Recent results on EW physics at LHCb

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on behalf of the LHCb Collaboration
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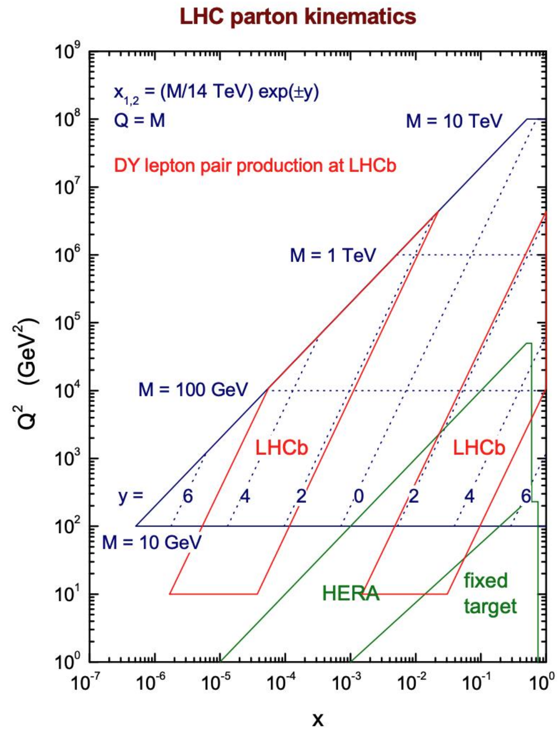
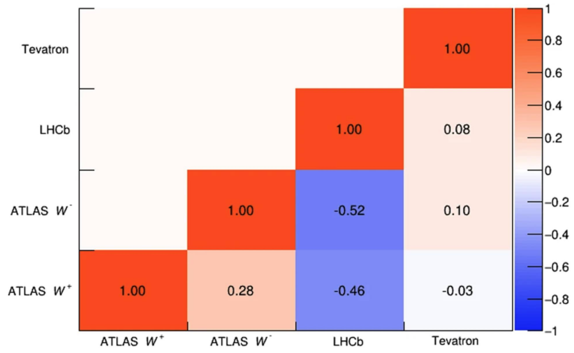
Why LHCb

- 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

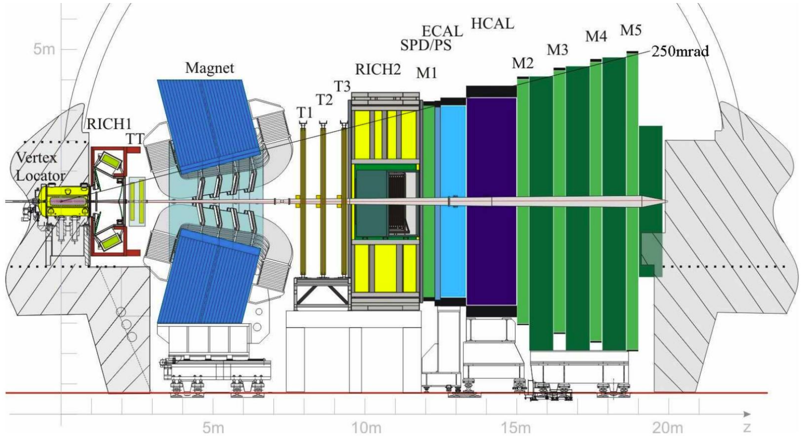
arXiv: 0808. 1847v1



EPJC 84 451 (2024)



(before latest CMS & ATLAS m_W measurement)



JINST 3 (2008) S08005

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
- $Z \to \mu^+\mu^-$ 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 paramters, e.g. m_W, m_Z and G_μ

- 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

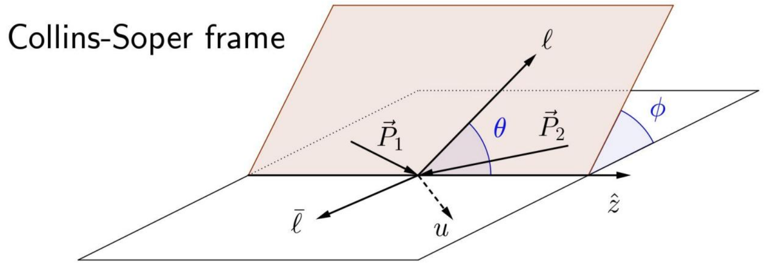
- W cross section and m_W measurement with 5.02 TeV data LHCb-PAPER-2025-031
- .....

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 $Z \to \mu^+\mu^-$ production, without requirements applied to final state leptons in Collis-Soper frame,

the differential cross section follows $\frac{d\sigma}{d\cos\theta^*} \propto 1 + \cos^2\theta^* + \alpha\cos\theta^*$

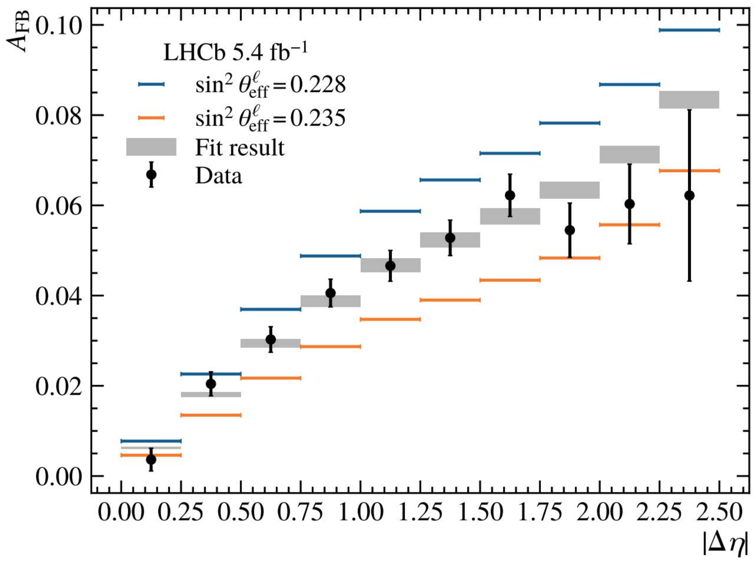
- Linear in $\cos\theta^*$ causes forward backward asymmetry, $A_{\text{fb}} = \frac{\sigma_{\text{f}}-\sigma_{\text{b}}}{\sigma_{\text{f}}+\sigma_{\text{b}}} = \frac{\sigma(cos\theta^*>0) - \sigma(cos\theta^*<0)}{\sigma(cos\theta^*>0) + \sigma(cos\theta^*<0)}$
- The measurement is challenging at LHC, 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

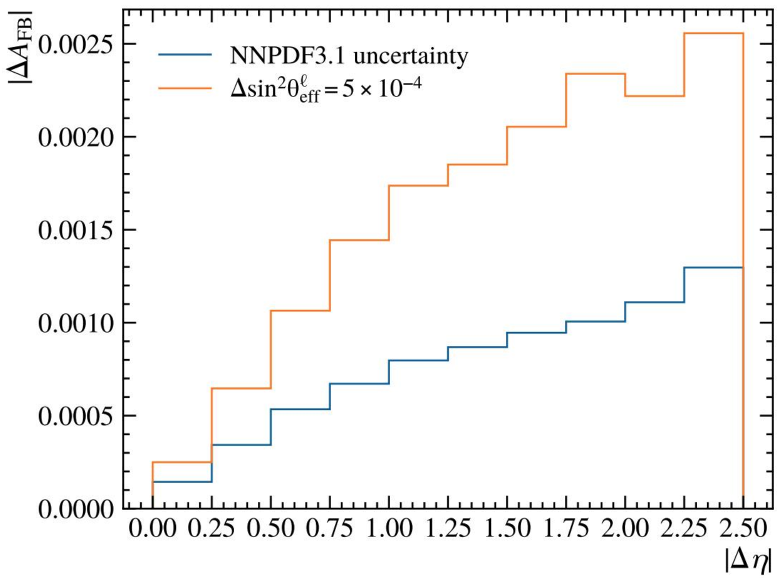


$\sin^2\theta_{\text{eff}}^{\text{lept}}$ Measurement at LHCb

JHEP 12 (2024) 026

- Comparing measured A_{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 ≪ statistical uncertainty because of the use of the LHCb acceptance
- We do not need profiling to reduce the PDF uncertainty





$$\cos\theta^* \sim \tanh(|\Delta\eta|/2)$$

$$\Delta\eta = \eta^- - \eta^+$$

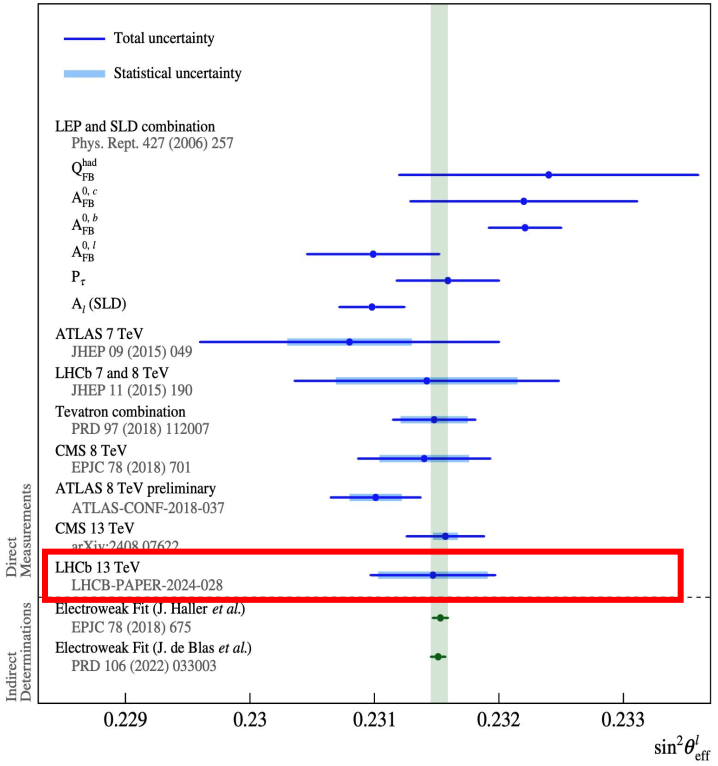
$\sin^2\theta_{\text{eff}}^{\text{lept}}$ Measurement at LHCb

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

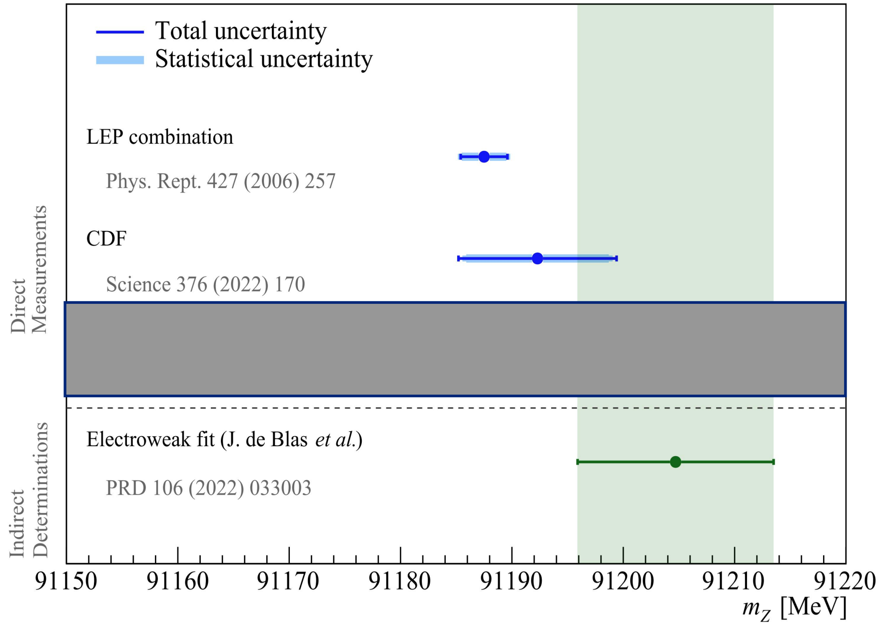
more details: CERN Seminar



m_Z Measurement

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

arXiv: 2505. 15582

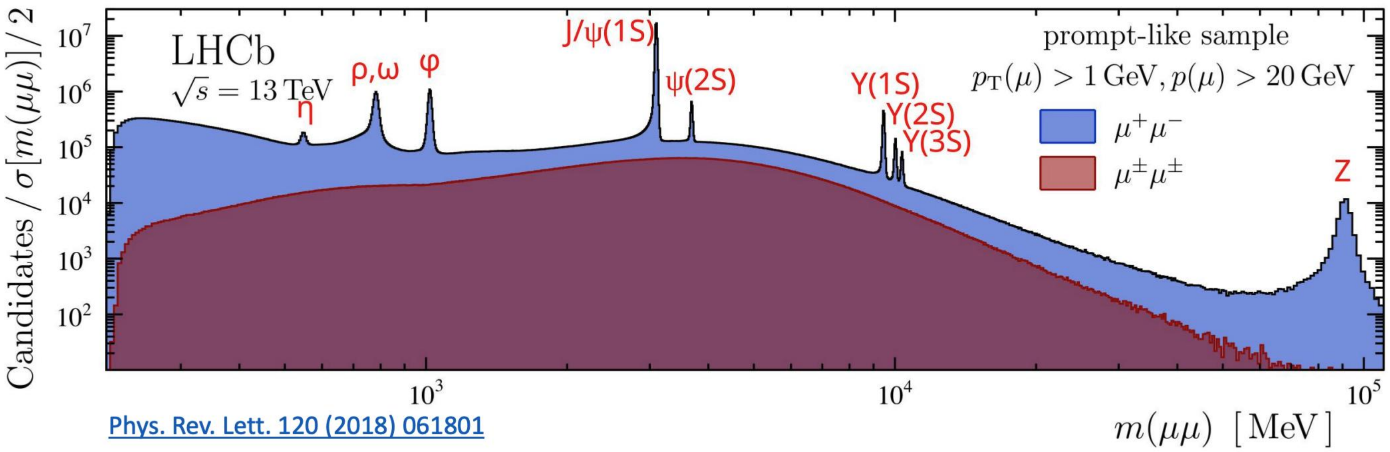


CMS-PAS-SMP-23-002:

calibration, and corrections. Although $Z \to \mu\mu$ events are not used to determine the values of the parameterized muon momentum scale calibration, they are used, together with the m_Z^{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.

Dedicated m_Z Measurement at LHCb

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



Phys. Rev. Lett. 120 (2018) 061801

Momentum Calibration

- A transformation to the measured momenta of charged particles

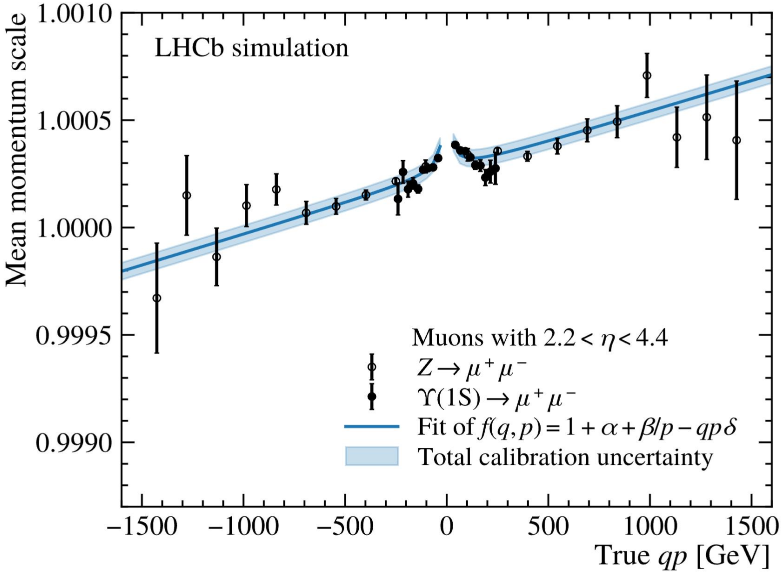
$$p \rightarrow (1 + \alpha + \beta/p - q\delta p)p$$

  - α: a momentum-scale offset caused by a miscalibration of the bending power of the magnet and/or the tracker length scale
  - β: a possible inaccuracy in the ionisation-energy-loss corrections
  - δ is a q/p bias due to a mis-alignment of the tracking detectors

JINST 19 (2024) P03010

- α and β are performed with $\Upsilon \rightarrow \mu^+\mu^-$ sample
- The momentum bias model captures the overall trend well

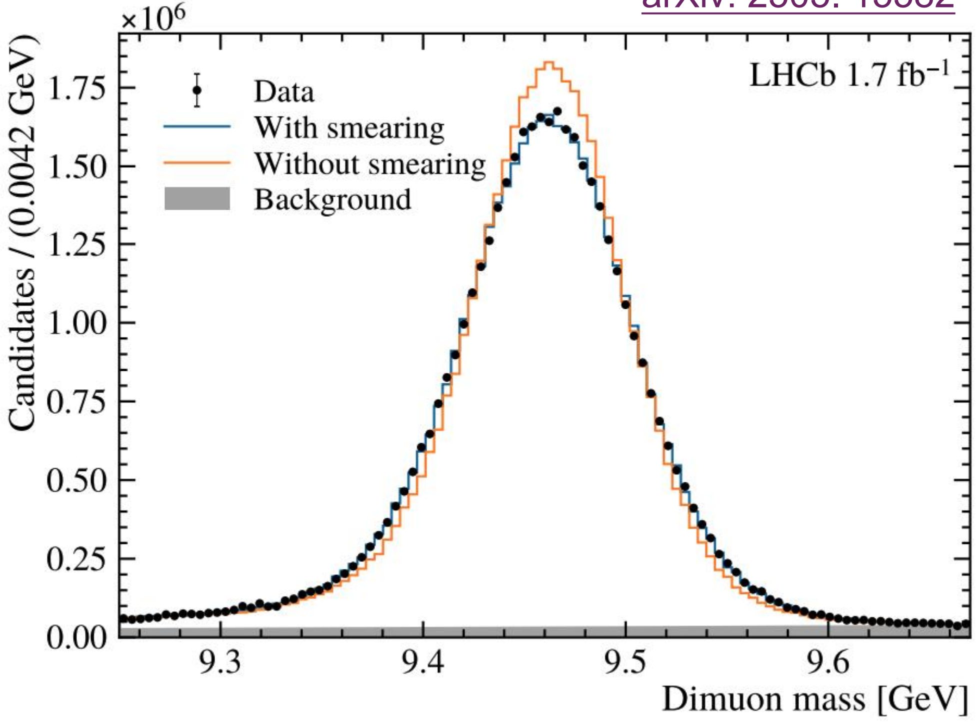
arXiv: 2505. 15582



Momentum Calibration

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

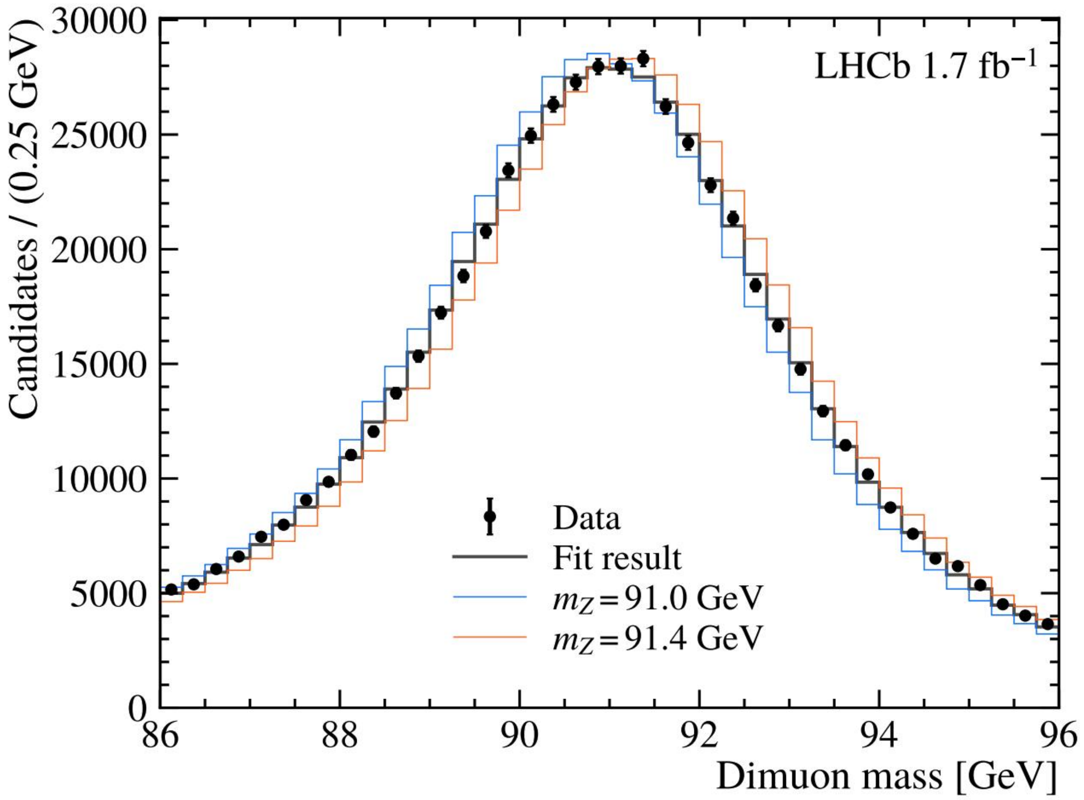
arXiv: 2505. 15582



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

arXiv: 2505. 15582

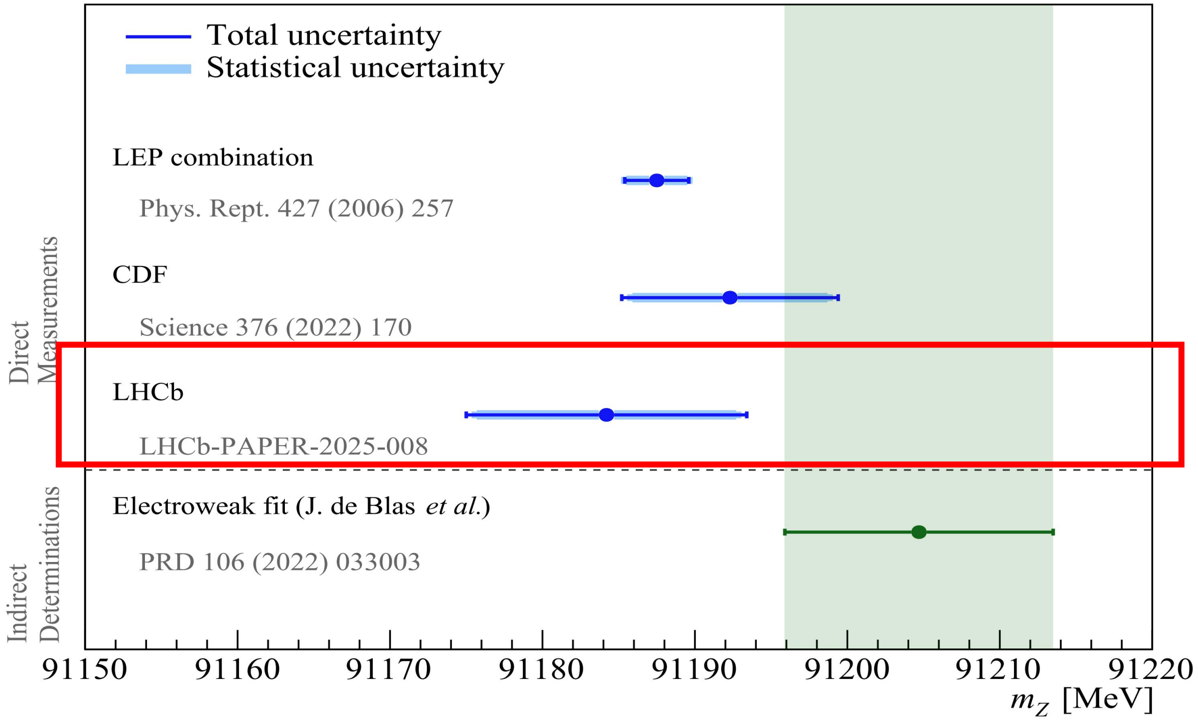


m_Z Result at LHCb

- Using 2016, 1.7 fb^{-1} dataset

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

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



arXiv: 2505. 15582

more details: CERN Seminar

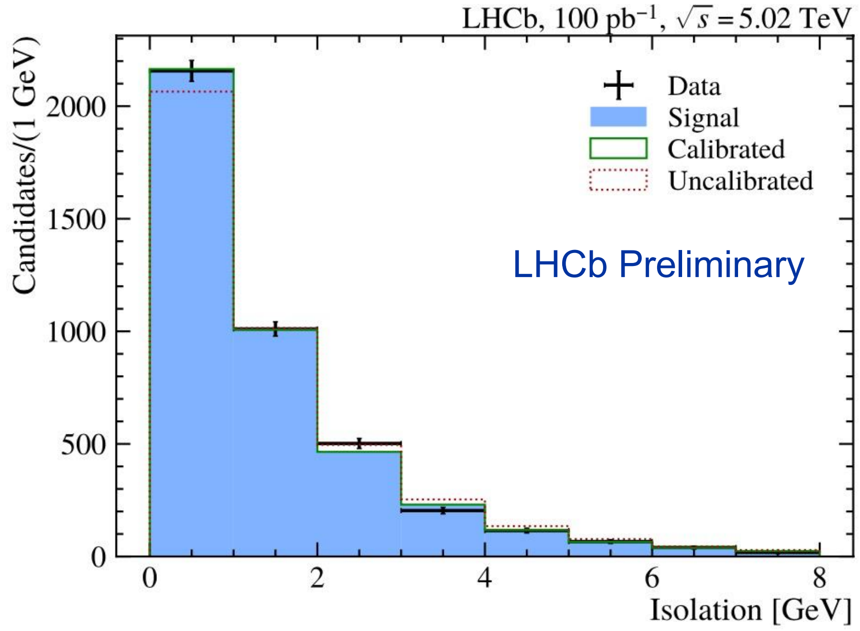
$W \to \mu\nu$ Cross Section

- $W \to \mu\nu$ cross section measurement is quite challenging at LHC(b)
  - W cannot be fully reconstructed with good precision as the undetected neutrino
  - large QCD background contribution
- Traditionally, μ p_{T} shape is used to subtract background → cross section measurements in μ p_{T} is impossible
- The production of W boson is the basis of m_W measurement by fitting μ p_{T} shape
- The theoretical modelling of the signal process is deeply embedded
- This compromises the responsiveness to theoretical developments and the engagement of the theoretical community in the analyses

$W \to \mu\nu$ Cross Section @ 5.02 TeV

LHCb–PAPER–2025–031 (in preparation)

- Use muon isolation information to subtract the background, then perform the differential cross-section, $\mathrm{d}\sigma_{W\to\mu\nu}/\mathrm{d}p_{\mathrm{T}}$
  - muon isolation: the scalar sum of the transverse momenta of all other charged particles and electromagnetic calorimeter clusters within a distance $(\Delta\eta)^2 + (\Delta\phi)^2 < 0.5^2$

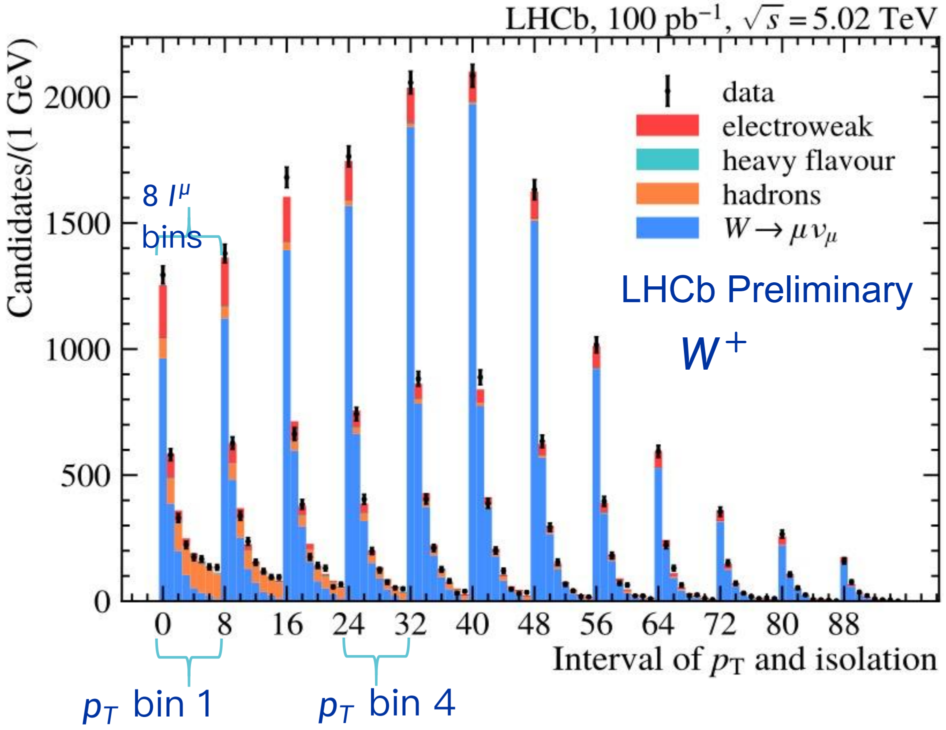


- Use $\sqrt{s} = 5.02$ TeV data, $\mathcal{L}_{int} = 100 \pm 2\ \mathrm{pb}^{-1}$ as a proof of principle
- External analysts can use the cross section result to perform their own extraction of m_W using different theoretical predictions

$W \to \mu\nu$ Differential Cross Section @ 5.02 TeV

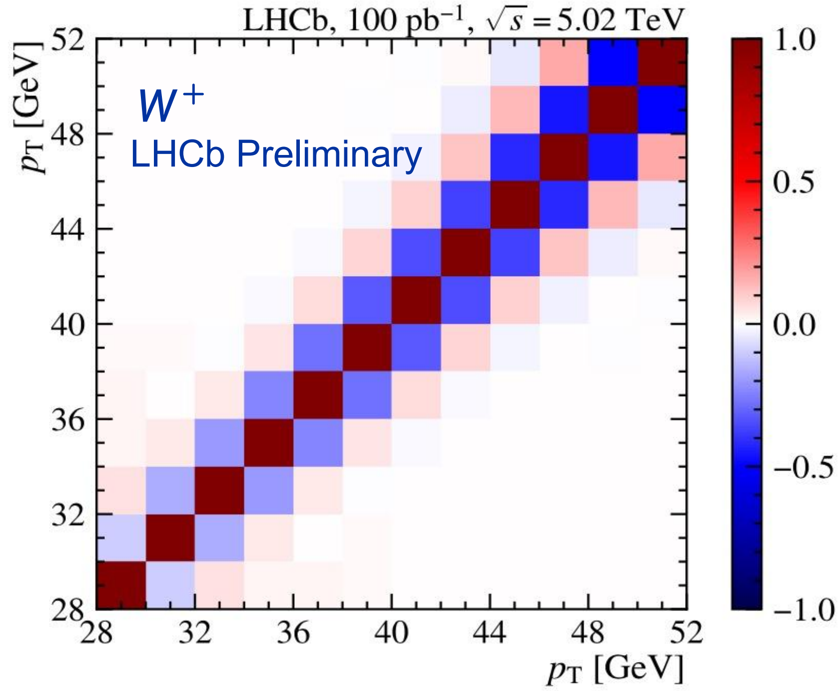
LLHCb-PAPER-2025-031 (in preparation)

- 12 bins of p_{T}, 8 bins of muon isolation, $2.2 < \eta < 4.4$, $28 < p_{\mathrm{T}} < 52$ GeV



LHCb Preliminary

Interval in p_{T} (GeV)	$\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$ (pb/GeV) $W^+ \to \mu^+\nu_\mu$	$W^- \to \mu^-\bar{\nu}_\mu$
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	$1.75 \pm 0.21 \pm 0.14$	$1.42 \pm 0.18 \pm 0.08$



statistical correlation matrix

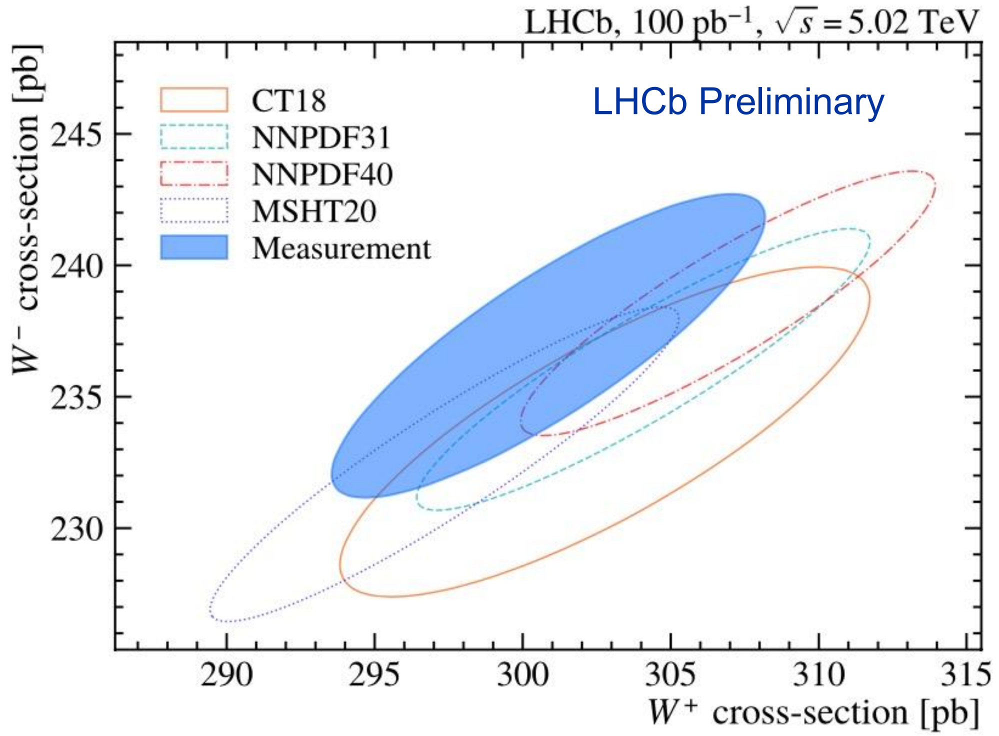
$W \rightarrow \mu\nu$ Integral Cross Section @ 5.02 TeV

LLHCb-PAPER-2025-031 (in preparation)

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

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

- The results are compared with predictions at NNLO from MCFM generator
- Predictions have uncertainties on varying PDF members and scale variations

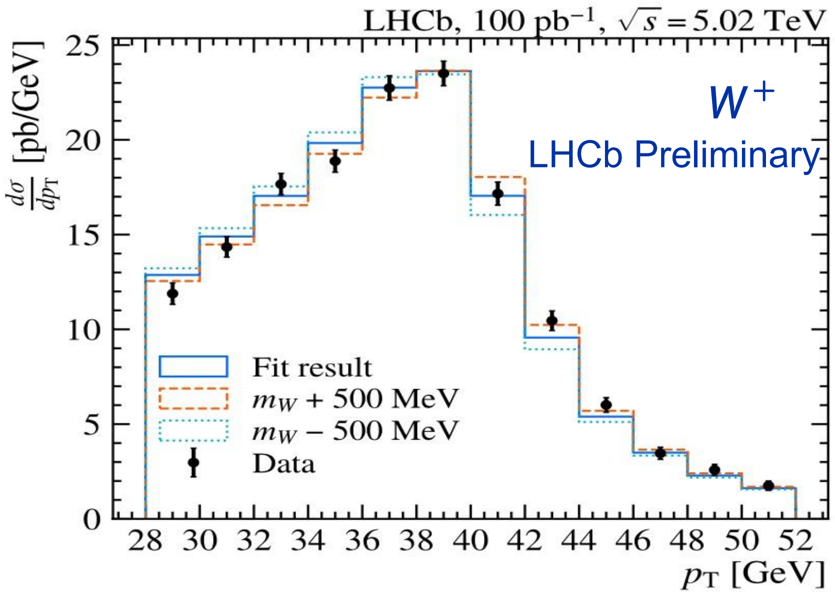


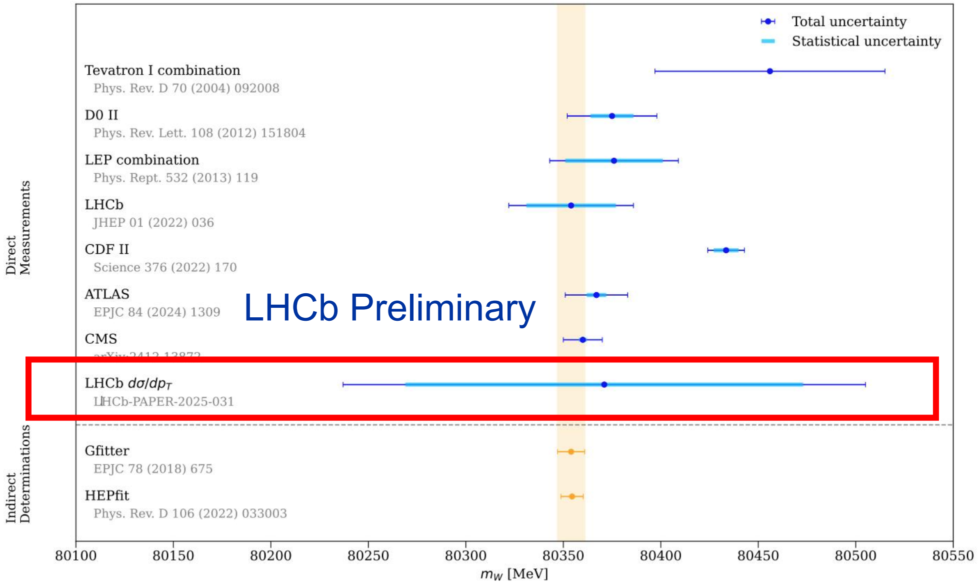
m_W Measurement

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 24×24 covariance matrix**
  - **fit can be performed with any model**
- Model in this analysis: Pythia, reweighted to DYTurbo (NNLO + NNLL unpolarised, NLO angular terms)

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





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

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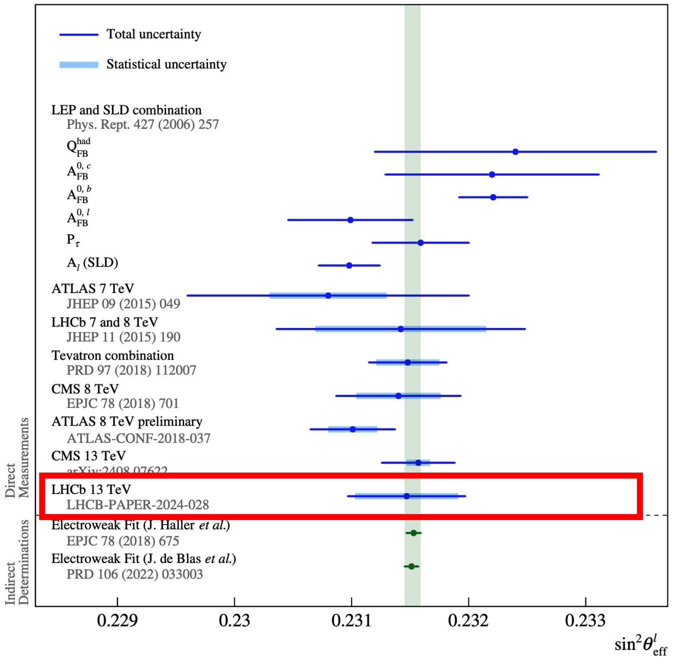
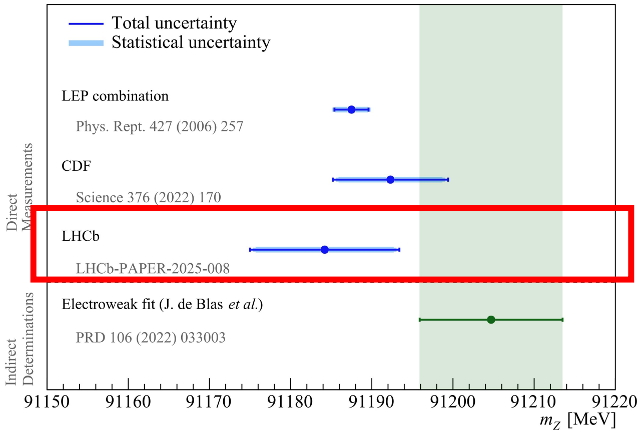
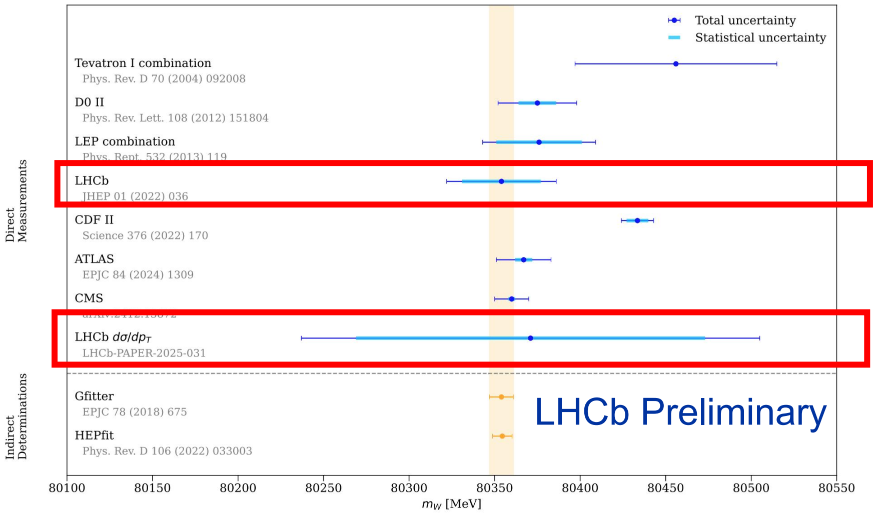


arXiv: 2505. 15582





LHCb-PAPER-2025-031 (in preparation)

Future Prospects

LHCb-TDR-023

LHC Run Year	Integrated luminosity fb^{-1}		
$cm^{-1}s^{-1}$	1.0×10^{34}	1.5×10^{34}	2.0×10^{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

- 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

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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, $\varepsilon(\mu) > 95\%$

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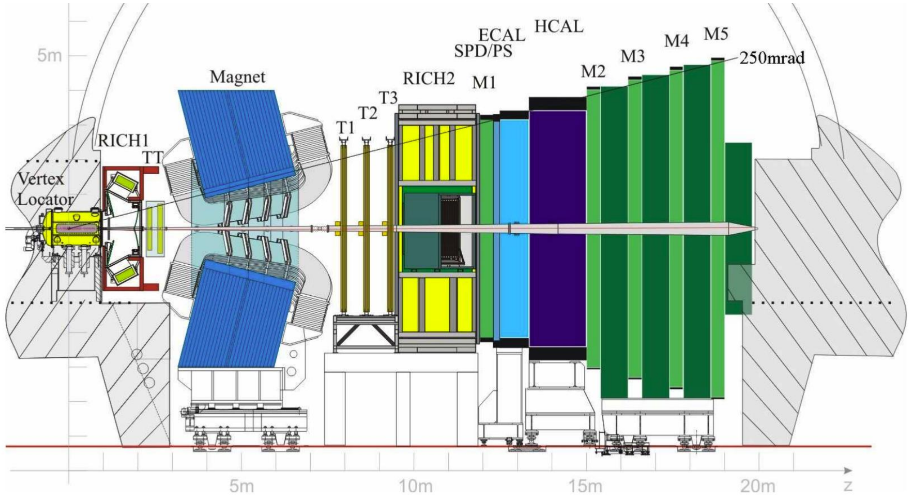
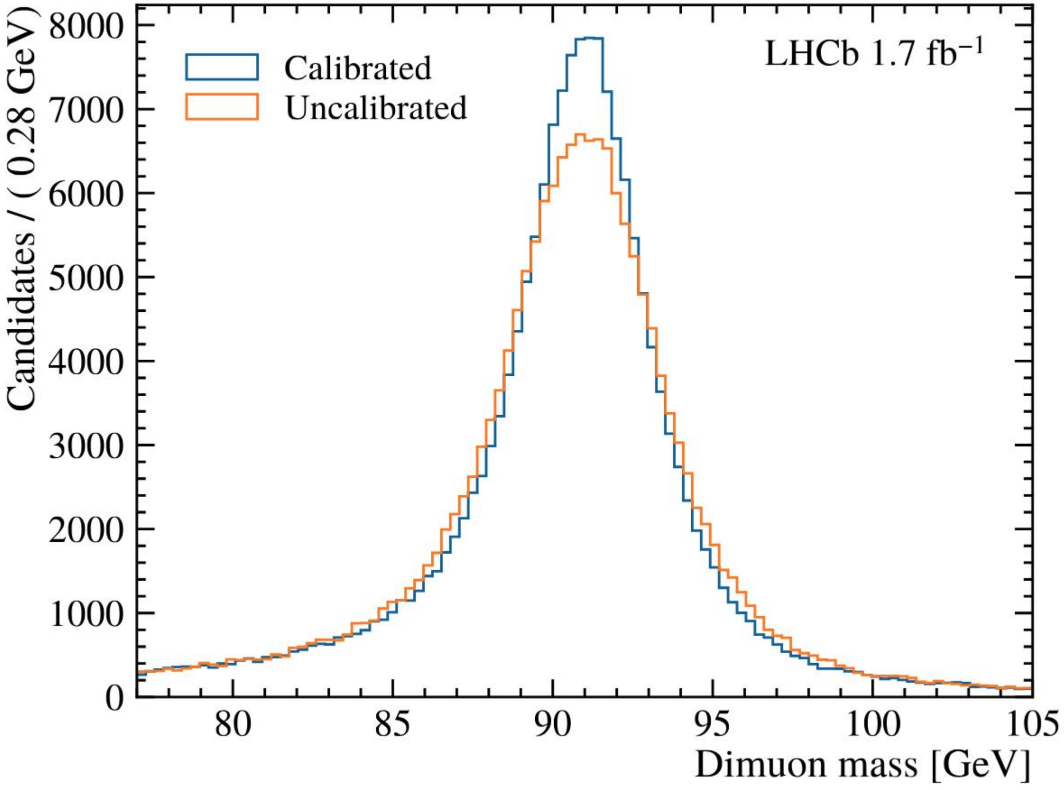
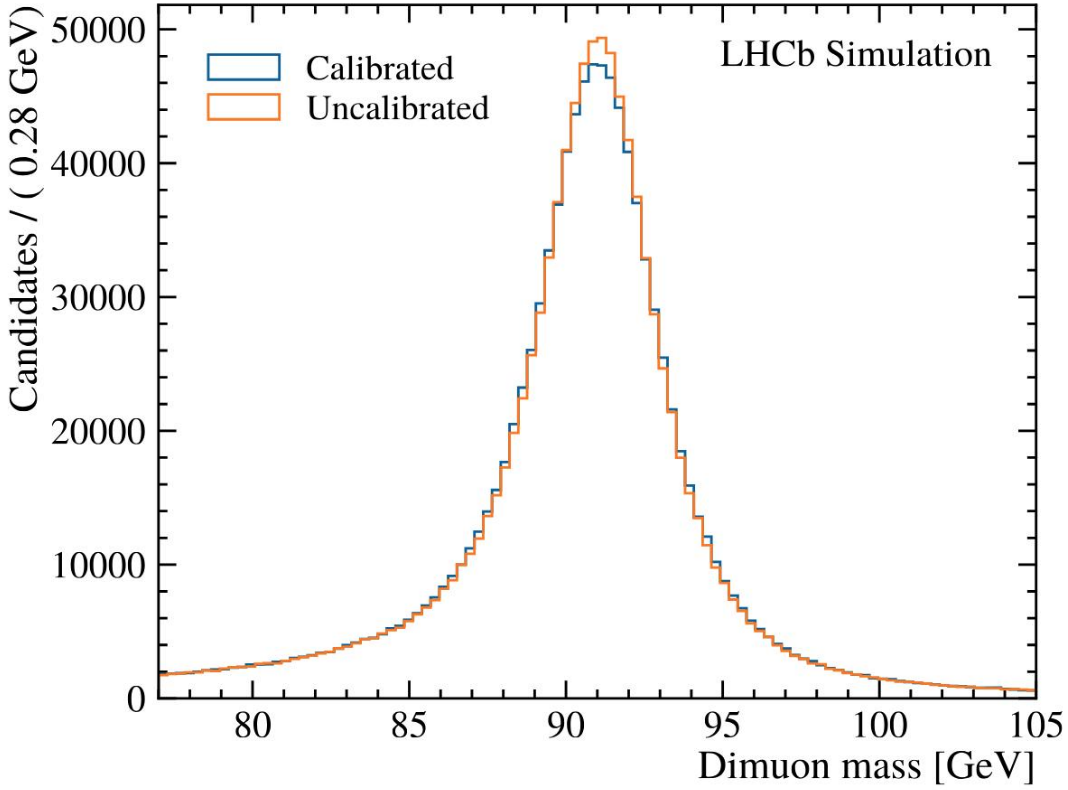


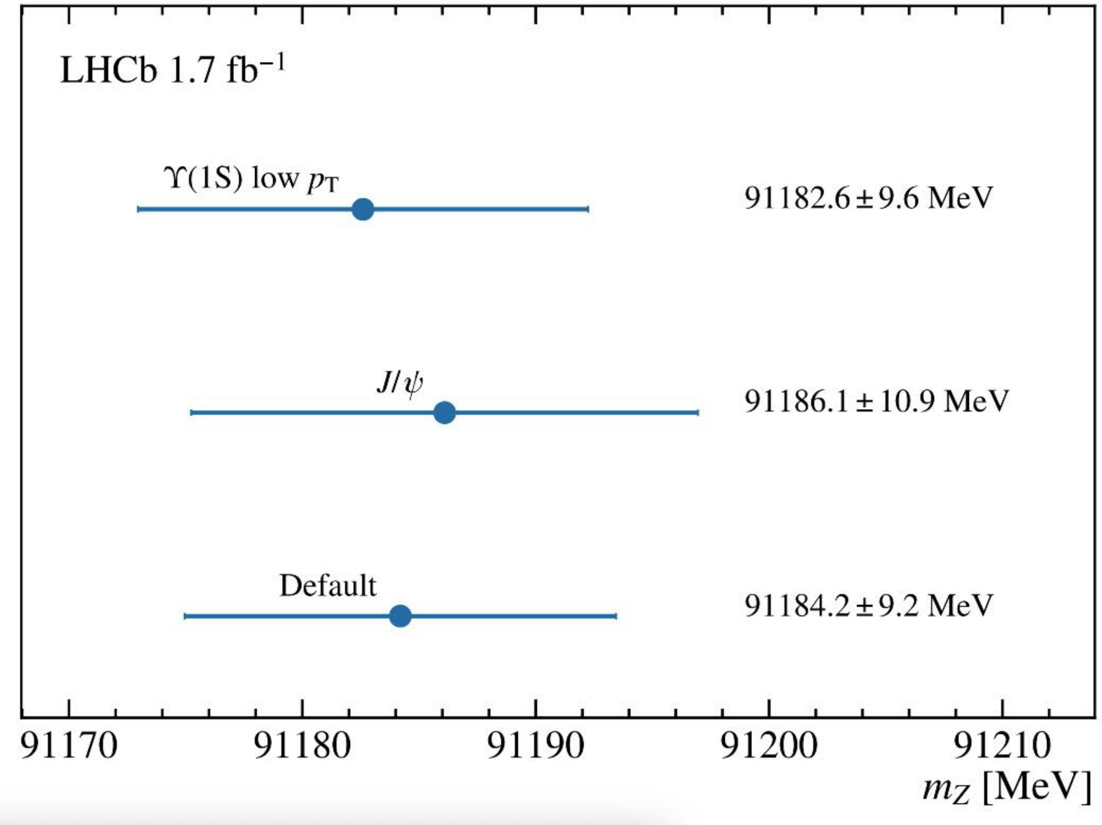
Z Mass Measurement Supplementary

arXiv: 2505. 15582





Z Mass Measurement Supplementary



arXiv: 2505. 15582

Z Mass Measurement Supplementary

arXiv: 2505. 15582

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
Statistical	**8.5**	
Total	**9.5**	

$W \to \mu\nu$ Cross Section @ 5.02 TeV Supplementary

- Integrating over isolation
- Largely diagonal due to excellent $\vec{p}$ resoluation

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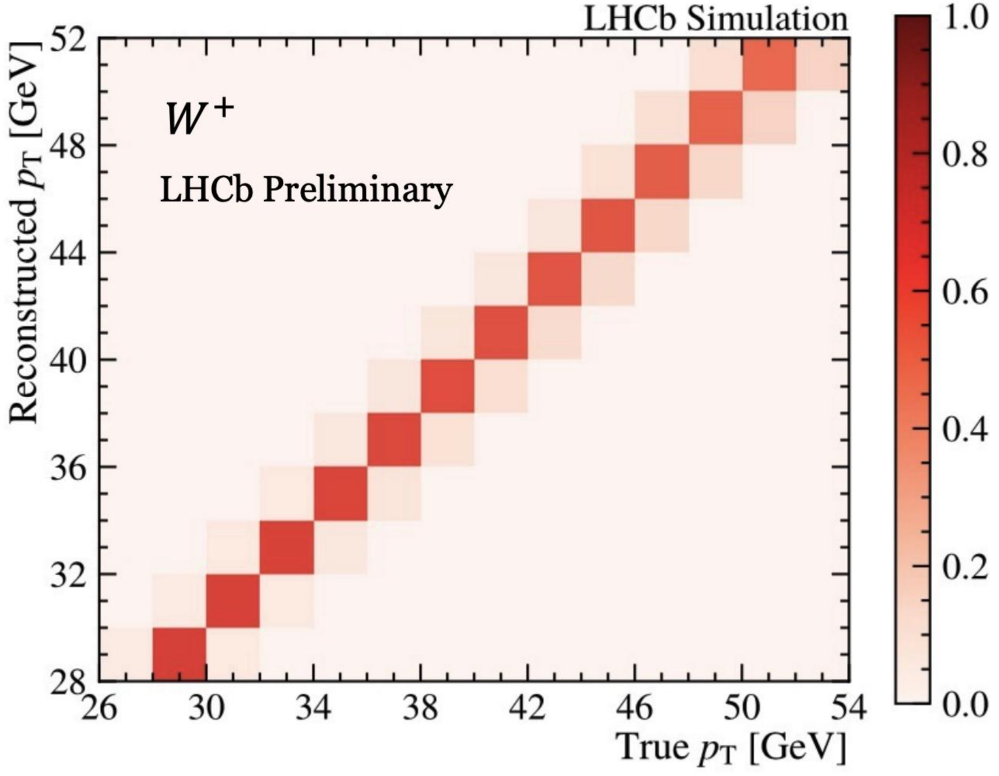

$W \to \mu\nu$ Cross Section @ 5.02 TeV Supplementary

- Relative systematic uncertainties on the differential cross-sections

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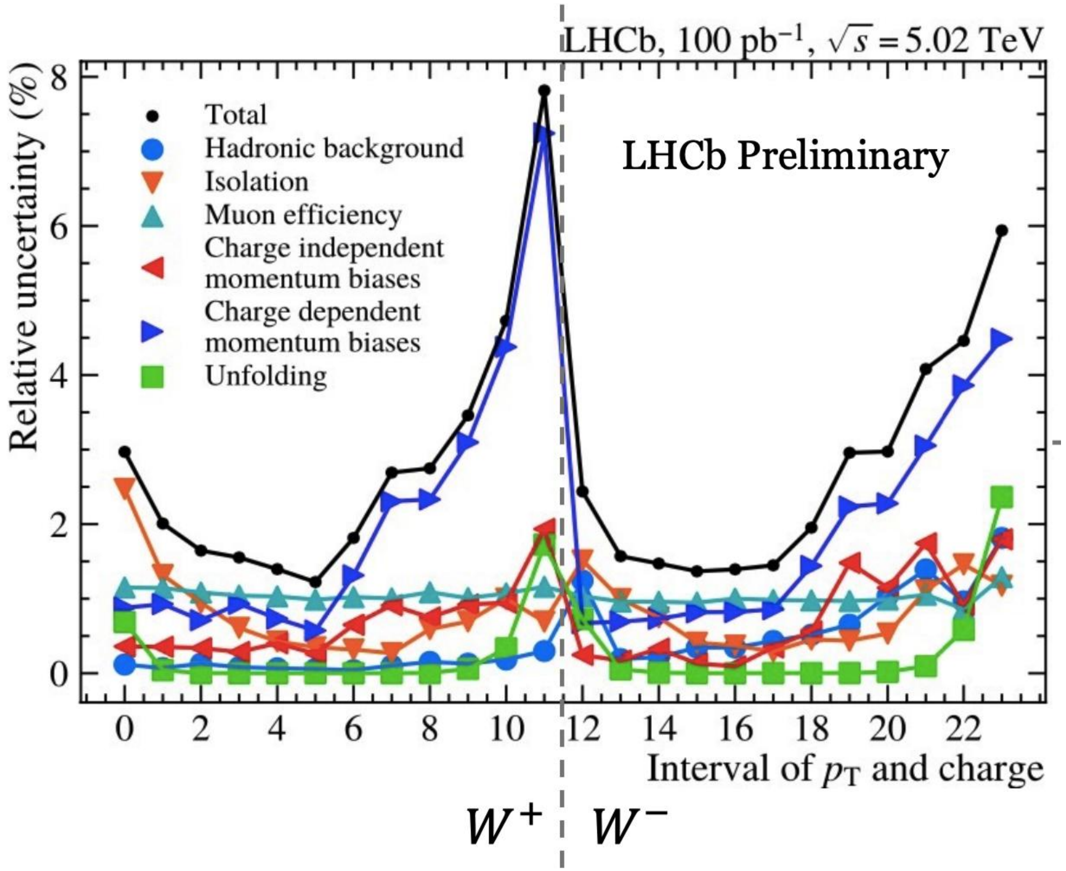

$W \to \mu\nu$ Cross Section @ 5.02 TeV Supplementary

- Correlation matrix corresponding to the total systematic uncertainty

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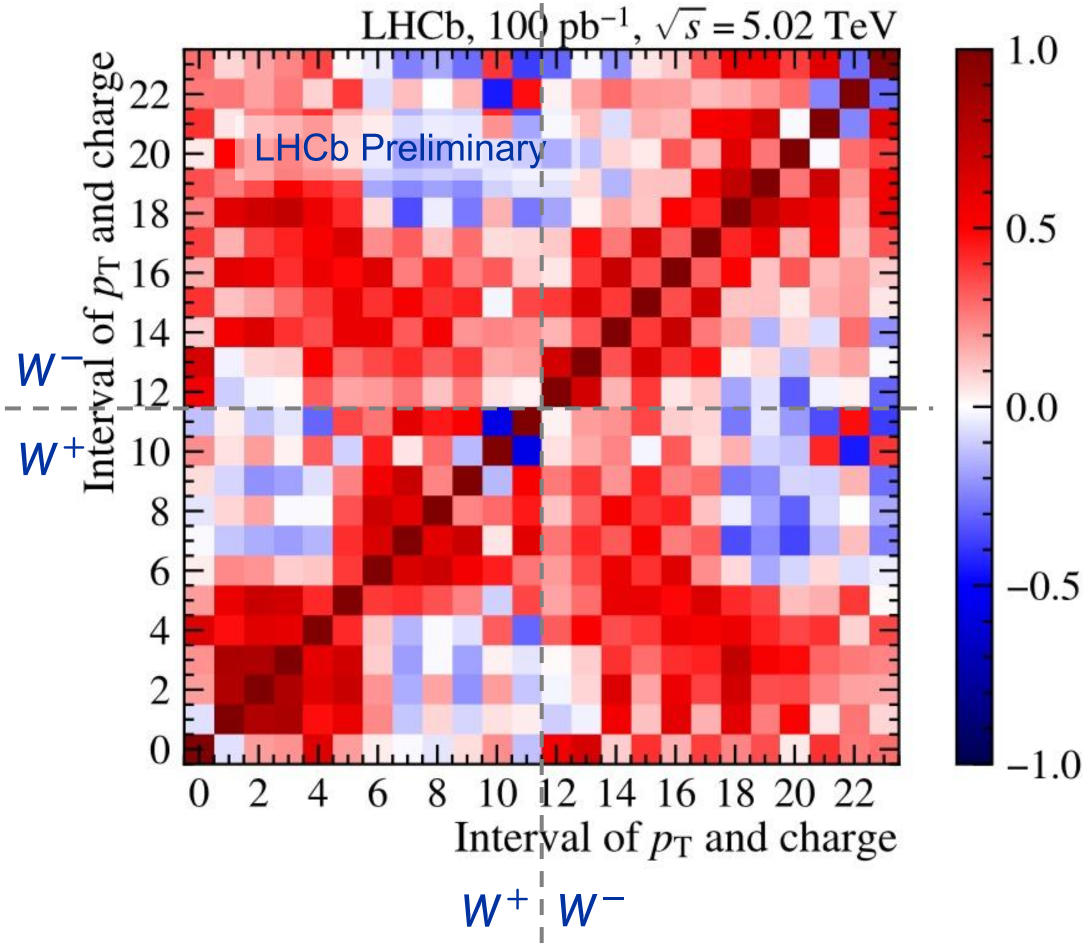

$W \rightarrow \mu\nu$ Cross Section @ 5.02 TeV Supplementary

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

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

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

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- 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_{fb} caused by a change in the $\sin^2\theta_{\text{eff}}^{\text{lept}}$ increases with $|\Delta\eta|$
- Increase of sensitivity, ~14% by studying A_{fb} as a function of dimuon pseudorapidity diffference