Towards a full Run 2 W mass measurement at LHCb

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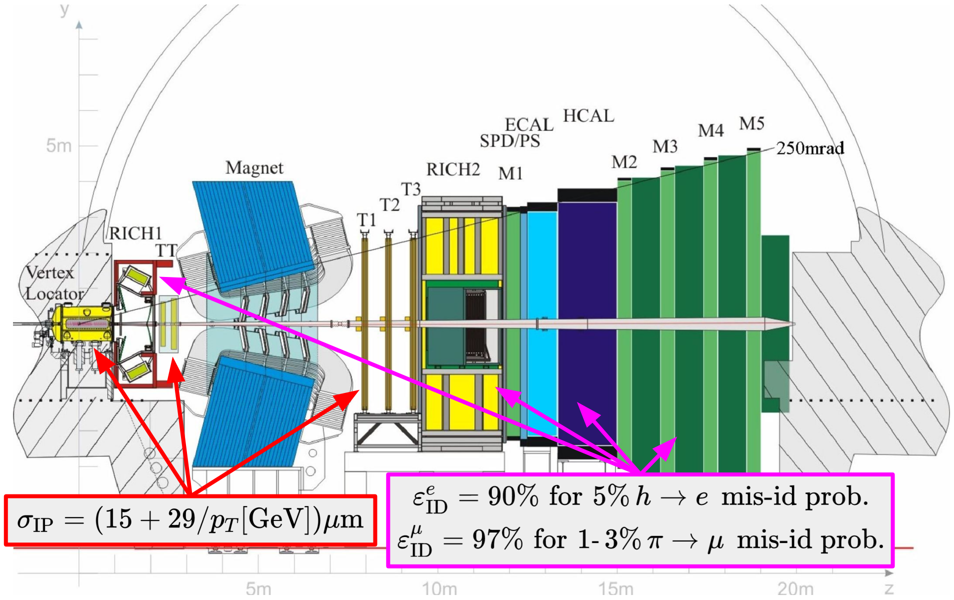
European Research Council
Established by the European Commission

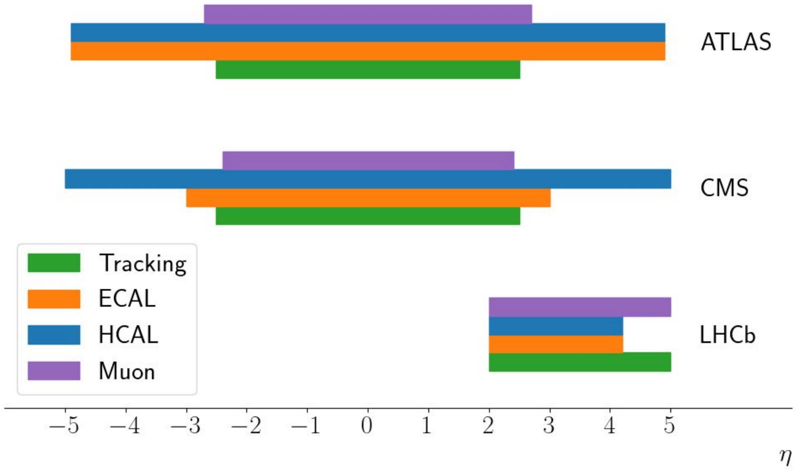
The LHCb detector at the LHC



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

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

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



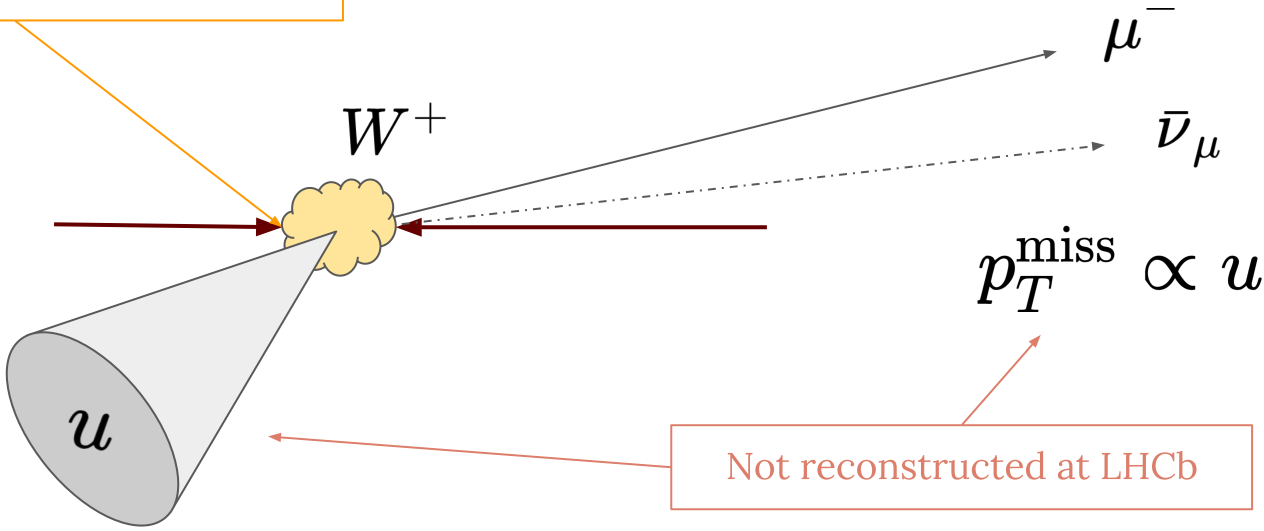
- Detector in the forward region with excellent momentum and vertex resolutions
- Coverage is complementary to ATLAS and CMS (with some overlapping at low pseudorapidity)

Single event signature

Must carefully determine the momentum of the outgoing muon

Precise modelling of the production of W bosons and backgrounds

$$p_T^{\mu} \sim \, m_W \times f(\theta, \phi) + p_T^W \times g(\theta, \phi)$$



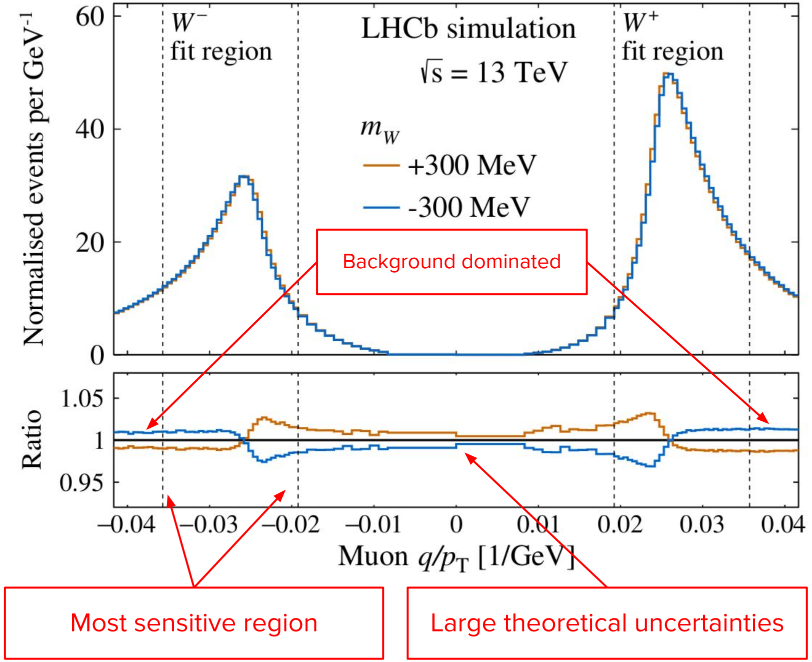
$$p_T^{\text{miss}} \propto u_T$$

Not reconstructed at LHCb

Analysis strategy

- Carefully measure the muon transverse momentum
- Use plain LHCb Pythia8 simulation and reweight using samples with generator-level information from different models
- Correct the simulation efficiencies of the different selection steps (reconstruction, trigger, topological, offline selection)
- Study and determine backgrounds through simulation and data-driven approaches
- Beeston-Barlow fit of the different templates and physics modelling to the data

[JHEP 01 (2022) 036]



Background dominated

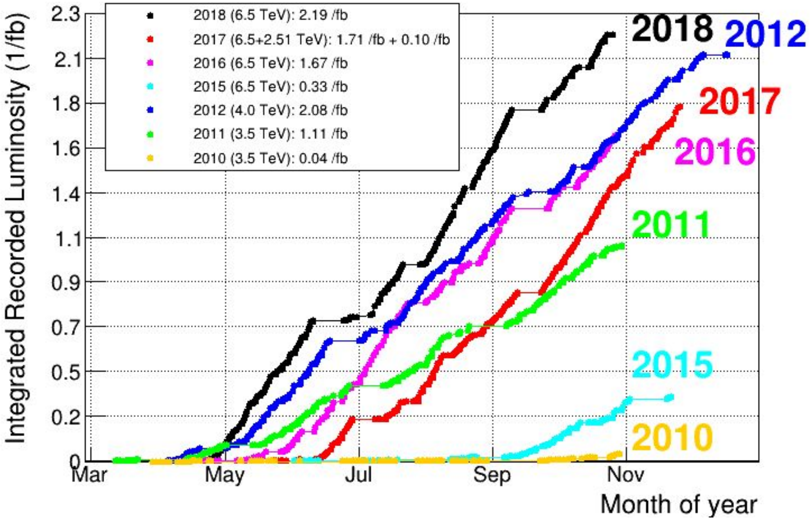
Most sensitive region

Large theoretical uncertainties

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

Expected sensitivity for the full Run 2 analysis

- We expect to reduce the overall experimental uncertainty to ~14 MeV
- The systematic uncertainties increase their relevance:
  - A more careful treatment of the detector effects must be adopted
  - Improvements in the physics modelling become crucial



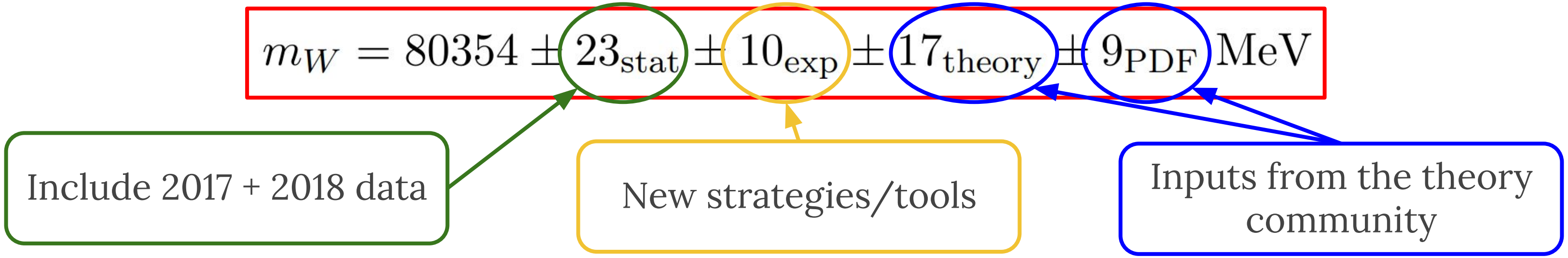
$$m_W = 80354 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 9_{\rm PDF}\ \text{MeV}$$

(2016 result) [JHEP 01 (2022) 036]

Is including 2017 and 2018 data straight-forward?

- We have currently measured the W mass with 2016 data only [JHEP 01 (2022) 036]
- Including 2017 and 2018 data 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 people in the community?
- 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

Overall summary of the 2016 result



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

Include 2017 + 2018 data

New strategies/tools

Inputs from the theory community

The overall strategy remains the same as for the 2016 analysis:

- Calibration using J/ψ, Υ(1S) and Z decays:
    - Dedicated alignment and momentum scaling
    - Momentum smearing and selection efficiencies
- Reweighting the simulation at generator level in 5 dimensions
- Template fit to W and Z events using a Beeston-Barlow method

Target sensitivity:

$$\sigma^{\rm Run\ 2}_{\rm stat.} \sim 14\,{\rm MeV}$$

$$\sigma^{\rm Run\ 2}_{\rm total} \sim 20\,{\rm MeV}$$

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

Uncertainties from the previous result (2016 analysis)

[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 NNPDF3.1, 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 Powheg-EW

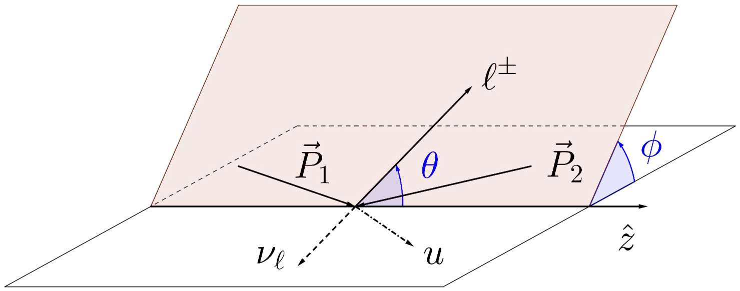
Variation of ranges, number of bins, parametrizations, ...

Current work

- Currently processing full Run 2 data (2016, 2017, 2018) with a similar strategy as for the 2016 analysis (additional 4 fb^{-1} of data)
- The result is blinded (for all years); currently revisiting different parts of the analysis:
    - Production model (QCD, QED)
    - Momentum scaling, curvature biases, efficiencies
- Keeping track of the evolution of the systematic uncertainties and their coverage
- Aim at updating the result to facilitate a prompt update of the LHC combination and reduce the combined uncertainty to the global EW fit precision (~6 MeV)

The W cross-section

Collins-Soper frame



Unpolarized part

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

(At order α_s^2)

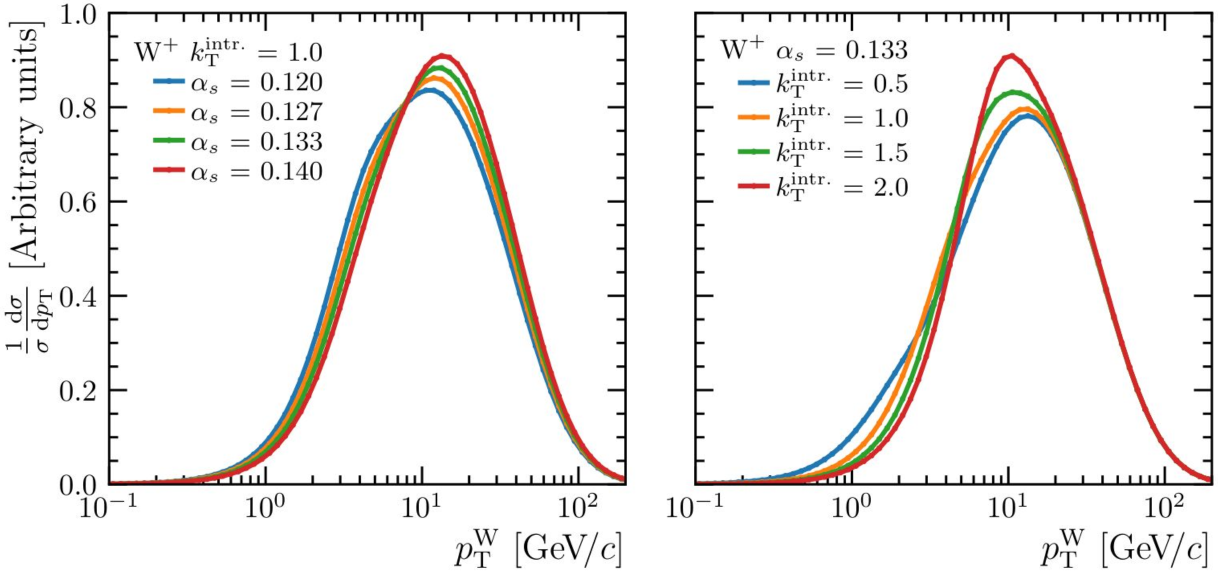
$$\boxed{\begin{aligned}&\{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1\sin 2\vartheta\cos\varphi\\ &+ A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta\\ &+ A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\}\end{aligned}}$$

Angular part

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

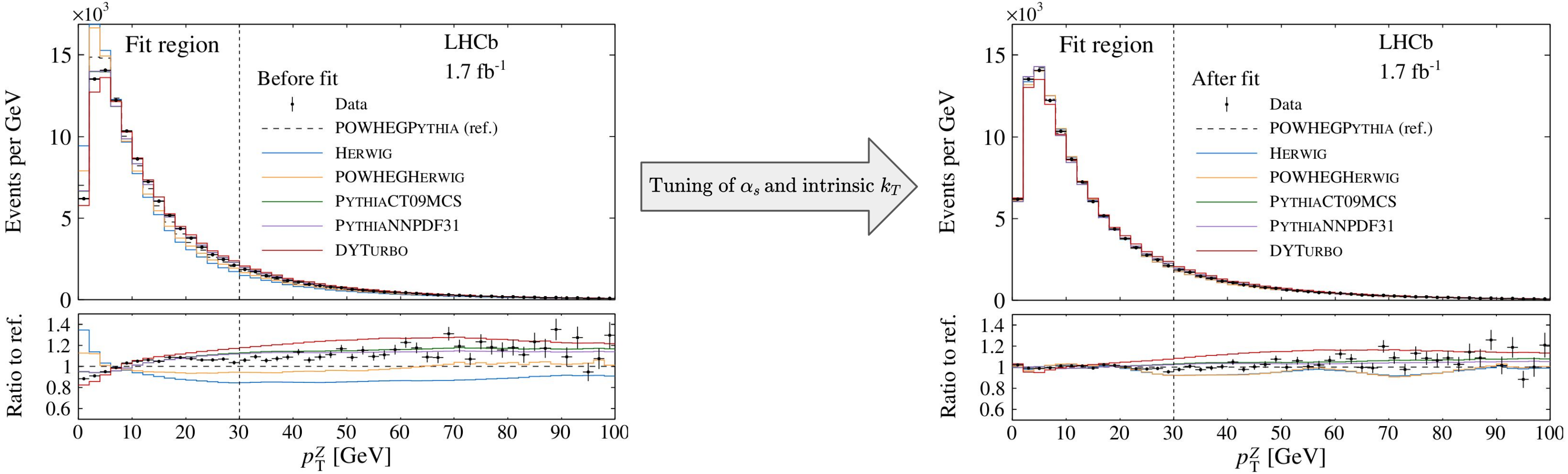
Modelling the W boson transverse momentum

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



Simulating signal decays (2016 analysis)

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

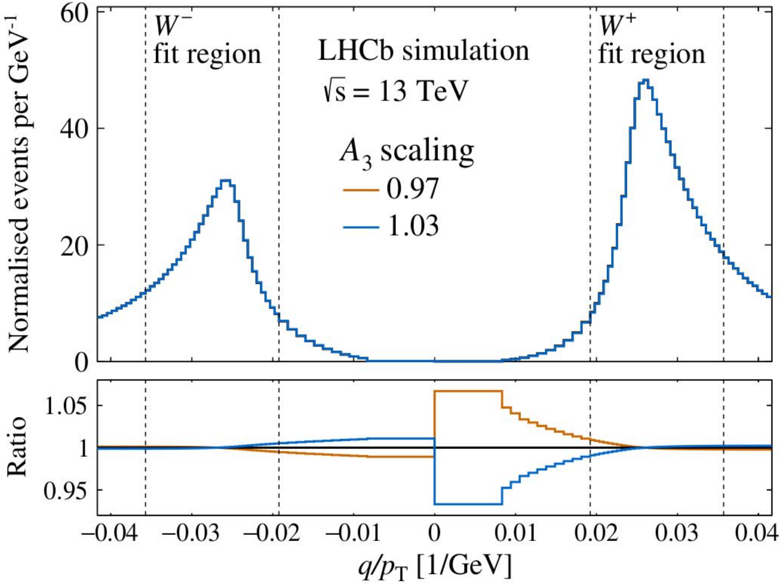


- POWHEG + Pythia gave the best description of the unpolarized cross-section in the 2016 analysis
  - Varied success with other generators, used to determine systematic uncertainties
- DYTurbo performed well at reproducing the angular cross-section, but prefers larger values of the Z transverse momentum

Polarized cross-section

- The angular part of the cross-section is better described with DYTurbo
- However, the 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(30 MeV)
    - The preferred value in the fit is however consistent with DYTurbo predictions

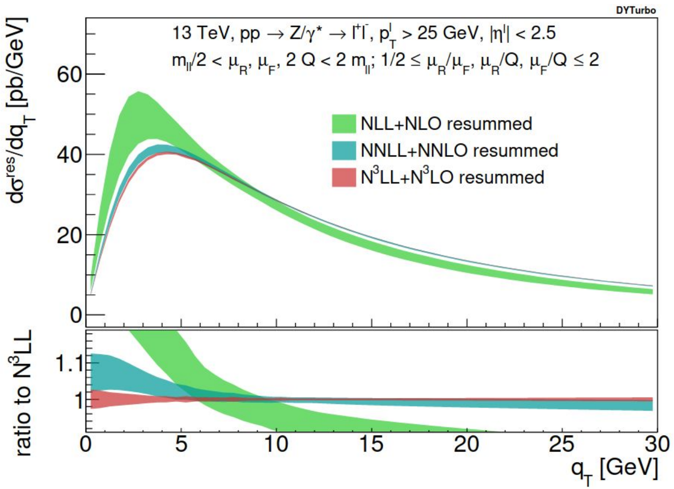
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

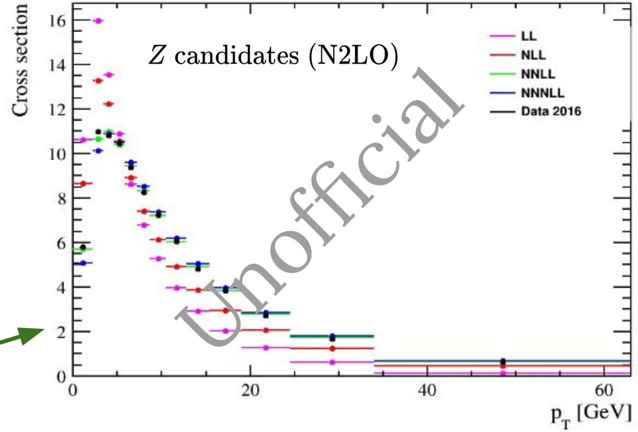


An updated production model

- Aim at using a single generator to describe the cross-section
- Considering to switch into more modern generators to fully describe the cross-section:
    - We expect that the difference between α_s for W and Z is reduced
    - Attempt to move to N2LO, N2LL predictions of both cross-sections
    - Partial calculations at N3LO, N3LL worth to study
    - Exploring the usage of NNPDF 4.0
- Cross-checks to be made with POWHEG + Pythia

[arXiv:2103.04974]





Comparison at N2LO to LHCb data from [LHCb-PAPER-2021-037] (unofficial)

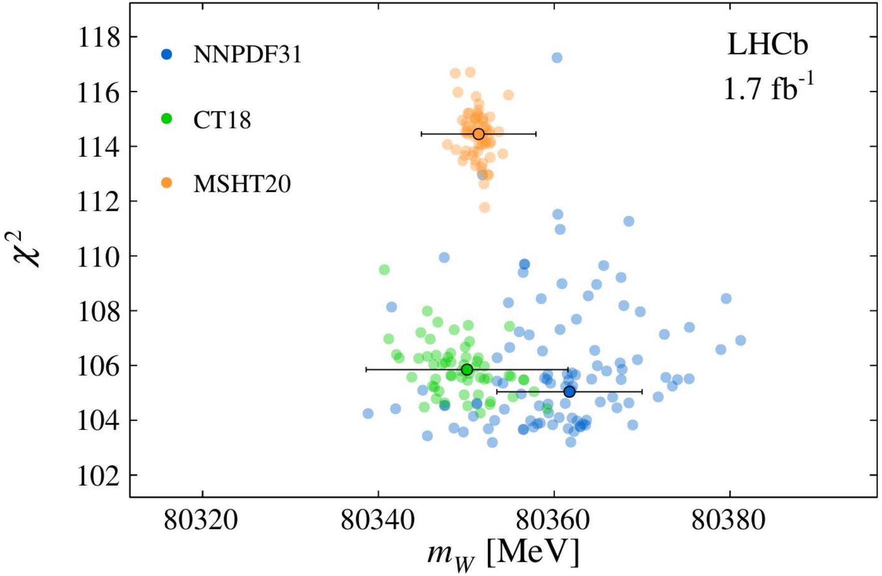
Studying QED effects

- Need a more careful study of final-state radiation to reduce the QED systematic uncertainty (currently 9 MeV):
    - 7 MeV comes from differences between bare- and born-level information (Pythia, Photos, Herwig)
    - An additional 5 MeV systematic comes from pseudoexperiments using POWHEG-EW
- Aim for a more systematic approach to the perturbative uncertainty
    - Currently exploring how to reweight the base (Pythia-based) full event simulation samples
    - Aim at using POWHEG-EW interfaced with Pythia/Photos

The average of PDF sets (2016 analysis)

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

- For 2016, the PDFs were 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 2016 result is an average of the three assuming 100% correlation
- There is no high cost of providing the result for any other set of PDFs



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

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 less accurate PDF sets
  - Revisit the way to handle the different predictors and the order in perturbative theory and resummation
- Ongoing studies, feedback is really welcome!

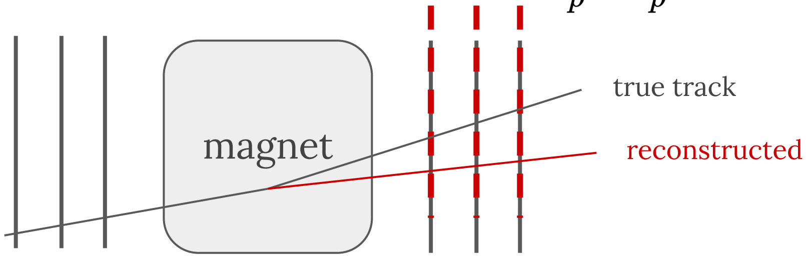
Experimental challenges

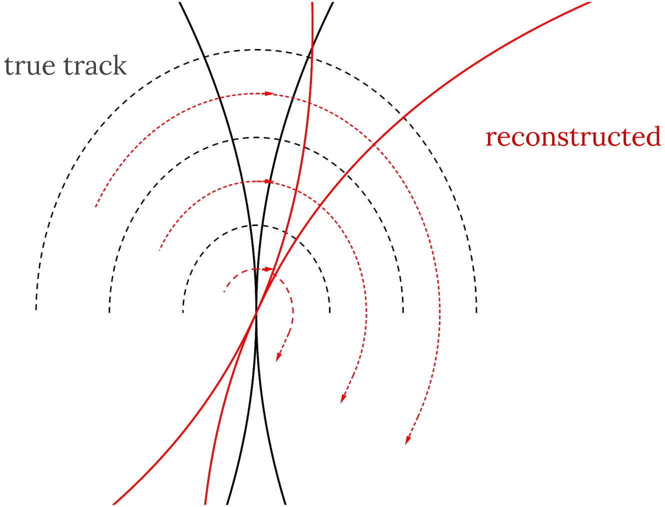
- Highly sensitive to detector misalignments
- Need to optimize (often re-run) the alignment using Z decays
- Some detector deformations do not modify the track quality or the momentum estimate of single muons

$$\chi^2_{\text{align.}}(\theta_j) = \frac{1}{N}\sum_{i=1}^{N}\chi^2_i(\theta_j)$$

- Different techniques adopted by different experiments:
    - CDF: using quarkonia to calibrate and cross-check with the Z mass
    - ATLAS: mass-constrained momentum variations in Z decays [EPJC 74 (2014) 3130]
    - LHCb : pseudomass method with the Z [Phys. Rev. D 91, 072002]

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





Curvature biases

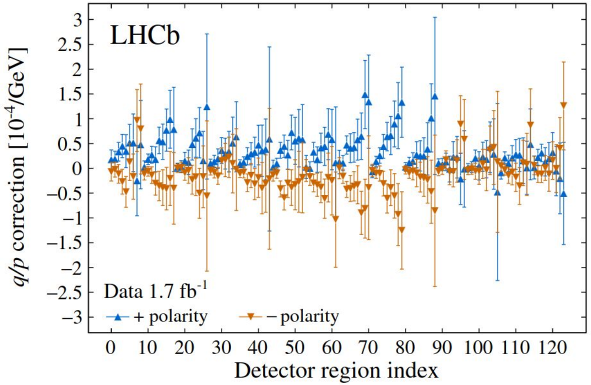
- The analysis relies highly on the detector alignment
    - Misalignment of 10μm translates into a O(50MeV) shift
- For the 2016 analysis we re-run the alignment and calibration offline using Z events
- Additionally, we corrected for charge-dependent curvature biases using the pseudo-mass method

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

Inspired by Phys. Rev. D 91, 072002

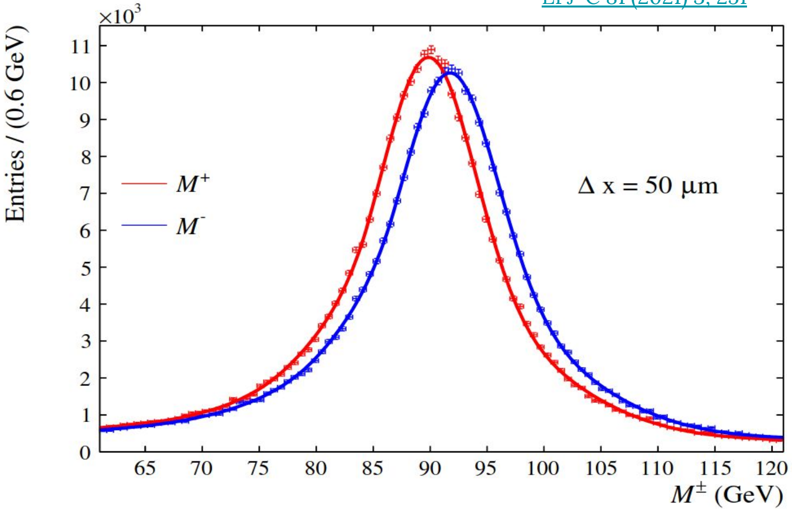
- For the full Run 2 measurement we fully rely on the pseudomass to account for curvature biases

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



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

EPJ-C 81 (2021) 3, 251



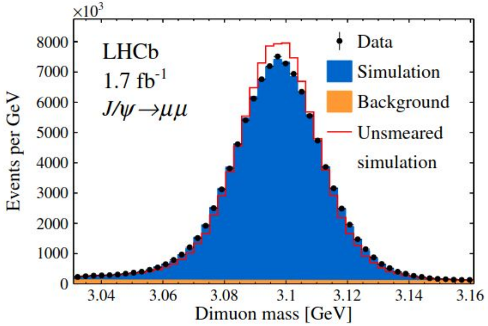
Corrections to simulation

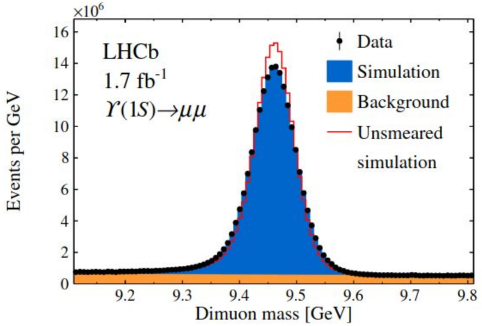
Need to smear the momentum determined from simulation to account for:

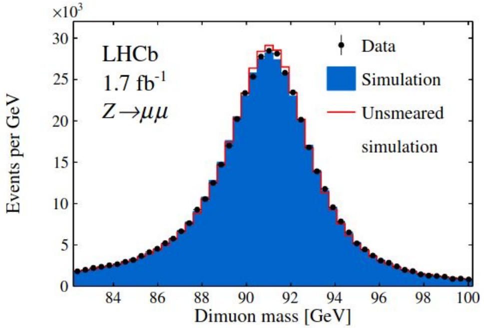
- momentum scale
- multiple scattering

Revisiting the model and the systematic uncertainties:

- Decouple the curvature bias parameters from the smearing model
- Avoid overcoverage when considering variations of the smearing and momentum scaling



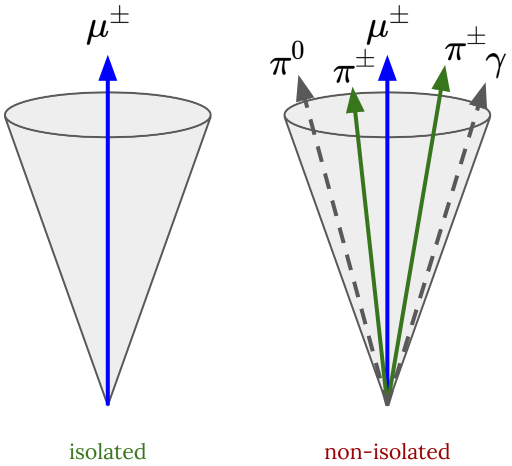




[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024] (supplementary)

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)
- Efficiency corrections are parametrized using simulation and real data
    - Associated systematic uncertainties determined by varying the binning scheme, parametrizations and selections



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

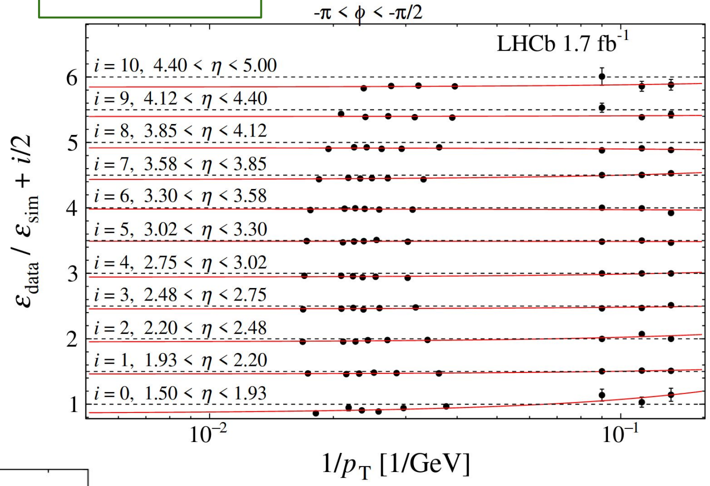
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2\left(\text{rad}^{-2}\right)}$$

Efficiencies

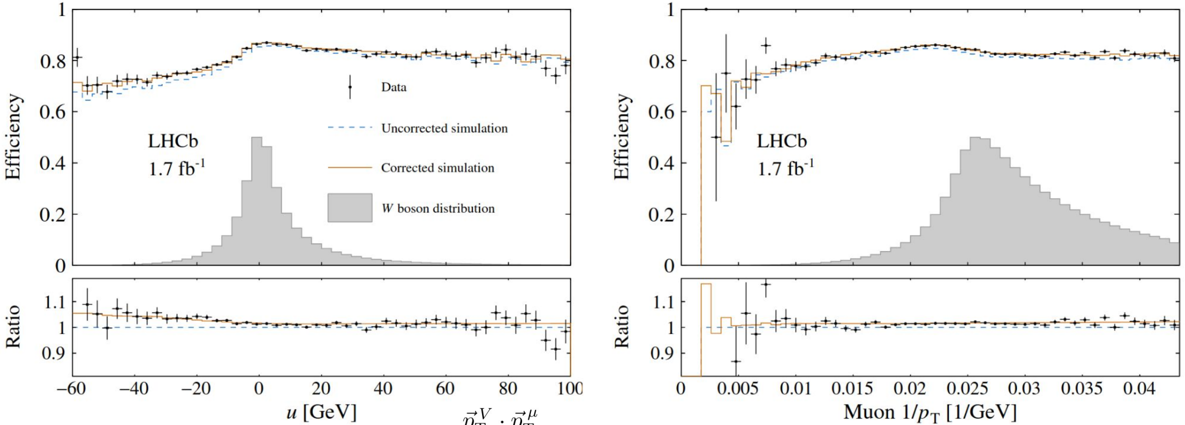
Three main sources of selection biases:

- Trigger efficiencies
- Muon-identification efficiencies
- Isolation requirements

Trigger efficiency



Isolation efficiency



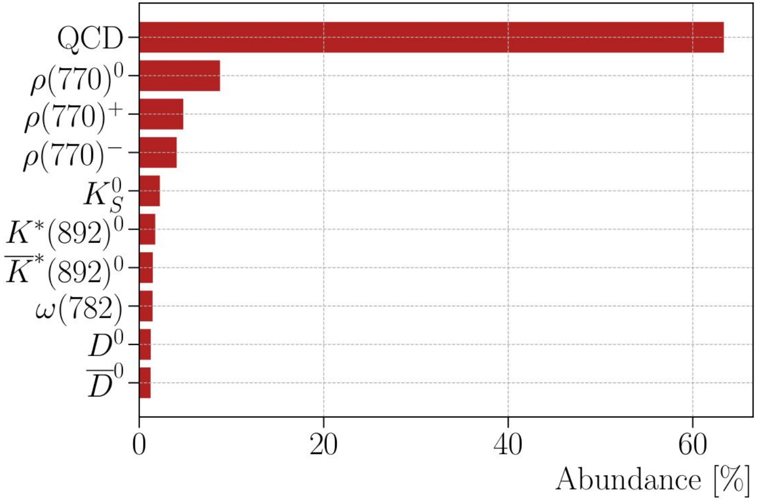
$$u = \frac{\vec{p}_T^{\,V} \cdot \vec{p}_T^{\,\mu}}{p_T^{\mu}}$$

Corrections predominantly at the percent level

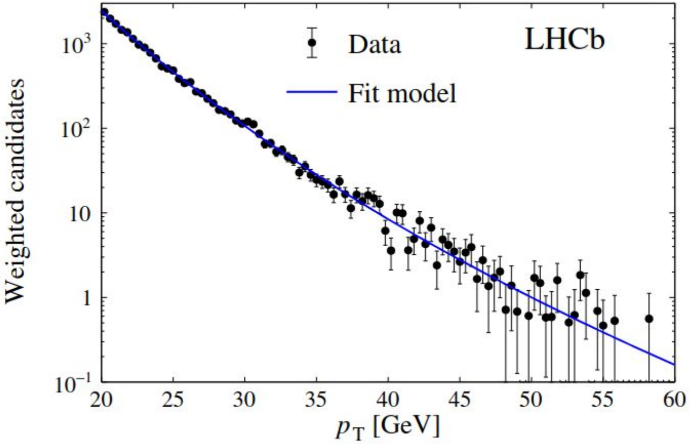
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

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 W and Z events
- Description of the QCD background (decays-in-flight) obtained from data in the 2016 analysis
    - Sample with inverted muon-identification requirements
    - Weight and parametrize the data using a Hagedorn distribution
    - Accurately describes the Jacobian peak (region with the highest sensitivity to m_W)



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

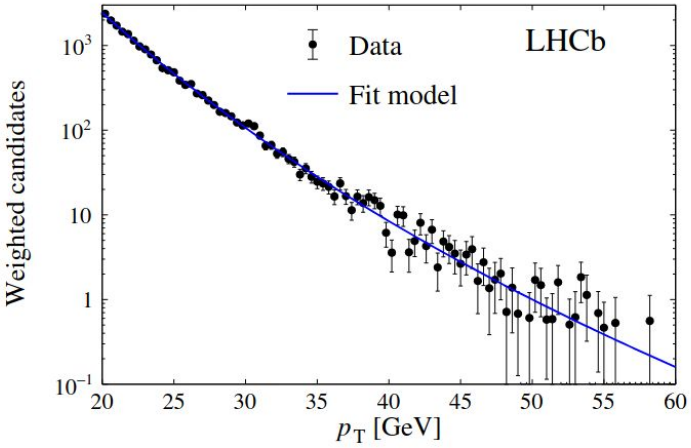


Modelling misidentified hadrons

- In the 2016 analysis we used fast simulation from a parametrization of real data
    - Misidentification rate assumed to be inversely proportional to the momentum

$$\text{decay probability} = 1 - e^{-\frac{md}{\tau p}} \sim \frac{md}{\tau p}$$

- For the full Run 2 analysis we now profit from samples with the full detector simulation
    - The charge asymmetry and corrections to the momentum distribution are also obtained from a data-driven approach
    - Different systematic uncertainties cover composition, mismodelling, …
    - The systematic uncertainty remains similar to the previous O(3 MeV)

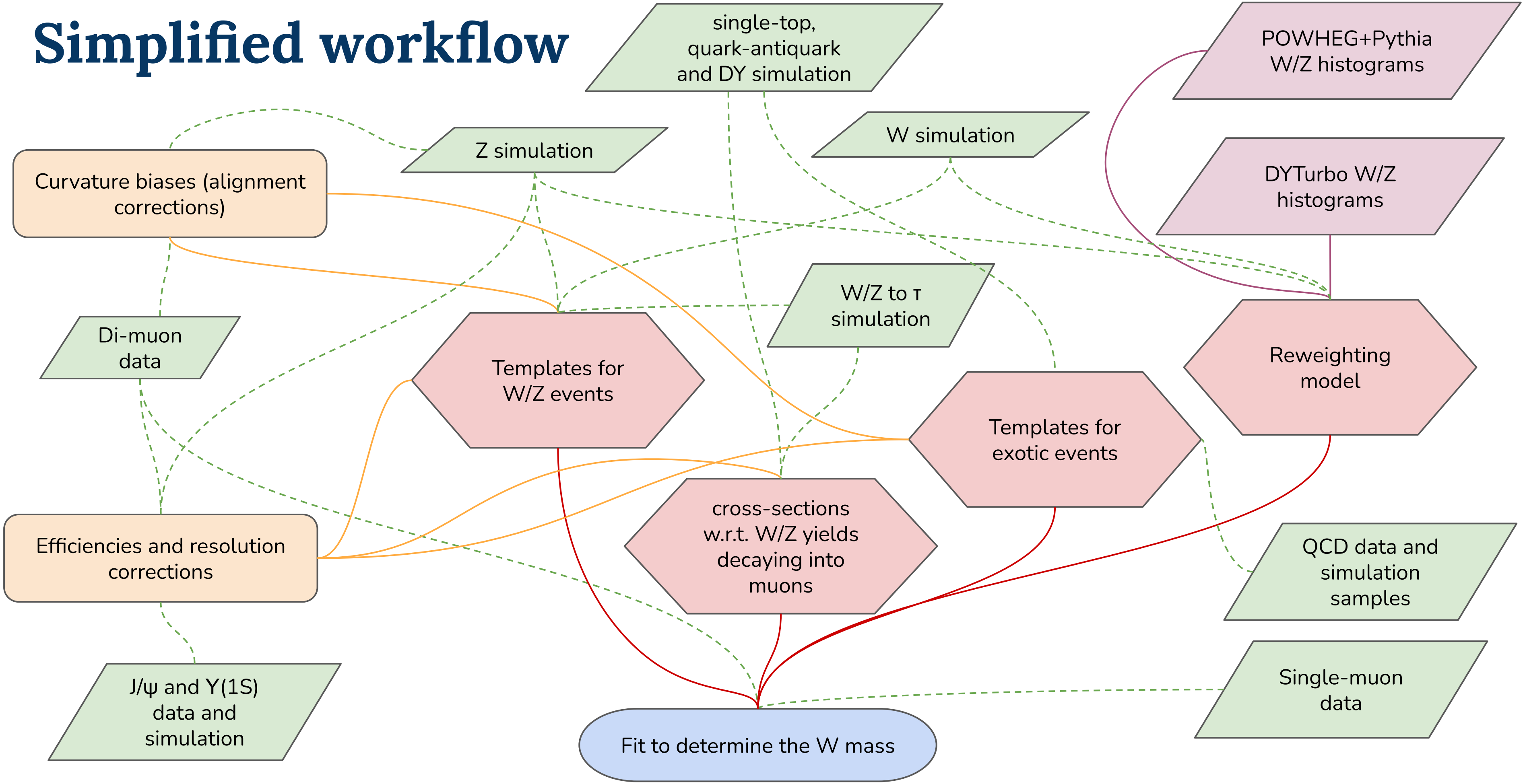


[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024] (supplementary)

$$\omega(p_T) \sim \frac{1}{\left(1 + \frac{a}{p_T}\right)^n}$$

Hagedorn PDF that accurately describes transverse momenta of hadrons at high energies [Riv. Nuovo Cim. 6N10 (1983) 1]

Simplified workflow



single-top, quark-antiquark and DY simulation

POWHEG+Pythia W/Z histograms

Z simulation

W simulation

Curvature biases (alignment corrections)

DYTurbo W/Z histograms

W/Z to τ simulation

Di-muon data

Templates for W/Z events

Reweighting model

Templates for exotic events

cross-sections w.r.t. W/Z yields decaying into muons

Efficiencies and resolution corrections

QCD data and simulation samples

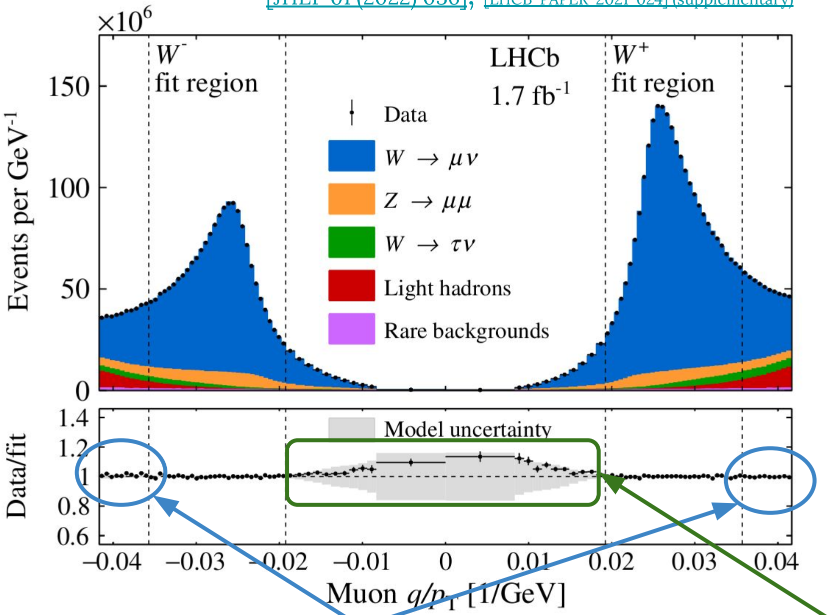
J/ψ and Υ(1S) data and simulation

Single-muon data

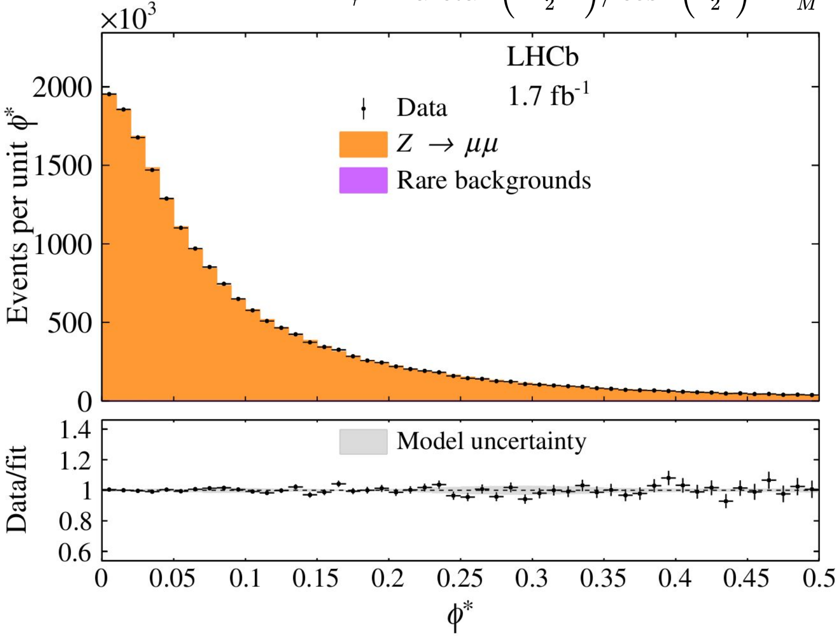
Fit to determine the W mass

Fitting the transverse momentum (2016 analysis)

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



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



Aim at improving the parametrization of the different components even in the far sideband

Expect different behaviours in the high transverse momentum region if using different generators

Cross-checks

Cross-checks are vital to validate different aspects of the analysis:

- Differences in magnet polarity
- Curvature biases in candidates bending in the same direction
- Possible detector biases in different η/φ regions
- W-like Z mass measurement, which validates the fit procedure (agreement at one standard deviation)
- Use of NNLO PDFs to test next-order effects of the PDFs (1 MeV variation)
- Separate W^+/W^- mass measurement, to study charge-dependent biases (results in agreement)

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

Additionally we also checked:

- Variations of the fit range
- Freedom of the fit model

More on this in the backup

Long-term plans

- The W mass determination at LHCb with full Run 2 data will allow to clarify the picture about this measurement
- Afterwards, LHCb can provide very useful data to further tune the generators and understand QCD and EW effects
  - Cross-sections at different energies (5 TeV, 13 TeV) of W and Z bosons
  - Drell-Yan studies
  - Weak mixing angle (forward-backward asymmetry)
- 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

Conclusions

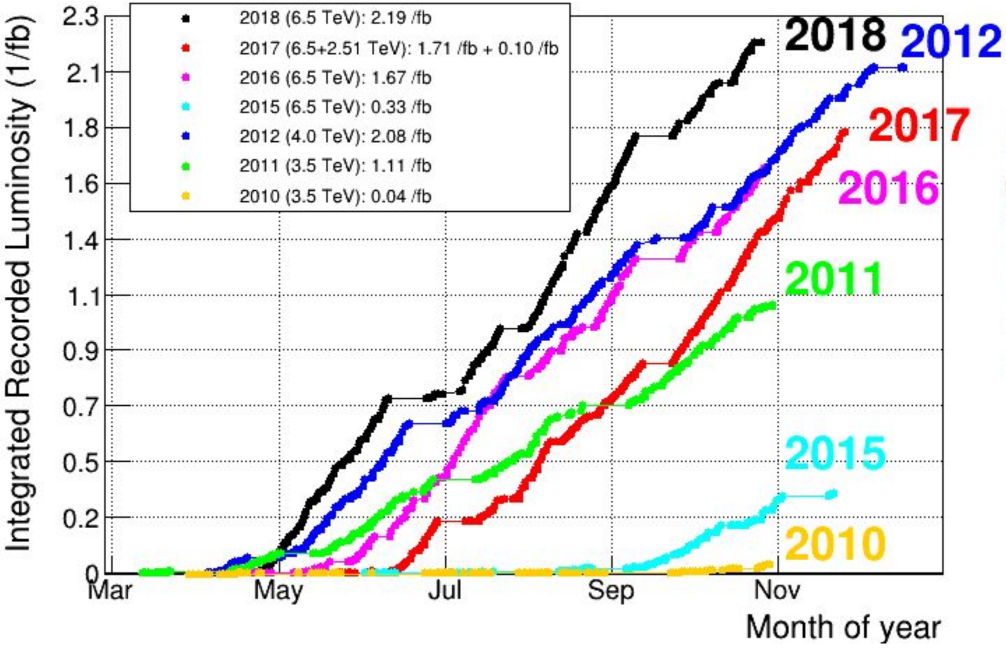
- Analysis in good shape and progressing with no big surprises
- Currently tackling the major sources of systematic uncertainty
- Tentative next steps:
  - Finalize the optimization of the momentum scaling
  - Improve the QED modelling
  - Carefully review all the parts of the analysis and polish the different parts
- Feedback on the theoretical description is highly valuable (QCD, QED, ...)
- Willing to provide any results that could facilitate combinations/cross-checks in the future

Thank you!

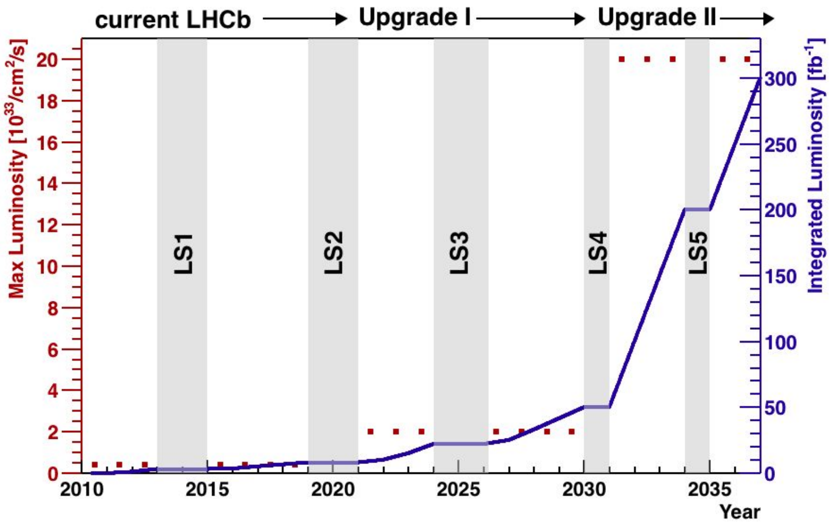
Backup

LHCb luminosities

[LHCb operation plots]

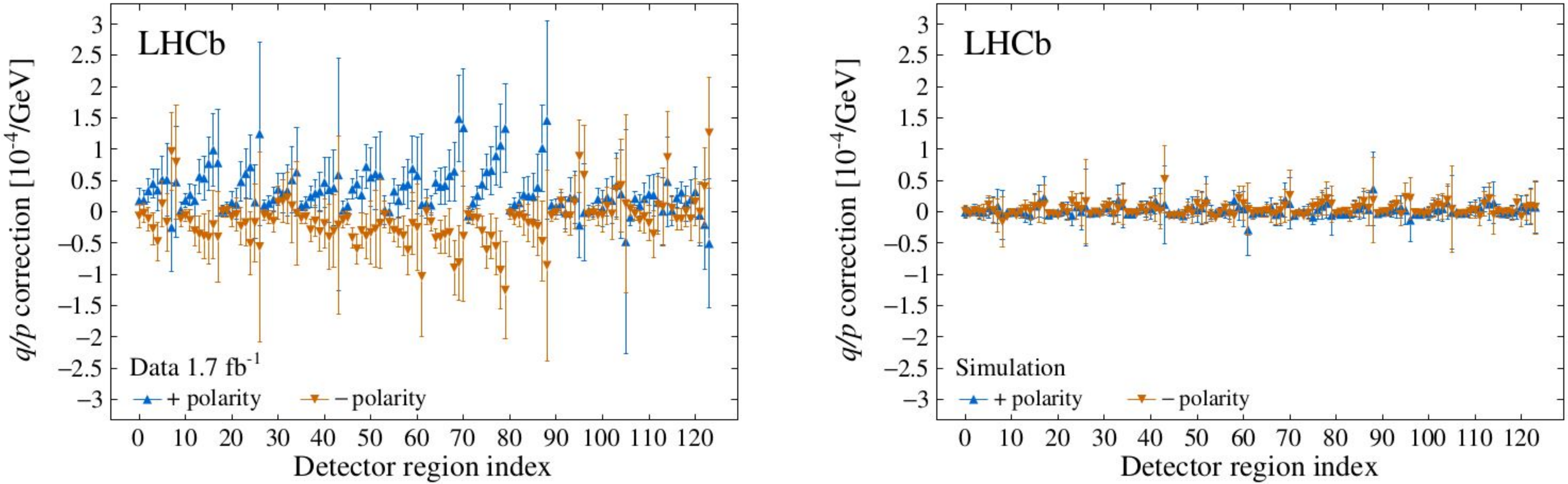


[LHCb-PUB-2018-009]



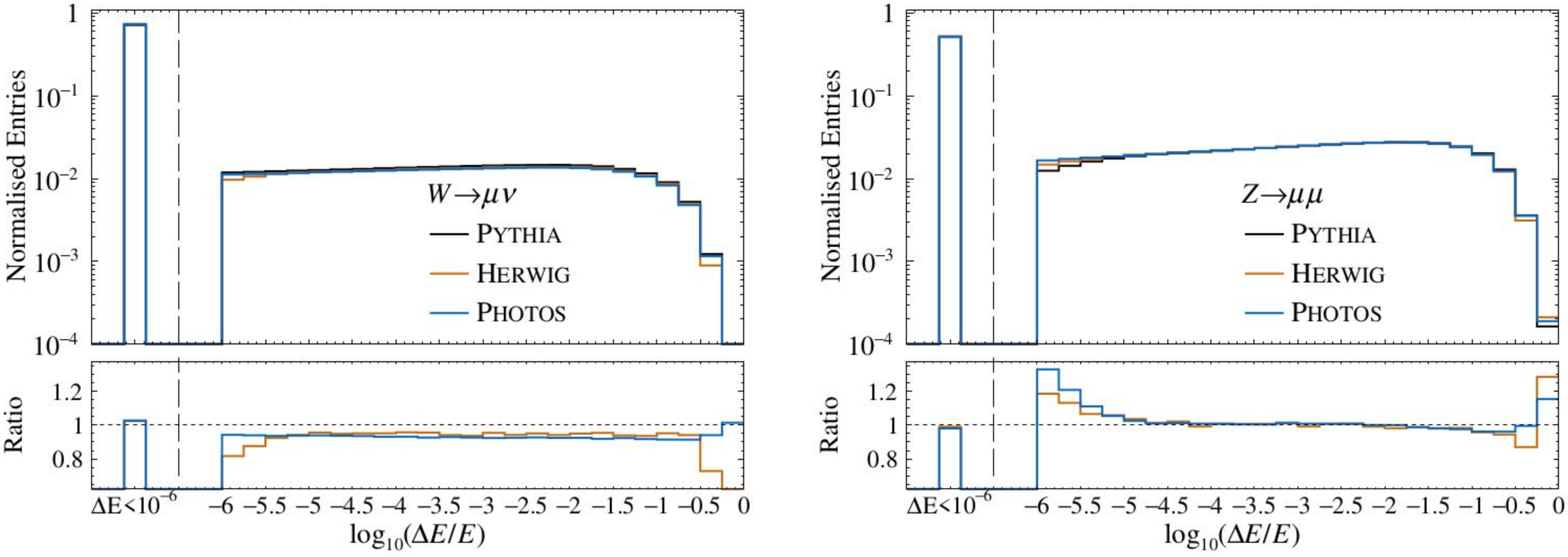
Curvature corrections (2016 analysis)

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



QED corrections (2016 analysis)

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



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

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

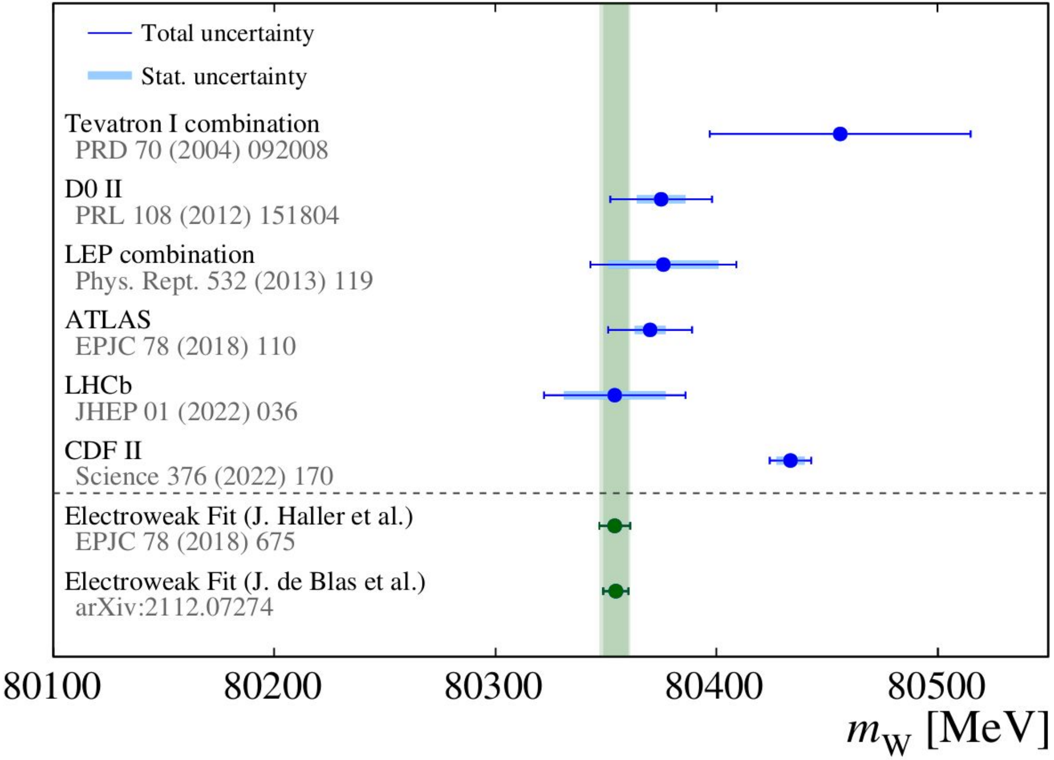
ATLAS: [EPJC 78 (2018) 110]

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

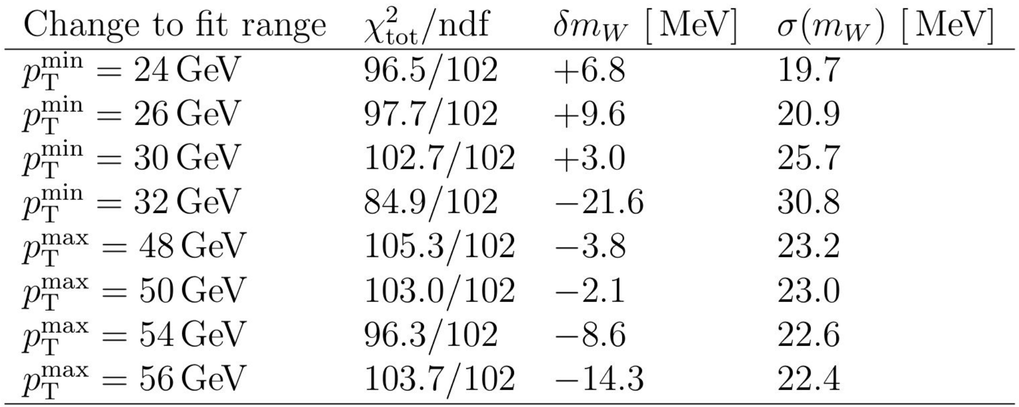
CDF: [Science, 376, 6589, (136-136), (2022)]

Current picture on the W mass

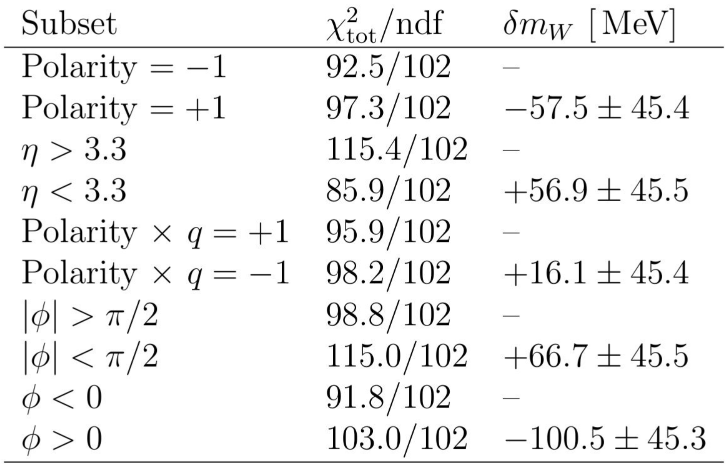
[LHCB-FIGURE-2022-003]



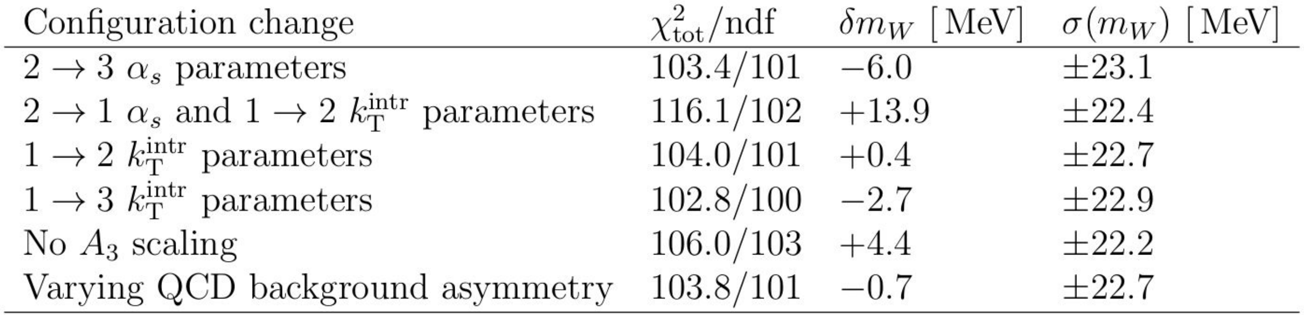
More on cross-checks (2016 analysis)



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



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



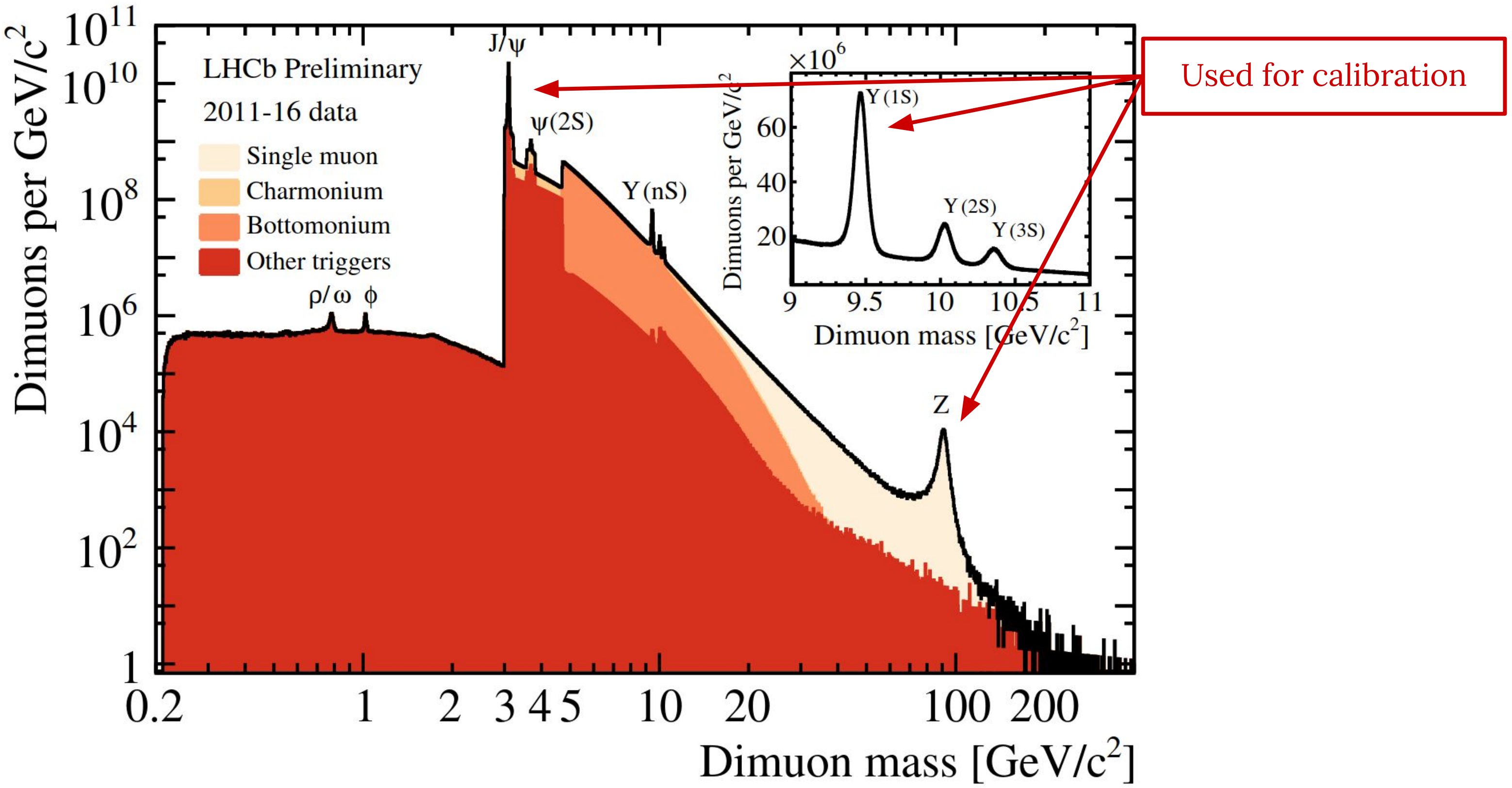
Configuration change	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$2 \to 3$ α_s parameters	103.4/101	−6.0	±23.1
$2 \to 1$ α_s and $1 \to 2$ $k_{\text{T}}^{\text{intr}}$ parameters	116.1/102	+13.9	±22.4
$1 \to 2$ $k_{\text{T}}^{\text{intr}}$ parameters	104.0/101	+0.4	±22.7
$1 \to 3$ $k_{\text{T}}^{\text{intr}}$ 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

Together with a W-like Z mass measurement, the usage of NNLO PDFs and separate W$^+$/W$^-$ mass measurements

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

Calibration using muons

[LHCb-CONF-2016-005]



Used for calibration