Heavy flavour production with the ATLAS detector at LHC

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Abstract

We present some recent results on heavy flavour production obtained with ATLAS during the LHC runs in 2011-2012.

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1. Introduction

The production of heavy flavours (HF) at hadron colliders provides particular opportunity to study the theory of Quantum Chromodynamics (QCD), in particular the boundary of the perturbative and non-perturbative regimes. At LHC, due to the high energy available $\sqrt{s} = (7 \div 8)$ TeV, it is possible to explore new kinematic regions (e.g., high¹ p_T up to $\sim 10^2$ GeV) to test the predictions of various theoretical models for both quarkonium and open state production. In most cases, corrections over the leading order (LO) are available (e.g., next-to-leading (NLO), next-to-leading-log (NLL)) and an accurate quantitative comparison of data with QCD predictions can be performed to discriminate among various quarkonium production models (color singlet (CS) [1], color octet (CO or NRQCD) [2], color evaporation (CE) [3], k_T factorization [4]).

2. Experimental aspects

2.1. Detector performances

ATLAS is a multipurpose apparatus to study pp interactions at LHC, the detailed description and performances of the detector can be found in Ref. [5]. Regarding the analysis on HF during the LHC runs of 2011-2012 at $\sqrt{s} = (7 \div 8)$ TeV, the main detector components are: (a) the Muon System (MS) with tracking capability up to pseudorapidity $|\eta| \leq 2.7$, with momentum resolution

$\sigma_{p_T}/p_T = 0.06$ up to 60 GeV; (b) the Inner Detector (ID) which reconstruct tracks up to $|\eta| \leq 2.5$ with efficiency $\epsilon_{trk} = 0.99$. The vertexing accuracy (primary and secondary) results in a resolution on the track impact parameter² $\sigma_\delta \simeq 10 \mu\text{m}$. The trigger for HF physics is based on di-muons up to $|\eta| \leq 2.4$ and with momentum thresholds $p_T^{(\mu)}(\text{GeV}) = 4 - 6$.

The invariant mass distribution for a final state Q is the key-tool for HF analyses; the typical resolutions are in the range $(50 \div 100)$ MeV for $\mu\mu$ pairs or other exclusive states, and the observed signal/background ratios are high. From vertices reconstruction, it is possible to obtain the *proper* lifetime³ to reduce background or disentangle prompt and non-prompt⁴ components. For example, figure 1 shows the invariant mass distribution for $\psi(2S) \rightarrow J/\psi(\mu\mu)\pi\pi$.

Figure 1: Mass distribution for $\psi(2S) \rightarrow J/\psi(\mu\mu)\pi\pi$.

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¹ p_T is the transverse momentum to the direction of colliding beams.

² δ is the distance of closest approach to the primary vertex.

³The (pseudo) proper lifetime is $t = L_T \cdot \frac{m_0}{P_T}$ where L_T is transverse decay length projected along the $\vec{P}_T$ of the resonance.

⁴Non-prompt component originates from decays of b-hadrons.

2.2. Cross section evaluation

Experimentally, for each channel $Q \rightarrow \text{final}$, the double differential cross section in p_T and rapidity y , is obtained from

$$\frac{d^2\sigma_Q}{dp_T dy} \cdot BR(Q \rightarrow \text{final}) = \frac{N_{corr}^{Q \rightarrow \text{final}}}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y}, \quad (1)$$

where $\mathcal{L}$ is the integrated luminosity⁵, $\Delta p_T(y)$ is the bin size of the differential variable, and $N_{corr}^{Q \rightarrow \text{final}}$ is the signal yield corrected for efficiency, acceptance and background subtraction. The extraction of the signals is obtained with unbinned maximum likelihood methods and the corresponding uncertainties are in general at the level of a few %. The efficiency corrections for tracking, reconstruction and triggering are obtained with data driven methods (e.g., tag and probe for the trigger) in order to reduce the systematic uncertainties which amount typically to (5÷10)%. The acceptance corrections, to recover the visible phase space in p_T and y for comparison with QCD predictions, are obtained with simulation. They depend on the unknown polarization status of Q (spin alignment [6]). The correction is evaluated for the isotropic case and an envelope of variations is computed for the various polarizations (e.g., the $\psi(2S) \rightarrow J/\psi \pi \pi$ state is shown in figure 2 as a function of p_T).

Figure 2: Acceptance correction ratios for $\psi(2S) \rightarrow J/\psi \pi \pi$.

3. Charmonium production

First studies on prompt charmonium production were based on the measurement of J/ψ [7]. However, comparisons with theoretical models are difficult for J/ψ due to the uncertain contributions from higher ($c\bar{c}$) states which decays to J/ψ (feed-down effect).

⁵The $\mathcal{L}$ may vary for each analysis (trigger, etc...).

3.1. ψ_{2S} and $\chi_{c n J}$ production

To overtake feed-down uncertainties, analyses were performed to study the production of $\psi(2S)$ [8] ($\chi_{c n J}$ [9]) the S-wave (P-wave) just below the open charm threshold for which the feed down effect is absent (reduced). The decay channels are $\psi(2S) \rightarrow J/\psi(\mu^+\mu^-) \pi^+\pi^-$ and $\chi_{c n J} \rightarrow J/\psi(\mu^+\mu^-) \gamma(e^+e^-)$; the prompt and non-prompt productions are disentangled using reconstruction of secondary vertices. The differential cross sections, as functions of p_T for different y intervals, for prompt production of $\psi(2S)$ and $\chi_{c n J}$ are shown in figures 3 and 4; the predictions for different theoretical models are also reported.

Figure 3: p_T -differential cross section for prompt $\psi(2S)$ production.

Figure 4: p_T -differential cross section for prompt $\chi_{c n J}$ production.

A good agreement is observed with NRQCD (LO and NLO) at low and medium p_T , while in the new high p_T regions some deviations appear. The CSM and k_T models may need higher order contributions. For non-prompt production, $\psi(2S)$ agrees with predictions at low p_T , but improvements are needed at higher p_T ; χ_{nJ} is generally in good agreement with predictions but the range in p_T is still limited.

3.2. $W + J/\psi$ associated production cross section

The study of associated production of prompt J/ψ with vector bosons (W or Z) allows testing the specific QCD predictions [10] and, moreover, it is sensitive to physics in the Higgs sector [11]. ATLAS has performed the measurement [12] in the decay channels $J/\psi \rightarrow \mu^+\mu^-$ and $W^\pm \rightarrow \mu^\pm\nu_\mu$. For this analysis, the single muon trigger with $p_T^{(\mu)} \geq 18$ GeV was used, a standard selection for J/ψ was applied disentangling prompt from non-prompt component with pseudo-proper lifetime. The W candidates were selected applying tight muon selection ($p_T \geq 25$ GeV and $|\eta| \leq 2.4$) associated with missing energy $E_T^{miss.} \geq 25$ GeV. The separation of signal from multijet background is obtained with the W transverse mass $m_T^{(W)} = \sqrt{2p_T^{(\mu)} \cdot E_T^{miss.} \cdot (1 - \cos \Delta\phi_{\mu\nu})} \geq 40$ GeV. The yield of prompt J/ψ production associated with W , was estimated to $N_{J/\psi+W} = 29.2^{+7.2}_{-6.5}$ of which 1.8 ± 0.2 originate from pile-up; the corresponding p -value of a background fluctuation is $2.1 \cdot 10^{-7}$ (5.1σ significance). To compare with predictions the yield should be corrected for double parton scattering (DPS) contribution, which is estimated through

$$d\sigma_{DPS} = d\sigma_W \cdot \mathcal{P}_{J/\psi|W} = \frac{d\sigma_W \cdot d\sigma_{J/\psi}}{\sigma_{eff}}, \quad (2)$$

where σ_W and $\sigma_{J/\psi}$ are from inclusive measurements and σ_{eff} is obtained from $W + 2jets$ analysis [13]. The estimated contribution is $N_{DPS} = 10.8 \pm 4.2$ events ($\sim 37\%$).

The experimental ratios $\frac{1}{\sigma_W} \frac{\Delta\sigma_{W+J/\psi}}{\Delta y}$, integrated over J/ψ intervals of p_T and y , are shown in figure 5. The result (fiducial) is corrected for J/ψ acceptance (inclusive) and for DPS contribution (DPS-subtracted). Both NLO-CO and LO-CS model predictions are almost one order of magnitude below the experimental value but uncertainties are still large.

4. Bottomonium production

The study of bottomonium production complements the studies of charmonium systems. Due to the larger mass

Figure 5: Ratio of cross section for $W + J/\psi$ production.

of the bottom quark compared to the charm quark, it allows more accurate theoretical calculations than in the charmonium family, which suffer from poorer perturbative convergence. The ATLAS analysis [14] on Υ_{nS} production, through the decay channel $\Upsilon \rightarrow \mu^+\mu^-$, extends the p_T range of previous cross section result up to 70 GeV, where new production mechanisms may play a more important role [15], and the impact of the dependence of the production cross section on the spin alignment and feed-downs is reduced.

The selection cuts of $\mu\mu$ candidates are adapted to the Υ mass region. The mass-resolution allows disentangling the yields for the states $\Upsilon(nS)$ for $n = 1, 2, 3$. The yields are used to determine the cross section as a function of p_T^Υ and y .

Figure 6: p_T -differential cross section for $\Upsilon(nS)$ production.

Figure 6 shows the $d\sigma_{\Upsilon(1S)}/dp_T$ for $|y| \leq 1.2$ with the predictions of CEM and CSM. Similar behaviour is observed for all Υ 's, an important disagreement is observed in the new high- p_T region where both feed-down and spin alignment effects are reduced.

5. Open B-state results

5.1. B^+ production

The NLO predictions for the b-hadron production cross-section have been improved with fixed order plus next-to-leading-logarithms (FONLL) calculations [16]. However, the dependence of the theoretical predictions on the factorisation and renormalisation scales and the b-quark mass results in theoretical uncertainties of up to 40%. Therefore, it is important to measure the b-hadron cross sections at high $\sqrt{s}$ and for B mesons of higher p_T . ATLAS measured [17] the B^+ production⁶ through the decay channel $B^+ \rightarrow J/\psi(\mu^+\mu^-) K^+$ up to $p_T \sim 100$ GeV and rapidity $|y| < 2.25$.

Figure 7: p_T -differential cross section for B^+ production.

The measured p_T -differential cross-section for B^+ production is reported in figure 7 with the some theoretical predictions (Powheg+Pythia and MC@NLO+Herwig generation models, and FONLL with $f_{b \rightarrow B^+} = 0.40 \pm 0.01$). Within the theoretical uncertainties (scales and m_b), there is an agreement with the measured integrated cross-sections and with the dependence on p_T .

5.2. Measurement of the $BR(B^+ \rightarrow \chi_c + K^+)$

ATLAS has measured [8] the $BR(B^+ \rightarrow \chi_c K^+)$ from the $\chi_c \rightarrow J/\psi \gamma$ sample and the reference $B^+ \rightarrow J/\psi K^+$:

$$BR(B^+ \rightarrow \chi_c K^+) = \mathcal{A}_B \cdot \frac{N_{\chi_c}^B}{N_{J/\psi}^B} \cdot \frac{BR(B^+ \rightarrow J/\psi K^+)}{BR(\chi_c \rightarrow J/\psi \gamma)} \quad (3)$$

In (3), the BRs are taken from [18]; the acceptance ratio $\mathcal{A}_B$ for the channels, determined with simulation, benefits of the cancellation of correlated uncertainties.

⁶Results correspond to both charged states assuming $\sigma_{B^+} = \sigma_{B^-}$.

Figure 8: Mass distributions for $B^+ \rightarrow \chi_c K^+$.

The signal yield is obtained from the mass distribution shown in figure 8, and the value is

$$BR(B^+ \rightarrow \chi_c K^+) = (4.8 \pm 0.8[\text{stat.}] \pm 0.6[\text{syst.}]) \cdot 10^{-4}$$

The result is in agreement with $(4.79 \pm 0.23) \cdot 10^{-4}$ [18] and competitive with the determinations at B-factories.

6. Conclusions

ATLAS performed several precision measurements on the HF production (charmonium, bottomonium and B^+) at LHC to test various QCD models. These studies are very important because they refer to new kinematic regions (e.g., high p_T up to $\sim 10^2$ GeV) and to channels less affected by uncertainties (e.g., $\psi(2S)$ and χ_c). ATLAS expects to exploit the full run-I and future run-II to probe new interesting phenomena in HF production (e.g., polarization, double quarkonium, associated production with W, Z).

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