How to Extract the Weak Mixing Angle

using Full Run 2 ATLAS Experimental Data

Lukas Bayer
Göttingen, 01.04.2025

HELMHOLTZ

DESY.

The Weak Mixing Angle

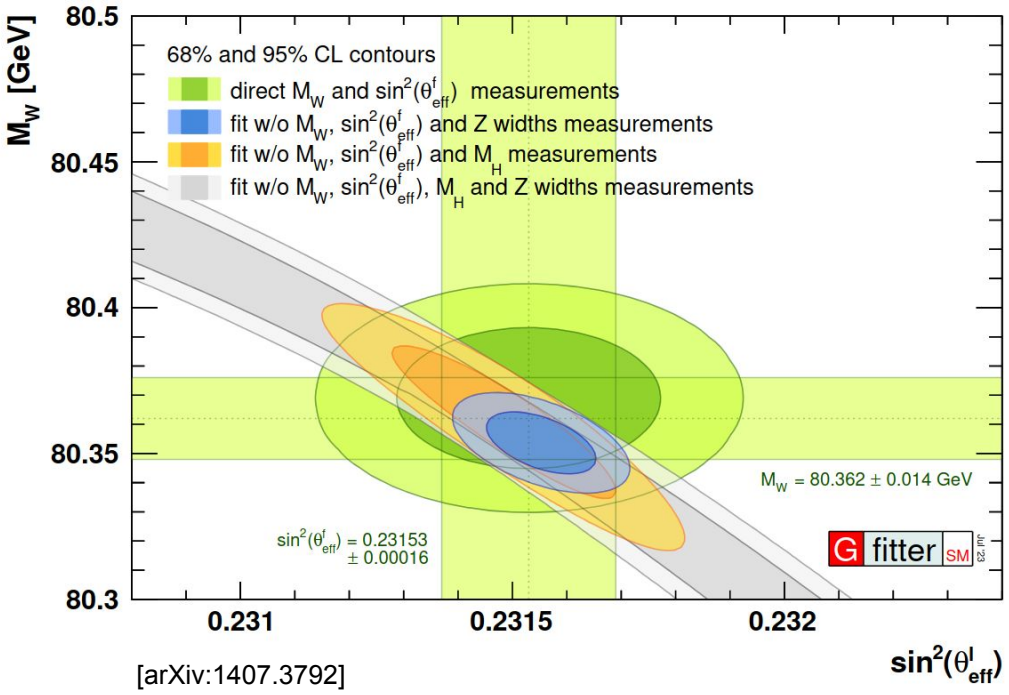
a.k.a. the Weinberg Angle

mixing of neutral $U(1)_Y$ and $SU(2)_L$ bosons to photon and Z boson

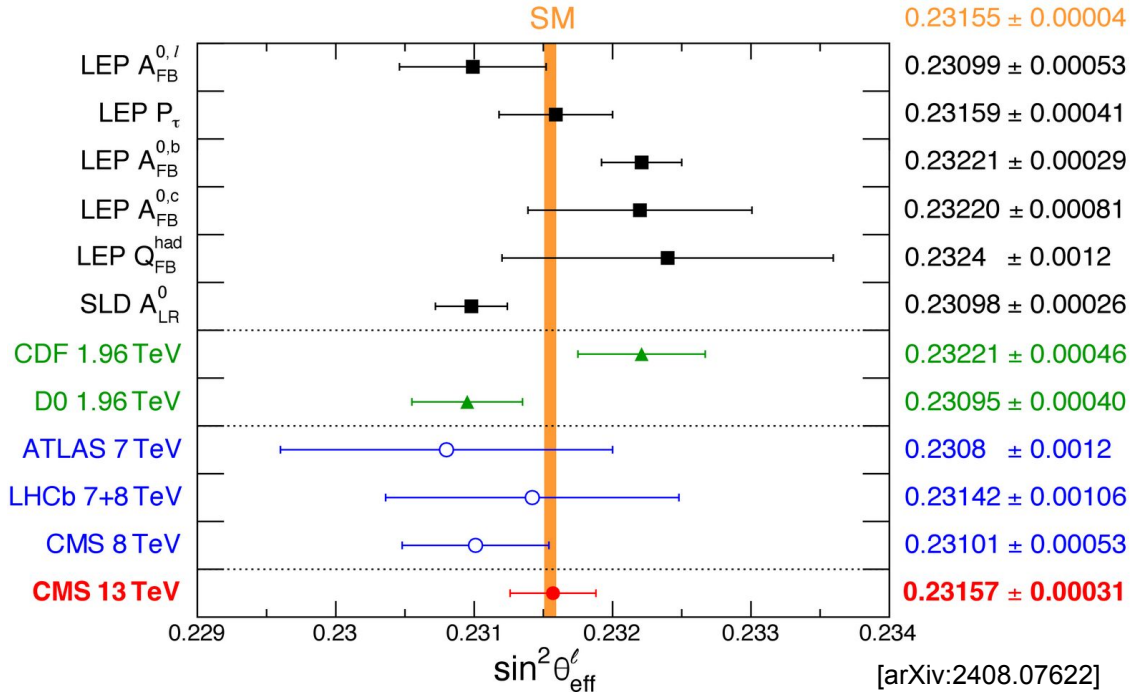
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

accounts for EW loop corrections

$$\sin^2_{\text{eff}}\,\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)\kappa$$



[arXiv:1407.3792]

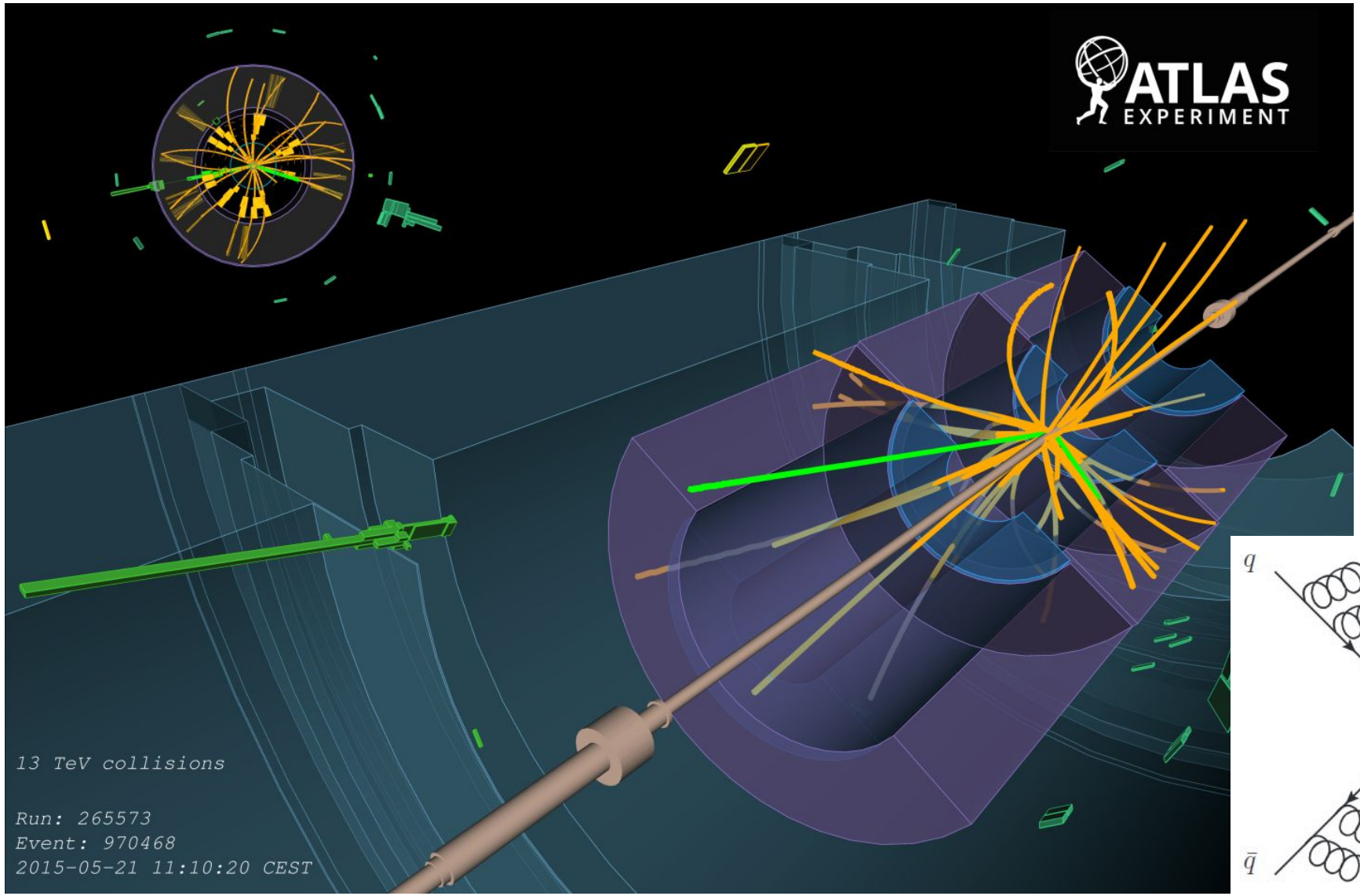


[arXiv:2408.07622]

- important SM parameter with more precise theory & indirect fit than direct measurements → need to improve!
- measurable (for example) via parity violation in Drell-Yan process!

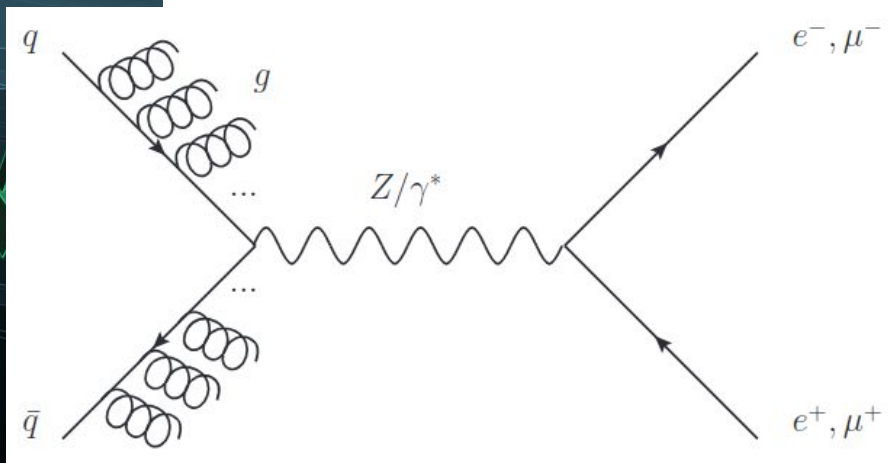
The Drell-Yan Process

in the ATLAS Detector



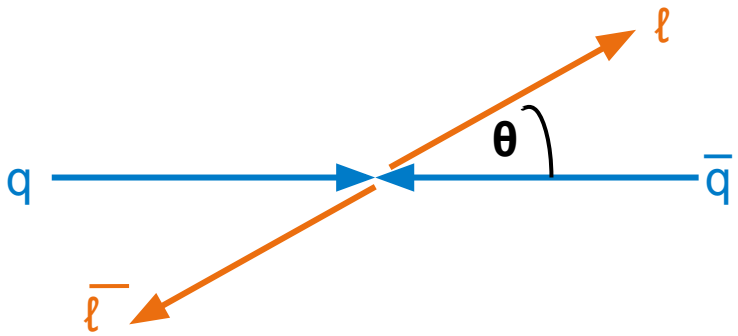
Full Run2:
140 fb^{-1} of pp collisions

After event selection:
~$85 \cdot 10^6$ $Z \rightarrow ee$ candidates



Forward-Backward Asymmetry

in the Drell-Yan Process



- parity violation in weak couplings
  → Z boson couples more to left-handed particles
  → Z polarization
  → Forward-Backward Asymmetry (A_{FB})

$$A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

- at leading order:

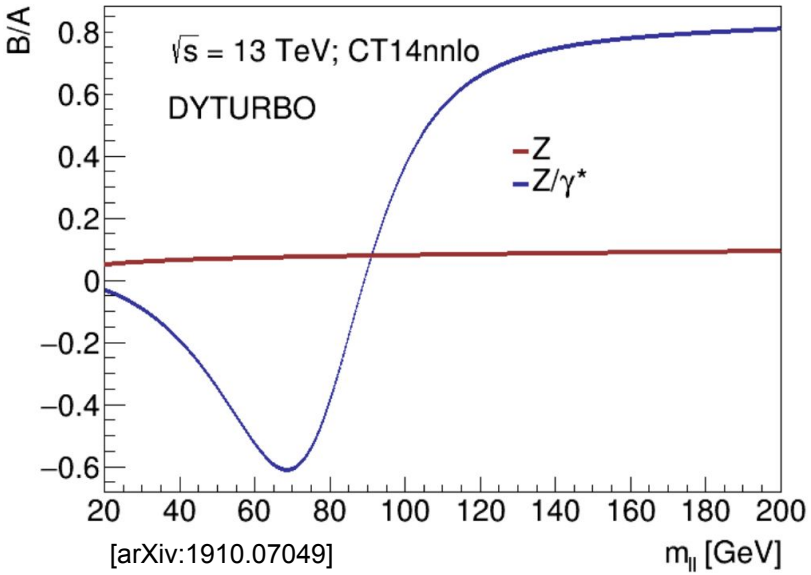
$$\frac{d\sigma}{d(\cos\theta)} = \frac{\alpha^2}{4s}\left[\frac{3}{8}A(1+\cos^2\theta) + B\cos\theta\right]$$

$$B = -4Q_l g_A^q g_A^l \chi_1 + 8 g_A^q g_V^q g_A^l g_V^l \chi_2$$

Z/γ interference

depend on WMA

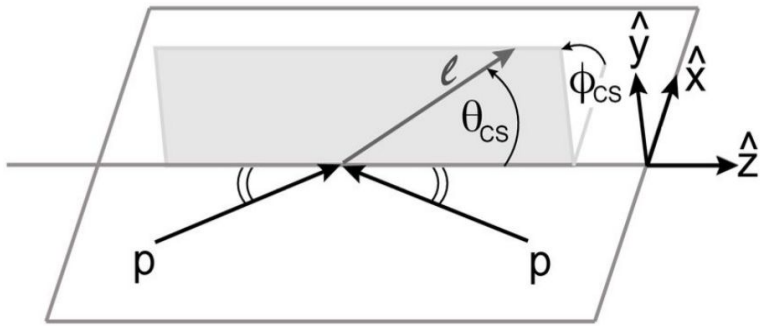
Z resonance



Forward-Backward Asymmetry

in the Drell-Yan Process

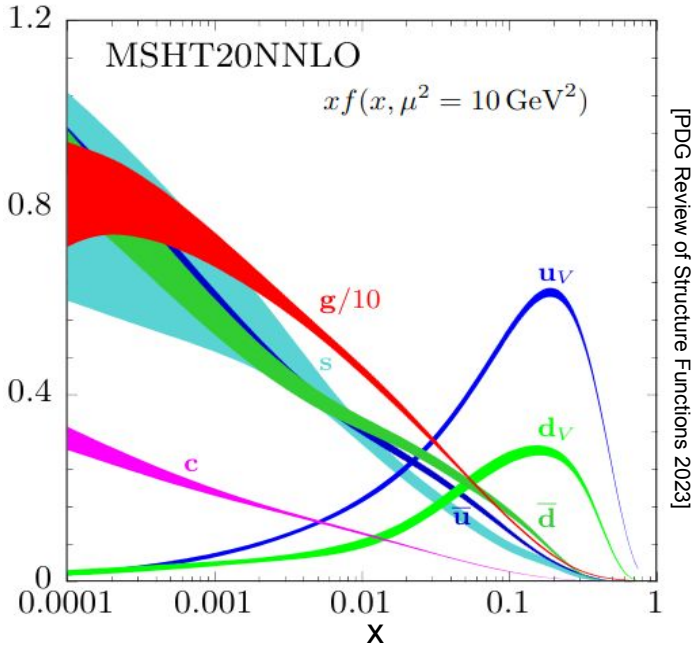
- A_{FB} is not observable in lab frame
  - symmetric pp initial state → quark direction unknown
- resolved in Collins-Soper frame!
  - special rest-frame of Z boson:



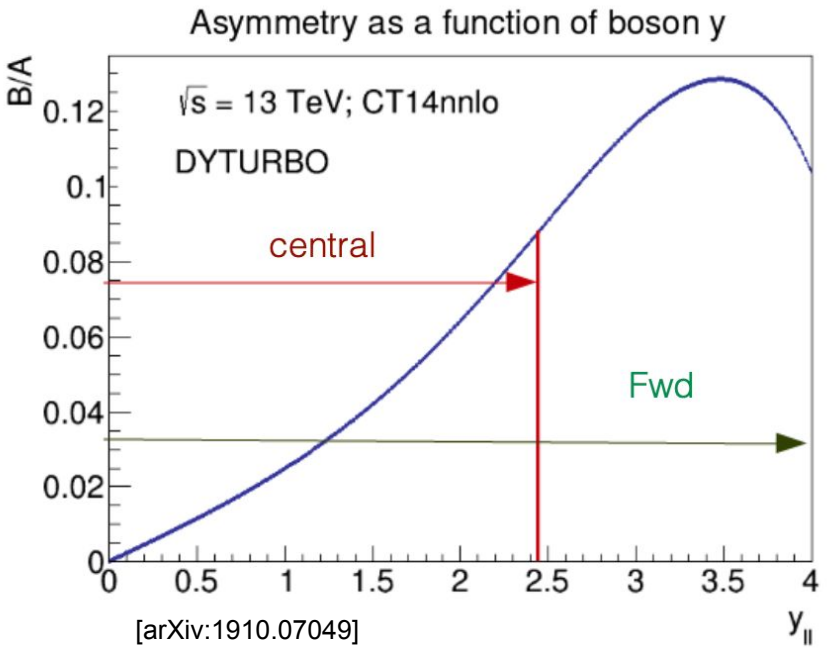
Collins-Soper Frame [arXiv:1606.00689]

  - valence quark PDF dominating at high momentum
    → quark direction likely to coincide with Z boost!

→ higher sensitivity to AFB in forward direction!



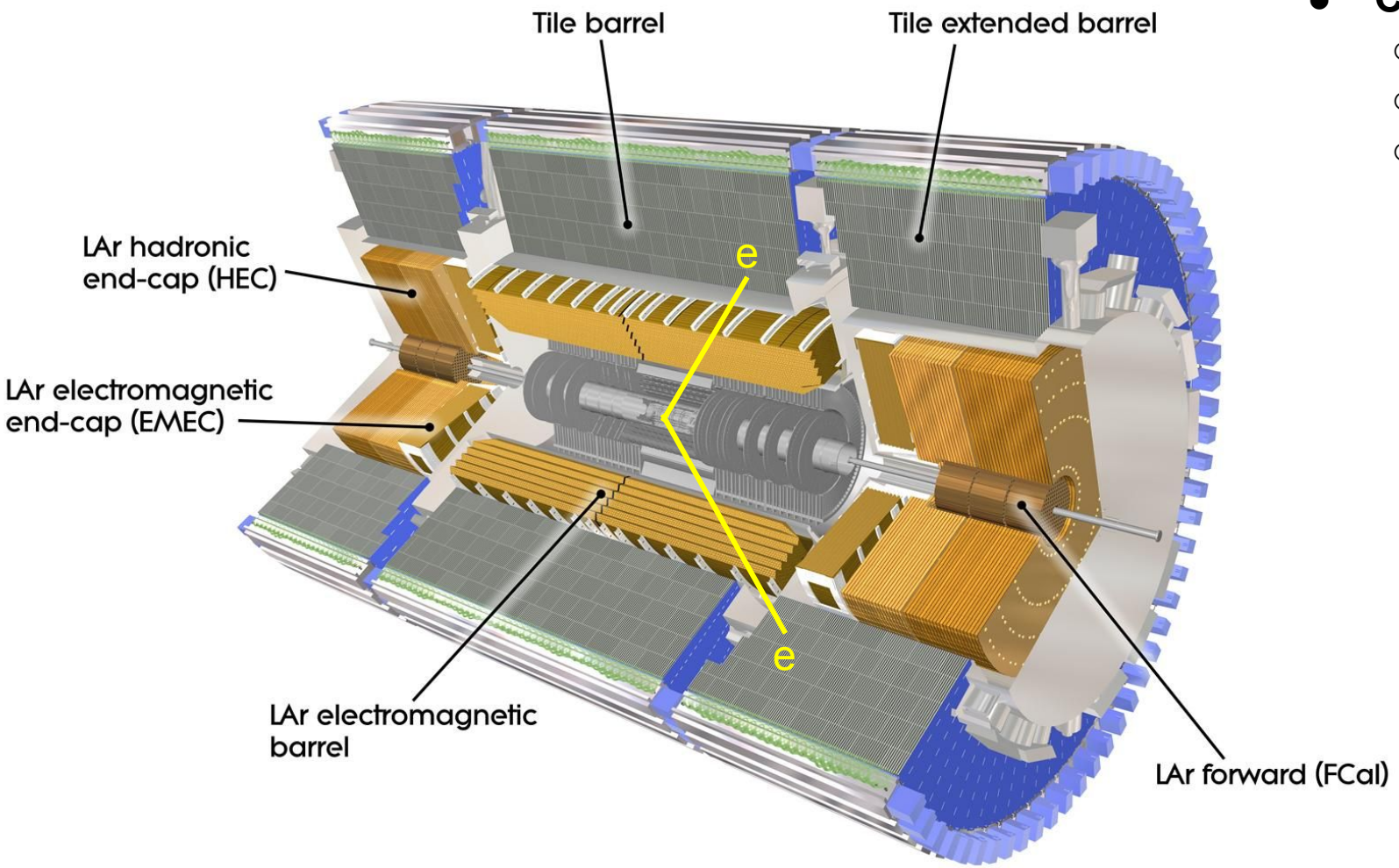
[PDG Review of Structure Functions 2023]



[arXiv:1910.07049]

Analysis Channels

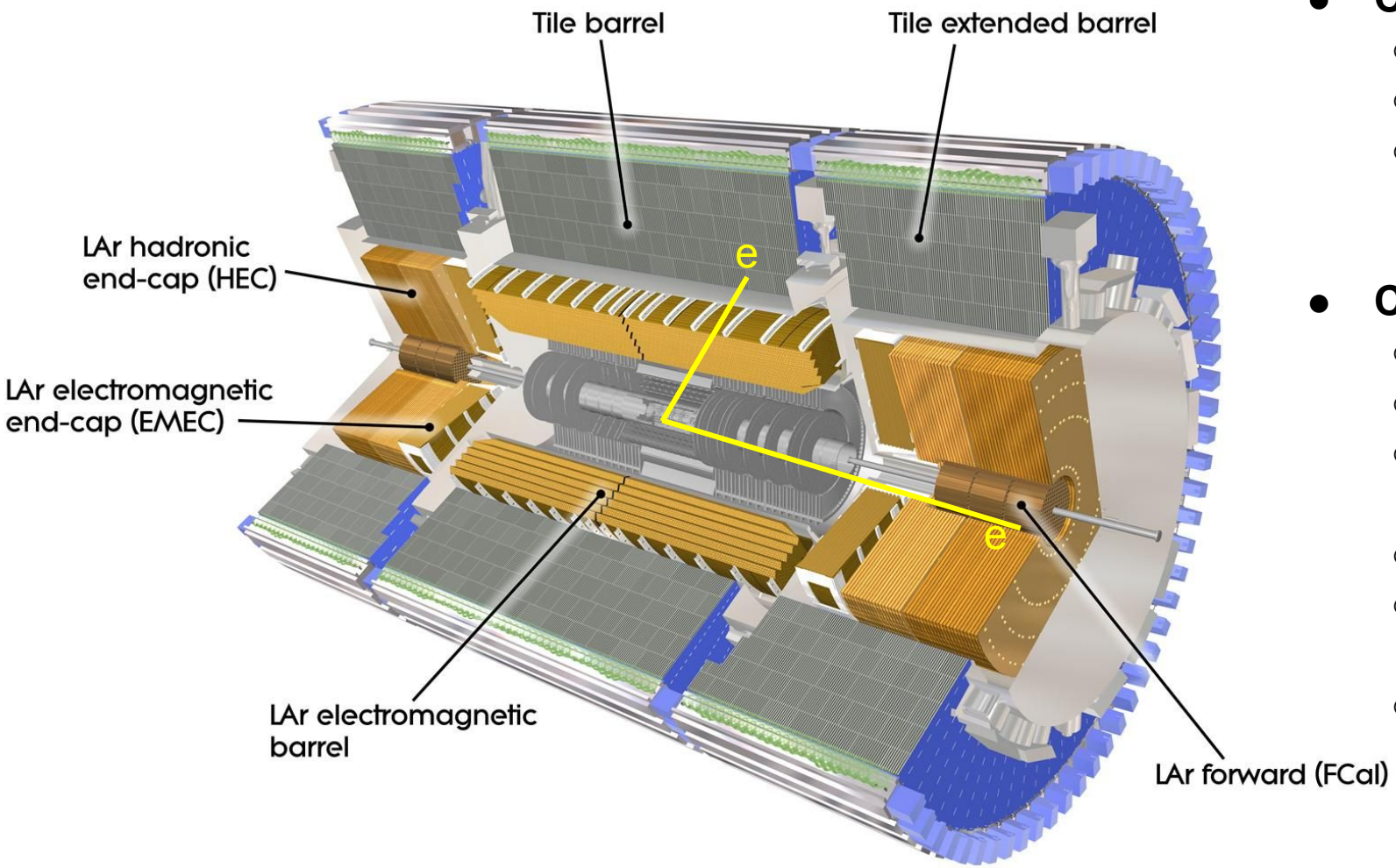
and ATLAS Geometry



- **CC** (central-central)
  - two central electrons or muons
  - central: $\eta < 2.5$
  - tracking (SCT and TRT) and high-granularity calorimeters

Analysis Channels

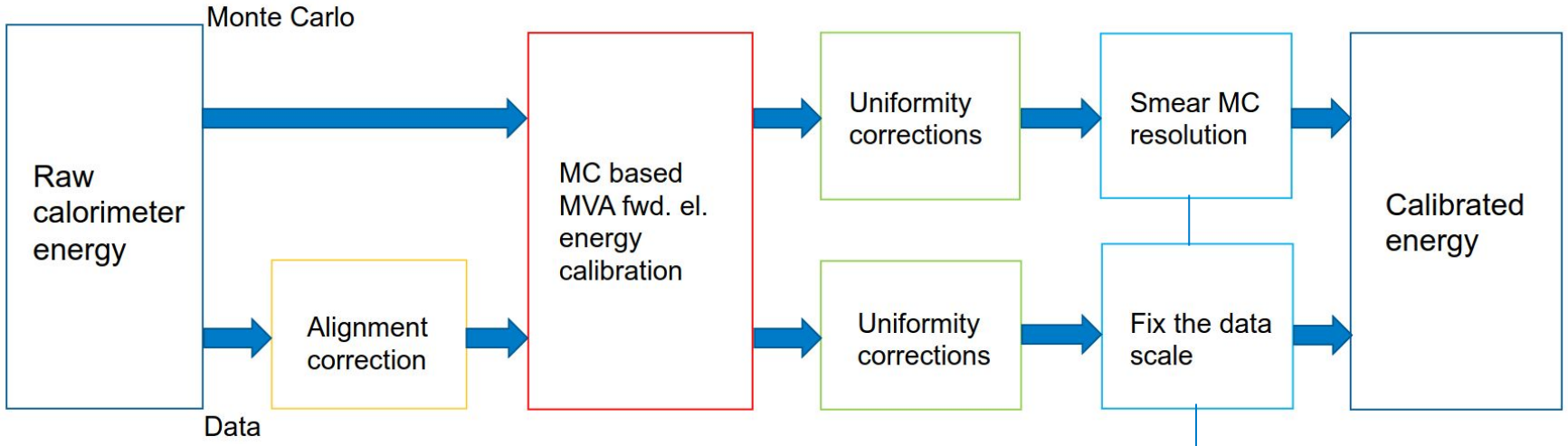
and ATLAS Geometry



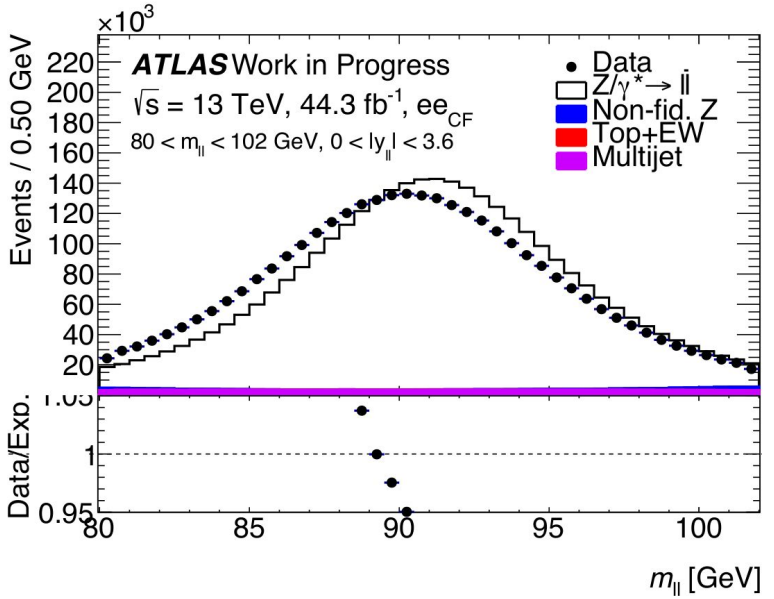
- **CC** (central-central)
  - two central electrons or muons
  - central: $\eta < 2.5$
  - tracking (SCT and TRT) and high-granularity calorimeters
- **CF** (central-forward)
  - one central, one forward electron
  - forward: $\eta > 2.5$
  - no tracking and lower granularity of calorimeters
  - higher levels of QCD background
  - challenging performance work necessary!
  - but higher sensitivity

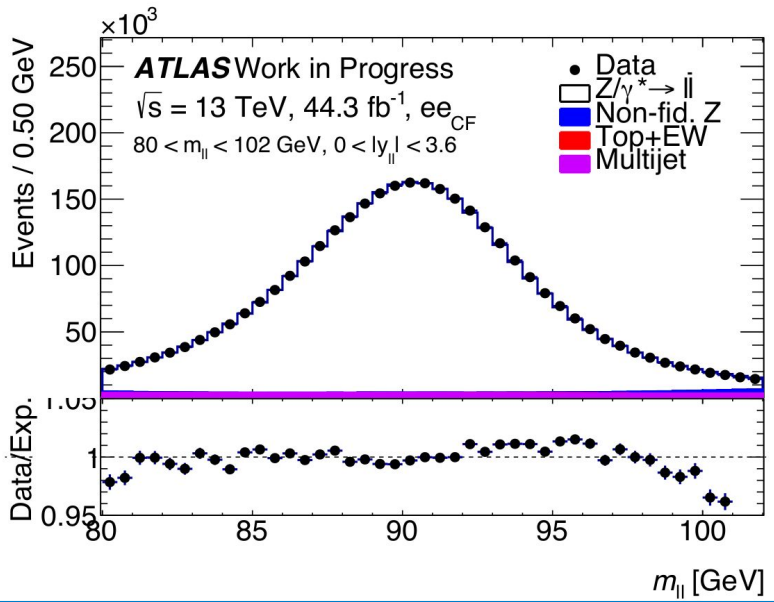
Forward Electron Energy Calibration

(Work in Progress)



- correcting the raw energy of forward electrons using multi-variate-analysis
- harmonizing the energy response of calorimeter cells
- matching the mass spectrum of the Z boson in data and Monte-Carlo (in-situ calibration)





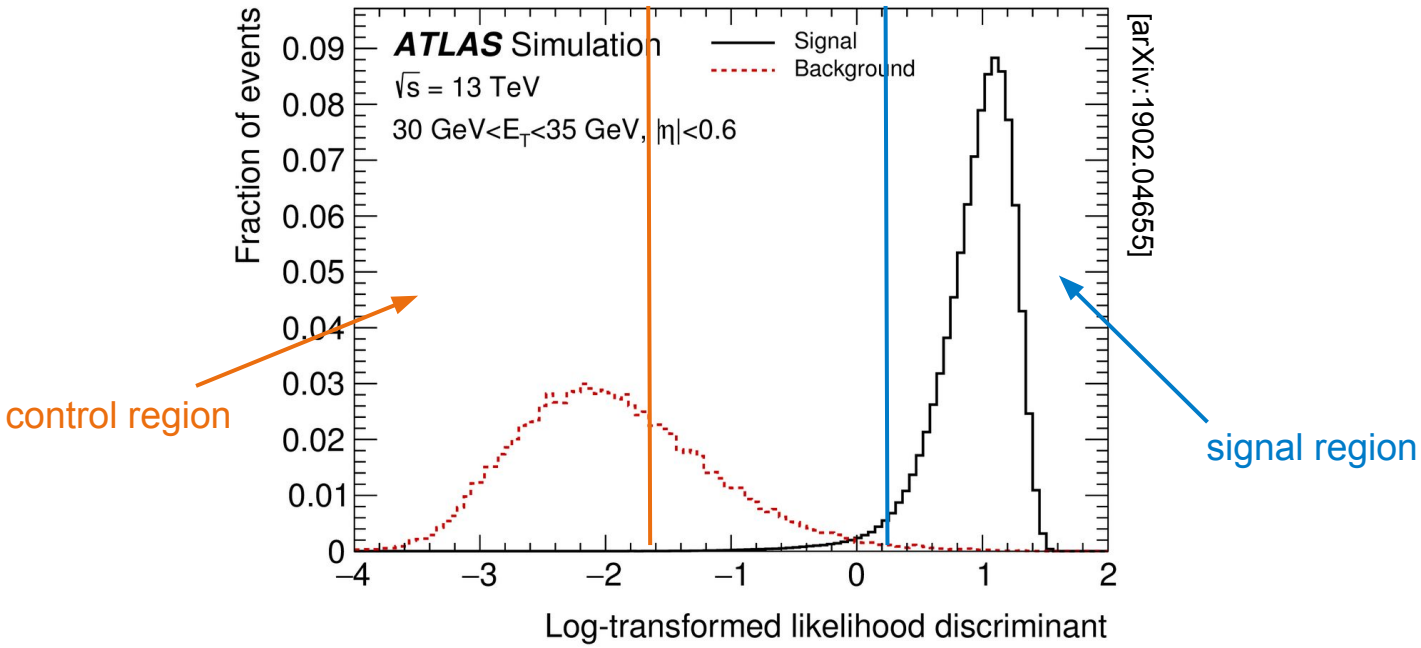
- fit double-sided Crystal-Ball function to MC and data
- smear MC to match data resolution
- shift data to match MC energy scale

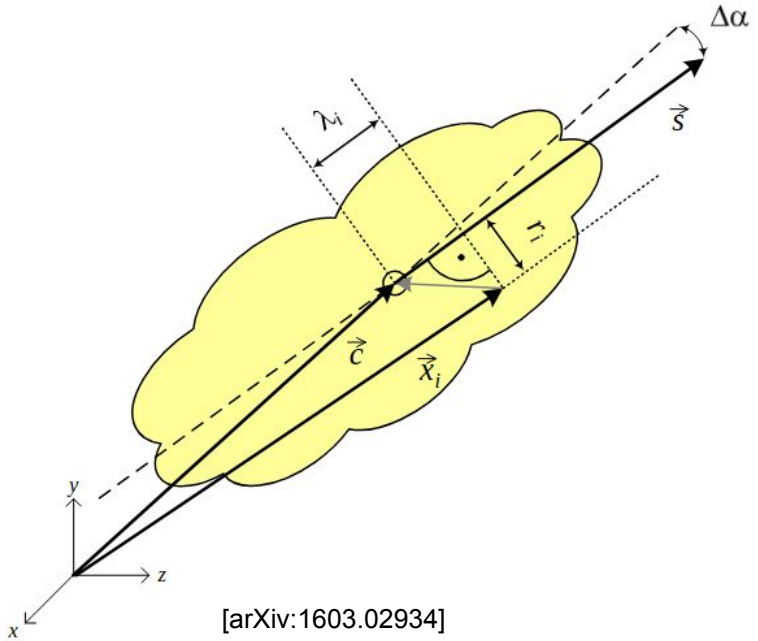
[see talk by Craig Wells]

Electron Identification

in the Forward Region of ATLAS

- no tracking!
- reconstruction using topological clustering algorithm
- identification based on shower-shapes in electromagnetic calorimeter
  - shower-shape parameters condensed into likelihood discriminant





- differences in shower-shapes between data and MC → different ID efficiencies
  - needs to be corrected!

Scale-Factors

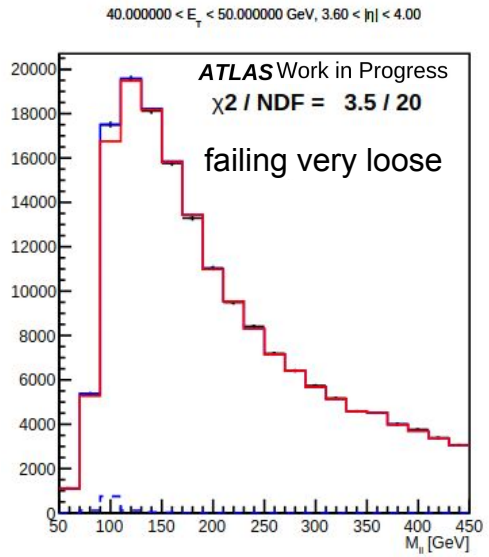
for Forward Electron Identification

- select sample of forward electron candidates from data (“tag and probe”)
- fit background and efficiencies in 3 ID regions
- calculate scale-factors (in bins of eta and pt)
- apply to MC events

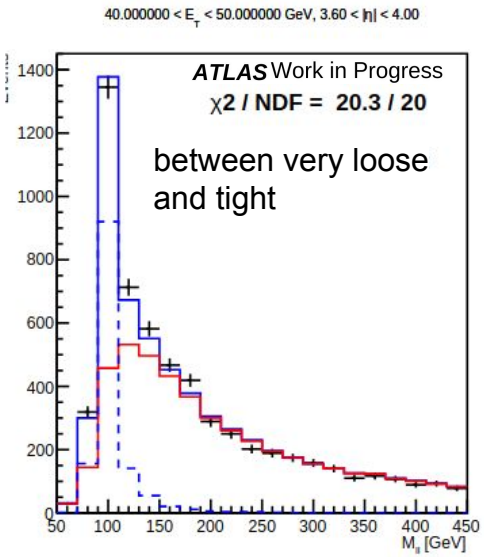
$$\epsilon_S^{ID} = \frac{N_S^{\text{passID}}}{N_S^{\text{all}}}$$

$$\text{SF} = \frac{\epsilon_S^{ID}(\text{data})}{\epsilon_S^{ID}(\text{MC})}$$

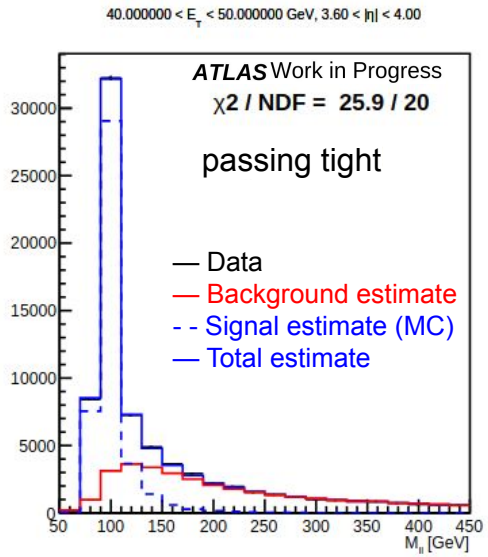
[0.76-1.14]



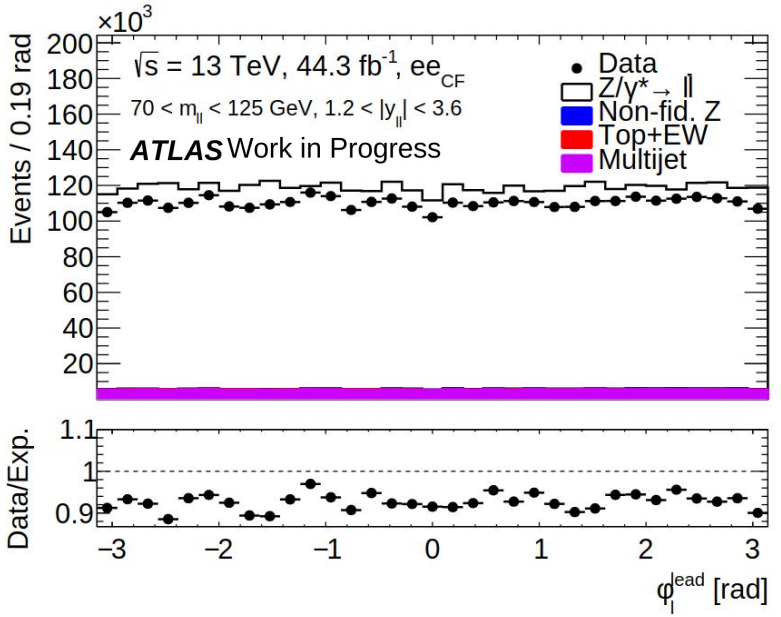
Control region important to estimate background

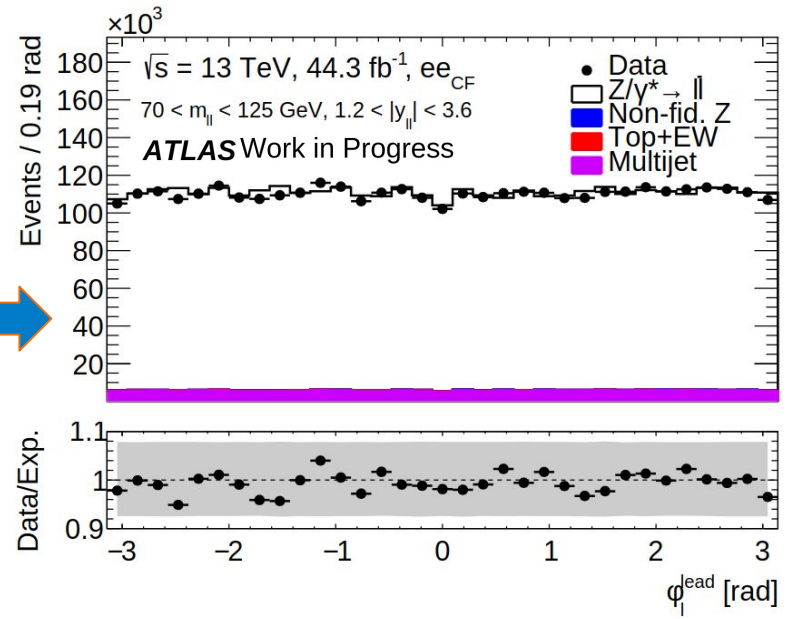


Intermediate region helps the fit to converge



Signal region has highest impact on the POI (signal efficiency)

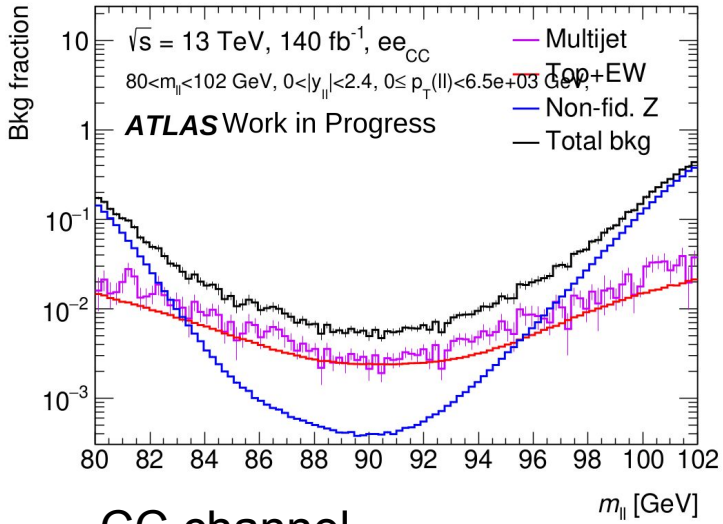




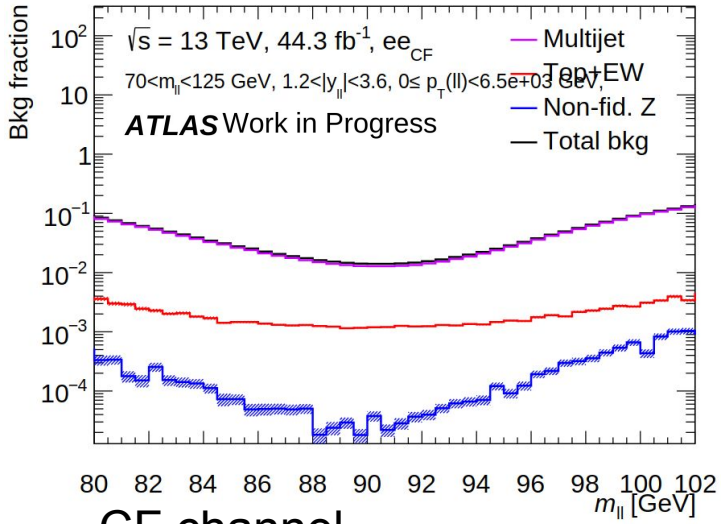
Forward Multi-Jet Background Estimation

via Fake-Factor Method

- no tracker in forward direction → more fake and non-prompt electrons



CC channel



CF channel

control region: on peak, failing ID (nLon)

MJ = data - MC

$$F = \frac{N_{\mathrm{MJ}}^{\mathrm{IDoff}}}{N_{\mathrm{MJ}}^{\mathrm{nLoff}}}$$

(control regions off-peak)

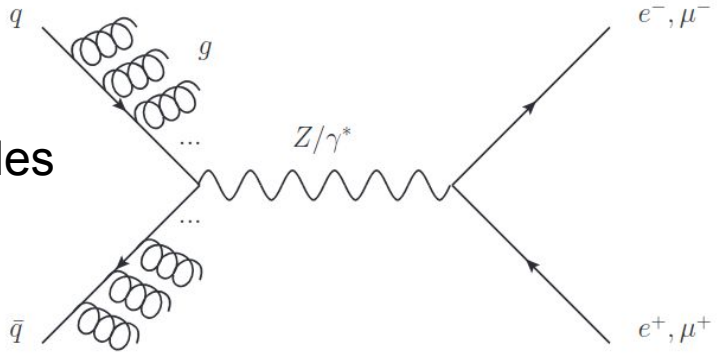
signal region: on peak, passing ID (IDon)

MJ estimate

- many possible sources:
  - heavy hadrons → electrons + jets
  - light hadrons with electron-like shower-shapes
  - photons and conversion electrons
- very difficult to simulate accurately
- make data-based approach to estimate MJ background!

Extraction of Cross-Section and Angular Coefficients

of the Drell-Yan Process



- expansion of cross-section into 9 harmonic polynomials of lepton decay angles
  - purely mathematical and valid to any order!

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{U+L}}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}}$$

$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi \quad \text{LO}$$

$$+\frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta \quad \text{NLO}$$

$$+A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}. \quad \text{NNLO}$$

forward-backward asymmetry!

- fit to data → simultaneous determination of angular coefficient and unpolarized cross-section
- differential (in p_T,y_Z or m_{ll},y_Z) cross-section measured in full lepton phase-space
- exceptional possibilities for phenomenological interpretations!
- ‰ level precision in the central region, sub-% uncertainties up to |y| < 3.6

How to Extract the Weak Mixing Angle

from A4 (+ Cross-Section)

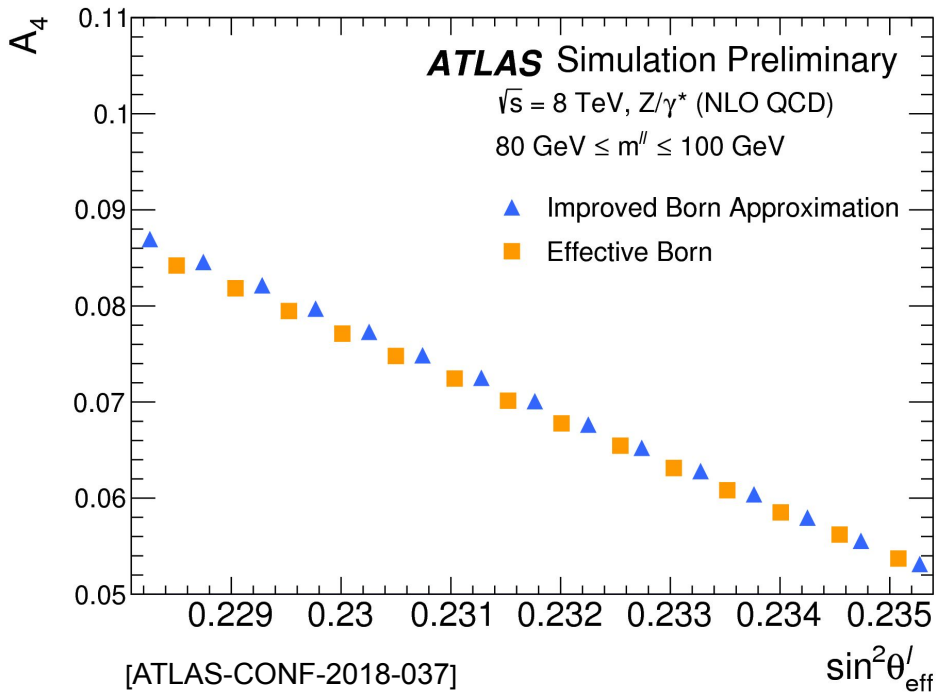
Initial sensitivity study on the extraction of WMA from A4 and cross-section

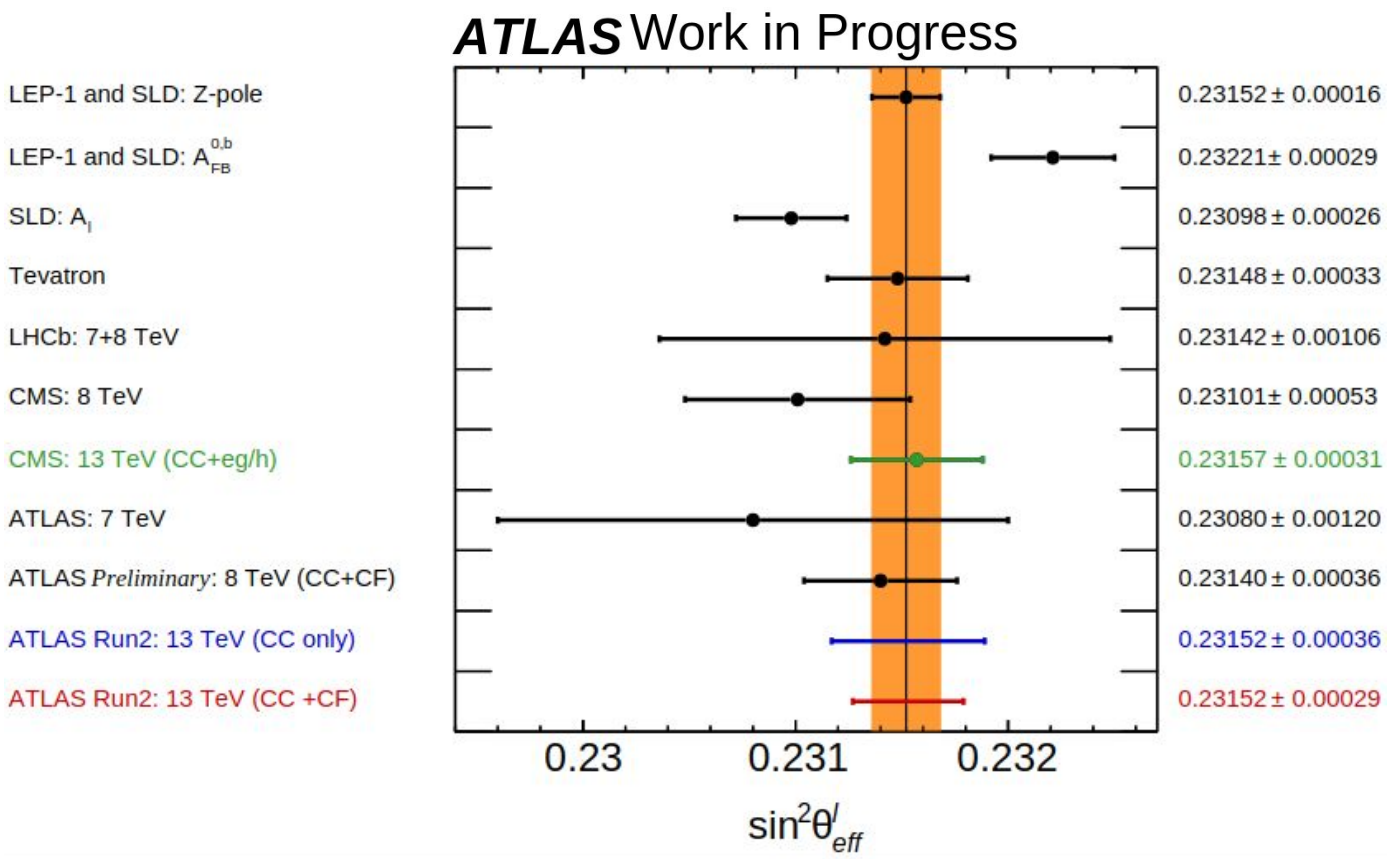
- using xFitter interfaced with DYTurbo
- using NNPDF4.0 PDF set
- very promising results!

high rapidity range
→ high sensitivity to WMA

wide m_{ll} range helps to constrain PDFs

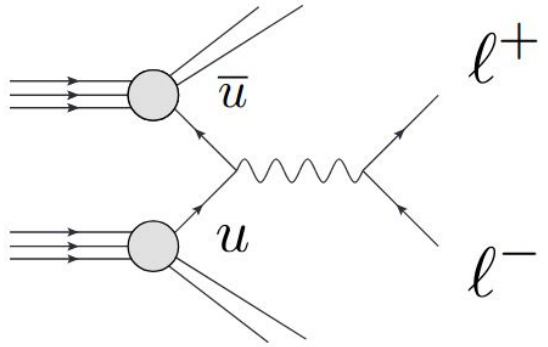
- 3 mass bins: [70,80,100,125]
- y bins CC/MM: [0,0.4,0.8,1.2,1.6,2.0,2.4]
- y bins CF: [1.2,1.6,2.0,2.4,2.8,3.2,3.6]





Summary

and Time for Questions



- WMA is an important SM parameter
  - with precise theory predictions
  - needs to be **measured** more precisely as well!
  - observable through forward-backward asymmetry in Drell-Yan $q\overline{q} \rightarrow Z \rightarrow ee$

- higher sensitivity in **forward** direction
  → measure in central-forward channel (in addition to central-central)

- challenges of forward electron performance
  - energy calibration
  - electron identification + efficiency determination
  - background estimation

- extraction of full 4-fold differential cross-section by fitting angular expansion to data

- expected sensitivity competitive with recent CMS result
  - same order of magnitude es LEP results, but now with hadron collider!

Thank you

for your attention

Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

Lukas Bayer
DESY ATLAS Standard Model Group
lukas.bayer@desy.de
office phone: 2432

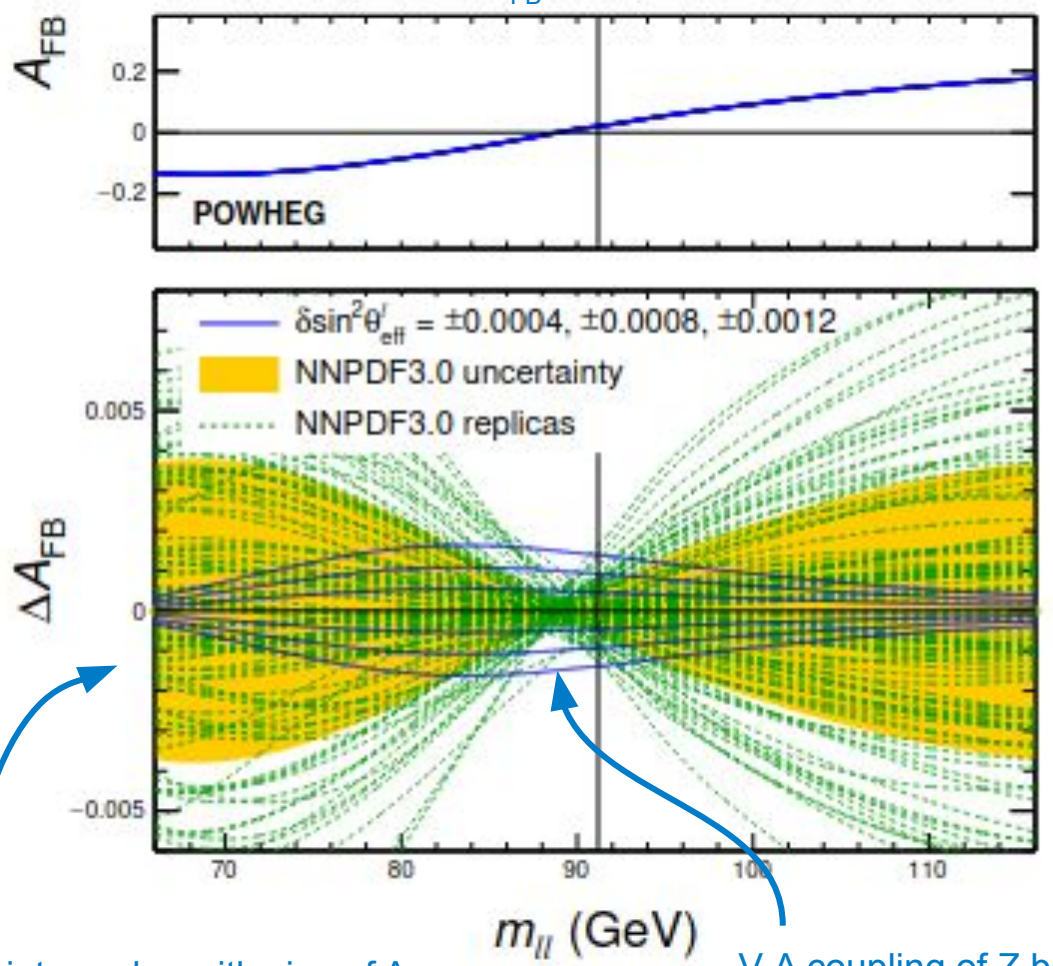
Backup

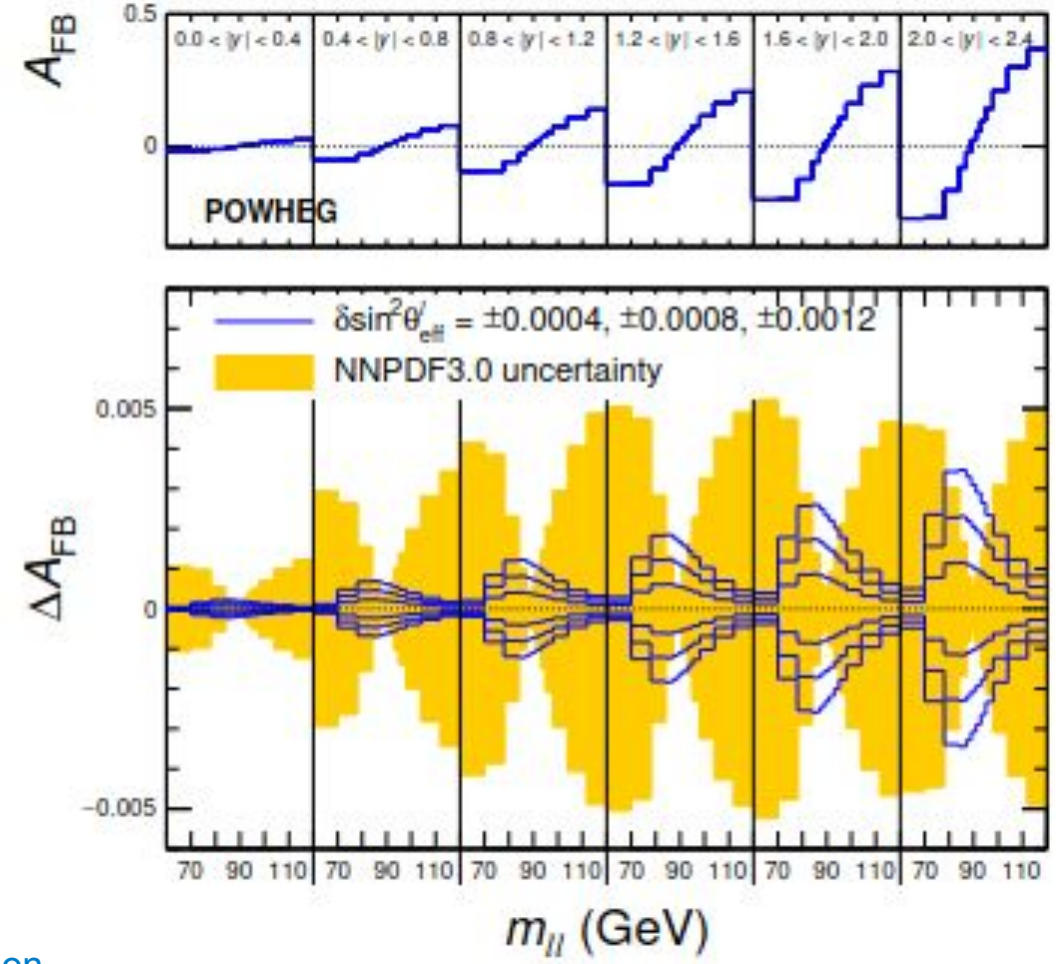
Forward-Backward Asymmetry

in the Drell-Yan Process

Z/γ interference → A_{FB} changes sign at Z pole

dilution effect → A_{FB} more pronounced in forward direction!





PDF uncertainty scales with size of A_{FB}
→ use low/high mll bins to constrain PDFs

V-A coupling of Z boson
→ WMA dependence strongest at Z pole!

[CMS, Eur.Phys.J.C 78 (2018) 9, 701]