ATLAS Heavy Flavor Production and Decay Properties

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Abstract. First measurements of non-prompt $J/\psi$ fraction in $pp$ collisions at $\sqrt{s} = 13$ TeV and new results from RUN 1 data analysis are presented for heavy flavor production and decays. RUN 1 results include observation and measurement of the $Z+J/\psi$ associated production, $f_s/f_d$ measurements and the branching ratio measurement for $\Lambda^0_b$ decays to $\psi(2S)+\Lambda^0$ and $J/\psi + \Lambda^0$.

INTRODUCTION

The studies of heavy flavor production and decay properties at the ATLAS experiment [1] brought many important results, especially concerning measurements at the highest transverse momentum of produced heavy particles. The year 2015 has opened a new stage of studies with a successful start of Large Hadron Collider operation at $\sqrt{s} = 13$ TeV of proton beam collisions. The first results with data collected by the ATLAS detector at the new energy for the lightest quarkonium state $J/\psi$ production [2] are presented in this paper.

There are three new results from data collected in RUN 1, including observation and measurements of the associated $J/\psi$ and $Z$ boson production in $pp$ collisions at $\sqrt{s} = 8$ TeV [3], determination of the ratio of $b$-quark fragmentation fractions $f_s/f_d$ at $\sqrt{s} = 7$ TeV [4] and measurement of the branching ratio $\frac{\Gamma(\Lambda^0_b \rightarrow \psi(2S)\Lambda^0)}{\Gamma(\Lambda^0_b \rightarrow J/\psi \Lambda^0)}$ [5].

EXPERIMENTAL RESULTS

Non-prompt $J/\psi$ fraction in $pp$ collisions at $\sqrt{s} = 13$ TeV

The fraction of $J/\psi$ mesons produced in $pp$ collisions at energy 13 TeV that are products of $b$-hadron decays (non-prompt $J/\psi$) is measured with the total integrated luminosity of approximately 6.4 pb$^{-1}$ [2]. The fraction is defined as the ratio of the number of $J/\psi$ mesons produced in these decays to the total number produced. The non-prompt $J/\psi$ are distinguished from the prompt ones by a longer decay time due to the primary $b$-hadron decay. This time is estimated from measurement of pseudo-proper decay time $\tau$ for di-muon vertexes. The calculations make use of the transverse momentum $p_T$ of the two muons and the transverse decay length $L_{xy}$ of the di-muon vertex, following the formula $\tau = L_{xy} m_{J/\psi} (PDG)/p_T$, where the world average value [6] for the $J/\psi$ mass $m_{J/\psi} (PDG)$ is used. An unweighted two-dimensional unbinned maximum likelihood fit to the data in the di-muon invariant mass ($2.65 < m(\mu^+\mu^-) < 3.55$ GeV) and pseudo-proper decay time ($-5.0 < \tau < 15.0$ ps) is performed. It allows both background discrimination and separation of the prompt and non-prompt $J/\psi$ mesons. The yields of non-prompt and prompt $J/\psi$ production are extracted from the fit and the fraction of non-prompt $J/\psi$ is calculated. Results for this fraction as a function of di-muon $p_T$ and rapidity $|y|$ are presented in Fig. 1(a). This value increases from 0.25 to 0.65 within the $p_T$ range from 8 GeV to 40 GeV and does not show significant dependence on rapidity within the precision of the measurement.

The centre-of-mass energy dependence of the fraction is shown in Fig. 1(b) for the $J/\psi$ rapidity interval $|y| < 0.75$ with ATLAS results and CDF measurements for $|y| < 0.6$. The difference of intervals can be ignored as no rapidity dependence of the measured fraction has been observed. Finally, no significant change in the non-prompt fraction is observed between the 7 and 13 TeV measurements, contrary to the significant difference between 7 TeV and lower energy measurements.
FIGURE 1. Measured non-prompt $J/\psi$ production fraction as a function of $J/\psi$ $p_T$ in three intervals of $J/\psi$ rapidity (a); Non-prompt differential $J/\psi$ production fraction for the most central rapidity interval $|y| < 0.75$ in comparison with similar measurements at lower energies (b) [2].

**Z+J/ψ associated production**

The production of a $Z$ boson in association with a $J/\psi$ meson in $pp$ collisions allows for the studies of multiple parton scattering. First observation and measurements of the associated $Z+J/\psi$ prompt and non-prompt productions are made with ATLAS detector in $pp$ collisions at $\sqrt{s} = 8$ TeV and total integrated luminosity of 20.3 fb$^{-1}$ [3]. An inclusive $Z$ sample with the $\mu^+\mu^-$ and $e^+e^-$ decay modes and $J/\psi$ decaying to $\mu^+\mu^-$ indicates 290 candidate events for the associated production after the following cuts:

- $Z$ decay leptons $p_T > 25$ GeV (trigger lepton) and $p_T > 15$ GeV (sub-leading lepton)
- their pseudorapidities $|\eta| < 2.5$
- $J/\psi$ candidate invariant mass $2.6 \leq m_{J/\psi} \leq 3.6$ GeV,
- $J/\psi$ $p_T$ in range between 8 GeV and 100 GeV and its rapidity $|y| < 2.1$.

FIGURE 2. Azimuthal angle between the $Z$ boson and the prompt $J/\psi$ meson (a) and such angle between the $Z$ boson and the non-prompt $J/\psi$ meson (b) distributions. The estimated DPS (yellow band) and pileup (cyan band) contributions to the data are overlaid [3].
The associated $Z + J/\psi$ production fractions relative to the $Z$ inclusive production cross section in this phase volume is measured to be $(36.8 \pm 6.7 \pm 2.5) \times 10^{-7}$ and $(65.8 \pm 9.2 \pm 4.2) \times 10^{-7}$ for prompt and non-prompt produced $J/\psi$ respectively. The azimuthal angle distributions between the $Z$ boson and the prompt and non-prompt $J/\psi$ mesons are presented in Fig. 2. The estimation of double parton scattering (DPS) contribution is calculated using parameter $\sigma_{\text{eff}} = 15 \pm 3(\text{stat.}) \pm 3(\text{syst.}) \text{mb}$ from ATLAS measurement of $W + 2$-jet events [7]. The DPS fraction is $(29 \pm 9)\%$ for the $Z +$ prompt $J/\psi$ signal and $(8 \pm 2)\%$ for the non-prompt signal. The pileup contribution is found to be two times smaller than DPS. Both are shown in Fig. 2 and used for estimation of single parton scattering (SPS) contribution to associated production.

The lowest bin in the azimuthal angle distribution in Fig. 2(a) is used for an independent calculation of the limit on maximum rate of the DPS contributions to the $Z +$ prompt $J/\psi$ production signal. This result is shown in Fig. 3. The lower limit on $\sigma_{\text{eff}}$ is calculated to be $5.3 \text{mb (3.7 mb)}$ at $68\%$ ($95\%$) confidence level. This result is presented in Fig. 3(b) in comparison with earlier measurements.

The measured SPS $Z +$ prompt $J/\psi$ production rates are compared to theoretical predictions at LO and NLO for the colour-singlet and colour-octet prompt production processes. The sum of the rates for these processes is found to be lower than the measured values by factors from 2 to 5 within the $J/\psi$ $p_T$ range studied. The comparison of these results is shown in Fig. 4.

**Measurement of the $b$-quark fragmentation fractions ratio $f_s/f_d$**

The ratio of $b$-quark fragmentation fractions $f_s/f_d$ is determined by the ATLAS experiment with an integrated luminosity of $2.47 \text{fb}^{-1}$ for $pp$ collisions at $\sqrt{s} = 7 \text{ TeV}$ [4]. The exclusive decays $B_s \rightarrow J/\psi\phi$ and $B_d^0 \rightarrow J/\psi K^{*0}$ are used for the analysis. The signal yields are found to be $6640 \pm 100(\text{stat.}) \pm 220(\text{syst.)}$ for the $B_s \rightarrow J/\psi\phi$ channel and $36290 \pm 320(\text{stat.}) \pm 650(\text{syst.})$ for $B_d^0 \rightarrow J/\psi K^{*0}$. The quantity $(f_s/f_d)(\text{BR}(B_s^0 \rightarrow J/\psi\phi)/\text{BR}(B_d^0 \rightarrow J/\psi K^{*0}))$ is estimated to be $0.199 \pm 0.004(\text{stat.}) \pm 0.010(\text{syst.})$. The ratio $f_s/f_d$ is measured to be $0.240 \pm 0.004(\text{stat.}) \pm 0.013(\text{syst.}) \pm 0.017(\text{th})$ with the use of perturbative QCD predictions for branching ratios [8].

To investigate the $p_T$ and $\eta$ dependences of $f_s/f_d$ the ratio is measured in six $p_T$ bins in the range from 8 GeV to 50 GeV and four bins in $\eta$ for $|\eta| < 2.5$. The results for different $p_T$ are shown in Fig. 5(a) in comparison with the results of other experiments. No significant dependence on $p_T$ or $\eta$ is observed. The $f_s/f_d$ ratio from the ATLAS measurement is compared with the LHCb [9], LEP [10] and CDF [11] results in Fig. 5(b). The ATLAS result is in agreement with the shown experiments.
Measurement of the branching fractions ratio \( \Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0) \)

The Large Hadron Collider provides a possibility for the extensive studies of the \( \Lambda_b^0 \) baryon properties. The observation of the \( \Lambda_b^0 \to \psi(2S)\Lambda^0 \) decay and measurement of the branching ratio of the \( \Lambda_b^0 \to \psi(2S)\Lambda^0 \) and \( \Lambda_b^0 \to \psi(2S)\Lambda^0 \) decays are performed with the ATLAS detector in \( pp \) collisions at \( \sqrt{s} = 8 \) TeV using the total integrated luminosity of 20.6 \( fb^{-1} \) [5]. The \( \Lambda_b^0 \) baryons are reconstructed with transverse momentum \( p_T > 10 \) GeV and \( |\eta| < 2.1 \). The invariant mass distributions \( m(J/\psi\Lambda^0) \) and \( m(\psi(2S)\Lambda^0) \), calculated using tracks from \( \Lambda_b^0 \) topology fit, for combined sample of the \( \Lambda_b^0 \) and \( \Lambda_b^0 \) baryons are presented in Fig. 6. The invariant mass distributions \( m(J/\psi K^0_S) \) and \( m(\psi(2S)K^0_S) \) are shown in the figures. The branching ratio of the two \( \Lambda_b^0 \) decays is calculated as

\[
\frac{\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)} = \frac{N_{\text{cor}}(\Lambda_b^0 \to \psi(2S)\mu^+\mu^-)\Lambda^0}{N_{\text{cor}}(\Lambda_b^0 \to \psi(2S)\mu^+\mu^-)\Lambda^0} \cdot \frac{\text{BR}(J/\psi \to \ell\ell)}{\text{BR}(\psi(2S) \to \ell\ell)},
\]

where \( N_{\text{cor}} \) denotes the number of corresponding signal events after all the necessary corrections.

The BR values are used from [6]. The measured branching ratio of the two \( \Lambda_b^0 \) decays is \( \Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0) = 0.501 \pm 0.033 \text{(stat)} \pm 0.016 \text{(syst)} \pm 0.011 \text{(BR)} \). The measured ratio lies within the range 0.5 – 0.8 found for the BR ratio of analogous B meson decays [6]. The only available theoretical prediction for this ratio 0.8 ± 0.1 [12] exceeds the measured value.
FIGURE 5. The $f_s/f_d$ ratio dependence on $B$-meson $p_T$ (a) and the ATLAS $f_s/f_d$ ratio in comparison with LHCb [9], LEP [10] average and CDF [11] results (b) [4].

FIGURE 6. The invariant mass distributions $m(J/\psi \Lambda^0)$ (a) and $m(\psi(2S)\Lambda^0)$ (b) for the combined sample of the selected $\Lambda^0_b$ and $\bar{\Lambda}^0_b$ candidates with $B^0$ decays reflections [5].
SUMMARY

The ATLAS experiment has successfully started the operation in RUN 2 at $\sqrt{s} = 13$ TeV. The first RUN 2 measurements of the $J/\psi$ non-prompt production are presented. New results for the heavy flavor production and decay properties with RUN 1 data are shown. They expand the set of results for $B$, $B_s$, $B_c$ and $\Lambda^0_b$ hadrons in wide $p_T$ regions from the ATLAS experiment presented on the collaboration website https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults.

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REFERENCES


