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Recent CMS Results on Rare Heavy Flavour Decays

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Abstract—Recent results on the B hadron decays from the CMS experiment at the LHC are reported. The observation of the $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_S$ decays is presented together with the first observation of the $\eta \to \mu^+\mu^-\mu^+\mu^-$ decay and the first observation of the $\Lambda^0_b \to J/\psi\Xi^-K^+$ decay. The results are based on data sample collected in pp collisions at 13 TeV.

Keywords: LHC, b hadron, rare decays

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1. INTRODUCTION

Experiments at the LHC are searching for physics beyond the Standard Model (SM). The CMS experiment [1] was designed to have an excellent detection efficiency and momentum resolution for muons in wide kinematic range, starting from few GeV and up to TeV in p_T. This enables CMS to make sensitive measurements in multimuon final states, including rare decays and exotic resonances.

2. OBSERVATION OF $\eta \to \mu^+\mu^-\mu^+\mu^-$ DECAY

So far the only the $\eta \to \mu^+\mu^-$, $\eta \to e^+e^-e^+e^-$, and $\eta' \to e^+e^-e^+e^-$ decays among the fully-leptonic decays of η and η' mesons have been observed. The predicted branching fraction of the $\eta \to \mu^+\mu^-\mu^+\mu^-$ decay is extremely small at about 4×10^{-9} [2]. Rare decays of light mesons are a sensitive test of the SM, in addition, pseudoscalar meson decays through (virtual) photons contributes to the anomalous magnetic moment of the muon.

In order to search for the $\eta \to \mu^+\mu^-\mu^+\mu^-$ decay, the CMS experiment used a special high-rate data stream, requiring only a pair of muons, where very limited information about each event was saved. A dimuon mass distribution from this data set exhibits a clear peak at the η muon mass as shown in Fig. 1 (left). The $\eta \to \mu^+\mu^-$ yield is estimated to be as large as about 4.5×10^6, despite very low branching fraction $\mathcal{B}(\eta \to \mu^+\mu^-) \sim 6 \times 10^{-6}$, thanks to high production cross section and integrated luminosity recorded by CMS. This signal is used to calibrate the η meson production spectra vs. transverse momentum and pseudorapidity.

The measured four muon mass distribution from the same data set is shown in Fig. 1 and shows a clear narrow peak at the η meson mass. The distribution is fit with a sum of threshold function for background and a Crystall Ball function for the signal. The fitted signal yield is 49.6 ± 8.1 at a statistical significance of over 5 standard deviations.

The branching fraction of the newly observed decay is measured relative to the $\eta \to \mu^+\mu^-$ decay as the efficiency-corrected ratio of the signal yields: $\mathcal{B}(\eta \to \mu^+\mu^-\mu^+\mu^-)/\mathcal{B}(\eta \to \mu^+\mu^-) = (0.86 \pm 0.14(\text{stat}) \pm 0.12(\text{syst})) \times 10^{-3}$ [3]. The dominant systematic uncertainties arise from imperfect knowledge of efficiencies extracted from simulation. Using the known value of the denominator, the $\mathcal{B}(\eta \to \mu^+\mu^-\mu^+\mu^-)$ is measured to be $(5.0 \pm 0.8(\text{stat}) \pm 0.7(\text{syst}) \pm 0.7(\text{PDG})) \times 10^{-9}$ [3] (where the last uncertainty is due to the uncertainty in $\mathcal{B}(\eta \to \mu^+\mu^-)$), which is in agreement with the SM predictions.

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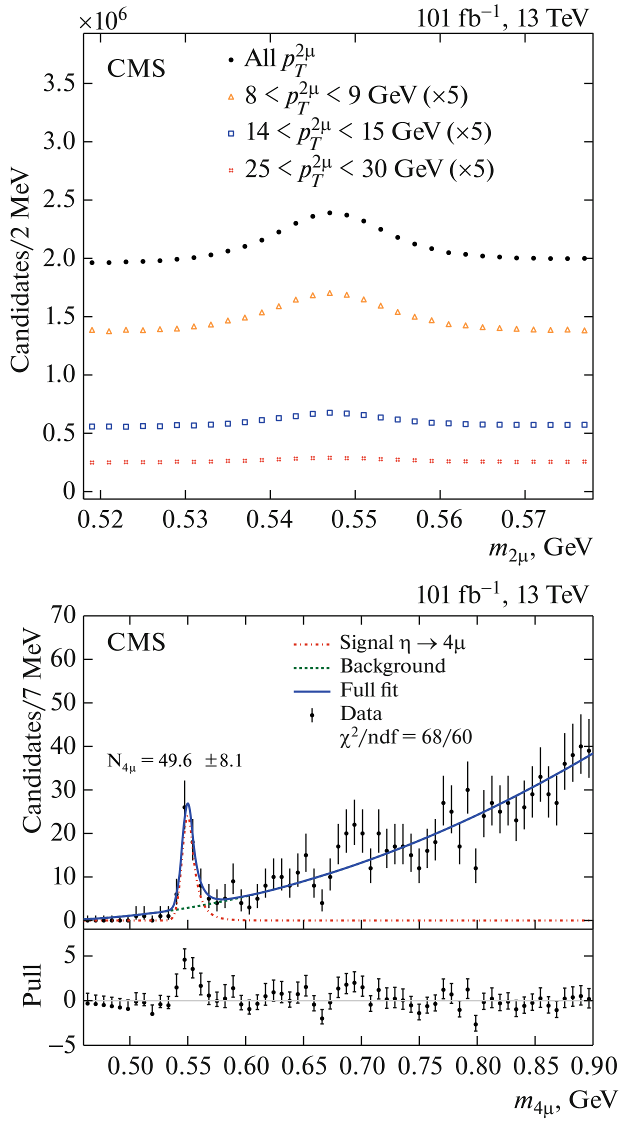

Fig. 1. The measured $m_{\mu^+\mu^-}$ (top) and $m_{\mu^+\mu^-\mu^+\mu^-}$ (down) distributions in CMS data [3].

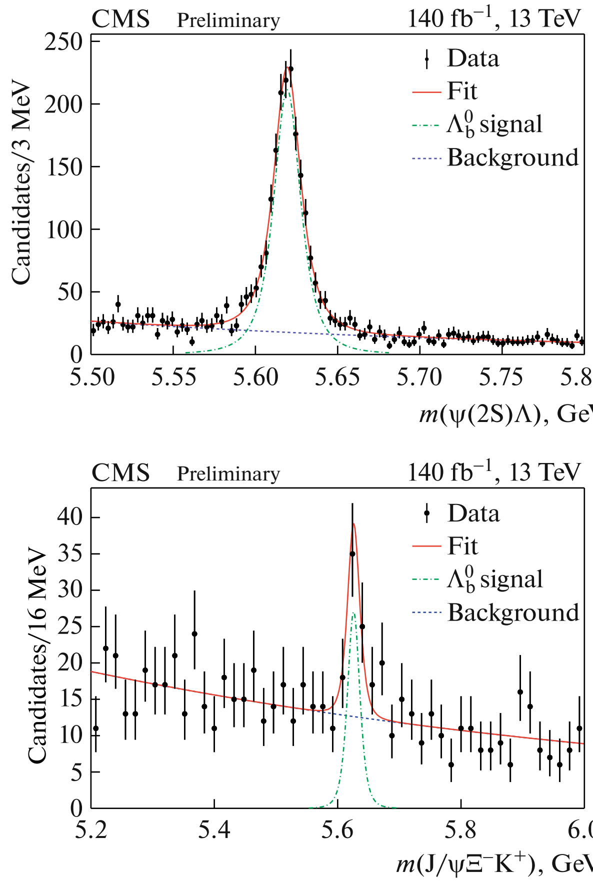

Fig. 2. The measured $\psi(2S)\Lambda$ (top) and $J/\psi\Xi^-K^+$ (down) invariant mass distribution with the fit results overlaid in CMS data [5].

3. OBSERVATION OF THE $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$ DECAY

Multibody decays of beauty hadrons present a rich laboratory to search for intermediate resonances in the decay products. In the case when decay products contain a charmonium state, such intermediate resonances could decay into a charmonium meson and a hadron, which could be a manifestation of an exotic quark content.

The normalization channel is chosen to be $\Lambda_b^0 \to \psi(2S)\Lambda$, because of its similar decay topology and kinematics to the signal decay. The mass distribution of the $\psi(2S)\Lambda$ candidates obtained in data is shown in Fig. 2 (top). We model the signal with a Student's t-distribution with all parameters (mean, σ, n) floating. The combinatorial background is described by an exponential function with a free parameter. The fitted mass of Λ_b^0 is in agreement with its known value, and the mass resolution of 8.90 ± 0.40 MeV is slightly larger than, yet in agreement with, its value of 8.52 MeV found in simulation. The measured yield is $N(\Lambda_b^0 \to \psi(2S)\Lambda) = 1744 \pm 63$.

The measured invariant mass distribution of the selected $J/\psi\Xi^-K^+$ candidates is shown in Fig. 2 (down). A narrow peak at the Λ_b^0 mass is seen on top of a smooth background. The Λ_b^0 signal is modelled with a Student's t-distribution with mass and σ floating, but the n parameter fixed to the value found by fitting the simulated distribution, because of the limited signal yield of $N(\Lambda_b^0 \to J/\psi\Xi^-K^+) = 46 \pm 11$. The background is fitted with an exponential function with free parameters. The Λ_b^0 mass returned by the fit (5625.9 ± 3.2 MeV) agrees with the world-average value of 5619.60 ± 0.17 MeV within two statistical uncertainties. The width of the signal peak (σ) is found to be 10.4 ± 3.3 MeV, consistent within 1.2 standard deviations with the value found in simulation, 6.6 ± 0.2 MeV. The significance obtained with

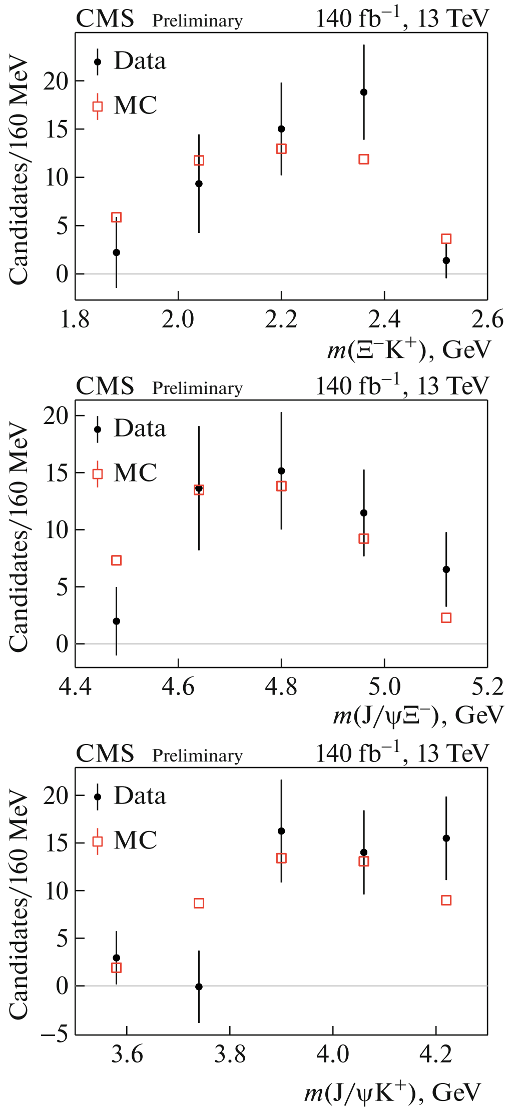

Fig. 3. Intermediate invariant mass distributions of the $\Lambda_b^0 \to J/\psi\Xi^- K^+$ decay in CMS data [5]. Black points represent the background-subtracted data, while red ones show the predictions of phase space simulation.

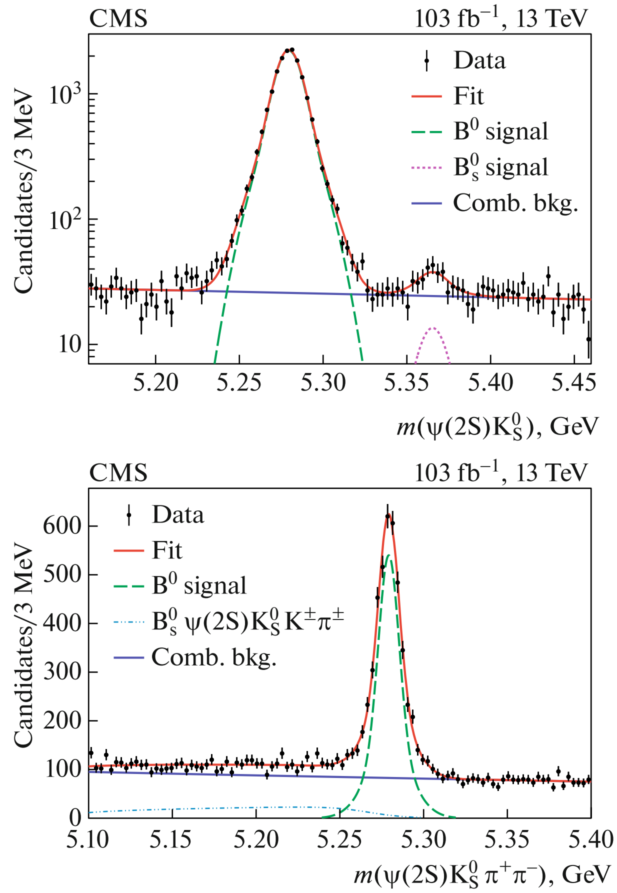

Fig. 4. Measured invariant mass distributions of $\psi(2S)K_S^0$ (top) and $\psi(2S)K_S^0\pi^+\pi^-$ (down) candidates in CMS data [4]. The overlaid results from the fit are described in the text.

the alternative models varies in the range from 5.27 to 5.85 standard deviations.

The sensitivity of this analysis to potential pentaquark signals in the intermediate invariant mass distributions of the $\Lambda_b^0 \to J/\psi\Xi^- K^+$ decay is limited by the low signal yield. The two-body invariant mass distributions obtained with the $_s\mathcal{P}$lot technique [7] have been examined and found to be consistent with the phase space simulation without any narrow peaks as shown on Fig. 3.

The branching fraction is measured with respect to the $\Lambda_b^0 \to \psi(2S)\Lambda$ decay to be $\mathcal{B}(\Lambda_b^0 \to J/\psi\Xi^- K^+)/\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda) = [2.5 \pm 0.8(\mathrm{stat}) \pm 0.9(\mathrm{syst})]\%$. This is the first discovered multibody decay containing the $J/\psi\Xi^-$ system, which opens the possibility to search for doubly-strange hidden-charm pentaquarks once more data are collected.

4. OBSERVATION OF $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ AND $B_s^0 \to \psi(2S)K_S^0$ DECAYS

Decays of neutral B mesons into charmonium resonances (J/ψ, $\psi(2S)$, etc.) are well suited to study the flavour sector of the standard model (SM) and to search for indications of new physics beyond the SM. In the last decade, interest in b hadron decays to final states containing a charmonium resonance has increased after several exotic hadrons have been observed as intermediate resonances in multibody decays.

As shown in Fig. 4, the measured $\psi(2S)K_S^0\pi^+\pi^-$ mass distribution presents a clear $B^0 \to \psi(2S) \times K_S^0\pi^+\pi^-$ signal peak on top of a relatively small background. The signal yield $N(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)$ is found to be 3498 ± 87, where the uncertainty is

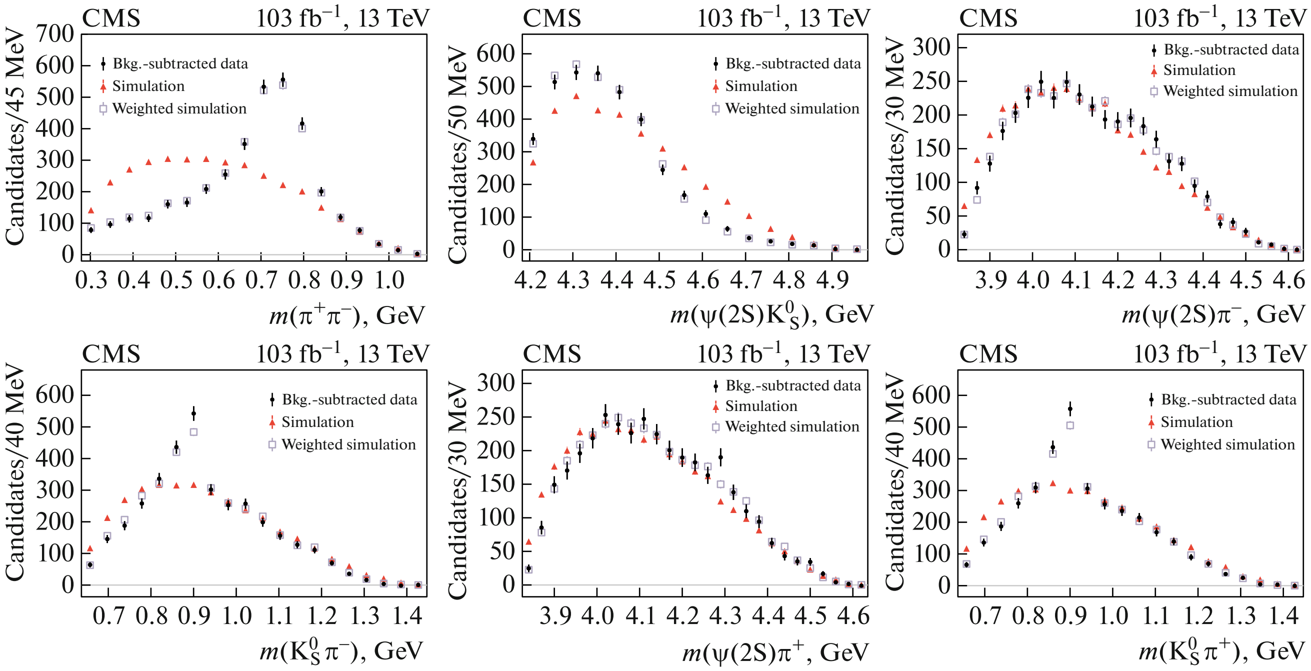

Fig. 5. Distributions of 2-body intermediate invariant masses from the $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ decay in CMS data [4]. The data distributions (black dots) are background subtracted. Overlaid are the predictions of phase space simulations (red triangles), as well as the predictions after applying the reweighting procedure (grey squares).

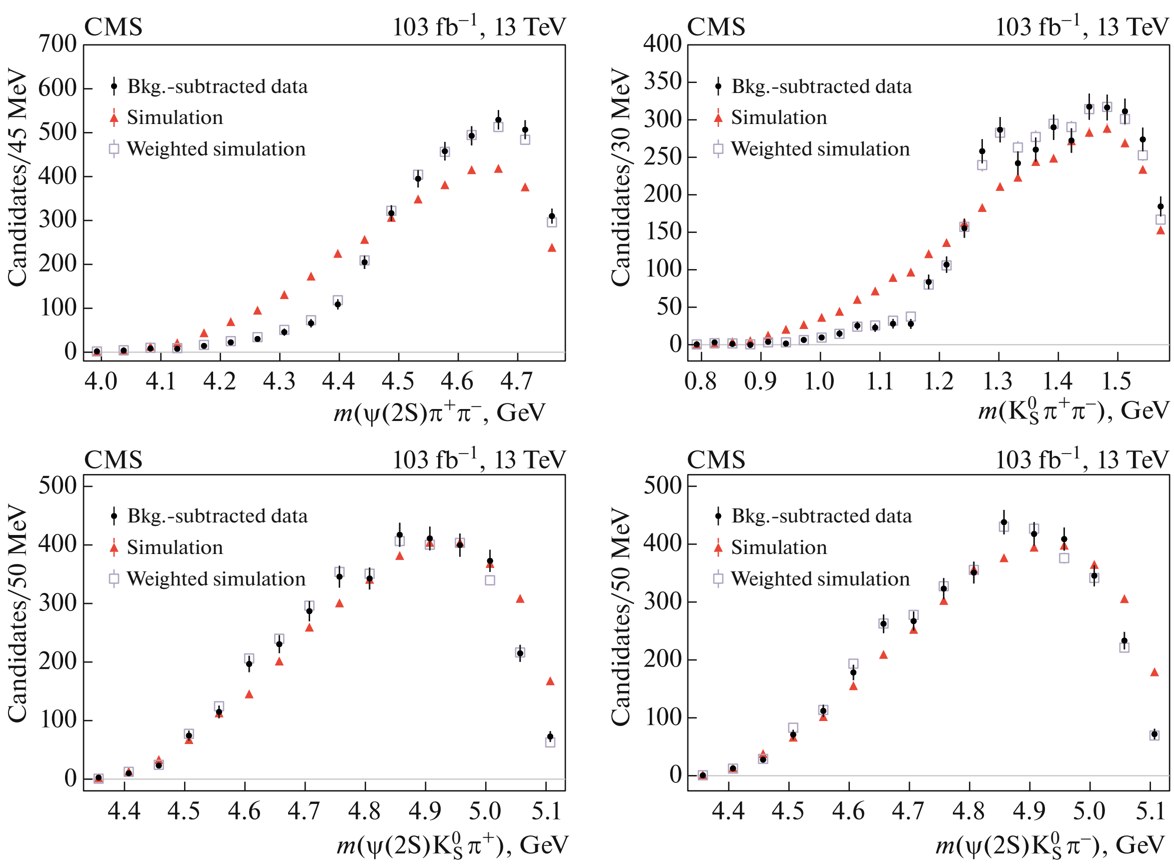

Fig. 6. Distributions of 3-body intermediate invariant masses from the $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ decay in CMS data [4]. Data distributions (black dots) are background subtracted. Overlaid are the predictions of phase space simulations (red triangles), as well as the predictions after applying the reweighting procedure (grey squares).

statistical only. The significance of the $B^0 \to \psi(2S) \times K^0_S\pi^+\pi^-$ signal exceeds 30 standard deviations.

Figures 5 and 6 show the 2- and 3-body invariant mass distributions. Overlaid are the predictions of the 4-body phase space simulations, which provide poor description of the data since the simulations do not account for the intermediate resonance structure. The simulation after application of the reweighting is also shown. The mass distributions of $\psi(2S)$ and one or two light mesons ($\psi(2S)K^0_S$, $\psi(2S)\pi^\pm$, $\psi(2S)K^0_S\pi^\pm$, $\psi(2S)\pi^+\pi^-$) do not present any significant narrow peak that could indicate a contribution from an exotic charmonium state. The small excess at about 4.3 GeV in the $m(\psi(2S)\pi^+)$ distribution (Fig. 5, bottom middle) is not significant, and there is no similar excess in the $m(\psi(2S)\pi^-)$ distribution (Fig. 5, top right). Moreover, exotic states previously found in this mass range are known to have large natural widths. Signs of the K^0_S (Fig. 5, bottom left and right), $\rho(770)^0$ (Fig. 5, top left), and $K^*(1270)^0$ (Fig. 5, top right) resonances are seen in the mass distributions of $K^0_S\pi^\pm$, $\pi^+\pi^-$, and $K^0_S\pi^+\pi^-$, respectively.

Their branching fractions are measured with respect to the $B^0 \to \psi(2S)K^0_S$ decay to be $\mathcal{B}(B^0_s \to \psi(2S)K^0_S)/\mathcal{B}(B^0 \to \psi(2S)K^0_S) = (3.33 \pm 0.69(\text{stat}) \pm 0.11(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2}$, and $\mathcal{B}(B^0 \to \psi(2S)K^0_S\pi^+\pi^-)/\mathcal{B}(B^0 \to \psi(2S)K^0_S) = 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst})$, where the last uncertainty in the first ratio corresponds to the uncertainty in the ratio of production cross sections of B^0_s and B^0 mesons.

5. SUMMARY

Decays $\Lambda^0_b \to J/\psi\Xi^-K^+$, $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$, $B^0_s \to \psi(2S)K^0_S$ and $\eta \to \mu^+\mu^-\mu^+\mu^-$ are observed for the first time and its branching fraction is found to be in agreement with the Standard Model predictions. The results are obtained using 13 TeV pp collision data recorded by the CMS experiment [1] at the LHC.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. S. Chatrchyan et al. (CMS Collab.), J. Instrum. **3**, S08004 (2008). https://doi.org/10.1088/1748-0221/3/08/S08004
2. R. Escribano and S. Gonzàlez-Solís, Chin. Phys. C **42**, 023109 (2019). https://doi.org/10.1088/1674-1137/42/2/023109
3. A. Hayrapetyan et al. (CMS Collab.) Phys. Rev. Lett. **131**, 091903 (2023). https://doi.org/10.1103/PhysRevLett.131.091903
4. A. Tumasyan, W. Adam, J. W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth, M. Jeitler, N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F. M. Pitters, J. Schieck, R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C. -E. Wulz, V. Chekhovsky, A. Litomin, et al. (CMS Collab.), Eur. Phys. J. C **82**, 499 (2022). https://doi.org/10.1140/epjc/s10052-022-10315-y
5. CMS Collab., Observation of the $\Lambda^0_b \to J/\psi\Xi^-K^+$ decay, CERN Report CMS-PAS-BPH-22-002 (CERN, 2023). http://cds.cern.ch/record/2859356.
6. R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, et al. (LHCb Collab.), Phys. Lett. B **772**, 265 (2017). https://doi.org/10.1016/j.physletb.2017.06.045
7. M. Pivk and F. R. Le Diberder, Nucl. Instrum. Methods Phys. Res., Sect. A **555**, 356 (2005). https://doi.org/10.1016/j.nima.2005.08.106