Z production in pPb collisions and charmonium production in Pb-Pb ultra-peripheral collisions (UPC) at LHCb

Hengne Li
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on behalf of the LHCb collaboration
Outline

❖ LHCb detector and datasets
❖ Z production in pPb collisions
❖ Charmonium production in PbPb UPC
LHCb provides unique datasets for Heavy Ion physics studies.
The LHCb detector is special

- LHCb is the only 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, precision vertex reconstruction and tracking.
LHCb running modes and kinematic coverage

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

Colliding beam mode (pPb and PbPb):

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$</th>
<th>2013</th>
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<tbody>
<tr>
<td></td>
<td>5.02 TeV</td>
<td>8.16 TeV</td>
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</tr>
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<td>$\mathcal{L}$</td>
<td>pPb 1.1 nb$^{-1}$</td>
<td>Pbp 0.5 nb$^{-1}$</td>
<td>pPb 13.6 nb$^{-1}$</td>
<td>Pbp 20.8 nb$^{-1}$</td>
<td>PbPb 10 $\mu$b$^{-1}$</td>
</tr>
</tbody>
</table>

Colliding beam mode (pPb and PbPb):

- $\sqrt{s_{NN}} = 8.2$ TeV
- $\sqrt{s_{NN}} = 5.0$ TeV
- $\sqrt{s_{NN}} = 110$ GeV
- $\sqrt{s_{NN}} = 69$ GeV

Fixed-target Mode (SMOG)

- $\mathcal{L}$
- p-SMOG
- p-Pb
- Pb-Pb

Kinematic Acceptance

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Setups for proton-ion collisions

- Rapidity coverage in center of mass frame considers a rapidity shift of about 0.47 w.r.t. the lab frame coverage $2.0 < y < 4.5$
- Common range for the measurements: $2.5 < |y^*| < 4.0$

- **Forward production:**
  - Center of mass rapidity coverage: $1.5 < y^* < 4.0$

- **Backward production:**
  - Center of mass rapidity coverage: $-5.0 < y^* < -2.5$
pPb Z boson production
Electroweak bosons are unmodified by the hot and dense medium created in heavy ion collisions, 

Their leptonic decays pass through the medium without being affected by the strong interaction. 

Therefore, electroweak boson productions well “conserved” the initial conditions of the collisions, can be: 

used to probe (cold) nuclear effects and constraint nPDFs for Bjorken-x from $\sim 10^{-4}$ to 1 at $Q^2 \sim 10^4$ GeV$^2$ 

and can be used as a calibration of the nuclear modification factor of other processes
pPb Z boson production

- Cross-sections measured in fiducial volume for both pPb and Pbp:
  \[ \sigma_{Z \rightarrow \mu^+ \mu^-} = \frac{N_{\text{cand}} \cdot \rho}{\mathcal{L} \cdot \varepsilon_{\text{tot}}}. \]

- Forward-backward ratio measured in fiducial volume + common rapidity coverage:
  \[ R_{\text{FB}}^{2.5 < |y^*| < 4.0} = \frac{\sigma_{Z \rightarrow \mu^+ \mu^-, \text{pPb}}}{\sigma_{Z \rightarrow \mu^+ \mu^-, \text{Pbp}}} \bigg|_{2.5 < |y^*| < 4.0} \]

Using pPb datasets at 5.02 TeV and 8.16 TeV

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- Fiducial volume:
  60 < \( m_{\mu\mu} \) < 120 GeV
  2.0 < \( \eta^\mu \) < 4.5, \( p_T^\mu > 20 \) GeV

- Purity \( \rho \) (signal fraction) is measured using same-sign muon pair and ABCD-method
- Efficiencies are estimated using MC and tag-and-probe data-driven corrections

【JHEP09(2014)030】【LHCb-CONF-2019-003】

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Quark Matter 2019, Wuhan
pPb $Z$ boson production at 5 TeV

- 5 TeV in 2016,
- Integrated luminosity: forward (1.099 ± 0.021 nb$^{-1}$) / backward(0.521 ± 0.011 nb$^{-1}$)
- Yields: forward (11 events) / backward (4 events)

![Invariant dimuon mass distribution of selected $Z$ candidates in (a) the backward and in (b) the forward sample.](image-url)

Figure 1: Rapidity distribution of selected $Z$ candidates in proton-lead and $pPb$ $Z$ boson production at 5 TeV with the MSTW08 PDF set normalised to the number of observed $Z$ candidates in (a) the backward and in (b) the forward sample. The red line shows the distribution obtained from simulation using Pythia8. The top figure shows the rapidity, $y$, from simulation using Pythia8 for $pPb$ at 5 TeV. The bottom figure shows the rapidity, $y$, for $pPb$ at 5 TeV. The black data points represent the observed ratio of candidates / (2 GeV/$c^2$) candidates / 0.25.

Figure 2: Invariant dimuon mass distribution of selected $Z$ candidates in (a) the backward and in (b) the forward sample. The red line shows the distribution obtained from simulation using Pythia8. The top figure shows the invariant dimuon mass, $m_{\mu^+\mu^-}$, in the centre-of-mass frame. The bottom figure shows the invariant dimuon mass, $m_{\mu^+\mu^-}$, in the laboratory frame, the bottom one the dimuon mass distribution obtained from simulation using Pythia8. The bottom figure shows the invariant dimuon mass, $m_{\mu^+\mu^-}$, in the laboratory frame, the bottom one the dimuon mass distribution obtained from simulation using Pythia8. The black data points represent the observed ratio of candidates / (2 GeV/$c^2$) candidates / 0.25.

【JHEP09(2014)030】
pPb $Z$ boson production at 5 TeV

- Fiducial cross-section results:
  - Forward:
    \[ \sigma_{Z\to\mu^+\mu^-}(\text{fwd}) = 13.5^{+5.4}_{-4.0}\text{(stat.)} \pm 1.2\text{(syst.)}\text{ nb} \]
  - Backward:
    \[ \sigma_{Z\to\mu^+\mu^-}(\text{bwd}) = 10.7^{+8.4}_{-5.1}\text{(stat.)} \pm 1.0\text{(syst.)}\text{ nb} \]
  - Compatible with theoretical predictions using FEWZ(NNLO pQCD+NLO pEW) with:
    - MSTW08(PDF) for both p and Pb
    - MSTW08(PDF) for p and EPS09(nPDF) for Pb

- 4. Results

- All systematic uncertainties are listed in table 1.

- Table 1

- The uncertainty on the luminosity is based on the statistical and systematic uncertainties of the calibration method mentioned in section 4.

- The uncertainty on the track multiplicity reweighting is assigned as the relative efficiency 0.0% 1.9%.

- The uncertainty on the candidate $e_\text{eff}$ efficiency includes the uncertainties on the determination of the purity as well as the reconstruction, selection, trigger and muon-identification efficiencies, as well as on the uncertainty in the ratio $\epsilon_{\text{eff}}(\text{stat.})$.

- For data from forward and backward di-hadron events with $y^\ast(Z) < -2.47$ and $1.53 < y^\ast(Z) < 4.03$ the acceptance in the ratio $R_{\text{eff}}$ is the correction factor for the di-hadron efficiency, with a 2% probability to observe a value of $R_{\text{eff}}$ different from unity.

- The probability is estimated with a toy Monte Carlo assuming non-Gaussian statistical uncertainties. The second uncertainty is systematic and includes the uncertainties on the theoretical predictions as well as on the experimental uncertainties on the production cross-sections in proton-lead collisions measured in the fiducial region.

- The uncertainty on the candidate $e_\text{eff}$ efficiency includes the uncertainties on the acceptance correction factor and those containing uncertainties on the efficiency 0.5% 0.5%.

- All systematic uncertainties are added in quadrature to give the total systematic uncertainty as they are considered uncorrelated.
pPb $Z$ boson production at 8 TeV

- 8 TeV in 2016,
- Integrated luminosity: forward (12.2 ± 0.3 nb$^{-1}$) / backward (18.6 ± 0.5 nb$^{-1}$)
- Yields: forward (268 events) / backward (167 events)

![Figure 1: Control plots of the dimuon system after the offline selection, which includes the dimuon invariant mass ($m_{\mu^+\mu^-}$) distributions for $pPb$ (a) and $PbP$ (b) configurations, the $p_T$ of the $Z$ candidates ($p_T(Z)$) for $pPb$ (c) and $PbP$ (d) configurations, and the rapidity of the dimuon system in the centre-of-mass frame ($y_{Z}$) for $pPb$ (e) and $PbP$ (f) configurations. The red line shows the distributions from simulation generated using Pythia 8 with CTEQ6L1 PDF set, normalised to the number of observed candidates.](image)

【LHCb-CONF-2019-003】
pPb Z boson production at 8 TeV

- 8 TeV in 2016
- Integrated luminosity:
  - forward \((12.2 \pm 0.3 \text{ nb}^{-1})\)
  - backward \((18.6 \pm 0.5 \text{ nb}^{-1})\)
- Yields:
  - forward (268 events)
  - backward (167 events)

【LHCb-CONF-2019-003】
**pPb Z boson production at 8 TeV**

**much higher precision**

**Fiducial cross-section results:**

\[ \sigma_{Z \rightarrow \mu^+\mu^-}, pPb \ (\text{forward}) \]

\[ = 28.5 \pm 1.7\,\text{(stat.)} \pm 1.2\,\text{(syst.)} \pm 0.7\,\text{(lumi.)}\,\text{nb} \]

\[ \sigma_{Z \rightarrow \mu^+\mu^-}, PbP \ (\text{backward}) \]

\[ = 13.4 \pm 1.0\,\text{(stat.)} \pm 1.4\,\text{(syst.)} \pm 0.3\,\text{(lumi.)}\,\text{nb} \]

**Compatible with theoretical predictions using FEWZ(NNLO pQCD+NLO pEW) with NNPDF3.1(PDF) for p and**

\[ \{ \text{NNPDF3.1(PDF)}, \text{EPPS16 (nPDF)} \} \text{ for Pb} \]

\[ \{ \text{NNPDF3.1(PDF)}, \text{EPPS16 (nPDF)} \} \text{ for Pb} \]

1.53 < y*(Z) < 4.03

-4.97 < y*(Z) < -2.47
Compare with results at 5 TeV

- Results are compatible with previous 5 TeV results from various experiments
- The 20 times higher statistics bring higher precision in the measurements

* only exp. uncert. shown on data/theory ratio, theo. PDF uncert. shown separately on the line at one.

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Forward-backward ratio

- Forward-backward ratio is derived based on cross-sections measured in the common rapidity range:

\[ \sigma_{Z^{\pm}}^{2.5<|y^{\tau}|<4.0} = 17.1 \pm 1.4\text{(stat.)} \pm 0.7\text{(syst.)} \pm 0.4\text{(lumi.)} \text{ nb}, \]

\[ \sigma_{Z^{\pm}}^{2.5<|y^{\tau}|<4.0} = 13.3 \pm 1.0\text{(stat.)} \pm 1.4\text{(syst.)} \pm 0.3\text{(lumi.)} \text{ nb}, \]

- Measured forward-backward ratio

\[ R_{FB}^{2.5<|y^{\tau}|<4.0} = 1.28 \pm 0.14\text{(stat.)} \pm 0.14\text{(syst.)} \pm 0.05\text{(lumi.)}. \]

- Compatible with theoretical predictions:

\[ R_{FB,NNPDF3.1}^{2.5<|y^{\tau}|<4.0} = 1.59 \pm 0.10\text{(theo.)} \pm 0.01\text{(num.)} \pm 0.05\text{(PDF)}, \]

\[ R_{FB,NNPDF3.1+EPPS16}^{2.5<|y^{\tau}|<4.0} = 1.45 \pm 0.10\text{(theo.)} \pm 0.01\text{(num.)} \pm 0.27\text{(PDF)}, \]

\[ R_{FB,NNPDF3.1+nCTEQ15}^{2.5<|y^{\tau}|<4.0} = 1.44 \pm 0.10\text{(theo.)} \pm 0.01\text{(num.)} \pm 0.20\text{(PDF)}. \]
Ultra-peripheral PbPb Collisions
Ultra-peripheral PbPb Collisions

- Ultra-peripheral collisions: Two nuclei bypass each other with an impact parameter larger than the sum of their radii.
- Photon-induced interactions are enhanced by the strong electromagnetic field of the nucleus.
- Coherent J/ψ production gives constraints on the gluon Probability Density Functions.
- The (J/ψ) / ψ(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]

Photon-Photon interactions

Precisely know at p-QED

Photon-induced quarkonium production:
A q̅q loop created by the photon interactions with a pair of gluon exchange (pomeron) to produce a quarkonium (c̅c, b̅b, etc.)

Coherent J/ψ production:
photon interact with the whole nucleus coherently

Incoherent J/ψ production:
photon interact with particular nucleons in the nucleus

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The charmonium measurement in PbPb UPC

Cross-sections

\[
\frac{d\sigma_{\text{coh.}, J/\psi}}{dy} = \frac{N_{\text{coh.}, J/\psi}}{\varepsilon_{\text{total}} \cdot B(J/\psi \rightarrow \mu^+ \mu^-) \cdot \mathcal{L} \cdot \Delta y}
\]

\[
\frac{d\sigma_{\text{coh.}, \psi(2S)}}{dy} = \frac{N_{\text{coh.}, \psi(2S)}}{\varepsilon_{\text{total}} \cdot B(\psi(2S) \rightarrow \mu^+ \mu^-) \cdot \mathcal{L} \cdot \Delta y}
\]

The signal yields are extracted from the dimuon mass fits

Acceptance is defined as:

- \(2.0 < \eta^\mu < 4.5\), \(p_T^\mu > 700\) MeV,
- \(p_T^{\mu\mu} < 1\) GeV, \(|\Delta \phi_{\mu\mu}| > 0.9\pi\)

Using PbPb datasets in 2015 and 2018

<table>
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<tr>
<th>(\sqrt{s_{NN}})</th>
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<th>2018</th>
</tr>
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<td>(\mathcal{L})</td>
<td>PbPb</td>
<td>PbPb</td>
</tr>
<tr>
<td>(5.02) TeV</td>
<td>(10 \mu b^{-1})</td>
<td>(\sim 210 \mu b^{-1})</td>
</tr>
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Event selection require a near empty detector with only two long tracks reconstructed.

Herschel detector is used to further reduce the multiplicities [JINST 13 (2018) 04 P04017]
Dimuon mass fits

- 2015 dataset: $1003 \pm 30 \ J/\psi$ and about $30 \ \psi(2S)$

![Dimuon mass spectrum](image)

- Figure 1: Dimuon invariant mass spectrum in the range between 2.7 and 4.0 GeV. The $J/\psi$ (solid blue line), $\psi(2S)$ (solid green line) and nonresonant (black dashed line) contributions are shown individually and the sum of all contributions is represented by the orange curve.

![Log distribution](image)

- Figure 2: Distribution of $\log(p^2 / T^2)$ of dimuon candidates after all requirements have been applied. The orange line represents the fit to the data points; the blue line shows the coherent contribution and the green (black) line shows the incoherent and feed-down (nonresonant) component. A fit is performed to data using three different templates obtained from the STARlight event generator.
$\ln(p_T^2)$ fits to extract the coherent component

- **2015 dataset**

![Graph showing data, coherent, incoherent+feed-down, non-resonant, and sum components for $J/\psi$ coherent: $713 \pm 28$.](image-url)

**LHCb Preliminary**

$\text{Pb-Pb } \sqrt{s_{_{NN}}} = 5 \text{ TeV}$

$J/\psi$ coherent: $713 \pm 28$
Coherent $J/\psi$ cross-section:
\[ \sigma = 5.27 \pm 0.21 \text{ (stat)} \pm 0.49 \text{ (syst.)} \pm 0.68 \text{ (lumi.)} \text{ mb} \]

The analysis is repeated in bins of half unit rapidity $y(J/\psi)$

Uncertainties for statistics, systematic and luminosity are of comparable magnitude

The LHCb acceptance is interesting to discriminate between the models

pQCD calculations: [PRC 93 (2016) 055206]

Color dipole models:
[PRD 96 (2017) 094027]
[PRC 97 (2018) 024901]
[PLB 772 (2017) 832]
The 2018 dataset

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<tr>
<td>L</td>
<td>10 μb⁻¹</td>
<td>~ 210 μb⁻¹</td>
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</table>

✧ About 20 times more statistics in 2018

✧ 2015 dataset: 1003 ± 30 J/ψ and about 30 Ψ(2S)

LHCB-Preliminary

Pb-Pb √s_{NN} = 5 TeV

【LHCb-CONF-2018-003】

Candidates / (13 MeV)

2.0 < y < 4.5

LHCB Preliminary

Pb-Pb 2018

√s_{NN} = 5 TeV

【https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlotsQM2019】

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Dimuon mass fits

- The 20 times high statistics make it possible to determine the cross-sections of both both J/ψ and ψ(2S) simultaneously in 5 rapidity bins.

- Can also measure the cross-section ratio (J/ψ) / ψ(2S)

\[
\frac{\sigma_{J/\psi}}{\sigma_{\psi(2S)}} = \frac{N_{J/\psi} \cdot \varepsilon_{\psi(2S)} \cdot \mathcal{B}(\psi(2S) \rightarrow \mu^+\mu^-)}{N_{\psi(2S)} \cdot \varepsilon_{J/\psi} \cdot \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}
\]

- 2018 dataset

- New!

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[https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlotsQM2019](https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlotsQM2019)
Conclusion

- LHCb provides a unique opportunity to probe the cold nuclear matter effects using Z boson production
- pPb->Z boson production at 5 TeV and 8 TeV results are presented
- Results are compatible with theoretical predictions
- 8 TeV results give much higher precision
- Charmonium production in Ultra-peripheral Pb-Pb collisions are of particular interests to probe gluon Parton Density Functions
- Results based on 2015 PbPb dataset at 5 TeV are presented
- Higher precision results using 2018 data set with 20 times higher statistics for both the J/ψ and ψ(2S) cross-sections are coming soon.