Production of Quarkonia and Heavy Flavor States in ATLAS

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Two recent analyses of data collected with the ATLAS detector at the Large Hadron Collider are presented. In the first, a measurement of b hadron pair production is presented, based on a data set corresponding to an integrated luminosity of 11.4 fb^{-1} of proton-proton collisions recorded at $\sqrt{s} = 8$ TeV. Events are selected in which a b hadron is reconstructed in a decay channel containing a muon. Results are presented in a fiducial volume defined by kinematic requirements on three muons based on those used in the analysis. The fiducial cross section is measured to be $17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst.})$ nb. A number of normalized differential cross sections are also measured and compared to predictions from the Pythia8, Herwig++, MadGraph5_aMC@NLO+Pythia8, and Sherpa event generators, providing new constraints on heavy flavor production. In the second analysis, the modification of the production of J/ψ, $\psi(2S)$, and $\Upsilon(nS)$ ($n = 1, 2, 3$) in p+Pb collisions with respect to their production in pp collisions has been studied. The p+Pb and pp data sets correspond to integrated luminosities of 28 nb^{-1} and 25 pb^{-1} respectively, collected at a center-of-mass energy per nucleon pair of 5.02 TeV. The quarkonium states are reconstructed in the dimuon decay channel. The yields of J/ψ and $\psi(2S)$ are separated into prompt and non-prompt sources. The measured quarkonium differential cross sections are presented as a function of rapidity and transverse momentum, as is the nuclear modification factor $R_{p\text{Pb}}$ for the J/ψ and $\Upsilon(nS)$. No significant modification of the J/ψ production is observed, while $\Upsilon(nS)$ production is found to be suppressed at low transverse momentum in p+Pb collisions relative to pp collisions. The production of excited charmonium and bottomonium states is found to be suppressed relative to that of the ground states in central p+Pb collisions.

I. INTRODUCTION

Two recent measurements involving quarkonium production and b- and c-quarks (hereafter called heavy flavor states), by the ATLAS Experiment [1] at the Large Hadron Collider, are presented.[1]

II. THE B-HADRON PAIR PRODUCTION CROSS SECTION

The production of heavy flavor states in proton-proton collisions provides a fruitful testing ground for the predictions of quantum chromodynamics (QCD). The mass of the b-quark introduces a scale, and the factorization of QCD calculations into parton distribution functions, hard matrix element, and softer parton shower components allows the mass to be introduced at different stages. Furthermore there are several possible schemes for the inclusion of the heavy quark masses at the various stages. The optimal settings must be determined by comparison to data. Previous measurements have highlighted disagreements both between different theoretical predictions and between those predictions and the data. The realm of small angle $b\bar{b}$ pair production is particularly sensitive to the details of the calculations but remains only loosely constrained by data. Searches for Higgs bosons produced in association with a vector boson and decaying to a $b\bar{b}$ pair rely extensively on the modelling of the background arising from QCD production of $b\bar{b}$ pairs in association with vector bosons.

Motivated by these facts, a measurement [2] has been made of the production of two b-hadrons, where one b-hadron decays to $J/\psi(\to \mu^+\mu^-) + X$ and the other to $\mu + Y$, resulting in three muons in the final state. The signal definition includes J/ψ mesons produced via feed-down from excited charmonium states as well as muons produced in semileptonic cascade decays. To probe b-hadron production, several differential cross sections are measured, based on the kinematics of the J/ψ (reconstructed from two muons) and the third muon. The variables considered are:

- the azimuthal separation $\Delta\phi(J/\psi, \mu)$ between the J/ψ and the third muon;
- the transverse momentum of the three-muon system, $p_{\text{T}}(J/\psi, \mu)$;
- the separation between the J/ψ and the third muon in the azimuth-rapidity plane, $\Delta R(J/\psi, \mu)$;
- the separation in rapidity $\Delta y(J/\psi, \mu)$ between the J/ψ and the third muon;
- the magnitude of the average rapidity of the J/ψ and the third muon, y_{boost};
- the mass of the three-muon system, $m(J/\psi, \mu)$;

- the ratio of the transverse momentum of the three-muon system to the invariant mass of the three-muon system, p_{T}/m, and its inverse, m/p_{T}.

The differential cross sections are measured and compared to predictions from several Monte Carlo generators.

Events are selected using a dimuon trigger where the muons are required to have opposite charge, be consistent with originating at the same production vertex, have $p_{\mathrm{T}}(\mu) > 4$ GeV and pseudorapidity $|\eta(\mu)| < 2.4$, and satisfy $2.5 < m(\mu^+\mu^-) < 4.3$ GeV. The integrated luminosity of the data set is 11.4 fb^{-1}. Following selection of the primary vertex (defined as the vertex formed from at least two tracks, each with $p_{\mathrm{T}} > 400$ MeV, that has the largest summed track p_{T}^2 in the event), muon candidates are formed, and J/ψ candidates are reconstructed from them. The third muon is then selected as the highest-p_{T} muon not used in the J/ψ candidate reconstruction. To extract the J/ψ mesons resulting from the decay of a b-hadron, a simultaneous fit is performed upon the distributions of dimuon mass and the pseudo-proper decay time τ, defined as

$$\tau = L_{xy} \cdot m(J/\psi_{\mathrm{PDG}})/p_{\mathrm{T}}(\mu^+\mu^-),$$

where L_{xy} is the signed transverse distance between the primary vertex and the dimuon vertex:

$$L_{xy} = \frac{\vec{L} \cdot \vec{p}_T}{p_{\mathrm{T}}}.$$

Because J/ψ mesons produced by most b-hadron decays are non-prompt, a selection $\tau > 0.25$ mm/c is applied.

Following the addition of the third muon, the yield of signal events relative to background is further improved using a simultaneous fit to the transverse impact parameter significance and the output of a boosted decision tree trained to separate signal muons from misreconstructed muons. The transverse impact parameter significance is defined as $S_{d_0} \equiv d_0/\sigma_{d_0}$, where d_0 is the signed distance of closest approach of the track to the primary vertex point in the $r-\phi$ projection and σ_{d_0} is the unsigned uncertainty on the reconstructed d_0. Some remaining irreducible sources of background are then subtracted from the fitted yields. Corrections for the effects of the selection on τ and for the effects of detector resolution are applied, and the analysis is repeated for every kinematic bin for each differential cross section, resulting in the cross section in that bin.

The total measured cross section in the fiducial region [2] is $\sigma(B(\to J/\psi[\to \mu^+\mu^-] + X)B(\to \mu + X)) = 17.7 \pm 0.1(\mathrm{stat}) \pm 2.0(\mathrm{syst})$nb.

The data are compared to predictions by various simulations including that for inclusive b-hadron pairs taken from Pythia8.186. These explore several options for the $g \to b\bar{b}$ splitting kernel as this process dominates small-angle b-hadron production. The settings explore whether to use the relative p_{T} or mass of the splitting to set the scale when determining the value of α_s to use in that splitting. It is found that in general, Pythia8 does not reproduce the shape of the angular distributions in data within uncertainties, and the p_{T}-based scale splitting kernels generally give a better description of the low $\Delta R(J/\psi, \mu)$ region.

The comparisons are then extended to predictions using Herwig++, MadGraph5_aMC@NLOv2.2.2 interfaced to the Pythia8.186 parton shower model, and Sherpa2.1.1. Options with 5-flavor and 4-flavor schemes are compared. The comparisons indicate that (1) agreement with data is slightly better for Herwig++ than Pythia8 in the $\Delta R(J/\psi, \mu)$ distribution; (2) the 4-flavor prediction by MadGraph+Pythia8 is generally closer in shape to the data than the 5-flavor prediction; (3) in $\Delta y(J/\psi, \mu)$, the MadGraph+Pythia and Sherpa predictions provide a good description of the data; (4) in y_{boost}, all models are comparable; (5) the 5-flavor MadGraph+Pythia8 prediction lies closer to data than the 4-flavor one in the low mass distribution; and (6) at high values of p_{T}/m, the 4-flavor prediction describes the data better than the 5-flavor prediction. Considering all distributions, the 4-flavor MadGraph+Pythia8 prediction provides the best description of the data overall, the predictions of Pythia8 and Herwig++ are comparable, and of the Pythia8 options considered, the p_{T}-based splitting kernel gives the best agreement with data. Figure 1 compares the various predictions to the measured normalized differential cross section in p_{T}/m.

III. QUARKONIUM PRODUCTION IN PROTON-LEAD AND PROTON-PROTON COLLISIONS

In order to understand quarkonium yields in nucleus-nucleus ($A + A$) collisions, it is necessary to disentangle effects due to interaction between quarkonium and the quark-gluon plasma (QGP) medium from those that can be ascribed to cold nuclear matter (CNM). In proton (deuteron)-nucleus collisions, $p(d) + A$, the formation of a large region of deconfined and hot QGP matter is not expected to occur. Therefore, suppression of quarkonium yields in these systems with respect to pp collisions has traditionally been attributed to CNM effects.

Among the CNM effects, three primary initial-state effects include: modifications of the nuclear parton distribution functions, parton saturation effects in the incident nucleus, and parton energy loss through interactions with the nuclear medium. On the other hand, the absorption of the heavy quark-antiquark

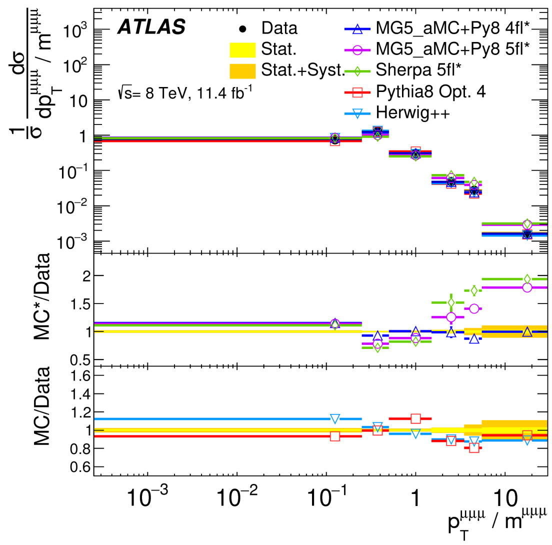

FIG. 1: The measured normalized differential cross section as a function of p_{T}/m [2]. Comparisons are made with predictions of PYTHIA8 and HERWIG++. MADGRAPH5_AMC@NLO+PYTHIA8 and SHERPA predictions are also compared having been corrected from the two-b-hadron production to the three-muon final state via transfer functions (indicated with *). The PYTHIA8 "Opt. 4" gluon splitting parameter settings use a splitting kernel $z^2 + (1-z)^2 + 8r_q z(1-z)$, normalized so that the z-integrated rate is $(\beta/3)(1+r/2)$, and with an additional suppression factor $(1 - m_{qq}^2/m_{\mathrm{dipole}}^2)^3$, which reduces the rate of high-mass $q\bar{q}$ pairs.

pair through interactions with the co-moving nuclear medium is considered to be a final-state effect. In proton-lead (p+Pb) collisions, the modification of quarkonium production with respect to that in pp collisions may be quantified by the nuclear modification factor, $R_{p\mathrm{Pb}}$, which is defined as the ratio of the quarkonium production cross section in p+Pb collisions to the cross section measured in pp collisions at the same center-of-mass energy, scaled by the number of nucleons in the lead nucleus:

$$R_{p\mathrm{Pb}} = \frac{1}{208}\frac{\sigma_{p+\mathrm{Pb}}^{O(nS)}}{\sigma_{pp}^{O(nS)}},$$

where $O(nS)$ represents one of five measured quarkonium states: J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$.

The CNM effects in excited quarkonium states with respect to the ground state can be quantified by the double ratio, defined as:

$$\rho_{p\mathrm{Pb}}^{O(nS)/O(1S)} = \frac{R_{p\mathrm{Pb}}(O(nS))}{R_{p\mathrm{Pb}}(O(1S))}$$

where $n = 2$ for charmonium and $n = 2$ or 3 for bottomonium. In the double ratio, most sources of detector systematic uncertainty cancel, and measurements of this quantity by different experiments can easily be compared. The initial state effects are expected to be largely cancelled out in the double ratio due to the same modifications affecting partons before the formation of both quarkonium states, so measuring the relative suppression of different quarkonium states should help in understanding the properties of the final-state effects separately from the initial ones.

Several classes of experimental measurements are reported [3]: differential production cross sections of J/ψ, $\psi(2S)$, and $\Upsilon(nS)$ ($n = 1, 2, 3$) in pp collisions at $\sqrt{s} = 5.02$ TeV and p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV; center-of-mass rapidity dependence and transverse momentum dependence of J/ψ and $\Upsilon(1S)$ nuclear modification factors, $R_{p\mathrm{Pb}}$; and charmonium and bottomonium double ratios, $\rho_{p\mathrm{Pb}}^{O(nS)/O(1S)}$.

The p+Pb collisions in this analysis result from the interactions of a proton beam with an energy of 4 TeV and a lead beam with an energy of 1.58 TeV per nucleon. In the p+Pb collision configuration, the proton-nucleon center-of-mass rapidity, y^*, had a shift of $\Delta y = 0.465$ with respect to y in the laboratory frame. After 60% of the data were recorded, the directions of the proton and lead beams were reversed. All data from both periods are presented in y^*. The proton beam always travels in the direction of positive y.

Candidate events in p+Pb collisions were collected with a dimuon trigger. Pairs of muon candidates satisfying various quality requirements, and with opposite charges, are selected as quarkonia candidate pairs. In order to characterize the p+Pb collision geometry, each event is assigned to a centrality class based on the total transverse energy measured in the Forward Calorimeter on the Pb-going side (backwards). Collisions with more (fewer) participating nucleons are referred to as central (peripheral).

The double-differential cross section multiplied by the dimuon decay branching fraction is calculated for each measurement interval as:

$$\frac{d^2\sigma_{O(nS)}}{dp_{\mathrm{T}}dy^*} \times B(O(nS) \to \mu^+\mu^-) = \frac{N_{O(nS)}}{\Delta p_{\mathrm{T}} \times \Delta y \times L},$$

where L is the integrated luminosity, Δp_{T} and Δy are the interval sizes in dimuon transverse momentum and center-of-mass rapidity, respectively, and $N_{O(nS)}$ is the observed quarkonium yield in the kinematic interval under study, extracted from fits and corrected for acceptance, trigger and reconstruction efficiencies.

The charmonium yield determination decomposes the yields into two sources of muon pairs: prompt and non-prompt. The prompt J/ψ and $\psi(2S)$ signal originates from the strong production of short-lived particles, including feed-down from other short-lived charmonium states, while non-prompt refers to J/ψ

and $\psi(2S)$ mesons which are the decay products of b-hadrons. To distinguish between these prompt and non-prompt processes, the pseudo-proper decay time, $\tau_{\mu\mu}$, is used. Two-dimensional unbinned maximum-likelihood fits are performed on weighted distributions of the dimuon invariant mass ($m_{\mu\mu}$) and pseudo-proper decay time to extract prompt and non-prompt signal yields, in intervals of $p_{\mathrm{T}}^{\mu\mu}$, rapidity, and centrality. To obtain the acceptance corrections, J/ψ acceptance is applied to events with $m_{\mu\mu} < 3.2$ GeV, $\psi(2S)$ acceptance is applied to events with $m_{\mu\mu} > 3.5$ GeV, and a linear interpolation of the two acceptances is used for events with $3.2 < m_{\mu\mu} < 3.5$ GeV.

The yields of bottomonium states are obtained by performing unbinned maximum likelihood fits of the weighted invariant mass distribution, in intervals of $p_{\mathrm{T}}^{\mu\mu}$, rapidity, and centrality. Due to overlaps between the invariant mass peaks of different bottomonium states, the linear acceptance interpolation used for the charmonium states is not appropriate to the bottomonium states. Instead, each interval is fitted three times to extract the corrected yields of the three different bottomonium states.

Figure 2 shows examples of charmonium fit projections onto the invariant mass axis.

Following the yield correction and signal extraction, the cross sections of the five quarkonium states are measured differentially in transverse momentum and rapidity. The results for non-prompt J/ψ and $\psi(2S)$ cross sections in pp collisions at $\sqrt{s} = 5.02$ TeV are compared to fixed order next-to-leading-logarithm (FONLL) predictions. The FONLL uncertainties include renormalization and factorization scale variations, charm quark mass, and parton distribution functions uncertainties. The measured non-prompt charmonium production cross sections agree with the FONLL predictions within uncertainties over the measured p_{T} range.

The measured prompt J/ψ and $\psi(2S)$ cross sections are compared with non-relativistic QCD (NRQCD) predictions. The theory predictions are based on long-distance matrix elements (LDMEs) with uncertainties originating from the choice of scale, charm quark mass, and LDMEs. The production cross section of $\Upsilon(nS)$ in pp collisions is compared to similar NRQCD model calculations.

The results for prompt and non-prompt production cross sections of J/ψ and $\psi(2S)$ in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are consistent with previous results within uncertainties. The measured differential production cross sections of $\Upsilon(2S)$ and $\Upsilon(3S)$ in p+Pb collisions are combined to obtain stable rapidity dependence of the production cross section.

Both the prompt and non-prompt J/ψ $R_{p\mathrm{Pb}}$ are consistent with unity across the p_{T} range from 8 to 40 GeV. No significant rapidity dependence is observed.

Using $R_{p\mathrm{Pb}}$, the $\Upsilon(1S)$ production in p+Pb collisions is found to be suppressed compared to pp collisions at $p_{\mathrm{T}} < 15$ GeV, and it increases with p_{T}. Low p_{T} $\Upsilon(1S)$ states can probe a smaller Bjorken-x region than can J/ψ measured in $8 < p_{\mathrm{T}} < 40$ GeV, so the observed suppression of $\Upsilon(1S)$ production at low p_{T} may come from the reduction of hard-scattering cross sections due to stronger nuclear PDF shadowing at smaller Bjorken-x. No significant rapidity dependence is observed.

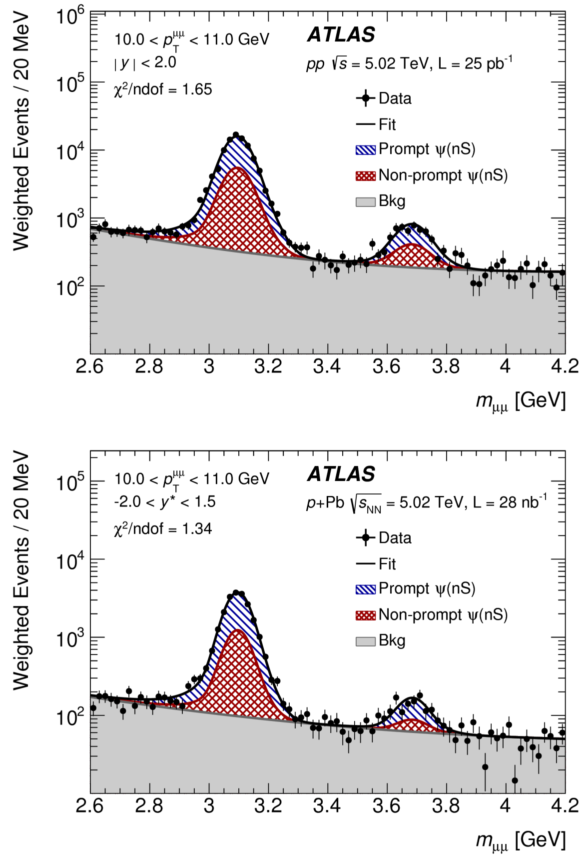

FIG. 2: Projection of the charmonium fit results [3] onto dimuon invariant mass $m_{\mu\mu}$ for pp collisions at $\sqrt{s} = 5.02$ TeV for the kinematic ranges $10 < p_{\mathrm{T}}^{\mu\mu} < 11$ GeV and $|y| < 2.0$ (upper), and p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the kinematic ranges $10 < p_{\mathrm{T}}^{\mu\mu} < 11$ GeV and $-2.0 < y^* < 1.5$ (lower).

The prompt charmonium double ratio is found by ATLAS to decrease slightly from the backward to the forward center-of-mass rapidity. The prompt $\psi(2S)$ production is suppressed with respect to prompt J/ψ production in p+Pb collisions with a significance of one standard deviation. The production of excited bottomonium states, $\Upsilon(2S)$ and $\Upsilon(3S)$, is found to be suppressed at the LHC with respect to $\Upsilon(1S)$ in the integrated kinematic ranges of $p_{\mathrm{T}} < 40$ 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 behavior in more central collisions. The decreasing trends from peripheral to central are at the significance level of one standard deviation. Thus a stronger cold nuclear matter effect is observed in excited quarkonium states compared to that in ground states. This work expands the kinematic range of measured charmonium and bottomonium cross sections in pp and p+Pb collisions. It thus serves as an additional dataset for constraining different models of cold nuclear matter effects and quantifying heavy quarkonium production.

Acknowledgments

This work was supported by U.S. Department of Energy grant de-sc0019101.

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[2] ATLAS Collaboration, *Measurement of b-hadron pair production with the ATLAS detector in proton-proton collisions at* $\sqrt{s} = 8$ *TeV*, JHEP 11 (2017) 062.

[3] ATLAS Collaboration, *Measurement of quarkonium production in proton-lead and proton-proton collisions at 5.02 TeV with the ATLAS detector*, Eur. Phys. J. C (2018) 78:171.