EPJ Web of Conferences **312**, 06004 (2024) https://doi.org/10.1051/epjconf/202431206004
FPCP 2024

New Structures in the J/ψ J/ψ Mass Spectrum at CMS

Xining Wang[1,2,*] and *Kai* Yi[1,2,**]

[1]Department of Physics, Tsinghua University, Haidian District, Beijing, China
[2]School of Physics and Technology, Nanjing Normal University, Wenyuan Road No. 1, Nanjing, China

Abstract. A search is reported for structures near the J/ψ J/ψ mass threshold using a dataset of proton-proton collisions at $\sqrt{s}$ = 13 TeV recorded with the CMS detector at the LHC, corresponding to an integrated luminosity of about 135 fb^{-1}. Two structures are observed with a significance exceeding 5σ and evidence of an additional structure is reported with a local significance of 4.7σ.

1 History of exotic hadrons

Gell-Mann's original 1964 quark paper [1] introduced the possibility of exotic hadrons, which are states that differ from the usual $q\bar{q}$ or qqq combinations. Since then, interest in observing these exotic states has fluctuated both theoretically and experimentally.

In 2003, the Belle Collaboration made a significant discovery by identifying the $X(3872)$ state [2] (now referred to as $\chi_{c1}(3872)$). This discovery propelled exotic hadrons from speculative ideas to the forefront of research in hadron physics.

Currently, while there are known candidates for doubly-heavy tetraquarks and heavy pentaquarks, their interpretations remain contentious. The main challenge lies in understanding the quark structure of these states, such as whether they can be modeled as molecules, diquarks, hybrids [3], or within a super-symmetric light front holographic QCD framework [4, 5]. Some theorists even challenge the notion of bound-state interpretation and suggest that certain structures are artifacts of kinematic thresholds [6].

2 All-charm tetraquark candidates

In 2020, the LHCb Collaboration observed a structure in the $J/\psi J/\psi$ mass spectrum, named $X(6900)$ [8]. It was subsequently confirmed by the ATLAS [9] and CMS [7] experiments, generating significant interest as a potential all-charm tetraquark [10–28]. In addition, the CMS Collaboration reported the discovery of a new structure, $X(6600)$, with a local significance of 7.9 standard deviations, along with evidence for another new structure provisionally named $X(7100)$, exhibiting a local significance of 4.7 standard deviations.

The search in the CMS experiment focuses on the $J/\psi J/\psi$ mass spectrum from proton-proton collisions, with J/ψ reconstructed from $\mu^+\mu^-$ [7]. The observed $J/\psi J/\psi$ spectrum and the fits, both without and with consideration of interference effects, are illustrated in Fig. 1 and discussed in detail below.

*e-mail: xining.wang@cern.ch
**e-mail: yik@fnal.gov

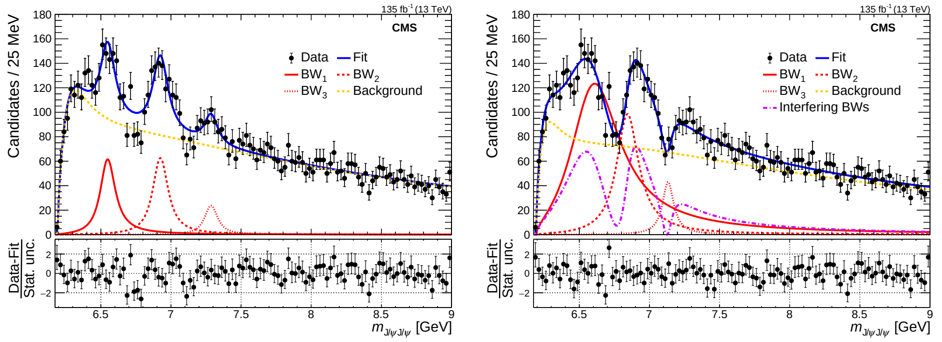

Figure 1. The fits to the $J/\psi J/\psi$ invariant mass spectrum in the CMS experiment [7]. The fit model incorporates three signal functions ($X(6600)[\mathrm{BW}_1]$, $X(6900)[\mathrm{BW}_2]$, and $X(7300)[\mathrm{BW}_3]$) along with a background model. The fitting outcomes are presented in the left plot without considering interference effect, and in the right plot with interference included.

The CMS detector is well-suited for studying exotic quarkonium states, thanks to its high-purity muon identification, excellent mass resolution for J/ψ, and precise vertex resolution. Moreover, specialized triggers based on muons are utilized to select quarkonium candidates. A more detailed description of the CMS detector can be found in Ref. [29].

3 Fit without interference

In order to extract resonance parameters, a fitting package has been designed to conduct the fit. The amplitude of the signal resonance is modeled by the relativistic Breit-Wigner function [30, 31]:

$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)}, \tag{1}$$

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{m_0}{m} \left(B'_L(q, q_0, d)\right)^2, \tag{2}$$

$$B'_L(q, q_0, d) = \frac{q^{-L} B_L(q, d)}{q_0^{-L} B_L(q_0, d)} = \left(\frac{q_0}{q}\right)^L \frac{B_L(q, d)}{B_L(q_0, d)}, \tag{3}$$

$$B_0(q, d) = 1, \tag{4}$$

$$B_1(q, d) = \sqrt{\frac{2z}{z+1}}, \tag{5}$$

$$B_2(q, d) = \sqrt{\frac{13z^2}{(z-3)^2 + 9z}}, \tag{6}$$

$$z = (|q|d)^2, z_0 = (|q_0|d)^2, \tag{7}$$

where q represents the magnitude of momentum of a daughter particle in the resonance rest frame, while L denotes the orbital angular momentum number between the two daughters, and the subscript 0 indicates the value at the peak mass. The default fit utilizes $L = 0$, but we explored other values of L as a part of systematic uncertainty studies. The term $B_L(q, d)$ corresponds to the Blatt-Weisskopf barrier factor [32, 33]. The parameter d is set to be 3

Table 1. The line-shape parameters of the states extracted from no-interference fits in the LHCb and CMS experiments. The first uncertainties are statistical while the second ones are systematic.

		$X(6600)$	$X(6900)$	$X(7100)$
LHCb	m [MeV]		$6905 \pm 11 \pm 7$	
	Γ [MeV]		$80 \pm 19 \pm 33$	
CMS	m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$

GeV^{-1} ($\sim$ 0.6 fm) as employed in Ref. [34]. We varied the value of d in the studies of the systematic uncertainty.

Simple summations of Breit-Wigner functions are employed to fit the $J/\psi J/\psi$ mass spectrum in both LHCb and CMS experiments, with the line-shape parameters summarized in Table 1. The fitting results are depicted in Fig. 1 (left) for CMS. However, these fits inadequately capture the $J/\psi J/\psi$ mass spectrum, as they fail to accurately describe the dips between the peaks.

4 Fit with interference

It's important to note that the dips in the $J/\psi J/\psi$ mass spectrum are observed in all LHCb, CMS and ATLAS experiments, which are poorly described by the no-interfering Breit-Wigner functions in LHCb and CMS experiments. Various ways to employ interference among fitting components were considered by the different experiments in order to explain the dips — but other explanations are conceivable.

In the CMS experiment, two dips are observed around 6750 MeV and 7150 MeV, and three structures are found in the $J/\psi J/\psi$ mass spectrum [35]. Interference models are developed to elucidate these dips. After investigating potential interference among the different components, the primary interference fit model is determined to involve the interference between three resonances $X(6600)$[BW1], $X(6900)$[BW2], and $X(7100)$[BW3], implemented with a term proportional to $\left|r_1 \exp(i\phi_1)\mathrm{BW}_1 + \mathrm{BW}_2 + r_3 \exp(i\phi_3)\mathrm{BW}_3\right|$, where $r_{1,3}$ and $\phi_{1,3}$ denote the relative magnitudes and phases of $\mathrm{BW}_{1,3}$ with respect to BW_2. The fit outcome is illustrated in Fig. 1 (right), demonstrating an improvement in the χ^2 probability in the signal region [6.2, 7.8] GeV to 65%, compared to only 9% in the no-interference fit. While the interference between pairs of components is also considered, their signal-region χ^2 probabilities remain below 30%, leading to their exclusion as the nominal interference fit model.

To account for the dip, the LHCb experiment incorporated interference between the non-resonant single parton scattering (NRSPS) background with the resonant production of an auxillary BW [8]. Analogous to LHCb approach, the ATLAS experiment constructed a model, referred as Model B, with a lower broad structure interfering with the NRSPS background. Another ATLAS model, denoted as Model A, introduced interference among the $X(6900)$ and two lower mass resonances.

The line-shape parameters of the states extracted from the interference fits in the three experiments are summarized in Table 2. Notably, the measured mass and width of $X(6900)$ are found to be comparable across all three experiments. The interference fit indicates that the unidentified J^{PC} quantum numbers of these states could be identical, suggesting they may originate from a coherent production process.

Table 2. The line-shape parameters of the states extracted from interference fit in LHCb, CMS and ATLAS experiments. Two kinds of interference models are considered in ATLAS experiment, named as Model A and Model B. The first uncertainties are statistical while the second ones are systematic.

			$X(6600)$	$X(6900)$	$X(7100)$
LHCb		m [MeV]		$6886 \pm 11 \pm 11$	
		Γ [MeV]		$168 \pm 33 \pm 69$	
CMS		m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
		Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}
ATLAS	Model A	m [MeV]		$6860 \pm 30^{+10}_{-20}$	
		Γ [MeV]		$110 \pm 50^{+20}_{-10}$	
	Model B	m [MeV]		$6910 \pm 10 \pm 10$	
		Γ [MeV]		$150 \pm 30 \pm 10$	

5 Comparison with some theoretical calculations

The measured masses in the CMS experiment from both no-interference and interference fits appear compatible with recent calculations of the $cc\bar{c}\bar{c}$ spectrum [28, 36, 37], the correctness of which will be determined by the preference of nature for no-interference or interference case. These three structures may be a family of radial excitations of the same J^{PC}, which is the case for both no-interference and interference masses, albeit for different theoretical models.

Many theoretical models predict the quantum numbers for $X(6900)$, including as a spin-0 state [28], or a spin-2 state [38]. The measurement of the spin and parity of these states is deemed crucial in distinguishing between competing theoretical models, enabling theorists to perform calculations based on accurate assumptions regarding the quantum numbers, finding out their position in the tetracharm spectroscopy, and better understanding the nature of exotic hadrons.

6 Summary

In summary, the analysis of the $J/\psi J/\psi$ invariant mass spectrum from proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, based on an integrated luminosity of 135 fb^{-1}, has revealed three distinct structures. These structures are effectively described by a model incorporating interference between three resonances. Among these findings, two new structures, provisionally designated as $X(6600)$ and $X(7100)$, have been identified with local statistical significances of 7.9 and 4.7 standard deviations, respectively. The observation of $X(6900)$ confirms the discovery by the LHCb experiment, which exhibited a local significance of 9.8 standard deviations measured by the CMS experiment.

References

[1] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. **8**, 214 (1964). 10.1016/S0031-9163(64)92001-3

[2] S.K. Choi et al. (Belle), Observation of a narrow charmonium-like state in exclusive $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays, Phys. Rev. Lett. **91**, 262001 (2003), `hep-ex/0309032`. 10.1103/PhysRevLett.91.262001

[3] N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C.P. Shen, C.E. Thomas, A. Vairo, C.Z. Yuan, The *XYZ* states: experimental and theoretical status and perspectives, Phys. Rept. **873**, 1 (2020), `1907.07583`. 10.1016/j.physrep.2020.05.001

[4] M. Nielsen, S.J. Brodsky, G.F. de Téramond, H.G. Dosch, F.S. Navarra, L. Zou, Supersymmetry in the Double-Heavy Hadronic Spectrum, Phys. Rev. D **98**, 034002 (2018), 1805.11567. 10.1103/PhysRevD.98.034002

[5] M. Nielsen, S.J. Brodsky, Hadronic superpartners from a superconformal and supersymmetric algebra, Phys. Rev. D **97**, 114001 (2018), 1802.09652. 10.1103/PhysRevD.97.114001

[6] A. Ali, L. Maiani, A.D. Polosa, Multiquark Hadrons (Cambridge University Press, Cambridge, 2019)

[7] A. Hayrapetyan et al. (CMS), New Structures in the J/ψJ/ψ Mass Spectrum in Proton-Proton Collisions at s=13 TeV, Phys. Rev. Lett. **132**, 111901 (2024), 2306.07164. 10.1103/PhysRevLett.132.111901

[8] R. Aaij et al. (LHCb), Observation of structure in the J/ψ -pair mass spectrum, Sci. Bull. **65**, 1983 (2020), 2006.16957. 10.1016/j.scib.2020.08.032

[9] G. Aad et al. (ATLAS), Observation of an Excess of Dicharmonium Events in the Four-Muon Final State with the ATLAS Detector, Phys. Rev. Lett. **131**, 151902 (2023), 2304.08962. 10.1103/PhysRevLett.131.151902

[10] J.Z. Wang, D.Y. Chen, X. Liu, T. Matsuki, Producing fully charm structures in the -pair invariant mass spectrum, Phys. Rev. D **103**, 071503 (2021), 2008.07430. 10.1103/PhysRevD.103.L071503

[11] A.V. Berezhnoy, A.V. Luchinsky, A.A. Novoselov, Heavy tetraquarks production at the LHC, Phys. Rev. D **86**, 034004 (2012), 1111.1867. 10.1103/PhysRevD.86.034004

[12] J. Wu, Y.R. Liu, K. Chen, X. Liu, S.L. Zhu, Heavy-flavored tetraquark states with the configuration, Phys. Rev. D **97**, 094015 (2018), 1605.01134. 10.1103/PhysRevD.97.094015

[13] H.X. Chen, W. Chen, X. Liu, S.L. Zhu, Strong decays of fully-charm tetraquarks into di-charmonia, Sci. Bull. **65**, 1994 (2020), 2006.16027. 10.1016/j.scib.2020.08.038

[14] Y. Bai, S. Lu, J. Osborne, Beauty-full tetraquarks, Phys. Lett. B **798**, 134930 (2019), 1612.00012. 10.1016/j.physletb.2019.134930

[15] Z.G. Wang, Analysis of the tetraquark states with QCD sum rules, Eur. Phys. J. C **77**, 432 (2017), 1701.04285. 10.1140/epjc/s10052-017-4997-0

[16] J.M. Richard, A. Valcarce, J. Vijande, String dynamics and metastability of all-heavy tetraquarks, Phys. Rev. D **95**, 054019 (2017), 1703.00783. 10.1103/PhysRevD.95.054019

[17] A. Esposito, A.D. Polosa, A di-bottomonium at the LHC?, Eur. Phys. J. C **78**, 782 (2018), 1807.06040. 10.1140/epjc/s10052-018-6269-z

[18] M. Karliner, S. Nussinov, J.L. Rosner, states: Masses, production, and decays, Phys. Rev. D **95**, 034011 (2017), 1611.00348. 10.1103/PhysRevD.95.034011

[19] M.A. Bedolla, J. Ferretti, C.D. Roberts, E. Santopinto, Spectrum of fully-heavy tetraquarks from a diquark+antidiquark perspective, Eur. Phys. J. C **80**, 1004 (2020), 1911.00960. 10.1140/epjc/s10052-020-08579-3

[20] M.N. Anwar, J. Ferretti, F.K. Guo, E. Santopinto, B.S. Zou, Spectroscopy and decays of the fully-heavy tetraquarks, Eur. Phys. J. C **78**, 647 (2018), 1710.02540. 10.1140/epjc/s10052-018-6073-9

[21] G. Yang, J. Ping, L. He, Q. Wang, Potential model prediction of fully-heavy tetraquarks $QQ\bar{Q}\bar{Q}$ $(Q = c, b)$ (2020), 2006.13756.

[22] X. Jin, Y. Xue, H. Huang, J. Ping, Full-heavy tetraquarks in constituent quark models, Eur. Phys. J. C **80**, 1083 (2020), 2006.13745. 10.1140/epjc/s10052-020-08650-z

[23] M.S. Liu, Q.F. Lü, X.H. Zhong, Q. Zhao, All-heavy tetraquarks, Phys. Rev. D **100**, 016006 (2019), 1901.02564. 10.1103/PhysRevD.100.016006

[24] M.S. liu, F.X. Liu, X.H. Zhong, Q. Zhao, Full-heavy tetraquark states and their evidences in the LHCb di-J/ψ spectrum (2020), 2006.11952.

[25] F.X. Liu, M.S. Liu, X.H. Zhong, Q. Zhao, Higher mass spectra of the fully-charmed and fully-bottom tetraquarks, Phys. Rev. D **104**, 116029 (2021), 2110.09052. 10.1103/PhysRevD.104.116029

[26] W. Chen, H.X. Chen, X. Liu, T.G. Steele, S.L. Zhu, Hunting for exotic doubly hidden-charm/bottom tetraquark states, Phys. Lett. B **773**, 247 (2017), 1605.01647. 10.1016/j.physletb.2017.08.034

[27] G.J. Wang, L. Meng, S.L. Zhu, Spectrum of the fully-heavy tetraquark state $QQ\bar{Q}'\bar{Q}'$, Phys. Rev. D **100**, 096013 (2019), 1907.05177. 10.1103/PhysRevD.100.096013

[28] R. Zhu, Fully-heavy tetraquark spectra and production at hadron colliders, Nucl. Phys. B **966**, 115393 (2021), 2010.09082. 10.1016/j.nuclphysb.2021.115393

[29] S. Chatrchyan et al. (CMS), The CMS Experiment at the CERN LHC, JINST **3**, S08004 (2008). 10.1088/1748-0221/3/08/S08004

[30] P. Zyla et al. (Particle Data Group), Review of Particle Physics, PTEP **2020**, 083C01 (2020). 10.1093/ptep/ptaa104

[31] A.R. Bohm, Y. Sato, Relativistic resonances: Their masses, widths, lifetimes, superposition, and causal evolution, Phys. Rev. D **71**, 085018 (2005), hep-ph/0412106. 10.1103/PhysRevD.71.085018

[32] F. Von Hippel, C. Quigg, Centrifugal-barrier effects in resonance partial decay widths, shapes, and production amplitudes, Phys. Rev. D **5**, 624 (1972). 10.1103/PhysRevD.5.624

[33] S.U. Chung, Helicity-coupling amplitudes in tensor formalism, Phys. Rev. D **48**, 1225 (1993), [Erratum: 10.1103/PhysRevD.56.4419]. 10.1103/PhysRevD.48.1225

[34] R. Aaij et al. (LHCb), Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays, Phys. Rev. Lett. **115**, 072001 (2015), 1507.03414. 10.1103/PhysRevLett.115.072001

[35] A.M. Sirunyan et al. (CMS), 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**, 135578 (2020), 2002.06393. 10.1016/j.physletb.2020.135578

[36] W.L. Wu, Y.K. Chen, L. Meng, S.L. Zhu, Benchmark calculations of fully heavy compact and molecular tetraquark states, Physical Review D **109** (2024). 10.1103/physrevd.109.054034

[37] R. Tiwari, D.P. Rathaud, A.K. Rai, Spectroscopy of all charm tetraquark states, Indian J. Phys. **97**, 943 (2023), 2108.04017. 10.1007/s12648-022-02427-8

[38] Y.Q. Ma, H.F. Zhang, Exploring the Di-J/ψ Resonances around 6.9 GeV Based on *ab initio* Perturbative QCD (2020), 2009.08376.