PDF4LHC: News from LHCb

Hengne Li

(South China Normal University)

on behalf of the LHCb collaboration
An incomplete summary of results from LHCb

**W, Z, top @ 7 & 8 TeV:**

- $W$ and $Z$ @ 7 TeV (36 pb$^{-1}$ partial dataset) (JHEP 06 (2012) 58)
- $Z$ @ 7 TeV (1 fb$^{-1}$ full dataset) (JHEP 08 (2015) 039)
- $W$ @ 7 TeV (1 fb$^{-1}$ full dataset) (JHEP 12 (2014) 079)
- $Z \rightarrow \tau\tau$ @ 7 TeV (JHEP 01 (2013) 111)
- $Z \rightarrow ee$ @ 7 TeV (JHEP 02 (2013) 106)
- $Z +Jets$ @ 7 TeV (JHEP 01 (2014) 33)
- $Z + D$ @ 7 TeV (JHEP 04 (2014) 91)
- $Z + b$-jets @ 7 TeV (JHEP 01 (2015) 064)
- $Z \rightarrow ee$ @ 8 TeV (JHEP 05 (2015) 109)
- $W + b/c$-jets @ 7 & 8 TeV (PRD92 (2015) 052001)
- $W$ and $Z$ @ 8 TeV (JHEP 01 (2016) 155)
- $W \rightarrow e\nu$ @ 8 TeV (JHEP 10 (2016) 030)
- $t\bar{t}, W + b\bar{b}, W + c\bar{c}$ @ 7 & 8 TeV (RLB 767 (2017) 110)
- $t\bar{t}$ @ 7 & 8 TeV (PRL 115 (2015) 112001)
- $Z \rightarrow b\bar{b}$ @ 8 TeV (PLB 776 (2018) 430)
- $Z \rightarrow \tau\tau$ @ 8 TeV (JHEP 09 (2018) 159)

**Z @ 13 TeV:**

- $Z$ @ 13 TeV (294 pb$^{-1}$ partial dataset) (JHEP 09 (2016) 136)
- $Z + c$-jets @ 13 TeV (PRL 128 (2022) 082001)
- $Z \rightarrow \mu\mu$ @ 13 TeV (5 fb$^{-1}$ full dataset) (JHEP 07 (2022) 26)

**Z in pPb collisions:**

- $Z$ in pPb @ 5.02 TeV (JHEP 09 (2014) 030)
- $Z$ in pPb @ 8.16 TeV (arXiv:2205.10213 (JHEP accepted))

**Exclusive photoproduction:**

- CEP $J/\psi$ and $\psi(2S)$ @ 7 TeV (J. Phys. G40 (2013) 045001)
- Updated CEP $J/\psi$ and $\psi(2S)$ at 7 TeV (J. Phys. G41 (2014) 055002)
- CEP $Y$ @ 7 TeV (JHEP 09 (2015) 084)
- CEP $J/\psi$ and $\psi(2S)$ @ 13 TeV (JHEP 10 (2018) 167)
- CEP $J/\psi$ @ 8.16 TeV 2015 PbPb UPC (JHEP 07 (2022) 117)
- CEP $J/\psi$ and $\psi(2S)$ @ 8.16 TeV 2018 PbPb UPC (arXiv: 2206.08221 (JHEP submitted))

**New results to be covered today.**
The LHCb detector

- LHCb is the only dedicated detector (at LHC) fully instrumented in forward region
- Unique kinematic coverage $2 < \eta < 5$
- A high precision device, down to very low-$p_T$; excellent particle ID, precise vertex and track reconstruction.

[ JINST 3 (2008) S08005 ]
[ IJMPA 30 (2015) 1530022 ]

- RICH detectors
  - $K/\pi/p$ separation
  - $\varepsilon(K\rightarrow K) \sim 95\%$
  - mis-ID $\varepsilon(\pi\rightarrow K) \sim 5\%$

- Vertex Detector
  - reconstruct vertices
  - decay time resolution: 45 fs
  - impact parameter resolution: 20 $\mu$m

- Dipole Magnet
  - bending power: 4 Tm

- Tracking system
  - momentum resolution $\Delta p/p = 0.5\% - 1.0\%$
  - (5 GeV/c $\sim 100$ GeV/c)

- Muon system
  - $\mu$ identification $\varepsilon(\mu\rightarrow\mu) \sim 97\%$
  - mis-ID $\varepsilon(\pi\rightarrow\mu) \sim 1-3\%$

- Calorimeters
  - energy measurement
  - $e/\gamma$ identification
  - $\Delta E/E = 1\% \oplus 10\% / \sqrt{E}$ (GeV)
Z boson as a probe

$Z + c$-jets @ 13 TeV

*PRL 128 (2022) 082001*

$Z \to \mu\mu$ @ 13 TeV (5 fb$^{-1}$ full dataset)

*JHEP 07 (2022) 26*

$Z$ in pPb @ 8.16 TeV

*arXiv:2205.10213 (JHEP accepted)*
Z boson as probes

- Can be precisely predicted by factorization theory. Once created, do not participate in strong interaction, unaffected by hadronic activities in the final states.
- Ideal probe of the initial conditions, such as proton PDFs, nuclear modifications, etc.
  - Bjorken-$x$ in $10^{-4} < x < 10^{-3}$ and $10^{-1} < x < 1$,
  - with $Q^2 \sim m_Z \sim 10^4 \text{GeV}^2$.
- Of particular interest in constraining u/d PDFs
  - Inconsistency show up in SeaQuest and NuSea results, LHCb data will be the only clean data to clarify it.
- Z @ LHC also sensitive to the intrinsic heavier quark flavors [Eur. Phys. J. C (2017) 77:488]
Probe intrinsic charm

- Intrinsic-charm vs. extrinsic-charm.
- $Z + c$-jets production:
  - Valence-like intrinsic charm contents in proton PDFs can enhance $c$-jet production especially at high Bjorken-$x$

\[ g c \rightarrow Z c \]

Leading-order Feynman diagrams for $g c \rightarrow Z c$

\[ \begin{array}{c}
  \text{Intrinsic-charm:} \\
  \text{Non-perturbative valence-quark-like long time scale}
  \\
  \text{Extrinsic-charm:} \\
  \text{Perturbative short time scale}
\end{array} \]
Probe intrinsic charm

• First study of $Z + c$-jets in the forward region, with optimized $c$-tagging.

• Measure ratio:
  $$\frac{\sigma(Z + c\text{ jets})}{\sigma(Z + \text{all jets})}$$

  • Percent-level intrinsic-charm contribution would significantly enhance the ratio at high $y(Z)$.
  • Models allowing intrinsic-charm are largely unconstrained at high $y(Z)$.
  • Jet-related systematic uncertainties can largely cancel in the ratio.
Probe intrinsic charm

LHCb Run2 (2015 – 2018) pp collisions at 13 TeV, about 6 fb\(^{-1}\), using \(Z \rightarrow \mu^+ \mu^-\) events:

\[ R_f^c = \frac{N(Z + c \text{ jets})}{N(Z + \text{all jets}) \epsilon(c - \text{tag})} \]

- C-jet is tagged using method based on displaced-vertex (DV, or secondary vertex)

Fiducial region/event selection

<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 and resolution</td>
<td>1%</td>
</tr>
<tr>
<td>Total</td>
<td>8%</td>
</tr>
</tbody>
</table>

Systematic uncertainties

- Leading systematic uncertainty due to c-tagging calibration
- Other systematic uncertainties almost cancelled in the ratio.
Probe intrinsic charm

- Clear enhancement in highest $y$ bin.
- Inconsistent with No-Intrinsic-Charm theory at $>3\sigma$.
- More consistent with intrinsic-charm-allowed predictions, such as the BHPS model based on light front QCD.
- High rapidity results should strongly constrain the large-$x$ charm PDF.
- Current results are statistically limited, Run3 dataset will allow for finer binning.

PRL 128 (2022) 08200
Z production in pp collisions

- LHCb pp data@13 TeV: $5.1 \pm 0.1$ fb$^{-1}$ (2016-2018).
  - Very high purity: $N_{bkg}/N_{sig} \sim 2\%$
- Fiducial volume:
  $p_T^\mu > 20$ GeV, $2.0 < \eta_\mu < 4.5$, $60 < m_{\mu\mu} < 120$ GeV
- Differential Cross-section:
  $$\frac{d\sigma_{Z \rightarrow \mu\mu}}{dy} = \frac{\Delta N_Z(y) \cdot f_{FSR}(y)}{L \cdot \epsilon(y) \cdot \Delta y}$$
  in bins of Z rapidity, $p_T^Z$, and $\varphi^*$. 

JHEP 07(2022)026
Z production in pp collisions

• Single differential cross-section vs Z boson rapidity
  • Compatible with theory prediction, difference observed at rapidity from 2 to 3
Z production in pp collisions

- Single differential cross-section vs. $p_T^Z$
  - Compatible with theory prediction, difference observed in large $p_T^Z$

JHEP 07(2022)026
Z production in pp collisions

• Single differential cross-section vs. $\phi^*$
  
  • Compatible with theory prediction,
  
  • Difference observed at large $\phi^*$ corresponds to large $p_T^Z$

$\phi^* = \tan(\phi_{acop}/2) / \cos(\Delta\eta/2)$, equivalent to $p_T^Z$, less impacted by detector resolution effects.

Prediction/data ratio
Z production in pp collisions

- Integrated cross-section Run2:

\[ \sigma(Z\rightarrow\mu^+\mu^-) = 196.4 \pm 0.2\text{(stat.)} \pm 1.6\text{(syst)} \pm 3.9\text{(lumi)}\text{ pb}, \]

Most precise measurement in the forward region at the moment.

Combined using “BLUE” method:

[\text{NIM A270}(1988) 110, NIM A500(2003) 391]

- Uncertainties from Lumi., FSR corr., background, closure test, are treated as 100% correlated.
- Other uncertainties are treated as not correlated.
Z production in pPb collisions

pPb data at 8.16 TeV about 30 nb\(^{-1}\).

- Fiducial volume:
  
  \[ p_T^{\mu} > 20 \text{ GeV}, \ 2.0 < \eta_\mu < 4.5, \ 60 < m_{\mu\mu} < 120 \text{ GeV} \]

- Cross-section:
  
  \[ \sigma_{Z \rightarrow \mu\mu} = \frac{N_{\text{cand}} \cdot \rho \cdot f_{\text{FSR}}}{\mathcal{L} \cdot \epsilon} \]

- Forward-backward ratio:
  
  \[ R_{FB} = \frac{\sigma_{(1.53 < y_\mu^* < 4.03)}}{\sigma_{(-4.97 < y_\mu^* < -2.47)}} \cdot k_{FB} \]

- Nuclear modification factors:
  
  \[ R_{pPb}^{fw.} = \frac{1}{208} \cdot \frac{\sigma_{(pPb, 1.53 < y_\mu^* < 4.03)}}{\sigma_{(pp, 2.0 < y_\mu^* < 4.5)}} \cdot k_{pPb} \]

- The cross-section, \( R_{FB} \) and \( R_{pPb} \) are measured as a function of \( y_\mu^* \), \( p_T^Z \), and \( \phi_\eta^* \)
  
  - \( k_{FB} \) and \( k_{pPb} \): muon rapidity acceptance correction factors.
  
  pp reference cross-section at 8.16 TeV is interpolated from LHCb 7, 8 and 13 TeV results.
Z production in pPb collisions

- **Total fiducial cross-section:**
  \[ \sigma_{Z \rightarrow \mu \mu, \text{fwd.}} = 26.9 \pm 1.6 \text{(stat.)} \pm 0.9 \text{(syst.)} \pm 0.7 \text{(lumi.) nb} \]
  \[ \sigma_{Z \rightarrow \mu \mu, \text{bwd.}} = 13.4 \pm 1.0 \text{(stat.)} \pm 0.5 \text{(syst.)} \pm 0.3 \text{(lumi.) nb} \]

- Compatible with theoretical calculations using POWHEG v2:
  - CTEQ61 (PDF) for both p and Pb
  - CT14 (PDF) for p and EPPS16 (nPDF) for Pb
  - CTEQ61 (PDF) for p and nCTEQ15 (nPDF) for Pb

- Forward (small Bjorken-x) results show strong constraining power on the nPDFs.
Z production in $p$Pb collisions

- Differential cross-section as a function of $y^*_Z$ and $\phi^*_\eta$:
  - In good agreement with theoretical predictions.
  - Forward: smaller uncertainty than prediction, constraints on nPDFs.
  - Backward: larger uncertainty than predictions.
Z production in pPb collisions

- Differential cross-section as a function of $p_T^Z$:
  - Compatible with theoretical predictions.
  - Smaller uncertainty than prediction for forward collisions, showing constraints on nPDFs.
  - Low-$p_T^Z$ results are given, useful for TMD (transverse-momentum-dependent PDFs) studies.
Z production in pPb collisions

- **Forward-backward ratio** measured in common rapidity window $2.5 < |y^*_Z| < 4.0$:
  - Total $R_{FB} = 0.78 \pm 0.10$
  - As a function of $y^*_Z$, $p_T^Z$, and $\phi^*_\eta$, see plots
- A general suppression below unity.
- Compatible with theoretical predictions.
- Higher precision in total $R_{FB}$ and certain bins as a function $y^*_Z$, $p_T^Z$, and $\phi^*_\eta$ can constrain the nPDFs.

**Plots:**

- Forward-backward ratio as a function of $|y^*_Z|$.
- Total $R_{FB}$ as a function of $y^*_Z$, $p_T^Z$, and $\phi^*_\eta$.

Hengne Li  PDF4LHC, 23 November 2022, CERN
Z production in $p$Pb collisions

- Inclusive nuclear modification factors:
  \[ R_{pPb}^{fw} = 0.94 \pm 0.07 \]
  \[ R_{pPb}^{bw} = 1.21 \pm 0.11 \]

- Compatible with theoretical predictions.

- Suppression in the **forward** and enhancement in the **backward** are visible.

- Forward (small Bjorken-$x$) results show strong constraining power on the nPDFs.
Exclusive photoproduction

CEP $J/\psi$ and $\psi(2S)$ @ 8.16 TeV 2018 PbPb UPC
arXiv: 2206.08221 (JHEP submitted)
**CEP in Ultra-peripheral collisions**

- **Ultra-peripheral collisions (UPC):** Two nuclei bypass each other with an impact parameter greater than the sum of their radii.

- **Photon-induced interactions are enhanced by the strong electromagnetic field of the nucleus:**
  - Coherent $J/\psi$ and $\psi(2S)$ production gives constraints on the gluon Probability Density Functions,
  - $(J/\psi) / \psi(2S)$ ratio measurement is helpful to constrain the choice of the vector meson wave function in dipole scattering models [e.g. PLB 772 (2017) 832, PRC (2011) 011902].

Coherent $J/\psi$ production: photon interact with the whole nucleus coherently

Incoherent $J/\psi$ production: photon interact with particular nucleons in the nucleus.
Charmonia in UPC

- PbPb at 5.02 TeV in 2018 (228 ± 10 μb⁻¹)

- Cross-sections:
  \[
  \frac{d\sigma_{\psi}^{\text{coh}}}{dx} = \mathcal{L} \times \varepsilon_{\text{tot}} \times \mathcal{B}(\psi \rightarrow \mu^+\mu^-) \times \Delta x
  \]

- Event selection:
  - require a near empty detector with only two long tracks reconstructed, with acceptance cuts:
    - \(2.0 < \eta^\mu < 4.5, p_T^\mu > 700\text{MeV}, p_T^{\mu\mu} < 1\text{GeV}, |\Delta\phi_{\mu\mu}| > 0.9\pi\)
  - HERSCHEL detector [JINST 13 (2018) 04 P04017] is used to further purify the selection

- Signal extraction: The (1) charmonium yields are extracted from dimuon mass fit, then the (2) coherent part is extracted from a ln\((p_T^2)\) fit
Charmonia in UPC

- The most precise coherent $J/\psi$ production measurement in PbPb UPC in forward rapidity to date
- The first coherent $\psi(2S)$ measurement in forward rapidity at the LHC

Compared to pQCD and color-dipole models

Hengne Li
MPI@LHC 2022, Madrid, Spain, Nov. 17, 2022
Charmonia in UPC

- The first cross-section ratio between $J/\psi$ and $\psi(2S)$ vs. rapidity measurement in forward rapidity region at the LHC

Compared to pQCD and color-dipole models

Charmonia in UPC

- The first measurement of the coherent $J/\psi$ and $\psi(2S)$ production cross-section vs. $p_T$ in PbPb UPC

Compared to pQCD and color-dipole models

Follow up discussion on the theoretical uncertainties

• Update the theoretical calculations on the same plot:
  • p-QCD calculations: include new NLO p-QCD calculation (arXiv:2203.11613), PDF uncert. and factorization / renormalization scale uncert.
  • Color-dipole models: draw different model tuning options as theoretical variations

• The high precision LHCb data are of great value in theoretical model fine-tuning

Thanks to Chris Flett, Heikki Mäntysaari, Vadim Guzey, Michal Krelina, Kari Eskola, et.al., for the important discussions after we get public our results!
Conclusion/Outlook

• A summary of previous LHCb results for PDF studies.
• The first study of $Z + c$-jets in the forward region.
• The most precise measurement of the $Z$ boson production in pp collisions at 13 TeV in the forward region.
• The first differential $Z$ boson result in pPb collisions at 8.16 TeV in the forward region.
• The most precise coherent $J/\psi$ production measurement and the first coherent $\psi(2S)$ measurement in forward rapidity in PbPb UPC
Backups
Z production in pp collisions

- Double differential cross-section: $\gamma_Z - p_T^Z$
  - Compatible with theoretical prediction

First double differential measurements in the forward region
Z production in pp collisions

- Double differential cross-section: $y_Z - \phi^*$
  - Compatible with theoretical prediction

First double differential measurements in the forward region
Z production in pPb collisions

- Nuclear modification factors as a function of $y^*_Z$, $p_T^Z$, and $\phi^*_\eta$

- Compatible with theoretical predictions.

- Constraints on nPDFs are visible in certain bins in case of forward collisions.

Integrated cross-section and cross-section ratio

- **Integrated cross-section and ratio (most precise measurements in the forward region at the moment):**

  \[
  \sigma_{J/\psi}^{\text{coh}} = 5.965 \pm 0.059 \,(\text{stat}) \pm 0.232 \,(\text{syst}) \pm 0.262 \,(\text{lumi}) \,\text{mb}, \\
  \sigma_{\psi(2S)}^{\text{coh}} = 0.923 \pm 0.086 \,(\text{stat}) \pm 0.028 \,(\text{syst}) \pm 0.040 \,(\text{lumi}) \,\text{mb}, \\
  \frac{\sigma_{J/\psi}^{\text{coh}}}{\sigma_{\psi(2S)}^{\text{coh}}} = 0.155 \pm 0.014 \,(\text{stat}) \pm 0.003 \,(\text{syst}).
  \]

- **Systematic uncertainties:**

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{J/\psi}^{\text{coh}})</td>
<td>(\sigma_{\psi(2S)}^{\text{coh}})</td>
<td></td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>0.5–2.0</td>
<td>0.5–2.0</td>
</tr>
<tr>
<td>PID efficiency</td>
<td>0.9–1.6</td>
<td>0.9–1.6</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2.7–3.7</td>
<td>2.1–2.5</td>
</tr>
<tr>
<td>HERSCHEL efficiency</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Background estimation</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Signal shape</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Momentum resolution</td>
<td>0.9–3.4</td>
<td>1.3–2.7</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>0.6</td>
<td>2.1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4.4</td>
<td>4.4</td>
</tr>
</tbody>
</table>
Charmonia in UPC

- The $J/\psi$ measurement is compatible with 2015 and ALICE results
  - The difference between the new results and 2015 measurement is about $2\sigma$
LHCb running modes and kinematic coverage

Both the collider mode and fixed-target mode running at the same time

Collider Mode

- $\sqrt{s_{NN}} = 8.2$ TeV
- $\sqrt{s_{NN}} = 5.0$ TeV
- Pp
- Pb

Fixed-target Mode (SMOG)

- $\sqrt{s_{NN}} = 110$ GeV
- $\sqrt{s_{NN}} = 69$ GeV
- p
- Gas (He, Ne, Ar...)
- Pb
- Gas (Ne, Ar)

Collider mode datasets:

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>2013</th>
<th>2016</th>
<th>2015</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.02</td>
<td>pPb</td>
<td>pPb</td>
<td>PbPb</td>
<td>XeXe</td>
<td>PbPb</td>
</tr>
<tr>
<td>8.16</td>
<td>1.1 nb^{-1}</td>
<td>13.6 nb^{-1}</td>
<td>10 $\mu$b^{-1}</td>
<td>0.4 $\mu$b^{-1}</td>
<td>$\sim$ 210 $\mu$b^{-1}</td>
</tr>
</tbody>
</table>

Kinematic acceptance

$y = \ln(s/m_p)$