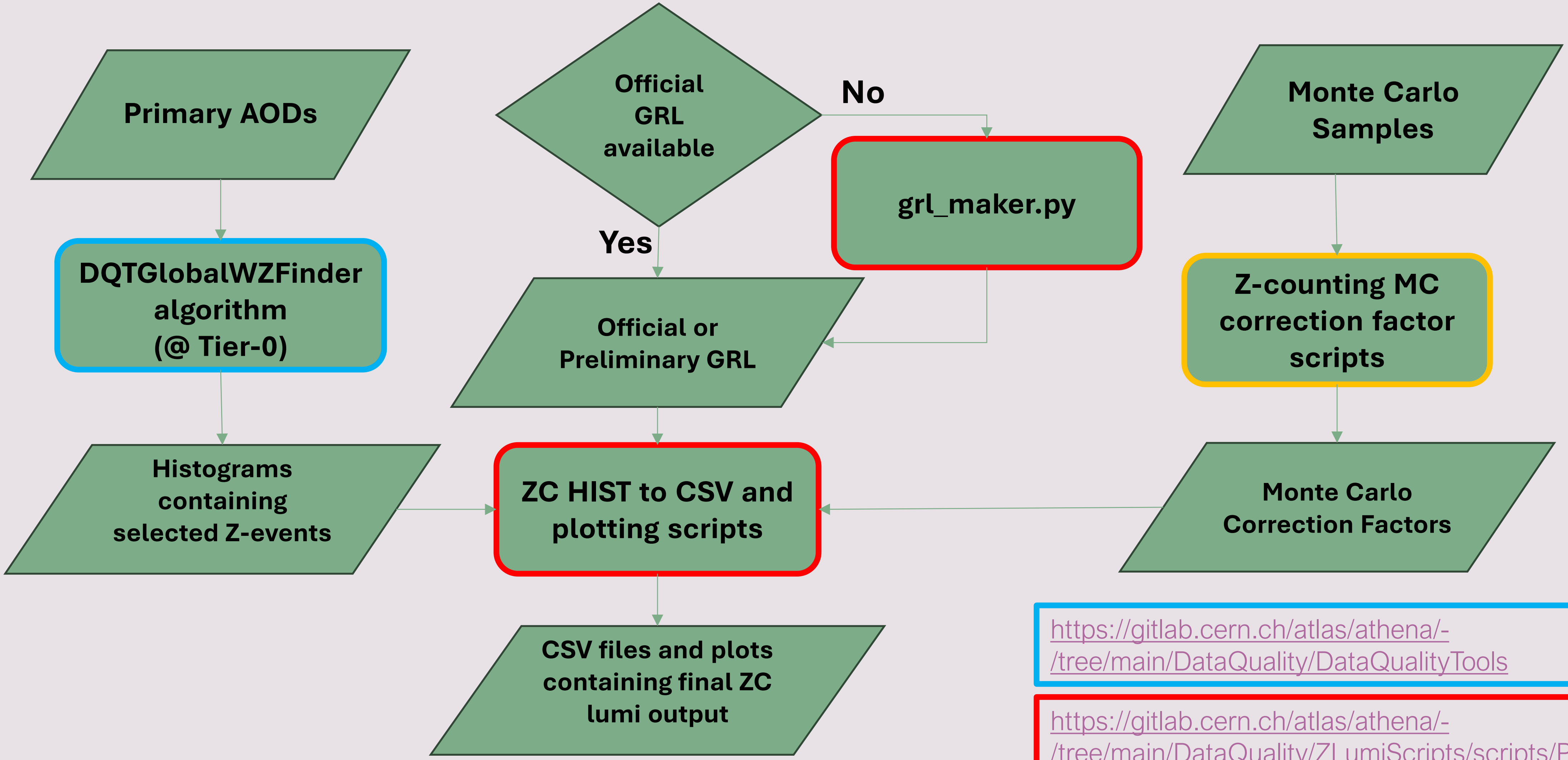
Z Counting Luminosity Measurement - 2025 Updates:

- Previous results for Run 3 had correction factors reflecting only 2022 data-taking conditions (MC23a campaign)
  NEW: Updated Monte Carlo correction factors determined using new MC samples reflecting data-taking conditions from individual years in Run 3
- Full Run 3 dataset processed with new correction factors
- 2024 results made public - shown at Lumi Days workshop

W Mass: In-situ Electron Energy Calibration:

- New precision electron energy calibration model for low pileup built and implemented (Athena 21.2.283)
- Validation plots produced – some discrepancies still to be investigated
- FSR studies (shown in previous talk):
  - $Z \rightarrow ee$ data (used in in-situ calibration) show an excess of tails in invariant mass distributions, since Run1
  - FSR mismodelling in MVA stage of calibration, most likely, cannot explain energy tails.
  - However including the effects of FSR photons in MVA training in the future might improve the resolution of the invariant mass spectra.
  - Results to be presented in E/Gamma meeting in late May/June

Z-counting Workflow



https://gitlab.cern.ch/atlas/athena/-/tree/main/DataQuality/DataQualityTools

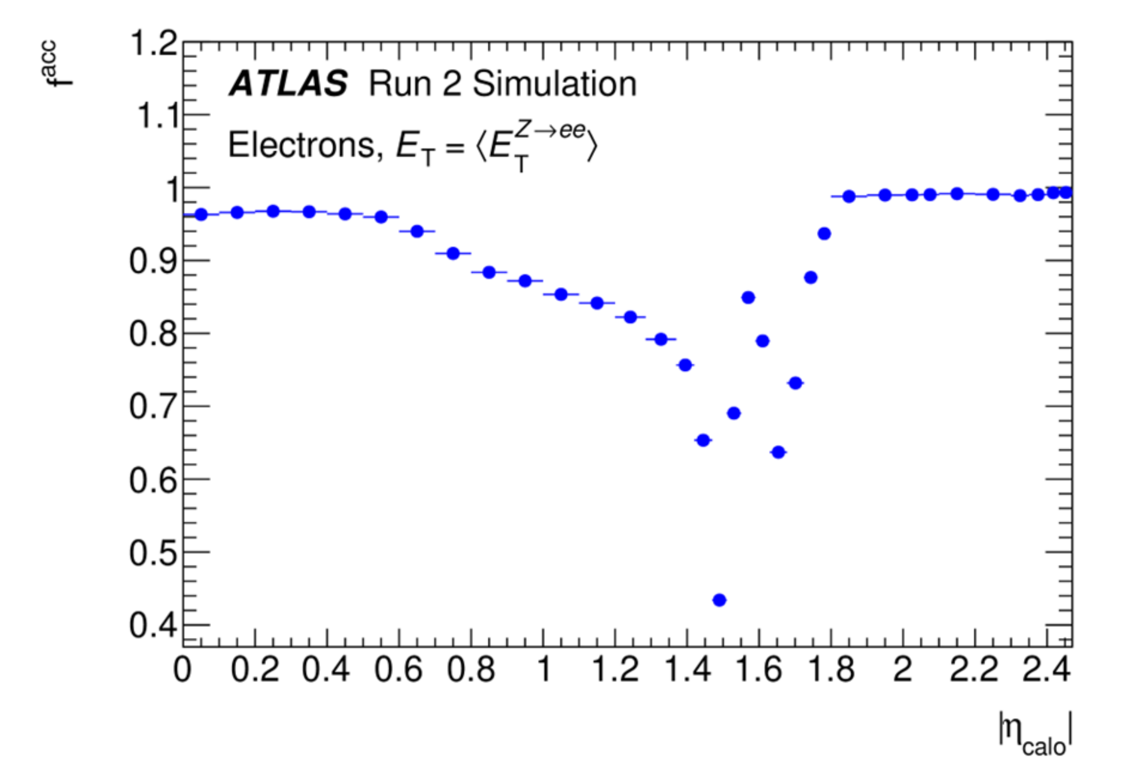
https://gitlab.cern.ch/atlas/athena/-/tree/main/DataQuality/ZLumiScripts/scripts/Pandas_scripts

https://gitlab.cern.ch/z-counting/monte-carlo

Conversion to accordion-level energy scale

- Electron-level energy scale is converted to accordion-level scale to improve energy linearity

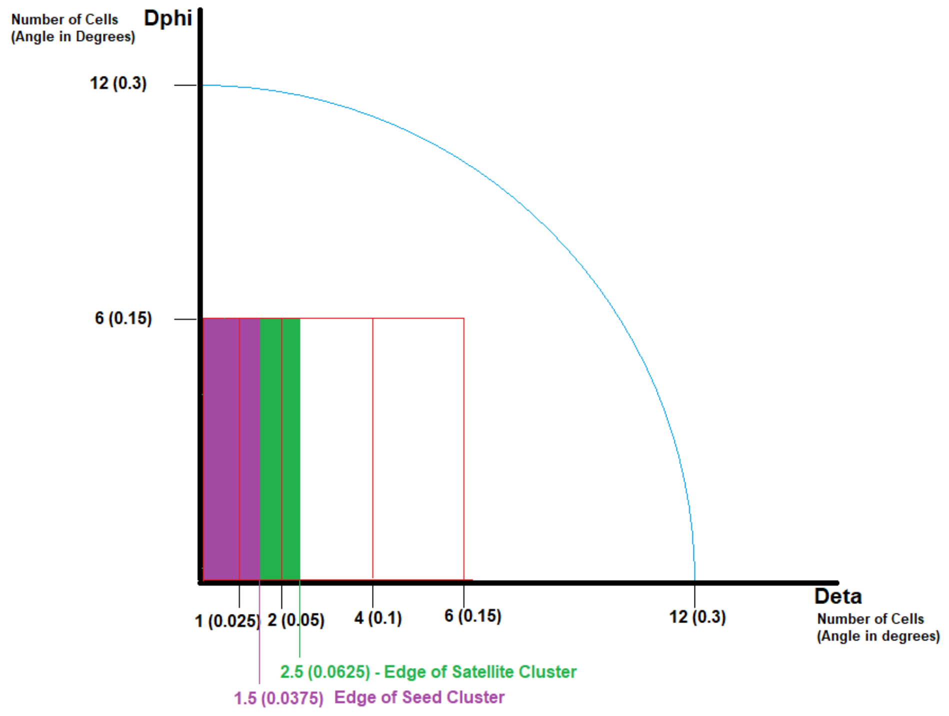
$$\alpha_{acc} = \alpha_{Zee} / \frac{dE_{tot}}{d\alpha_{acc}}$$



- dEtot/dαacc factor taken from high-mu assuming sensitivity is similar between both regimes
- Closure in-situ scale is determined to ensure accordion scale has expected effect

Categorising events based on QED FSR

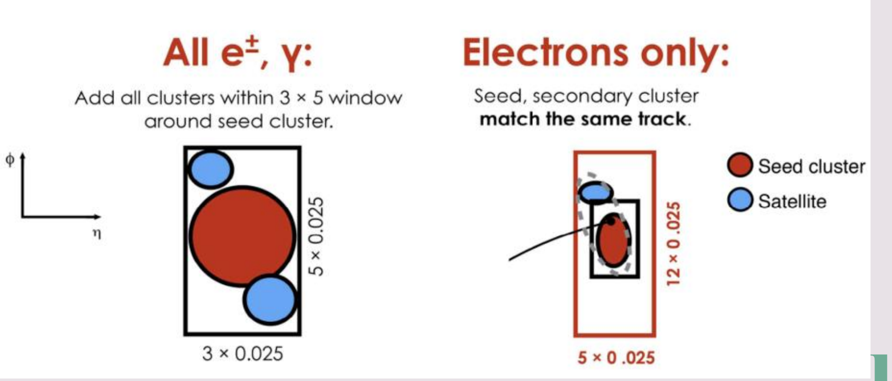
Events are categorised to probe various kinematic configurations to see how they affect the data/MC discrepancies



Categorise based on dR region containing highest total FSR pT:

- Match all FSR photons with either leading or subleading electron based on minimum dR – w.r.t. reco electron
- Calculate sum of FSR pT in each region (defined by segments in dEta, dPhi and dR, shown top right)
- Sort electrons accordingly by region with highest total FSR pT

Then investigate differences between various calorimeter and kinematic observables which are relevant to the MVA or in-situ calibration



NOTE: Electron trajectory bends in magnetic field (in phi direction only):

- dR chosen with respect to reco electron instead of truth
- FSR categories are more granular in dEta than dPhi – FSR emitted in phi direction ~ Bremsstrahlung