



# EW Precision Measurements at LHCb

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CERN

on behalf of the LHCb Collaboration

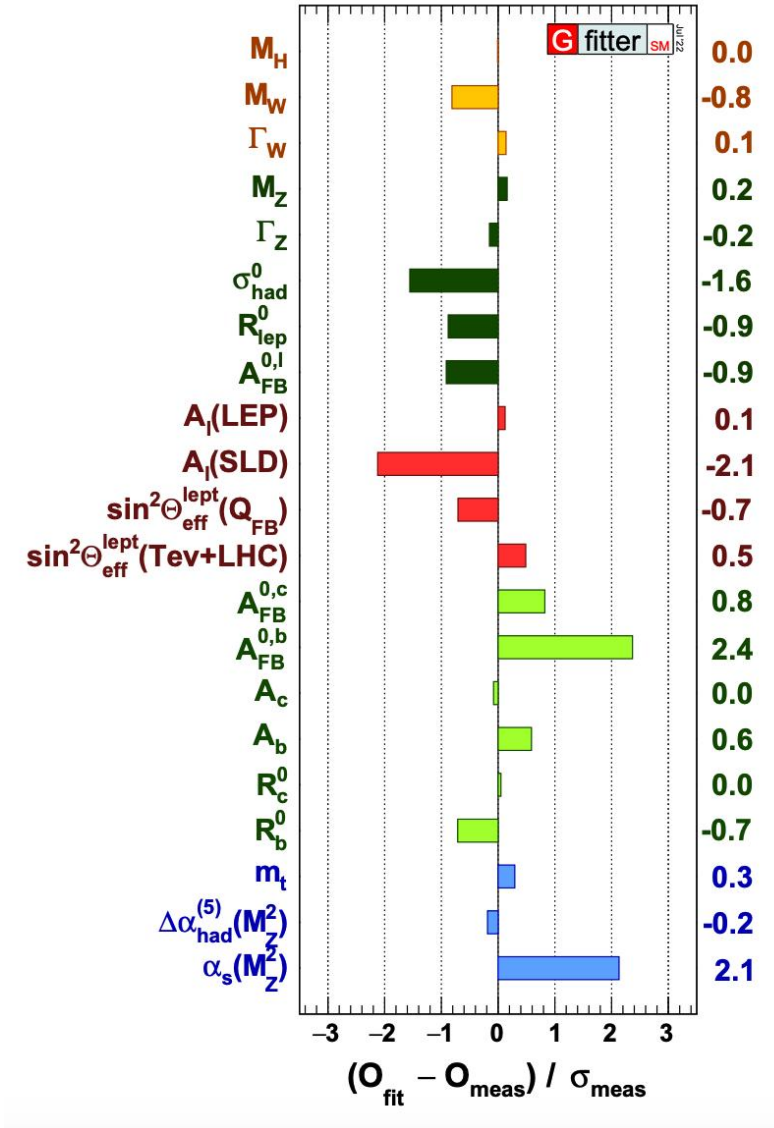
ICNFP2025, 24 July 2025, Kolymbari



# Electroweak (EW) Physics

- The EW sector is one of the best understood sectors of the SM  
the highest precision possible
- Both theoretical predictions and experimental measurements have remarkable precision
- Deviations potentially indicate the presence of BSM physics
- High-precision EW physics is sensitive to NP at multi-TeV scales, and new particles we might not be able to directly produce at the LHC

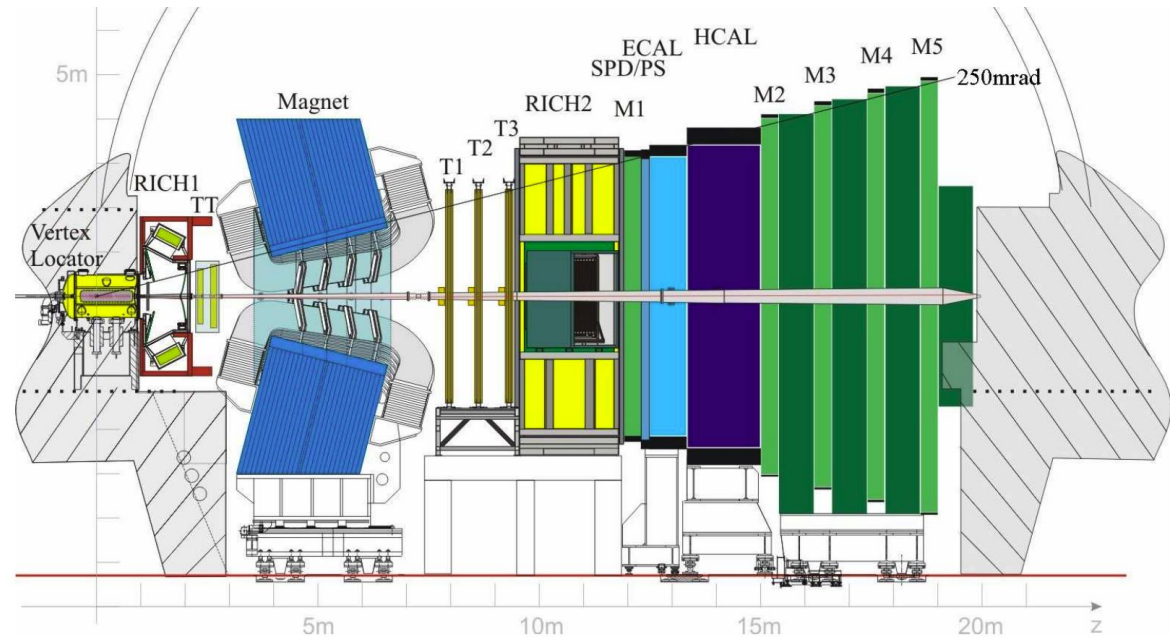
[arXiv:2211.07665v1](https://arxiv.org/abs/2211.07665v1)



# The LHCb Run2 Detector

- Small angle spectrometer, covering the forward region,  $2 < \eta < 5$
- The detector has a high-precision tracking system
- Momentum resolution,  $\Delta p/p \sim 0.5\%$
- High purity PID for muons,  $\varepsilon(\mu) > 95\%$

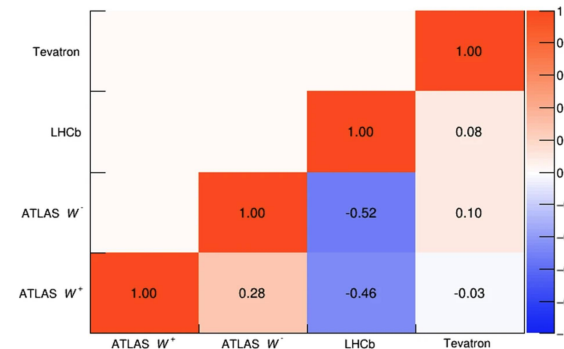
JINST 3 (2008) S08005



# Why LHCb

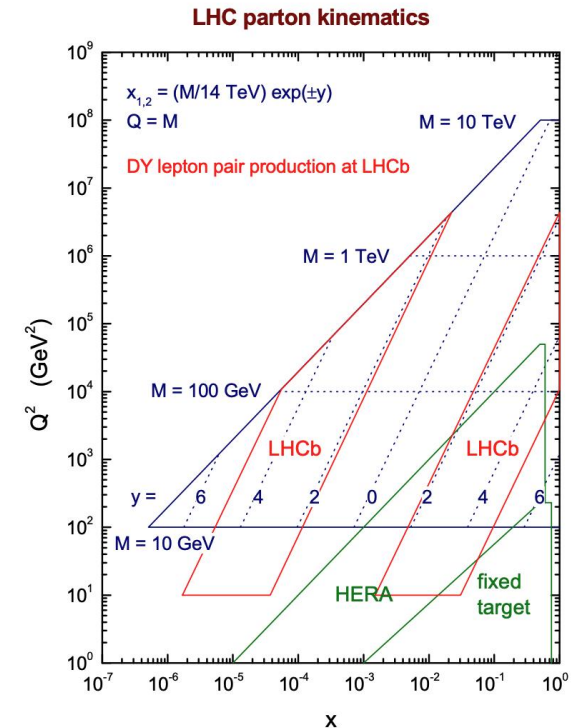
- LHCb covers the forward region
  - measurements can constrain the PDFs at both high and low parton momentum fractions
- The complementarity to ATLAS and CMS has remarkable effects in LHC combinations
  - for  $m_W$  measurement, PDF uncertainty is anticorrelated, including LHCb data helps reduce the overall PDF uncertainty

[arXiv: 0808.1847v1](https://arxiv.org/abs/0808.1847v1)



(before latest CMS & ATLAS  $m_W$  measurement)

[EPJC 84 451 \(2024\)](https://arxiv.org/abs/2401.12345)



# Electroweak Measurements at LHCb [full shopping list](#)

- $W$  and  $Z$  boson cross section measurement [JHEP 01 \(2016\) 155](#), [JHEP 01 \(2022\) 026](#) ...
- $m_W$  measurement with 2016 data [JHEP 01 \(2022\) 036](#)
- $Z \rightarrow \mu^+ \mu^-$  angular coefficients measurements with Run2 data [Phys. Rev. Lett. 129 \(2022\) 091801](#)
- Measurement of the effective leptonic weak mixing angle with Run2 data [JHEP 12 \(2024\) 026](#)
- $m_Z$  measurement with 2016 data [arXiv: 2505. 15582](#)
- $W$  cross section and  $m_W$  measurement with 5.02 TeV data [LHCb-PAPER-2025-031](#)
- .....



# Electroweak Measurements at LHCb [full shopping list](#)

- The entire EW sector, at LO, can be determined with three parameters, e.g.  $m_W$ ,  $m_Z$  and  $G_\mu$
- At LO, through EW unification  $\sin^2\theta_w = (1 - \frac{m_W^2}{m_Z^2})$ 
  - $\sin^2\theta_w$  encapsulates the vector and axial-vector couplings of fermions to the boson

- Measurement of the effective leptonic weak mixing angle with Run2 data [JHEP 12 \(2024\) 026](#)



- $m_Z$  measurement with 2016 data [arXiv: 2505. 15582](#)



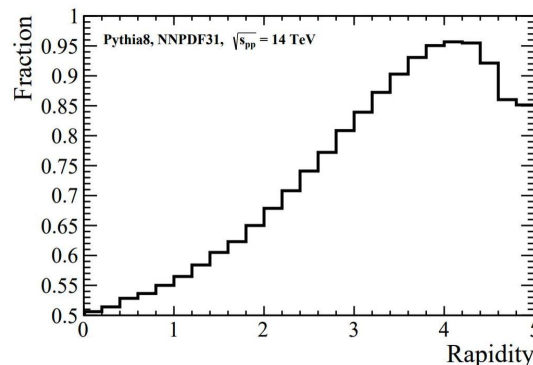
- $W$  cross section and  $m_W$  measurement with 5.02 TeV data [LHCb-PAPER-2025-031](#)

- .....

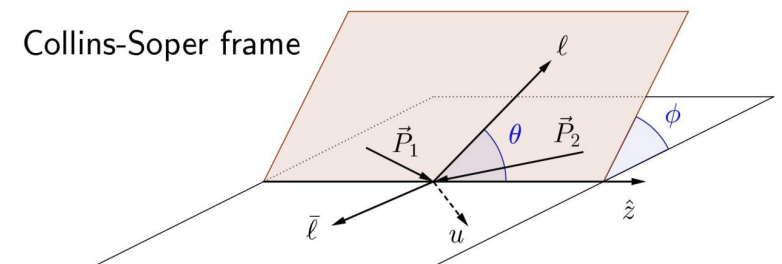
# Effective Leptonic Weak Mixing Angle, $\sin^2 \theta_{\text{eff}}^{\text{lept}}$

- At higher order,  $\sin^2 \theta_{\text{eff}}^{\text{lept}} = k_f \sin^2 \theta_W$ , absorbing the higher order corrections
- In  $Z \rightarrow \mu^+ \mu^-$  production, without requirements applied to final state leptons in Collins-Soper frame, the differential cross section follows  $\frac{d\sigma}{d\cos\theta^*} \propto 1 + \cos^2\theta^* + \alpha\cos\theta^*$
- Linear in  $\cos\theta^*$  causes forward backward asymmetry,  $A_{\text{fb}} = \frac{\sigma_{\text{f}} - \sigma_{\text{b}}}{\sigma_{\text{f}} + \sigma_{\text{b}}} = \frac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}$
- The measurement is challenging at LHC, the quark parton interacting can be in either proton
- At high rapidities, the definition of the Z axis at proton-level matches **more closely** that at parton-level

fraction of events where the Z boson travels in direction of initial state quark

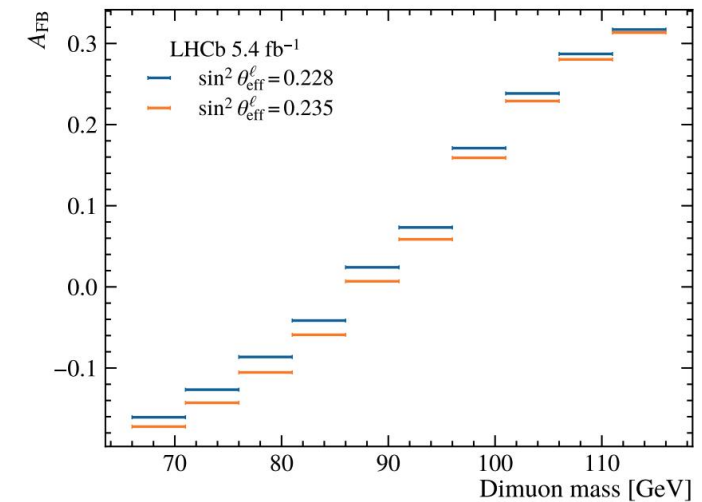
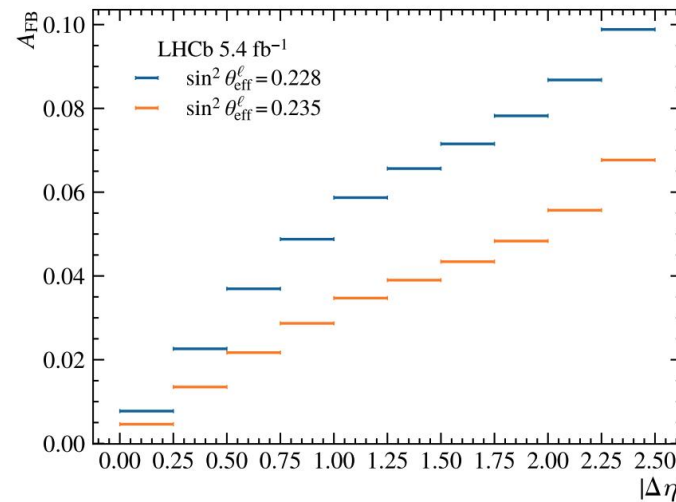
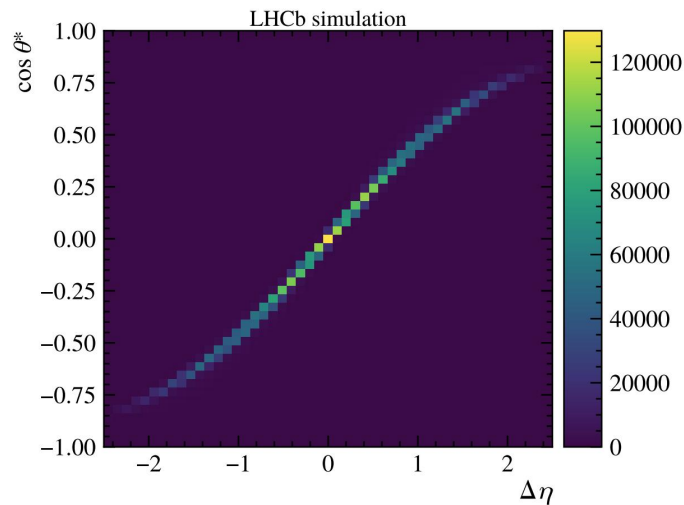


[LHCb-PUB-2018-013](#)



# $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ Measurement at LHCb - $A_{\text{fb}}$

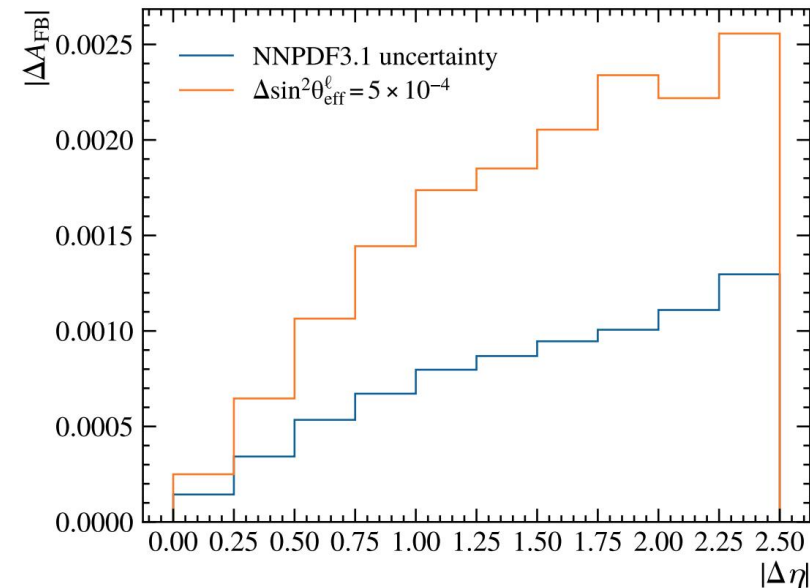
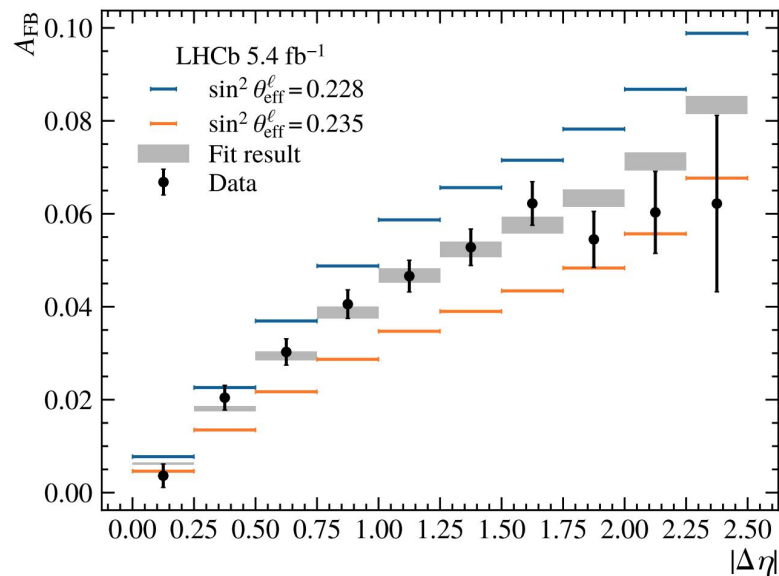
- Separating the events by  $|\cos\theta^*|$  enhances the sensitivity to the coefficient of the linear term
  - $\cos\theta^* \sim \tanh(|\Delta\eta|/2)$ ,  $\Delta\eta = \eta^- - \eta^+$
- The difference in  $A_{\text{fb}}$  caused by a change in the  $\sin^2 \theta_{\text{eff}}^{\text{lept}}$  increases with  $|\Delta\eta|$
- Increase of sensitivity,  $\sim 14\%$  by studying  $A_{\text{fb}}$  as a function of dimuon pseudorapidity difference



# $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ Measurement at LHCb

JHEP 12 (2024) 026

- Comparing measured  $A_{\text{fb}}$  with Powheg-Box EW predictions at NLO in strong and EW couplings allows  $\sin^2 \theta_{\text{eff}}^{\text{lept}}$  to be extracted
- The PDF uncertainty  $\ll$  statistical uncertainty because of the use of the LHCb acceptance
- Profiling techniques are not necessary to reduce the PDF uncertainty in this analysis



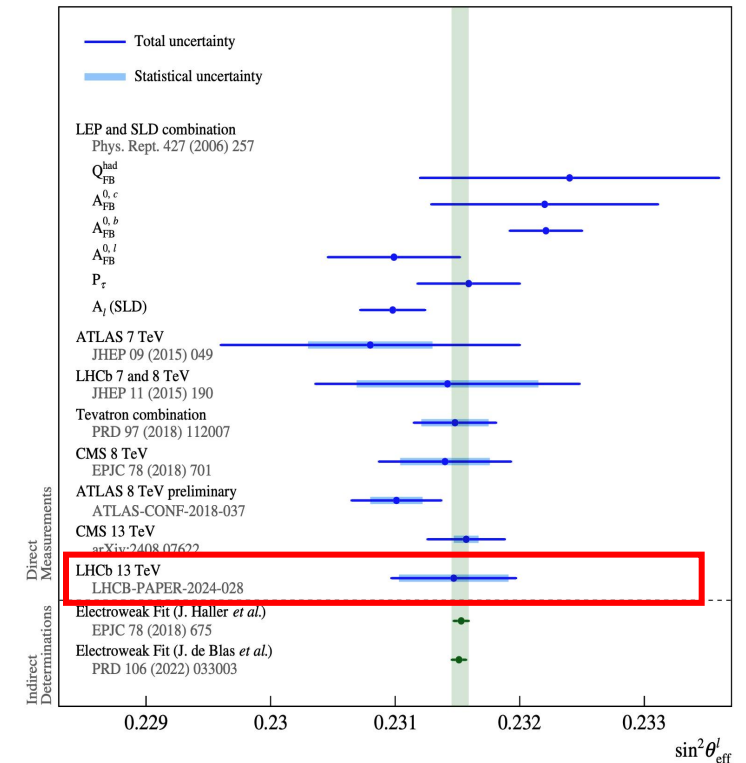
# $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ Measurement at LHCb

JHEP 12 (2024) 026

$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23147 \pm 0.00044 \text{ (stat.)} \pm 0.00005 \text{ (exp.)} \pm 0.0023 \text{ (theo.)}$$

- The result is consistent with other direct measurements and with predictions from the global EW fit
- Theoretical uncertainty includes PDF uncertainty, and uncertainties from QCD and EW correction
- **The total uncertainty is dominated by statistics**

more details: [CERN Seminar](#)



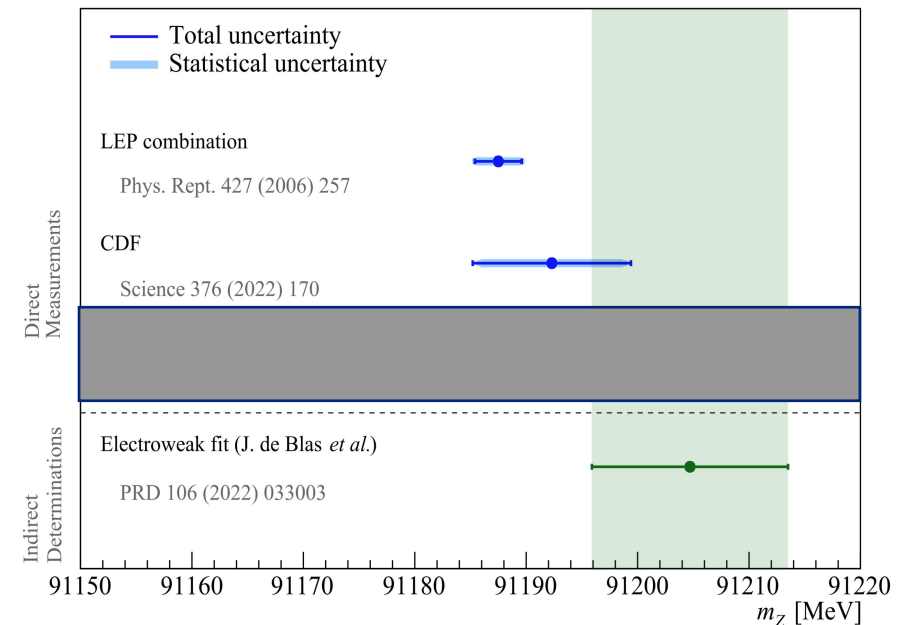
# $m_Z$ Measurement

- $m_Z$  can be indirectly determined in a global EW fit:  $91204.7 \pm 8.8$  MeV
- At LEP, (an  $e^+e^-$  collider),  $m_Z$  was measured with beam-energy scan,  $91187.6 \pm 2.1$  MeV
- At hadron collider, measuring  $m_Z$  is very challenging as many particles are produced simultaneously
  - CDFII:  $91192.3 \pm 7.1$  MeV
  - CMS:  $m_Z - m_{\text{PDG}} = -2.2 \pm 4.8$  MeV

## CMS-PAS-SMP-23-002:

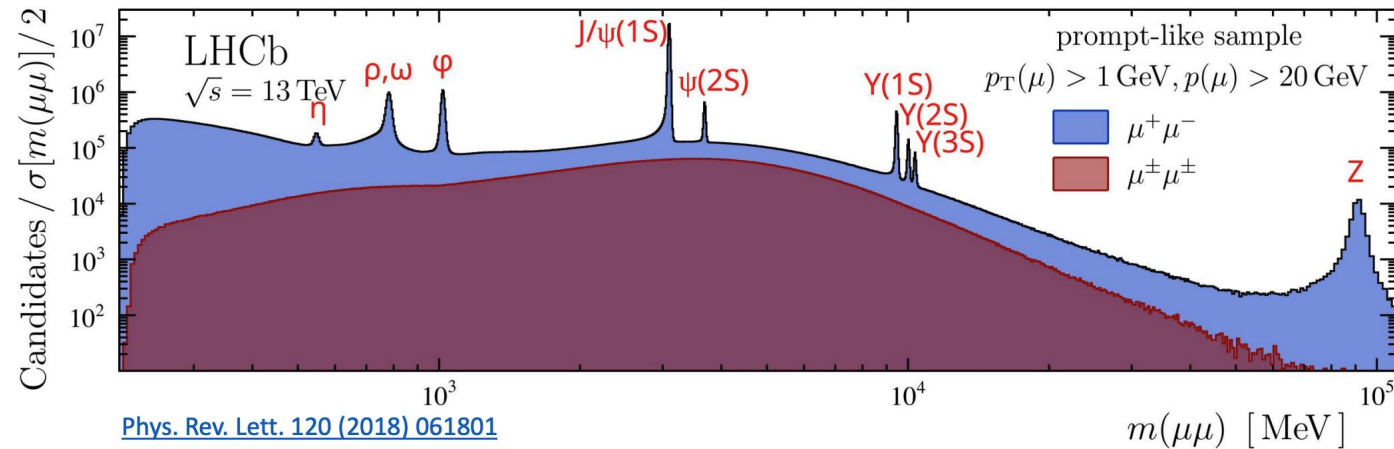
calibration, and corrections. Although  $Z \rightarrow \mu\mu$  events are not used to determine the values of the parameterized muon momentum scale calibration, they are used, together with the  $m_Z^{\text{PDG}}$  value [5], to define the systematic uncertainties. Therefore, our  $m_Z$  value is not a measurement that is independent of the experimental world average.

[arXiv: 2505.15582](https://arxiv.org/abs/2505.15582)



# Dedicated $m_Z$ Measurement at LHCb

- $m^2 \simeq 2p^+p^-(1 - \cos\theta)$ , neglecting the final state particle mass  $p$ : momentum
- $\theta$  is determined with extremely high precision in  $Z$  and  $\Upsilon$  decays
- The main challenges are
  - detailed detector calibration to control momentum measurement biases
  - cannot use  $Z$  information for the calibration



# Momentum Calibration

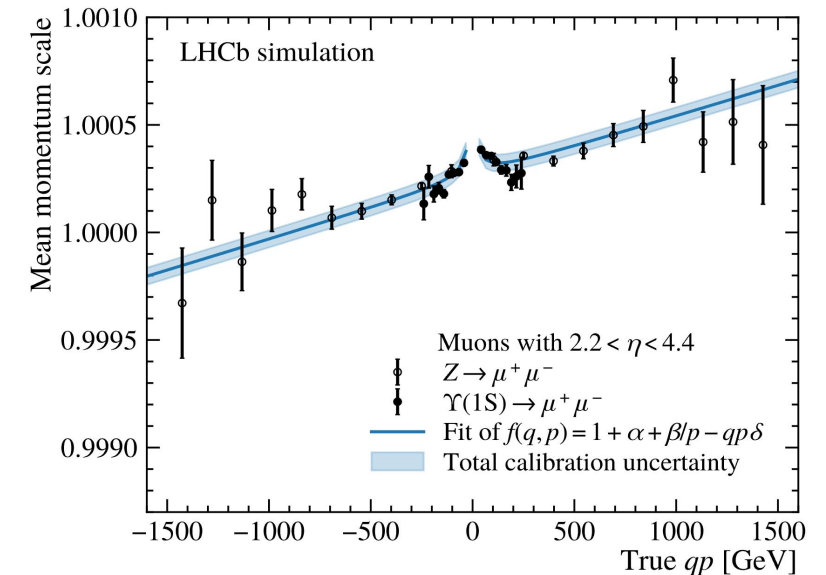
- A transformation to the measured momenta of charged particles

$$p \rightarrow (1 + \alpha + \beta/p - q\delta p)p$$

- $\alpha$ : a momentum-scale offset caused by a miscalibration of the bending power of the magnet and/or the tracker length scale
  - $\beta$ : a possible inaccuracy in the ionisation-energy-loss corrections
  - $\delta$  is a  $q/p$  bias due to a mis-alignment of the tracking detectors
- $\alpha$  and  $\beta$  are performed with  $\Upsilon \rightarrow \mu^+ \mu^-$  sample
  - The momentum bias model captures the overall trend well

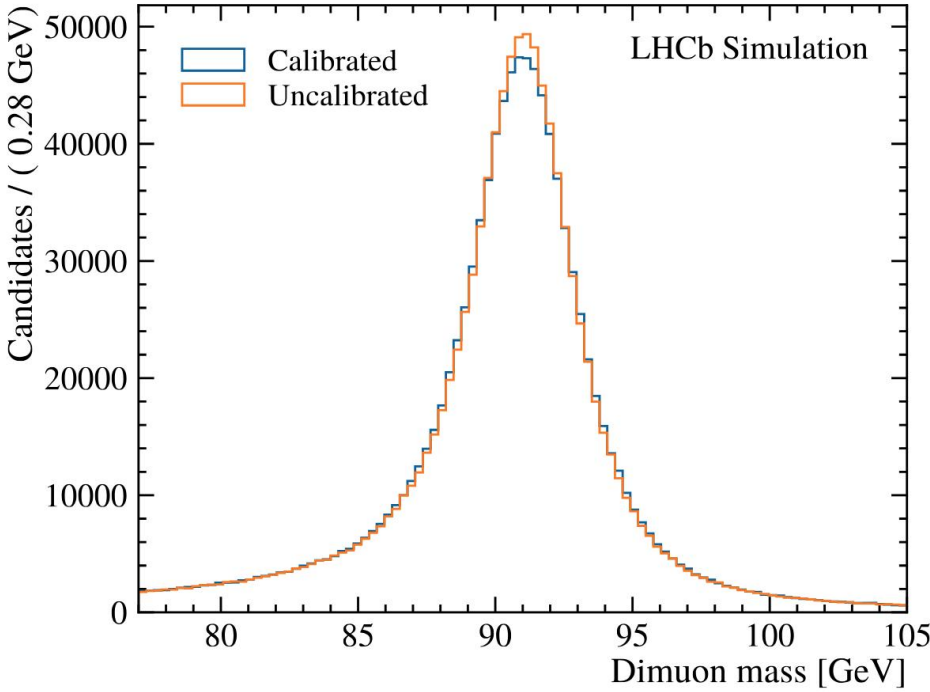
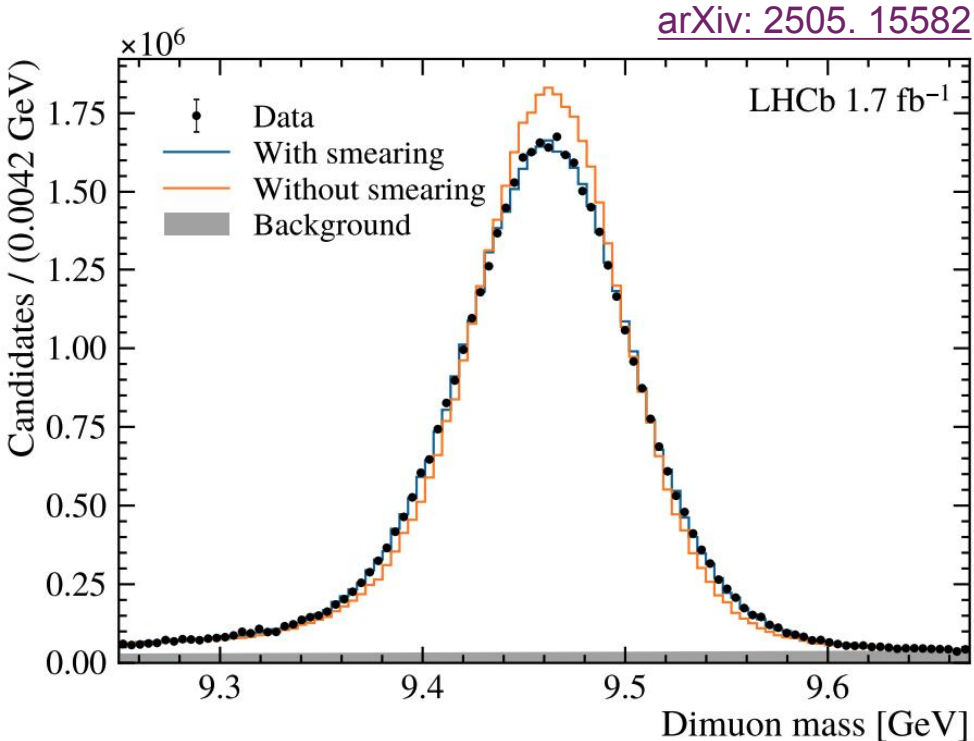
[JINST 19 \(2024\) P03010](#)

[arXiv: 2505. 15582](#)



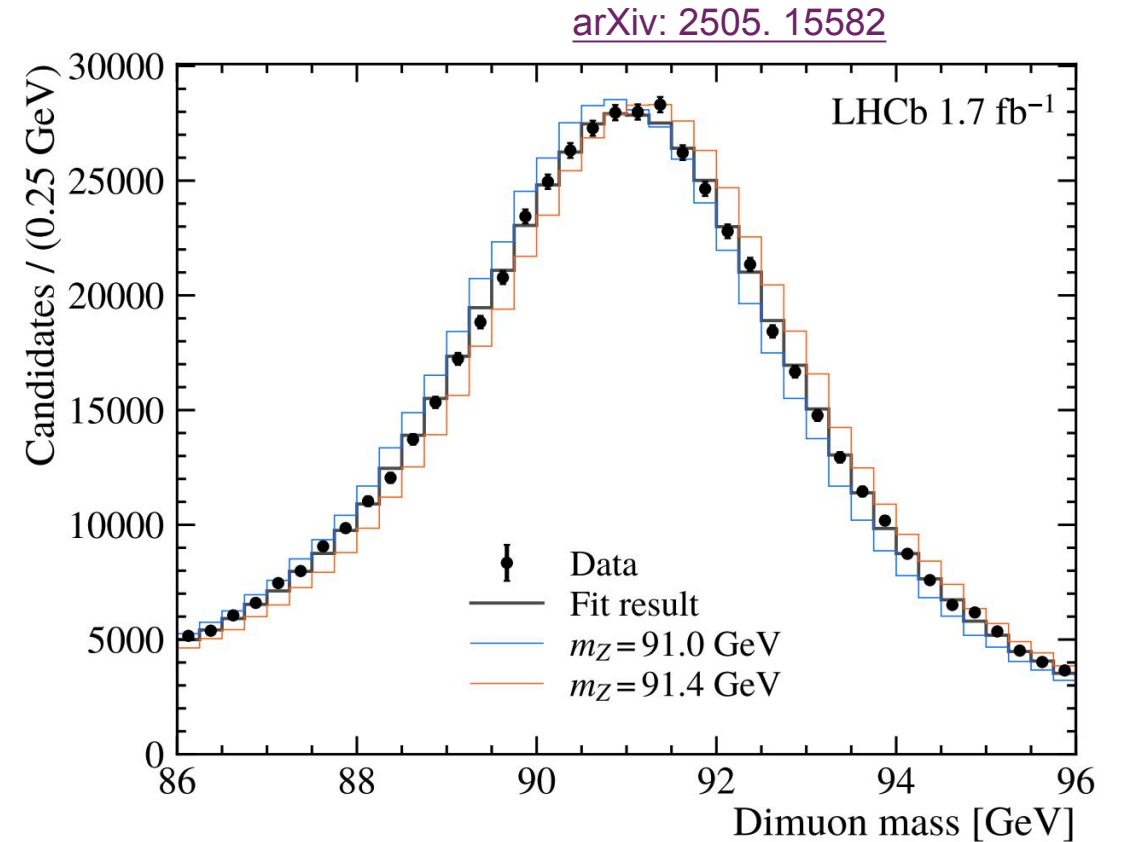
# Momentum Calibration

- The  $\Upsilon \rightarrow \mu^+ \mu^-$  mass distribution shows good agreement between data and simulation after calibration



# $m_Z$ Result at LHCb

- Sensitive via the dimuon mass distribution
- Dimuon mass templates are generated from Powheg-Box [[Eur. Physcs. J. C 73 \(2013\) 6](#)], with EW theory input scheme:  $(G_F, m_W, m_Z)$ 
  - the NNPDF3.1 PDF are used
  - processed with photos for modelling of additional photon radiation and with Pythia for simulating the rest of the event



# $m_Z$ Result at LHCb

more details: [CERN Seminar](#)

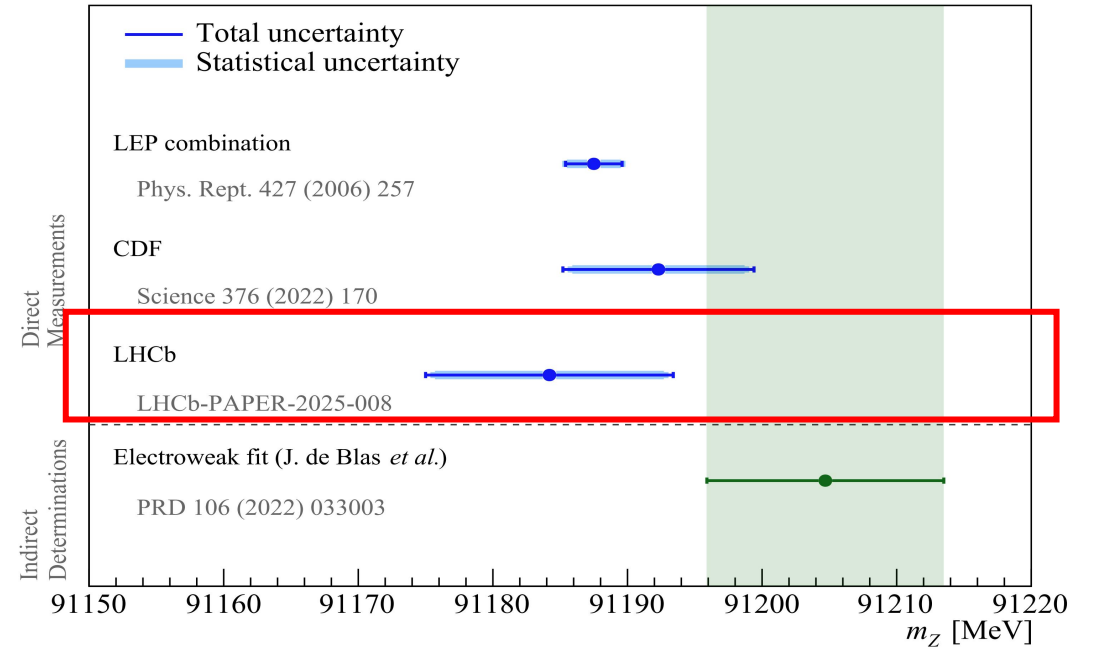
[arXiv: 2505. 15582](#)

- Using 2016,  $1.7 \text{ fb}^{-1}$  dataset

$$m_Z = 91184.2 \pm 8.5 \text{ (stat.)} \pm 3.8 \text{ (syst.) MeV}$$

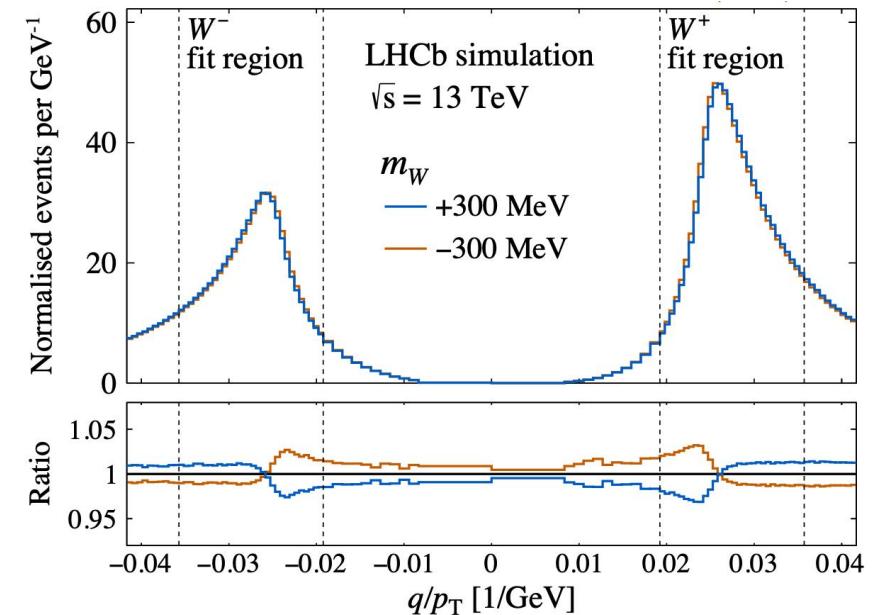
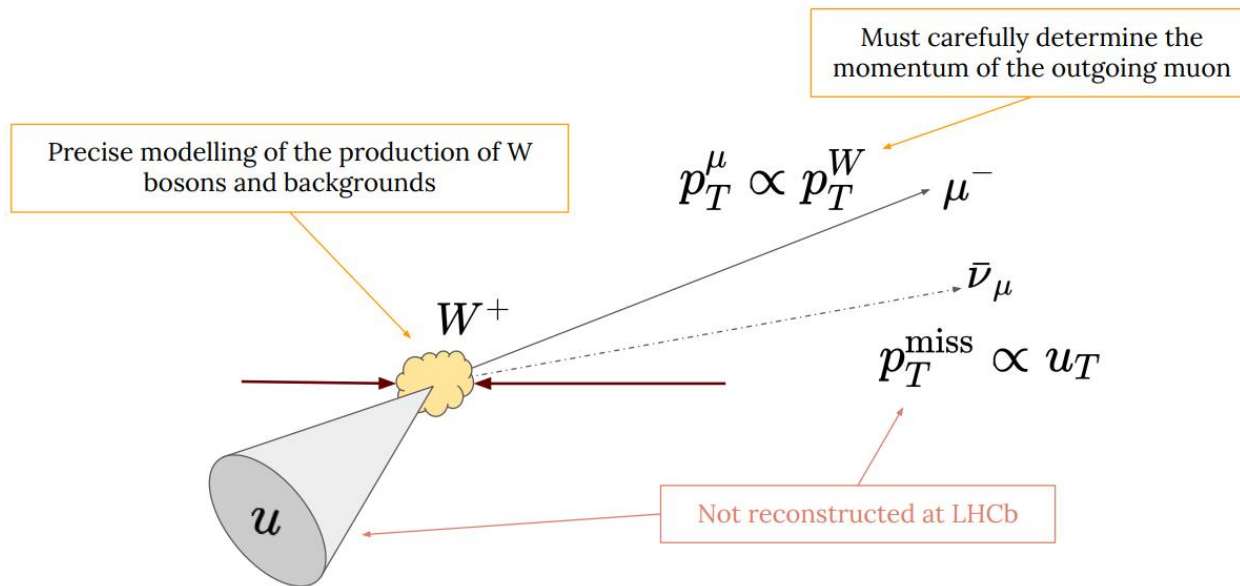
- Demonstrate the feasibility of a dedicated  $m_Z$  measurement at the LHCb and LHC

Source	Size [MeV]	
Momentum scale and resolution modelling	3.6	Detector material, stat. unc., external inputs
QED corrections	0.8	Pythia instead of PHOTOS
Parton distribution functions	0.7	Envelope from NNPDF31, CT18, MSHT20
Muon ID, trigger and tracking efficiency	0.1	Statistical uncertainties; method choices
<b>Statistical</b>	<b>8.5</b>	
<b>Total</b>	<b>9.5</b>	



# $m_W$ Measurement at LHCb

- Experimental challenges:
  - $W$  cannot be fully reconstructed with good precision as the undetected neutrino
  - a significant amount of QCD background complicates signal extraction
- $m_W$  sensitivity from  $p_T^\mu$ ,  $m_W$  is extracted through a template fit to the  $p_T^\mu$  shape



# $m_W$ Measurement at LHCb

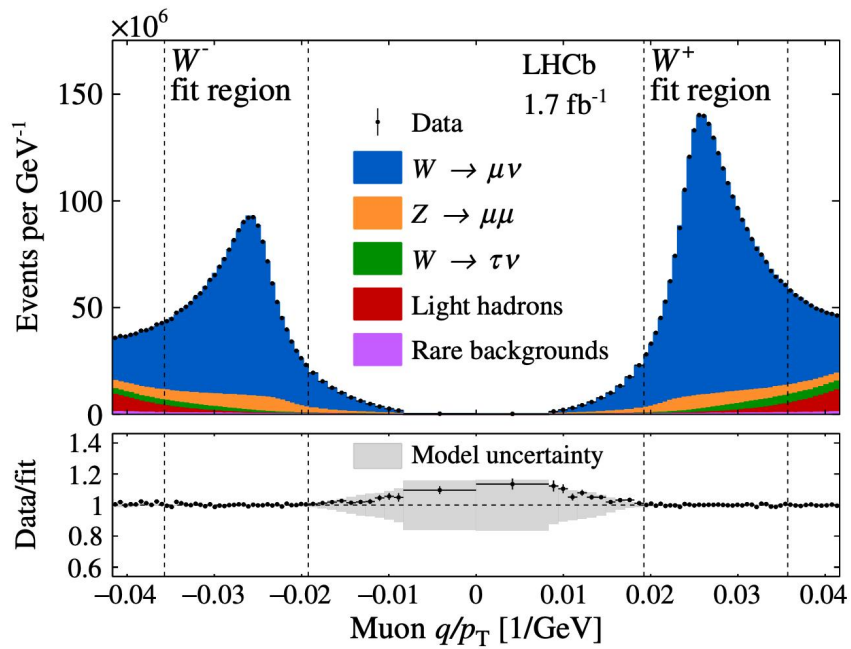
- A proof-of-principle measurement, using 2016,  $1.7 \text{ fb}^{-1}$  dataset

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

- Demonstrate the feasibility of  $m_W$  measurement at the LHCb

[JHEP01 \(2022\) 036](#)

- The theoretical modelling of the signal process is deeply embedded in the fit.



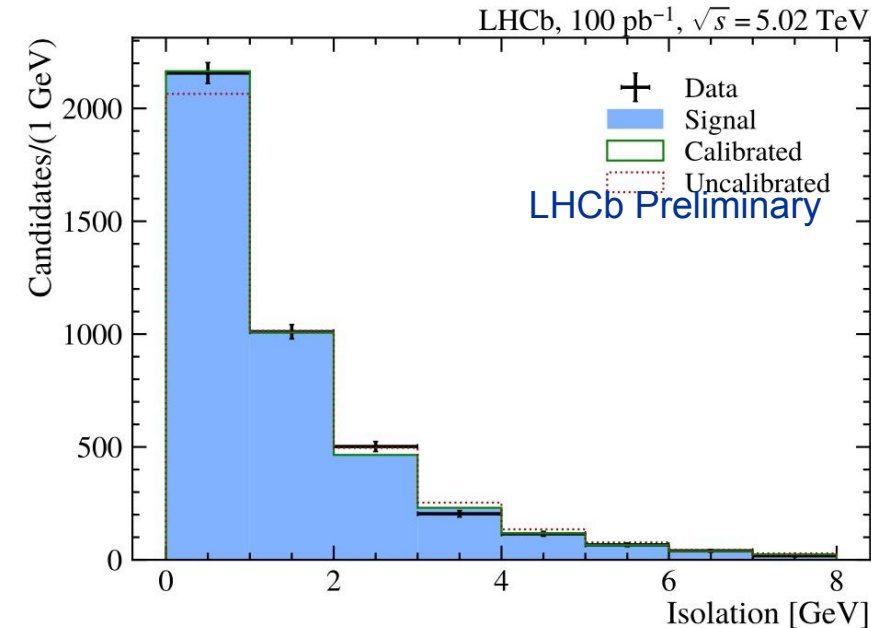
Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

# $W \rightarrow \mu\nu$ Cross Section @ 5.02 TeV

LHCb-PAPER-2025-031 (in preparation)



- It would be much simpler to measure  $\frac{d\sigma}{dp_T^\mu}$  first, then extract  $m_W$
- Use muon isolation information to subtract the background, then perform the differential cross-section,  $d\sigma_{W \rightarrow \mu\nu}/dp_T$ 
  - muon isolation: the scalar sum of the transverse momenta of all other charged particles and electromagnetic calorimeter clusters within a distance  $(\Delta\eta)^2 + (\Delta\phi)^2 < 0.5^2$
- External analysts can use our published cross-section to extract  $m_W$  based on their own theoretical predictions or assumptions

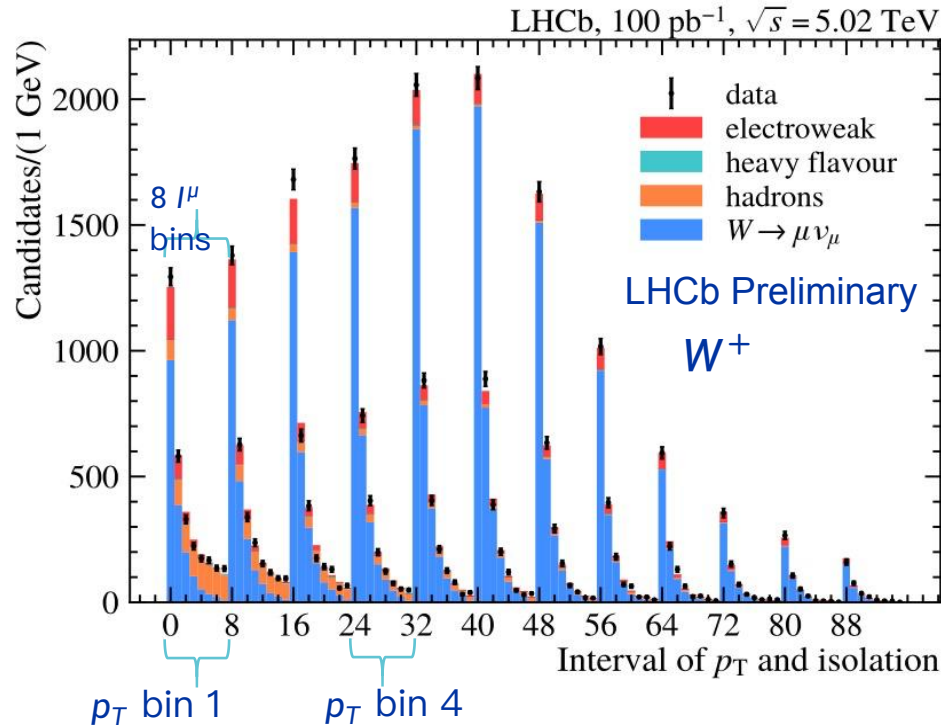


# $W \rightarrow \mu\nu$ Differential Cross Section @ 5.02 TeV



- Use  $\sqrt{s} = 5.02$  TeV data,  $\mathcal{L}_{int} = 100 \pm 2$  pb<sup>-1</sup> as a proof of principle
- 12 bins of  $p_T$ , 8 bins of muon isolation,  $2.2 < \eta < 4.4$ ,  $28 < p_T < 52$  GeV

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Interval in $p_T$ (GeV)	$d\sigma/dp_T$ (pb/GeV)	
	$W^+ \rightarrow \mu^+\nu_\mu$	$W^- \rightarrow \mu^-\bar{\nu}_\mu$
28–30	$11.89 \pm 0.44 \pm 0.35$	$14.77 \pm 0.47 \pm 0.36$
30–32	$14.35 \pm 0.46 \pm 0.29$	$15.69 \pm 0.48 \pm 0.25$
32–34	$17.66 \pm 0.48 \pm 0.29$	$15.60 \pm 0.48 \pm 0.23$
34–36	$18.88 \pm 0.51 \pm 0.29$	$16.10 \pm 0.48 \pm 0.22$
36–38	$22.74 \pm 0.56 \pm 0.32$	$16.54 \pm 0.49 \pm 0.23$
38–40	$23.50 \pm 0.58 \pm 0.29$	$14.58 \pm 0.48 \pm 0.21$
40–42	$17.16 \pm 0.53 \pm 0.31$	$10.27 \pm 0.42 \pm 0.20$
42–44	$10.45 \pm 0.43 \pm 0.28$	$6.14 \pm 0.35 \pm 0.18$
44–46	$6.01 \pm 0.35 \pm 0.17$	$3.29 \pm 0.28 \pm 0.10$
46–48	$3.46 \pm 0.30 \pm 0.12$	$2.42 \pm 0.24 \pm 0.10$
48–50	$2.59 \pm 0.26 \pm 0.12$	$1.66 \pm 0.22 \pm 0.07$
50–52	$1.75 \pm 0.21 \pm 0.14$	$1.42 \pm 0.18 \pm 0.08$

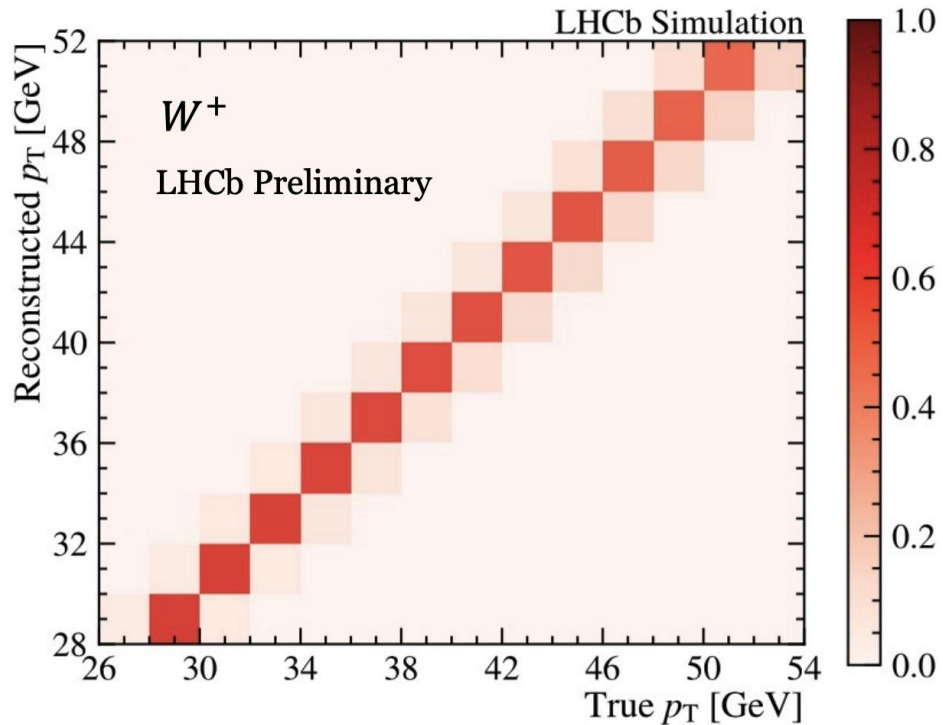
LHCb Preliminary

# $W \rightarrow \mu\nu$ Differential Cross Section @ 5.02 TeV

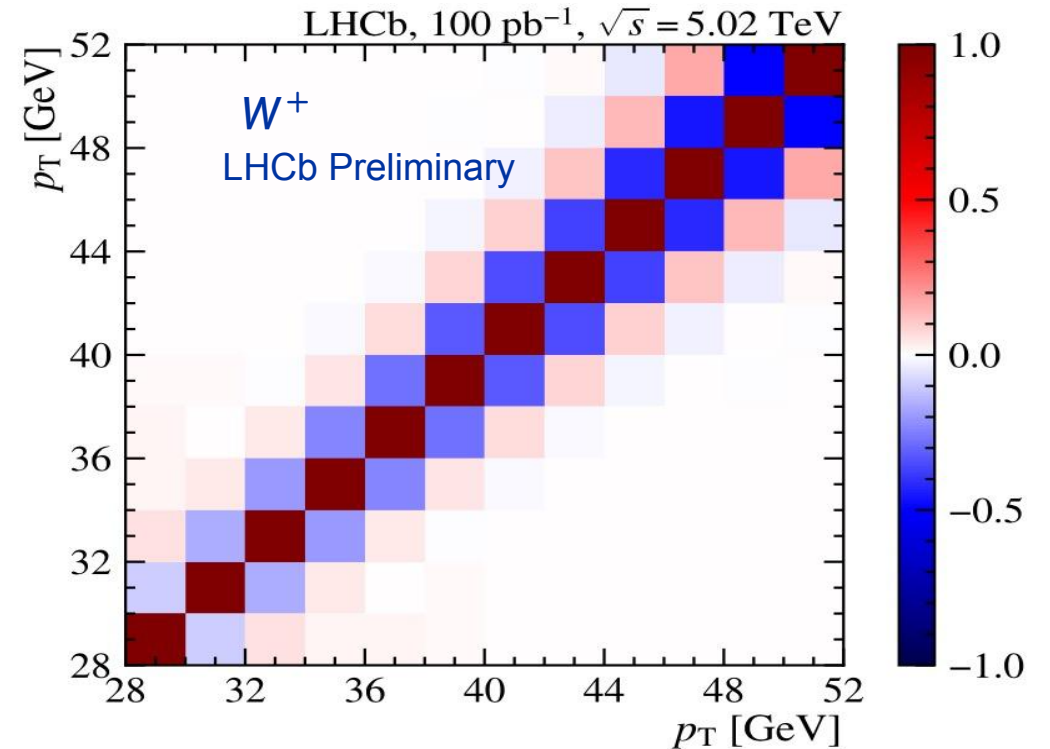


LLHCb-PAPER-2025-031 (in preparation)

- Largely diagonal due to excellent  $\vec{p}$  resolution
- The unfolding can be performed **without regularisation**



response matrix



statistical correlation matrix

# $W \rightarrow \mu\nu$ Integral Cross Section @ 5.02 TeV

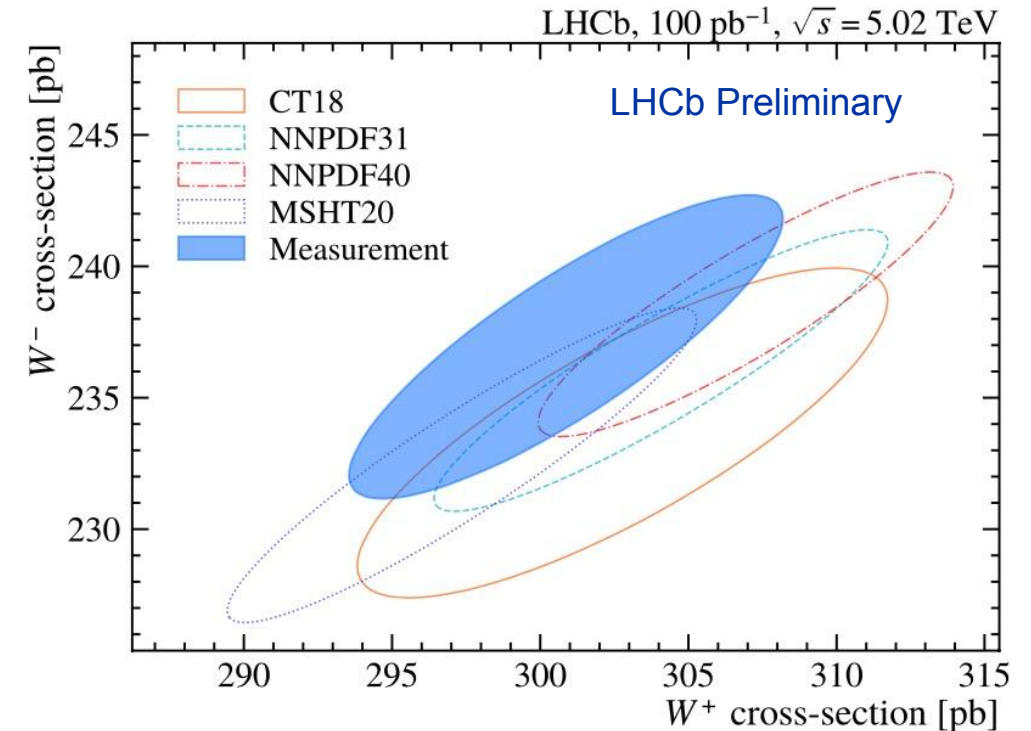


LLHCb-PAPER-2025-031 (in preparation)

$$\sigma_{W^+ \rightarrow \mu^+ \nu_\mu} = 300.9 \pm 2.4 \text{ (stat.)} \pm 3.8 \text{ (syst.)} \pm 6.0 \text{ (lumi) pb}$$

$$\sigma_{W^- \rightarrow \mu^- \nu_\mu} = 236.9 \pm 2.1 \text{ (stat.)} \pm 2.8 \text{ (syst.)} \pm 4.7 \text{ (lumi) pb}$$

- The results are compared with predictions at NNLO from MCFM generator, [link](#)
- Predictions have uncertainties on varying PDF members and scale variations

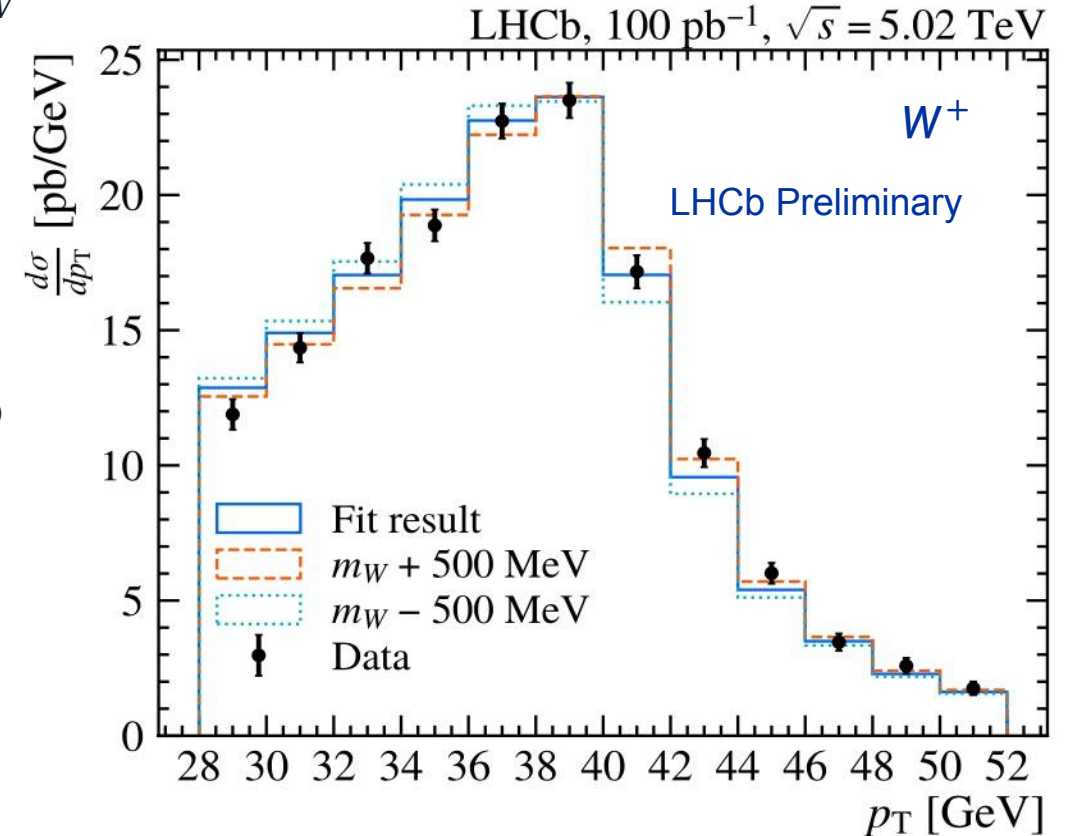


# $m_W$ Measurement

LLHCb-PAPER-2025-031 (in preparation)



- Fit  $d\sigma/dp_T^\mu$  with a semi-arbitrary model to extract  $m_W$ 
  - inputs: **24  $d\sigma/dp_T^\mu$  values and one  $24 \times 24$  covariance matrix**
  - fit can be performed with any model
- Model in this analysis: Pythia, reweighted to DYTurbo (NNLO + NNLL unpolarised, NLO angular terms)



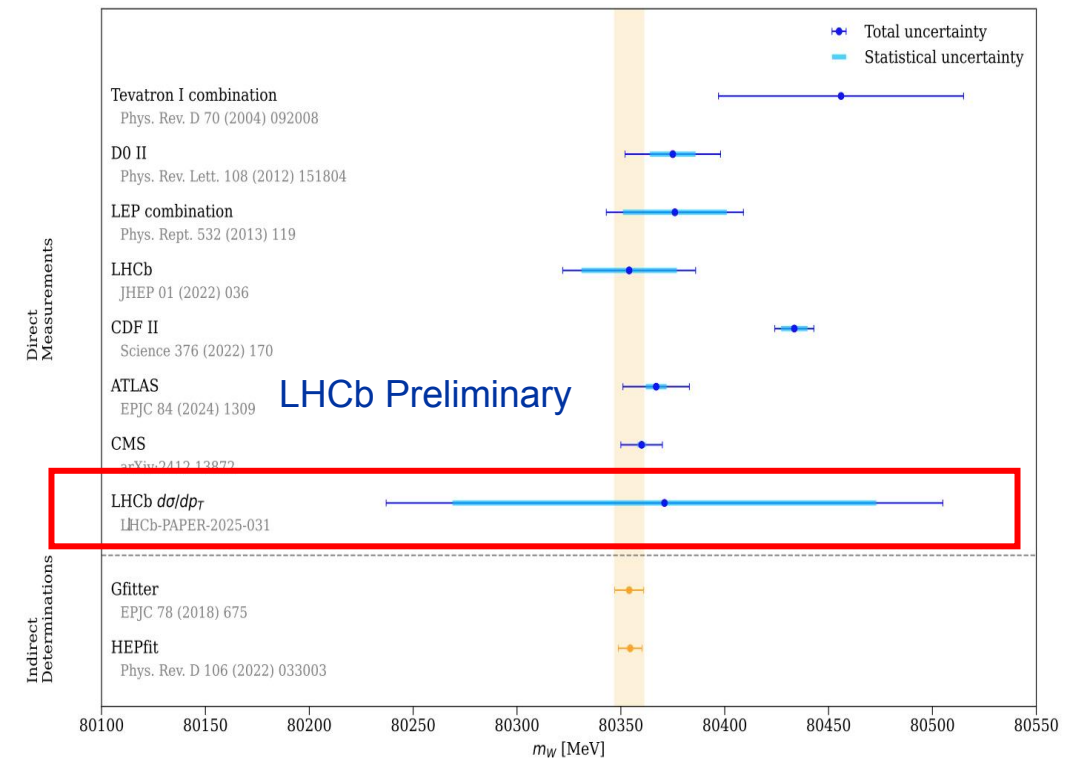
# $m_W$ Measurement

LLHCb-PAPER-2025-031 (in preparation)



$$m_W = 80371 \pm 130(\text{exp.}) \pm 32 (\text{theo.}) = 80371 \pm 145 \text{ MeV}$$

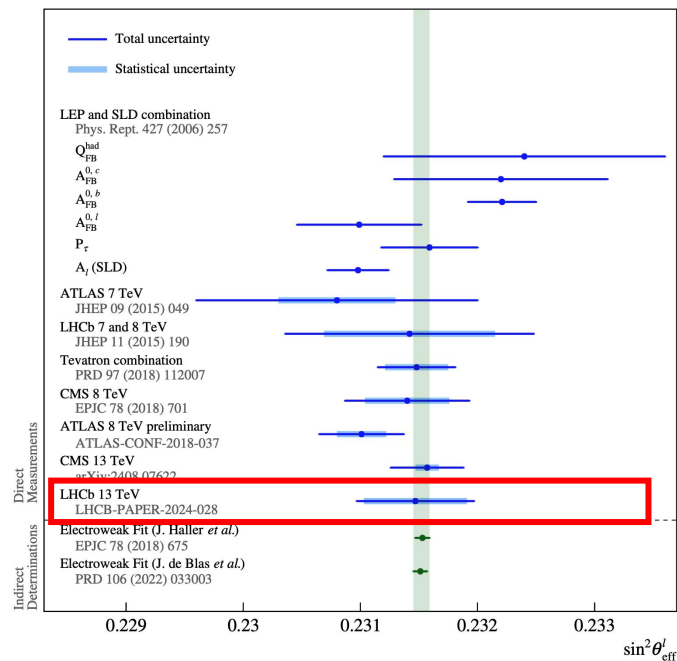
- First analysis to measure  $d\sigma/dp_T^\mu$  at a hadron collider
- Proof-of-principle with 5.02 TeV dataset
- Same method on 2017+2018 13 TeV data gives a  $\sim 12$  MeV statistical uncertainty



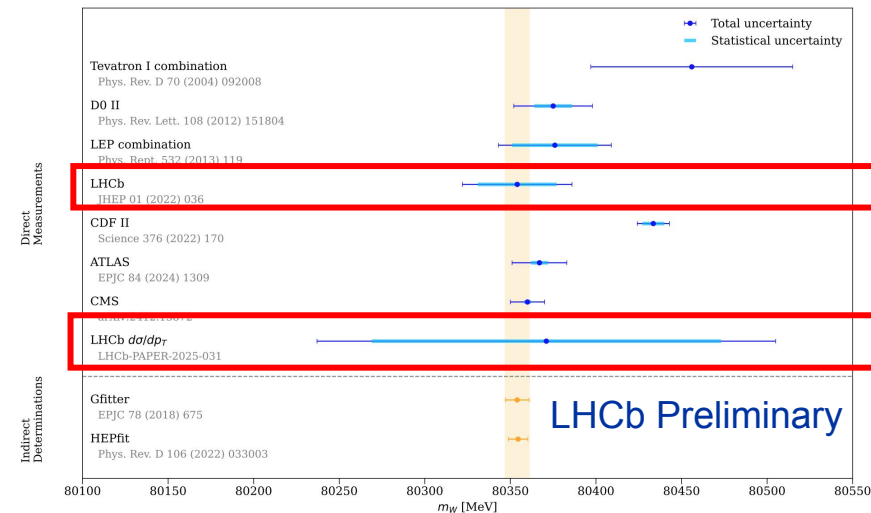
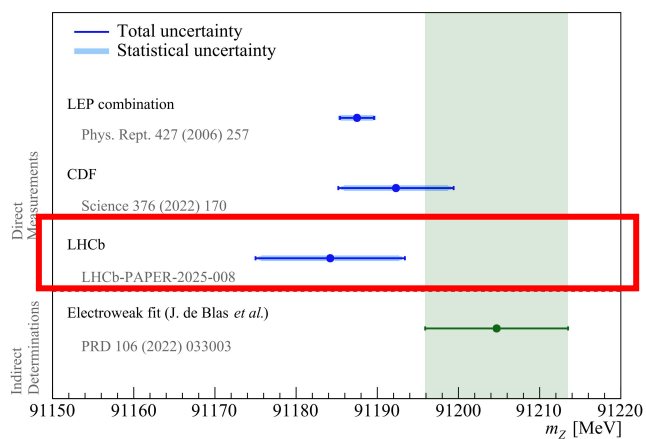
# Summary

- LHCb measured  $m_W$  with 2016 data, the weak mixing angle with 2016-2018 data,  $m_Z$  with 2016 data and  $m_W$  with 2017, 5.02TeV data
- The precision of all those measurements is limited by the statistics

JHEP 12 (2024) 026



arXiv: 2505.15582



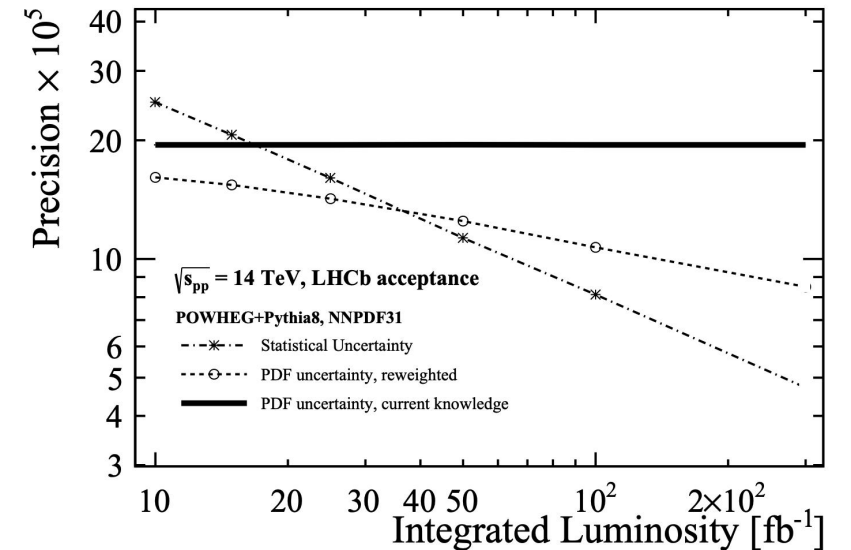
LHCb-PAPER-2025-031 (in preparation)

# Future Prospects

- Upgrade I (LHC's Run3 and Run4):
  - increase the instantaneous lumi. by more than a factor of 5
  - Run3  $W$  and  $Z$  cross section measurements are not far away
  
- Upgrade II:
  - further increase instantaneous lumi. by a factor of 10
  - improved calorimetry potentially allows electron channels to contribute equivalent precision to muon channels

LHC Run Year $\text{cm}^{-1}\text{s}^{-1}$	Integrated luminosity $\text{fb}^{-1}$		
	$1.0 \times 10^{34}$	$1.5 \times 10^{34}$	$2.0 \times 10^{34}$
Run 1-4	50	50	50
LS4	—	—	—
Run 5 Year 1	21	25	26
Run 5 Year 2	43	50	51
Run 5 Year 3	43	50	51
LS5	—	—	—
Run 6 Year 1	43	50	51
Run 6 Year 2	43	50	51
Run 6 Year 3	43	50	51
Total	284	325	331

[LHCb-PUB-2018-013](#)



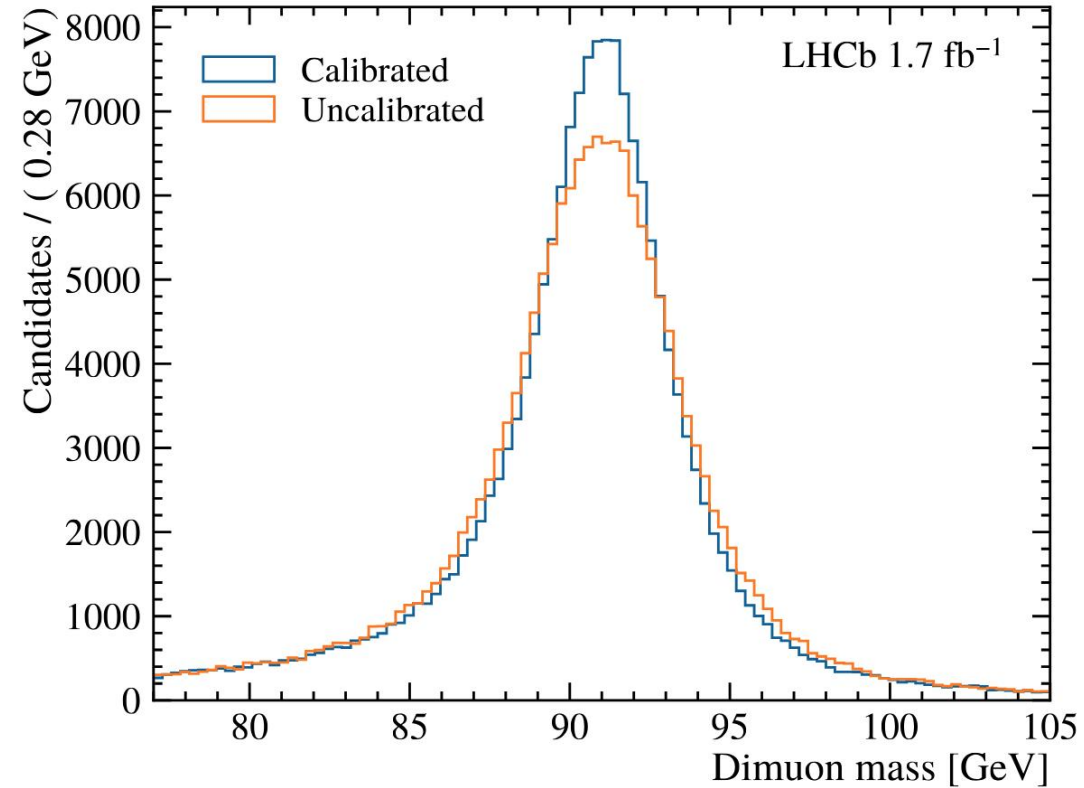
# Back Up



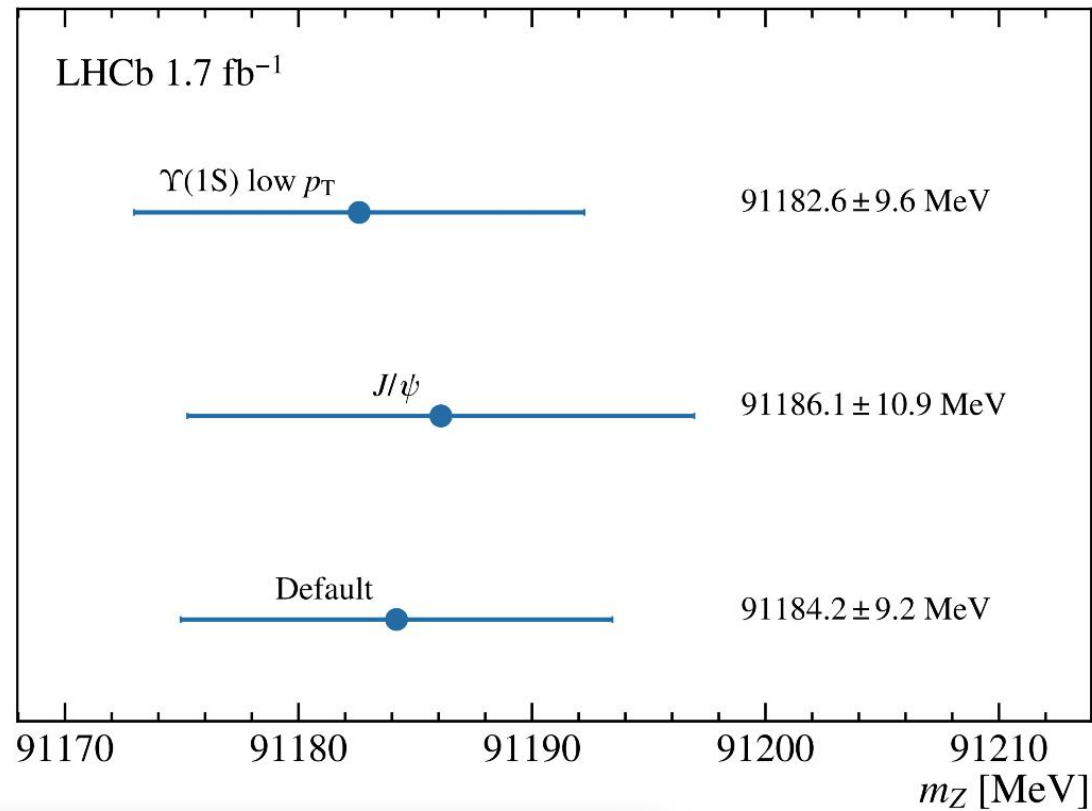
[home.cern](http://home.cern)

# Z Mass Measurement Supplementary

[arXiv: 2505. 15582](https://arxiv.org/abs/2505.15582)



# Z Mass Measurement Supplementary

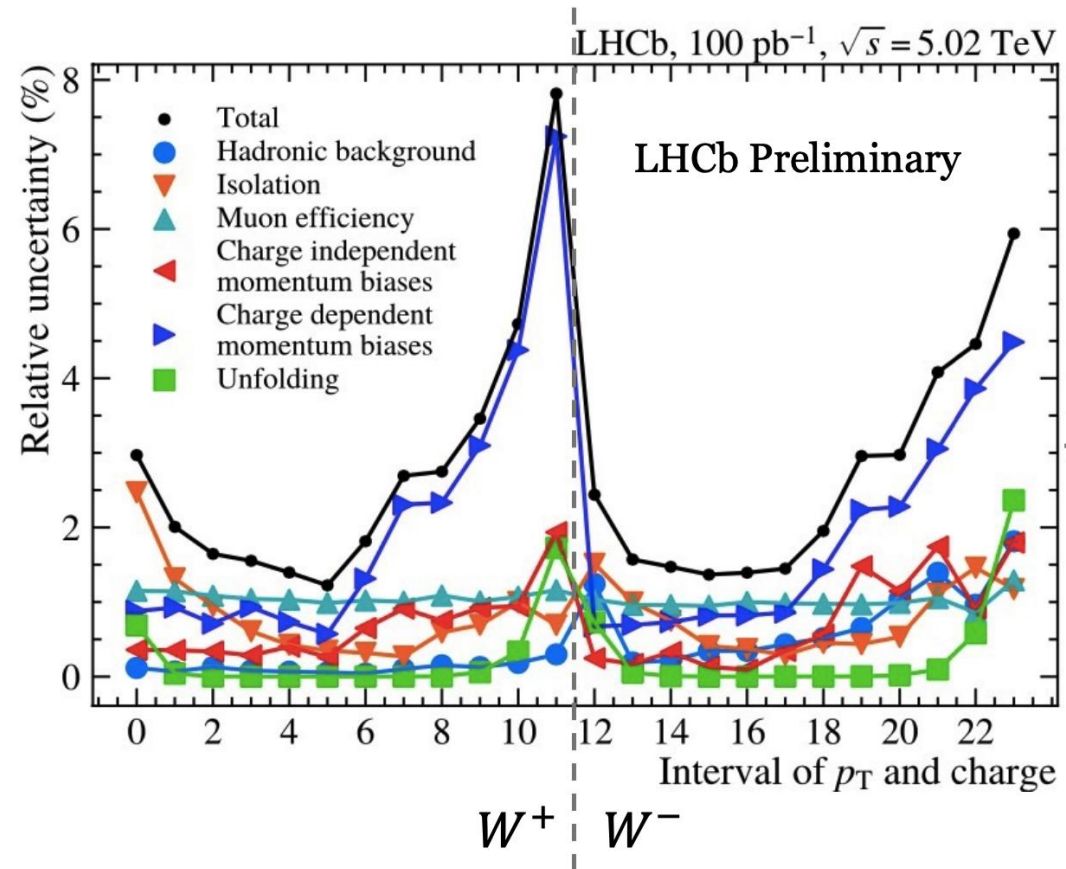


[arXiv: 2505. 15582](https://arxiv.org/abs/2505.15582)

# $W \rightarrow \mu\nu$ Cross Section @ 5.02 TeV Supplementary

- Relative systematic uncertainties on the differential cross-sections

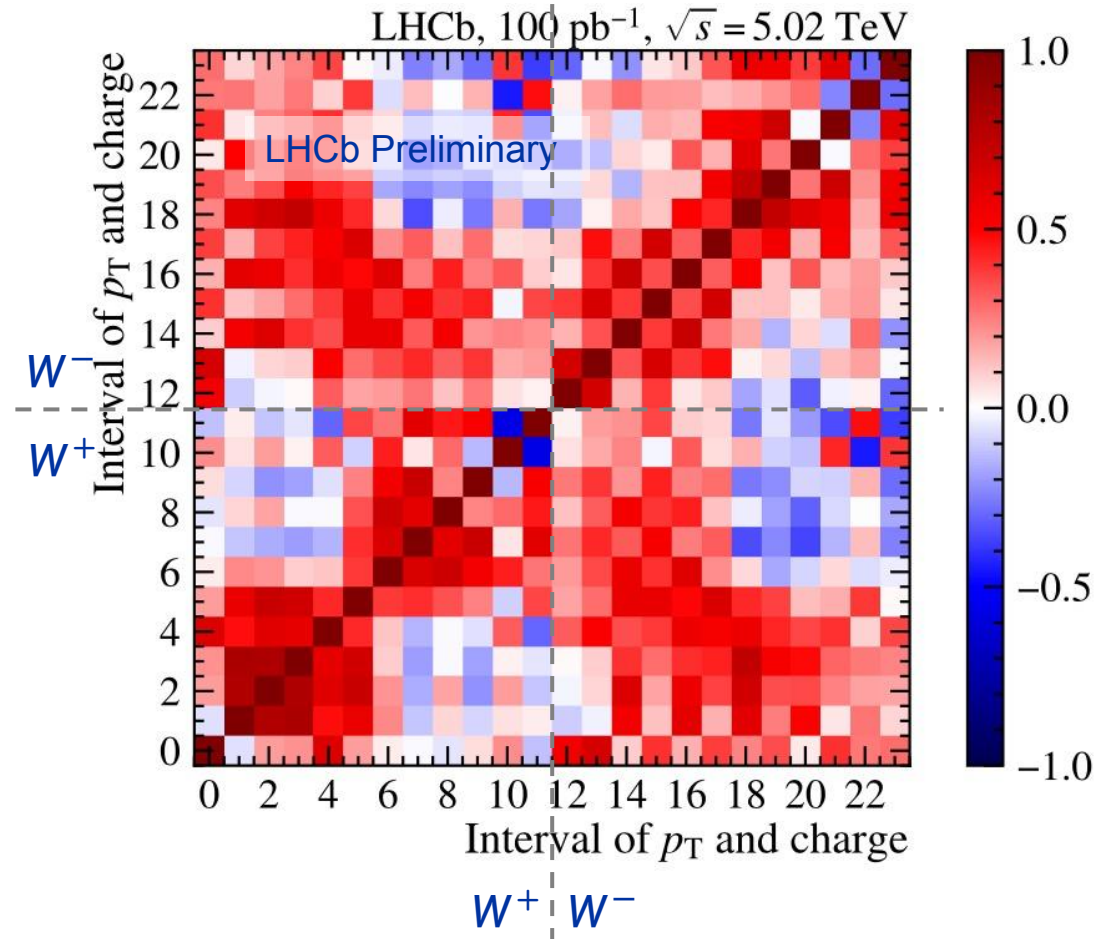
LLHCb-PAPER-2025-031 (in preparation)



# $W \rightarrow \mu\nu$ Cross Section @ 5.02 TeV Supplementary

- Correlation matrix corresponding to the total systematic uncertainty

LLHCb-PAPER-2025-031 (in preparation)



# $W \rightarrow \mu\nu$ Cross Section @ 5.02 TeV Supplementary

- Results of the  $m_W$  fit with three different PDF sets compared to the baseline (NNPDF 3.1).

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PDF set	$\chi^2$	$m_W$ [MeV]	Shift [MeV]	PDF uncertainty [MeV]
NNPDF3.1	26/21	$80368 \pm 130$	–	28
MSHT20	28/21	$80382 \pm 130$	+14	14
CT18	25/21	$80363 \pm 130$	–5	23