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Heavy flavor spectroscopy and exotic states at LHC

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Abstract

The proton proton collision data collected at high centre of mass energies in the Large Hadron Collider provide an excellent environment for precision spectroscopy studies of beauty and charm hadrons. The general purpose experiments, ATLAS and CMS, and the forward-spectrometer experiment LHCb have investigated many interesting aspects of hadron spectroscopy over the years. Some of the latest results on spectroscopy of conventional and exotic hadrons are reviewed.

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Heavy Flavour Spectroscopy and Exotic States at LHC

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Abstract. The proton proton collision data collected at high centre of mass energies in the Large Hadron Collider provide an excellent environment for precision spectroscopy studies of beauty and charm hadrons. The general purpose experiments, ATLAS and CMS, and the forward-spectrometer experiment LHCb have investigated many interesting aspects of hadron spectroscopy over the years. Some of the latest results on spectroscopy of conventional and exotic hadrons are reviewed.

Keywords: heavy flavour spectroscopy, hadrons, mesons, quark bound states

1 Introduction

In the last fifteen years, experimental evidence of new multi-quark bound states has been collected that does not fit the expectations for the conventional qqq baryons or the $q\bar{q}$ mesons. The exact nature of many of these new states still remains a puzzle. Even when confirmed by more than one experiment, most of the quantum numbers of these states have not yet been experimentally determined. Spectroscopic studies of heavy quark states provide deeper understanding of the physics and dynamics of quarks at the hadron level and valuable insight into the various QCD inspired phenomenological models. Proton-proton collisions at high centre of mass energies at the LHC ensure abundant production of $b\bar{b}$ and $c\bar{c}$ pairs which provides great opportunities for performing heavy flavour spectroscopy studies.

1.1 LHC and the Detectors

The detectors at the LHC are complementary to each other in the study of heavy flavour spectroscopy by covering different acceptance and kinematic ranges as seen in Fig. 1. The general purpose detectors ATLAS[1] and CMS[2] have excellent tracking and muon identification in the central region combined with a robust trigger system to collect data at high luminosities and high pile-up scenarios. LHCb[3] on the other hand is optimized for strongly forward peaked

heavy quark production. It has excellent track momentum and vertex resolution, calorimetry and particle identification over the whole acceptance region.

Fig. 1: Detector acceptance of the LHC experiments

2 X(5568)

2.1 X(5568) at the TeVatron

On Feb 2016, the D $\emptyset$ collaboration reported evidence for a narrow structure with mass $M = 5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV and width $\Gamma = 21.9 \pm 6.4^{+5}_{-2.5}$ MeV from a possible decay $X(5568)^{\pm} \rightarrow B_S^0 \pi^{\pm}$, where $B_S^0 \rightarrow J/\psi \phi$, $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$ [4] (Fig.2). This is a potential tetraquark candidate with all four different quark flavours - b,u,d,s. A similar structure was also seen in the semileptonic decay channel where $B_S^0 \rightarrow \mu^{\mp} D_S^{\pm} X$ and $D_S^{\pm} \rightarrow \phi \pi^{\pm}$ [5]. The high rate of B_S^0 production from X(5568) is rather puzzling. The ratio of the yield of the new state X(5568) to the yield of the B_S^0 meson is given by $\rho_x^{D^0} \equiv \frac{\sigma(p\bar{p} \rightarrow X + \text{anything}) \times \mathcal{B}(X \rightarrow B_S^0 \pi)}{\sigma(p\bar{p} \rightarrow B_S^0 + \text{anything})} = (8.6 \pm 1.9 \pm 1.4)\%$.

2.2 X(5568) at the LHC

In LHCb The combined $B_S^0 \rightarrow D_S \pi$ and $B_S^0 \rightarrow J/\psi \phi$ sample in the Run 1 dataset (3 fb^{-1}) is much larger than the D $\emptyset$ sample. Assuming the same production rate, LHCb should observe a huge signal. However, no significant deviation from background is observed in Fig. 3.

Fig. 2: The $B_s^0 \pi^\pm$ mass distribution together with the background distribution and the fit results at D0 [4]

Fig. 3: Results of the fit to the $B_s^0 \pi^\pm$ mass distribution for candidates (both $B_s^0 \rightarrow D_S \pi$ and $B_s^0 \rightarrow J/\psi \phi$ modes combined). The component for the claimed X(5568) state is included in the fit but is not significant. [6]

In ATLAS and CMS For every case of different selection criteria, background parameterization, fit range and method of data description, the yield for X(5568) remains consistent with zero. Stringent limits have been set to ρ_X as seen in Fig. 4. In conclusion, ATLAS, CMS, and LHCb do not confirm the presence of the X(5568) state.

3 $\chi_{b1}(3P) - \chi_{b2}(3P)$ Mass Split in CMS

Analyzing the full LHC Run 2 dataset (13 TeV, 80 fb^{-1}), CMS has observed for the first time the split in the $\chi_{b1}(3P) - \chi_{b2}(3P)$ doublet and measured the masses of the two states [9]. $\chi_b(3P)$ is reconstructed in the $\Upsilon(3S) + \gamma$ mode where the low energy γ is detected through $\gamma \rightarrow e^+ e^-$ conversion inside the silicon tracker. The photon energy scale is calibrated using high yield $\chi_{c1} \rightarrow J/\psi + \gamma$ processes and tested with $\chi_b(1P, 2P)$ states for high accuracy mass measurements. This observation significantly constrains theoretical predictions, which predict mass splits in a wide range $[-2, 18] \text{ GeV}$. This is the first time that the $J = 1$ and $J = 2$ states are well resolved and their masses are individually measured. (Fig. 5)

Fig. 4: Upper limits on ρ_X at 95% C.L. at different masses of a hypothetical resonant state $X(5568)^\pm \rightarrow B_S^0 \pi^\pm$

Fig. 5: Invariant mass distribution of the $\chi_{bJ}(3P) \rightarrow \Upsilon(3S)\gamma$ [9]
 $M1 = 10513.42 \pm 0.41(\text{stat}) \pm 0.18(\text{syst}) \text{ MeV}$
 $M2 = 10524.02 \pm 0.57(\text{stat}) \pm 0.18(\text{syst}) \text{ MeV}$
 $\Delta M = 10.6 \pm 0.64(\text{stat}) \pm 0.17(\text{syst}) \text{ MeV}$

4 Beauty-ful Tetraquarks at LHCb

It is interesting to notice that none of the (30+) exotic hadrons observed since 2003 contain more than two heavy quarks. Recent studies predict that $b\bar{b}b\bar{b}$ tetraquarks below the $\eta_b\eta_b$ threshold (18.8 GeV) can decay to $\Upsilon(nS)\mu^+\mu^-$ [10]. The corresponding cross section times branching fraction is expected to be $\sim 4 \text{ fb}$ and the width $\sim 1.2 \text{ MeV}$. LHCb looked at 6.3 fb^{-1} of 7, 8 and 13 TeV data where $\Upsilon(nS)$ was reconstructed through $\mu^+\mu^-$ decays. But no significant excess was observed in the $M(X_{b\bar{b}b\bar{b}})$ mass range [16, 26] GeV [11]. In the limits on $\sigma \times \mathcal{B}$ in the range [17.5, 20] GeV, the largest deviation from background of 2.5σ (local) is seen at $M(X_{b\bar{b}b\bar{b}}) = 19.35 \text{ GeV}$ which is above the $\eta_b\eta_b$ and $\Upsilon(1S)\Upsilon(1S)$ thresholds (Fig.6). Improved sensitivity for this state will be obtained with data collected during future running periods of the LHC using an upgraded LHCb detector.

Fig. 6: The 95 % CL upper limits on $S \equiv \sigma(pp \rightarrow X) \times \mathcal{B}(X \rightarrow \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(X \rightarrow \Upsilon(1S)\mu^+\mu^-)$ as functions of the X mass hypothesis [11]

5 A New B_{S2}^* Decay at CMS

CMS studied the excited B_S states $B_{S1}(5830)^0$ and $B_{S2}^*(5840)^0$ in the B^+K^- and $B^0K_S^0$ decay modes [12] (Fig. 7). The study reports the first observation of $B_{S2}^* \rightarrow B^0K_s^0$ and $B_{S1} \rightarrow B^{0*}K_s^0$. A few highlights of this study include the measurement of the B_{S2}^* natural width $\Gamma_{B_{S2}^*} = 1.52 \pm 0.34(\text{stat}) \pm 0.3(\text{syst})$ MeV and the first measurement of the mass difference between neutral and charged excited mesons, $m_{B^{*0}} - m_{B^{*+}} = 0.91 \pm 0.24(\text{stat}) \pm 0.09(\text{syst}) \pm 0.02(\text{PDG})$ MeV.

Fig. 7: Invariant mass distributions of $B^0K_S^0$ candidates with the results of the fit overlaid. The three peaks correspond to (from the left) $B_{S1} \rightarrow B^{0*}K_s^0$, $B_{S2} \rightarrow B^{0*}K_s^0$ and $B_{S2}^* \rightarrow B^0K_s^0$ respectively [12]

6 A New Ξ_b^- Resonance At LHCb

LHCb observed a peak in both $\Lambda_0^b K^-$ and $\Xi_b^0 \pi^-$ spectra with 4.5 fb^{-1} of proton-proton collision data at $\sqrt{s} = 7, 8$ and 13 TeV (Fig. 8). This corresponds to a new resonance $\Xi_b(6627)^-$ [13]. Fully reconstructed candidates from

its hadronic decay mode $\Xi_b(6627)^- \rightarrow \Lambda_0^b K^-$, $\Lambda_0^b \rightarrow \Lambda_c^+ \pi^-$ have been used for mass measurements while the semileptonic decay modes have been used to determine its production. The mass and natural width are measured to be $m_{\Xi_b(6627)^-} = 6226.9 \pm 2.0(\text{stat}) \pm 0.3(\text{sys}) \pm 0.2(\text{PDG}) \text{ MeV}$ and $\Gamma_{\Xi_b(6627)^-} = 18.1 \pm 5.4(\text{stat}) \pm 1.8(\text{sys}) \text{ MeV}$. The relative production rate is reported to be $\mathcal{B}(\Xi_b(6627)^- \rightarrow \Lambda_0^b K^-) / \mathcal{B}(\Xi_b(6627)^- \rightarrow \Xi_b^0 \pi^-) \sim 1 \pm 0.5$. The new state can be either $\Xi_b(1P)^-$ or $\Xi_b(2S)^-$. More precise measurements of the width and the relative branching fractions could help to determine the J^P quantum numbers of this state.

Fig. 8: Spectra of mass differences for $\Xi_b(6627)^-$ candidates, reconstructed in the different final states along with the results of the fits [13]

7 $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ Decay at LHCb

The decay $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ has been observed by LHCb with 3 fb^{-1} of pp data collected at $\sqrt{s} = 7$ and 8 TeV [14]. The ratio of branching fractions is measured to be :

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032$$

Two resonances have been observed in the $\Lambda_c^+ \pi^-$ invariant mass spectrum corresponding to $\Sigma_c(2455)^0$ and $\Sigma_c^*(2520)^0$ resonances (Fig.9). The ratios of branching fractions of the resonant modes with respect to the total are :

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^0 p \bar{p}) \times \mathcal{B}(\Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-)} = 0.089 \pm 0.015 \pm 0.006$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*0} p \bar{p}) \times \mathcal{B}(\Sigma_c^{*0} \rightarrow \Lambda_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-)} = 0.119 \pm 0.020 \pm 0.014$$

However, no evidence of any peaking structure of a suspected dibaryon resonance $[cd][ud][ud]$ has been found in the $\Lambda_c^+ \pi^- p$ invariant mass spectrum (Fig.10).

Fig. 9: Observation of the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$ by LHCb [14]

8 Searches for Excited B_c States

A narrow resonance in the $B_c \pi^+ \pi^-$ mass spectrum, interpreted as the $B_c(2S)$ state was first reported by ATLAS in 2014 [15]. The peak was seen in both 7 and 8 TeV data with $M = 6842 \pm 4 \pm 5 \text{ MeV}$ with a 5.2σ global significance (with Look Elsewhere Effect) (Fig.11(a)). LHCb performed a new search for $B_c(2S)$ with 2 fb^{-1} of 8 TeV pp collision data but no evidence of a resonance was seen [16] (Fig.11(b)). Upper limits on the ratio of $\sigma \times \mathcal{B}$ of the $B_c(2S)$ relative to the B_c cross section in the range $[0.02, 0.14]$ @ 95% CL (as a function of mass) have been provided. The ATLAS result still awaits confirmation.

Fig. 10: Background-subtracted mass spectrum of the $\Lambda_c^+ \pi^- p$ system [14] Fig. 11: Search for excited $B_c^\pm$ states at ATLAS and LHCb

Summary

The LHC experiments are significantly contributing to exotic hadron spectroscopy and will continue to do so with Run-II data while facing new experimental challenges. Although designed for high p_T physics, ATLAS and CMS have produced valuable results in heavy flavour physics. Spectroscopy measurements keep filling in the missing tiles of the spectroscopy puzzle. Among the latest results are the observation of a new Ξ_b^- resonance and of a new Λ_b decay by LHCb, and of a new B_{S2}^* decay by CMS. The measurement of the $\chi_{b1}(3P) - \chi_{b2}(3P)$ mass splitting by CMS rules out most models and favours those predicting a direct mass hierarchy. The X(5568) state claimed to have been seen by DØ at the Tevatron has not been confirmed by ATLAS, CMS, and LHCb. An unresolved discrepancy remains between LHCb and ATLAS for the existence of the $B_c(2S)$ state. Many more fascinating results are anticipated from the LHC experiments in the near future.

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