Observation of a family of all-charm tetraquarks and determination of their spin and parity at CMS

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On behalf of CMS Collaboration

KRAKÓW, POLAND , June 25, 2026

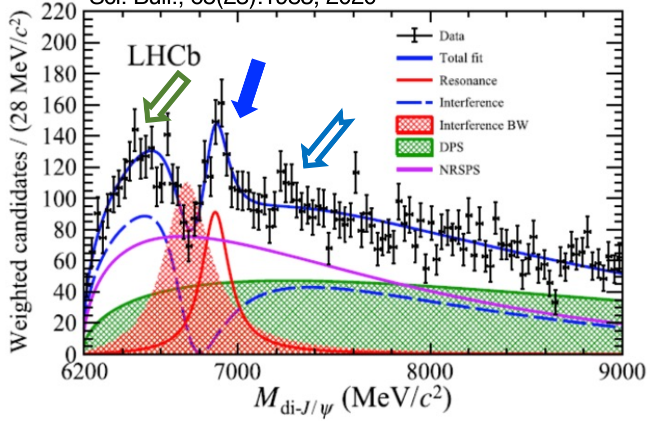
Outline

- $J/\psi J/\psi$ structures
- $J/\psi\psi(2S)$ result
- Spin-parity measurement
- Discussion--Preliminary picture
- Summary

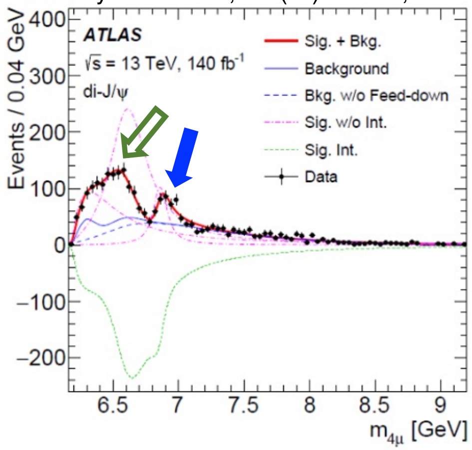
Status of $J/\psi J/\psi$ structures

❖ **All-charm Tetraquark on LHC in J/ψJ/ψ channel**

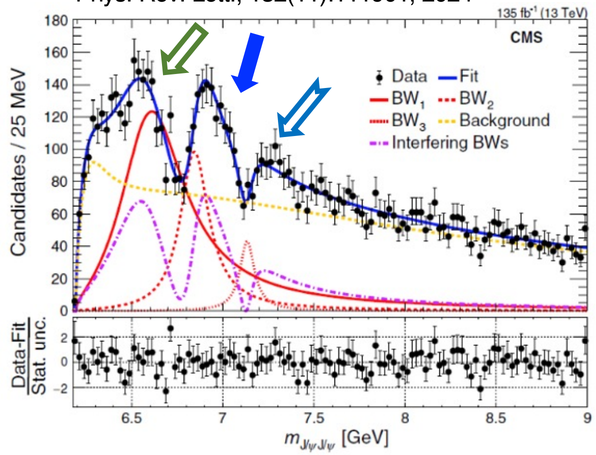
Sci. Bull., 65(23):1983, 2020



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



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



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

➢ **Only CMS claimed X(6600) & X(7100)**

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

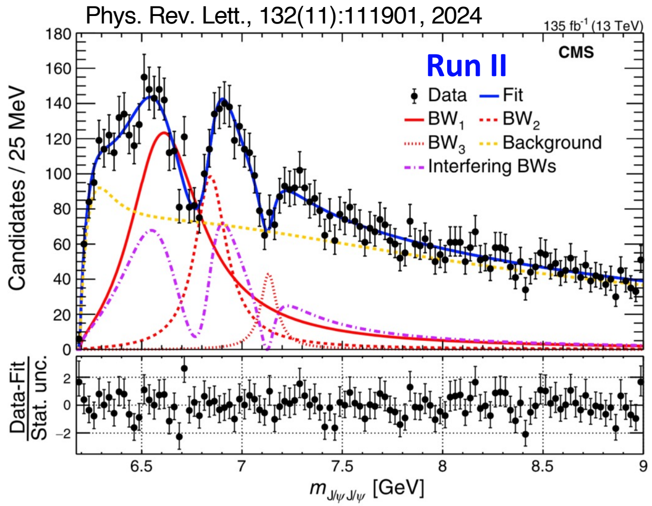
❑ **All exp use interference, but in diff ways**

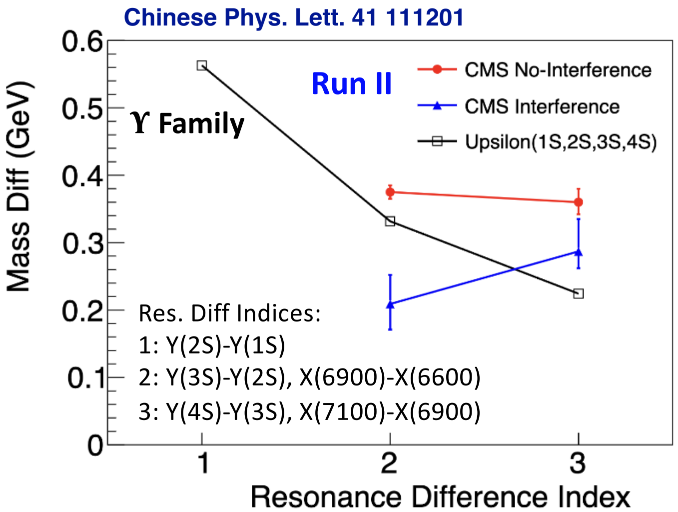
- LHCb: extra BW interfere with SPS, *X(6900) NOT interfering!*
- ATLAS and CMS: different multi-resonance interference

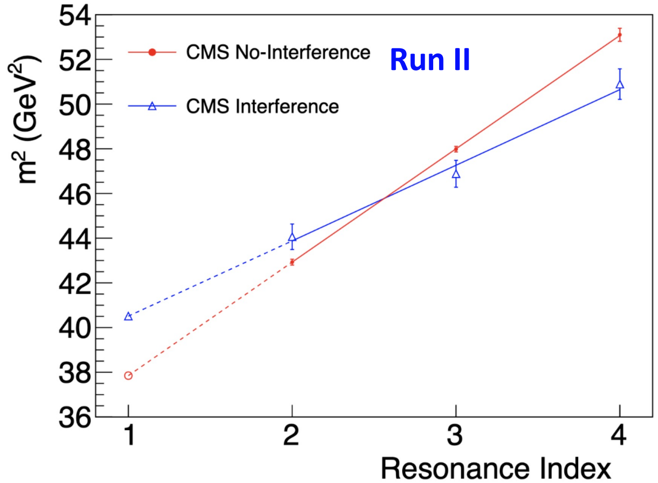
🔎 *A number of unresolved questions !*

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

Status of $J/\psi J/\psi$ structures







Run 2 result:

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

With 3.6X statistics:

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

> ➢ 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} ?

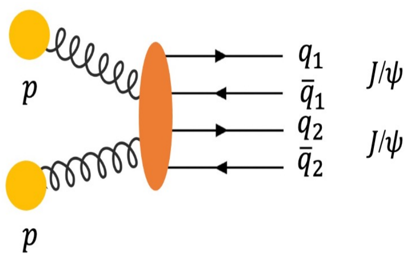
Datasets, MC, trigger, and event selection

❖ Data samples (315 fb^{-1})

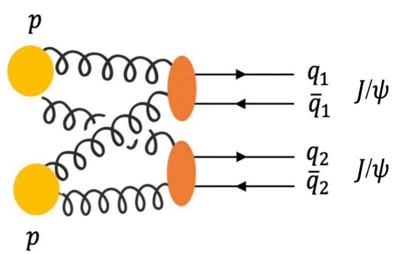
- Run 2: 135 fb^{-1} data taken in 2016, 2017 and 2018
- Run 3: 180 fb^{-1} data taken in 2022, 2023 and 2024

❖ Signal and Background simulated events:

- **Signal** $X \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ by JHUGen
- **NRSPS** and **Feeddown** by Pythia8
- **DPS** event-mixing
- **Feeddown**: $X(6900) \to J/\psi\psi(2S) \to J/\psi J/\psi + anything$



SPS



DPS

❖ Triggers

➢ **Run 2 trigger:**

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

➢ **Run3 trigger (new with parked data):**

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

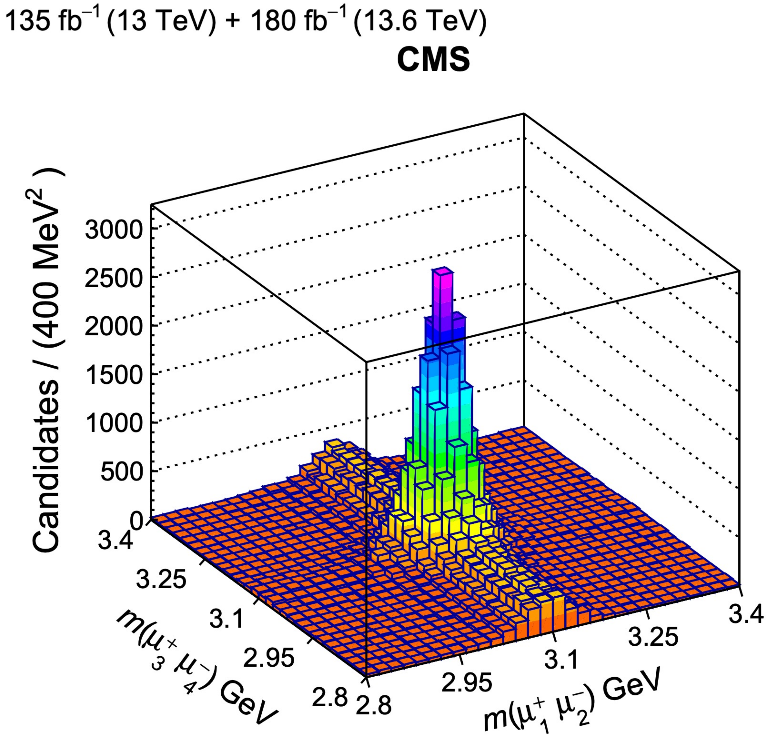
➢ **increase 30% $J/\psi J/\psi$ statistics compared to old trigger**

❖ Event selection

- Follow Run 2 cuts + new trigger for Run 3

arXiv:2602.02252, submitted to Science Advances

$J/\psi J/\psi$ yield: two-dimensional fit



- ***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}

- Run 2+3 ***$J/\psi J/\psi$ yield*** is ***3.6X*** of Run 2
- Run 2+3 ***luminosity*** is ***2.3X*** of Run 2

Signal and background models

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

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

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

❖ **Non-interference model:**

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

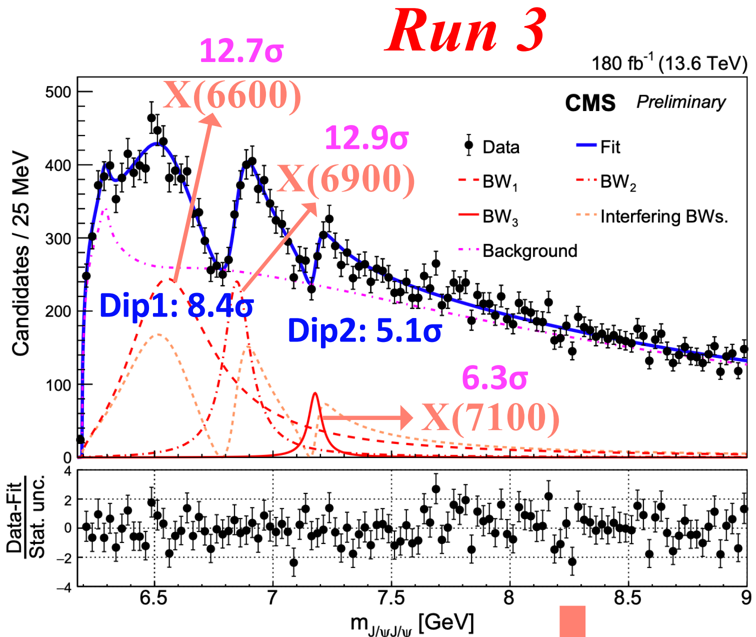
$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m)$$
$$+ N_{NRDPS} \cdot f_{NRDPS}(m) + N_{Comb} \cdot f_{Comb}(m) + N_{Feedown} \cdot f_{Feedown}(m)$$

❖ **Interference model:**

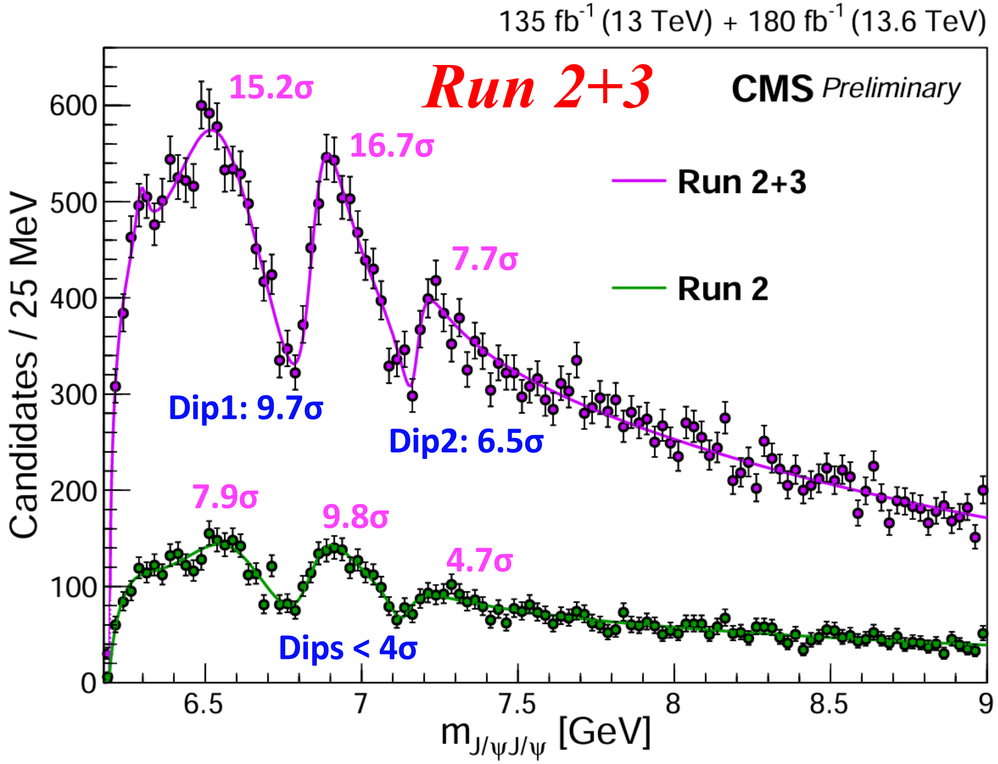
- **Signal-hypothesis:** NRSPS + NRDPS + Comb + Feeddown + BW0 + **BW123 Interf. Term**

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

Confirmation of 3 structures



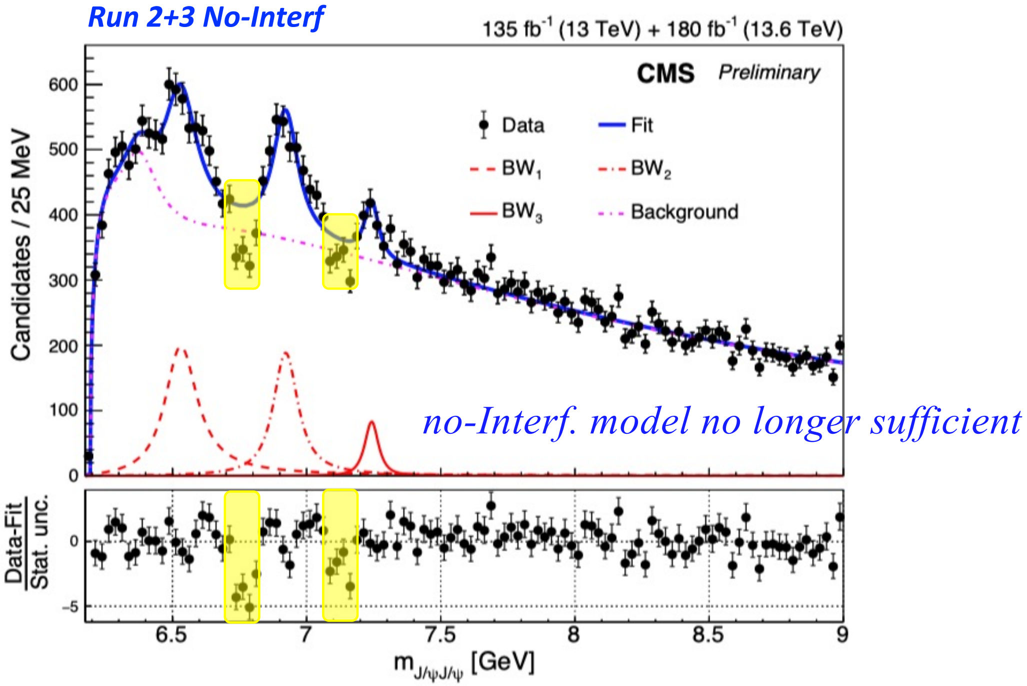
Parameter	Run 2 [Interf.]		Run 3 [Interf.]	
$m(\mathrm{BW}_1)$	6638	$^{+43+16}_{-38-31}$	6588	± 19
$\Gamma(\mathrm{BW}_1)$	440	$^{+230+110}_{-200-240}$	454	± 74
$m(\mathrm{BW}_2)$	6847	$^{+44+48}_{-28-20}$	6849	± 12
$\Gamma(\mathrm{BW}_2)$	191	$^{+66+25}_{-49-17}$	136	± 18
$m(\mathrm{BW}_3)$	7134	$^{+48+41}_{-25-15}$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

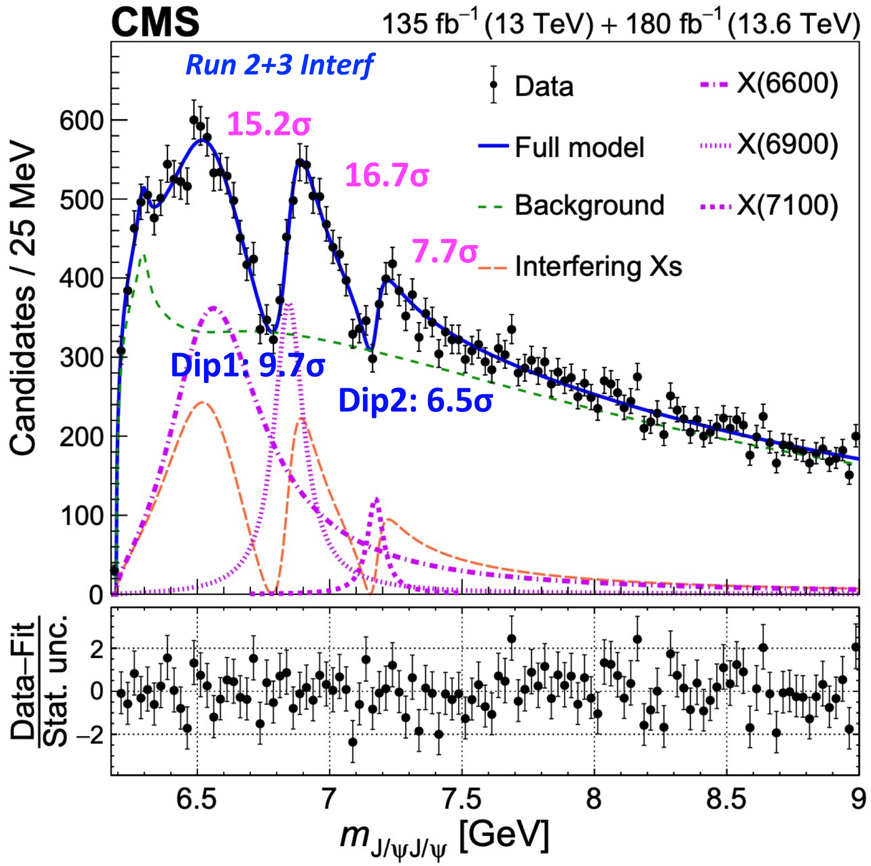


- ✓ ***Confirm Run 2 results with Run 3 data only***
- ✓ ***All states and dips above 5σ***

Confirmation of interferences among 3 structures

❖ **Interference model with Run 2 + 3:**





✓ All states and dips (interference) >> 5σ !

✓ 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, submitted to Science Advances

Params	M(BW1)	Γ(BW1)	M(BW2)	Γ(BW2)	M(BW3)	Γ(BW3)
Run II & III Interf. [MeV]	$\mathbf{6593^{+15}_{-14} \pm 25}$	$\mathbf{446^{+66}_{-54} \pm 87}$	$\mathbf{6847 \pm 10 \pm 15}$	$\mathbf{135^{+16}_{-14} \pm 14}$	$\mathbf{7173^{+9}_{-10} \pm 13}$	$\mathbf{73^{+18}_{-15} \pm 10}$
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**

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

- 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 $\boldsymbol{J/\psi\psi(2S)}$ **yield** ***~2.6 X of Run 2***

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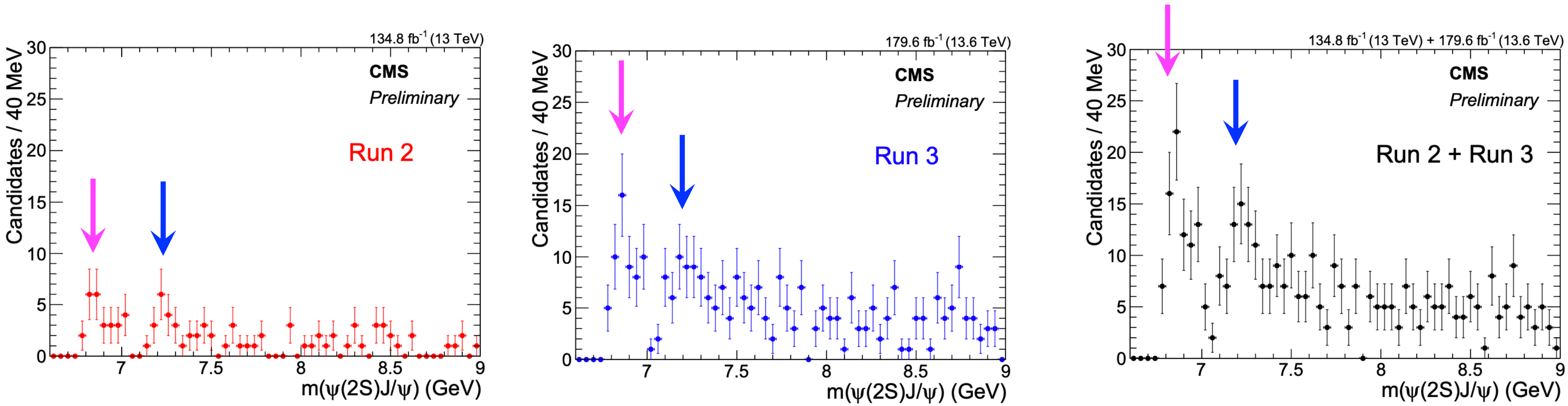
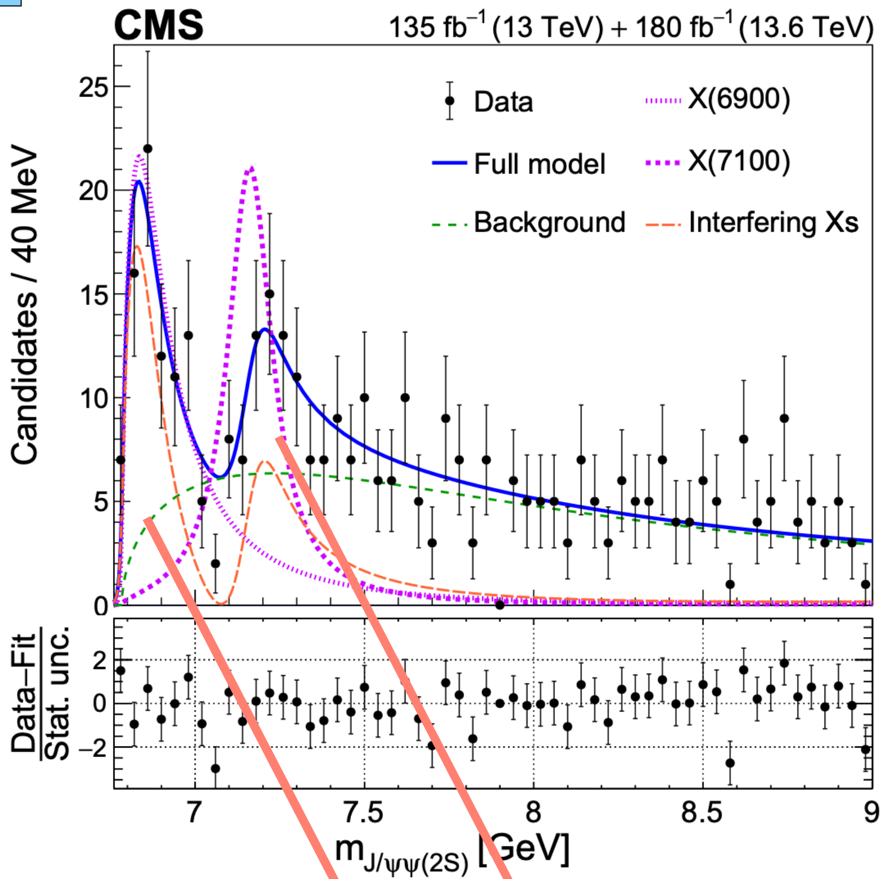
Run 2 ~109 ± 14
Run 3 ~281 ± 22
Run 2+3 ~386 ± 26



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



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arXiv:2602.02252

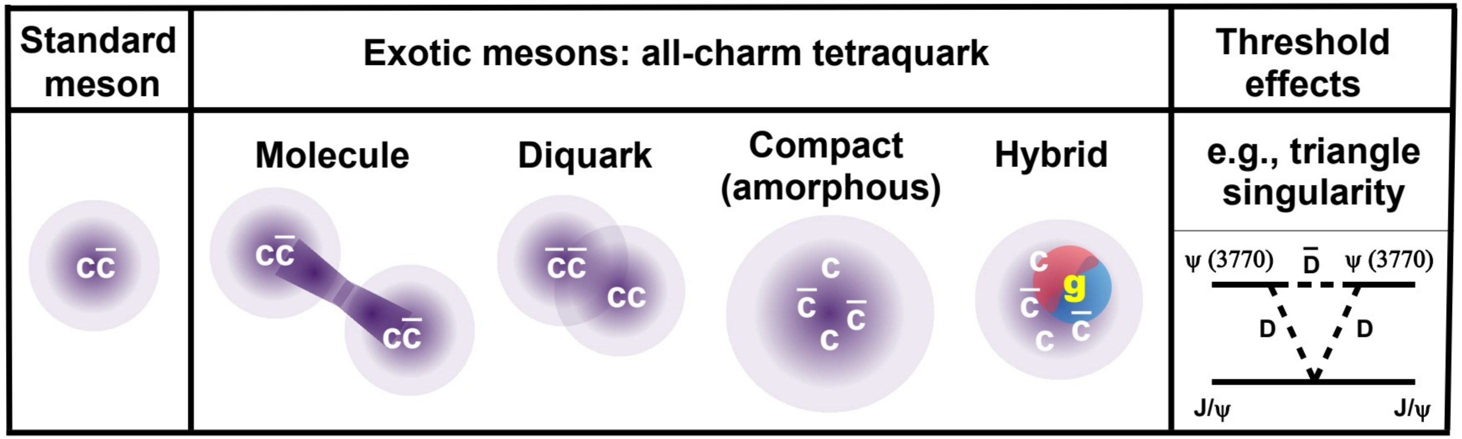
Param.	$J/\psi\psi(2S)$ [MeV]	$J/\psi J/\psi$ [MeV]
M(X(6900))	$6876^{+46+111}_{-29-112}$	$6847 \pm 10 \pm 15$
Γ(X(6900))	$253^{+290+140}_{-100-134}$	$135^{+16}_{-14} \pm 14$
M(X(7100))	7169^{+26+80}_{-52-72}	$7173^{+9}_{-10} \pm 13$
Γ(X(7100))	$154^{+110+140}_{-82-181}$	$73^{+18}_{-15} \pm 10$

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

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

Theoretical models

arXiv:2602.02252



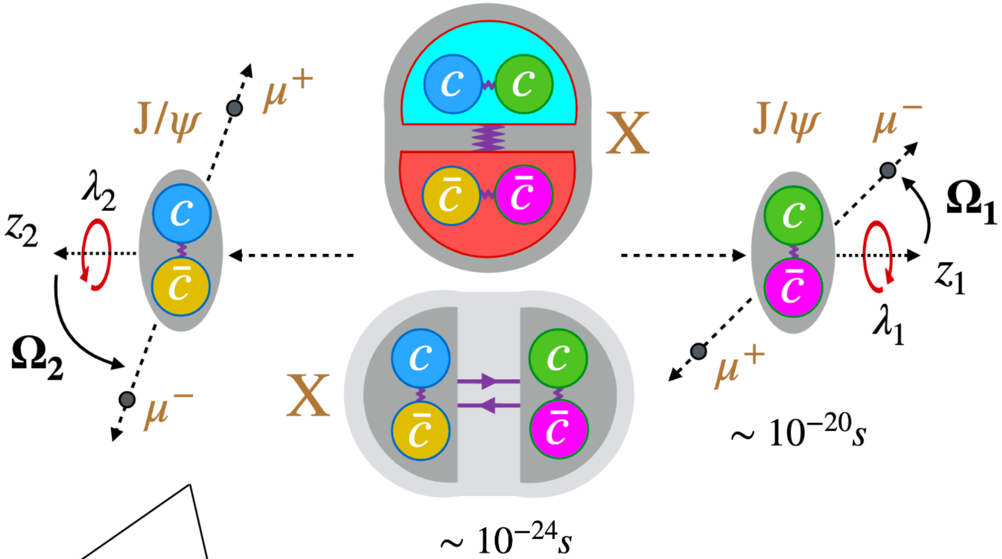
❖ Models of potential quark configurations for J/ψJ/ψ mesons.

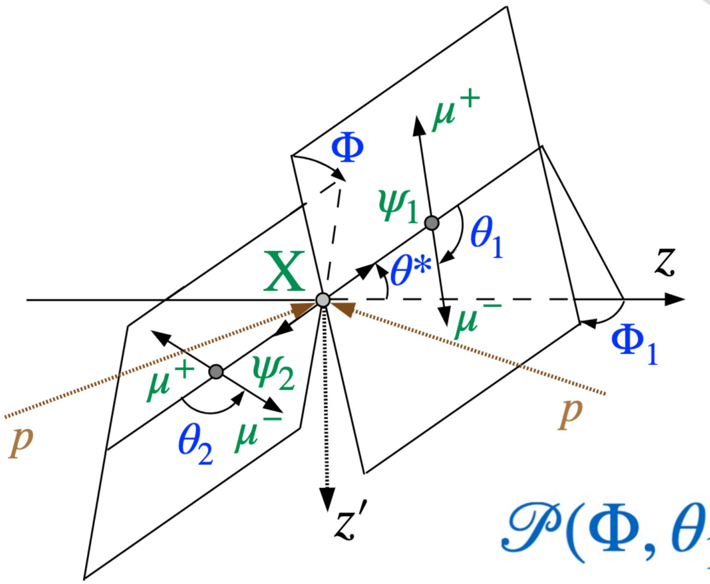
- Meson-meson "molecule" ($c\bar{c}$- $c\bar{c}$)
- Pair of diquarks (cc-$\bar{c}\bar{c}$)
- Hybrid with a valence gluon
- Peaks as artifact of dicharmonia production thresholds
- ……

➢ *What are their internal structures?*

➢ *Spin-parity measurement provide critical insights*

Spin parity analysis





$$J^{PC} = ?$$

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

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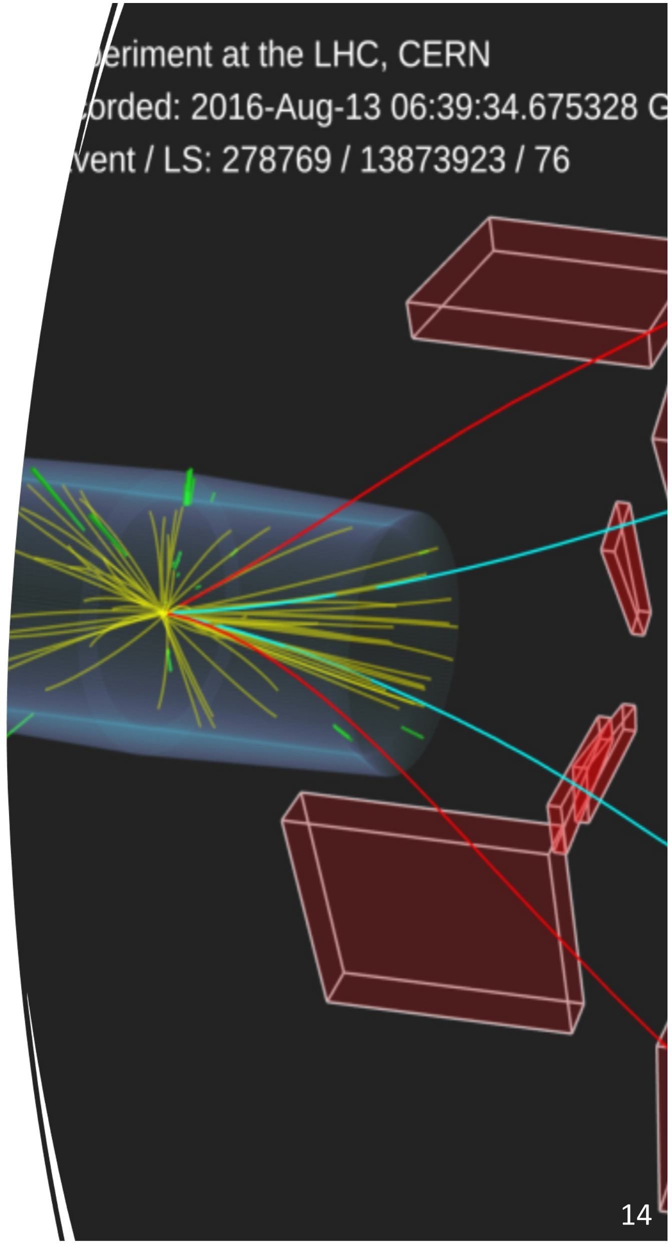
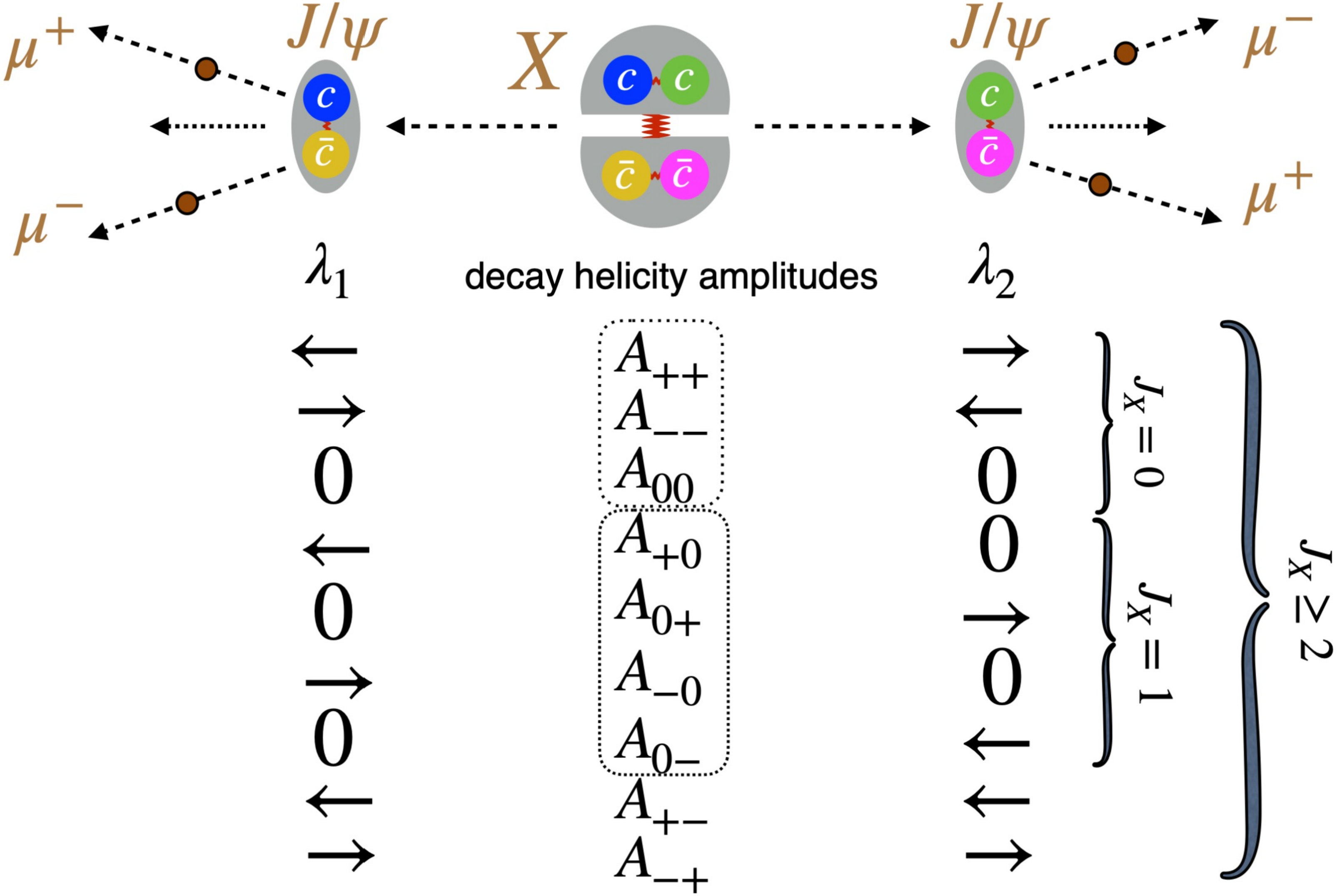


J/ψ polarizations



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

Simplification in angular analysis

- Full model possible, but very complex

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

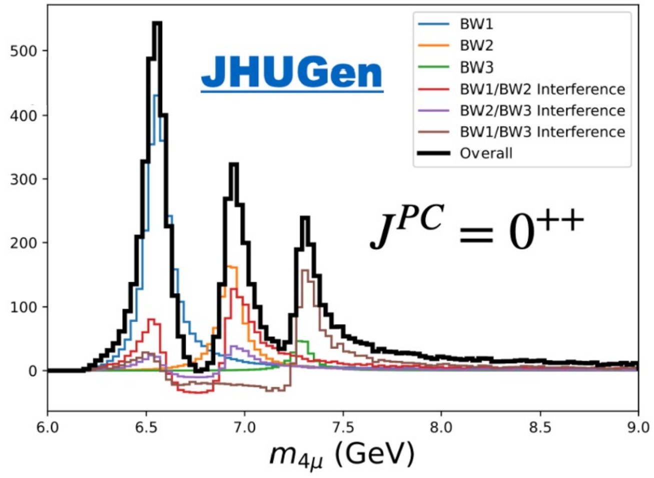
- **Simplifications**
  - Assume same properties of 3 resonances
  - Create optimal discriminant, hypothesis test for i and j

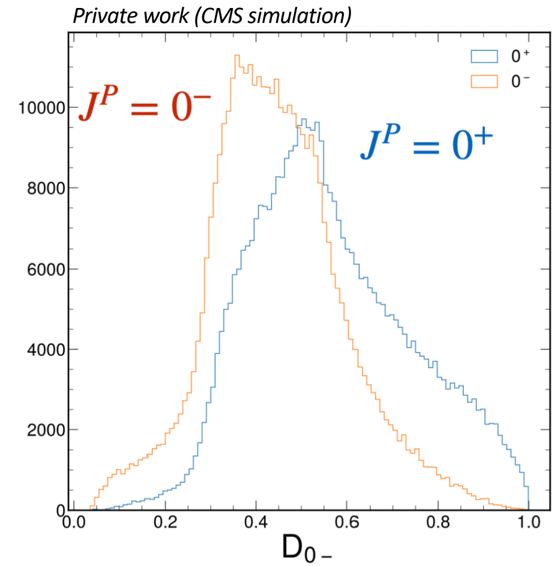
$$\mathscr{D}_{ij}(\overrightarrow{\Omega}\,|\,m_{4\mu}) = \frac{\mathscr{P}_i(\overrightarrow{\Omega}\,|\,m_{4\mu})}{\mathscr{P}_i(\overrightarrow{\Omega}\,|\,m_{4\mu}) + \mathscr{P}_j(\overrightarrow{\Omega}\,|\,m_{4\mu})}$$

- **Final 2D model**

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

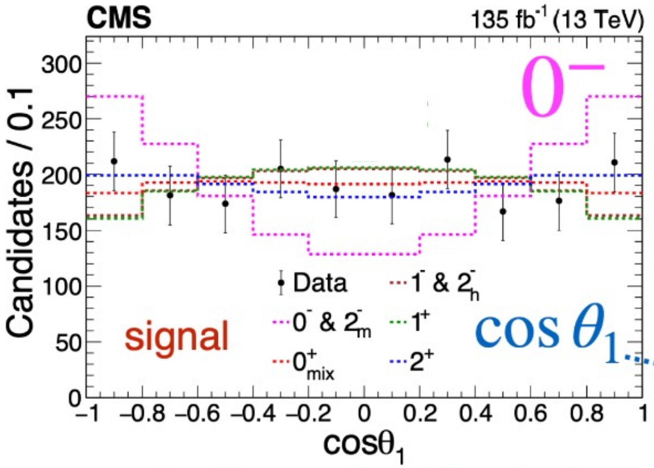
Empirical *Angular*

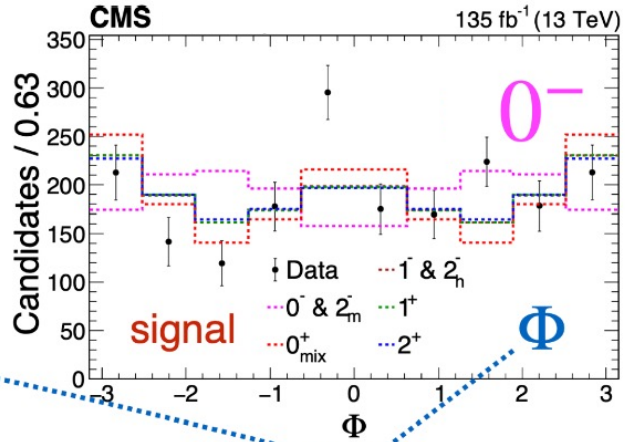




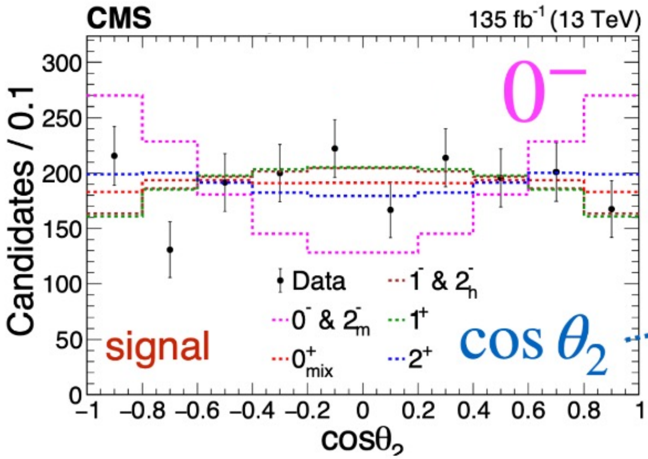
Decay Angles

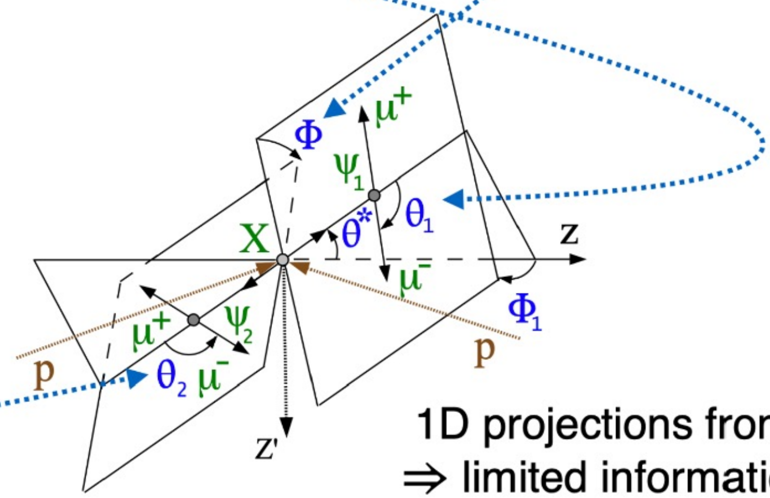
decay angles (consistency check): distinguish models   Nature 648 (2025) 58





background-subtracted

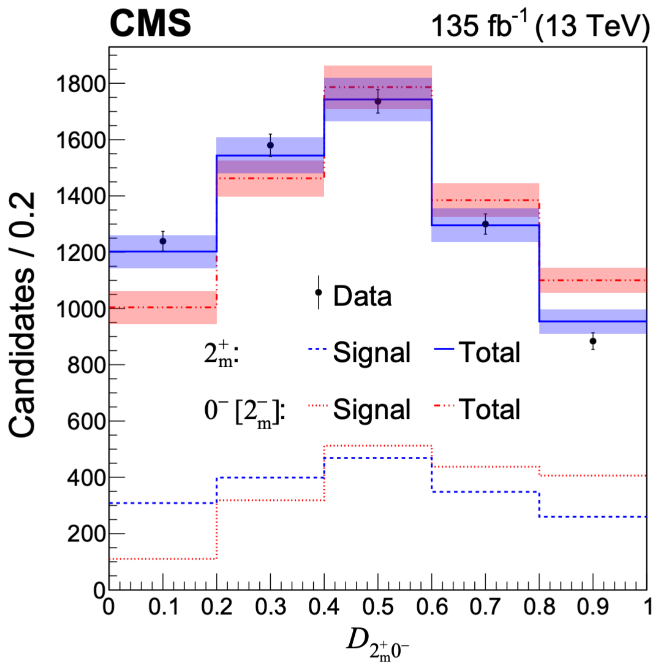


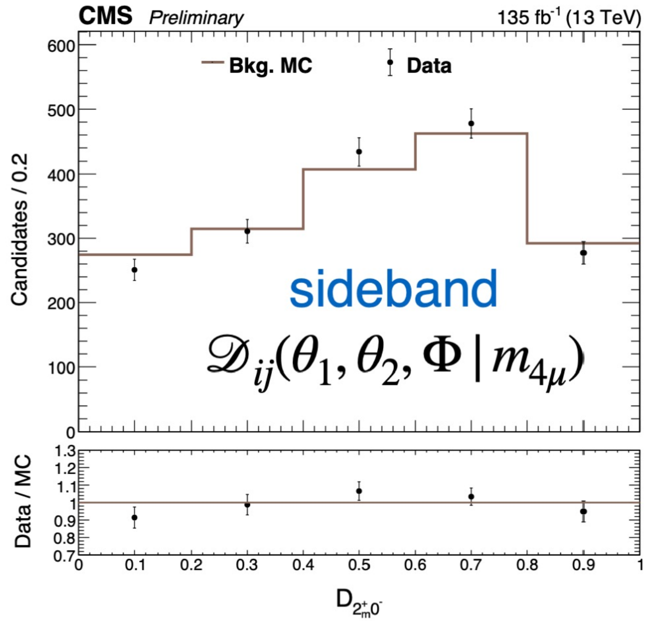


1D projections from 4D
⇒ limited information

Optimal Observable

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





background model from MC
control in sidebands
systematic variations

optimal observable

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

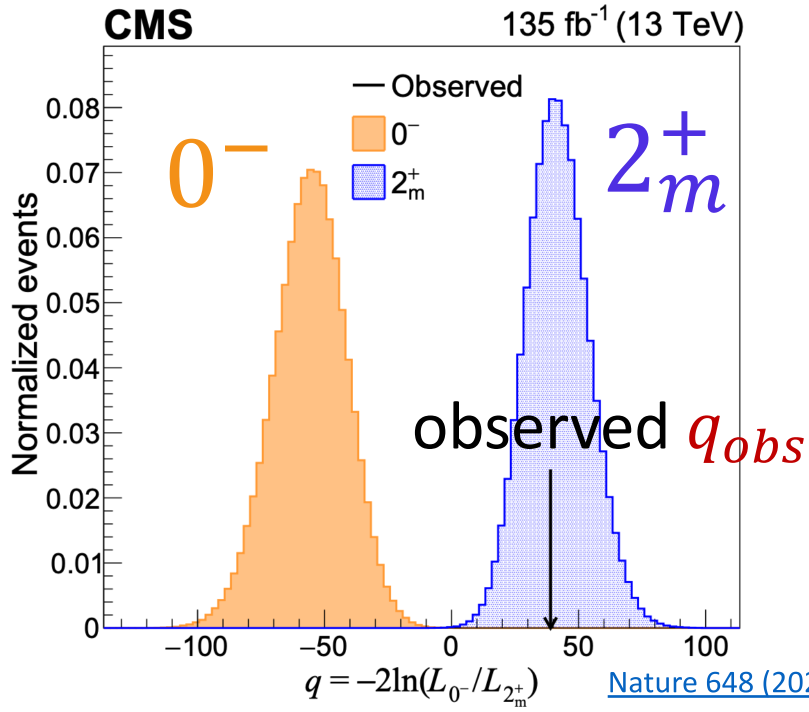
1D projections from 2D
⇒ limited information

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

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



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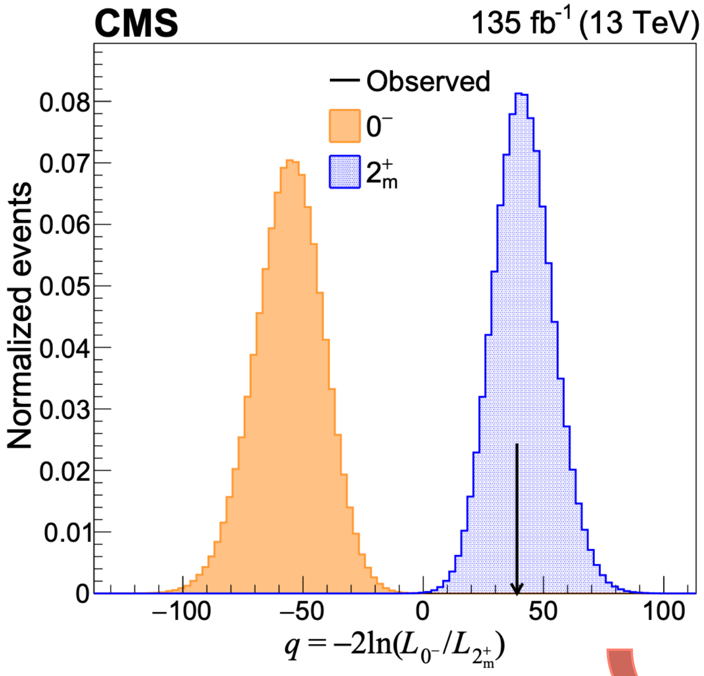
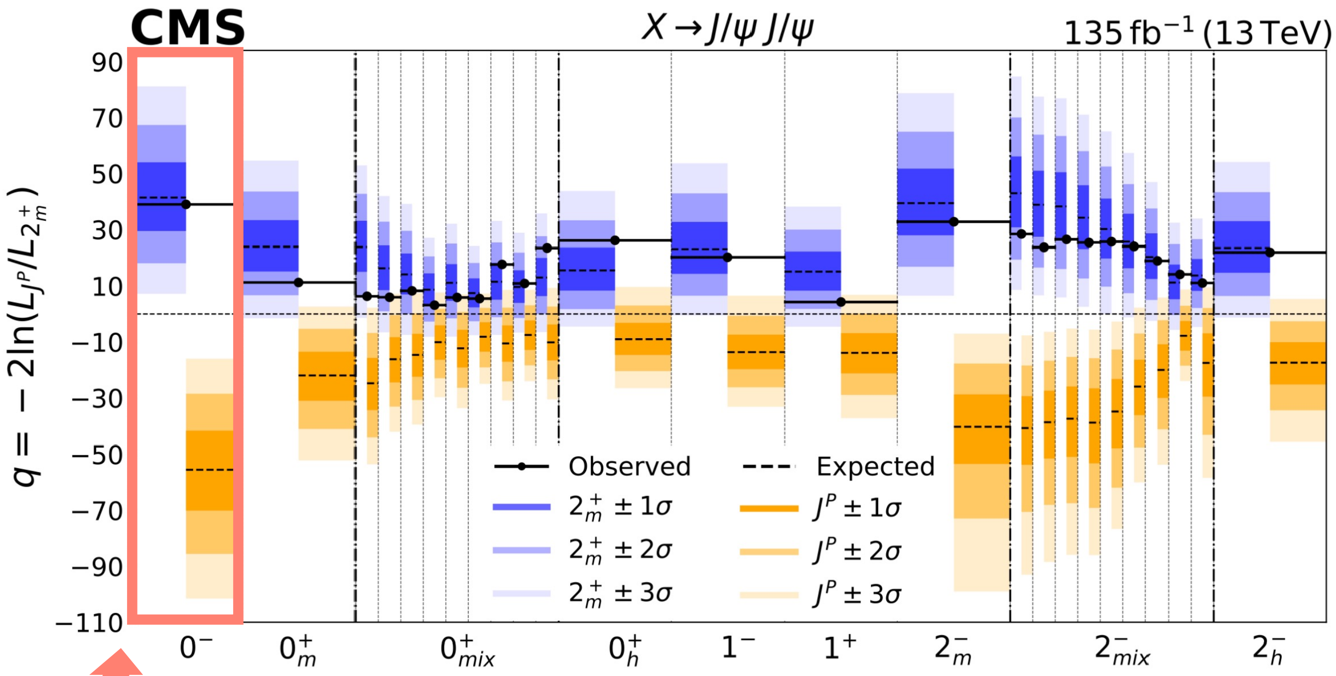
		Observed p-value	Observed Z-score	Expected p-value	Expected Z-score
0^- vs 2_m^+	0^-	2.7×10^{-13}	7.2	6.5×10^{-14}	7.4
	2_m^+	4.2×10^{-1}	0.2	0.50	0.0

Statistical Analysis





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PC* =+ + *very certain

J* ≠ 1 *at* > 99% *CL

J* ≠ 0 *at* > 95% *CL

J* > 2 *less likely

J* = 2 *consistent, rare in nature

Scan mixture of 0^{++} amplitudes

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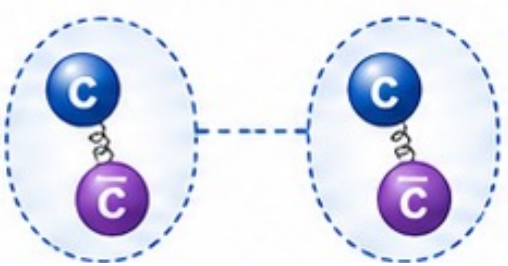
Scan mixture of 2^{-+} amplitudes

Internal structure

Molecule (meson-meson)

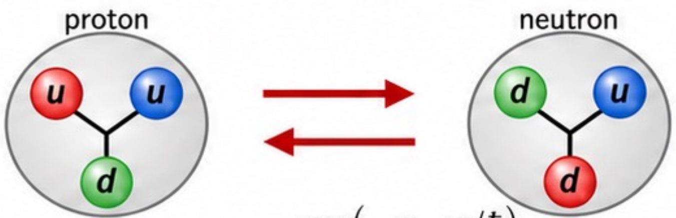
Bound state of two mesons



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

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

Analogy: deuteron (loosely bound nuclear molecule)



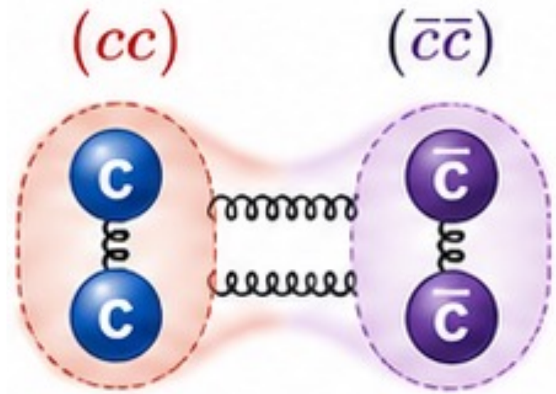
$$V(r) = g \cdot \frac{\exp(-m_\pi c r/\hbar)}{r}$$

π exchange

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

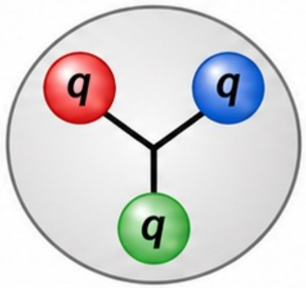
?

Compact tetraquark (diquark-antidiquark)

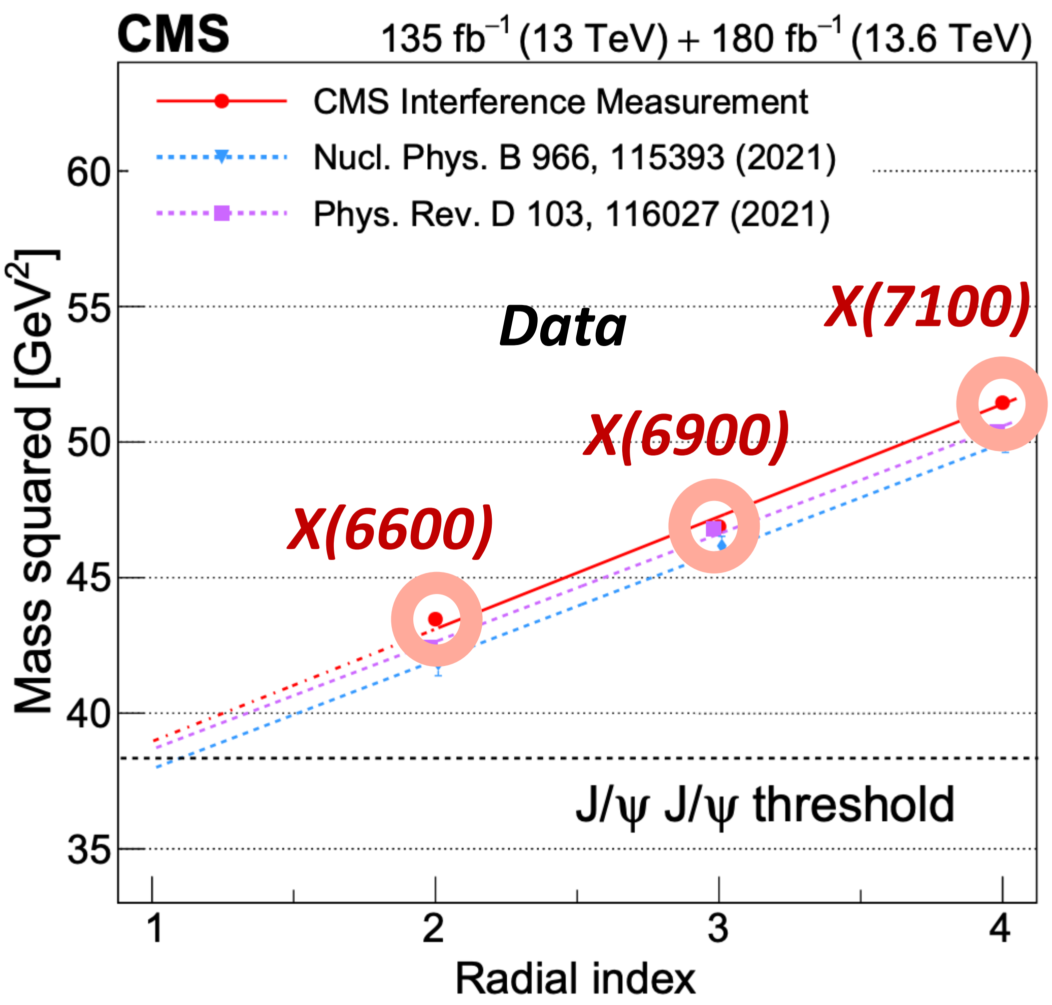


Connects two colored objects through direct strong interactions, like quarks in a proton or neutron.

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

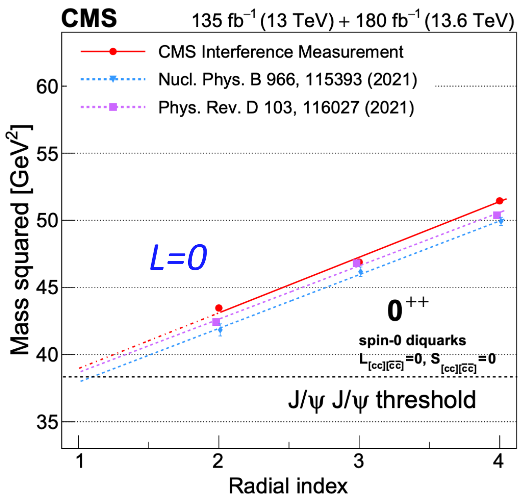


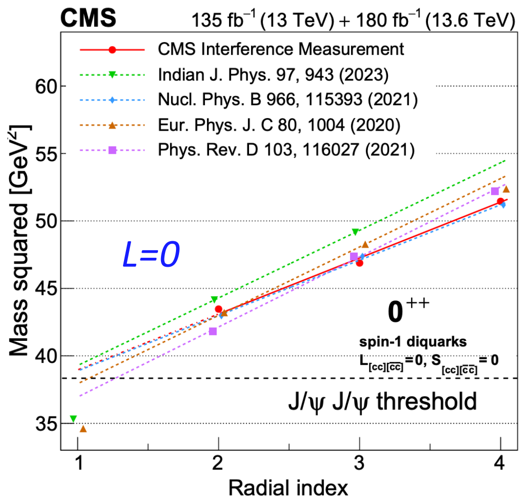
Discussion—Regge trajectory

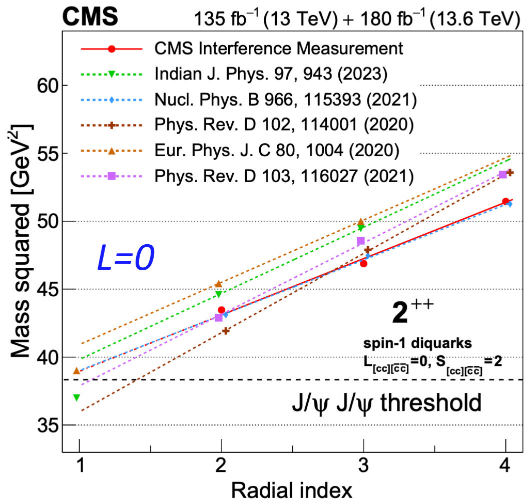


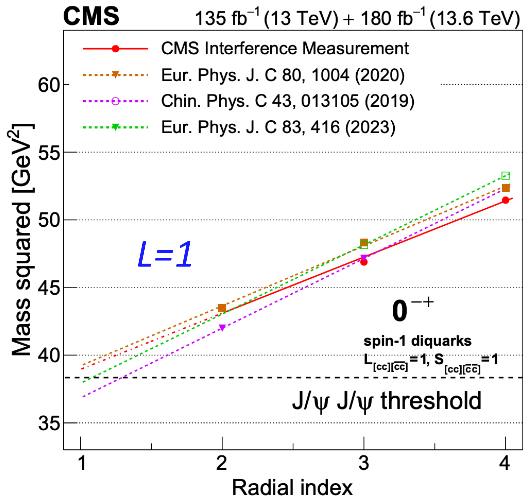
- *Mass squared align Regge trajectory*
- *Interference—family indication*
- *A few predictions for a family*
- *Most are diquark-antidiquark model*
- *Compare to available predictions*

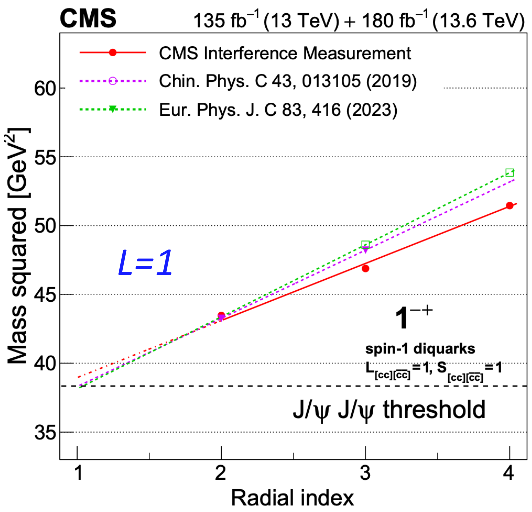
Discussion—comparisons to diquark predictions

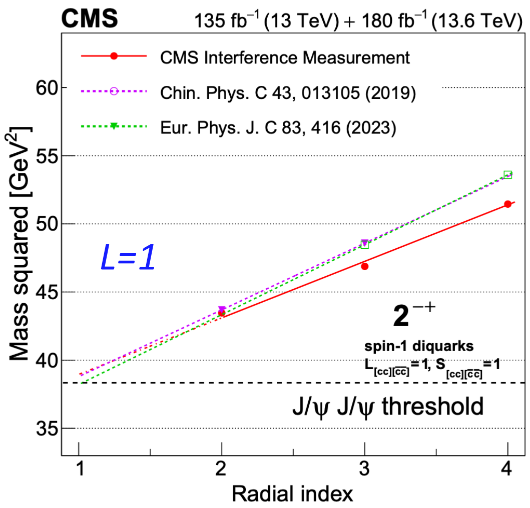


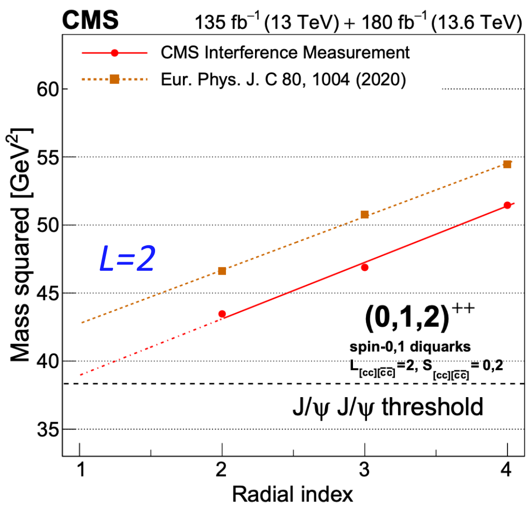








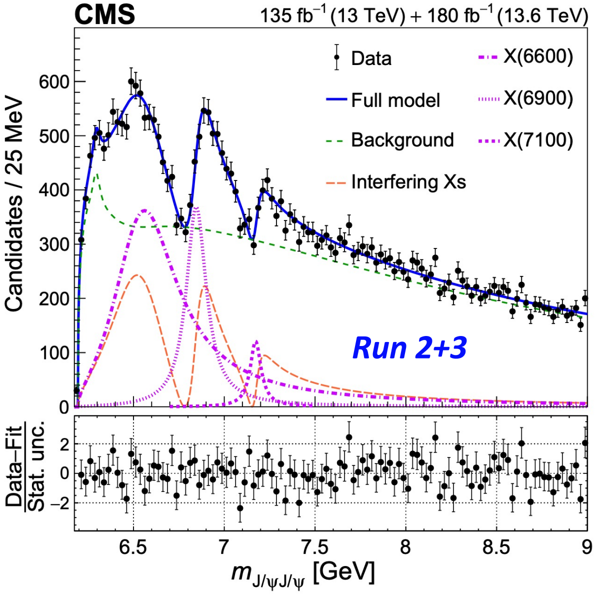


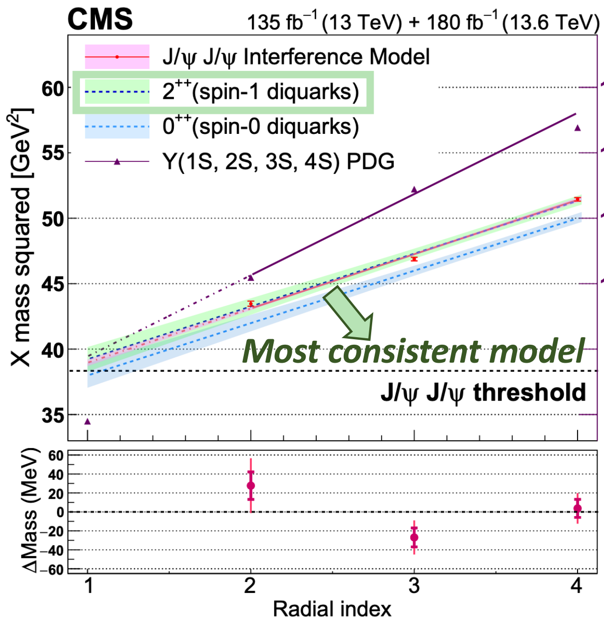


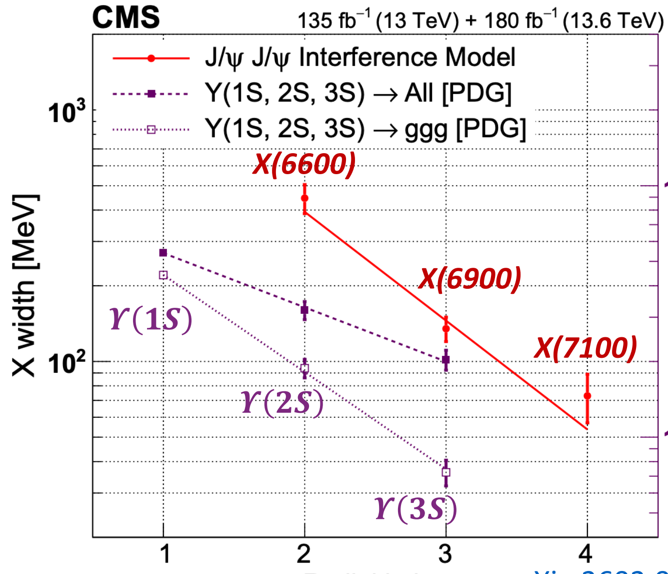
Most consistent one

Spin-1 diquark

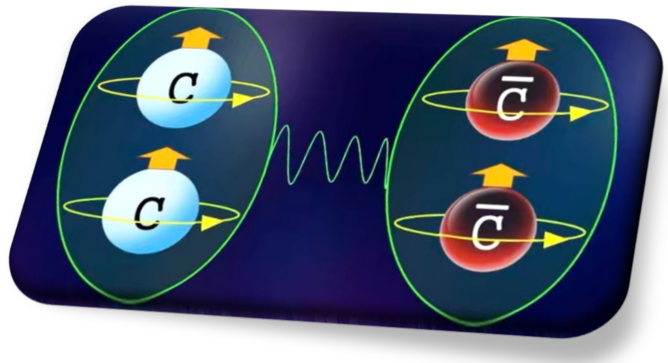
Discussion—preliminary physics picture







arXiv:2602.02252



- Interference imply same J^{PC} quantum numbers
- >200 MeV mass splittings among triplet similar to ϒ family
- Squared masses of triplet align Regge trajectory ==> Radial excitations
- Regge plot favors spin-1 diquark model
- Width trend similar to ϒ family

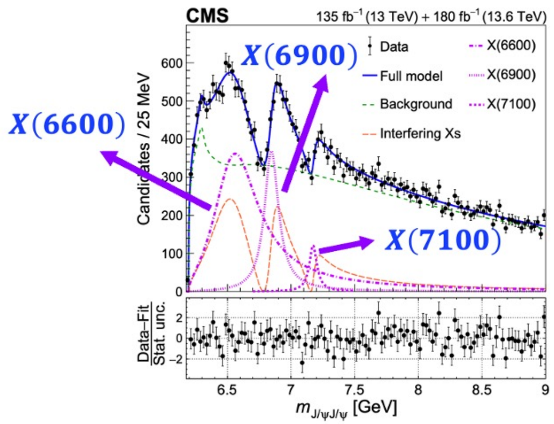
Same quark ==> spin-1 diquark

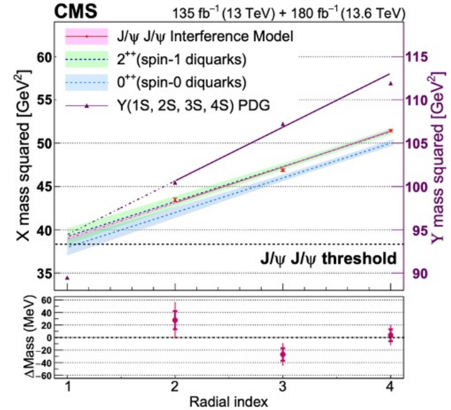
Let's check other related VV systems:

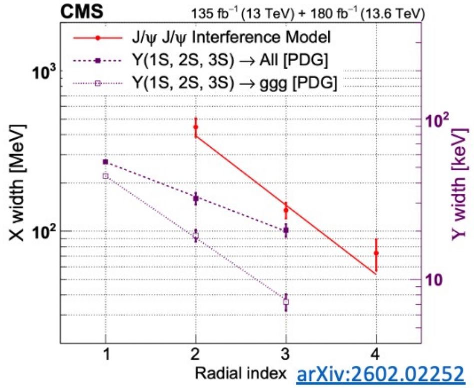
$J/\psi J/\psi$, $\phi\phi$ and $J/\psi\phi$

$J/\psi J/\psi$ system

Same flavor ~ 2^+



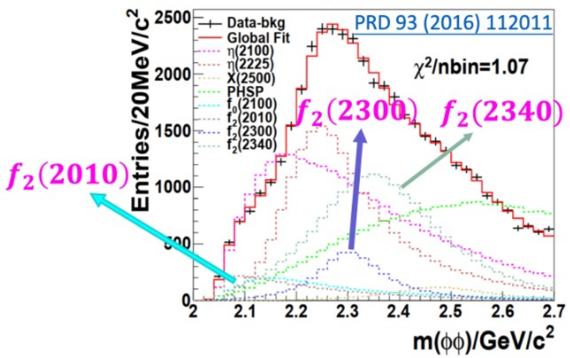


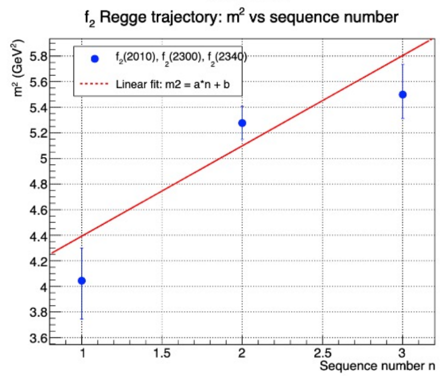


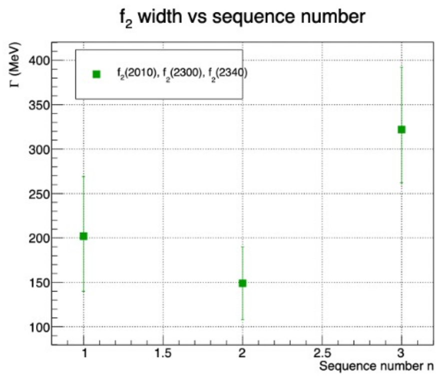
$\phi\phi$ system

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

Same flavor ~ 2^+



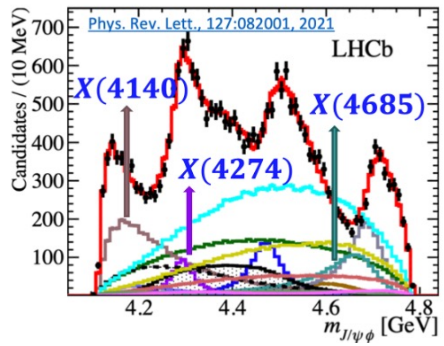


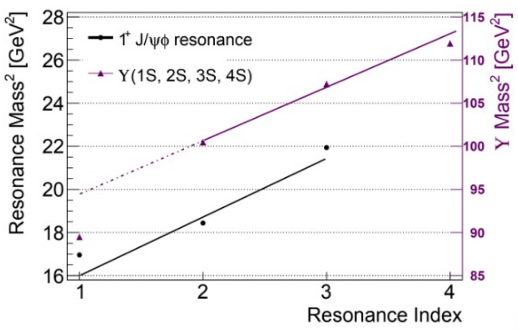


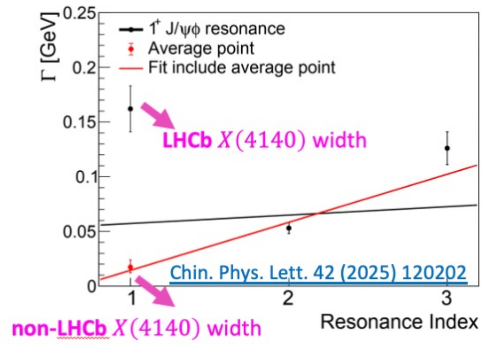
$J/\psi\phi$ system

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

Different flavor ~ 1^+



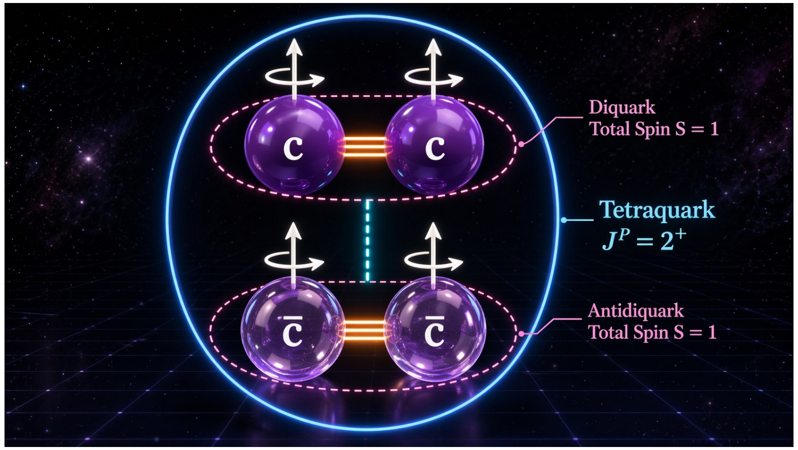




Summary

- Three structures X(6600), X(6900), X(7100) well established
- Quantum interference among structures well established
- Rresonance 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 $\boldsymbol{\phi\phi}$ and $J/\psi\boldsymbol{\phi}$ systems?

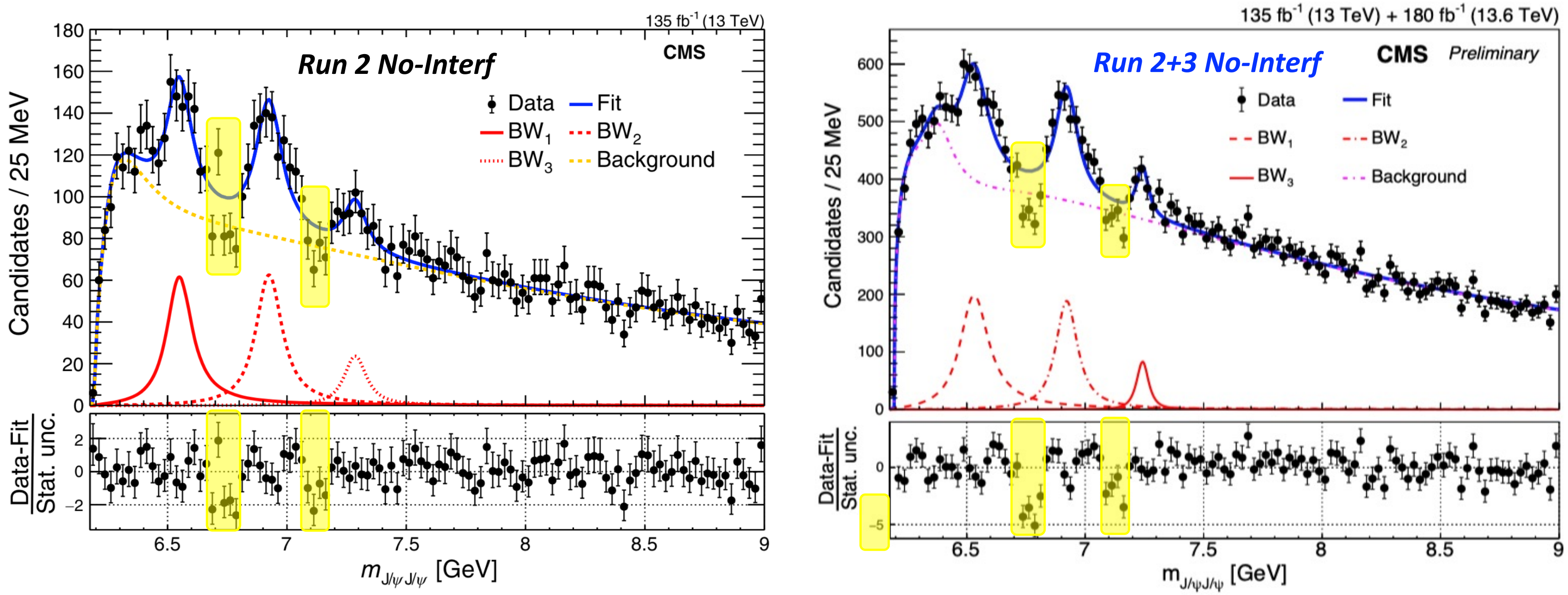
Stay tuned!

Backup

Run 2 & 3 no-interference fit result

- **No-interference model:**
  - **Signal-hypothesis:** NRSPS + NRDPS + Comb + Feeddown + BW0 + **BW1 + BW2 + BW3**

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



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

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:

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

0_m^+ $\quad$ 0_h^+ $\quad$ 0^-

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

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

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

arXiv:1001.3396

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

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

1^- $\quad$ 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:

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

arXiv:1001.3396

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

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

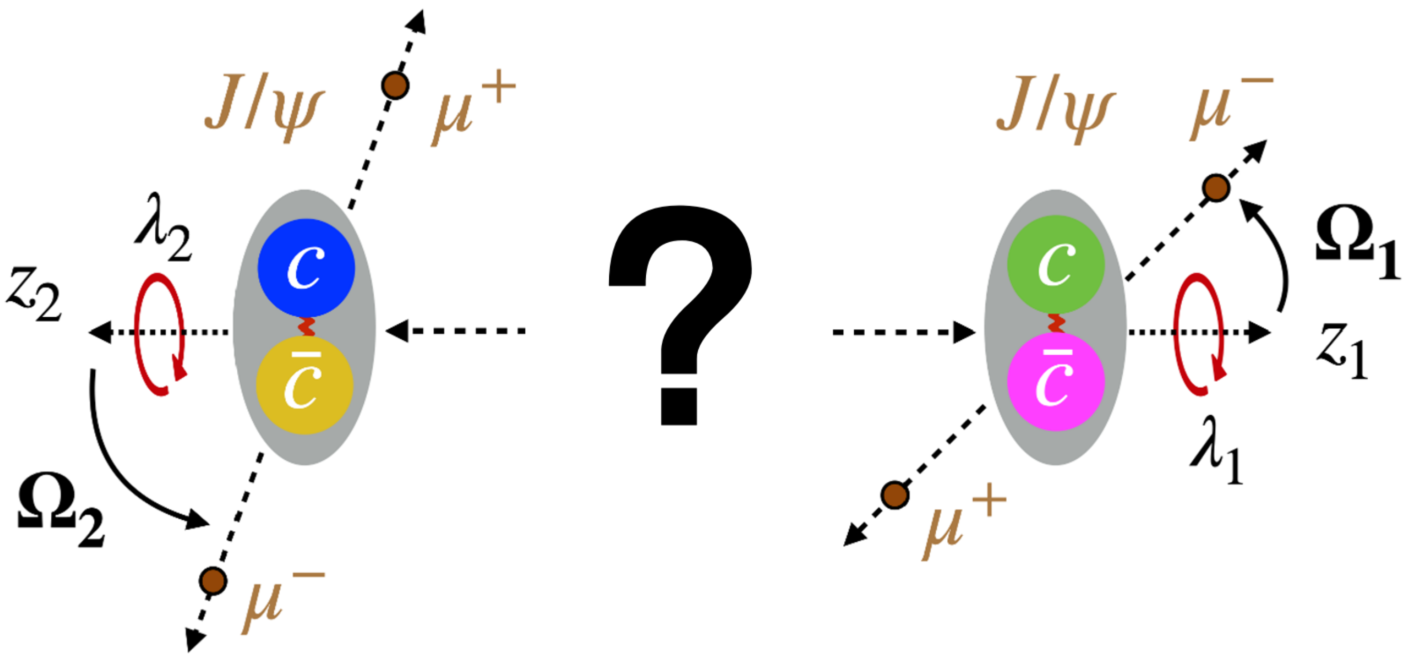
2^+_m — minimal representative model including all amplitudes:

4 d.o.f. $A_{00}, A_{++} = A_{--}; A_{+0} = A_{0+} = A_{-0} = A_{0-}; A_{+-} = A_{-+}$; 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 $J \geq 2$)

Everything was prepared Blinded



Ready to Unblind…