PROCEEDINGS OF SCIENCE

CMS results on flavor spectroscopy

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The CMS experiment at the LHC has reported new discoveries in flavor spectroscopy. In this talk the observation of $\Xi_b(6100)^-$ baryon, the decay $\Lambda_b^0 \rightarrow J/\psi\Xi^- K^+$, the first observation of $\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$decay, and exotic resonances near the $J/\psi J/\psi$ threshold are presented. All these results use the CMS data collected in proton-proton collisions at 13 TeV.

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1. Observation of $\Xi_b(6100)^-$ baryon

In 2012, the CMS Collaboration [1] first observed a new b baryon via its strong decay into $\Xi_b^-\pi^+$ (plus charge conjugates) with a data sample of pp collisions at $\sqrt{s}$ = 7 TeV collected at the LHC, corresponding to an integrated luminosity of 5.3 fb^{-1} [2]. The LHCb Collaboration [3] has reported the identification of the $\Xi_b(6227)^-$ decay into $\Lambda_b^0 K^-$ and $\Xi_b^0\pi^-$ [4]. Recently, the $\Xi_b(6227)^0$ decay to $\Xi_b^-\pi^+$ was also observed [5]. Simultaneously, CMS conducted a search for excited states of the Ξ_b^- using data from 2016, 2017, and 2018 (140 fb^{-1}) in the $\Xi_b^-\pi^+\pi^-$ invariant mass spectrum. The ground state Ξ_b^- was reconstructed through the channels J/$\psi\Xi^-$ and J/$\psi\Lambda K^-$, where J/ψ decays into $\mu^+\mu^-$, Ξ^- into $\Lambda\pi^-$, and Λ into $p\pi$. The invariant masses of J/$\psi\Xi^-$ and J/$\psi\Lambda K^-$ were examined as shown in Fig. 1. The partially reconstructed background is from the J/$\psi\Sigma^0 K^-$ decay with lost photon from Σ^0 decay . In analyzing the J/$\psi\Xi^-$ invariant mass as shown in the left plot of Fig. 1, a model employing double Gaussians is used to describe the signal and a 1st order polynomial is used to describe the background. J/$\psi\Xi^-$ yield of 859 ± 36, with a mass peak at 5797.0 ± 0.7 MeV is measured. For the J/ψ^- reconstructed mass, signal is modeled with double Gaussians and background is modeled with an Exponential function. Yields of 815 ± 74 for J/$\psi\Lambda K^-$ and 820 ± 158 for J/$\psi\Sigma^0 K^-$ (represented by the dotted-dashed curve) are reported with mean at 5800.1 ± 1.2 MeV as shown in the right plot of Fig. 1. Both the results are consistent with each other and with the world-average value, 5797.0 ± 0.6 MeV [7].

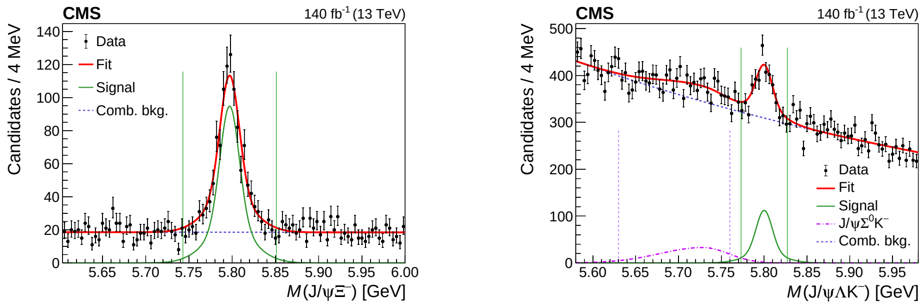

Figure 1: Invariant mass distributions of the selected Ξ_b candidates in the J/$\psi\Xi^-$ (left) and J/$\psi\Lambda K^-$ (right) decay channels with the fit results superimposed. The vertical solid (dashed) lines show the mass windows used in the reconstruction of the $\Xi_b^-\pi^+\pi^-$ candidates in J/$\psi\Xi^-$ and J/$\psi\Lambda K^-$ (J/$\psi\Sigma^0 K^-$) channels [6].

The invariant mass distribution of the $\Xi_b^-\pi^+\pi^-$ candidates is shown in Fig. 2, using the mass difference variable ΔM. The left plot represents the data from the modes $\Xi_b^- \to J/\psi\Xi^-$ and $\Xi_b^- \to J/\psi\Lambda K^-$. Both of them have identical mass resolutions, according to simulation studies (the Ξ_b^- is fully reconstructed in both channels). The right plot shows the events that use the partially reconstructed $\Xi_b^- \to$ J/$\psi\Sigma^0 K^-$ channel, with a 30% larger mass resolution. A simultaneous unbinned extended maximum-likelihood fit is performed on the two data samples shown in Fig. 2. The signal is modeled with a Relativistic Breit–Wigner (RBW) function for the $\Xi_b(6100)^- \to \Xi_b^{*0}\pi^-$ decay, convolved with a double-Gaussian resolution function. The mass and natural width of the signal function are the two parameters of interest in the fit. The mass difference $M(\Xi_b(6100)^-) - M(\Xi_b^-) - 2m_{\pi^\pm}^{\mathrm{PDG}}$ is measured to be 24.14 ± 0.22 (stat) ± 0.09 (syst) MeV. The PDG mass of Ξ_b^- i.e. 5797.0 ± 0.6 MeV [7] is used to obtain M($\Xi_b(6100)^-$) = 6100.3 ± 0.2 (stat) ± 0.1 (syst) ± 0.6 (Ξ_b^-) MeV. The most important fact is a mass increase of 13 MeV of the

$\Xi_b(6100)^-$ baryon could have potentially allowed the decay to $\Lambda_b^0 K^-$ channel. Further more, the natural width of this resonance is compatible with zero and a 95% confidence level upper limit of 1.9 MeV has been set. The local statistical significance of the $\Xi_b(6100)^-$ signal is evaluated with the likelihood ratio technique. The resulting significance of the $\Xi_b(6100)^-$ signal varies between 6.2 and 6.7 standard deviations, depending on the fit model variations used to evaluate the systematic uncertainties.

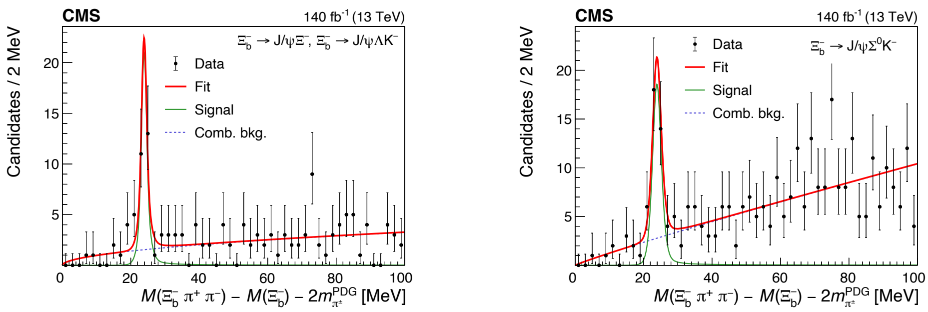

Figure 2: Distributions of the invariant mass difference ΔM for the $\Xi_b^- \pi^+ \pi^-$ candidates, with the Ξ_b^- reconstructed in the J/$\psi \Xi^-$ and J/$\psi \Lambda K^-$ (left) or partially reconstructed in the J/$\psi \Sigma^0 K^-$ channel (right) [6].

2. Observation of $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay

The LHCb Collaboration [3] has achieved a groundbreaking advancement in exotic baryon spectroscopy by identifying significant J/$\psi\, p$ structures in Λ_b^0 decays, particularly leading to J/$\psi\, p K^-$ [8]. This discovery of hidden-charm pentaquarks is particularly notable in the J/$\psi\, p$ and J/$\psi \Lambda$ systems. The exploration of heavier baryon channels, such as Ξ^- and Ω^-, holds the promise of unveiling doubly or even triply strange pentaquark states. In the quest for a deeper understanding of these phenomena, the CMS Collaboration [1] conducted a search for the $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay, utilizing data from 2016, 2017, and 2018 with luminosity of 140 fb^{-1}. The intermediate decay products are reconstructed, with J/ψ decaying into $\mu^+\mu^-$, Ξ^- into $\Lambda\pi^-$, and Λ into $p\pi$ channels. In this analysis, the $\Lambda_b^0 \to \psi(2S)\Lambda$ decay is utilized as the normalization channel for its similar decay topology and kinematics as the signal decay. This strategic choice serves to mitigate systematic uncertainties in the analysis. The invariant mass distributions of $\psi(2S)\Lambda$ shown in left plot of Fig. 3. The model employed for the fit comprises a Student-T function to represent the signal and an Exponential function to describe the background. The mass of the Λ_b^0 particle is determined to be 5619.3 ± 0.3 MeV, and the yield is measured to be 1744 ± 63.

A distinct peak at the Λ_b^0 mass is observed in the J/$\psi \Xi^- K^+$ decay ($> 5\sigma$), marking the first detection of a multibody decay involving the J/$\psi \Xi^-$ system. The analysis model uses a Student-T function for the signal, allowing mass and width to vary, while fixing the n parameter based on simulation results due to limited signal yield. Background modeling employs an Exponential function. The measured Λ_b^0 yield is 46 ± 11, mass is 5625.9 ± 3.2 MeV, consistent with the world-average value of 5619.60 ± 0.17 MeV. However, the sensitivity to the pentaquark is limited due to low signal yields, highlighting the need for further exploration and data accumulation. The branching fraction ratio of $\Lambda_b^0 \to J/\psi \Xi^- K^+$ over $\Lambda_b^0 \to \psi(2S)\Lambda$ is measured to be [2.5 ± 0.8 (stat) ± 0.9 (syst)]%.

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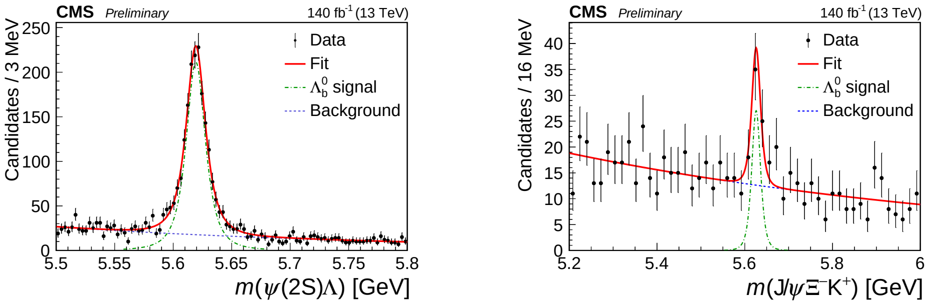

Figure 3: The measured $\psi(2S)\Lambda$ (left) and $J/\psi\Xi^- K^+$ (right) invariant mass distribution with the fit results overlaid [9]

3. Observation of $\eta \to \mu^+\mu^-\mu^+\mu^-$

The η and η' mesons have masses of 547.9 MeV and 957.8 MeV, respectively, and are made up of combinations of up, down, and strange quarks. Some aspects of these mesons, such as their behavior in leptonic radiative decays and Dalitz decays, have not been fully explored. Dalitz decays involve the interaction of these mesons with photons. Among the observed leptonic radiative decays are $\eta \to \mu^+\mu^-$, $\eta \to e^+e^-e^+e^-$, and $\eta' \to e^+e^-e^+e^-$. However, certain decays like $\eta \to e^+e^-$, $\eta \to \mu^+\mu^-\mu^+\mu^-$, $\eta \to e^+e^-\mu^+\mu^-$, and many η' decays are still not well understood or observed. Rare decays provide precise examinations of the Standard Model and offer insights into potential new physics scenarios. The Standard Model predicts a branching fraction of $(3.98 \pm 0.15) \times 10^{-9}$ for the decay $\eta \to \mu^+\mu^-\mu^+\mu^-$, as reported in Ref. [11]. The CMS Collaboration [1] has achieved a milestone by observing the $\eta \to \mu^+\mu^-\mu^+\mu^-$ decay for the first time. The utilization of high-rate triggers in CMS enhances sensitivity to dimuon and four-muon resonances, leading to a significant improvement in precision by five orders of magnitude compared to previous methods. The data used for this observation spans the years 2017 and 2018, with an integrated luminosity of 101 fb^{-1}.

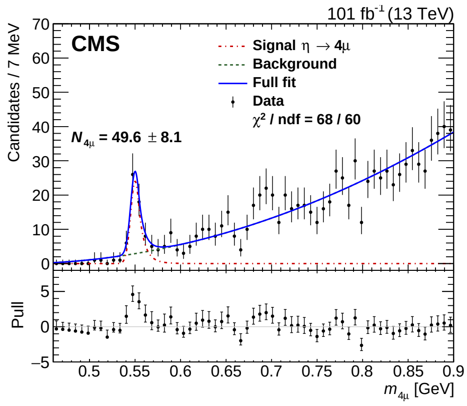

Figure 4: The measured four muon invariant mass distribution using CMS data [12]

The measured four muon mass distribution from the same data set is shown in Fig. 4 and shows a clear narrow peak at the η meson mass. A distinct peak, with approximately 50 events at a significance over 5σ, has been observed in the data collected during 2017-2018. This marks the first-ever observation of the $\eta \to \mu^+\mu^-\mu^+\mu^-$ decay. The analysis involved a fit using the Crystall-

Ball for signal modeling and a threshold model to describe the background. For the branching fraction measurement, normalization from the well-established $\eta \rightarrow \mu^+\mu^-$ decay was employed, allowing the determination of the branching fraction for $\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$. The branching fraction of the observed decay relative to the $\eta \rightarrow \mu^+\mu^-$ decay, $B(\eta \rightarrow \mu^+\mu^-\mu^+\mu^-))/B(\eta \rightarrow \mu^+\mu^-) = (0.86 \pm 0.14(\text{stat}) \pm 0.12(\text{syst})) \times 10^{-3}$. The branching fraction of $\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$ is measured to be $B(\eta \rightarrow \mu^+\mu^-\mu^+\mu^-) = 5.0 \pm 0.8(\text{stat}) \pm 0.7(\text{syst}) \pm 0.7(B_{2\mu}) \times 10^{-9}$. The measurement is in agreement with the theoretical prediction [11].

4. Near-threshold resonances in J/ψJ/ψ mass spectrum

Over the past two decades, a substantial number of exotic resonances have been reported. In 2020, the LHCb Collaboration [3] identified a noteworthy structure in the J/ψJ/ψ channel, a peak at X(6900), as reported in Ref. [13]. This finding was subsequently validated by the ATLAS [10] experiment [14]. Additionally, the CMS Collaboration [1] released a report on the J/ψJ/ψ invariant mass spectrum, utilizing a dataset comprising 135 fb^{-1} of integrated luminosity at a center-of-mass energy of 13 TeV. The major background components, namely NRSPS and DPS, have shapes derived from simulated events. The signal is characterized by Relativistic Breit-Wigner functions convolved with resolution functions. Notably, three resonance structures have been observed with statistical significance: X(6550) at 6.5σ (BW1), X(6900) at 9.4σ (BW2), and X(7300) at 4.1σ (BW3). The X(6900) structure, initially identified by LHCb, has been corroborated with a mass measurement of 6927 ± 9 (stat) ± 4 (syst) MeV.

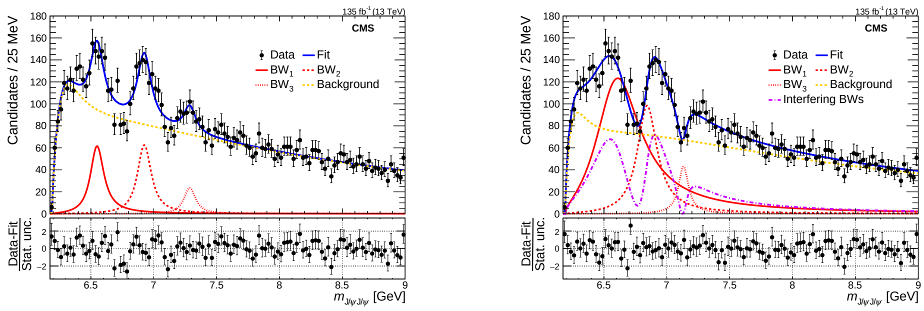

Figure 5: The J/ψJ/ψ invariant mass spectrum in the range up to 9 GeV, with fits consisting of three signal functions (BW1 , BW2 and BW3) and a background model. The left plot shows the fit without interference. The right plot shows the fit that includes interference, where “Interfering BWs” refers to the total contribution of all the interfering amplitudes, and their cross-terms. For clarity, only the sum of the three background components (NRSPS+DPS+BW0) is shown on the plots. The lower portion of the plots shows the pulls, i.e., the number of standard deviations (statistical uncertainties only) that the binned data differ from the fit [15]

The data shows dips around 6750 and 7150 MeV, which are challenging to accurately describe. The interference model used by LHCb doesn’t effectively fit our data. However, incorporating interference terms between the three resonances has significantly improved the fit, providing a better description of the dips and resulting in shifts in resonance parameters when compared to a fit without interference terms.

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5. Summary

The $\Xi_b(6100)^-$ is the first ever observation whose natural width is compatible with zero and a 95% confidence level upper limit of 1.9 MeV has been set. $\Lambda_b^0 \to$J/$\psi\Xi^- K^+$, a multibody decay involving the J/$\psi\Xi^-$ system is observed. The $\eta \to \mu^+\mu^-\mu^+\mu^-$ decay is observed for the very first time. Further, three resonance structures near J/ψJ/ψ threshold are observed with statistical significance: X(6550) at 6.5σ, X(6900) at 9.4σ, and X(7300) at 4.1σ.

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