Heavy ion physics at LHCb

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Abstract. Proton-ion collisions are probed in the forward acceptance by the LHCb detector in a unique kinematic range, complementary to the other LHC experiments. The production of \( \psi(2S) \) and \( \Upsilon(1S) \) mesons decaying into two muons is studied in proton-lead collisions at a proton-nucleon centre-of-mass energy \( \sqrt{s_{NN}} = 5 \text{ TeV} \). The results are based on a data sample corresponding to an integrated luminosity of 1.6 \( \text{nb}^{-1} \). The nuclear modification factor and the forward-backward production ratio are determined for \( \psi(2S) \) and \( \Upsilon(1S) \) mesons. Significant suppression of prompt \( \psi(2S) \) production is observed with respect to the production in pp collisions at large rapidity, while the suppression of \( \psi(2S) \) from b-hadron decays is less pronounced. The nuclear modification factor for \( \Upsilon(1S) \) mesons in the forward region is found to be similar to those for \( \psi(2S) \) from b-hadron decays. First observation of \( Z \) bosons in proton-lead collisions at a proton-nucleon centre-of-mass energy \( \sqrt{s_{NN}} = 5 \text{ TeV} \) is also reported.

1. Introduction
In ultra-relativistic heavy-ion collisions, the production of heavy quarkonia or electroweak bosons is expected to be suppressed with respect to proton-proton (pp) collisions, if a quark-gluon plasma, QGP, is created \(^1\). This suppression of heavy quarkonia and Z boson production with respect to pp collisions can also take place in proton-nucleus (pA) collisions, where a quark-gluon plasma is not expected to be created and only cold nuclear matter effects, such as nuclear absorption, parton shadowing and parton energy loss in initial and final states, occur \(^2\). Therefore, pA collisions studies provide important input to disentangle the QGP effects from cold nuclear effects, probe nuclear parton distribution functions, which are poorly constrained, and provide a reference sample for nucleus-nucleus collisions.

The LHCb detector \(^5\) collected two data samples corresponding to 1.6 \( \text{nb}^{-1} \) of proton-lead 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, with the proton (lead) beam into the direction of LHCb, referred to as forward (backward). 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. Studies on \( J/\psi \) \(^6\), \( \Upsilon \) \(^7\) and \( Z \) \(^8\) production are reported below.

2. \( J/\psi \) and \( \Upsilon \) production
The \( J/\psi \) and \( \Upsilon \) candidates are reconstructed with the dimuon final states in events with at least one primary vertex, which requires of no less than five tracks. The meson candidate is selected from pairs of oppositely charged particles with \( p_T > 0.7 \text{ GeV} \) and that have a track fit \( \chi^2 \).
The dimuon system is restricted to \( p_T < 14 \text{ GeV} \) (\( p_T < 15 \text{ GeV} \)) for J/\( \psi \) (\( \Upsilon \)). The excellent vertexing capability of LHCb allows a separation of prompt J/\( \psi \) mesons and J/\( \psi \) mesons from b-hadron decays (J/\( \psi \) from b). The number of prompt J/\( \psi \) and J/\( \psi \) from b candidates are determined by a combined fit to the dimuon invariant mass and pseudo-proper time distributions. The pseudo-proper time is defined as

\[
t_z = \frac{(z_{J/\psi} - z_{PV})M_{J/\psi}}{p_z},
\]

where \( z_{J/\psi} \) is the \( z \) position of the J/\( \psi \) decay vertex, \( z_{PV} \) that of the primary vertex, \( p_z \) the \( z \) component of the measured J/\( \psi \) momentum, and \( M_{J/\psi} \) the mass of the J/\( \psi \).

The projections of the combined fit in two rapidity (\( y \)) bins in the forward and the backward region for the J/\( \psi \) production are shown in Fig. 1. The number of candidates for J/\( \psi \) from b is about a factor of 10 smaller than for prompt J/\( \psi \).

![Figure 1: Projections of the combined fit on (a, b) dimuon invariant mass and (c, d) \( t_z \) in two representative bins in the (a, c) forward and (b, d) backward samples.](image)

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 fit range \( 8400 < m_{\mu^+\mu^-} < 11400 \text{ MeV} \). The invariant dimuon mass distribution for the \( \Upsilon \) candidates of the two samples are shown in Fig. 2.

![Figure 2: Invariant dimuon mass distribution for \( \Upsilon \) candidates in the two samples.](image)
performed in three bins of rapidity; the low statistics of the \( \Upsilon \) sample do not allow a differential measurement.

3. Cold nuclear effects

Nuclear effects are usually characterised by the nuclear modification factor \( R_{pPb} \)

\[
R_{pPb} = \frac{d\sigma_{pPb}/dy}{Ad\sigma_{pp}/dy},
\]

which depends on the production cross-section of a given particle in pPb and in pp collisions at the same centre-of-mass energy. The forward-backward production ratio \( R_{FB} \)

\[
R_{FB} = \frac{d\sigma_{pPb(y>0)}/dy}{d\sigma_{pPb(y<0)}/dy}
\]

also depends on the production cross-section of a given particle in pPb collisions but it does not rely on the knowledge of the production cross-section in pp collisions. For both observables the experimental systematic uncertainties and theoretical scale uncertainties cancel partially.

To determine the nuclear modification factor \( R_{pPb} \), the reference cross-sections in pp collisions at \( \sqrt{s_{NN}} = 5 \text{ TeV} \) are needed \(^{[9,10]}\). These are obtained by a power-law fit to the previous LHCb measurements of \( J/\psi \) and \( \Upsilon \) production at 2.76 TeV, 7 TeV and 8 TeV. Figure 3 shows the nuclear modification factors (left two plots) and the forward-backward production ratios, for prompt \( J/\psi \) mesons and \( J/\psi \) from b as functions of rapidity, compared to different theoretical predictions \(^{[2–4,11]}\). A clear suppression of about 40% at large rapidity is observed for prompt \( J/\psi \) production. The measurements agree with most predictions. The data show a modest suppression of \( J/\psi \) 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 \( J/\psi \) from b reflect that cold nuclear matter effects on b hadrons are less pronounced than for \( J/\psi \).

Measurements of \( R_{pPb} \) and \( R_{FB} \) for \( \Upsilon(1S) \) are shown in Fig. 4. The data are consistent with a suppression in the forward region and a possible enhancement in the backward region. In the
Figure 3: Nuclear modification factor $R_{pPb}$ as a function of $y$ for (a) prompt $J/\psi$ mesons and (b) $J/\psi$ from $b$ [6], together with the theoretical predictions from (yellow dashed line and brown band) refs. [2,11] (blue band) ref. [3], and (green solid and blue dash-dotted lines) ref. [4]. The inner error bars (delimited by the horizontal lines) show the statistical uncertainties; the outer ones show the statistical and systematic uncertainties added in quadrature. The uncertainty due to the interpolated $J/\psi$ cross-section in $pp$ collisions at $\sqrt{s_{NN}} = 5$ TeV is 5.5% (8.4%) for prompt $J/\psi$ ($J/\psi$ from $b$).

forward region, the suppression of $\Upsilon(1S)$ mesons is smaller than that of prompt $J/\psi$ mesons and similar to $J/\psi$ from $b$, indicating that the cold nuclear matter effects on $\Upsilon(1S)$ mesons and $J/\psi$ from $b$ are similar. Data and theoretical predictions which include coherent energy loss and nuclear shadowing as parametrised with EPOS09 [4] agree within the large experimental uncertainties.

Figure 4: $R_{pPb}$ (left) and $R_{FB}$ (right) compared theoretical predictions [7]. The black dots, red squares, and blue triangles indicate the LHCb measurements for $\Upsilon(1S)$ mesons, prompt $J/\psi$ mesons, and $J/\psi$ from $b$, respectively. The inner error bars (delimited by the horizontal lines) show the statistical uncertainties; the outer ones show the statistical and systematic uncertainties added in quadrature. The data are compared with theoretical predictions for $\Upsilon$ and prompt $J/\psi$ mesons including energy loss and nuclear shadowing [4].

4. First observation of $Z$ boson in pPb collisions

The $Z$ candidates are selected from reconstructed pairs of oppositely charged muons. Selection criteria are applied to reject background candidates that fake $Z \rightarrow \mu^+\mu^-$ decays: the impact parameter of each track with respect to the closest primary vertex must be less than 100 $\mu$m,
and the sum of the energy measured in the calorimeter associated to each track has to be less than 0.5 times the track momentum measured in the tracking system. The $\chi^2$-probability of the track fit is required to be larger than 1% for both tracks.

Figure 5 shows the invariant mass distribution of the selected candidates for the two beam configurations together with the predictions from simulation. There is a good agreement between data and simulation. In total, eleven candidates are selected in the forward sample and four in the backward sample.

Figure 5: Invariant dimuon mass distribution of selected Z candidates in the backward (left) and the forward (right) sample are shown by the black data points with error bars [8]. The red line shows the distribution obtained from simulation using Pythia 8 with the MSTW08 PDF set normalised to the number of observed candidates.

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