Recent results from ATLAS: Onia, heavy-flavor, and more

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Abstract. In this short report we review the recent results obtained using the ATLAS experiment at the LHC on quarkonia and heavy flavor measurements in heavy-ion collisions.

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In this short report we review the recent results obtained using the ATLAS experiment [1] at the LHC on quarkonia and heavy flavor measurements in heavy-ion collisions. The text is divided into two sections. The first section briefly discusses the final state effects in the production of quarkonia and heavy flavor and it describes the measurements of suppression and flow of quarkonia and heavy-flavor in Pb+Pb collisions. The second section discusses the initial state effects and describes the measurements done in p +Pb collisions.

1 Suppression and flow of quarkonia and heavy-flavor in Pb+Pb collisions

It was predicted a long time ago that the Debye screening of the quark colour charge in a hot quark-gluon plasma (QGP) would lead to a dissociation of quarkonium bound state in the medium, when the Debye length becomes smaller than the quarkonium binding radius [2]. While the strong suppression of quarkonia in nucleus-nucleus collisions is firmly established experimental fact, its interpretation remains open. Besides initial state effects and the interaction with co-moving hadrons, which are discussed in the context of p +Pb measurements in Section 2, it is also the parton energy loss which was recently suggested as an alternative physics mechanism for the observed quarkonia suppression [3, 4]. To help address the origin of the quarkonium suppression, ATLAS published a measurement [5] of prompt charmonia, originating from the formation of $c\bar{c}$ bound state which follows immediately after the hard process, and non-prompt charmonia, originating from b -hadron decays. In that measurement, prompt and non-prompt per-event yields, non-prompt fraction and nuclear modification factors, R_{AA} , of the J/ψ and $\psi(2S)$ is performed. The measurement is performed

Fig. 1. Left: Comparison of R_{AA} for prompt J/ψ production with different theoretical models. The statistical uncertainty of each point is indicated by a narrow 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. Plot taken from Ref. [5]. Right: Comparison of the Pb+Pb heavy-flavor muon v_2 with calculations from the TAMU [6] and DABMod [7] models. Each panel represents a different centrality interval. For the 20 – 30% and 30 – 40% centrality intervals, the plotted TAMU values correspond to the 20 – 40% centrality interval. For the data, the error bars and shaded bands represent statistical and total uncertainties, respectively. For the model calculations, the bands represent theoretical systematic uncertainties. Plot taken from Ref. [8].

in the dimuon decay channel in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, for quarkonia with transverse momentum $9 < p_T < 40$ GeV and rapidity $|y| < 2.0$.

Strong suppression of prompt and non-prompt J/ψ and $\psi(2S)$ mesons is observed in Pb+Pb data. In the 0 – 10%, the R_{AA} of prompt J/ψ is approximately 0.2 for $p_T = 10$ GeV and it grows and achieves a value of 0.3 at $p_T \approx 25$ GeV. The R_{AA} of non-prompt J/ψ in 0 – 10% is approximately 0.3 and remains independent of p_T within the full p_T range of this measurement. The dependence of the R_{AA} on centrality is approximately the same for prompt and non-prompt J/ψ . The ratio of $\psi(2S)$ to J/ψ meson production is measured for both the prompt and non-prompt mesons, and as a function of centrality. Values consistent with unity are measured for the non-prompt mesons, while the values observed for the prompt mesons are below unity. The left panel of Figure 1 shows a comparison of the J/ψ R_{AA} measured in 0 – 20% central collisions with theoretical calculations.

ATLAS also measured the elliptic flow coefficient (v_2) of prompt and non-prompt J/ψ in Pb+Pb collisions [9]. The measurement is done using similar techniques and kinematic cuts and using the same dataset as used for the measurement of the R_{AA} of J/ψ and $\psi(2S)$. In that measurement, the v_2 coefficient is evaluated relative to the event plane and the results are presented as a func-

tion of p_T , y and centrality. It is found that both prompt and non-prompt J/ψ mesons have non-zero elliptic flow. Prompt J/ψ v_2 is found to decrease as a function of p_T , while the non-prompt J/ψ is found to be, with limited statistical significance, consistent with a flat behaviour over the studied kinematic region. There is no observed dependence on y or centrality.

The suppression and the azimuthal anisotropy was measured also for muons from heavy-flavor decays in 2.76 TeV Pb+Pb collisions [8]. The measurement is performed over the muon transverse momentum range $4 < p_T < 14$ GeV. Backgrounds arising from in-flight pion and kaon decays, hadronic showers, and misreconstructed muons is statistically removed using a template-fitting procedure. The resulting R_{AA} is observed to be independent of p_T within uncertainties. For the 10% most central Pb+Pb events, the measured R_{AA} is approximately 0.35 indicating a clear suppression of production of heavy-flavor muons in Pb+Pb collisions.

The azimuthal modulation of the heavy-flavor muon yields is measured and the associated Fourier coefficients v_n for $n = 2, 3$ and 4 are given as a function of p_T and centrality. Significant v_2 values up to about 0.08 are observed at $p_T = 4$ GeV. In the 10 – 20%, 20 – 30%, and 30 – 40% intervals, the v_2 decreases with p_T but is still significant at 10 GeV. At fixed p_T , the v_2 values show a systematic variation with centrality which is typical of elliptic-flow measurements. For most centrality intervals, v_3 also decreases with increasing p_T over the 4 – 8 GeV p_T range. At a given p_T and centrality, the v_3 values are smaller than the v_2 values by a factor of 2 – 4. The v_3 values show a much weaker centrality dependence than the v_2 . The right panel of Figure 1 shows a comparison of heavy-flavor muon v_2 in five centrality bins with theory calculations.

2 Quarkonia and heavy flavor in $p + Pb$ collisions

In order to understand quarkonium suppression in Pb+Pb collisions it is necessary to disentangle effects due to interaction between quarkonium and the QGP medium from those that can be ascribed to initial state effects, such as: modifications of the nuclear parton distribution functions, parton saturation effects in the incident nucleus, and parton energy loss through interactions with the nuclear medium of the initial state. These effects can be accessed in $p+Pb$ collisions where a large region of hot QGP is a priori not expected to occur. At the same time, modification of quarkonia production is also expected even in $p+Pb$ collisions to originate from final state effects, namely from the absorption of the heavy quark-antiquark pair through interactions with the co-moving hadrons. For a review of these physics mechanisms see e.g. Ref. [10].

To help disentangle the role of the above mentioned phenomena, ATLAS measured the production cross sections of five quarkonium states, J/ψ , $\psi(2S)$, and $\Upsilon(nS)$ ($n = 1, 2, 3$) in $p+Pb$ collisions at 5.02 TeV with an integrated luminosity of 28 nb^{-1} [11]. The resulting nuclear modification factor, R_{pPb} , is found to be consistent with unity for prompt and non-prompt J/ψ for the kinematic range of the measurement, $8 < p_T < 40$ GeV. The prompt $\psi(2S)$ production

Fig. 2. Left: Nuclear modification factor, R_{pPb} , as a function of p_T for $\Upsilon(1S)$ (in green) and prompt J/ψ (in blue). The vertical error bars cover the statistical uncertainties and horizontal error bars represent the bin size. The horizontal position of data point indicates the mean of the weighted p_T distribution. The vertical size of colored boxes underneath the data points represent the systematic uncertainties. The R_{pPb} of inclusive J/ψ measured by ALICE from [12] is also shown in red. Figure taken from Ref. [11]. Right: The v_2 as a function of number of reconstructed charged particles (N_{ch}^{rec}) obtained from the template fits to hadron-hadron (circles) and to hadron- μ correlations (squares). The error bars and shaded bands indicate statistical and systematic uncertainties, respectively. For the hadron-hadron correlations, the statistical errors are too small to be seen. Figure taken from Ref. [13].

is suppressed with respect to prompt J/ψ production in $p+Pb$ collisions with a significance of one standard deviation.

The R_{pPb} for $\Upsilon(1S)$ is measured for $p_T < 40$ GeV and is found to be smaller than unity at $p_T < 15$ GeV, increasing with p_T and becoming compatible with unity at high p_T . The production of $\Upsilon(2S)$ and $\Upsilon(3S)$ is found to be suppressed with respect to $\Upsilon(1S)$ in the integrated kinematic ranges of $p_T < 40$ GeV and $-2 < y^* < 1.5$ in $p+Pb$ collisions with significance at the level of two standard deviations. Both the prompt $\psi(2S)$ to J/ψ and $\Upsilon(2S)$ to $\Upsilon(1S)$ double ratios show decreasing trend with increasing centrality of $p+Pb$ collisions. The left panel of Figure 2 shows a compilation of results on R_{pPb} measured as a function of p_T for $\Upsilon(1S)$ and prompt J/ψ .

The initial stage effects can also be studied using measurements of heavy quarks. ATLAS measured prompt D^0 mesons (D^0 and $\bar{D}^0$) and D^* mesons (which are not coming from the sequential decays of b -hadrons) using $p+Pb$ collisions at 8.16 TeV with an integrated luminosity of $76.3 \mu b^{-1}$ [14]. The D^0 and D^* mesons are reconstructed in the decay channels with kaons in the range of transverse momentum $3 < p_T < 30$ GeV and $5 < p_T < 30$ GeV, respectively. The relative D meson productions at forward and backward center of mass rapidities is studied via the forward ($0 < y < 0.5$) to backward ($-0.5 < y < 0$) production ratio, R_{FB} , as a function of transverse momentum. No significant forward-backward asymmetry for prompt D^0 and D^* mesons is observed. The azimuthal correlations between inclusive D^* mesons and charged particles is also

measured. The second-order harmonic coefficients for D^* -hadron correlations are extracted using template fits to remove the “non-flow” contributions. The D^* -hadron correlations are broadly consistent with the measurement of muon-hadron correlations.

A detailed measurement of long-range pseudorapidity correlations between muons and charged particles was done using p +Pb data at 8.16 TeV [13]. The template fitting method is used to obtain the second-order Fourier coefficient, $v_{2,2}$, corresponding to the genuine long-range correlations. The $v_{2,2}$ is factorized to obtain the single-particle anisotropy coefficient, v_2 , of the muons. The right panel of Figure 2 shows a comparison of hadron- μ and hadron-hadron v_2 . Significant v_2 values are observed for muons over the transverse momentum interval $4 < p_T < 8$ GeV and over the range of the charged particle multiplicity of 100 – 300. The muon- v_2 values are largest at 4 GeV and decrease with increasing p_T . Given that nearly all the prompt muons over this p_T range are produced from decays of heavy-flavor particles, these results confirm a significant azimuthal anisotropy in the distribution of heavy-flavor particles produced in p +Pb collisions.

3 Conclusions

The ATLAS Experiment at the LHC provides a wealth of new results on quarkonia and heavy flavor measurements in Pb+Pb and p +Pb collisions. The new results from Pb+Pb collisions provide a precise quantification of strong suppression effects and flow phenomena. The new results from p +Pb collisions should allow constraints to be put on the origin of flow phenomena in small collision systems and quantify the role of initial state effects in the studied data.

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