LHCb results in proton-nucleus collisions at the LHC

Katharina Müller
Winterthurerstr. 190, CH-8057 Zurich, Switzerland
E-mail: kmueller@physik.uzh.ch

Abstract. The forward acceptance of the LHCb detector allows it to probe proton-ion collision in a unique kinematic range, complementary to the other LHC experiments. The production of $J/\Psi$ and $\Upsilon$-mesons decaying into two muons is studied at the LHCb experiment in proton-lead collisions at a proton-nucleon centre-of-mass energy $\sqrt{s_{NN}} = 5$ TeV. The analysis is 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 $J/\Psi$ and $\Upsilon(1S)$ mesons. Clear suppression of prompt $J/\Psi$ production is observed with respect to the production in $pp$ collisions at large rapidity, while the suppression of $J/\Psi$ 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 $J/\Psi$ from $b$-hadron decays. Furthermore, a first observation of $Z$ bosons in proton-lead collisions is 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 collisions, if a quark-gluon plasma, QGP, is created [1]. Such a 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 but only cold nuclear matter effects, such as nuclear absorption, parton shadowing and parton energy loss in initial and final states can occur [2, 3, 4]. The study of $pA$ collisions therefore provides 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.

In early 2013, 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 $\sqrt{s_{NN}} = 5$ TeV. The two data samples correspond to two different beam configurations, with either the proton or the lead beam into the direction of LHCb. These are referred to as forward and backward configuration respectively. Owing 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 $J/\Psi$ [6], $\Upsilon$ [7] and $Z$ [8] production are reported below.

2. $J/\Psi$ and $\Upsilon$ production

$J/\Psi$ [6] and $\Upsilon$ [7] mesons are reconstructed in the di-muon final state with the transverse momentum, $p_T$, of the di-muon system restricted to $p_T < 14 \text{ GeV}/c$ ($p_T < 15 \text{ GeV}/c$) 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 is determined by a combined fit to the di-muon invariant mass and pseudo-proper time distributions. The pseudo-proper time is defined as

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

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 signal di-muon invariant mass distribution in each \( p_T \) and rapidity \((y)\) bin is modelled with a Crystal Ball function [9], and the combinatorial background with an exponential function. The \( t_z \) signal distribution is described by the sum of a \( \delta \)-function at \( t_z = 0 \) for prompt \( J/\Psi \) production and an exponential decay function for \( J/\Psi \) from \( b \), both convolved with a double-Gaussian resolution function whose parameters are free in the fit. Figure 1 shows the projections of the combined fit in two rapidity bins in the forward and backward configuration.

![Figure 1](image_url)

**Figure 1.** Projections of the combined fit on (a, b) di-muon invariant mass and (c, d) \( t_z \) in two representative bins in the (a, c) forward and (b, d) backward samples. For the mass projections the (red solid curve) total fitted function is shown together with the (blue dotted curve) \( J/\Psi \) signal and (green dotted curve) background contributions. For the \( t_z \) projections the total fitted function is indicated by the solid red curve, the background by the green hatched area, the prompt signal by the blue area and \( J/\Psi \) from \( b \) by the solid black curve [6].

The di-muon invariant mass distribution for the \( \Upsilon \) candidates in the two samples are shown in Fig. 2. While all three \( \Upsilon \) 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 Υ(1S), Υ(2S) and Υ(3S) mesons in a fit range $8400 < m_{\mu^+\mu^-} < 11400$ MeV/c$^2$. A sum of three Crystal Ball functions is used to describe the Υ(1S), Υ(2S) and Υ(3S) signal components, while the combinatorial background is modelled with an exponential function.

**Figure 2.** Invariant mass distribution of di-muon pairs in the (a) forward and (b) backward samples of pPb collisions. The transverse momentum is restricted to $p_T < 15$ GeV. The rapidity range is $1.5 < y < 4.0$ for the forward (backward) sample. 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 [7].

Higher combinatorial background in the backward configuration is observed for J/Ψ and Υ production due to the larger multiplicity in lead-proton collisions.

Figure 3 shows the single differential production cross-sections for prompt J/Ψ and J/Ψ from $b$ as functions 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 very similar $p_T$ dependence similar to what was observed by LHCb in $pp$ collisions [10].

**Figure 3.** Single differential production cross-sections for (black dots) prompt J/Ψ and (red squares) J/Ψ from $b$ as functions of $p_T$ in the (a) forward and (b) backward region [6].
3. Cold nuclear effects

![Graph](image_url)

**Figure 4.** Forward-backward production ratios ($R_{FB}$) for (a) prompt $J/\Psi$ and (b) $J/\Psi$ from $b$ as functions of rapidity [6] together with theoretical predictions from (yellow dashed line and brown band) [2, 11], (blue band) [3], and (green solid and blue dash-dotted lines) [4].

![Graph](image_url)

**Figure 5.** Nuclear modification factor ($R_{pA}$) for (a) prompt $J/\Psi$ and (b) $J/\Psi$ from $b$ as functions of rapidity [6] together with theoretical predictions from (yellow dashed line and brown band) [2, 11], (blue band) [3], and (green solid and blue dash-dotted lines) [4].

Nuclear effects are usually characterised by the nuclear modification factor $R_{pA}$ and the forward-backward production ratio $R_{FB}$,

$$R_{pA} = \frac{d\sigma_{pA}/dy}{Ad\sigma_{pp}/dy}, \quad R_{FB} = \frac{d\sigma_{pA(y>0)}/dy}{d\sigma_{pA(y<0)}/dy},$$

which depend on the production cross-section of a given particle in $pA$ collisions and for $R_{pA}$ also on the cross-section in $pp$ collisions at the same centre-of-mass energy as well as the atomic number $A$. 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 $R_{pA}$, the reference cross-sections in $pp$ collisions at $\sqrt{s_{NN}} = 5$ TeV are needed. Since there is no direct measurement, 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 [12, 13]. Cold nuclear effects are studied in three rapidity bins for $J/\Psi$; the low statistics of the $\Upsilon$ sample only allow a measurement for $\Upsilon(1S)$ in one rapidity bin.

Figure 4 and 5 show the nuclear modification factors and the forward-backward production ratios, for prompt $J/\Psi$ mesons and $J/\Psi$ from $b$ as functions of rapidity [6], compared to different theoretical predictions [2, 11, 3, 4]. 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 $J/\Psi$.

Figure 6 shows $R_{pA}$ and $R_{FB}$ for $\Upsilon(1S)$ [7] together with the LHCb results of prompt $J/\Psi$ and $J/\Psi$ from $b$ with theoretical predictions. 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 $J/\Psi$ mesons and similar to $J/\Psi$ 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. Inclusive $Z$ boson production in proton-lead collisions

The $Z$ candidates are reconstructed in the di-muon final state. Background contributions from muon mis-identification and the decay of heavy flavour mesons are determined from data. A total of 15 candidates are selected with a purity of above 99%, corresponding to a significance of 10.4σ (6.8σ) for the $Z$ signal in the forward (backward) direction. Figure 7 shows the di-muon invariant mass of the $Z$ candidates in the forward and backward direction. The inclusive $Z$ boson production cross-section is measured to be $\sigma(Z \to \mu\mu) = 13.5^{+5.4+1.2}_{-4.0}$ nb in the forward and $\sigma(Z \to \mu\mu) = 10.7^{+8.5+1.0}$ nb in the backward configuration. Here, the first uncertainty is statistical and the second systematic. The measurements are compared to theoretical predictions calculated at NNLO using the FEWZ generator [14] and computed with and without considering nuclear effects based on the EPS09 nuclear PDF set [15] in Fig. 8. The statistical precision of
the measured cross-sections prevents conclusions on the presence of nuclear effects. However, the observation of Z production in proton-nucleus collisions demonstrates the excellent potential of the study of electroweak bosons in proton-lead collisions at LHCb.

5. Conclusions
The production of prompt J/Ψ mesons, J/Ψ from b-hadron decays and Υ is studied in pPb collisions with the LHCb detector at the nucleon-nucleon centre-of-mass energy √s_{NN} = 5 TeV. The measurement is performed as a function of the transverse momentum and rapidity of the J/Ψ (Υ) in the region p_T < 14 (15) GeV/c and 1.5 < y < 4.0 (forward) and 5.0 < y < 2.5 (backward). The measurements indicate that cold nuclear matter effects are less pronounced for J/Ψ from b-hadron decays and Υ, 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. The limited statistics of the $Z$ production cross-section does not allow a conclusion on the presence of cold nuclear effects.

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