Measurement of forward Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV

Menglin Xu
On behalf of LHCb Collaboration

Implications Workshop
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Motivation

- Precise measurements of $W$ and $Z$ provide an important test of the SM
- Potential to improve constraints on parton distribution functions (PDFs)
- $Z$ boson production decaying into leptons is one of the best understood processes at LHC
- Measurements of the $Z$ boson rapidity are particularly important for constraining $u$-, $d$-quark PDFs
Motivation

- Recently, the SeaQuest Collaboration report the results on the $\bar{d}/\bar{u}$ PDFs
- Tensions between SeaQuest and NuSea results are seen at high $x$ region
- As SeaQuest and Nusea are lower energy experiments, which are largely affected by nuclear effects
- The LHCb data will be the only clean data to constraint the $\bar{d}/\bar{u}$ PDFs

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Chin.Phys.C 45 (2021) 2, 023110
Dataset and fiducial region

- 2016-2018 Data: $5.1 \pm 0.1 \text{ fb}^{-1}$
  - $Z \rightarrow \mu^+\mu^-$ sample
  - Same-sign sample: (background study)
- Very high purity, $N_{\text{bkg}} / N_{\text{sig}} \sim 2\%$

Fiducial region

\[
\begin{array}{c|c}
\mu^\pm & \text{di-muon} \\
\hline
p_T > 20 \text{ GeV}/c & \ \\
2 < \eta < 4.5 & 60 < M_{\mu^+\mu^-} < 120 \text{ GeV}/c^2 \\
\end{array}
\]
Cross-section definition

- Cross-section measured in bin of $Z$, $y$, $P_T$ and $\phi_\eta^*$ is given by
  \[ \frac{d\sigma_{Z \rightarrow \mu^+\mu^-}}{dy}(i) = \frac{N_Z(i) \cdot f_{FSR}^Z(i)}{L \cdot \varepsilon_{REC}^Z(i) \cdot \Delta y(i)} \]

- $\phi_\eta^* = \frac{\tan((\pi - \Delta \phi^ll)/2)}{\cosh(\Delta \eta/2)}$: similar physics as the boson $p_T$, but could be measured with better resolution in most detectors
  - $\Delta \phi^ll$: the difference in azimuthal angle

- Total cross-section is obtained by summing the differential cross-section
In order to be directly compared with different theoretical predictions, the measured cross-section is corrected to the Born level.
QED FSR correction evaluated through ResBos.
Taking differences of FSR corrections between ResBos+Photos and Powheg+Pythia as a systematic uncertainty.
Systematic uncertainties

- Luminosity determination precision: 2.0%
  - Uncertainty is quoted separately to the other sources of systematic uncertainty
- Efficiency systematic uncertainties: 0.77%
  - From size of control channel
  - From the track modeling: dominated one

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta \sigma / \sigma$ [%]</th>
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<tbody>
<tr>
<td>Statistical</td>
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<tr>
<td>Background</td>
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<tr>
<td>Alignment &amp; calibration</td>
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<td>Efficiency</td>
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<td>FSR</td>
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<td>Total Systematic (excl. lumi.)</td>
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<tr>
<td>Luminosity</td>
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<tr>
<td>Total</td>
<td>2.15</td>
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LHCb preliminary
Statistical correlation matrix

- Determined using the simulation events
- Large correlations between events in low $p_T^Z$ region, small correlations in the high $p_T^Z$ region
- For $y_Z$ and $\phi_{\eta}^*$, the correlations between different bins are negligible

$p_T^Z$ LHCb preliminary

$y_Z$ LHCb preliminary

$\phi_{\eta}^*$ LHCb preliminary
Systematic correlation matrix

- Systematic uncertainties from background, alignment, efficiency closure test, and FSR are considered to be uncorrelated
- Luminosity uncertainties are considered to be 100% correlated

Efficiency systematic

LHCb preliminary
Single differential cross-section: $y_Z$

LHCb $\sqrt{s} = 13$ TeV

- $p_T(\mu) > 20$ GeV/$c$
- $2.0 < \eta(\mu) < 4.5$
- $60 < M(\mu^+\mu^-) < 120$ GeV/$c^2$

Statistical Uncertainty
Total Uncertainty

- Resbos
- Pythia, LHCb tune
- POWHEG+Pythia
- MatchBox

FEWZ+CT14
FEWZ+NNPDF3.0
FEWZ+MMHT14
FEWZ+ABM12

LHCb preliminary

2021/10/21
Reasonable agreement between data and predictions
Double differential cross-section: $y_Z - P_T$
Double differential cross-section: $y_Z - \phi_Z^*$

LHCb preliminary

2.0 < $y_Z$ < 2.5

2.5 < $y_Z$ < 3.0

3.0 < $y_Z$ < 3.5

3.5 < $y_Z$ < 4.0

4.0 < $y_Z$ < 4.5

LHCb $\sqrt{s} = 13$ TeV
$p_T(\mu) > 20$ GeV/$c$
$2.0 < \eta(\mu) < 4.5$
$60 < M(\mu^+\mu^-) < 120$ GeV/$c^2$

Statistical Uncertainty
Total Uncertainty
ResBos

2021/10/21
Integrated cross-section

- Combined with ‘Best Linear Unbiased Estimate’ (BLUE)
  - luminosity uncertainty, systematic uncertainties from FSR, background modelling, and closure test are treated as 100% correlated.
  - Other systematic uncertainties are treated as having no correlation

\[
\begin{align*}
\text{RunII: } \sigma_{Z \rightarrow \mu^+ \mu^-} &= 195.0 \pm 0.2 \text{ (stat)} \pm 1.5 \text{ (sys)} \pm 3.9 \text{ (lumi) pb} \\
\text{2015: } \sigma_{Z \rightarrow \ell^+ \ell^-} &= 194.3 \pm 0.9 \text{ (stat)} \pm 3.3 \text{ (sys)} \pm 7.6 \text{ (lumi) pb}
\end{align*}
\]
The most precise measurement of the $Z$ boson production cross-section in the forward region, using the $\sqrt{s} = 13$ TeV pp collision data in muon channel

The integrated cross-section is measured to be

$$\sigma_{Z \rightarrow \mu^+ \mu^-} = 195.0 \pm 0.2 \text{ (stat)} \pm 1.5 \text{ (sys)} \pm 3.9 \text{ (lumi)} \text{ pb (LHCb preliminary)}$$

Reasonable agreement between the data and the theoretical predictions is seen

Provide important and unique information to the PDFs global fitting, especially in the large and small $x$ region
Back up
## High purity

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<td>4496</td>
<td>6528</td>
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<tr>
<td>Bkg/Signal</td>
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<td><strong>2.01%</strong></td>
<td><strong>1.97%</strong></td>
<td><strong>2.09%</strong></td>
</tr>
</tbody>
</table>
Statistical correlation matrix – two dimensional

\[ \gamma_Z - p_T^Z \]

LHCb preliminary

\[ \gamma_Z - \phi_{\eta}^* \]

LHCb preliminary
Efficiency uncertainties correlation matrix – 2D

\[ y_Z - p_T^Z \]

LHCb preliminary

\[ y_Z - \phi_{\eta}^* \]

LHCb preliminary
FSR correction

LHCb preliminary

LHCb preliminary
Tracking efficiencies – uncertainty summary

- Total systematic uncertainty from the tracking: 0.47% for each track
  - Matching correction: 0.28%
  - Data and MC matching efficiency differences: 0.33%
  - Data and MC MuonTT finding efficiency differences: 0.1%
  - Differences between the MC-truth eff and the corrected MC tag-and-probe eff
- In previous study, this uncertainty is assigned as 1% for each track

![Graphs showing tracking efficiencies](image-url)