W mass measurement at LHCb

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THE UNIVERSITY OF WARWICK

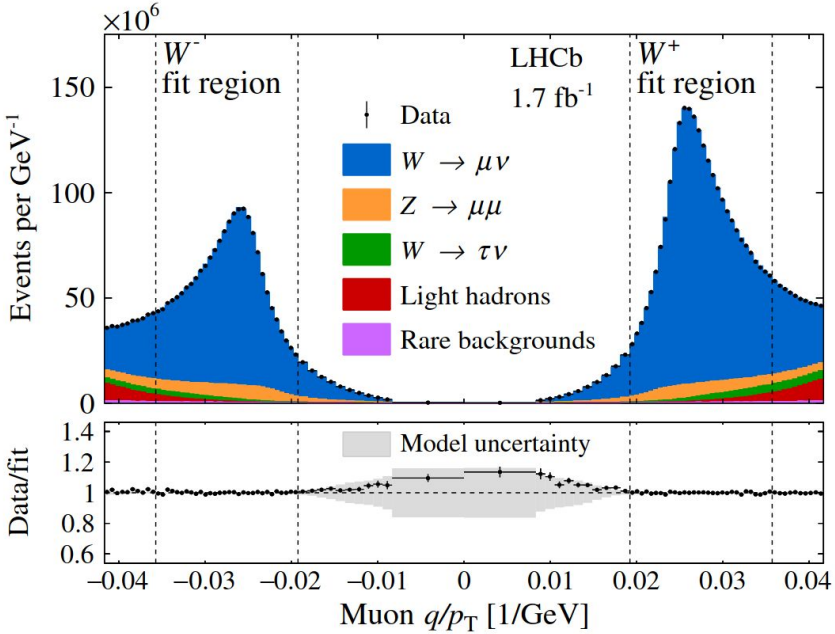
LHCb

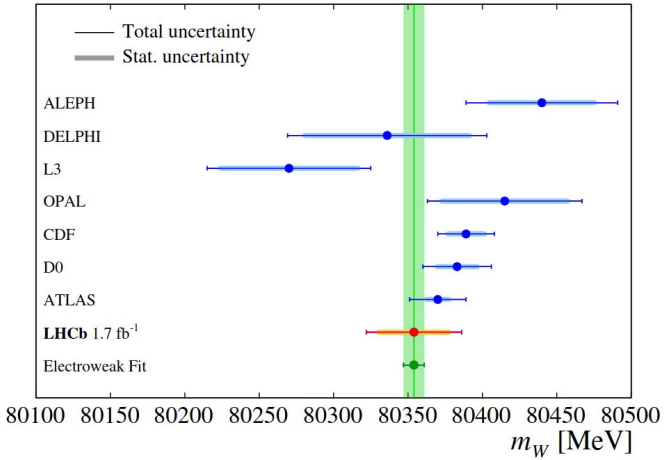
European Research Council

Established by the European Commission

LHCb measures the W mass!

- Measurement of the W mass using 2016 data
- Published on January 2022 [JHEP 01 (2022) 036]
- Shows the LHCb capabilities of doing high-precision measurements



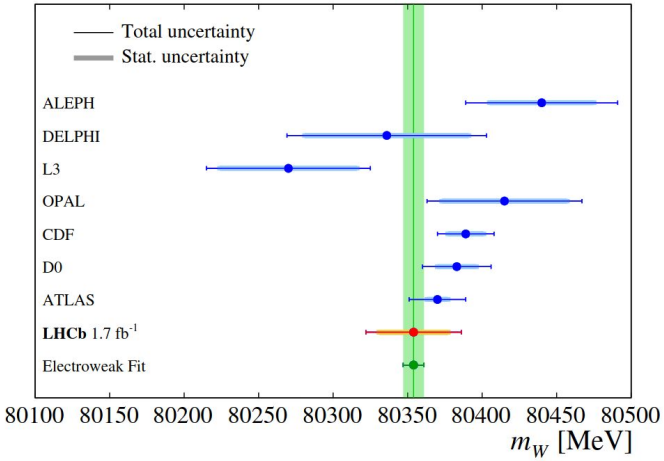


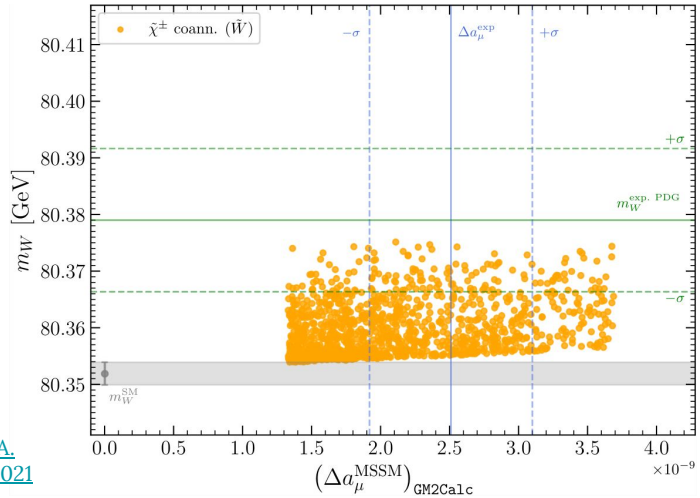
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

Context of the W mass measurement

- Fundamental magnitude related to other EW observables
- Experimental average still away from the theoretical best fit 12 MeV / 7 MeV
- Interesting implications in BSM models with other magnitudes of interest

[JHEP 01 (2022) 036]

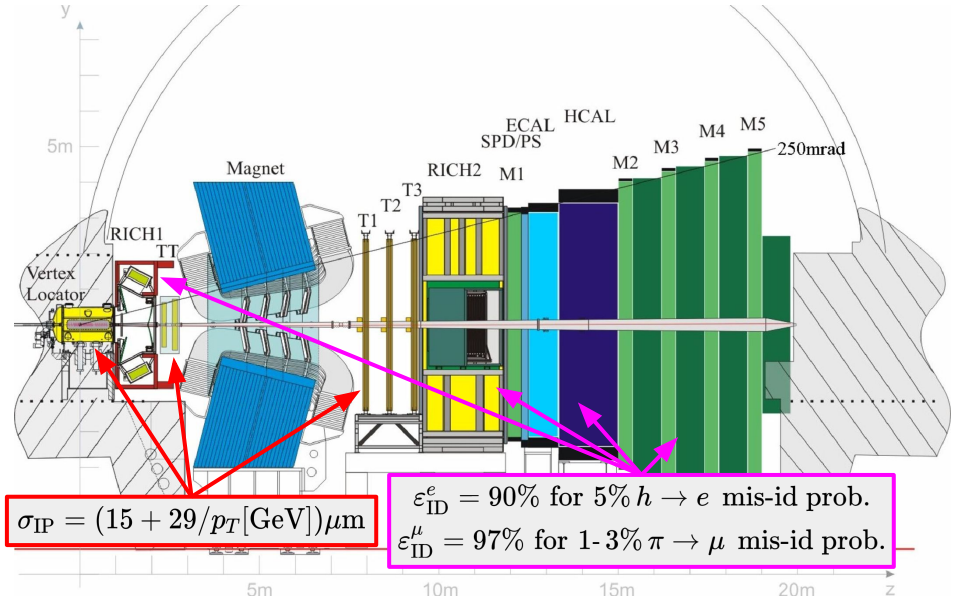


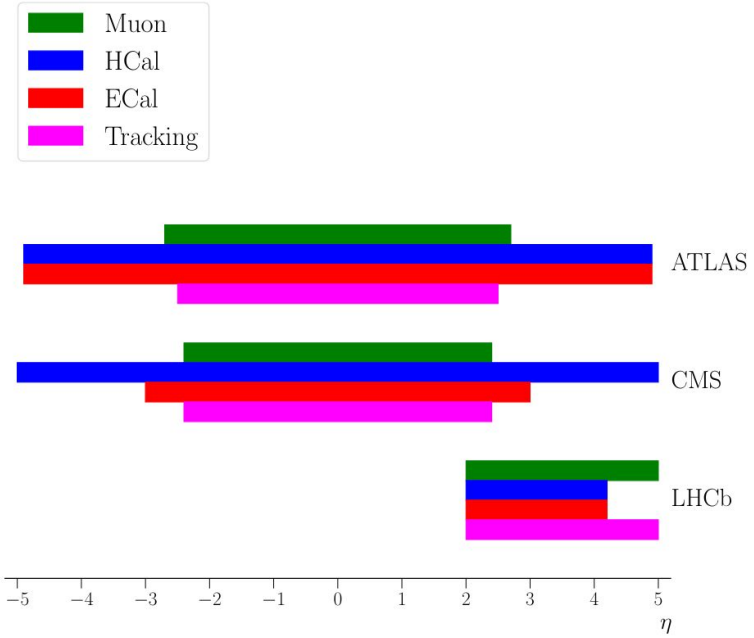


$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

Talk by Emanuele A. Bagnaschi at SUSY 2021

Related detector features



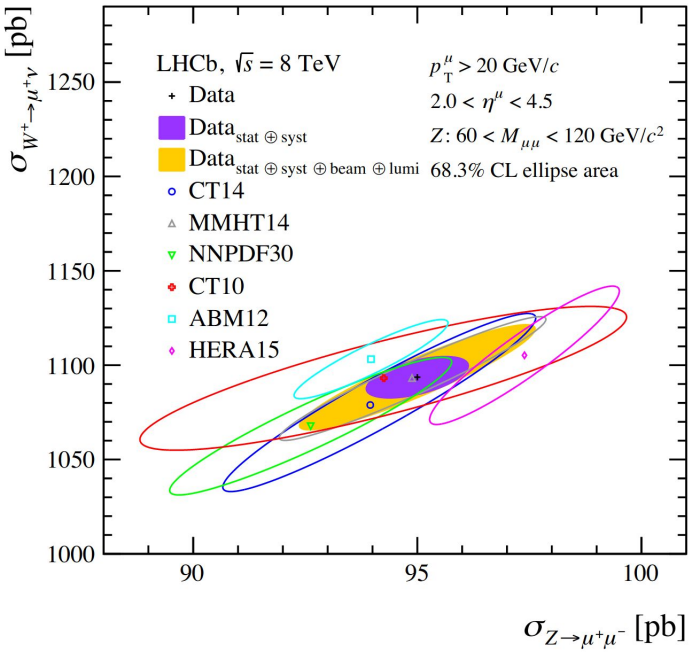


- Detector in the forward region with excellent momentum and vertex resolutions
- Coverage is complementary to ATLAS and CMS (with some overlapping at low pseudorapidity)

W and Z production at LHCb

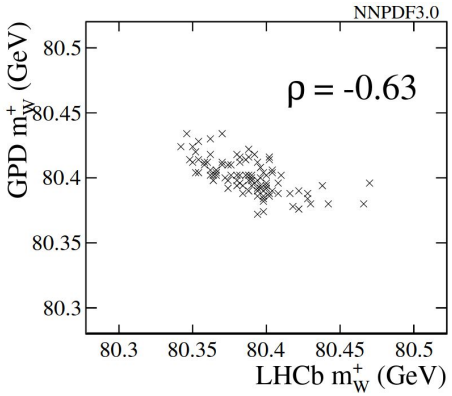
- Z decays constitute the most natural way of controlling muons from W decays and the cross-section
- Anti-correlation of the PDF uncertainties at low Bjorken-x allows achieving a similar precision of the LHC experiments to the theoretical best fit for the W mass

[JHEP01(2016)155]



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

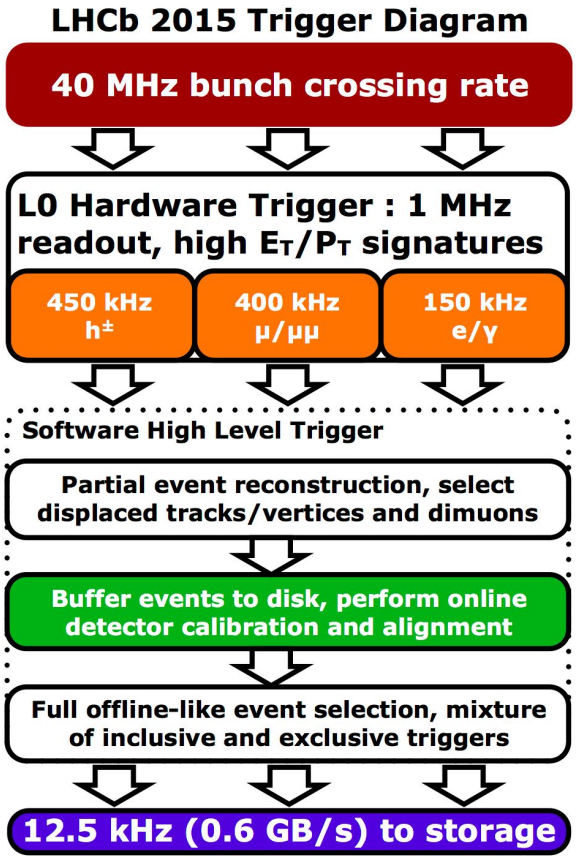
CMS & ATLAS



Up to a factor of 2 of reduced systematic uncertainty from PDFs

Detector alignment and calibration

- The LHCb trigger changed significantly for Run 2
- Real-time alignment and calibration can be optimized offline for EW studies
- Need to re-process the data using dedicated tools
- Apply corrections and smearing to simulation to account for subtle effects that significantly affect the momenta distributions



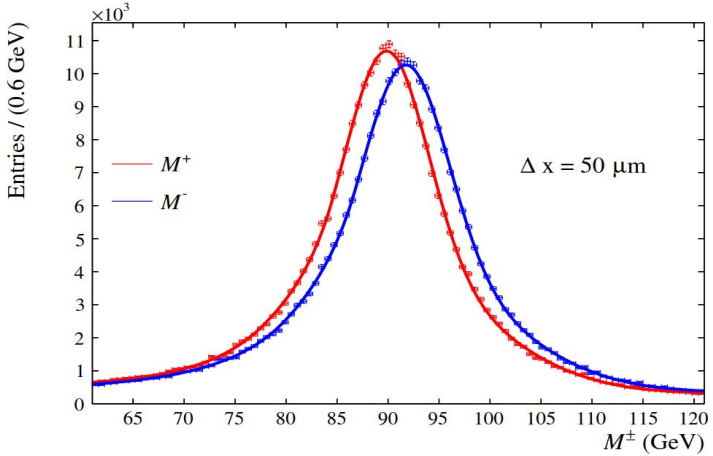
Detector alignment and calibration

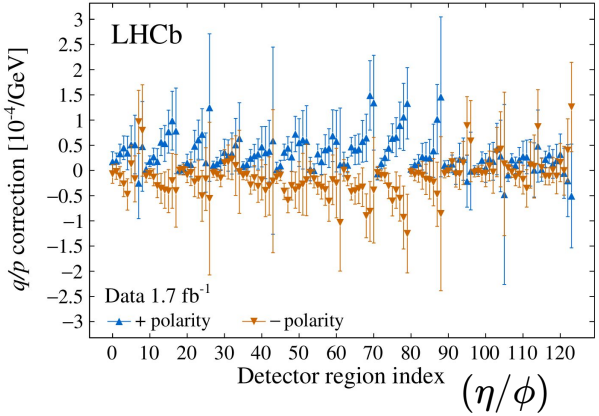
EPJ-C 81 (2021) 3, 251

- 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

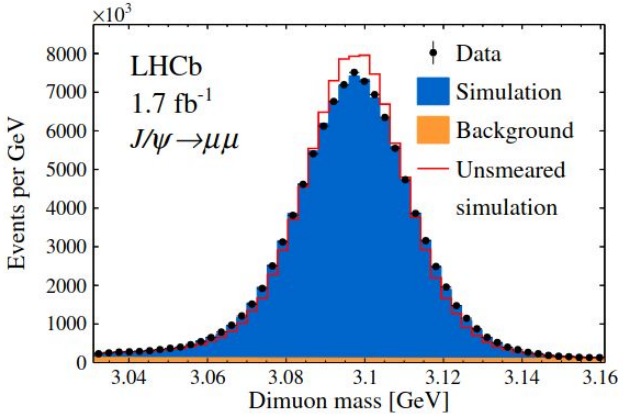


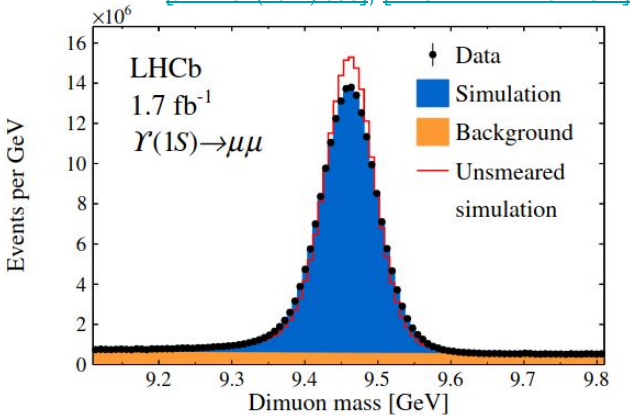


[JHEP 01 (2022) 036], [LHCb-PAPER-2021-024]

Corrections to the simulation

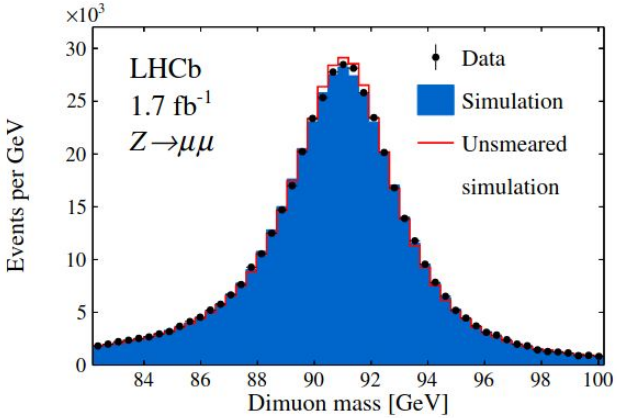
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]





Need to smear the momentum to account for:

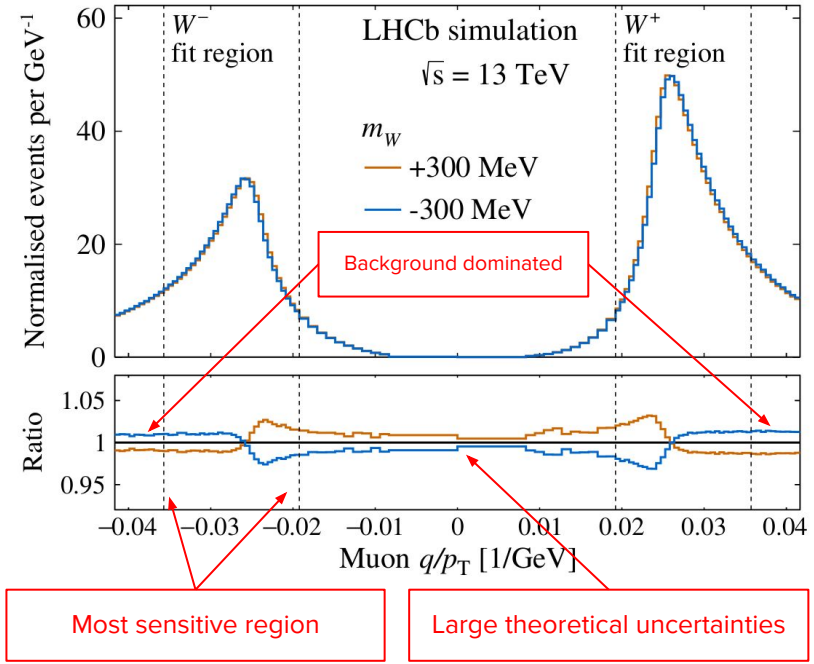
- curvature biases (previous slide)
- momentum scale
- multiple scattering



Analysis strategy

- Carefully measure the muon transverse momentum
- Use plain LHCb Pythia8 simulation and reweight using samples with generator-level information from different models
- Corrections due to the efficiencies of the different selection steps (reconstruction, trigger, topological, offline selection)
- Study and determine background from simulation (except for the contribution from hadrons originating decays-in-flight)

[JHEP 01 (2022) 036]



The W cross-section

Unpolarized part: POWHEG + Pythia8

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

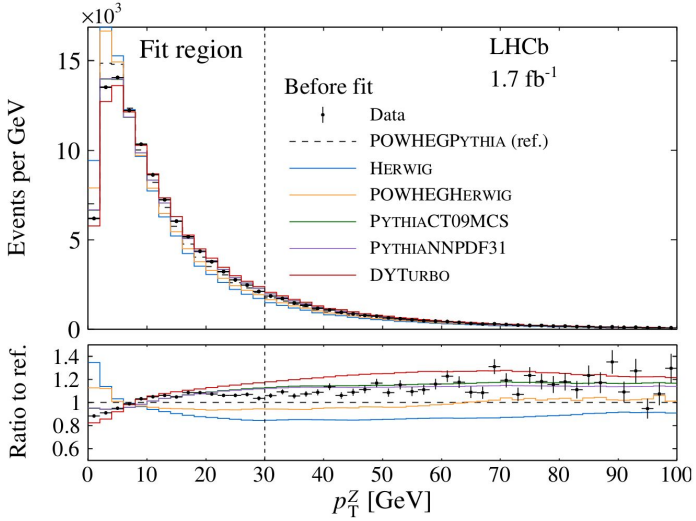
(At order α_s^2)

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

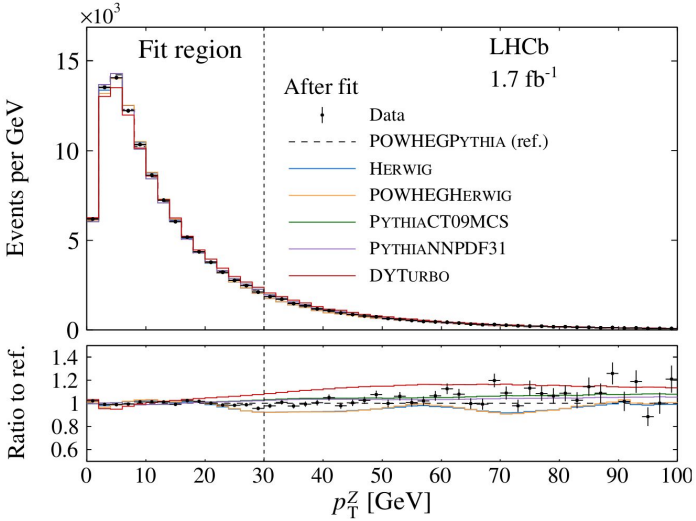
Angular part: DYTurbo

The simulation process (generator)

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



Tuning of α_s and intrinsic k_T

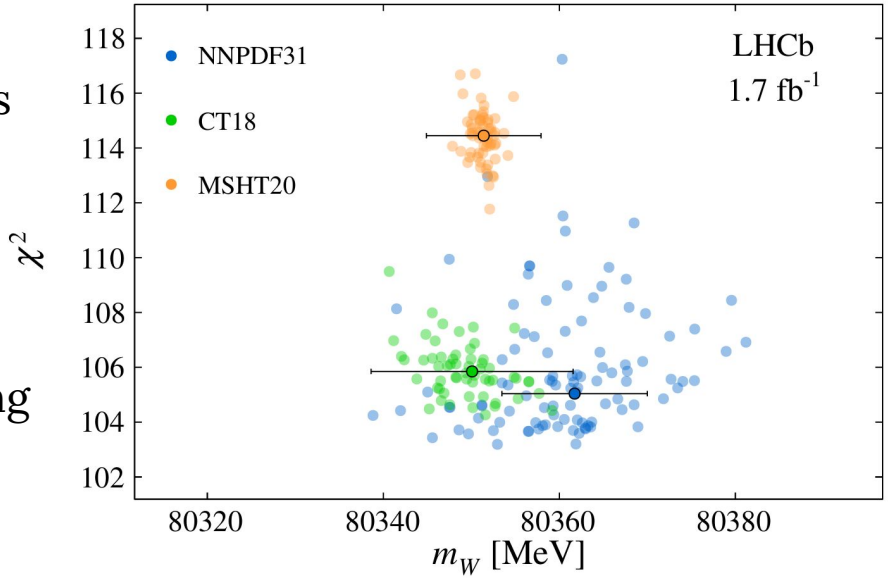


- POWHEG + Pythia gives the best description of the unpolarized cross-section and is chosen as the baseline generator
  - Varied success with other generators, used to determine systematic uncertainties
- DYTurbo performs well at reproducing the angular cross-section

The simulation process (PDF set)

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

- PDFs chosen from three different recent sets
  - NNPDF3.1: [Eur. Phys. J. C 77, 663 (2017)]
  - CT18: [Phys. Rev. D 103, 014013]
  - MSHT20: Eur. Phys. J. C 81, 341 (2021)
- The result is an average of the three assuming 100% correlation



Selections

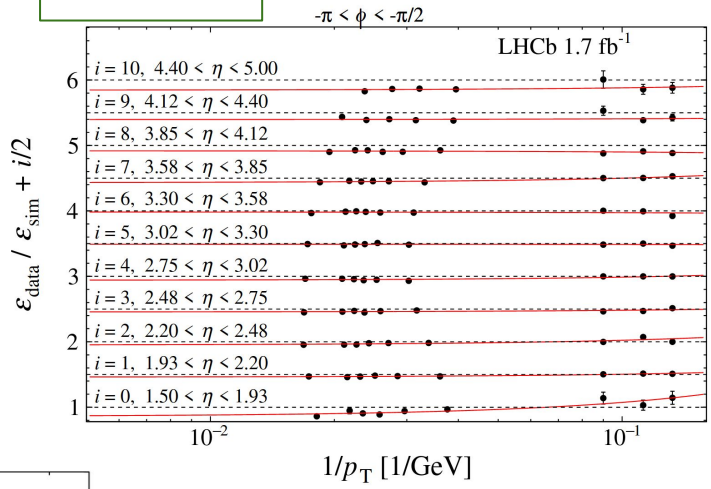
- EW physics with leptons in the final state can be done at LHCb with simple selections based on the transverse momentum, impact parameter, isolation and particle identification
- Selection biases studied in data and simulation for Z and Y(1S) decays (isolation biases only studied in the former)
    - Associated systematic uncertainties determined by varying the binning scheme, parametrizations and selections

Determining the efficiencies

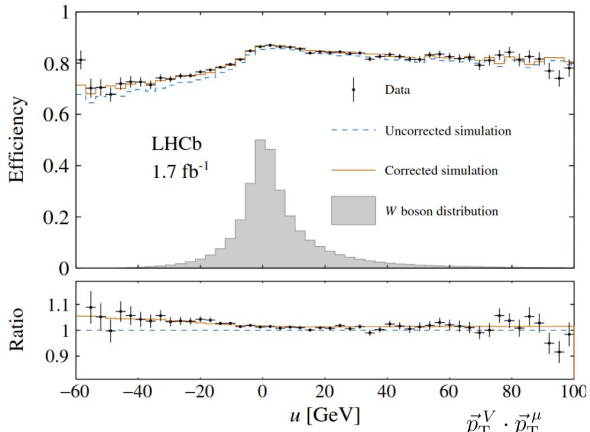
Three main sources of acceptance biases:

- Trigger efficiencies
- Muon-identification efficiencies
- Isolation requirements

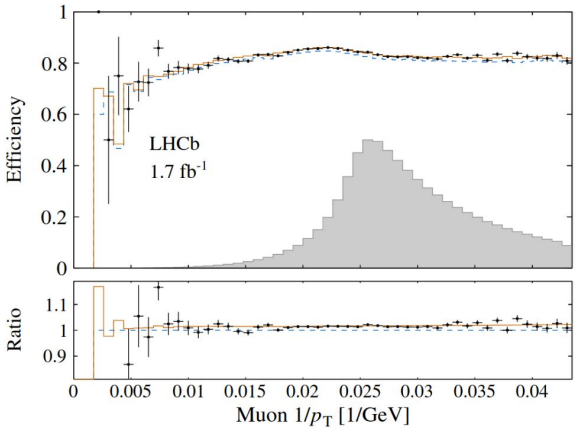
Trigger efficiency



Isolation efficiency



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

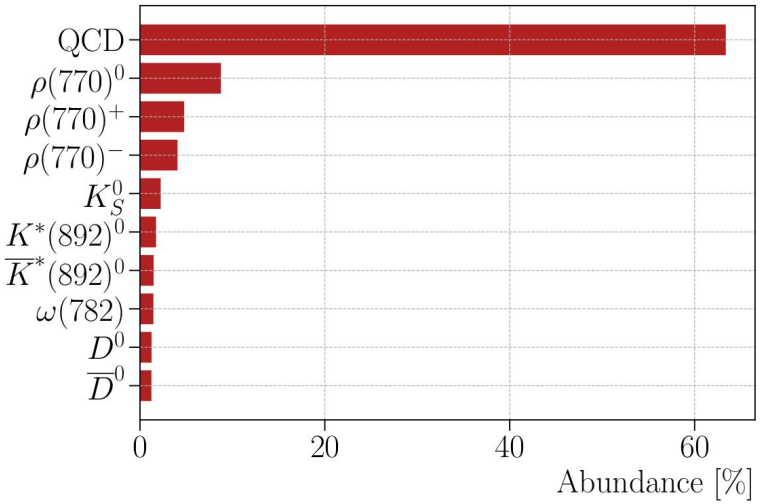


Corrections predominantly at the percent level

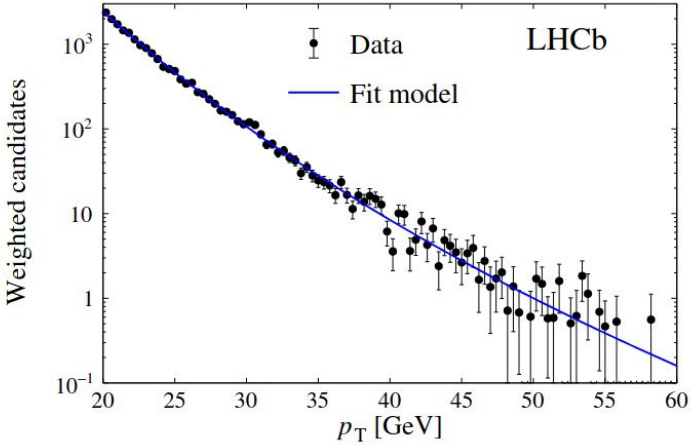
arXiv:2109.01113, submitted to JHEP

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]



Systematic uncertainties

[JHEP 01 (2022) 036]

Source	Size (MeV)
Parton distribution functions	**9.0**
Total theoretical syst. uncertainty (excluding PDFs)	**17.4**
Transverse momentum model	12.0
Angular coefficients	9.0
QED FSR model	7.2
Additional electroweak corrections	5.0
Total experimental syst. uncertainty	**9.7**
Momentum scale and resolution modelling	7.5
Muon ID, tracking and trigger efficiencies	4.3
Isolation efficiency	3.9
QCD background	2.3
Statistical	**22.7**
Total uncertainty	**31.4**

Average of NNPDF31, CT18 and MSHT20 systematic uncertainties

Envelope of five different models

Uncertainty due to scale variations

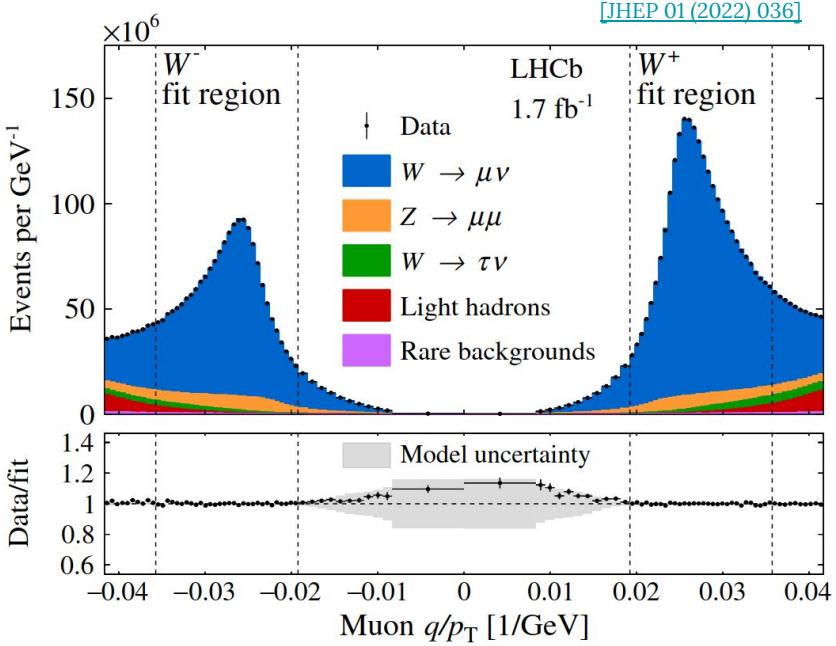
Envelope of the QED FSR from Pythia, Photos and Herwig. Additional correction from PowhegEW

Already thinking of ways to improve most of these uncertainties!

The W mass fit

- 5D-weighted fit using the Beeston-Barlow approach
- Result obtained from a simultaneous fit to W and Z data
- Accurate physics modelling, also in the regions outside the fit boundaries

[JHEP 01 (2022) 036]



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

Include 2017 + 2018 data

New strategies/tools?

Inputs from the theory community

Is including 2017 and 2018 data straight-forward?

- It is straight-forward, but we must ask ourselves the following questions:
  - Can we optimize any part of the analysis strategy
  - Can we use any of the new options available in the market?
  - Are there ways to make the result more accessible/easy to use for people outside the collaboration?
- The result using 2016 data shows the capabilities of the LHCb detector to contribute to this measurement, but it is worth re-considering our strategy before studying the full Run 2 data sample
  - Usage of new PDF sets and generator conditions
  - Optimization of our fitting procedure
  - Publishing the corrected differential cross-section (unfolding)

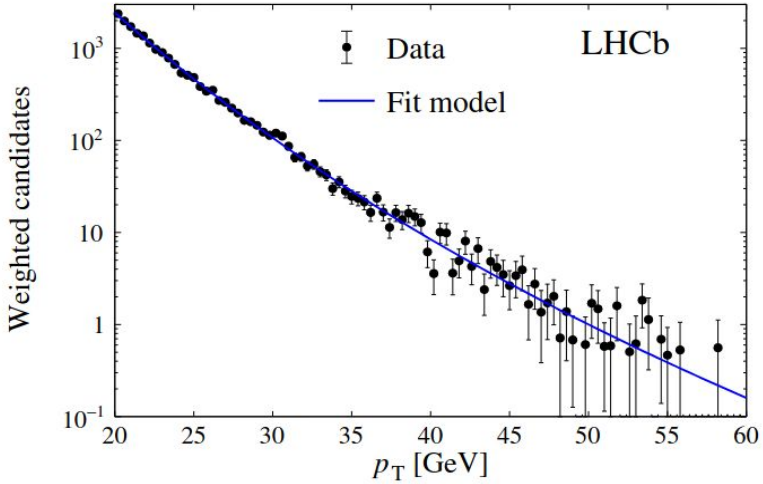
Improving the simulation

- Take advantage of the latest developments on the theory side
  - Switch to more accurate predictors of the boson production
  - New PDF sets (NNPDF 4.0)
- Change the treatment generators / PDF sets when calculating systematic uncertainties
  - Drop known inaccurate PDF sets
  - Revisit the way to handle the different predictors and the order of the accuracy (NLL, NNLL, ...)
- Ongoing studies, feedback is really welcome!

Towards doing an unfolded measurement

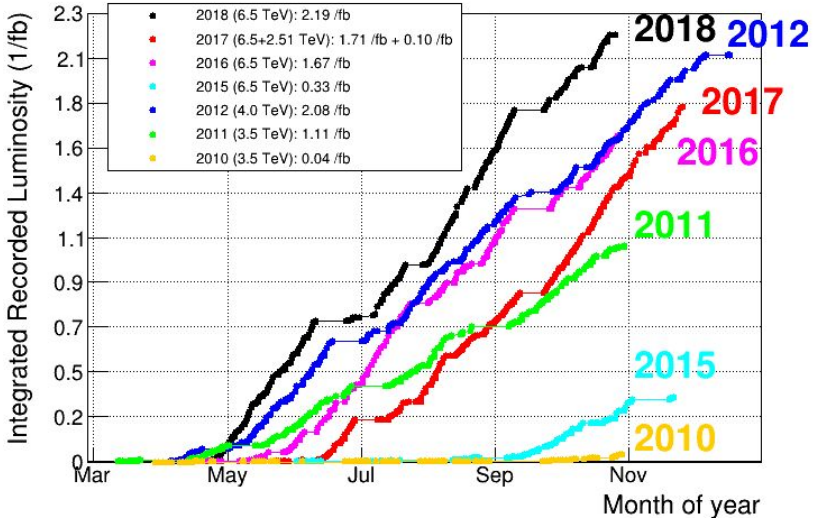
[JHEP 01 (2022) 036]

- Ongoing studies to see if we can publish the unfolded transverse momentum distribution
- Facilitate comparing prediction and observables
- Quite challenging from the experimental point of view:
  - Must have a good control of the backgrounds (especially in the selection variables)
  - The systematic uncertainties might turn much bigger with the unfolding methods



Expected sensitivity for the full Run 2 analysis

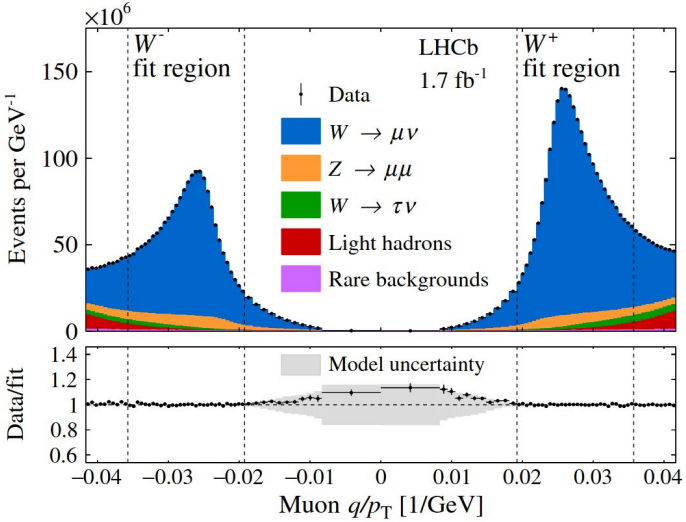
- We expect to reduce the overall experimental uncertainty to 15 MeV
- The analysis becomes systematically dominated
  - A more careful description of the physics is necessary
- Looking forward to seeing the result of combining the measurements of all the LHC experiments

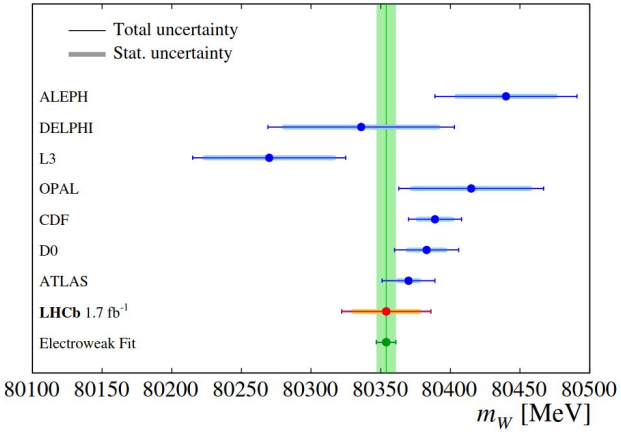


$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

Summary

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





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

- The LHCb detector has proved its capability to do high-precision measurements of EW observables
- Long-awaited result, with high relevance in the particle physics community
- Good prospects for the future, with an experimental uncertainty below 20 MeV
- The usage of new tools and strategies is necessary, we look forward to collaborate with other people in the community to achieve an unprecedented precision on the W mass measurement

Thank you!