Towards a W boson mass measurement with LHCb

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on behalf of the LHCb Collaboration

This talk is based on [arXiv:1902.04323]

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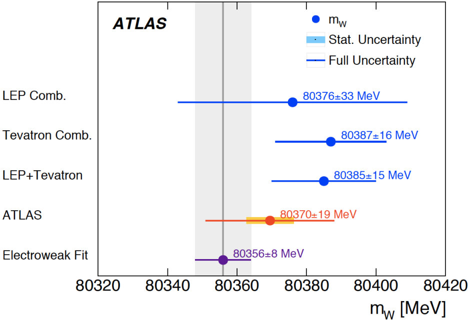
Overview

Precision electroweak tests are a powerful probe of physics beyond the Standard Model

- Currently limited by the precision of M_W measurements
- First LHC result from ATLAS[1] already competitive with Tevatron results
  - Limited by W production uncertainties, particularly on the PDFs



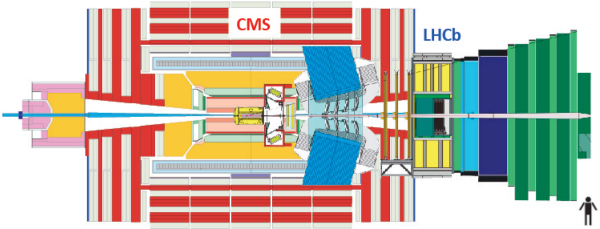
[1] ATLAS, "Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector", Eur. Phys. J. C78, 110 (2018), arXiv:1701.07240

Why LHCb?

LHCb is a forward spectrometer primarily designed to study the decays of beauty and charm hadrons

Acceptance:
$2 < \eta < 5$

Almost orthogonal to that of ATLAS and CMS



- Strong track record in measurements of W and Z boson production in muonic final states (LHCb-PAPER-2015-049, LHCb-PAPER-2016-021, ...)
- LHCb has already measured $\sin^2\theta_{\text{eff}}^{\text{lept}}$ (LHCB-PAPER-2015-039)
- **Potential for a M_W measurement recently realised**

Why LHCb?

A new measurement of M_W by LHCb was proposed in 2015[2]

- Based on the muon transverse momentum (p_T^μ) distribution from $W \to \mu\nu$ decays
- Plenty of $W^\pm$ data in LHCb Run 1 + 2 - $\mathcal{O}(10M)$ decays
  - **Expected $\mathcal{O}(10)$ MeV/c^2 of statistical uncertainty**
- Larger PDF uncertainties but partially anticorrelated with those of ATLAS and CMS[2]
  - **Significant impact of LHCb on the LHC average**

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In this talk

What drives the PDF uncertainty in LHCb?
How can we reduce it?

Analysis strategy

Events are generated with POWHEG[3]+Pythia[4]:

- selected those with $30 < p_T^{\mu} < 50\,\mathrm{GeV/c}$ and $2 < \eta < 4.5$
- **Toy dataset**: scaling to the $6\,\mathrm{fb}^{-1}$ of LHCb Run 2 data ($\sqrt{s} = 13\,\mathrm{TeV}$)
- **Template** fit to the p_T^{μ} distribution:
  - M_W & PDF hypothesis weight (NNPDF3.1 set, 1000 replicas)

[arXiv:1902.04323]

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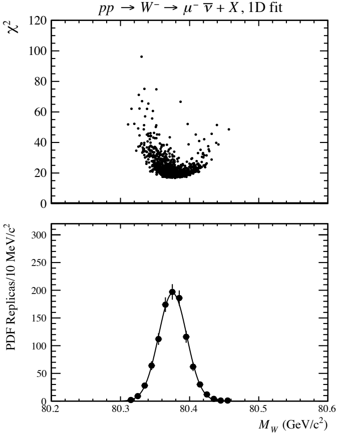


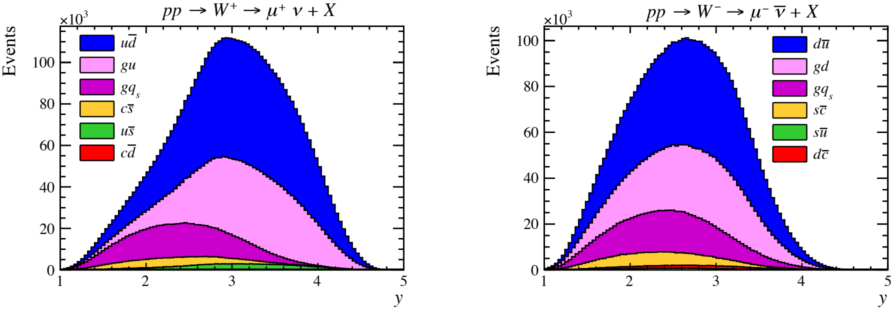
Start with a single toy dataset

For each PDF hypothesis $\to$ M_W value that minimises χ^2(toy, templates)

The PDF uncertainty is the width of the PDF spread in M_W

[arXiv:1902.04323]

W production in LHCb

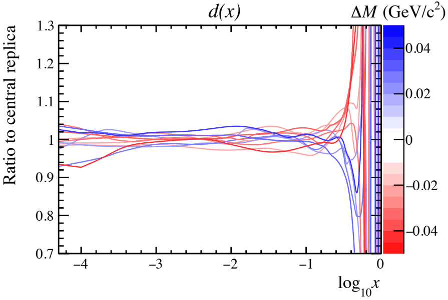


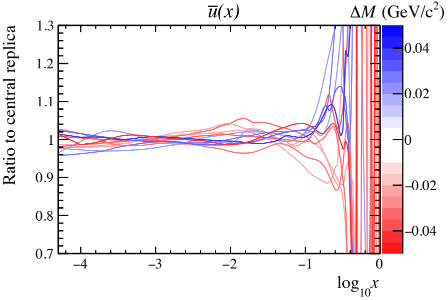
- $W^+(W^-)$ production dominated by processes involving valence $u(d)$ quarks
- Contributions from only second generation quark annihilation below 10%

[arXiv:1902.04323]

Understanding the PDF uncertainties

Looking at u, $\bar{d}$, d and $\bar{u}$ PDFs for the replicas corresponding to biased M_W determinations:



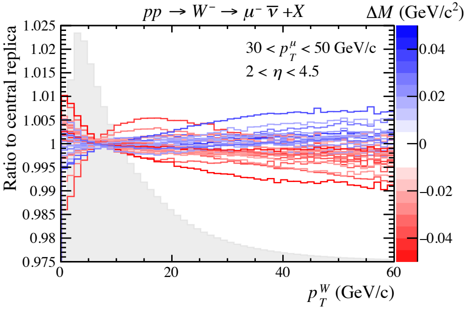


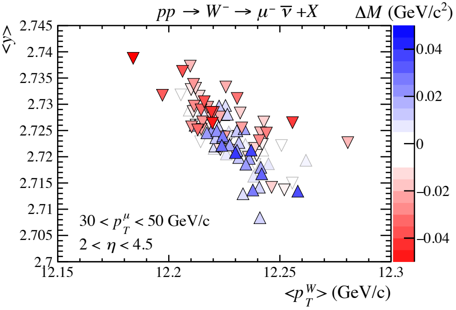
- Interesting features at high-x ($x \gtrsim 0.1$) for d and $\bar{u}$ PDFs
- No obvious pattern in the u and $\bar{d}$ PDFs

[arXiv:1902.04323]

The role of the W kinematics

- Biases in the determination of M_W strongly correlated with mismodelling of the W kinematics
- These are characterised by p_T^W, y and $\cos\theta^*$
  - Also looked at all the *combinations* of these variables

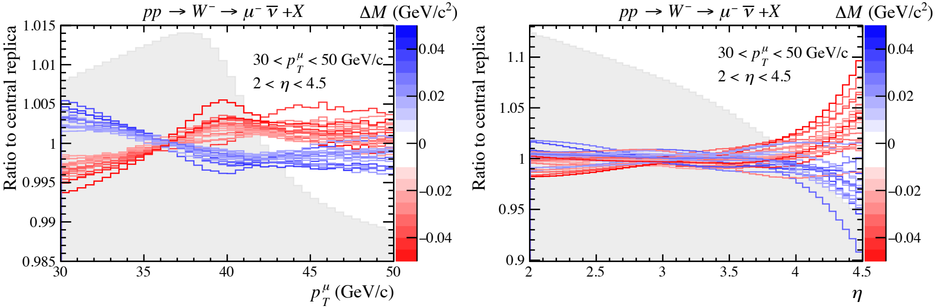




[arXiv:1902.04323]

The role of the W kinematics

Looking at the distributions of *measurable* quantities: p_T^μ, η

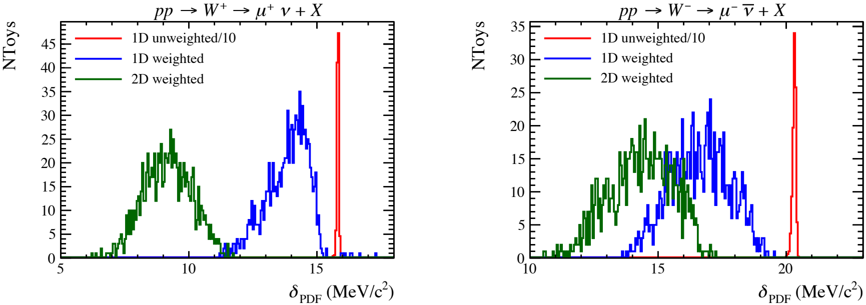


! The replicas with the largest $|\Delta M|$ lead to variations of several percent in the shape of the η distribution

$\Rightarrow$ **2D (p_T^μ, η) fit with PDF replica reweighting**, already suggested by [5] [arXiv:1902.04323]

The proposed method

- p_T^μ fit $\rightarrow$ **(p_T^μ, η) fit + PDF reweighting**
  - to each replica: $P(\chi^2) \propto \chi^{n-1} e^{-\chi^2/2}$ (following NNPDF prescription[6])
- $\delta_{\rm PDF}$ distribution for several toy datasets:

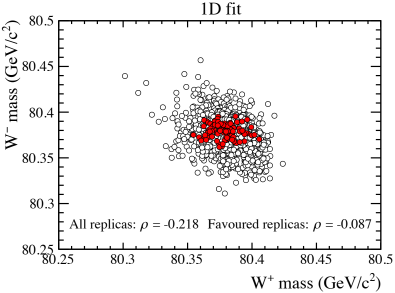


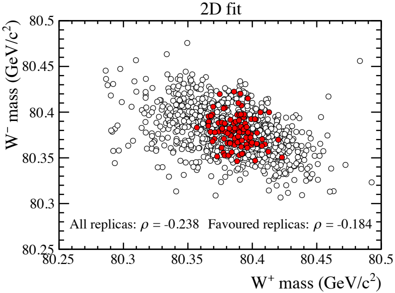
Significant reduction of the PDF uncertainty with respect to the original approach

[arXiv:1902.04323]

Combining W^+ and W^-

- For each PDF replica extracted $(M_W^+, M_W^-)_{\text{1D, 2D fit}}$
- Highlighted 10% of replicas giving largest $P(\chi^2) = P(\chi^2_+) \cdot P(\chi^2_-)$





PDF reweighting:

✓ reduces δ_{PDF} in a standalone W^+ (W^-) measurement

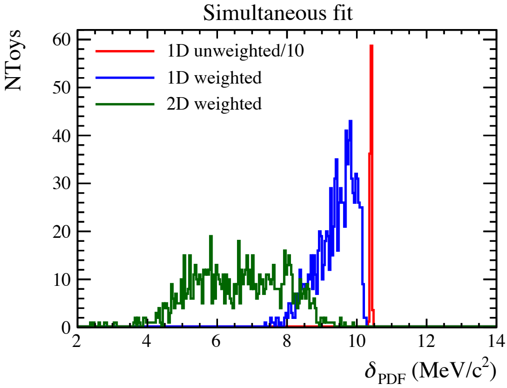
✕ reduces observed partial W^+/W^- anticorrelation

[arXiv:1902.04323]

Simultaneous fit

Using a **simultaneous fit** of the W^+ and W^- data with their templates **sharing the same normalisation** factor:

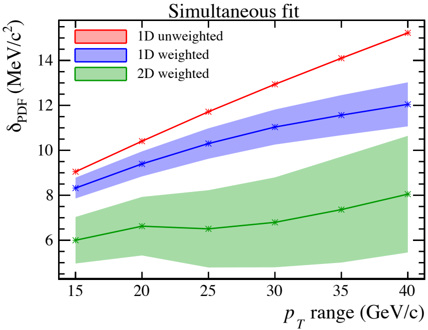
- Integrated charge asymmetry included as an additional constraint



[arXiv:1902.04323]

Dependence on the detector acceptance

- p_T^μ varies by an amount $\Delta p_T^\mu/2$ around the Jacobian peak position
- The bands show the mean and RMS of PDF uncertainty distribution for 1000 toy datasets.



- Enforced the power of the proposed method
- Performed similar study for the η range (see backup)

[arXiv:1902.04323]

Summary and Outlook

- A characterisation of the PDF uncertainty in a future measurement of M_W with LHCb has been performed[7].
- A (p_T^μ, η) fit + PDF reweighting can reduce δ_{PDF} by roughly a factor 2 with respect to a simple p_T^μ fit
  - improvements in both standalone and simultaneous $W^\pm$ fits
  - the yields are assuming LHCb Run 2 dataset

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Future challenges:

- Application of the new fit approach to the analysis of the real data
  - need to understand the η dependence of the muon efficiencies at the level of 1%
- Accurate model of the p_T^W spectrum
- Muon momentum scale: correct for misalignment effects
- Control of the background

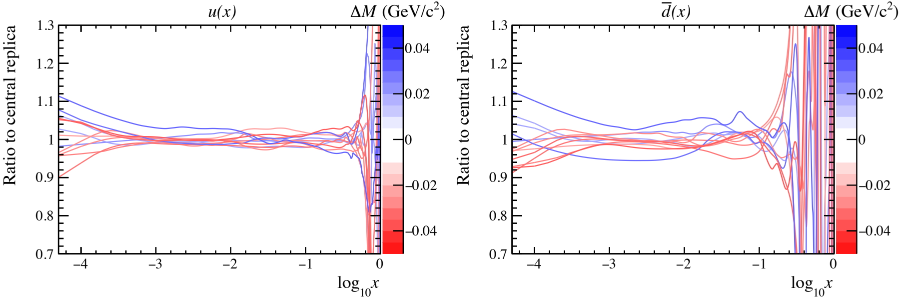
References

1. ATLAS, "Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ with the ATLAS detector", Eur. Phys. J. C78, 110 (2018), arXiv:1701.07240
2. G. Bozzi, L. Citelli, M. Vesterinen, and A. Vicini, "Prospects for improving the LHC W boson mass measurement with forward muons", Eur. Phys. J. C75, 601 (2015), arXiv:1508.06954
3. S. Alioli, P. Nason, C. Oleari, and E. Re, "NLO vector-boson production matched with shower in POWHEG", JHEP 07 (2008) 060, arXiv:0805.4802
4. T. Sjostrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 Physics and Manual", JHEP 05 (2006) 026, arXiv:hep-ph/0603175
5. E. Manca, O. Cerri, N. Foppiani, and G. Rolandi, "About the rapidity and helicity distributions of the W bosons produced at LHC", JHEP 12 (2017) 130, arXiv:1707.09344
6. R. D. Ball et al., "Reweighting and Unweighting of Parton Distributions and the LHC W lepton asymmetry data", Nucl. Phys. B855 (2012) 608, arXiv:1108.1758
7. S. Farry, O. Lupton, M. Pili and M. Vesterinen, "Understanding and constraining the PDF uncertainties in a W boson mass measurement with LHCb". arXiv:1902.04323 (2019).

Backup slides

Understanding the PDF uncertainties (2)

Looking at u, $\bar{d}$PDFs for the replicas corresponding to biased M_W determinations:



- No obvious pattern in the u and $\bar{d}$ PDFs

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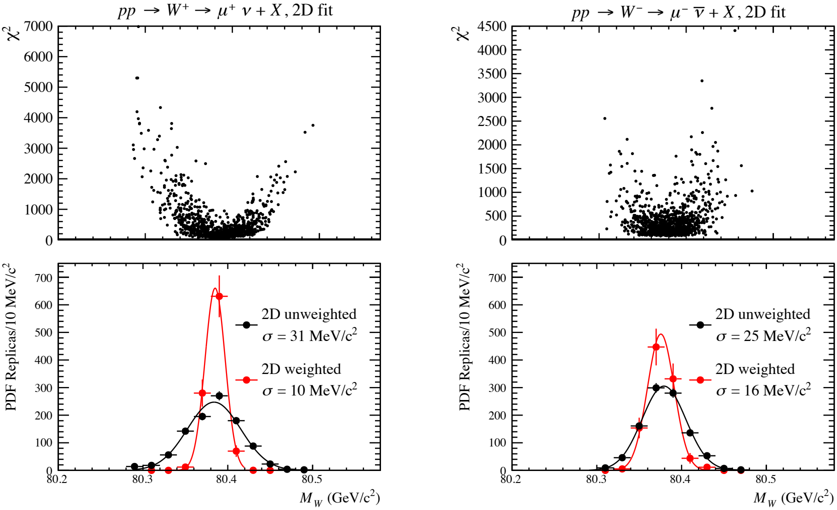
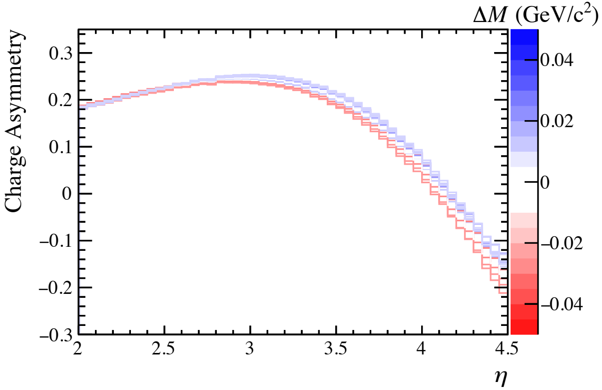
Effect of the PDF reweighting



Charge Asymmetry

The variation between the replicas of the integrated charge asymmetry between the W^+ and W^- cross sections, as a function of η:



η Range Study

- $30 < p_T < 50$ GeV/c range fixed
  - Lower η cut varies - upper cut fixed to 4.5
  - Upper η cut varies - lower cut fixed to 2