Physics with Electroweak bosons at LHCb

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on behalf of the LHCb collaboration

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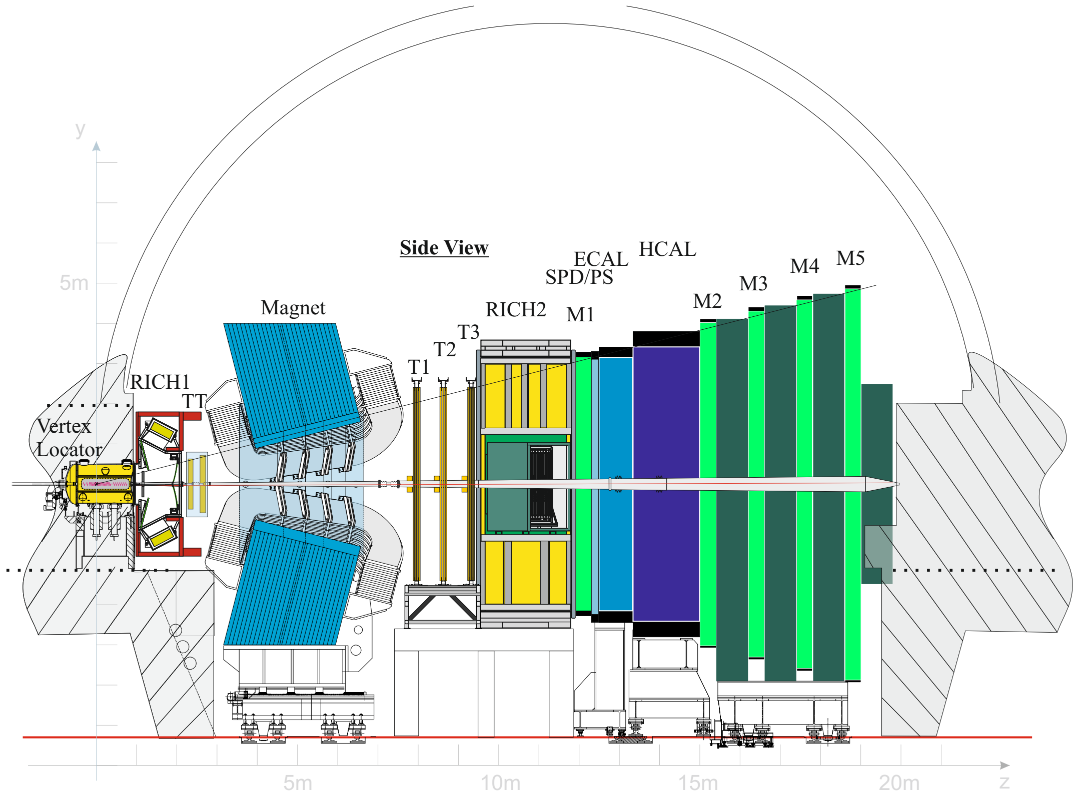
Overview

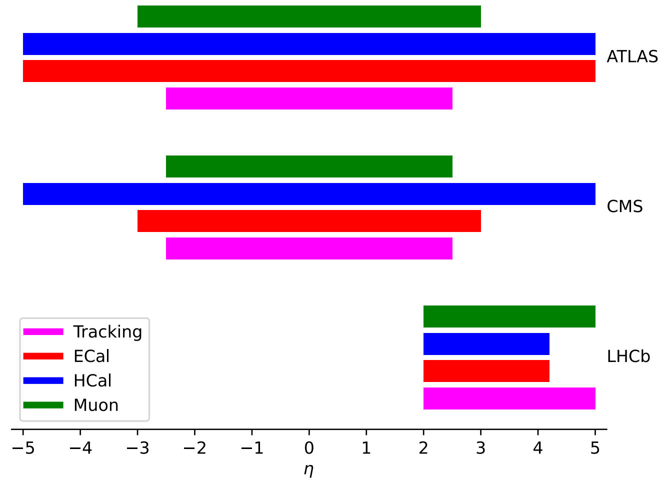
- **The LHCb detector**
- **Probing QCD with electroweak bosons**
  - Measurement of the Z boson production cross-section in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV
- **Precision electroweak measurements**
  - Curvature-bias corrections using a pseudomass method
  - Measurement of the W boson mass
  - Measurement of the effective leptonic weak mixing angle

The LHCb detector

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)

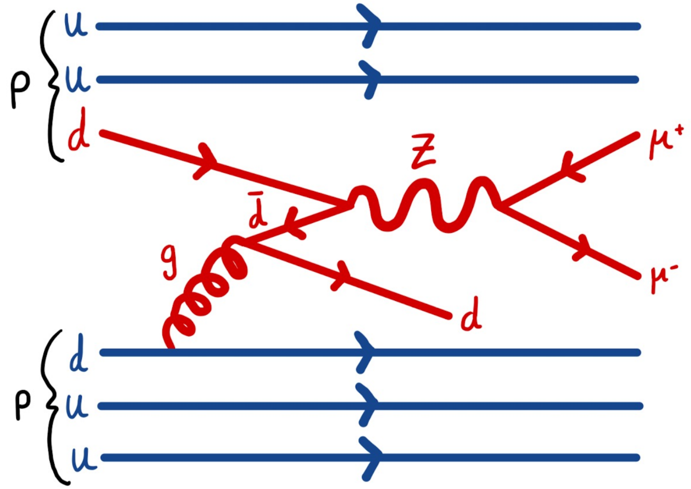


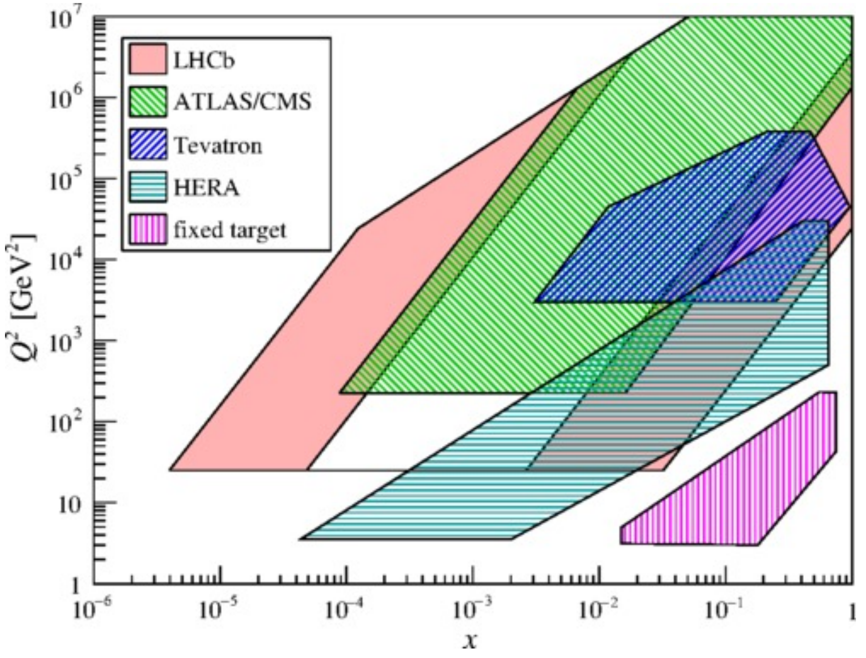
- Single arm forward spectrometer
- Designed for heavy flavour physics but can also be used as a general-purpose forward detector
- Suitability for electroweak physics:
  - Very good momentum resolution for high momentum particles
  - Excellent particle identification efficiencies
  - Occupies complementary region of phase space to ATLAS and CMS



Probing QCD with electroweak bosons

Phys. Rev. D 93, 074008 (2016)





- An accurate model of QCD is critical in understanding the LHC collision environment
- Measurements of W and Z production cross-section facilitate precise tests of the SM predictions obtained from perturbative QCD calculations
- Also provide constraints on the proton PDFs
- Large uncertainties on PDFs in very large and very small Bjorken-x regions ($x{\sim}0.8$ and $x{\sim}10^{-4}$, respectively)
- LHCb's forward acceptance allows measurements of highly boosted Zs ⇒ sensitive to these regions

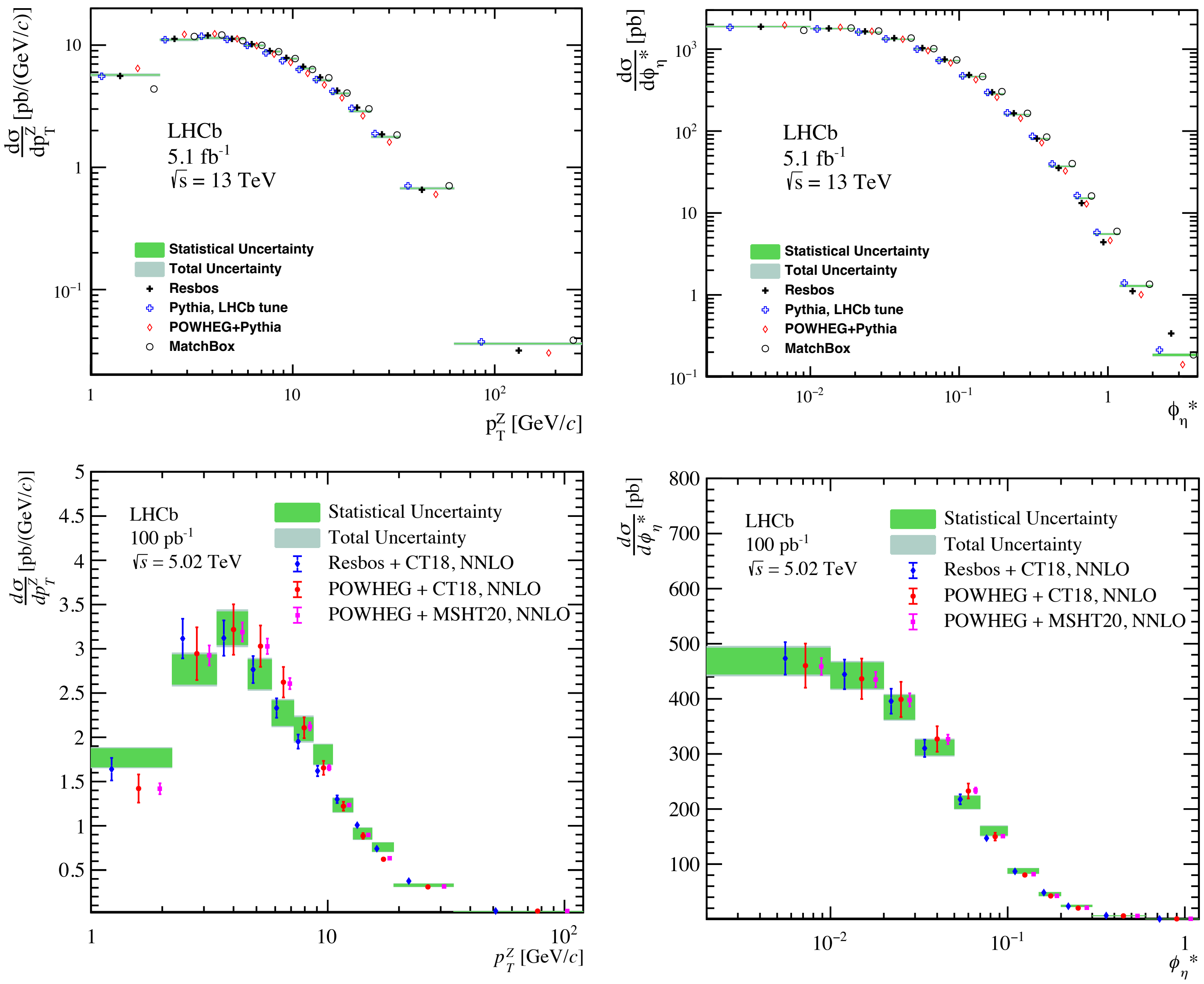
Z production cross-section

JHEP 02 (2024) 070

JHEP 07 (2022) 026

- Measurements of Z production cross-section made using Run 2 data at both $\sqrt{s} = 5.02$ and 13 TeV
  - Previously published measurements at 7 and 8 TeV
- Differential cross-sections determined in bins of y^Z, p_T^Z and ϕ_η^*, with reasonable agreement between data and theoretical predictions

$$\phi_\eta^* = \tan\left[\left(\pi - \Delta\phi^{ll}\right)/2\right]\sin\left(\theta_\eta^*\right) \approx \frac{p_T^Z}{M}$$

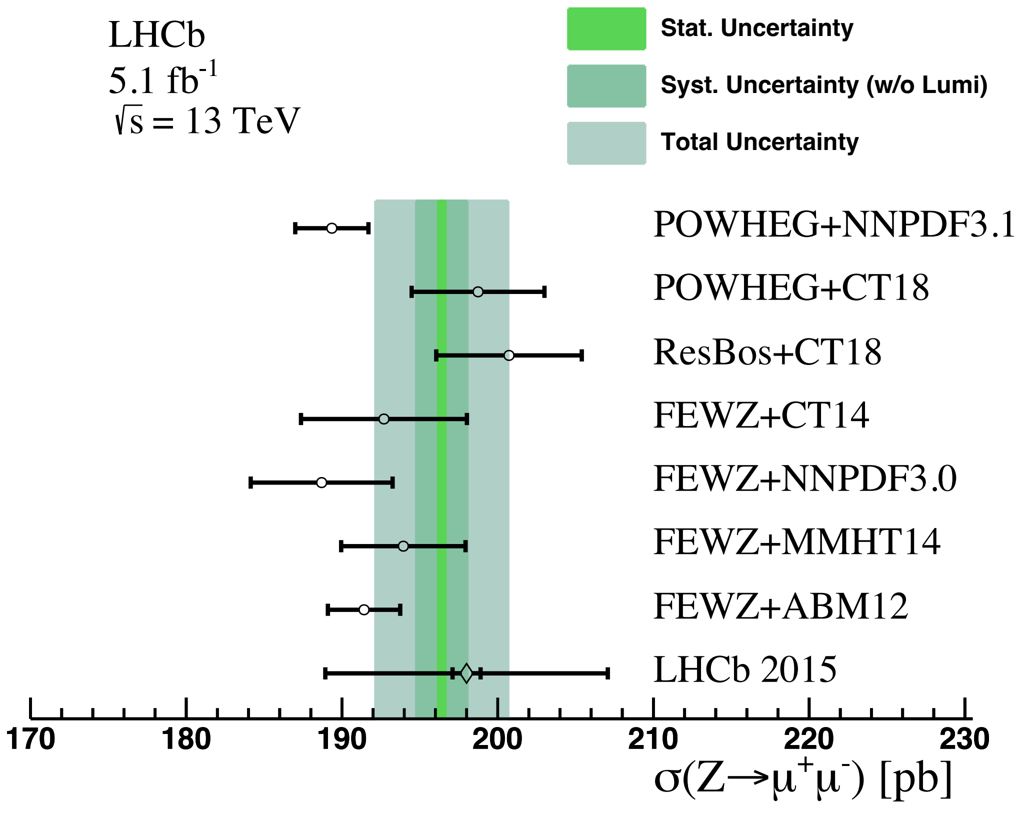


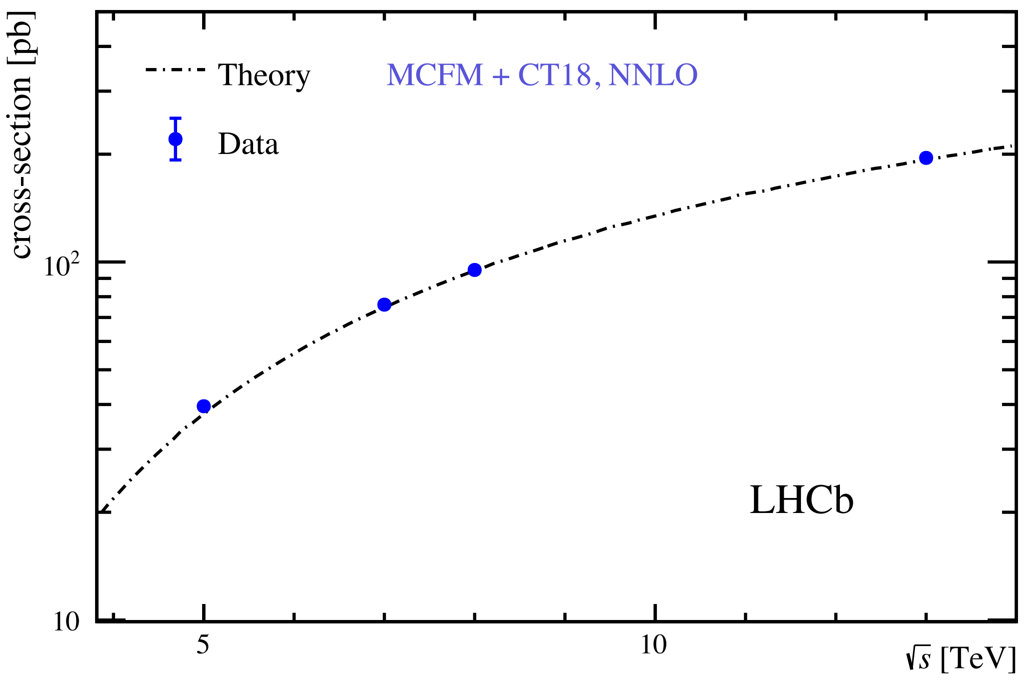
Z production cross-section

JHEP 02 (2024) 070
JHEP 07 (2022) 026

$$\sigma^{5.02\ \mathrm{TeV}}_{Z\to\mu^+\mu^-} = 39.6 \pm 0.7_{\mathrm{stat}} \pm 0.6_{\mathrm{syst}} \pm 0.8_{\mathrm{lumi}}\ \mathrm{pb}$$

$$\sigma^{13\ \mathrm{TeV}}_{Z\to\mu^+\mu^-} = 196.4 \pm 0.2_{\mathrm{stat}} \pm 1.6_{\mathrm{syst}} \pm 3.9_{\mathrm{lumi}}\ \mathrm{pb}$$

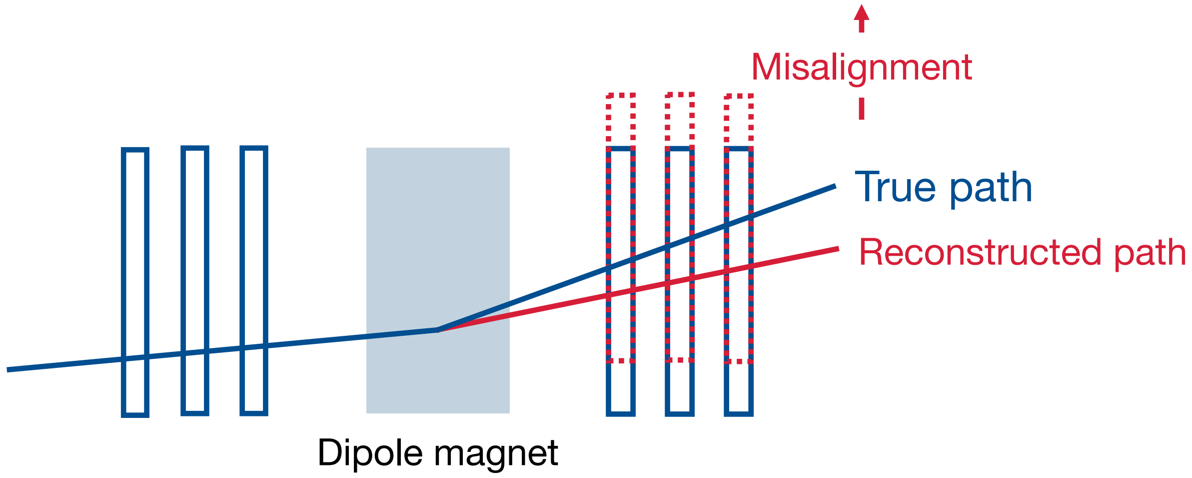




Precision electroweak measurements

- Can also use W and Z bosons to investigate the fundamental electroweak interaction
- Whilst studies of QCD are carried out with $O(1)\%$ precision, competitive electroweak measurements have a precision of $O(10^{-4})$
- Measurements with this precision provide compelling tests of the Standard Model theory
- Requires excellent understanding of QCD, the collision environment and the detector itself

Curvature-bias corrections



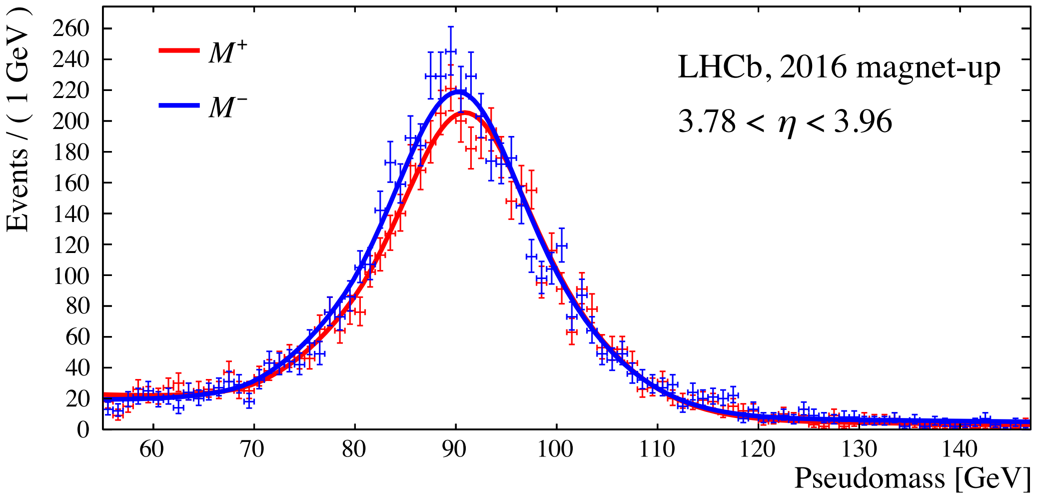
- Good understanding of detector alignment critical for accurately measuring muon p_{T}
  - $5\mu\mathrm{m}$ misalignment can lead to $O(50)$ MeV bias in m_W
- Misalignments cause curvature-biases of the form

$$\frac{q}{p} \to \frac{q}{p'} = \frac{q}{p} + \delta$$

- Such biases are the leading experimental systematic in the measurement of m_W

- Corrected for using the pseudomass ($M^{\pm}$) method with $Z \to \mu^+\mu^-$ decays

$$M^{\pm} \equiv \sqrt{\frac{p_T^{\pm}}{p_T^{\mp}}}M = \sqrt{2p^+p^-\frac{p_T^{\pm}}{p_T^{\mp}}(1-\cos\theta)} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)}$$

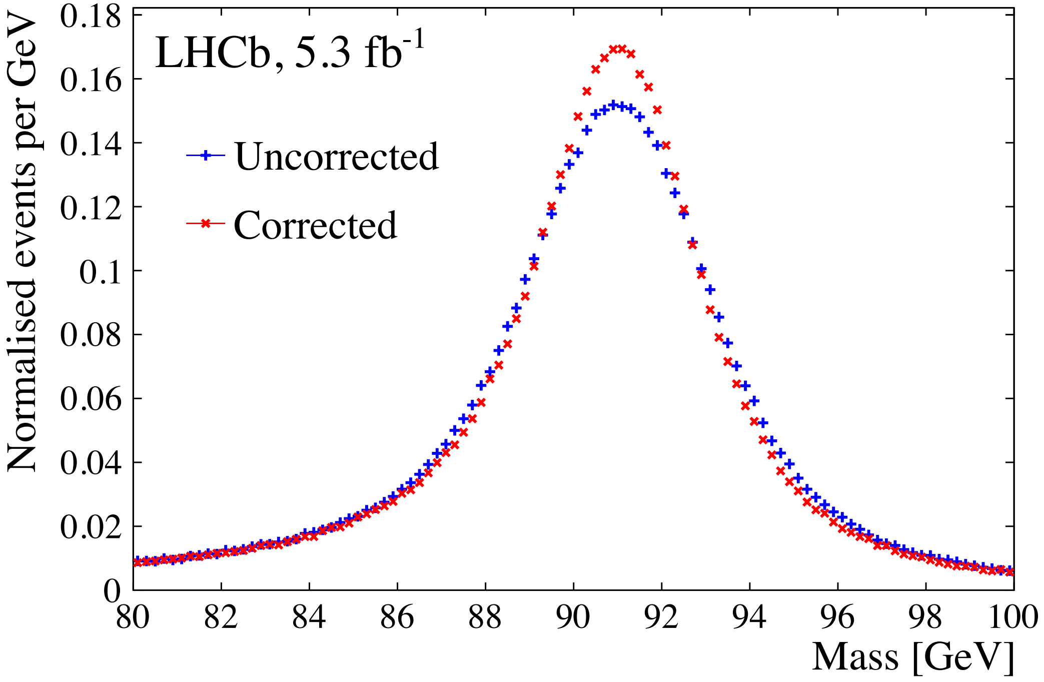


- δ proportional to asymmetry in peak position of M^+ and M^-

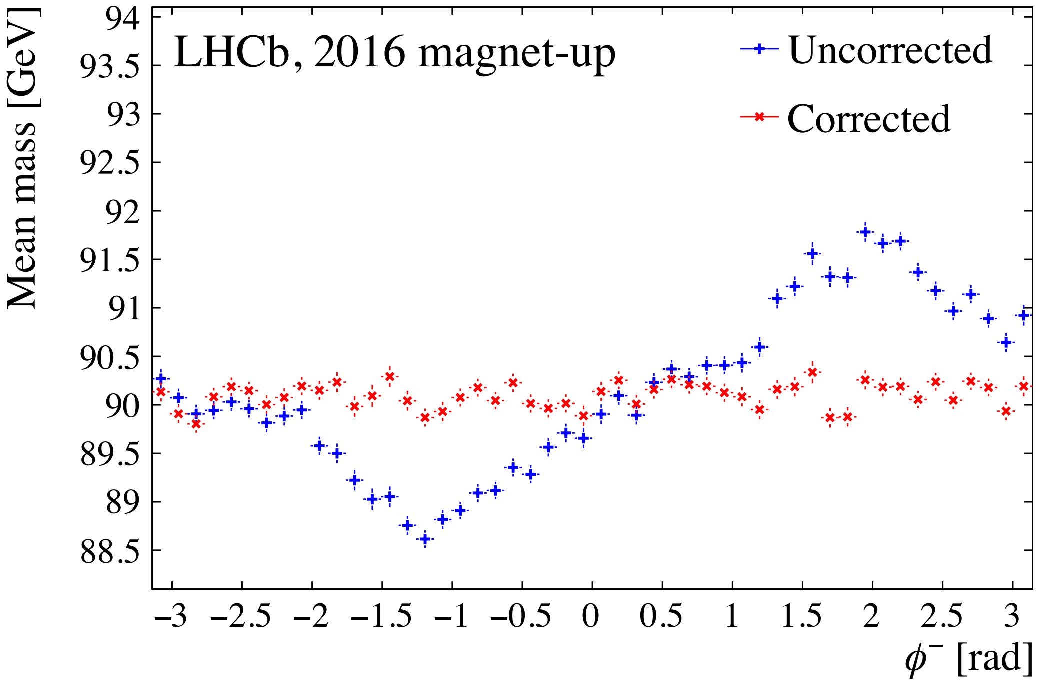
Curvature-bias corrections

JINST 19 (2024) P03010

- $O(20\%)$ improvement in resolution of width of Z mass peak



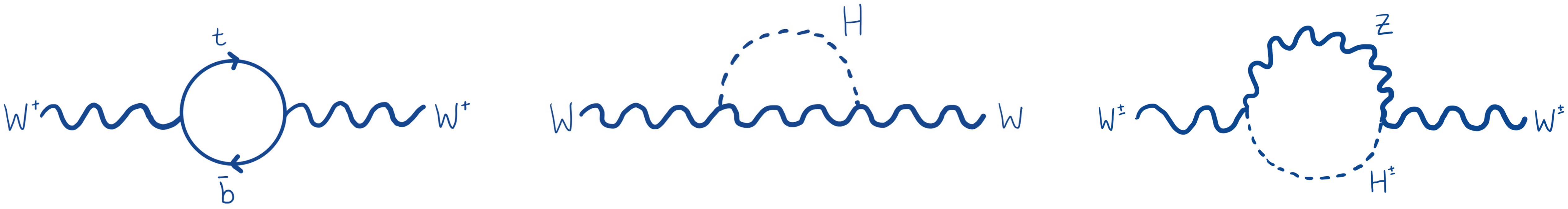
- Non-physical trends in $m_{\mu\mu}$ as a function of ϕ removed



W mass measurement

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

Δ represents loop corrections

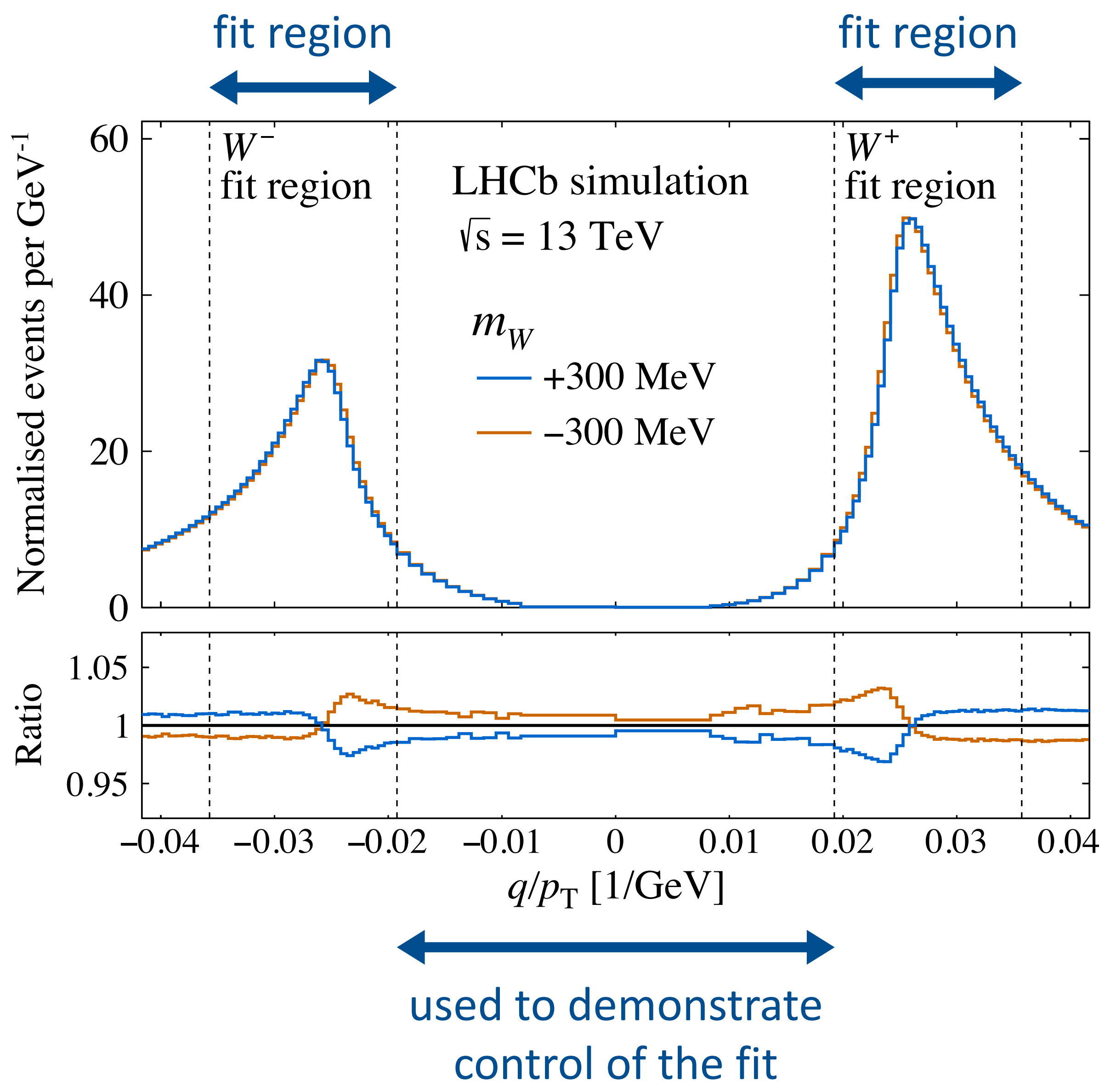


- Precision measurements of m_W sensitive to BSM physics

- Hadron collider measurements limited by uncertainties in modelling, in particular PDF uncertainties
  - LHCb's forward acceptance allows PDF uncertainty to partially cancel in LHC combination

W mass measurement

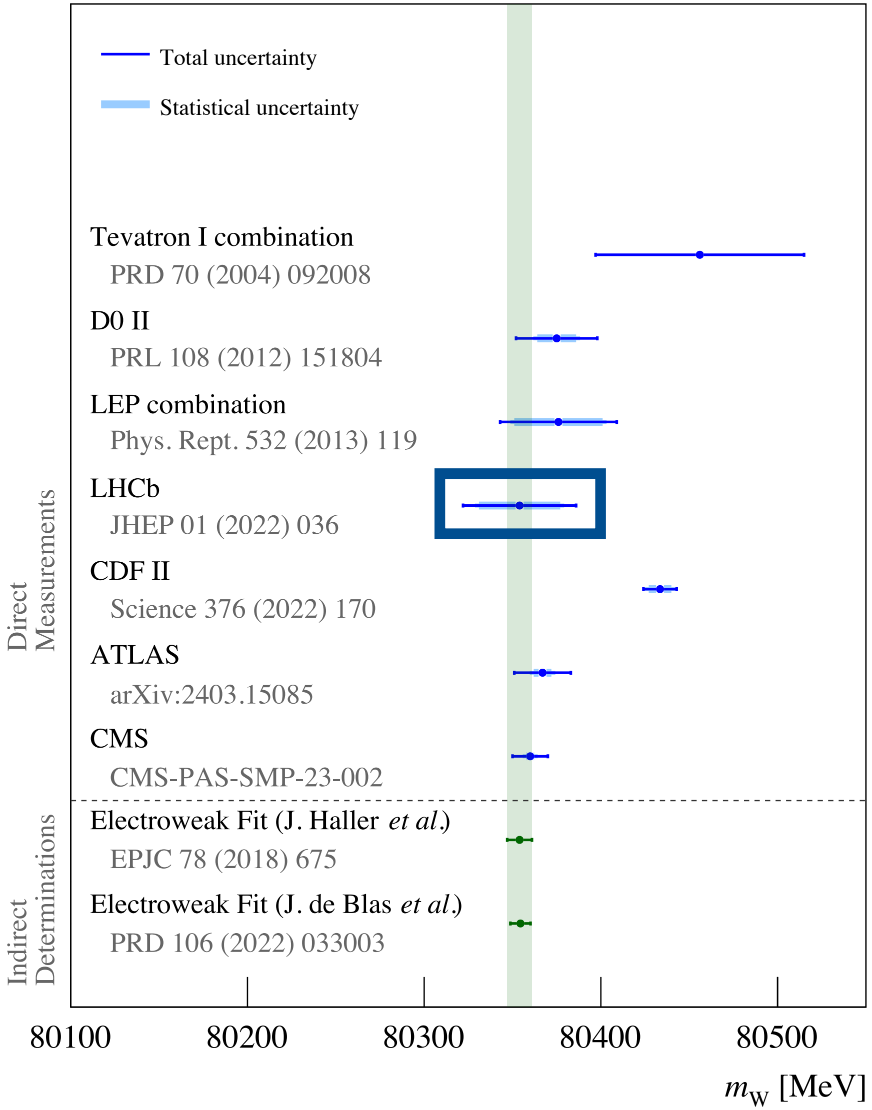
JHEP 01 (2022) 036



- m_W measured using the lepton q/p_T distribution in the $W \to \mu\nu_\mu$ channel
- Location of peak set by m_W

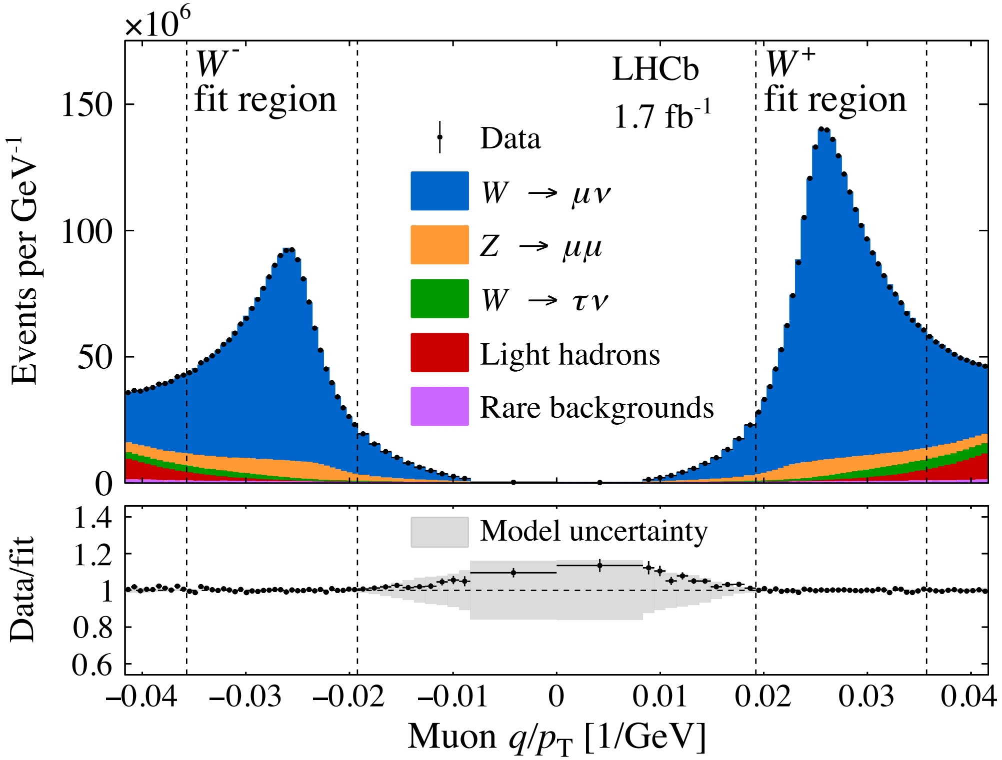
W mass measurement

JHEP 01 (2022) 036



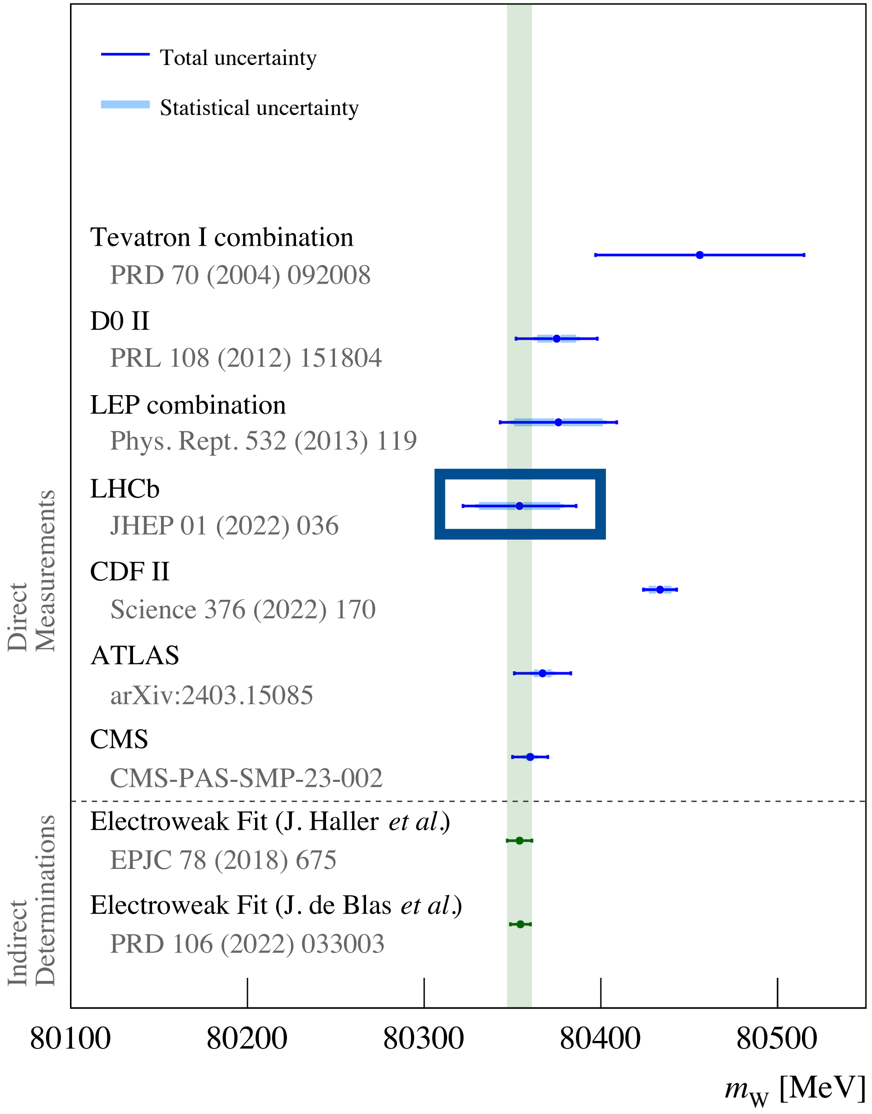
- Measurement made using 2016 dataset; 1.7 fb^{-1} pp collision data at $\sqrt{s} = 13$ TeV

$$m_W = 80\,354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$



W mass measurement

JHEP 01 (2022) 036



- Measurement made using 2016 dataset; $1.7\ \text{fb}^{-1}$ pp collision data at $\sqrt{s} = 13\ \text{TeV}$

$$m_W = 80\,354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

- Ongoing work to include data from 2017 and 2018
  - Predicted statistical precision of $\sim 14\ \text{MeV}$
  - Further studies of theoretical aspects carried out
  - Calibrations, momentum scale and efficiencies optimised

Effective leptonic weak mixing angle

arXiv:2410.02502 [hep-ex]

- At lowest-order the weak mixing angle relates the $\mathrm{U}(1)$ and $SU(2)$ gauge coupling

$$\sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$$

- $\sin^2\theta_{\text{eff}}^{\ell}$ describes higher-order terms

- Measured using $Z \to \mu^+\mu^-$ production

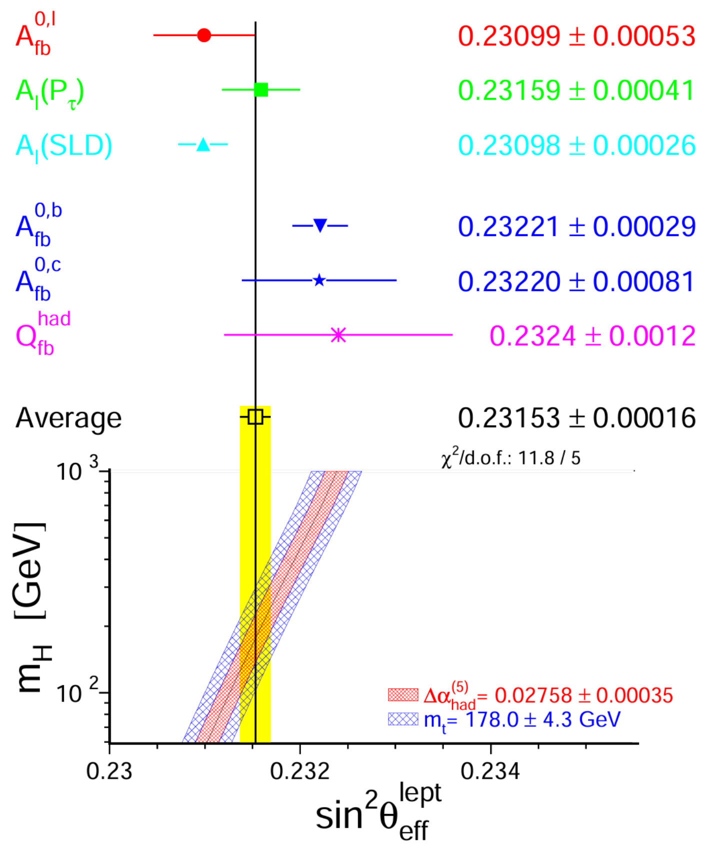
$$\frac{d\sigma}{d\cos\theta^*} \propto 1 + \cos^2\theta^* + \alpha\cos\theta^*$$

- α comes from products of vector and axial-vector couplings ⇒ sensitive to the weak mixing angle

- Linear in $\cos\theta^*$ ⇒ causes forward backward asymmetry in $Z \to \mu^+\mu^-$ production

$$A_{\mathrm{FB}} \equiv \frac{N(\eta^- > \eta^+) - N(\eta^+ > \eta^-)}{N(\eta^- > \eta^+) + N(\eta^+ > \eta^-)}$$

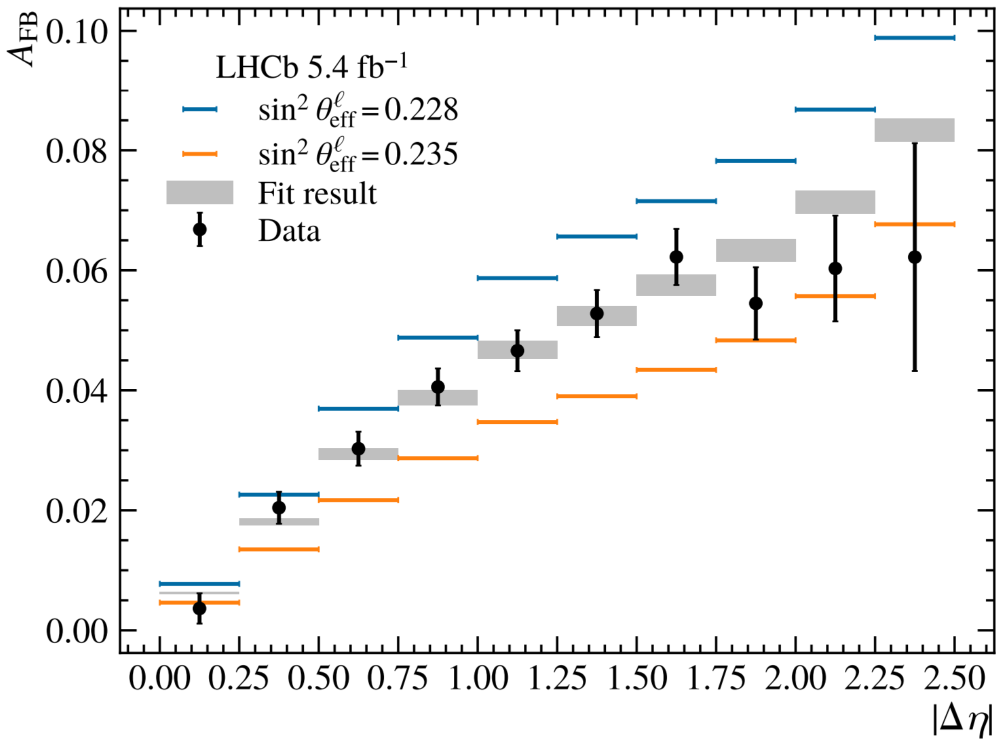
Phys. Rept. 427:257-454, 2006



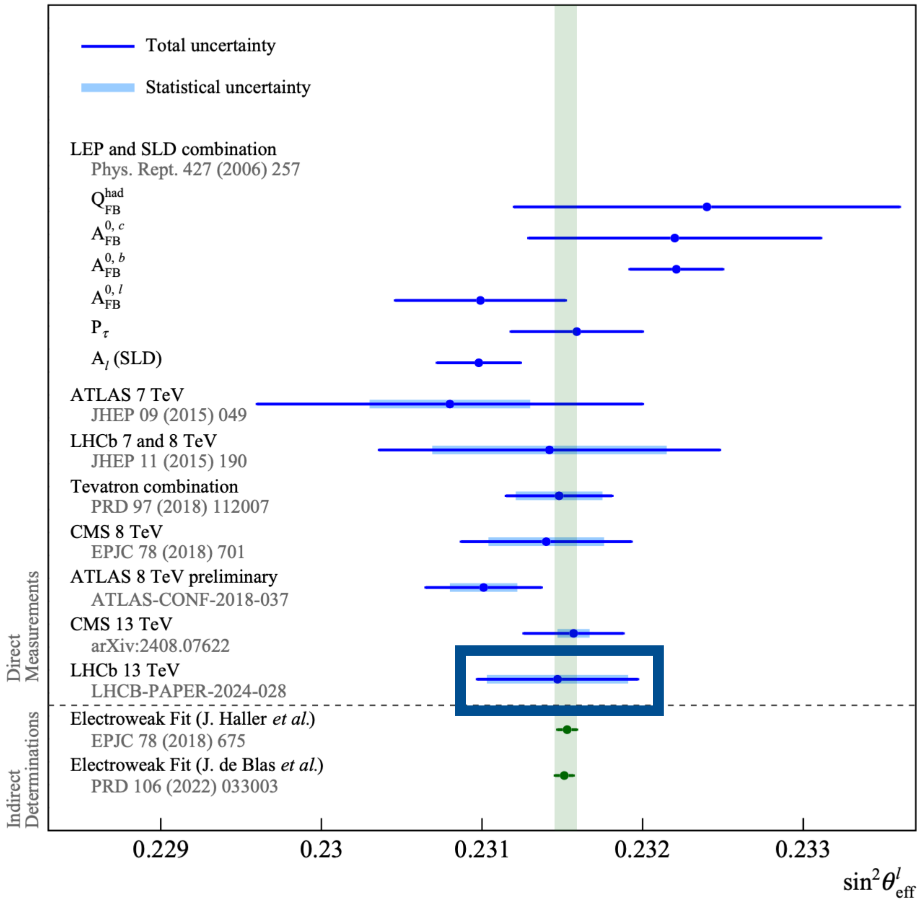
Over 3σ difference between two most precise determinations (LEP and SLD)

Effective leptonic weak mixing angle

arXiv:2410.02502 [hep-ex]



- Result agrees with previous direct measurements and global electroweak fit



- Comparing $A_{\rm FB}$ with predictions at NLO in strong and EW couplings allows $\sin^2\theta^\ell_{\rm eff}$ to be extracted

$$\sin^2\theta^\ell_{\rm eff} = 0.23147 \pm 0.00044_{\rm stat} \pm 0.00005_{\rm syst} \pm 0.00023_{\rm theory}$$

Summary

- LHCb's forward coverage offers a unique and important role in the study of electroweak physics
- Measurements of the Z production cross-section provide constraints on PDFs in the large and small Bjorken-x regions
- A deep understanding of the detector conditions allow precision electroweak measurements to be made
- Competitive measurements of m_W and $\sin^2\theta^{\ell}_{\mathrm{eff}}$ have been made, with the future analysis of Run 3 data predicted to significantly improve the statistical uncertainty

Backup

Curvature-bias corrections

JINST 19 (2024) P03010

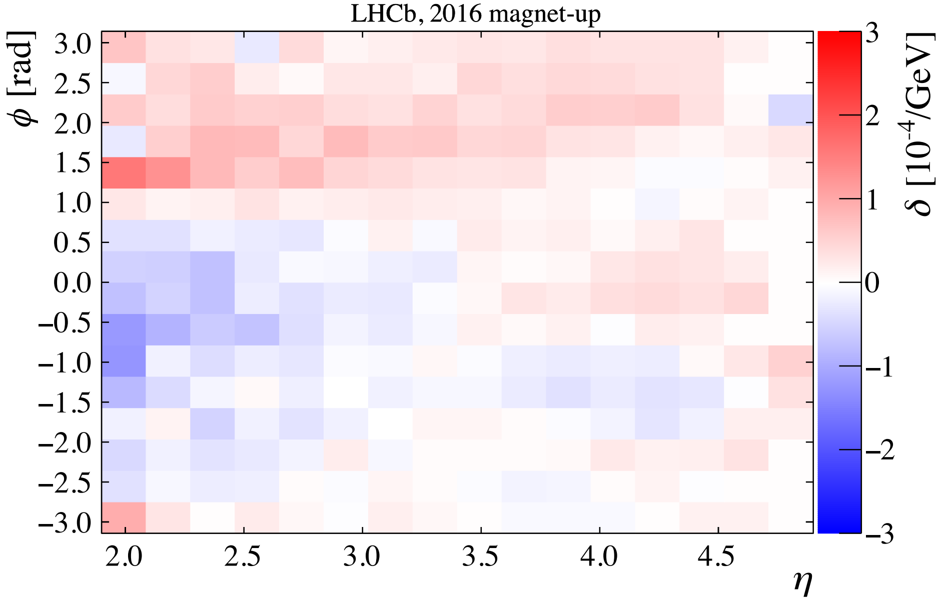
- Pseudomass method used in measurement of m_W using 2016 dataset

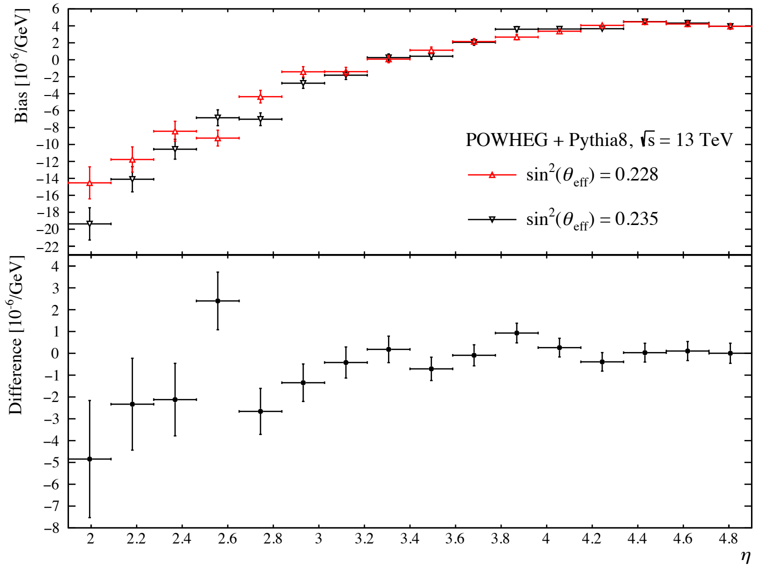
- Implementation has since been updated:
  - Assumption that $p_T^+ = p_T^-$ not perfect ⇒ some of asymmetry in peak positions due to fundamental physics
  - To avoid correcting this physics bias out of the data, calculate δ as

$$\delta = \delta_{\mathrm{DATA}} - \delta_{\mathrm{MC}}$$

  - δ_{MC} 1 – 2 order of magnitude smaller than δ_{DATA}

- Verified that corrections do not depend on physics modelling using generator level simulation with varied values for the weak mixing angle

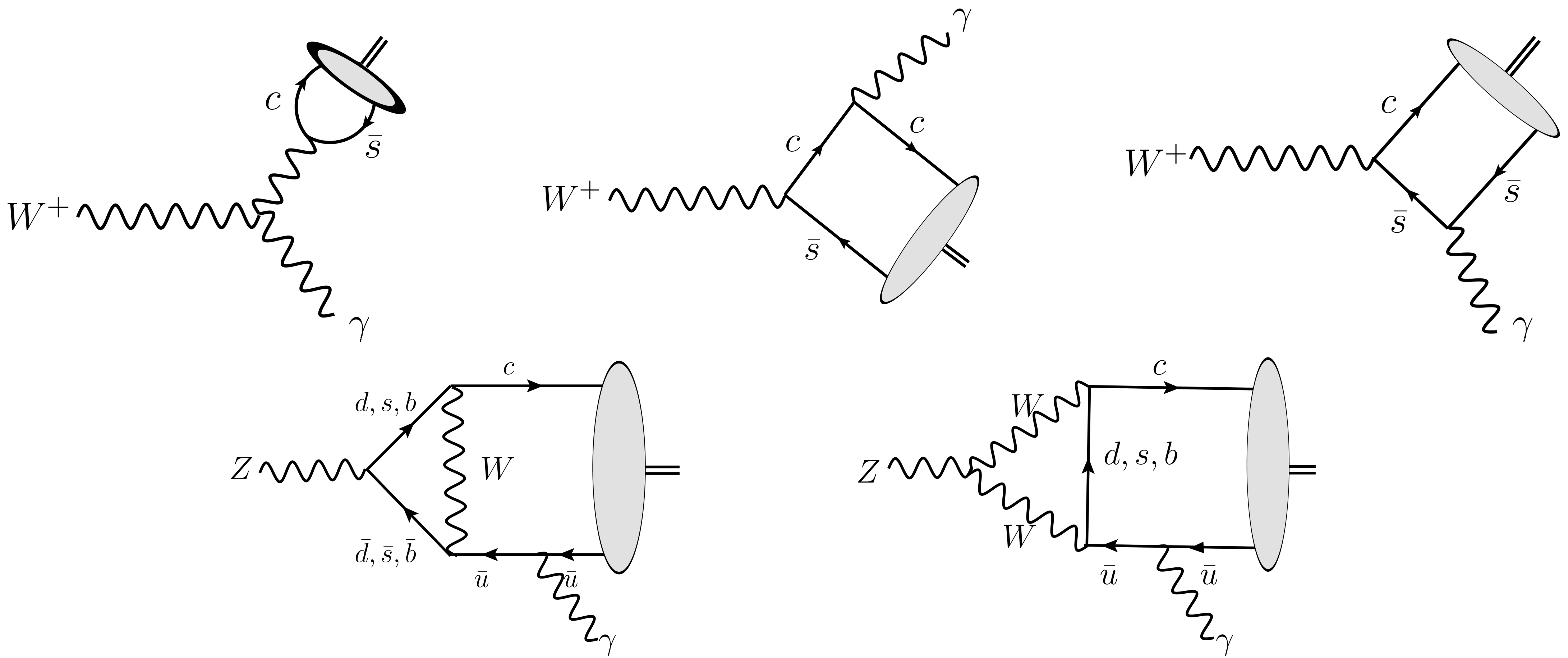




Rare W and Z decays

Chin. Phys. C 47 93002

- First reported search for $Z \to D^0\gamma(\to K^-\pi^+)$ and an updated study of $W^+ \to D_s^+\gamma(\to K^+K^-\pi^+)$
- Uses 2018 dataset; $2.0\ \text{fb}^{-1}$ collected at $\sqrt{s} = 13\ \text{TeV}$



Rare W and Z decays

Chin. Phys. C 47 93002

- No significant excesses observed

- Absolute branching ratio upper limits at 95% confidence level:
  - 6.5×10^{-4} for $W \rightarrow D_s^+\gamma$
  - 2.1×10^{-3} for $Z \rightarrow D^0\gamma$