Recent Heavy Flavour Results from ATLAS

Marcella Bona, on behalf of the ATLAS Collaboration

School of Physics and Astronomy, Queen Mary, University of London, Mile End Road, London E1 4NS, UK
E-mail: m.bona@qmul.ac.uk

Abstract. We present here a selection of heavy flavour physics results from the ATLAS experiment taking data at the Large Hadron Collider. The ATLAS analyses allowed a variety of heavy flavour measurements, reproducing essential $B$-hadron properties and demonstrating a good performance of the detector. We include in this report the measurement of the centrality dependence of $J/\psi$ yields in lead-lead collisions, observations of $\chi_{cJ}$ and $\chi_{b}$ states with a first observation of a $\chi_{b}(3P)$ state, the search for the rare decay $B_{s}^{0} \to \mu^{+}\mu^{-}$ and, finally, a measurement of $B_{s} \to J/\psi\phi$ decay parameters.

1. Introduction

The ATLAS (A Toroidal LHC ApparatuS) experiment [1] is a general purpose experiment operating at the Large Hadron Collider (LHC) at CERN. It has a rich heavy flavour program including measurements of $b$-quark production, studies of $b$-hadron decays, as well as measurements of quarkonium and exotic states production. ATLAS is now performing also indirect searches for new physics, such as the rare decays of $B_{s}^{0} \to \mu^{+}\mu^{-}$, and measurements of CP-violating phase in the $B_{s}^{0} \to J/\psi\phi$ decay. These provide important constraints to the Standard Model (SM) and are complementary to direct searches for new physics.

2. Measurement of the centrality dependence of $J/\psi$ yields

The centrality dependence is studied in the yield of $J/\psi$ mesons produced in the collisions of lead ions at the LHC [2, 3, 4]. In a sample of minimum-bias lead-lead collisions at a nucleon-nucleon centre of mass energy $\sqrt{s_{NN}} = 2.76$ TeV, corresponding to an integrated luminosity of about 6.7 $\mu$b$^{-1}$, $J/\psi$ mesons are reconstructed via their decays to $\mu^{+}\mu^{-}$ pairs. In ATLAS, the $J/\psi$ yields are normalised to the 40–80% centrality bin (peripheral) to obtain the “relative yield”. These are then compared to $R_{\text{coll}}$, where $R_{\text{coll}}$ is the ratio of the mean number of binary collisions in each centrality bin to that of the most peripheral (40–80%) bin.

A clear difference is observed as a function of centrality between the measured relative $J/\psi$ yield and the prediction based on $R_{\text{coll}}$, indicating a deviation from the simplest expectation based on elementary nucleon-nucleon collision scaling. The ratio of these two values, $R_{\text{cp}}$, is shown as a function of centrality in Figure 1. The data points are not consistent with their average value; instead, a significant decrease of $R_{\text{cp}}$ as a function of centrality is observed.

3. Heavy quarkonium physics

Quarkonia are formed from a quark-antiquark pair of same flavour and should represent one of the simplest systems described by QCD theory. Heavy quarkonium allows for rigorous tests
Figure 1. Relative $J/\psi$ yield as a function of centrality normalised to the most peripheral bin (black dots) [3]. The expected relative yields are shown (boxes) with 1σ systematic uncertainties).

3.1. Charmonium: $J/\psi$ Differential Production Cross-section
Using 2.2 fb$^{-1}$ of data from 2010, ATLAS has measured the inclusive $J/\psi \rightarrow \mu^+\mu^-$ cross-section and the fraction of $J/\psi$ which are produced non-promtply via decay of a B-hadron [5]. By combining these two measurements, separate cross-sections for the prompt and non-prompt $J/\psi$’s are also made.

Figure 2 shows the central rapidity values of the non-prompt and prompt $J/\psi$ production cross-sections as a function of $J/\psi$ transverse momentum compared to theoretical predictions. Overlaid on the plots is a band representing the variation of the result under various spin-alignment scenarios representing a theoretical uncertainty on the prompt component. The measured non-prompt cross-section is in good agreement with Fixed-Order Next-to-Leading-Log (FONLL) theoretical predictions. The prompt cross-section is compared to Colour Singlet (CSM) next-to-leading order (NLO) and partial next-to-next-leading order (NNLO*) predictions and to the phenomenological Colour Evaporation Model (CEM).

3.2. Charmonium Spectroscopy: Observation of $\chi_c J(1P)$ State
ATLAS has performed the observation of the $\chi_c J(1P)$ and $\chi_{c2} J(1P)$ charmonium states in $\chi_c \rightarrow J/\psi\gamma$ decays using 39 pb$^{-1}$ of 2010 $pp$ collision data. [7]. $J/\psi$ candidates are reconstructed from the decay $J/\psi \rightarrow \mu^+\mu^-$ while photons are reconstructed using calorimetric measurements. An extended unbinned maximum likelihood fit is performed to the invariant mass difference of the $\mu^+\mu^-$ and $\mu^+\mu^-\gamma$ systems to yield a total of $2960 \pm 120$(stat.)$\pm90$(syst.) $\chi_c J(1P)$ and $\chi_{c2} J(1P)$ candidates (see Figure 3).

3.3. Bottomonium Spectroscopy: Observation of $\chi_b$ state
The P-wave $b\bar{b}$ $\chi_b$ states can be reconstructed in ATLAS through the radiative decay to $\Upsilon$. The $\chi_b J(1P)$ and $\chi_b J(2P)$ states have already been observed through this decay mode. Using 4.4 fb$^{-1}$ of data from 2011, ATLAS has made the first observation of the $\chi_b J(3P)$ state [8].

Photons are reconstructed either directly in the calorimeter or through a conversion to $e^+e^-$. Figure 4 shows the mass distribution for unconverted photons and converted photons, where the
mass is defined as $\tilde{m}_b = m(\mu\mu\gamma) - m(\mu\mu) + m_{\Upsilon(kS)}$ and $m_{\Upsilon(kS)}$ are the world average masses of the $\Upsilon(kS)$ states [9]. In addition to the expected peaks for $\chi_b(2P,1P) \rightarrow \Upsilon(2S,1S)\gamma$, structures are observed at an invariant mass of approximately 10.5 GeV. These additional structures are interpreted as the radiative decays of the previously unobserved $\chi_b(3P)$ states, $\chi_b(3P) \rightarrow \Upsilon(2S)\gamma$ and $\chi_b(3P) \rightarrow \Upsilon(1S)\gamma$. The measurement with converted photons is used for the final mass determination of $10.539 \pm 0.005(\text{stat.}) \pm 0.009(\text{syst.})$ GeV.

4. B-hadron Masses and Lifetimes

In ATLAS, B-hadrons can be reconstructed exclusively from their decays to $J/\psi$, i.e. $B \rightarrow J/\psi(\mu^+\mu^-)X$. A number of B-hadrons have been observed in ATLAS through such decays [10, 11, 12, 13, 14, 15, 16] and masses and lifetimes have been measured showing consistency with PDG values [9].

5. Rare B Decay $B_s^0 \rightarrow \mu^+\mu^-$

The rare decays $B_s^0 \rightarrow \mu^+\mu^-$ cannot proceed at tree level via flavour-changing neutral-current processes as they are forbidden in the SM and can only occur via higher order diagrams. These decays are also helicity suppressed, resulting in expected SM branching ratios (BR) of $(3.2 \pm 0.2) \times 10^{-8}$ [17]. A larger branching fraction would potentially indicate contributions from New Physics. Until now neither an enhancement of the branching fraction has been observed nor the theoretical limit has been reached experimentally [18, 19, 20, 21].

The first search for $B_s^0 \rightarrow \mu^+\mu^-$ in ATLAS is using 2.4 fb$^{-1}$ of the 2011 collision data [22]. ATLAS obtains an observed limit of $2.2 \times 10^{-8}$ at 95% CL, while the expected limit obtained with the background only hypothesis is $2.3^{+1.0}_{-0.5} \times 10^{-8}$ at 95% CL. These limits are shown in Figure 5.

6. $\Delta\Gamma_s$ and $\phi_s$ Measurement from $B_s^0 \rightarrow J/\psi\phi$

A measurement of $B_s \rightarrow J/\psi\phi$ decay parameters, including the CP-violating weak phase $\phi_s$ and the decay width difference $\Delta\Gamma_s$ is reported, using 4.9 fb$^{-1}$ of 2011 collision data [23]. The mean decay width $\Gamma_s$ and the transversity amplitudes $|A_0(0)|^2$ and $|A_{\parallel}(0)|^2$ are also measured.
Figure 5. Observed CLs (circles) as a function of BR($B_0^0 \rightarrow \mu^+ \mu^-$) [22]. The 95% CL limit is indicated by the horizontal (red) line. The dark (green) and light (yellow) bands correspond to ±1σ and ±2σ fluctuations on the expectation (dashed line).

Figure 6. Left: Likelihood contours in the $\phi_S - \Delta \Gamma_S$ plane [23]. 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. Right: Likelihood contours in the $\phi_S - \Delta \Gamma_S$ plane [23]. The 68% (solid lines) and 95% (dashed lines) contours are based on statistical errors only. The single black point corresponds to the SM theory value.

Results for $\phi_S$ and $\Delta \Gamma_S$ are presented in Figure 6, which show agreement with SM expectations. The measured values are: $\phi_S = 0.22 \pm 0.41$ (stat.) $\pm 0.10$ (syst.) rad $\Delta \Gamma_S = 0.053 \pm 0.021$ (stat.) $\pm 0.008$ (syst.) ps$^{-1}$ where these correspond to the solution compatible with the external measurements to which the strong phase $\delta_1$ is constrained to the LHCb value of $2.95 \pm 0.39$ rad [24] and where $\Delta \Gamma_S$ is constrained to be positive following the LHCb measurement [25].

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