PROCEEDINGS OF SCIENCE

ATLAS and CMS measurements on spectroscopy

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This proceeding contribution presents a selected number of studies performed by the ATLAS and the CMS experiments on b-hadron spectroscopy. Both collaborations have a rich b-hadron physics program on exploiting the large cross section of b-hadrons at the high energies of the LHC. For the ATLAS collaboration, we report the observation of an excited B_c^+ meson state and the search for a structure in the $B_s^0\pi^{\pm}$ invariant mass spectrum. For the CMS collaboration, recent results in study of the $B^+ \to J/\psi\Lambda p$ decay and observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass.

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1. Introduction

The spectroscopy for hadrons with b quarks has been an essential experimental tool to understand QCD, and for this reason, several experiments at CERN and Fermilab had included these as an important part of their programs. With the full Run 2 of the LHC, the b-hadron spectroscopy at energies never reached before provides a new input to test theoretical calculations. Besides, the large statistics gives us the opportunity to look for new and exotic decay channels.

A wide program of studies of heavy flavor spectroscopy at the LHC is performed by the ATLAS [1] and CMS [2] collaborations and a number of recent results in this field are reviewed in this paper. However, several other contributions in this conference include some of the new results not covered here.

2. Study of excited B_c^+ mesons decays to $B_c^+\pi^+\pi^-$

The states of the B_c^+ meson family are unique in the Standard Model, consisting of charged mesons composed by a beauty quark and a charm antiquark (or vice versa). Although the ground state was discovered in 1998 by the CDF Collaboration [3], only at the LHC it became possible to perform a wide range of studies of its characteristics and searches for excited states, providing an excellent test ground for the existing theoretical calculations. The spectrum of this heavy quarkonium family is predicted to be very populated, but spectroscopic observations and measurements of production properties remain scarce. Indeed, their production yields are significantly smaller than those of the charmonium and bottomonium states, the $\bar{b}c$ production cross sections being proportional to the fourth power of the strong coupling constant, α^4 (since two pairs of heavy quarks need to be produced). While the masses and sizes of these beauty-charm quark-antiquark pairs place them between the charmonium and bottomonium systems, so that many properties can be theoretically inferred by interpolation of existing knowledge, the unequal quark masses and velocities could lead to more complex dynamics, where some (nonrelativistic) approximations might break down. Since the $\bar{b}c$ mesons can not annihilate into gluons, the excited states decay to the ground state via the cascade emission of photons or pion pairs, leading to total widths that are less than a few hundred KeV.

Both experiments, ATLAS and CMS, have studied excited states of B_c^+ meson based mainly on the reconstruction of $B_c^+\pi^+\pi^-$ decays with the B_c^+ being reconstructed in the $B_c^+ \to J/\psi\pi^+$ decay. Next subsections report the results from ATLAS and CMS respectively.

2.1 Observation of an Excited B_c^+ meson state with the ATLAS Detector

The first observation of an excited state of B_c^+ meson was reported [4] using 4.9 fb^{-1} of 7 TeV and 19.2 fb^{-1} of 8 TeV pp collision data collected by the ATLAS experiment at the LHC. The state appears in the distribution of the mass difference $Q = m(B_c^+\pi\pi) - m(B_c^+) - m(2\pi)$. Figure 1 shows this distribution for 7 and 8 TeV data with clear signal peaks visible in both.

The mass of the observed state is $6842 \pm 4(\text{stat}) \pm 5(\text{syst})$ MeV, where the first error is statistical and the second is systematic, and it is consistent with the expectations for second S-wave excitations of the $\bar{b}c$ family, $B_c^+(2S)$ and $B_c^{*+}(2S)$. Therefore, the signal can be attributed either to the decay $B_c^+(2S) \to B_c^+\pi^+\pi^-$ or the decay $B_c^{*+}(2S) \to B_c^{*+}\pi^+\pi^-$ with a subsequent transition

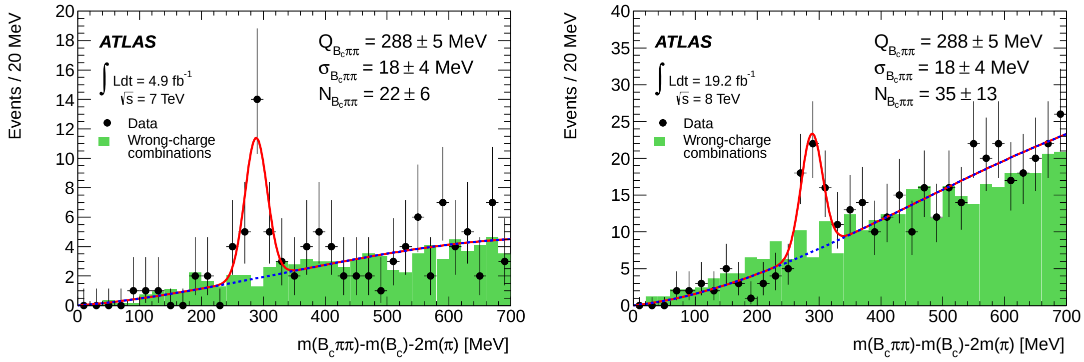

Figure 1: From Ref [4]. The $Q = m(B_c^+\pi\pi) - m(B_c^+) - m(2\pi)$ distribution for the right-charge combinations (points with error bars) and for the same (wrong) pion charge combinations (shaded histogram) in 7 TeV (left) and 8 TeV(right). The wrong-charge combinations are normalized to the same yield as the right-charge background. The solid line is the projection of the results of the unbinned maximum likelihood fit to all candidates in the range $0-700$ MeV. The dashed line is the projection of the background component of the same fit.

$B_c^{*+} \to B_c^+\gamma$ where the photon is not reconstructed, or the peak could be the superposition of the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states, too closely spaced with respect to the resolution of the measurement.

Later, the LHCb Collaboration reported [5] that their 8 TeV data sample did not show any significant sign of the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states. Furthermore, upper limits set by the LHCb experiment on the relative $B_c^+(2S)$ and $B_c^{*+}(2S)$ production rate appear to be in apparent tension with the ATLAS Collaboration result, although at that moment it was not possible to make a definite conclusion on the consistency. That tension clearly motivated further studies by the experiments, in particular searches for these excitations in the full Run-2 data.

2.2 Observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at 13 TeV

Signals consistent with the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states have been separately observed for the first time [6] by investigating the $B_c^+\pi^+\pi^-$ invariant mass spectrum measured by CMS. The analysis is based on the entire LHC sample of proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of 143 fb^{-1}. Figure 2 shows the final $M(B_c^+\pi^+\pi^-) - M(B_c^+) + m_{B_c^+}$ mass distribution along with the result of an extended unbinned maximum likelihood fit, where $M(B_c^+\pi^+\pi^-)$ and $M(B_c^+)$ are, respectively, the reconstructed invariant masses of the $B_c^+\pi^+\pi^-$ and B_c^+ candidates, and $m_{B_c^+}$ is the world-average B_c^+ mass [7]. The two states are reconstructed as two well-resolved peaks, with a measured mass difference $29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV. The observation of two peaks, rather than one, is established with a significance exceeding five standard deviations. The mass of the $B_c^+(2S)$ meson is measured to be $6871.0 \pm 1.2(\text{stat}) \pm 0.5(\text{syst})$ MeV, where the last term corresponds to the uncertainty in the world-average B_c^+ mass. Since the low-energy photon emitted in the $B_c^+\gamma$ radiative decay is not reconstructed, the observed $B_c^{*+}(2S)$ peak has a mass lower than the true value, which remains unknown.

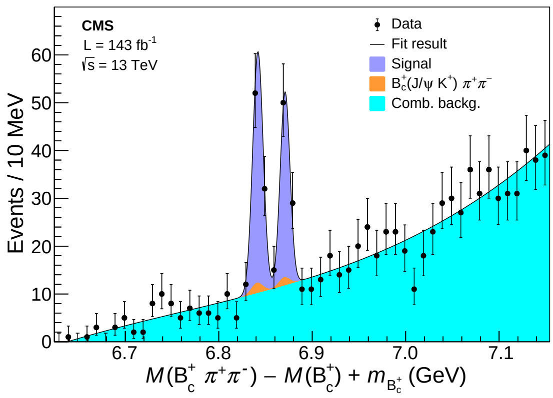

Figure 2: From Ref [6]. The $M(B_c^+\pi^+\pi^-) - M(B_c^+) + m_{B_c^+}$ distribution. The $B_c^+(2S)$ is assumed to be the right-most peak. The vertical bars on the points represent the statistical uncertainty in the data. The contributions from the various sources are shown by the stacked distributions. The solid line represents the result of the fit.

Recently, LHCb collaboration presented an updated search for excited B_c^+ mesons in the $B_c^+\pi^+\pi^-$ mass distribution [8], and confirmed the two peaks observed by the CMS experiment.

3. Search for a structure in the $B_s^0\pi^\pm$ invariant mass spectrum with the ATLAS Experiment

The evidence of a new narrow structure, $X(5668)$, in the decay $X(5668) \to B_s^0\pi^\pm$ reported by the D∅ Collaboration [9, 10] awakened a lot of interest within the community that studies exotic hadrons [11] and triggered this search at several hadron collider experiments, including ATLAS [12], CMS [13], LHCb [14] and CDF [15].

The search for the $X(5668)$ state by the ATLAS experiment at the LHC, by studying resonance-like structures in the $B_s^0\pi^\pm$ invariant mass spectrum was performed based on a combined sample of pp collision data at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV corresponding to integrated luminosities of 4.9 and 19.5 fb^{-1}, respectively. The B_s^0 candidates are reconstructed in the decay chain $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$. The $B_s^0\pi^\pm$ invariant mass distributions do not show any unexpected structures. The results of the fits are shown in Figure 3. Within the acceptance in which this analysis is performed, upper limits on the number of signal events, (N(X)), and on the X production rate relative to B_s^0 mesons (ρ_X), were determined at 95% C.L., resulting in $N(X) < 382$ and $\rho_X < 0.015$ for $p_T(B_s^0) > 10$ GeV, and $N(X) < 356$ and $\rho_X < 0.016$ for $p_T(B_s^0) > 10$ GeV. Limits are also set for potential $B_s^0\pi^\pm$ resonances in the mass range 5550 to 5700 MeV. The results are shown in Figure 4.

4. Study of the $B^+ \to J/\psi\Lambda p$ decay in proton-proton collisions at 8 TeV

Recently, the LHCb experiment reported the observation of structures in the $J/\psi p$ mass spectrum from $\Lambda_b^0 \to J/\psi K p$ decays [16, 17]. A natural extension of these searches is the study of the mass spectra in other b-hadrons channels like $B^+ \to J/\psi\Lambda p$. The CMS experiment performed

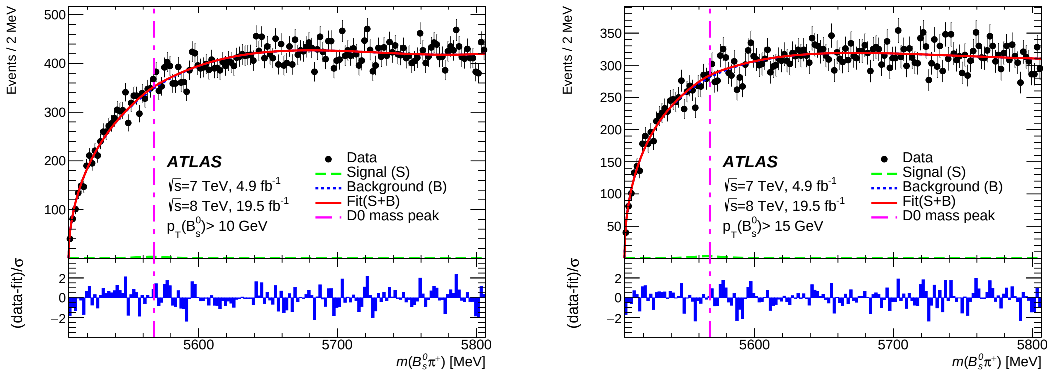

Figure 3: From Ref [12]. Results of the fit to the $B_s^0\pi^{\pm}$ mass distribution for candidates with $p_T(B_s^0\pi) > 10$ GeV (left) and $p_T(B_s^0\pi) > 15$ GeV (right). The bottom panels show the difference between each data point and the fit divided by the statistical uncertainty of that point.

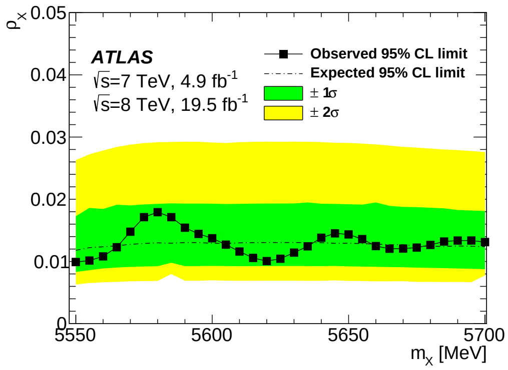

Figure 4: From Ref [12]. Upper limits on ρ_X at 95% CL (black squares connected by line) at different masses of a hypothetical resonant state X decaying to $B_s^0\pi^{\pm}$, for events with $p_T(B_s^0\pi) > 10$ GeV. A Breit Wigner width of $21.9 \pm 6.4(\text{stat})^{+5.0}_{-2.5}(\text{syst})$ MeV is assumed, as reported by D∅. The values include systematic uncertainties. The expected 95% CL upper limits (central black dot-dashed line) with $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) uncertainty bands on ρ_X are shown as a function of the assumed resonance mass.

such studies and reported [18][1] the branching fraction measurement of $B^+ \to J/\psi \Lambda p$, which is the most precise to date and consistent with the previous Belle measurement [20].

Using the data set of proton-proton collisions, collected by the CMS experiment at $\sqrt{s} =$ 8 TeV and corresponding to an integrated luminosity of 19.6 fb^{-1}, the branching fraction ratio $\frac{\beta(B^+ \to J/\psi \Lambda p)}{\beta(B^+ \to J/\psi K^{*+})} = (1.054 \pm 0.087(\text{stat}) \pm 0.028(\text{syst}) \pm 0.011(\beta)) \times 10^{-2}$ was measured. Using the world-average branching fraction of the $B \to J/\psi K^{*+}$ decay, it can be obtained $\beta(B \to J/\psi \Lambda p) = (15.07 \pm 0.81(\text{stat}) \pm 0.40(\text{syst}) \pm 0.86(\beta)) \times 10^{-6}$. The invariant mass distribution of the selected $B^+ \to J/\psi \Lambda p$ candidates is shown in Figure 5. The study of two-body invariant mass distributions of the $B^+ \to J/\psi \Lambda p$ decay products was performed, showing that the spectra can not be satisfactory modeled with a phase space distribution. Figure 6 shows the invariant mass distributions of the $J/\psi p$, $J/\psi \Lambda$ and Λp systems. A model-independent approach was used to conclude that the

[1]The preliminary results shown in this contribution are superseded in this paper [19], submitted to JHEP.

agreement is improved significantly, once the contribution from K^* resonances with spins up to 4 in the Λp system is accounted for.

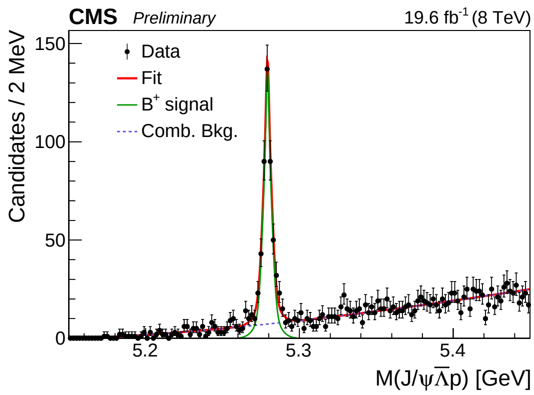

Figure 5: From Ref [18]. Invariant mass distribution of the selected $B^+ \to J/\psi\Lambda p$ candidates. The points are data and the curves are results of the fits.

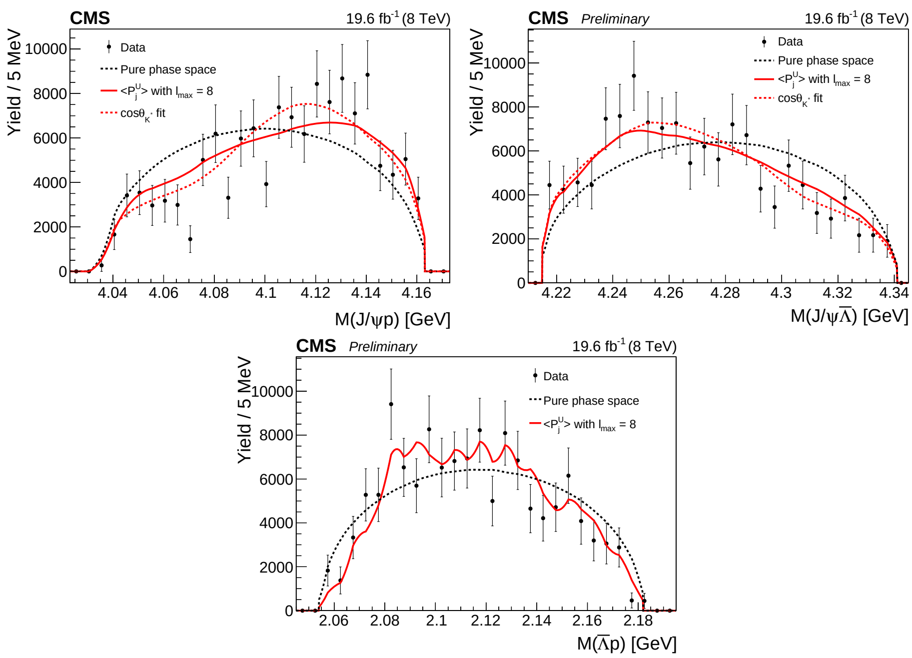

Figure 6: From Ref [18]. The invariant mass distributions of the $J/\psi p$ (upper left), $J/\psi\Lambda$ (upper right), and Λp (lower) systems from the $B^+ \to J/\psi\Lambda p$ decay. The points are efficiency-corrected and background-subtracted data. Superimposed curves are obtained from simulation: the red curve represents the phase space distribution corrected by the Λp angular structure with the inclusion of the first eight moments corresponding to the resonances in the Λp system; the dashed red curve is the fit to the phase space distribution reweighted.

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