Production of exotic and conventional quarkonia and open beauty/open charm at ATLAS

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Abstract. The ATLAS experiment at LHC is carrying on a wide programme to study the production properties of conventional and exotic quarkonium, beauty, and charm bound states. The latest results on J/ψ, ψ(2s) and X(3872) production at 7, 8, and 13 TeV, together with D meson production with Run-1 are presented. Studies of associated production of charmonium with vector bosons, searches for exotic states in the bottomonium sector and a new measurement of the ratio of b-quark fragmentation functions are also briefly presented.

1. Introduction

The production of heavy flavors (HF) in high energy hadron collisions is characterized by a large cross-section. Since the first measurements done at Tevatron [1] it was clear that models based on pQCD were not able to account for such a large production cross-section. The theoretical estimate of these cross-section is a challenge for QCD. Infact many ingredients are needed to obtain consistent estimates to be compared with experimental values, including proton Parton Density Functions (PDFs), hard-scattering cross-sections and hadronization models. Several approaches have been developed in the most recent years to provide theoretical environments for these calculations. Among them the Color Singlet Model (CSM) and the Non-Relativistic QCD (NRQCD including Color Singlet and Color Octet production models) are considered to account for quarkonia production; GM-VFNS (General Mass Variable Flavour Number Scheme), FONLL (Fixed Order + Next to Leading Logs) and MC@NLO and POWHEG complemented by Pythia/Herwig for the hadronization are the methods considered to interpret open HF production. A recent comprehensive review on these models can be found in Ref.[2].

In the following we present a summary of the most recent measurements performed by the ATLAS experiment at LHC on quarkonia and open HF production.

2. The ATLAS experiment

The results presented here are based on the data taken by the ATLAS experiment [3] at LHC during the Run-1 in 2011 and 2012 (7 and 8 TeV c.o.m. energies corresponding to integrated luminosities of $\sim$ 5 and $\sim$ 21 fb^{-1} respectively) and on the first data of Run-2 taken in 2015 (13 TeV, $\sim$ 4 fb^{-1}).

The possibility to perform HF physics in ATLAS is based on two main ingredients: low p_T muon triggers and track reconstruction in the inner detector. The muon spectrometer allows to obtain di-muon triggers with muons of p_T down to 4÷6 GeV and up to $|\eta|$ <2.4, in an invariant mass region between the J/ψ and the Υ using the RPC (in the barrel) and TGC (in the endcap) trigger detectors. The inner detector provides a tracking in a 2T magnetic field using silicon pixels, silicon strips and transition radiation detectors. In Run-2 an additional pixel layer (the so called Insertable B-layer (IBL)) has been added closer to the beam interaction point. Tracks are detected up to $|\eta|$ <2.5. The typical resolution in di-muon invariant mass ranges between 50 MeV (at the J/ψ peak) and 150 MeV (at the Υ peak).

In the case of charmonium, two distinct production mechanisms are possible at LHC: prompt and non-prompt production. Prompt particles are directly produced in the primary pp interaction or through feed-down from decays of heavier (directly produced) states; non-prompt particles are produced in the decays of b-hadrons. The two categories can be separated experimentally exploiting the long b-hadron lifetime. The discrimination is based on the so called "pseudo-proper time" τ:

$$\tau = \frac{L_{xy} m(\mu\mu)}{|\vec{p}_T(\mu\mu)|} \tag{1}$$

where L_{xy} is the travel distance of the quarkonium in the transverse plane, $m(\mu\mu)$ and $\vec{p}_T(\mu\mu)$ are the mass and the transverse momentum of the muon pair respectively.

3. Quarkonia production

For each considered charmonium final state prompt and non-prompt production cross-sections are obtained separately by counting the events through a combined fit of invariant mass and pseudo-proper time. An example of fit for the $\mu\mu$ final state involving J/ψ and $\psi(2S)$ [4] is shown in Fig.1. All the different contributions are shown. This kind of analysis has been performed for J/ψ [4], $\psi(2S)$ [5, 6], χ_{c1} and χ_{c2} [7]. In general the prompt charmonium production turns out to be well described by NLO NRQCD. Predictions based on NNLO* colour-singlet model calculations clearly underestimate the data, especially at high transverse momenta. The non-prompt charmonium production is reasonably well described by FONLL. The comparison between data and theory for the J/ψ data at 7 TeV c.o.m. energy is shown as a function of $p_T(\mu\mu)$ for different $|\eta|$ ranges in Fig.2.

The same analysis has been applied on the first bunch of data from Run-2. Fig.3 compares the non-prompt fraction as a function of $p_T(\mu\mu)$ of ATLAS data at different

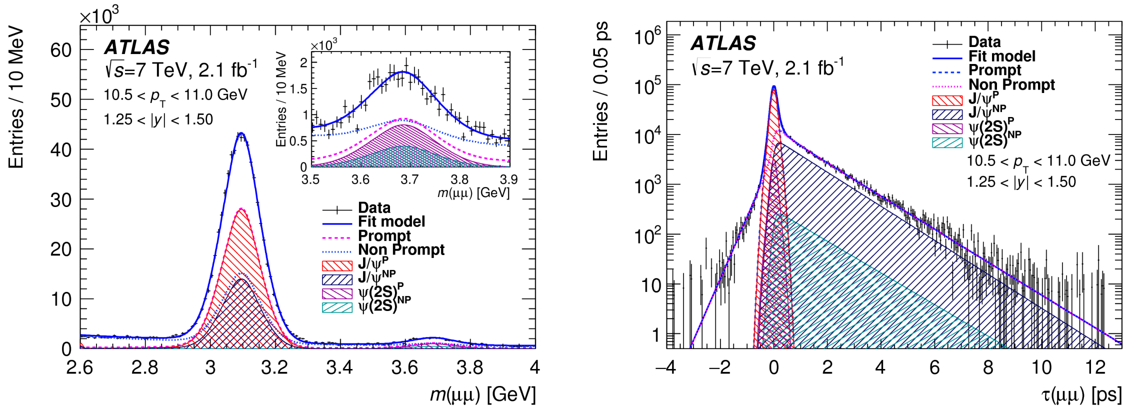

Figure 1. Invariant mass (left plot) and pseudo-proper decay time (right plot) spectra of $\mu\mu$ final states for a given region in $p_T(\mu\mu)$ and $y(\mu\mu)$. The signals of the J/ψ and $\psi(2S)$ (also in the insert of the left plot) can be easily seen. The result of the combined fit is also shown with the detail of the single components.(From Ref.[4])

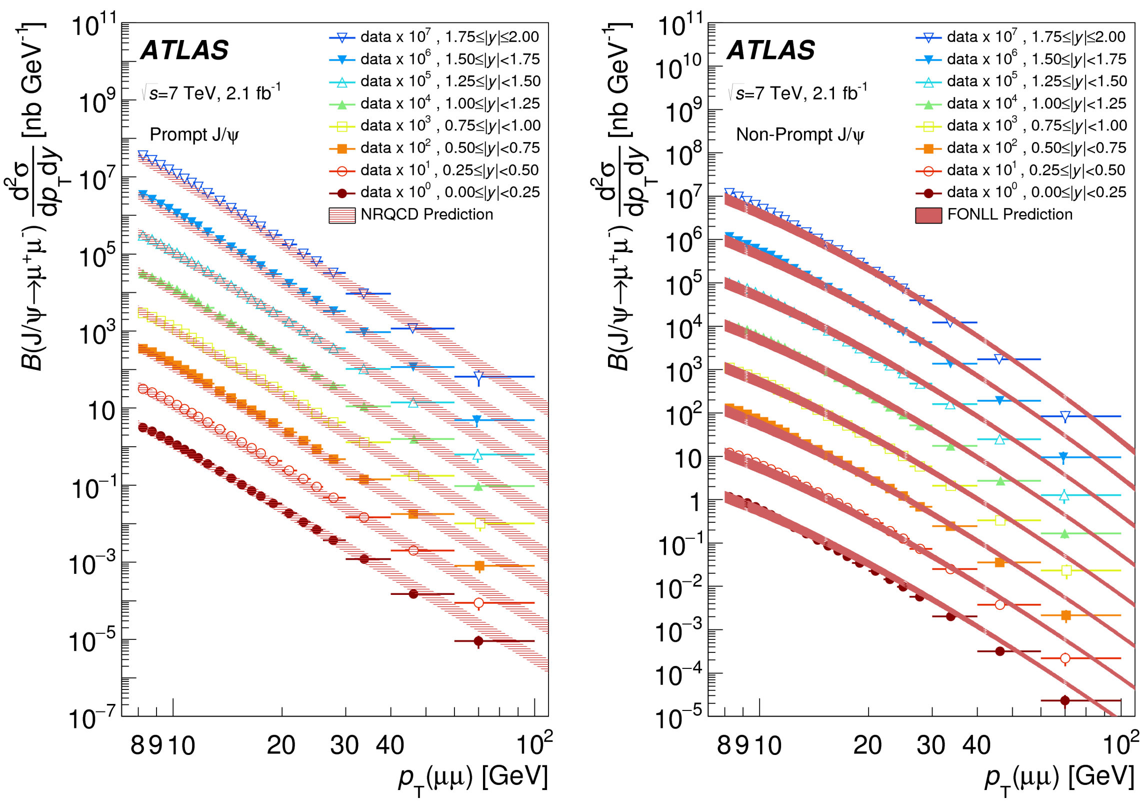

Figure 2. Prompt (left plot) and non-prompt (right plot) J/ψ production cross-section as a function of $p_T(\mu\mu)$ up to 100 GeV in slices of $y(\mu\mu)$. The data are compared with predictions from NRQCD (left) and FONLL (right). A reasonable agreement is found in both cases in a large kinematical range.(From Ref.[4])

center of mass energies [8]. The plot includes data from the Tevatron [9] at 1.96 TeV c.o.m. energy. The comparison shows that the non-prompt fraction behavior with $p_T(\mu\mu)$ doesn't depend on the c.o.m. energy. Only some discrepancy is observed in the absolute scale with respect to lower energy data.

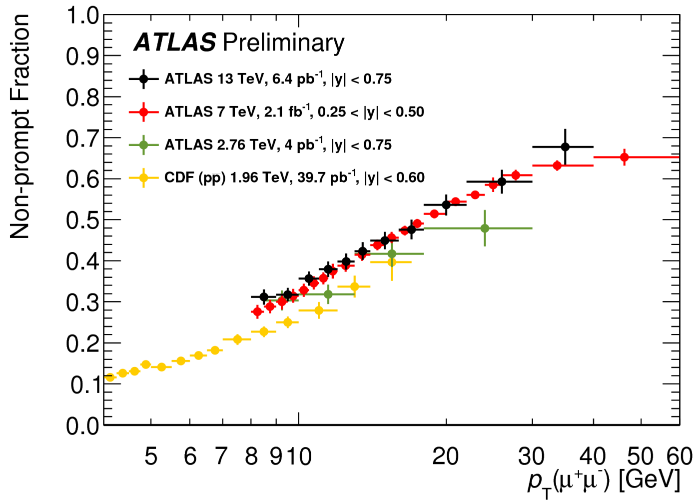

Figure 3. Non-prompt J/ψ production fraction compared to previous measurements from ATLAS in pp collisions at 2.76 and 7 TeV, and from CDF in p$\overline{\text{p}}$ collisions at 1.96 TeV. (From Ref.[8])

In the analysis of the J/$\psi\pi^+\pi^-$ final state [6] we find (see Fig.4), in addition to the ψ(2S) peak, a clear signal from the X(3872), well-known exotic candidate. A good description of the prompt X(3872) production cross-section is obtained assuming that this meson is a mixing of a "molecular state" and a χ_c state [10]. On the other hand the non-prompt production cross-section is overestimated by all considered models.

A search for possible exotic X_b states decaying to $\Upsilon(1S)\pi^+\pi^-$, replica of the X(3872) in the beauty sector with masses in the range 10.5 ÷ 10.7 GeV has been also performed [11]. No signal is found. Upper limits ranging between 0.02 and 0.03 at the different masses are obtained for the ratio between X_b and Υ(2S) production.

Finally it is worth mentioning the measurement of associated production of the J/ψ with vector bosons W and Z [12, 13]. In both cases ATLAS finds a cross-section significantly larger than the one expected by NLO NRQCD calculations. Results with increased statistical significance are expected soon from Run-2 data.

4. Open Charm/Beauty production

A systematic study of the production of $D^{*\pm}$, $D^\pm$ and $D_s^\pm$ has been performed [14] using the final states $K\pi\pi$ and $KK\pi$. D mesons are reconstructed for p_T up to 100 GeV. Fig.5 shows the peaks corresponding to the three mesons in the relevant invariant mass plots.

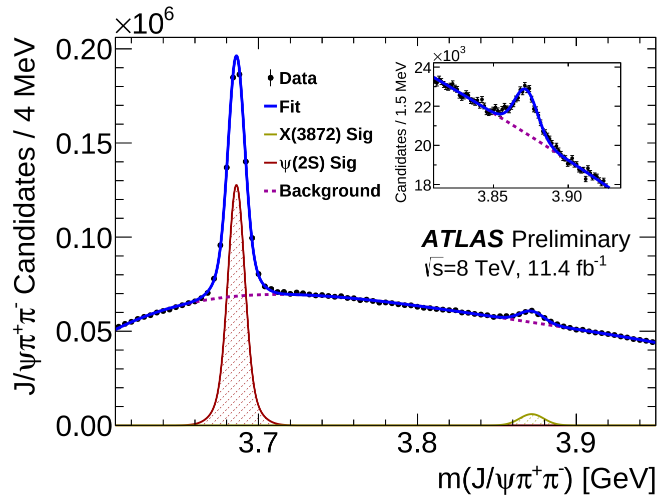

Figure 4. Invariant mass spectrum of $J/\psi\pi^+\pi^-$ with $J/\psi \to \mu\mu$. In addition to the ψ(2S) peak, a clear signal (see also insert) is observed corresponding to the X(3872) meson.(From Ref.[6])

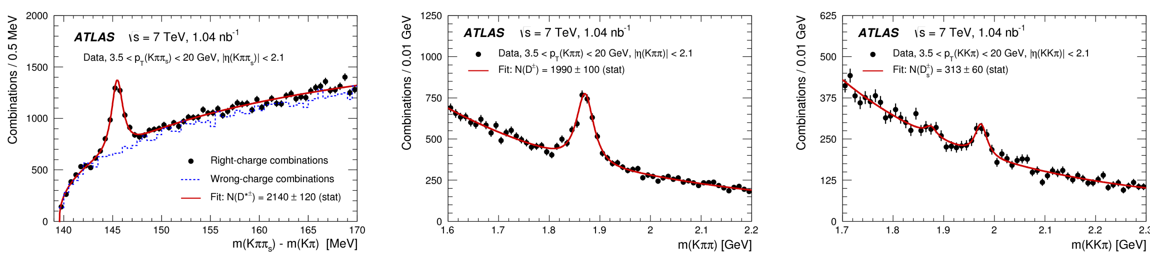

Figure 5. From left to right, three examples of $D^{*\pm}$, $D^{\pm}$ and $D_s^{\pm}$ peaks in the p_T and η regions specified in each plot. The number of resulting candidates is also given.(From Ref.[14])

The measured D^* and D meson production cross-sections integrated in η are shown in Fig.6 as a function of $p_T(D)$ and are compared to different models. The best agreement is obtained in both cases for the GM-VFNS model, that is able to describe both shape and normalization of the distributions.

An important ingredient in the interpretation of the rare B decays is the ratio of b-quark fragmentation functions f_s/f_d. This quantity can be extracted in pp collisions from the ratio of the decays $B_d^0 \to J/\psi K^{*0}$ with $K^{*0} \to K^+\pi^-$ and $B_s^0 \to J/\psi\phi$ with $\phi \to K^+K^-$. Both decays are observed with high statistics in ATLAS [15] and the obtained resulting value of f_s/f_d is:

$$\frac{f_s}{f_d} = 0.240 \pm 0.004(stat) \pm 0.010(syst) \pm 0.017(th) \qquad (2)$$

in agreement with results from other experiments. This result extends the knowledge of this quantity to higher $p_T(B)$ values.

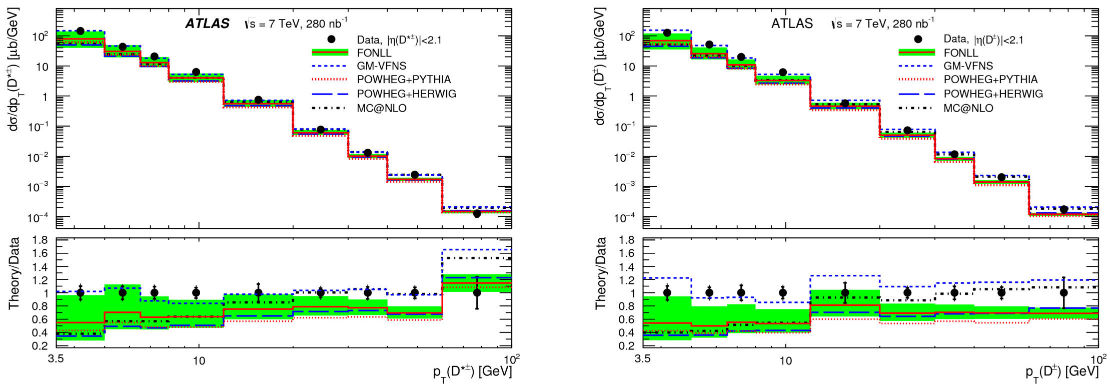

Figure 6. $D^{*\pm}$ (left) and $D^{\pm}$ production cross-section as a function of $p_T(D)$ and integrated in η. The data are compared with several different predictions. The lower plots show the ratio between theory and experiment.(From Ref.[14])

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