ATLAS results on hadron spectroscopy, including exotic states

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ABSTRACT

Recent results of the ATLAS experiment at LHC on hadron spectroscopy, including exotic states, are presented. Comparison of the results with various theoretical predictions is discussed.

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1 Introduction

The ATLAS detector [1] at the Large Hadron Collider (LHC) consists of several subsystems including the inner detector (ID), the electromagnetic and hadronic calorimeters, and the muon spectrometer (MS). Muon reconstruction at ATLAS makes use of both the ID and the MS, and covers the pseudorapidity range $|\eta| < 2.5$. A three-level trigger system allows ATLAS to effectively select events containing single muons with large transverse momentum $p_T$ (above $\sim 20\text{ GeV}$), events with two muons with the minimal muon $p_T$ thresholds of $4-6\text{ GeV}$, and events with three muons with the muon $p_T$ threshold of $4\text{ GeV}$. During 2011-2012 data taking ATLAS has accumulated data samples of $pp$ collisions corresponding to luminosities of $\sim 5\text{ fb}^{-1}$ at $\sqrt{s} = 7\text{ TeV}$ and $\sim 20\text{ fb}^{-1}$ at $\sqrt{s} = 8\text{ TeV}$.

In this proceeding, recent results of the ATLAS experiment at LHC on hadron spectroscopy, including exotic states, are presented. The $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay is observed and the branching ratio of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ and $\Lambda_b^0 \to J/\psi\Lambda^0$ decays is measured [2]. The decays $B^+_s \to J/\psi D^+_s$ and $B^+_s \to J/\psi D^{*+}_s$ are studied and their branching fractions are measured relative to that of the $B^+_s \to J/\psi\pi^+$ decay [3]. The production cross sections and properties of the hidden-charm states $X(3872)$ and $\psi(2S)$ are measured in their decays to $J/\psi\pi^+\pi^-$ [4]. A search for a hidden-beauty analogue of the $J/\psi\pi(2S)$ signal is conducted by reconstructing $Y(1S) \to \mu^+\mu^-\pi^+\pi^-$ events [5]. Corrections for detector effects are done with high-statistics Monte Carlo (MC) samples. Uncertainties due to simulation of physics processes and detector, MC statistic, luminosity measurement and assumptions of the analysis procedures are included into systematic errors. The measurements are compared to theoretical predictions and to the measurements by other experiments.

2 Observation of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay

In all events with $J/\psi$ or $\psi(2S)$ candidates, pairs of tracks from particles with opposite charge are combined to form $\Lambda^0$ candidates. Tracks of the selected charmonium and $\Lambda^0$ candidates are simultaneously refitted with the dimuon and dihadron masses constrained to the world average masses of $J/\psi$ or $\psi(2S)$ and $\Lambda^0$ [6], respectively. The combined momentum of the refitted $\Lambda^0$ track pair is required to point to the dimuon vertex. To control $B^0$ reflections to the $\Lambda_b^0$ signal distribution, a $B^0$ decay topology fit is also attempted for each track quadruplet successfully fitted to the $\Lambda_b^0$ topology, i.e. the pion mass is assigned to both hadron tracks and the dihadron mass is constrained to the world average mass of $K_S^0$ [6]. To suppress the $B^0$ background the requirement $\mathcal{P}(\Lambda_b^0) > \mathcal{P}(B^0)$ is applied, where $\mathcal{P}(\Lambda_b^0)$ and $\mathcal{P}(B^0)$ are the $\chi^2$ probabilities of the quadruplet fits with $\Lambda_b^0$ and $B^0$ topologies, respectively.

![Invariant mass distributions](image)

Figure 1: The invariant mass distributions for the combined sample of the selected $\Lambda_b^0$ and $\Lambda_b^0$ candidates obtained after their fits to the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ (left plot) and $B^0 \to \psi(2S)K^0_S$ (right plot) topologies [2]. The solid histograms represent fit results. The $\Lambda_b^0$ and $B^0$ signals and their mutual reflections are also shown.

Figure 1 shows the invariant mass distributions for the combined sample of the selected $\Lambda_b^0$ and $\Lambda_b^0$ candidates obtained after their fits to the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ and $B^0 \to \psi(2S)K^0_S$ topologies. Clear $\Lambda_b^0$ and $B^0$...
signals are seen. The \( m(\psi(2S)\Lambda^0) \) and \( m(\psi(2S)K_S^0) \) distributions are simultaneously fitted to sums of signal and two-component background distributions. The signals are described by modified Gaussian functions [7]. The non-resonant backgrounds are described by independent exponential functions. The mutual \( B^0 \) and \( \Lambda^0 \) reflections are described by MC templates normalised to the numbers of \( B^0 \) and \( \Lambda^0 \) hadrons obtained in the fit. The fit yields \( N(\Lambda^0 \to \psi(2S)\Lambda^0) = 603 \pm 38 \). A similar fit of the \( m(J/\psi(2S)\Lambda^0) \) and \( m(J/\psi(2S)K_S^0) \) distributions yields \( N(\Lambda^0 \to J/\psi(2S)\Lambda^0) = 6940 \pm 130 \). Using these yields and correcting for detector effects and for the branching fractions of the \( J/\psi \) and \( \psi(2S) \) decays to two muons, the branching ratio of the \( \Lambda^0 \to \psi(2S)\Lambda^0 \) and \( \Lambda^0 \to J/\psi\Lambda^0 \) decays is measured to be

\[
\frac{\Gamma(\Lambda^0 \to J/\psi\Lambda^0)}{\Gamma(\Lambda^0 \to J/\psi\Lambda^0)} = 0.501 \pm 0.033 \text{ (stat)} \pm 0.016 \text{ (syst)} \pm 0.011 \text{ (B)},
\]

where the third uncertainty originates from the uncertainties of the charmonium branching fractions.

The measured ratio lies in the range 0.5–0.8 found for the branching ratios of analogous \( B \) meson decays [6]. The only available calculation for the branching ratio of the two \( \Lambda^0 \) decays \((0.8 \pm 0.1) \) [8, 9]) exceeds the measured value.

3 Study of the \( B_c^+ \to J/\psi D_s^+ \) and \( B_c^+ \to J/\psi D_s^{*-} \) decays

For the \( D_s^+ \to \phi(K^+K^-)\pi^+ \) reconstruction, tracks of particles with opposite charges are assigned kaon mass hypotheses and combined in pairs to form \( \phi \) candidates. An additional track is assigned a pion mass and combined with the \( \phi \) candidate to form a \( D_s^+ \) candidate.

Figure 2: The invariant mass distribution for the selected \( J/\psi D_s^+ \) candidates (left plot) and the \( |\cos \theta'(\mu^+)\) distribution (right plot), where the helicity angle \( \theta'(\mu^+) \) is the angle between the \( \mu^+ \) and \( D_s^+ \) candidate momenta in the rest frame of the muon pair from \( J/\psi \) decay [3]. The red solid lines represent the projection of the likelihood fit to the model described in the text. The contributions of the \( B_c^+ \to J/\psi D_s^+ \) decay are shown with the magenta long-dashed lines; the brown dash-dot and green dotted lines show the \( B_c^+ \to J/\psi D_s^{*-} \), \( A_0^0 \) and \( A_{\pm\pm} \) component contributions, respectively; the blue dashed lines show the background model.

The \( B_c^+ \to J/\psi D_s^+ \) candidates are built by combining the five tracks of the \( J/\psi \) and \( D_s^+ \) candidates. Figure 2 shows the invariant mass distribution for the selected \( J/\psi D_s^+ \) candidates and the \( |\cos \theta'(\mu^+)\) distribution, where the helicity angle \( \theta'(\mu^+) \) is the angle between the \( \mu^+ \) and \( D_s^+ \) candidate momenta in the rest frame of the muon pair from \( J/\psi \) decay. The peak near the \( B_c^+ \) is attributed to the signal of \( B_c^+ \to J/\psi D_s^+ \) decay while a wider structure between 5900 MeV and 6200 MeV corresponds to \( B_c^+ \to J/\psi D_s^{*-} \) with subsequent \( D_s^{*-} \to D_s^+ \eta \) or \( D_s^{*-} \to D_s^+ \pi^0 \) decays where the neutral particle is not reconstructed. A two-dimensional extended unbinned maximum-likelihood fit of the \( m(J/\psi D_s^+) \) and \( |\cos \theta'(\mu^+)\) distributions is performed using four two-dimensional probability density functions (PDFs) to describe the \( B_c^+ \to J/\psi D_s^+ \) signal, the \( A_{\pm\pm} \) and \( A_{00} \) components of the \( B_c^+ \to J/\psi D_s^{*-} \) signal, and the
The mass distribution of the \( B \) mesons is used to derive the ratios of branching fractions \( \Gamma \). For the \( D \) of the branching fraction of \( D \) models. There is an indication of underestimation of the decay rates for the of the branching fraction are generally described by perturbative QCD, sum rules, and relativistic quark QCD potential model, QCD sum rules, relativistic constituent quark model, light-front quark model, perturbative QCD (pQCD), and relativistic independent quark model (RIQM) [3].

The measured differential cross section (times the product of the relevant branching fractions) for prompt production of \( J/\psi \) and \( D_s^{(*)} \) is shown in Figure 4. It is described within the theoretical uncertainty by the theoretical predictions of the NRQCD model which, in this case, considers the prediction for the \( X(3872) \) to be a mixture of \( \chi_{c1}(2P) \) and a \( D_0^{(*)}D_s^{(*)} \) molecular state [11]. However, the prediction for the \( X(3872) \) prompt production is dominated by the \( \chi_{c1}(2P) \) component.

4 Measurement of the hidden-charm states \( X(3872) \) and \( \psi(2S) \)

Two muon tracks are fitted to a common vertex. The dimuon invariant mass is then constrained to the \( J/\psi \) mass, and the four-track vertex fit of the two muon tracks and pairs of non-muon tracks is performed to find \( J/\psi \pi^+\pi^- \) candidates. Only \( J/\psi \pi^+\pi^- \) combinations with rapidity within the range \(|y| < 0.75\) and transverse momenta within the range \( 10 < p_T < 70 \text{ GeV} \) are considered.

Figure 4(Left) shows the invariant mass of the selected \( J/\psi \pi^+\pi^- \) candidates. The fitted function is the sum of a fourth-order polynomial background and two double-Gaussian functions. The double-Gaussian functions for \( \psi(2S) \) and \( X(3872) \) contain about 470 k and 30 k candidates, respectively. To separate prompt production of the \( \psi(2S) \) and \( X(3872) \) states from the non-prompt production occurring via the decays of long-lived particles such as b-hadrons, the pseudo-proper lifetime \( \tau \) is used. The pseudo-proper lifetime is defined as \( \tau = L_{xy} m / p_T \), where \( L_{xy} \) is the transverse decay length, \( m \) is the invariant mass and \( p_T \) is the transverse momentum of the \( J/\psi \pi^+\pi^- \) candidate.

The measured differential cross section (times the product of the relevant branching fractions) for prompt production of \( X(3872) \) is shown in Figure 4(Right). It is described within the theoretical uncertainty by the prediction of the NRQCD model which, in this case, considers \( X(3872) \) to be a mixture of \( \chi_{c1}(2P) \) and a \( D_0^{(*)}D_s^{(*)} \) molecular state [11]. However, the prediction for the \( X(3872) \) prompt production is dominated by the \( \chi_{c1}(2P) \) component.
Figure 4: (Left) Invariant mass of the selected $J/\psi\pi^+\pi^-$ candidates collected over the full $p_T$ range 10–70 GeV and the rapidity range $|y| < 0.75$ [4]. The curve shows the results of the fit using double-Gaussian functions for the $\psi(2S)$ and $X(3872)$ peaks and a fourth-order polynomial for the background. The $X(3872)$ mass range is highlighted in the inset. (Right) Measured cross section times branching fractions as a function of $p_T$ for prompt $X(3872)$ production [4] compared to NLO NRQCD predictions [11].

Figure 5: (Left) Measured effective pseudo-proper lifetimes for non-prompt $X(3872)$ and $\psi(2S)$ [4]. (Right) Ratio of cross sections times branching fractions, $X(3872)/\psi(2S)$, for the total non-prompt ratio (black circles), short-lived (red squares) and long-lived (blue triangles) components for the $X(3872)$, shown with respective fits described in the text [4]. The data points are slightly shifted horizontally for visibility.

Figure 5(Left) shows the measured effective pseudo-proper lifetimes for non-prompt $X(3872)$ and $\psi(2S)$ in bins of $p_T$. While for $\psi(2S)$ the fitted values of $\tau_{\text{eff}}$ are measured to be around 1.45 ps in all $p_T$ bins, the signal from $X(3872)$ at low $p_T$ tends to have shorter lifetimes, possibly hinting at a different production mechanism at low $p_T$ with the short-lived part due to the contribution of $B_s^-$ mesons. To study this the non-prompt production cross section of $X(3872)$ is split into short-lived ($\tau_{\text{SL}} = 0.40 \pm 0.05$ ps) and long-lived ($\tau_{\text{LL}} = 1.45 \pm 0.05$ ps) components. The ratio of short-lived non-prompt $X(3872)$ to non-prompt $\psi(2S)$, shown in Figure 5(Right), is fitted with a function $a/p_T^2$ [12]. The value of $a$, and the measured non-prompt yields of $X(3872)$ and $\psi(2S)$ states, are used to determine the fraction of non-prompt $X(3872)$ from short-lived sources, integrated over the $p_T$ range ($p_T > 10$ GeV) covered in this measurement, giving:

$$\frac{\sigma(pp \rightarrow B_c + \text{any}) B(B_c \rightarrow X(3872) + \text{any})}{\sigma(pp \rightarrow X(3872) + \text{any})} = (25 \pm 13 \text{ (stat)} \pm 2 \text{ (sys)} \pm 5 \text{ (spin)}) \%,$$

where the last uncertainty comes from varying the spin-alignment of $X(3872)$.

The distributions of the dipion invariant mass $m_{\pi\pi}$ in the $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ and $X(3872) \rightarrow J/\psi\pi^+\pi^-$ decays are measured by determining the corrected yields of $\psi(2S)$ and $X(3872)$ signals in narrow bins of
Also shown is the normalised distribution of $m_{\pi\pi}$ phase-space (red shaded histogram). Figure 6 shows normalised differential decay widths of $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\rho^0(\rightarrow \pi^+\pi^-)$ in bins of $m_{\pi\pi}$ mass. The distribution for $\psi(2S)$ is well described by the Voloshin–Zakharov model [13]. For $X(3872)$, the normalised differential decay width in bins of $m_{\pi\pi}$ is well described by MC simulation of the $X(3872) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\rho^0(\rightarrow \pi^+\pi^-)$ decay.

## 5 Search for a hidden-beauty analogue of the $X(3872)$, $X_b$

Each pair of oppositely charged muons is subjected to a common vertex fit. Any dimuon with an invariant mass within $350$ MeV of the $\Upsilon(1S)$ mass is retained and considered an $\Upsilon(1S) \rightarrow \mu^+\mu^-$ candidate. Dipion candidates are formed from oppositely charged pions. The $\Upsilon(1S)$ candidate and the dipion system are

![Diagram](https://example.com/diagram.png)

Figure 7: (Left) The $\pi^+\pi^-\Upsilon(1S)$ invariant mass distribution in the kinematic bin most sensitive to an $X_b$ signal: $|y| < 1.2$, $p_T > 20$ GeV, and $\cos\theta^* > 0$ [5]. (Right) Observed 95% CL$_s$ upper limits (solid line) on the relative production rate $R = (\sigma B)/(\sigma B)_{2S}$ of a hypothetical $X_b$ parent state decaying isotropically to $\pi^+\pi^-\Upsilon(1S)$, as a function of mass [5]. The median expectation (dashed) and the corresponding 1σ and 2σ bands (green and yellow respectively) are also shown. The bar on the right shows typical shifts under alternative $X_b$ spin-alignment scenarios, relative to the isotropic case shown with the solid point.
combined by performing a four-track common-vertex fit, with the $\mu^+\mu^-$ mass constrained to the $\Upsilon(1S)$ mass.

Figure 7(Left) shows the $\pi^+\pi^-\Upsilon(1S)$ invariant mass distribution in the kinematic bin most sensitive to an $X_b$ signal: $|y| < 1.2$, $p_T > 20$ GeV, and $\cos \theta^* > 0$. The angle $\theta^*$ is defined as the angle, in the parent rest frame, between the dipion momentum and the lab-frame parent momentum. The only apparent peaks are at the masses of the $\Upsilon(2S)$ (10023 MeV) and $\Upsilon(3S)$ (10355 MeV). A hypothesis test for the presence of a narrow $X_b$ peak is performed every 10 MeV from 10 GeV to 11 GeV. At each mass, the presence of a signal is tested by performing simultaneous fits to the nearby $\pi^+\pi^-\Upsilon(1S)$ mass spectrum in these bins; no evidence for new narrow states is found for masses $10.05 - 10.31$ GeV and $10.40 - 11.00$ GeV. Upper limits are also set on the ratio $R = \frac{[\sigma(pp \to X_b)B(X_b \to \pi^+\pi^-\Upsilon(1S))]}{[\sigma(pp \to \Upsilon(2S))B(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))]}$.

Figure 7(Right) shows the observed 95% CL upper limits on the relative production rate. The results range from 0.8% to 4.0% depending on the $X_b$ mass. The analogous ratio for the $X(3872)$ is 6.56%: such or larger value is excluded for all $X_b$ masses considered.

6 Summary
The $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay is observed and the branching ratio of the $\Lambda_b^0 \to \psi(2S)\Lambda^0$ and $\Lambda_b^0 \to J/\psi\Lambda^0$ decays is measured. The decays $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ are studied and their branching fractions are measured relative to that of the $B_c^+ \to J/\psi\pi^+$ decay. The production cross sections and properties of the hidden-charm states $X(3872)$ and $\psi(2S)$ are measured in their decays to $J/\psi\pi^+\pi^-$. A search for a hidden-beauty analogue of the $X(3872)$, $X_b$, is conducted by reconstructing $\Upsilon(1S)(\to \mu^+\mu^-)\pi^+\pi^-$ events.

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