Prospects on the W mass measurement

Miguel Ramos Pernas

on behalf of the LHCb collaboration

University of Warwick

miguel.ramos.pernas@cern.ch

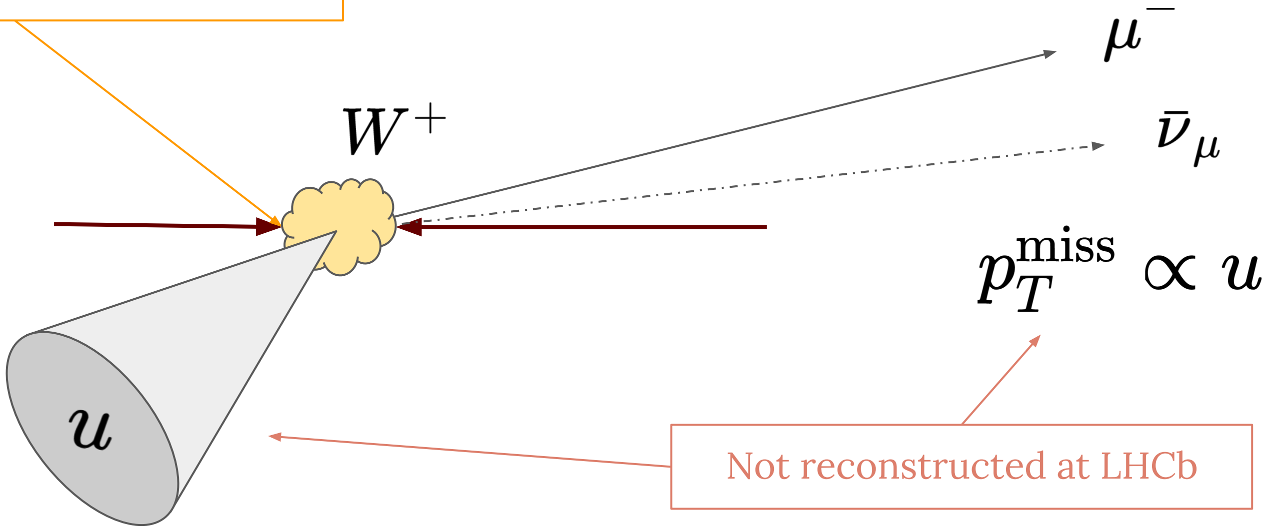
W mass workshop, Orsay 24/02/2023

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

Current work

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

- 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, FSR)
  - Momentum scaling, curvature biases, efficiencies
  - Backgrounds
- Keeping track of the evolution of the systematic uncertainties and their coverage
- Aiming for a LHC combination to reduce the uncertainty to the global EW fit precision (~6 MeV)

Uncertainties from the previous result

[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

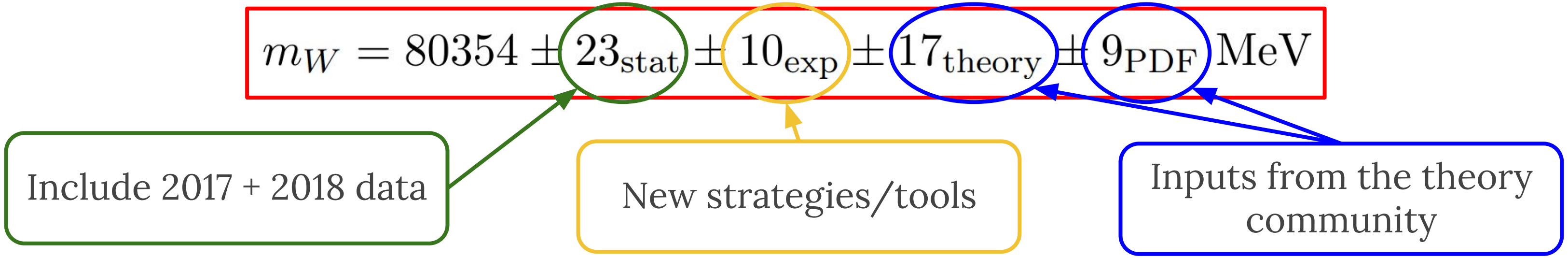
Envelope of five different models

Uncertainty due to scale variations

Envelope of the QED FSR from Pythia, Photos and Herwig. Additional correction from Powheg-EW

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

Analysis strategy for the full Run 2 result



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

Include 2017 + 2018 data

New strategies/tools

Inputs from the theory community

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 the muon transverse momentum using a Beeston-Barlow method in the minimization

Target sensitivity:

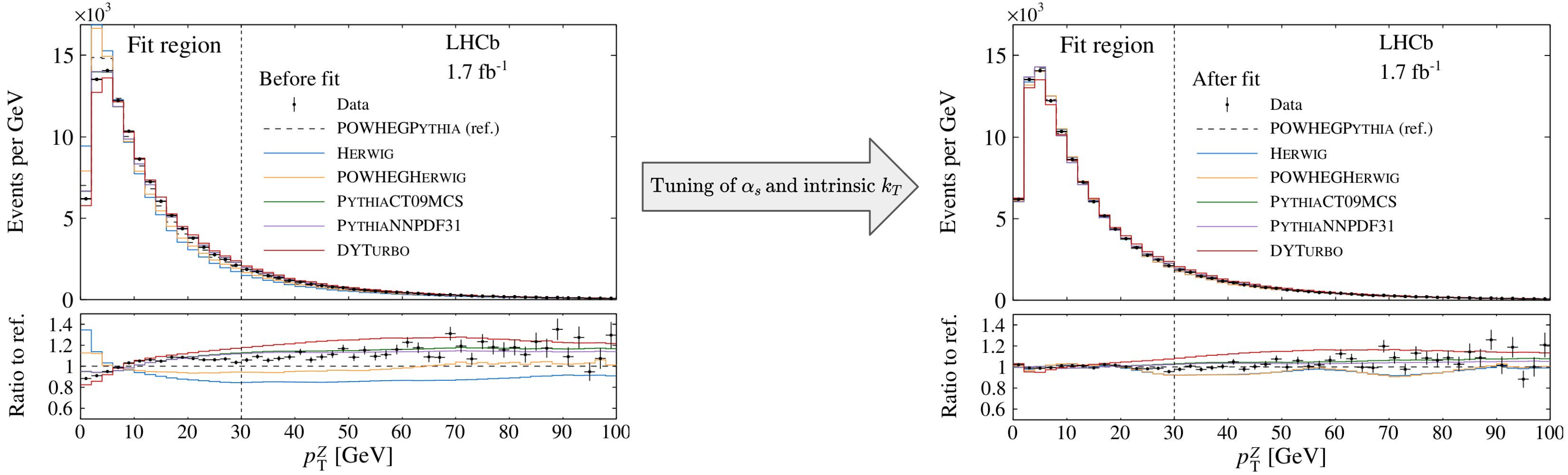
$$\sigma_{\text{stat.}}^{\text{Run 2}} \sim 14\,\text{MeV}$$

$$\sigma_{\text{total}}^{\text{Run 2}} \sim 20\,\text{MeV}$$

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

Simulating signal decays

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

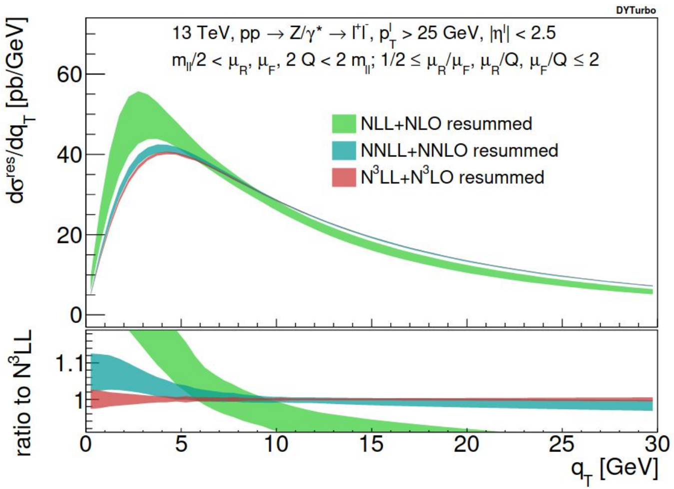


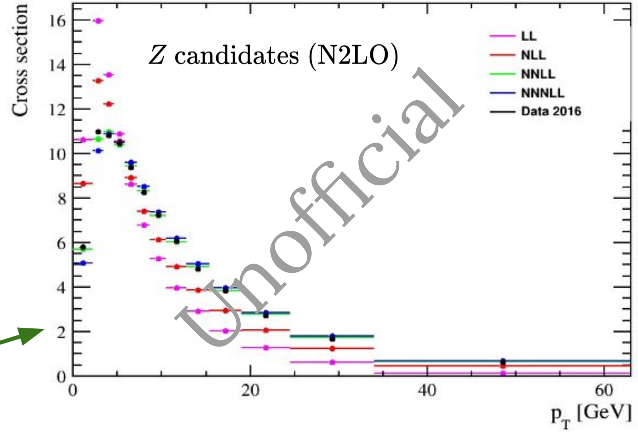
- POWHEG + Pythia gave the best description of the unpolarized cross-section in the 2016 analysis
    - Varied success with other generators, used to determine systematic uncertainties
- DYTurbo performed well at reproducing the angular cross-section, but prefers larger values of the Z transverse momentum

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 would 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 final-state radiation

- Need a more careful study of final-state radiation to reduce the FSR 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

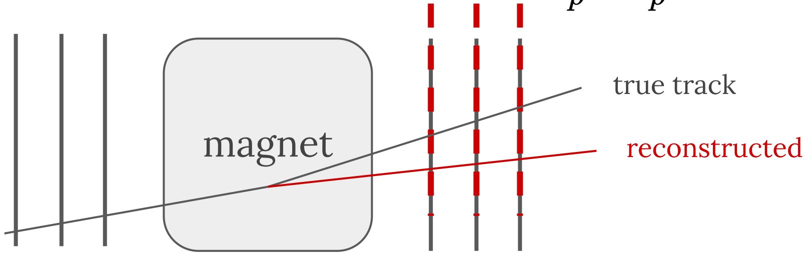
Experimental challenges

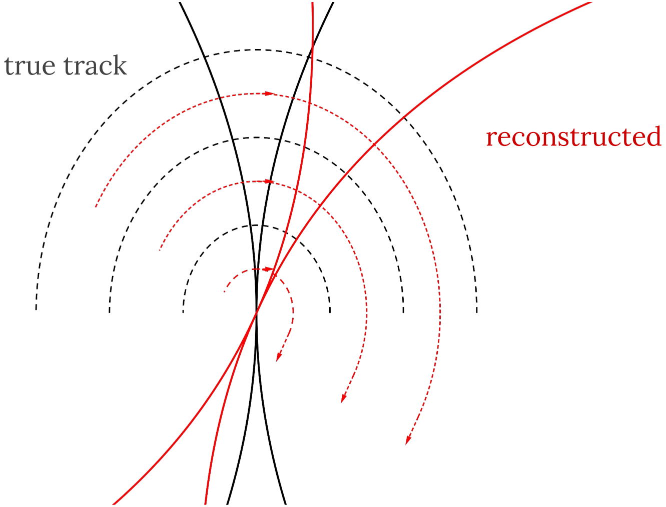
- Highly sensitive to detector misalignments
- Need to optimize (often re-run) the alignment using Z decays
- Some detector deformations do not modify the track quality or the momentum estimate of single muons

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

- 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]

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





Curvature biases

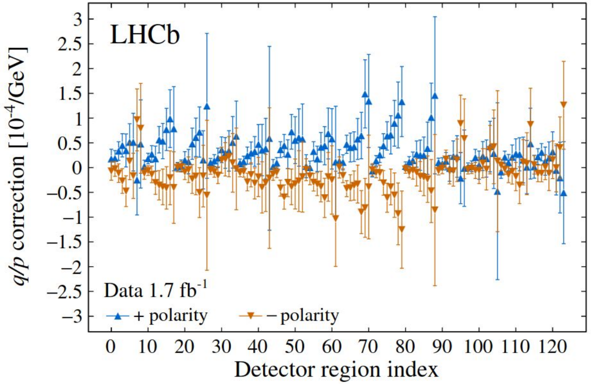
- The analysis relies highly on the detector alignment
  - Misalignment of 10μm translates into a O(50MeV) shift
- Need to re-run the alignment and calibration offline using Z
- Avoid double bias from the momentum resolution using the pseudo-mass method

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

Inspired by Phys. Rev. D 91, 072002

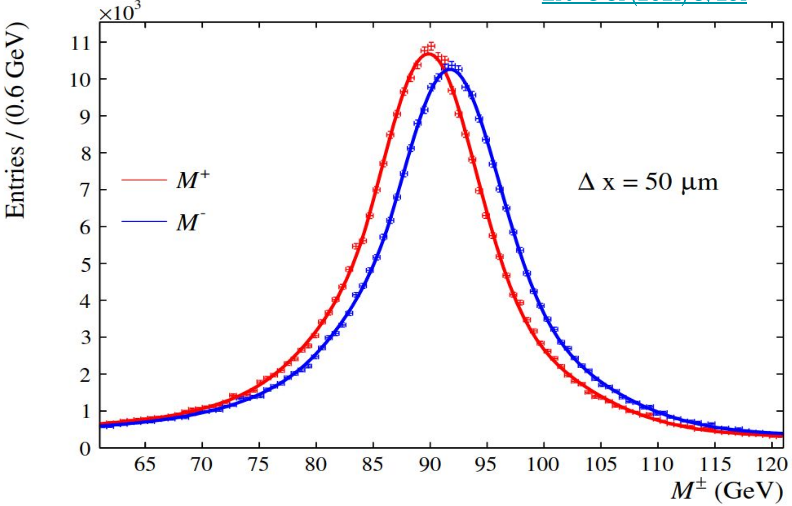
- We encourage the other experiments to give this method a try

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



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

EPJ-C 81 (2021) 3, 251



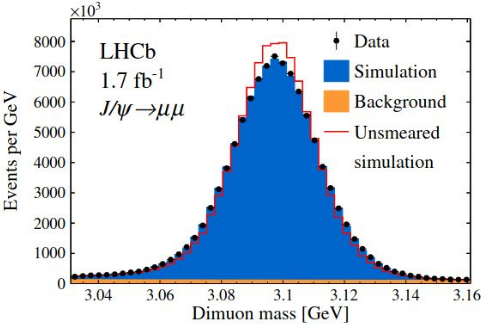
Corrections to simulation

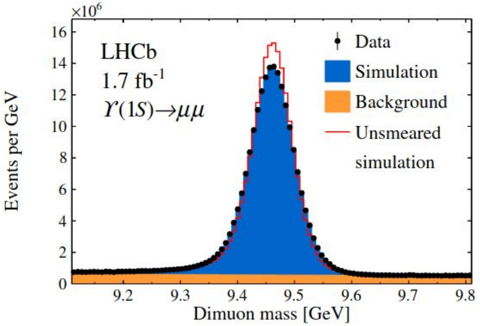
Need to smear the momentum determined from simulation to account for:

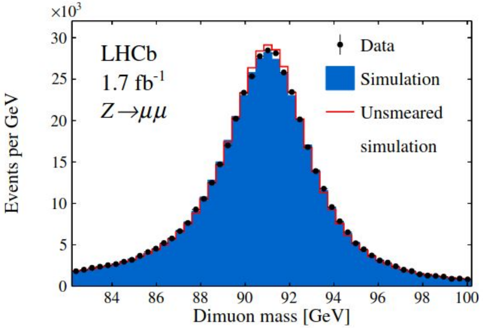
- momentum scale
- multiple scattering

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







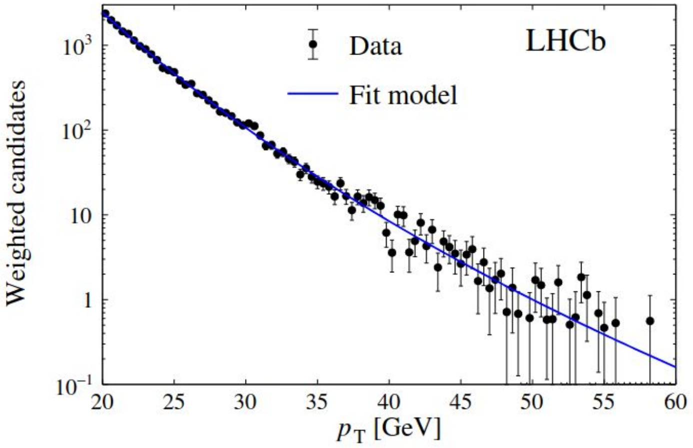
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024] (supplementary)

Modelling misidentified hadrons

- In the 2016 analysis we used fast simulation using a parametrization from real data
- Charge asymmetry also obtained from a data-driven approach
- Misidentification rate assumed to be inversely proportional to the momentum

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

- Different systematic uncertainties covering composition, mismodelling, … O(3 MeV)
- For the full Run 2 analysis we now profit from samples with the full detector simulation
    - The systematic uncertainty remains similar to the previous



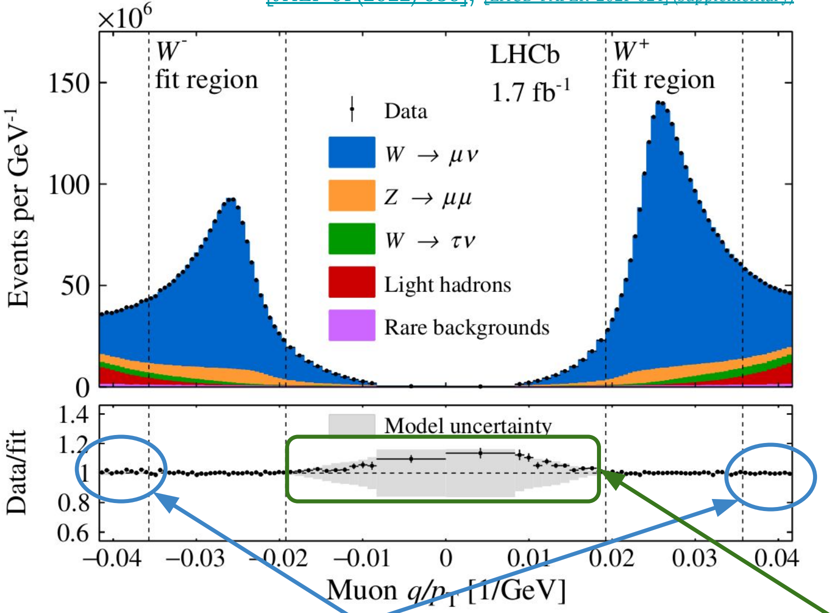
[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024] (supplementary)

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

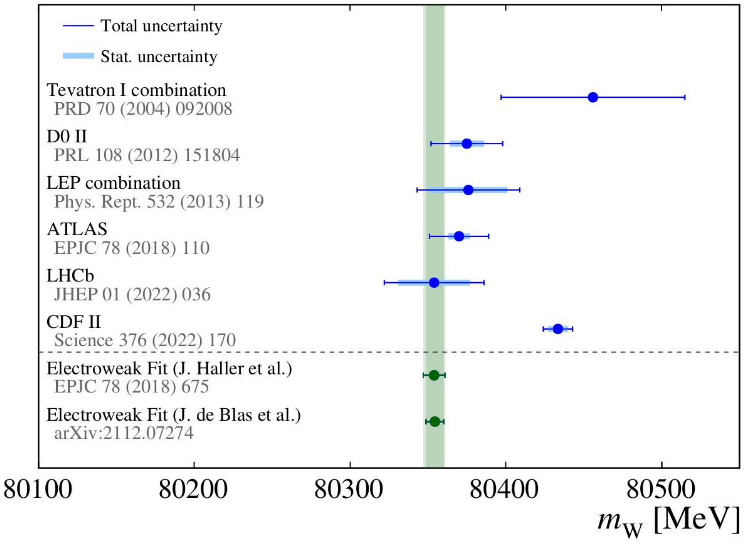
Hagedorn PDF that accurately describes transverse momenta of hadrons at high energies [Riv. Nuovo Cim. 6N10 (1983) 1]

Fitting the transverse momentum

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



[LHCB-FIGURE-2022-003]



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

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

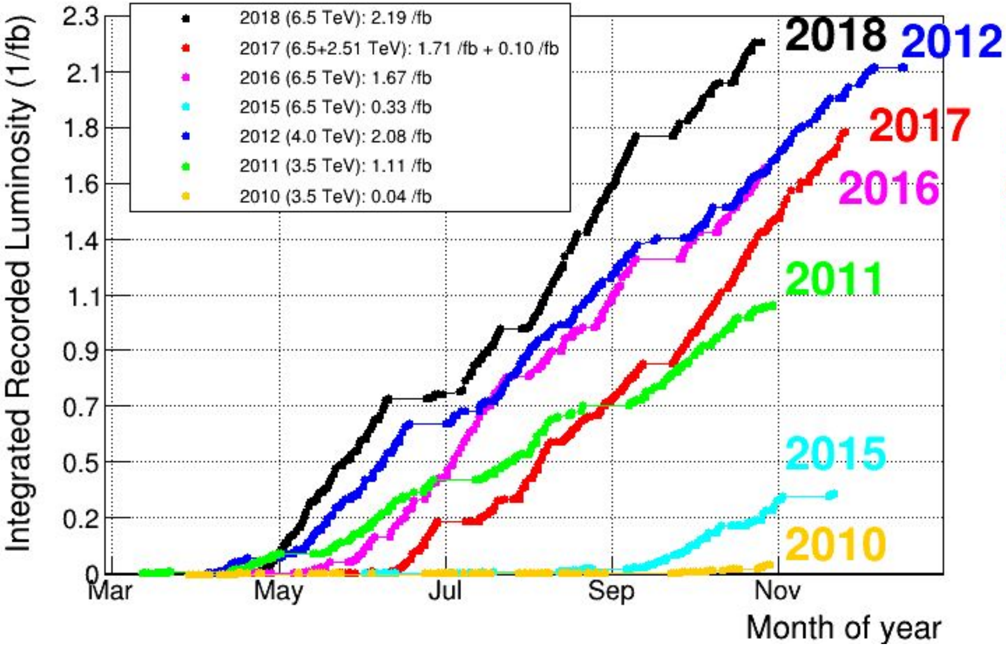
- Analysis in good shape and progressing with no big surprises
- Currently tackling the major sources of systematic uncertainty
- Tentative next steps:
    - Finalize the optimization of the momentum scaling
    - Fully understand the composition and parametrizations of the QCD background
    - Improve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

Thank you!

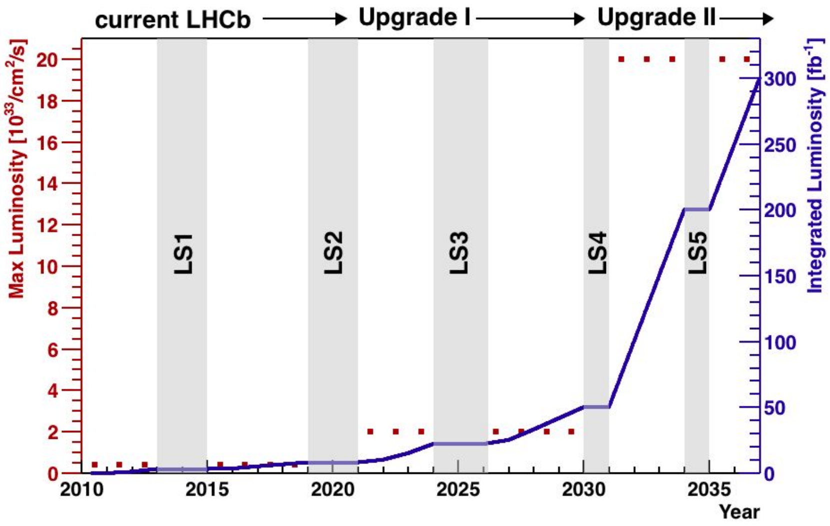
Backup

LHCb luminosities

[LHCb operation plots]

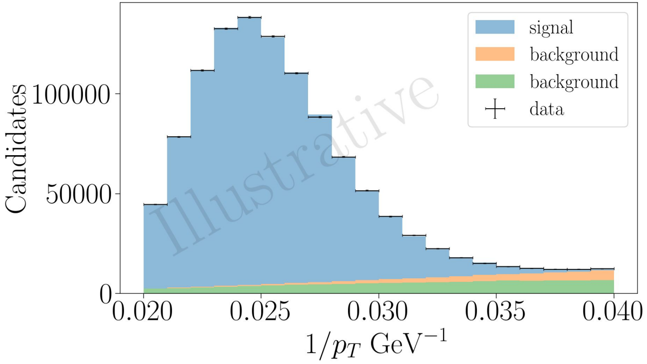


[LHCb-PUB-2018-009]

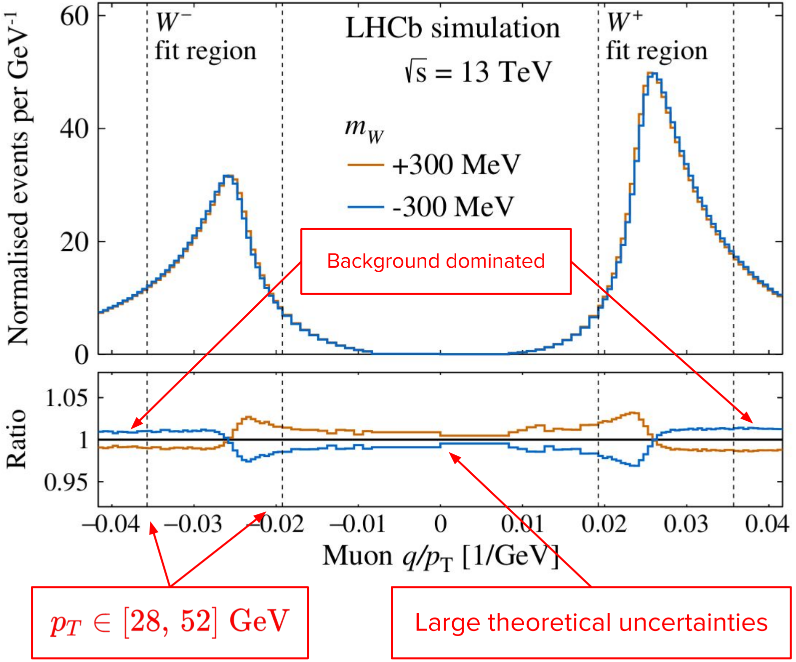


Analysis strategy at LHCb

- LHCb analysis included 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)



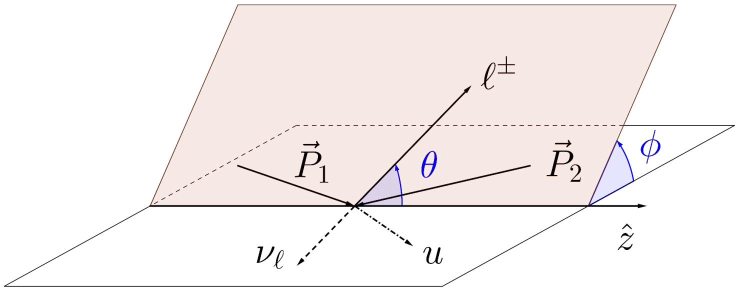
Background dominated

$p_T \in [28,\ 52]$ GeV

Large theoretical uncertainties

The W cross-section

Collins-Soper frame



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

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

(At order α_s^2)

Unpolarized part

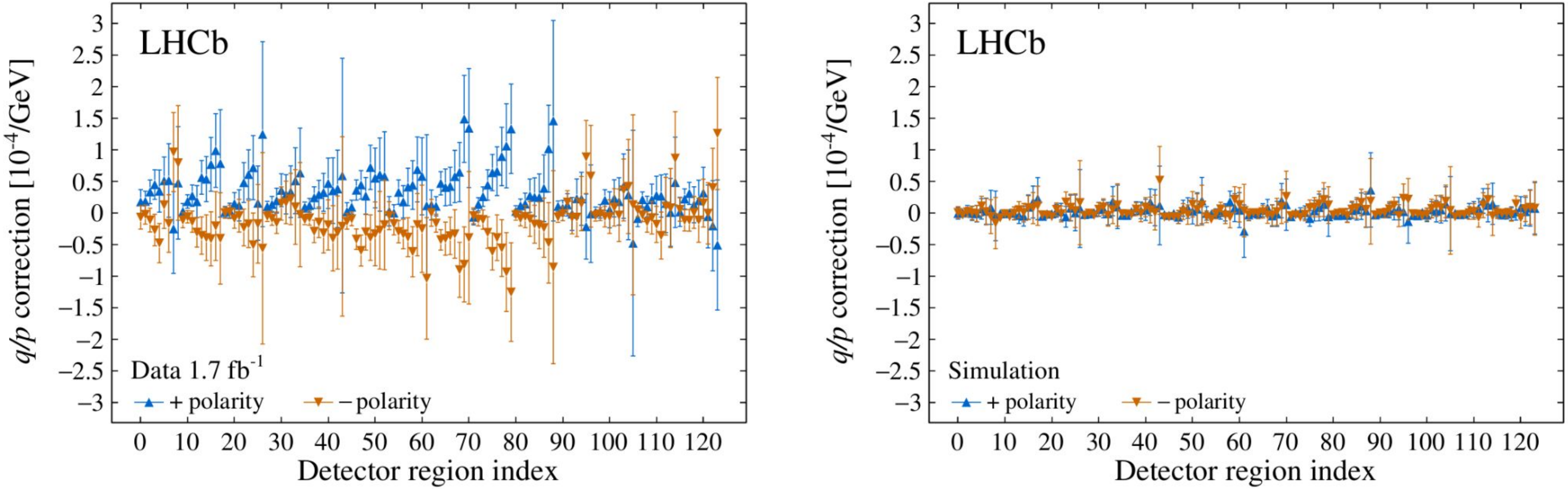
Angular part

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

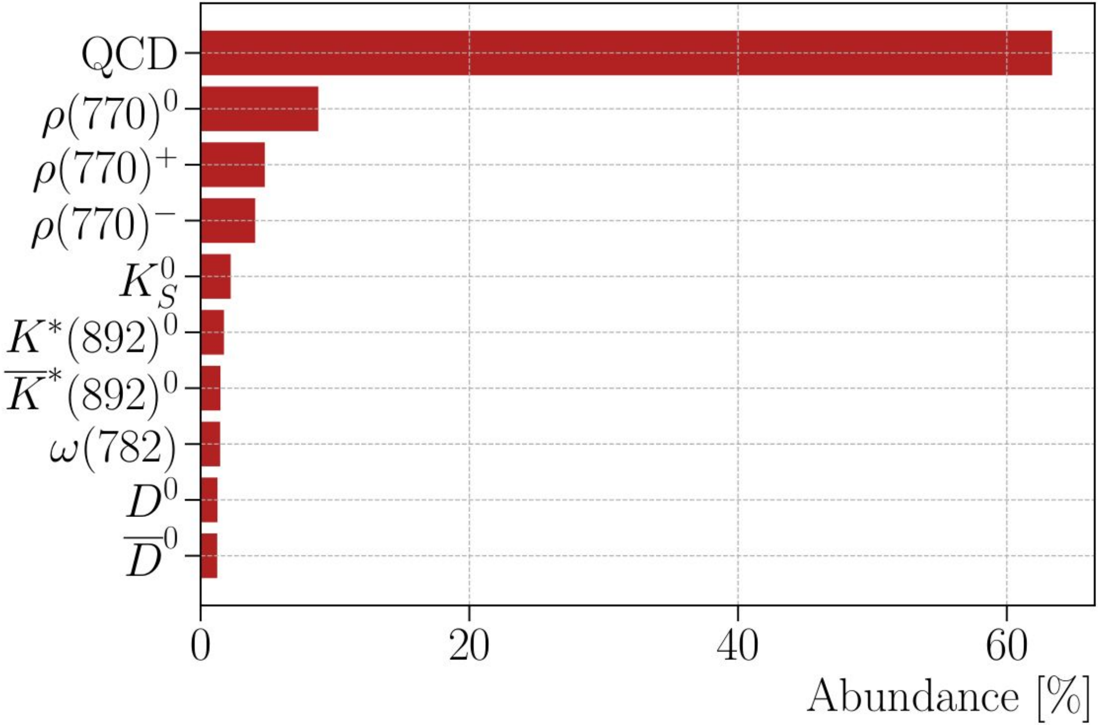
Charge-dependent curvature biases

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

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



Backgrounds from Pythia



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

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)]