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Recent CMS results in conventional and exotic hadron spectroscopy

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The present report summarizes recent CMS results in conventional and exotic hadron spectroscopy, obtained using the data collected at the Large Hadron Collider during the Run-2 data taking (2015-2018) either with proton-proton collisions at $\sqrt{s}$ = 13 TeV or lead-lead collisions at $\sqrt{s_{NN}}$ = 5.02 TeV per nucleon pair. The results include the first observation of the $B_s^0 \to X(3872)\phi$ decay mode, evidence of X(3872) production in lead-lead collisions, a search for intermediate resonances in the $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ multi-body decay, and the observation of Λ_b^{**} and Ξ_b^{**} excited states.

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The heavy flavour production cross section at the Large Hadron Collider (LHC) is several orders of magnitude greater than at e^+e^- colliders. The CMS experiment [1] at LHC exploits its 4π coverage and high resolution to perform challenging measurements in the Heavy Flavor sector, despite the complex initial state and high background in environments such as proton-proton (*pp*) and lead-lead (*PbPb*) collisions. Some of the recent CMS measurements concerning both conventional and exotic spectroscopy in the charm and beauty sectors are presented here.

1. Recent CMS results on B meson spectroscopy

X(3872) production in weak decays from beauty mesons: The observed spectrum of $c\bar{c}$ states below the $D\bar{D}$ threshold agrees well with theoretical predictions [2, 3]. The Belle Collaboration observed the X(3872) state for the first time in 2003 [4], a resonance above the $D\bar{D}$ threshold but with a very small natural width, that does not fit in the predicted mass spectrum.

CMS reported the first observation of the $B_s^0 \to X(3872)\phi$ decay, with $X(3872) \to J/\psi\pi^+\pi^-$ and $\phi \to K^+K^-$ [5]. The analysis is performed using *pp* collision data recorded by CMS during the LHC Run-2 in 2016-2018 at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 140 fb^{-1}. The analysis uses the decay $B_s^0 \to \psi(2S)\phi$ in the same final state as normalisation channel. The ratio R is measured:

$$R = \frac{\mathcal{B}(B_s^0 \to X(3872)\phi) \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi) \cdot \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = \frac{N[B_s^0 \to X(3872)\phi] \cdot \varepsilon_{B_s^0 \to \psi(2S)\phi}}{N[B_s^0 \to \psi(2S)\phi] \cdot \varepsilon_{B_s^0 \to X(3872)\phi}}$$

where N and ε are respectively the signal yield and the overall efficiency for the decay channel. The nearly identical kinematics of the decay topology of the signal and normalisation channels leads to the cancellation of many systematic uncertainties in the ratio.

The signal yields are separately extracted for the two decay channels using a 2D unbinned maximum likelihood (UML) fit, while the efficiencies are estimated by means of Monte Carlo (MC) techniques. The measured ratio is $R = [2.21 \pm 0.29\,(\text{stat.}) \pm 0.17\,(\text{syst.})]\%$, which is consistent with the measurement published by the LHCb Collaboration [6] in 2021.

Since the properties of the decay involving the $\psi(2S)$ are well-known, it is found that $\mathcal{B}[B_s^0 \to X(3872)\phi]\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-] = (4.14 \pm 0.54\,(\text{stat.}) \pm 0.32\,(\text{syst.}) \pm 0.46\,(\mathcal{B}))\,10^{-6}$. This can be compared to the analogous branching fraction products in B^0 and B^+ decays: the measured value for B_s^0 is consistent with the B^0 result, but it is about two times smaller than the one for B^+. Furthermore, the ratio for B_s^0 and B^+ results for the $X(3872)$ is significantly lower than the corresponding one for the decays involving the $\psi(2S)$. An explanation of the observed difference has been proposed within the tetraquark model of the X(3872) state [7].

First evidence of X(3872) production in *PbPb* collisions: Information on the X(3872) state can be obtained from studying its production and survival in a quark-gluon plasma [8, 9]. The X(3872) production has been studied in *PbPb* collisions at $\sqrt{s_{NN}} = 5.02$ TeV per nucleon pair, using the decay chain $X(3872) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ [10]. The analysis uses 1.7 nb^{-1} of data collected by the CMS detector in 2018. The measurement is performed in the rapidity and transverse momentum ranges |y| < 1.6 and $15 < p_T < 50$ GeV/c.

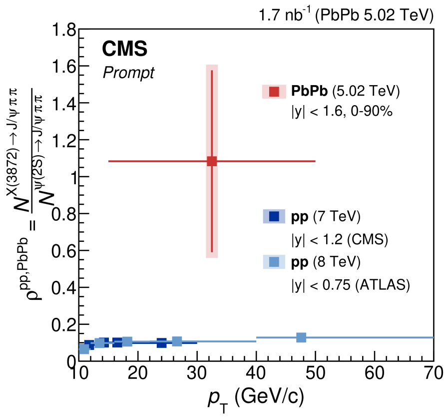

Figure 1: The prompt X(3872) over $\psi(2S)$ yields ratio ρ^{PbPb} in *PbPb* collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [10]. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The yield ratios ρ^{pp} in *pp* collisions at $\sqrt{s}$ = 8 TeV, measured by ATLAS [11], and at $\sqrt{s}$ = 7 TeV, measured by CMS [12] are shown.

The analysis focuses on promptly-produced X(3872), from charm quark fragmentation. The $\psi(2S)$ decay in the same final state is considered as control channel. The candidates are reconstructed and selected inclusively, i.e. with no requirement on the production mechanism, then the signal yields are extracted with an UML fit. Finally the inclusive yields are corrected to consider the overall efficiency, estimated with MC simulations, and to factor out the non-prompt contribution coming from b-hadrons, estimated on data. The ratio ρ^i (i = *pp*, *PbPb*) between the corrected signal yields for X(3872) and $\psi(2S)$ is measured (Fig. 1); with the available level of statistics, ρ^{PbPb} is compatible with both 1, within 1 σ, and $\rho^{pp} \simeq 0.1$, within 2 σ. The larger data sample expected in Run-3 at the LHC will improve the measurement, thus leading to further understanding of the internal structure of X(3872) and its production mechanism.

Intermediate resonances in B meson decays: CMS also recently reported the two decays $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_s^0$, observed using a data sample of 103.7 fb^{-1} of *pp* collisions collected at $\sqrt{s}$ = 13 TeV in 2017 and 2018 [13].

The multi-body decay $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ allows the search for intermediate exotic resonances. The two-body and three-body invariant mass distributions of the B^0 decay products are investigated and do not show any significant exotic narrow structure in addition to the already known light meson resonances ($\rho(770)$, $K^*(892)^\pm$, $K_1(1270)^0$) with the current sample size.

2. Recent CMS results on baryon spectroscopy

Observation of excited Λ_b states: A study of the $\Lambda_b^0\pi^+\pi^-$ invariant mass distribution in the 5.9-6.4 GeV range is performed using up to 140 fb^{-1} of *pp* collisions data at $\sqrt{s}$ = 13 TeV collected by CMS during the 2016-2018 period [14]. The Λ_b^0 candidates are reconstructed in three different channels separately: (1) $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)\Lambda^0$, (2) $\Lambda_b^0 \to \psi(2S)(\to \mu^+\mu^-)\Lambda^0$, and (3) $\Lambda_b^0 \to \psi(2S)(\to \mu^+\mu^-\pi^+\pi^-)\Lambda^0$, with $\Lambda^0 \to p\pi^-$.

The $\Lambda_b^0\pi^+\pi^-$ candidates are then built by adding two opposite-sign tracks to the Λ_b^0 candidate, while same-sign track pairs are used to define the control region. Further selection is applied, separately optimized for the two regions $m_{\Lambda_b^0\pi^+\pi^-} \lessgtr 5.95$ GeV. Two signals corresponding to the excitations $\Lambda_b(5912)$ and $\Lambda_b(5920)$, already observed by LHCb [15] and CDF [16], are observed near the kinematic threshold with significance of 5.7 σ and well over 6 σ, respectively (Fig. 2, left).

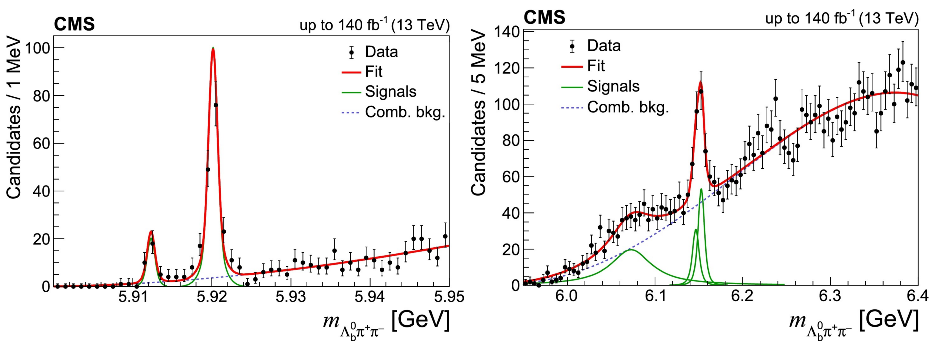

Figure 2: Invariant mass distribution of the selected $\Lambda_b^0\pi^+\pi^-$ candidates near the kinematic threshold (left) and in the high-mass region (right) [14]. Four signals are considered corresponding to the known Λ_b excitations: Λ_b(5912), Λ_b(5920), Λ_b(6146), Λ_b(6152). An additional contribution is introduced to describe the broad enhancement observed in the region below 6.1 GeV.

In the high-mass region (Fig. 2, right) a narrow peak at 6150 MeV with a resolution of 3.8 MeV is observed, consistent with the superposition of the two Λ_b excited states Λ_b(6146) and Λ_b(6152), already observed at LHCb [17]. There is evidence of a broad enhancement in the region below 6.1 GeV, not present in the control region. A veto on possible contributions from intermediate states ($\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^\pm$) improves the agreement between the signal and control regions, but this hypothesis cannot be tested with the available sample size. A similar structure has been later observed at LHCb and it has been interpreted as a further excited state, Λ_b^0(6072) [18].

Observation of a new excited Ξ_b state: CMS has also reported the observation of a new state in the $\Xi_b^-\pi^+\pi^-$ system using up to 140 fb^{-1} of *pp* collisions data at $\sqrt{s}$ = 13 TeV collected during the 2016-2018 period at LHC [19]. The event selection requires a combination of dimuon triggers targeting $J/\psi \to \mu^+\mu^-$, then Ξ_b^- candidates are reconstructed in three decay channels separately: (1) $\Xi_b^- \to J/\psi\Xi^-$, (2) $\Xi_b^- \to J/\psi\Lambda^0K^-$ and (3) $\Xi_b^- \to J/\psi\Sigma^0K^-$, with $\Xi^- \to \Lambda^0\pi^-$, $\Lambda^0 \to p\pi^-$ and $\Sigma^0 \to \Lambda^0\gamma_{soft}$, where the soft photon γ_{soft} is not reconstructed. The candidates are selected with criteria optimized for each decay channel and the signal yields are extracted with an UML fit.

Excited Ξ_b^- candidates are reconstructed by adding two opposite-sign tracks from the same *pp* collision vertex as Ξ_b^- to it, while same-sign tracks are used to define the control region. Since the contribution of the intermediate resonance $\Xi_b^{*0} \to \Xi_b^-\pi^+$ is expected to be dominant [20, 21], the requirement $m(\Xi_b^{*0})$ - $m(\Xi_b^-)$ - m_π^{PDG} < 20.73 MeV is added (peak expected at 15.73 MeV). The fully reconstructed channels (1) and (2) are combined as they have similar resolution.

A simultaneous UML fit is performed on the two data samples, which results in the observation of a narrow peak at $m(\Xi_b^{**-})$ = 6100.3 ± 0.2 (stat.) ± 0.1 (syst.) ± 0.6 (Ξ_b^-) MeV, where the last term originates from the uncertainties on the Ξ_b^- mass, with local statistic significance greater than 6 σ. An upper limit on the resonance width is set at 95% confidence level: $\Gamma(\Xi_b^{**-})$ < 1.9 MeV. Since the new $\Xi_b(6100)^-$ is consistent with the lightest orbitally excited baryon, the analogy with the Ξ_c system [20, 21] suggests its spin and light diquark angular momentum are $J^P = 3/2^-$ and $j_{ds} = 1$.

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