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Z production in pPb collisions and charmonium production in PbPb ultra-peripheral collisions at LHCb

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Abstract

This article presents recent results of the Z boson production in the proton-lead collisions and the charmonium production in the ultra-peripheral lead-lead collisions at the LHC collected during 2013 to 2018 by the LHCb detector. The potential heavy ion programs in these topics are also discussed.

Keywords: Heavy-ion collisions, nuclear modification, Z boson production, ultra-peripheral collisions, charmonium production, LHCb experiment, LHC

1. Introduction

The LHCb detector [1, 2] is a fully instrumented single-arm spectrometer in the forward region covering a pseudorapidity acceptance of $2 < \eta < 5$, providing a high tracking momentum resolution down to very low transverse momentum (p_T) and precise vertex reconstruction capability. The detector is originally designed for heavy-flavour measurements, precision tests of the standard model (SM), and searches for physics beyond the SM. As a young member of the LHC heavy ion program, the LHCb experiment also provides the unique datasets for the heavy ion physics studies at LHC. The heavy ion program at LHCb includes proton-lead (pPb), lead-lead (PbPb), and xenon-xenon (XeXe) collisions, together with fixed-target collisions of p or Pb with noble gases nuclei injected around the interaction point. The summary of the LHCb heavy ion data in collision mode and recorded integrated luminosities are given in Table 1.

In this article, we present recent results of the Z boson production in the proton-lead collisions [3, 4] and the charmonium production in the ultra-peripheral lead-lead collisions [5] at the LHC using datasets collected during 2013 to 2018 by the LHCb detector.

$\sqrt{s_{NN}}$	2013 5.02 TeV		2016 8.16 TeV		2015 5.02 TeV	2017 5.02 TeV	2018 5.02 TeV
	pPb	Pbp	pPb	Pbp	PbPb	XeXe	PbPb
\mathcal{L}	1.1 nb^{-1}	0.5 nb^{-1}	13.6 nb^{-1}	20.8 nb^{-1}	$10 \mu\text{b}^{-1}$	$0.4 \mu\text{b}^{-1}$	$\sim 210 \mu\text{b}^{-1}$

Table 1. Summary of the LHCb heavy ion collisions and the recorded integrated luminosities.

2. Z boson production in proton-lead collisions

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 strong interactions. Therefore, electroweak boson productions well retained the initial conditions of the collisions, can be used to probe nuclear matter effects and constraint nuclear parton distribution functions (nPDFs) for Bjorken- x from $\sim 10^{-4}$ to 1 at $Q^2 \sim 10^4 \text{ GeV}^2$ [6, 7], and can be used as a calibration of the nuclear modification factor of other processes.

Using pPb datasets collected by the LHCb detector at 5.02 TeV and 8.16 TeV as summarized in Table 1, the Z boson production cross-sections in the muon decay channel are measured in the fiducial volume in both the forward (p-Pb) and backward (Pb-p) collision configurations [3, 4] based on the following equation: $\sigma_{Z \rightarrow \mu^+ \mu^-} = [N_{\text{cand}} \cdot \rho] / [\mathcal{L} \cdot \epsilon]$, where $\sigma_{Z \rightarrow \mu^+ \mu^-}$ is the production cross-section to be measured, N_{cand} is the number of $Z \rightarrow \mu^+ \mu^-$ candidates pass signal selection, ρ is the signal purity of the selected Z candidates, \mathcal{L} is the integrated luminosity, and ϵ is the total efficiency includes trigger, reconstruction and selection efficiencies. The fiducial volume is defined as $60 < m_{\mu^+ \mu^-} < 120 \text{ GeV}$, $2.0 < \eta_{\mu^\pm} < 4.5$, and $p_T^{\mu^\pm} > 20 \text{ GeV}$. The purity is measured using data-driven methods, and the efficiencies are estimated using Monte-Carlo (MC) samples together with tag-and-probe data driven corrections.

The invariant mass distributions of selected signal candidates are shown in Fig. 1 for datasets taken in 2016 at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$.

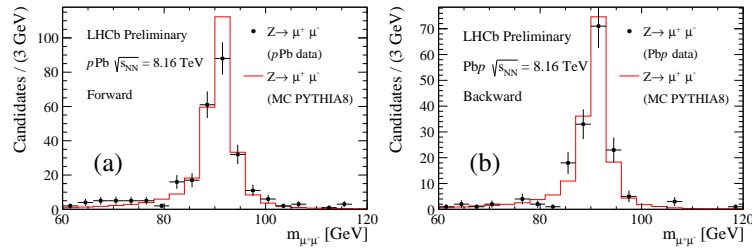


Fig. 1. (color online) The dimuon invariant mass distributions after the offline selection for pPb (a) and Pbp (b) configurations, using datasets taken in 2016 at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$. The red line shows the distributions from simulation generated using PYTHIA 8 [8] with CTEQ6L1 [9] PDF set, normalised to the number of observed candidates.

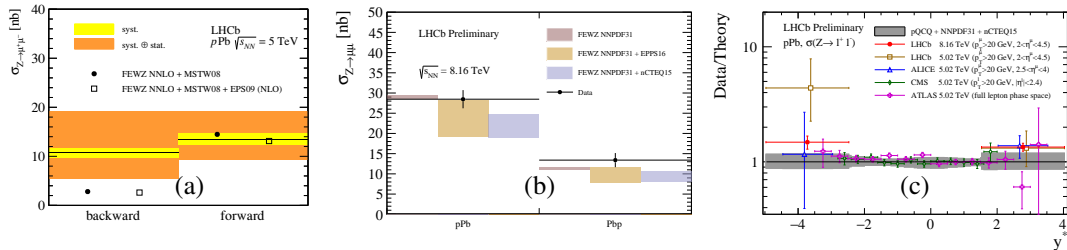


Fig. 2. (color online) (a, b) Measured fiducial cross-sections of Z production and theoretical calculations using various PDF sets with or without nuclear modification. Figure (a) is for dataset taken in 2013 at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ and figure (b) is for dataset taken in 2016 at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$. (c) Comparison of LHCb 8.16 TeV results with previous 5.02 TeV results from ATLAS, CMS, ALICE, and LHCb. The uncertainties on the data over theory ratios include only the experimental statistical and systematic uncertainties; the PDF uncertainties are shown separately on the line at one. The central values of the LHCb and ALICE results at 5.02 TeV are shifted to left and right by 0.1 units in rapidity, respectively, for better visibility.

The resulting fiducial cross-sections for centre-of-mass energies at 5.02 TeV and 8.16 TeV [3, 4] are shown in Fig. 2 (a) and (b), respectively. The results are compared with theoretical calculations using FEWZ [10, 11] with MSTW08 [12] free nucleon PDF together EPS09 (NLO) [13] nPDF for dataset at 5.02 TeV, and with NNPDF 3.1 [14] free nucleon PDF together EPPS16 (NLO) [7] and nCTEQ15 (NLO) [6, 15] nPDFs for dataset at 8.16 TeV. The results are also compared with previous 5.02 TeV results from LHCb [3], ATLAS [16], CMS [17], and ALICE [18], as shown in Fig. 2 (c). The new LHCb

8.16 TeV results are compatible with previous 5.02 TeV results at LHCb, but with about 20 times higher statistics, it is the most precise measurement at forward region at LHC.

The ratio of the Z boson production cross-sections for forward and backward configurations, R_{FB} , is particularly sensitive to nuclear effects. R_{FB} is measured in the common rapidity region ($2.5 < |y^*| < 4.0$) in the centre-of-mass frame of the produced Z boson using 2016 dataset [4] as $R_{FB}^{2.5 < |y^*| < 4.0} = 1.28 \pm 0.14(\text{stat}) \pm 0.14(\text{syst}) \pm 0.05(\text{lumi})$, which is compatible with theoretical calculations using FEWZ with the following nPDFs: $R_{FB, \text{NNPDF3.1+EPPS16}}^{2.5 < |y^*| < 4.0} = 1.45 \pm 0.10(\text{theo.}) \pm 0.01(\text{num.}) \pm 0.27(\text{nPDF})$, and $R_{FB, \text{NNPDF3.1+nCTEQ15}}^{2.5 < |y^*| < 4.0} = 1.44 \pm 0.10(\text{theo.}) \pm 0.01(\text{num.}) \pm 0.20(\text{nPDF})$, where, the uncertainty num. from the numerical precision.

3. Charmonium production in ultra-peripheral lead-lead collisions

Ultra-peripheral collisions (UPC) [19, 20] refer to the photon-induced interactions when two nuclei pass each other with an impact parameter larger than the sum of their radii. In case of nuclei with higher atomic numbers such as lead (Pb), the photon-induced interactions are enhanced by the strong electromagnetic field, which include photon-photon and photon-pomeron interactions. Charmonium can be produced in the photon-pomeron interactions, where a photon emitted from one nucleus converted to a $c\bar{c}$ pair interacts with a pair of gluon exchanges (pomeron) emitted from the other nucleus. These productions can be distinguished as (1) coherent if the photon interact coherently with the whole nucleus, or (2) incoherent if the photon interacts with a single nucleon inside the nucleus. Because of the gluon exchange mechanism in the UPC charmonium production, such production is expected to probe the nuclear gluon distribution functions for Bjorken- x between $\sim 10^{-5}$ and 10^{-2} with a hard scales of $Q^2 \sim m_{J/\psi, \psi(2S)}^2/4$. The UPC charmonium productions are therefore essential to constrain the uncertainty over the initial state, which is currently limiting the measurements of certain fundamental properties of the quark gluon plasma, such as the viscosity, to a high precision.

Considering the extremely low transverse momentum exchange, the event selection of the UPC charmonium production requires a near empty detector with two long muon tracks reconstructed. The inclusive J/ψ and $\psi(2S)$ production yields are extracted from the dimuon invariant mass fit, as shown in Fig. 3 (a) for the LHCb 2015 PbPb dataset corresponding to an integrated luminosity of about $10 \mu\text{b}^{-1}$ [5], and (b) for the 2018 PbPb dataset corresponding integrated luminosity about 20 times higher than the 2015 dataset. The coherent and incoherent parts are then distinguished using a fit to the $\log(p_T^2)$ spectrum, as shown in Fig. 4 (a) for the 2015 dataset. The same $\log(p_T^2)$ fit is performed for five separated charmonium rapidity bins to extract the coherent J/ψ production yields differentially. The resulting coherent J/ψ production differential

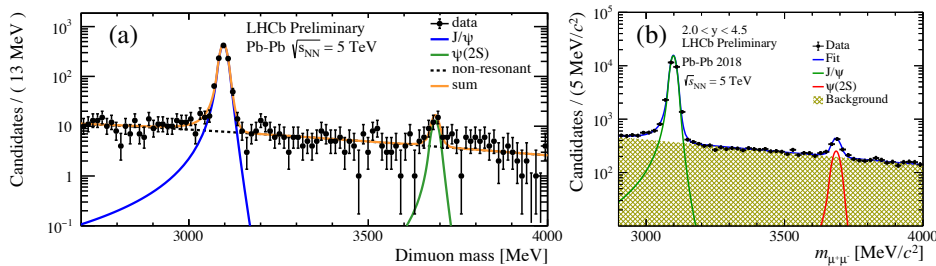


Fig. 3. (color online) Mass distributions fit to determine the fractions of J/ψ and $\psi(2S)$ and non-resonant events. Figure (a) is for 2015 dataset, and figure (b) is for 2018 dataset.

cross-section measured using the 2015 data sample is shown in Fig. 4 (b), which is compatible with most of the theoretical predictions shown in the figure, including pQCD calculations [21] and parametrisation based on the framework of colour-dipole model [22, 23, 24].

4. Conclusion and outlook

LHCb provides a unique opportunity to probe the cold nuclear matter effects using Z boson production. Results of pPb collisions at 5.02 TeV and 8.16 TeV results are presented, which are compatible with theoret-

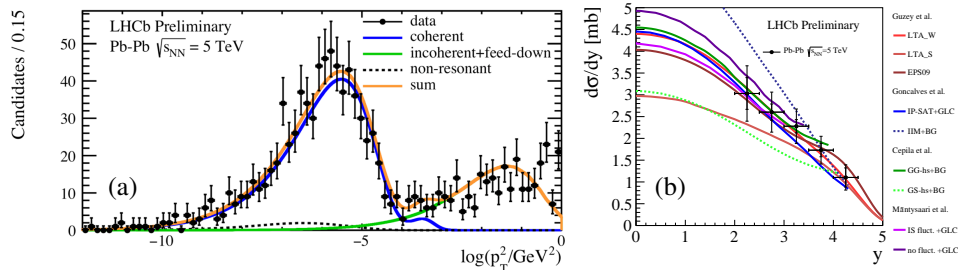


Fig. 4. (color online) (a) Fit to the distribution of $\log(p_T^2)$ of dimuon candidates after all requirements have been applied to extract the yields of coherent and incoherent J/ψ productions. (b) Differential cross-section for coherent J/ψ production measured using 2015 PbPb dataset compared to different phenomenological predictions.

ical predictions involving nPDFs, where 8.16 TeV results give the highest precision in the forward region at LHC. Charmonium production in ultra-peripheral PbPb collisions are of particular interests to probe gluon PDFs. Results based on 2015 PbPb dataset at 5.02 TeV are presented. Higher precision results using 2018 dataset with 20 times higher statistics for both the J/ψ and $\psi(2S)$ cross-sections are coming soon.

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