W mass measurement at LHCb

Miguel Ramos Pernas

on behalf of the LHCb collaboration

University of Warwick

miguel.ramos.pernas@cern.ch

ICHEP 2022, Bologna 7/7/2022

THE UNIVERSITY OF WARWICK

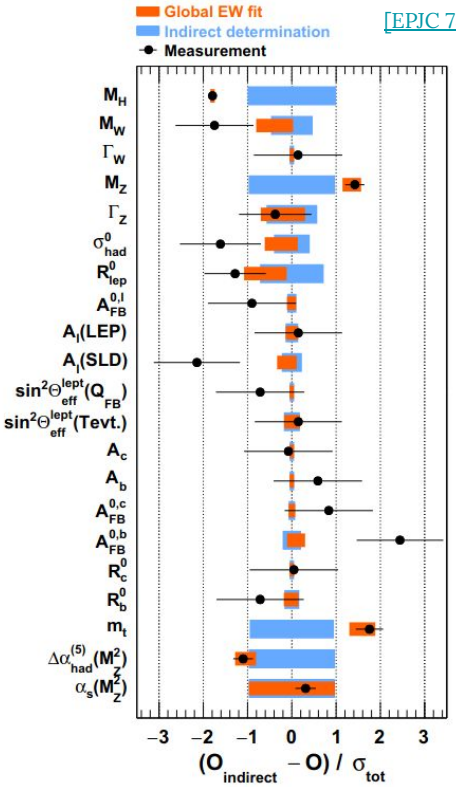
LHCb

European Research Council

Established by the European Commission

Current picture on the W mass

Higher order corrections



[EPJC 78, 675 (2018)]

High correlation with other observables

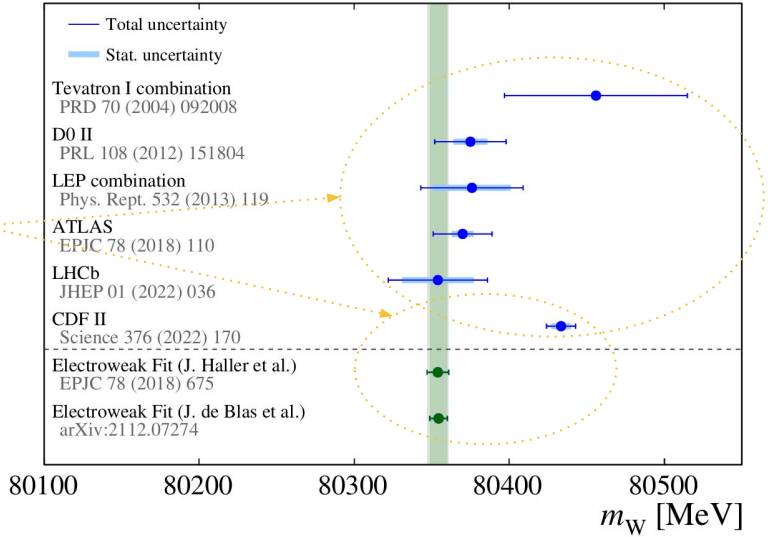
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

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

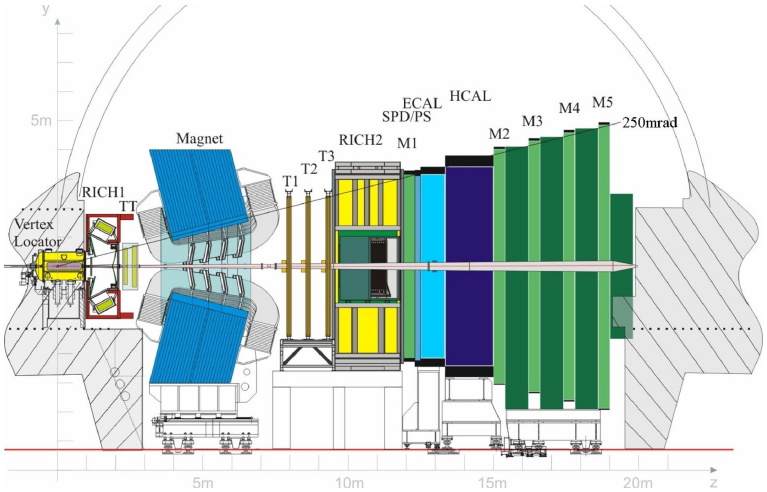
$$\Gamma_W \propto G_F m_W^3$$

[LHCB-FIGURE-2022-003]

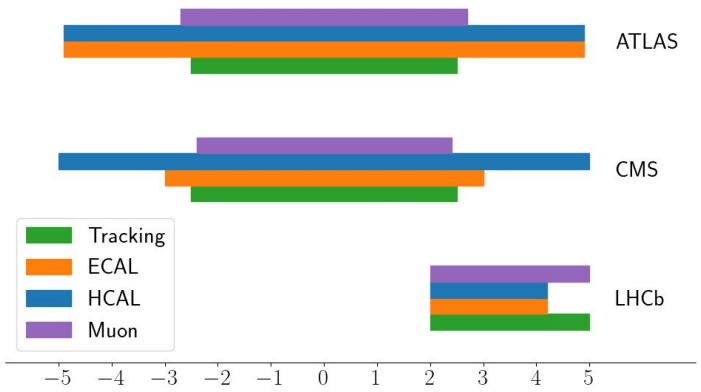
Must understand differences between experiments and with respect to the SM prediction



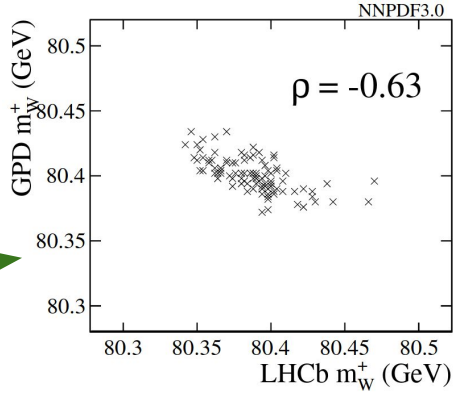
The LHCb experiment studying EW physics



[Int. J. Mod. Phys. A 30 (2015) 1530022]



Eur. Phys. J. C 75, 601 (2015)

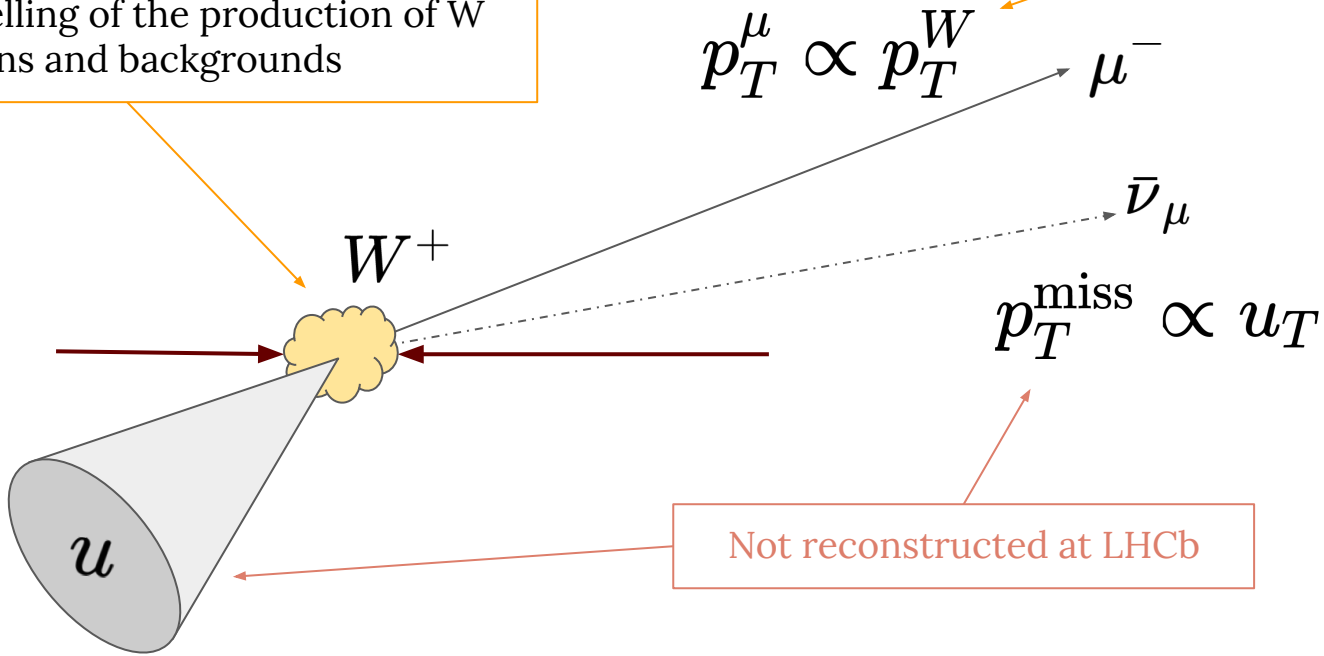


- High precision measurement of the W mass is possible at LHCb
- PDF uncertainties anti-correlated with respect to ATLAS and CMS
  - PDF systematic uncertainty can be reduced by a factor 2

Single event signature

Must carefully determine the momentum of the outgoing muon

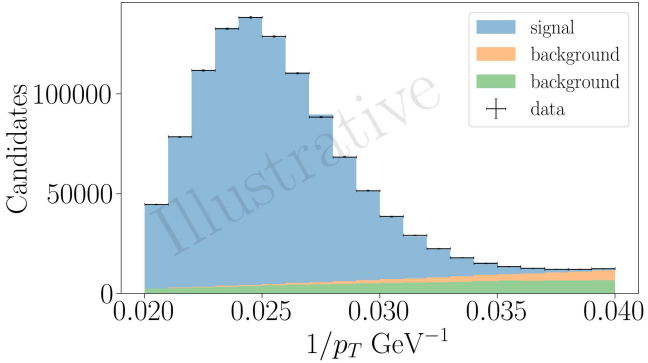
Precise modelling of the production of W bosons and backgrounds



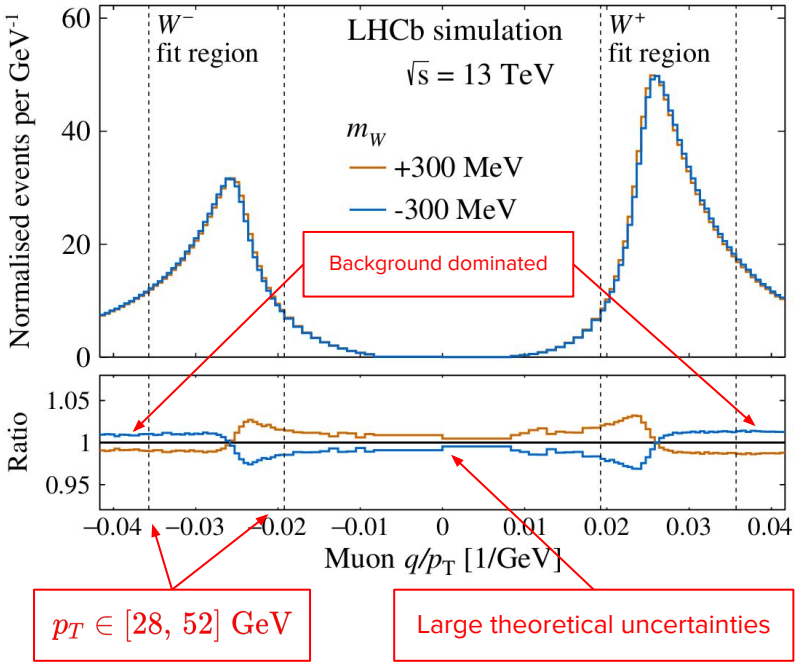
Not reconstructed at LHCb

Analysis strategy

- LHCb analysis including 2016 data and O(10^6) candidates
- Measure the W mass by carefully studying the muon transverse momentum
  - Offline reprocessing of the alignment with Z decays
  - Determination of curvature biases and momentum scaling
  - Small variations on the physics modelling translate into O(MeV) changes in the W mass measurement
- Fit templates predominantly obtained from simulation to data

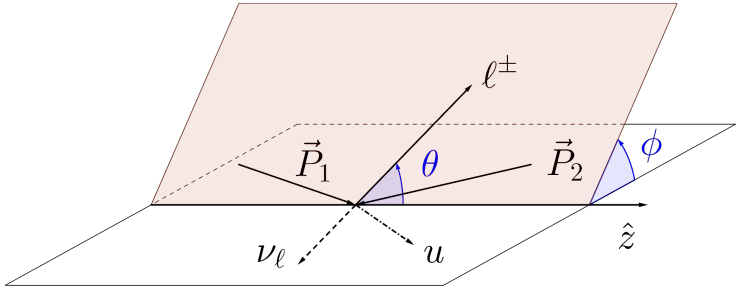


[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024] (supplementary)



The W cross-section

Collins-Soper frame



$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{W}\,\mathrm{d}y\mathrm{d}M\mathrm{d}\cos\vartheta\mathrm{d}\varphi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{\mathrm{unpol.}}}{\mathrm{d}p_{\mathrm{T}}^{W}\,\mathrm{d}y\mathrm{d}M}$$

Unpolarized part

(At order α_s^2)

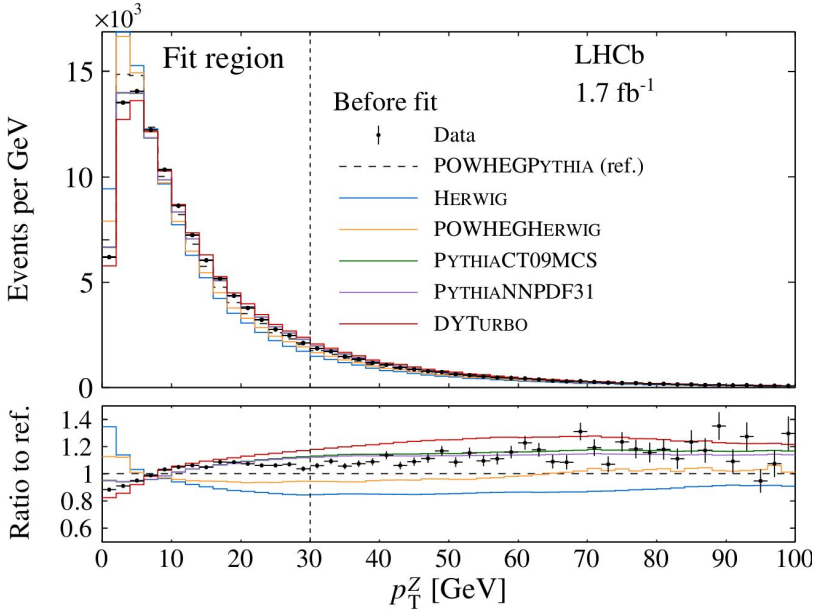
$$\{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1\sin 2\vartheta\cos\varphi$$
$$+ A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta$$
$$+ A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\}$$

Angular part

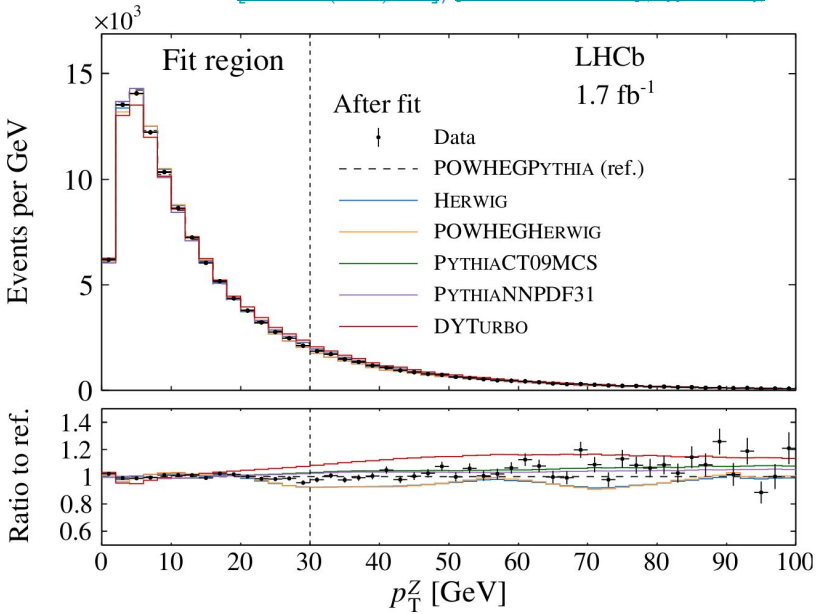
Small dependency on the angular coefficients for the W mass measurement at LHCb except for A_3

Tuning the generators

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



Tuning of α_s and $\hat{k}_T$



- Most reliable description of the unpolarized cross-section coming from POWHEG + Pythia
- Polarized cross-section better described with DYTurbo

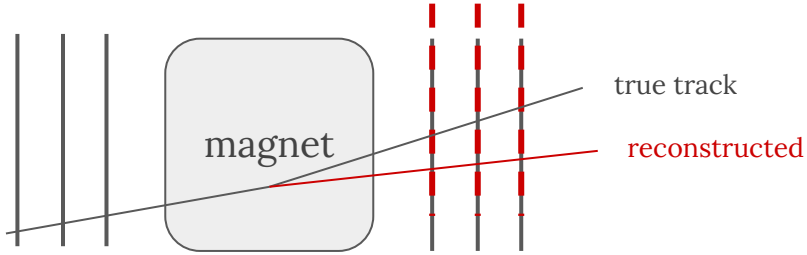
Charge-dependent curvature biases

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

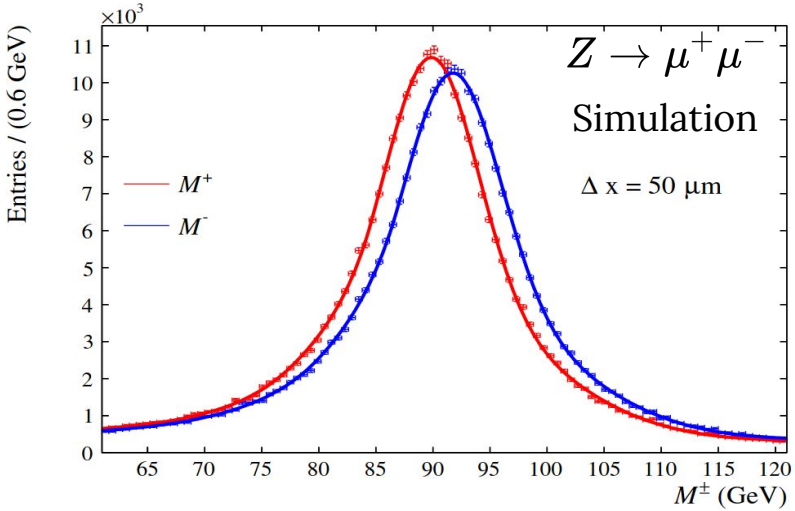
- The analysis relies highly on the detector alignment
  - Misalignment of 10μm translates into a O(50MeV) shift
- Default LHCb alignment and calibration not suitable to study candidates with high transverse momentum
- Need to re-run the alignment and calibration offline using Z
- Avoid double bias from the momentum resolution using the pseudo-mass method

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

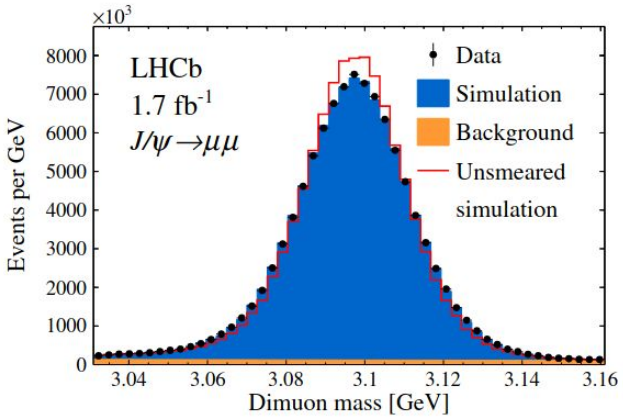
Inspired by Phys. Rev. D 91, 072002

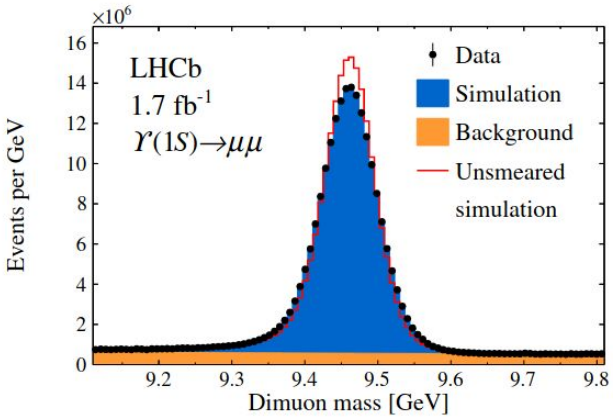


EPJ-C 81 (2021) 3, 251



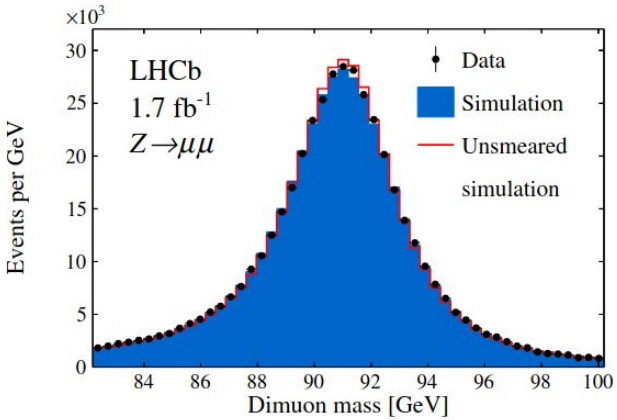
Corrections to the simulation





Need to smear the momentum to account for:

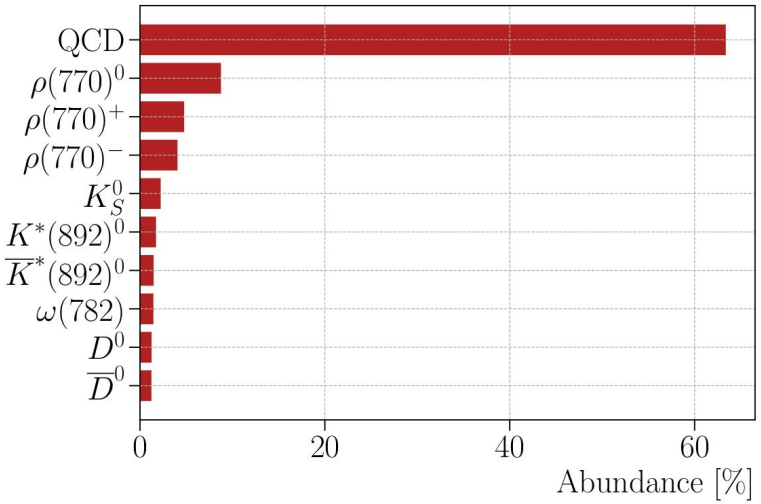
- residual curvature biases
- momentum scale
- multiple scattering



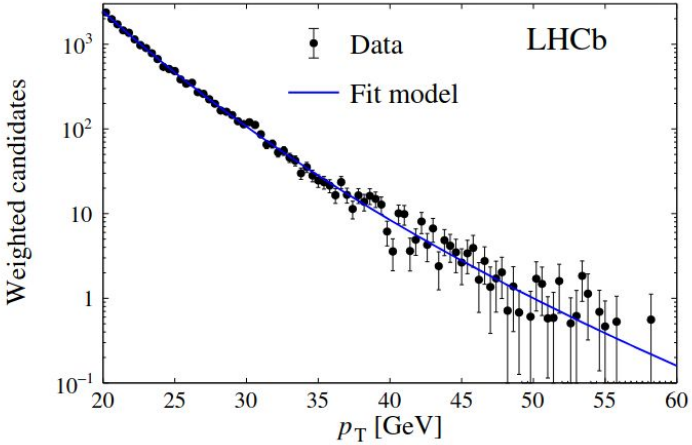
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024] (supplementary)

Backgrounds

- Most of them modelled from dedicated simulated samples
  - Single-top, quark/anti-quark (t, b, c), Z/W decays, Drell-Yan
  - Cross-sections normalized to the W
- Description of the QCD background (decays-in-flight) obtained from data
  - Sample with inverted muon-identification requirements
  - Weight and parametrize the data using a Hagedorn distribution
- Accurately describes the Jacobian peak (region with highest sensitivity to m_W)



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



Uncertainties

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

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 systematic uncertainties

Envelope of five different models

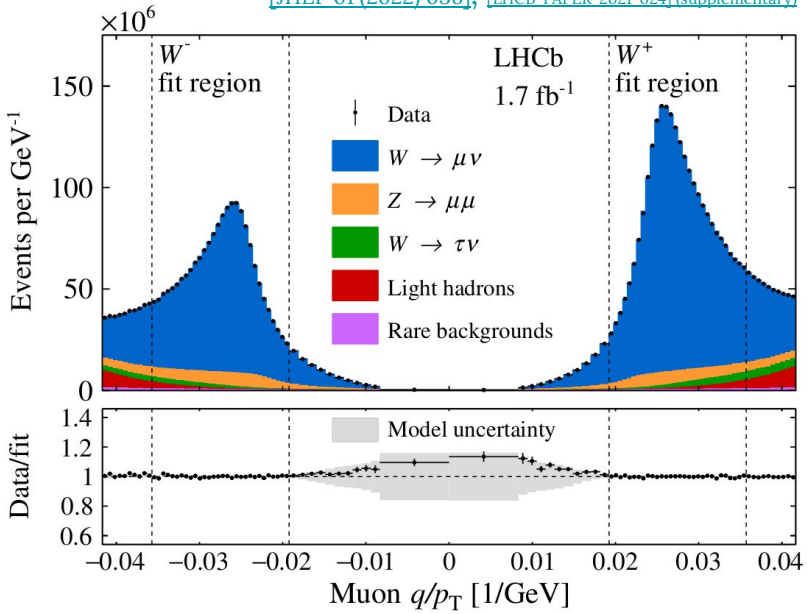
Uncertainty due to scale variations

Envelope of the QED FSR from Pythia, Photos and Herwig. Additional correction from PowhegEW

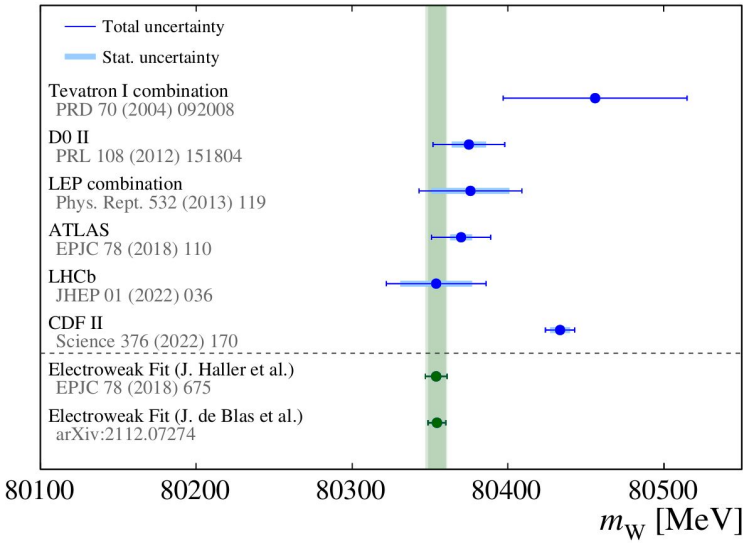
Variation of ranges, number of bins, parametrizations, ...

The W mass measurement at LHCb

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



[LHCB-FIGURE-2022-003]



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

Short- and long-term plans

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

- Analysis of 2017 and 2018 data ongoing (4 fb^{-1} of data), with an expected statistical uncertainty of ~10 MeV
- Reconsidering the way we calculate some systematic uncertainties
  - Study more carefully differences among generators and update the interpolation samples
  - Reoptimization of the momentum scaling
- Get advantage of new PDF sets (e.g. NNPDF 4.0) to reduce the uncertainties
- Aiming for a LHC combination to reduce the uncertainty to the global EW fit precision (~6 MeV)

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

Include 2017 + 2018 data

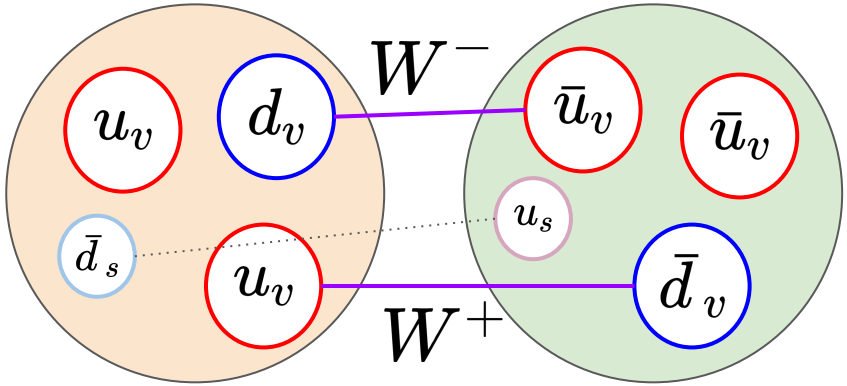
New strategies/tools

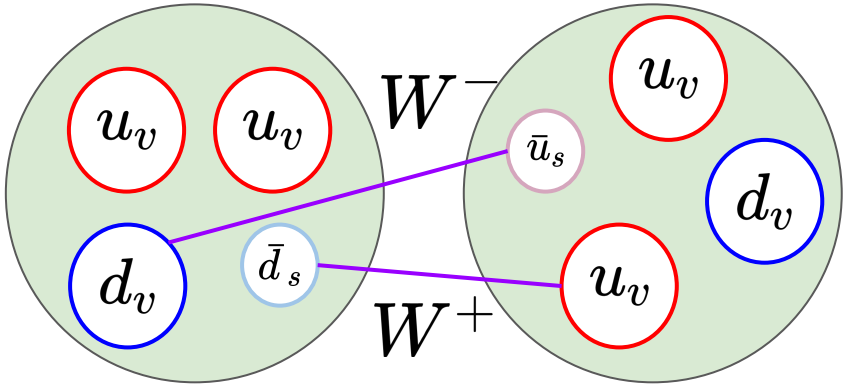
Inputs from the theory community

Thank you!

Backup

Production mechanism

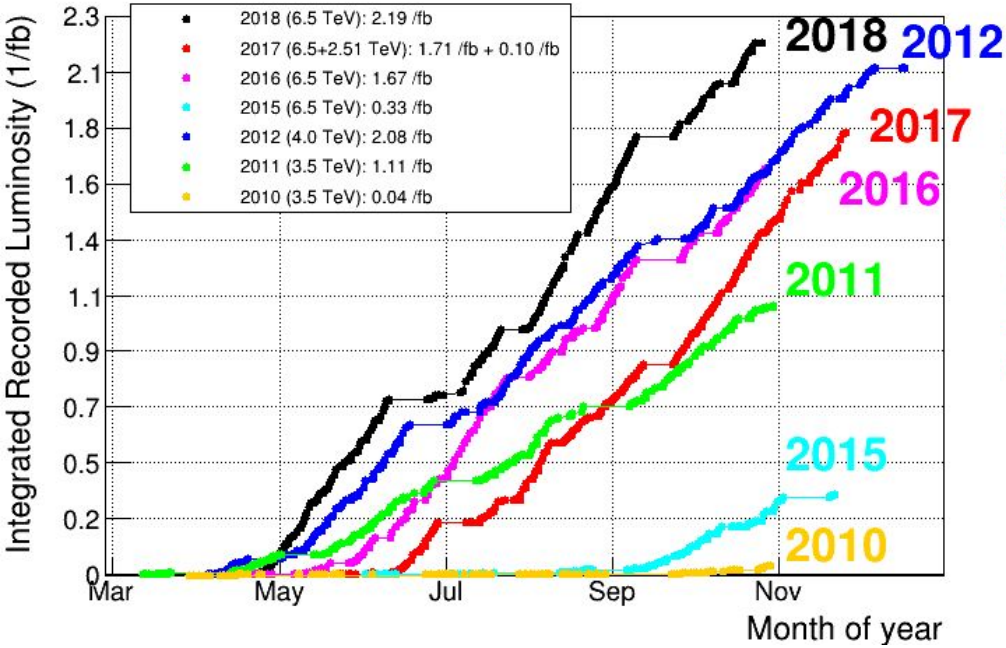




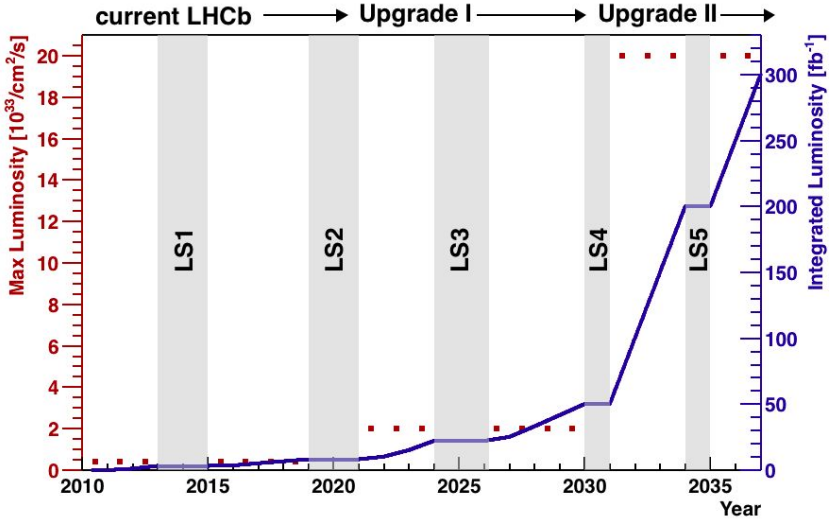
- A proton-proton collider is more challenging to measure the W mass:
  - W bosons are produced in a mixture of positive and negative helicity states
  - Must accurately describe the angular cross-section (larger uncertainties)
  - More backgrounds through heavy-flavour processes
- But much higher total production cross-section and larger calibration samples
  - One of the main objectives is being able to extrapolate the Z measurements to the W.

LHCb luminosities

[LHCb operation plots]



[LHCb-PUB-2018-009]



Number of candidates per experiment

Experiment	Muon channel	Electron channel	Result (MeV)	Stat. Unc. (MeV)	Total Unc. (MeV)
ATLAS	7.8×10^6	5.9×10^6	80370	7	19
LHCb	2.4×10^6	N/A	80354	23	32
CDF-II	2.4×10^6	1.8×10^6	80433.5	6.4	9.4

ATLAS: [EPJC 78 (2018) 110]

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

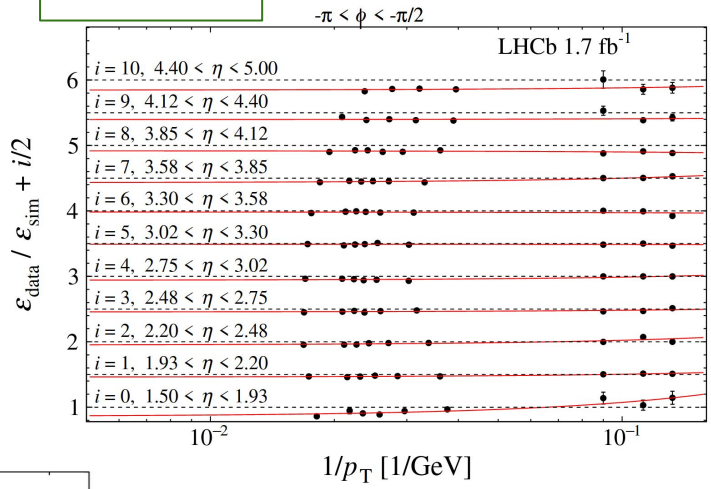
CDF: [Science, 376, 6589, (136-136), (2022)]

Efficiencies

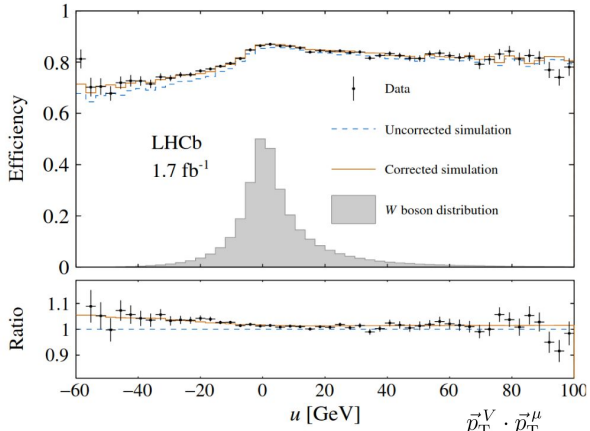
Three main sources of acceptance biases:

- Trigger efficiencies
- Muon-identification efficiencies
- Isolation requirements

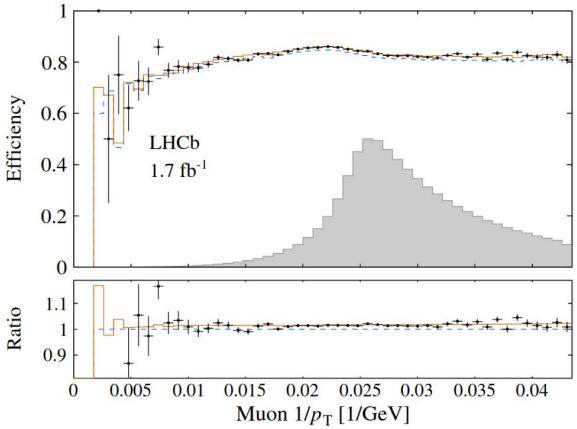
Trigger efficiency



Isolation efficiency



$$u = \frac{\vec{p}_T^{\,V} \cdot \vec{p}_T^{\,\mu}}{p_T^{\mu}}$$

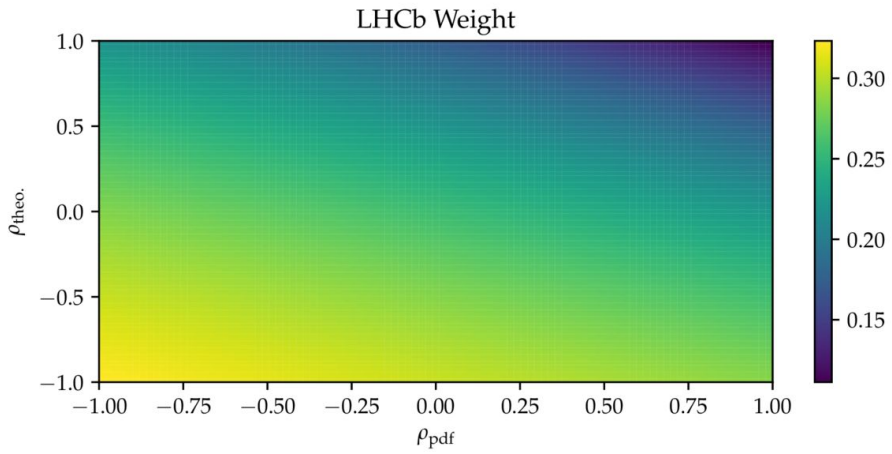


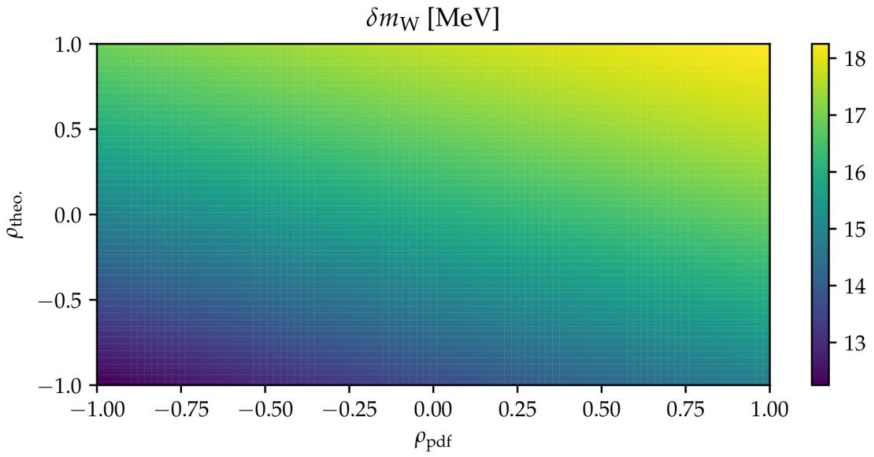
Corrections predominantly at the percent level

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

Effects of the uncertainty correlations

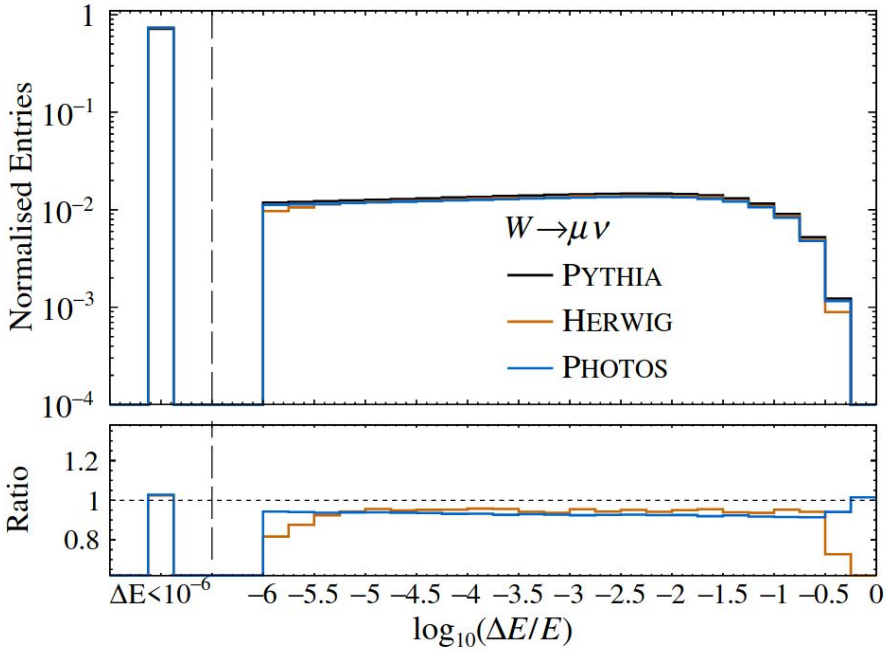
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024] (supplementary)

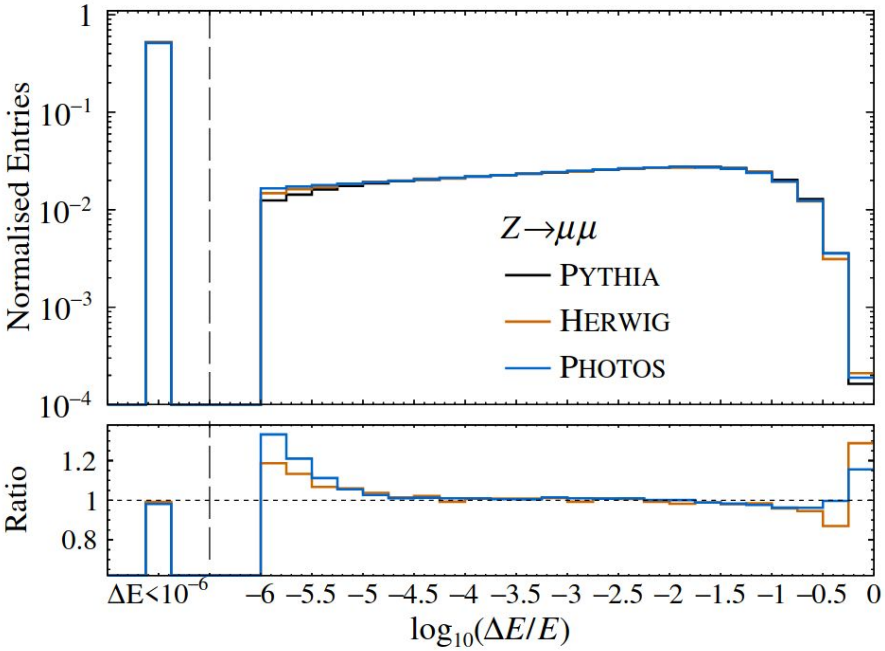




Final-state radiation losses

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





Variations of m_W with the PDF set

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