Weak Mixing Angle, W Mass, and EW Cross Sections

Nate Grieser, on behalf of the collaboration

University of Cincinnati

2024 Implications Workshop

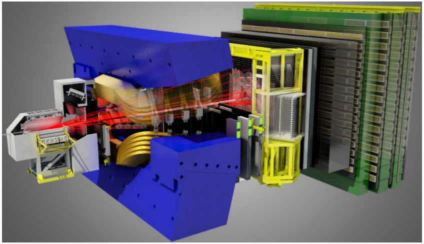
25-10-2024

LHCb Detector Overview

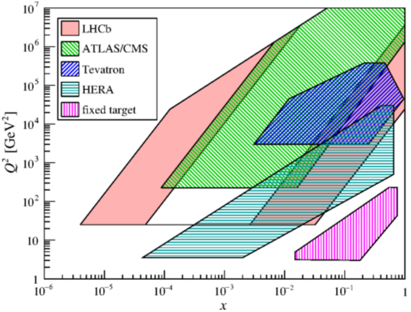
JINST 3 (2008) S08005

$\rightarrow$ LHCb Strengths of Design:

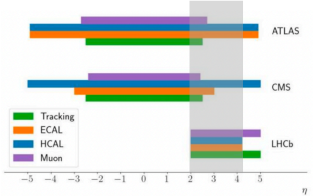
- Long tracking distances for improved flavour physics
- Ring-Imaging Cherenkov (RICH) detectors for particle identification (PID)



- Forward design allows for LHC-unique coverage of low- and high-x partons



PRD 93, 074008 (2016)



Overview

→ EW group covers an incredibly wide range of SM physics processes, leveraging the unique qualities of the LHCb experiment

What We Can Cover Today:

- Properties of EW theory (Weak Mixing Angle)
- Production cross sections of EW processes (Z boson XSecs)
- Properties of EW bosons (W Boson Mass)

Moving Beyond: What EW analyses are already planned, and what we need from our theory colleagues to make the best use of the unique LHCb datasets

▸ Ezra's QEE Overview

▸ Felicia's Exotics Presentation

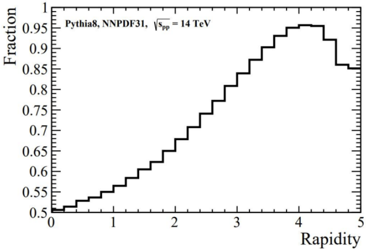
Measurement of the Effective Leptonic Weak Mixing Angle arXiv:2410.02502

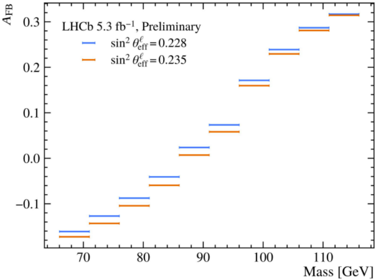
Significant probe of EW theory; relation of U(1) and SU(2) gauge couplings

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

q–$\bar{q}$ differences at high-x and low-x has significant sculpting of Z relations to initial-state partons

Fraction of events with Z in line with initial-state quark ↓





↑ Extract $\sin\theta_W$ using A_{FB}:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Mass dependent $\sin\theta_W$ no gain,

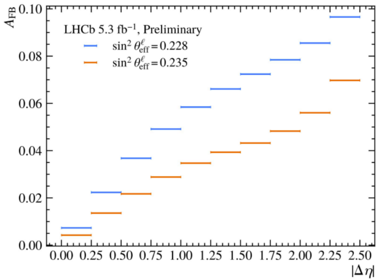
Could be used for PDF profiling

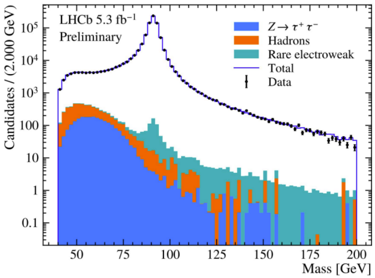
Measurement of the Effective Leptonic Weak Mixing Angle arXiv:2410.02502

Separate events at large and small $\cos\theta^*$ to increase sensitivity

$$\frac{d\sigma}{d\cos\theta^*} \propto 1 + \cos^2\theta^* + \frac{8}{3} A_{FB} \cos\theta^*$$

Bin the measurement of A_{FB} in $\Delta\eta$ of the muons shows significant sensitivity to $\sin\theta_W$ ↓



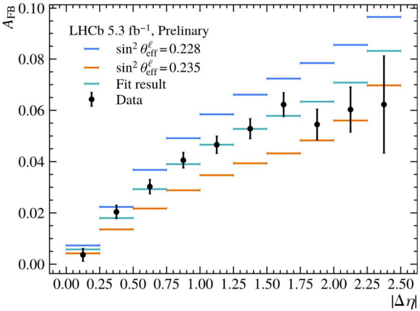


↑ Can use single, large window mass bin due to very pure signal selection

$$66\text{GeV} \leq M_Z \leq 116\text{GeV}$$

Measurement of the Effective Leptonic Weak Mixing Angle arXiv:2410.02502

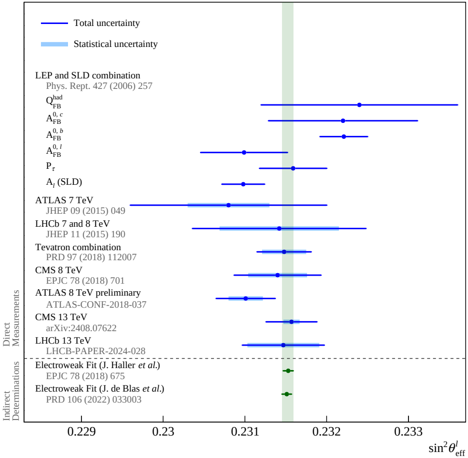
Results: $\sin\theta^{\ell}_{\text{eff}} = 0.23152 \pm 0.00044\ (\text{stat.}) \pm 0.00005\ (\text{syst.}) \pm 0.00022\ (\text{theory})$



Stats are significant limitation in the most sensitive bins

No deviation from SM observed

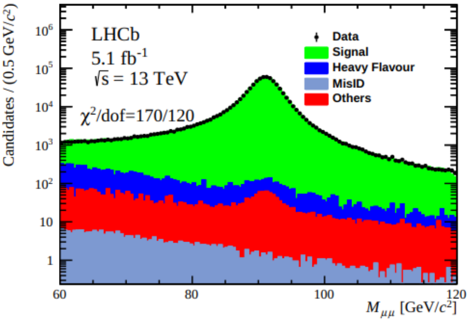
Menglin's CERN Seminar



13 TeV Forward Z Boson Precision Measurement

JHEP 07 (2022) 026

Motivation: Probe ends of the Bjorken-x spectrum for improved understanding of PDFs in these ranges
Compliment the W boson mass and cross section, along with weak mixing angle analyses, reducing future systematics



Very pure channel with basic selections:

1. m_Z window:
   $60 < m_{\mu^+\mu^-} < 120$ GeV
2. $\mu^\pm$ acceptance:
   $p_T^\mu > 20$ GeV
   $2.0 < \eta^\mu < 4.5$

Uses ϕ_η^* to probe similar physics as p_T^Z but with better resolution at collider detectors:

$$\phi_\eta^* \equiv \tan\left(\frac{\left(\pi - \Delta\phi^{\ell\ell}\right)}{2}\right) \cdot \sin\left(\theta_\eta^*\right)$$

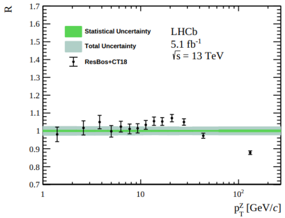
PRL 106, 122001 (2011)

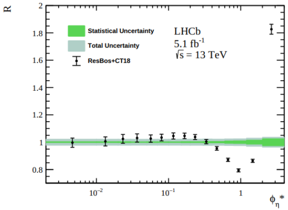
13 TeV Forward Z Boson Precision Measurement

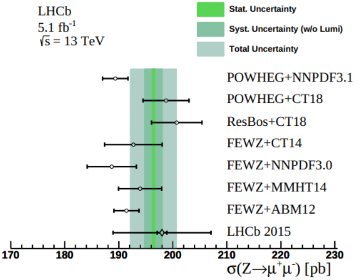
JHEP 07 (2022) 026

Results: $\sigma_{Z\to\mu^+\mu^-} = 196.4 \pm 0.2\ (\text{stat.}) \pm 1.6\ (\text{syst.}) \pm 3.9\ (\text{lumi.})\ \text{pb}$

$\to$ High statistics allows for single- and double-differential measurement in y^Z, p_T^Z, or ϕ_η^*







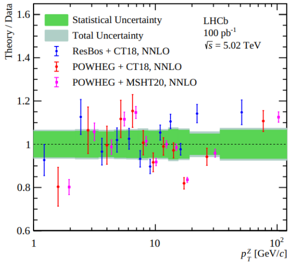
$\uparrow$ Integrated cross-section results show agreement with theoretical predictions and the previous LHCb measurement

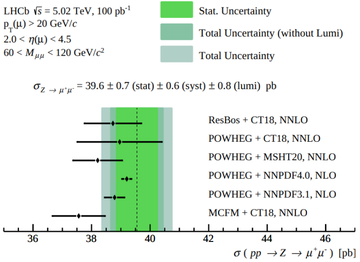
$\leftarrow$ Sizable disagreements from theory are observed in high p_T^Z and ϕ_η^* regions, which need further investigation ResBos Generator

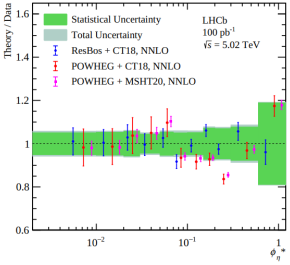
5.02 TeV Forward Z Boson σ Measurement

JHEP 02 (2024) 070

Results: $\sigma_{Z\to\mu^+\mu^-} = 39.6 \pm 0.7$ (stat.) ± 0.6 (syst.) ± 0.8 (lumi.) pb







↑ Integrated cross-section results show agreement with theoretical predictions
← Agreements from theory for multiple generators are observed in p_T^Z, ϕ^*_η, and y^Z differential calcuations → Strongly statistically limited

Nuclear modification factors are calculated with respect to the pPb measurement:

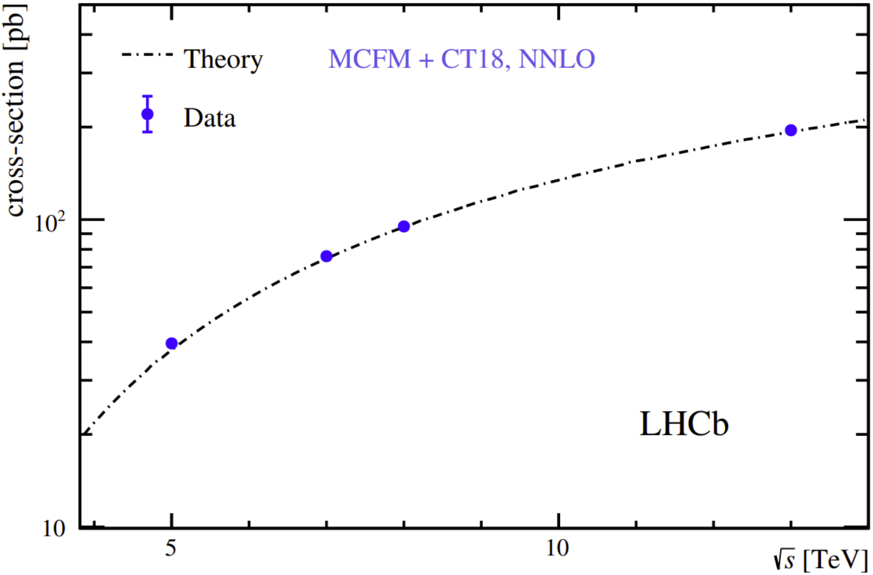
$R^F_{pPb} = 1.2^{+0.5}_{-0.3}$ (stat.) $\pm$ 0.1 (syst.)

$R^B_{pPb} = 3.6^{+1.6}_{-0.9}$ (stat.) $\pm$ 0.2 (syst.)

JHEP 09 (2014) 030

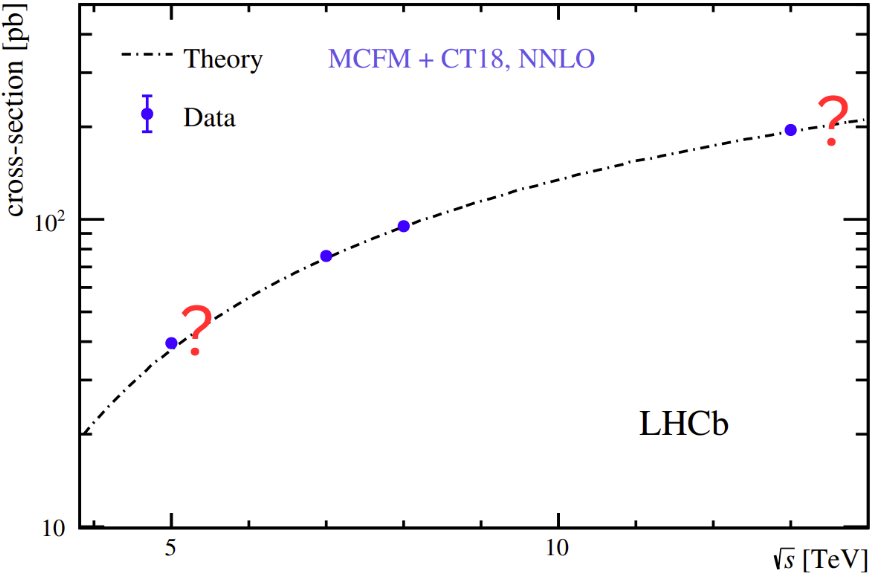
Z Cross Sections – To the Future

JHEP 02 (2024) 070



Z Cross Sections – To the Future

JHEP 02 (2024) 070



Measurement of the W Boson Mass

JHEP 01 (2022) 036

Mass of the W boson is one of three free parameters of electroweak theory:

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

Measured values deviating from prediction can give evidence of new physics in the higher order corrections (Δr)

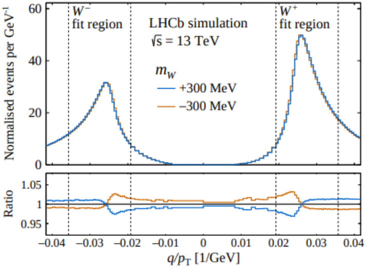
→ A lot of recent activity on this front with numerous collaborations producing interesting measurements

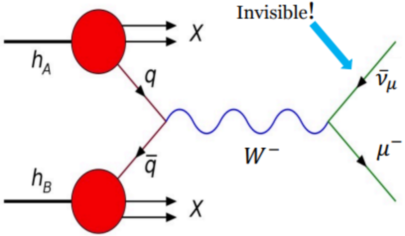
Measurement of the W Boson Mass

JHEP 01 (2022) 036

Analysis Strategy: Select well-isolated muons, performing significant momentum calibrations to ensure precision

The analysis uses q/p_T^{μ} to allow for visualization of all muons with $p_T > 24$ GeV $\downarrow$



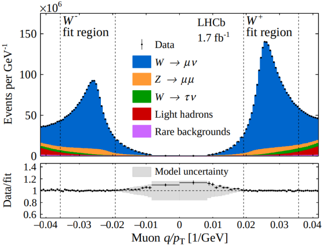


Calibrations of p_T^{μ} are carried out using $\Upsilon(1S) \to \mu\mu$ and $J/\Psi \to \mu\mu$ channels, validated with $Z \to \mu\mu$ distributions

Measurement of the W Boson Mass

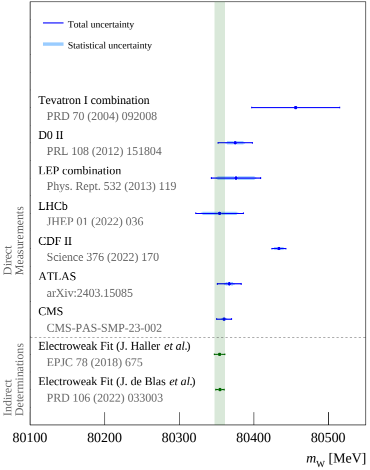
JHEP 01 (2022) 036

Results: $m_W = 80354 \pm 23\,(\text{stat.}) \pm 10\,(\text{exp.}) \pm 17\,(\text{theory}) \pm 9\,(\text{PDF})$ MeV

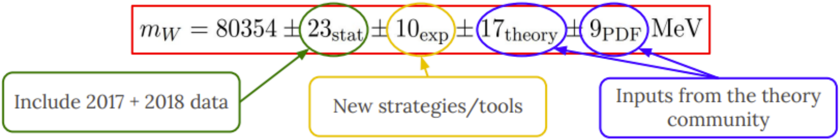


→Current analysis based only on 1/3 of LHCb Run-2 dataset (2016)

PDF uncertainties are anti-correlated between central and forward measurements → Significant contribution to global fits!



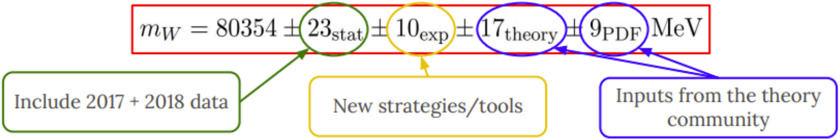
Measurement of the W Boson Mass – Making Progress



1. Cross checks between years, polarities, etc.; Selection validation and improvements
2. More robust application of pseudo-mass method for curvature bias corrections JINST 19 (2024) P03010
3. Full detector simulation for misidentified hadron background
4. State-of-the-art modelling of boson production (PowPy $\rightarrow$ DYTurbo up to N2LL)
5. New PDF sets (NNPDF4.0) $\rightarrow$ Have feedback?

Miguel's mW Days Talk

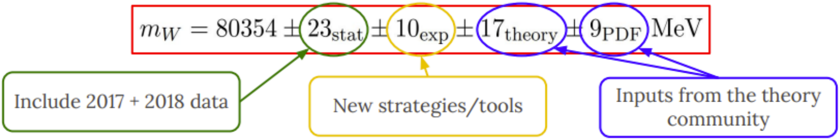
Measurement of the W Boson Mass – Making Progress



1. Cross checks between years, polarities, etc.; Selection validation and improvements
2. More robust application of pseudo-mass method for curvature bias corrections JINST 19 (2024) P03010
3. Full detector simulation for misidentified hadron background
4. State-of-the-art modelling of boson production (PowPy $\rightarrow$ DYTurbo up to N2LL)
5. New PDF sets (NNPDF4.0) $\rightarrow$ Have feedback?

Miguel's mW Days Talk

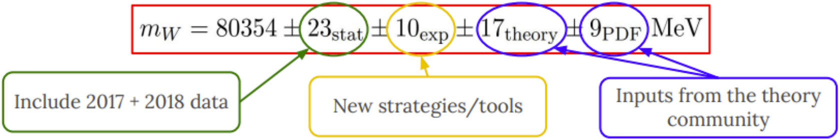
Measurement of the W Boson Mass – Making Progress



1. Cross checks between years, polarities, etc.; Selection validation and improvements
2. More robust application of pseudo-mass method for curvature bias corrections JINST 19 (2024) P03010
3. Full detector simulation for misidentified hadron background
4. State-of-the-art modelling of boson production (PowPy $\rightarrow$ DYTurbo up to N2LL)
5. New PDF sets (NNPDF4.0) $\rightarrow$ Have feedback?

Miguel's mW Days Talk

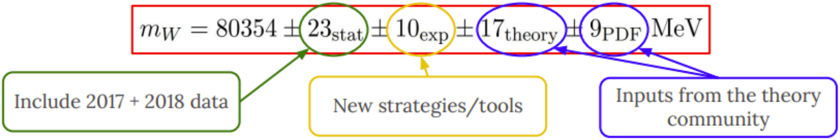
Measurement of the W Boson Mass – Making Progress



1. Cross checks between years, polarities, etc.; Selection validation and improvements
2. More robust application of pseudo-mass method for curvature bias corrections JINST 19 (2024) P03010
3. Full detector simulation for misidentified hadron background
4. State-of-the-art modelling of boson production (PowPy → DYTurbo up to N2LL)
5. New PDF sets (NNPDF4.0) → Have feedback?

Miguel's mW Days Talk

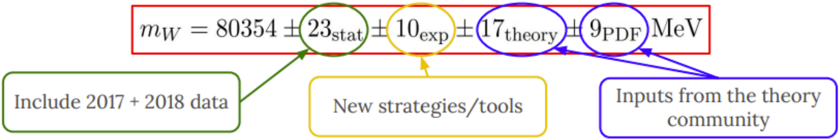
Measurement of the W Boson Mass – Making Progress



1. Cross checks between years, polarities, etc.; Selection validation and improvements
2. More robust application of pseudo-mass method for curvature bias corrections JINST 19 (2024) P03010
3. Full detector simulation for misidentified hadron background
4. State-of-the-art modelling of boson production (PowPy $\rightarrow$ DYTurbo up to N2LL)
5. New PDF sets (NNPDF4.0) $\rightarrow$ Have feedback?

Miguel's mW Days Talk

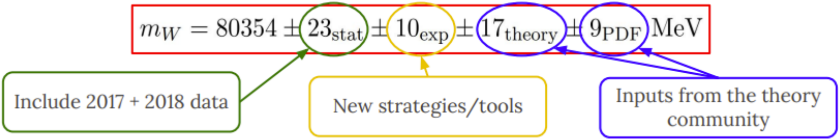
Measurement of the W Boson Mass – Making Progress



1. Cross checks between years, polarities, etc.; Selection validation and improvements
2. More robust application of pseudo-mass method for curvature bias corrections JINST 19 (2024) P03010
3. Full detector simulation for misidentified hadron background
4. State-of-the-art modelling of boson production (PowPy $\rightarrow$ DYTurbo up to N2LL)
5. New PDF sets (NNPDF4.0) $\rightarrow$ Have feedback?

Miguel's mW Days Talk

Measurement of the W Boson Mass – Making Progress



1. Cross checks between years, polarities, etc.; Selection validation and improvements
2. More robust application of pseudo-mass method for curvature bias corrections JINST 19 (2024) P03010
3. Full detector simulation for misidentified hadron background
4. State-of-the-art modelling of boson production (PowPy $\rightarrow$ DYTurbo up to N2LL)
5. New PDF sets (NNPDF4.0) $\rightarrow$ Have feedback?

Goal: 20 MeV Sensitivity

Miguel's mW Days Talk

Continuing to Leverage Run 2 Dataset

New, unique measurements are still to come from Run 2

1. Cross Section Measurements:
   - W XSec, 5 TeV W XSec, Leptonic WW XSec, DPS measurements, ...
2. Properties of EW bosons:
   - Mass of W/Z Boson, W Helicity distributions, ...
3. Jet-involved measurements:
   - Hbb, W + Jets XSec, Semi-Leptonic WW XSec, ...

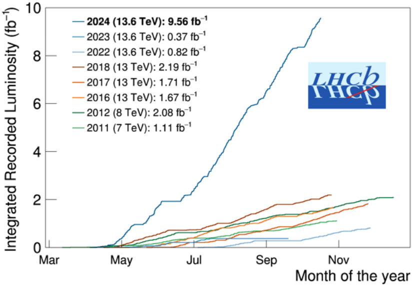
Getting the Most Out of Run 3 Dataset

→ LHCb Run 3 will offer a unique environment for EW physics at the LHC and is already underway

- Forward fiducial region with relatively low pile-up
- Expected luminosity above 25 fb^{-1} → More opportunities!
- Malleable fully software-based trigger

Caveat: EW-scale analysis activity is a small group with a huge phase-space to cover

→ **Need collaboration with theorists to make sure we are covering the most impactful measurements to the community**



BACKUP