Heavy Flavour Production in ATLAS with a focus on inclusive onia

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ATLAS has a wide programme to study the production cross section and decay properties of particles with beauty, as well as charmonium and bottomonium states. This paper covers only the ATLAS results in the domain of charmonium production, including J/ψ, $\psi(2S)$ and χ_c states, B^+ production, a brief discussion of the Υ states and updates on the $D(^*)$ meson cross-section analysis. The analyses discussed include double-differential production cross-section measurements of the J/ψ, $\psi(2S)$ and P-wave charmonium states χ_{cJ}, extending upon previous measurements in precision and kinematic reach. Prompt and non-prompt modes are distinguished, as well as J/ψ vs $\psi(2S)$ and the contribution to J/ψ production from χ_c feed-down. Alongside the latter analysis, a competitive measurement of the branching fraction $B^\pm \to \chi_{c1} K^\pm$ was also performed. Results of these measurements are compared with the latest theoretical predictions from a variety of theoretical approaches.

1 Heavy flavour production in ATLAS

The ATLAS experiment at the Large Hadron Collider has copious heavy flavour production in pp collisions. It has the advantage of very high integrated luminosities, but largely relies on multi-muon triggers to select heavy flavour events. This paper will concentrate on the production of b and c hadrons in jets and has a focus on onium production. The two key sub-detector systems for the measurements here presented are the inner tracker immersed in a 2T solenoidal field, which has a coverage out to $|\eta| < 2.5$, and the muon system with coverage $|\eta| < 2.7$. The resultant tracking has a p_T resolution $\sim 0.05\% p_T(\mathrm{GeV}) \oplus 1.5\%$ and $\sim 10\mu m$ impact parameter resolution, which are important for the mass and lifetime resolutions in the analyses.

2 Open charm production

ATLAS has published results on $D^{*\pm}$ and D^0 production in jets [1]. It was found that neither leading order nor p_T and angular-ordered models give a good description of the momentum fraction carried but the charmed hadrons in jets, especially at low values of the fraction. A subsequent study of the $D^{*\pm}$, $D^\pm$ and D^0 differential cross sections as a function of the η and p_T of the charmed hadron show that these are described within the large uncertainty bands by models based on perturbative QCD [2].

3 Beauty hadron production

D^* mesons can be combined with muons as a signature of beauty hadron production in jets. ATLAS has used this technique to extract the single differential cross-sections for beauty hadrons in terms of the p_T and η of the hadron [3]. The results show that Next to Leading Order (NLO) models tend to underestimate the observed rates, despite the shapes of the distributions being reasonably reproduced by the several Monte Carlo models.

The production of B^+ hadrons has been studied using the decay to $J/\psi(\mu\mu)K^+$, where the double differential cross-sections in terms of p_T and rapidity y have been obtained [4]. The predictions from Monte Carlo and Fixed Order Next-to-Leading-Logarithm (FONNL) models [5] agree reasonably with the data, but again have a tendency to underestimate the cross-section.

4 Onium production

4.1 Prompt and non-prompt J/ψ production

ATLAS has made extensive studies of the production of heavy onia, using the production of dimuons in their decays to trigger the events. The J/ψ provides the template for the analyses [6]; the prompt and non-prompt components are separated using the pseudo-proper time of the decay candidates. The studies are in principle complicated by the different spin alignments possible, although recent CMS studies have indicated that there is little polarisation in the J/ψ production.

The production of prompt J/ψ agrees between the four main LHC experiments, though with some differences in the rapidity dependence. A multitude of models: Colour Singlet (CS); Colour Evaporation (CE); Colour Octet (CO), in various forms give a reasonable description of the observed ATLAS data, but none are perfect. It is clear that p_T spectra alone cannot distinguish between the models. (Please see the references in the ATLAS paper for the detailed models compared to the data.)

The fraction of non-prompt J/ψs is below 10% at low p_T and central rapidity, but rises with p_T to $\sim 70\%$; however, this increase is slower for forward rapidities. There is little evidence of an energy dependence in the behaviour, and comparing with CDF data, even the underlying process can have little effect. The non-prompt production with respect to p_T and rapidity is well described by perturbative QCD FONLL models with no free parameters.

4.2 Prompt and non-prompt $\psi(2S)$ production

A recent ATLAS study of the production of $\psi(2S)$ mesons has been published [7]. This study has many similarities with that of the J/ψ, except that instead of using the lower purity $\psi(2S) \to \mu\mu$ decays, the more copious $\psi(2S) \to J\psi(\mu\mu)\pi\pi$ mode is used instead. Again the prompt and non-prompt components are studied, the non-prompt fraction still rising to $\sim 70\%$ but less at high rapidity, see Figure 1. There is negligible feed-down to the $\psi(2S)$ from heavier states. ATLAS has extended the kinematic range of the studies of the prompt and non-prompt production as a function of p_T and rapidity; in the regions of overlap with studies by other LHC experiments, the agreement is good. For the prompt production, NLO combined with Non Relativistic QCD (NRQCD) predictions describe the data well across the range. However, Next-to-Next-to-Leading Order (NNLO) colour singlet models undershoot the data at higher p_T values, and k_T factorisation models undershoot the data for all values of p_T and rapidity.

The non-prompt production reveals a softer p_T spectrum and less variation with p_T than the NLO and FONLL approximation predictions. For the details of the all the predictions used for comparison, please see the references in [7].

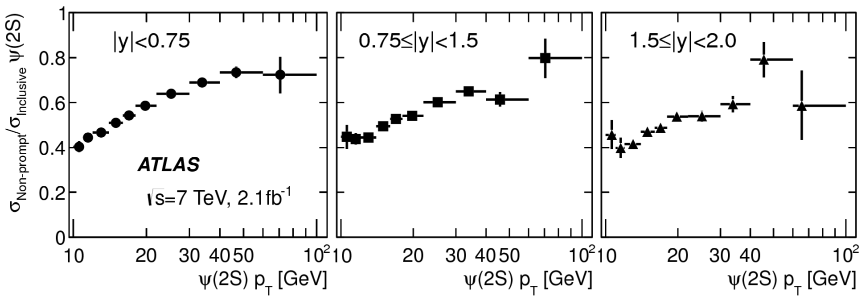

Figure 1: The non-prompt fraction with respect to the p_T of the $\psi(2S)$ for three regions of rapidity.

4.3 Prompt and non-prompt $\chi_{c1,2}$ production

ATLAS has recently studied the production of the $\chi_{c1,2}$ by reconstructing their de-excitation decays to $J/\psi\gamma$ [8]. The production differential cross-sections have been measured for both states in terms of the p_T of the χ_c and of the J/ψ. The prompt production for both states and p_T definitions is well predicted by NLO NRQCD models [9] . However, the non-prompt production shows a tendency to fall below the FONNL prediction at higher p_T. The relative production of χ_{c1} to χ_{c2} has been studied, and, under the assumption of isotropic decay, the measurements agree with NLO NRQCD predictions, though less so at higher p_T, see Figure 2. The figure also shows the fraction of prompt J/ψ produced from χ_c radiative decays, which again agrees with the NLO NRQCD predictions within the uncertainties. The relative fraction of non-prompt production shows that the production of the $\chi_{c1,2}$ is mostly prompt, even at high p_t, in contrast to the J/ψ and $\psi(2S)$ cases. Finally, ATLAS has also extracted a branching

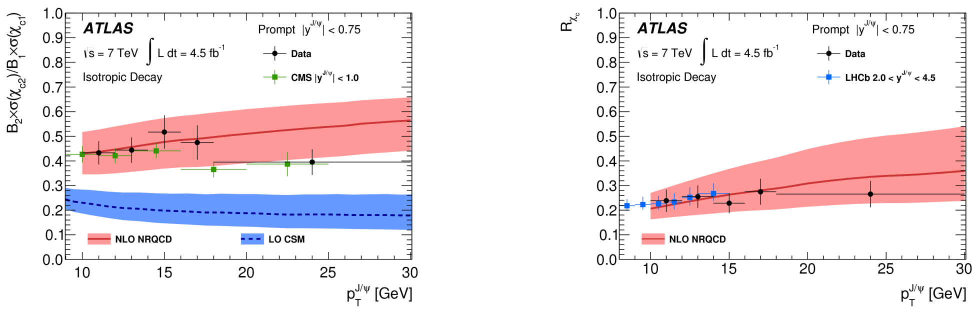

Figure 2: The relative production of prompt χ_{c1} and χ_{c2} with respect to the p_T of the J/ψ (left) and fraction of J/ψ produced from χ_c radiative decays (right).

fraction $B(B^+ \to \chi_{c1}K^+) = 4.9 \pm 0.9\,stat. \pm 0.6\,sys. \times 10^{-4}$; this is both in agreement with and a significant improvement on measurements at previous hadron collider experiments, and is in agreement with existing B-factory measurements, thus showing good prospects for improved precision in Run 2.

4.4 The $\Upsilon(1S), \Upsilon(2S)$ and $\Upsilon(3S)$ production

Finally, ATLAS has produced double-differential cross-sections for $\Upsilon(1,2,3S)$ states[10], extending the available p_T range and providing finer detail than previous measurements from CMS and LHC. The measurements agree well with the previous measurements in the regions of overlap. Colour Singlet, Octet and Evaporation models all agree reasonably with the measured p_T spectra. The ratios of $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ production are dependent on the p_T of the upsilon, see Figure 3, confirming the existence of multiple mechanisms.

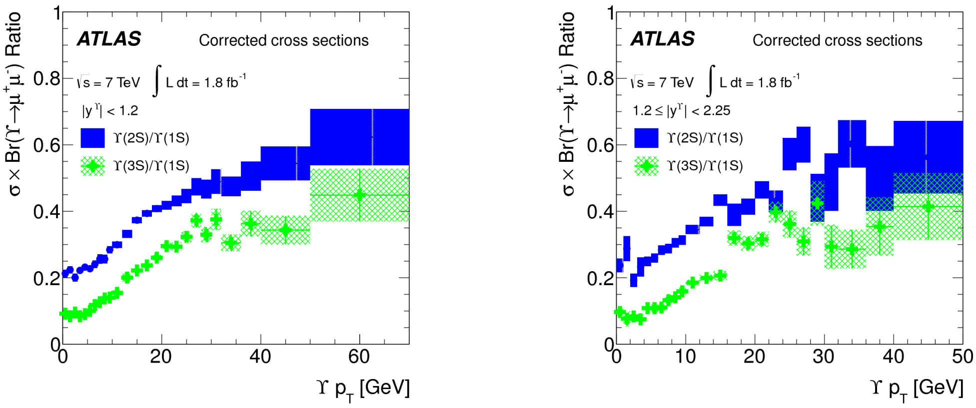

Figure 3: The relative production of prompt $\Upsilon 2S$ to $\Upsilon 1S$ and $\Upsilon 3S$ to $\Upsilon 1S$ with respect to the p_T of the Υ in the central (left) and forward (right) regions.

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