Heavy flavour production in proton-lead and lead-lead collisions with LHCb

Michael Winn

Laboratoire de l’Accélérateur Linéaire

Abstract

The LHCb experiment offers the unique opportunity to study heavy-ion interactions in the forward region ($2 < \eta < 5$), in a kinematic domain complementary to the other 3 large experiments at the LHC. The detector has excellent capabilities for reconstructing quarkonia and open charm states, including baryons, down to zero $p_T$. It can separate the prompt and displaced charm components. In $p\bar{p}$ collisions, both forward and backward rapidities are covered thanks to the possibility of beam reversal. Results include measurements of the nuclear modification factor and forward-backward ratio for charmonium, open charm and bottomonium states. These quantities are sensitive probes for nuclear effects in heavy flavour production. Perspectives are given with the large accumulated luminosity during the 2016 $p\bar{p}$ run at the LHC. In 2015, LHCb participated successfully for the first time in the PbPb data-taking. The status of the forward prompt $J/\psi$ nuclear modification factor measurement in lead-lead collisions is discussed.

Keywords: keywords, LHC, QCD, heavy-ion collisions, heavy-flavour, quarkonium, LHCb
VELO detector. Two RICH detectors allow charged particle identification in the momentum range between 10 to 100 GeV/c. An electromagnetic calorimeter, a hadronic calorimeter and a muon system for particle identification, photon detection and hardware triggers complete the detector set-up.

In 2015, LHCb collected for the first time PbPb collisions. The detector recorded about 50 million minimum bias collisions with a data taking efficiency of around 90% excluding dead-time. The detector is designed for running in pp collisions at an average number of visible interactions of order one. The limitations of the detector in central PbPb collisions can be seen in Fig.1 on the left hand side: it becomes evident that the tracker occupancy saturates at 100% for most central collisions. With the current tracking algorithms, it is possible to reconstruct events up to a centrality of about 50%. An analysis is ongoing aiming at the extraction of the nuclear modification factor of prompt \(J/\psi\) production in peripheral collisions.

The signal extraction of the \(J/\psi\) is shown for the centrality interval 50-70% in Fig. 1 on the right hand side. A mass resolution of about 10 MeV/\(c^2\) is achieved similar to the resolution in pp collisions. The analysis efforts concentrate in PbPb at the moment on the tracking efficiency evaluation with data-driven methods.

LHCb participated successfully in the pPb data taking 2013 at \(\sqrt{s_{NN}} = 5\) TeV. The forward acceptance implies coverage down to Bjorken-\(x\) values of \(10^{-6}\) with heavy quarks, a regime, where no experimental data exists prior to the LHC in nuclear collisions. In Fig.2, the nuclear modification factor of prompt \(J/\psi\) and prompt \(\psi(2S)\) is shown compared with different phenomenological calculations. Collinear pQCD calculations using nuclear parton distribution functions can describe the data within uncertainties as well as the coherent energy loss model. Color Glass Condensate calculations published after the publication of the experimental data in the dilute-dense limit are also able to describe the data at forward rapidity. However, the behaviour of the excited \(\psi(2S)\) bound state production, an additional nuclear suppression by about a factor two compared to the \(J/\psi\) has been observed in Run 1, cannot be explained by those models. One calculation tries to solve the puzzle by the introduction of late stage interactions of the resonant state. It can describe the additional suppression within the current experimental precision. Another approach with late stage interaction is also able to describe the additional \(\psi(2S)\) suppression fairly well. In Fig. 2 the forward-backward ratio of \(D^0\)-meson production at \(\sqrt{s_{NN}} = 5\) TeV is shown and compared with a calculation using the nuclear parton distribution function set EPS09. The approach describes well the data. This preliminary result will be soon superseded by a publication exploiting the full data sample, corresponding to about a factor 10 more statistics compared to the analysis presented here.

The vast majority of heavy-flavour observables with the 2013 pPb data sample, the \(\Upsilon\) and Z-boson analyses even to a larger extent, are strongly statistically limited or not yet accessible. In 2016, the LHC provided an integrated luminosity larger by about a factor 10 for the pPb \((1.1\text{ nb}^{-1}\text{ versus about } 13\text{ nb}^{-1})\) and a factor 30 for the PbPb \((0.5\text{ nb}^{-1}\text{ versus about } 17\text{ nb}^{-1})\) beam configuration at \(\sqrt{s_{NN}} = 8.2\) TeV. These data samples will allow for more precise measurements in the charm and beauty sector as the performance plots of various particle species depicted in Fig.3 already promise. In addition, it will be possible to
add to the heavy-flavour programme significant measurements of electro-weak or electromagnetic probes as Drell-Yan production at low masses as well as Z and W production. These theoretical clean measurements will allow to constrain further possible nuclear modification mechanisms in the asymmetric pPb collision system, see e.g. in Ref. [23].

The upgrade of the LHCb experiment is aiming at a continuous read-out of the detector at 40 MHz at around 5 times higher luminosities implying also 5 times larger number of simultaneous collisions per bunch crossing [24]. The replacement of the strip VELO detector with a pixel detector and of all tracking stations with detectors with larger granularity [25, 26] will be beneficial for the heavy-ion programme of LHCb.

LHCb allows to measure heavy-flavour production at forward rapidity providing unique coverage down to vanishing transverse momentum. Measurements of open and closed heavy-flavour hadrons are possible with detectors with larger granularity [25, 26] will be beneficial for the heavy-ion programme of LHCb.

**Acknowledgement:** The contact author acknowledges support from the European Research Council (ERC) through the project EXPLORINGMATTER, founded by the ERC through a ERC-Consolidator-Grant.

**References**

[1] A. Andronic, et al., Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions, Eur. Phys. J. C76 (2016) 07. arXiv:1506.03981 doi:10.1140/epjc/s10052-015-3819-5

[2] A. Mocsy, P. Petreczky, M. Strickland, Quarkonia in the Quark Gluon Plasma, Int. J. Mod. Phys. A28 (2013) 1340012. arXiv:1302.2180 doi:10.1142/S0217751X13400125

[3] K. J. Eskola, H. Paukkunen, C. A. Salgado, EPS09: A New Generation of NLO and LO Nuclear Parton Distribution Functions, JHEP 04 (2009) 065. arXiv:0902.4154 doi:10.1088/1126-6708/2009/04/065

[4] K. Kovarik, et al., nCTEQ15 - Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework, Phys. Rev. D93 (2016) 085037. arXiv:1509.00792 doi:10.1103/PhysRevD.93.085037

[5] K. J. Eskola, P. Paukkunen, H. Paukkunen, C. A. Salgado, EPS09: Nuclear parton distributions with LHC data, Eur. Phys. J. C77 (3) (2017) 163. arXiv:1612.05741 doi:10.1140/epjc/s10052-017-4725-9

[6] H. Fujii, F. Gelis, R. Venugopalan, Quark pair production in high energy pA collisions: General features, Nucl. Phys. A780 (2006) 146–174. arXiv:hep-ph/0603099 doi:10.1016/j.nuclphysa.2006.09.012

[7] F. Arleo, S. Peigné, Heavy-quarkonium suppression in p-A collisions from parton energy loss in cold QCD matter, JHEP 03 (2013) 122. arXiv:1212.0434 doi:10.1007/JHEP03(2013)122

[8] R. Aaij, et al., LHCb detector performance, Int. J. Mod. Phys. A30 (2015) 1530022. arXiv:1412.6362 doi:10.1142/S0217751X15300227

[9] R. Aaij, et al., Study of J/ψ production and cold nuclear matter effects in pPb collisions at √s_{NN} = 5 TeV, JHEP 02 (2014) 072. arXiv:1308.6729 doi:10.1007/JHEP02(2014)072

[10] R. Aaij, et al., Study of φ(2S) production cross-sections and cold nuclear matter effects in pPb collisions at √s_{NN} = 5 TeV, JHEP 03 (2016) 133. arXiv:1601.07870 doi:10.1007/JHEP03(2016)133
Fig. 3. Invariant mass peaks from the 2016 pPb data taking campaign: J/ψ in PbPb collisions (top left), Λ_c in pPb collisions, B_0 in pPb (bottom left) and Λ_b in pPb (bottom right).

[11] J. L. Albacete, et al., Predictions for p+Pb Collisions at \( \sqrt{s_{NN}} = 5 \) TeV, Int. J. Mod. Phys. E22 (2013) 1330007. arXiv:1301.3395, doi:10.1142/S0218301313300075.

[12] E. G. Ferreiro, F. Fleuret, J. P. Lansberg, A. Rakotozafindrabe, Impact of the Nuclear Modification of the Gluon Densities on J/ψ production in pPb collisions at \( \sqrt{s_{NN}} = 5 \) TeV, Phys. Rev. C88 (4) (2013) 047901. arXiv:1305.4569, doi:10.1103/PhysRevC.88.047901.

[13] Y.-Q. Ma, R. Venugopalan, H.-F. Zhang, J/ψ production and suppression in high energy proton-nucleus collisions, Phys. Rev. D92 (2015) 071901. arXiv:1503.07772, doi:10.1103/PhysRevD.92.071901.

[14] B. Ducloue, T. Lappi, H. Maentiysaari, Forward J/ψ production in proton-nucleus collisions at high energy, Phys. Rev. D91 (11) (2015) 114005. arXiv:1503.02789, doi:10.1103/PhysRevD.91.114005.

[15] B. Ducloue, T. Lappi, H. Maentiysaari, Forward J/ψ production at high energy: centrality dependence and mean transverse momentum, Phys. Rev. D94 (7) (2016) 074031. arXiv:1605.05680, doi:10.1103/PhysRevD.94.074031.

[16] E. G. Ferreiro, Excited charmonium suppression in proton-nucleus collisions as a consequence of comovers, Phys. Lett. B749 (2015) 98–103. arXiv:1411.0549, doi:10.1016/j.physletb.2015.07.066.

[17] X. Du, R. Rapp, Sequential Regeneration of Charmonia in Heavy-Ion Collisions, Nucl. Phys. A943 (2015) 147–158. arXiv:1504.00670, doi:10.1016/j.nuclphysa.2015.09.006.

[18] Study of Cold Nuclear Matter effect with prompt D_0 meson production in pPb collisions at LHCb (Mar 2016).

[19] M. L. Mangano, P. Nason, G. Ridolfi, Heavy quark correlations in hadron collisions at next-to-leading order, Nucl. Phys. B373 (1992) 295–345. doi:10.1016/0550-3213(92)90435-E.

[20] D. Stump, J. Huston, J. Pumplin, W.-K. Tung, H. L. Lai, S. Kuhlmann, J. F. Owens, Inclusive jet production, parton distributions, and the search for new physics, JHEP 10 (2003) 046. arXiv:hep-ph/0303013, doi:10.1088/1126-6708/2003/10/046.

[21] R. Aaij, et al., Study of \( \Upsilon \) production and cold nuclear matter effects in pPb collisions at \( \sqrt{s_{NN}} = 5 \) TeV, JHEP 07 (2014) 094. arXiv:1405.5152, doi:10.1007/JHEP07(2014)094.

[22] R. Aaij, et al., Observation of \( Z \) production in proton-lead collisions at LHCb, JHEP 09 (2014) 030. arXiv:1406.2885, doi:10.1007/JHEP09(2014)030.

[23] F. Arteo, S. Peigné, Disentangling Shadowing from Coherent Energy Loss using the Drell-Yan Process, Phys. Rev. D95 (1) (2017) 011502. arXiv:1512.01794, doi:10.1103/PhysRevD.95.011502.

[24] Framework TDR for the LHCb Upgrade: Technical Design Report, LHCb-TDR-012 (2012).

[25] LHCb VELO Upgrade Technical Design Report, IHCb-TDR-013 (2013).

[26] LHCb Tracker Upgrade Technical Design Report, IHCb-TDR-015 (2014).