



Vector-Vector Exotic Hadrons: $J/\psi J/\psi$ Tetraquarks and Related $\phi\phi$, $J/\psi\phi$ Resonances

Kai Yi

Nanjing Normal University

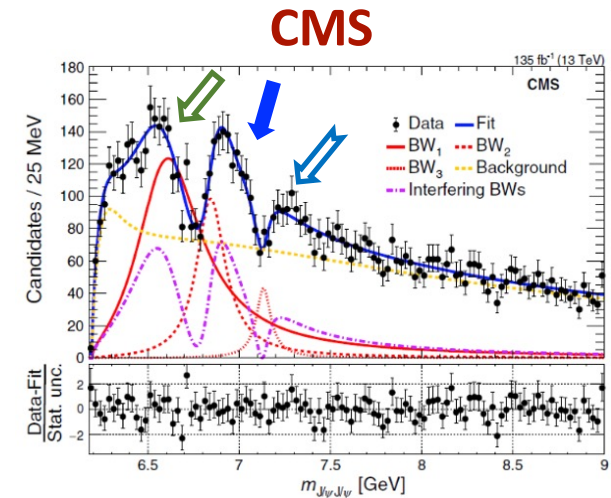
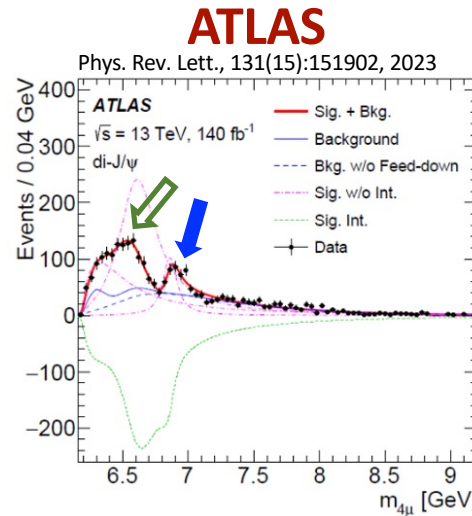
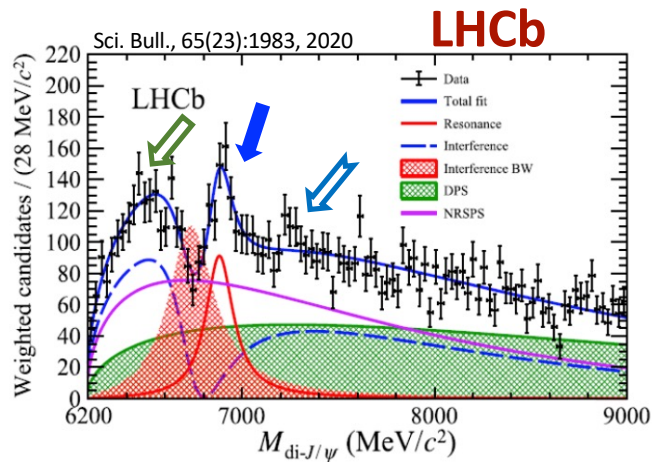
第八届粒子物理天问论坛， 广西桂林， 2026年8月27--31

Outline

- ❑ Structures in $J/\psi J/\psi$ system
- ❑ Structures in $\phi\phi$ and
- ❑ Structures in $J/\psi\phi$ systems
- ❑ Summary
- ❑ Outlook

Status before CMS update with Run 3

❖ All-charm Tetraquark at LHC in $J/\psi J/\psi$ channel



❑ ALL exp observe **X(6900)** + additional structure

➤ Only CMS claimed states **X(6600)** & **X(7100)**

- **Hump @ 6.6 GeV**: Multiple models offered
- **Hint @ 7.2 GeV**: LHCb not consider; ATLAS 3 σ hint in $J/\psi\psi(2S)$

❑ All exp use **interference**, but in diff ways

- LHCb: extra BW interfere with SPS, **X(6900) NOT interfering!**
- ATLAS and CMS: different multi-resonance interference

❑ All exp see a **threshold excess**, NOT explained! Classified as background

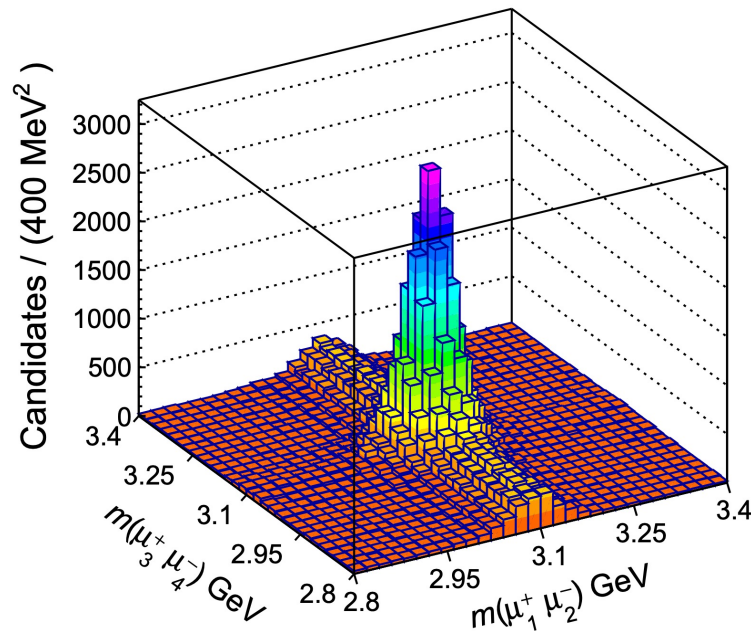


A number of unresolved questions !

CMS $J/\psi J/\psi$ yield adding run 3: two-dimensional fit

135 fb⁻¹ (13 TeV) + 180 fb⁻¹ (13.6 TeV)

CMS



☐ *Luminosity*

Run 2 135 fb⁻¹

Run 3 180 fb⁻¹

☐ *$J/\psi J/\psi$ yield*

Run 2: 12622 ± 165

Run 2+3 44936 ± 692

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

Run 2 ~ 93 events / fb⁻¹

Run 3 ~ 177 events / fb⁻¹

Parked data!!!

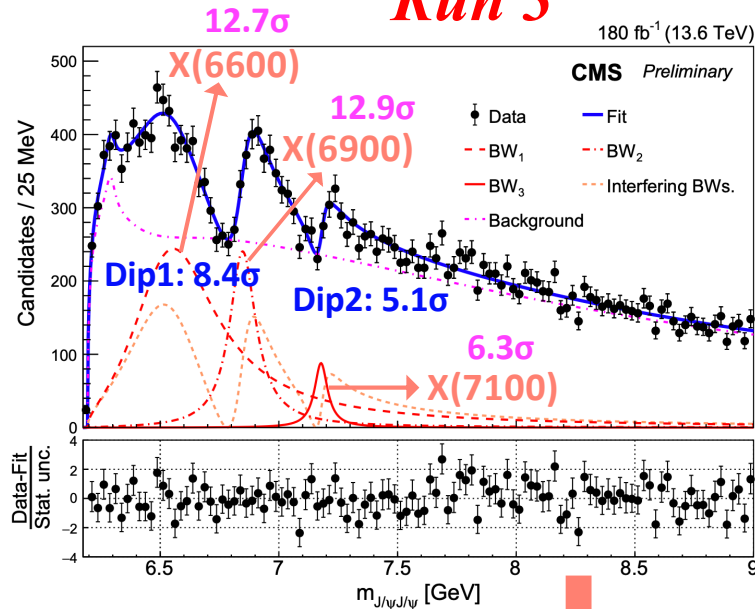
➤ Run 2+3 $J/\psi J/\psi$ yield is **3.6X** of Run 2

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

[arXiv:2602.02252](https://arxiv.org/abs/2602.02252), submitted to science advances

Confirmation of 3 structures

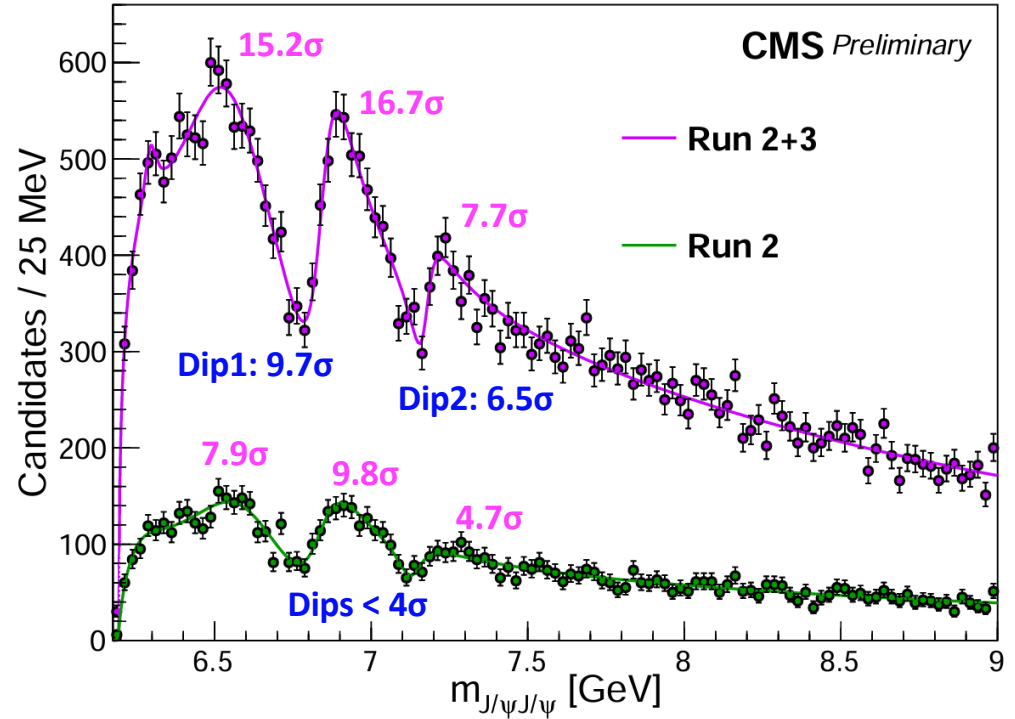
Run 3



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

Run 2+3

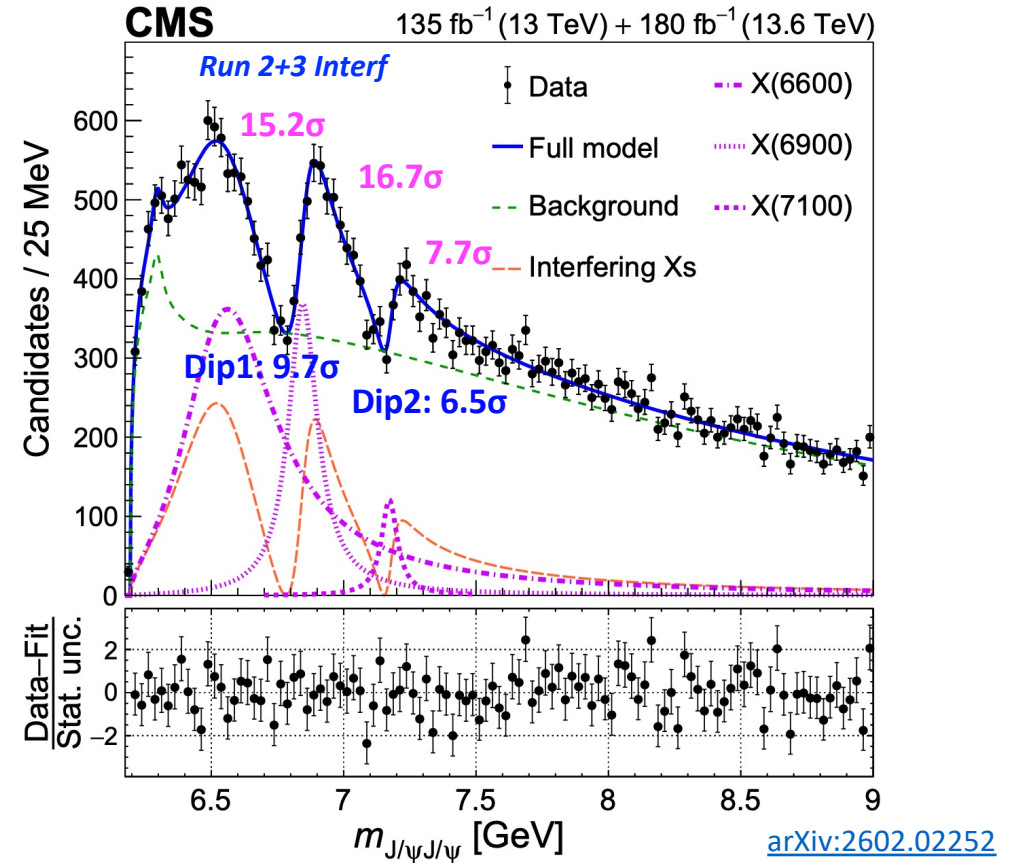
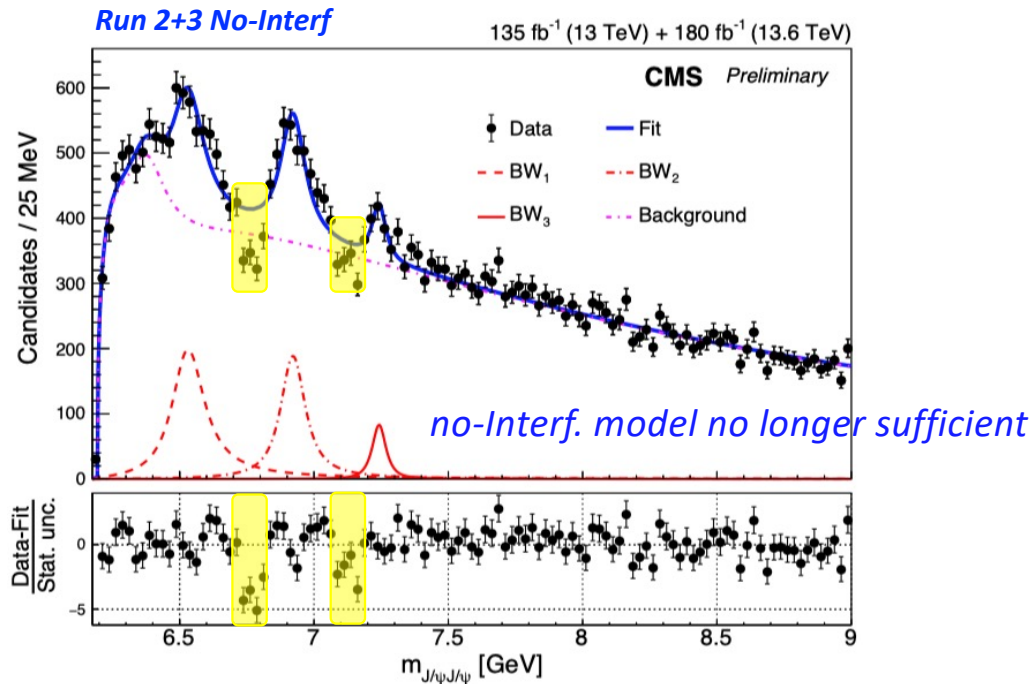
135 fb⁻¹ (13 TeV) + 180 fb⁻¹ (13.6 TeV)



- ✓ Confirm Run 2 results **with Run 3 data only**
- ✓ All states and dips above **5 sigma**

Confirmation of interferences among 3 structures

❖ Interference model with Run 2 + 3:



- ✓ All states and dips (interference) $\gg 5\sigma$!
- ✓ Strongly imply that they have **same** J^{PC}
- ✓ VS. Run 2 result, precision improves, **stat. (syst.) uncertainty** reduced by a factor of 3 (2)

Improved resonance parameters

Dominant sources	Δm_{BW_1}	$\Delta \Gamma_{BW_1}$	Δm_{BW_2}	$\Delta \Gamma_{BW_2}$	Δm_{BW_3}	$\Delta \Gamma_{BW_3}$
Signal shape	25	52	2	11	3	5
NRSPS shape	3	7	<1	1	<1	5
DPS shape	<1	5	<1	<1	<1	1
Combinatorial bkg shape	<1	22	<1	2	<1	4
Feeddown	<1	1	<1	<1	<1	<1
Mass resolution	4	58	15	7	12	5
Efficiency	<1	4	<1	<1	<1	<1
Without BW_0	<1	29	2	3	2	1
Total uncertainty	25	87	15	14	13	10

[arXiv:2602.02252](https://arxiv.org/abs/2602.02252), submitted to science advances

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

❖ VS. Run 2 result

- ✓ Statistical uncertainty reduced by a factor of 3
- ✓ Systematic uncertainty reduced by about a factor of 2
- ✓ Large mass splittings (> 200MeV) still exist, with improved precision

Status of $J/\psi\psi(2S)$ channel before CMS result

❖ ATLAS 2023 result for $J/\psi\psi(2S) \rightarrow 4\mu$

[Phys. Rev. Lett., 131\(15\):151902, 2023](#)

4.7 σ for X(6900) in Model α

3.0 σ for the stand-alone resonance

❖ ATLAS new result (2025) $J/\psi\psi(2S) \rightarrow 4\mu + 2\pi$

[arXiv:2509.13101](#)

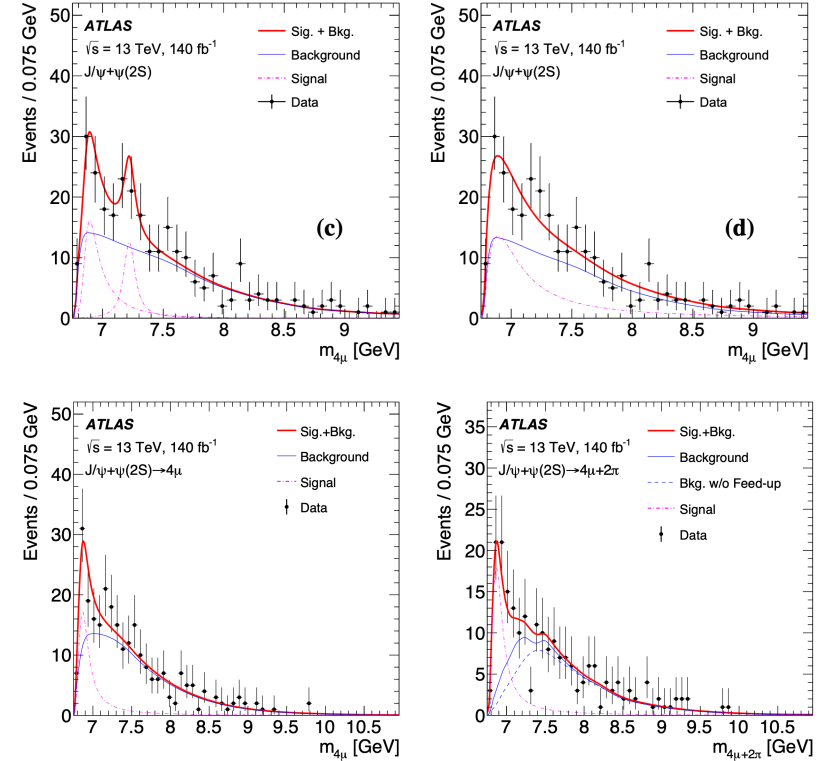
Simultaneous fit of 2 channels:
 $J/\psi\psi(2S)$ [4μ and $4\mu+2\pi$]

8.9 σ for X(6900) in $J/\psi\psi(2S)$ with 4μ
and $4\mu+2\pi$ final state

Set a upper limit for X(7200)

$X(7200) / X(6900) = 0.12 \pm 0.11$

(UL < 0.41, 95% CL)



	model A	model B	model C
m / GeV	$6.860 \pm 0.023 \pm 0.010$	$6.902 \pm 0.008 \pm 0.010$	$6.884 \pm 0.017^{+0.058}_{-0.005}$
Γ / GeV	$0.082 \pm 0.032 \pm 0.015$	$0.183 \pm 0.025 \pm 0.007$	$0.178 \pm 0.054^{+0.176}_{-0.024}$
R	$1.08 \pm 0.20^{+0.40}_{-0.09}$	$0.93 \pm 0.17 \pm 0.11$	—

Explore $J/\psi\psi(2S)$ channel at CMS

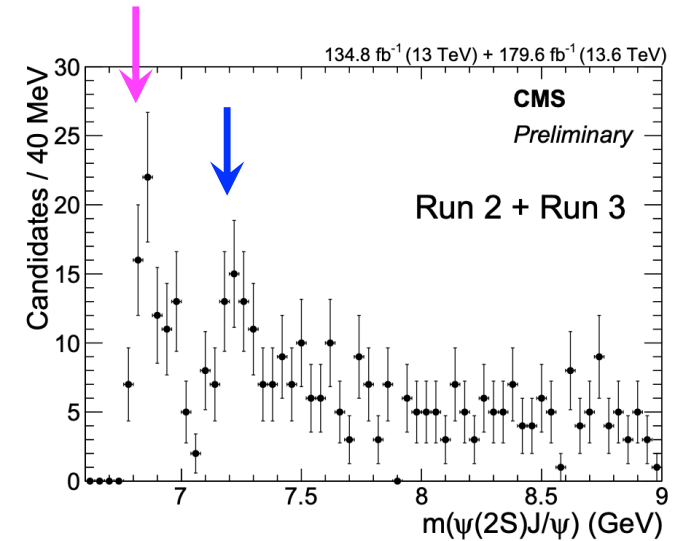
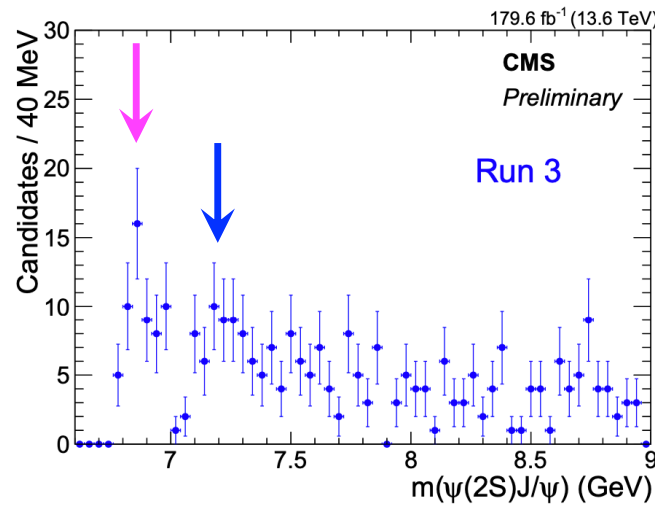
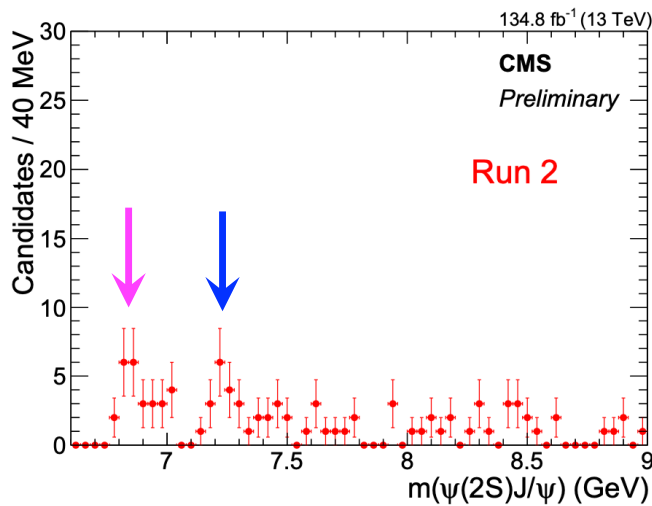
- $X(6900)$ near threshold obvious
- $X(7100)$ is visible
- According to $J/\psi J/\psi$ channel, should be an $X(6900)$ and an $X(7100)$
- Signal dominated by Run 3
- Two dimensional fit for $J/\psi\psi(2S)$ yield **$\sim 2.6 \times$ of Run 2**

[arXiv:2602.02252](https://arxiv.org/abs/2602.02252), submitted to science advances

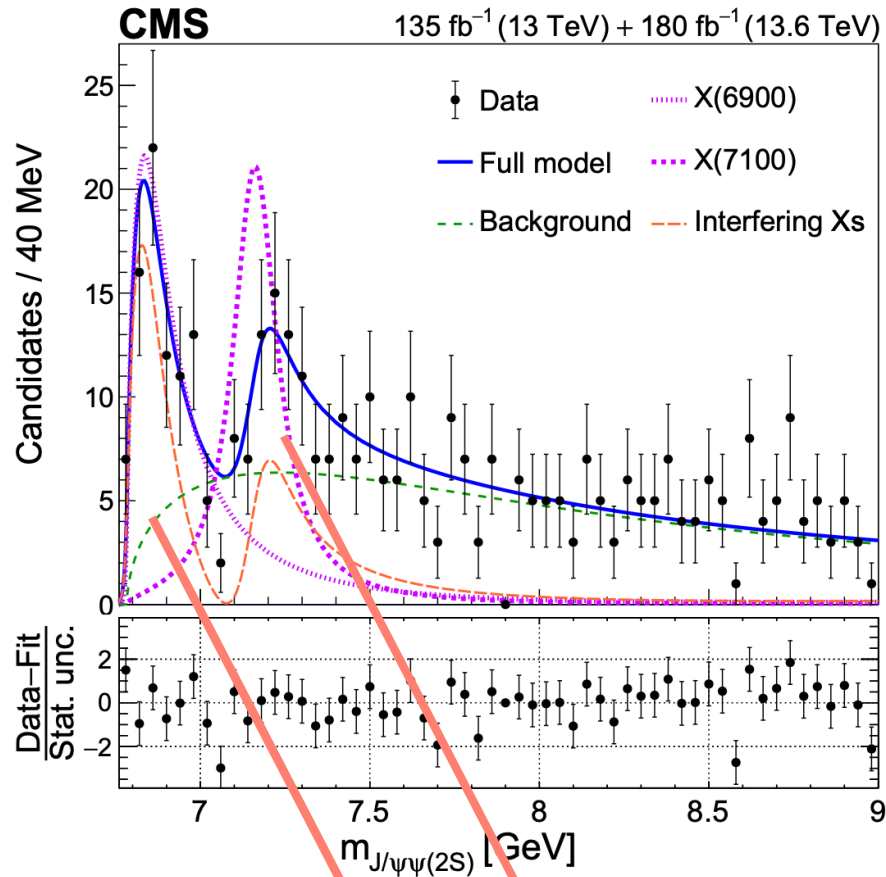
Run 2 $\sim 109 \pm 14$

Run 3 $\sim 281 \pm 22$

Run 2+3 $\sim 386 \pm 26$



Explore $J/\psi\psi(2S)$ channel at CMS



- Significance of **X(6900) = 8.1σ**
- Significance of **X(7100) = 4.3σ**

[arXiv:2602.02252](https://arxiv.org/abs/2602.02252), submitted to science advances

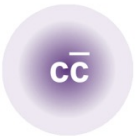
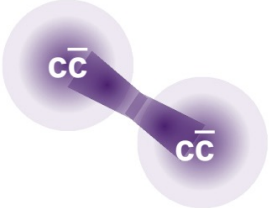
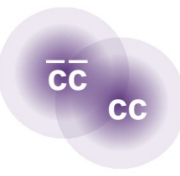
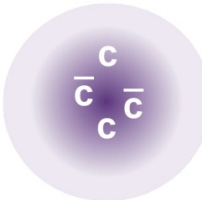
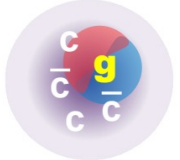
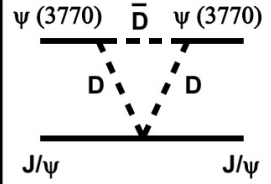
[arXiv:2602.02252](https://arxiv.org/abs/2602.02252)

Param.	$J/\psi\psi(2S)$ [MeV]	$J/\psi J/\psi$ [MeV]
$M(X(6900))$	$6876^{+46+111}_{-29-112}$	$6847 \pm 10 \pm 15$
$\Gamma(X(6900))$	$253^{+290+140}_{-100-134}$	$135^{+16}_{-14} \pm 14$
$M(X(7100))$	7169^{+26+80}_{-52-72}	$7173^{+9}_{-10} \pm 13$
$\Gamma(X(7100))$	$154^{+110+140}_{-82-181}$	$73^{+18}_{-15} \pm 10$

- ✓ **Consistent with $J/\psi J/\psi$ result!**
- ✓ **Confirmed in a different channel!**
- **Interference significance: 2.5 σ**

Theoretical models

[arXiv:2602.02252](https://arxiv.org/abs/2602.02252)

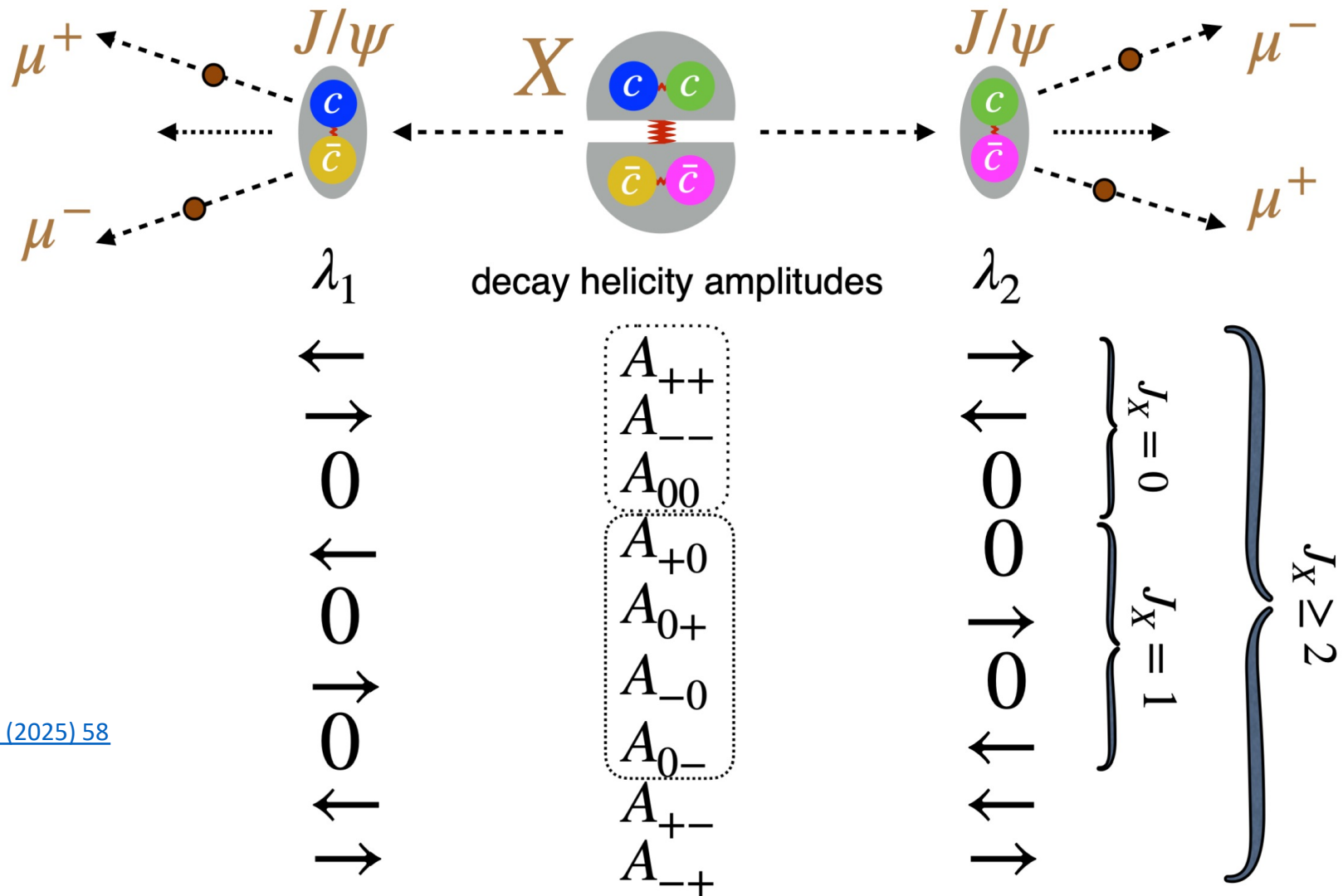
Standard meson	Exotic mesons: all-charm tetraquark				Threshold effects
	Molecule 	Diquark 	Compact (amorphous) 	Hybrid 	e.g., triangle singularity 

❖ Models of potential quark configurations for $J/\psi J/\psi$ 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 dicharmonia production thresholds
-

- *What are their internal structures? What we can do experimentally?*
- *Spin-parity measurement provide critical insights*

J/ψ polarizations



Simplification in angular analysis

- Full model possible, but very complex

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

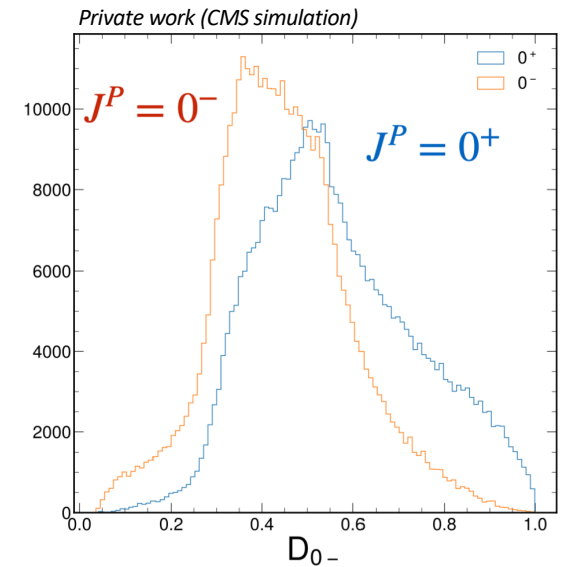
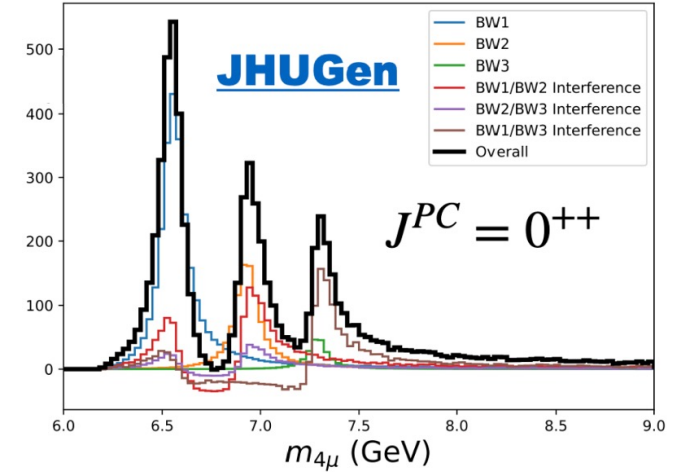
➤ Simplifications

- Assume same properties of 3 resonances (as implied by interference)
- Create **optimal discriminant**, **hypothesis test** for i and j

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

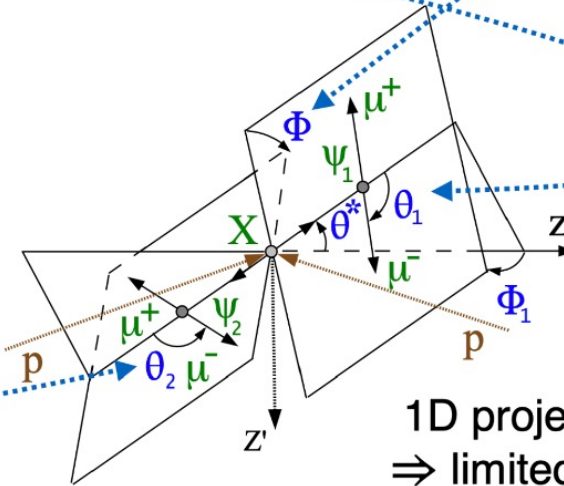
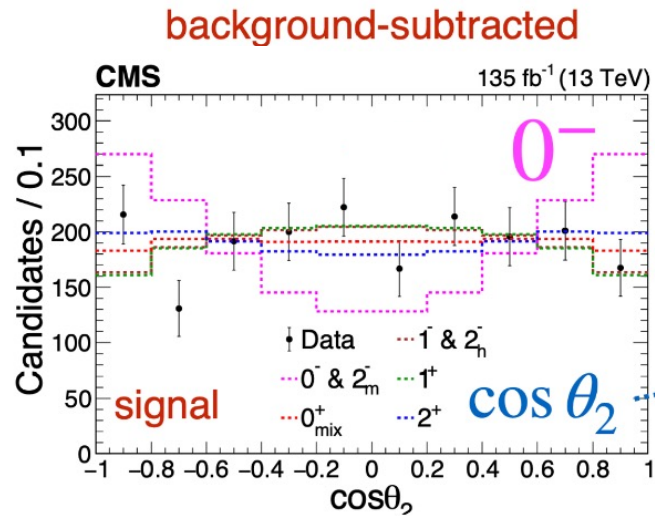
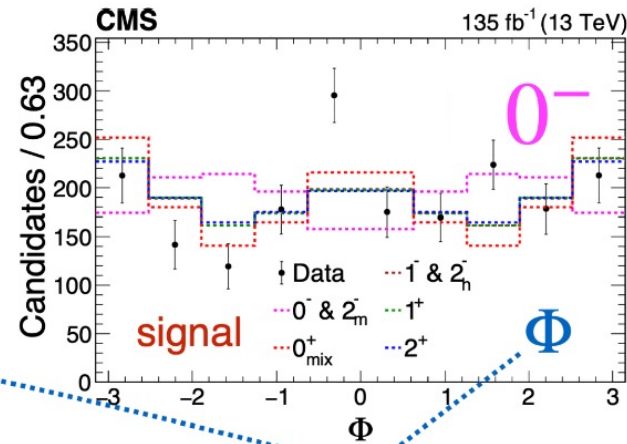
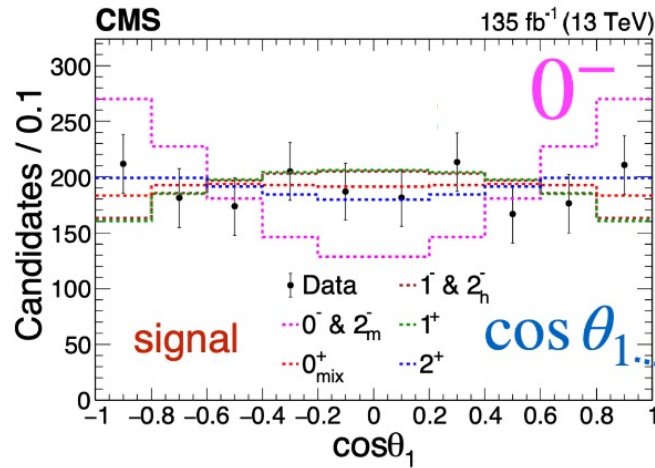
➤ Final 2D model

$$\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \underbrace{\mathcal{P}_k(m_{4\mu})}_{\text{Empirical}} \cdot \underbrace{T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})}_{\text{Angular}}$$



Decay Angles

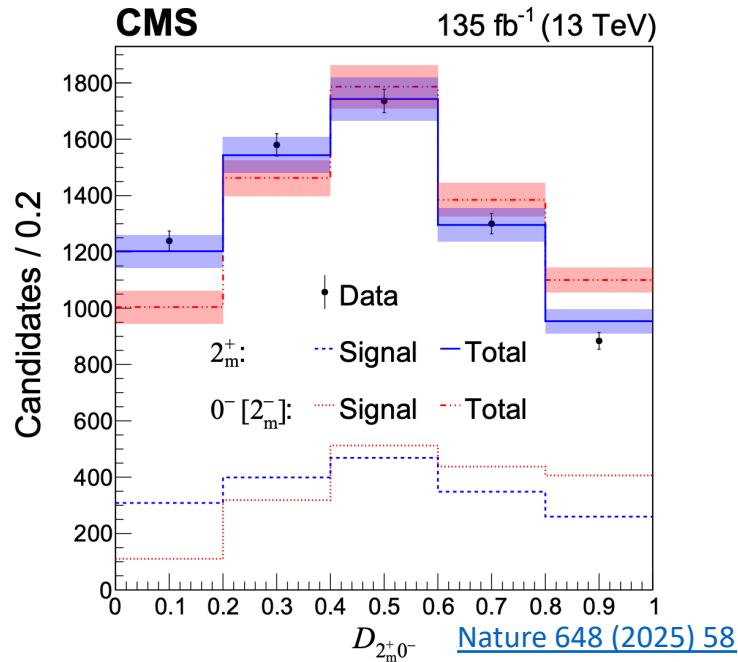
decay angles (consistency check): **distinguish** models [Nature 648 \(2025\) 58](#)



1D projections from 4D
⇒ limited information

Optimal Observable

- 1D projection of data, optimal for $j = 0^-(2_m^-)$ vs $i = 2_m^+$

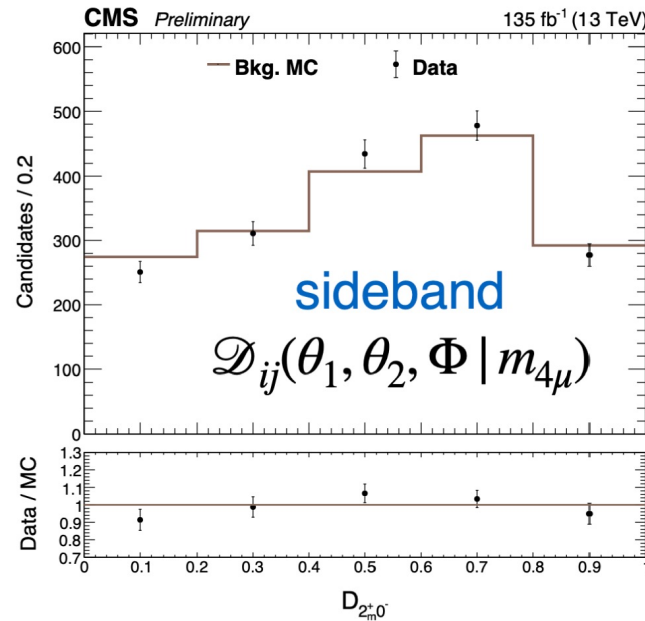


optimal observable

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

1D projections from 2D

⇒ limited information

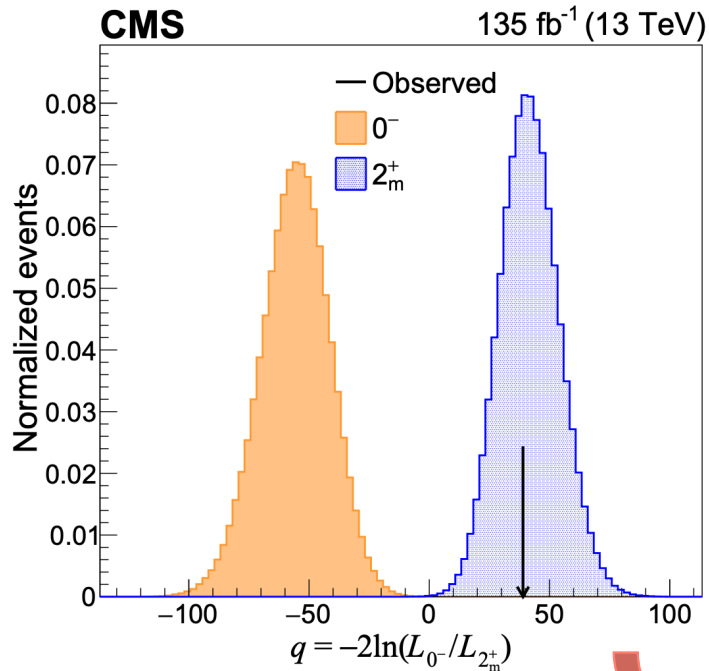


background model from MC
control in sidebands
systematic variations

2D parameterization:

$$\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})$$

Statistical Analysis



[Nature 648 \(2025\) 58](#)

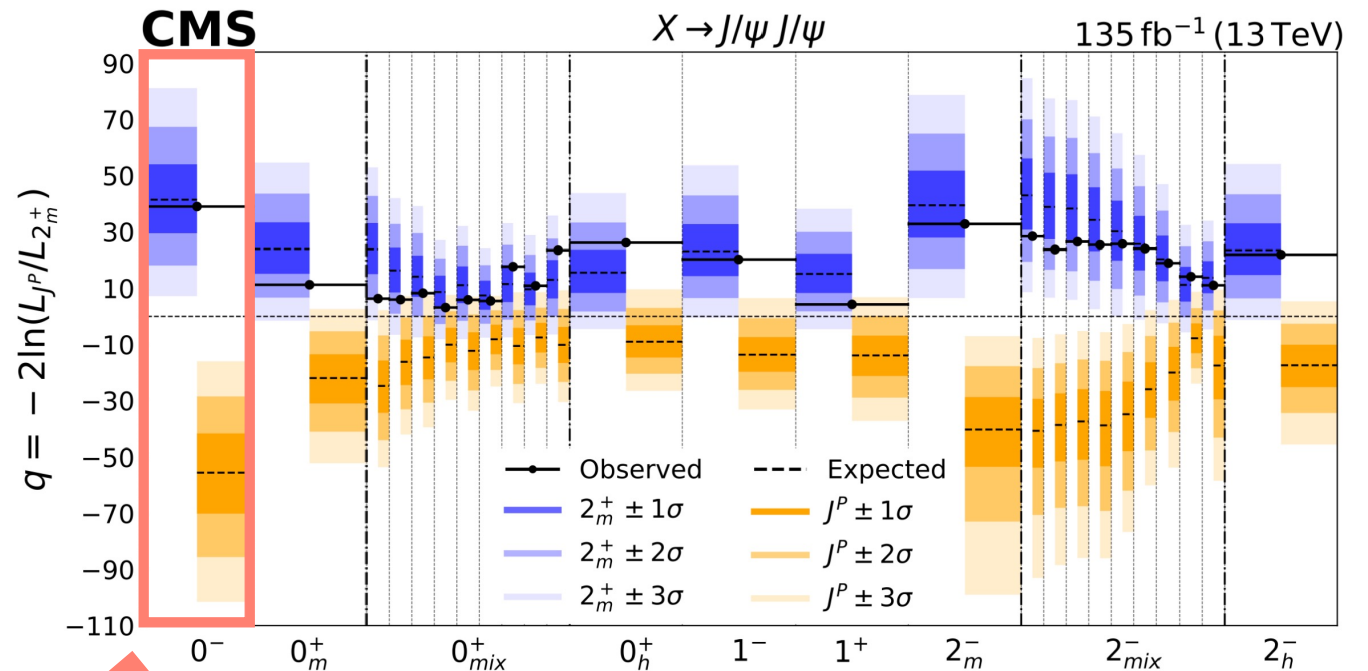
PC = + + very certain

$J \neq 1$ at > 99% CL

$J \neq 0$ at > 95% CL

$J > 2$ less likely

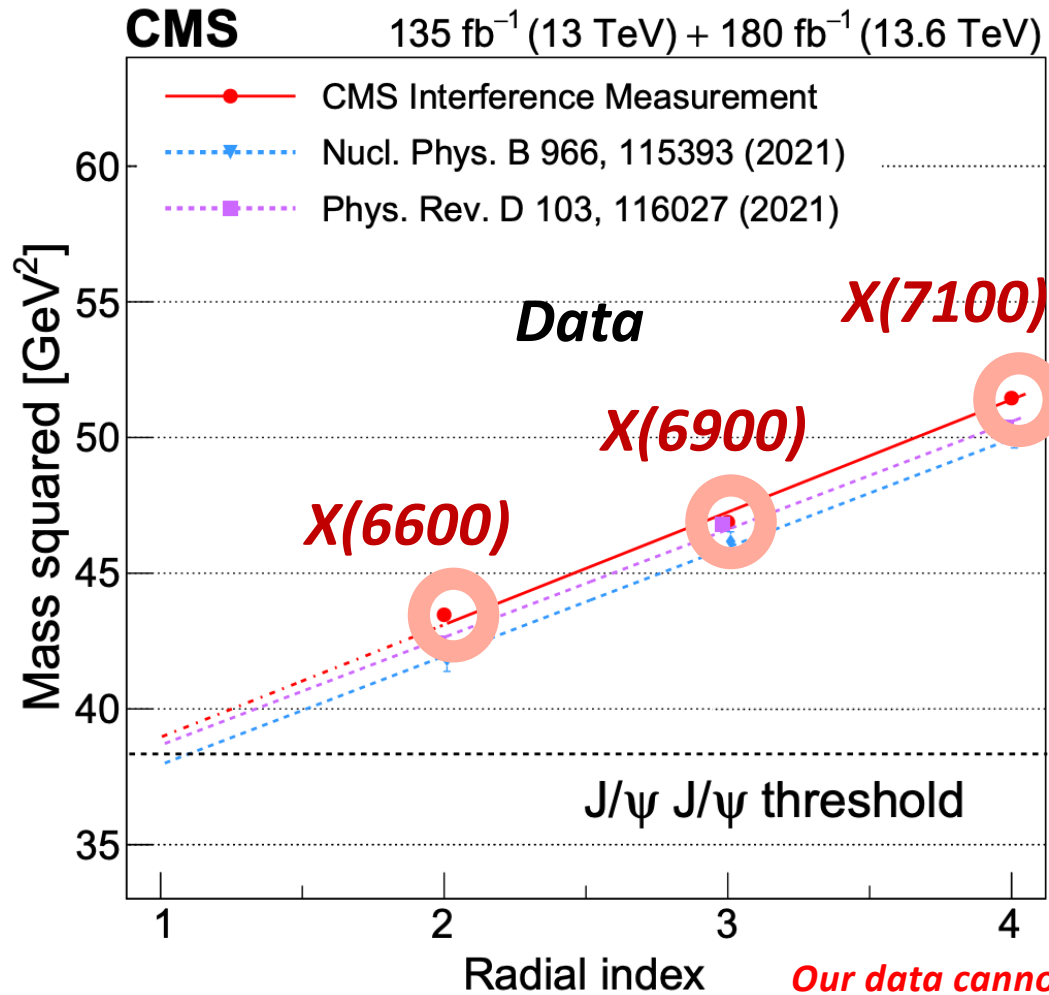
$J = 2$ consistent, *rare* in nature



Scan mixture of **0⁺⁺** amplitudes

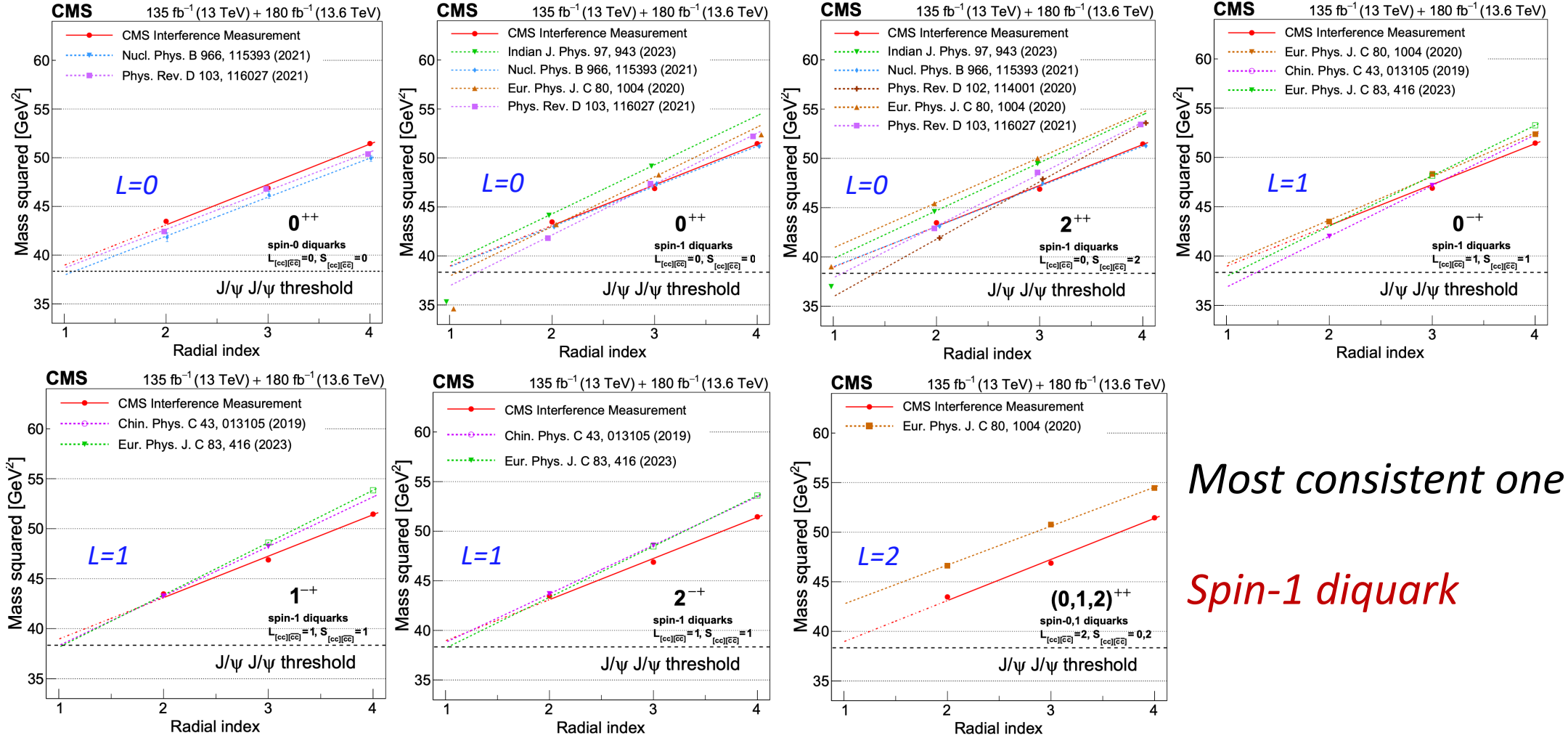
Scan mixture of **2⁻⁺** amplitudes

Discussion—Radial Regge trajectory



- *Mass squared align Regge trajectory*
- *Interference—family indication*
- *A few predictions for a family*
- *Most are diquark-antidiquark model*
- *Compare to available predictions*

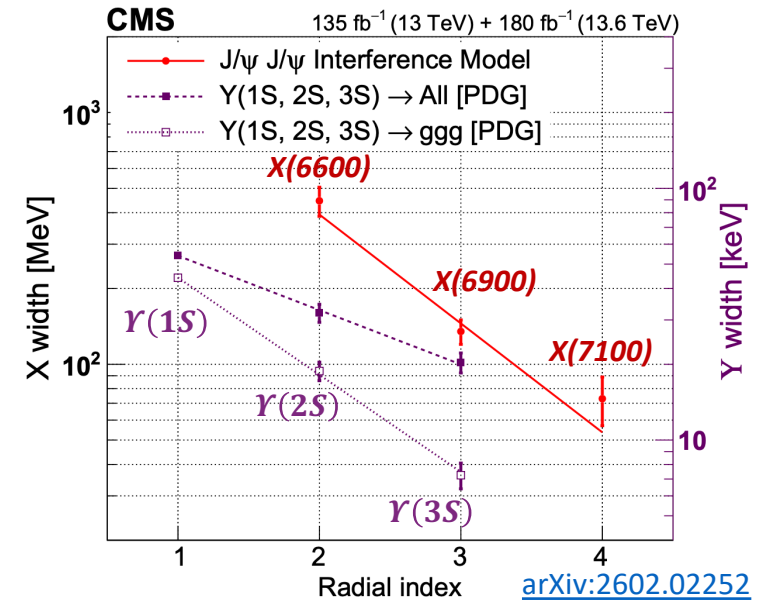
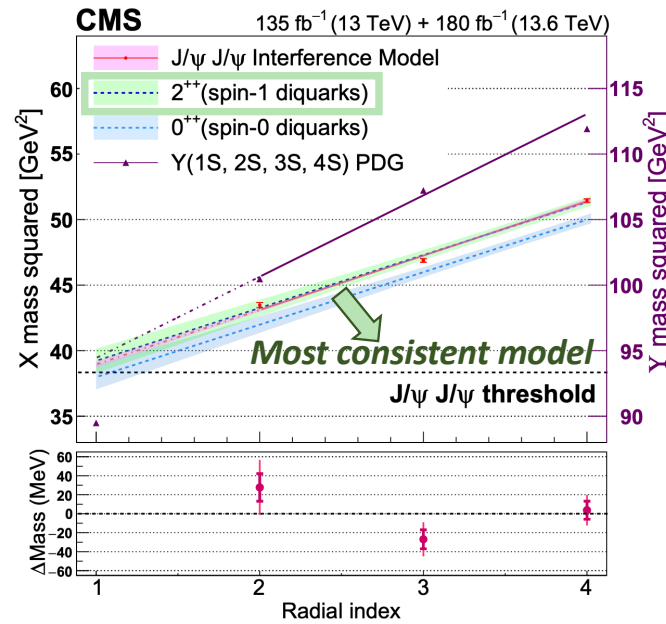
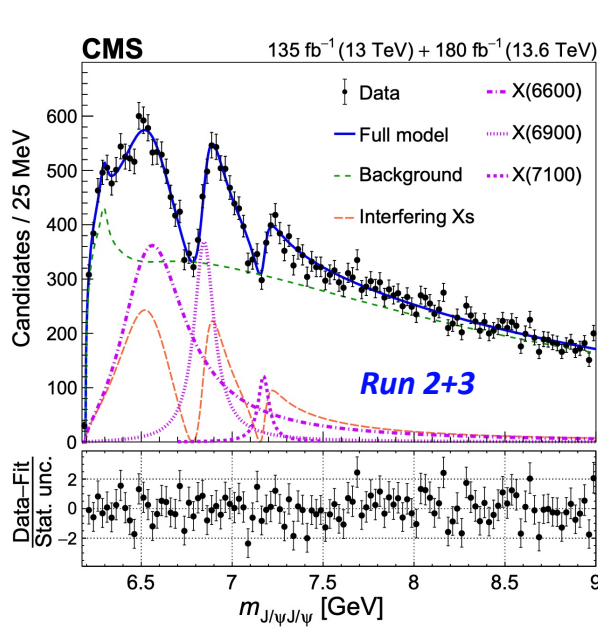
Discussion—comparisons to diquark predictions



Most consistent one

Spin-1 diquark

Discussion—preliminary physics picture

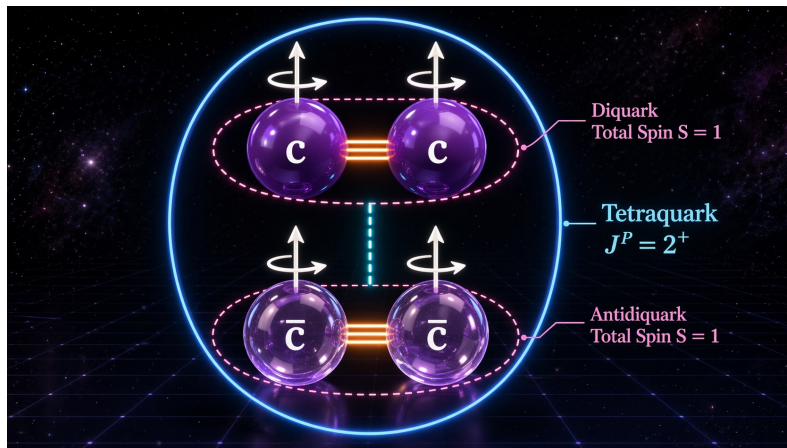


- Interference imply same J^{PC} quantum numbers
- > 200 MeV mass splittings among triplet similar to Y family
- Squared masses of triplet align Regge trajectory ==> **Radial excitations**
- Regge plot favors **spin-1 diquark model**
- Width trend similar to Y family --- again pointing to familial relationship for X's'

Discussion—preliminary physics picture

“Although it does not rule out either theory, the 2^{++} result favours the compact tetraquark rather than the loosely bound pair of mesons. ... Studying exotic hadrons might improve scientists’ knowledge of the strong force. This knowledge, in turn, could help to explain how hadrons formed a few microseconds after the Big Bang; aid the development of accurate models of neutron stars; and help scientists to search for physics not described in the standard model.”

[Elena Santopinto](https://www.nature.com/articles/d41586-025-03591-7): Nature News and View (2025) <https://www.nature.com/articles/d41586-025-03591-7>



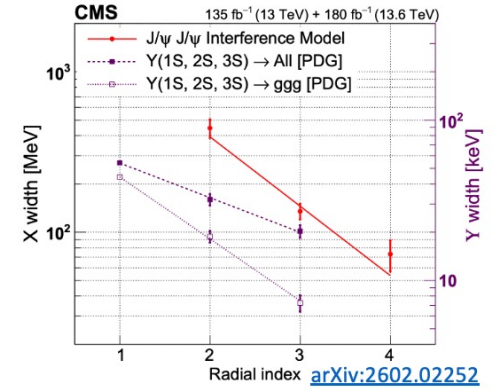
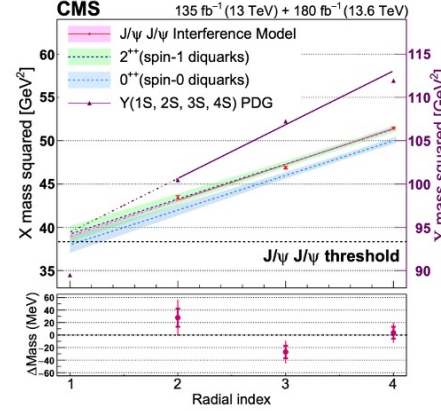
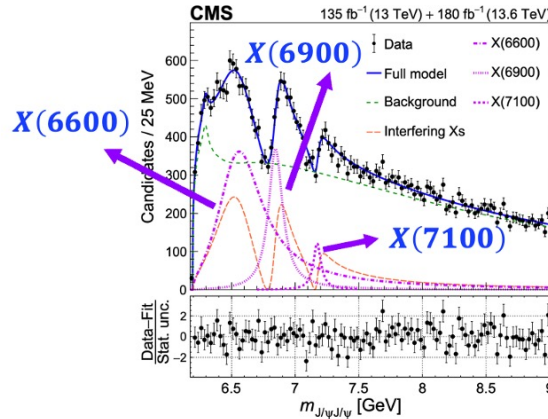
Same quark $\implies$ spin-1 diquark ($L=0$)

Let's check other related VV systems:

$J/\psi J/\psi, \phi\phi$ and $J/\psi\phi$

$J/\psi J/\psi$ system

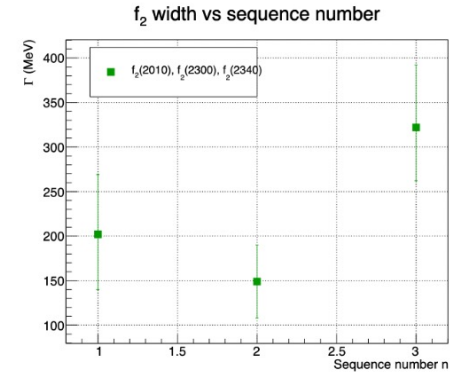
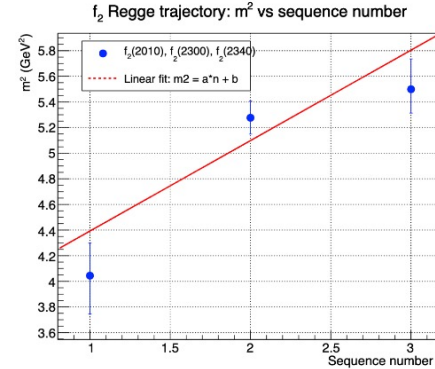
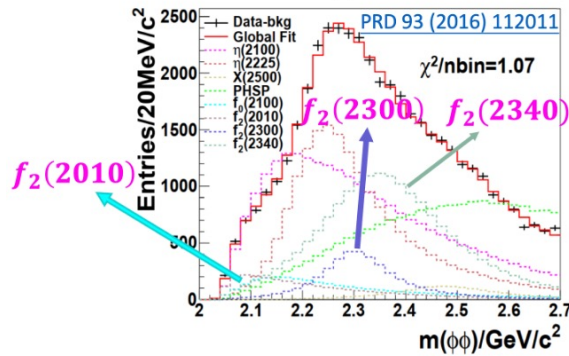
Same flavor $\sim 2^+$



$\phi\phi$ system

BESIII $J/\psi \rightarrow \phi\phi\gamma$

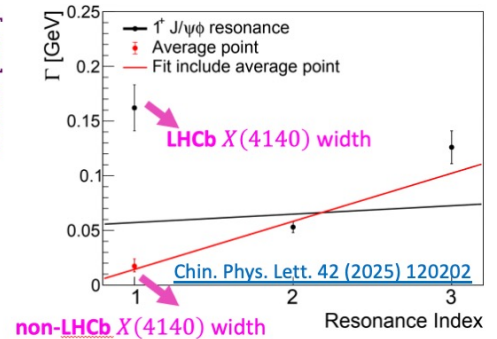
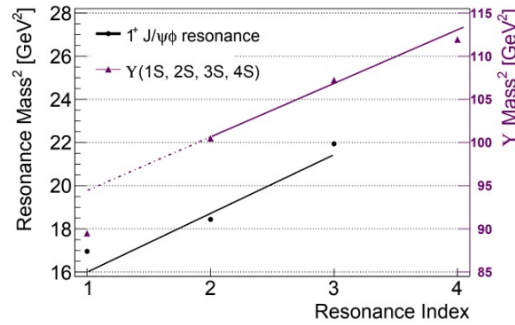
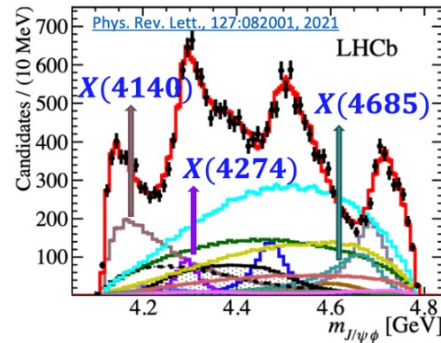
Same flavor $\sim 2^+$



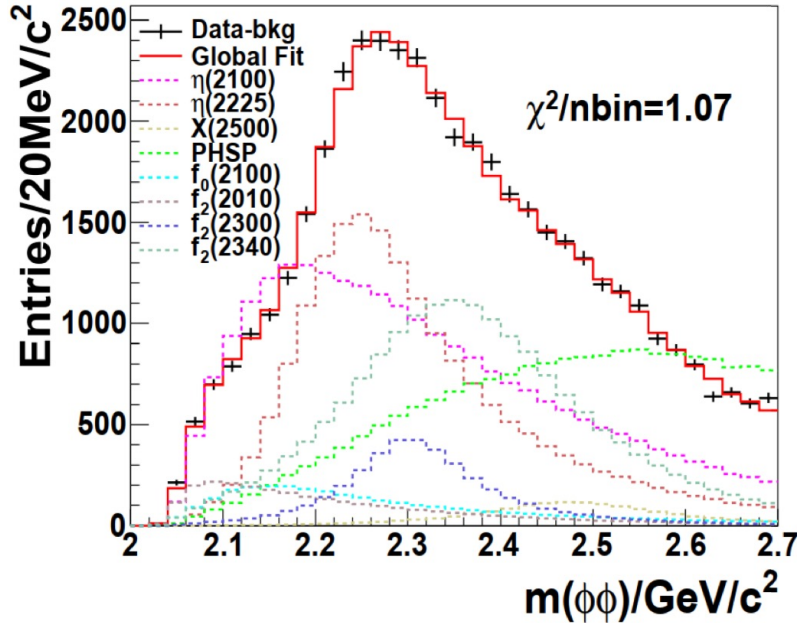
$J/\psi\phi$ system

LHCb $B \rightarrow J/\psi\phi K$

Different flavor $\sim 1^+$



$\phi\phi$ system

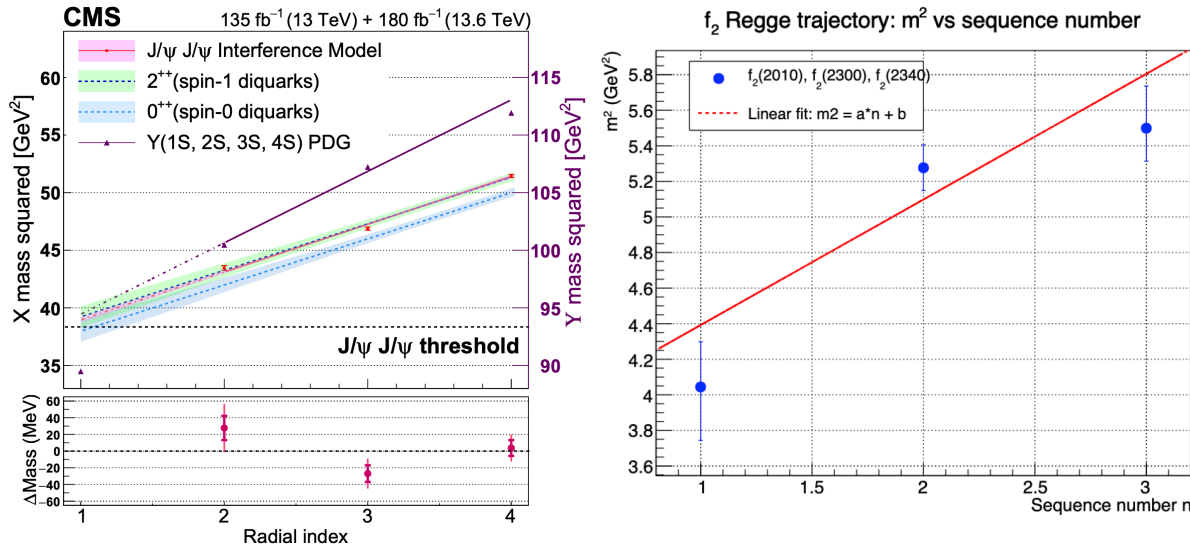


Resonance	M(MeV/c ²)	Γ(MeV/c ²)	B.F.(×10 ⁻⁴)	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	11σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

[PRD 93 \(2016\) 112011](#)

- Large uncertainties on the masses and widths of these three tensor structures from PDG
- No systematic study these structures
- ✓ Partial wave analysis of $J/\psi \rightarrow \phi\phi\gamma$ has been performed by BESIII with ~ 1.3 billion J/ψ events (09+12 data)
 - Confirm $\eta(2225)$, observe $\eta(2100)$ and $X(2500)$
 - Three tensor states $f_2(2010)$, $f_2(2300)$, and $f_2(2340)$ with significance all $> 5\sigma$
 - While their masses and widths are fixed in the published paper

Similarities between $J/\psi J/\psi$ and $\phi\phi$ systems



[arXiv:2602.02252](https://arxiv.org/abs/2602.02252)

Component	M [MeV]	Γ [MeV]	J^P
X(6600)	$6593^{+15}_{-14} \pm 25$	$446^{+66}_{-54} \pm 87$	2^+
X(6900)	$6847 \pm 10 \pm 15$	$135^{+16}_{-14} \pm 14$	2^+
X(7100)	$7173^{+9}_{-10} \pm 13$	$73^{+18}_{-15} \pm 10$	2^+

[PDG 2025](https://pdg.lbl.gov/2025/)

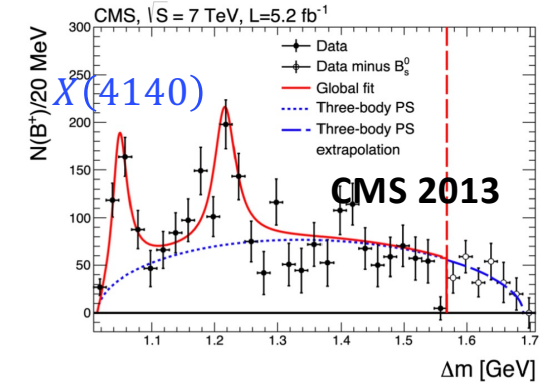
Component	M [MeV]	Γ [MeV]	J^P
$f_2(2010)$	$2011 + 62 - 76$	$202 + 67 - 62$	2^+
$f_2(2300)$	2297 ± 28	149 ± 41	2^+
$f_2(2340)$	$2339 + 50 - 40$	$322 + 70 - 60$	2^+

- Similarities between $J/\psi J/\psi$ and $\phi\phi$ systems:
- Three $J^{PC} = 2^{++}$ structures
 - Masses align with Regge-like trajectory
 - Large widths (hundreds of MeV)
 - System with same flavor, restriction in wave function
 - $J/\psi J/\psi$ triplet ($J^{PC} = 2^{++}$):
 - consistent with diquark-antidiquark model with spin-1 diquarks and $L = 0$

Are we close to the inside configuration for family nature?...

Experimental status of $J/\psi\phi$ structures

Year	Experiment	Luminosity [fb ⁻¹]	Process/Yield $B \rightarrow J/\psi\phi K$	Structure	Mass [MeV]	Width [MeV]	J^P	Significance [σ]
2009	CDF	2.7	75 ± 10	$X(4140)$	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$		3.8*
2010	Belle	825	$\gamma\gamma \rightarrow J/\psi\phi$	$X(4350)$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$		3.2
2011	CDF	6.0	115 ± 12	$X(4140)$	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$		> 5.0*
				$X(4274)$	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32.3^{+21.9}_{-15.3} \pm 7.6$		3.1*
2012	LHCb	0.37	346 ± 20	$X(4140)$	4143.0 (fixed)	15.3 (fixed)		
2013	CMS	5.2	2480 ± 160	$X(4140)$	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$		> 5.0*
2013	DØ	10.4	215 ± 37	$X(4140)$	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$		3.1*
2014	BaBar	422.5	189 ± 14	$X(4140)$	4143.4 (fixed)	15.3 (fixed)		1.6
2014	BESIII		$e^+e^- \rightarrow \gamma J/\psi\phi$	—	—	—		—
2015	DØ	10.4	$p\bar{p} \rightarrow J/\psi\phi + \text{anything}$	$X(4140)$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$		4.7
Average				$X(4140)$	4146.8 ± 2.4	$17.3^{+6.6}_{-5.3}$		
2016	LHCb	3	4289 ± 151	$X(4140)$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^+	8.4
				$X(4274)$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^+	6.0*
				$X(4500)$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^+	6.1*
				$X(4700)$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^+	5.6*
2021	LHCb	9	24220 ± 170	$X(4140)$	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	1^+	13
				$X(4150)$	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	2^-	4.8
				$X(4274)$	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	1^+	18
				$X(4500)$	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	0^+	20
				$X(4630)$	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	1^-	5.5
				$X(4685)$	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	1^+	15
				$X(4700)$	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	0^+	17
2024	LHCb	5	$pp \rightarrow J/\psi\phi + \text{anything}$	$X(4274)$	$4298 \pm 6 \pm 9$	$92^{+22}_{-18} \pm 57$		4.1
				$X(4500)$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$65^{+20}_{-16} \pm 32$		6.1

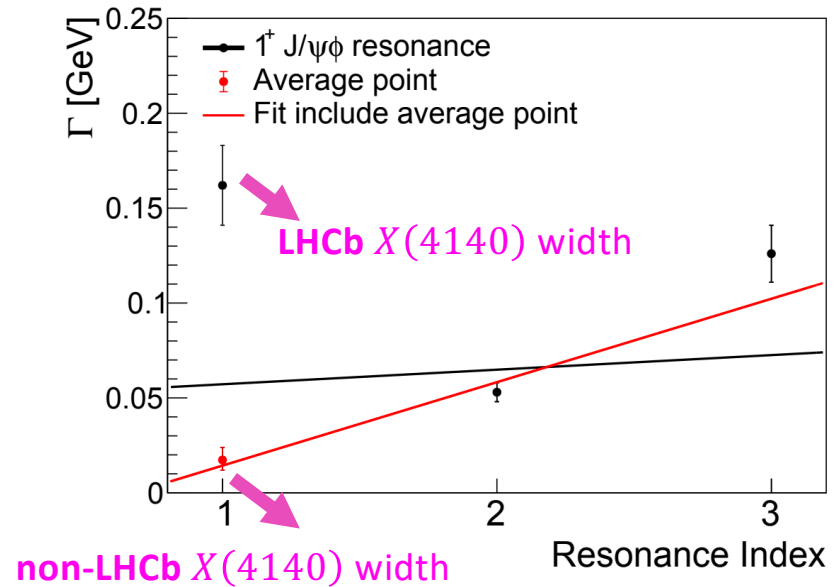
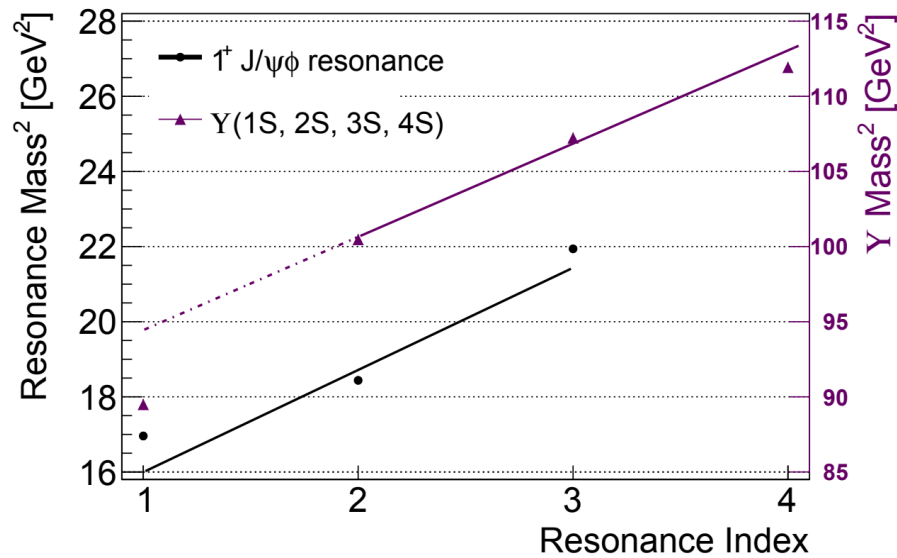


[Phys. Lett. B, 734:261, 2014](#)

[Chin. Phys. Lett. 2025 42\(12\): 120202](#)

- 10 new $J/\psi\phi$ and $J/\psi K$ structures have been claimed in $B \rightarrow J/\psi\phi K$ decays by LHCb
- Not confirmed by other experiments apart from $X(4140)$ and $X(4274)$
- Width of $X(4140)$ by LHCb is inconsistent with previous measurements

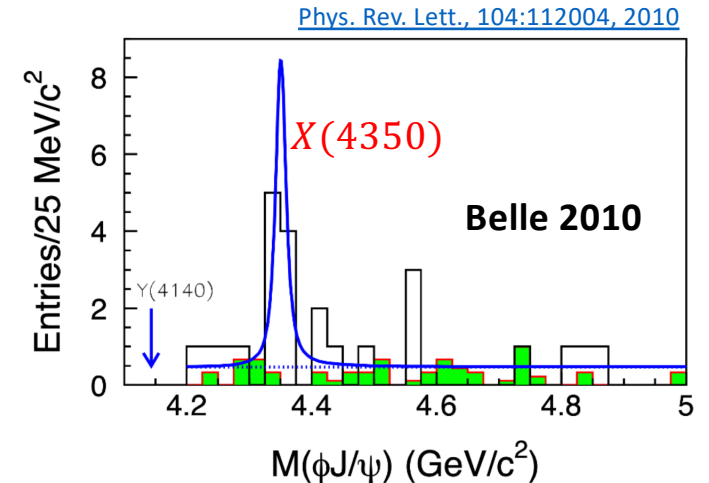
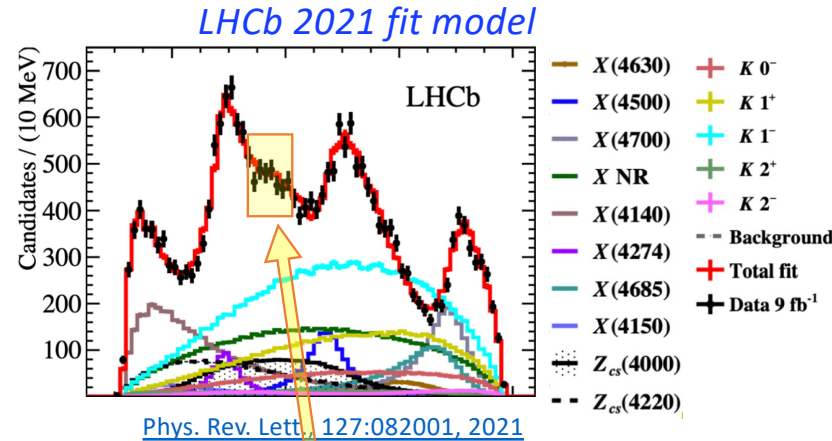
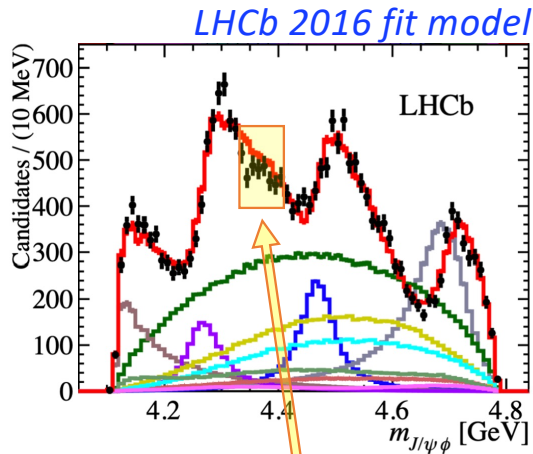
$J/\psi\phi$ system



➤ Similarities in the $J/\psi\phi$ system

- Two neutral vector mesons with hidden flavor
- LHCb studied $B^+ \rightarrow J/\psi\phi K^+$
 - Three 1^{++} states decaying to $J/\psi\phi$: $X(4140)$, $X(4274)$, and $X(4685)$
 - The squared masses of these 1^{++} $J/\psi\phi$ resonances align with Regge-like trajectory
 - Different width trends: non-LHCb $X(4140)$ width vs LHCb $X(4140)$ width

Potential state around 4.35 GeV



- **Notable shoulder** between 4.32 and 4.39 GeV in the $J/\psi\phi$ mass spectrum
- In updated model, shoulder is described by tails from $X(4274)$, $X(4500)$, other ϕK and $J/\psi K$ resonances
 - Cost of invoking a larger set of states, many of which remain to be confirmed
- **Remind:** 2010, Belle, $\gamma\gamma \rightarrow J/\psi\phi$, **Evidence of $X(4350)$** , 3.2σ , $M = 4350.6_{-5.1}^{+4.6} \pm 0.7$ MeV; $\Gamma = 13.9_{-9}^{+18} \pm 4$ MeV
 - Spin is 0 or 2 according to Landau-Yang theorem
- Several tetraquarks have been predicted around 4.3 GeV [Phys. Rev. D, 94:094031, 2016](#)
- **Explore alternative descriptions for the shoulder:**
 - Potential resonance around 4.35 GeV
 - **High spin:** production suppression from spin-0 B meson
 - **Hybrid:** suppressed in B decay

Potential state around 4.35 GeV

- Perform amplitude fit with $X(4350)$ to toy sample (generated based on LHCb 2021 model) [Chin. Phys. Lett. 2025 42\(12\): 120202](#)
 - Scan masses and widths under different J^P for $X(4350)$ and evaluate its significance

➤ Results

Full-set model

J^P	$M = 4320$ $\Gamma = 15$	$M = 4340$ $\Gamma = 15$	$M = 4360$ $\Gamma = 15$	$M = 4320$ $\Gamma = 50$	$M = 4340$ $\Gamma = 50$	$M = 4360$ $\Gamma = 50$	$M = 4320$ $\Gamma = 100$	$M = 4340$ $\Gamma = 100$	$M = 4360$ $\Gamma = 100$
0^+	2.0	1.4	0.5	2.3	1.9	1.4	2.3	2.1	1.9
0^-	1.5	1.4	1.2	1.4	1.5	1.2	1.2	1.1	1.0
2^+	2.7	3.0	2.2	3.4	3.3	3.0	3.7	3.6	3.4
2^-	1.7	2.3	1.7	2.6	2.3	2.8	3.7	3.4	3.5
1^+	2.4	1.5	2.2	2.0	1.9	2.1	1.7	1.6	1.8
1^-	2.3	2.8	1.8	2.8	2.9	2.7	3.0	3.0	3.1

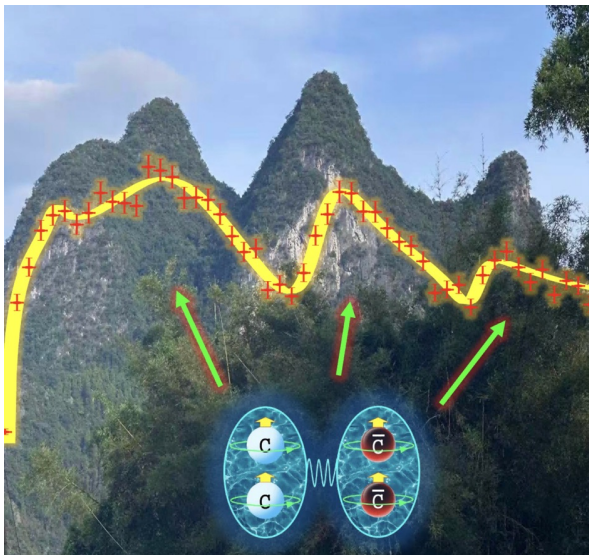
Reduced-set model

J^P	$M = 4320$ $\Gamma = 15$	$M = 4340$ $\Gamma = 15$	$M = 4360$ $\Gamma = 15$	$M = 4320$ $\Gamma = 50$	$M = 4340$ $\Gamma = 50$	$M = 4360$ $\Gamma = 50$	$M = 4320$ $\Gamma = 100$	$M = 4340$ $\Gamma = 100$	$M = 4360$ $\Gamma = 100$
0^+	3.5	2.6	1.3	3.5	3.3	2.6	3.4	3.3	3.1
0^-	2.0	3.3	3.4	4.8	5.3	5.5	6.2	6.4	6.5
2^+	3.5	3.2	2.8	4.7	4.4	4.3	5.8	5.5	5.4
2^-	4.9	3.5	3.9	8.6	7.3	6.9	11.9	10.8	10.1
1^+	3.7	2.7	4.3	5.7	5.5	6.0	7.1	7.3	7.7
1^-	3.8	5.2	5.3	6.2	7.3	8.0	7.8	8.8	9.6

- Spin-2 hypotheses generally yield higher significances than spin-0
 - *Possibility of potential high-spin $J/\psi\phi$ structure near 4.35 GeV*
- Independent information from other experiments could help to clarify with larger statistics

Summary

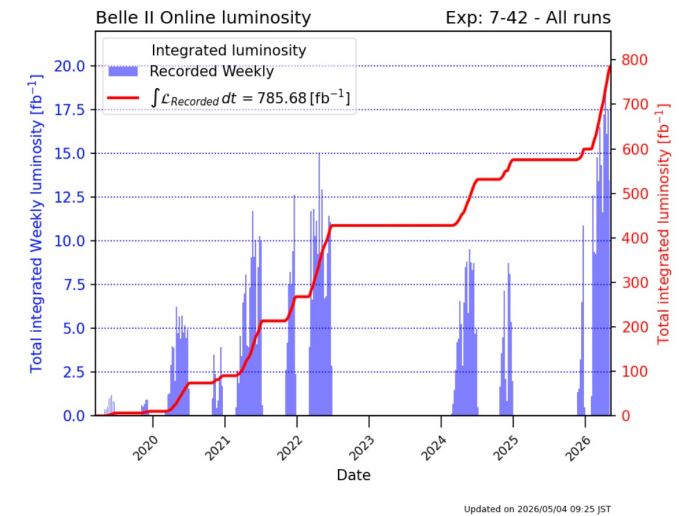
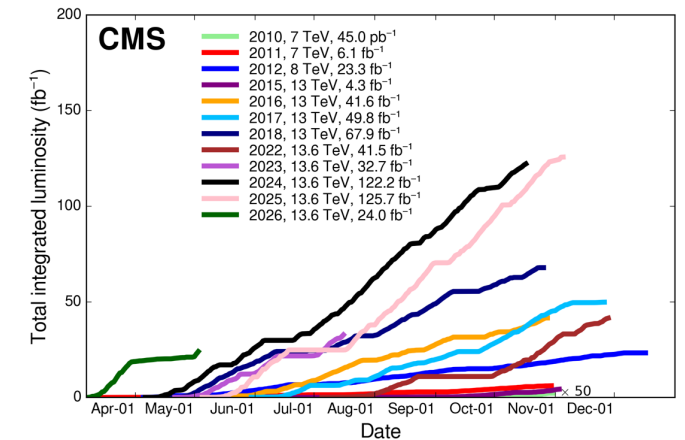
- Three structures X(6600), X(6900), X(7100) well established
- Quantum interference among structures well established
- Resonance parameters precision much improved
- Spin parity measured to favor 2^{++}
- Large mass splittings, Regge trajectory, width trend, spin parity
 - ➔ *Radial spin-1 diquark-antidiquark all charm tetraquark*



Any connection with $\phi\phi$ and $J/\psi\phi$ systems?

Outlook

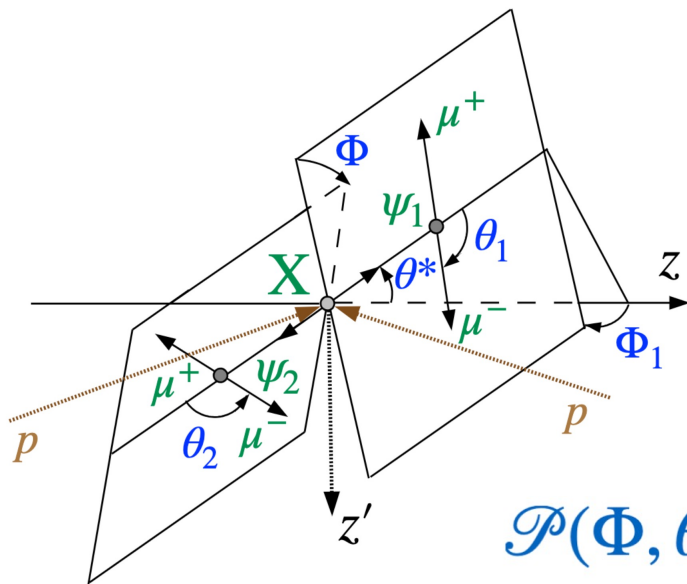
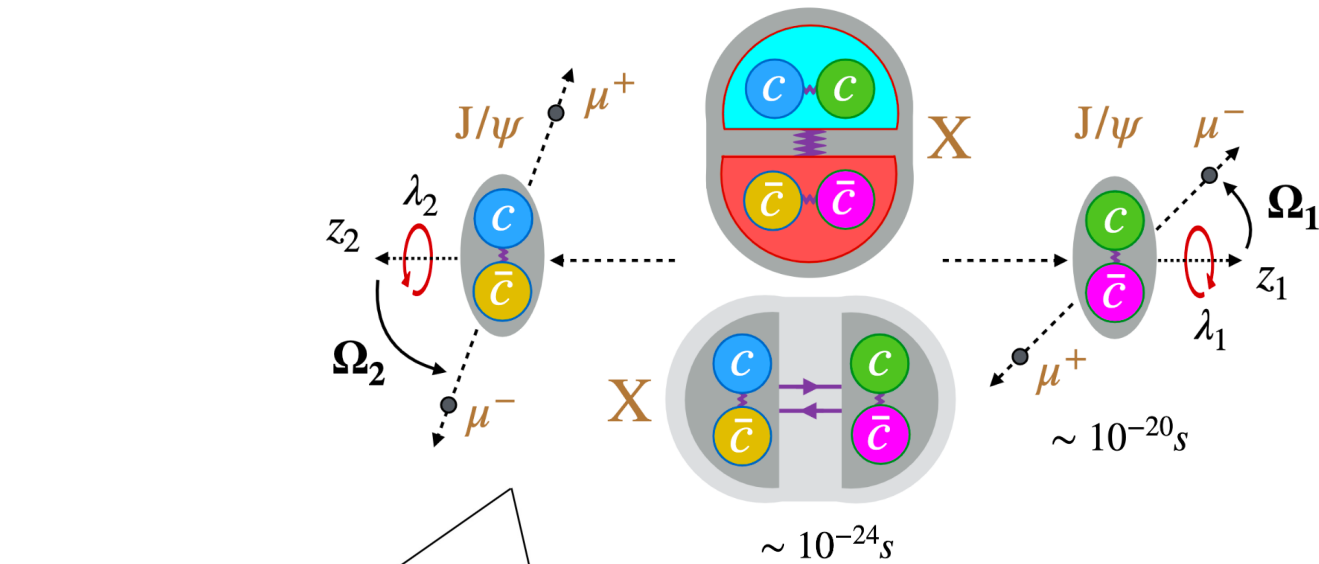
- **More data collected in Run3 (2025+2026~150 fb⁻¹)**
- **From family-level to state-by-state quantum-number measurements**
- **Beyond $X \rightarrow J/\psi J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ and $X \rightarrow J/\psi \psi(2S) \rightarrow \mu^+ \mu^- \mu^+ \mu^-$**
 - $X \rightarrow J/\psi J/\psi \rightarrow \mu^+ \mu^- e^+ e^-$
 - $X \rightarrow J/\psi \psi(2S) \rightarrow \mu^+ \mu^- \mu^+ \mu^- \pi^+ \pi^-$
 - $X \rightarrow J/\psi \psi(2S) \rightarrow \mu^+ \mu^- e^+ e^-$
 - *Interference?*
- **Beyond Spin-Parity: production cross section measurement of X family**
- **Near-threshold enhancements in vector-vector systems:**
 $J/\psi \phi, J/\psi J/\psi, \phi \phi, J/\psi \omega, \omega \phi$
- **How about vector-vector structures composed entirely of c and b quarks?**



Stay tuned!

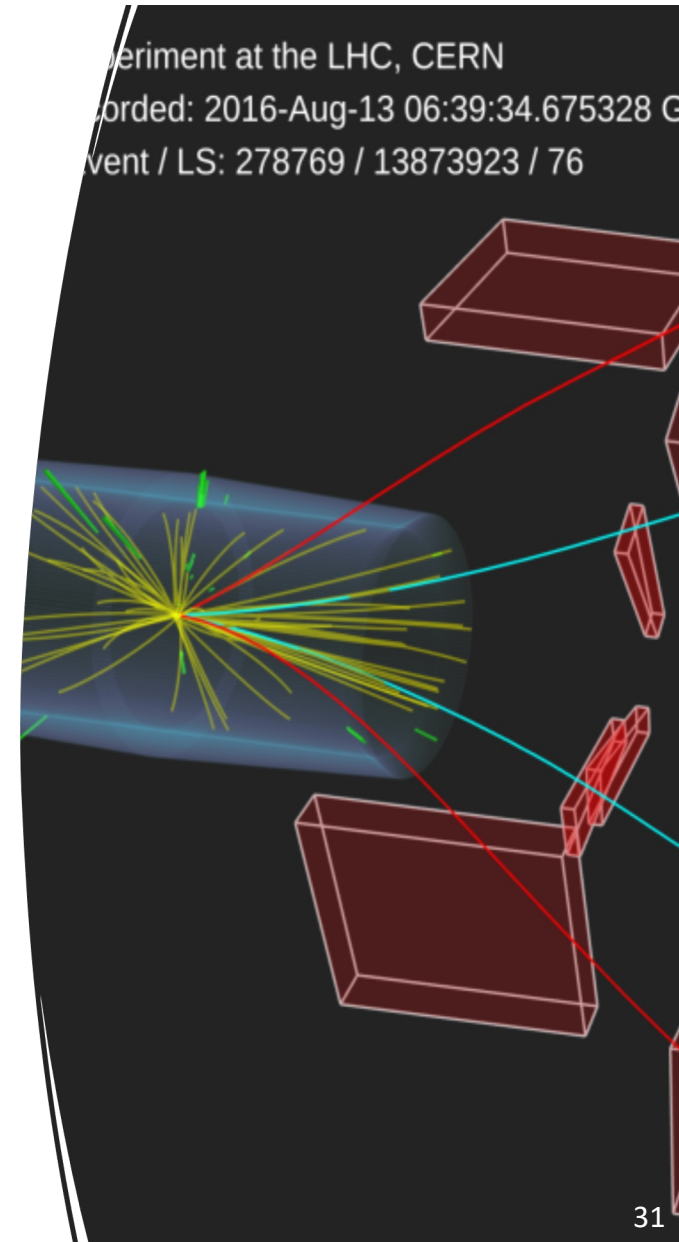
backup

Spin parity analysis



$$J^{PC} = ?$$

[Nature 648 \(2025\) 58](#)



Statistical Analysis

- Hypothesis test with toy MC for $J_1^P = 2_m^+$ vs $J_2^P = 0^-$

- Test statistic $q = -2\ln(\mathcal{L}_{J_2^P} / \mathcal{L}_{J_1^P})$

- Consistency of data with J_1^P / J_2^P using p-value:

$$p = P(q \leq q_{obs} | J_1^P + bkg)$$

$$p = P(q \geq q_{obs} | J_2^P + bkg)$$

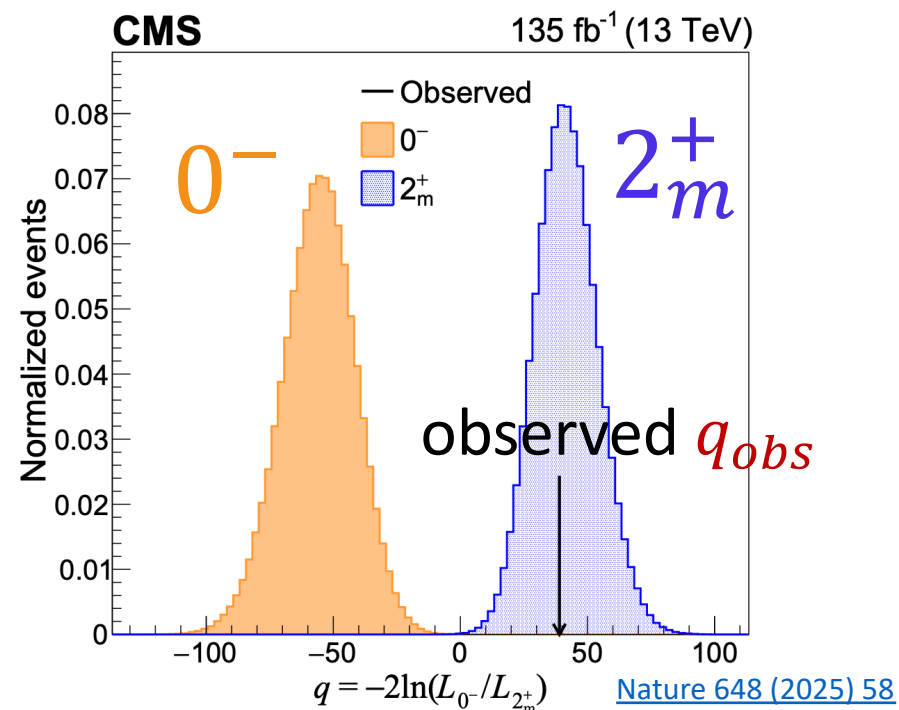
- Significance:

Converted from p-value

via Gaussian one-sided tail integral

- Confidence level

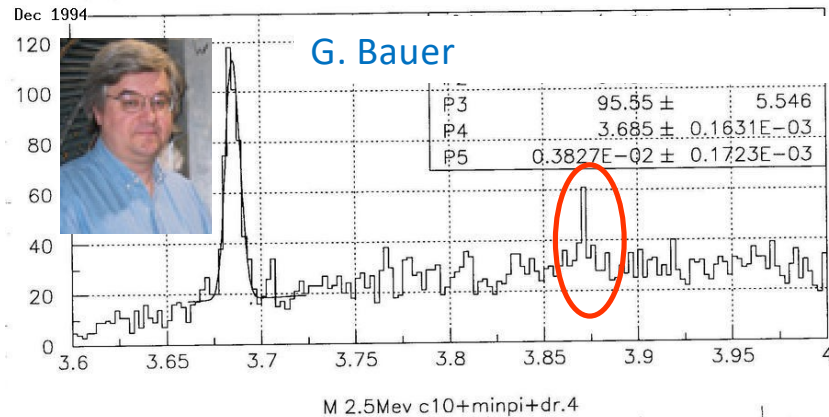
$$CL_s = \frac{P(q \geq q_{obs} | J_2^P + bkg)}{P(q \geq q_{obs} | J_1^P + bkg)}$$



		Observed		Expected	
		p-value	Z-score	p-value	Z-score
0 ⁻ vs 2 _m ⁺	0 ⁻	2.7 × 10 ⁻¹³	7.2	6.5 × 10 ⁻¹⁴	7.4
	2 _m ⁺	4.2 × 10 ⁻¹	0.2	0.50	0.0

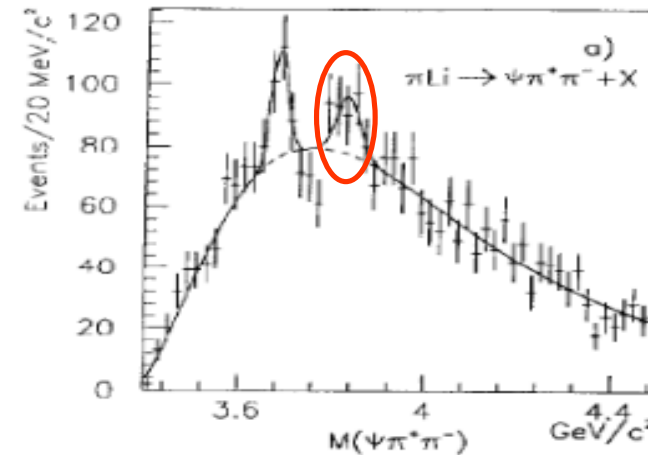
Hints before the discovery of $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

CDF internal, 1994

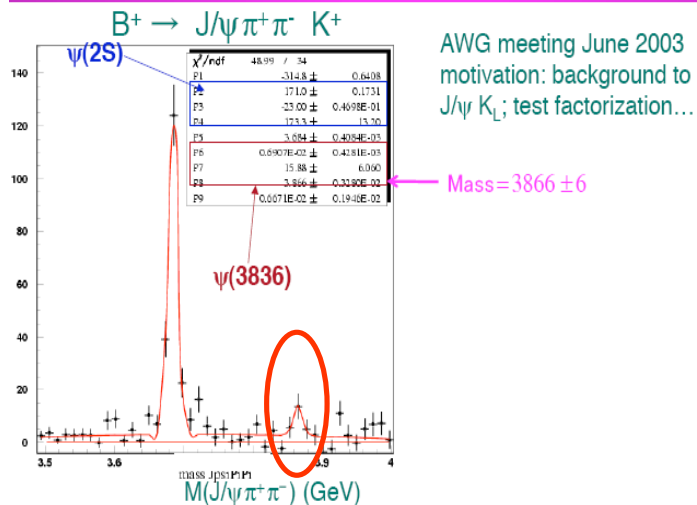


E705, PRD 50, 4258 (1994)

E705 saw $\psi(3836) (2^-)$ in 1994, 3.836 ± 0.013 GeV
PRL 115 011803, PRL 111 032001



BaBar internal, 2003



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

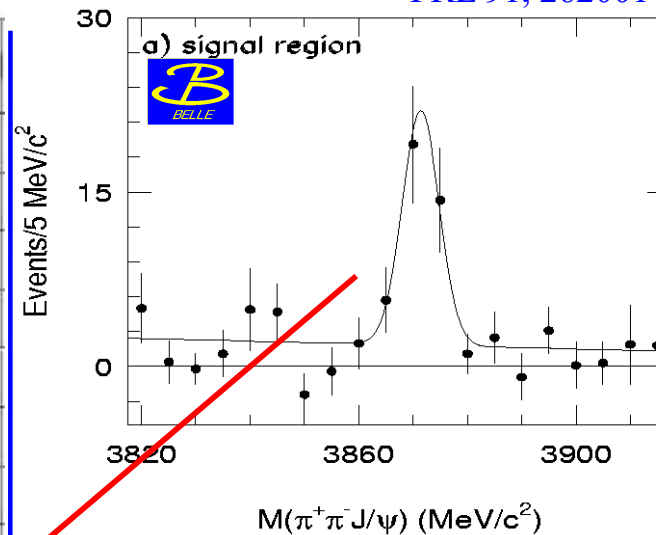
Both CDF and Babar spotted hints of $X(3872)$ before its discovery!

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

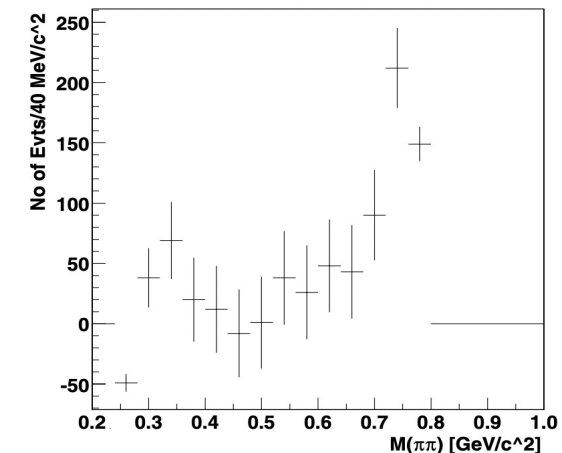
History: X(3872)—2003 (a slide from 2003)

PRL 91, 262001 (2003)

$N^{2S+1}L_J$	J^{PC}	$u\bar{d}, u\bar{u}, d\bar{d}$ $I = 1$	$u\bar{u}, d\bar{d}, s\bar{s}$ $I = 0$	$c\bar{c}$ $I = 0$
1^1S_0	0^{-+}	π	η, η'	$\eta_c(1S)$
1^3S_1	1^{--}	ρ	ω, ϕ	$J/\psi(1S)$
1^1P_1	1^{+-}	$b_1(1235)$	$h_1(1170), h_1(1380)$	$h_c(1P)$
1^3P_0	0^{++}	$a_0(1450)^*$	$f_0(1370)^*, f_0(1710)^*$	$\chi_{c0}(1P)$
1^3P_1	1^{++}	$a_1(1260)$	$f_1(1285), f_1(1420)$	$\chi_{c1}(1P)$
1^3P_2	2^{++}	$a_2(1320)$	$f_2(1270), f_2'(1525)$	$\chi_{c2}(1P)$
1^1D_2	2^{-+}	$\pi_2(1670)$	$\eta_2(1645), \eta_2(1870)$	
1^3D_1	1^{--}	$\rho(1700)$	$\omega(1650)$	$\psi(3770)$
1^3D_2	2^{--}			??
1^3D_3	3^{--}	$\rho_3(1690)$	$\omega_3(1670), \phi_3(1850)$	
1^3F_4	4^{++}	$a_4(2040)$	$f_4(2050), f_4(2220)$	
2^1S_0	0^{-+}	$\pi(1300)$	$\eta(1295), \eta(1440)$	$\eta_c(2S)$
2^3S_1	1^{--}	$\rho(1450)$	$\omega(1420), \phi(1680)$	$\psi(2S)$
2^3P_2	2^{++}	$a_2(1700)$	$f_2(1950), f_2(2010)$	
3^1S_0	0^{-+}	$\pi(1800)$	$\eta(1760)$	



$X(3872) \rightarrow J/\psi \pi^+ \pi^-$
 $M = 3871.8 \pm 0.7 \pm 0.4 \text{ MeV}$
 $\Gamma < 3.5 \text{ MeV @ 90\% CL}$



(Problematic) features
 mass $\sim 70 \text{ MeV} > 1^3D_2$ charmonium
 $M(\pi^+ \pi^-)$ peaks as a ρ , $C=+$, isospin=1 (charmonium--0)

Mass close to DD^* , molecule is speculated

First particle challenging charmonium model,
 Revitalized exotic meson study

Heavy—a factor to make us easier to identify “exotic”

Possible explanations of J/ψ-J/ψ states

2⁺⁺ four-quark states, PRD29 (1984) 426

TABLE I. Parameters used in Eq. (8) to calculate the cross sections for vector-meson pair production. (+) and (−) denote two degenerate 2⁺⁺ Q²Q̄² states. Except in the case of JJ, we take 4π/f_L²=0.03, due to the fact that the 2⁺⁺ Q²Q̄² are expected to lie not far above the threshold. α_s is determined from Eq. (11).

$V_1 V_2$	$a \not{V}_1 V_2 / a$	$b_{\alpha\beta}^j / \alpha_s \frac{a}{\sqrt{8}} \delta_{\alpha\beta}$	M_j (GeV)	α_s	m_1
$J\phi^{(+)}$	$-1/\sqrt{6}$	$\frac{-1}{\sqrt{3}} \frac{4\pi}{f_L f_\phi}$	4.40	0.2	
$J\phi^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2} \frac{4\pi}{f_L f_\phi}$	4.40	0.2	
$J\omega^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2} \frac{4\pi}{f_L f_\omega}$	4.05	0.2	
$\Upsilon J^{(+)}$	$1/\sqrt{6}$	$\frac{-1}{\sqrt{3}} \frac{4\pi}{f_\Upsilon f_L}$	13.5	0.167	
$\Upsilon J^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2} \frac{4\pi}{f_\Upsilon f_L}$	13.5	0.167	
$B_c^* \bar{B}_c^{*(+)}$	$-1/\sqrt{6}$	$\frac{-1}{\sqrt{3}} \frac{4\pi}{f_\Upsilon f_L}$	13.5	0.167	6.60
$B_c^* \bar{B}_c^{*(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2} \frac{4\pi}{f_\Upsilon f_L}$	13.5	0.167	

There were other attempts

New Domain of Exotics: All-Heavy Tetra-quarks

(cccc)

Phys. Rev. D 86, 034004 (2012)

$0^{++'}$	$M = 5.966 \text{ GeV},$	$M - M_{\text{th}} = -228. \text{ MeV},$	] Below double J/ψ threshold Search via $J/\psi\mu^+\mu^-$, J/ψ^*
$1^{+-'}$	$M = 6.051 \text{ GeV},$	$M - M_{\text{th}} = -142. \text{ MeV},$	
2^{++}	$M = 6.223 \text{ GeV},$	$M - M_{\text{th}} = 29.5 \text{ MeV}.$	Above double J/ψ threshold Search via $J/\psi J/\psi$

(bbcc)

0^{++a}	$M = 12.359 \text{ GeV},$	$M - M_{\text{th}} = -191. \text{ MeV}$	] Below double B_c threshold $J/\psi Y(1S)$ threshold ? ...
0^{++b}	$M = 12.471 \text{ GeV},$	$M - M_{\text{th}} = -78.7 \text{ MeV},$	
1^{+-a}	$M = 12.424 \text{ GeV},$	$M - M_{\text{th}} = -126. \text{ MeV}$	
1^{+-b}	$M = 12.488 \text{ GeV},$	$M - M_{\text{th}} = -62.5 \text{ MeV},$	
1^{++}	$M = 12.485 \text{ GeV},$	$M - M_{\text{th}} = -64.9 \text{ MeV},$	
2^{++}	$M = 12.566 \text{ GeV},$	$M - M_{\text{th}} = 16.1 \text{ MeV}.$	

(bbbb)

$0^{++'}$	$M = 18.754 \text{ GeV},$	$M - M_{\text{th}} = -544. \text{ MeV},$	] Above double B_c threshold $J/\psi Y(1S)$ threshold Search via the above two channels
$1^{+-'}$	$M = 18.808 \text{ GeV},$	$M - M_{\text{th}} = -490. \text{ MeV},$	
2^{++}	$M = 18.916 \text{ GeV},$	$M - M_{\text{th}} = -382. \text{ MeV}.$	Below double $Y(1S)$ threshold Search via $Y(1S)\mu^+\mu^-$

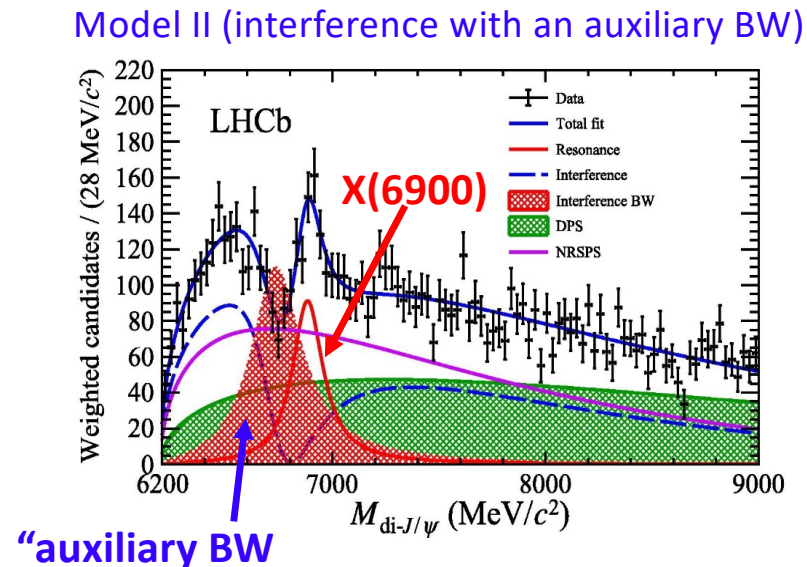
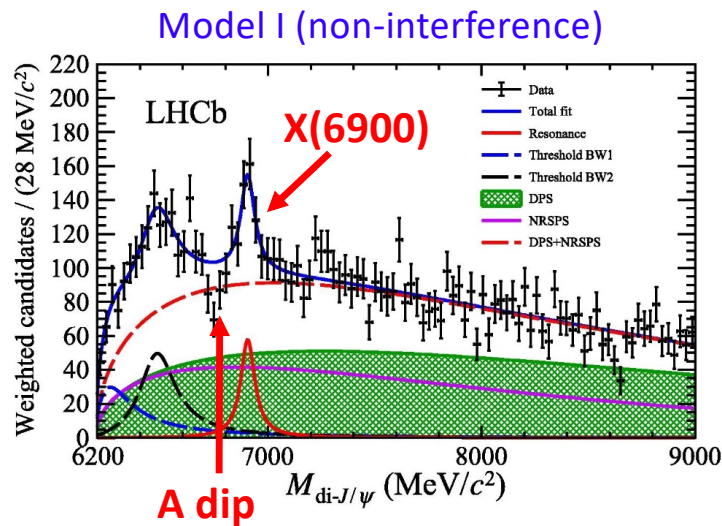
Many recent theoretical studies on $(c\bar{c}c\bar{c})$, $(b\bar{b}b\bar{b})$, $(b\bar{b}c\bar{c})$:

controversial on existence of bound states below $\eta_b\eta_b$ threshold;

consistent on existence of resonant states above $\eta_b\eta_b$ threshold.

X(6900) reported by LHCb

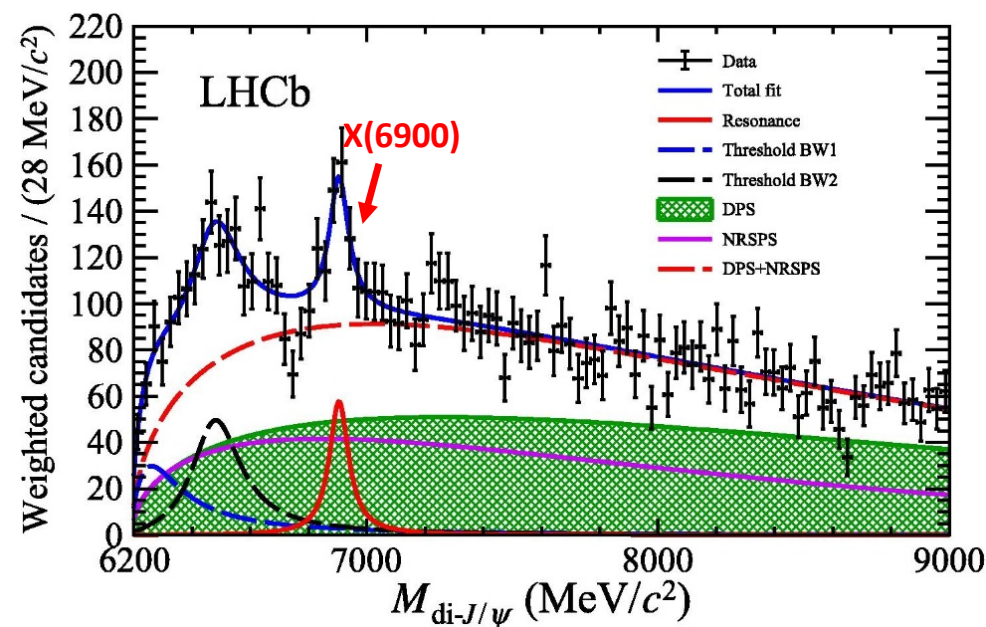
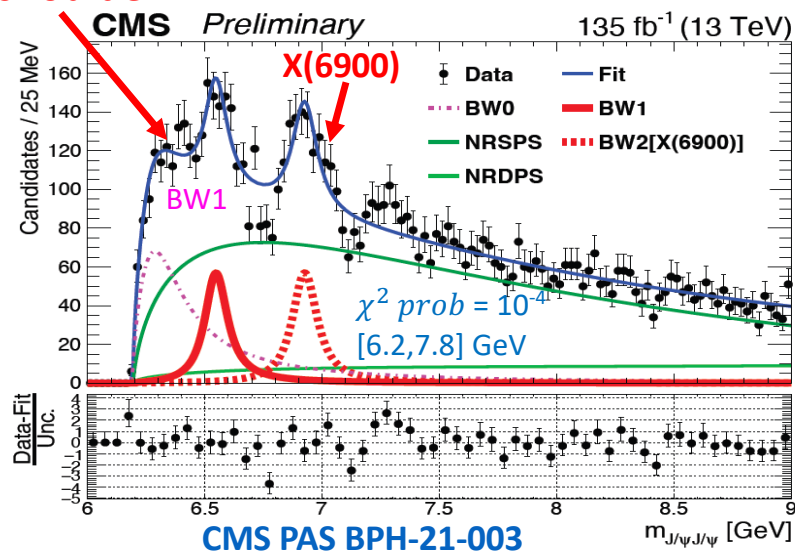
- In 2020, LHCb reported X(6900) state in $J/\psi J/\psi$ final state, [Sci.Bull.65 \(2020\) 23](#)
- Tried two different models
 - Model I: background+2 auxiliary BWs+ X(6900) $\rightarrow$ poor description of 'dip' around 6.7 GeV
 - Model II: a “virtual” auxiliary BWs to interfere with NRSPS background to account for dip
- LHCb agnostic on which one is to be preferred



- What happens if fit CMS data using LHCb models?

Fit with LHCb model I: background+2 auxiliary BWs+ X(6900)

A shoulder



Exp.	Fit	$m(\text{BW1})$	$\Gamma(\text{BW1})$	$m(6900)$	$\Gamma(6900)$
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

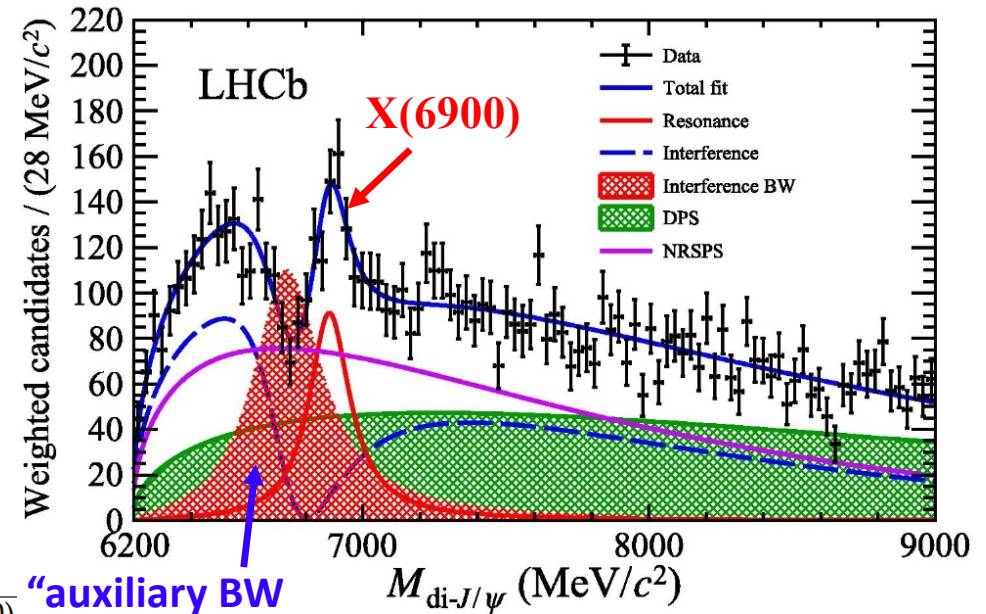
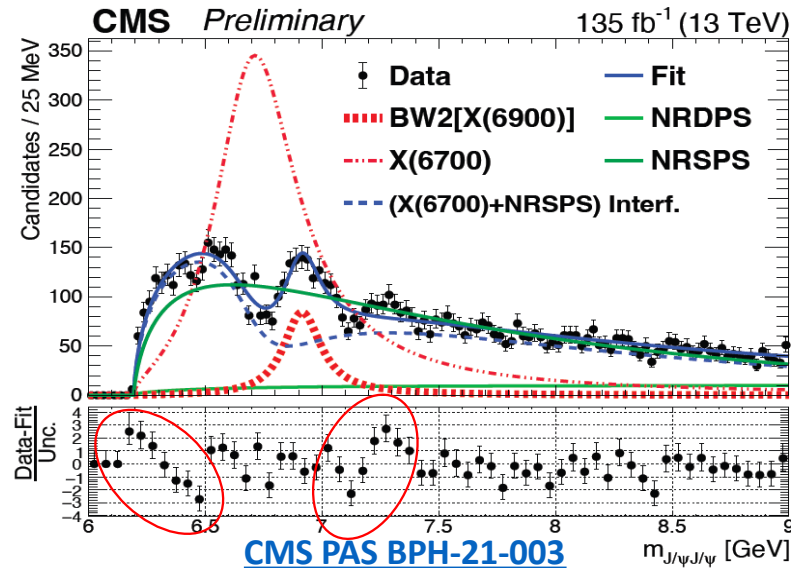
X(6900) parameters are in good agreement with LHCb
LHCb did not give parameters for another 2 BWs

- CMS Data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct
- Does not describe well dips

• CMS vs LHCb comparisons:

- $135/9 \approx 15X$ (int. lum.)
- $(5/3)^4 \approx 8X$ (muon acceptance due to pseudo-rapidity range)
- Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
- Similar number of final events, but much less DPS
- 2X yield @CMS for X(6900)

Fit with LHCb model II: DPS + X(6900) + auxiliary BW interferes with NRSPS



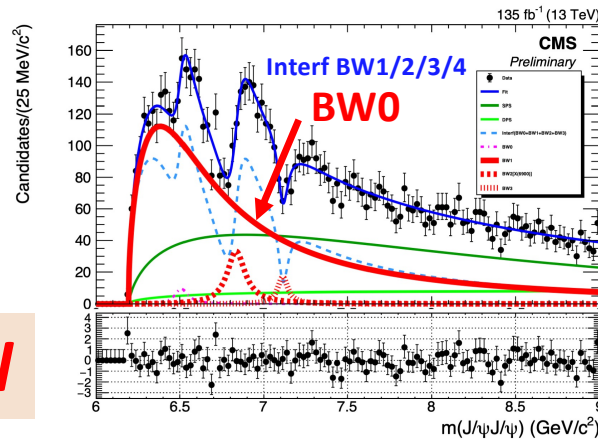
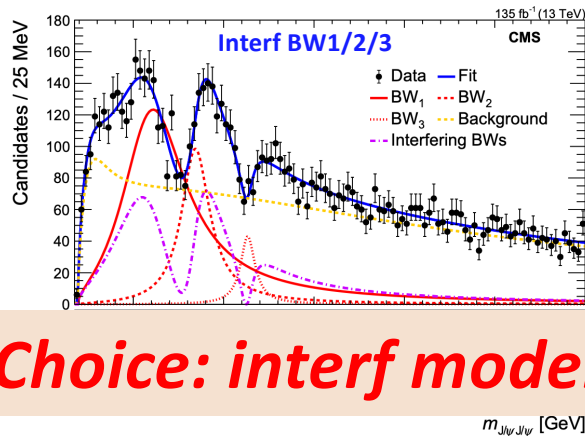
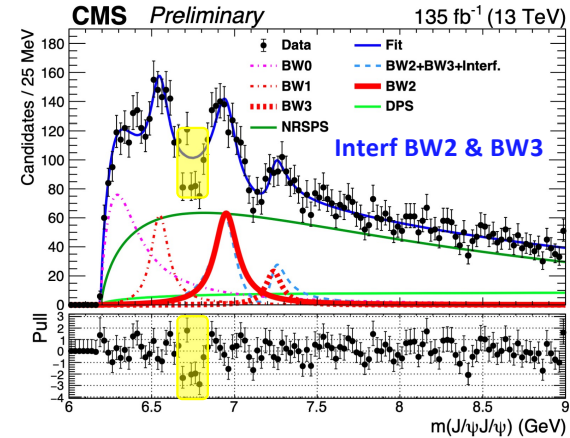
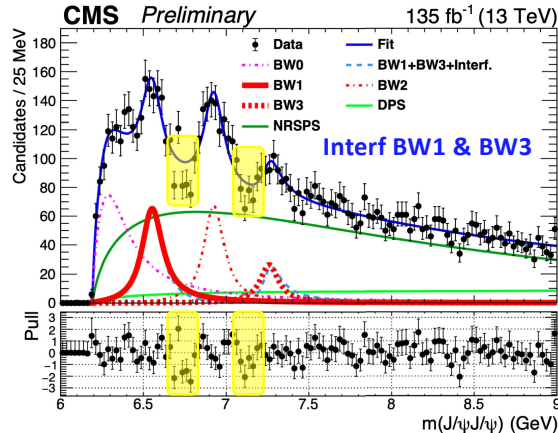
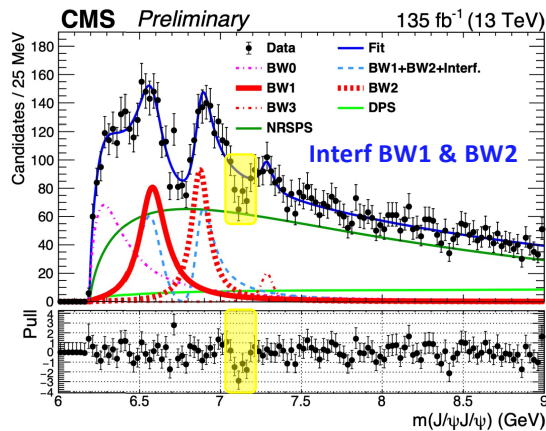
Exp.	Fit	$m(\text{BW1})$	$\Gamma(\text{BW1})$	$m(6900)$	$\Gamma(6900)$
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

All CMS fits presented are not very good:
...need other interference scenarios

- X(6900) parameters are consistent
- CMS obtained larger amplitude and natural width for BW1
 - Fast CMS threshold turn-on drives NRSPS high, which drives large aux. BW
- CMS's X(6600) is 'eaten' –does not describe X6600 and below
- Does not describe X(7200) region

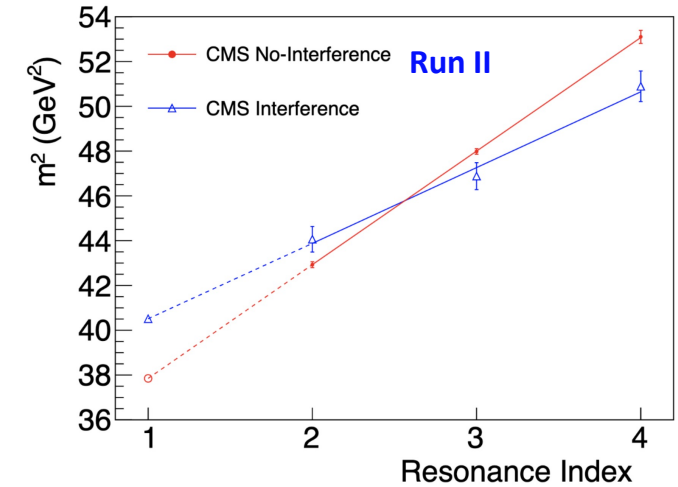
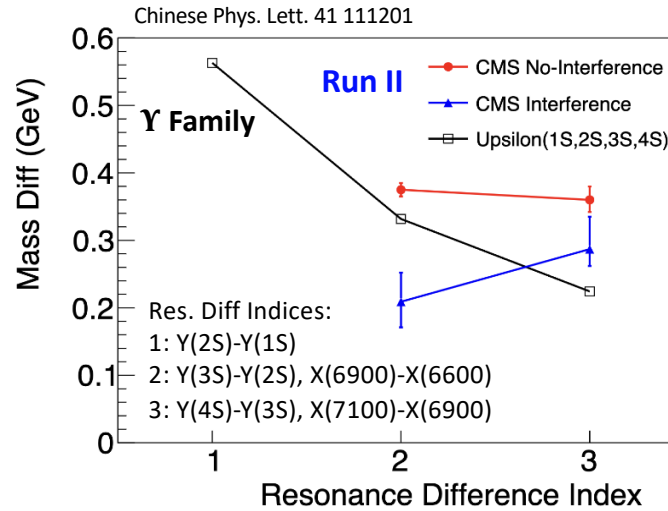
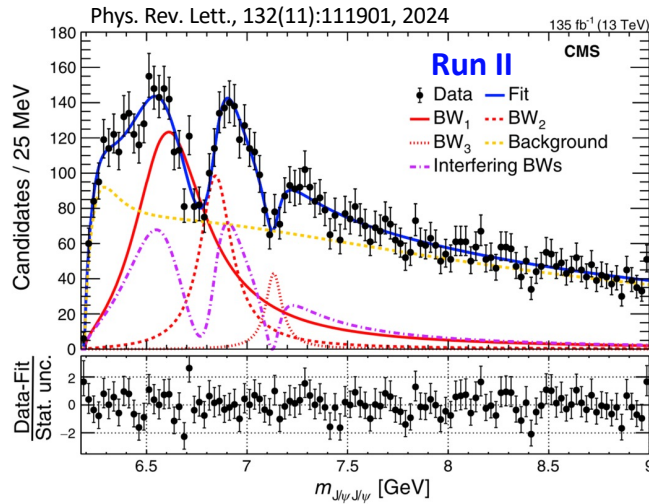
Exploration of interference

- Interference among resonances: two/three/four-body



- Choice: interference between BW1, BW2, BW3
 - χ^2 prob < 30% for 2-body
 - No significant better description for 4-body
 - BW0 – background-like

Status



Run 2 result:

- **X(7100): 4.7 σ**
- **Interference < 4 σ**

With 3.6X statistics:

- ☐ Significance of **ALL states** over 5 σ ?
- ☐ Significance of **interference** over 5 σ ?

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

A FAMILY of all-charm tetraquark states with same J^{PC} ?

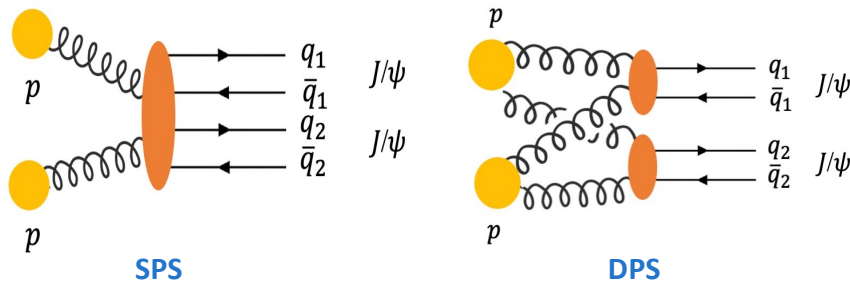
Datasets, MC, trigger, and event selection

❖ Data samples (315 fb^{-1})

- Run 2: 135 fb^{-1} data taken in 2016, 2017 and 2018
- Run 3: 180 fb^{-1} data taken in 2022, 2023 and 2024

❖ Signal and Background simulated events:

- Signal $X \rightarrow J/\psi J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ by JHUGen
- NRSPS and Feddown by Pythia8
- DPS event-mixing
- Feddown: $X(6900) \rightarrow J/\psi \psi(2S) \rightarrow J/\psi J/\psi + \text{anything}$



❖ Triggers

➤ Run 2 trigger:

- Level 1 requirements: 3 muons
- $2.95 < M(\mu^+ \mu^-) < 3.25 \text{ GeV}$
- $p_T(\mu) > 3.5 \text{ GeV}$

➤ Run3 trigger (new):

- Level 1 requirements: 2 muons
- $0.2 < M(\mu^+ \mu^-) < 8.5 \text{ GeV}$
- One muon $p_T(\mu) > 4 \text{ GeV}$; The other $p_T(\mu) > 3 \text{ GeV}$
- $p_T(\mu^+ \mu^-) > 4.9 \text{ GeV}$

➤ increase 30% $J/\psi J/\psi$ statistics compared to old trigger

❖ Event selection

- Follow Run 2 cuts + new trigger for Run 3

Signal and background models

- **Signal shape: Relativistic Breit-Wigner**
- **Background component:** NRSPS + NRDPS + Feeddown + Comb + BW0

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

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

❖ Non-interference model:

- **Signal-hypothesis:** NRSPS + NRDPS + Comb + Feeddown + BW0 + **BW1 + BW2 + BW3**

$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m) \\ + N_{NRDPS} \cdot f_{NRDPS}(m) + N_{Comb} \cdot f_{Comb}(m) + N_{Feeddown} \cdot f_{Feeddown}(m)$$

❖ Interference model:

- **Signal-hypothesis:** NRSPS + NRDPS + Comb + Feeddown + BW0 + **BW123 Interf. Term**

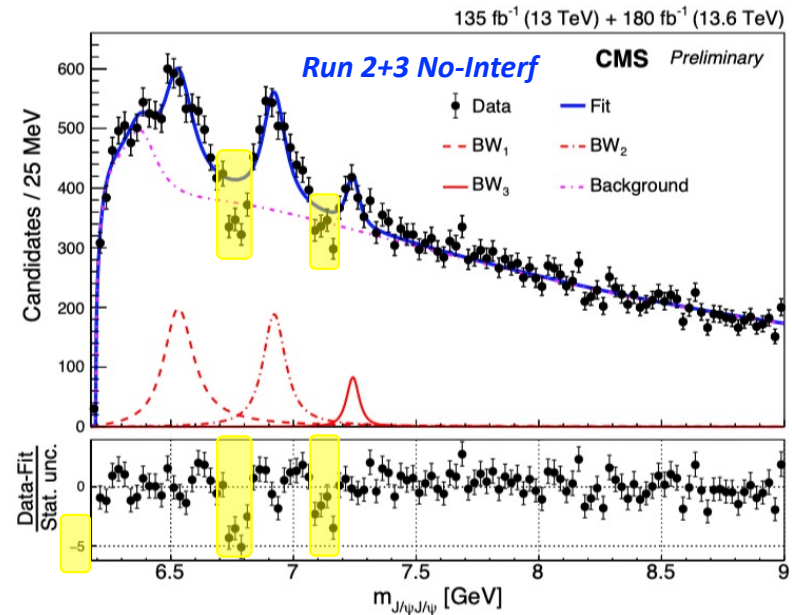
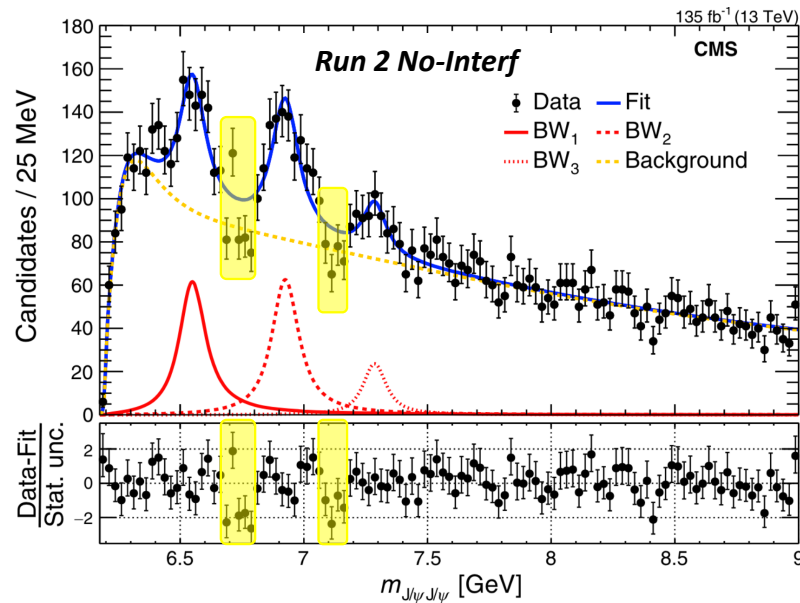
$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \otimes R(M_0) \\ + N_{X \text{ and interf}} \cdot |r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2 \\ + N_{NRSPS} \cdot f_{NRSPS}(m) + N_{DPS} \cdot f_{DPS}(m) \\ + N_{Feeddown} \cdot f_{Feeddown}(m) + N_{Comb} \cdot f_{Comb}(m),$$

Run 2 & 3 no-interference fit result

❖ No-interference model:

- **Signal-hypothesis:** NRSPS + NRDPS + Comb + Feeddown + BW0 + **BW1 + BW2 + BW3**

$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m) \\ + N_{NRDPS} \cdot f_{NRDPS}(m) + N_{Comb} \cdot f_{Comb}(m) + N_{Feeddown} \cdot f_{Feeddown}(m)$$



➤ Dips poorly described — *no-Interf. model no longer sufficient !*

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}

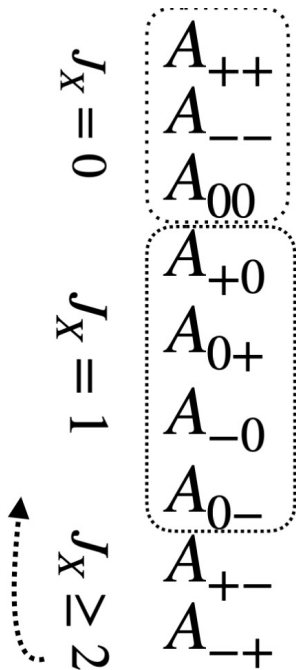
$$C = +1$$

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

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

$$\begin{array}{c}
 A_{++} \\
 A_{--} \\
 A_{00} \\
 A_{+0} \\
 A_{0+} \\
 A_{-0} \\
 A_{0-} \\
 A_{+-} \\
 A_{-+}
 \end{array}$$

$$\begin{aligned}
 F_{0,0}^J(\theta^*) \times & \left[4|A_{00}|^2 \sin^2 \theta_1 \sin^2 \theta_2 + 2|A_{++}| |A_{--}| \sin^2 \theta_1 \sin^2 \theta_2 \cos(2\Phi - \phi_{--} + \phi_{++}) \right] \\
 & + |A_{++}|^2 (1 + 2A_{f_1} \cos \theta_1 + \cos^2 \theta_1) (1 + 2A_{f_2} \cos \theta_2 + \cos^2 \theta_2) \\
 & + |A_{--}|^2 (1 - 2A_{f_1} \cos \theta_1 + \cos^2 \theta_1) (1 - 2A_{f_2} \cos \theta_2 + \cos^2 \theta_2) \quad \text{spin} = 0 \ \& \geq 1 \\
 & + 4|A_{00}| |A_{++}| (A_{f_1} + \cos \theta_1) \sin \theta_1 (A_{f_2} + \cos \theta_2) \sin \theta_2 \cos(\Phi + \phi_{++}) \\
 & + 4|A_{00}| |A_{--}| (A_{f_1} - \cos \theta_1) \sin \theta_1 (A_{f_2} - \cos \theta_2) \sin \theta_2 \cos(\Phi - \phi_{--})
 \end{aligned}$$

$$\begin{aligned}
 +F_{1,1}^J(\theta^*) \times & \left[2|A_{+0}|^2 (1 + 2A_{f_1} \cos \theta_1 + \cos^2 \theta_1) \sin^2 \theta_2 + 2|A_{0-}|^2 \sin^2 \theta_1 (1 - 2A_{f_2} \cos \theta_2 + \cos^2 \theta_2) \right. \\
 & + 2|A_{-0}|^2 (1 - 2A_{f_1} \cos \theta_1 + \cos^2 \theta_1) \sin^2 \theta_2 + 2|A_{0+}|^2 \sin^2 \theta_1 (1 + 2A_{f_2} \cos \theta_2 + \cos^2 \theta_2) \\
 & + 4|A_{+0}| |A_{0-}| (A_{f_1} + \cos \theta_1) \sin \theta_1 (A_{f_2} - \cos \theta_2) \sin \theta_2 \cos(\Phi + \phi_{+0} - \phi_{0-}) \\
 & + 4|A_{0+}| |A_{-0}| (A_{f_1} - \cos \theta_1) \sin \theta_1 (A_{f_2} + \cos \theta_2) \sin \theta_2 \cos(\Phi + \phi_{0+} - \phi_{-0}) \left. \right] \quad \text{spin} \geq 1 \\
 +F_{1,-1}^J(\theta^*) \times & \left[4|A_{+0}| |A_{0+}| (A_{f_1} + \cos \theta_1) \sin \theta_1 (A_{f_2} + \cos \theta_2) \sin \theta_2 \cos(2\Psi - \phi_{+0} + \phi_{0+}) \right. \\
 & + 4|A_{0-}| |A_{-0}| (A_{f_1} - \cos \theta_1) \sin \theta_1 (A_{f_2} - \cos \theta_2) \sin \theta_2 \cos(2\Psi - \phi_{0-} + \phi_{-0}) \\
 & + 4|A_{+0}| |A_{-0}| \sin^2 \theta_1 \sin^2 \theta_2 \cos(2\Psi - \Phi - \phi_{+0} + \phi_{-0}) + 4|A_{0-}| |A_{0+}| \sin^2 \theta_1 \sin^2 \theta_2 \cos(2\Psi + \Phi - \phi_{0-} + \phi_{0+}) \left. \right]
 \end{aligned}$$

$$\begin{aligned}
 +F_{2,2}^J(\theta^*) \times & \left[|A_{+-}|^2 (1 + 2A_{f_1} \cos \theta_1 + \cos^2 \theta_1) (1 - 2A_{f_2} \cos \theta_2 + \cos^2 \theta_2) \right. \\
 & + |A_{-+}|^2 (1 - 2A_{f_1} \cos \theta_1 + \cos^2 \theta_1) (1 + 2A_{f_2} \cos \theta_2 + \cos^2 \theta_2) \left. \right] \quad \text{spin} \geq 2
 \end{aligned}$$

$$+F_{2,-2}^J(\theta^*) \times \left[2|A_{+-}| |A_{-+}| \sin^2 \theta_1 \sin^2 \theta_2 \cos(4\Psi - \phi_{+-} + \phi_{-+}) \right] + \text{other 26 interference terms for spin}$$

$$\text{where } \Psi = \Phi_1 + \Phi/2 \quad \text{and} \quad F_{ij}^J(\theta^*) = \sum_{m=0,\pm 1,\pm 2} f_m d_{im}^J(\theta^*) d_{jm}^J(\theta^*)$$

Valid
for any J

[arXiv:1001.3396](https://arxiv.org/abs/1001.3396)

Lorentz-Invariant Amplitude

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

$$A(X_{J=0} \rightarrow V_1 V_2) = \left(a_1(q^2) m_V^2 \epsilon_1^* \epsilon_2^* + a_2(q^2) f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3(q^2) f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

0_m^+

0_h^+

0^-

$A_{00} = A_{++} = A_{--}$ at $2m_{J/\psi}$ threshold

$A_{++} = -A_{--}$

A_{00} at large m_X $A_{++} = A_{--}$

[arXiv:1001.3396](https://arxiv.org/abs/1001.3396)

empirical **form factors** ($m_{4\mu}^2$)

$$A(X_{J=1} \rightarrow V_1 V_2) = \left(b_1(q^2) \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2(q^2) \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*\mu} \epsilon_2^{*\nu} \tilde{q}^\beta \right)$$

1^-

1^+

more for spin-2

$A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$

$A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$

Lorentz-Invariant Amplitude

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

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

[arXiv:1001.3396](https://arxiv.org/abs/1001.3396)

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. $A_{00}, A_{++} = A_{--}, A_{+0} = A_{0+} = A_{-0} = A_{0-}, A_{+-} = A_{-+}$ for 2^{++} (or $J \geq 2$)

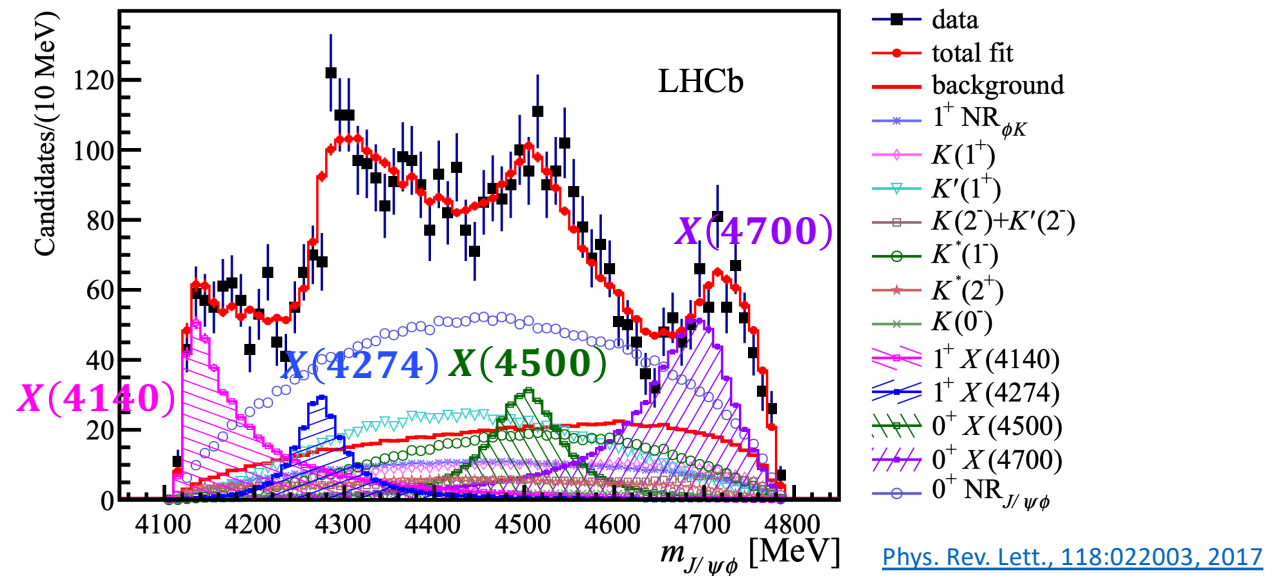
unique

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

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

Latest results with LHCb amplitude analyses

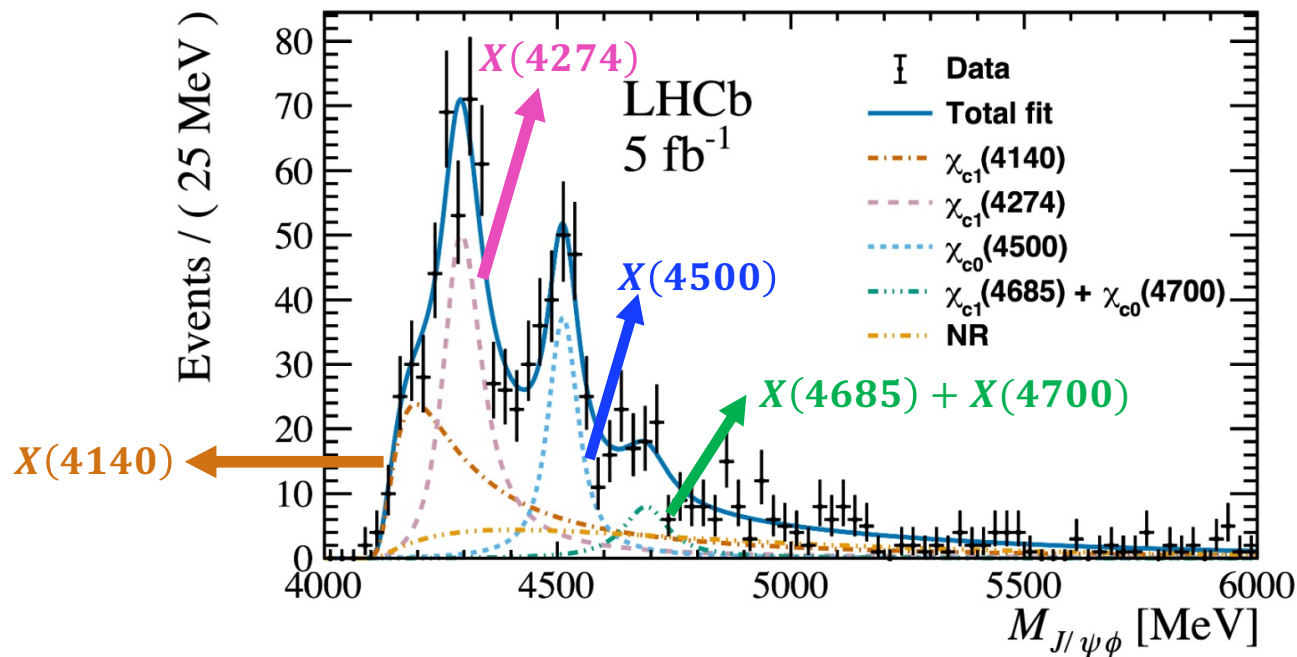
- Amplitude fit with multidimensional kinematic information
 - Disentangle overlapping enhancements, determine J^{PC} , account for interference among intermediate states
- 2016, LHCb, $B^+ \rightarrow J/\psi \phi K^+$ with Run 1 data
 - Reestablish $X(4140)$ and $X(4274)$, measured $J^{PC} = 1^{++}$
 - $X(4140)$: $M = 4146.5 \pm 4.5^{+4.6}_{-2.8}$ MeV; $\Gamma = 83 \pm 21^{+21}_{-14}$ MeV
 - $X(4274)$: $M = 4273.3 \pm 8.3^{+17.2}_{-3.6}$ MeV; $\Gamma = 56 \pm 11^{+8}_{-11}$ MeV
 - Explore high-mass region with good sensitivity for the first time: $X(4500)$ and $X(4700)$, measured $J^{PC} = 0^{++}$
 - Width of $X(4140)$ much larger than previously determined (vs $\Gamma_{avg} = 17.3^{+6.6}_{-5.3}$ MeV)



Review of $J/\psi\phi$ structures

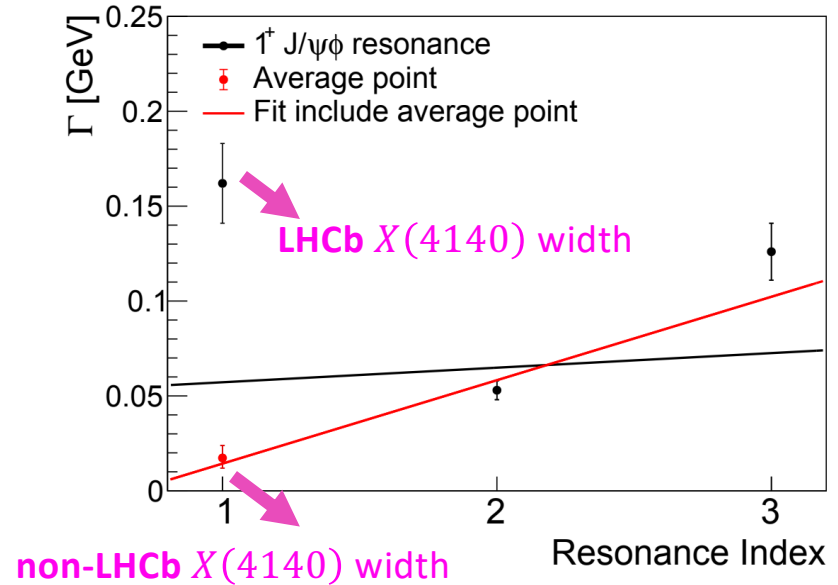
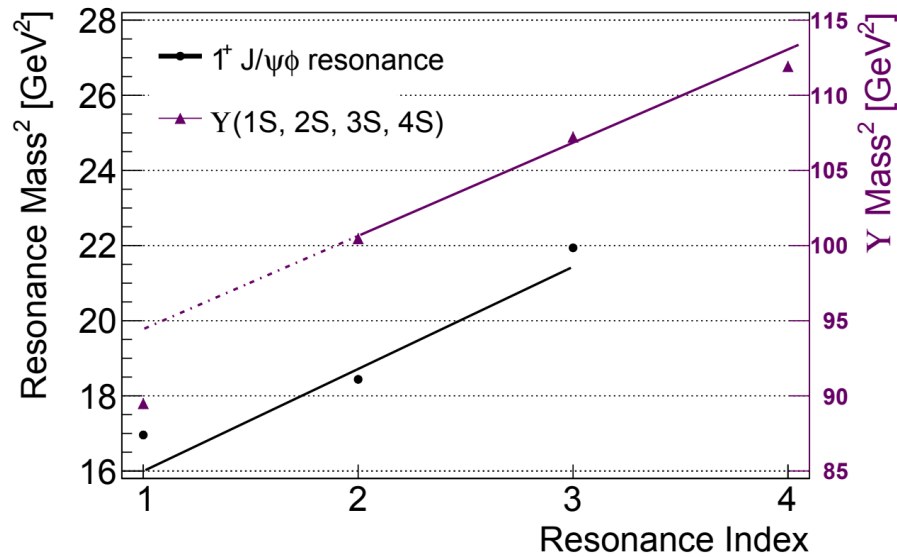
➤ 2024, LHCb, $pp \rightarrow J/\psi\phi + \text{anything}$

- First study of $J/\psi\phi$ production in diffractive pp collisions
- Protons typically remain or dissociate only slightly
- Low multiplicity, large rapidity gaps devoid of particles
- Suppressed hadronic activity may enhance the sensitivity to rare produced states
- 5 structures in the fit model: $X(4140)$, $X(4274)$, $X(4500)$, $X(4685)$, and $X(4700)$
- $X(4140)$, $X(4685)$ and $X(4700)$ fixed to LHCb 2021 results due to limited statistics
- $X(4274)$ $X(4500)$ consistent with previous results



[Phys. Rev. Lett., 134:031902, 2025](#)

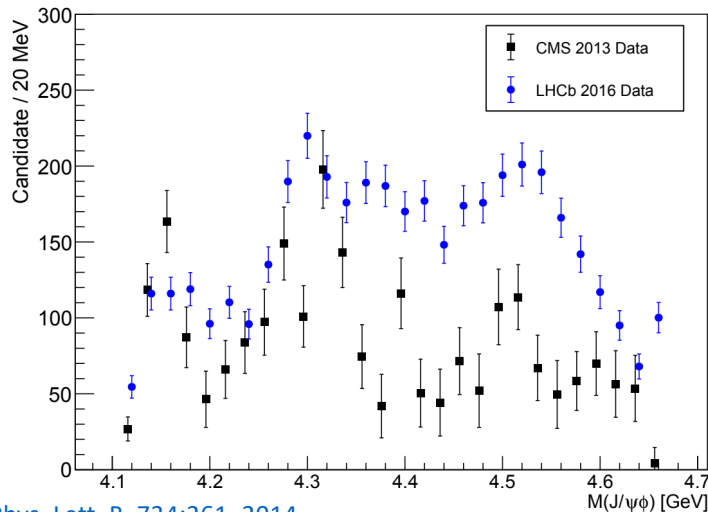
$J/\psi\phi$ system



➤ Similarities in the $J/\psi\phi$ system

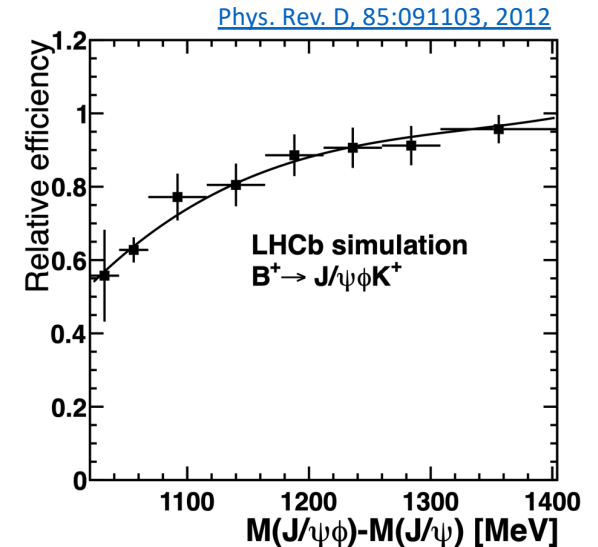
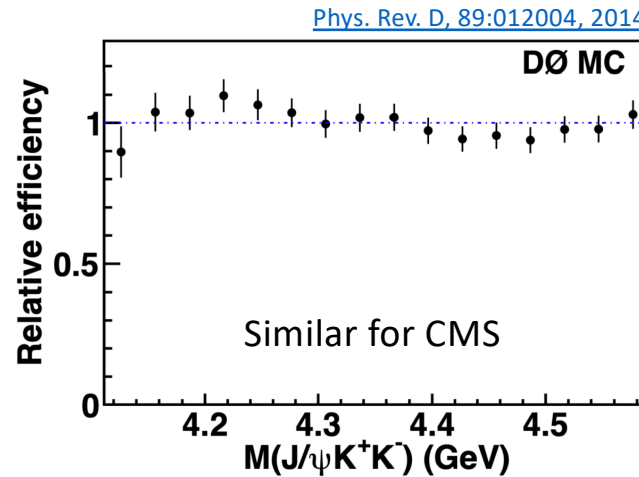
- Two neutral vector mesons with hidden flavor
- LHCb studied $B^+ \rightarrow J/\psi\phi K^+$
 - Three 1^{++} states decaying to $J/\psi\phi$: $X(4140)$, $X(4274)$, and $X(4685)$
 - The squared masses of these 1^{++} $J/\psi\phi$ resonances align with Regge-like trajectory
 - Different width trends: non-LHCb $X(4140)$ width vs LHCb $X(4140)$ width

Comparison of $J/\psi\phi$ between CMS and LHCb



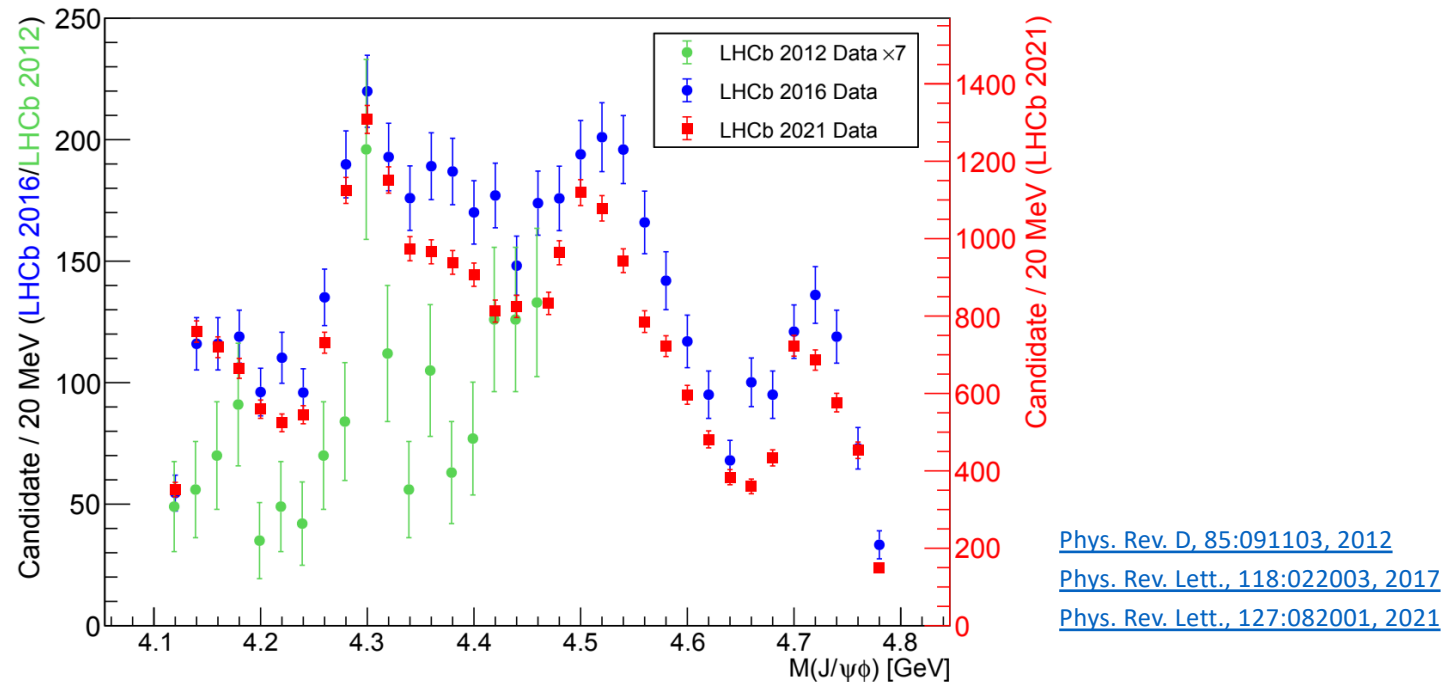
[Phys. Lett. B, 734:261, 2014](#)

[Phys. Rev. Lett., 118:022003, 2017](#)



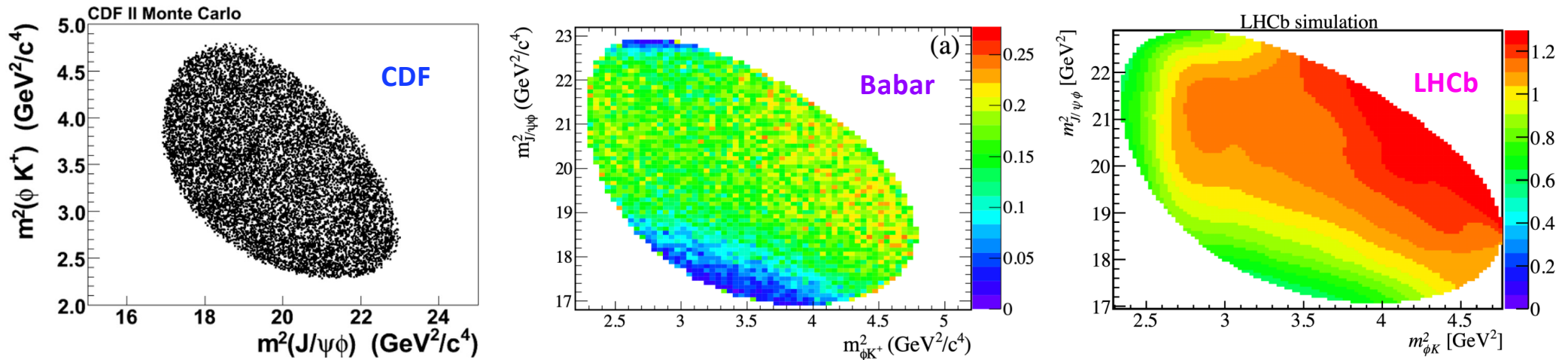
- Limited statistic in other experiments except for CMS and LHCb
- **CMS vs LHCb**: comparable statistic in low-mass region, larger difference above 4.3 GeV
- **Possible reasons for shape inconsistency:**
 - Larger background in CMS data
 - Different efficiencies:
 - **CMS** eff. **~20% higher** in low-mass threshold than in the high-mass region
 - **LHCb** eff. **> 40% lower** near the threshold compared with high-mass region
 - *Higher sensitivity in high-mass region: two additional resonances claimed*
 - *Lower sensitivity in low-mass region: failed to confirm $X(4140)$ and $X(4274)$ with 2012 data*

Comparison of LHCb $J/\psi\phi$ from different years



- Comparison of LHCb $J/\psi\phi$ mass spectrum from 2012, 2016, and 2021
 - 2012 data statistically limited, exhibit excess features around 4140 and 4274 MeV after scaling up
 - Some inconsistencies across mass spectrum between 2016 and 2021 LHCb data
 - Not expected since there is no apparent change for LHCb tracker
 - Possible reasons:
 - Efficiency variations due to different triggers and event selection
 - Statistical fluctuations amplified by the rich resonances

Detector efficiency



- Efficiency maps from different experiments
 - **CDF**: relatively flat, expected similar for CMS due to comparable detector design
 - **BaBar**: mostly flat, but drops by $\sim 25\%$ near the low/edge regions of $m^2(J/\psi\phi)$
 - **LHCb**: large efficiency variation
- Detector configurations help explain these behaviors
 - **BaBar/Belle(e^+e^-)** reconstruct nearly **at-rest** B mesons in the transverse plane
 - Near threshold ϕ -decay **kaons have little p_T** , reduce acceptance at Dalitz edges
 - **CDF, D0, CMS**: central detector at hadron collider
 - B mesons are highly **boosted with near- 4π coverage**, yielding flatter efficiencies
 - **LHCb**: forward detector
 - Yield strong longitudinal but modest transverse boosts, producing more pronounced Dalitz variations.

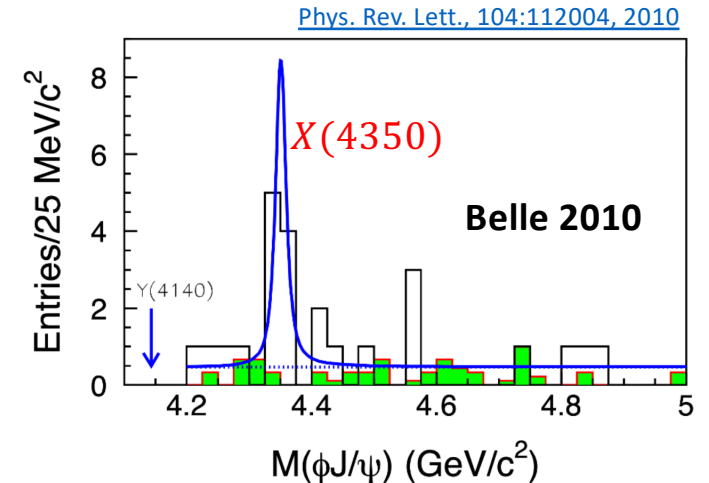
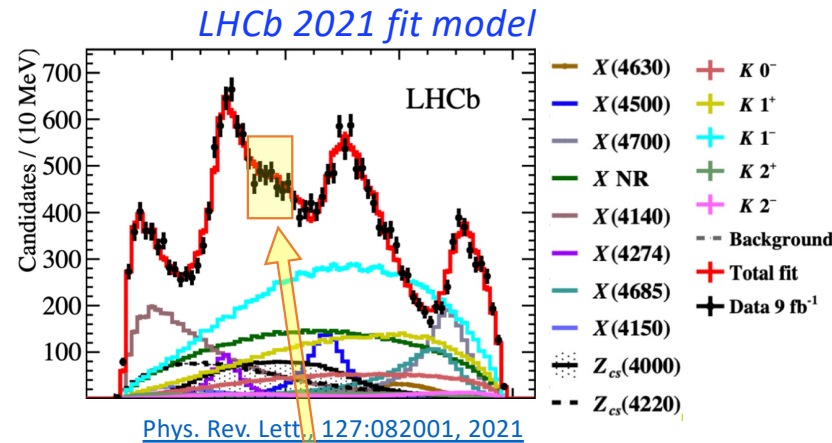
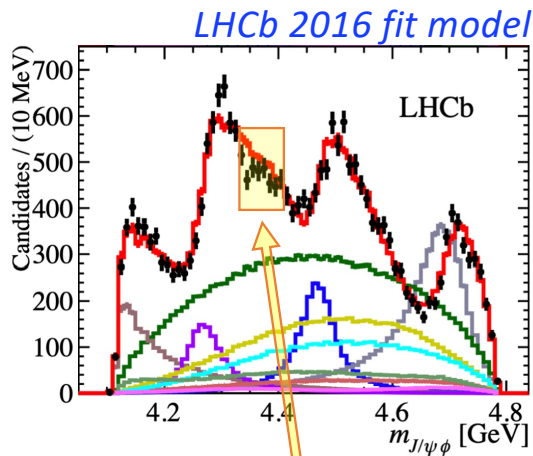
X(4140) measurements

- Revisit X(4140) measurements

Detector	$M[X(4140)]$ [MeV]	$\Gamma[X(4140)]$ [MeV]
CDF	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$
CMS	$4148.0 \pm 2.4 \pm 6.3$	$28.0^{+15}_{-11} \pm 19$
DØ 2013	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$
DØ 2015	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$
LHCb 2016 (Run 1 data)	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$
LHCb 2021 (Run 1 and Run 2 data)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$
Average excluding LHCb	4146.6 ± 2.4	$17.3^{+6.6}_{-5.3}$

- LHCb reports mass consistent with non-LHCb average within 1σ
 - Width differs by more than 2σ
- Imperfect efficiency corrections can bias the extracted resonance parameters
- Complementary measurements with flatter Dalitz-plane efficiency will be essential for cross-checks
 - From ATLAS, Belle II, and CMS ...

Potential state around 4.35 GeV



- **Notable shoulder** between 4.32 and 4.39 GeV in the $J/\psi\phi$ mass spectrum
- In updated model, shoulder is described by tails from $X(4274)$, $X(4500)$, other ϕK and $J/\psi K$ resonances
 - Cost of invoking a larger set of states, many of which remain to be confirmed
- **Remind:** 2010, Belle, $\gamma\gamma \rightarrow J/\psi\phi$, **Evidence of $X(4350)$** , 3.2σ , $M = 4350.6_{-5.1}^{+4.6} \pm 0.7$ MeV; $\Gamma = 13.9_{-9}^{+18} \pm 4$ MeV
 - Spin is 0 or 2 according to Landau-Yang theorem
- Several tetraquarks have been predicted around 4.3 GeV [Phys. Rev. D, 94:094031, 2016](#)
- **Explore alternative descriptions for the shoulder:**
 - Potential resonance around 4.35 GeV
 - **High spin:** production suppression from spin-0 B meson
 - **Hybrid:** suppressed in B decay

Potential state around 4.35 GeV

- Perform amplitude fit with $X(4350)$ to toy sample (generated based on LHCb 2021 model) [Chin. Phys. Lett. 2025 42\(12\): 120202](#)
 - Scan masses and widths under different J^P for $X(4350)$ and evaluate its significance

➤ Results

Full-set model

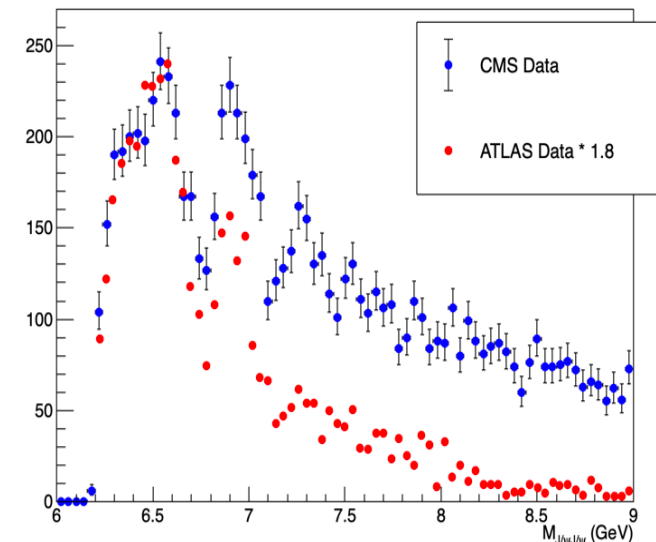
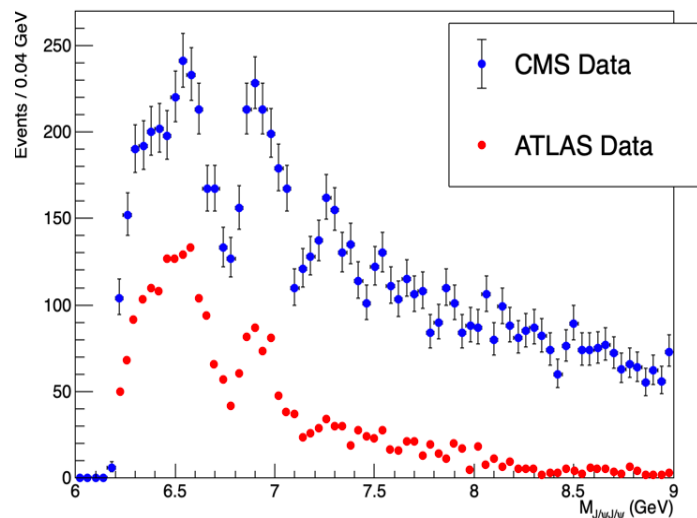
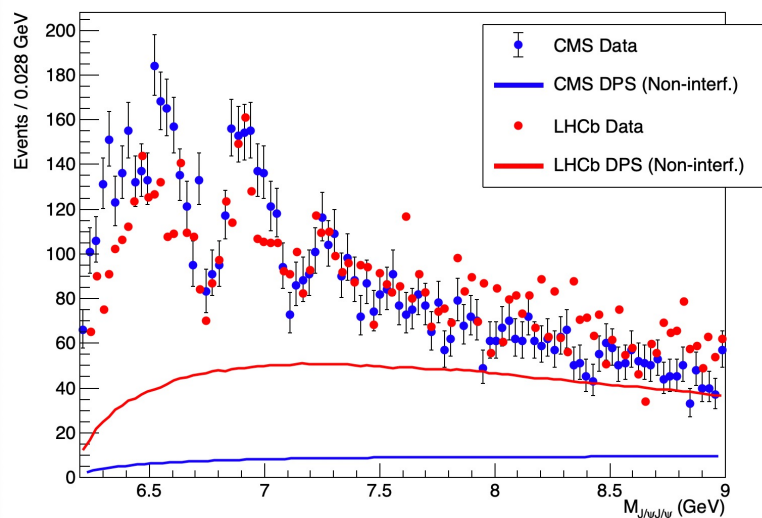
J^P	$M = 4320$ $\Gamma = 15$	$M = 4340$ $\Gamma = 15$	$M = 4360$ $\Gamma = 15$	$M = 4320$ $\Gamma = 50$	$M = 4340$ $\Gamma = 50$	$M = 4360$ $\Gamma = 50$	$M = 4320$ $\Gamma = 100$	$M = 4340$ $\Gamma = 100$	$M = 4360$ $\Gamma = 100$
0^+	2.0	1.4	0.5	2.3	1.9	1.4	2.3	2.1	1.9
0^-	1.5	1.4	1.2	1.4	1.5	1.2	1.2	1.1	1.0
2^+	2.7	3.0	2.2	3.4	3.3	3.0	3.7	3.6	3.4
2^-	1.7	2.3	1.7	2.6	2.3	2.8	3.7	3.4	3.5
1^+	2.4	1.5	2.2	2.0	1.9	2.1	1.7	1.6	1.8
1^-	2.3	2.8	1.8	2.8	2.9	2.7	3.0	3.0	3.1

Reduced-set model

J^P	$M = 4320$ $\Gamma = 15$	$M = 4340$ $\Gamma = 15$	$M = 4360$ $\Gamma = 15$	$M = 4320$ $\Gamma = 50$	$M = 4340$ $\Gamma = 50$	$M = 4360$ $\Gamma = 50$	$M = 4320$ $\Gamma = 100$	$M = 4340$ $\Gamma = 100$	$M = 4360$ $\Gamma = 100$
0^+	3.5	2.6	1.3	3.5	3.3	2.6	3.4	3.3	3.1
0^-	2.0	3.3	3.4	4.8	5.3	5.5	6.2	6.4	6.5
2^+	3.5	3.2	2.8	4.7	4.4	4.3	5.8	5.5	5.4
2^-	4.9	3.5	3.9	8.6	7.3	6.9	11.9	10.8	10.1
1^+	3.7	2.7	4.3	5.7	5.5	6.0	7.1	7.3	7.7
1^-	3.8	5.2	5.3	6.2	7.3	8.0	7.8	8.8	9.6

- Spin-2 hypotheses generally yield higher significances than spin-0
 - *Possibility of potential high-spin $J/\psi\phi$ structure near 4.35 GeV*
- Independent information from other experiments could help to clarify with larger statistics

Comparison with LHCb & ATLAS



- CMS vs LHCb comparisons:

- $135/9 \approx 15X$ (int. lum.)
- $(5/3)^4 \approx 8X$ (muon acceptance)
- Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
- Similar number of final events, but much less DPS
- $2X$ yield @CMS for X(6900)

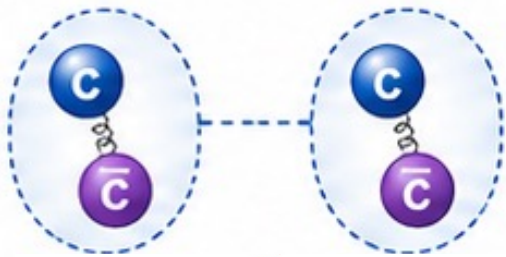
- CMS vs ATLAS comparisons:

- ATLAS is $1/3 - 1/2$ of CMS data (trigger?)
- ATLAS used dR cut—remove high mass events
- ATLAS has slightly worse resolution

Internal structure

Molecule (meson-meson)

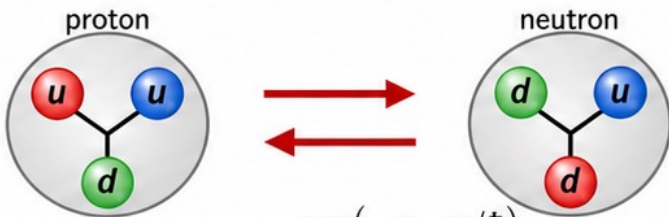
Bound state of two mesons



$$V(r) = g \cdot \frac{e^{-\frac{m_{\eta_c} c}{\hbar} r}}{r}$$

note $(c\bar{c})$ mass
× 22 heavier
than π

Analogy: deuteron (loosely bound nuclear molecule)

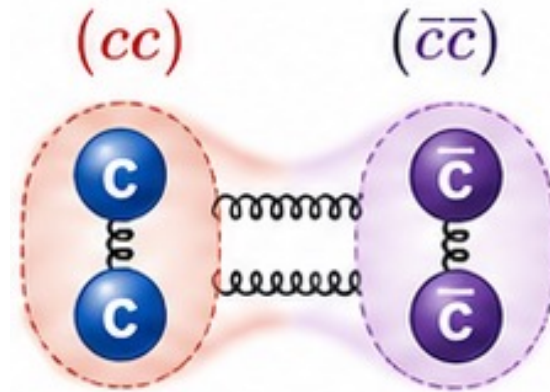


$$V(r) = g \cdot \frac{\exp(-m_{\pi} cr/\hbar)}{r}$$

π exchange

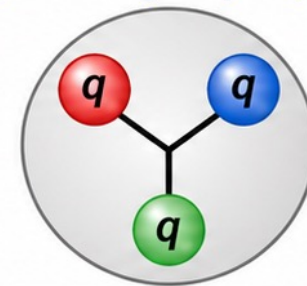
connected by residual strong (nuclear) force,
like proton and neutron in a nucleus.

Compact tetraquark (diquark-antidiquark)

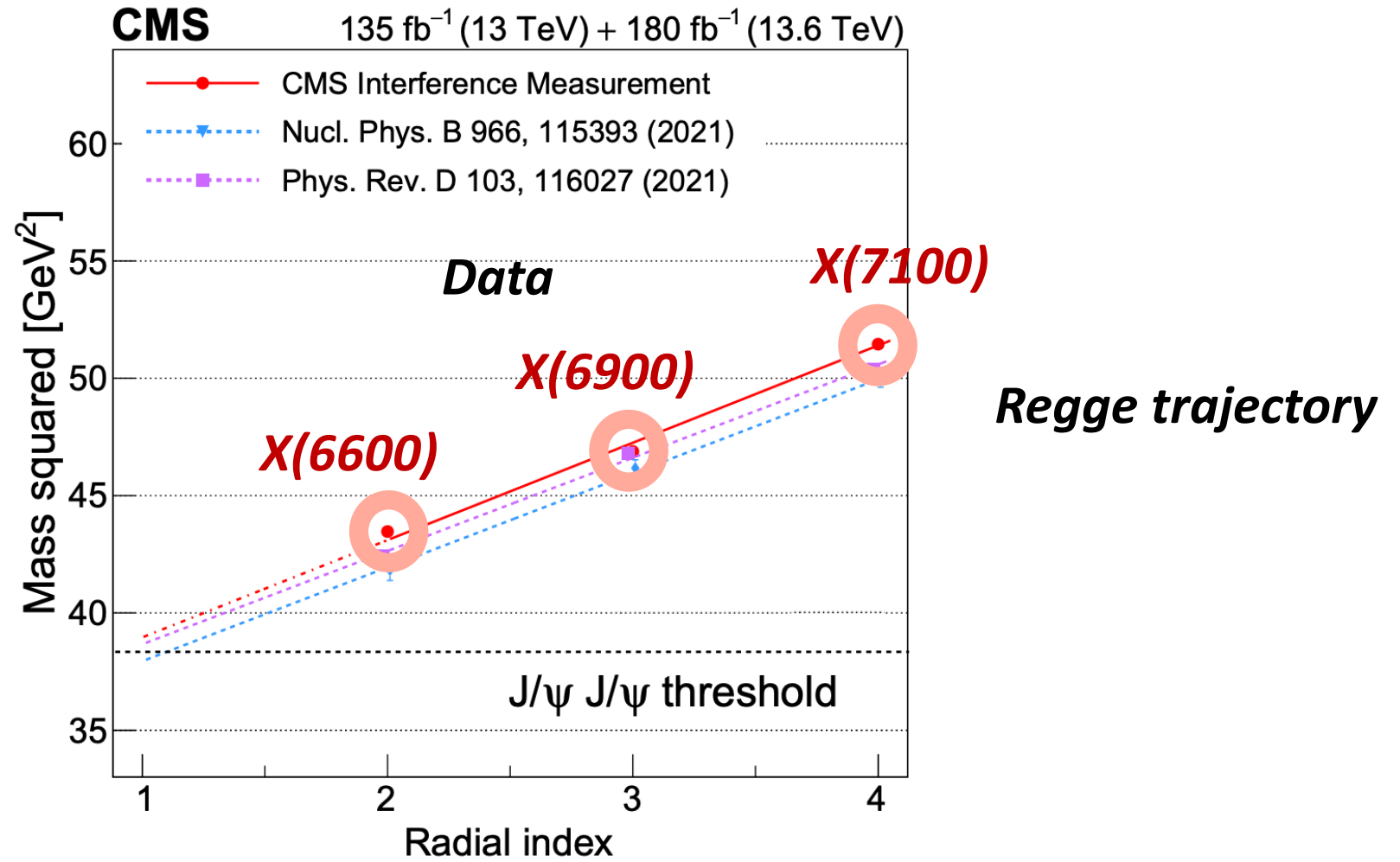


Connects two colored objects through
direct strong interactions, like quarks in
a proton or neutron.

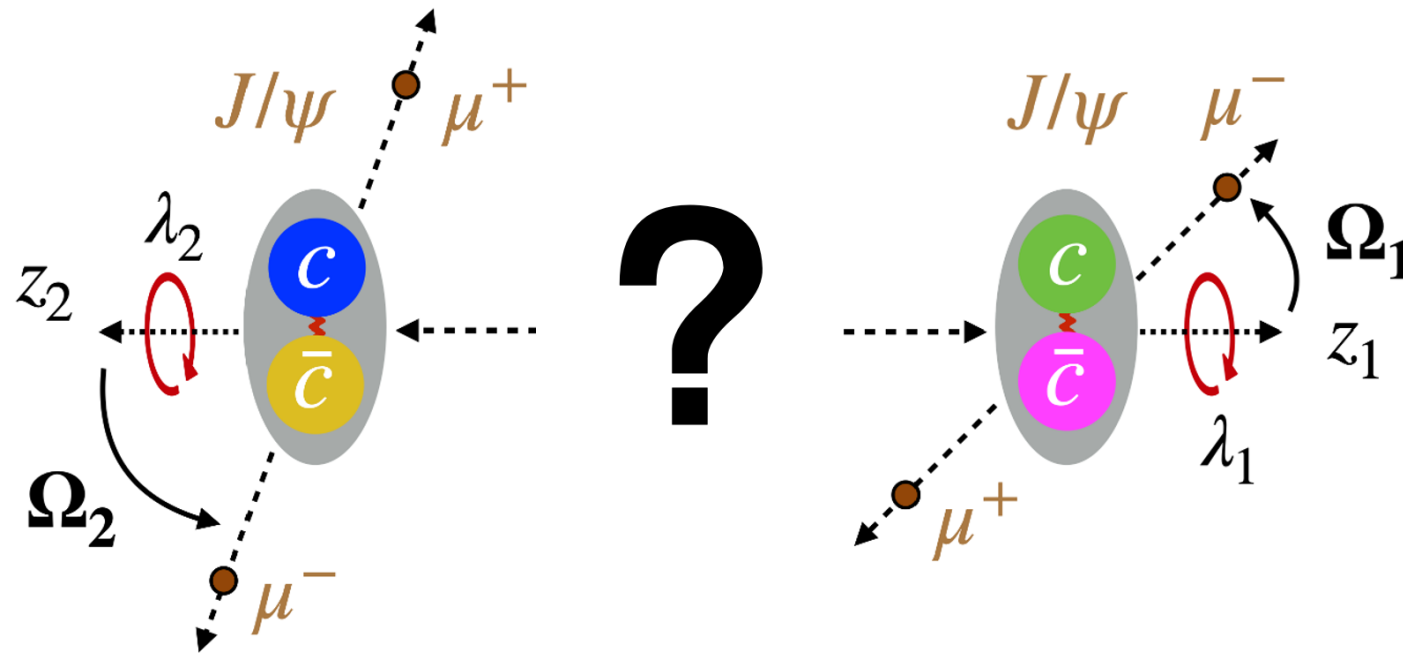
Analogy: ordinary baryon (e.g., proton)



Discussion



Everything was prepared Blinded

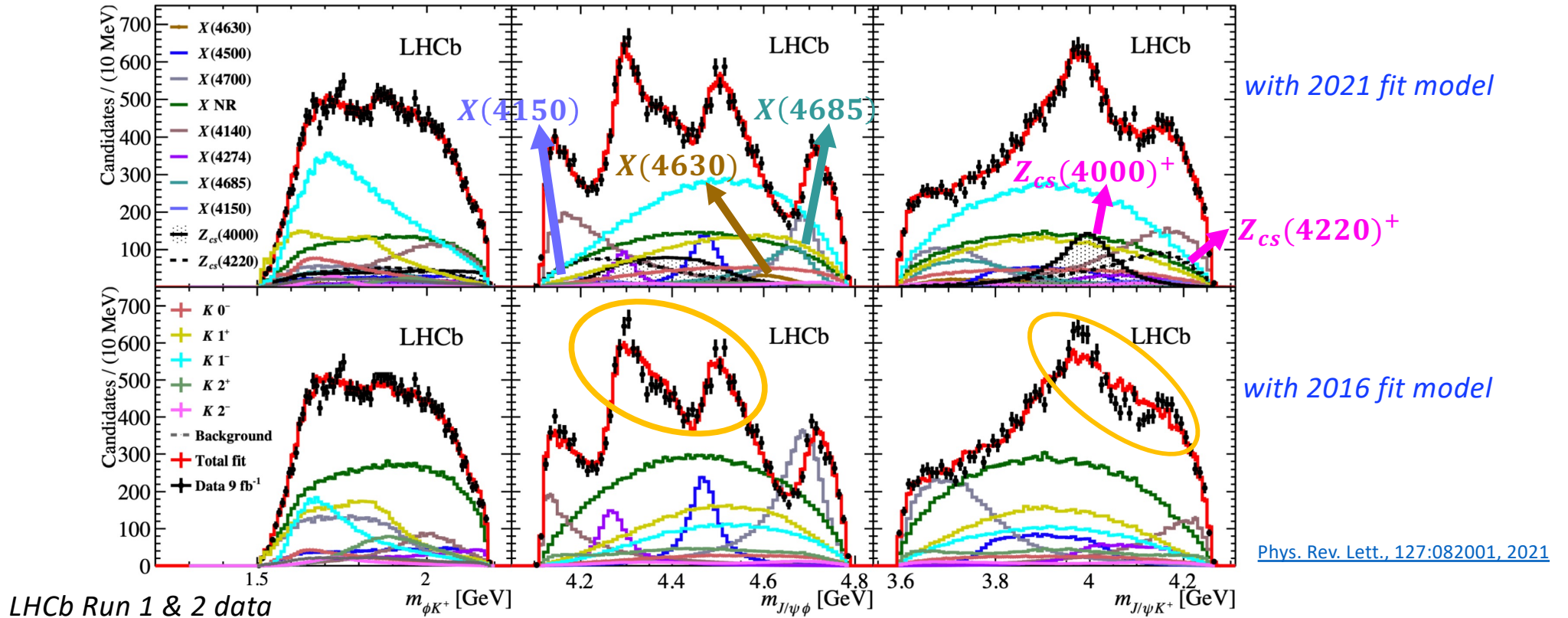


Ready to Unblind...

Latest results with LHCb amplitude analyses

➤ 2021, LHCb, $B^+ \rightarrow J/\psi\phi K^+$ with Run 1 and Run 2 data (6x higher statistic vs 2016)

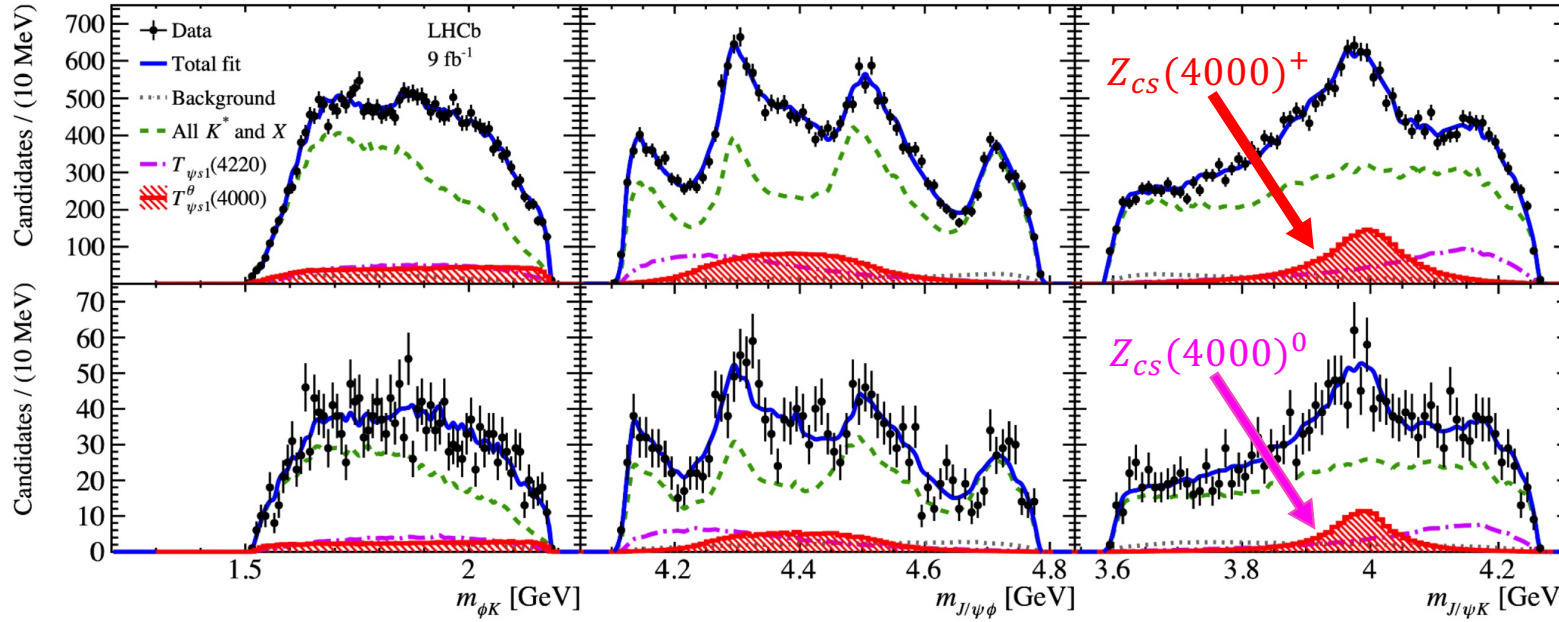
- Increased statistics required improved fit model
- New model by adding more component with stat. significance $> 5\sigma$
 - $J/\psi\phi$: $X(4150)$, $X(4685)$, $X(4630)$
 - $J/\psi K^+$: $Z_{cs}(4000)^+$, $Z_{cs}(4220)^+$



Latest results with LHCb amplitude analyses

- 2023, LHCb, $B^0 \rightarrow J/\psi \phi K_S^0$ with Run 1 and Run 2 data
- All parameters fixed to 2021 LHCb $B^+ \rightarrow J/\psi \phi K^+$ model except for $Z_{cs}(4000)^0$
 - Under assumption of isospin symmetry
 - $J/\psi K_S^0$: $Z_{cs}(4000)^0$ (4σ), possible isospin partner of $Z_{cs}(4000)^+$

Year	Experiment	Luminosity [fb ⁻¹]	Process $B \rightarrow J/\psi \phi K$	Structure	Mass [MeV]	Width [MeV]	Significance [σ]
2021	LHCb	9	$B^+ \rightarrow J/\psi \phi K^+$	$Z_{cs}(4000)^+$	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	15.0
				$Z_{cs}(4220)^+$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	5.9
2023	LHCb	9	$B^0 \rightarrow J/\psi \phi K_S^0$	$Z_{cs}(4000)^0$	3991^{+12+9}_{-10-17}	105^{+29+17}_{-25-23}	4.0

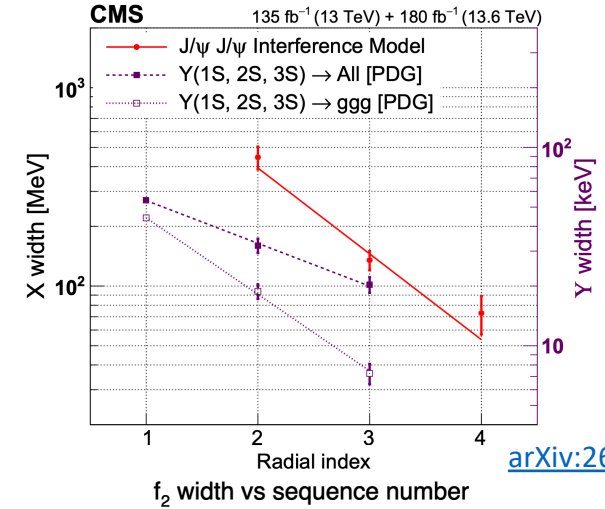
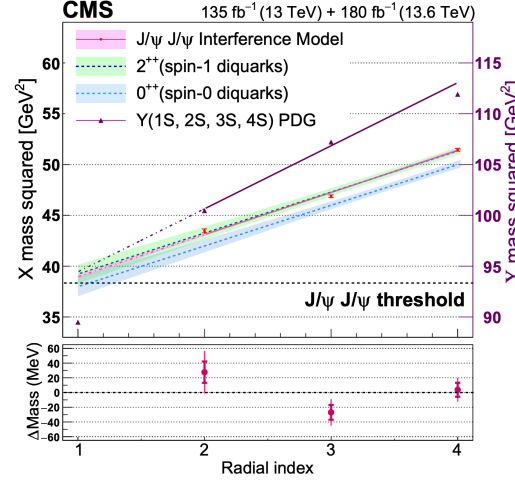
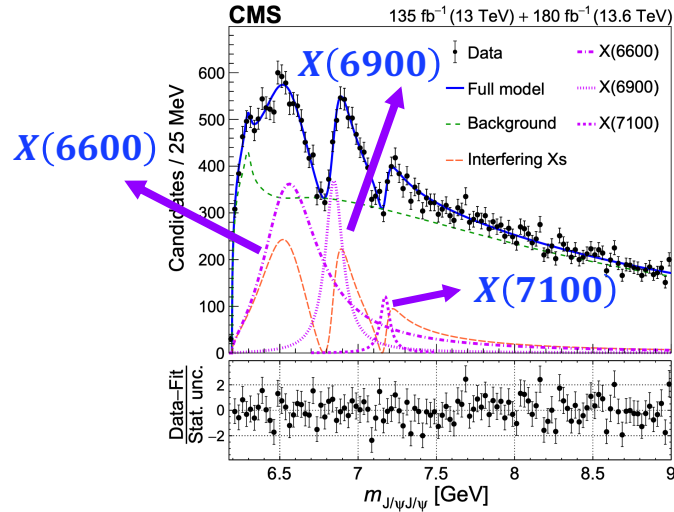


$B^+ \rightarrow J/\psi \phi K^+$ data

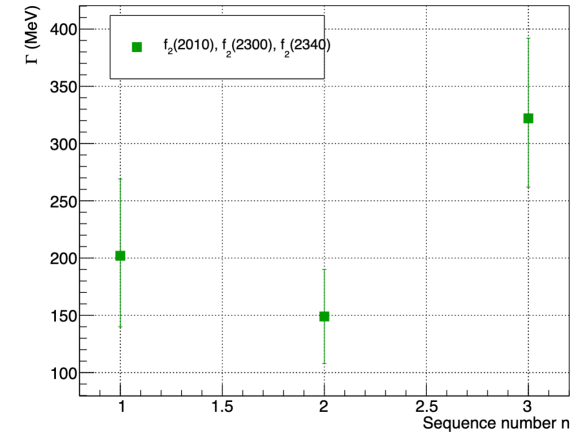
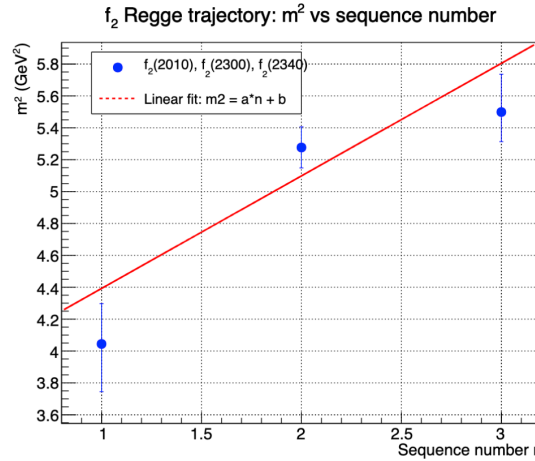
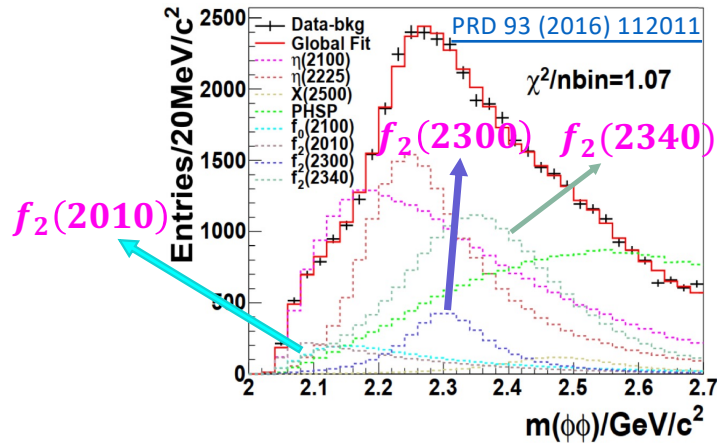
$B^0 \rightarrow J/\psi \phi K_S^0$ data

[Phys. Rev. Lett., 131:131901, 2023](#)

$J/\psi J/\psi$ and $\phi\phi$ systems



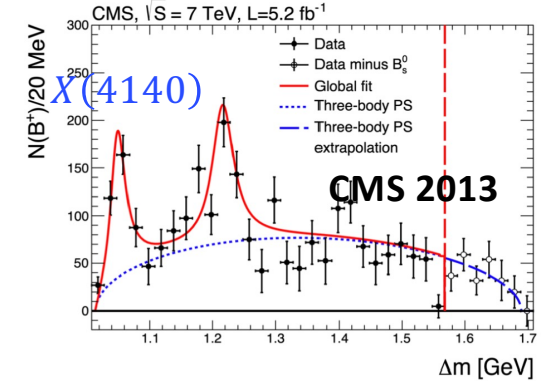
[arXiv:2602.02252](https://arxiv.org/abs/2602.02252)



- $J/\psi J/\psi$ system: CMS observed a family of all-charm tetraquark: X(6600), X(6900), X(7100)
- $\phi\phi$ systems: partial wave analysis of $J/\psi \rightarrow \phi\phi\gamma$ has been performed by BESIII with ~1.3 billion J/ψ events
 - Observe three tensor states $f_2(2010)$, $f_2(2300)$, $f_2(2340)$

Experimental status of $J/\psi\phi$ structures

Year	Experiment	Luminosity [fb ⁻¹]	Process/Yield $B \rightarrow J/\psi\phi K$	Structure	Mass [MeV]	Width [MeV]	J^P	Significance [σ]
2009	CDF	2.7	75 ± 10	$X(4140)$	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$		3.8*
2010	Belle	825	$\gamma\gamma \rightarrow J/\psi\phi$	$X(4350)$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$		3.2
2011	CDF	6.0	115 ± 12	$X(4140)$	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$		> 5.0*
				$X(4274)$	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32.3^{+21.9}_{-15.3} \pm 7.6$		3.1*
2012	LHCb	0.37	346 ± 20	$X(4140)$	4143.0 (fixed)	15.3 (fixed)		
2013	CMS	5.2	2480 ± 160	$X(4140)$	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$		> 5.0*
2013	DØ	10.4	215 ± 37	$X(4140)$	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$		3.1*
2014	BaBar	422.5	189 ± 14	$X(4140)$	4143.4 (fixed)	15.3 (fixed)		1.6
2014	BESIII		$e^+e^- \rightarrow \gamma J/\psi\phi$	–	–	–		–
2015	DØ	10.4	$p\bar{p} \rightarrow J/\psi\phi + \text{anything}$	$X(4140)$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$		4.7
Average				$X(4140)$	4146.8 ± 2.4	$17.3^{+6.6}_{-5.3}$		
2016	LHCb	3	4289 ± 151	$X(4140)$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^+	8.4
				$X(4274)$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^+	6.0*
				$X(4500)$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^+	6.1*
				$X(4700)$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^+	5.6*
2021	LHCb	9	24220 ± 170	$X(4140)$	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	1^+	13
				$X(4150)$	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	2^-	4.8
				$X(4274)$	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	1^+	18
				$X(4500)$	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	0^+	20
				$X(4630)$	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	1^-	5.5
				$X(4685)$	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	1^+	15
				$X(4700)$	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	0^+	17
2024	LHCb	5	$pp \rightarrow J/\psi\phi + \text{anything}$	$X(4274)$	$4298 \pm 6 \pm 9$	$92^{+22}_{-18} \pm 57$		4.1
				$X(4500)$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$65^{+20}_{-16} \pm 32$		6.1



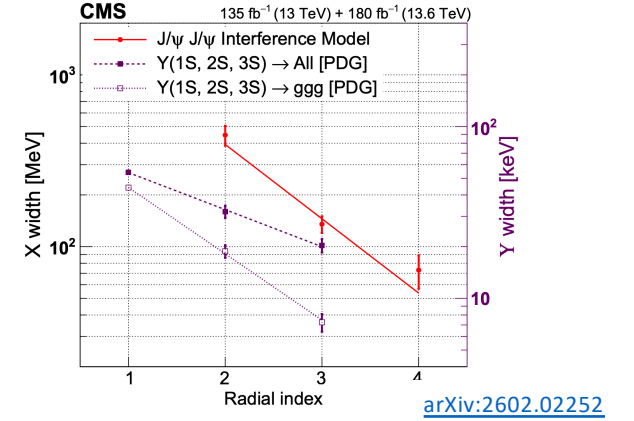
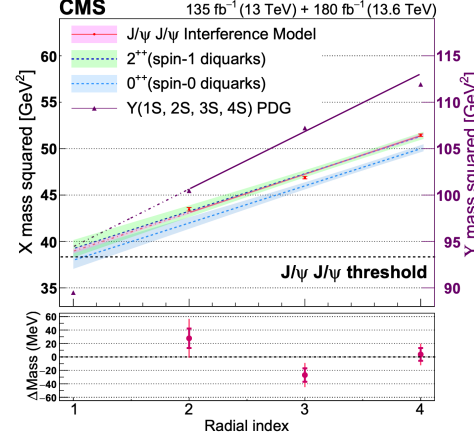
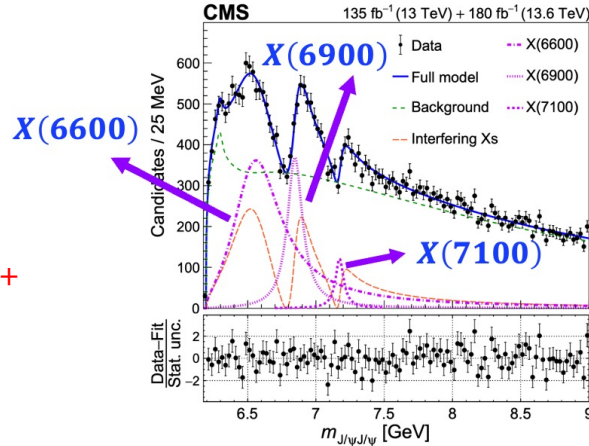
[Phys. Lett. B, 734:261, 2014](#)

[Chin. Phys. Lett. 2025 42\(12\): 120202](#)

- 10 new $J/\psi\phi$ and $J/\psi K$ structures have been claimed in $B \rightarrow J/\psi\phi K$ decays by LHCb
- Not confirmed by other experiments apart from $X(4140)$ and $X(4274)$
- Width of $X(4140)$ by LHCb is inconsistent with previous measurements

$J/\psi J/\psi$ system

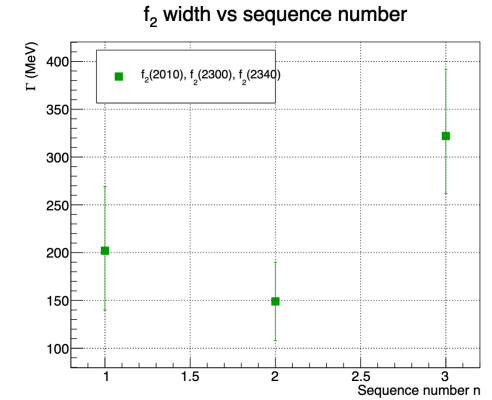
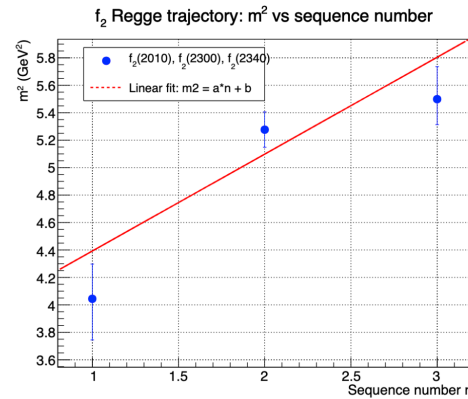
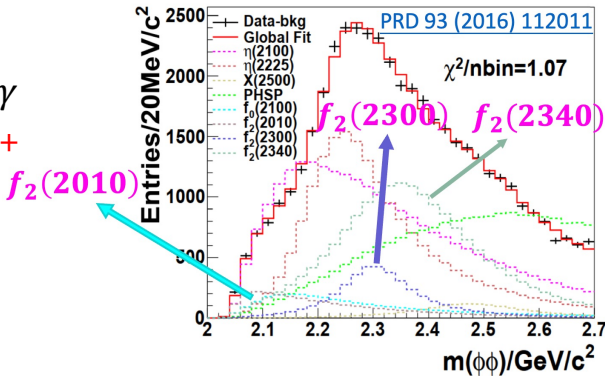
Same flavor $\sim 2^+$



$\phi\phi$ system

BESIII $J/\psi \rightarrow \phi\phi\gamma$

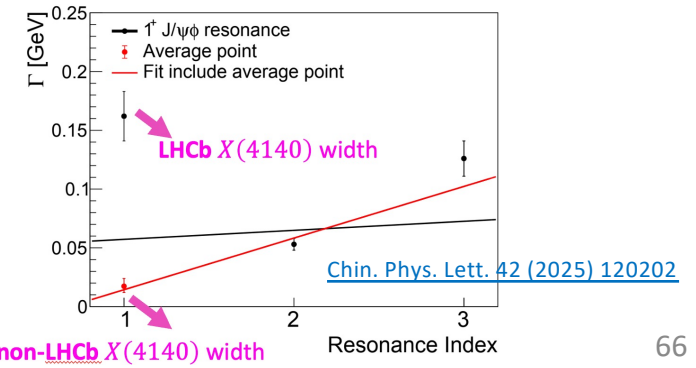
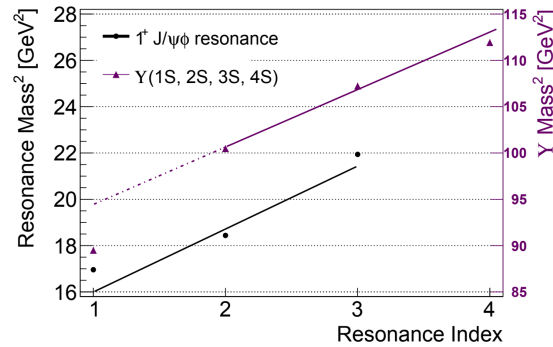
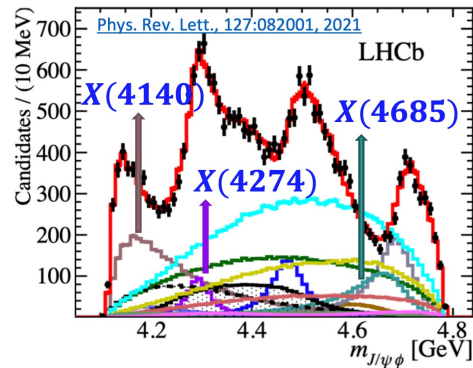
Same flavor $\sim 2^+$

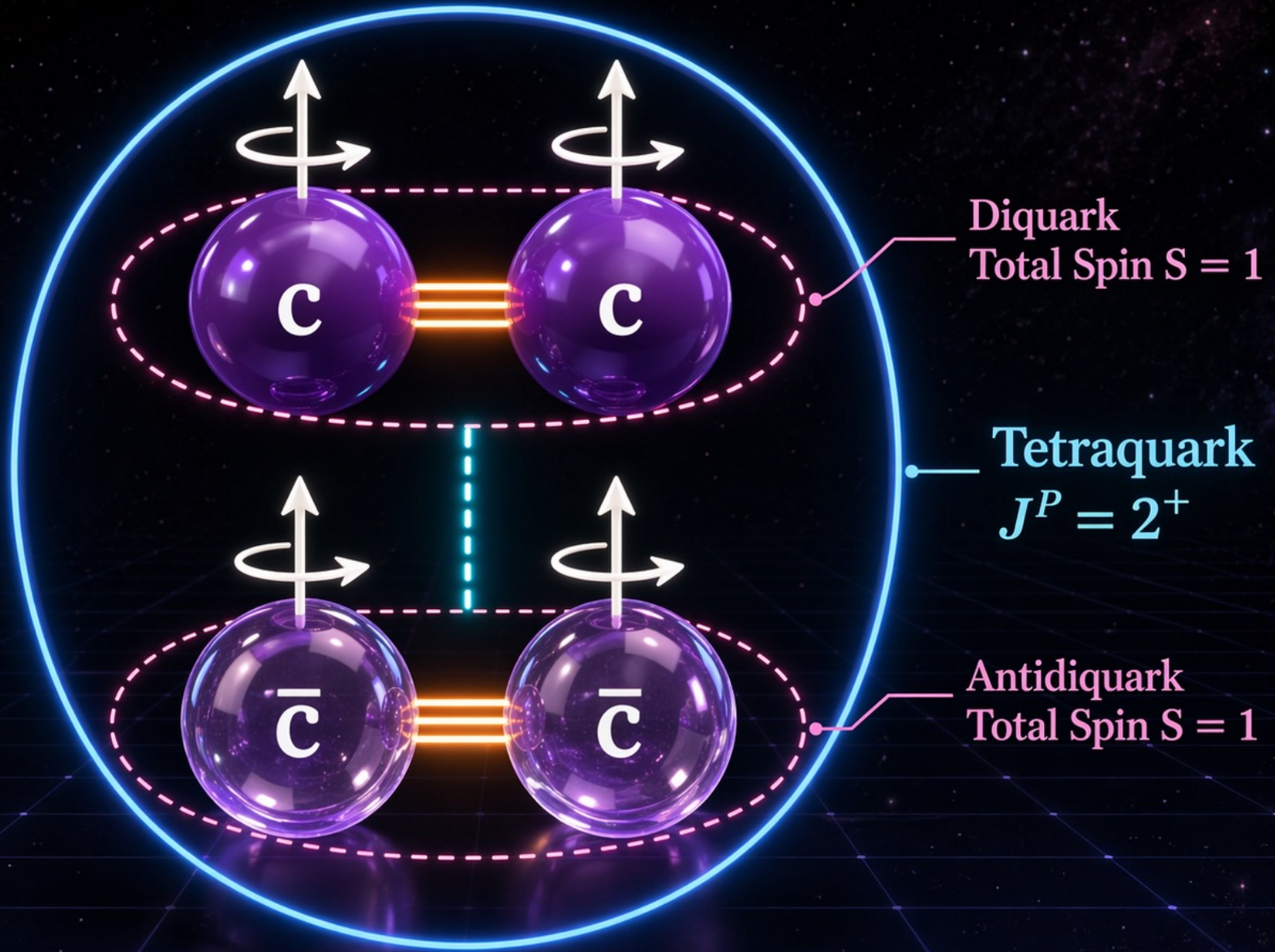


$J/\psi\phi$ system

LHCb $B \rightarrow J/\psi\phi K$

Different flavor $\sim 1^+$





❖ Data

Run 2: 140 fb^{-1} data at 13 TeV

❖ Consider $J/\psi\psi(2S) \rightarrow 4\mu$

➤ Model α with two resonances

The first same as $X(6900)$ in di- J/ψ channel
(parameter fixed)

The second is standalone

No interference between two resonances

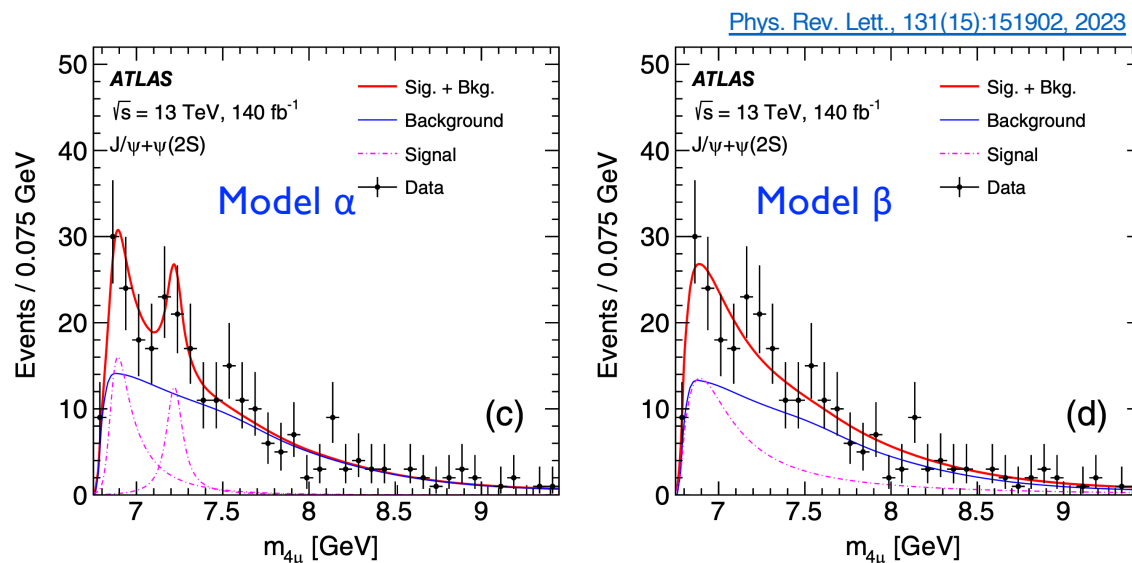
4.7σ for $X(6900)$ in Model α

3.0σ for the stand-alone resonance

➤ Model β with a single resonance

4.3σ for $X(6900)$ in Model β

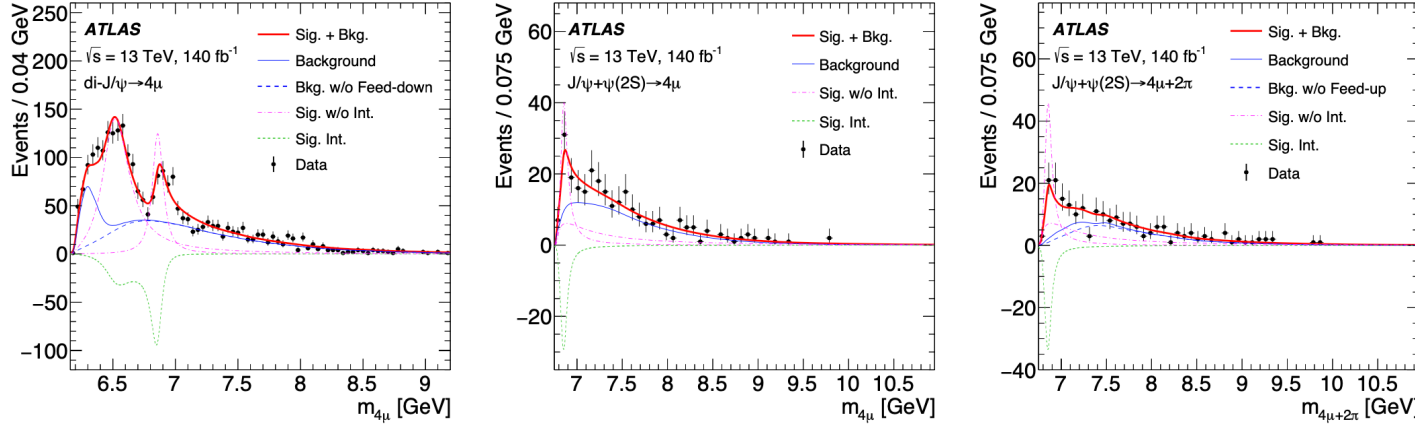
BUT very wide



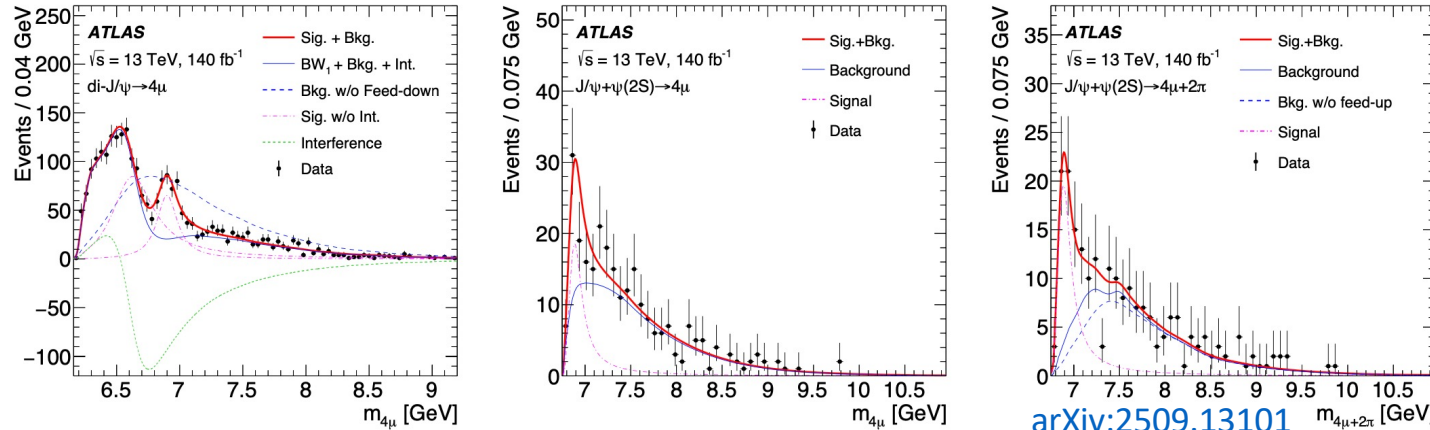
$J/\psi + \psi(2S)$	Model α	Model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

❖ Consider $J/\psi\psi(2S) \rightarrow 4\mu + 2\pi$

Model A: extra BW interferes with X(6900)



Model B: extra BW interferes with SPS, X(6900) not interfering



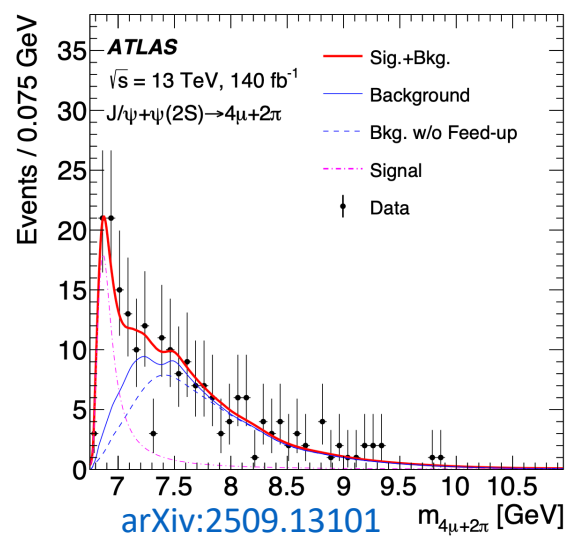
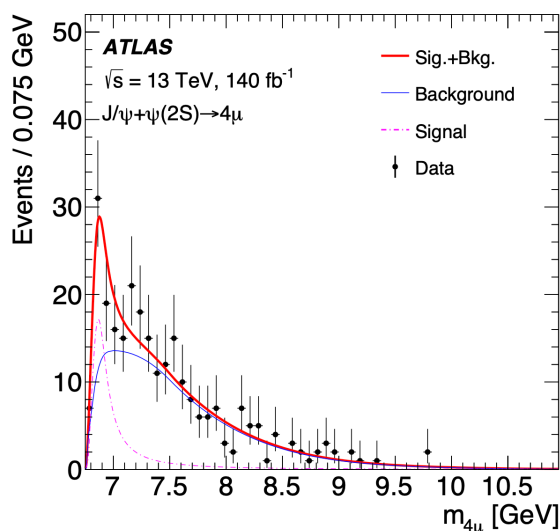
Simultaneous fit of 3 channels:
 $J/\psi J/\psi, J/\psi\psi(2S) [4\mu \text{ and } 4\mu+2\pi]$

$$R = \frac{\Gamma_{X(6900) \rightarrow J/\psi + \psi(2S)}}{\Gamma_{X(6900) \rightarrow \text{di-}J/\psi}} = 1.08 \pm 0.20^{+0.40}_{-0.09}$$

$$R = \frac{\Gamma_{X(6900) \rightarrow J/\psi + \psi(2S)}}{\Gamma_{X(6900) \rightarrow \text{di-}J/\psi}} = 0.93 \pm 0.17 \pm 0.11$$

Simultaneous fit of 2 channels:
 $J/\psi\psi(2S)$ [4μ and $4\mu+2\pi$]

Model C: single $X(6900)$ in baseline, plus test $X(7200)$



	model A	model B	model C
m / GeV	$6.860 \pm 0.023 \pm 0.010$	$6.902 \pm 0.008 \pm 0.010$	$6.884 \pm 0.017^{+0.058}_{-0.005}$
Γ / GeV	$0.082 \pm 0.032 \pm 0.015$	$0.183 \pm 0.025 \pm 0.007$	$0.178 \pm 0.054^{+0.176}_{-0.024}$
R	$1.08 \pm 0.20^{+0.40}_{-0.09}$	$0.93 \pm 0.17 \pm 0.11$	—

Models A and B indicate **a ratio of partial decay widths** of $X(6900) \rightarrow J/\psi + \psi(2S)$ and $X(6900) \rightarrow 2J/\psi$ **near 1**

8.9σ for $X(6900)$ in $J/\psi\psi(2S)$ with 4μ and $4\mu+2\pi$ final state

Set a upper limit for $X(7200)$

$X(7200) / X(6900) = 0.12 \pm 0.11$
 (UL < 0.41, 95% CL)

The inclusion of $X(7200)$ in models A and B yields consistent results.