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Heavy flavour production and decay at ATLAS

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Summary. — The ATLAS experiment at the LHC is taking advantage of its large integrated luminosity and sophisticated muon and dimuon triggers to make competitive measurements of heavy flavour production and decay. Inclusive heavy quark production and heavy flavour jet production is discussed before turning to charm particle and onium production. The production and decay of individual B hadron species is then addressed, including the current best measurement of the Λ_b lifetime. A much improved analysis of CP related quantities in B_s decays is presented, before turning to recent results and prospects for rare B decays.

PACS 25.75.Dw – Particle and resonance production.
PACS 14.20.Mr – Bottom baryons ($|B| > 0$).
PACS 14.40.Nd – Bottom mesons ($|B| > 0$).
PACS 14.40.Lb – Charmed mesons ($|C| > 0, B = 0$).

1. – ATLAS and inclusive heavy flavours

By the end of 2012, ATLAS had recorded $21.7\,\mathrm{fb}^{-1}$ of proton-proton data at the LHC, adding to $5.3\,\mathrm{fb}^{-1}$ in 2011 and 2010. Large samples suitable for heavy flavour studies have been recorded using single and multi-muon triggers, and indeed the available sample is being increased by analysing a delayed stream of heavy flavour triggers taken in 2012 but processing it in 2013. ATLAS is well suited to studying heavy flavour decays to leptons, given a large acceptance in the central region, an efficient and precise tracking system (covering $|\eta| < 2.5$) and an excellent muon system (covering $|\eta| < 2.7$) [1]. There are useful overlaps in the accessible phase space that allow comparison with production in the froward region studied by dedicated heavy flavour experiments.

In addition to pp collisions, ATLAS has studied PbPb collisions at 2.76 TeV; in these collisions, the inclusive muon production is dominated by heavy flavour decays, and falls with increasing p_T and collision centrality [2]. Similar features have also been observed for J/ψ production in the same samples [3]. In pp collisions, the inclusive muon production is dominated by heavy flavours up to a p_T of around 40 GeV [4]. Perturbative calculations match the data well at lower p_T, but deviate at higher values; Fixed Order Next-to-Leading-Log (FONNL) calculations reproduce the full range well [5,6]. Further details of ATLAS heavy flavour production, including that in association with $W^{\pm}$ and the flavour composition of di-jet events, can be found in A Buckley's paper in this volume.

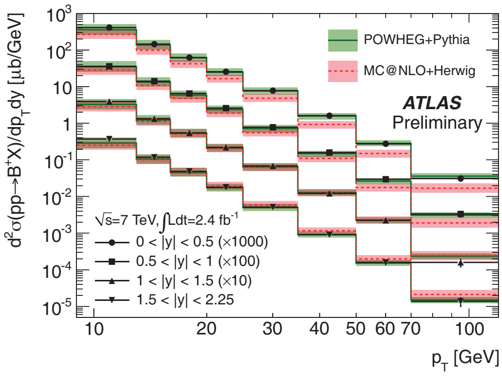

Fig. 1. – The inclusive B^+ double differential cross-section with respect to p_T and rapidity [12].

2. – Open heavy flavour production

ATLAS has studied $D^{*\pm}$ production in jets from 7 TeV collisions. Anti-kT jets are found within $|\eta| < 2.5$ for jet momentum between 25 and 70 GeV. Production is studied as a fraction of the jet energy carried by the $D^{*\pm}$. The dominant source is from the hadronisation of charm quarks, and it is found that neither leading order nor angular ordered models give a good description of the data.

Open charm production has also been studied for $D^{*\pm}$ and $D^\pm$ as a function of the p_T and η of the hadrons for $|\eta| < 2.1$ [7]. Perturbative QCD-based models describe the data distributions, but the data sits on the high edge of the allowed uncertainties in almost all cases.

Beauty production has been studied using the decays to $D^*\mu X$ [8]. The $D^*\mu$ mass range from about 3 to 5 GeV is dominated by beauty production. Next-to-leading order models slightly underestimate the observed rates, but the shapes of the p_T and $|\eta|$ distributions are reasonably reproduced in several models.

ATLAS has also made studies of the Λ_b making a competitive mass determination $m_{\Lambda_b} = 5619.7 \pm 0.7(\text{stat}) \pm 1.1(\text{syst})\,\text{MeV}$ and the current most precise Λ_b lifetime determination, $\tau_{\Lambda_b} = 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst})\,\text{ps}$ [9].

ATLAS has also studied the $B_c^\pm$ state [10], and the $B^\pm$ [11,12]. The latter now includes a measurement of the differential cross-section as a function of p_T and of rapidity. The rapidity cross-sections are matched better by the POWHEG+PYTHIA NLO [13, 14] predictions than by those from MC@NLO+HERWIG [15, 16], as illustrated in fig. 1. The p_T cross-section is well matched by the FONNL calculations [5, 17].

3. – Onium production

Onium production is a particularly strong area for study in ATLAS. ATLAS has extended the p_T range to 70 GeV for the J/ψ production studies [18], and the prompt production is separated using the pseudo proper lifetime from the non-prompt production (coming from B-hadron decays). The J/ψ production is subject to uncertainties due to the various possible spin-alignments, which have not yet been measured at the LHC. This can be parameterised by two angles, and ATLAS chooses to consider the full allowed range of values in assigning the uncertainty.

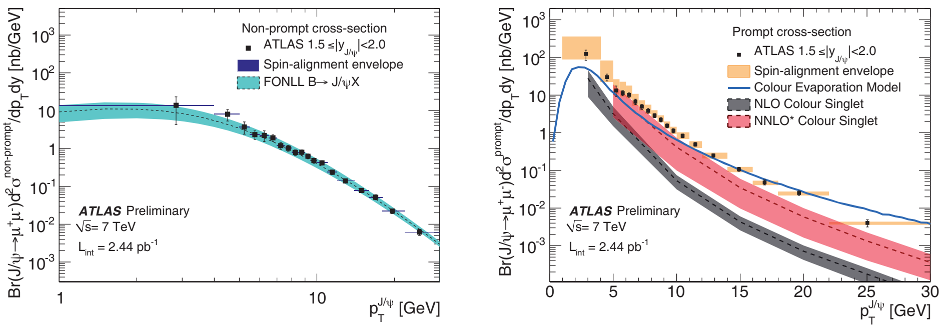

Fig. 2. – The prompt (left) and non-prompt (right) J/ψ production cross-section with respect to p_T for one of the four $|y|$ bins, $1.5 < |y| < 2.0$ [18].

The prompt J/ψ production as a function of p_T and rapidity matches well the observations from ALICE, CMS and LHCb in the regions of overlap [19-21]. The Colour Singlet Model, Colour Evaporation Model (neither of which have many free parameters) and Colour Octet Model match the data reasonably, but are not perfect. Further study is needed to refine the models, as p_T spectra alone do not resolve their differences.

The non-prompt fraction and differential cross-section with p_T have been measured, as illustrated in fig. 2 for one of the rapidity bins studied. The fraction rises from 10% to $\sim$ 70% with increasing p_T. Not only is there a very weak energy dependence at best, the non-prompt fraction seems to be essentially independent of collision process. The non-prompt differential cross-section can then be extracted. FONNL calculations [5, 17] describe the non-prompt cross-sections reasonably well. Similar measurements have been made by all LHC experiments, and in proton-antiproton collisions at CDF.

ATLAS has also studied the production of the $\Upsilon(nS)$ states [22], with $n = 1, 2, 3$, despite the $2S$ and $3S$ states not being fully resolved. Double differential cross-sections have been obtained in p_T and rapidity. Although these agree well with those found by CMS and LHCb, ATLAS again extends the p_T range accessed. Colour Singlet, Colour Evaporation and Colour Octet models all reproduce the cross-sections reasonably, but again not perfectly. There is an intriguing p_T dependence of the $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ ratios, as illustrated in fig. 3; this may be evidence of multiple production mechanisms that evolve with p_T.

ATLAS has also studied the χ_{c1}, χ_{c2} [23] and $\chi_b(nP)$ states, and discovered the existence of the $\chi_b(3P)$ [24]; this state has subsequently been confirmed by other experiments, although with a lower significance. The states are revealed using both converted and unconverted photons; the converted photon case is illustrated in fig. 4.

4. – CP-related parameters in the decay $B_s \to J/\psi\phi$

ATLAS has analysed its 2011 $B_s \to J/\psi\phi$ sample [25], allowing a good determination of the lifetime difference, $\Delta\Gamma_s$ and an important contribution to the measurement of the week phase, ϕ_s. The results for the weak phase, lifetime difference, average lifetime and helicity amplitudes are given in table I, and the likelihood contours in the ϕ_s-$\Delta\Gamma_s$ plane are shown in fig. 5. Further data is now being added from the considerably larger 2012 sample.

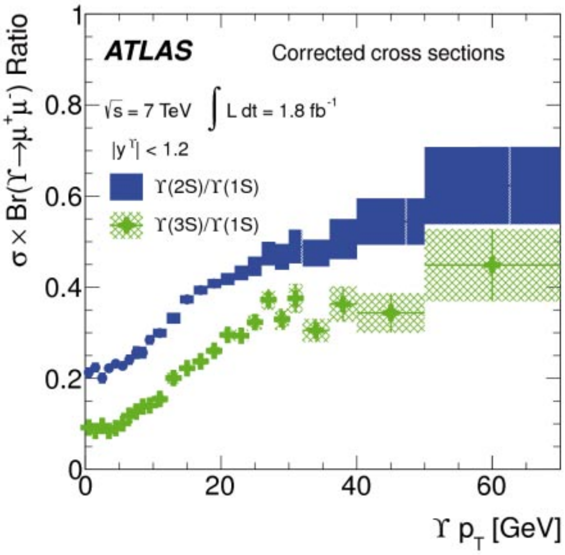

Fig. 3. – Ratios of differential $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ cross-sections multiplied by the dimuon branching fractions *versus* Υ p_T in the central rapidity region [22].

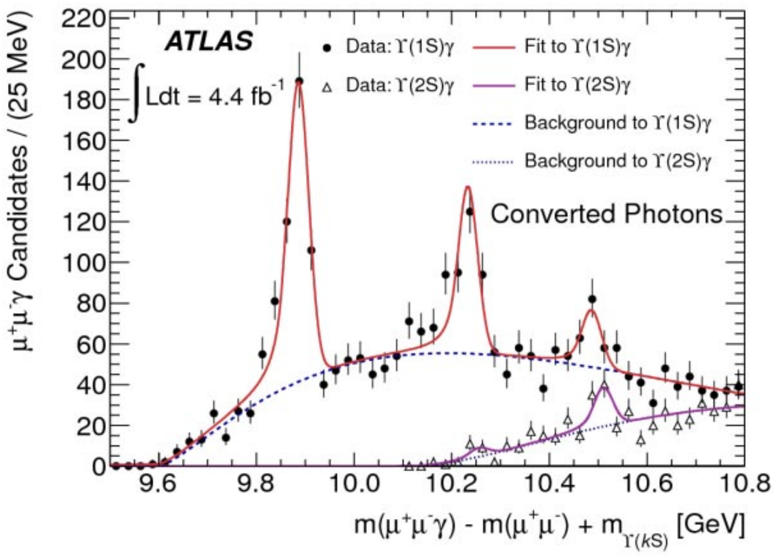

Fig. 4. – The mass distributions of $\chi_b \to \Upsilon(kS)\gamma$ $(k = 1, 2)$ candidates formed using photons which have converted and been reconstructed in the tracking system [24].

TABLE I. – *The measured parameters in the decay $B_s \to J/\psi\phi$ [25], as presented; these values have now been superseded by an extended analysis, with the ϕ_s uncertainty halved using the same data sample* [26].

		stat.	syst.	
ϕ_s	0.22	± 0.41	± 0.10	rad
$\Delta\Gamma_s$	0.053	± 0.021	± 0.010	ps^{-1}
Γ_s	0.677	± 0.007	± 0.004	ps^{-1}
$\lvert A_0(0)\rvert^2$	0.528	± 0.006	± 0.009	
$\lvert A_{\lvert\lvert}(0)\rvert^2$	0.220	± 0.008	± 0.007	

5. – Rare B decays

ATLAS has published results on the searches for the rare decay $B_s \to \mu\mu$ [27] based on only 2.4 fb^{-1} of 7 TeV data from 2011. It determined that $Br(B_s \to \mu\mu) < 4.2 \times 10^{-9}$ at 95% when combined with CMS and LHCb measurements, or 2.2×10^{-8} for ATLAS alone. With the 2012 data and analysis improvements, a precision better than the standard model expectation is anticipated.

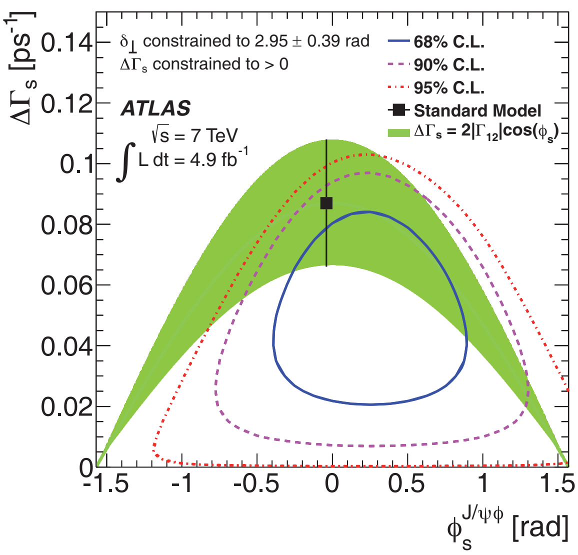

Fig. 5. – Likelihood contours in the ϕ_s-$\Delta\Gamma_s$ plane [25]. Three contours show the 68%, 90% and 95% confidence intervals (statistical errors only). The green band is the theoretical prediction of mixing-induced CP violation. The probability density function contains a fourfold ambiguity. Three minima are excluded by applying the constraints from the LHCb measurements.

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