W mass measurement and other Electroweak searches at LHCb

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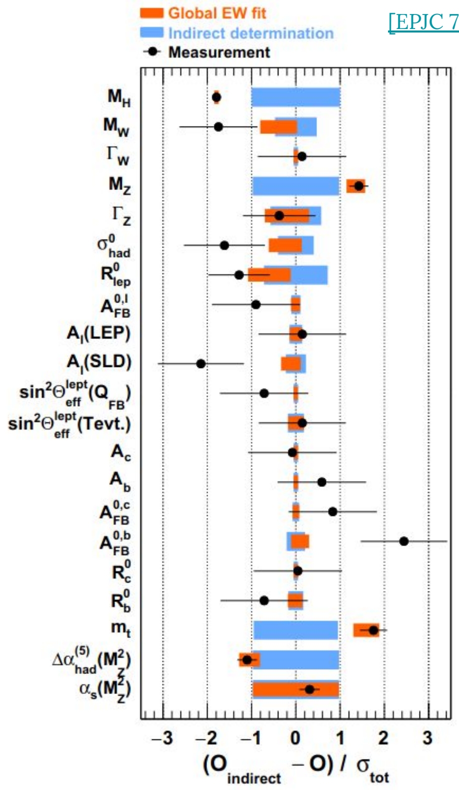
Electroweak physics



[EPJC 78, 675 (2018)]

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

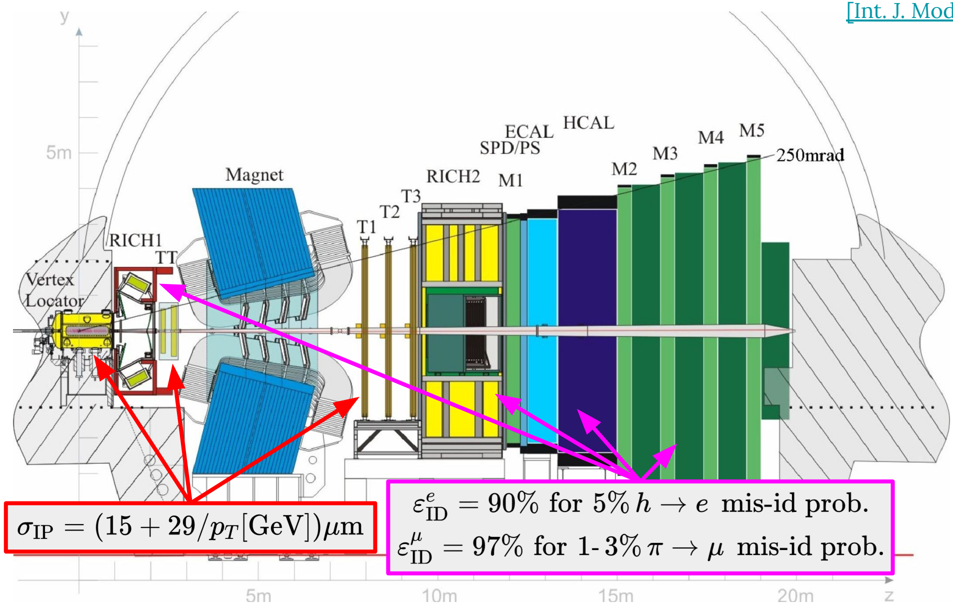
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \qquad \Gamma_W \propto G_F m_W^3$$

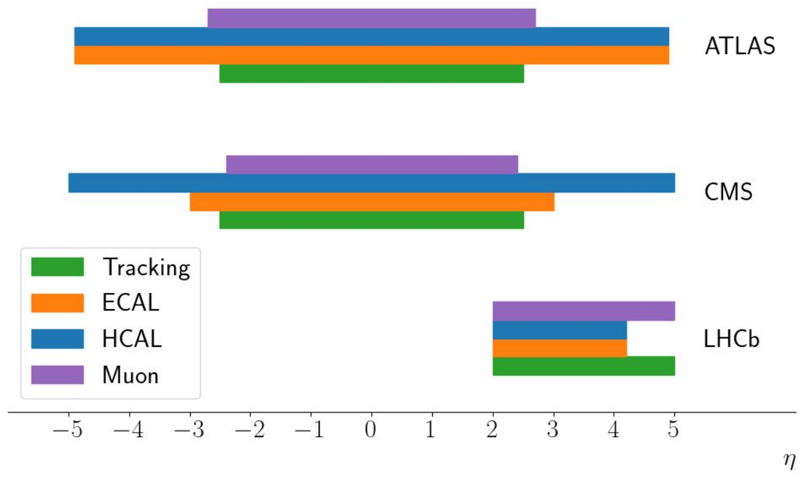
Higher order corrections

- Current measurements of electroweak observables are consistent with the SM predictions (with some tensions)
- Precision measurements of these quantities allow to search for new physics effects
- Challenging both from the theoretical (modelling) and experimental points of view

The LHCb detector to study EW signatures

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





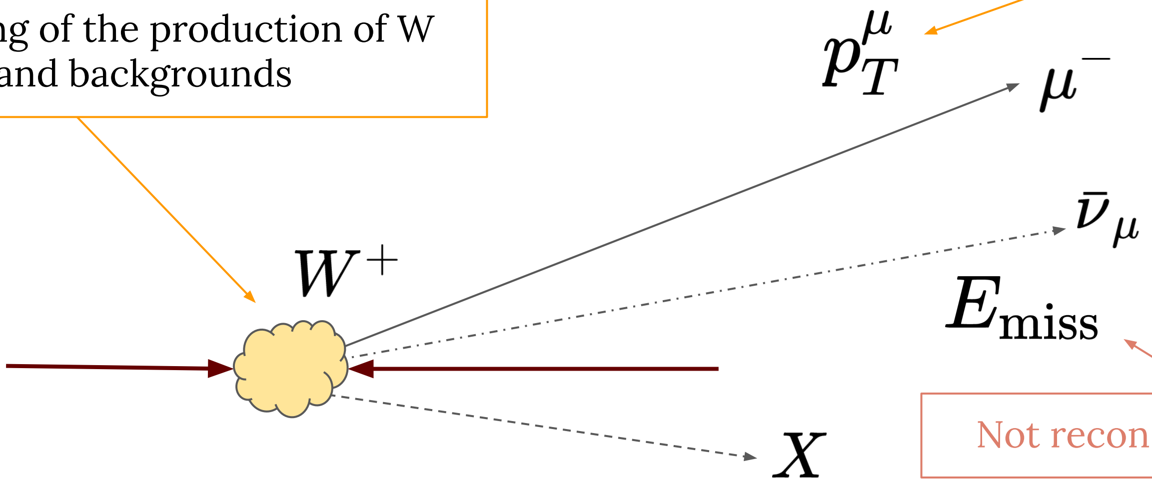
- Detector in the forward region with excellent momentum and vertex resolutions
- Coverage is complementary to ATLAS and CMS (with some overlapping at low pseudorapidity)

The W mass measurement

Single event signature at LHCb

Must carefully determine the momentum of the outgoing muon

Precise modelling of the production of W bosons and backgrounds



Not reconstructed at LHCb

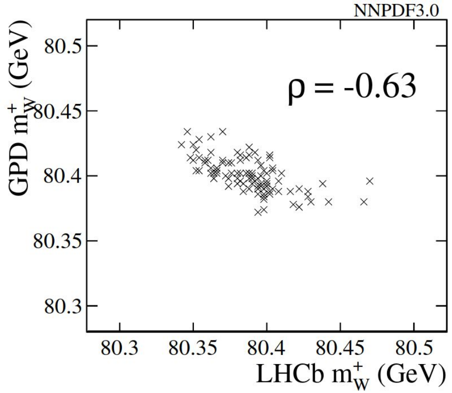
Get rid of background with kinematic and isolation requirements

Analysis strategy

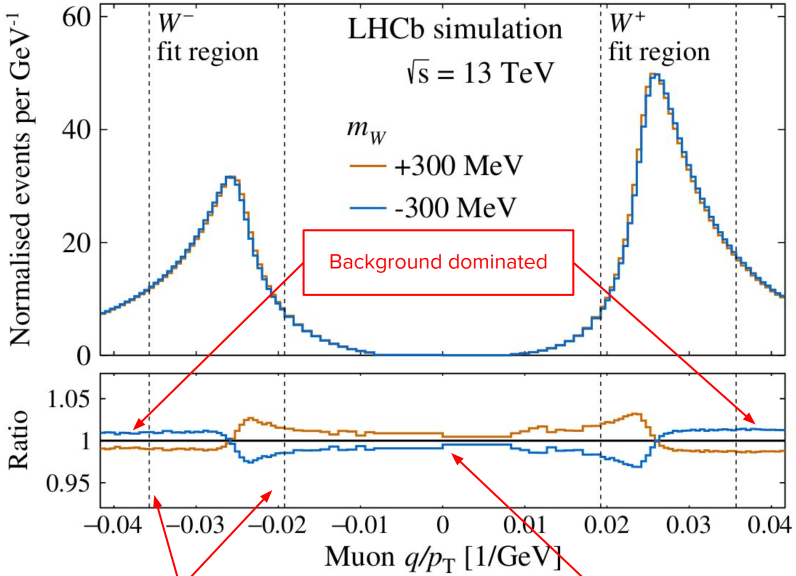
- Measure the W boson mass by studying the transverse momentum spectrum of the outgoing muon
- Uncertainty from PDFs is anticorrelated to that of ATLAS/CMS ⇒ LHC experiments can achieve a sensitivity closer to the global EW fit (~7 MeV)

CMS & ATLAS

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



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



Most sensitive region

Large theoretical uncertainties

Analysis using 2016 data only

The W cross-section

Unpolarized part

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

(At order α_s^2)

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

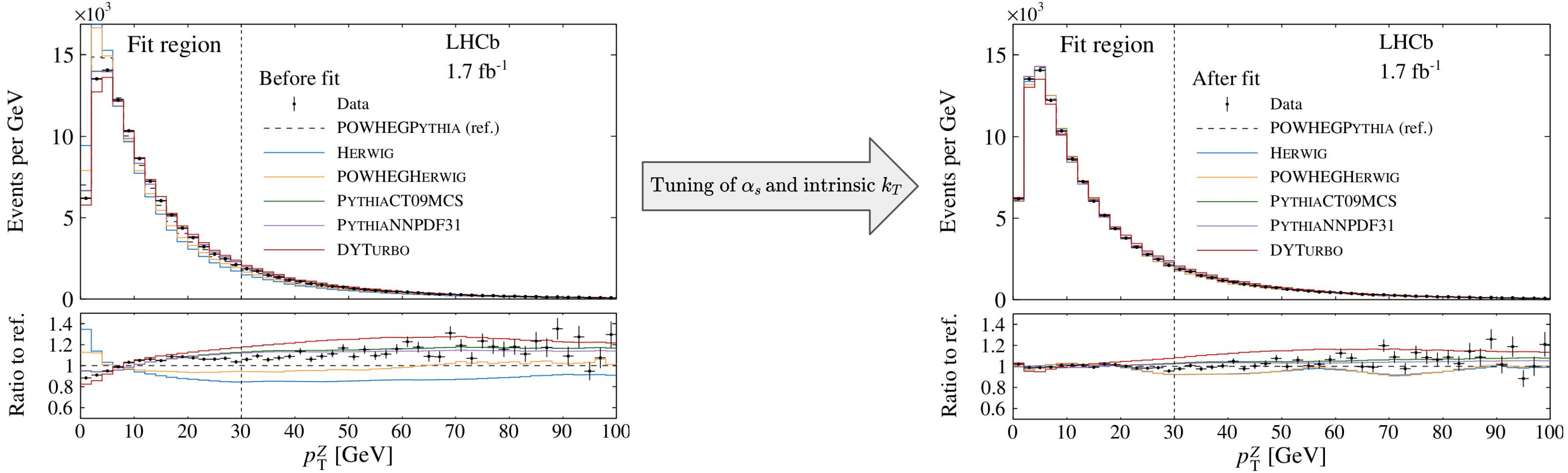
Angular part

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

(See talk by Menglin Xu for more details)

Simulating signal decays

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

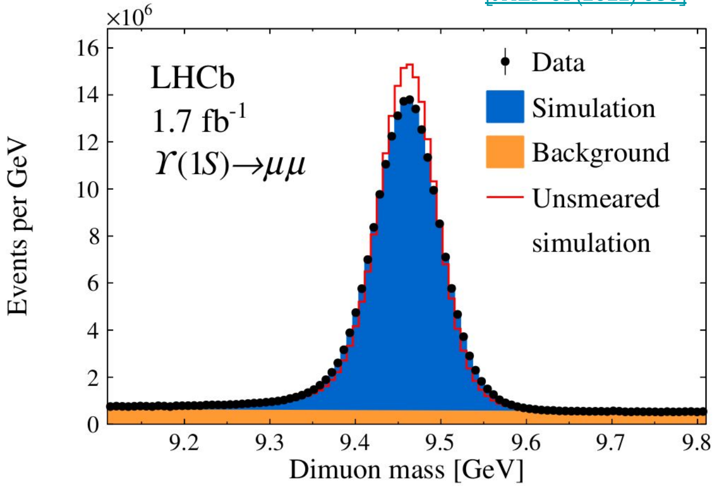


- POWHEG + Pythia gives the best description of the unpolarized cross-section and is chosen as the baseline generator
  - Varied success with other generators, used to determine systematic uncertainties
- DYTurbo performs well at reproducing the angular cross-section

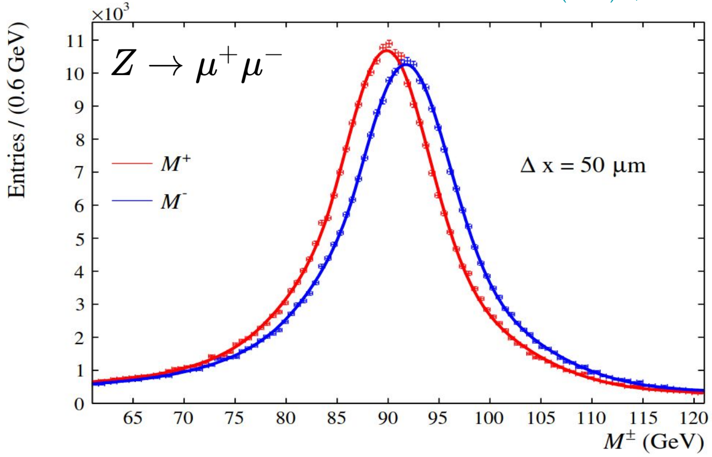
Alignment and calibration of the detector

- The W mass determination is highly sensitive to misalignments and misclabrations of the detector
- Offline tools used to improve the determination of the transverse momentum

[JHEP 01 (2022) 036]



EPJ-C 81 (2021) 3, 251

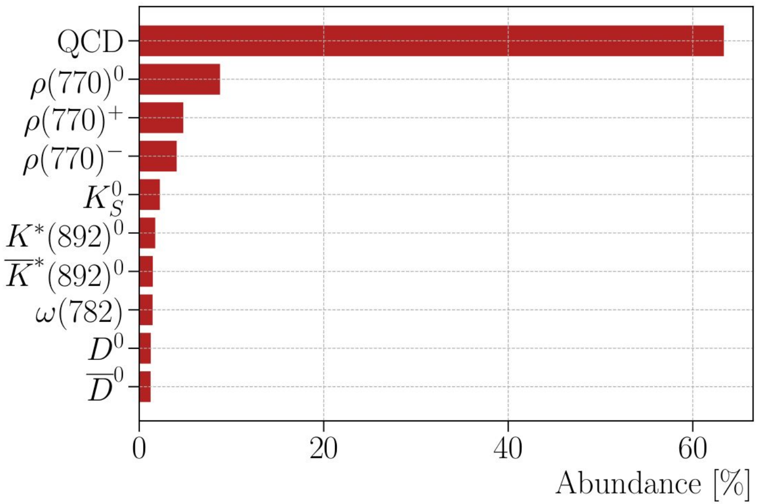


$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1 - \cos\theta)}$$

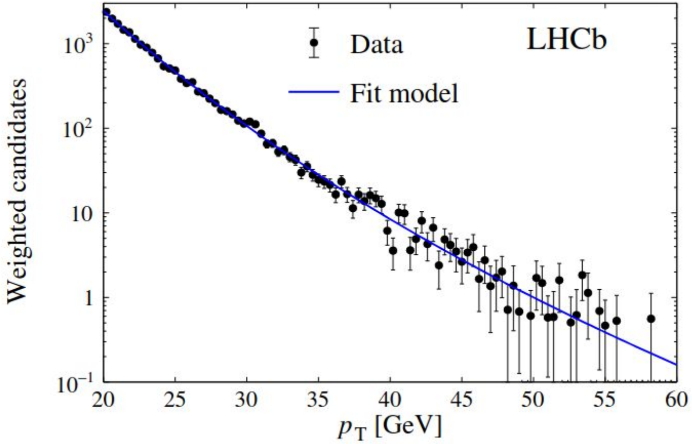
Inspired by Phys. Rev. D 91, 072002

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

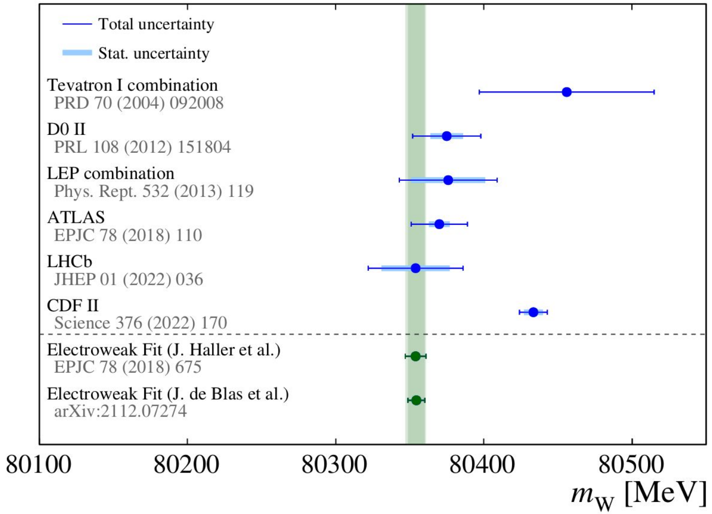
Uncertainty due to scale variations

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

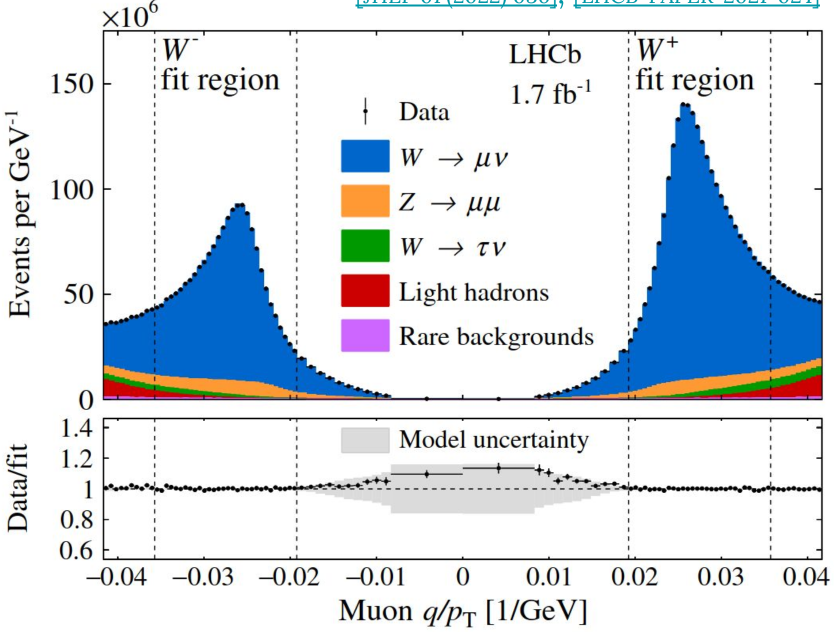
Already thinking of ways to improve most of these uncertainties!

The W mass fit

[LHCB-FIGURE-2022-003]



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



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

Including 2017 + 2018 data $\Rightarrow$ < 20 MeV

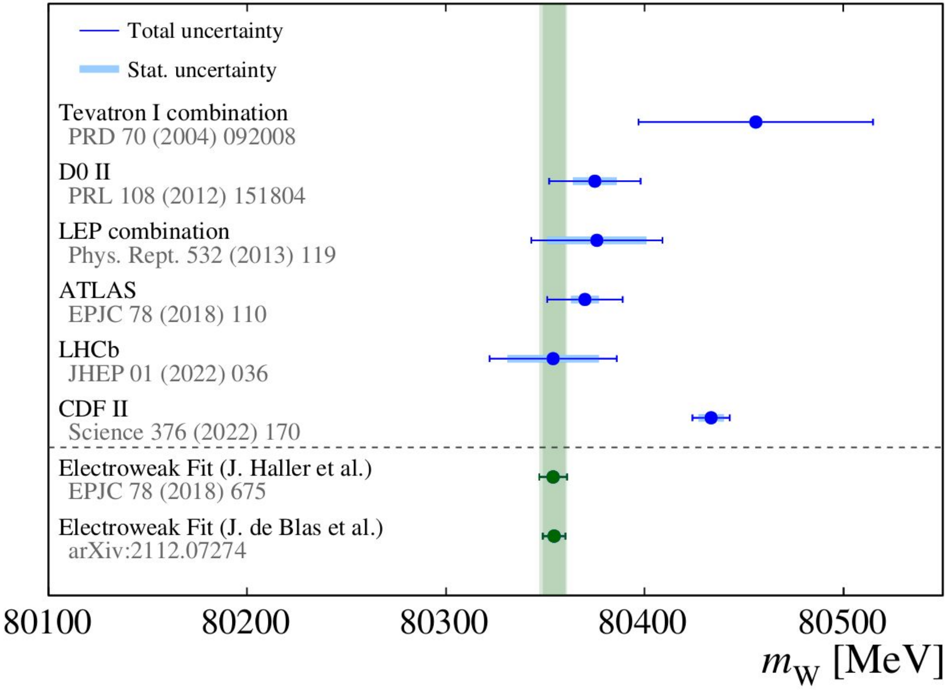
New strategies/tools?

Improvements to the physics modelling

The current picture of the measurement

- Striking result from the CDF II collaboration in early April [Science, 376, 6589, (136-136), (2022)], with unprecedented precision
- 7σ away from the electroweak fits, and in tension with other experimental results
- Open questions now being raised:
  - Resolution, efficiency and detector response
  - Physics modelling (proton-proton, proton-antiproton, PDFs, ...)
- Encouraging the full LHC combination

[LHCB-FIGURE-2022-003]

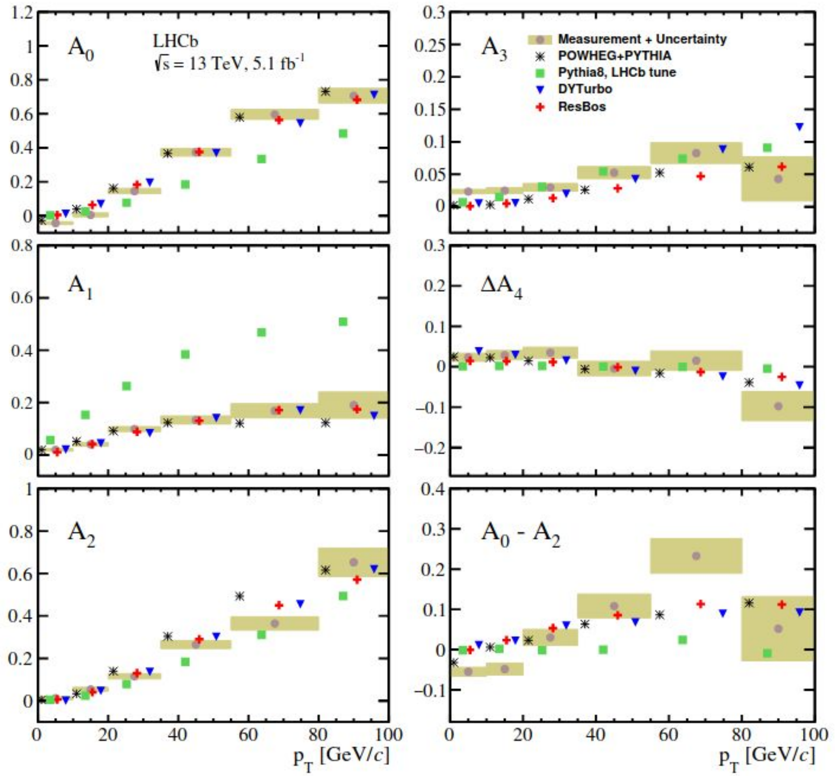


Other Electroweak measurements

Angular coefficients

[arXiv:2203.01602 (submitted to PRL)]

- Study of dimuon decays around the Z peak using 2016-2018 data
- Z production studied in the past at LHCb [EPJC 71:1600, 2011], but the angular information had not been analysed yet
- Valuable input to understand momentum-spin correlations of the proton
- Interesting violation Lam-Tung relation (A_0=A_2) in agreement with ATLAS [JHEP 2016, 159 (2016)] and CMS [PLB 750 (2015) 154] results



Sensitive to the weak-mixing angle; not reported

Fixed to zero due to small number of candidates at high transverse momentum

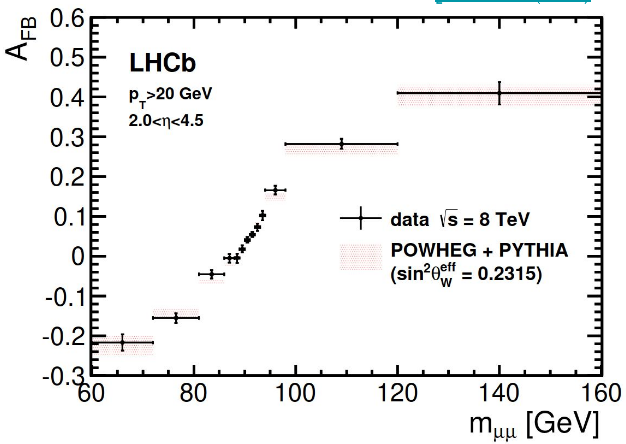
$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi$$
$$+A_3 \sin\theta\cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi$$

(See talk by Menglin Xu for more details)

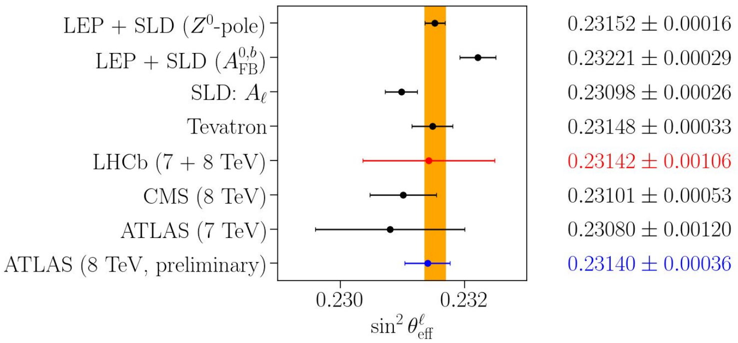
Forward-backward asymmetry in Z decays

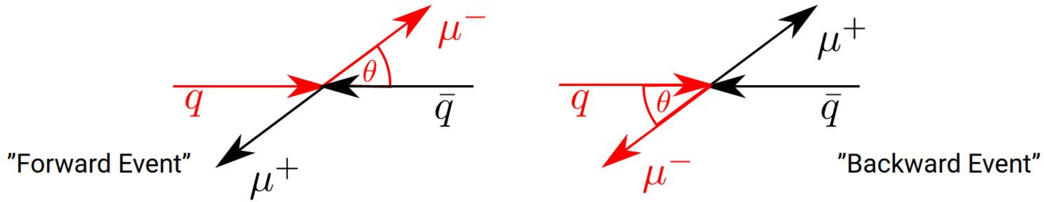
- Test of vector and axial-vector couplings in the SM, which induce a forward-backward asymmetry in Z boson decays
- Dependency with the weak mixing angle
- The asymmetry must be measured with respect to the direction of motion of the quarks
  - Assume that quarks travel in the direction of the Z boson
- Possibility to beat LEP + SLD measurements in the HL-LHC [CERN-LHCC-2018-027]

[JHEP 1511(2015)]



[ATLAS-CONF-2018-037]





Prospects and summary

Prospects and summary

- LHCb has proved to be competitive with the previous and current experiments for a precise W mass measurement
- The new result from the CDF-II collaboration constitutes a drastic change to the current scenario
    - Pushes the LHC towards releasing a combined result and theorists towards a better understanding of the physics modelling
- LHCb also offers a unique opportunity to study other EW observables in the forward region, usually complementary to other experiments

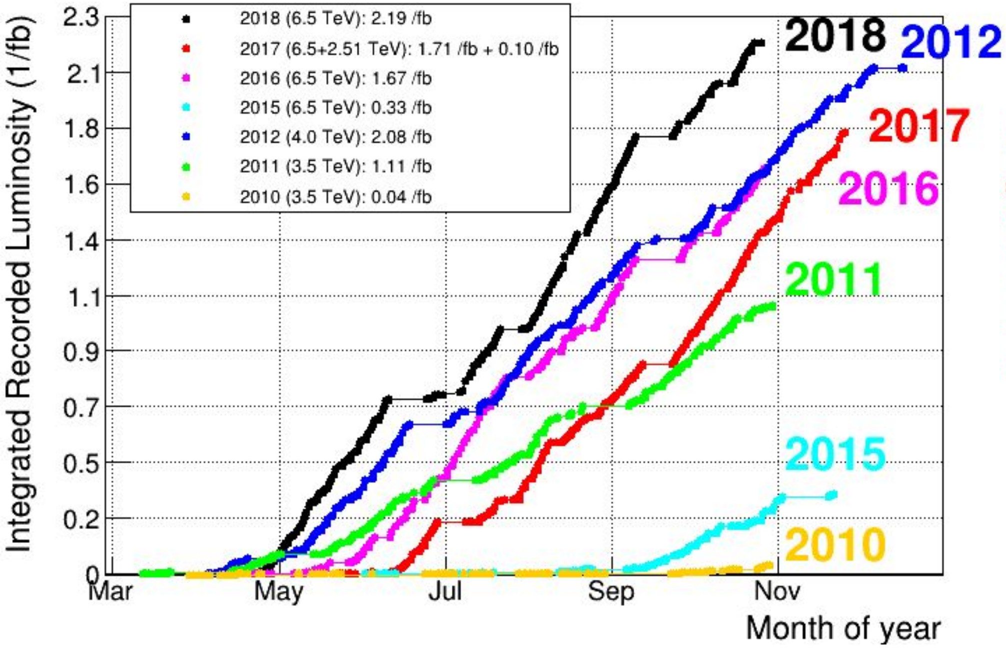
Exciting times ahead of us!


W^+ Z^0 H
Thank you!
τ^-
μ^-
e^-

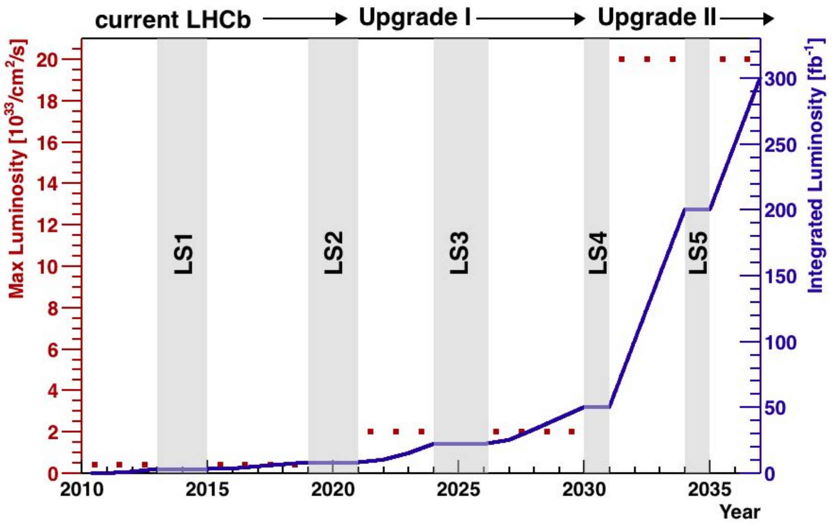
Backup

LHCb luminosity

[LHCb operation plots]



[LHCb-PUB-2018-009]

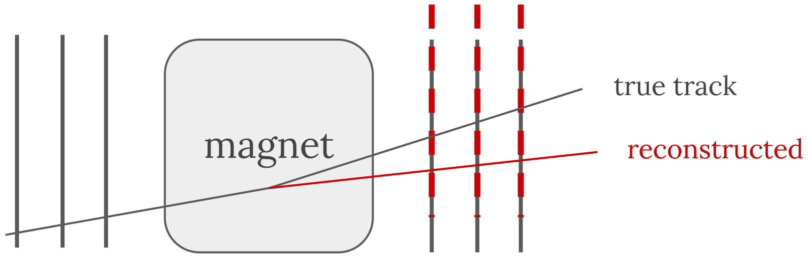


Charge-dependent curvature biases

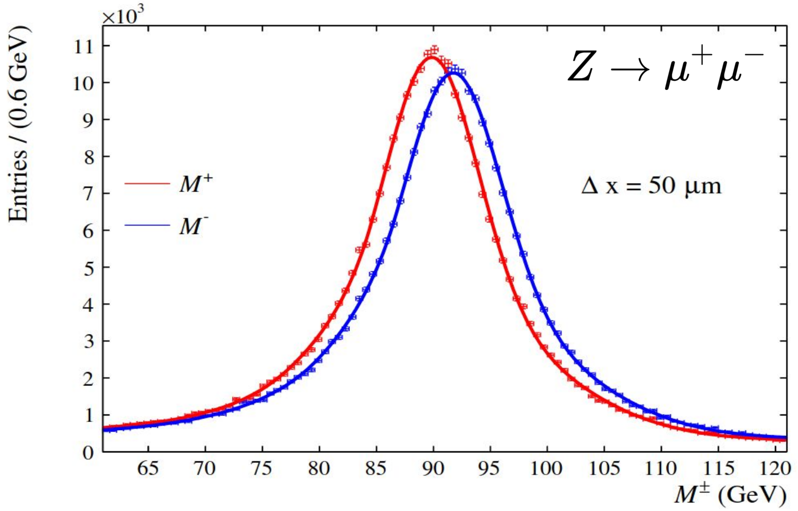
- The analysis relies highly on the detector alignment
  - Misalignment of 10μm translates into a O(50MeV) shift
- Default LHCb alignment and calibration not suitable to study candidates with high transverse momentum
- Need to re-run the alignment and calibration offline using Z decays
- Avoid double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



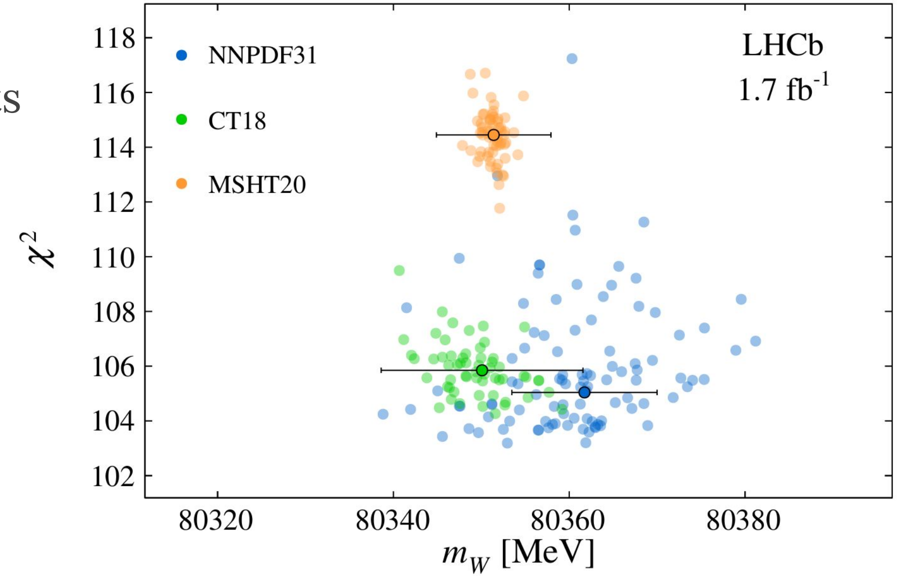
[EPJ-C 81 (2021) 3, 251]



The simulation process (PDF set)

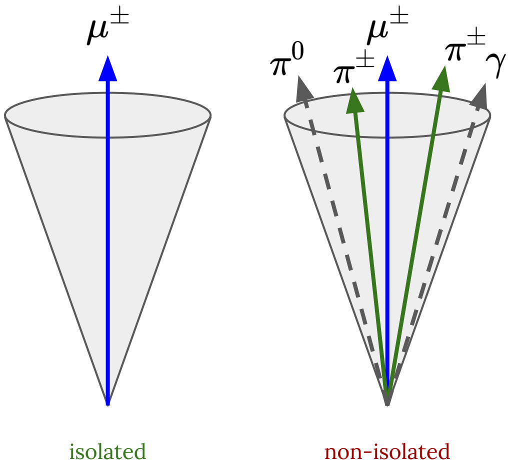
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

- 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



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



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

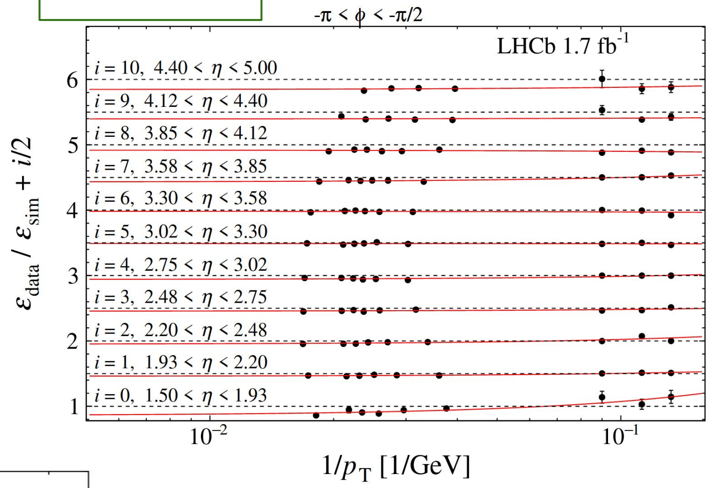
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2\left(\text{rad}^{-2}\right)}$$

Determining the efficiencies

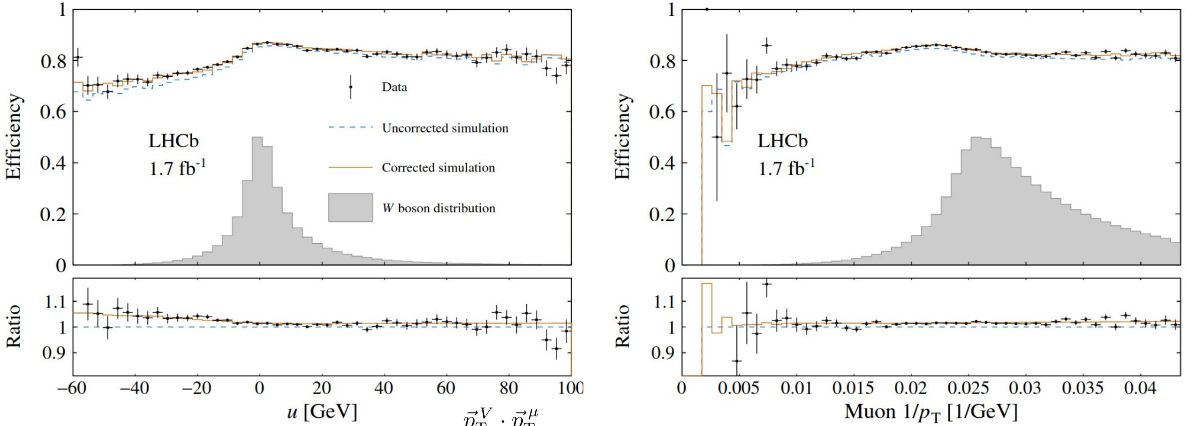
Three main sources of acceptance biases:

- Trigger efficiencies
- Muon-identification efficiencies
- Isolation requirements

Trigger efficiency



Isolation efficiency



$$u = \frac{\vec{p}_{\mathrm{T}}^{V} \cdot \vec{p}_{\mathrm{T}}^{\mu}}{p_{\mathrm{T}}^{\mu}}$$

Corrections predominantly at the percent level

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

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]

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

W boson mass correlations

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