Measurements of quarkonia and open heavy-flavour production in heavy-ion collisions with the ATLAS detector

Jakub Kremer on behalf of the ATLAS Collaboration

AGH University of Science and Technology
Faculty of Physics and Applied Computer Science
al. Mickiewicza 30, 30-059 Kraków, Poland
E-mail: jakub.kremer@cern.ch

Abstract. Measurements of quarkonia produced in ultrarelativistic Pb+Pb collisions provide a means to probe the properties and evolution of the hot and dense medium created in those collisions. Promptly produced quarkonia are directly affected by the interaction with the hot nuclear matter, while non-prompt production allows for the study of $b$-quark energy loss. The studies of quarkonia production are complemented by measurements of the azimuthal modulation of $J/\psi$ production. Studies of quarkonia and open-charm production in $p+Pb$ collisions provide an additional insight, as they directly probe cold nuclear matter effects. This report will present the most recent ATLAS measurements of charmonia production and flow in Pb+Pb collisions, as well as charmonia and bottomonia production in $p+Pb$ collisions. In addition, results on $D$ meson production and flow will be presented.

1. Introduction

Ultrarelativistic heavy-ion collisions at the Large Hadron Collider (LHC) produce a hot and dense state of nuclear matter called quark-gluon plasma (QGP). Heavy quarks can be used to probe its properties, since they are produced at the earliest stage of a collision and survive the full QGP evolution \cite{1,2}. The interactions of heavy quarks with partons forming the QGP can result in a suppression of observed yields and significant azimuthal anisotropy. These final-state effects are measured in nucleus–nucleus collisions, but have to be separated from initial-state effects including energy loss of incoming partons or nuclear modifications to parton distribution functions (nPDFs). A direct handle on initial-state effects can be obtained from heavy-quark measurements in proton–nucleus collisions, in which the formation of QGP is not expected.

Any modifications of heavy-quark production in proton–lead ($p+Pb$) collisions can be studied by comparing the production cross-sections of relevant probes to those measured in proton–proton ($pp$) collisions. For this purpose, a nuclear modification factor can be defined as:

$$R_{pPb} = \frac{1}{A_{Pb}} \frac{\sigma_{p+Pb}}{\sigma_{pp}}$$  \hspace{1cm} (1)

1 Copyright 2018 CERN for the benefit of the ATLAS Collaboration. CC-BY-4.0 license.
where $\sigma_{p+Pb}$ and $\sigma_{pp}$ are production cross-sections measured in $p+Pb$ and $pp$ collisions, respectively. A correct reference is obtained from the scaling of $\sigma_{pp}$ by the mass number of lead nuclei collided at the LHC, $A_{Pb} = 208$.

In the case of lead–lead (Pb+Pb) collisions, the comparison of heavy-quark production to $pp$ collisions has also to take into account the geometry of nucleus–nucleus collisions. Therefore, the nuclear modification factor is defined in the following way:

$$R_{AA} = \frac{N_{AA}/N_{evt}}{\langle T_{AA} \rangle \cdot \sigma_{pp}} \quad (2)$$

where $N_{AA}/N_{evt}$ is the heavy-flavour yield measured per minimum-bias Pb+Pb collision, while a reference is obtained by scaling $\sigma_{pp}$ by the average nuclear overlap function $\langle T_{AA} \rangle$.

The information about modifications of production can be complemented by studying the collective effects introduced by nuclear matter. These effects are typically quantified by flow coefficients $v_n$ which arise in the Fourier expansion of the particle yields $N$ in the azimuthal angle $\phi$:

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos [n(\phi - \Psi_n)]. \quad (3)$$

Here, $\Psi_n$ is the $n$-th harmonic of the event-plane angle.

In this report, several measurements using data collected by the ATLAS detector [4] are presented:

- charmonia production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [5],
- $J/\psi$ flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [6],
- charmonia and bottomonia production in $pp$ and $p+Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV [7],
- production and flow of muons from heavy-flavour decays in $pp$ and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [8],
- $D$-meson production and flow in $p+Pb$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV [9].

2. Quarkonia measurements

The ATLAS experiment performs measurements of quarkonia production in heavy-ion collisions using their dimuon decay channels. Quarkonia candidates are reconstructed in events collected with triggers requiring the presence of at least two muons. Pairs of oppositely charged muons, which originate from a common decay vertex, are considered to be candidates if their invariant mass falls in one of the ranges: $2.6 < m_{\mu\mu} < 4.2$ GeV (charmonia candidates) or $8.2 < m_{\mu\mu} < 11.7$ GeV (bottomonia candidates). After applying corrections for trigger and reconstruction efficiencies, as well as for detector acceptance, the quarkonia yields are extracted using maximum likelihood fits. For charmonia yields, the fits are done simultaneously in $m_{\mu\mu}$ and the pseudo-proper lifetime $\tau_{\mu\mu}$, while for bottomonia they consider only $m_{\mu\mu}$. The inclusion of $\tau_{\mu\mu}$ in the charmonia yield fits allows to separate contributions from prompt and non-prompt production. The former directly gives information about final-state effects related to $c$ quarks, while the latter is sensitive to $b$-quark interactions with the QGP, since it is dominated by $B$-hadron decays outside of the QGP volume.

Figure 1 presents the $R_{AA}$ measured for prompt $J/\psi$ as a function of transverse momentum $p_T$ in several classes of collision centrality. The measurement shows a strong suppression of $J/\psi$ production with respect to $pp$ collisions, which increases with centrality. The magnitude of suppression is similar for non-prompt $J/\psi$ (see Ref. [5]), which indicates a possible similarity of energy loss mechanisms for $c$ and $b$ quarks. Figure 1 also shows a comparison of the prompt $J/\psi$ $R_{AA}$ measured in the 0–20% centrality class to predictions from several theoretical calculations.
Both energy loss models and colour screening models are able to reproduce the data, but none of them describes the full $p_T$ dependence of the $R_{AA}$.

Figure 1. The nuclear modification factor as a function of $p_T$ for the prompt $J/\psi$ for $|y| < 2$, in 0–10%, 20–40%, and 40–80% centrality bins (left). Comparison of the $R_{AA}$ for prompt $J/\psi$ production with different theoretical models (right). The statistical uncertainty of each point is indicated by an error bar. The error box plotted with each point represents the uncorrelated systematic uncertainty, while the shaded error box at $R_{AA} = 1$ represents correlated scale uncertainties [5].

Harmonic coefficients $v_2$, which quantify the elliptic flow of the $J/\psi$, are extracted from fits to azimuthal distributions of $J/\psi$ yields. The $v_2$ measured using simultaneous fits for prompt and non-prompt $J/\psi$ mesons is presented in Figure 2 as a function of centrality. In both cases, there is no significant dependence of $v_2$ on centrality, and the measurement favours non-zero elliptic flow with limited significance.

Figure 3 shows the $R_{pPb}$ measured for $\Upsilon(1S)$ mesons as a function of $p_T$ and centre-of-mass rapidity $y^*$. The production of $\Upsilon(1S)$ mesons is found to be significantly suppressed with respect to $pp$ collisions in the $p_T < 15$ GeV range. In addition, the $R_{pPb}$ is constant as a function of $y^*$ at the level of 0.8. This is an indication of strong nuclear shadowing of parton distribution functions in the small-$x$ region. Contrary to bottomonia, the $R_{pPb}$ measured for charmonia does not show any dependence on $p_T$ or significant deviation from unity [7].

3. Open heavy-flavour measurements

For open heavy-flavour mesons, it is more difficult to perform a direct candidate reconstruction than for quarkonia, since ATLAS does not provide explicit particle identification for hadrons. However, it is possible to use muons produced in semileptonic decays to extract information about interactions of open heavy-flavour mesons with the QGP. The separation of muons produced in these decays from background muons is based on template fits in momentum imbalance. This quantity is defined as the relative difference between the muon momentum measured in the ATLAS inner detector and muon spectrometer, adjusted for energy loss in the calorimeters.

Figure 4 presents the $R_{AA}$ for heavy-flavour muons measured in $|\eta| < 1$ as a function of $p_T$ in several centrality classes. It is observed that the heavy-flavour muons are significantly
Figure 2. Prompt (left) and non-prompt (right) $J/\psi$ $v_2$ as a function of average number of nucleons participating in the collision for transverse momentum in the range $9 < p_T < 30$ GeV and rapidity $|y| < 2$. The statistical and systematic uncertainties are shown using vertical error bars and boxes respectively. The centrality interval associated to a given value of $\langle N_{\text{part}} \rangle$ is written below each data point [6].

Figure 3. The nuclear modification factor, $R_{p\text{Pb}}$, as a function of transverse momentum $p_T$ (left) and centre-of-mass rapidity $y^*$ (right) for $\Upsilon(1S)$. The horizontal position of each data point indicates the mean of the weighted $p_T$ or $y^*$ distribution. The vertical error bars correspond to the statistical uncertainties. The vertical sizes of coloured boxes around the data points represent the uncorrelated systematic uncertainties, and the horizontal sizes of coloured boxes represent the bin sizes. The vertical size of the rightmost (left) and leftmost (right) grey boxes around $R_{p\text{Pb}} = 1$ represent the correlated systematic uncertainty [7].

suppressed compared to $pp$ collisions. The suppression has no significant dependence on $p_T$ in all considered centrality classes, and is increasing with centrality. The measured $R_{AA}$ values are compared with predictions calculated using the heavy-quark energy-loss model DABMod [10] and the transport model TAMU [11]. The DABMod model fails to reproduce the data, in particular at low $p_T$, while the TAMU model describes the measured $R_{AA}$ well except for the most central collisions. On the other hand, DABMod is in better agreement with the measured elliptic flow of heavy-flavour muons than TAMU [8].

The ATLAS $D$-meson measurements attempt a direct reconstruction of $D^0 \rightarrow K\pi$ and
Figure 4. Comparison of the measured heavy-flavor muon $R_{AA}$ with the values predicted from the TAMU transport model and the DABMod model. Each panel represents a different centrality interval. For the 20–30% and 30–40% centralities, the plotted TAMU values correspond to the 20–40% centralities. For the data, the error bars represent statistical uncertainties, the shaded bands represent the experimental systematic uncertainties, and the boxes indicate theoretical uncertainties from $\langle T_{AA} \rangle$. For the model calculations the bands indicate the theoretical systematic uncertainties [8].

$D^* \rightarrow D^0 \pi$ candidates from charged particle tracks. Candidates for $D^0$ mesons are built from oppositely-charged pairs of tracks with an invariant mass in the range $1.75 < m(K\pi) < 1.96$ GeV, where $m(K\pi)$ is calculated after assigning kaon and pion masses to individual tracks in different configurations. Additional requirements related to the event topology are applied in order to improve the significance of signal over background. Candidates for $D^*$ mesons are constructed by adding a soft track to $D^0$ candidates. The yields of $D^0$ mesons are extracted from maximum likelihood fits to $m(K\pi)$ distributions, while for $D^*$-meson yields fits to the distributions of the difference between the three-track invariant mass, $m(K\pi\pi)$, and $m(K\pi)$ are used. The subtraction of non-prompt $D$-meson production is based on theoretical calculations of the $b \rightarrow D$ cross-sections.

Since there is no available measurement of $D$-meson production in $pp$ collisions at $\sqrt{s} = 8.16$ TeV, the $R_{ppb}$ is replaced by the forward-to-backward ratio of differential production cross-sections $d^2\sigma/dp_Tdy^*$:

$$R_{FB} = \frac{d^2\sigma/dp_Tdy^* (0 < y^* < 0.5)}{d^2\sigma/dp_Tdy^* (-0.5 < y^* < 0)}.$$  

(4)

The $R_{FB}$ measured for prompt $D^{0}$- and $D^*$-meson production is shown in Figure [as a function of $p_T$. In the considered central rapidity range, $|y^*| < 0.5$, no significant modification of $D$-meson production is observed. However, the additional measurements of harmonic flow coefficients for $D^*$ mesons suggest a non-zero elliptic flow measured in all considered event activity classes [9].
4. Summary

This report presents a summary of recent ATLAS measurements of quarkonia and open heavy-flavour production in $pp$, $p+Pb$ and $Pb+Pb$ collisions at centre-of-mass energies in the range $\sqrt{s_{NN}} = 2.76–8.16$ TeV.

In $Pb+Pb$ collisions, a significant suppression of yields is observed for both charmonia and muons coming from semileptonic heavy-flavour decays. These measurements form together with elliptic flow measurements a clear signature of heavy-quark interactions with the QGP.

In $p+Pb$ collisions, charmonia production is not significantly modified, but $Y(1S)$ production is suppressed at low $p_T$. This is an indication of nuclear shadowing affecting parton distribution functions in the low-$x$ region. The studies of $D$-meson production do not support the presence of initial-state effects, however an indication of a non-zero $D^*$ elliptic flow is observed.

Acknowledgements

This work was partly supported by the National Science Center of Poland under grants UMO-2016/23/B/ST2/01409 and UMO-2018/28/T/ST2/00048, by the AGH UST grant No. 15.11.220.717/17 within subsidy of the Ministry of Science and Higher Education, and by PL-Grid infrastructure.

References

[1] Matsui T and Satz H 1986 Phys. Lett. B 178 416
[2] van Hees H and Rapp R 2005 Phys. Rev. C 71 034907
[3] Cao S, Qin G-Y and Bass S A 2013 Phys. Rev. C 88 044907
[4] ATLAS Collaboration 2008 JINST 3 S08003
[5] ATLAS Collaboration 2018 Eur. Phys. J. C 78 762
[6] ATLAS Collaboration 2018 Eur. Phys. J. C 78 784
[7] ATLAS Collaboration 2018 Eur. Phys. J. C 78 171
[8] ATLAS Collaboration 2018 Phys. Rev. C 98 044905
[9] ATLAS Collaboration 2017 Preprint ATLAS-CONF-2017-073
[10] Prado C A G et al. 2017 Phys. Rev. C 96 064903
[11] He M, Fries R J and Rapp R 2014 Phys. Lett. B 735 145
[12] ATLAS Collaboration 2017 Phys. Rev. C 96 024908