Precision electroweak measurements in LHCb

Miguel Ramos Pernas

on behalf of the LHCb collaboration

University of Warwick

miguel.ramos.pernas@cern.ch

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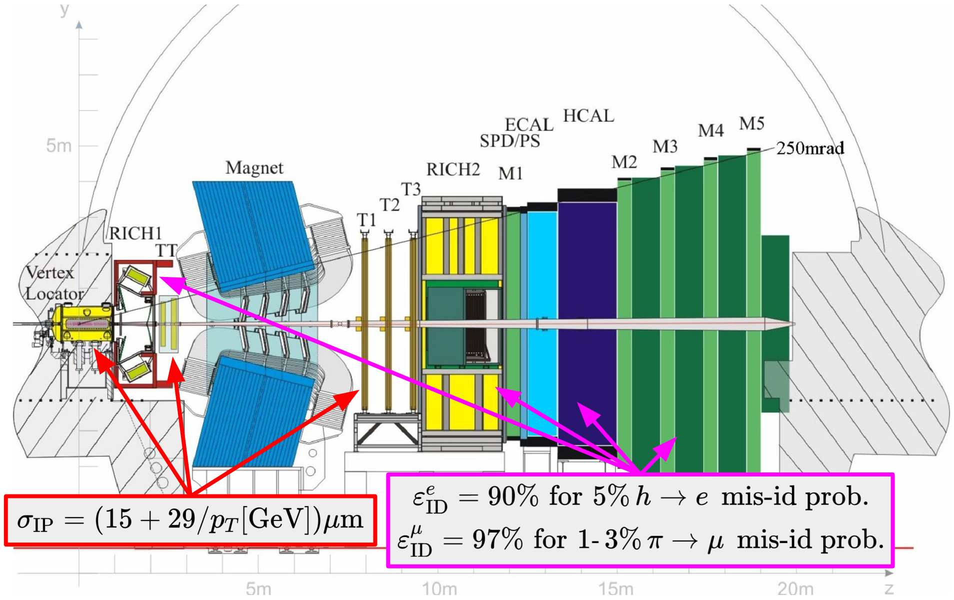
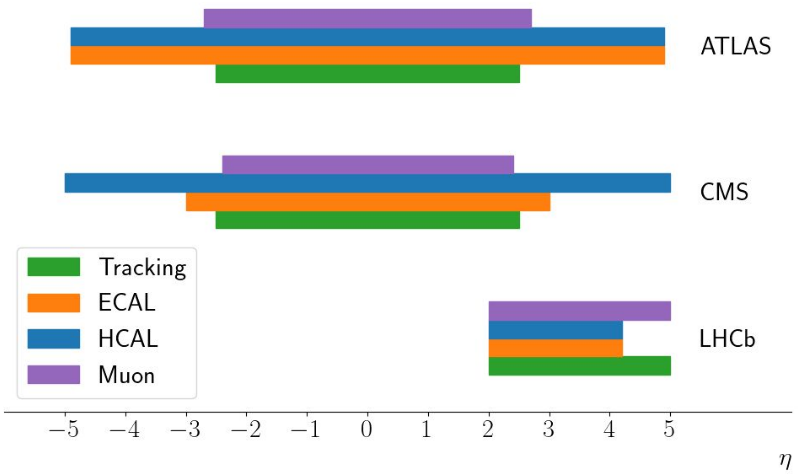
The LHCb detector





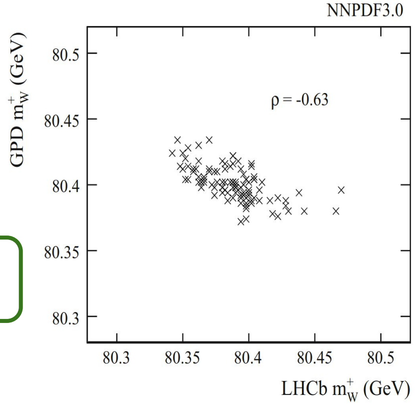
- Detector in the forward region with excellent momentum and vertex resolutions
- Coverage is complementary to ATLAS and CMS (with some overlapping at low pseudorapidity)

The unique scope of the LHCb detector

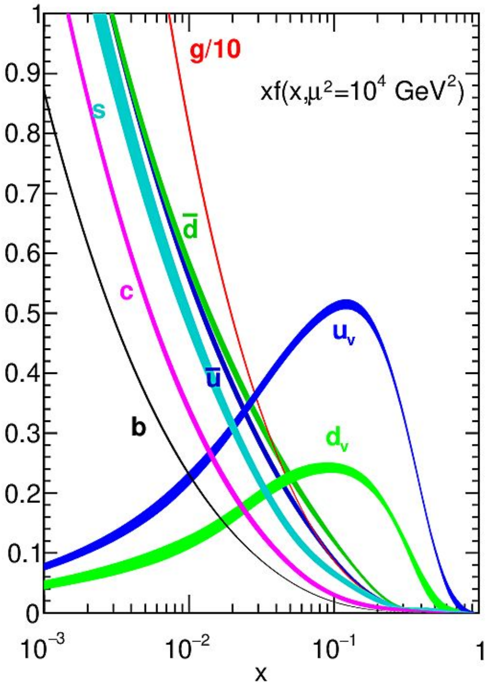
- The **enhanced coverage in the forward region** offers unique opportunities for studies at LHCb
  - Low and high Bjorken-x regions can be studied, hardly accessible for ATLAS and CMS
- The LHCb detector can provide valuable **measurements of cross-sections** and **fundamental quantities**
  - Competitive measurements with muonic modes
  - Possibility of studying associate production thanks to jet reconstruction
- The complementarity to ATLAS and CMS has **remarkable effects in LHC combinations**

CMS & ATLAS

Up to a factor of 2 of reduced systematic uncertainty from PDFs in the W mass measurement



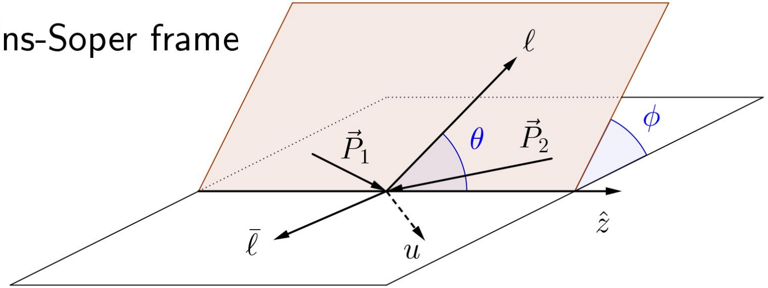
[EPJC 75, 601 (2015)]



NNPDF, [CERN-TH-2017-077]

The single-boson production cross-section

Collins-Soper frame



Unpolarized part

$$\frac{d\sigma}{dp_T dy dM d\cos\theta d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T dy dM}$$

(At order α_s^2)

$$\{(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+ A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\}$$

Angular part

Cross-section studies

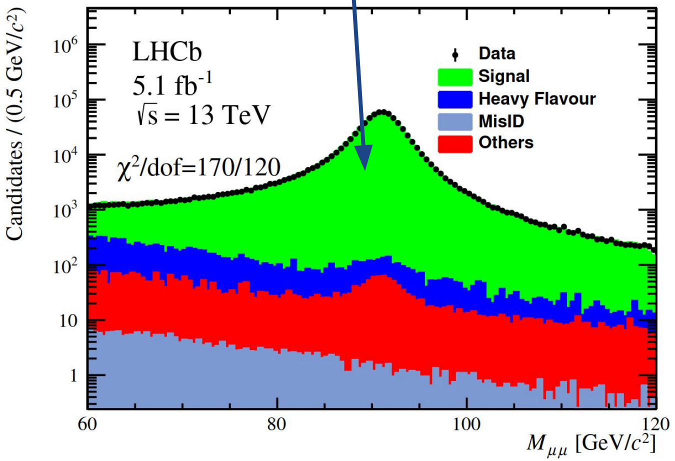
Z production cross-section at 5 and 13 TeV

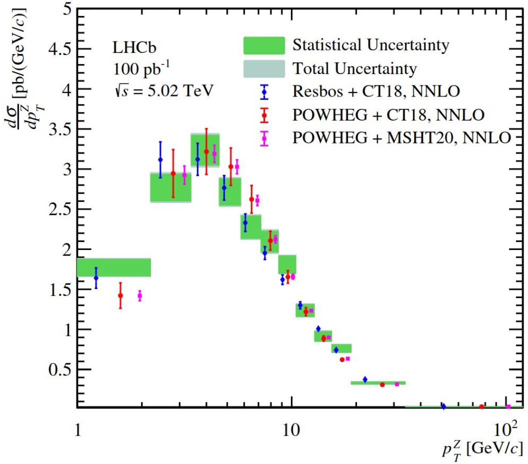
[JHEP 02 (2024) 070]

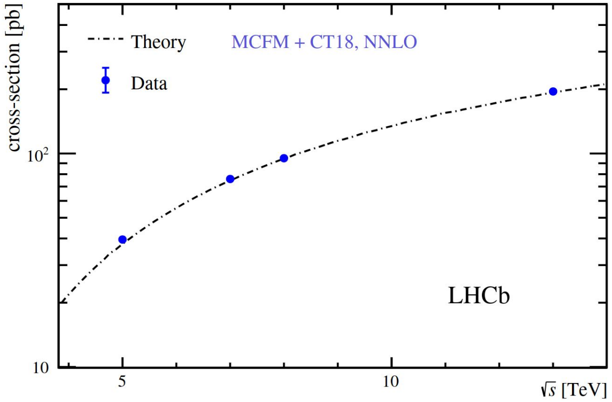
- **Testing NNLO perturbative QCD** with similar precision experiment/theory O(1%)
- Using Run 2 data (2016-2018), **normalized** to the **measured luminosity at LHCb**
- LHCb has published Z cross-section measurements at 7, 8, 13 and **lately 5.02 TeV**

Heavy flavour and particle-misidentification backgrounds taken from data; use simulation for the rest (total 2%)

[JHEP 07 (2022) 026]





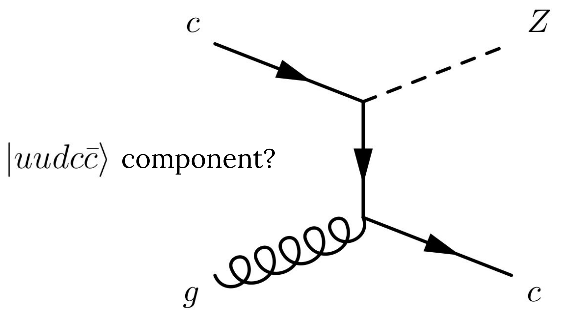


- Possibility to cross-check the QCD parameters or **tune generators for other analyses** e.g. W mass measurement
- In the future, **profit from luminometers** like PLUME to **reduce the luminosity uncertainty** [LHCB-TDR-022]

$$\sigma^{13\ \mathrm{TeV}}_{\mathrm{fiducial}}(Z \to \mu^+\mu^-) = 196.4 \pm 0.2 \pm 1.6 \pm 3.9\ \mathrm{pb}$$

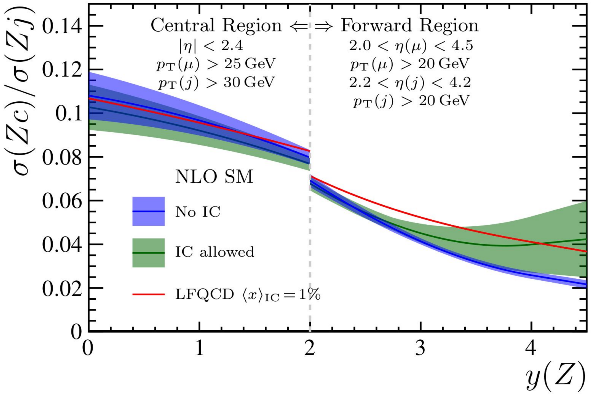
$$\sigma^{5.02\ \mathrm{TeV}}_{\mathrm{fiducial}}(Z \to \mu^+\mu^-) = 39.6 \pm 0.7 \pm 0.6 \pm 0.8\ \mathrm{pb}$$

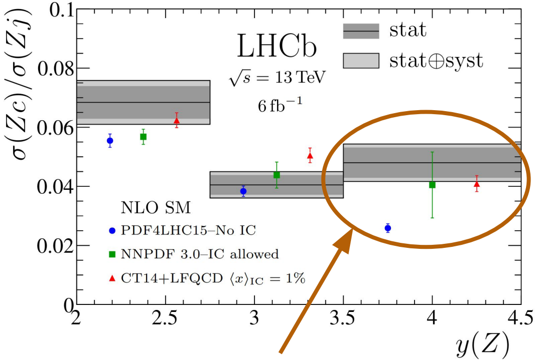
Z + charm production



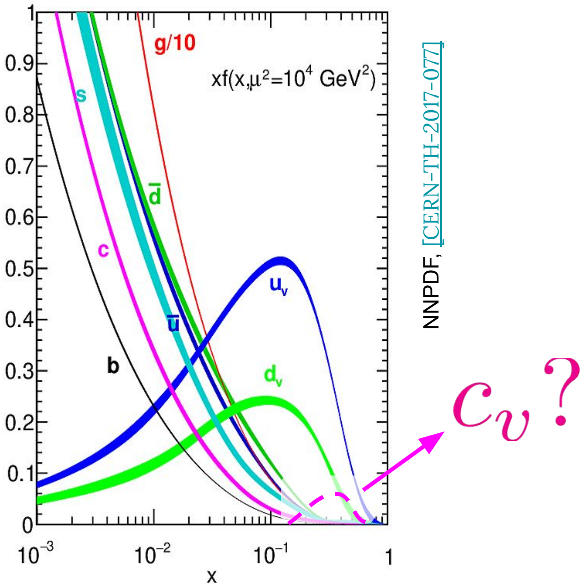
- Test for the presence of **charm quarks in the proton wave-function**
  - Having charm valence quarks opens new channels for W and Z production mechanisms
  - Strong implications in the definition of the PDFs and the understanding of the proton structure
- Several tests done in the past and recently, with **inconclusive results so far**
- The **LHCb analysis using full Run 2 data** shows some tension at high rapidity with non-IC models

[PRL 128 (2022) 082001]





Sizeable difference if no IC component is considered

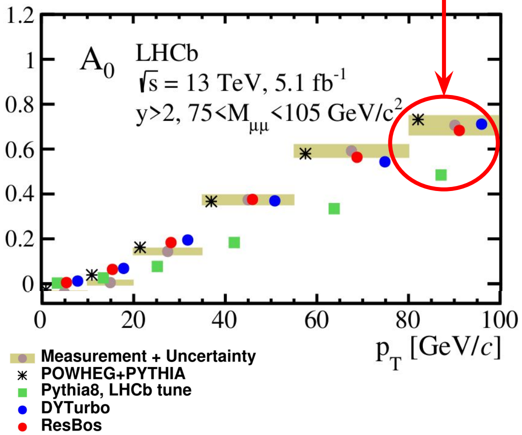


Measuring the weak-mixing angle

The angular coefficients

Pythia @ LO gives a poor description of the coefficients

- The angular **cross-section** of bosons (S=1) can be expressed as a function of **9 harmonic spherics**, with their accompanying coefficients A_i
- All the A_i are highly sensitive to next-to-leading order corrections, in such a way that all of them are close to zero at LO except for **A_4, related to the weak mixing angle**
- **LHCb measured** these **coefficients** with **full Run 2 data** at **13 TeV**
  - Especially valuable to validate predictions at low transverse momentum



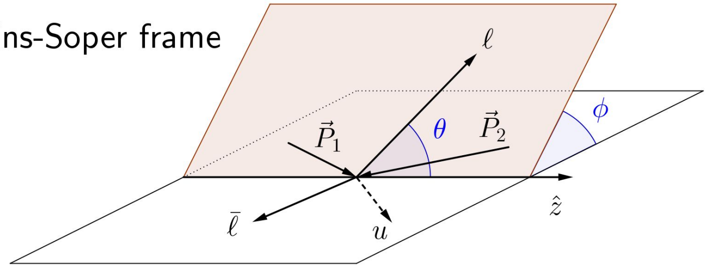
[PRL 129 (2022) 091801]

$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi$$
$$+A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi$$

Condenses information on the parity violation in weak interactions

$A_0 = A_2$ at LO for quark-antiquark and gluon-quark processes (Lam-Tung relation)

The weak mixing angle



- It is an useful quantity to **test the custodial symmetry** of the Standard Model
  - Measuring the weak-mixing angle can also be seen as an indirect measurement of the W boson mass:

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

- The treatment of A_4 deserves a special attention, since **condenses information** about the **vector** and **axial-vector couplings** of the Z boson, and is related to the weak-mixing angle
- It becomes interesting to perform singular measurements that **maximize** the **sensitivity to the weak mixing angle** (e.g. dilepton mass)
- The measurement is **more challenging at** the **LHC compared to LEP**, since it condenses information on the proton polarization

The definition of **"forward"** and **"backward"** is more ambiguous due to the **difference between quark** and **hadron level** information

$$A_{\mathrm{fb}} = \frac{\sigma_f - \sigma_b}{\sigma_f + \sigma_b} = \frac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}$$

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

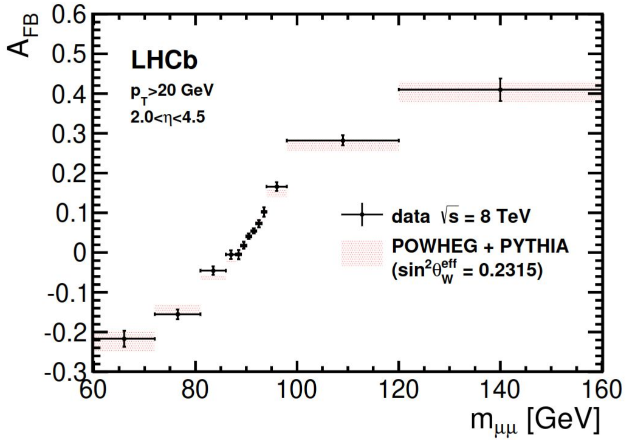
$$\cos\theta^* = \frac{2(p_\ell^+ p_{\bar\ell}^- - p_\ell^- p_{\bar\ell}^+)}{m_{\ell\bar\ell}\sqrt{m_{\ell\bar\ell}^2 + p_{T,\ell\bar\ell}^2}}\mathrm{sign}(p_{z,\ell\bar\ell})$$

$$p^\pm_{\ell(\bar\ell)} = \frac{1}{\sqrt{2}}\left(E_{\ell(\bar\ell)} \pm p_{z,\ell(\bar\ell)}\right)$$

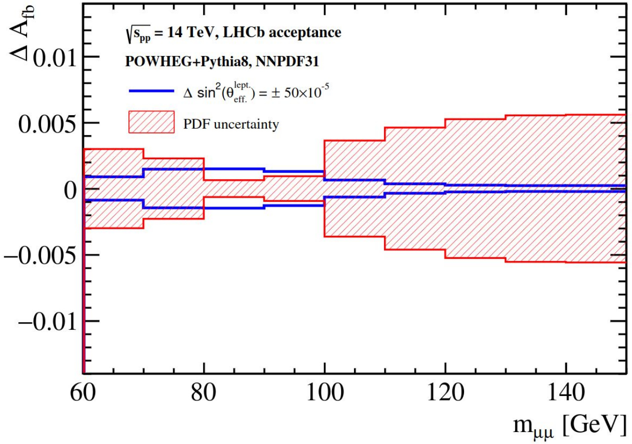
The weak mixing angle

- The **measurement** of the **weak mixing** angle at the LHC is highly dependent on the **interplay between proton-level and quark-level** quantities (especially in the definition of the z axis)
  - The PDF uncertainties dominate and restrict the precision
- **These effects are reduced in** the forward region (**LHCb**), where the dilution between proton and parton level is reduced
  - A high-x parton (typically a valence quark) interacts with a low-x parton (typically a sea anti-quark)
  - Mitigating the effect of the PDF uncertainties becomes crucial through e.g. profiling in ATLAS & CMS, but not in LHCb
- At **LHCb** we have **published** the measurement at **7 and 8 TeV**
  - With 13 TeV data we expect the sensitivity to be around $5 \cdot 10^{-4}$

$$\sin^2 \theta_W^{\text{eff.}} (\text{Run 1}) = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056$$

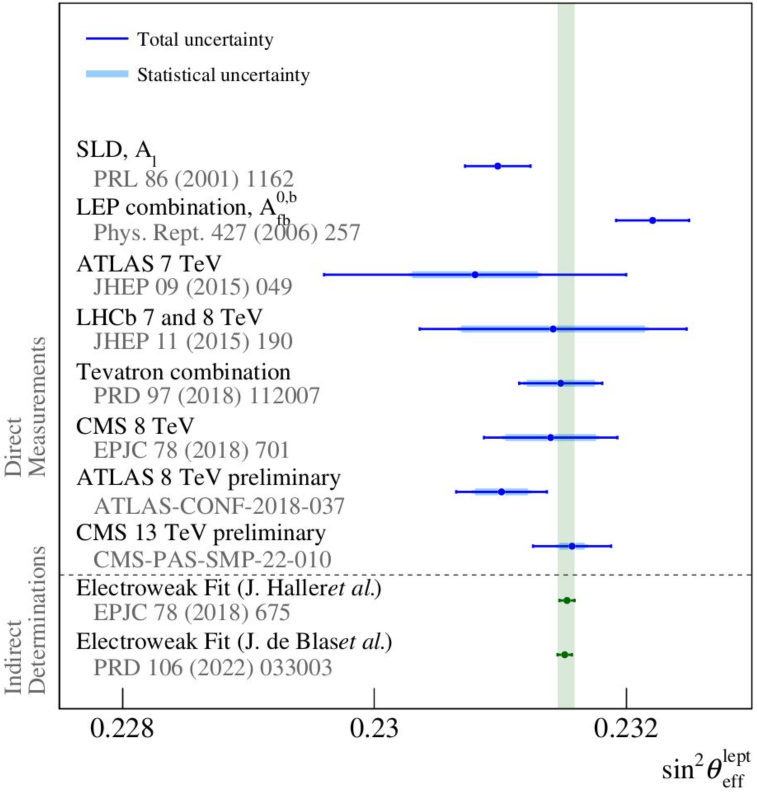


[JHEP 1511(2015) 190]



[LHCb-PUB-2018-013]

The weak mixing angle



0.00027 coming from PDFs!

- CMS has recently published

$$\sin^2\theta^{\rm lept}_{\rm eff}(\text{CMS @ 13TeV}) = 0.23157 \pm 0.00031$$

- At LHCb we still need to **process** the **data collected in Run 2 at 13 TeV**
  - Similar experimental improvements as for the W mass
  - Expected to fall in the same ballpark as the GPDs
- The **HL-LHC** has a **big potential** to drastically improve the accuracy
  - Improved detectors
  - x10 more luminosity
- **Beating** the **LEP** experiments **is possible** in the future

$$\sin^2\theta^{\rm lept}_{\rm eff}(\text{LEP}) = 0.23221 \pm 0.00029$$

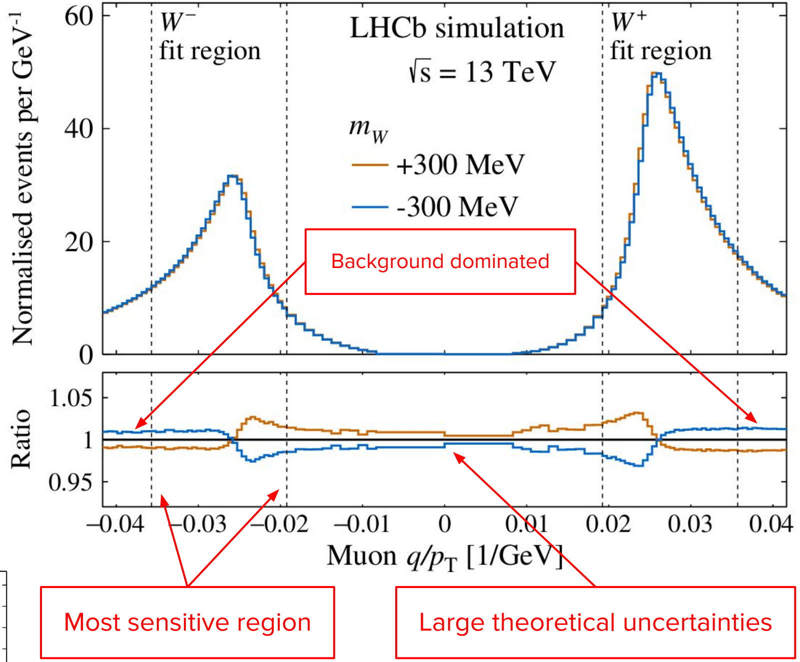
$$\sin^2\theta^{\rm lept}_{\rm eff}(\text{Tevatron}) = 0.23148 \pm 0.00033$$

W mass measurement at LHCb

Analysis strategy

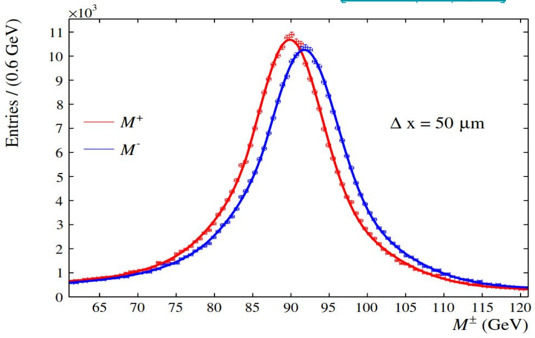
[JHEP 01 (2022) 036]

- Similar sensitivity to that of ATLAS can be achieved using the **muonic mode**
- **Template fit in a 5D space** floating the W mass and nuisance parameters
  - Based on Pythia8 and reweighted at generator level on the fly
- Use the **J/ψ, Υ(1S) and Z** to **calibrate** the simulation, momentum scale and efficiencies



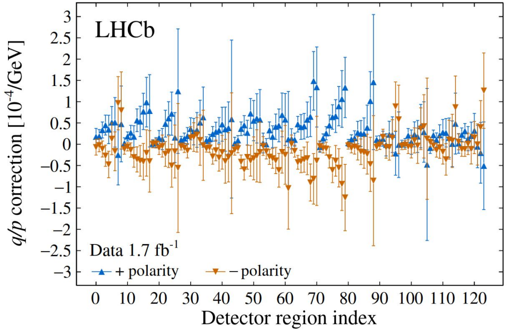
$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)}$$

[EPJ-C 81 (2021) 3, 251]



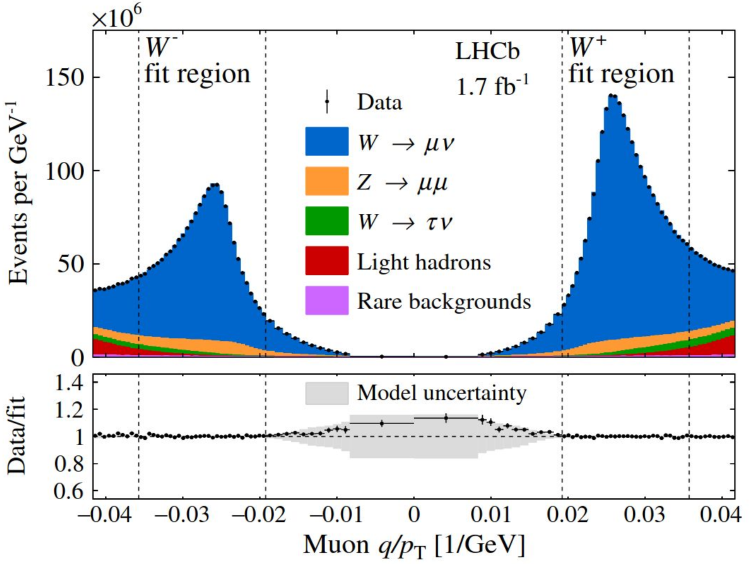
$$\frac{q}{p} \rightarrow \frac{q}{p} + \delta(\eta,\phi) \text{ where } \delta(\eta,\phi) \sim 10^{-4}$$

[JHEP 01 (2022) 036]



$$p_T^{\mu} \sim \frac{m_W}{2}\sin\theta + p_T\cos\phi$$

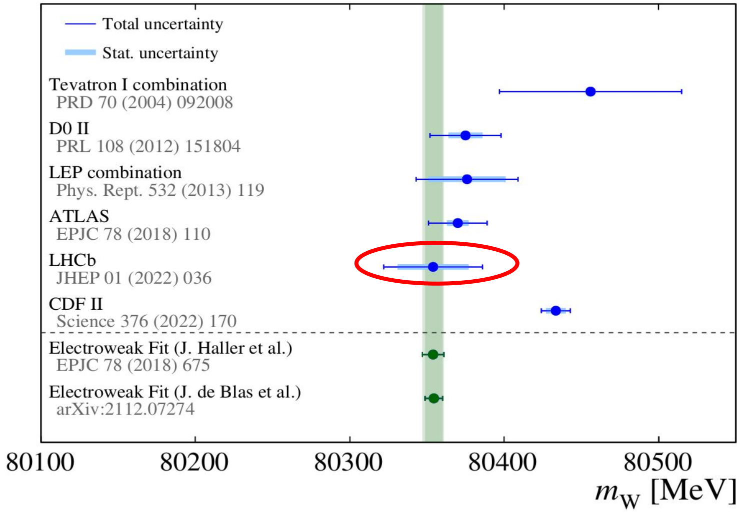
The result

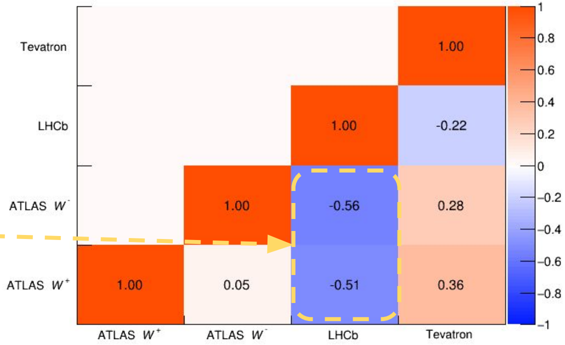


[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

[LHCB-FIGURE-2022-003]

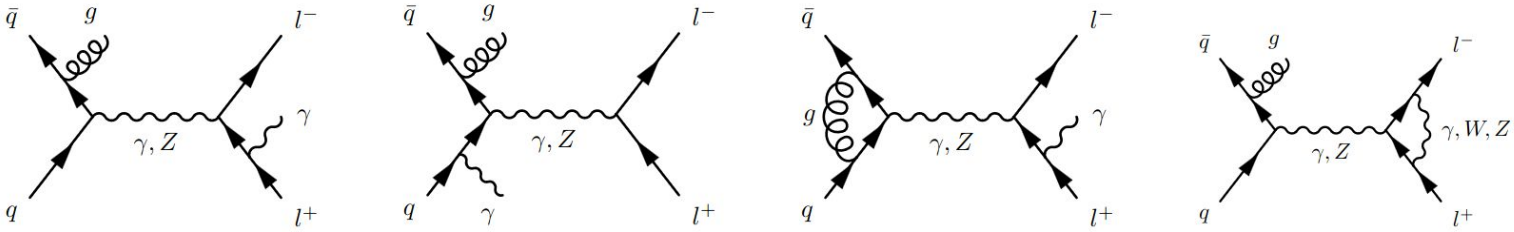




The compatibility of the measurements is studied in [arXiv:2308.09417 (submitted to EPJC)]. The observed anticorrelation of the PDF uncertainties between ATLAS and LHCb agrees with the expectations.

The main source of improvements

- **The analysis** is currently being **completely revisited** to include data from 2017 and 2018
  - An optimization of the calibrations, momentum scale and efficiencies has been done
  - The experimental systematic uncertainties have been re-evaluated, and correlations have been taken into account more carefully
- A more **careful study** is being done on the **theoretical aspects**
  - Drop known inaccurate PDF sets or combination of generators
  - Use more accurate predictions of the cross-section NLO+NLL → N2LO+N2LL
  - Completely revisit the QED (+FSR) modelling using POWHEG-EW: NLO(QCD) + NLO(EW)



Reducing the systematic uncertainties

[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

Source	Size (MeV)
Parton distribution functions	**9**
Total theoretical syst. uncertainty (excluding PDFs)	**17**
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Total experimental syst. uncertainty	**10**
Momentum scale and resolution modelling	7
Muon ID, tracking and trigger efficiencies	6
Isolation efficiency	4
QCD background	2
Statistical	**23**
Total uncertainty	**32**

Previous result (2016 data)

Switch to N2LO, N2LL

21 to 7 point variation in DYTurbo

better estimates of QED corrections and FSR

improvement on the treatment of correlated uncertainties

New background model

Tentative values for the full Run 2 data set

Source	Size (MeV)
Total theoretical syst. uncertainty (excluding PDFs)	**8**
Transverse momentum model	6
Angular coefficients	4
QED model	4
Total experimental syst. uncertainty	**8**
Momentum scale and resolution modelling	5
Muon ID, tracking and trigger efficiencies	4
Isolation efficiency	4
QCD background	2
Statistical	**14**
Total uncertainty	**18**

These are **simple guesstimates** of the values based on some quick calculations and due to the luminosity increase **(don't take them too seriously)**

Conclusions

- The **LHCb** detector offers **unique capabilities** to do precision electroweak measurements in the **forward region**
  - Complementary coverage to ATLAS and CMS
  - Interesting benefits in analyses like the weak mixing angle (e.g. PDF uncertainties)
  - Helps to reduce the PDF uncertainties when doing LHC combinations
- LHCb has achieved **competitive measurements** in fundamental quantities with **Run 1 data** and only **part of Run 2 data**
  - Much more data available on tape currently being processed
  - Some related analyses are close to completion
- We foresee an **exciting future ahead of us** with new measurements and an increased data sample in Run 3

Thank you!