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Recent Results on Heavy Flavour from CMS

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Abstract

In this talk I report recent results on heavy flavor physics from pp collisions at CMS. It includes spectroscopy of open or hidden beauty hadrons from pp collision data at $\sqrt{s} = 8$ and 13 TeV. These studies are aimed to gain new knowledge on the properties of beauty hadrons which enhance our understanding of QCD.

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Recent Results on Heavy Flavour from CMS

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Abstract. In this talk I report recent results on heavy flavor physics from pp collisions at CMS. It includes spectroscopy of open or hidden beauty hadrons from pp collision data at $\sqrt{s} = 8$ and 13 TeV. These studies are aimed at gaining new knowledge on the properties of beauty hadrons which enhance our understanding of QCD.

Keywords: LHC, CMS, bottomonium, B mesons, pentaquarks

1 Introduction

The CMS [1] experiment at LHC is designed mainly for high- p_t physics including studies of the Higgs boson, precision measurements of the Standard Model processes and parameters and numerous searches for New Physics. Nevertheless, CMS is contributing intensively in heavy flavor physics. This is possible due to several features of the experiment, including:

- a) A redundant muon system with large rapidity coverage provides high-purity muon-ID with standalone $\delta p_t/p_t = 10\%$;
- b) A very efficient hardware Level 1 trigger and highly flexible High Level Trigger with paths dedicated to b-hadron specific decays with muons in the final state.
- c) A good p_t resolution in tracker with high efficiency ($> 99\%$ in CMS) and good secondary vertex reconstruction with impact parameter resolution down to $\approx 15 \mu\text{m}$.

In this article I will discuss the results on b-hadrons recently obtained by CMS from the analyses of the Run 1 and Run 2 data.

2 Study of $B_{s1}(5830)^0$ and $B_{s2}^*(5840)$ decaying into B^+K^- and $B^0K_s^0$ in CMS

In 2018 the CMS Collaboration published results from a study of excited B_s^0 states, the $B_{s2}^*(5840)^0$ and $B_{s1}(5830)^0$, using 19.6 fb^{-1} of pp data at $\sqrt{s} = 8$ TeV. Previously these states were observed by the CDF [2] and D0 [3] Collaborations and confirmed by the LHCb Collaboration [4] in the charged decay mode B^+K^- . In the present work CMS confirmed all previous measurements and observed the new decay mode $B_{s2}^*(5840)^0 \rightarrow B^0K_s^0$ and obtained evidence for the

analogous neutral mode for the $B_{s1}(5830)^0$ state (see Fig. 1). Various mass and mass difference measurements along with the ratios of production cross-sections times branching fractions were measured [5]. As a by-product of this analysis, the first measurement of the mass difference between spin excited B-meson states was obtained: $M(B^{*0}) - M(B^{*+}) = (0.91 \pm 0.24 \pm 0.09 \pm 0.02(PDG))$ MeV.

Fig. 1. Invariant mass distributions of $B^0 K_S^0$ candidates with the results of the fit overlaid [5]. The points represent the data, the thick solid curves are the results of the overall fits, and the thin solid lines display the signal contributions. The short-dashed lines show the combinatorial background contributions. The long-dashed lines show the contributions from swapping $K^\pm \rightarrow \pi^\pm$ in the reconstruction of the B^0 mesons.

3 Observation of two Resolved States $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ in CMS

The bottomonium system plays very important role in our understanding of the dynamics of quarks inside the hadrons and permits thoroughly tests of various theoretical models describing the potential within the $b-\bar{b}$ system. The $\chi_{bJ}(3P)$ triplet is a special place since the masses of the triplet members are nearly at the open beauty threshold. In charmonium system such a proximity of $\chi_{c1}(2P)$ state to the $D^0 \bar{D}^{*0}$ threshold results in the existence of the $X(3872)$. The question about whether this state is just the ordinary $\chi_{c1}(2P)$ with the mass modified by the interaction with the $D^0 \bar{D}^{*0}$ threshold or it is a mixture of $\chi_{c1}(2P)$ and $D^0 \bar{D}^{*0}$ molecular or even tetraquark, remains open. The study of the $\chi_{bJ}(3P)$ triplet states could shed new light on the existence of possible X_b state, beauty

analogue of $X(3872)$. Also, this study tests theoretical models describing the spin-orbit interaction term of the inter-quark potential within the bottomonium system.

In 2018, by using the data collected at $\sqrt{s} = 13$ TeV (from 2015 to 2017 with the integrated luminosity of 80 fb^{-1}), the CMS Collaboration published the first observation of resolved $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states along with the measurement of their masses and mass difference [6]. These measurements become possible due to the good mass resolution in $\chi_{b1,2}(3P) \rightarrow \Upsilon(3S)\gamma$ decay, where $\Upsilon(3S) \rightarrow \mu^+\mu^-$ and photons are detected through the conversion into the e^+e^- pairs. Fig. 2 shows the $\Upsilon(3S)\gamma$ invariant mass distribution after the photon energy correction as well as the overlaid fit. The $\chi_{b1,2}(3P)$ masses were measured to be $M_1 = 10513.42 \pm 0.41 \pm 0.18 \text{ MeV}$, $M_2 = 10524.02 \pm 0.57 \pm 0.18 \text{ MeV}$. The mass difference was obtained to be $\Delta M = 10.6 \pm 0.64 \pm 0.17 \text{ MeV}$. From 20 theoretical predictions for ΔM , 19 of them fall into the interval $[8-18] \text{ MeV}$ and only 1 gives for the ΔM the value of -2 MeV . The negative sign, i.e. unnatural mass hierarchy, is due to the regarding by that model of the coupling with open-beauty threshold. The obtained experimental result favors the natural mass hierarchy when the $J=2$ state is heavier than the $J=1$ state.

Fig. 2. The invariant mass distribution of the $\chi_{b1,2}(3P) \rightarrow \Upsilon(3S)\gamma$ candidates [6]. The vertical bars are the statistical uncertainties. The curves represent the fitted contributions of the two signal peaks, the background, and their sum.

4 Observation of two excited B_c^+ states

The spectrum of B_c^+ ($\bar{b}c$) states will help to understand in a greater depth the dynamics of heavy-heavy quark systems. In 2014, using Run 1 data, the

Fig. 3. The invariant mass distribution of $B_c^+ \pi^+ \pi^-$ combinations. The points are data and the curve is the result of the fit.

ATLAS Collaboration reported the observation (5.4σ) of a new state decaying into $B_c^+ \pi^+ \pi^-$ ($B_c^+ \rightarrow J/\psi \pi^+$) with mass consistent with the predictions for $B_c(2S)^+$ [7]. Then, the LHCb Collaboration, with 8 TeV data, in the same decay chain, found no significant signal and set upper limit on the $B_c^+(2S)$ production cross-section depending on its mass [8].

In 2019, using full Run 2 statistics, the CMS Collaboration observed two well resolved peaks in $B_c^+ \pi^+ \pi^-$ ($B_c^+ \rightarrow J/\psi \pi^+$) invariant mass [9] (see Fig. 3). The lower mass peak is attributed to the reflection from the $B_c(2S)^{*+}$ meson that firstly decays into $B_c^{*+} \pi^+ \pi^-$. Then the B_c^{*+} decays to B_c^+ ground state and a soft photon which is not reconstructed. The higher mass peak is just a signal from fully reconstructed $B_c(2S)^+$ in $B_c^+ \pi^+ \pi^-$ final state. The significance of each peak was found to be larger than 5σ . The mass difference between two peaks was measured to be $29.1 \pm 1.5 \pm 0.7$ MeV and the mass of $B_c(2S)^+$ was measured to be $6871.0 \pm 1.2(stat.) \pm 0.8(syst.) \pm 0.8(B_c)$ MeV, in agreement with theoretical predictions.

5 Search for exotic states in $B^+ \rightarrow J/\psi \bar{\Lambda} p$ decay

15 years ago the Belle Collaboration discovered the first exotic charmonium-like state, the X(3872), decaying into $J/\psi \pi^+ \pi^-$. During all following 15 years, many charmonium-like states were observed including charged states. There are several theoretical interpretations of these states. Among them one can mention hadrocharmonium, tetraquarks and molecular states. No one is sufficient for describing all properties of all observed states. Observation of new states will widen our understanding of dynamics of quarks in different configurations. Recently, the LHCb Collaboration by analysing the $\Lambda_b^0 \rightarrow J/\psi K^- p$ observed three

pentaquark states in $J/\psi p$ system. It is interesting to find such b-hadron decay mode in which it is possible to search for new pentaquarks in the same $J/\psi p$ system and in a new system, with strangeness, e.g. $J/\psi \Lambda$. Such hidden charm strange are predicted recently close to their threshold [11].

Fig. 4. The invariant mass distribution of $B^+ \rightarrow J/\psi \bar{\Lambda} p$ candidates. The points are data and the curve is the result of the fit.

In 2019 the CMS Collaboration released the results from the study of $B^+ \rightarrow J/\psi \bar{\Lambda} p$ decay [10]. The invariant mass distribution of the $J/\psi \bar{\Lambda} p$ combinations is shown in Fig. 4 demonstrated a very clean signal from this decay. The ratio $\frac{\mathcal{B}(B^+ \rightarrow J/\psi \bar{\Lambda} p)}{\mathcal{B}(B^+ \rightarrow J/\psi K^{*+})}$ was measured which corresponds to the branching fraction $\mathcal{B}(B^+ \rightarrow J/\psi \bar{\Lambda} p) = (15.1 \pm 0.8(stat.) \pm 0.5(syst.) \pm 0.9(Br))$. This is the most precise measurement of this decay to date. Also, the invariant mass distributions of the $\bar{\Lambda} p$, $J/\psi p$ and $J/\psi \bar{\Lambda}$ systems are studied and found to be inconsistent with pure phase space hypothesis. Then, the model-independent angular amplitude analysis was used to test for a presence of exotic resonances in $J/\psi p$ and $J/\psi \Lambda$ systems. It was found that the inclusion of three excited kaons $K_4^*(2045)^+$ ($J^P = 4^+$), $K_2^*(2250)^+$ ($J^P = 2^-$), $K_3^*(2320)^+$ ($J^P = 3^+$) decaying into $\bar{\Lambda} p$ is enough to describe the data. The significance of incompatibility of data with this hypothesis is less than 3σ including systematics.

6 Summary

CMS observed new decay modes of excited B_s^0 state, $B_{s2}^*(5840)^0 \rightarrow B^0 K_s^0$ and obtained evidence for $B_{s1}(5830)^0 \rightarrow B^0 K_s^0$. CMS observed for the first time two resolved states $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$, measured their masses and mass difference.

The latter supports the standard mass hierarchy (the $J=2$ state is heavier than the $J=1$ one). CMS observed for the first time two excited B_c^+ states, one of which is fully reconstructed ($B_c(2S)^+$) and the second one partially ($B_c(2S)^{*+}$) due to lost soft photon. The measured mass of the former state is in agreement with theoretical predictions. CMS studied the $B^+ \rightarrow J/\psi \bar{A} p$ decay in which a model independent angular analysis was performed. It was shown that data, i.e. intermediate two-body masses $M(J/\psi p)$ and $M(J/\psi \bar{A})$ are well described by the presence of excited kaons decaying into $\bar{A} p$.

Although designed for high transverse momentum physics, CMS is a very suitable experiment for heavy flavor physics.

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