Quarkonium Production in ATLAS

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The production of Quarkonium is an important testing ground for QCD calculations. The J/\(\psi\) and \(\Upsilon\) (1S) production cross-sections are measured in proton-proton collisions at the ATLAS detector at the LHC. Differential cross sections as a function of transverse momentum and rapidity have been measured. Charmonium states \(\chi_{c1}(1P)\) and \(\chi_{c2}(1P)\) have been observed through radiative decays, as well as a new \(\chi_b\) state. Results are compared to perturbative QCD predictions.

1 Introduction

Despite being among the most studied of the bound quark systems, there is still no clear understanding of the production mechanisms for quarkonium states like the J/\(\psi\) and the \(\Upsilon\) that can consistently explain both the production cross-section and spin alignment measurements in \(e^+e^-\), hadron and heavy ion collisions. Data from the LHC allow tests of theoretical models of quarkonium production in a new energy regime. Details of the ATLAS detector may be found in [1]. The sub-detectors of greatest importance to the analyses presented here are the Inner Detector (ID) and Muon Spectrometer systems.

2 Measurement of the differential cross-sections of inclusive, prompt and non-prompt J/\(\psi\) production

The inclusive J/\(\psi\) production cross-section is measured at ATLAS in the di-muon decay channel using 2.3 pb\(^{-1}\) of 2010 data [2]. The number of J/\(\psi\) candidates are extracted from the observed di-muon pairs, applying event weights to unfold the response of the detector, reconstruction and trigger efficiency. The J/\(\psi\) yields are then determined in regions of the di-muon \(p_T\) and rapidity. The spin alignment of the J/\(\psi\) is unknown, as yet, at the LHC. An envelope of all possible spin alignment assumptions is taken as an additional theoretical uncertainty.

Prompt J/\(\psi\) are produced directly from the hard-scat ter of the p-p collision, as well as through decays from higher charmonium states. Non-prompt J/\(\psi\) are produced via the decay of a B-hadron and can be distinguished experimentally due to the associated displacement of the J/\(\psi\) vertex in the transverse plane, due to the long lifetime of the B hadron.

Figure 1 shows the inclusive J/\(\psi\) production cross-section as a function of \(p_T\), in two regions of J/\(\psi\) rapidity. The prompt and non-prompt J/\(\psi\) production cross-sections, as a function of \(p_T\), are also shown in Figure 1. The non-prompt component is seen to be in good agreement.
with the FONLL predictions. For the prompt component, the data are reasonably consistent with NNLO* Colour Singlet calculations at low $p_T$, but does less well at high $p_T$.

3 Observation of the $\chi_c1(1P)$ and $\chi_c2(1P)$ charmonium states

The $\chi_c1(1P)$ and $\chi_c2(1P)$ charmonium states in $\chi_c \rightarrow J/\psi \gamma$ decays are observed using an integrated luminosity of 39 pb$^{-1}$ [3]. $J/\psi$ candidates are reconstructed via the decay $J/\psi \rightarrow \mu^+\mu^-$ while photons are reconstructed with a calorimetric measurements. $\chi_c$ candidates are observed in the kinematic range $p_T^\chi_c > 10$ GeV and rapidity $|y_{\chi_c}| < 2.4$. An extended unbinned maximum likelihood fit is performed to the invariant mass difference of the $\mu^+\mu^-$ and $\mu^+\mu^-\gamma$ systems to yield $2960 \pm 120$ (stat.) $\pm 90$ (syst.) $\chi_c1$ and $\chi_c2$ candidates. The result of a simultaneous fit to the signal sample and background sample is shown in Figure 2. The small mass difference between the two $\chi_c$ states is comparable to the achievable mass resolution, which is dominated by the photon energy resolution.

Figure 2: $\chi_c \rightarrow J/\psi \gamma$ decays. The result of a simultaneous fit to the signal selection (top) and background ($J/\psi$ sideband) selection (bottom). The individual signal components are shown (dashed lines).
4 Measurement of the centrality dependence of J/ψ yields and observation of Z production in lead-lead collisions

A centrality-dependent suppression has been observed in the yield of J/ψ mesons produced in the collisions of lead ions in ATLAS [4]. In a sample of 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/ψ mesons are reconstructed via their decays to $\mu^+\mu^-$ pairs. The measured J/ψ yield, normalized to the number of binary nucleon-nucleon collisions, is found to significantly decrease from peripheral (glancing) to central (head-on) collisions, as shown in Figure 3. The centrality dependence is found to be qualitatively similar to the trends observed at previous, lower energy experiments. The same sample is used to reconstruct Z bosons in the $\mu^+\mu^-$ final state, and a total of 38 candidates are selected in the mass window of 66 to 116 GeV. No centrality-dependent suppression is seen in the Z boson yield, as expected. This analysis provides the first results on J/ψ and Z production in lead-lead collisions at the LHC.

5 Measurement of the Υ(1S) Production Cross-Section

A measurement of the cross-section for $\Upsilon(1S) \to \mu^+\mu^-$ production is made as a function of the $\Upsilon(1S)$ transverse momentum, where both muons have $p_T > 4$ GeV and $|\eta| < 2.5$. The results, as shown in Figure 4, are based on an integrated luminosity of 1.13 $\mu$b$^{-1}$ [5]. When the cross-section measurement is compared to theoretical predictions, it agrees to within a factor of two with a prediction based on the NRQCD model including colour-singlet and colour-octet matrix elements as implemented in PYTHIA while it disagrees by up to a factor of ten with the NLO prediction based on the Colour Singlet Model. This measurement is independant of the unknown Υ spin-alignment and as such offers a precise test of theoretical descriptions of quarkonium production.
6 Observation of a New $\chi(b)$ State in Radiative Transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$

The $\chi_b(nP)$ quarkonium states are studied using a data sample corresponding to an integrated luminosity of 4.4 $fb^{-1}$. These states are reconstructed through their radiative decays to $\Upsilon(1S,2S)$ with $\Upsilon \rightarrow \mu^+\mu^-$. Photons are reconstructed with both calorimetric measurements (unconverted) and ID tracking (converted photons). In addition to the mass peaks corresponding to the decay modes $\chi_b(1P,2P) \rightarrow \Upsilon(1S)\gamma$, a new structure centered at a mass of $10.530 \pm 0.005$ (stat.) $\pm 0.009$ (syst.) GeV is also observed, in both the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decay modes. This is interpreted as the $\chi_b(3P)$ system. The mass difference $m(\mu^+\mu^-) - m(\mu^+\mu^-)$ distributions are shown in Figure 5.

Figure 5: The mass distribution of $\chi(b)(nP) \rightarrow \Upsilon(1S)\gamma$ candidates for unconverted photons reconstructed using the electromagnetic calorimeter (left). The mass distributions of $\chi(b)(nP) \rightarrow \Upsilon(kS)\gamma$ ($k = 1, 2$) candidates formed using converted photons and been reconstructed in the ID (right).

7 Conclusions

In the first year of 7 TeV data-taking ATLAS has observed and measured charmonium and bottomonium states, including a new $\chi_b$ state. The production of heavy quarkonium provides particular insight into QCD theory as its mechanisms of production operate at the boundary of the perturbative and non-perturbative regimes. These measurements provide input towards an improved understanding and theoretical description of QCD.

References