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Recent CMS results on exotic resonances

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Many exotic resonances have been recently observed at the LHC and other experiments. In this report, CMS studies of exotic multiquark states are reported using the data collected in pp collisions at $\sqrt{s}$ = 13 TeV.

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1. Selected CMS contributions to heavy exotic states

Quantum chromodynamics (QCD) is an important part of the standard model (SM) in particle physics and has gotten much support from experimental results as has the rest of the SM. In the QCD framework, hadrons beyond the quark configurations of $q\bar{q}$ and qqq ($\bar{q}\bar{q}\bar{q}$) are 'exotic' and are allowed in the QCD theory. Experimental studies on the exotic hadrons will help deepen our understanding of QCD.

The CMS experiment [1] at the LHC has performed many important studies in hadron spectroscopy and the exotic hadron sector [2–9], which include the measurement of the $X(3872)$ production cross section [2], the confirmation of the $Y(4140)$ in $B^{\pm} \to J/\psi\phi K^{\pm}$ decays [4], and observation of the $B_s^0 \to X(3872)\phi$ decay [9] —all in proton-proton collisions.

Here we present recent results on exotic resonances from the CMS experiment: evidence for the $X(3872)$ in heavy-ion collisions [10]; observation of the $B_s^0 \to \psi(2S)K_S^0$ and the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decays [11], and observation of new structures in the $J/\psi J/\psi$ mass spectrum [12].

2. Evidence for $X(3872)$ in PbPb collisions

The $X(3872)$ was first observed by the Belle Collaboration [13]. Although its quantum numbers have been determined to be $J^{PC} = 1^{++}$ by the LHCb collaboration [14], its nature is still not fully understood. The production and survival of the $X(3872)$ in relativistic heavy ion collisions is expected to depend on the $X(3872)$'s internal structure [15, 16]. Therefore, study of the $X(3872)$ production in relativistic heavy-ion collisions provides new opportunities to probe the nature of the $X(3872)$.

The CMS Collaboration performed a study of $X(3872)$ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using 1.7 nb^{-1} sample collected in 2018 [10]. The candidates for the $X(3872)$ and $\psi(2S)$ are reconstructed via their decays into $J/\psi\pi^+\pi^-$, where the J/ψ decays into $\mu^+\mu^-$. Figure 1 shows the observed $m_{\mu\mu\pi\pi}$ distribution for the $X(3872)$ and $\psi(2S)$ candidates, where the upper plot shows the inclusive sample and the bottom one shows the b-enriched (nonprompt dominated, i.e. transverse decay length $l_{xy} > 0.1$ mm) sample. The significance of the inclusive $X(3872)$ signal is 4.2 standard deviations. The prompt $X(3872)$ to $\psi(2S)$ yield ratio is found to be $1.08 \pm 0.49(stat) \pm 0.52(syst)$, whereas the typical value is around 0.1 in pp collisions.

3. Observation of the $B_s^0 \to \psi(2S)K_S^0$ and the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decays

Multibody decays of the B mesons are well suited to the search for, and study of, exotic resonances. For example, the discovery of $X(3872)$ was in $B \to KJ/\psi\pi\pi$ decays [13], and that of the first charged tetraquark candidate, $Z(4430)^+$, was in $B \to \psi(2S)K\pi^{\pm}$ [17].

The CMS experiment performed the first measurement of the $B_s^0 \to \psi(2S)K_S^0$ and $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decays, using a data sample of proton-proton collisions at $\sqrt{s} = 13$ TeV, and an integrated luminosity of 103 fb^{-1}, collected in 2017 and 2018 [11]. The $\psi(2S)$ and K_S^0 mesons are reconstructed using their decays into $\mu^+\mu^-$ and $\pi^+\pi^-$, respectively. The observed invariant mass distribution of $\psi(2S)K_S^0$ (left) and $\psi(2S)K_S^0\pi^+\pi^-$ (right) are shown in Fig. 2. Using the $B^0 \to \psi(2S)K_S^0$ as a reference channel, the relative branching fractions of $B_s^0 \to \psi(2S)K_S^0$ and

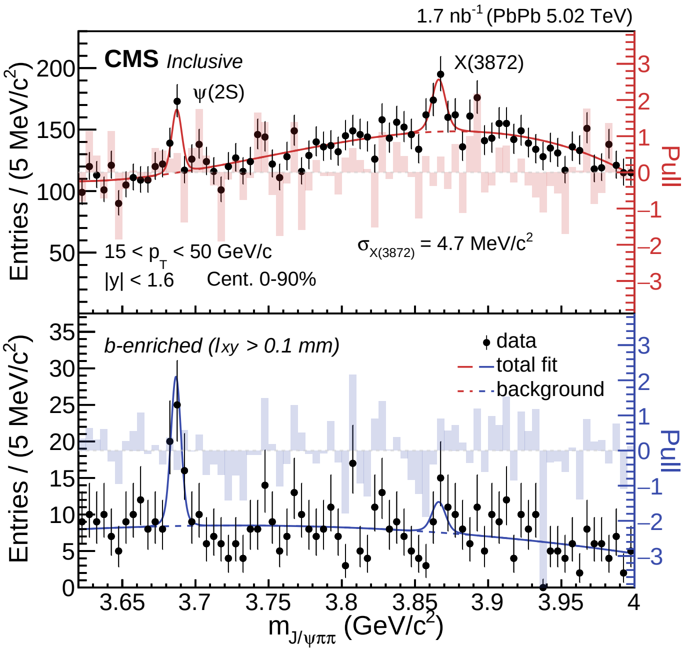

Figure 1: Invariant mass distribution of $m_{\mu\mu\pi\pi}$ in Pb-Pb collisions, for the inclusive (upper) and b-enriched (bottom) samples [10]. The vertical lines on points represent statistical uncertainties in the data. The results of the unbinned maximum-likelihood fits for the signal + background, and background alone, are also shown by the solid and dashed lines, respectively. The pull distribution is represented by the shaded bars. The $X(3872)$ peak mass resolution, $\sigma_{X(3872)}$, calculated at the half-maximum of the signal peak, is also listed for reference.

$B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decays are measured to be $\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)/\mathcal{B}(B^0 \to \psi(2S)K_S^0) = (3.33\pm 0.69(stat)\pm 0.11(syst)\pm 0.34(f_s/f_d))\times 10^{-2}$, and $\mathcal{B}(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)/\mathcal{B}(B^0 \to \psi(2S)K_S^0) = 0.480 \pm 0.013(stat) \pm 0.032(syst)$, where the last uncertainty in the first ratio corresponds to the uncertainty in the ratio of the production cross sections of B_s^0 and B^0 mesons. With the currently available, statistics-limited data, the 2- and 3- body invariant mass distributions of the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay products do not show significant exotic narrow structures in addition to the known light meson resonances.

4. Observation of new structures in the $J/\psi J/\psi$ mass spectrum in pp collisions

The $X(3872)$ and many other exotic candidates contain two heavy quarks ($c\bar{c}$). An analogue to heavy quarkonia would be fully heavy tetraquarks, which have been explored in theoretical models and are expected to be experimentally observable. The recent observation of the $X(6900)$ decaying into $J/\psi J/\psi$ has been reported by the LHCb Collaboration [18].

The CMS experiment performed a study of the low-mass region of the $J/\psi J/\psi$ mass spectrum in pp collisions, using a data sample corresponding to an integrated luminosity of 135 fb^{-1} at a center-of-mass energy of 13 TeV [12]. The two J/ψ candidates are reconstructed using their $\mu^+\mu^-$ mode, and the final $J/\psi J/\psi$ mass distribution is shown in Fig. 3, where three signal Breit-Wigner structures and a background component are used to fit the distribution. The statistical significance

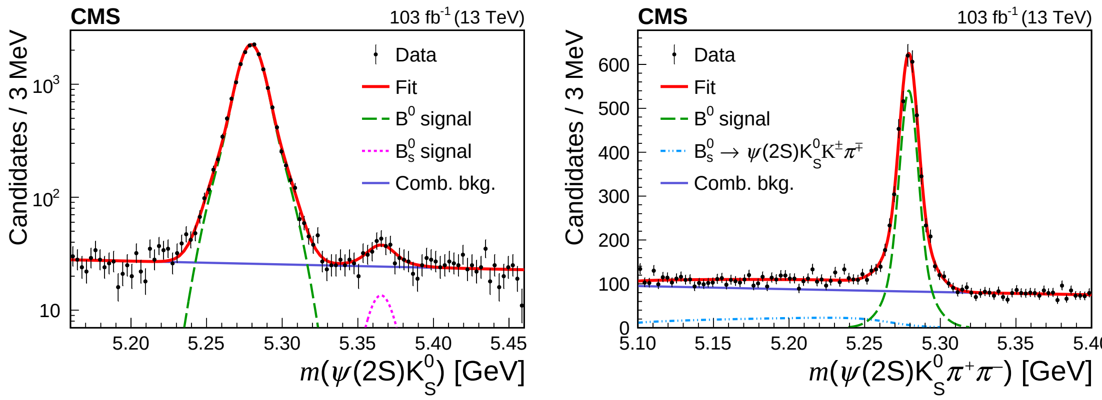

Figure 2: Measured mass distribution of $\psi(2S)K^0_S$ (left) and $\psi(2S)K^0_S\pi^+\pi^-$ (right) candidates [11].

of the three structures are 6.5σ, 9.4σ, and 4.1σ for $X(6600)$, $X(6900)$ and $X(7300)$, respectively. The measured masses and widths of three structures are summarized in Table 1.

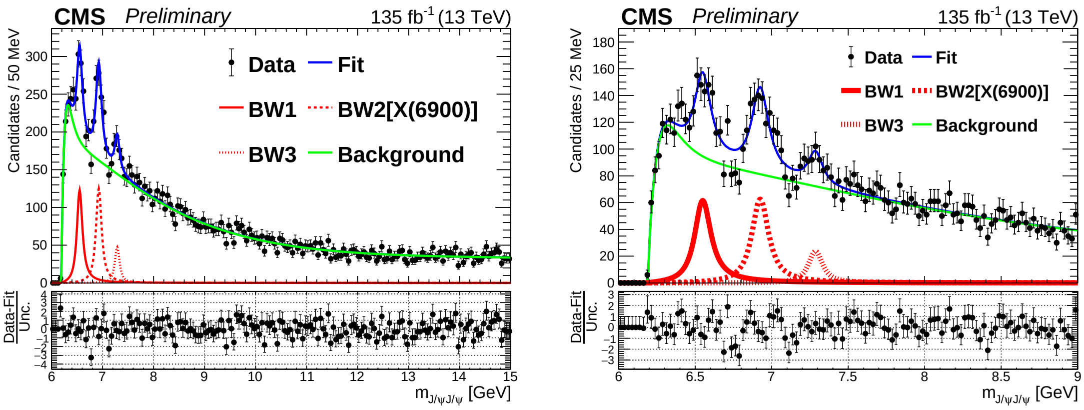

Figure 3: The CMS $J/\psi J/\psi$ mass spectrum with a fit consisting of three signal BW functions and a background model [12]. The left plot shows the fit over the full mass range, and on the right is the same fit expanded by only displaying masses below 9 GeV.

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

Table 1: Summary of the fit results of the CMS $m(J/\psi J/\psi)$ distribution: the mass m and natural width Γ, in MeV, and the signal yields N are given for three signal structures [12]. The first uncertainties are statistical and the second systematic.

Our $X(6900)$ parameters are in a good agreement with LHCb's non-interference result, while the $X(6600)$ and $X(7300)$ are new structures. In order to remove potential model dependencies in a comparison of the $X(6900)$ results, we also apply the principal two LHCb fit models to the CMS data, but using CMS-specific background shapes. Figure 4 shows the application of LHCb's

Model I (left, non-interference) and Model II (right, non-resonant single parton scattering (NRSPS) interfering with a Breit-Wigner structure – the $X(6700)$ in our application). LHCb's Model I consists of the $X(6900)$ signal, NRSPS, non-resonant double parton scattering (NRDPS) and two more BWs – around 6300 (BW0) and 6500 MeV (BW1) – to account for the threshold enhancement. LHCb's Model II consists of the $X(6900)$ signal, NRDPS, and the interference contribution of a Breit-Wigner structure $X(6700)$ and NRSPS.

In both models, the $X(6900)$ parameters are in a good agreement with LHCb's measurements, while our $X(6700)$ in Model II has a much larger amplitude and width compared to the LHCb's interfering Breit-Wigner, and none of the LHCb models provide a satisfactory description of our data.

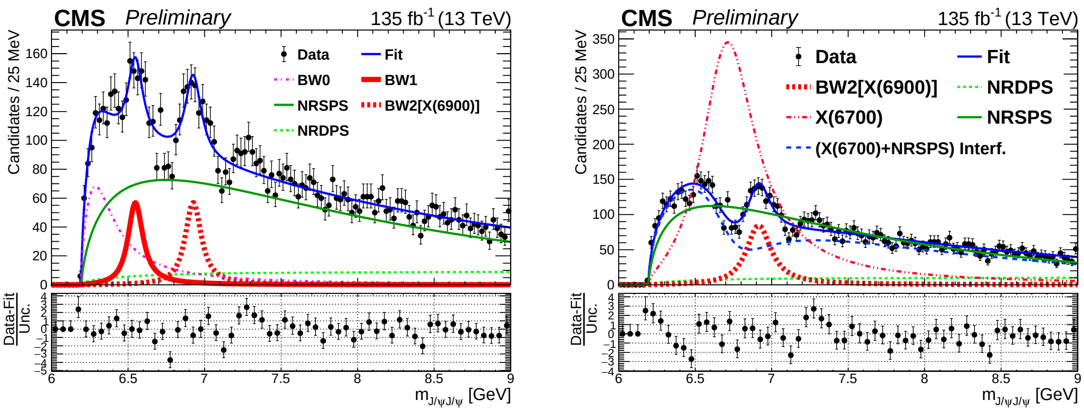

Figure 4: The CMS $J/\psi J/\psi$ mass spectrum [12]. The data are fit using LHCb models: Model I (non-interference) on the left and Model II (interference) on the right.

5. Summary

In summary, recent CMS results are presented, including the first evidence for the $X(3872)$ production in heavy ion collisions, the first observation of the $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_S$, and the observation of new structures in $J/\psi J/\psi$ mass spectrum in pp collisions.

References

[1] CMS collaboration, S. Chatrchyan et al., *The CMS Experiment at the CERN LHC*, *JINST* **3** (2008) S08004.

[2] CMS collaboration, S. Chatrchyan et al., *Measurement of the X(3872) Production Cross Section Via Decays to $J/\psi\pi^+\pi^-$ in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **04** (2013) 154 [1302.3968].

[3] CMS collaboration, S. Chatrchyan et al., *Search for a New Bottomonium State Decaying to $\Upsilon(1S)\pi^+\pi^-$ in pp Collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett. B* **727** (2013) 57 [1309.0250].

[4] CMS collaboration, S. Chatrchyan et al., *Observation of a Peaking Structure in the $J/\psi\phi$ Mass Spectrum from $B^\pm \to J/\psi\phi K^\pm$ Decays*, *Phys. Lett. B* **734** (2014) 261 [1309.6920].

[5] CMS collaboration, A. M. Sirunyan et al., *Search for the X(5568) state decaying into* $B_s^0\pi^\pm$ *in proton-proton collisions at* $\sqrt{s}$ *= 8 TeV*, Phys. Rev. Lett. **120** (2018) 202005 [1712.06144].

[6] CMS collaboration, A. M. Sirunyan et al., *Study of the* $B^+ \to J/\psi\overline{\Lambda}p$ *decay in proton-proton collisions at* $\sqrt{s} = 8$ *TeV*, JHEP **12** (2019) 100 [1907.05461].

[7] CMS collaboration, A. M. Sirunyan et al., *Observation of the* $\Lambda_b^0 \to J/\psi\Lambda\phi$ *decay in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*, Phys. Lett. B **802** (2020) 135203 [1911.03789].

[8] CMS collaboration, A. M. Sirunyan et al., *Measurement of the* $\Upsilon(1S)$ *pair production cross section and search for resonances decaying to* $\Upsilon(1S)\mu^+\mu^-$ *in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*, Phys. Lett. B **808** (2020) 135578 [2002.06393].

[9] CMS collaboration, A. M. Sirunyan et al., *Observation of the* $B_s^0 \to X(3872)\phi$ *decay*, Phys. Rev. Lett. **125** (2020) 152001 [2005.04764].

[10] CMS collaboration, A. M. Sirunyan et al., *Evidence for X(3872) in Pb-Pb Collisions and Studies of its Prompt Production at* $\sqrt{s_{NN}}$*=5.02 TeV*, Phys. Rev. Lett. **128** (2022) 032001 [2102.13048].

[11] CMS collaboration, A. Tumasyan et al., *Observation of* $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ *and* $B_S^0 \to \psi(2S)K_S^0$ *decays*, Eur. Phys. J. C **82** (2022) 499 [2201.09131].

[12] CMS collaboration, *Observation of new structures in the* $J/\psi J/\psi$ *mass spectrum in* pp *collisions at* $\sqrt{s} = 13$ *TeV*, CMS-PAS-BPH-21-003 (2022) .

[13] Belle collaboration, S. K. Choi et al., *Observation of a narrow charmonium-like state in exclusive* $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ *decays*, Phys. Rev. Lett. **91** (2003) 262001 [hep-ex/0309032].

[14] LHCb collaboration, R. Aaij et al., *Determination of the X(3872) meson quantum numbers*, Phys. Rev. Lett. **110** (2013) 222001 [1302.6269].

[15] H. Zhang, J. Liao, E. Wang, Q. Wang and H. Xing, *Deciphering the Nature of X(3872) in Heavy Ion Collisions*, Phys. Rev. Lett. **126** (2021) 012301 [2004.00024].

[16] B. Wu, X. Du, M. Sibila and R. Rapp, $X(3872)$ *transport in heavy-ion collisions*, Eur. Phys. J. A **57** (2021) 122 [2006.09945].

[17] Belle collaboration, S. K. Choi et al., *Observation of a resonance-like structure in the* $\pi^\pm\psi'$ *mass distribution in exclusive* $B \to K\pi^\pm\psi'$ *decays*, Phys. Rev. Lett. **100** (2008) 142001 [0708.1790].

[18] LHCb collaboration, R. Aaij et al., *Observation of structure in the* J/ψ *-pair mass spectrum*, Sci. Bull. **65** (2020) 1983 [2006.16957].