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

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)
Past and present of the W mass measurement

[EPJC 78 (2018) 110]
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

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

- 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.

Up to a factor of 2 of reduced systematic uncertainty from PDFs.
Anti-correlation of uncertainties from PDFs

\[ \rho = -0.63 \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Run-I 3 fb(^{-1})</th>
<th>Run-II 7 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( W^+ )</td>
<td>( W^- )</td>
</tr>
<tr>
<td>Signal yields, ( \times 10^6 )</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>( Z/\gamma^* ) background, ( (B/S) )</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>QCD background, ( (B/S) )</td>
<td>0.15</td>
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</tr>
<tr>
<td>( \delta_{m_W} ) (MeV)</td>
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</tr>
<tr>
<td>Statistical</td>
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<td>29</td>
</tr>
<tr>
<td>Momentum scale</td>
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<td>7</td>
</tr>
<tr>
<td>Quadrature sum</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

Single event signature

Precise modelling of the production of $W$ bosons and backgrounds

Must carefully determine the momentum of the outgoing muon

Get rid of background with kinematic and isolation requirements

$W^+$

$p_T^\mu$

$\mu^-$

$E_{\text{miss}}$

$X$

Not reconstructed at LHCb
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)

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Most sensitive region

Large theoretical uncertainties

Background dominated

Normalized events per GeV⁻¹

\[ m_W \quad \text{fit region} \]

LHCb simulation \( \sqrt{s} = 13 \text{ TeV} \)

Muon \( q/p_T \) [1/GeV]

[JHEP 01 (2022) 036]
• 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
Calibration using muons

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

\[ M^\pm = \sqrt{2p^\pm p_T^\pm p_T^\pm (1 - \cos \theta)} \]

Inspired by Phys. Rev. D 91, 072002
**Charge-dependent curvature biases**

Fit the asymmetries to the pseudomass and translate this into shifts in $q/p$.
Corrections to the simulation

- curvature biases (previous slide)
- momentum scale
- multiple scattering
The W cross-section

\[
\frac{d\sigma}{dp_T^W dy dm d\cos \vartheta d\varphi} = \frac{3}{16\pi} \frac{d\sigma^{\text{unpol.}}}{dp_T^W dy dm}
\]

(At order $\alpha_s^2$)

\[
\left\{ (1 + \cos^2 \vartheta) + A_0 \frac{1}{2} (1 - 3 \cos^2 \vartheta) + A_1 \sin 2\vartheta \cos \varphi \\
+ A_2 \frac{1}{2} \sin^2 \vartheta \cos 2\varphi + A_3 \sin \vartheta \cos \varphi + A_4 \cos \vartheta \\
+ A_5 \sin^2 \vartheta \sin 2\varphi + A_6 \sin 2\vartheta \sin \varphi + A_7 \sin \vartheta \sin \varphi \right\}
\]

Angular part: DYTurbo

Unpolarized part: POWHEG + Pythia8
Simulating signal decays

- 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

- 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

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

[EPJC 71, 1600 (2011)]

[arXiv:2112.07458 (submitted to JHEP)]
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 $O(20 \text{ MeV})$
The simulation process (PDF set)

- PDFs chosen from three different recent sets
  - CT18: [Phys. Rev. D 103, 014013]
- 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 Y(1S) decays (isolation biases only studied in the former)
  - Associated systematic uncertainties determined by varying the binning scheme, parametrizations and selections

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

\[
\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2 \text{ (rad}^{-2})}
\]
Determining the efficiencies

Three main sources of acceptance biases:

- Trigger efficiencies
- Muon-identification efficiencies
- Isolation requirements

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 $m_W$)
Systematic uncertainties

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

- 5D-weighted fit using the Beeston–Barlow approach
- Fit simultaneously W and Z data
LHCb measures the W mass!

- 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

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

[\text{JHEP} 01 (2022) 036], [\text{LHCB-PAPER-2021-024}]
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

- 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

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

\[ m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \ \text{MeV} \]
Thank you!