W mass measurement at LHCb

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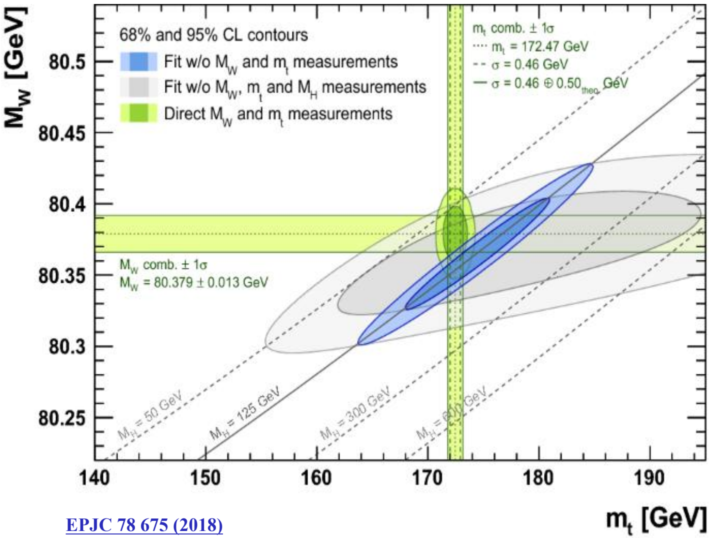
on behalf of the LHCb collaboration
WIN 2023, 07/07

Motivation

- m_W is directly related to electroweak symmetry breaking in the SM



EPJC 78 675 (2018)

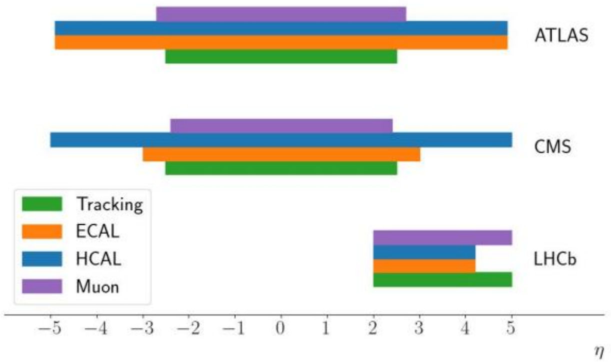
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F(1 - m_W^2/m_Z^2)(1 - \Delta r)}$$

Δr: loop corrections

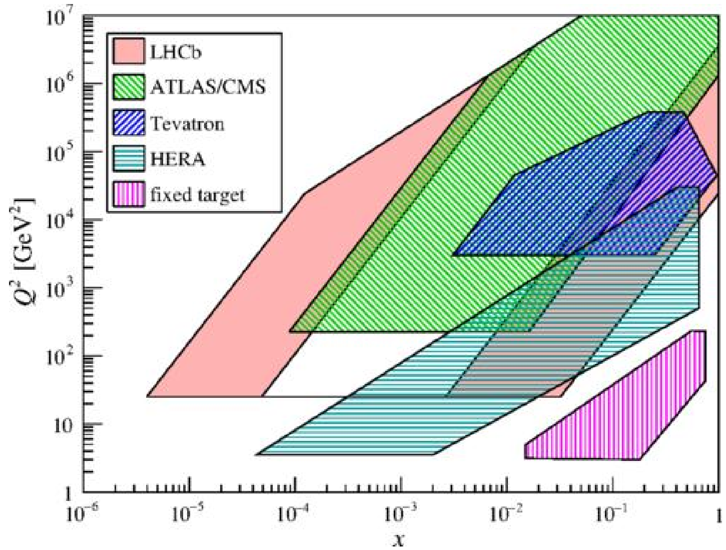
- Sensitivity to BSM physics is primarily limited by precision of **direct** measurements of m_W

LHCb forward region

- Low pile-up environment
- Forward region, $2 < \eta < 5$: **high/low-x** partons involved



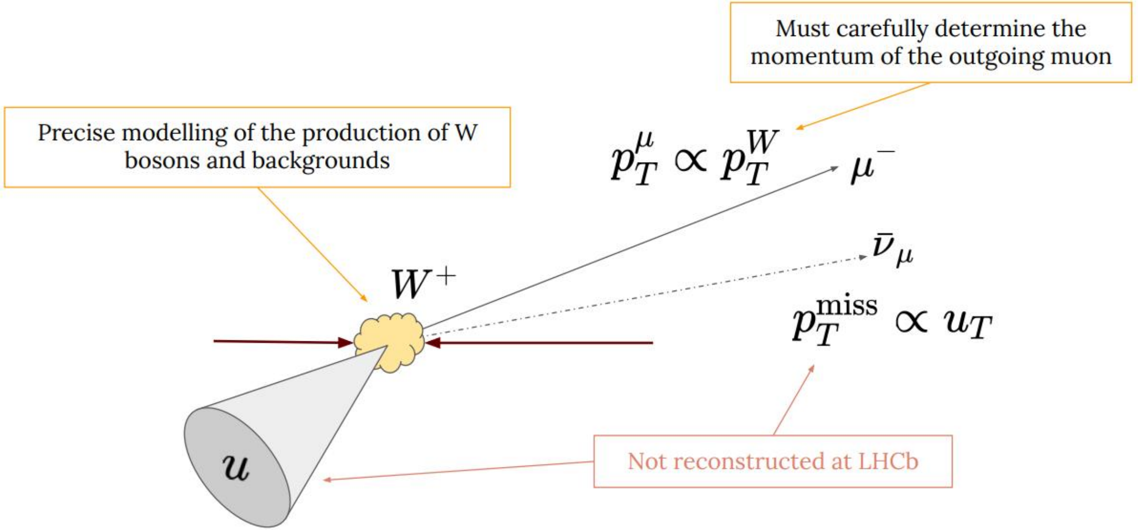
Phys. Rev. D 93, 074008 (2016)



x: parton longitudinal momentum fraction
Q^2: momentum transfer

Signal event signature

- **Identified muon** candidate matched to single muon trigger path
- Hadronic background suppressed to the percent level by an isolation requirement
- Second-muon ($p_{\mathrm{T}} > 20\mathrm{GeV}$ and $2.2 < \eta < 4.4$) veto suppressed $Z \to \mu\mu$ background



Fitting the muon q/p_{T} distribution

- Measurements based on muon p_{T}

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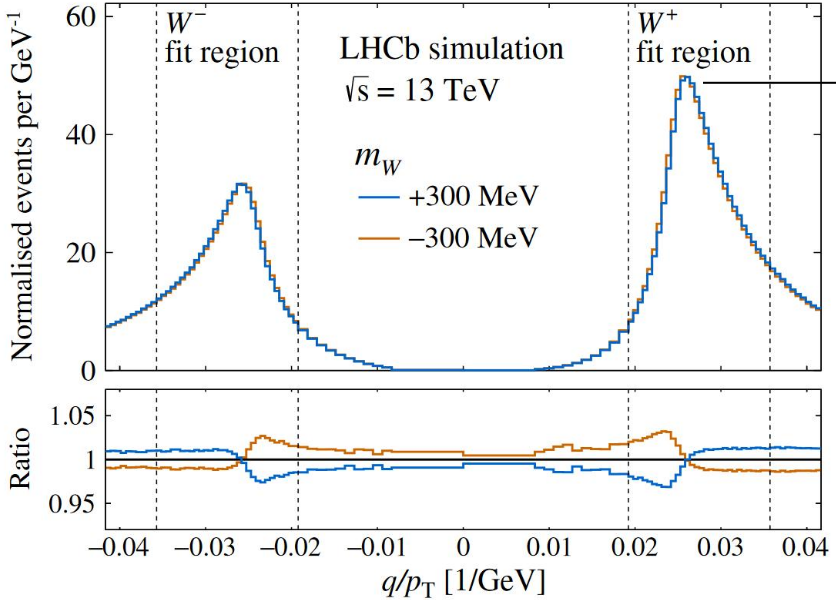


$q/p_T \approx \frac{2}{m_W}$

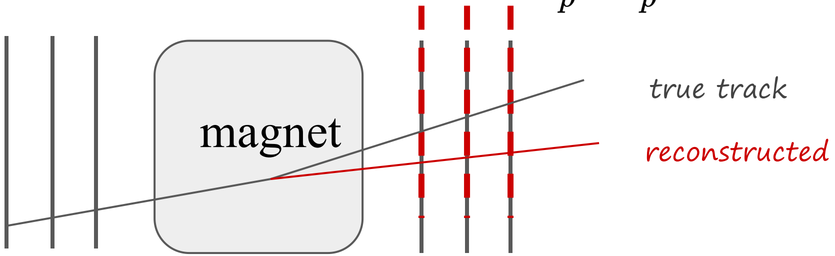
fit region $\Rightarrow \eta \in [2.2,\ 4.4],\ p_T^{\mu} \in [28,\ 52]$ GeV

Detector and physics modelling

- Detector response
  - Muon momentum, reconstruction and selection efficiency
    - Correct the simulation efficiencies of the different selection steps
- W boson production
  - Modelling of the W p_{T} distribution, boson polarisation and electroweak corrections
  - Use plain LHCb Pythia8 simulation
  - A variety of models are used to fully reweight the events to/beyond next-to-leading-order accuracy

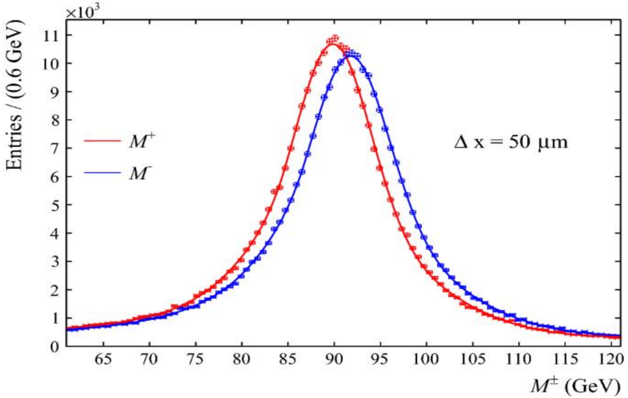
Curvature biases

- m_W determination is highly sensitive to misalignments and miscalibrations of the detector
  - **Misalignment of 10µm translates into a *O* (50MeV) shift**
- Re-run the alignment and calibration offline using *Z* events
- Corrected for charge-dependent curvature biases using the pseudomass method



$$\frac{q}{p} \to \frac{q}{p} + \delta(\eta, \phi)$$

EPJC 81 (2021) 3, 251



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

Phys. Rev. D 91, 072002

MC Smearing

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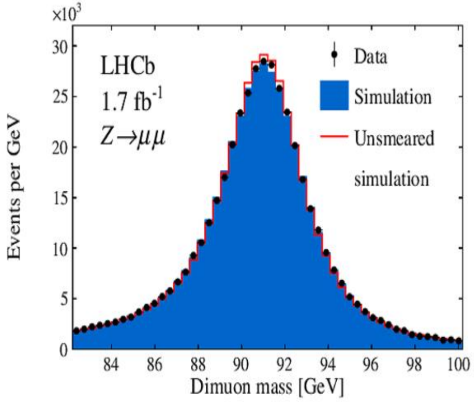
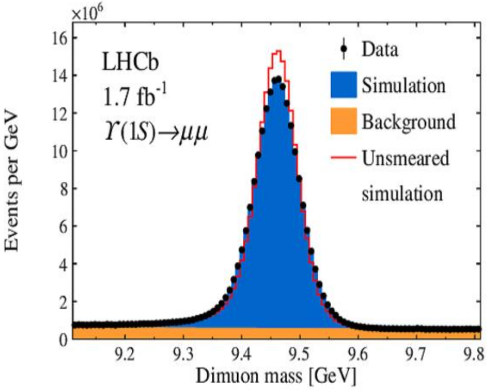
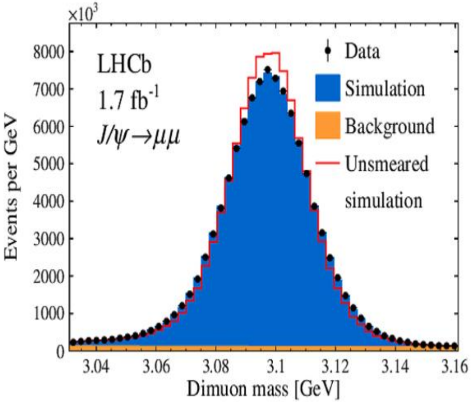
- Smearing of the muon momentum in simulation to account for
  - momentum scale
  - multiple scattering
- **Simultaneous fit** of Z, $\Upsilon(1S)$ and J/Ψ
- Systematic uncertainties: variations in the PDG resonance masses, detector material budget, final state radiation and the form of the smearing function







Selection efficiency modelling

- The selection efficiencies are measured in data and simulation with the same method
- Three main sources of selection biases
  - Trigger efficiencies
  - Muon-identification efficiencies
  - Isolation requirements
- **The simulated events are subsequently corrected with $\varepsilon_{data}/\varepsilon_{mc}$**

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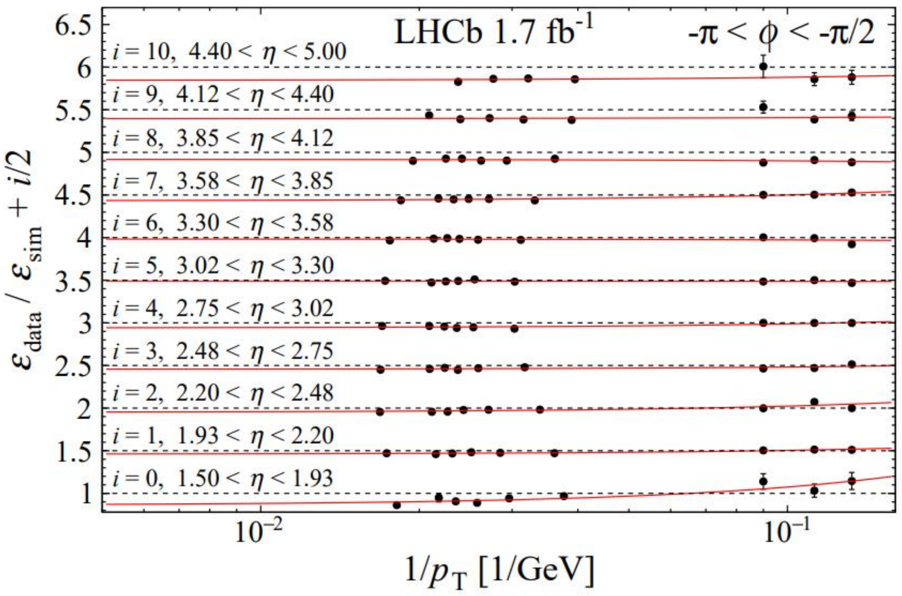

Backgrounds

- Eletroweak electroweakbackgrounds and heavy flavour hadrons are modelled with the simulation
- Hadronic background (decays-in-flight of pions and kaons)
  - A parametric model is trained on a sample of hadrons with weights to account for the variation of the decay-length acceptance on the Lorentz boos

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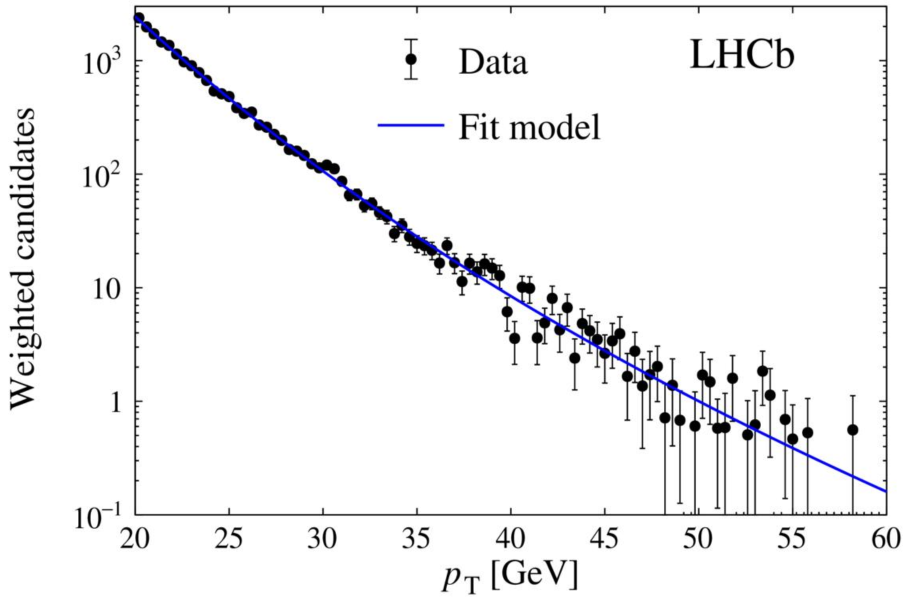
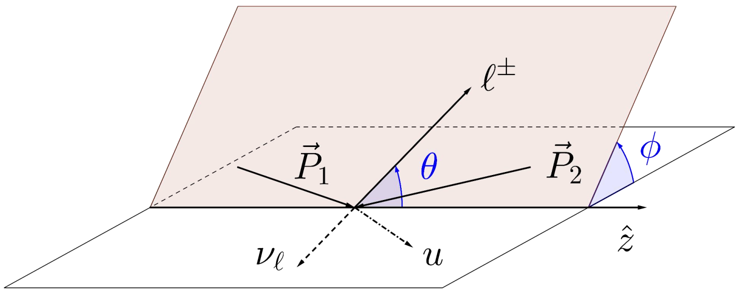


Vector boson production model

Collins-Soper frame



Unpolarized part

$$\frac{d\sigma}{dp_T^W\, dy\, dM\, d\cos\vartheta\, d\varphi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T^W\, dy\, dM}$$

Angular part

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

Physics model

- **POWHEG + Pythia** gives the best description of the **unpolarized** cross-section
  - Varied success with other generators, used to determine systematic uncertainties
- The **angular part** of the cross-section is better described with **DYTurbo**

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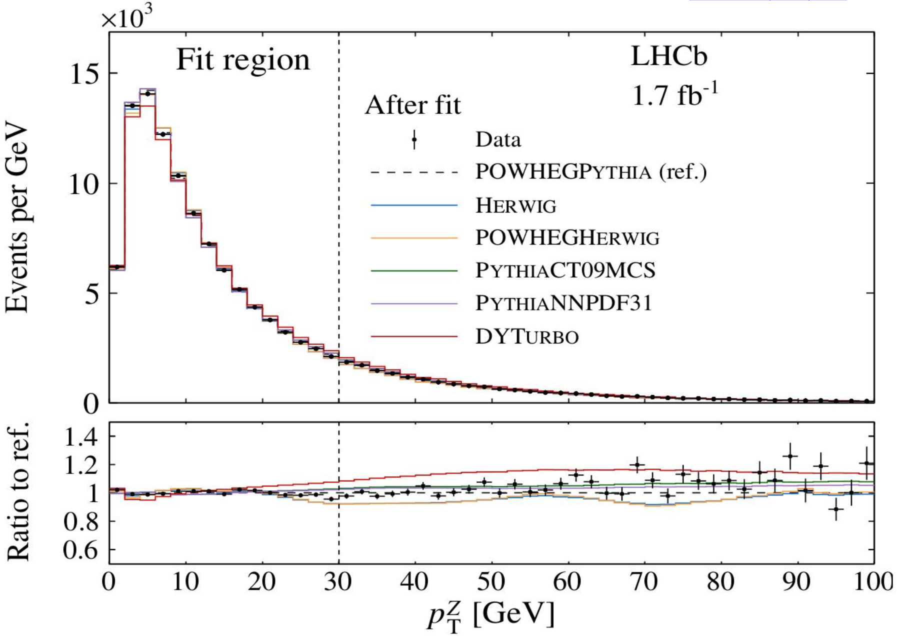

Electroweak corrections

- Pythia, Photos and Herwig models of QED final state radiation considered
- Central result based on the **average** of the three, while the uncertainty is based on the envelope over the three individual models

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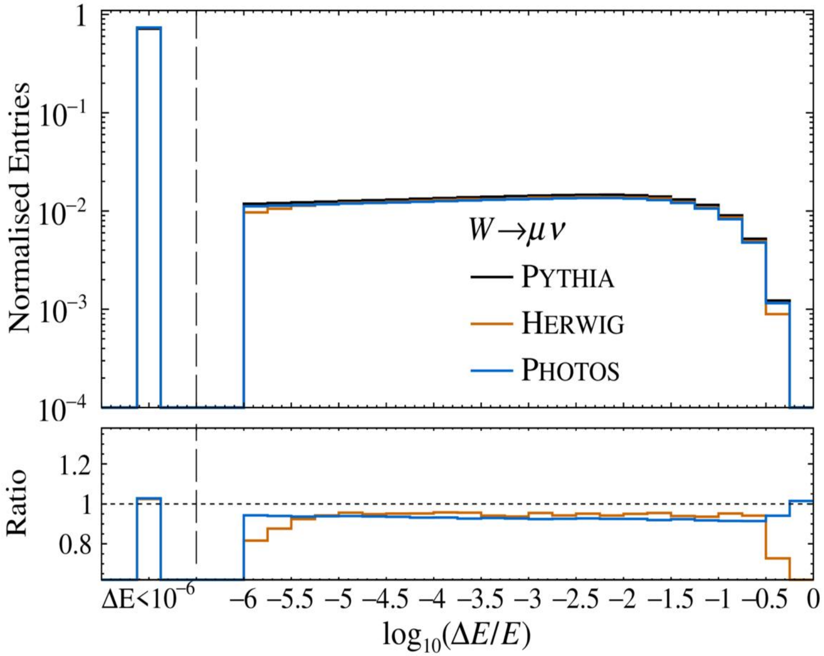

$$\Delta E/E = \frac{E_{\text{boson}} - E_{\text{dilepton}}^{\text{bare}}}{E_{\text{boson}}}$$

Extract m_W

- In a template fit to the q/p_T^{μ} distribution
- In a **simultaneous** fit of W and Z data

[EPJC 71 1600 (2011)]

$$\phi^* \equiv \arctan\left(\frac{\pi-\Delta\phi}{2}\right)/\cosh\left(\frac{\Delta\eta}{2}\right) \sim \frac{p_T}{M}$$

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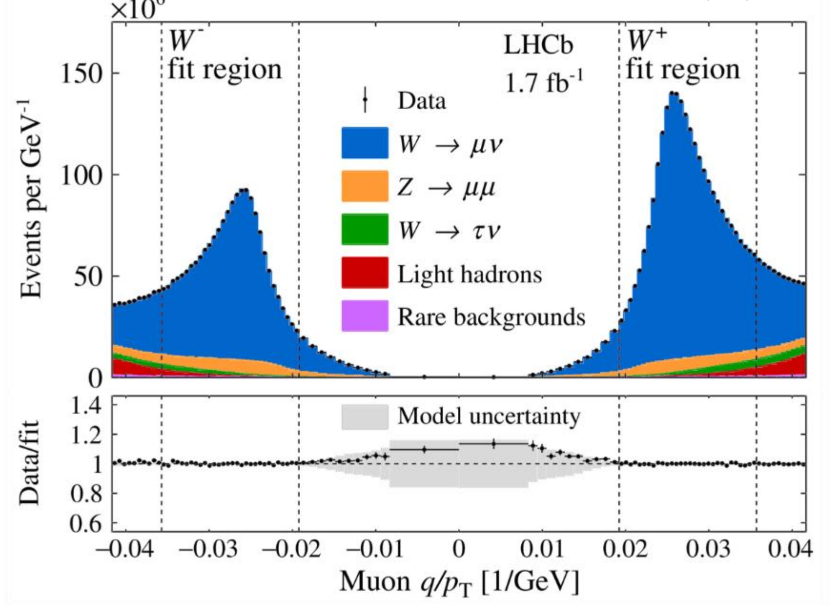

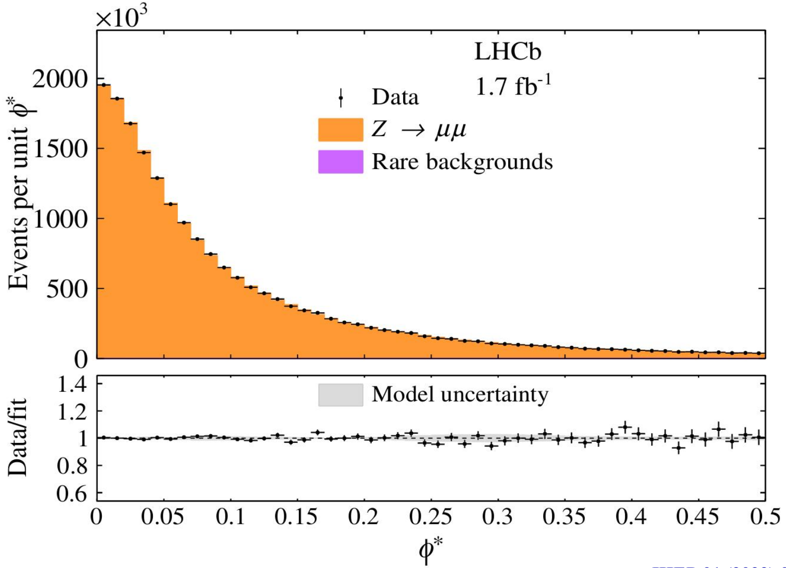

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PDF uncertainties

- The uncertainties are evaluated with specific prescriptions from each of the three groups
- Central m_W result is an average of the three results with the individual PDF sets assuming **100%** correlation

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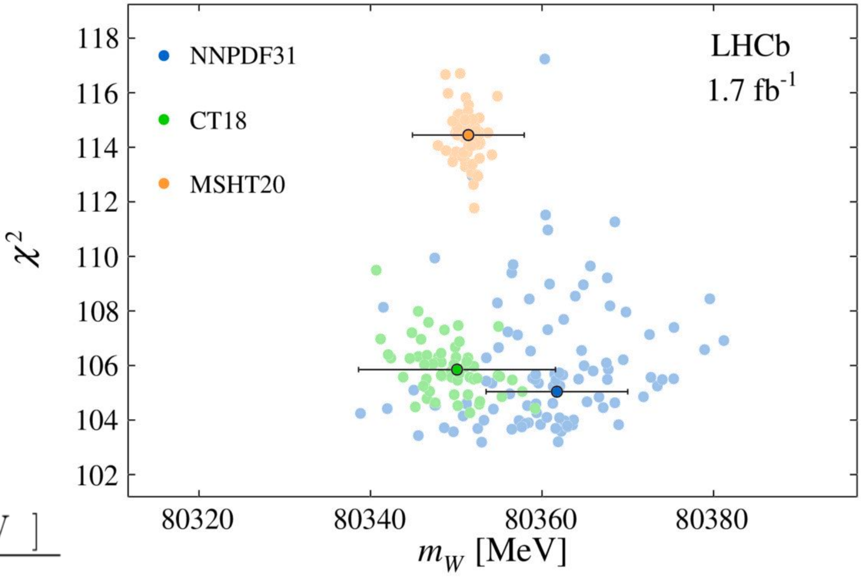

Set	$\sigma_{\text{PDF,base}}$ [MeV]	$\sigma_{\text{PDF},\alpha_s}$ [MeV]	σ_{PDF} [MeV]
NNPDF3.1	8.3	2.4	8.6
CT18	11.5	1.4	11.6
MSHT20	6.5	2.1	6.8

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Measurement uncertainty summary

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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**

→ average of NNPDF31, CT18 and MSHT20

→ from five different models

→ scale variation

→ envelope of the QED FSR from PYTHIA8 Photos and Herweig

→ statistical uncertainties, details of method (e.g. binning, smoothing)

Cross Checks

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- Orthogonal splits: differences within 2σ
- Fit range: the result is stable with the variations in the upper/lower limits
- W-like m_Z measurement: with μ^+ and μ^- agree to better than 1σ and their average agrees with in the PDG value at 1σ

Subset	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]
Polarity $= -1$	92.5/102	–
Polarity $= +1$	97.3/102	-57.5 ± 45.4
$\eta > 3.3$	115.4/102	–
$\eta < 3.3$	85.9/102	$+56.9 \pm 45.5$
Polarity $\times\ q = +1$	95.9/102	–
Polarity $\times\ q = -1$	98.2/102	$+16.1 \pm 45.4$
$\lvert\phi\rvert > \pi/2$	98.8/102	–
$\lvert\phi\rvert < \pi/2$	115.0/102	$+66.7 \pm 45.5$
$\phi < 0$	91.8/102	–
$\phi > 0$	103.0/102	-100.5 ± 45.3

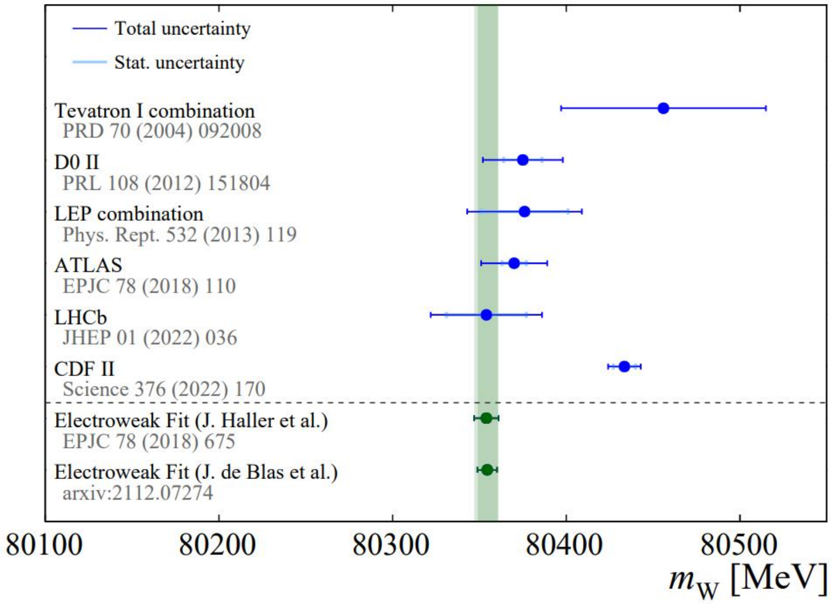
- Alternative fit with the difference between the m_{W+} and m_{W-} as another floating parameter: this parameter ~0 within 1σ
- Additional tests with NNLO PDFs instead of NLO PDFs, variations in the charm quark mass, etc… affect m_W at the $\lesssim 1$ MeV level

2016 result

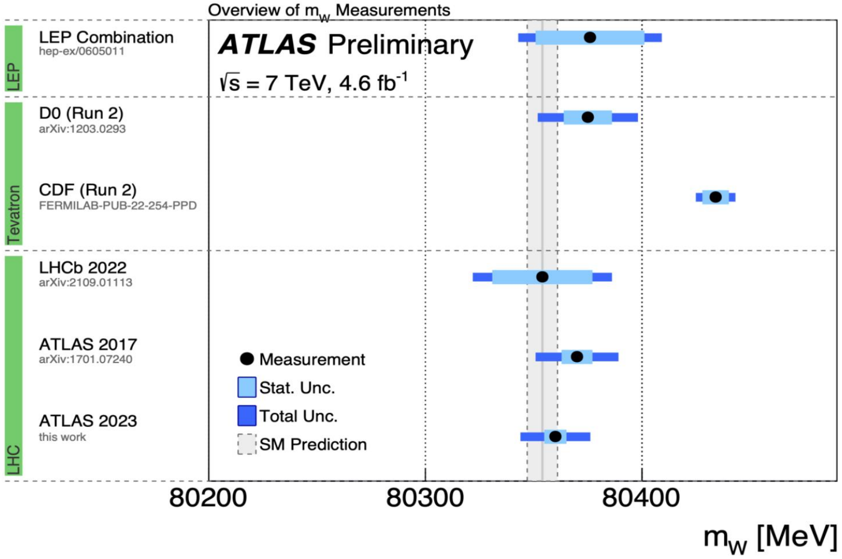
- LHCb achieves a precision of ~ 32 MeV using roughly 1/3 of the Run-II dataset

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

LHCB-FIGURE-2022-003



ATLAS-CONF-2023-004

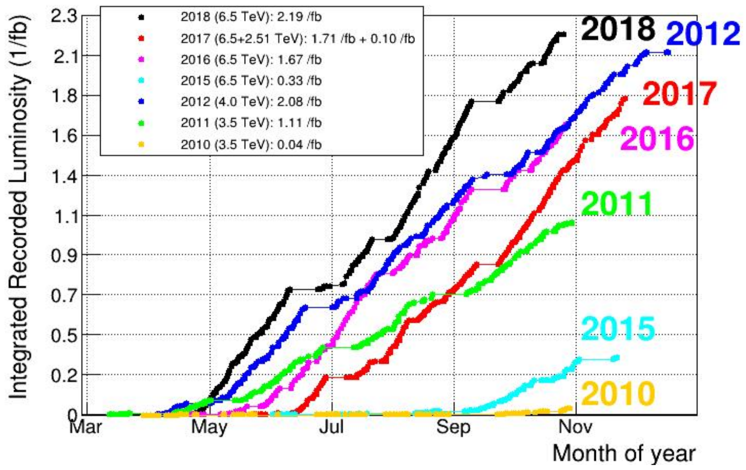


With the full Run 2 dataset

- Including 2017 and 2018 data is straight-forward
    - More careful treatment of the detector effects
    - Improvements in the physics modelling

Target sensitivity:

$$\sigma^{\text{Run 2}}_{\text{stat.}} \sim 14\text{MeV}$$
$$\sigma^{\text{Run 2}}_{\text{total}} \sim 20\text{MeV}$$



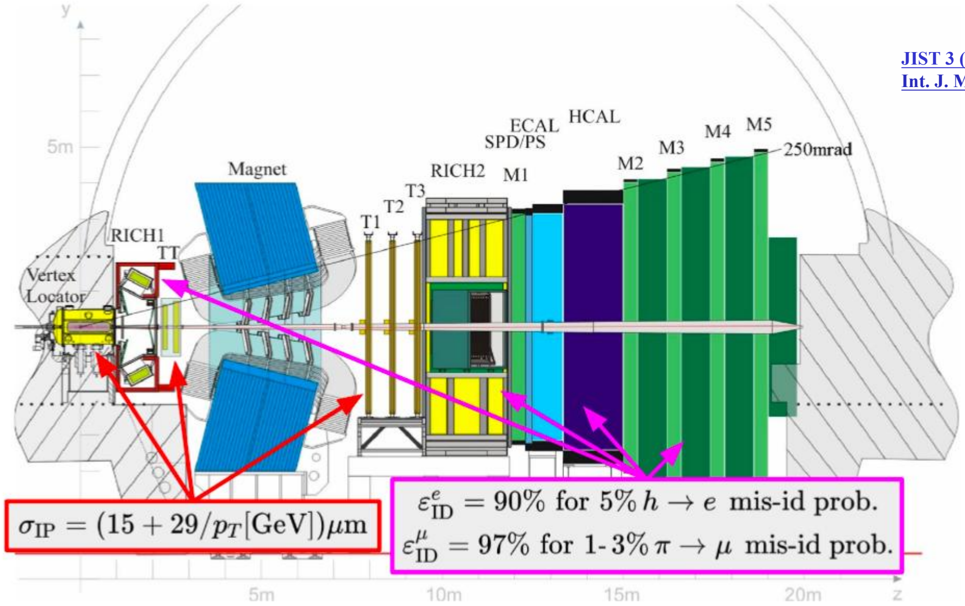
Conclusions and outlook

- First measurement of m_W from LHCb with 32 MeV uncertainty is consistent with the prediction
- A total uncertainty of $\lesssim$ 20 MeV looks achievable with existing LHCb data
- On Run 3, with a similar detector and analysis environment the precision will increase with the square root of the luminosity
- On Run 4 and beyond, an improved electromagnetic calorimeter system might open the door to study the electron mode at LHCb
- Look forward to working with the other LHC experiments, and the theory community, to fully exploit LHCb's unique/complementary rapidity coverage to achieve the ultimate precision on m_W

Back Up

LHCb Detector

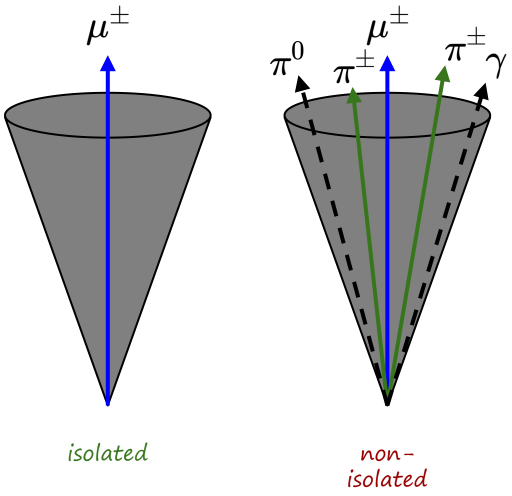
- Single-arm **forward** spectrometer
- Designed for the heavy flavour physics with $\mathbf{2 < \eta < 5}$
- Extended to **EW** measurements: excellent performance of tracking and muon detector



JIST 3 (2008) S08005
Int. J. Mod. Phys. A30(2015) 1530022

Selections

- EW physics with leptons in the final state can be done at LHCb with simple selections based on the transverse momentum, impact parameter, isolation and particle identification



$$I = \sum_i^n p_T^i \in \text{cone}$$

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2\left(\text{rad}^{-2}\right)}$$

Curvature corrections

- Fit the pseudomass asymmetries (between M^+ and M^- peak positions) in fine detector regions (bins in η and ϕ) and translate these to curvature corrections (shifts in q/p)

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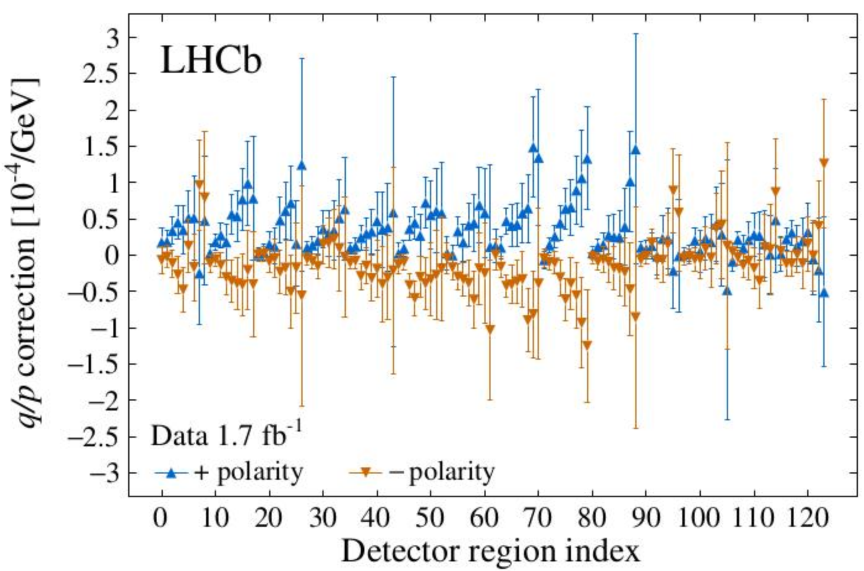

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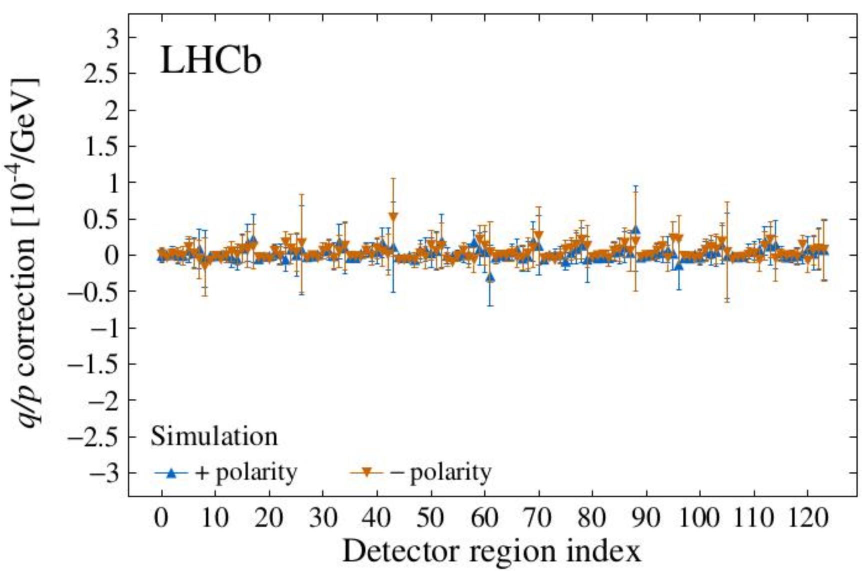
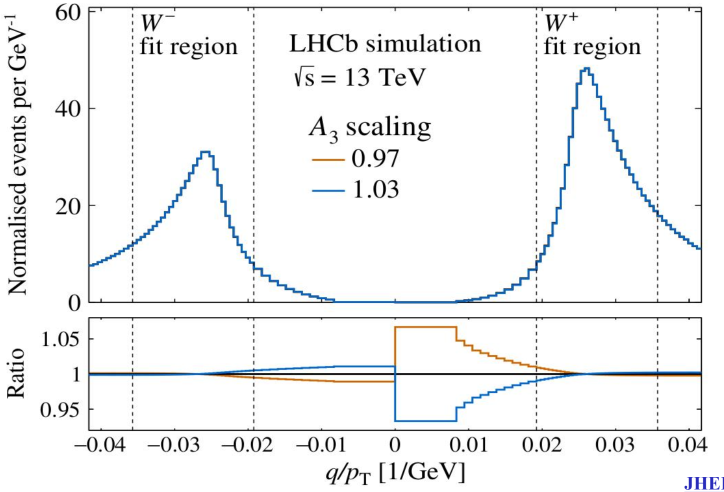


Polarized cross-section

- Uncertainties from DYTurbo mitigated by floating A_3
  - Otherwise the uncertainty would be $O(30\ \text{MeV})$
  - The preferred value in the fit is however consistent with DYTurbo predictions



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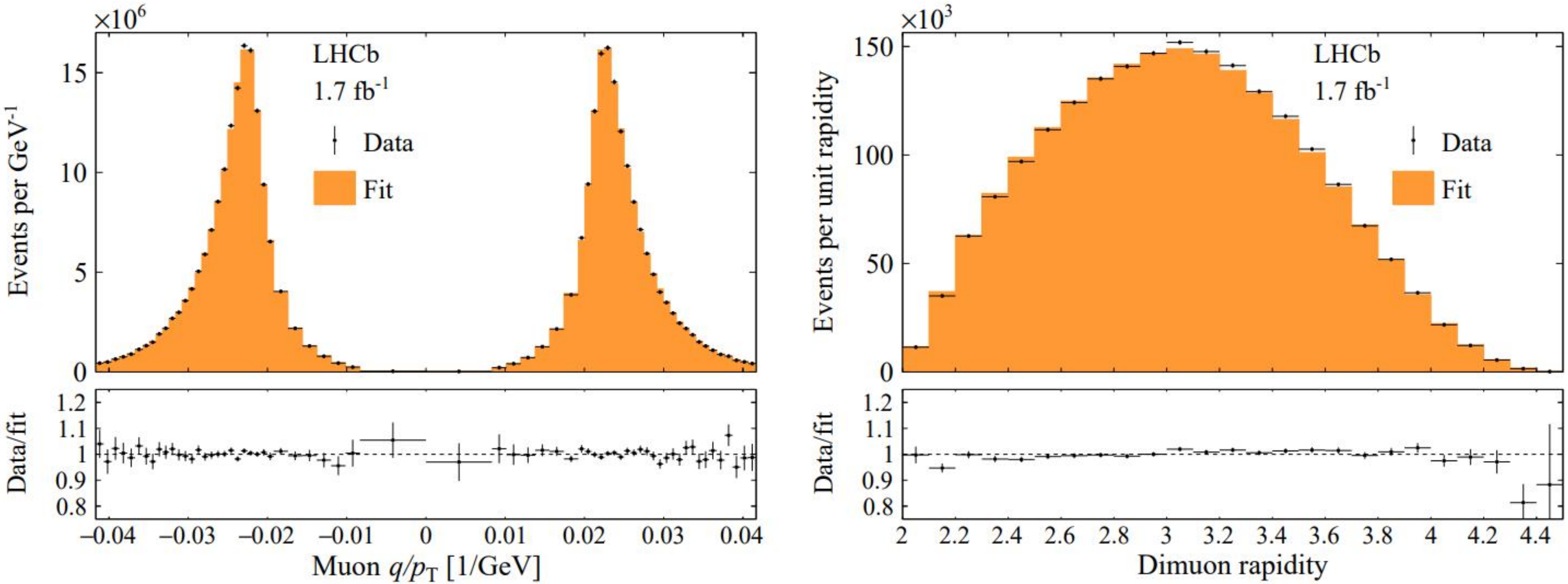
Postfit Plots

- The model is in good agreement with the data, which confirms that the momentum smearing is reliably determined and applied



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Cross checks

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Change to fit range	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$p_T^{\text{min}} = 24\,\text{GeV}$	96.5/102	+6.8	19.7
$p_T^{\text{min}} = 26\,\text{GeV}$	97.7/102	+9.6	20.9
$p_T^{\text{min}} = 30\,\text{GeV}$	102.7/102	+3.0	25.7
$p_T^{\text{min}} = 32\,\text{GeV}$	84.9/102	−21.6	30.8
$p_T^{\text{max}} = 48\,\text{GeV}$	105.3/102	−3.8	23.2
$p_T^{\text{max}} = 50\,\text{GeV}$	103.0/102	−2.1	23.0
$p_T^{\text{max}} = 54\,\text{GeV}$	96.3/102	−8.6	22.6
$p_T^{\text{max}} = 56\,\text{GeV}$	103.7/102	−14.3	22.4

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Configuration change	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$2 \rightarrow 3$ α_s parameters	103.4/101	−6.0	±23.1
$2 \rightarrow 1$ α_s and $1 \rightarrow 2$ k_T^{intr} parameters	116.1/102	+13.9	±22.4
$1 \rightarrow 2$ k_T^{intr} parameters	104.0/101	+0.4	±22.7
$1 \rightarrow 3$ k_T^{intr} parameters	102.8/100	−2.7	±22.9
No A_3 scaling	106.0/103	+4.4	±22.2
Varying QCD background asymmetry	103.8/101	−0.7	±22.7