Electroweak Physics at LHCb
State of the art and future prospects

Davide Zuliani* - University and INFN of Padova
on behalf of the LHCb Collaboration

10th International Conference on New Frontiers in Physics (ICNFP 2021)

* davide.zuliani@cern.ch
Overview

What to talk about

- LHCb detector
- Latest Electroweak Physics measurements at LHCb:
  - $W$ and $Z$ cross-section measurements
  - $W/Z+$jet production
  - $Z + c$-jet production
  - $W$ mass
- Future prospects
LHCb detector

A “general purpose forward detector”

- LHCb, originally designed for $b$- and $c$-hadron physics, is now considered a general purpose forward detector
- Track momentum resolution: 0.4% at 5 GeV and 0.6% at 100 GeV
- Muon ID efficiency: 97% with 1-3% $\mu \rightarrow \pi$ misidentification
- Electron ID efficiency: 90% with 5% $h \rightarrow e$ misidentification
- Electron reconstruction: bremsstrahlung recovery and well-measured direction
- Excellent vertex reconstruction system: tagging of $b$- and $c$-jets with reconstruction of secondary vertices formed by tracks inside the jet cone
LHCb detector

Studying the forward region

- LHCb allows to test perturbative QCD (pQCD) predictions in a phase space ($2 < \eta < 5$) complementary to General Purpose Detectors
- Parton distribution functions (PDFs) and proton structure can be studied in regions not accessible by other LHC experiments
  - At high $x$ values
  - At low $x$ values and high $Q^2$, unexplored by other experiments
- Interesting region to study Electroweak (EW) and Jet Physics
Electroweak Physics
W production

$W \rightarrow e\nu$ at $\sqrt{s} = 8$ TeV

- Important measurement to validate the high $p_T(e)$ reconstruction and identification at LHCb
- Fiducial region: $p_T(e) > 20$ GeV, $2.0 < \eta(e) < 4.25$
- Fit to the electron $p_T$ distribution to extract the $W$ yield
- Differential cross section as a function of the electron $\eta$ is compatible with the prediction
**Z production**

$Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ at $\sqrt{s} = 13$ TeV

- Lepton final states $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$, 294 pb$^{-1}$
- Fiducial region: $2.0 < \eta(\mu/e) < 4.5$, $p_T(\mu/e) > 20$ GeV, $60 < M_{\mu\mu/ee} < 120$ GeV
- High purity samples: 99.2% for $Z \rightarrow \mu\mu$ and 92.2% for $Z \rightarrow ee$
- $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ measured cross-section are compatible within the uncertainties
Z production

$Z \to \tau\tau$ at $\sqrt{s} = 8$ TeV

- $\tau$ lepton is reconstructed in 4 final states
- Analysis with 8 TeV data, $\sim 2$ fb$^{-1}$, fiducial region: $2.0 < \eta < 4.5$, $p_T > 20$ GeV, $60 < M_{\tau\tau} < 120$ GeV
- Combined cross sections from all channel, taken in to account uncertainties correlation:
  $\sigma(pp \to Z \to \tau\tau) = 95.8 \pm 2.1 \pm 4.6 \pm 0.2 \pm 1.1$ pb
- All ratios consistent with 1
$W/Z+\text{jet}$

Run I analysis at $\sqrt{s} = 8$ TeV

- $W \rightarrow \mu\nu$ and $Z \rightarrow \mu\mu$ decay channels
- Fiducial region: $p_T(\mu) > 20$ GeV, $2.0 < \eta(\mu) < 4.5$, $p_T(\text{jet}) > 20$ GeV, $2.2 < \eta(\text{jet}) < 4.2$, $\Delta R(\text{jet}, \mu) > 0.5$
- Fit to the muon isolation to extract the $W/Z+\text{jet}$ yield
- $W/Z$ ratios and $W^+/W^-$ asymmetry are also determined
- Measurements are in good agreement with theory predictions
**Z + c-jet production**

**Intrinsic charm**

- In proton content charm can be extrinsic (produced by gluon splitting) or intrinsic (bound to valence quarks)
- Intrinsic charm PDF can be valence-quark-like or sea-quark-like, clear signature at $x > 0.1$
- Valence-like intrinsic charm is predicted by Light Front QCD (LFQCD, not-perturbative)

- Current limits do not rule out the intrinsic charm content at % level
- The Z+c-jet production in the forward region is sensitive to the high $x$ and high $Q^2$ intrinsic charm component
Z + c-jet production
Analysis in the forward region

- The 13 TeV dataset is used, for a total integrated luminosity of 6 fb⁻¹ (Run II condition)
- $Z$ boson is reconstructed in the di-muon final state → high purity sample
- Heavy flavour jets are tagged with a Displaced Vertex (DV) technique
- The corrected DV-mass and the number of tracks in the DV are fitted to obtain the flavour components
- Templates are obtained from calibration samples (heavy flavour enriched di-jets)
Z + c-jet production

Analysis in the forward region

- Systematic uncertainty dominated by the c-tagging efficiency systematic, obtained from calibration samples.
- Hint of the intrinsic charm component in the high rapidity interval (3.5 < y(Z) < 4.5).
- Result is statistically limited → more data is needed!

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>c tagging</td>
<td>6-7%</td>
</tr>
<tr>
<td>DV-fit templates</td>
<td>3-4%</td>
</tr>
<tr>
<td>Jet reconstruction</td>
<td>1%</td>
</tr>
<tr>
<td>Jet $p_T$ scale &amp; resolution</td>
<td>1%</td>
</tr>
<tr>
<td>Total</td>
<td>8%</td>
</tr>
</tbody>
</table>
$W$ mass measurement
At LHCb vs. GPD

- High precision measurement of the $W$ mass is possible at LHCb
- PDF uncertainties are anti-correlated with respect to ATLAS and CMS
- First “proof-of-principle” measurement with 2016 data
  - Reaching a $\sim 20$ MeV precision
- Sensitivity to the $W$ mass by carefully measuring the muon $q/p_T$ distribution

\[
\frac{d\sigma}{dp_T^W dydM d\cos\theta d\phi} = \frac{3}{16\pi} \frac{d\sigma^{\text{unpol}}}{dp_T^V dydM} \left\{ (1 + \cos^2\theta) + A_0 \frac{1}{2} (1 - 3 \cos^2\theta) + A_1 \sin 2\theta \cos \phi + A_2 \frac{1}{2} \sin^2\theta \cos 2\phi + A_3 \sin \theta \cos \phi + A_4 \cos \theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi \right\}
\]

Unpolarised cross-section

Davide Zuliani
Electroweak Physics at LHCb
$W$ mass measurement

Detector alignment

- To measure $W$ mass detector alignment is necessary
  - Misalignment of $\mathcal{O}(10)\mu m$ translates into a $\mathcal{O}(50)\text{MeV}$ shift in $W$ mass
- Default LHCb alignment and calibration are not suitable → custom alignment for high $p_T$ muons
- “Pseudo-mass” method included for finer analysis
- Correction applied independently to both charges
- Differences in fitted $M^\pm$ → curved bias correction

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

- Total uncertainty is 32 MeV
- Only 2016 data have been used so far (almost 1/3 of total Run II data)
- Remarkable results:
  - 9 MeV for PDFs
  - 10 MeV for experimental uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>Size [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parton distribution functions</td>
<td>9</td>
</tr>
<tr>
<td>Theory (excl. PDFs) total</td>
<td>17</td>
</tr>
<tr>
<td>Transverse momentum model</td>
<td>11</td>
</tr>
<tr>
<td>Angular coefficients</td>
<td>10</td>
</tr>
<tr>
<td>QED FSR model</td>
<td>7</td>
</tr>
<tr>
<td>Additional electroweak corrections</td>
<td>5</td>
</tr>
<tr>
<td>Experimental total</td>
<td>10</td>
</tr>
<tr>
<td>Momentum scale and resolution modelling</td>
<td>7</td>
</tr>
<tr>
<td>Muon ID, trigger and tracking efficiency</td>
<td>6</td>
</tr>
<tr>
<td>Isolation efficiency</td>
<td>4</td>
</tr>
<tr>
<td>QCD background</td>
<td>2</td>
</tr>
<tr>
<td>Statistical</td>
<td>23</td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
</tr>
</tbody>
</table>
$W$ mass measurement

First result at LHCb!

- Result obtained from a simultaneous fit to the muon spectrum and $\varphi^*$ of the $Z$
- EW and rare backgrounds determined from simulation
- QCD background parametrized from data

$$\varphi^* = \frac{\tan(\phi_{acop}/2)}{\cosh(\Delta \eta/2)} \sim \frac{p_T}{M}$$

$$m_W = 80364 \pm 23_{\text{stat}} \pm 11_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

Davide Zuliani

Electroweak Physics at LHCb
Future prospects at LHCb

Going to HL-LHC

- LHCb will go through an intense upgrade in the following years
- Several EW measurements where LHCb could play an interesting role:
  - Weak mixing angle $\sin^2 \theta_{W}^{\text{eff}}$, improving both statistics and systematic uncertainties
  - $W$ mass measurement using $W \rightarrow e\nu$ decay, given a new upgraded ECAL
  - ...
  - Not only EW physics, also top and Higgs!
Conclusions

Wrap it up

• Not only flavour physics: LHCb is now considered a general purpose forward experiment

• LHCb performed measurements of EW physics in the forward region of $pp$ collisions, unexplored by other experiments
  
  • All results are in agreement with SM predictions

• The first measurement of the $W$ boson mass at LHCb is a big achievement, towards a similar sensitivity to the global electroweak fit

• With the future upgrades LHCb could play an interesting role in measuring EW quantities

Stay tuned!
Thank you for your attention

Any questions?
Backup slides

For further details...