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Spectroscopy studies from the ATLAS and CMS experiments

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Recent spectroscopy results from the ATLAS and CMS experiments at the LHC are shedding new light on the hadronic spectrum. These include the first precise measurements of the excited vector mesons B^{*+}, B^{*0}, and B_s^{*0}, alongside the observation of a new family of tetraquark candidates in the di-J/ψ channel. CMS has further determined the spin-parity quantum numbers of this new family to be $J^{PC} = 2^{++}$. Both collaborations have extended these studies to other decay channels, such as $J/\psi + \psi(2S)$. Collectively, these results underscore the LHC's unparalleled capability to explore the spectrum of hadronic states, providing crucial insights into non-perturbative QCD and the quark model.

The 17th International Conference on Heavy Quarks and Leptons (HQL 2025)
15-19 September, 2025
Peking University, Beijing, China

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 ISSN 1824-8039 . Published by SISSA Medialab.

PoS(HQL2025)075

1. Introduction

The traditional quark model, proposed independently by Gell-Mann [1] and Zweig [2] in 1964, predicts the existence of baryons (three quarks) and mesons (quark-antiquark pairs). However, exotic states including tetraquarks and pentaquarks have been proposed in subsequent decades and only recently observed [3]. Until now, many light-heavy tetraquark candidates have been discovered, yet it is unclear whether these new states are truly exotic hadrons or bound states with certain internal structure such as molecules or diquarks [4–6].

The discovery of X(3872) in 2003 marked a turning point in exotic hadron physics [7]. Observed through its decay to $J/\psi\pi^+\pi^-$, this state presented a puzzle: while its properties were consistent with an excited charmonium ($c\bar{c}$) configuration, its mass differed substantially from theoretical expectations. The proximity of its mass to the $D^0\bar{D}^{*0}$ threshold suggested an alternative interpretation as a loosely bound molecular state of $D^0\bar{D}^{*0}$ ($[c\bar{u}][u\bar{c}]$) [8]. This breakthrough opened the door to numerous exotic hadron candidates [3, 9], such as the charmonium-like $Z(3930)^+$ observed in $J/\psi\pi^+$ decays [10, 11] and the pentaquark states [12].

The extensive data collected at the LHC during Run 2 (2016-2018) enabled the observation of the first full-heavy tetraquark candidates. The full-heavy (c, b) sector with enhanced quark mass compared to $\Lambda_{\rm QCD}$, offers clearer experimental signatures for exotic states. In the $J/\psi J/\psi$ decay channel ($J/\psi \to \mu^+\mu^-$), three tetracharm states have emerged: X(6600), X(6900), and X(7100). Among these, the X(6900) stands as the most firmly established, having been discovered by LHCb in 2020 [13] and subsequently confirmed by ATLAS [14] and CMS [15] experiments with global significances above 5σ [16, 17]. The X(6600), first reported by CMS in 2024 with nearly 8σ local significance [17], received supporting evidence from structures seen in the $J/\psi J/\psi$ mass spectrum by both ATLAS and LHCb [13, 16], though neither collaboration has formally claimed its discovery or given significance. The status of X(7100) was more ambiguous in these early studies.

The new full-heavy tetraquark family is further studied by CMS with larger data samples [18–20], and by ATLAS and CMS with additional decay channels [20, 21]. Especially, by angular distribution studies and hypothesis testing on the system, CMS determined that the quantum numbers $J^{PC} = 2^{++}$ are strongly preferred for these newly observed states $4c$ states [22]. Notably, in a separate study, CMS performed the first full reconstruction of vector B mesons B^{*+}, B^{*0}, and B_s^{*0}, measuring their mass differences with unprecedented precision [23]. The following sections will introduce these latest and featured results from the ATLAS and CMS experiments.

2. Observation of a new family of $4c$ exotic states in di-J/ψ channel

The search for exotic hadrons, particularly fully-charm tetraquarks, has been a focal point in particle physics. The ATLAS experiment at the LHC conducted a comprehensive search for potential $c\bar{c}c\bar{c}$ tetraquarks decaying into pairs of charmonium states in the four-muon final state [16]. Using proton-proton collision data at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 140 fb^{-1}, ATLAS studied the $J/\psi + J/\psi \to 4\mu$ decay channel. Backgrounds were estimated using a hybrid approach of Monte Carlo simulations and data-driven methods, including single parton scattering (SPS) and double parton scattering (DPS). Figure 1 shows the di-J/ψ mass spectrum with the ATLAS data, yielding significant excess of events (far exceeding 5σ) near the di-J/ψ mass

threshold. Similar to the earlier LHCb results [13], a broad structure at lower mass and a narrow resonance at 6.9 GeV are observed.

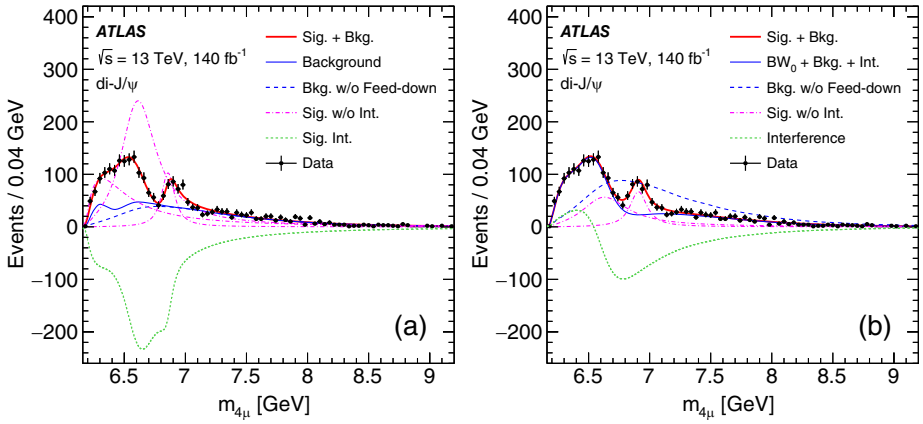

Figure 1: ATLAS: Using the LHC Run 2 data, two models A (left), *B* (right) on the invariant mass of X in di-J/ψ spectrum for the near-threshold $4c$ exotic states [16].

Using the full LHC Run 2 data, the CMS Collaboration observed a new resonance, X(6600) with mass $6638^{+43}_{-38}(\text{stat})^{+16}_{-31}(\text{syst})$ MeV, and confirmed the X(6900) with mass $6847^{+44}_{-28}(\text{stat})^{+48}_{-20}(\text{syst})$ MeV, both with local significances above 5σ (Figure 2 left). In addition, CMS also reported another new structure X(7100) at $7134^{+48}_{-25}(\text{stat})^{+41}_{-15}(\text{syst})$ MeV with a local significance at 4.7σ [17].

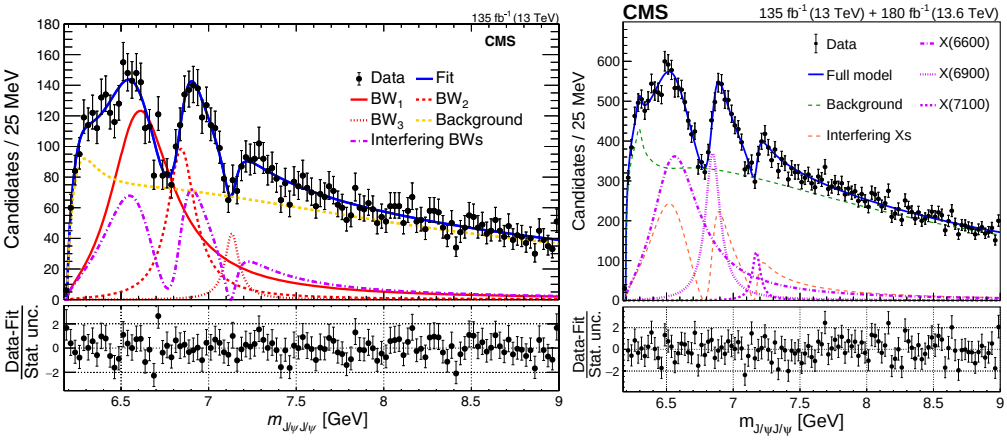

Figure 2: CMS: Observation of a new family X(6600), X(6900), and X(7100) of $4c$ exotic states in the di-J/ψ channel, on LHC Run 2 data, interference model (left) [17] and LHC Run 2 and Run 3 data, interference model (right) [19].

Combined with the most recent data in LHC Run 3 [19], achieving 3.6 times more di-J/ψ pairs than previous studies [17], CMS further studied the newly discovered family of $4c$ exotic states in di-J/ψ channel. The signals and interference patterns compared to solely Run 2 data, is more significant and clear (Figure 2 right). The local significance for each of the three states exceeds 5σ with CMS Run 3 data, firmly establishing a collection of three structures. The significances of the interference dips around 6750 MeV and 7150 MeV also exceed 5σ. Notably, the X(7100) structure

in CMS's observation achieves a local significance of 7.7σ in the di-J/ψ channel, marking the first time the 5σ level has been surpassed for this candidate in a single experimental analysis.

3. The $4c$ exotic states in $J/\psi + \psi(2S)$ channel

Extending the analysis on the new $4c$ exotic states to the $J/\psi + \psi(2S)$ decay channel provides crucial confirmation of the exotic nature of the observed structures. ATLAS reported an excess with LHC Run 2 data in this channel (Figure 3 left). CMS investigated the $J/\psi\psi(2S) \to \mu^+\mu^-\mu^+\mu^-$ final state using an integrated luminosity of 315 fb^{-1} from Run 2 and Run 3 data (Figure 3 right). The CMS fittings incorporating interfering X(6900) and X(7100) signals, along with NRSPS, DPS, and combinatorial backgrounds, confirmed the presence of these states in the $J/\psi\psi(2S)$ channel, as shown in Figure 3 right. In this channel, the X(6900) is observed for the first time at 8.1σ and the evidence of X(7100) is found at 4.3σ. The statistical significance of the X(6900)-X(7100) interference is 2.5σ. Very recently (after the HQL talk was given by the author), ATLAS provided updated results confirming the existence of X(6900) with two channels ($J/\psi + \psi(2S) \to 4\mu$ and $J/\psi + \psi(2S) \to 4\mu + 2\pi$) combined significance greater than 5σ [21].

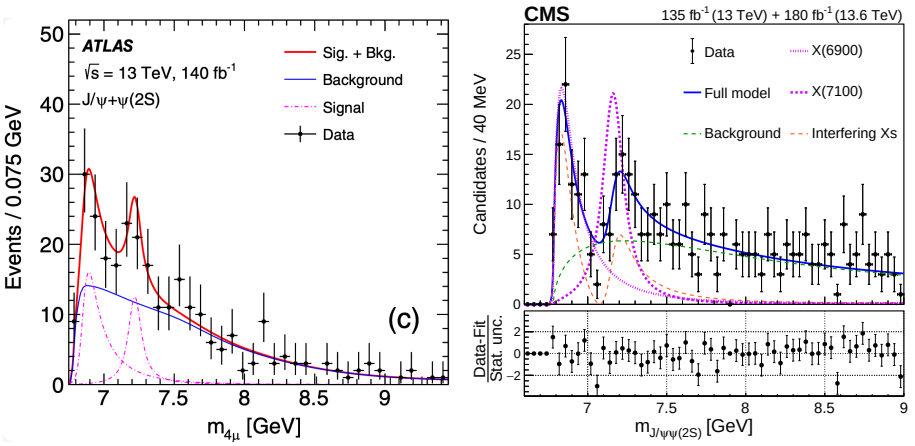

Figure 3: Left: ATLAS, using the LHC Run 2 data, the invariant mass of $J/\psi + \psi(2S)$ spectrum [16]. Right: CMS, using the LHC Run 2 and Run 3 data, the interference fit on the invariant mass of $J/\psi + \psi(2S)$ mass spectrum [19].

In summary, with the LHC Run 2 and Run 3 data, three $4c$ structures and two interference dips among them have been established with 5σ statistical benchmark in the $J/\psi J/\psi$ channel; X(6900) is also observed in the $J/\psi + \psi(2S) \to 4\mu$ channel. An overview of the masses, widths, and significances for $4c$ states reported by the LHCb [13], CMS [19, 20], and ATLAS [16] collaborations is in Table 1

4. Spin-Parity analysis of the $4c$ exotic states

The determination of the quantum numbers of the all-charm tetraquarks provides crucial insights into their internal structure [25–27]. Using data collected from 2016 to 2018 at $\sqrt{s} = 13$ TeV, corresponding to 135 fb^{-1}, CMS performed an angular analysis of the $X \to J/\psi J/\psi \to 4\mu$ decays, adapting techniques originally developed for Higgs boson studies [22].

Table 1: Summary of the masses m (MeV), widths Γ (MeV), and significances for $4c$ states reported by the LHCb, CMS, and ATLAS collaborations [24]. The uncertainties are statistical followed by systematic.

$T_{c\bar{c}c\bar{c}}$	LHCb	CMS		ATLAS	
	$J/\psi J/\psi$	$J/\psi J/\psi$	$J/\psi\psi(2S)$	$J/\psi J/\psi$	$J/\psi\psi(2S)$
$m_{X(6600)}$		$6593^{+15}_{-14} \pm 25$			
$\Gamma_{X(6600)}$	-	$446^{+66}_{-54} \pm 87$	-	-	-
significance		15.2σ [19]			
$m_{X(6900)}$	$6886 \pm 11 \pm 11$	$6847^{+10}_{-10} \pm 15$	$6876^{+46+110}_{-29-110}$	$6910 \pm 10 \pm 10$	$6960 \pm 50 \pm 30$
$\Gamma_{X(6900)}$	$168 \pm 33 \pm 69$	$135^{+16}_{-14} \pm 14$	$253^{+290+120}_{-100-120}$	$150 \pm 30 \pm 10$	$510 \pm 170^{+110}_{-100}$
significance	5.1σ [13]	16.7σ [19]	7.9σ [20]	$> 5.0\sigma$ [16]	4.3σ [16]
$m_{X(7100)}$		$7173^{+9}_{-10} \pm 13$	7169^{+26+74}_{-52-70}		$7220 \pm 30^{+10}_{-40}$
$\Gamma_{X(7100)}$	-	$73^{+18}_{-15} \pm 10$	$154^{+110+140}_{-82-160}$	-	$90 \pm 60^{+60}_{-50}$
significance		7.7σ [19]	4.0σ [20]		3.0σ [16]

The angular observables θ_1, θ_2, and Φ describe the directions of the decay muons relative to the J/ψ rest frames. These distributions are sensitive to the spin (J) and parity (P) of the X states. Various J^{PC} hypotheses were tested, including 0^-, 0^+, 1^-, 1^+, 2^-, and 2^+, using optimal discriminants D_{ij} derived from likelihood ratios between models. Figure 4 shows the summary of statistical tests against the 2^+_m model in the CMS study.

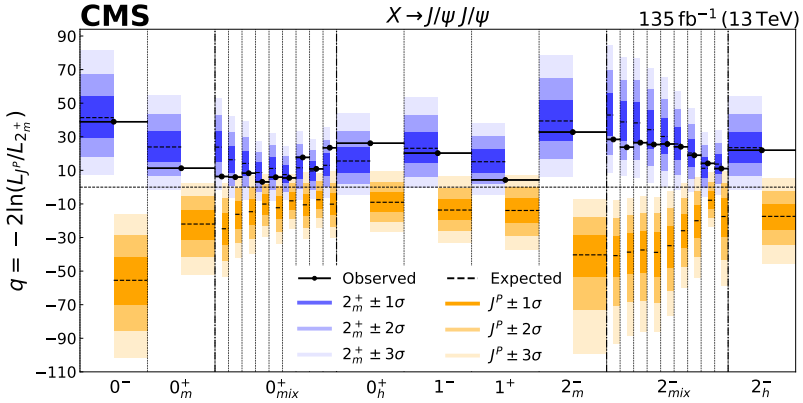

Figure 4: CMS: Distributions of the test statistic q are shown for various J^P_i hypotheses tested against the preferred 2^+_m model [22].

The analysis favored the 2^{++} assignment, with $P = +1$ and $C = +1$ determined from the decay final state. Specifically, $J = 0$ and $J = 1$ were excluded at 95% and 99% confidence levels, respectively, against the 2^{++} model. Higher spins ($J \geq 3$) cannot be ruled out but are less probable due to higher excitation energies.

The $J^{PC} = 2^{++}$ assignment supports a tightly bound tetraquark configuration with two spin-1 diquark pairs in a symmetric spatial state ($L = 0$), consistent with the observed interference patterns and radial Regge trajectory of the X family [22].

5. The first exclusive reconstruction of B^{*+}, B^{*0}, and B_s^{*0} mesons

CMS performed the first exclusive reconstruction of the vector B meson states B^{*+}, B^{*0}, and B_s^{*0} using 140 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV from 2016–2018 [23], as shown in Fig. 5. Low-energy photons from $B^* \to B\gamma$ decays were reconstructed through their conversions into e^+e^- pairs in the detector material, overcoming previous experimental limitations.

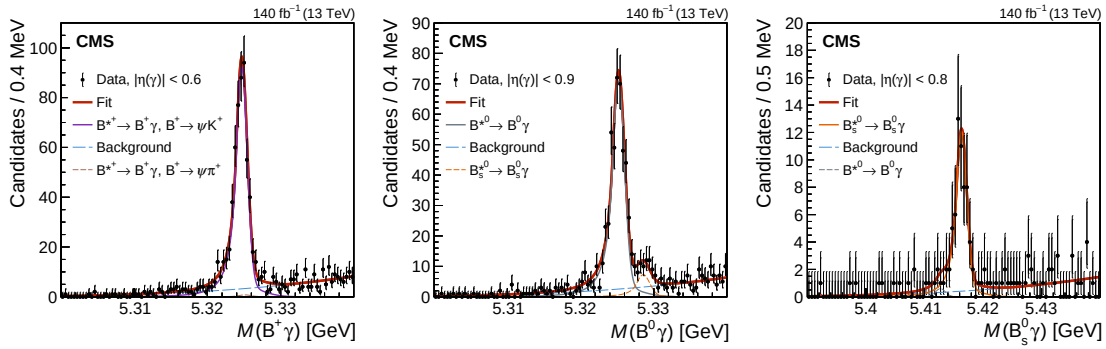

Figure 5: The measured distributions of the $B^+\gamma$, $B^0\gamma$, and $B_s^0\gamma$ invariant mass in the lowest $|\eta(\gamma)|$ range [23].

Ground-state B mesons were reconstructed in decays $B^+ \to \psi K^+$, $B^0 \to \psi K^{*0}$, and $B_s^0 \to \psi\phi$, where ψ denotes either J/ψ or $\psi(2S)$, decaying to $\mu^+\mu^-$. A simultaneous fit to the $B\gamma$ invariant mass distributions in multiple pseudorapidity ranges yielded the mass differences [23]:

$$\Delta m(B^{*+}) = m(B^{*+}) - m(B^+) = 45.277 \pm 0.039 \pm 0.027 \text{ MeV} \quad (1)$$

$$\Delta m(B^{*0}) = m(B^{*0}) - m(B^0) = 45.471 \pm 0.056 \pm 0.028 \text{ MeV} \quad (2)$$

$$\Delta m(B_s^{*0}) = m(B_s^{*0}) - m(B_s^0) = 49.407 \pm 0.132 \pm 0.041 \text{ MeV} \quad (3)$$

These measured mass splittings, combined with precisely known ground-state B meson masses from the Particle Data Group [28], enable the determination of differences between the vector B meson masses. Specifically, under the assumption of uncorrelated uncertainties, the following values are used: $m(B^0) - m(B^+) = 0.31 \pm 0.05$ MeV and $m(B_s^0) - \frac{1}{2}[m(B^0) + m(B^+)] = 87.37 \pm 0.12$ MeV. This yields the vector mass differences, such as $m(B^{*0}) - m(B^{*+})$, which agrees with the only previous measurement (from P-wave B_s^0 mesons [29]) but with approximately threefold improved precision. The other vector mass differences are reported here for the first time.

These results enhance our understanding of heavy meson spectroscopy by providing high-precision benchmarks for lattice QCD calculations and heavy quark effective theory [30–32].

6. Summary

The latest spectroscopy studies at the LHC, particularly by the ATLAS and CMS experiments, have ushered in a new era for the exploration of exotic hadrons and heavy meson structure. The robust observation of a new family of fully-charmed tetraquark states, and the first exclusive reconstruction of vector B mesons with unprecedented mass precision, not only confirm the existence of exotic multi-quark states at the LHC, but also provide crucial benchmarks that challenge and refine our theoretical understanding of QCD, marking a significant step forward in hadron spectroscopy.

References

[1] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. **8**, 214 (1964).

[2] G. Zweig, An SU(3) model for strong interaction symmetry and its breaking. Version 2, CERN Report No. 8182/TH.412, 1964, doi:10.17181/CERN-TH-412.

[3] A. Ali, L. Maiani, and A. D. Polosa, Multiquark hadrons, Cambridge University Press, Cambridge, England, 2019.

[4] N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C.-P. Shen, C. E. Thomas, A. Vairo, and C.-Z. Yuan, The XYZ states: Experimental and theoretical status and perspectives, Phys. Rep. **873**, 1 (2020).

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

[6] J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, S. C. C. Ting, S. L. Wu, and Y. Y. Lee, Experimental observation of a heavy particle J, Phys. Rev. Lett. **33**, 1404 (1974).

[7] S. K. Choi *et al.* (Belle Collaboration), Observation of a Narrow Charmonium-like State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays, Phys. Rev. Lett. **91**, 262001 (2003).

[8] F. E. Close and P. R. Page, The $D^{*0}\bar{D}^{*0}$ threshold resonance, Phys. Lett. B **578**, 119 (2004).

[9] H.-X. Chen *et al.*, An updated review of the new hadron states, Rept. Prog. Phys. **86**, 026201 (2023).

[10] BESIII Collaboration, Observation of a charged charmonium-like structure in $e^{+}e^{-} \to \pi^{+}\pi^{-}J/\psi$ at $\sqrt{s} = 4.26$ GeV, Phys. Rev. Lett. **110**, 252001 (2013).

[11] Belle Collaboration, Study of $e^{+}e^{-} \to \pi^{+}\pi^{-}J/\psi$ and observation of a charged charmonium-like state at Belle, Phys. Rev. Lett. **110**, 252002 (2013).

[12] LHCb Collaboration, 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).

[13] LHCb Collaboration, Observation of structure in the J/ψ-pair mass spectrum, Sci. Bull. **65**, 1983 (2020).

[14] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST **3**, S08003 (2008).

[15] CMS Collaboration, The CMS Experiment at the CERN LHC, JINST **3**, S08004 (2008).

[16] ATLAS Collaboration, Observation of an excess of dicharmonium events in the four-muon final state with the ATLAS detector, Phys. Rev. Lett. **131**, 151902 (2023).

[17] CMS Collaboration, New structures in the $J/\psi J/\psi$ mass spectrum in proton-proton collisions at $\sqrt{s}$ = 13 TeV, Phys. Rev. Lett. **132**, 111901 (2024).

[18] CMS Collaboration, Development of the CMS detector for the CERN LHC Run 3, JINST **19**, P05064 (2024).

[19] CMS Collaboration, Observation of a family of all-charm tetraquark candidates at the LHC, Report No. CMS-PAS-BPH-24-003 (2025), url:https://cds.cern.ch/record/2929472.

[20] CMS Collaboration, Observation of X(6900) and evidence of X(7100) in the $\psi(2S)J\psi$ to 4μ mass spectrum in pp collisions at CMS, Report No. CMS-PAS-BPH-22-004 (2025), url:https://cds.cern.ch/record/2929529.

[21] ATLAS Collaboration, Observation of structures in the $J/\psi + \psi(2S)$ mass spectrum with the ATLAS detector, Report No. CERN-EP-2025-182 (2025), arXiv:2509.13101.

[22] CMS Collaboration, Determination of the spin and parity of all-charm tetraquarks, Nature **648**, 58–63 (2025).

[23] CMS Collaboration, First exclusive reconstruction of the B^{*+}, B^{*0}, and B_s^{*0} mesons and precise measurement of their masses, Report No. CERN-EP-2025-162 (2025), arXiv:2508.05820.

[24] Y. Zhao *et al.*, Experimental Review of the Quarkonium Physics at the LHC, Symmetry **17(9)**, 1521 (2025).

[25] C. Becchi *et al.*, A study of $cc\bar{c}\bar{c}$ tetraquark decays in 4 muons and in $D^{(*)}\bar{D}^{(*)}$ at LHC, Phys. Lett. B **811**, 135952 (2020).

[26] W. Wu *et al.*, Benchmark calculations of fully heavy compact and molecular tetraquark states, Phys. Rev. D **109**, 054034 (2024).

[27] H. Zhang *et al.*, Perturbative QCD evidence for spin-2 particles in the di-J/ψ resonances, Sci. Bull. **70**, 1915 (2025).

[28] Particle Data Group, S. Navas *et al.*, Review of particle physics, Phys. Rev. D **110**, 030001 (2024).

[29] CMS Collaboration, Studies of $B_{s2}^*(5840)^0$ and $B_{s1}(5830)^0$ mesons including the observation of the $B_{s2}^*(5840)^0 \to B^0K_S^0$ decay in proton-proton collisions at $\sqrt{s}$ = 8 TeV, Eur. Phys. J. C **78**, 939 (2018).

[30] J. L. Rosner and M. B. Wise, Meson masses from SU(3) and heavy quark symmetry, Phys. Rev. D **47**, 343 (1993).

[31] J. L. Goity and C. P. Jayalath, Strong and electromagnetic mass splittings in heavy mesons, Phys. Lett. B **650**, 22 (2007).

[32] M. Karliner and J. L. Rosner, Status of isospin splittings in mesons and baryons, Phys. Rev. D **100**, 073006 (2019).