The W mass measurement at LHCb

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THE UNIVERSITY OF WARWICK

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KAON 2016

Outline

- Introduction to EW physics
  - Constraining EW observables
  - Overview of the current measurements and experiments
- The W mass measurement at LHCb
  - EW physics at LHCb
  - The analysis of 2016 data
  - Ongoing studies with the full Run 2 dataset
- Prospects for the future

Electroweak theory

The Electroweak theory

Abdus Salam, Steven Weinberg and Sheldon Lee Glashow

Main magnitudes ruling EW interactions are related to each other:

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

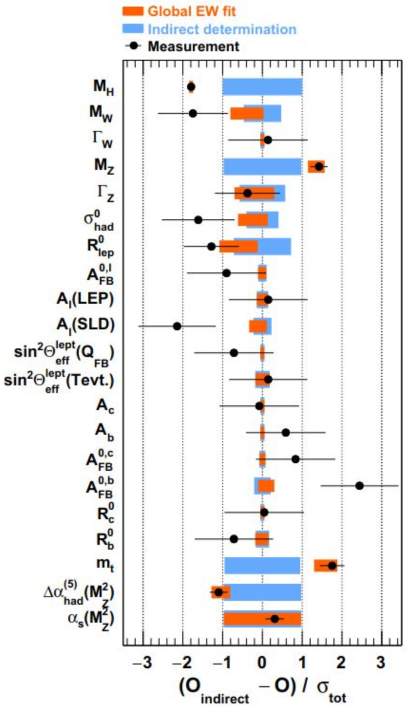
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

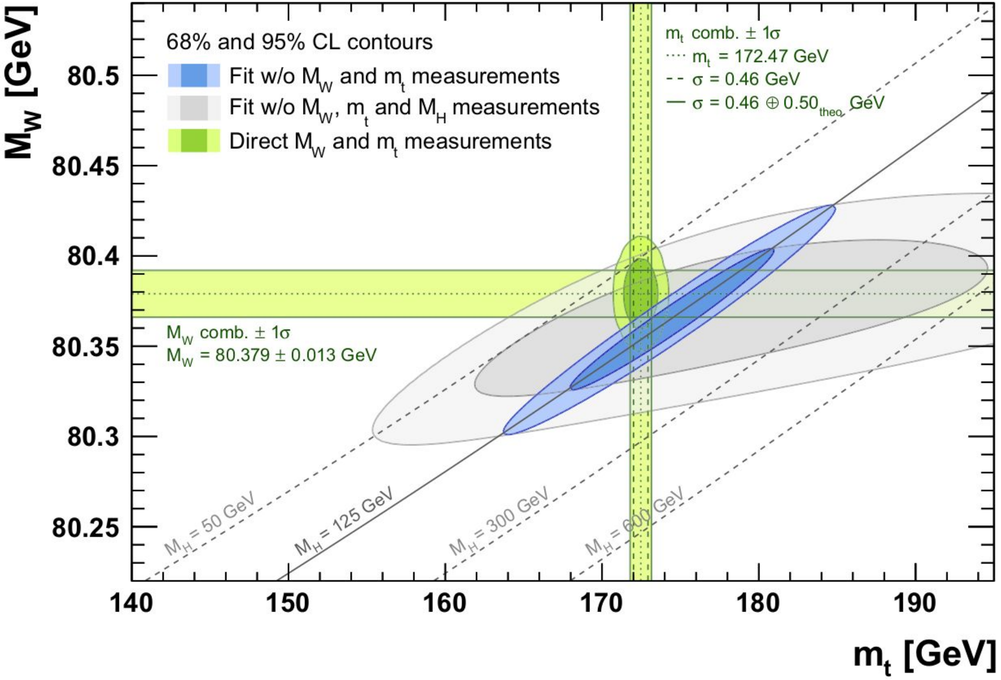
$$\Gamma_W \propto G_F m_W^3$$

Higher order corrections

The global EW fit

Global fits to EW observables allow to test current (and new) theoretical model(s)

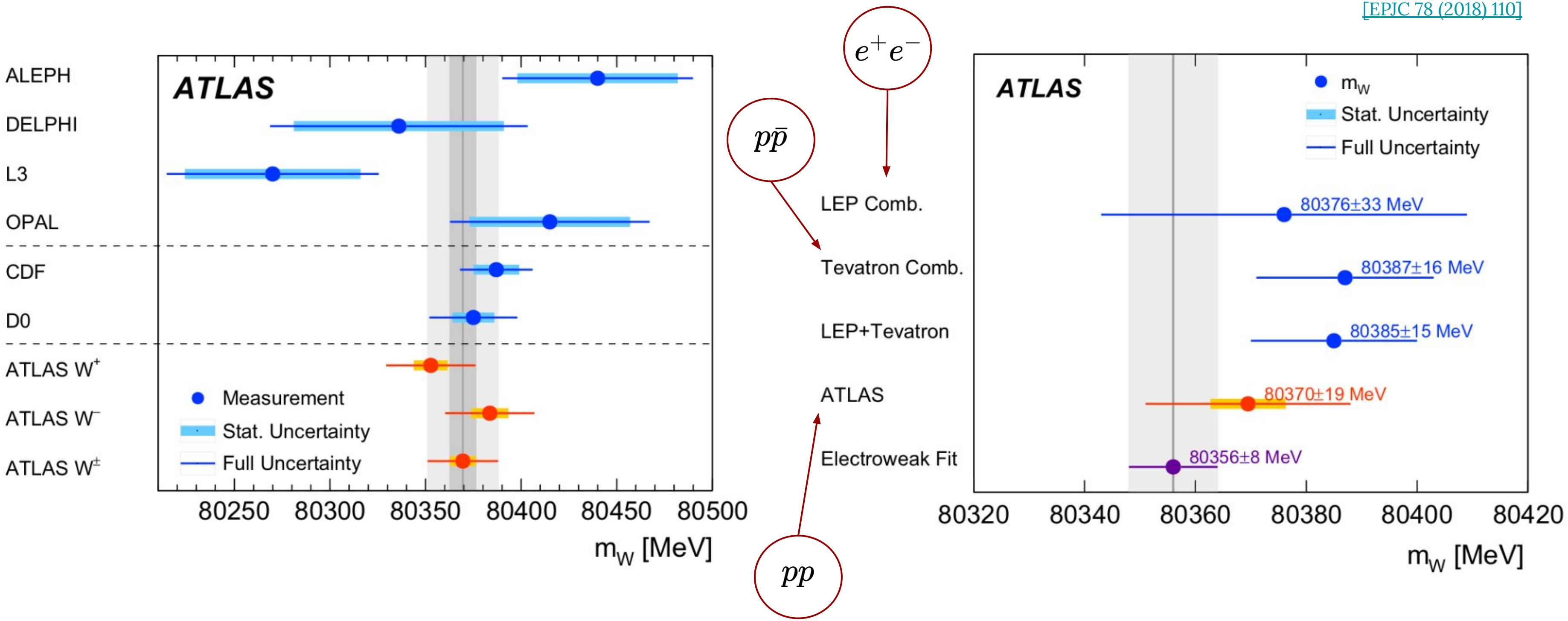




[EPJC 78, 675 (2018)]

Past and present of the W mass measurement

[EPJC 78 (2018) 110]



e^+e^-

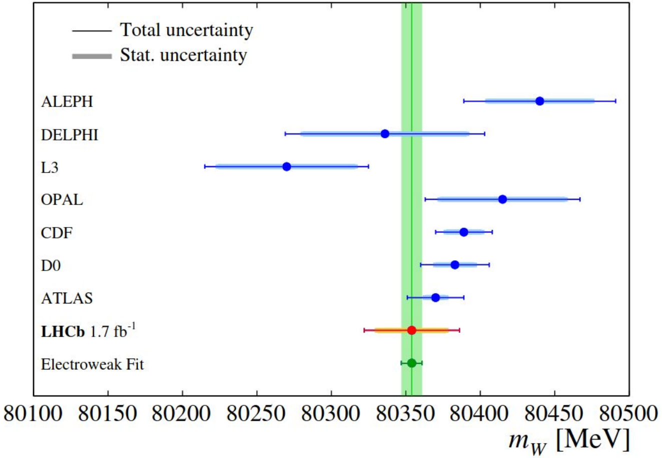
$p\bar{p}$

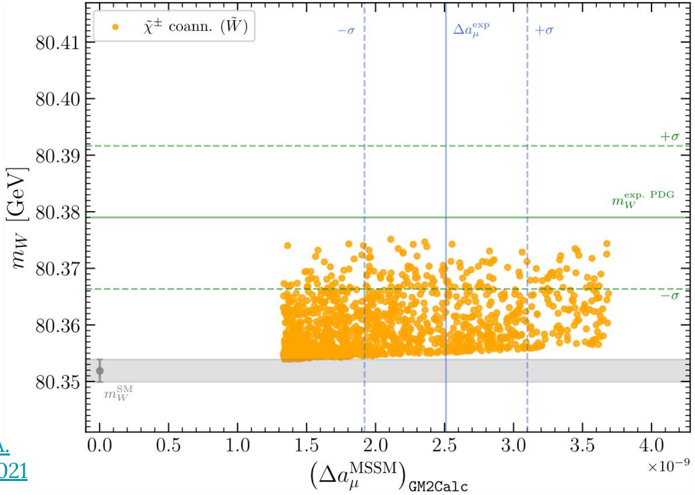
pp

A wider theoretical picture

- Fundamental magnitude related to other EW observables
- The experimental sensitivity is 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]



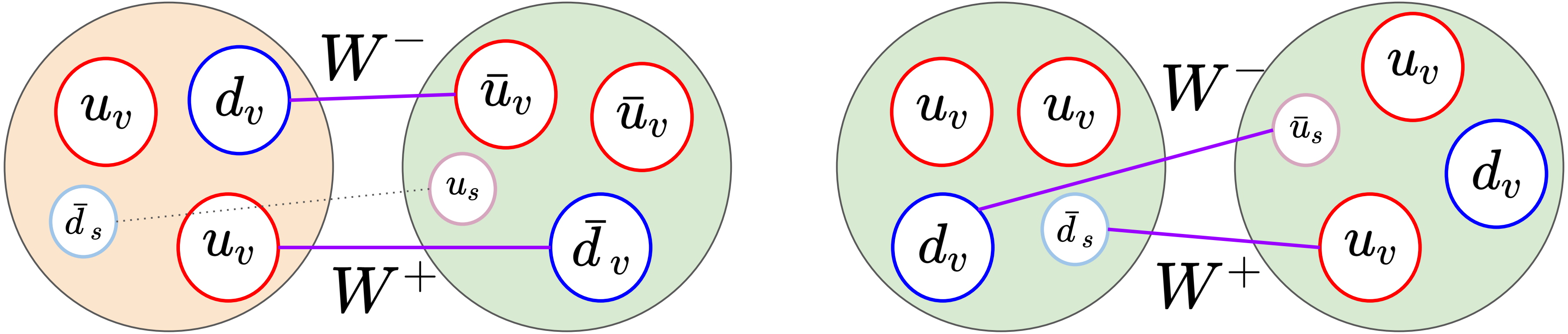


Talk by Emanuele A. Bagnaschi at SUSY 2021

E.g. correlation with g-2 in SUSY models

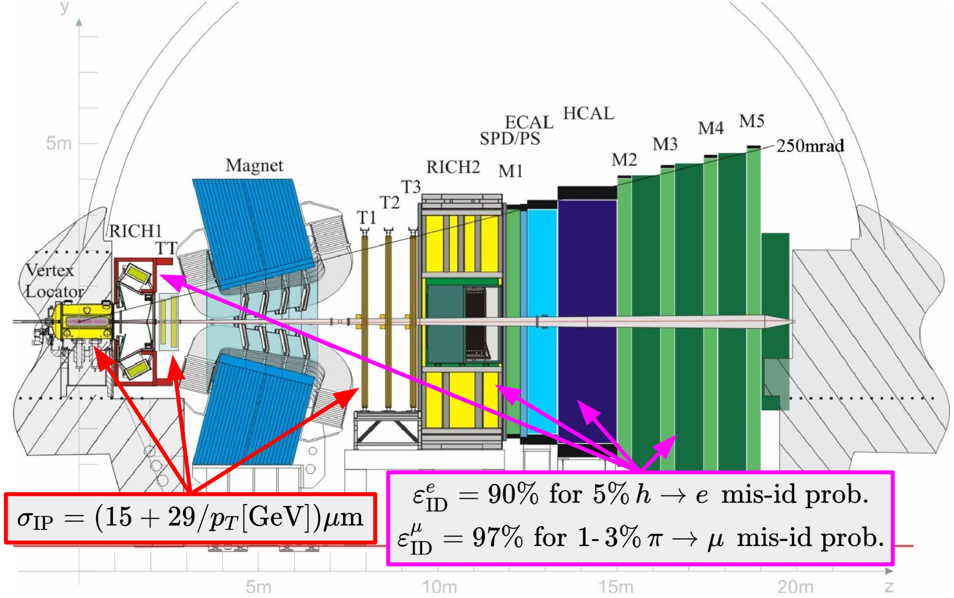
The W mass measurement at LHCb

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.

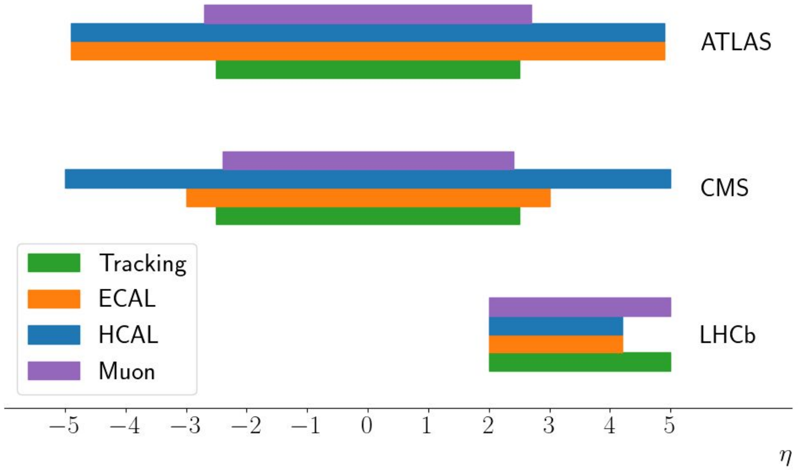
Related detector features



$\sigma_{\text{IP}} = (15 + 29/p_T[\text{GeV}])\mu\text{m}$

$\varepsilon^{e}_{\text{ID}} = 90\%$ for $5\%\, h \to e$ mis-id prob.

$\varepsilon^{\mu}_{\text{ID}} = 97\%$ for 1-$3\%\, \pi \to \mu$ mis-id prob.

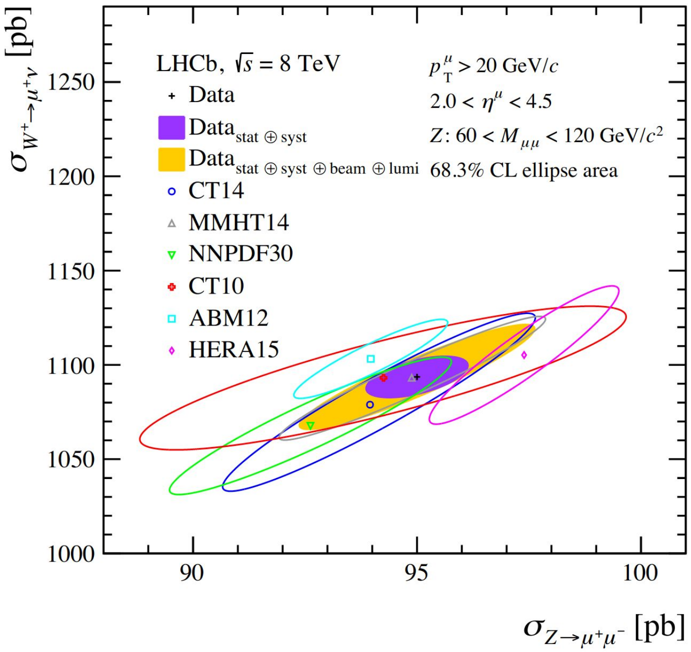


- Detector in the forward region with excellent momentum and vertex resolutions
- Coverage is complementary to ATLAS and CMS (with some overlapping at low pseudorapidity)

W and Z production at LHCb

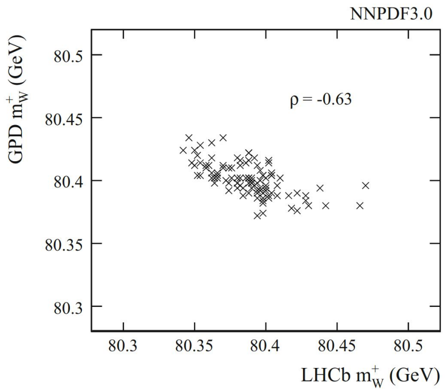
- Z decays constitute the most natural way of controlling muons from W decays and the cross-section
- Anti-correlation of the PDF uncertainties at low Bjorken-x allows achieving a similar precision of the LHC experiments to the theoretical best fit for the W mass

[JHEP01(2016)155]



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

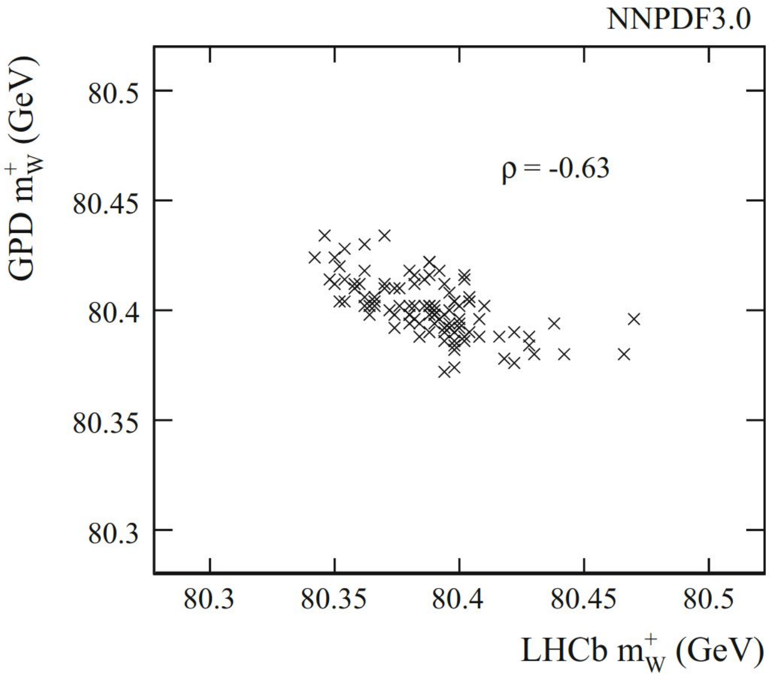
CMS & ATLAS

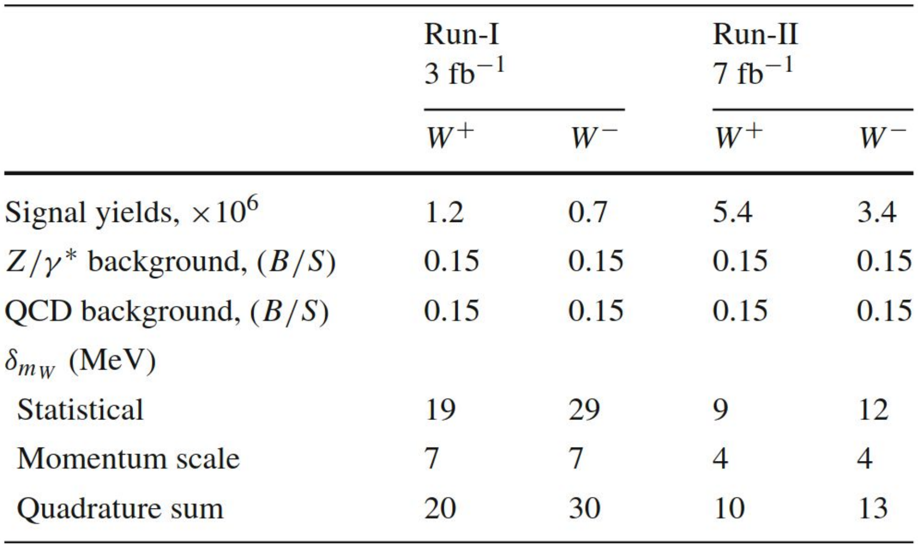


Up to a factor of 2 of reduced systematic uncertainty from PDFs

Anti-correlation of uncertainties from PDFs

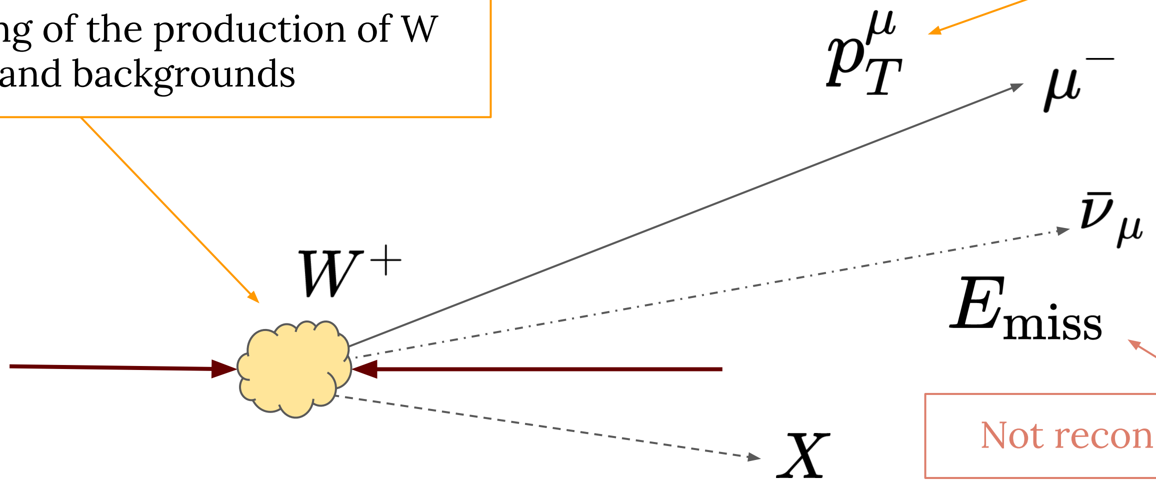
Eur. Phys. J. C 75, 601 (2015)





	Run-I 3 fb^{-1}		Run-II 7 fb^{-1}	
	W^+	W^-	W^+	W^-
Signal yields, $\times 10^6$	1.2	0.7	5.4	3.4
Z/γ^* background, (B/S)	0.15	0.15	0.15	0.15
QCD background, (B/S)	0.15	0.15	0.15	0.15
δ_{m_W} (MeV)				
Statistical	19	29	9	12
Momentum scale	7	7	4	4
Quadrature sum	20	30	10	13

Single event signature



Must carefully determine the momentum of the outgoing muon

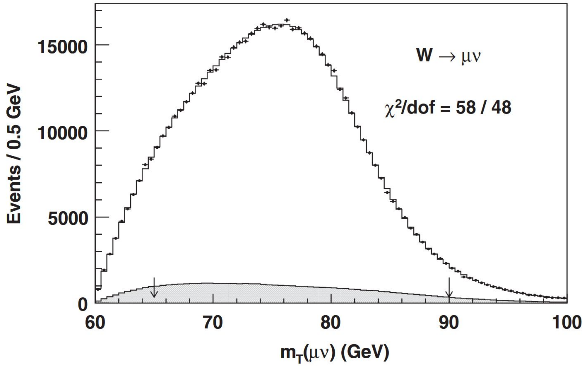
Precise modelling of the production of W bosons and backgrounds

Not reconstructed at LHCb

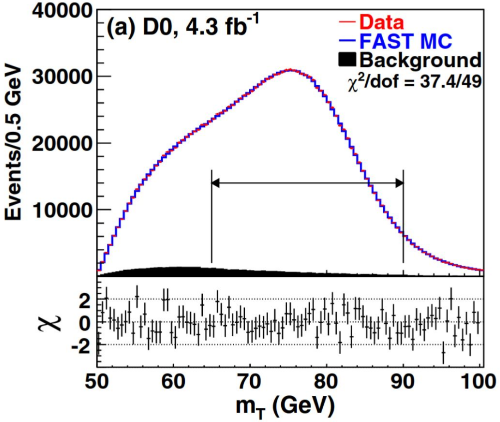
Get rid of background with kinematic and isolation requirements

Results from other experiments

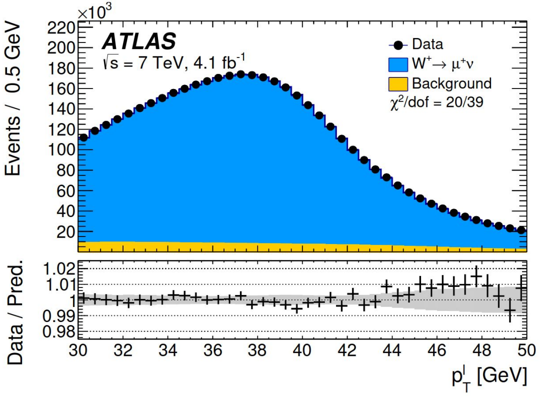
CDF:[PRL 108, 151803]



D0: [PRD 89, 012005]



ATLAS: [EPJC 78 (2018)]



$m_W = 80387 \pm 12_{\text{stat}} \pm 15_{\text{syst}}\text{MeV}$

$m_W = 80367 \pm 13_{\text{stat}} \pm 22_{\text{syst}}\text{MeV}$

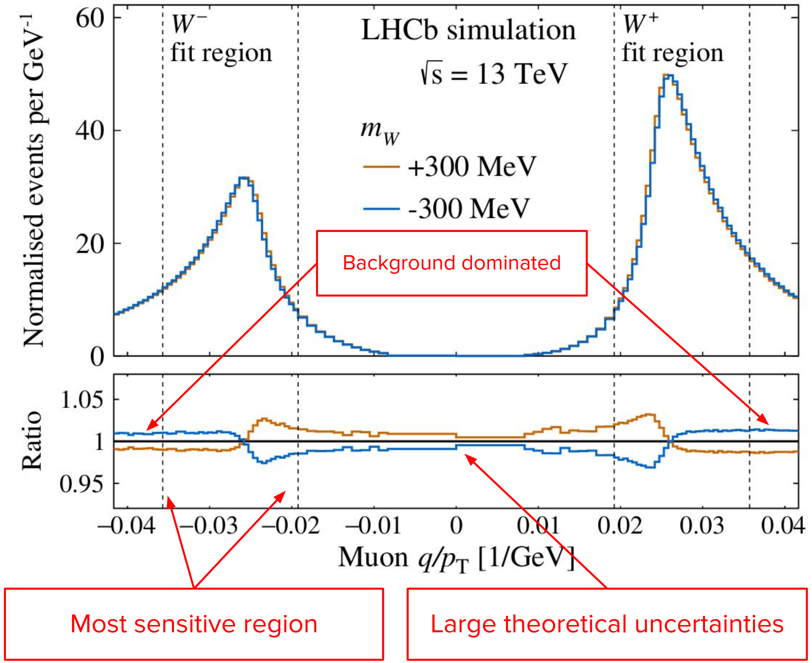
$m_W = 80370 \pm 7_{\text{stat}} \pm 11_{\text{exp. syst.}} \pm 14_{\text{theo. syst.}}\text{MeV}$

- Barrel-like detectors allow to measure missing transverse energy and the transverse mass
  - Measurement can be done measuring different quantities
- In modern experiments, a similar sensitivity can be obtained measuring the momentum of the outgoing lepton

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]



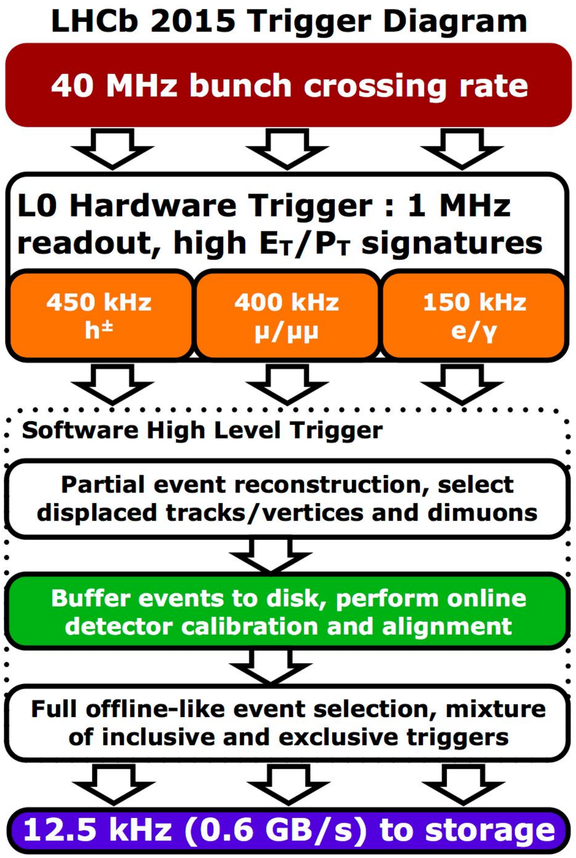
Background dominated

Most sensitive region

Large theoretical uncertainties

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



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

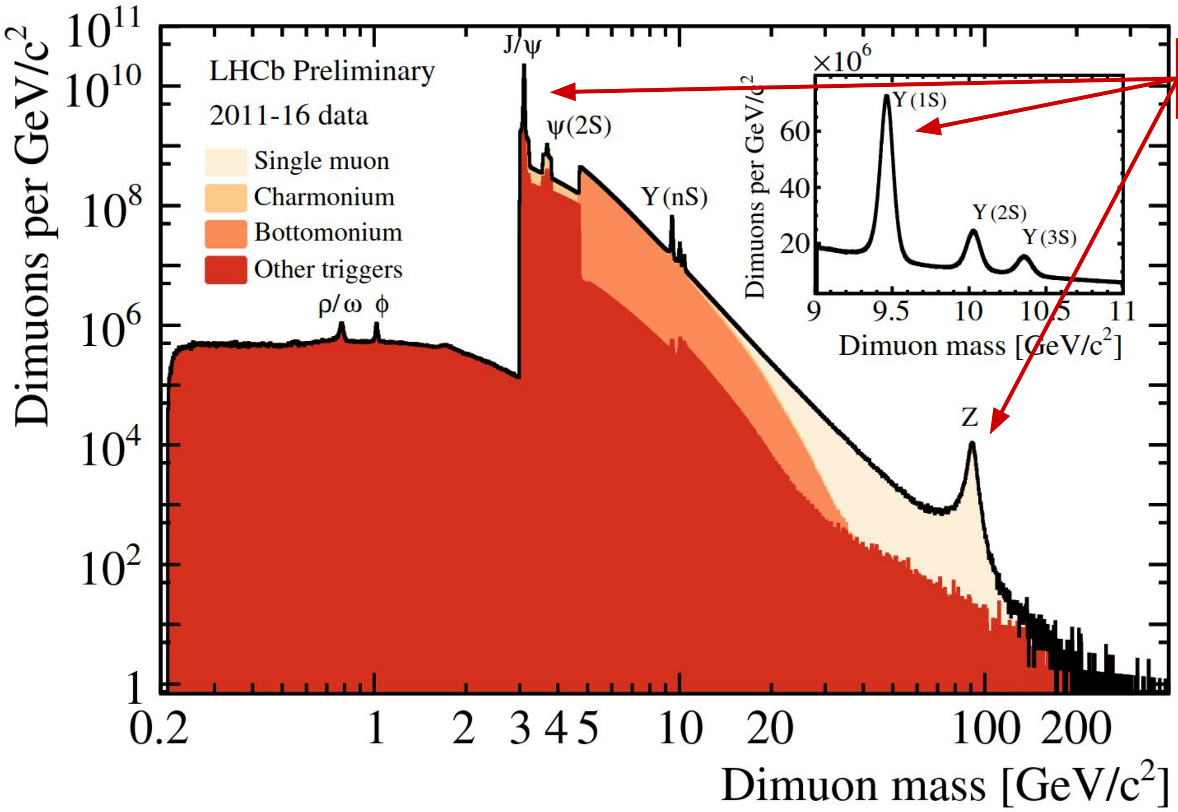
Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

Calibration using muons

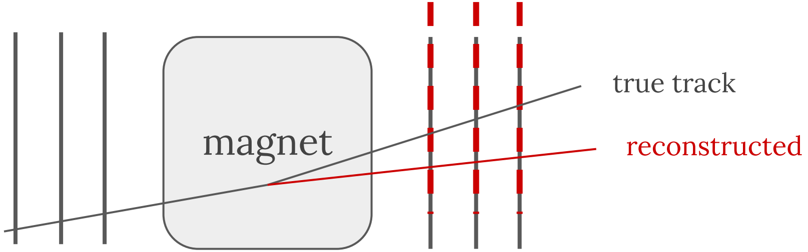
[LHCb-CONF-2016-005]



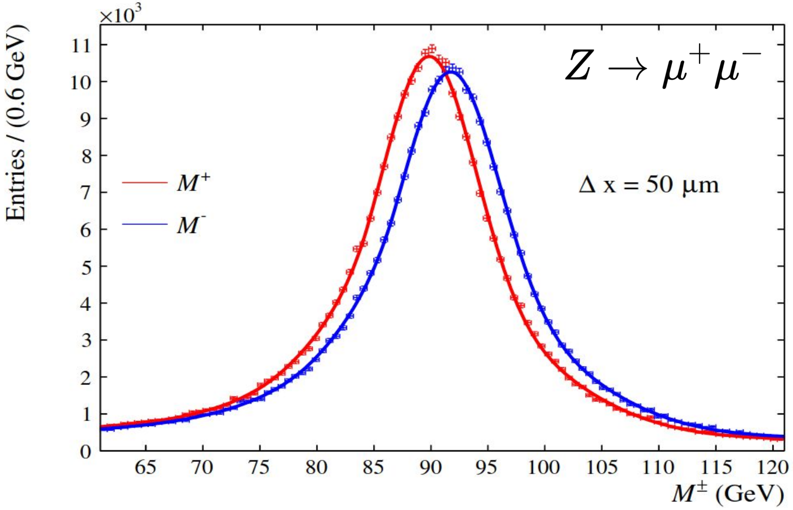
Used for calibration

Charge-dependent curvature biases

- 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



EPJ-C 81 (2021) 3, 251



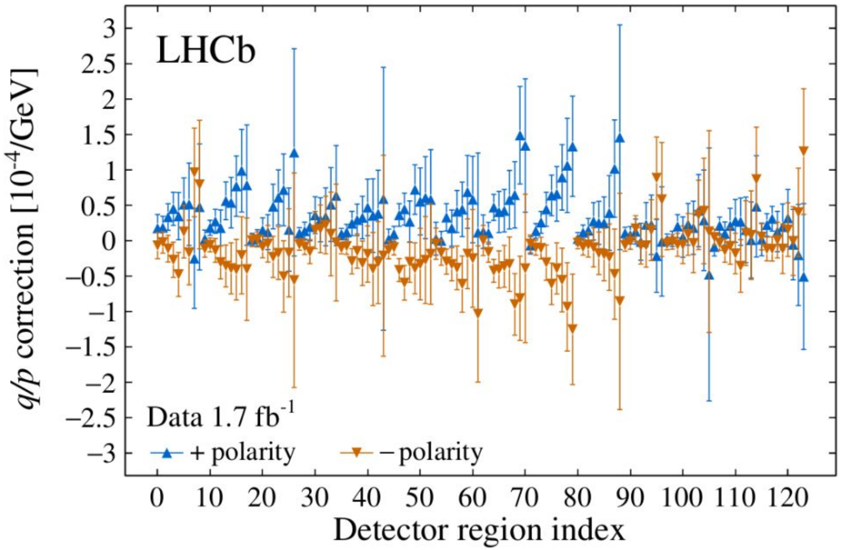
$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)}$$

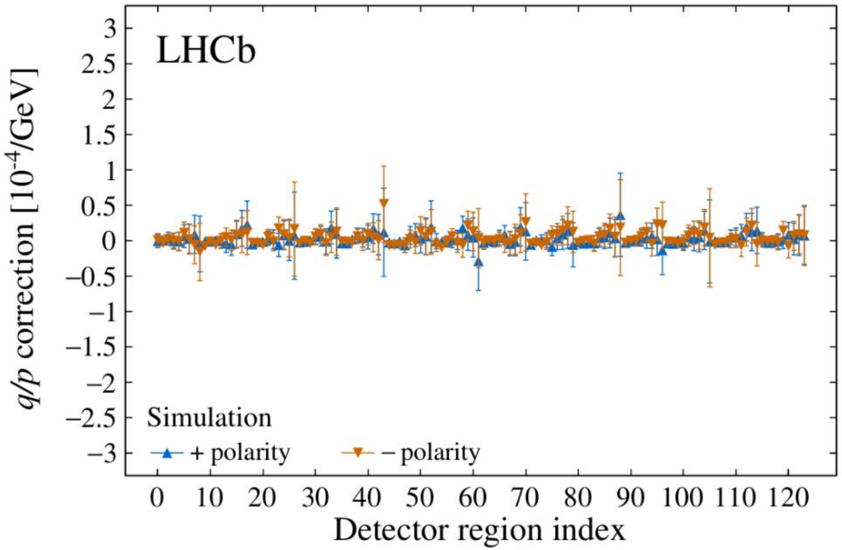
Inspired by Phys. Rev. D 91, 072002

Charge-dependent curvature biases

Fit the asymmetries to the pseudomass and translate this into shifts in q/p

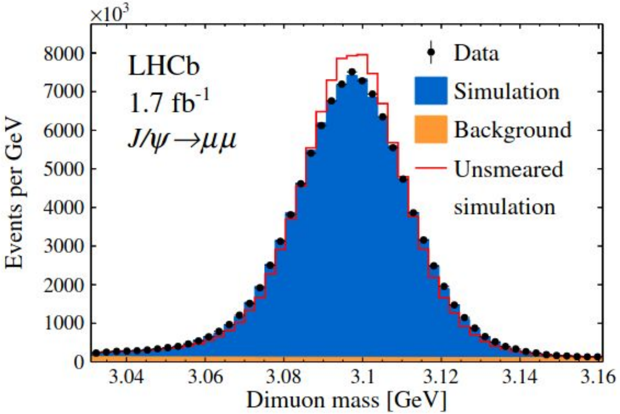
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

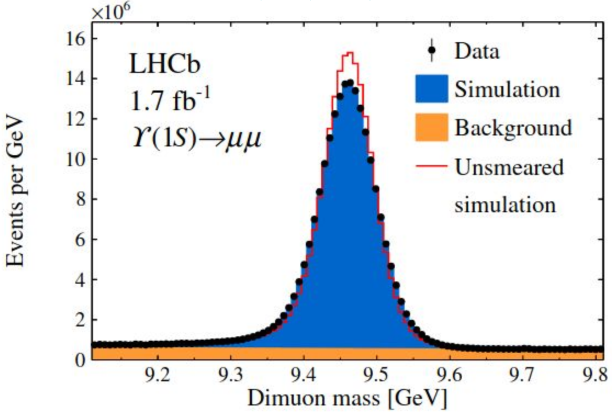




Corrections to the simulation

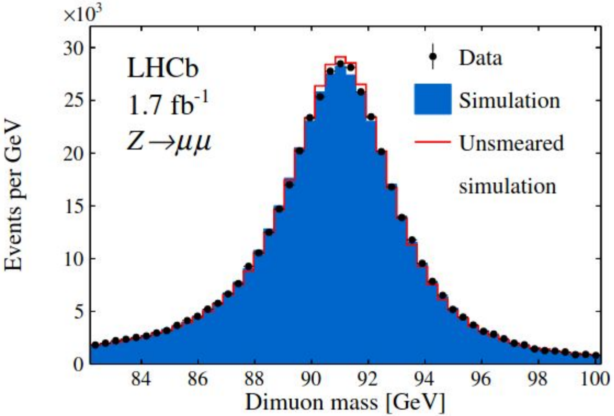
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]





Need to smear the momentum to account for:

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



The W cross-section

Unpolarized part: POWHEG + Pythia8

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

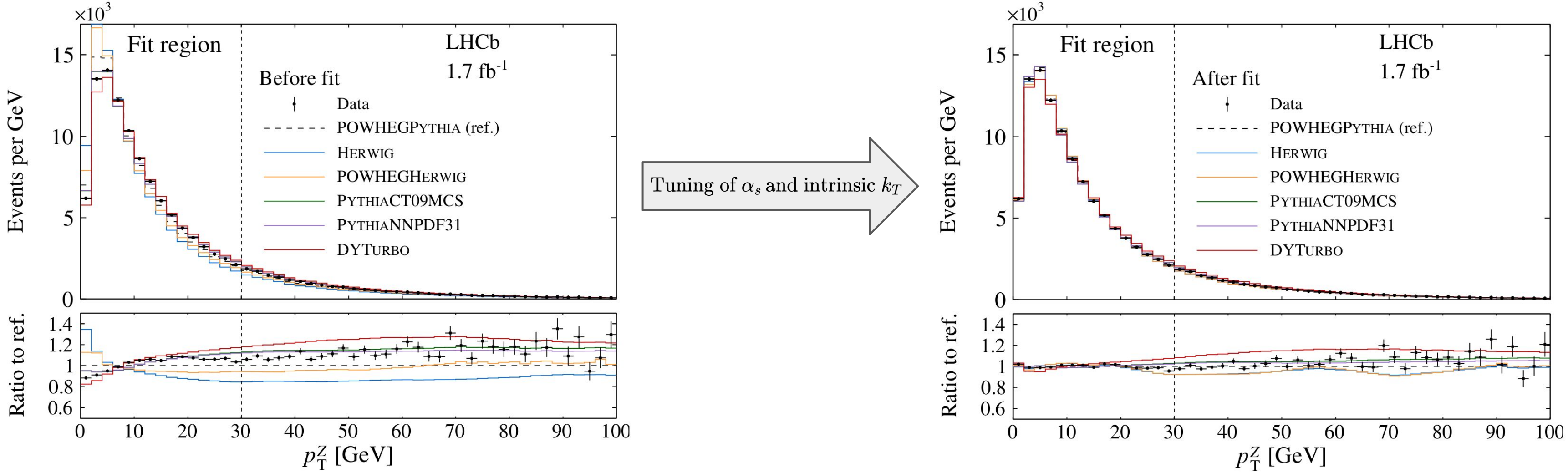
(At order α_s^2)

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

Angular part: DYTurbo

Simulating signal decays

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

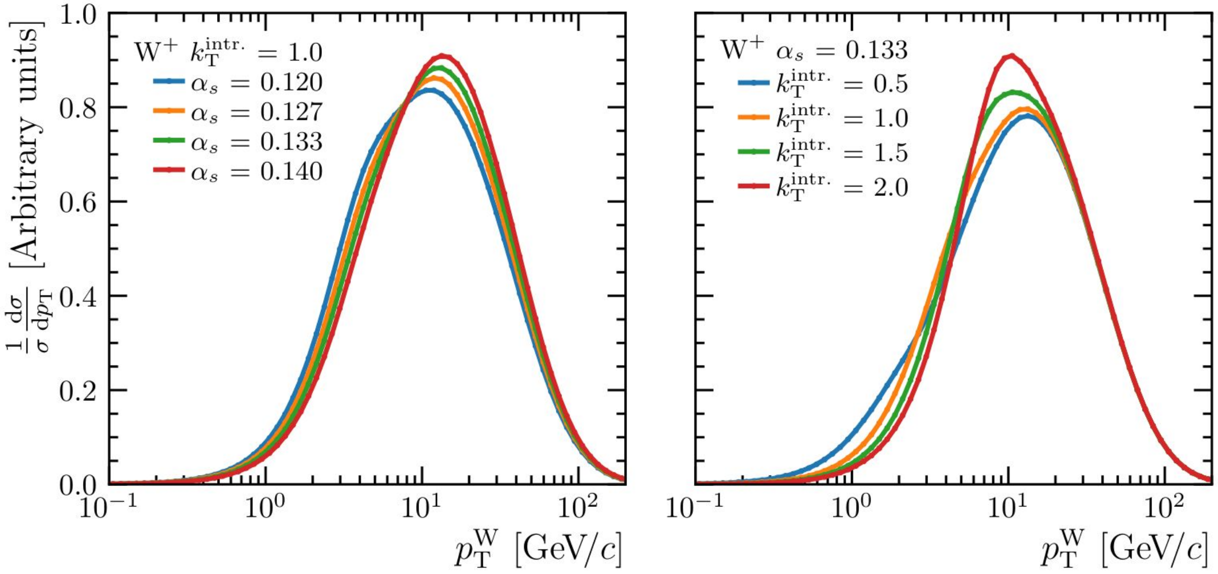


Tuning of α_s and intrinsic k_T

- 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

Modelling the W boson transverse momentum

The limited knowledge on the transverse momentum of the W bosons can be compensated by floating QCD floating parameters [arXiv:1907.09958]



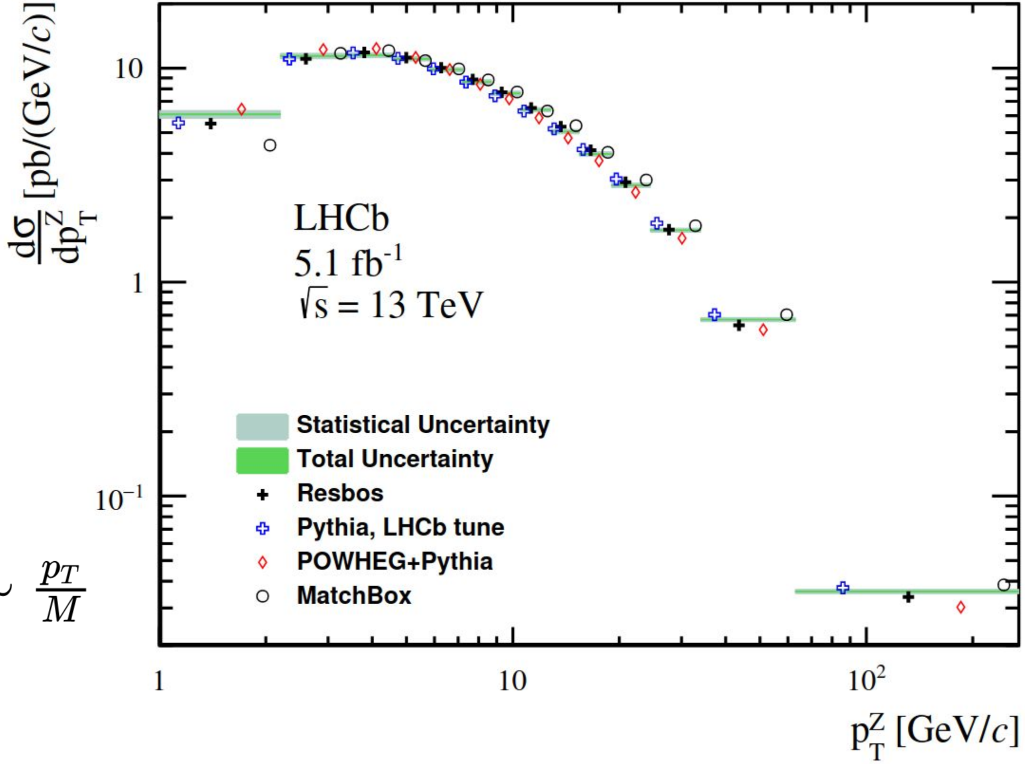
Modelling the boson transverse momentum

[arXiv:2112.07458 (submitted to JHEP)]

- The momentum of the outgoing muon is strictly related to that of the boson
- Must ensure the correlation is maintained after the fit
    - Fit Z variables simultaneously

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

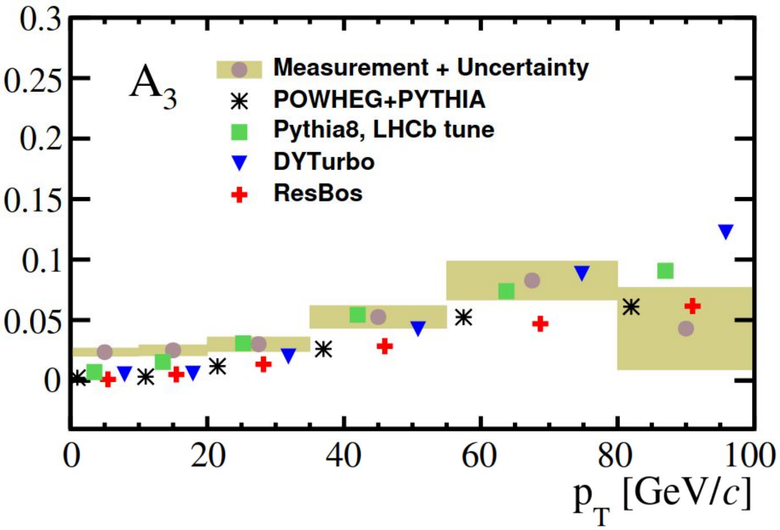
[EPJC 71, 1600 (2011)]



Polarized cross-section

- Angular part is better described with DYTurbo
- However, there angular coefficients suffer low accuracy at low transverse momentum values [JHEP 11 (2017) 003]
- Uncertainties from DYTurbo mitigated by floating A_3
    - Otherwise the uncertainty would be O(20 MeV)

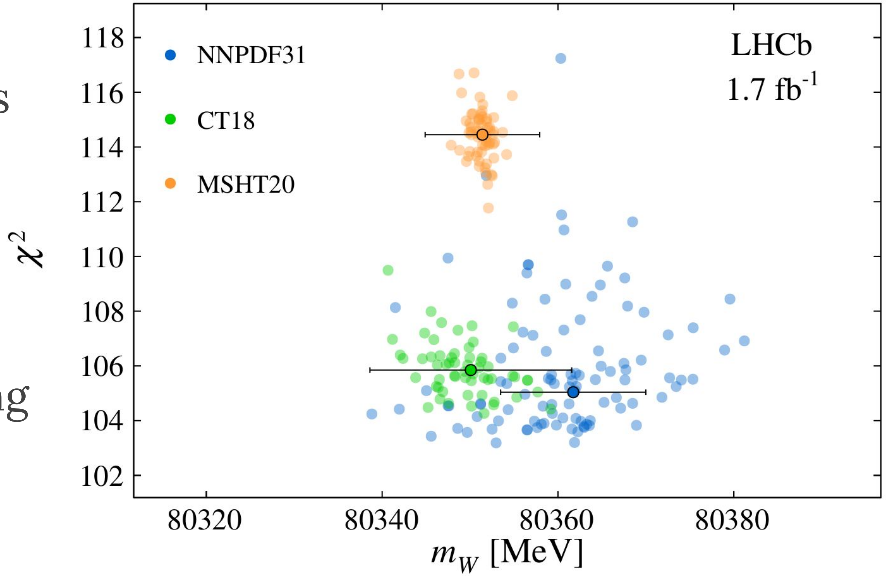
[arXiv:2203.01602 (submitted to PRL)]



The simulation process (PDF set)

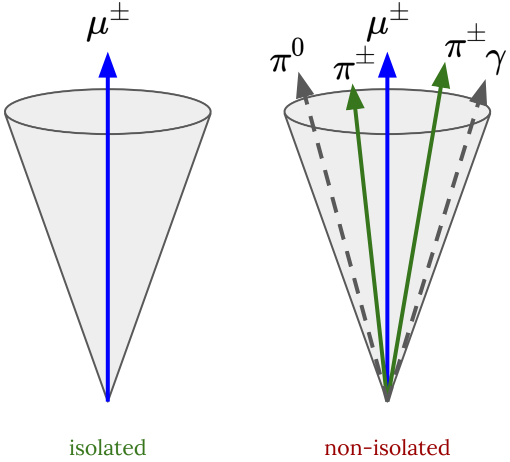
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

- 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 Υ(1S) decays (isolation biases only studied in the former)
    - Associated systematic uncertainties determined by varying the binning scheme, parametrizations and selections



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

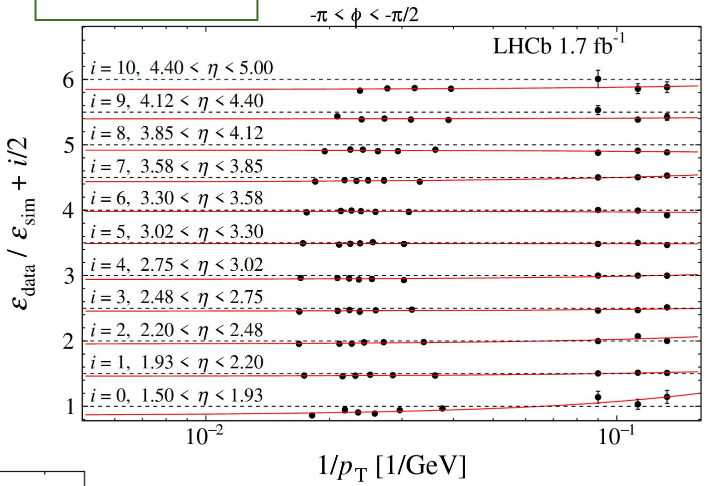
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2 \left(\text{rad}^{-2}\right)}$$

Determining the efficiencies

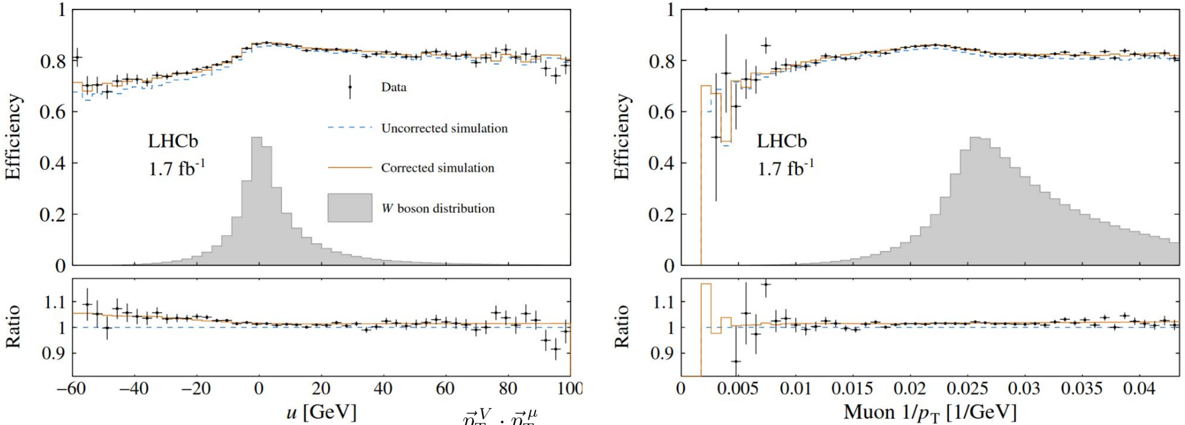
Three main sources of acceptance biases:

- Trigger efficiencies
- Muon-identification efficiencies
- Isolation requirements

Trigger efficiency



Isolation efficiency



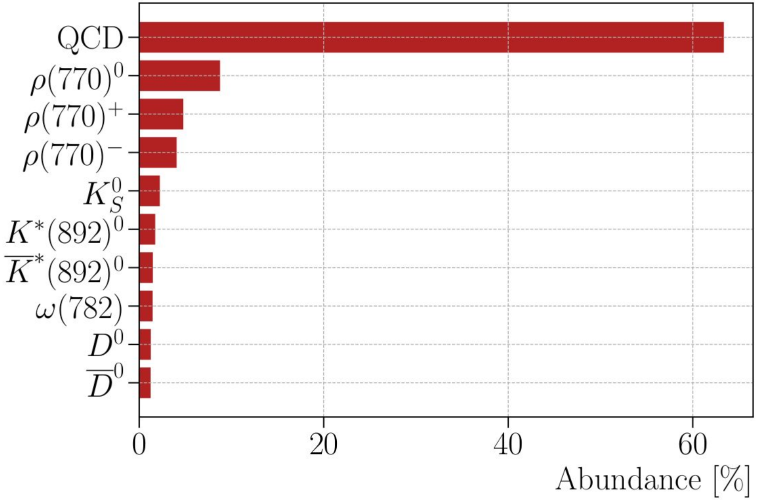
$$u = \frac{\vec{p}_T^{\,V} \cdot \vec{p}_T^{\,\mu}}{p_T^{\mu}}$$

Corrections predominantly at the percent level

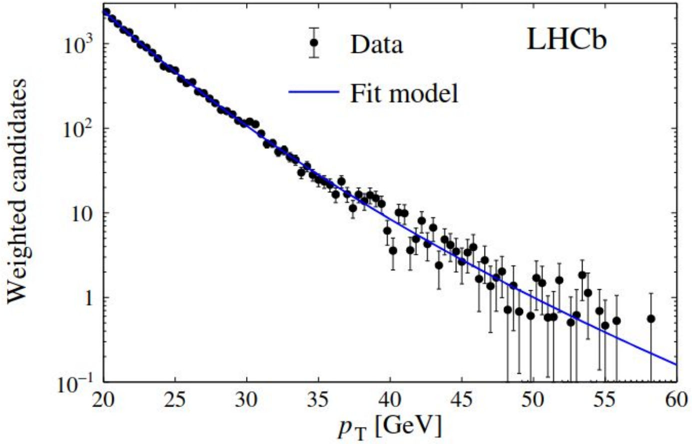
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

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)



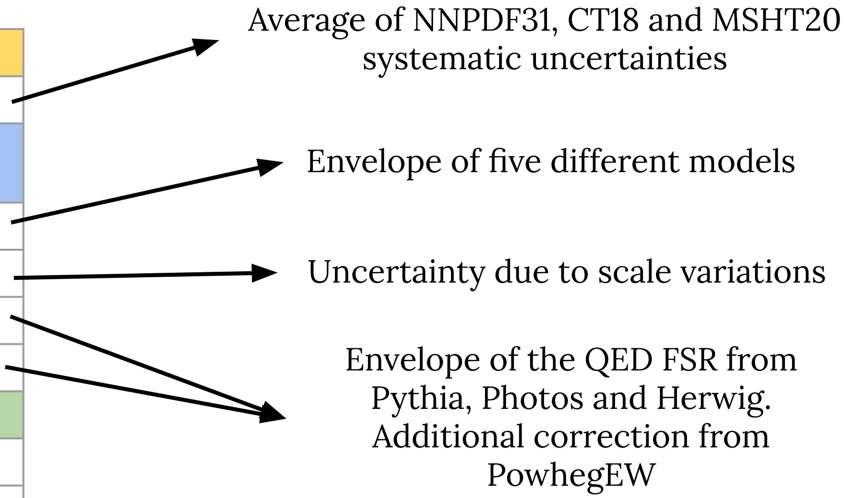
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]



Systematic uncertainties

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

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

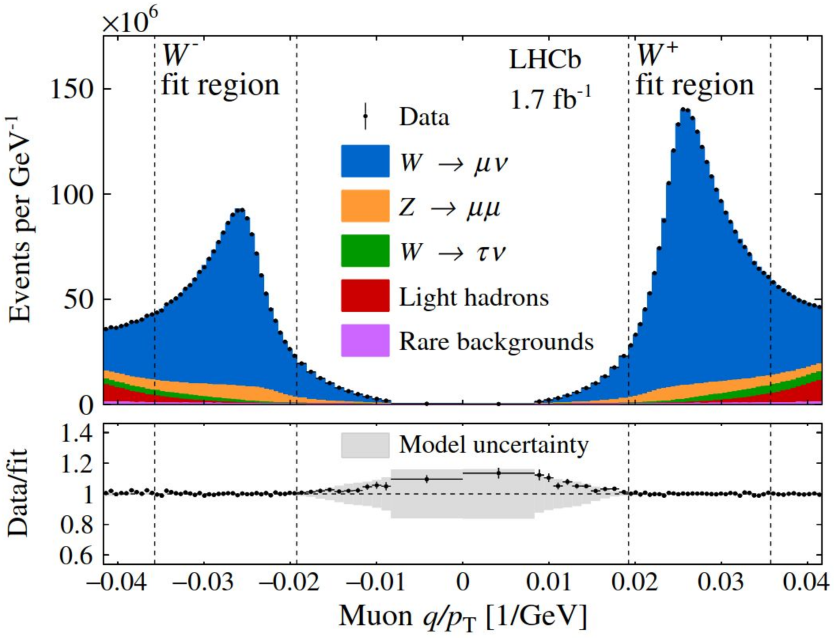
Uncertainty due to scale variations

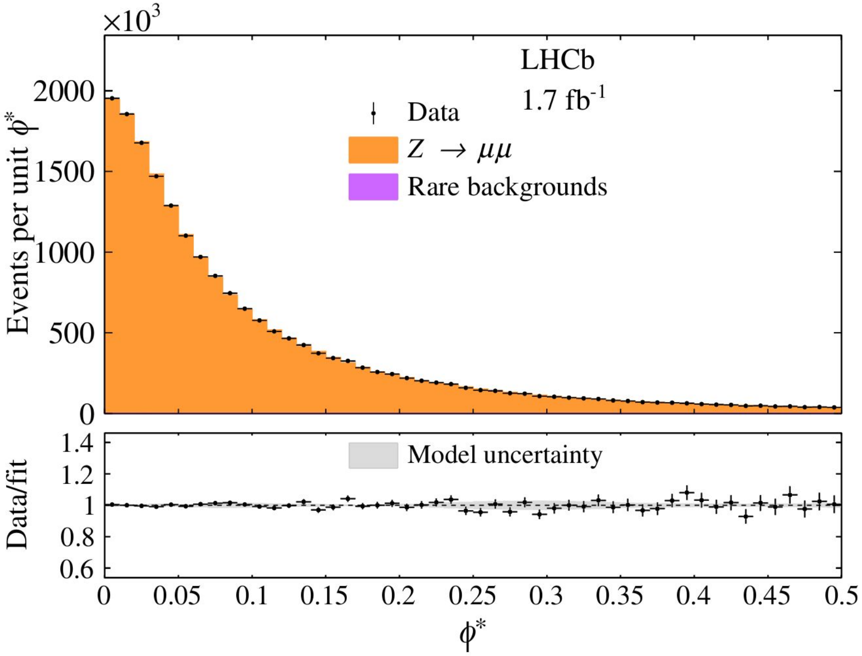
Envelope of the QED FSR from Pythia, Photos and Herwig. Additional correction from PowhegEW

Already thinking of ways to improve most of these uncertainties!

Fit to extract the W mass

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



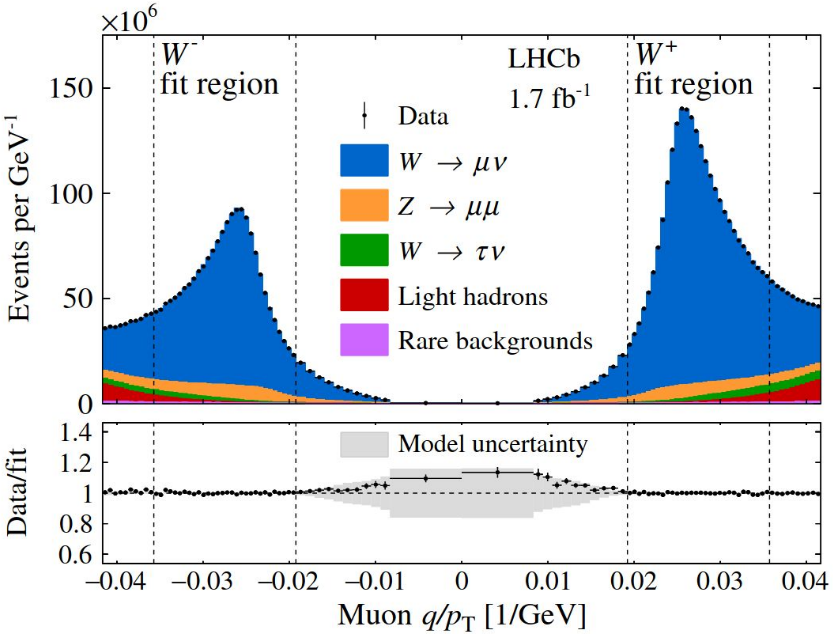


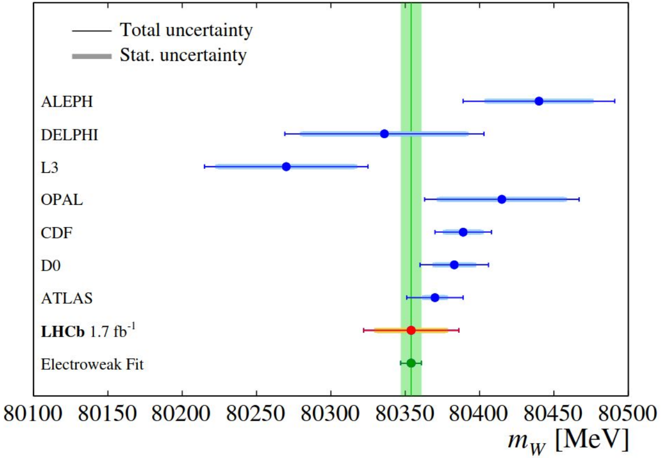
- 5D-weighted fit using the Beeston-Barlow approach
- Fit simultaneously W and Z data

LHCb measures the W mass!

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

- Measurement of the W mass using 2016 data
- Published on January 2022
- Shows the LHCb capabilities of doing high-precision measurements





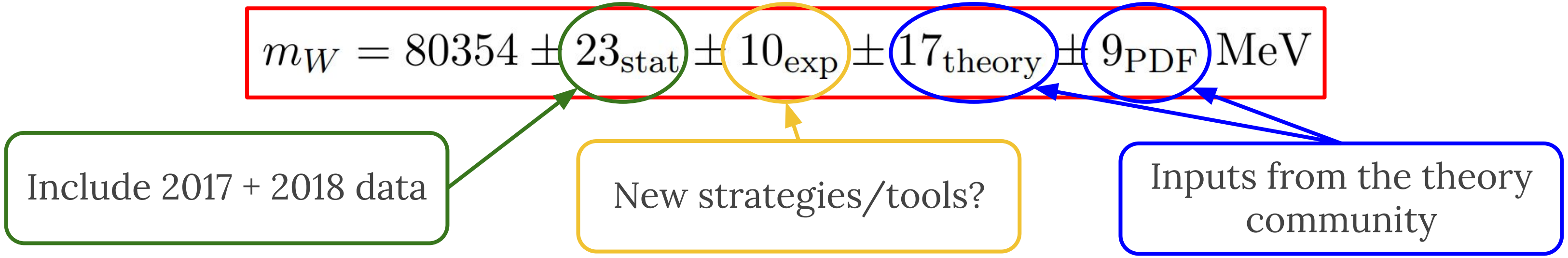
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Prospects for the future

Prospects

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

What can we do in the near future?



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

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

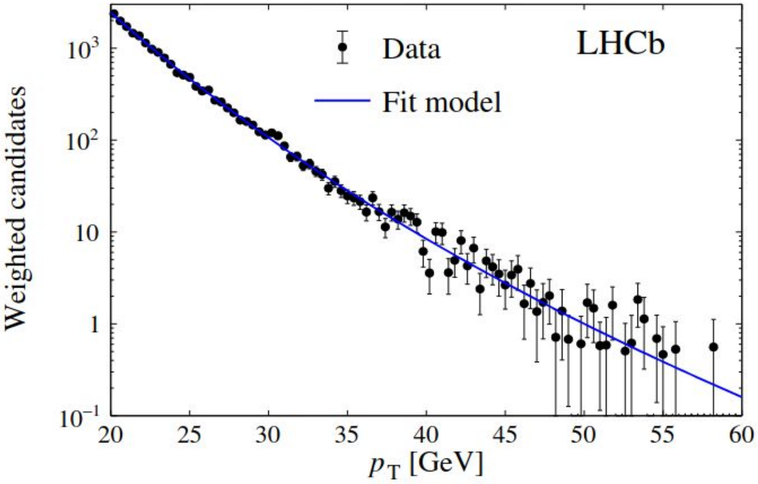
Improving the simulation

- 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

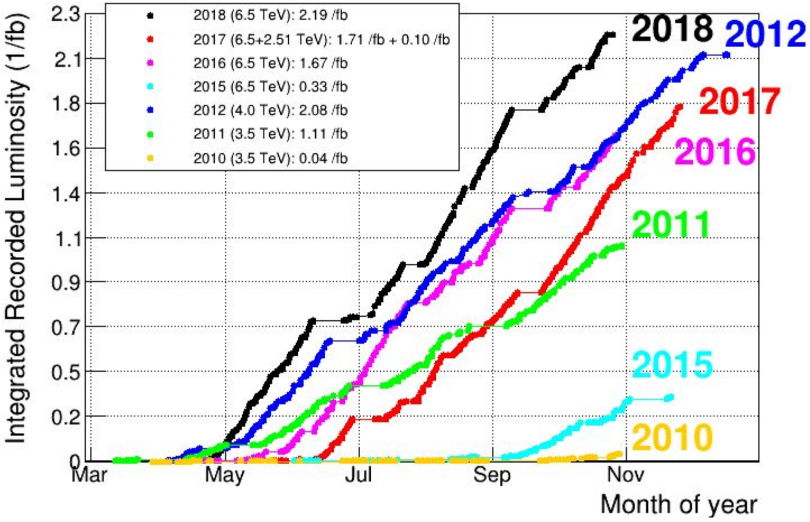
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

- 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
- Eager to see the result of combining the measurements of all the LHC experiments

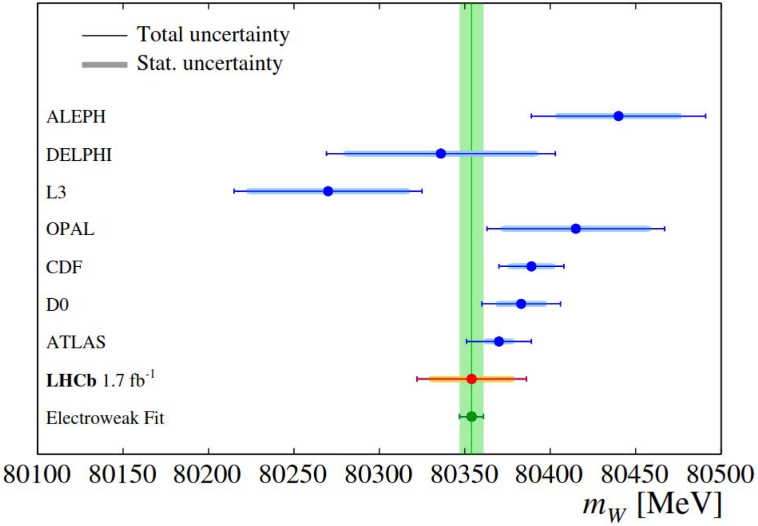


$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

Summary

Summary

- The W mass measurement using 2016 data is a big milestone at LHCb
- Already exploring new strategies to improve the result with the full Run 2 data sample
- Improvements on the physics modelling are strictly necessary to be competitive



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Looking forward to hearing your comments and suggestions

Thank you!