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CMS studies of excited B_c states

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In this work, the search for excited $B_c^+(2S)$ states, through their decay to $B_c^+\pi^+\pi^-$, is presented. For the first time, signals consistent with the $B_c^+(2S)$ and $B_c^{+*}(2S)$ states are observed in proton-proton collisions at $\sqrt{(s)} = 13$ TeV, in an event sample corresponding to an integrated luminosity of 143 fb^{-1}, collected by the CMS experiment during the 2015-2018 LHC running periods. These excited $\bar{b}c$ states are observed in the $B_c^+\pi^+\pi^-$ invariant mass spectrum, with the ground state B_c^+ reconstructed through its decay to $J/\psi\pi^+$. The two states are reconstructed as two well-resolved peaks, separated in mass by $29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ 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 $6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)$ MeV, where the last term corresponds to the uncertainty in the world-average B_c^+ mass.

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1. Introduction

During the Run-2 period, started in 2015 and concluded in 2018, the Large Hadron Collider (LHC) provided proton-proton collisions with unprecedented intensity. The luminosity, integrated over the four years, delivered to the two largest particle detectors is about 150 fb^{-1}, six times the correspondent luminosity of the Run-1 period. The Compact Muon Solenoid (CMS) detector has been very efficient in collecting good quality data in Run-2.

Many of the analyses related to the physics of the heavy-flavour hadrons and leptons are limited by the available statistics of signal events, either because of the low production cross section, or because of the low branching fraction of the analysed decay. For these analyses, Run-2 data provide an opportunity to improve the precision of the measurement or the reach of the search.

New challenges do arise with the increased luminosity of LHC collisions in Run-2. More ingenious algorithms for online event selection (trigger) have been deployed during the data taking to maintain high efficiency for signal events, while reducing background contamination. In addition, sophisticated analysis techniques have been studied, to face the increased combinatorial background caused by a higher number of simultaneous collisions.

2. $B_c^+(2S)$ and $B_c^{*+}(2S)$ observation

The study of the set of bound states of a b quark and a c anti-quark (or vice versa), is very important to probe the QCD models that describe the production of heavy-flavour hadrons in hadronic collisions.

The lowest-mass bound state of this family is the B_c^+ meson, whose production cross-section in pp collisions is $\sim 10^{-3}$ of the other B meson families, and the low number of mesons produced makes more difficult to explore the set of its excited states. With Run-1 data, the ATLAS Collaboration observed [1] for the first time an excited state $B_c^+(2S)$ decaying in $B_c^+\pi^+\pi^-$.

The CMS Collaboration searched [2] for B_c excited states decaying to $B_c^+\pi^+\pi^-$, using the data collected in full Run-2 period, corresponding to an integrated luminosity of 143 fb^{-1}. This is the first published LHC analysis using the full statistics of the Run-2 data taking period.

The events have been collected using a trigger requiring two oppositely charged muons, with an invariant mass compatible with a J/ψ, and a hadronic particle, whose trajectories are compatible with a common vertex that is displaced, in the transverse plane of the experiment, from the proton-proton interaction region. The B_c^+ candidates are selected from two muons with an invariant mass compatible with a J/ψ, and a hadronic particle, to which is assigned the pion mass. They are required to be compatible with the particles that satisfied the trigger requirements. The muons (pion) are required to have transverse momenta larger than 4 GeV (3.5 GeV), while the B_c^+ candidate is selected to have transverse momentum larger than 15 GeV. The trajectories of the three particles have to be compatible with coming from a common vertex, which is displaced more than 100 μm from the interaction point. A maximum likelihood fit is performed to the invariant mass spectrum of the B_c^+ candidates, as shown in Figure 1 (left). The fitted yield of signal B_c^+ candidates is 7495 ± 225. The sources of background considered are the partially reconstructed background from $B_c^+ \to J/\psi + \pi + X$, which is excluded by selecting a narrow region around the peak of the signal events, the combinatorial background, whose yield is estimated from the fit, and the peaking background from $B_c^+ \to J/\psi + K$ decay, whose contribution has been studied with simulations and is kept fixed with respect to the signal yield in the whole analysis. The $B_c^+(2S)$ candidates are built by adding two oppositely charged hadronic particles, to which is assigned the pion mass, whose trajectories, together with the B_c^+ candidate's line of flight, are compatible with a common vertex. The leading and trailing pions transverse momenta are required to be larger than 800 MeV and 600 MeV, respectively.

A maximum likelihood fit is performed to the $B_c\pi\pi$ invariant mass spectrum, as shown in Figure 1 (right). Gaussian functions are used to parameterise the signal peaks, as well as for the peaking background contribution. The combinatorial background is modelled with a third-order polynomial function. Many sources of systematic uncertainty have been studied and included in the fit results; the dominant one is obtained using different functions to parameterise the signal.

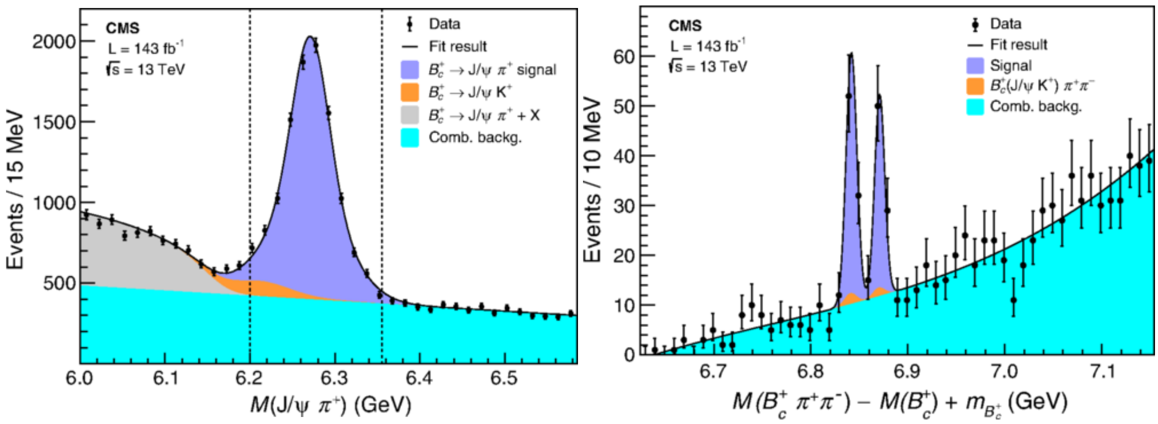

Figure 1: Left: the invariant mass distribution of the B_c^+ candidates. The vertical dashed lines indicate the mass window retained for the reconstruction of the $B_c^+(2S)$ and $B_c^{+*}(2S)$ candidates. The vertical bars on the points represent the statistical uncertainty. The contributions from various sources are shown by the stacked distributions. The solid line represents the result of the fit. Right: 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. The contributions from the various sources are shown by the stacked distributions. The solid line represents the result of the fit. Figures from reference [2].

The fit results in the first observation of two resolved exited states, identified as $B_c^+(2S)$ and $B_c^{+*}(2S)$. Each state has a significance greater than five standard deviations, and the significance of the peaks being two instead of one is greater than six standard deviations. The measured mass of the $B_c^+(2S)$ excited state is

$$M(B_c^+(2S)) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)\,\text{MeV} \quad ,$$

where the last uncertainty is due to the current precision of the B_c^+ mass in literature. Since the excited state $B_c^{+*}(2S)$ decays in $B_c^{+*} + \pi\pi$, and the B_c^{+*} decays in the unexcited state emitting a photon that is not detected, the mass difference visible in the $B_c\pi\pi$ mass spectrum is

$$\Delta M = [M(B_c^{+*}) - M(B_c^+)] - [M(B_c^{+*}(2S)) - M(B_c^+(2S))] \quad ,$$

which is measured to be $\Delta M = 29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})\,\text{MeV}$. All the results are compatible with Standard Model expectations.

3. Conclusions

Thanks to the large amount of data collected and the high resolution on the momenta of the reconstructed particles, CMS was able to resolve for the first time a pair of states in the invariant mass spectra of $B_c^+\pi^+\pi^-$, identified as $B_c^+(2S)$ and $B_c^{*+}(2S)$. 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}. The two peaks are well resolved, with a measured mass difference of $\Delta M = 29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV. The $B_c^+(2S)$ mass is measured to be $6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)$ MeV, where the last term is the uncertainty in the world-average B_c^+ mass. Because the low-energy photon emitted in the $B_c^{*+} \to B_c^+\gamma$ radiative decay is not reconstructed, the observed $B_c^{*+}(2S)$ peak has a mass lower than the true value, which remains unknown. These measurements contribute significantly to the detailed characterisation of heavy meson spectroscopy and provide a rich source of information on the nonperturbative QCD processes that bind heavy quarks into hadrons.

References

[1] G. Aad *et al.*, ATLAS Collaboration, PRL 113 212004 (2014)

[2] A.M. Sirunyan *et al.*, CMS Collaboration, PRL 122 132001 (2019)