Experimental observation of all-charm tetraquark states at high energy colliders

Kai Yi (Nanjing Normal University)

Henan Normal University, Nov. 9, 2025

Outline

- Exotic Hadrons
- $J/\psi J/\psi$ mass spectra status before 2025
- Open questions
- $J/\psi J/\psi$ update and ψ(2S)J/ψ
- $J/\psi\phi$ mass spectrum
- Remaining open questions & Summary

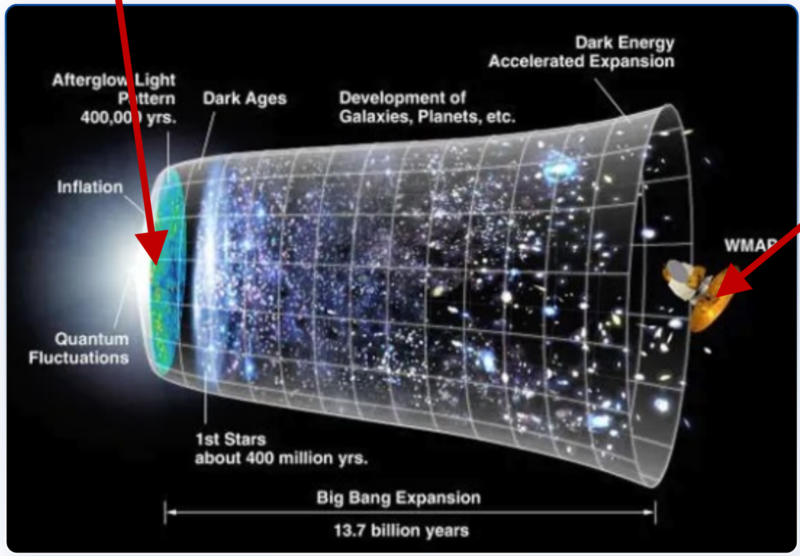
Top 10 fundamental scientific questions—AI overview

- 01 What is the universe made of?
- 02 How did life begin?
- 03 What is consciousness?
- 04 Are we alone in the universe?
- 05 What is the fate of the universe?
- 06 Why is there more matter than antimatter?
- 07 How do quantum mechanics and general relativity unify?
- 08 What is the cause of gravity?
- 09 How do we achieve nuclear fusion?
- 10 How much can human life be extended?

5 out of 10 related to physics science

Top concern–our universe!

Early universe: quarks and gluons confined to nucleons, shrinking to occupy only about 10^{-45} of the observable universe's volume



Later on distant planet(s): off in the expanding universe, some sentient beings heard the sounds of this particular tree falling in the woods and approximated it by the QCD sector of the Standard Model

From inside nuclei, the quarks speak to the outside world through the rest of the Standard Model --they got discovered!

Quarks, Gluons, and QCD Success

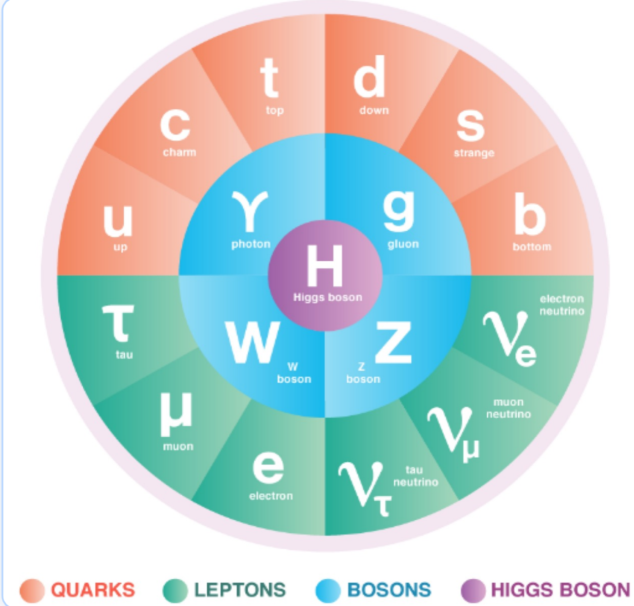
- **Seclusion driven by nonabelian phase invariance:**

Six flavors, three colors each | **Bound by gluonic excitations**

- **This is called Quantum Chromodynamics (QCD)**

- **Experimentally tested at high energies; asymptotic freedom**
  →Nobel Prize 2004

- **Success of Conventional Hadrons at low energies: non-perturbative quark model (confinement)**
  →Nobel Prize 1969

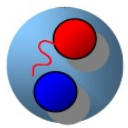


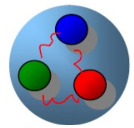
1969

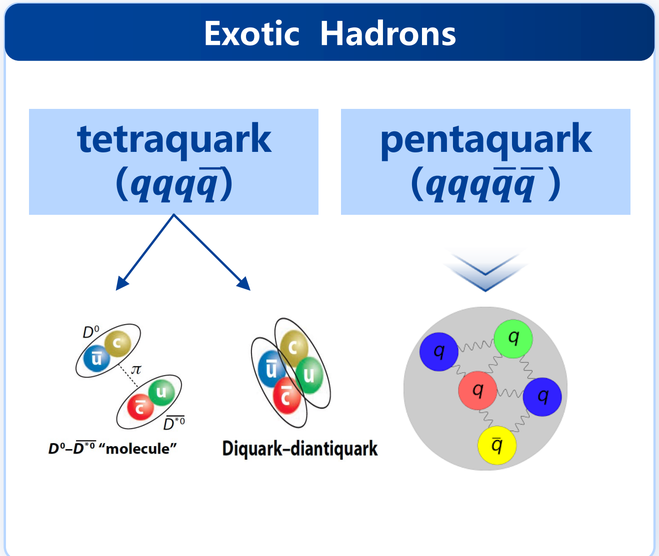
2004

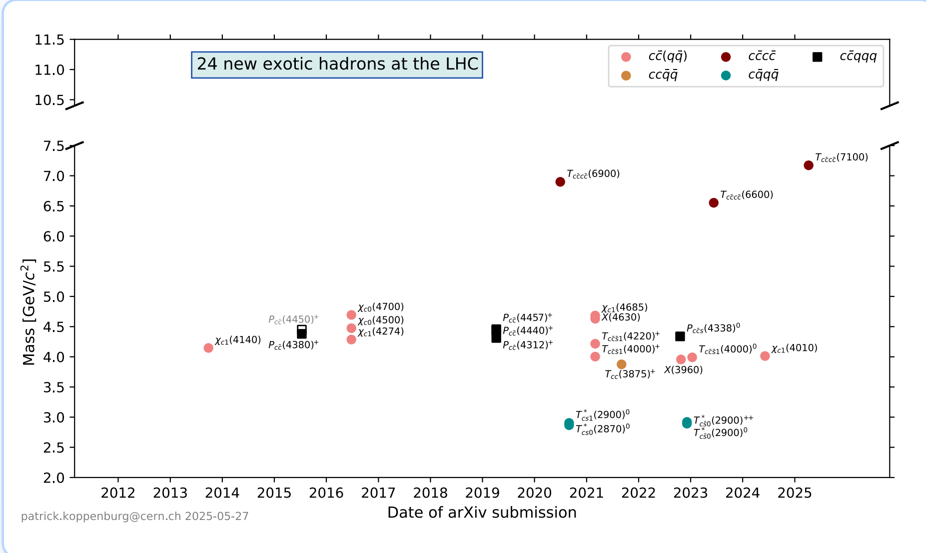
Conventional Hadrons

meson ($q\bar{q}$)	baryon (qqq)



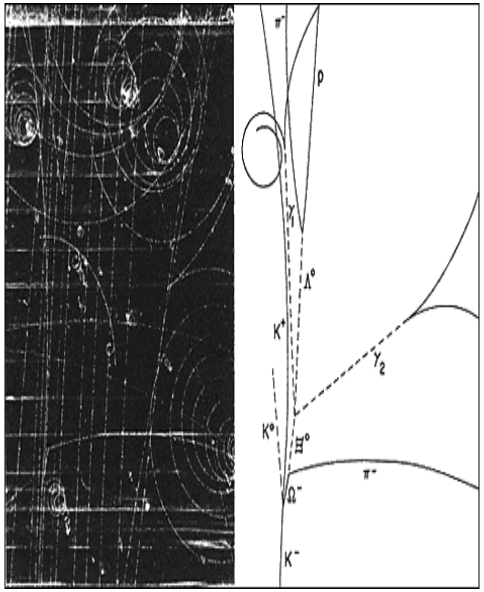






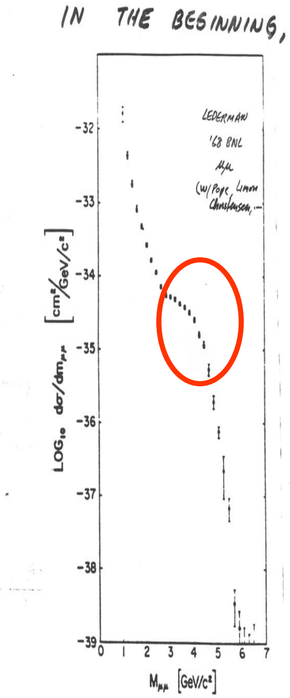
- **Exotic Hadrons (Non-Conventional)-- no definitive conclusion yet – currently a hot topic**
- **X(3872)** (2003), kicked off a boom in **(heavy-flavor) exotic hadron,** dozens of XYZ found.
- Nature of XYZ remain a mystery, looking for **experimental input**
- **Fully-heavy exotic hadrons**, promising and more accessible for theoretical exploration.

Ω^- (sss) discovery

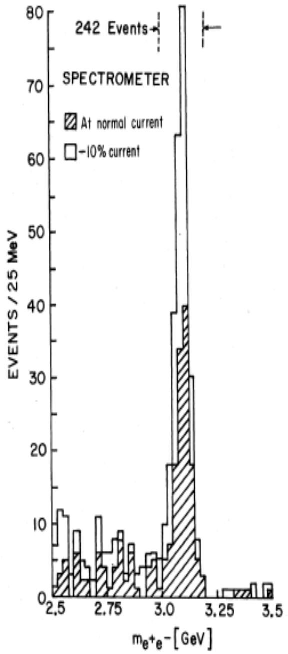


BNL-1964

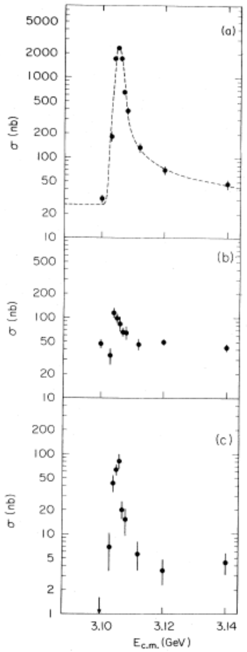
J/ψ (cc) discovery



BNL-1968

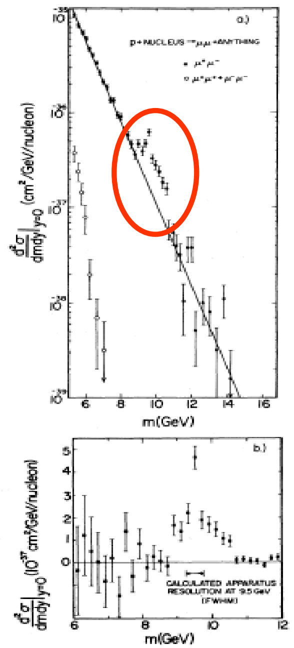


BNL-1974



SLAC-1974

ϒ (bb) discovery

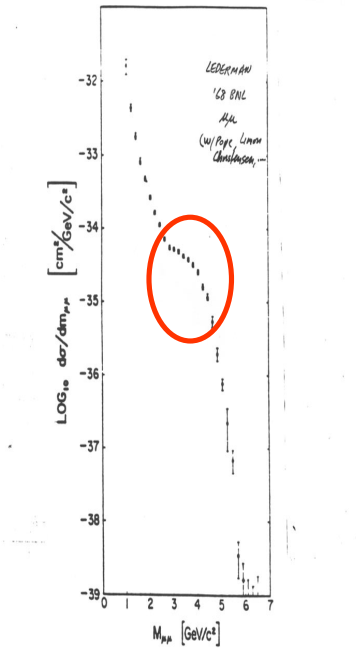


FNAL-1977

- **Standard model important milestones!**
- **The discovery of X(3872) started the hot discussion of exotic hadrons**

Oops-Leon

IN THE BEGINNING,......



BNL-1968

Volume 56B, number 5 PHYSICS LETTERS 26 May 1975

OBSERVATION OF HIGH MASS ELECTRON-POSITRON PAIRS PRODUCED IN PROTON-PROTON COLLISIONS AT THE CERN ISR

F.W. BÜSSER[1], L. CAMILLERI, L. Di LELLA, B.G. POPE and A.M. SMITH
CERN, Geneva, Switzerland

B.J. BLUMENFELD and S.N. WHITE
Columbia University[2], N.Y., USA

A.F. ROTHENBERG, S.L. SEGLER and M.J. TANNENBAUM
The Rockefeller University[3], N.Y., USA

M. BANNER, J.B. CHÈZE, J.L. HAMEL, H. KASHA[4], J.P. PANSART, G. SMADJA, J. TEIGER, H. ZACCONE and A. ZYLBERSTEJN
CEN, Saclay, France

Received 22 April 1975

In an experiment performed at the CERN Intersecting Storage Rings (ISR), 11 e^+e^- pairs of high invariant mass value (> 2.5 GeV/c^2) have been observed. Of these events, 9 can be interpreted as arising from the reaction $p + p \to J(3.1)$ + anything. The cross-section for this reaction is estimated and compared with the result obtained at lower centre-of-mass energies.

Volume 56B, number 5 PHYSICS LI

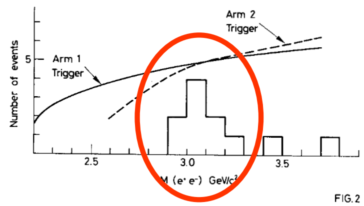


FIG.2

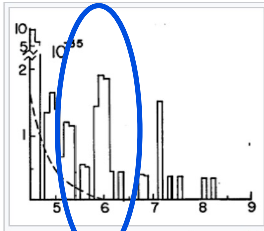
Fig. 2. Invariant mass distribution for the observed e^+e^- pairs. The curves represent the shapes of the acceptance, as a function of the e^+e^- invariant mass value, for the Arm 1 and Arm 2 triggers, respectively.

cluded that the 11 e^+e^- pairs are genuine and correspond to the occurrence of reaction (1).

The invariant mass of each pair was calculated using the momenta of the particles as measured in the magnetic spectrometers. The distribution of invariant

CERN ISR-1975

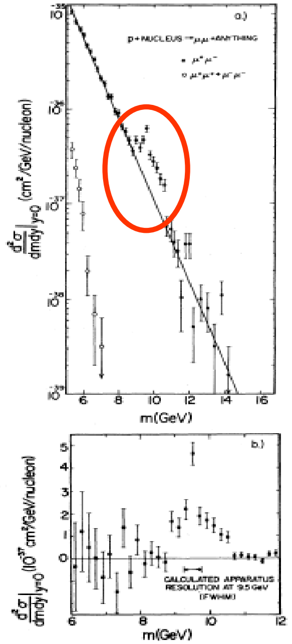
Oops-Leon is the name given by particle physicists to what was thought to be a new subatomic particle "discovered" at Fermilab in 1976. The E288 experiment team, a group of physicists led by Leon Lederman who worked on the E288 particle detector, announced that a particle with a mass of about 6.0 GeV, which decayed into an electron and a positron, was being produced by the Fermilab particle accelerator.[1] The particle's initial name was the greek letter Upsilon (ϒ). After taking further data, the group discovered that this particle did not actually exist, and the "discovery" was named "Oops-Leon" as a pun on the original name and the first name of the E288 collaboration leader.[2]



A plot counting the rate of production of electron–positron pairs as a function of invariant mass (in GeV). The apparent peak around 6 GeV was initially identified as a new particle,[1] but named **Oops-Leon** when it turned out not to exist.

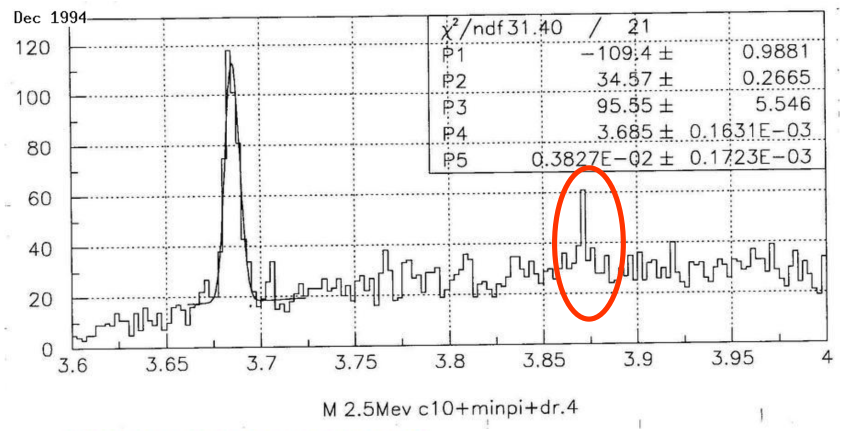
The original publication was based on an apparent peak (resonance) in a histogram of the invariant mass of electron-positron pairs produced by protons colliding with a stationary beryllium target, implying the existence of a particle with a mass of 6 GeV which was being produced and decaying into two leptons. An analysis showed that there was "less than one chance in fifty" that the apparent resonance was simply the result of a coincidence.[1] Subsequent data collected by the same experiment in 1977 revealed that the resonance had been such a coincidence after all.[2] However, a new resonance at 9.5 GeV was discovered using the same basic logic and greater statistical certainty,[3] and the name was reused (see Upsilon particle).

FNAL-1976

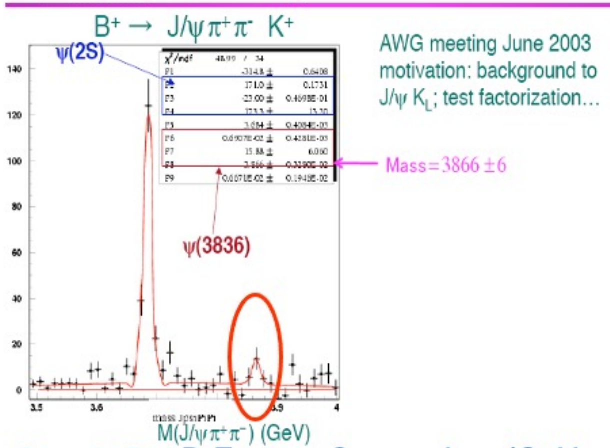


FNAL-1977

CDF internal, 1994



BaBar internal, 2003

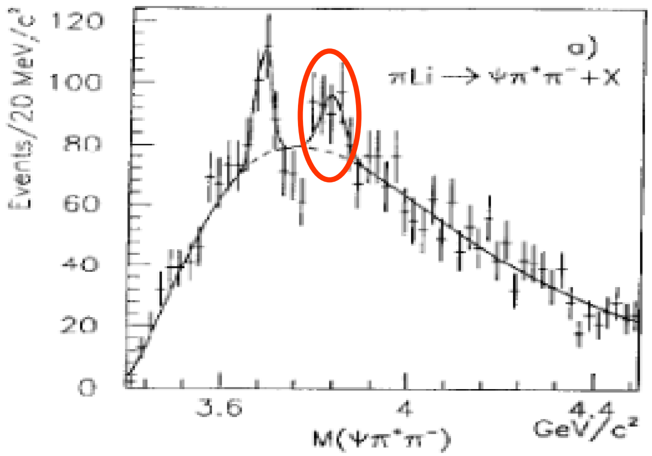


From BaBar B-Factory Symposium (C. Hearty)
http://www-conf.slac.stanford.edu/b-factory-symposium/talks.asp

E705, PRD 50, 4258 (1994)

E705 saw ψ(3836) (2^{--})in 1994, 3.836±0.013 GeV

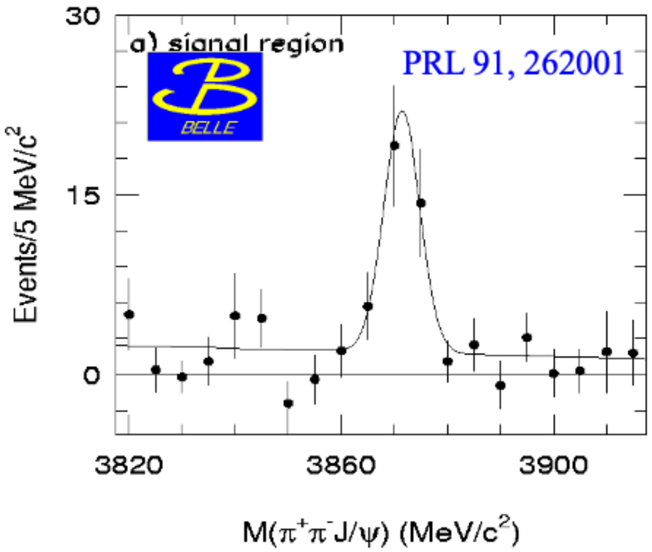
PRL 115 011803, PRL 111 032001



CDF saw a hint in 1994, unpublished
BaBar saw a hint in 2003, unpublished

Both CDF and Babar spotted hints of X(3872) before its discovery!

X(3872) (Belle)--2003



2017 Laureates

2017 Korean Ho-Am Science Prize

UH Physics emeritus professor wins Panofsky Prize

University of Hawai'i at Mānoa

Contact: Thomas Browder, (808) 956-2936
Professor , Physics and Astronomy
Pui Lam, (808) 956-2988
Chair, Physics and Astronomy

Posted: Oct 8, 2015

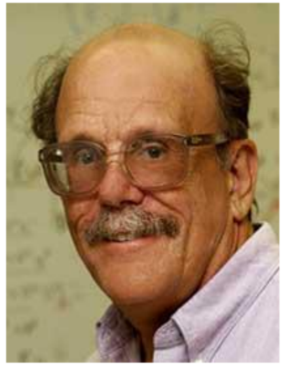
The American Physical Society (APS) has awarded the 2016 W.K.H. Panofsky Prize in Experimental Particle Physics to Stephen Olsen, Fumihiko Takasaki, Jonathan Dorfan and David Hitlin. This is APS' highest award for experimental particle physics. It recognizes the B factory experiments (Belle at KEK and BaBar at SLAC), which observed large CP violation (matter-antimatter asymmetry) in the B meson sector in 2001, and also provided experimental confirmation of the Kobayashi-Maskawa hypothesis for the origin of CP violation, which was later recognized by the 2008 Nobel Prize in Physics.

Steve Olsen was a UHM faculty from 1992-2009. He led the high energy physics group at UHM for many years and was one of the founders of the Belle experiment at KEK in Tsukuba, Japan. In addition to his work on CP violation (matter-antimatter asymmetries), he discovered a series of unexpected new particles referred to as the X, Y and Z mesons. These have revolutionized the field of hadron spectroscopy in particle physics.

Olsen was also one of the first western scientists to do collaborative research in particle physics in Japan and China.

Upon retirement from UHM, he moved to Seoul National University and is at now working on the AMORE double-beta decay underground experiment at the Center for Undergound Physics
in Daejeon, Korea.

For more information, visit: http://www.phys.hawaii.edu/

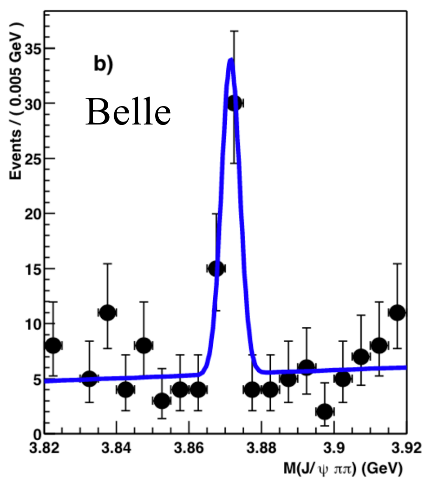


Steve Olsen

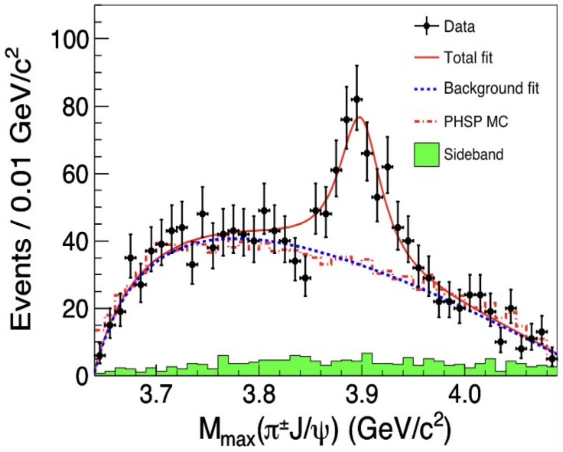
"…The X(3872) was discovered by Dr. Sookyung Choi and Dr. Stephen Olsen with their colleagues in the Belle experiment among the final states of the decay of B mesons. The X(3872) was confirmed by seven other experimental groups thereafter and is the first example of a new type of XYZ meson and the most well-established state among them. …"

Tetraquark candidates with heavy-flavor

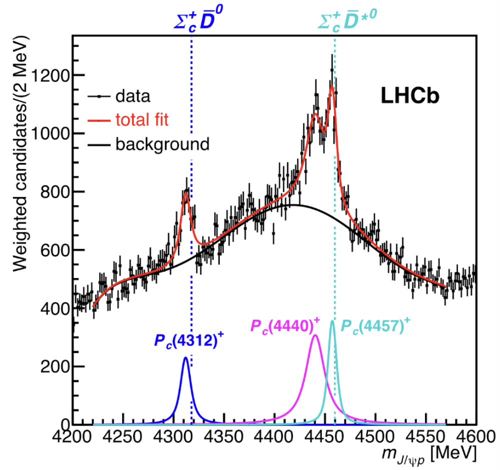
X(3872) [$uc\bar{u}\bar{c}$]



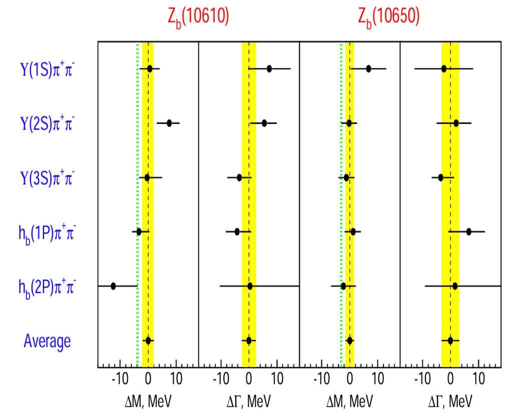
$Z_c^+(3900)$



pentaquark



bottomonium-like

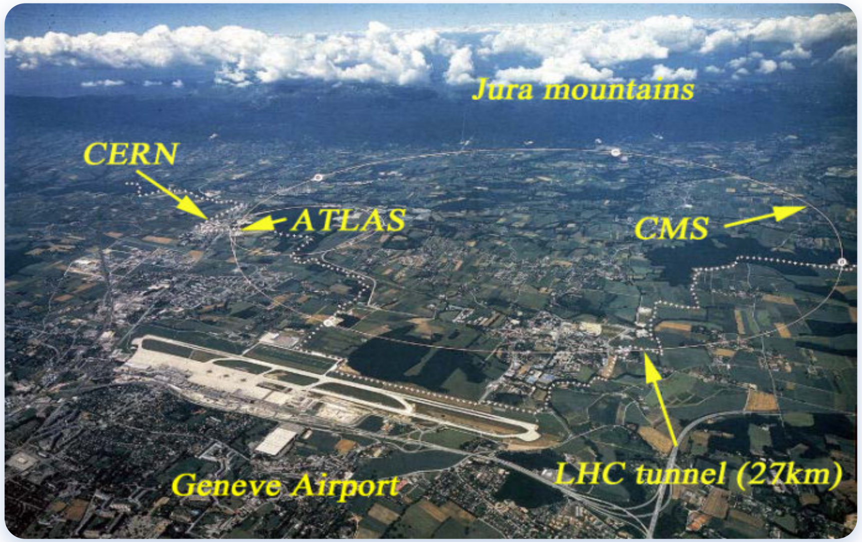


- **Light exotics** likely exist, but the light-meson sector is too messy for clear identification.
- **Heavy-flavor exotics**: larger quark mass relative to Λ_{QCD} => theoretical treatments more reliable
- The discovery of **X(3872), Zc⁺(3900)**, **Pentaquarks**
- **Z_b^+(10610)** and **Z_b^+(10650)** two charged bottomonium-like resonances

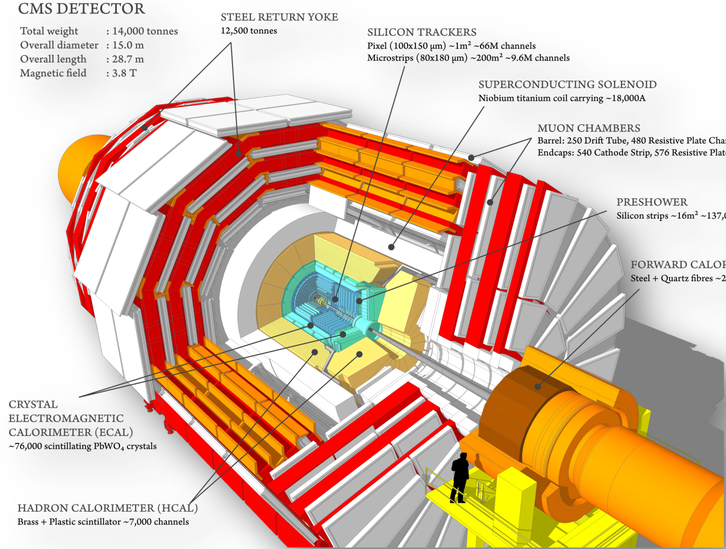
- Move to all-heavy exotics

The LHC and CMS Detector

The Large Hadron Collider



CMS Detector



The Large Hadron Collider (LHC)

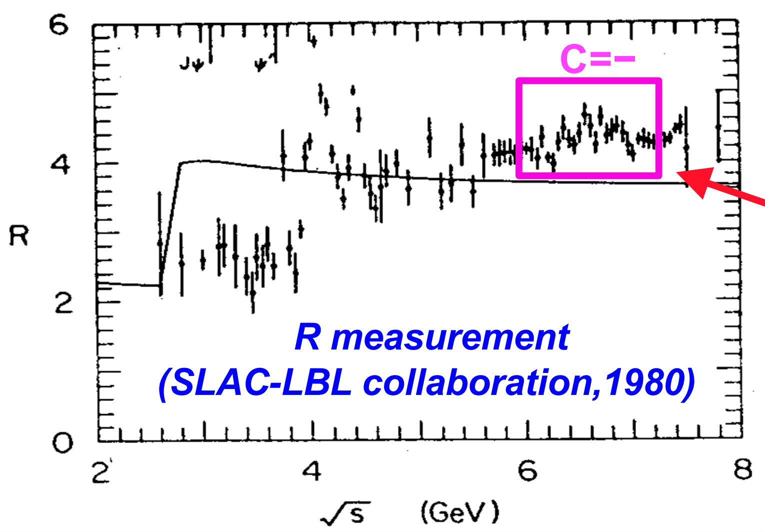
- Smash protons moving **at 99.999999% c**
- 27 km circular tunnel, located 50–175 m underground
- Currently operates **at 13.6 TeV** center-of-mass energy

The Compact Muon Solenoid (CMS) Detector

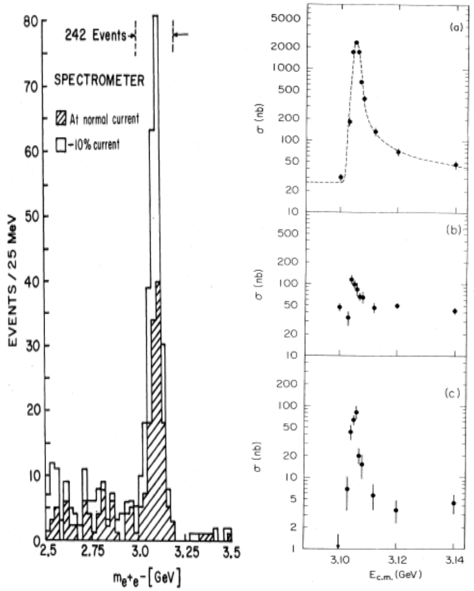
- A **general-purpose** detector
- 14,000 tones, 15 m high × 21 m long
- Built in cylindrical layers (inside → outside):

  Tracker, ECAL, HCAL, Solenoid Magnet, Muon System

SLAC-LBL collaboration,1980



2X mass



- **First mention of 4c states at 6.2 GeV (1975):**

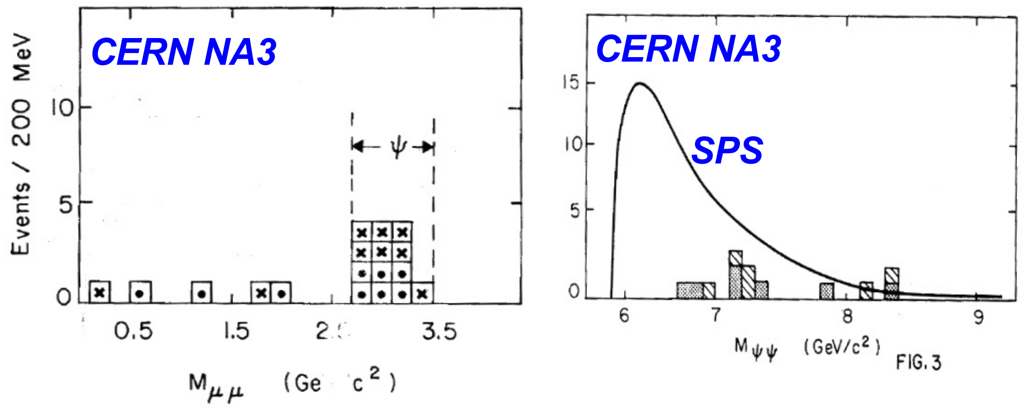
  Y. Iwasaki, Prog. of Theo. Phys. Vol. 54, No. 2

- **Inspired by 1980 R curve, first calculation of 4c states (1981):**

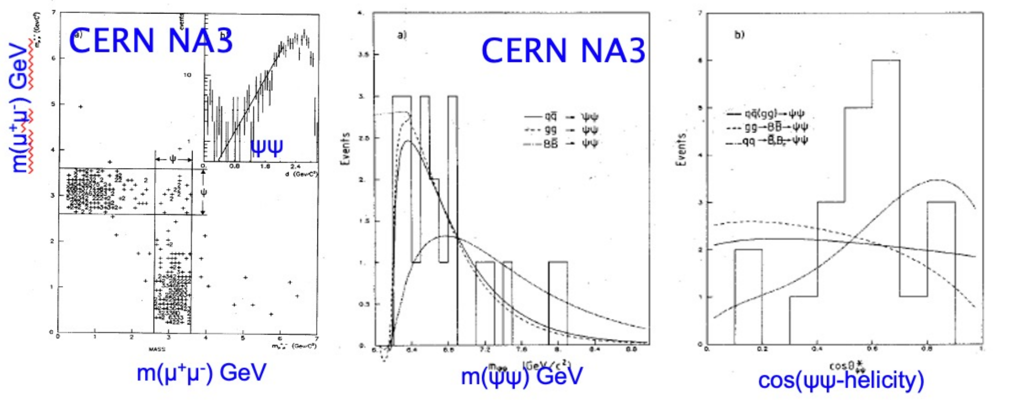
  K.-T. Chao, Z. Phys. C 7 (1981) 317

J/ψJ/ψ events—first evidence (1982)

PLB114 (1982) 457



PLB158 (1985) 85

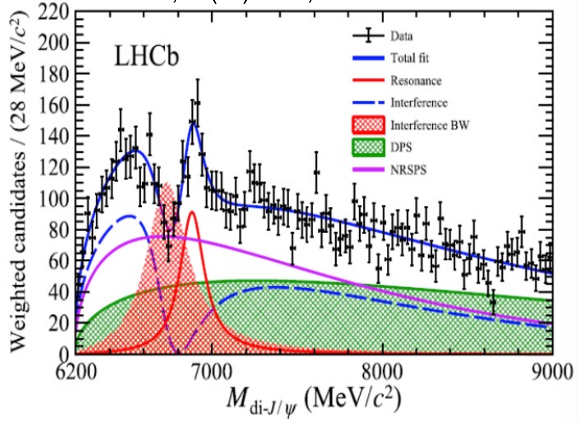


- **Lack of statistics in early experiments**
- **Unclear for any conclusion**
- **Game changer for LHC experiments**

Status of of all-charm tetraquark

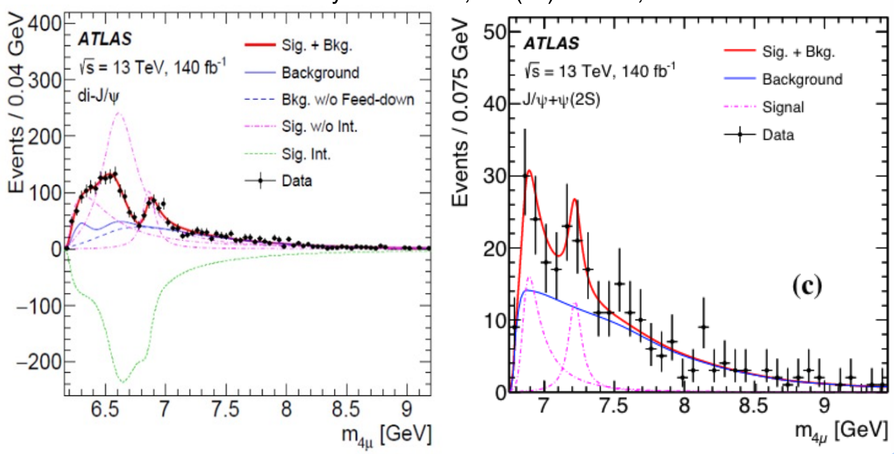
LHCb

Sci. Bull., 65(23):1983, 2020



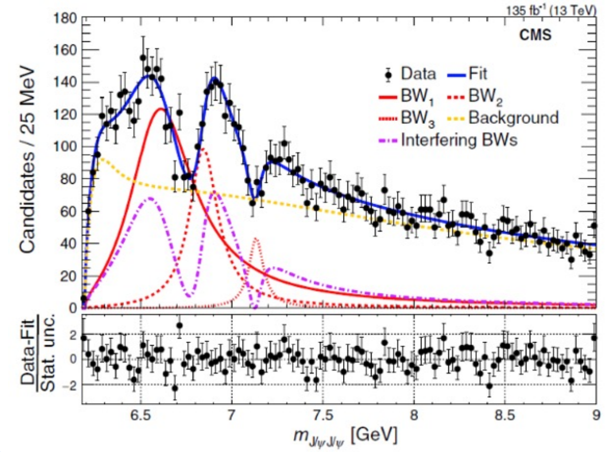
ATLAS

Phys. Rev. Lett., 131(15):151902, 2023



CMS

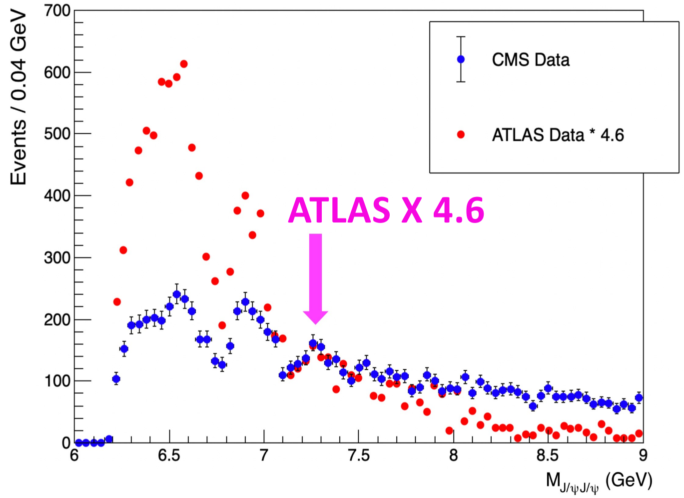
Phys. Rev. Lett., 132(11):111901, 2024



- **All exp observe X(6900)**
- **CMS first observed X(6600) & evidence of X(7100)**
- **All exp use interference, but in different ways**
- **All exp see a threshold excess, NOT explained! Classified as background**
- **Many open questions**

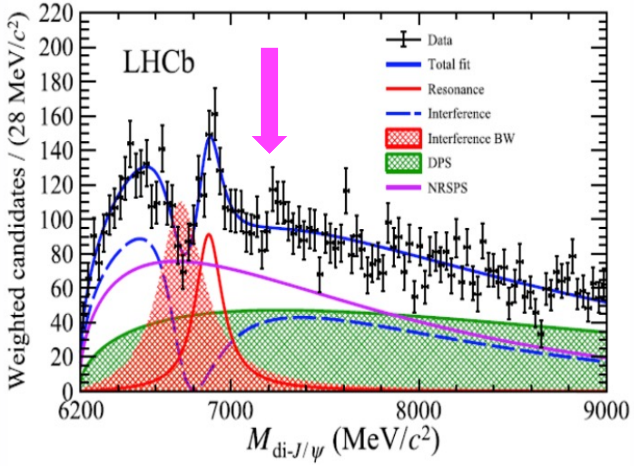
Open question 1—X(7100) existence?

CMS v.s. ATLAS * 4.6



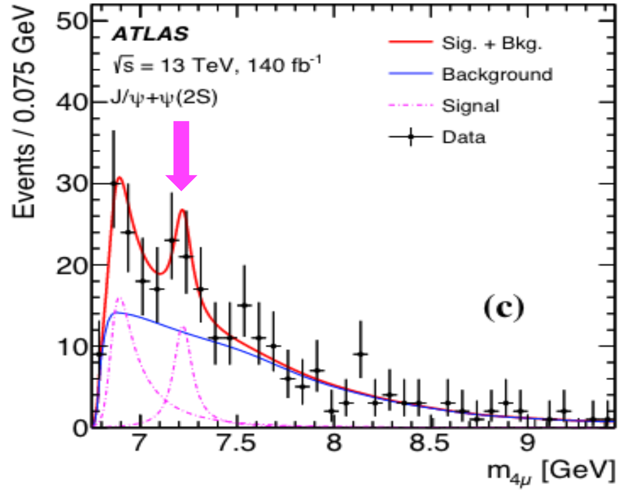
LHCb

Sci. Bull., 65(23):1983, 2020



ATLAS

Phys. Rev. Lett., 131(15):151902, 2023

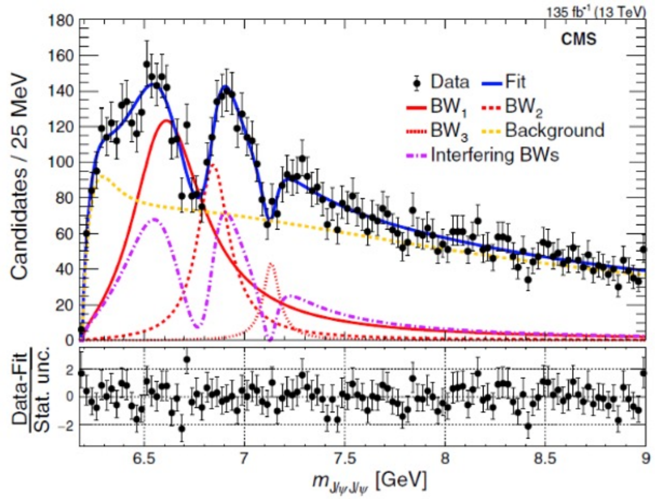


- **CMS has evidence (4.7sigma) for X(7100)**
- **ATLAS and LHCb have hints of it**
- **Is it real?**

Open question 2—X(6600) a resonance?

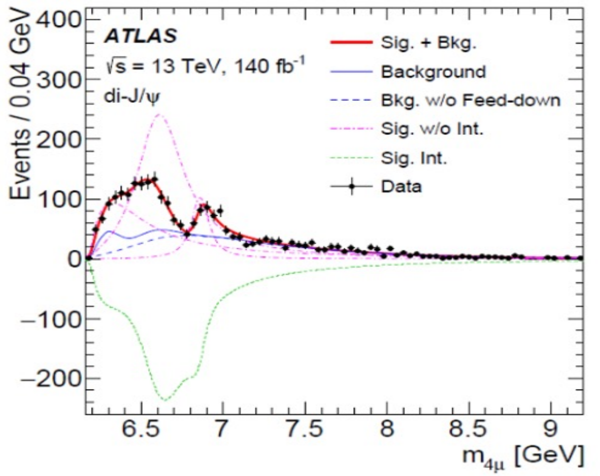
CMS

Phys. Rev. Lett., 132(11):111901, 2024



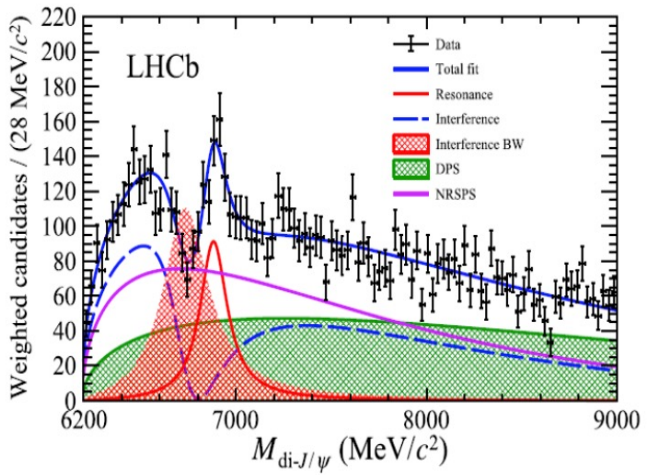
ATLAS

Phys. Rev. Lett., 131(15):151902, 2023



LHCb

Sci. Bull., 65(23):1983, 2020

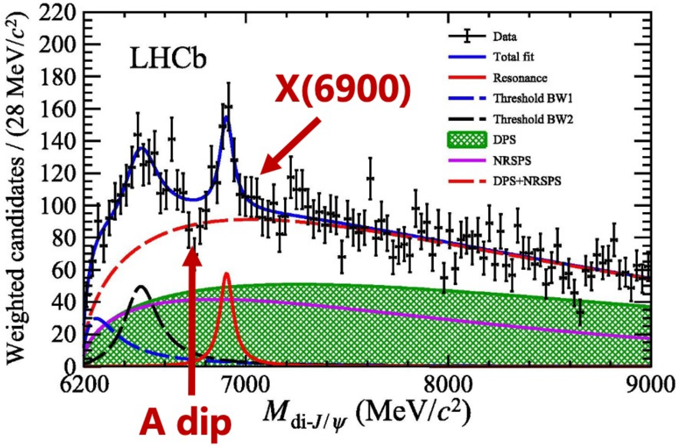


- **All spectroscopy show excess near threshold**
- **Only CMS claimed X(6600)**
- **Is it real resonance?**

Open question 3—Interference?

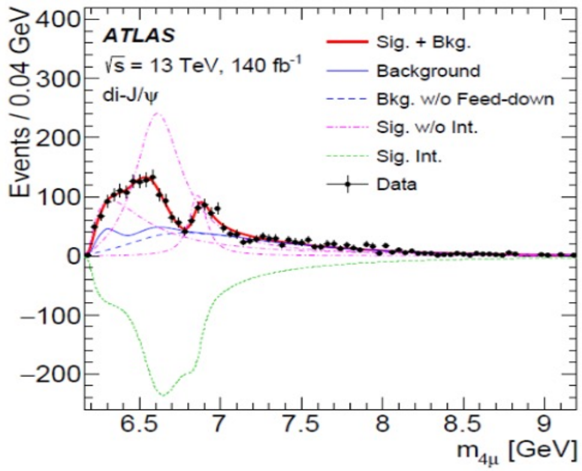
LHCb Model I

Sci. Bull., 65(23):1983, 2020



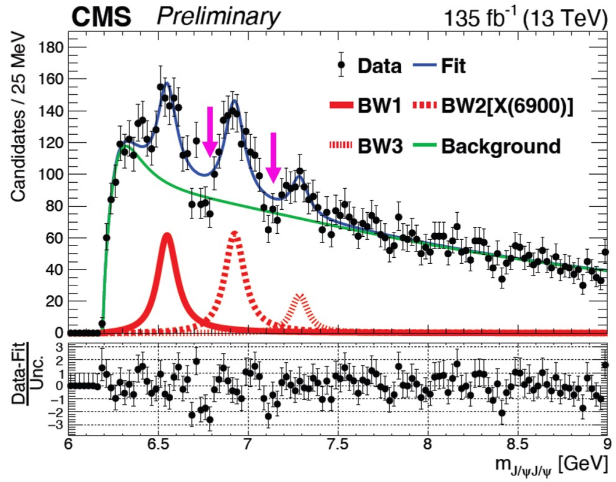
ATLAS

Phys. Rev. Lett., 131(15):151902, 2023



CMS

Phys. Rev. Lett., 132(11):111901, 2024

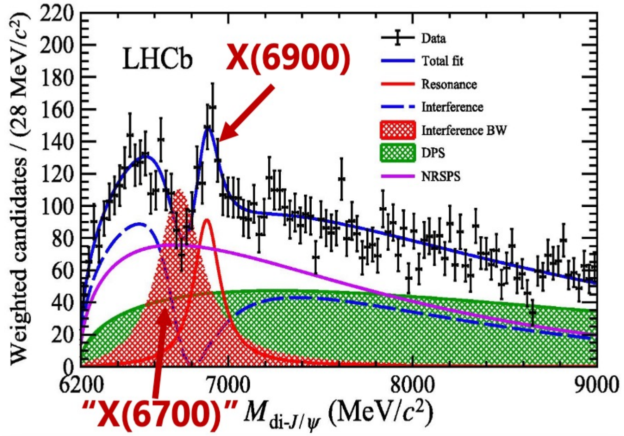


- All spectroscopy show dip(s)
- Introducing interference improves the data description
- Is the interference real?

Open question 4—How to interfere?

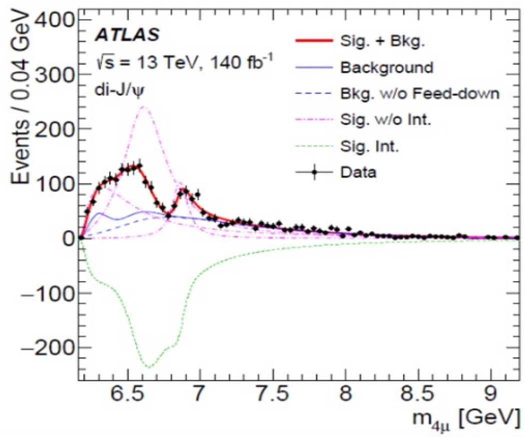
LHCb Model II

Sci. Bull., 65(23):1983, 2020



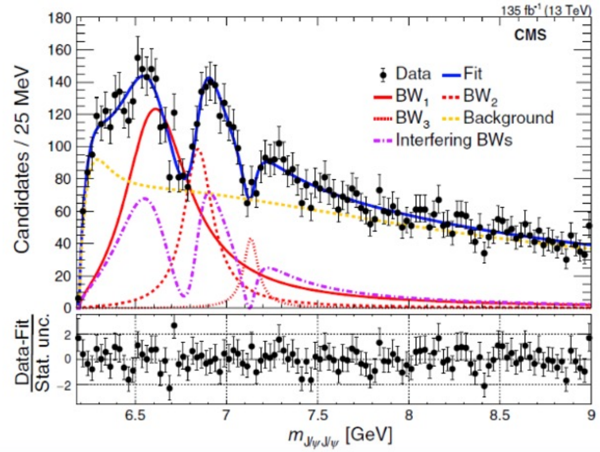
ATLAS

Phys. Rev. Lett., 131(15):151902, 2023

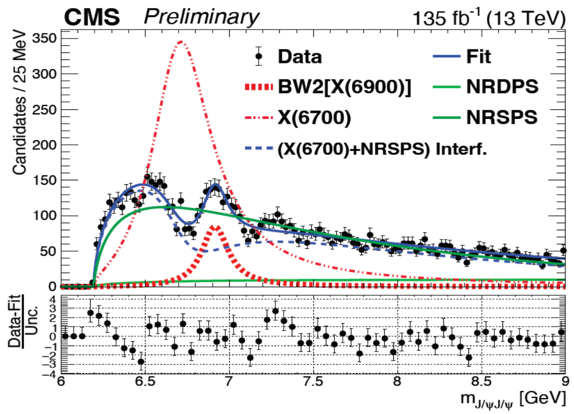


CMS

Phys. Rev. Lett., 132(11):111901, 2024



CMS using LHCb Model II



- **All exp use interference, but in different ways**

  LHCb: extra BW interfere with SPS, *X(6900) NOT interfering!*

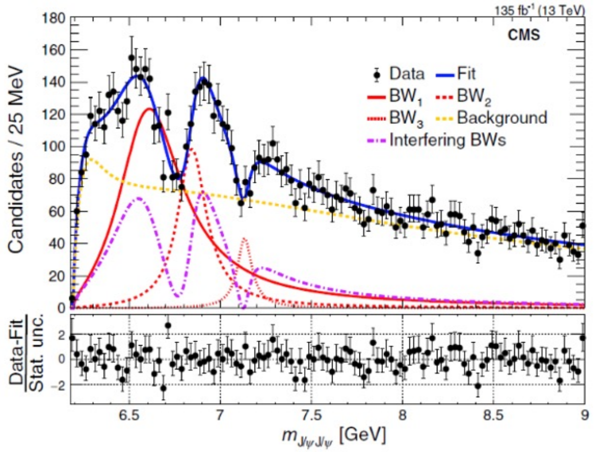
  ATLAS and CMS: different multi-resonance interference

- **How does the interference actually work?**

Mass splitting and Regge plot

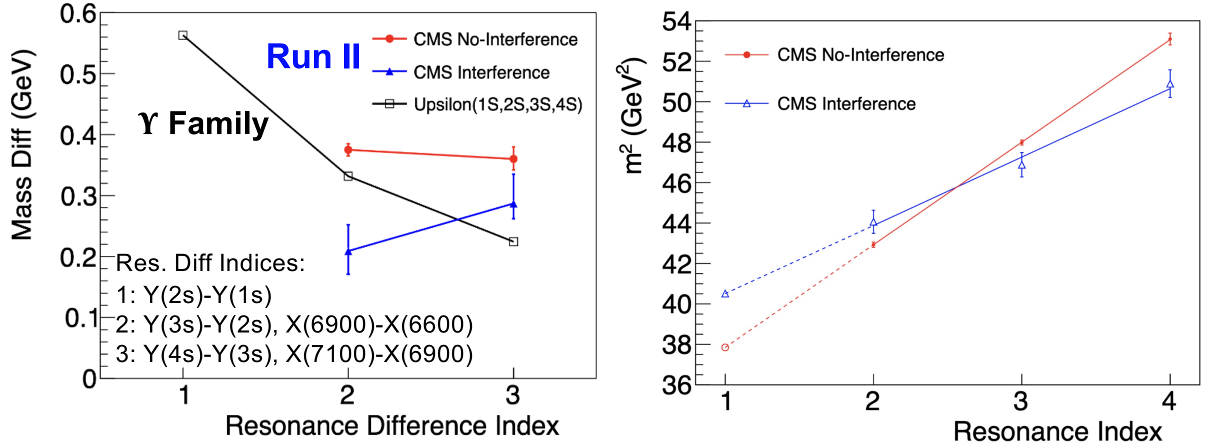
CMS Run 2 mass spectrum

Phys. Rev. Lett., 132(11):111901, 2024



CMS Run 2 Regge plot

Chinese Phys. Lett. 41 111201



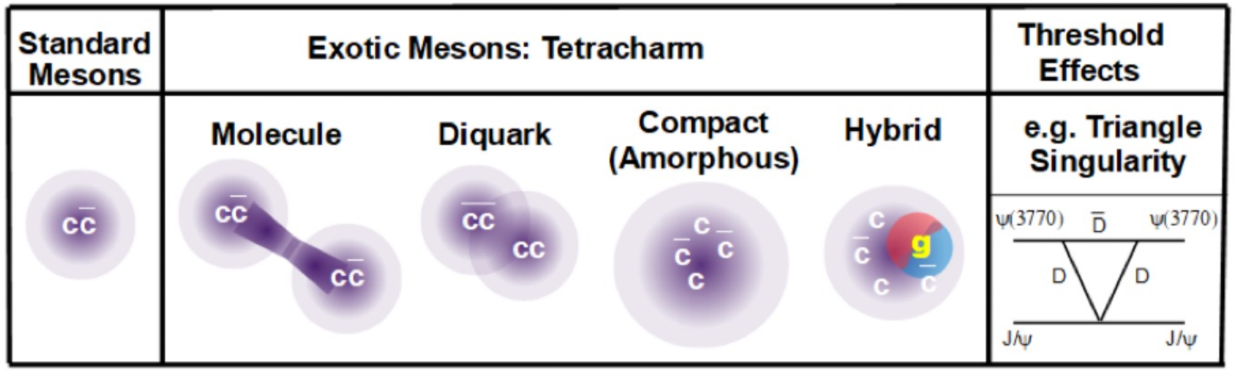
Cornell Model: $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r + \ldots$

- Interference imply same J^{PC} quantum numbers
- > 200 MeV mass splittings ==> Radial excitations ?
- A **family** of all-charm tetraquarks ?

Based on CMS result only

Open question 5—What is their nature?

Idealized models of potential all-charm structures



- Found **repulsive between two charmoniums** in Lattice QCD: 2411.11533 [hep-lat]

- **Models of potential quark configurations for J/ψJ/ψ mesons**

  Meson-meson “molecule” ($c\bar{c}$- $c\bar{c}$)

  Pair of diquarks (cc-$\bar{c}\bar{c}$)

  Hybrid with a valence gluon

  Peaks as artifact of di-charmonia production thresholds

  Properties such as JPC, cross section, new decay channels if resonance?

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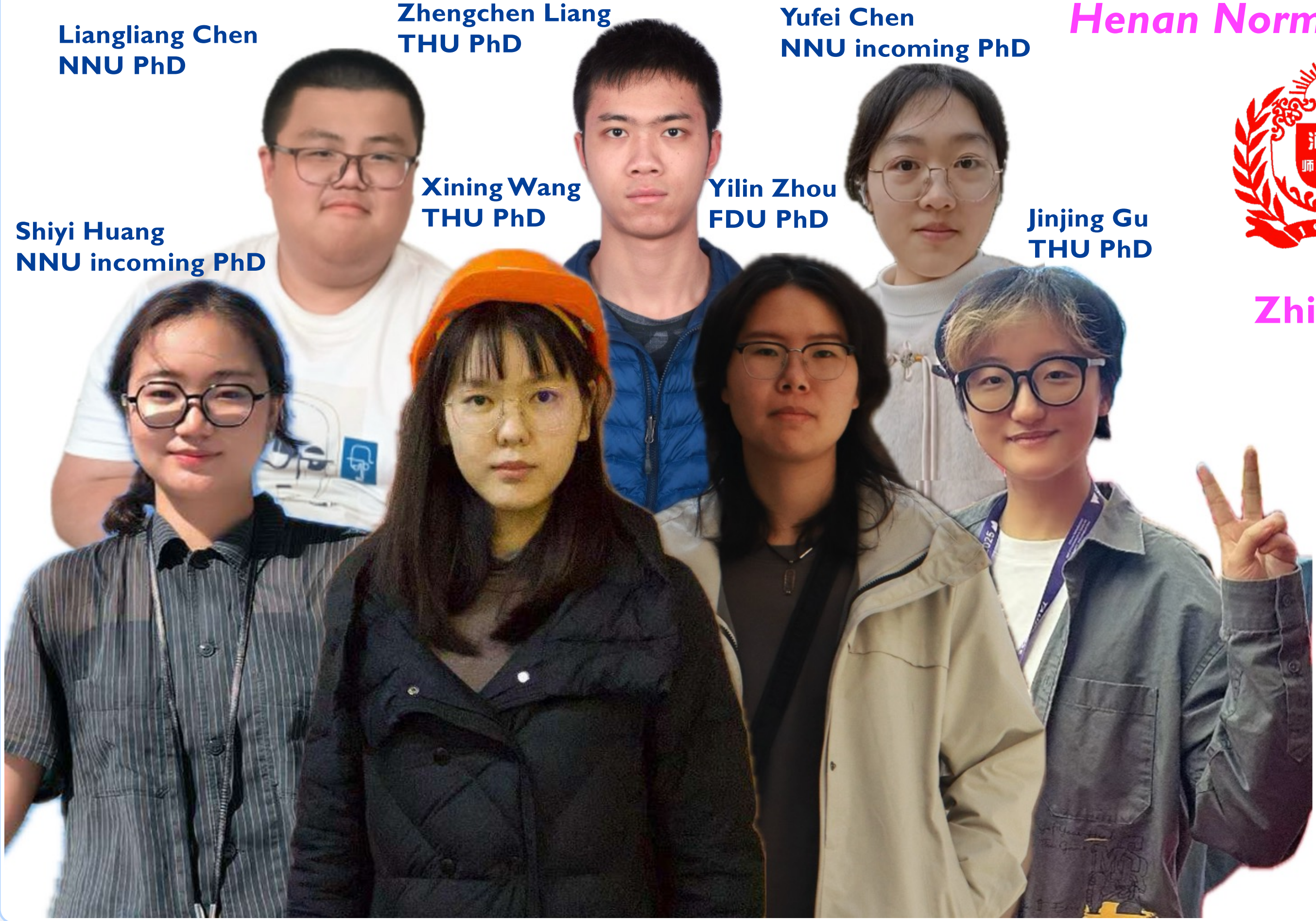


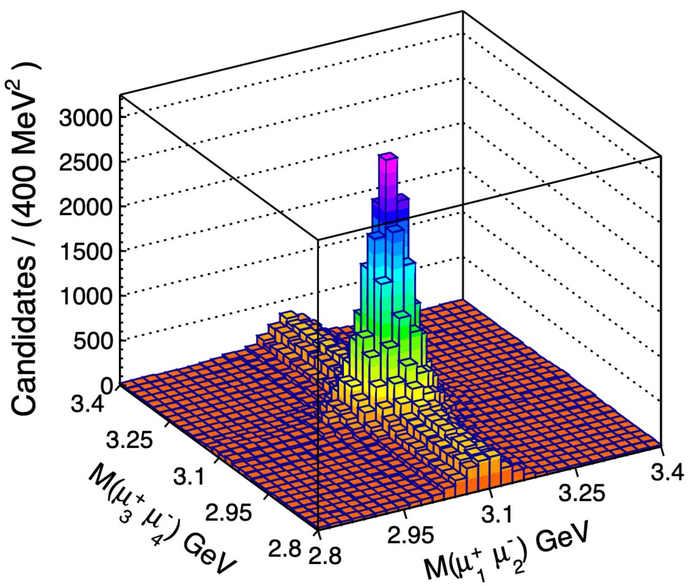
With participation from
Henan Normal University !

河南师范大学 1923

Zhipeng Cui

Gerry Bauer

CMS Run 2+3



- **Data samples** [315 fb^{-1}]

Run II: 135 fb^{-1} data taken in 2016, 2017 and 2018.

Run III: 180 fb^{-1} data taken in 2022, 2023 and 2024.

- **Luminosity**

Run 2: 135 fb^{-1}

Run 3: 180 fb^{-1}

- **$J/\psi J/\psi$ yield**

Run 2 ~12622 ± 165

Run 3 ~31802 ± 476

New triggers in parked data

- **$J/\psi J/\psi$ yield per unit luminosity**

Run 2 ~93 events / fb^{-1}

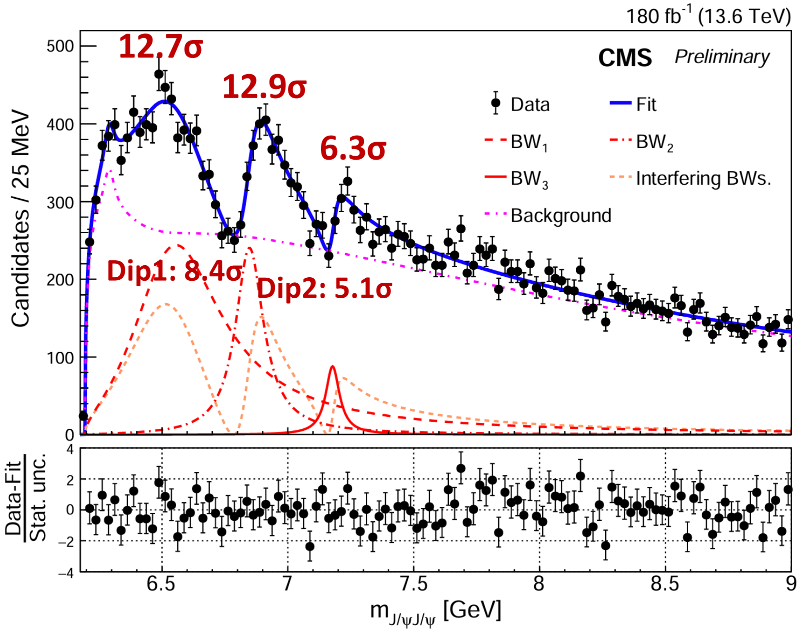
Run 3 ~177 events / fb^{-1}

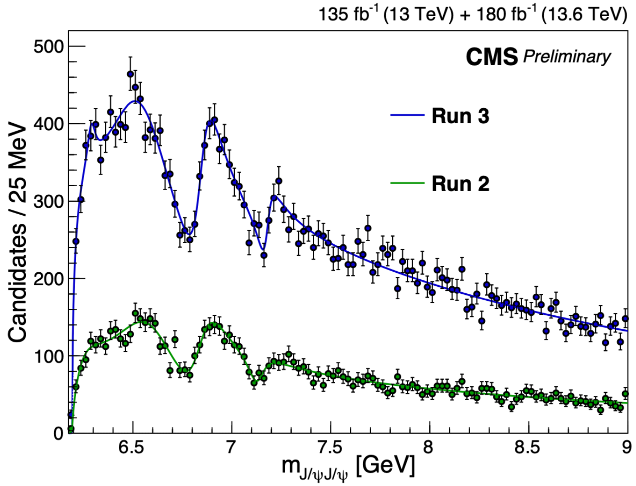
➢ **Run 2+3 $J/\psi J/\psi$ yield is 3.6X of Run 2**

➢ **Run 2+3 luminosity is 2.3X of Run 2**

Run 3 interference fit result

CMS Run 3



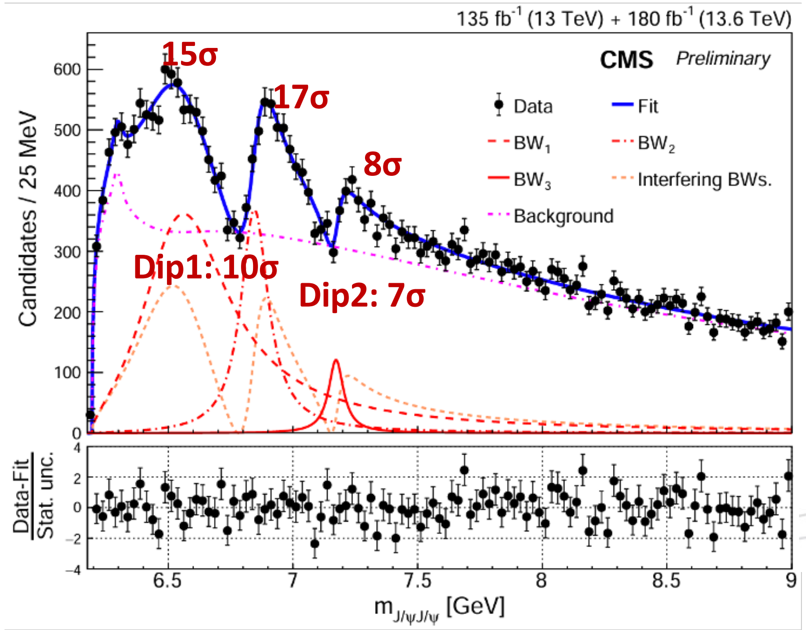


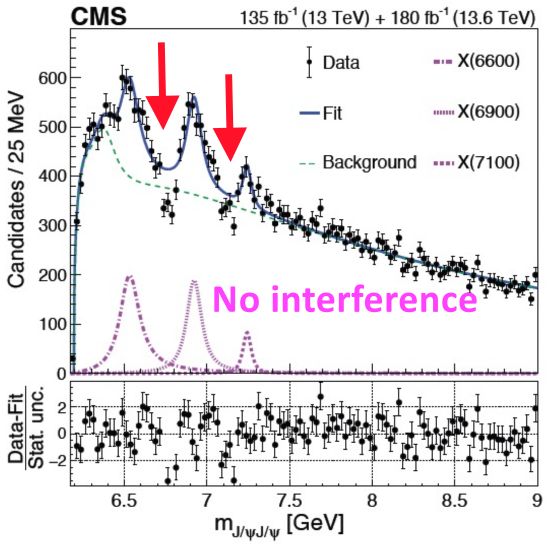
Parameter	Run 2 [Interf.]		Run 3 [Interf.]	
$m(\mathrm{BW}_1)$	6638	$^{+43+16}_{-38-31}$	6588	$\pm$ 19
$\Gamma(\mathrm{BW}_1)$	440	$^{+230+110}_{-200-240}$	454	$\pm$ 74
$m(\mathrm{BW}_2)$	6847	$^{+44+48}_{-28-20}$	6849	$\pm$ 12
$\Gamma(\mathrm{BW}_2)$	191	$^{+66+25}_{-49-17}$	136	$\pm$ 18
$m(\mathrm{BW}_3)$	7134	$^{+48+41}_{-25-15}$	7179	$\pm$ 10
$\Gamma(\mathrm{BW}_3)$	97	$^{+40+29}_{-29-26}$	67	$\pm$ 18

- **Confirm Run II results with Run III data only** ***---with better precision!***
- **All states and dips above 5σ !** ***---already achieve our goals!***

Run 2+3 interference fit result

CMS Run 2+3





Params [MeV]	Run II&III Interf.	Run II Interf.
M(BW1)	$6593^{+15}_{-14} \pm 25$	6638^{+43+16}_{-38-31}
Γ(BW1)	$446^{+66}_{-54} \pm 87$	$440^{+230+110}_{-200-240}$
M(BW2)	$6847 \pm 10 \pm 15$	6847^{+44+48}_{-28-20}
Γ(BW2)	$135^{+16}_{-14} \pm 14$	191^{+66+25}_{-49-17}
M(BW3)	$7173^{+9}_{-10} \pm 13$	7134^{+48+41}_{-25-15}
Γ(BW3)	$73^{+18}_{-15} \pm 10$	97^{+40+29}_{-29-26}

s. Run II result:

- ✓ **Statistical uncertainty** reduced by **a factor of 3**
- ✓ **Systematic uncertainty** reduced by about **a factor of 2**

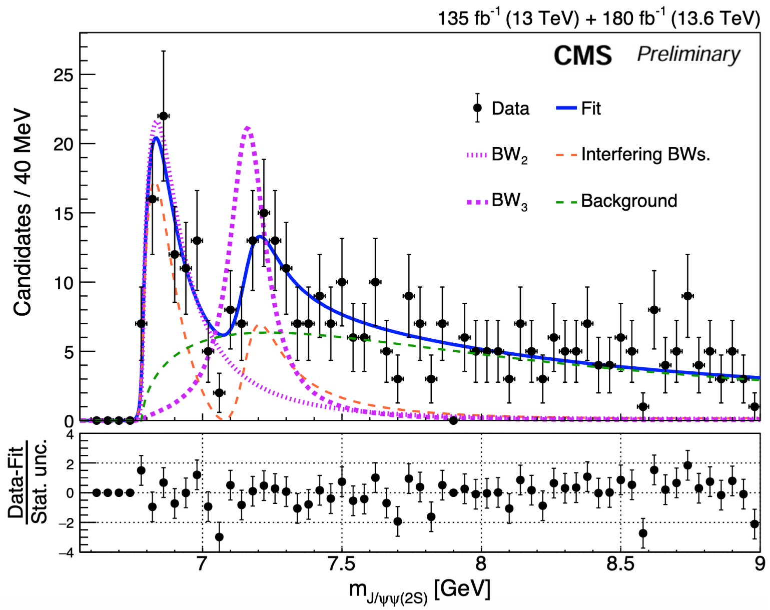
- ➢ **All states and dips well above 5σ !**
- ➢ **Quantum interference among structures validated!**
- ➢ **With improved precision, large mass splittings persist**

Open Questions

- **Open question 1—X(7100) existence?** *X(7100) well above 5σ !*
- **Open question 2—X(6600) a resonance?** *X(6600) well above 5σ !*
- **Open question 3—Is the interference effect real?** *All dips well above 5σ !*
- **Open question 4—How does the interference actually work?**
- **Open question 5—What is their nature?**

$J/\psi\psi(2S)$ Run II & III interference fit result

CMS Run 2+3



Dominant sources	$M_{X(6900)}$	$\Gamma_{X(6900)}$	$M_{X(7100)}$	$\Gamma_{X(7100)}$
Signal shape	± 29	± 79	± 22	± 131
NRSPS shape	± 14	± 54	± 14	± 29
Combinatorial background shape	± 15	± 51	± 15	± 20
Mass resolution	± 5	± 7	± 5	± 9
Efficiency	± 7	± 27	± 7	± 10
Add X(6600) peak	± 104	± 14	± 61	± 31
Fitter bias	$^{+9}_{-11}$	$^{+43}_{-37}$	$^{+29}_{-14}$	$^{0}_{-80}$
Total	$^{+110}_{-110}$	$^{+120}_{-120}$	$^{+74}_{-70}$	$^{+140}_{-160}$

Params	$J/\psi\psi(2S)$ [MeV]	$J/\psi J/\psi$ [MeV]
M(BW2)	$6876^{+46+110}_{-29-110}$	$6847 \pm 10 \pm 15$
Γ(BW2)	$253^{+290+120}_{-100-120}$	$135^{+16}_{-14} \pm 14$
M(BW3)	7169^{+26+74}_{-52-70}	$7173^{+9}_{-10} \pm 13$
Γ(BW3)	$154^{+110+140}_{-82-160}$	$73^{+18}_{-15} \pm 10$

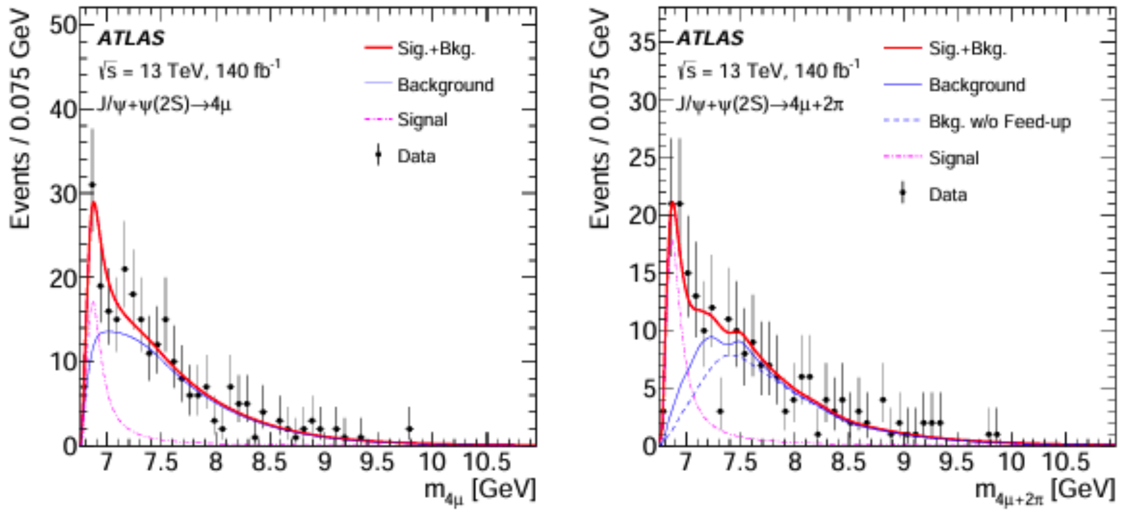
- Significance of **X(6900) = 7.9σ**
- Significance of **X(7100) = 4.0σ**

ATLAS only claim X(6900) 4.7σ in $J/\psi\psi(2S)$ channel

Update of $J/\psi\psi(2S)$ from ATLAS

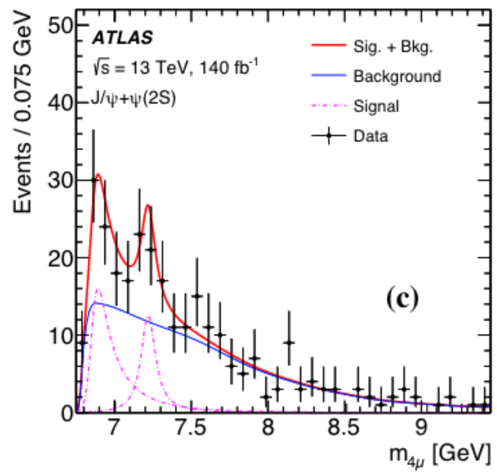
- **Simultaneous fit of 3 channels:** arXiv:2509.13101
  J/ψJ/ψ, **J/ψψ(2S) [4μ]**, **J/ψψ(2S) [4μ+2π]**

Model C: Simultaneous fit for J/ψψ(2S) [4μ and 4μ+2π]



ATLAS 2023 paper

Phys. Rev. Lett., 131(15):151902, 2023



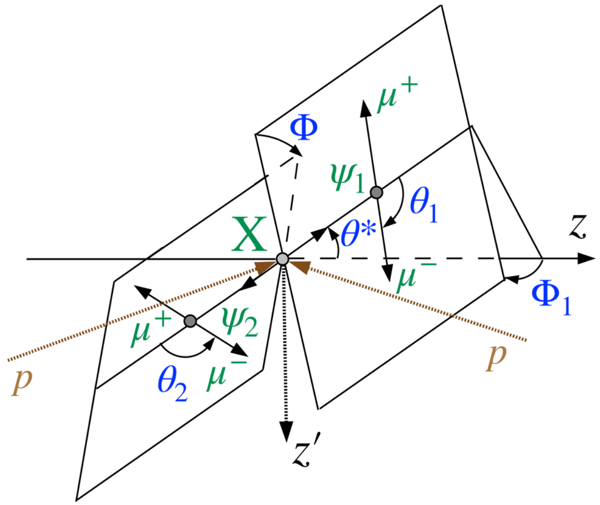
- **X(6900) 8.9σ** from model C
- Set a upper limit of **0.41 @95%CL** for X(7200)
- **In ATLAS 2023 paper, X(7200) 3σ in J/ψψ(2S) [4μ]**

Answers to the Open Questions

Open Questions

- **Open question 1—X(7100) existence?** *X(7100) well above 5σ !* *Also found X(7100) evidence*
- **Open question 2—X(6600) a resonance?** *X(6600) well above 5σ !*
- **Open question 3—Is the interference effect real?** *All dips well above 5σ !* *2.5σ in $J/\psi\psi(2S)$*
- **Open question 4—How does the interference actually work?**
- **Open question 5—What is their nature?**

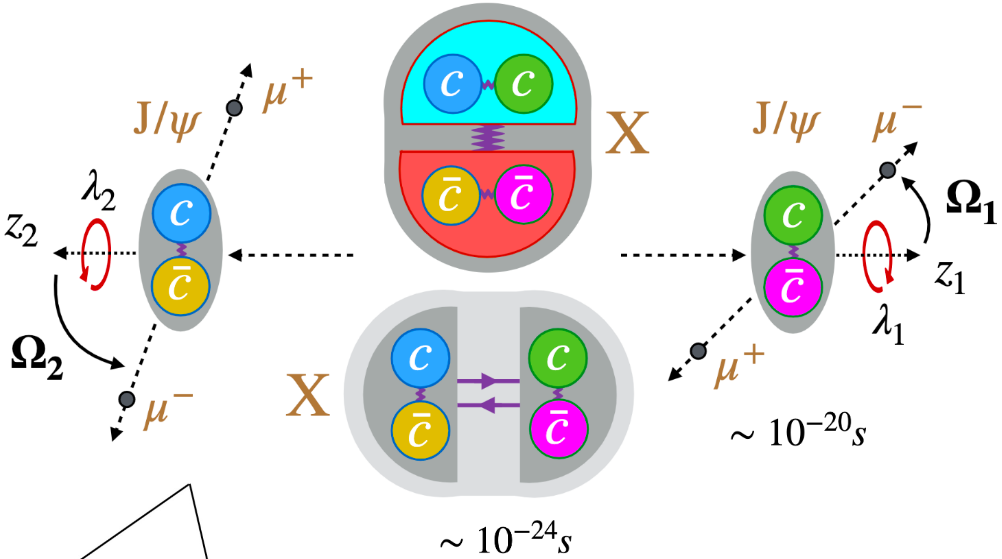
- Framework
  - $m_{4\mu}$ spectrum $X \rightarrow 4\mu$ — identical to Phys. Rev. Lett. 132 (2024) 111901
  - p_T and p_Z of $X \rightarrow 4\mu$ — match MC to data
  - Polarization of X — assume unpolarized

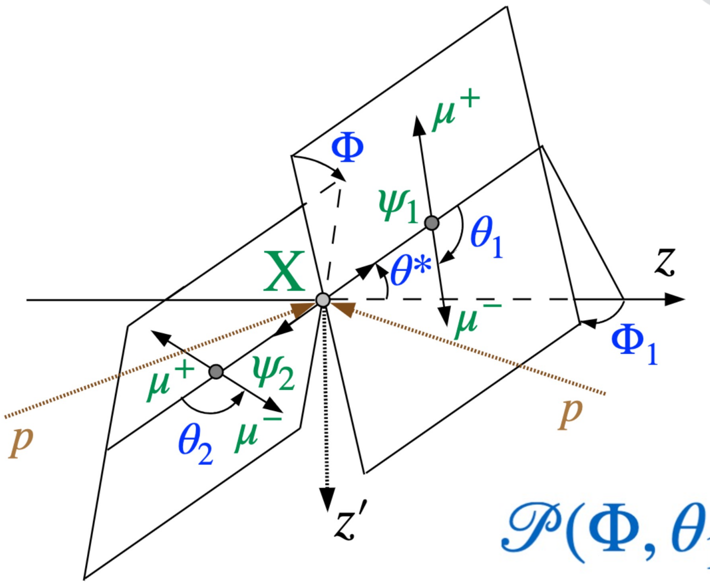


- **Production angles** *[for data test]*
  - ϑ^* : angle between beam line and J/ψ momentum in X rest frame
  - Φ_1: azimuthal angle between production plane and decay plane in X rest frame

- **Decay angles** *[for data analysis]*
  - Φ : azimuthal angle between two l^+l^- decay planes defined in X rest frame
  - ϑ_1 : helicity angle between opposite of J/ψ_2 momentum and l momentum defined in J/ψ_1 rest frame
  - ϑ_2 : helicity angle between opposite of J/ψ_1 momentum and l momentum defined in J/ψ_2 rest frame

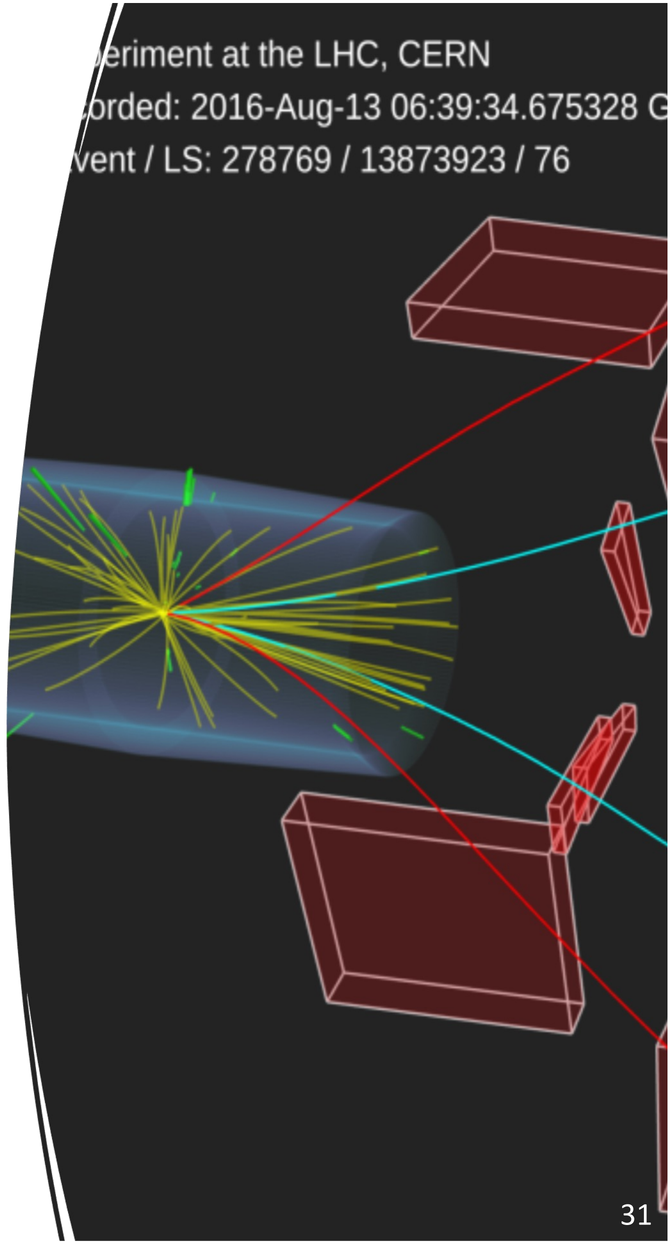
Spin parity analysis



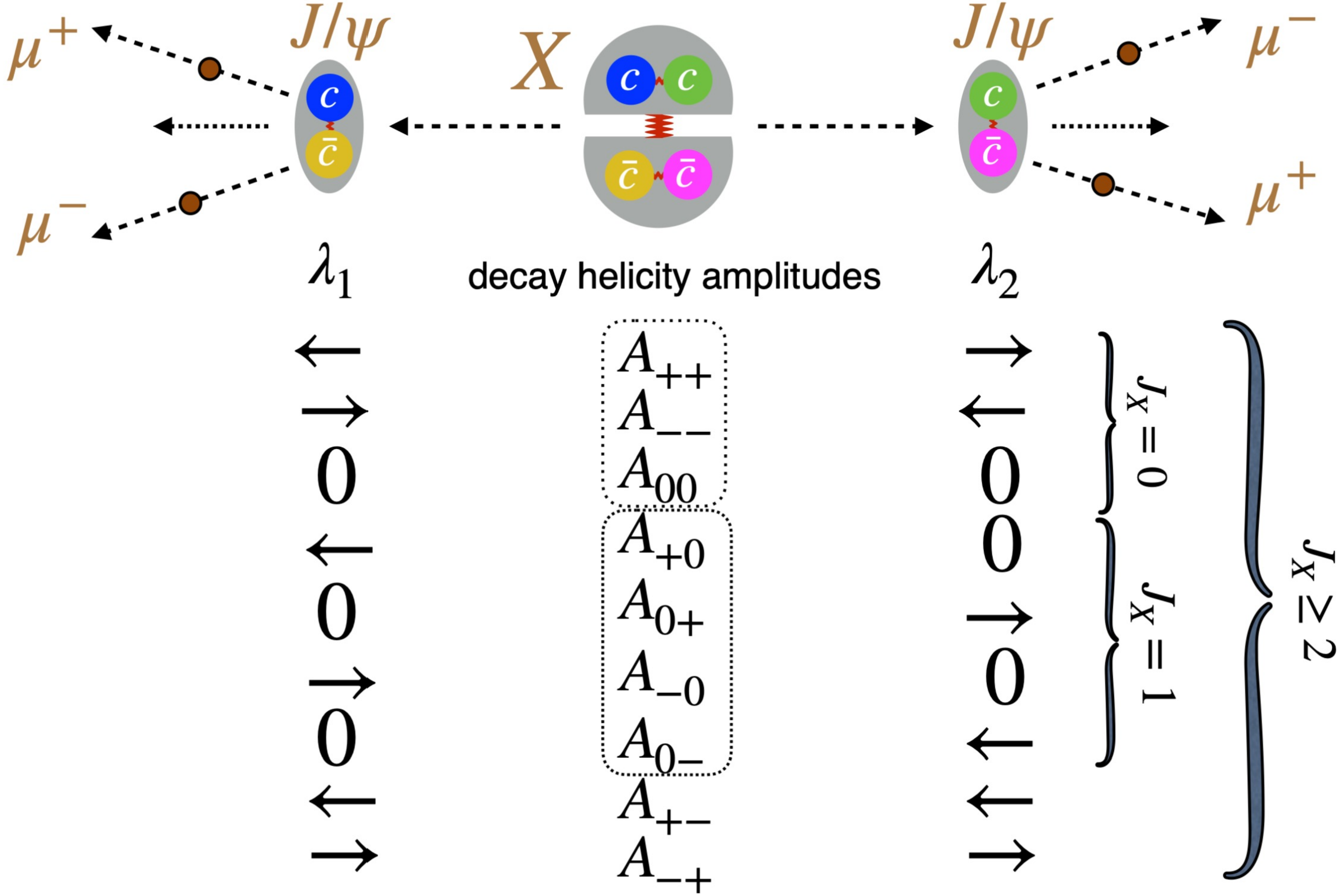


$$\mathscr{P}(\Phi, \theta_1, \theta_2; m_{4\mu})$$

$$J^{PC} = ?$$



J/ψ polarizations



J/ψ polarizations

- Symmetries:
  - angular momentum: $|\lambda_1 - \lambda_2| \leq J$
  - identical J/ψ bosons $A_{\lambda_1\lambda_2} = (-1)^J A_{\lambda_2\lambda_1}$
  - P & C conserved in QCD:

X with definite J^{PC}

$C = +1$

$A_{\lambda_1\lambda_2} = P(-1)^J A_{-\lambda_1-\lambda_2}$

$J_X = 0$: A_{++}, A_{--}, A_{00}

$J_X = 1$: A_{+0}, A_{0+}, A_{-0}, A_{0-}

$J_X \geq 2$: A_{+-}, A_{-+}

Test 8+ J_X^P models:

0^{-+}	0^-	$A_{++} = -A_{--}$	
0^{++}	0_m^+ and 0_h^+	$A_{++} = A_{--}$ and A_{00}	← note 2 d.o.f.
1^{-+}	1^-	$A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$	
1^{++}	1^+	$A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$	
2^{-+}	2_m^- and 2_h^-	$A_{++} = -A_{--}$ and $A_{+0} = A_{0+} = -A_{-0} = -A_{0-}$	← note 2 d.o.f.
2^{++}	2_m^+	$A_{++} = A_{--}$, A_{00}, $A_{+0} = A_{0+} = A_{-0} = A_{0-}$, and $A_{+-} = A_{-+}$	

note 4 d.o.f. for 2^{++}, test one model

Angular Analysis

A_{++} A_{--} A_{00}

A_{+0} A_{0+} A_{-0} A_{0-}

A_{+-} A_{-+}

$$F^J_{0,0}(\theta^*) \times \Big[4|A_{00}|^2 \sin^2\theta_1 \sin^2\theta_2 + 2|A_{++}||A_{--}|\sin^2\theta_1\sin^2\theta_2\cos(2\Phi - \phi_{--} + \phi_{++})\Big]$$
$$+|A_{++}|^2\left(1+2A_{f_1}\cos\theta_1+\cos^2\theta_1\right)\left(1+2A_{f_2}\cos\theta_2+\cos^2\theta_2\right)$$
$$+|A_{--}|^2\left(1-2A_{f_1}\cos\theta_1+\cos^2\theta_1\right)\left(1-2A_{f_2}\cos\theta_2+\cos^2\theta_2\right)$$
$$+4|A_{00}||A_{++}|(A_{f_1}+\cos\theta_1)\sin\theta_1(A_{f_2}+\cos\theta_2)\sin\theta_2\cos(\Phi+\phi_{++})$$
$$+4|A_{00}||A_{--}|(A_{f_1}-\cos\theta_1)\sin\theta_1(A_{f_2}-\cos\theta_2)\sin\theta_2\cos(\Phi-\phi_{--})$$

spin $= 0$ & ≥ 1

$$+F^J_{1,1}(\theta^*) \times \Big[2|A_{+0}|^2(1+2A_{f_1}\cos\theta_1+\cos^2\theta_1)\sin^2\theta_2 + 2|A_{0-}|^2\sin^2\theta_1(1-2A_{f_2}\cos\theta_2+\cos^2\theta_2)$$
$$+2|A_{-0}|^2(1-2A_{f_1}\cos\theta_1+\cos^2\theta_1)\sin^2\theta_2 + 2|A_{0+}|^2\sin^2\theta_1(1+2A_{f_2}\cos\theta_2+\cos^2\theta_2)$$
$$+4|A_{+0}||A_{0-}|(A_{f_1}+\cos\theta_1)\sin\theta_1(A_{f_2}-\cos\theta_2)\sin\theta_2\cos(\Phi+\phi_{+0}-\phi_{0-})$$
$$+4|A_{0+}||A_{-0}|(A_{f_1}-\cos\theta_1)\sin\theta_1(A_{f_2}+\cos\theta_2)\sin\theta_2\cos(\Phi+\phi_{0+}-\phi_{-0})\Big]$$

spin ≥ 1

$$+F^J_{1,-1}(\theta^*) \times \Big[4|A_{+0}||A_{0+}|(A_{f_1}+\cos\theta_1)\sin\theta_1(A_{f_2}+\cos\theta_2)\sin\theta_2\cos(2\Psi-\phi_{+0}+\phi_{0+})$$
$$+4|A_{0-}||A_{-0}|(A_{f_1}-\cos\theta_1)\sin\theta_1(A_{f_2}-\cos\theta_2)\sin\theta_2\cos(2\Psi-\phi_{0-}+\phi_{-0})$$
$$+4|A_{+0}||A_{-0}|\sin^2\theta_1\sin^2\theta_2\cos(2\Psi-\Phi-\phi_{+0}+\phi_{-0}) + 4|A_{0-}||A_{0+}|\sin^2\theta_1\sin^2\theta_2\cos(2\Psi+\Phi-\phi_{0-}+\phi_{0+})\Big]$$

$$+F^J_{2,2}(\theta^*) \times \Big[|A_{+-}|^2(1+2A_{f_1}\cos\theta_1+\cos^2\theta_1)(1-2A_{f_2}\cos\theta_2+\cos^2\theta_2)$$
$$+|A_{-+}|^2(1-2A_{f_1}\cos\theta_1+\cos^2\theta_1)(1+2A_{f_2}\cos\theta_2+\cos^2\theta_2)\Big]$$

spin ≥ 2

$$+F^J_{2,-2}(\theta^*) \times \Big[2|A_{+-}||A_{-+}|\sin^2\theta_1\sin^2\theta_2\cos(4\Psi-\phi_{+-}+\phi_{-+})\Big] +$$ other 26 interference terms for spin

where $\Psi = \Phi_1 + \Phi/2$ and $F^J_{ij}(\theta^*) = \sum_{m=0,\pm1,\pm2} f_m\, d^J_{im}(\theta^*) d^J_{jm}(\theta^*)$

Valid for any J

arXiv:1001.3396

Lorentz-Invariant Amplitude

- Expect three X resonances to have the same tensor structure:

arXiv:1001.3396

$$A(X_{J=2} \to V_1 V_2) = 2c_1(q^2) t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2(q^2) t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}$$
$$+ c_3(q^2) \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + c_4(q^2) \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+ m_V^2 \left(2c_5(q^2) t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2c_6(q^2) \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}) + c_7(q^2) \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
$$+ c_8(q^2) \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_{10}(q^2) \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)),$$

2^-_m $(A_{++} = -A_{--})$

2^-_h $(A_{+0} = A_{0+} = -A_{-0} = -A_{0-})$

2^+_m — minimal representative model including all amplitudes:

4 d.o.f.: $A_{00}, A_{++} = A_{--}; A_{+0} = A_{0+} = A_{-0} = A_{0-}; A_{+-} = A_{-+}$; unique for 2^{++} (or $J \geq 2$)

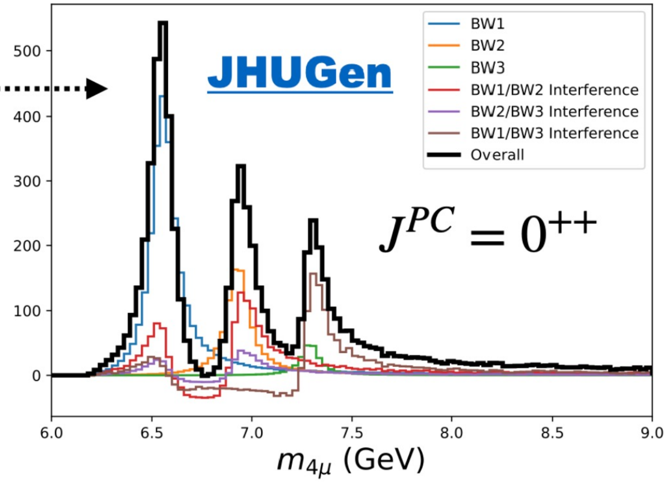
basis of 2^{++} could be equivalent to $2^+_m, 0^+_m, 0^+_h, 1^+$

if data consistent with 2^+_m $\Rightarrow$ unambiguously 2^{++} (or $J \geq 2$)

Simplification in Angular Analysis

- Full model possible, but very complex

$$\mathscr{P}(\Phi, \theta_1, \theta_2; m_{4\mu})$$



(1) Same properties of 3 resonances:

$$\mathscr{P}(m_{4\mu}, \vec{\mathbf{\Omega}}) = \mathscr{P}(m_{4\mu}) \cdot T(\vec{\mathbf{\Omega}} \,|\, m_{4\mu})$$

empirical — angular

(2) Pairwise tests of J_X^P hypotheses i and j:

arXiv:1208.4018

MELA $$\mathscr{D}_{ij}(\vec{\Omega} \,|\, m_{4\mu}) = \frac{\mathscr{P}_i(\vec{\Omega} \,|\, m_{4\mu})}{\mathscr{P}_i(\vec{\Omega} \,|\, m_{4\mu}) + \mathscr{P}_j(\vec{\Omega} \,|\, m_{4\mu})}$$

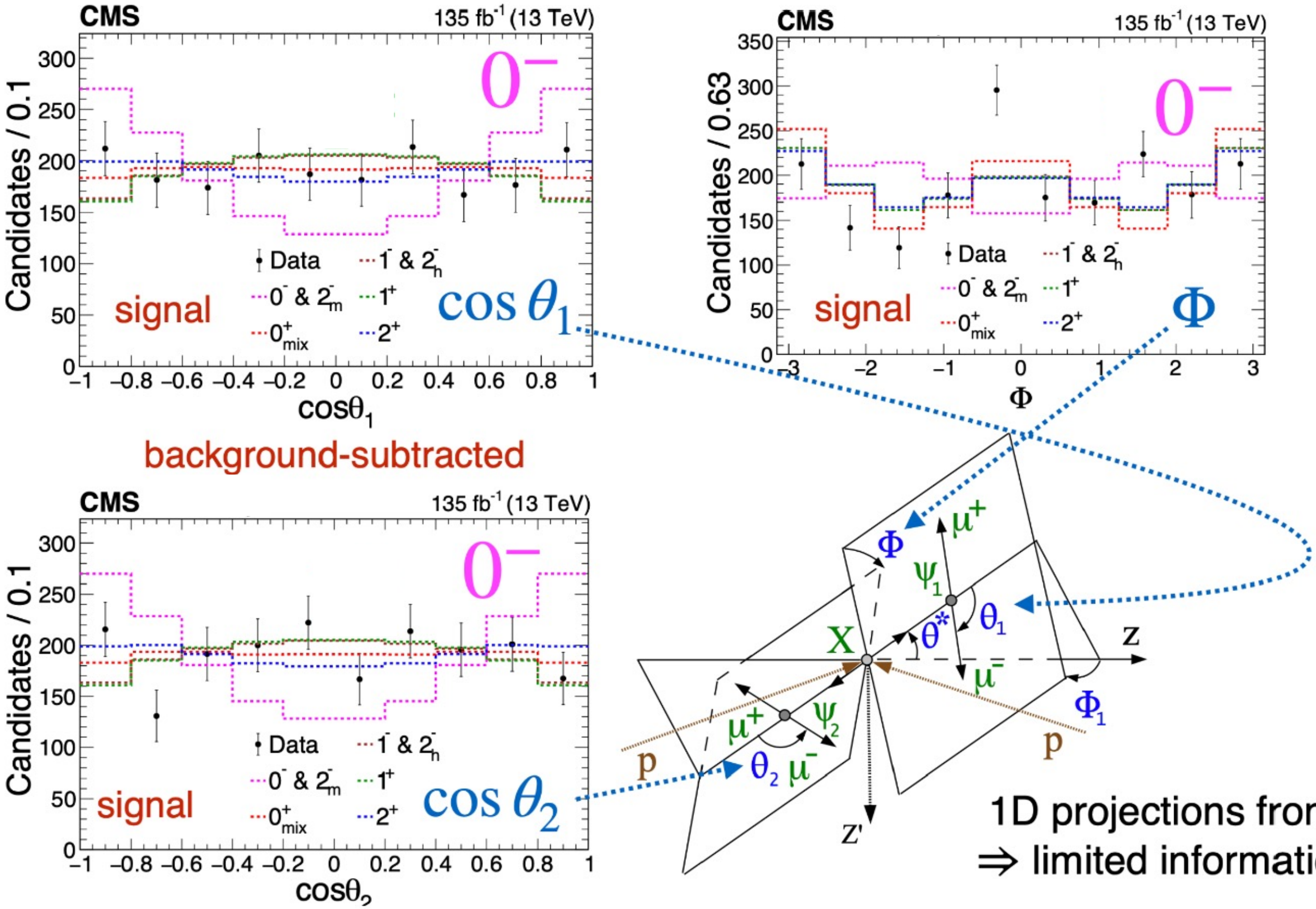
1 optimal observable

- Final 2D model: $$\mathscr{P}_{ijk}(m_{4\mu}, \mathscr{D}_{ij}) = \mathscr{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathscr{D}_{ij} \,|\, m_{4\mu})$$

Decay Angles

Production angles not use
Consistent with unpolarized (backup)

decay angles (consistency check): distinguish models



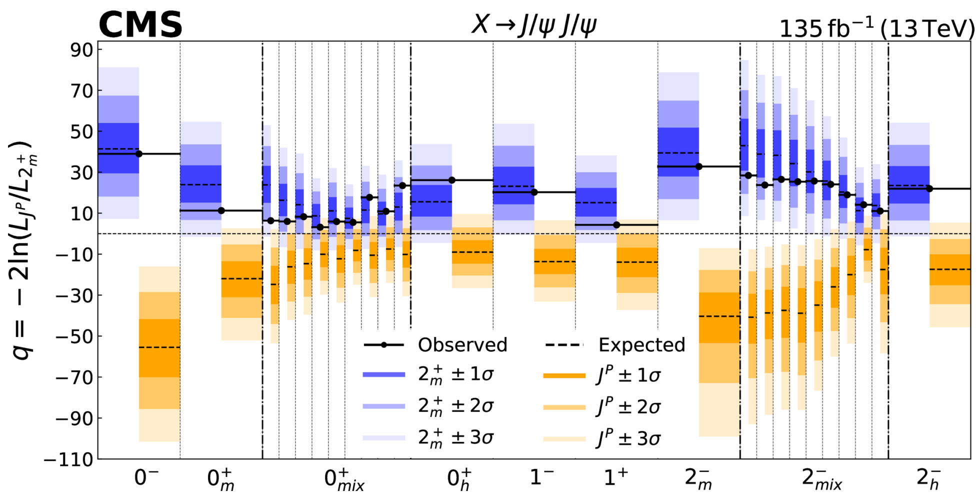
1D projections from 4D
⇒ limited information

Results of spin-parity measurement

❖ **Combine 2D fit** $\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij})$

- $PC = ++$ **very certain,** $P \neq -1$ **very certain =>** $L \neq 1$
- $J \neq 1$ **at 99% CL**
- $J \neq 0$ **at 95% CL**
- $J > 2$ **unlikely, require** $L \geq 2$, $L = 0$ **most likely**

➢ $J^P = 2_m^+$ ***model survives***



J_X^P	p-value	Z-score reject J_X^P	
0^-	2.7×10^{-13}	7.2	
0_m^+	4.3×10^{-5}	3.9	
0_{mix}^+	1.4×10^{-2}	2.2	***mix***
0_h^+	3.1×10^{-9}	5.8	
1^-	8.0×10^{-8}	5.2	
1^+	4.7×10^{-3}	2.6	
2_m^-	4.1×10^{-12}	6.8	
2_{mix}^-	6.5×10^{-4}	3.2	***mix***
2_h^-	2.2×10^{-8}	5.5	

Open Questions

- Open question 1—X(7100) existence?

  X(7100) well above 5σ !

  Also found X(7100) evidence

- Open question 2—X(6600) a resonance?

  X(6600) well above 5σ !

- Open question 3—Is the interference effect real?

  All dips well above 5σ !

  2.5σ in $J/\psi\psi(2S)$

- Open question 4—How does the interference actually work?
- Open question 5—What is their nature?

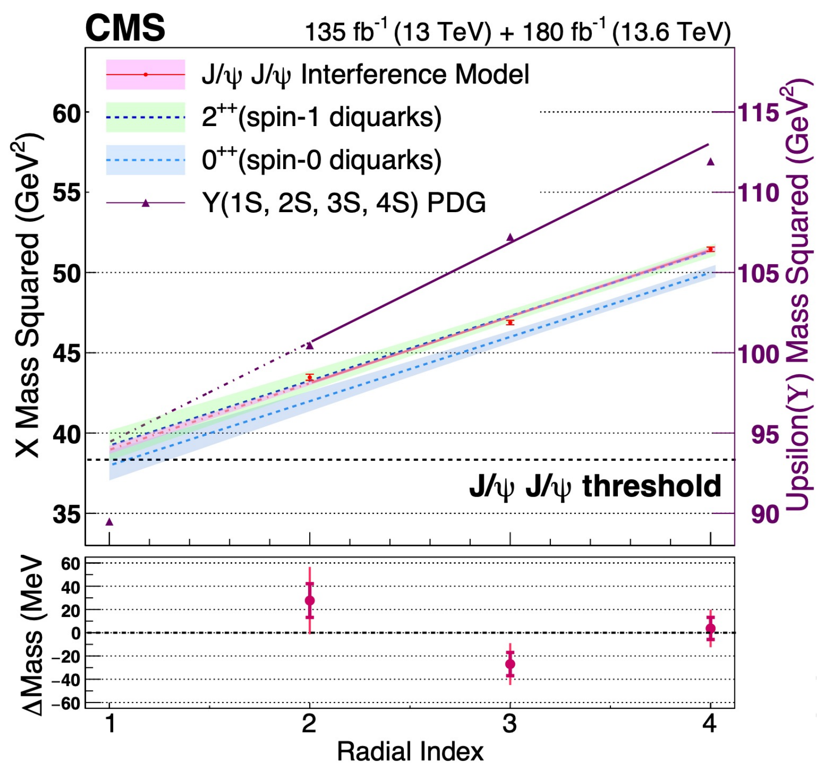
Discussion and Interpretation

- **Large X-mass splittings (> 250 MeV)**
  - *X(6900)-X(6600)~254 MeV*
  - *X(7100)-X(6900)~326 MeV*
- **Imply radial, rather than L/S excitations**

- **Regge trajectory:** $n = \beta m^2 + \beta_0$
  - **Squared masses of X triplet (stat. uncert. only)**
  - **Upsilon families versus radial indices *n* = 2, 3, 4**
  - **Trajectories from diquark model of spin-0 and spin-1**

➢ **Also, 2^{++} trajectory comparable with X's**

Regge trajectory of CMS Run 2+3



Discussion and Interpretation

- **Additional family members ?**
  - **Extrapolate n = 1 state ~6240 MeV**

    $\Upsilon(1S)$ lies below *the line, tightly bound in Coulombic part of potential*

    an excess uninterpreted near-threshold *reported by three experiments*

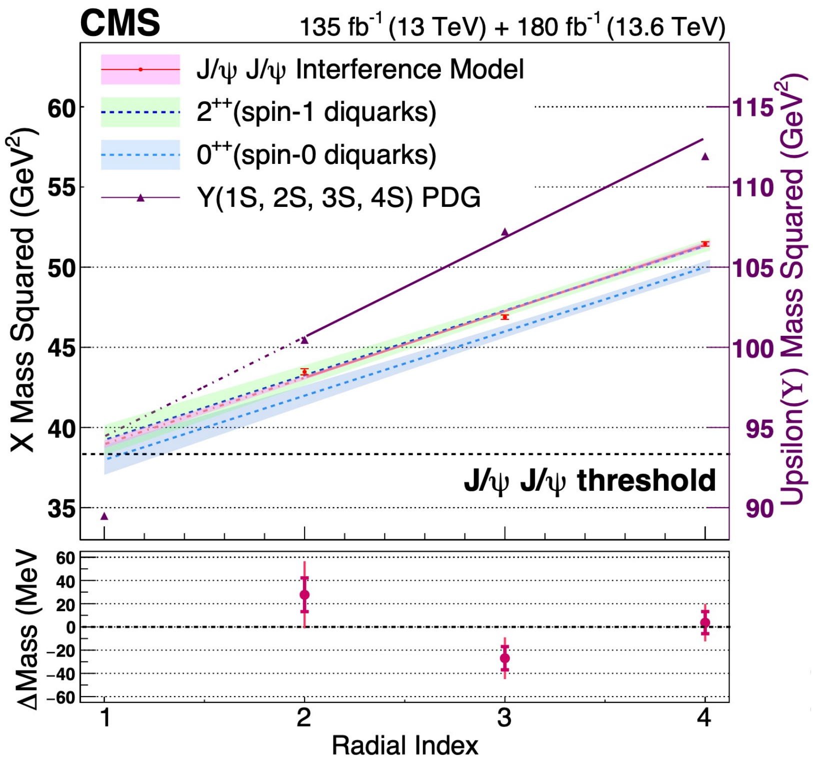
    better understanding of threshold *is necessary to draw a conclusion*

  - **Next higher family member, ~7453 MeV**

    data offer ***no visual hint*** *of such a state*

    Predicted mass is well above $\Xi_{cc}^{+}\Xi_{cc}^{-}$ and $\Xi_{cc}^{++}\Xi_{cc}^{--}$ thresholds

Regge trajectory of CMS Run 2+3



Discussion and Interpretation

- **The X widths systematically decrease**

  can be described by exponential function

- **Widths known to decrease with radial for $q\bar{q}$ mesons**

  particularly decays dominated by quark-antiquark annihilation

  - **Similarity of width slopes for X and Υ**

$$\frac{\Gamma(n+1)}{\Gamma(n)} = 0.369 \pm 0.067 \qquad \frac{\Gamma_{3g}(n+1)}{\Gamma_{3g}(n)} = 0.411 \pm 0.021$$

3g partial widths of Υ

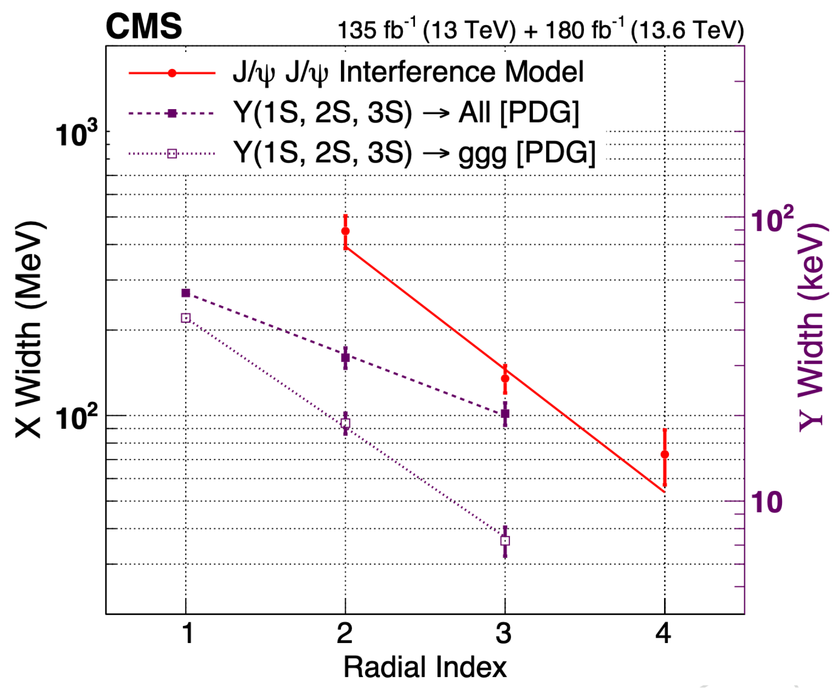
- **"Diquark-onium" ?**
  - **Quasi-2-body (cc)($\bar{c}\bar{c}$) ~3 GeV ←→ ($b\bar{b}$) ~5 GeV**

    similar dynamics, tetraquark decays may similar to $b\bar{b}$ annihilation of Υ

    decrease in Υ widths due to spatial spreading of their wave functions with radial excitation

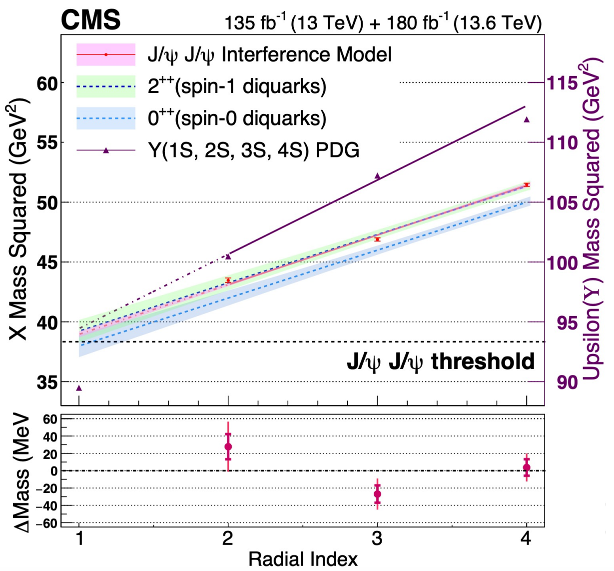
    may also occur for diquark/antidiquark systems

Width trend of CMS Run 2+3

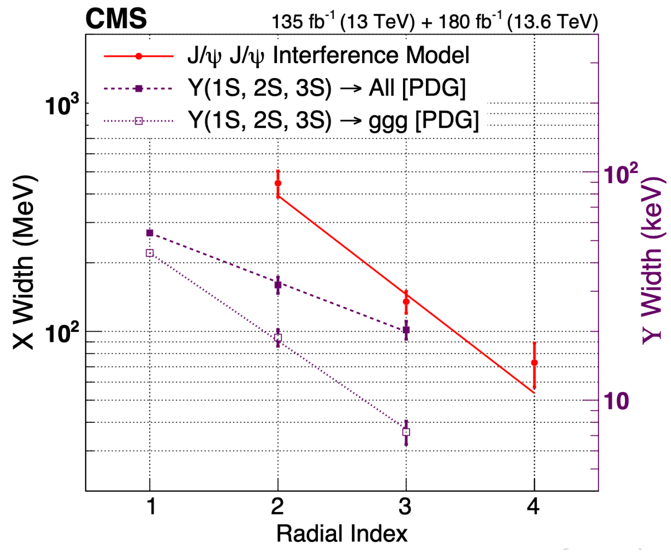


Discussion and Interpretation

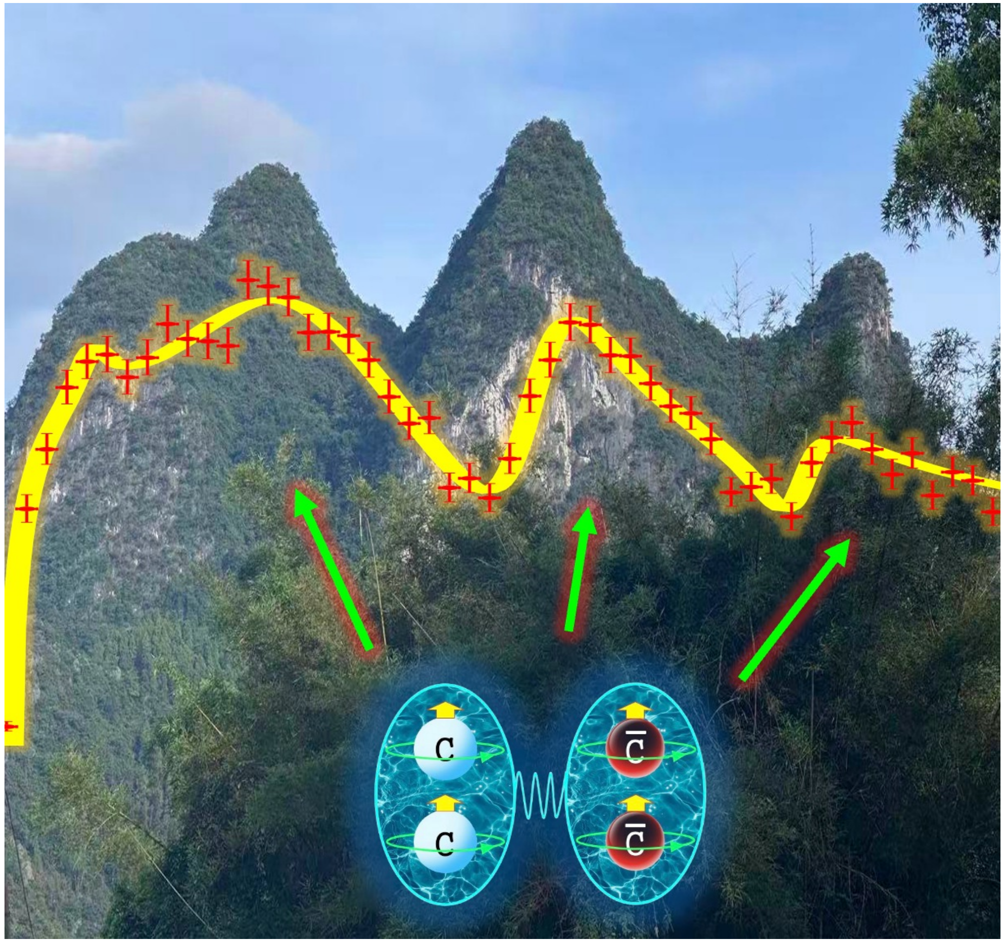
Regge trajectory of CMS Run 2+3

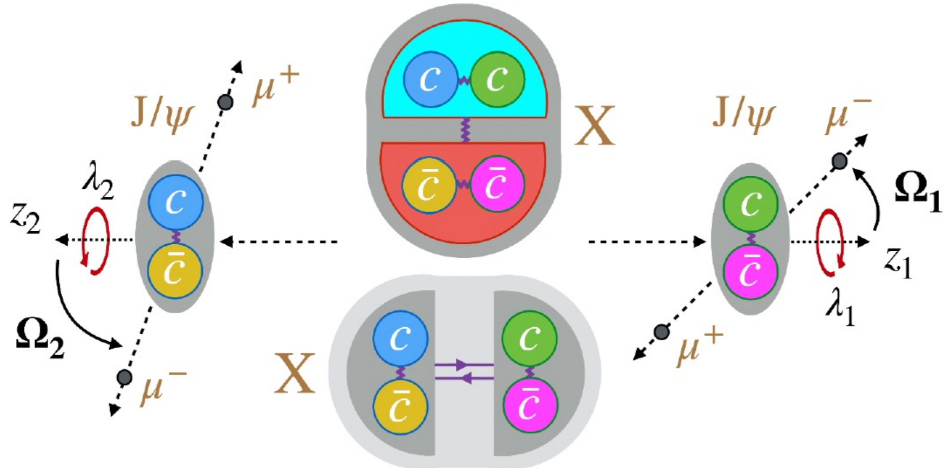


Width trend of CMS Run 2+3



- **Diquarks** seems suited to from their patterns of masses and decreasing widths
- Molecular or threshold interpretations are problematic, since numerous charmonia pairings possible
- Cannot rule out **amorphous/unstructured** system, unless detailed theoretical calculations are done
- Hybrid models predict ccccg near X(6900, 0++) & X(7100, 0−+), but not X(6600).



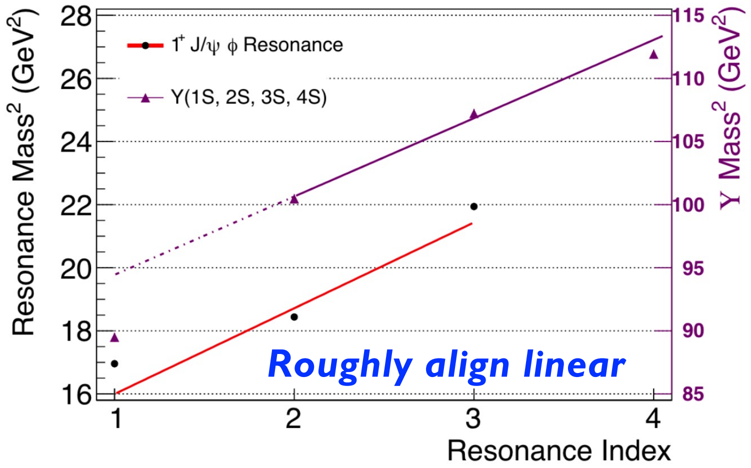


Looks like
Tightly bound diquark pairs

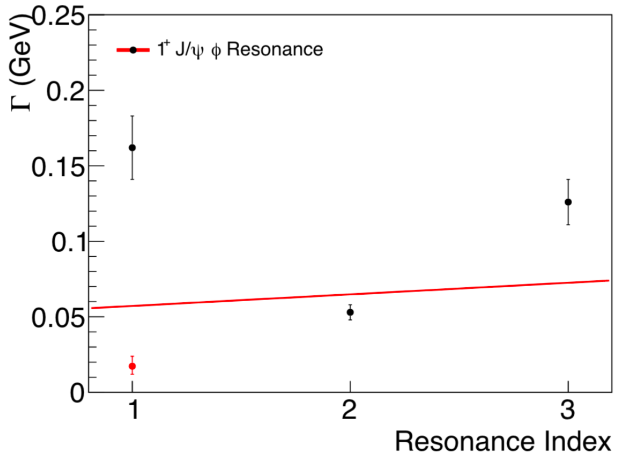
Any other family?

Three states with same JPC in $J/\psi\phi$ system

Regge plot: M^2 $v.s.$ n_r



Regge plot: Γ $v.s.$ n_r



Structures in $J/\psi\phi$ system

in the $J/\psi\phi$ mass spectrum.

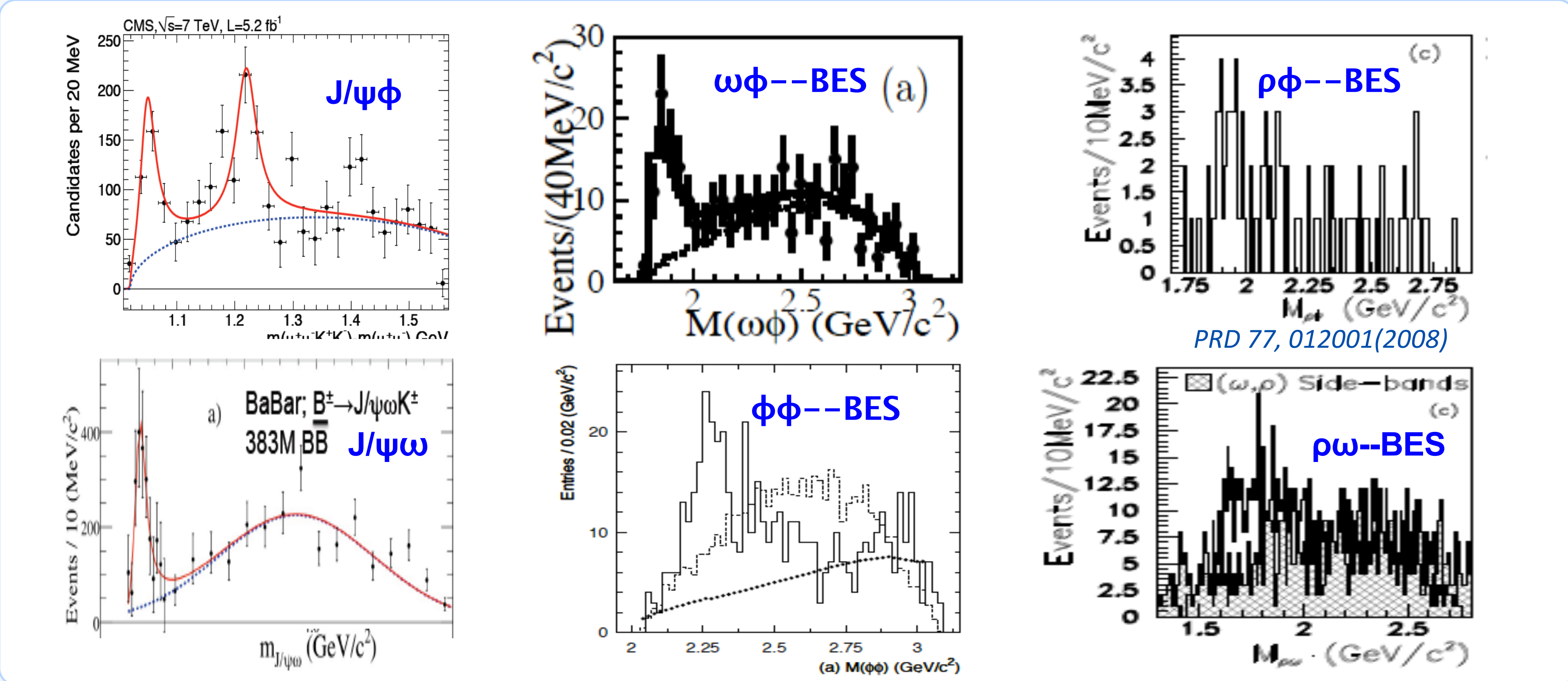
Mass [MeV]	Width [MeV]	J^P	Significance [σ]
$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^+	8.4
$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^+	6.0
$4506 \pm 11^{+12}_{-15}$	$92 \pm^{+21}_{-20}$	0^+	6.1
$4704 \pm 10^{+14}_{-2}$	$120 \pm 31^{+42}_{-33}$	0^+	5.6
$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	1^+	13
$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	2^-	4.8
$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	1^+	18
$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	0^+	20
$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	1^-	5.7
$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	1^+	15
$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	0^+	17
$4274 \pm 6 \pm 9$	$92^{+22}_{-18} \pm 57$		4.3
$4512.5^{+6.0}_{-6.2} \pm 3.0$	$65^{+20}_{-16} \pm 32$		5.5

❖ $X(4140)$, $X(4274)$, and $X(4685)$ with same $J^{PC} = 1^{++}$ from LHCb result

- Potential **width** increase ?
  OR
- Potential trend of decrease then increase ?

Mass splitting ~200 MeV ==> From radial excitation?

Connection with other VV final states--BESIII



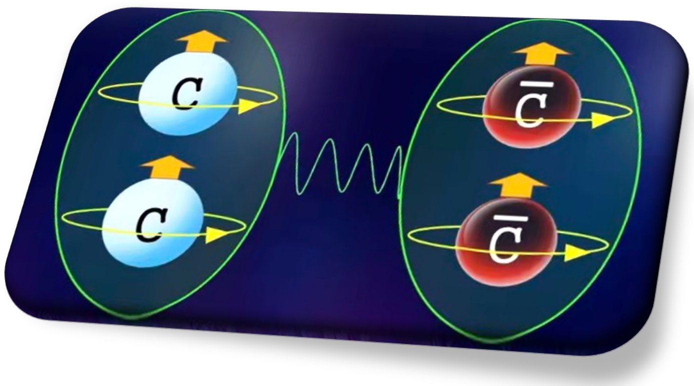
- **Observed near V(I=0)V (I=0) threshold enhancement. Strong decay. Above (qq'+q'q) threshold**

  Is there similar structures at J/ψY, YY threshold? Re-investigate **J/ψ to ϕϕ+gamma**

Remaining open questions

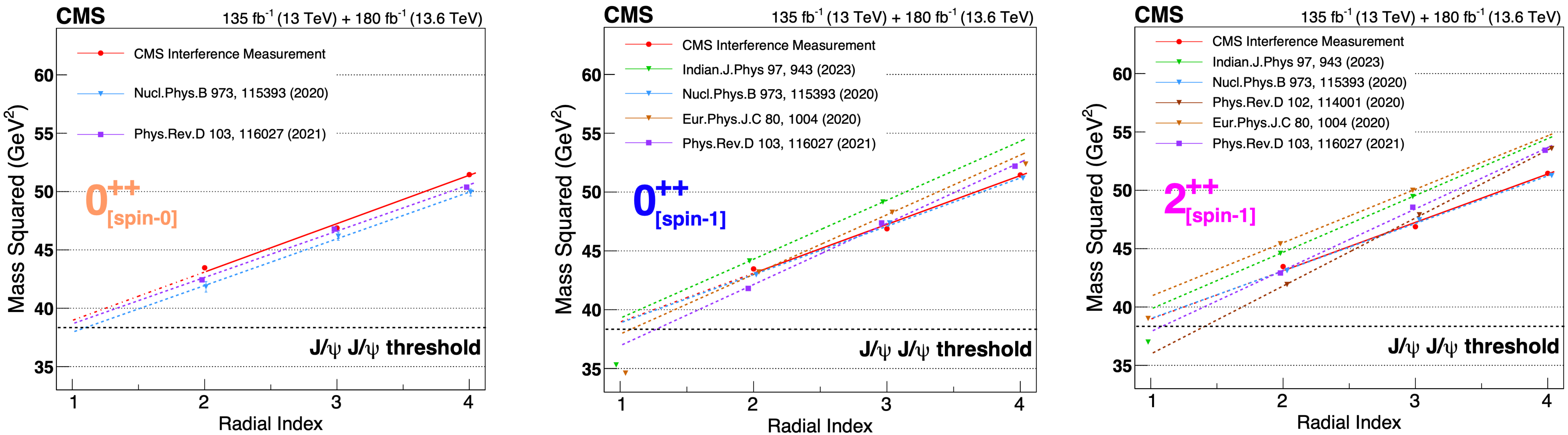
- **Do the triplet interfere with background?**
- **Is X(6600) a real resonance?**
- **Does X(7100) decay into $J/\psi\psi(2S)$**
- **Determine each state JPC?**
- **What is their nature? A decision answer?**

- **A family of all-charm tetraquarks identified**
  - X(7100) well above 5sigma, join previously identified X(6600) and X(6900)
  - X(6900) well above 5sigma in $J/\psi\psi(2S)$ channel
  - Inteference effect well above 5sigma
- **$\mathbf{J^{PC}}$ measured as $\mathbf{2^{++}}$**
  - First J^{PC} analysis of exotic hadrons not from B decay at LHC
  - First spin-2 for well-established exotic hadrons
- **Another family structures in $\boldsymbol{J/\psi\phi}$ system ?**
- **More to come…**



BACKUP

❖ **Comparison of CMS X trajectory with theoretical calculations**



➢ The Regge trajectories for **spin-1 diquark-antidiquark model,** for both **0^{++} and 2^{++} states,** are indistinguishable from X data.

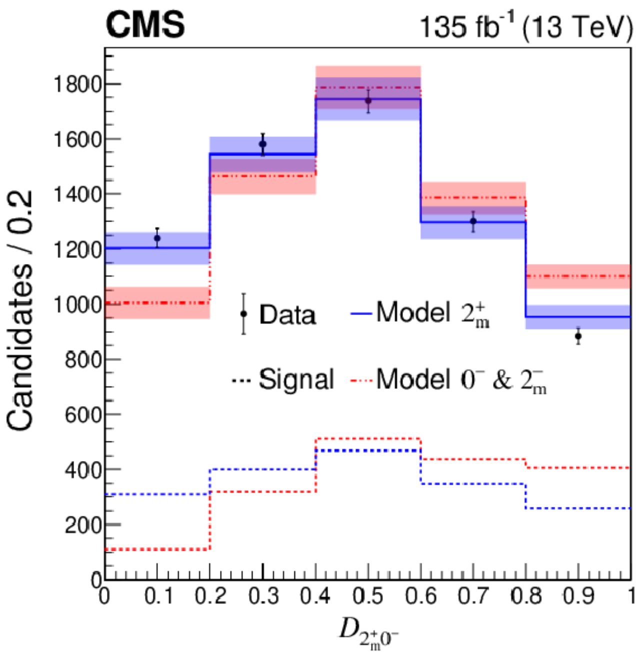
❖Optimal Observable

- **1D projection of data**

$$\mathcal{D}_{ij}(\vec{\Omega}\,|\,m_{4\mu}) = \frac{\mathcal{P}_i(\vec{\Omega}\,|\,m_{4\mu})}{\mathcal{P}_i(\vec{\Omega}\,|\,m_{4\mu}) + \mathcal{P}_j(\vec{\Omega}\,|\,m_{4\mu})}$$

1 optimal observable

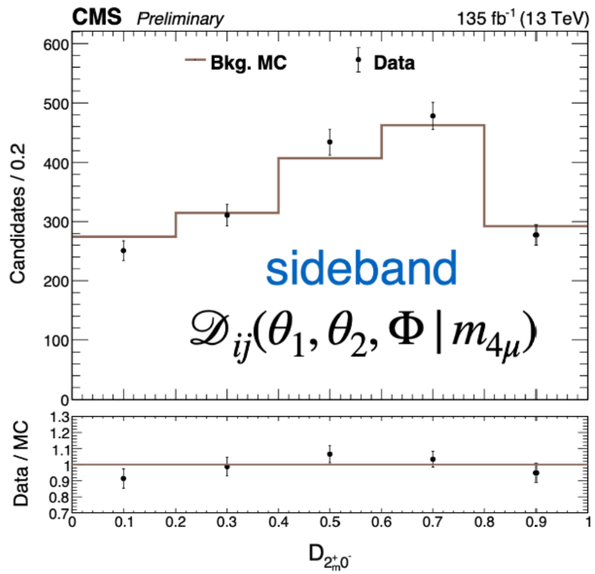
MELA *Higgs discovery and spin-parity*



$j = 0^-(2^-_m)$ vs $i = 2^+_m$

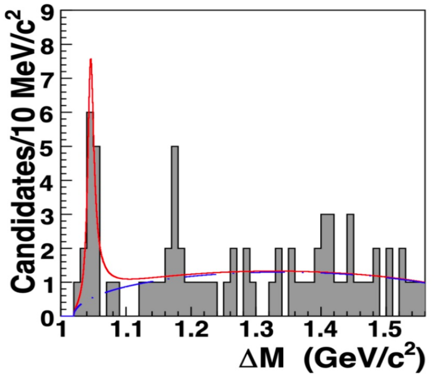
- **Background 1D projection**

Control Background MC using Data sideband

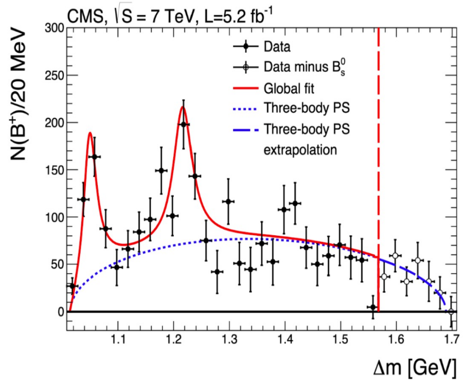


The rich structures in $J/\psi\phi K$ system

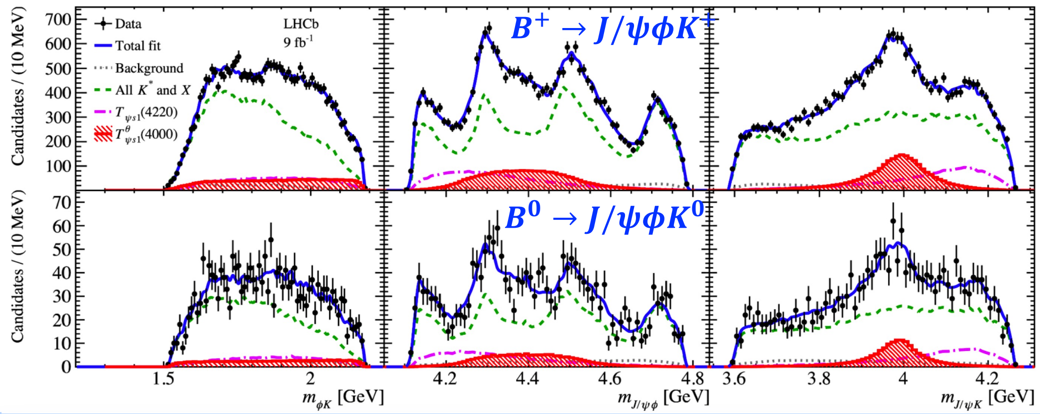
CDF 2009



CMS 2013



LHCb: Full amplitude analysis



- ❖ $X(4140), X(4274)$, and $X(4685)$ with same $J^{PC} = 1^{++}$ from LHCb result

Structures in $J/\psi\phi$ system

Table 1: Structures reported in the $J/\psi\phi$ mass spectrum.

Year	Experiment	Luminosity $[\mathrm{fb}^{-1}]$	Process/Yield $B \to J/\psi\phi K$	Mass [MeV]	Width [MeV]	J^P	Significance $[\sigma]$
2016	LHCb [21]	3	4289 ± 151	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^+	8.4
				$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^+	6.0
				$4506 \pm 11^{+12}_{-15}$	$92 \pm^{+21}_{-20}$	0^+	6.1
				$4704 \pm 10^{+14}_{-2}$	$120 \pm 31^{+42}_{-33}$	0^+	5.6
2021	LHCb [4]	9	24220 ± 170	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	1^+	13
				$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	2^-	4.8
				$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	1^+	18
				$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	0^+	20
				$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	1^-	5.7
				$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	1^+	15
				$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	0^+	17
2024	LHCb [22]	5	$pp \to J/\psi\phi$ + anything	$4274 \pm 6 \pm 9$	$92^{+22}_{-18} \pm 57$		4.3
				$4512.5^{+6.0}_{-6.2} \pm 3.0$	$65^{+20}_{-16} \pm 32$		5.5