RESULTS ON HEAVY ION COLLISIONS AT LHCb

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Heavy flavor production is important in heavy ion collisions to study both cold and hot nuclear matter effects. The LHCb experiment can make unique contribution to heavy ion physics, owing to the full particle identification of the detector in the forward region and the ability to collect fixed target data with proton or lead beams. This report describes recent results with proton-lead collision data collected in 2013 and the prospect of heavy-ion studies at LHCb.

1 Introduction

At high energy densities, hadrons are transformed into quark gluon plasma (QGP), a new state of matter in which quarks and gluons are deconfined and move like freely. The hot QGP medium is expected to be produced in high energy heavy nucleus-nucleus collisions. The formation and properties of the QGP can be studied with heavy flavor production. Heavy flavors are produced via hard interactions at the early stage of the nucleus-nucleus collision, so they will interact with the QGP when they traverse the medium later on. In nucleus-nucleus collisions, the heavy flavor production is also affected by cold nuclear matter effects (CNM), which are present regardless of the formation of QGP. To disentangle the CNM effects from the QGP effects, heavy flavor production in proton-nucleus collisions could be studied. In this report, we present the heavy-ion physics programs at LHCb and summarize the results on heavy flavor production studies in proton-lead data collected by the LHCb detector.

2 LHCb detector and data taking

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. The LHCb experiment is designed for precision measurements in the $b$ and $c$ quark sectors, but it is becoming a general purpose detector in the forward rapidity range. The LHCb detector consisting of the tracking systems, the hadron particle identification, calorimeters and the muon system, is fully instrumented in the fiducial region. This feature makes it possible to study the heavy flavors in a unique kinematic region, namely low transverse momentum $p_T$, large rapidity $y$, very large or small Feynman $x_F$, complementary to other LHC experiments. The details of the design and performances of the LHCb detector could be found in the references $^1,^2$.

So far the LHCb detector has collected data of proton-proton ($pp$), proton-lead ($p\text{Pb}$) and lead-lead (PbPb) collisions, and also proton- or lead-gas fixed target collisions thanks to the System for Measuring the Overlap with Gas (SMOG) $^3$ at LHCb. The fixed target data will be discussed in detail later. These data are collected at different discrete nucleon-nucleon center-of-mass energies, $\sqrt{s_{NN}}$, from 54 GeV to 13 TeV. The analyses presented in this report are based on the $p\text{Pb}$ data taken at $\sqrt{s_{NN}} = 5$ TeV in 2013. Since the LHCb detector covers only one direction of the full acceptance, there are two distinctive beam configurations at LHCb for the
LHCb preliminary

The distribution of the number of tracks in simulation is corrected to match that in data. Reconstruction efficiency and particle identification efficiency are calibrated using data, and the hadron decays ($D^0$) over all kinematic bins, are given in Fig. 1. LHCb is the unique experiment that could separate binary colliding pairs ($A_{NN}^{pp}$) that in $p$-$p$ collisions. In the forward (backward) configuration, the proton (lead) beam enters LHCb detector from the interaction point. The proton beam and the lead beam have different energies per nucleon in the laboratory frame, so the nucleon-nucleon center-of-mass frame is boosted in the proton direction with a rapidity shift $\Delta y = 0.46$. The LHCb acceptance for forward (backward) collision is $1.5 < y^* < 4 \; (-5 < y^* < -2.5)$ \(^a\) and the corresponding integrated luminosity is about $1.1 \, \text{nb}^{-1} \; (0.5 \, \text{nb}^{-1})$ for the forward (backward) collisions.

### 3 Prompt $D^0$ production

At LHCb, the $D^0$ candidate is fully reconstructed in the $D^0 \to K^- \pi^+$ decay mode, and selections are applied exploring the large impact parameter and particle identification of the $K^- \pi^+$ tracks, and vertex displacement of the $D^0$ candidate \(^4\). The signal and background events are discriminated by fitting the invariant mass distribution, and the prompt $D^0$ and $D^0$ from $b$ hadron decays ($D^0$-from-$b$) are separated by fitting the impact parameter significance ($\chi^2_{IP}$) of the $D^0$ candidate. The $\chi^2_{IP}$ and invariant mass distribution for the forward sample, integrating over all kinematic bins, are given in Fig. 1. LHCb is the unique experiment that could separate the $D^0$-from-$b$ component down to zero $p_T$ region. For the cross-section measurements, the reconstruction efficiency and particle identification efficiency are calibrated using data, and the distribution of the number of tracks in simulation is corrected to match that in data.

The double differential cross-section as a function of $p_T$ and $y^*$ is measured in the range $0 < p_T < 8$ GeV, and $1.5 < y^* < 4 \; (-5 < y^* < -2.5)$ for the forward (backward) sample. The nuclear modification factor, $R_{pPb}$, is determined to be the cross-section in $pPb$ collisions over that in $pp$ collisions at the same center-of-mass collideing energy, normalized by the number of binary colliding pairs $A$ ($A = 208$ for $pPb$ collisions), as $R_{pPb}(y^*, p_T) = \frac{1}{A} \times \frac{\sigma_{pPb}(y^*, p_T, \sqrt{s_{NN}})}{\sigma_{pp}(y^*, p_T, \sqrt{s_{NN}})}$.

The reference cross-section in $pp$ collisions at 5 TeV is determined by extrapolation from results at 7 and 13 TeV \(^5,6\) with the method described in reference \(^7\). The reference cross-section measurements in $pp$ collisions at 5 TeV is underway. In Fig. 2, the $R_{pPb}$, as a function of $p_T$ integrated over the rapidity range $2.5 < |y^*| < 4$ are given for the backward (left) and forward (right) data. The large uncertainties are dominated by the extrapolated reference cross-section. Generally speaking, the nuclear modification factor in the forward sample is smaller than that in the backward sample. Good agreements are found between LHCb measurements and the MNR calculations \(^10\) with CTEQ6M \(^11\) and EPS09NLO \(^12\) parton distribution functions.

\(^a\)The rapidity $y^*$ is defined in the nucleon-nucleon rest frame with the momentum direction of proton as positive $z$-axis.
The forward-backward ratio, $R_{FB}$, is defined as $R_{FB}(|y^*|, p_T) = \frac{\sigma_{pPb}(+|y^*|, p_T)}{\sigma_{pPb}(-|y^*|, p_T)}$, and systematic uncertainties largely cancel in the ratio. The $R_{FB}$ as a function of $p_T$ and $y^*$ is given in Fig. 3, and the results suggest significant production asymmetry between the forward and backward acceptance, indicating strong nuclear matter effects. The measurements are in reasonable agreement with MNR calculations.

### 4 Quarkonium productions

LHCb also studied the CNM effects in pPb data using the productions of quarkonia, including $J/\psi$, $\psi(2S)$ and $\Upsilon$ mesons. The prompt $J/\psi$ and $\psi(2S)$ mesons are separated from those from $b$-hadron decays, allowing to study the CNM effects for both components. The results of $R_{pPb}$ for the quarkonium states are given in Fig. 4. It can be seen that in the forward sample, $J/\psi$ production in pPb is strongly suppressed compared to that in pp, the suppression for $\psi(2S)$ is even stronger, while that for $\Upsilon(1S)$ is modest. In the backward data sample, $R_{pPb}$ is compatible with unity for $J/\psi$ and $\Upsilon$ mesons, but intriguing strong suppression is seen for $\psi(2S)$, suggesting that the mechanism for $\psi(2S)$ production in pPb collisions is not the same as that for $J/\psi$, which is to be understood. In the forward sample, $R_{pPb}$ for $\psi$-from-$b$ is closer to unity than for prompt $\psi$ mesons, which indicates that the open bottom hadrons in pPb are less suppressed compared to prompt charmonium. The measurements of $R_{pPb}$ for $J/\psi$ and $\Upsilon$ are in good agreements with various theoretical calculations referred to in the corresponding paper.
5 Prospects of LHCb heavy ion studies

At LHCb, the fixed target program benefits from the SMOG device. When noble gas is injected in SMOG, the proton and lead beams can collide with the gas similar to fixed target collisions. With different choices of noble gases, we are able to explore different sizes of colliding systems. In the past, LHCb has already collected short runs of SMOG collisions, including pNe at $\sqrt{s_{NN}} = 110$ GeV, and PbNe at $\sqrt{s_{NN}} = 54$ GeV, and clear $J/\psi$ signals are observed in these samples. LHCb also collected PbPb collisions in 2015, and more will be available in the coming years.

6 Summary

In conclusion, heavy flavors are good tools to study the physics in heavy ion collisions, and LHCb has demonstrated its capabilities to contribute significantly to heavy ion studies. LHCb has studied cold nuclear matter effects using quarkonia and open charm productions with the $p$Pb data at $\sqrt{s_{NN}} = 5$ TeV. LHCb also collected PbPb collisions, allowing to study rich physics programs covering heavy flavours, electroweak, soft QCD and QGP physics. LHCb is also unique to do fixed target physics, exploiting colliding systems of different sizes at low energies using the SMOG system.

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References

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