Results from p Pb collisions and prospects for heavy-ion interactions with LHCb

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Abstract

The forward acceptance of the LHCb detector allows to probe proton and ion collisions in a unique kinematic range, complementary to the other LHC experiments. In the first part of these proceedings the production of J/ψ and Υ mesons decaying into two muons is presented. It has been studied with the LHCb experiment in proton-lead collisions at a proton-nucleon centre-of-mass energy $\sqrt{s_{NN}} = 5$ TeV. The nuclear modification factor and the forward-backward production ratio have been determined for J/ψ and $\Upsilon(1S)$ mesons. In the second part the prospects are summarized to collect data with the LHCb detector in three additional configurations: the collection of data from lead-lead collisions, and the operation of the experiment in fixed-target mode, collecting data from collisions of the proton or lead beams with nuclei of a noble gas injected in the interaction region. The physics motivation for these additional data taking modes are presented.

1. Introduction

The quark-gluon plasma (QGP) is a state of matter with asymptotically free partons, which is expected to exist at extremely high temperature and density. It is predicted that heavy quarkonium production will be significantly suppressed if a QGP is created in ultrarelativistic heavy-ion collisions [1]. This suppression is regarded as one of the most important signatures of the formation of the QGP. Heavy quarkonium production in proton-nucleus (pA) collisions can also be suppressed, where hot nuclear matter (QGP) is not expected to be created and only cold nuclear matter (CNM) effects exist. The main cold nuclear matter effects, which could affect quarkonium production, include initial-state nuclear effects on the parton densities (shadowing) [2], coherent energy loss, consisting of initial-state parton energy loss and final-state energy loss [3], and final-state absorption by nucleons, which is expected to be

negligible at LHC energies [4]. The study of pA collisions is important to disentangle the effects of quark-gluon plasma from those of cold nuclear matter, and to provide essential input to the understanding of nucleus-nucleus collisions. Nuclear effects are usually characterized by the nuclear modification factor, defined as the production cross-section of a given particle per nucleon in pA collisions divided by that in proton-proton (pp) collisions at the same centre-of-mass energy,

$$R_{pA}(y, p_T) \equiv \frac{1}{A} \frac{d^2\sigma_{pA}(y, p_T)/dydp_T}{d^2\sigma_{pp}(y, p_T)/dydp_T}, \quad (1)$$

where A is the atomic mass number of the nucleus and $y^1(p_T)$ the rapidity (transverse momentum) of the produced particle. Working in the nucleon-nucleon rest frame, the “forward” and “backward” directions are defined with respect to the direction of the proton beam. The ratio R_{FB} is defined as

$$R_{FB}(y, p_T) \equiv \frac{\sigma_{pPb}(+|y|, p_T)}{\sigma_{pPb}(-|y|, p_T)}. \quad (2)$$

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¹ In this proceedings y always indicates the rapidity in the nucleon-nucleon centre-of-mass system.

Figure 1: Single differential production cross-sections for (black dots) prompt J/ψ and (red squares) J/ψ from b as function of p_T in the forward (a) and backward (b) region.

In early 2013, the LHCb detector [5] collected two data samples corresponding to 1.6 nb^{-1} of proton-lead ($p\text{Pb}$) collisions at a centre-of-mass energy per proton-nucleon pair of $\sqrt{s_{NN}} = 5 \text{ TeV}$. The two data samples correspond to two different beam configurations, where either the proton (forward) or the lead (backward) beam traversed the LHCb detector from the vertex locator to the muon system. Due to the asymmetric beam configuration, the LHCb acceptance corresponds to $1.5 < y < 4.0$ ($-5.0 < y < -2.5$) for the forward (backward) configuration. Results on J/ψ [6] and Υ [7] production and CNM effects are reported in the following.

2. J/ψ and Υ production

The J/ψ and Υ candidates are reconstructed in the dimuon final state with the transverse momentum of the dimuon system restricted to $p_T < 14 \text{ GeV}/c$ ($15 \text{ GeV}/c$) for J/ψ (Υ). The excellent vertexing capability of LHCb allows a separation of prompt J/ψ mesons and J/ψ mesons from b -hadron decays (J/ψ from b). The number of prompt J/ψ and J/ψ from b candidates is determined by a combined fit to the dimuon invariant mass and pseudo-proper time distributions.

Figure 1 shows the single differential production cross-sections for prompt J/ψ and J/ψ from b as function of p_T in the forward and backward regions. The cross-section for J/ψ from b is about a factor of ten smaller than for prompt J/ψ with a p_T dependence similar to what was observed by LHCb in pp collisions [8].

The dimuon invariant mass distribution for the Υ candidates in the two samples is shown in Fig 2. While all

three Υ resonances are observed in the forward direction, only $\Upsilon(1S)$ gives a significant signal in the backward configuration. An unbinned extended maximum likelihood fit to the invariant mass distribution of the selected candidates is performed to determine the signal yields of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons in a range $8400 < m_{\mu^+\mu^-} < 11400 \text{ MeV}/c^2$. The production ratios of excited Υ mesons, $R^{(nS)/(1S)}$, have been measured as well. They show clear sequential suppression of Υ production, which indicates stronger (cold or hot) nuclear matter effects on the excited Υ states.

3. Cold Nuclear Matter Effects

As mentioned in Sec.1, nuclear effects are usually characterised by the nuclear modification factor R_{pA} and the forward-backward production ratio R_{FB} . The advantage of measuring the R_{FB} is that it does not rely on the knowledge of the production cross-section in pp collisions and that experimental systematic uncertainties and theoretical scale uncertainties cancel partially.

To determine the nuclear modification factor R_{pPb} the reference cross-section in pp collisions at $\sqrt{s_{NN}} = 5 \text{ TeV}$ is needed. Since there is no direct measurement, the reference cross-sections of J/ψ and Υ production are obtained by a power-law fit to existing LHCb measurements at 2.76 TeV, 7 TeV and 8 TeV [9, 10]. Cold nuclear effects are studied in three rapidity bins for J/ψ ; the low statistics of the Υ sample only allow a measurement for $\Upsilon(1S)$ in one rapidity bin. Figure 3 shows the nuclear modification factors and the forward-backward production ratios, for prompt J/ψ mesons and J/ψ from

Figure 2: Invariant mass distribution of dimuon pairs in the forward (a) and backward (b) samples of $p\text{Pb}$ collisions. The black dots are the data points, the blue dashed curve indicates the signal component, the green dotted curve represents the combinatorial background, and the red solid curve is the sum of the signal and background components.

Figure 3: Forward-backward production ratios R_{FB} (a) and R_{pA} (b) for prompt J/ψ , J/ψ from b and $\Upsilon(1S)$ as function of rapidity. The results are compared with theoretical predictions including energy loss and nuclear shadowing [3].

b as functions of rapidity [6], compared to different theoretical predictions [2, 3, 4]. A clear suppression at large rapidity is observed for prompt J/ψ production. The data show a modest suppression of J/ψ from b production in the forward region with respect to that in pp collisions. This is the first indication of the suppression of b hadron production in proton-lead collisions. The nuclear modification factor and forward-backward production ratio for J/ψ from b reflect that cold nuclear matter effects on b hadrons are less pronounced than for J/ψ .

Figure 3 shows also R_{pPb} and R_{FB} for $\Upsilon(1S)$ [7]. The data are consistent with a suppression in the forward region and a possible enhancement in the backward region. In the forward region, the suppression of $\Upsilon(1S)$ mesons is smaller than that of prompt J/ψ

mesons and similar to J/ψ from b . Data and theoretical predictions [3], which include coherent energy loss and nuclear shadowing as parametrised with EPOS09 [4], agree within the large experimental uncertainties.

4. Prospects of LHCb with heavy ion interactions

Beyond the rich program in flavour physics based on pp collisions, LHCb has participated so far only in the $p\text{Pb}$ run of 2013, but not in the PbPb runs of 2010 and 2011. The reason has been that the detector occupancy in the forward region for central PbPb collisions is too large. However, detector occupancy is no problem for $p\text{Pb}$ collisions, neither for more peripheral PbPb collisions. Therefore LHCb intends to record events in forthcoming PbPb runs up to a centrality of at least 50%.

Figure 4: Fixed target production of K_S^0 mesons in p -Ne collisions at $\sqrt{s_{NN}} = 87$ GeV (a) and Pb-Ne collisions $\sqrt{s_{NN}} = 54$ GeV (b). The points are the experimental data, red line indicates the assumed background for p -Ne collisions.

Since LHCb is fully instrumented in the forward region, it can study nucleon-nucleon collisions in a unique kinematic range.

A key feature of the planned heavy-ion program of LHCb uses the fact that data can be taken in both colliding-beam and fixed-target mode. In fixed target mode a noble gas such as Neon or Argon is injected in the interaction region. The system used for the injection, called SMOG (System for Measuring the Overlap with Gas), was originally designed for precise luminosity measurements in dedicated runs [11]. However, it allows also to study collisions of protons or lead-ions with the nuclei of the noble gas over longer periods of time at centre-of mass energies of 87-115 GeV (p -GAS) and 54-72 GeV (Pb-GAS), where 'GAS' stands for He, Ne or Ar gas. The rapidity coverage in the nucleon-nucleon centre-of-mass frame is about $-3 < y < 1$. In two pilot runs in 2012 and 2013 LHCb looked at strangeness production in p -Ne and Pb-Ne collisions [12]. As shown in Fig. 4, clear signals for K_S^0 mesons are observed in the detector.

In colliding beam mode data will be taken in the forward rapidity range between $2 < y < 5$ at centre of mass energies of about 5 - 5.5 TeV (for PbPb collisions) and about 8 TeV (for p Pb collisions). The comparison of the two colliding beam configurations allows to disentangle Quark-Gluon-Plasma (QGP) from Cold-Nuclear-Matter (CNM) effects. The various beam configurations are illustrated in Fig. 5.

Table 1 shows which beam target combinations and which nucleon-nucleon centre-of-mass energies are accessible for LHCb beyond the pp physics program. About 10 additional data sets for physics analysis can be taken, not counting the various gas targets separately which can be considered.

Figure 5: Illustration of the data taking modes in heavy-ion physics with LHCb

Table 1: Beam-target configurations and nucleon-nucleon centre-of-mass energies accessible for LHCb. Here 'GAS' stands for He, Ne or Ar gas injected in the LHCb fixed target running setup (SMOG).

$E_{\text{beam}}(p)$	p -GAS	p Pb	Pb-GAS	Pb-Pb
4.0 TeV	87 GeV	5 TeV	54 GeV	
6.5 TeV	110 GeV	8.2 TeV	69 GeV	5.1 TeV
7.0 TeV	115 GeV	8.8 TeV	72 GeV	5.5 TeV

The kinematic coverage of the LHCb detector is shown in Fig. 6. A sizeable fraction of the phase space is covered by the detector, which compared to other experiments has the unique advantage to have precise tracking and vertexing, calorimetry and powerful particle identification in the full acceptance. In colliding beam mode the forward/backward region is covered, for fixed target running, with the beam direction defining positive rapidity, the acceptance is central to backward.

Since Pb-GAS collisions in fixed target mode with heavy nuclei generate energy densities between those achieved at the SPS and those probed at RHIC, doing

Figure 6: Kinematic coverage in the nucleon-nucleon centre-of-mass system of the LHCb detector for different beam-beam or beam-target combinations. The diagonal lines indicate the beam rapidities. For asymmetric configuration positive rapidity is in the direction of the proton or, in case of fixed target operation, the beam direction.

measurements both in fixed target and in colliding beam mode allows to bridge the gap between the SPS and the LHC in a single experiment. In colliding beam mode LHCb has forward coverage, in fixed target mode the central to backward region is seen. In fixed target mode it has about the same total central and backward coverage as the PHENIX experiment at RHIC, but without gaps, in colliding beam mode it adds about 3 units of rapidity both to the forward and backward region. In the following a few measurements and their physics interest are highlighted, which can be performed with the LHCb detector in the configurations proposed.

4.1. Quarkonium production measurements

One of the studies which can be performed are the measurement of the production cross-sections of charmonium (J/ψ , $\psi(2S)$, $\chi_c(nP)$) and bottomonium ($\Upsilon(nS)$, $\chi_b(nP)$) as a function of their momentum and rapidity in the various data taking configurations mentioned before. J/ψ , $\psi(2S)$ and $\Upsilon(nS)$ states will be detected in their decay to two muons, in order to use the excellent performances of muon triggering and identification at LHCb. The $\chi_c(nP)$ and $\chi_b(nP)$ mesons will be reconstructed adding a photon, through their decay

into $\mu\mu\gamma$. Preliminary studies with the LHCb simulation, based on the EPOS generator for PbAr collisions with SMOG, show the feasibility to reconstruct J/ψ and χ_c mesons. About 50,000 J/ψ and 1,000 $\chi_c(1P)$ candidates per year are expected in the LHCb kinematic region, assuming the luminosity of 0.7 nb^{-1} and a pressure of about 10^{-6} mbar .

Another type of interesting events are ultraperipheral collisions. Unexpected large signals have recently been found by the ALICE collaboration [13] in peripheral collisions which LHCb could study in detail, since multiplicities in this case are very similar to the ones of pp collisions. Measurement of displaced J/ψ production, possible since LHCb has excellent decay vertex resolution, will give access to measurement of B production cross-sections.

4.2. Open heavy-flavour measurements

LHCb can also measure the production of open charm and beauty hadrons. Since the most efficient way to reconstruct charm hadrons is through their fully hadronic decays, the challenges of these measurements will be different from those of quarkonium, and will require the use of minimum bias triggers or dedicated hadronic triggers. Similarly to the quarkonium, prompt D mesons will be separated from D mesons of b -hadron decays; the impossibility to do so was the most limiting factor of previous measurements by other experiments. The study of open beauty can also be performed through decays $B \rightarrow D\mu X$, which have large yields and are experimentally clean because of the presence of muons. The measurements of D and B production in heavy-nuclei collisions down to $p_T < 1 \text{ GeV}$ in the forward region will be a unique feature of LHCb and will have a huge impact on the theoretical models describing hot and cold nuclear matter effects. Open heavy-flavour hadrons are not sensitive to the same effects as quarkonium: they will for example suffer from energy loss in the medium but not from nuclear break-up or QGP melting. For this reason, quarkonium measurements alone are not sufficient to disentangle all effects, and measurements of open heavy flavour must be done simultaneously to reach the full power of the charm and beauty probes. It is also important to study both types of quarks, charm and beauty: for example, since beauty is much heavier than charm, the energy they lose via radiation will not be the same. This feature will help discriminating between the different types of energy-loss processes that are causing heavy-flavour suppression in cold matter. Additionally, there is a strong interest from the theorists in the measurement of the ratio of J/ψ cross-section

over the open charm cross-section. Since many systematic uncertainties cancel in the ratio, a high precision could be reached. This could be a very interesting measurement from the theory point of view.

4.3. Soft QCD and Electroweak measurements

Even more than 40 years after the formulation of QCD as a non-abelian gauge theory of strong interactions, there is still a long list of open questions regarding the phenomenological implications of the theory, especially in the soft sector which cannot be described by perturbative methods. The fields where LHCb can make significant contributions are:

- properties of hadronic matter at extreme conditions,
- structure of the nucleon,
- dynamics of the hadronization process,
- dynamics of diffractive scattering,
- cosmic ray physics,
- QED at extreme conditions and central exclusive production.

LHCb is in the unique position to contribute to all these subjects both in colliding beam and in fixed target mode, thereby covering a kinematic range not accessible to any of the existing LHC experiments.

5. Summary

The production of prompt J/ψ mesons, J/ψ from b -hadron decays and Υ has been studied in $p\text{Pb}$ collisions with the LHCb detector at the nucleon-nucleon centre-of-mass energy $\sqrt{s_{NN}} = 5$ TeV. The measurements indicate that cold nuclear matter effects are less pronounced for J/ψ from b -hadron decays and $\Upsilon(1S)$, than for prompt J/ψ . The results show good agreement with the available theoretical predictions and provide useful constraints to the parameterisation of theoretical models. The measured nuclear modification factor for prompt J/ψ mesons shows that it is necessary to include cold nuclear matter effects in the interpretation of quark-gluon plasma signatures in heavy-ion collisions.

LHCb plans to extend its physics reach by collecting data in three scenarios, in addition to the baseline pp program and the participation in the $p\text{Pb}$ datataking, of which some results have been discussed before. These are:

1. Collection of data from PbPb collisions provided by the LHC (colliding beam mode).
2. Collection of data from collisions of heavy nuclei in a fix target setup, using the SMOG system. In this scenario LHCb will record interactions of the Pb-beam with noble gas nuclei in the interaction region.
3. Collection of data from collisions of protons with gas nuclei using the SMOG system. Here LHCb will record interactions of the proton beam with nuclei of the gas target in the interaction region.

By pursuing these scenarios LHCb can access a number of very interesting measurements in heavy flavour, soft QCD and electroweak physics, many of them unique. Through the fixed target program, exploiting the SMOG system, LHCb can bridge the gap from the SPS to the LHC in a single experiment. This confirms that LHCb is a general purpose detector in the forward direction.

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