All-charm tetraquark candidates at CMS

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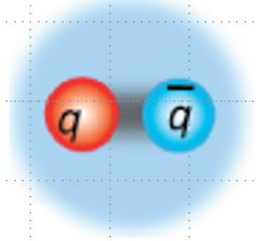
Outline

- Introduction
- Spin-parity of all-charm tetraquarks — arXiv:2506.07944
- X(6900) and X(7100) in $J/\psi\psi(2S)$ — CMS-PAS-BPH-22-004
- All-charm tetraquarks using CMS run 2 + run 3 data — CMS-PAS-BPH-24-003
- Summary

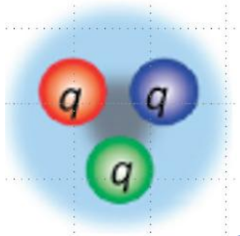
Exotic hadrons

Conventional hadrons in quark model

Meson

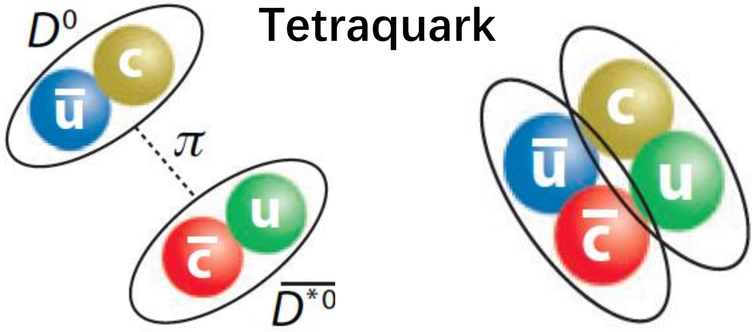


Baryon



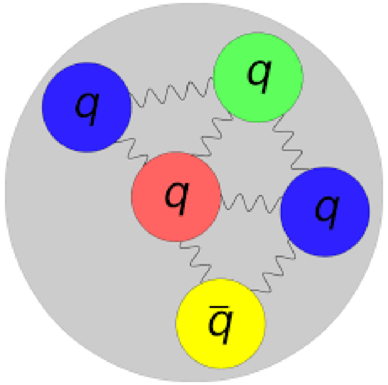
Exotic hadrons in QCD

Tetraquark

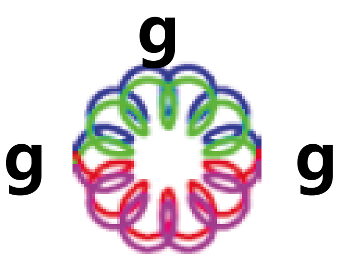


D^0–$\overline{D}^{*0}$ "molecule" **Diquark–diantiquark**

Pentaquark



Glueball



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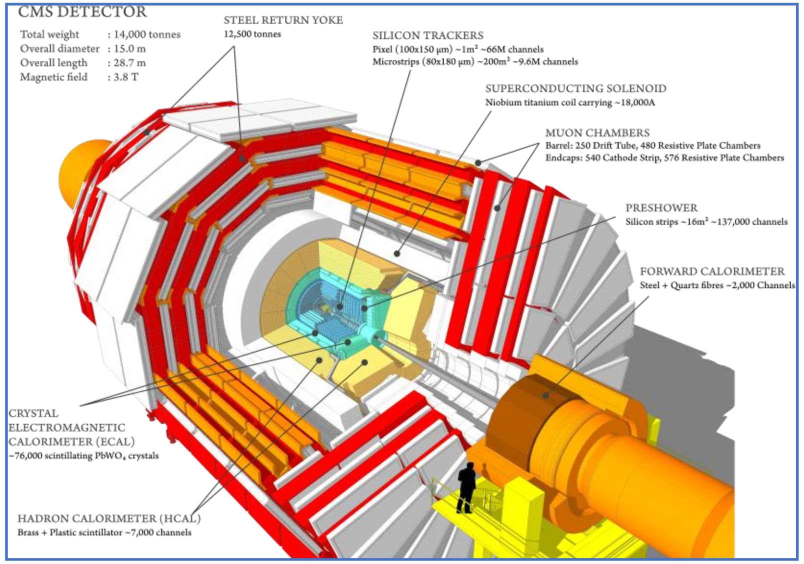
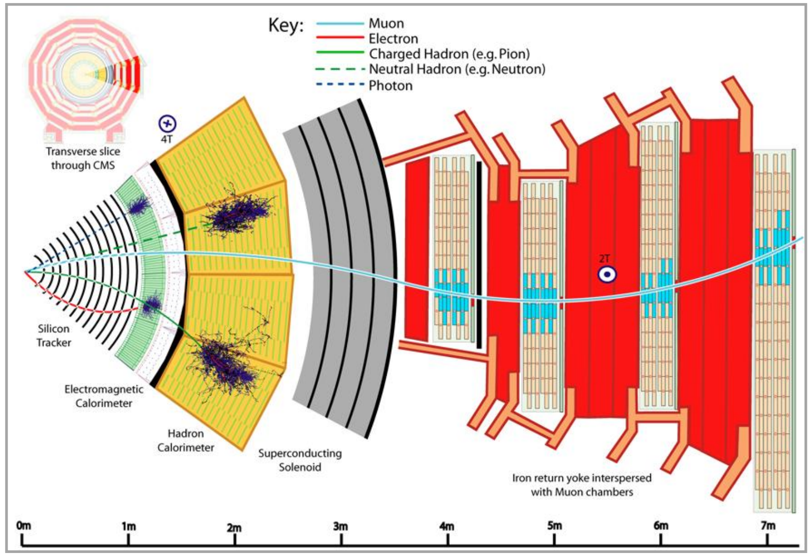
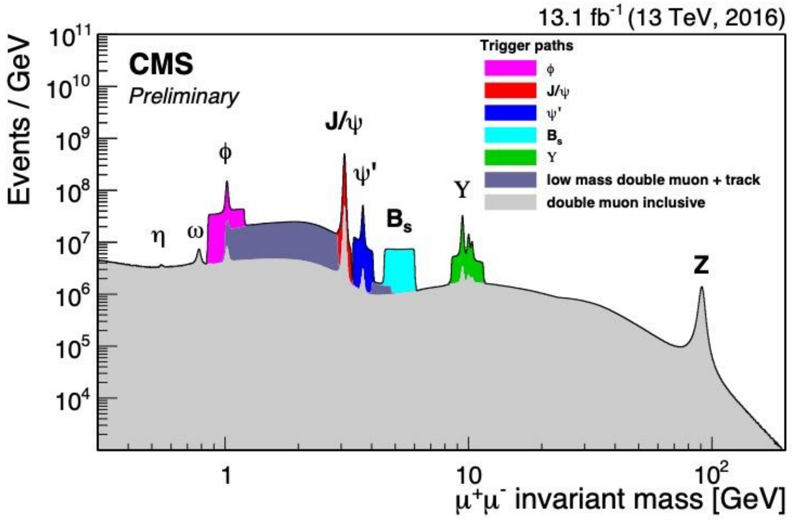
CMS detector



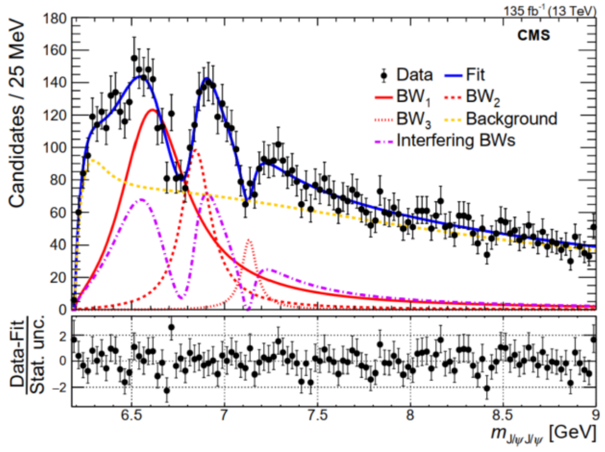




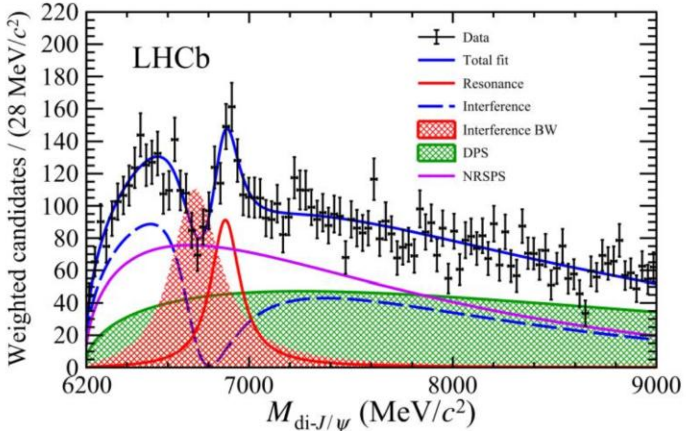
- ➢ Excellent detector for (exotic) quarkonium
- Good muon system
  - High-purity muon ID, $\frac{\Delta m}{m}\sim 0.6\%$ for J/ψ
- Silicon tracking detector
  - B = 3.8 T, $\frac{\Delta p_T}{p_T}\sim 1\%$ & good vertex resolution
- Different triggers for different physics programs/purposes

The tetraquark candidates at LHC

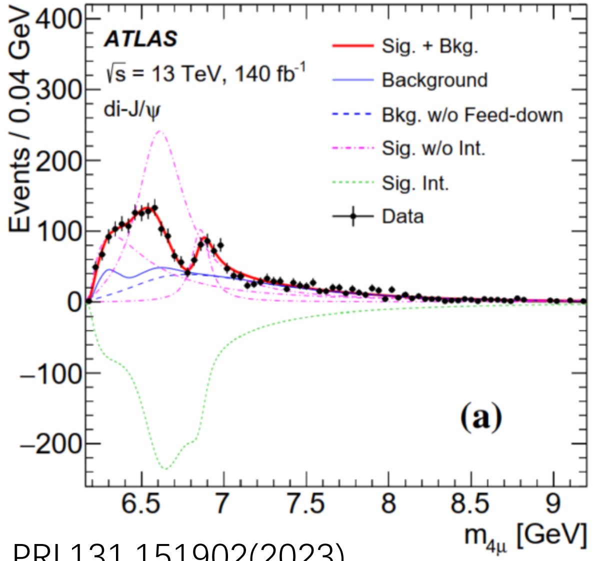
- Structures in $J/\psi J/\psi$ mass spectrum at CMS, LHCb and ATLAS from the LHC run 2 data
- Structures established but need more study to understand them



PRL132.111901(2024)



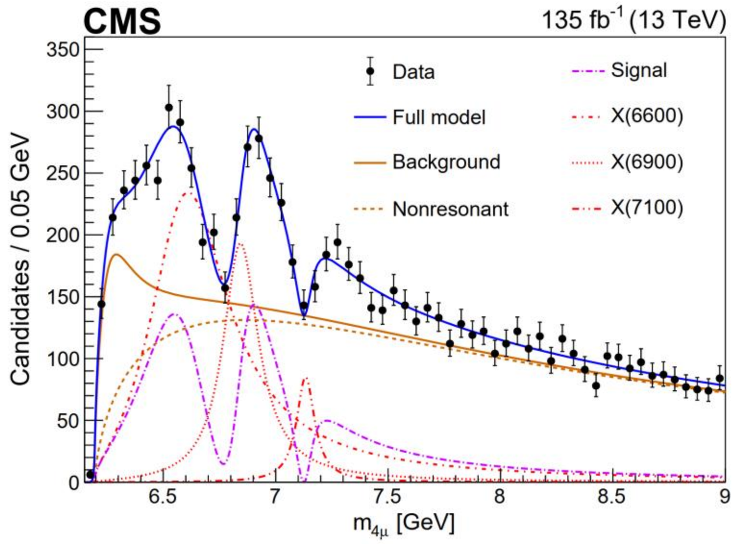
Sci.Bull.65(2020)23,1983-1993

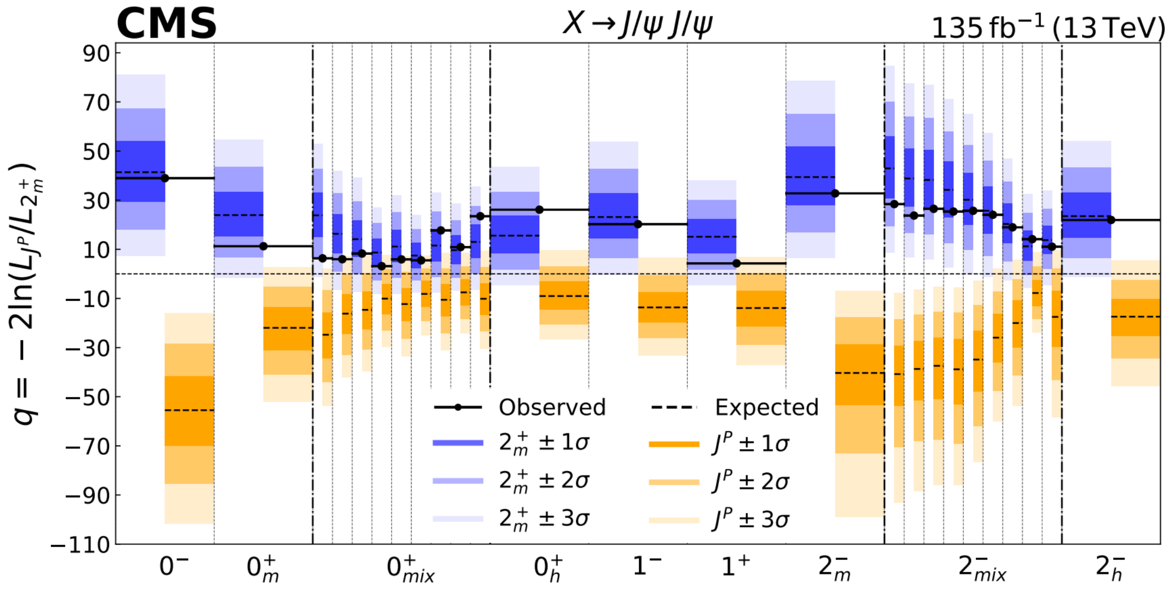


PRL131.151902(2023)

Determination of the spin and parity of all-charm tetraquarks

arXiv:2506.07944

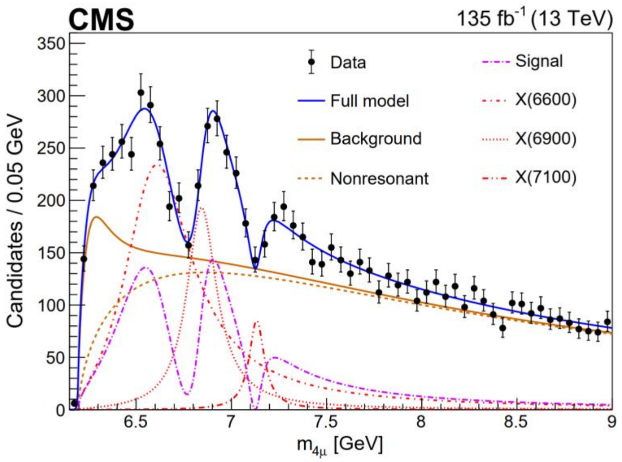




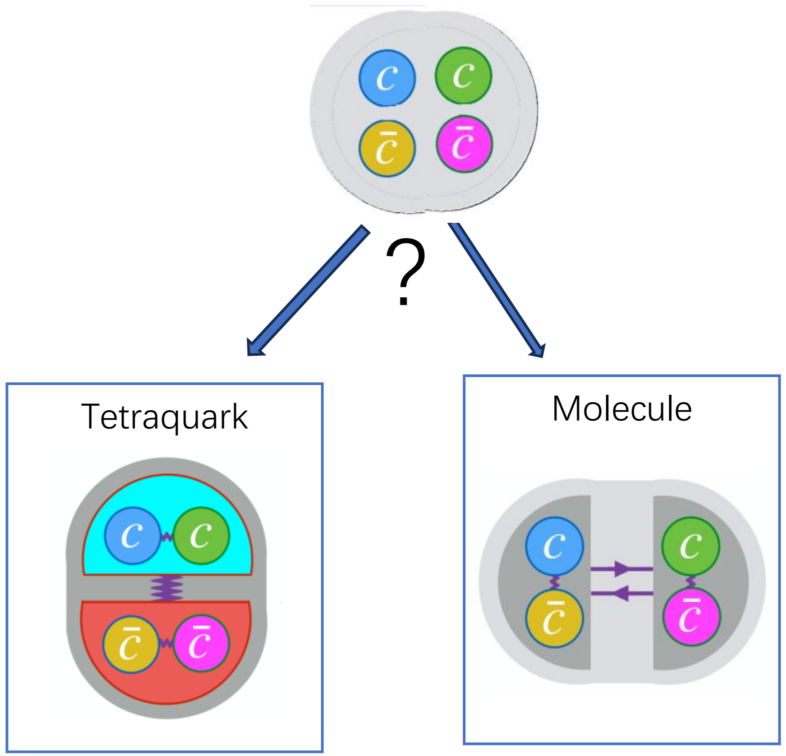
Internal Structure of the tetraquarks

arxiv:2506.07944

- Tetraquark candidates observed in experiments



$X \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$

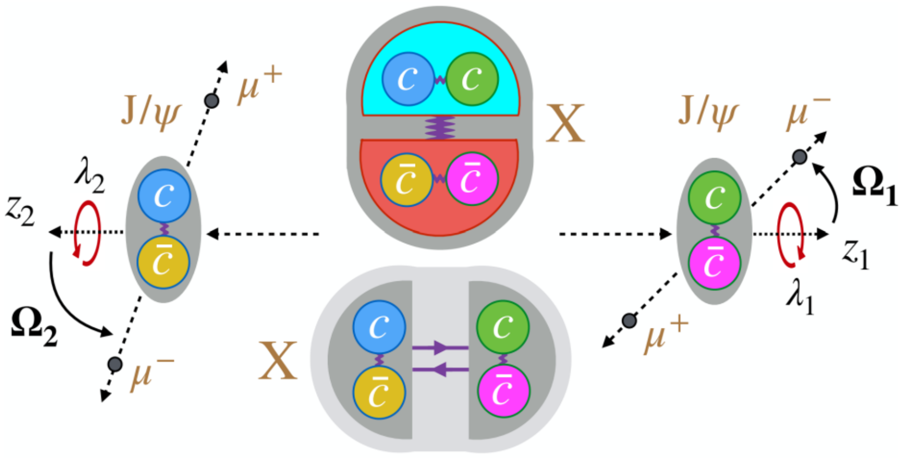


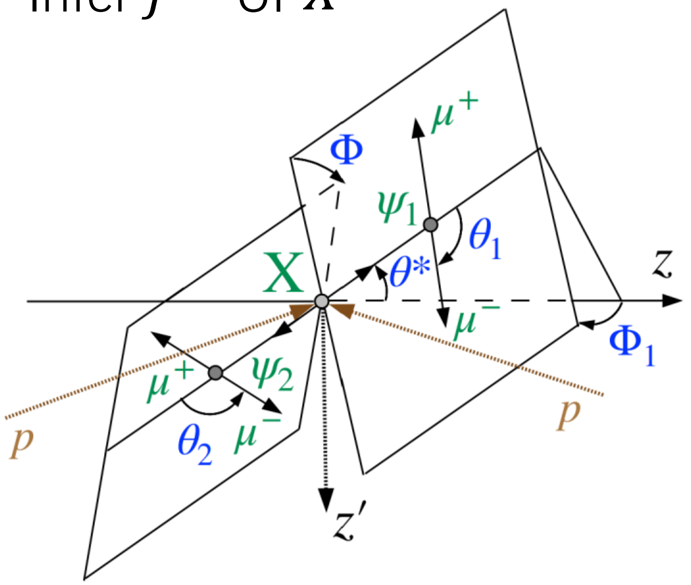
- Don’t know internal structure
  - Tetraquark, molecule, ⋯?
- Don’t know spin-parity either
  - How to study their spin-parity?

Infer spin-parity of X

arxiv:2506.07944

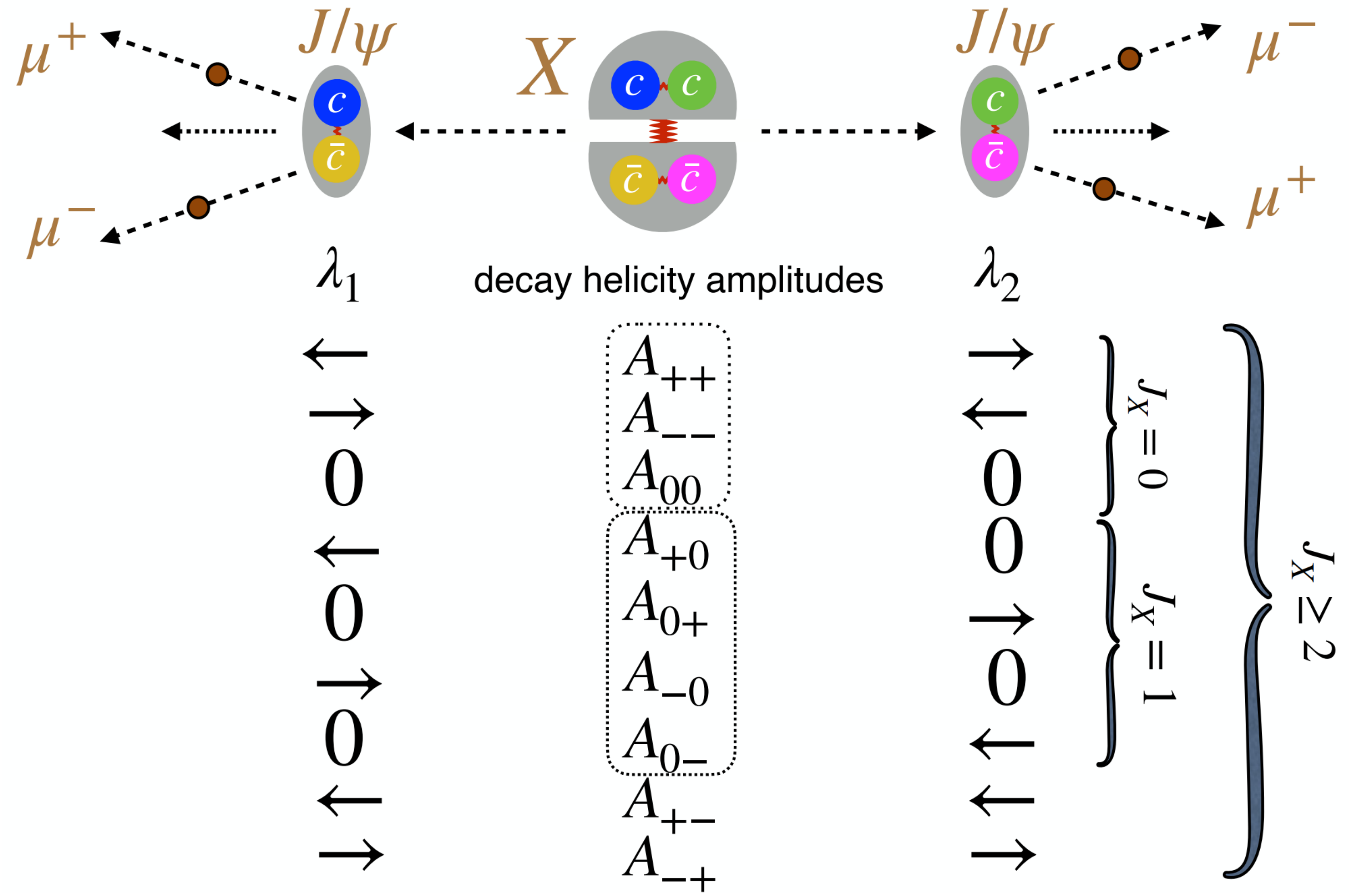
- Infer J^{PC} of X from angular distributions
  - Theory
    - $A(X \to VV)$ depends on J_X^{PC} polarization of J/ψ
    - $A(X \to VV)$ derermines angular distributions
  - Experiment
    - Measure angular distributions of $J/\psi, \mu$ etc.
    - Infer J^{PC} of X





J/ψ polarizations

arxiv:2506.07944



J/ψ polarizations

arxiv:2506.07944

- 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

Lorentz invariant amplitude

arxiv:2506.07944

- Expect three 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^+ 0_h^+ 0^-

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

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

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

recall (22 years):
$B \to \varphi K^*$ expect A_{00}
found ~50% A_{++}

Higgs (12 years):
$H \to 4\ell \Rightarrow 0_m^+$

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^- 1^+

more for spin-2

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

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

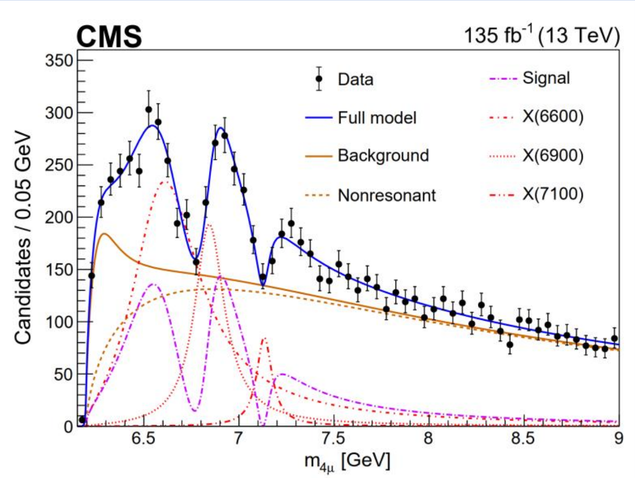
Helicities (0, -) of two J/ψ

Simplification in angular analysis

arxiv:2506.07944

- Full amplitude analysis possible, but very complex

$$\mathscr{P}(\Phi, \theta_1, \theta_2; m_{4\mu}) \propto |A(X \to VV)|^2$$



- Simplification in angular analysis

(1) Same properties of 3 resonances:

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

empirical angular

(2) Pairwise tests of J_X^P hypotheses i and j: arXiv:1208.4018

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

1 optimal observable $\Leftarrow$ Higgs boson discovery and spin-parity

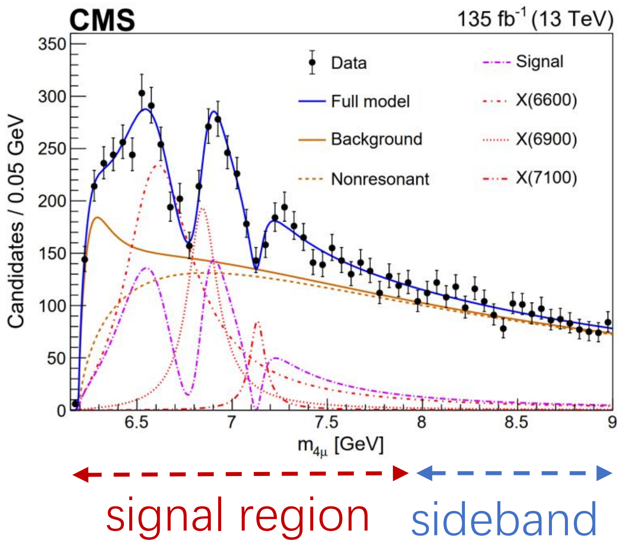
- Final 2D model: $$\mathscr{P}_{ijk}(m_{4\mu}, \mathscr{D}_{ij}) = \mathscr{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathscr{D}_{ij} \,|\, m_{4\mu})$$

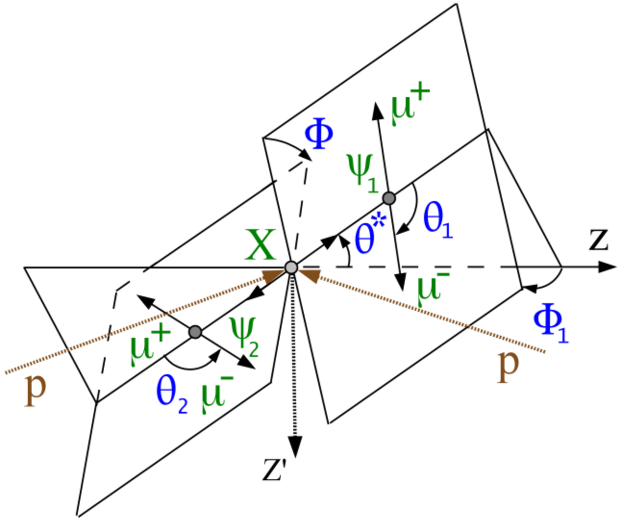
Analysis of data

arxiv:2506.07944

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

- Two dimensions $(m_{4\mu}, D_{ij})$ analysis:
  - Event selection from observation paper arxiv:2306.07164
  - BKG: data sideband & MC simulation with Pythia
  - $m_{4\mu}$ shapes: arxiv:2306.07164
  - Decay angles Φ, θ_1, θ_2 to identify $D_{ij}(\Phi, \theta_1, \theta_2; m_{4\mu})$



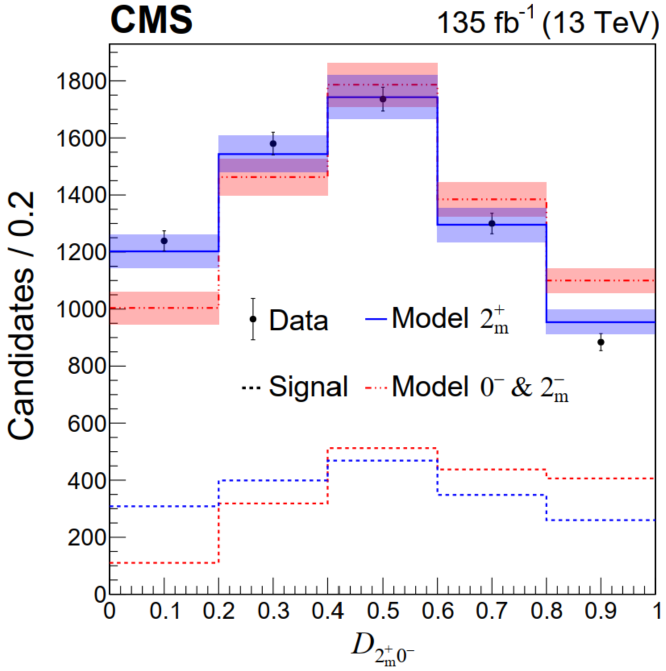


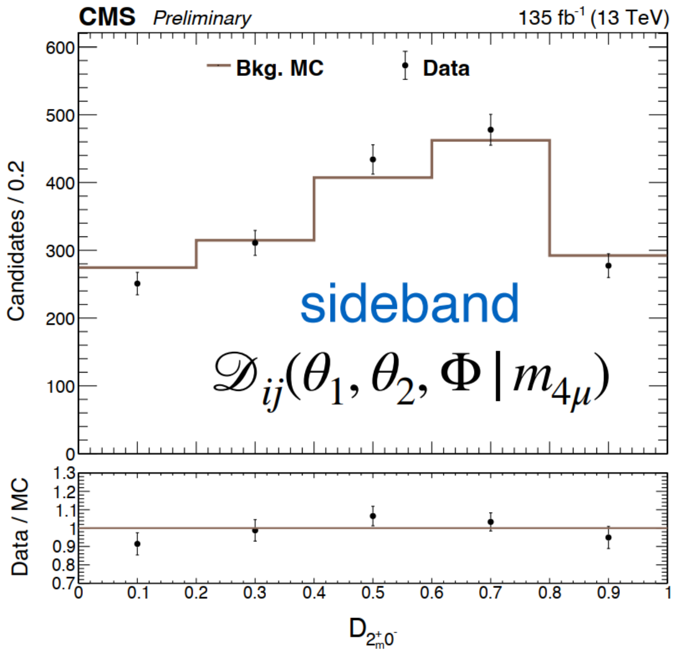
All steps till here prepared blinded

Optimal Observables

[arxiv:2506.07944]

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





optimal observable

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

1D projections from 2D
$\Rightarrow$ limited information

background model from MC
control in sidebands
systematic variations

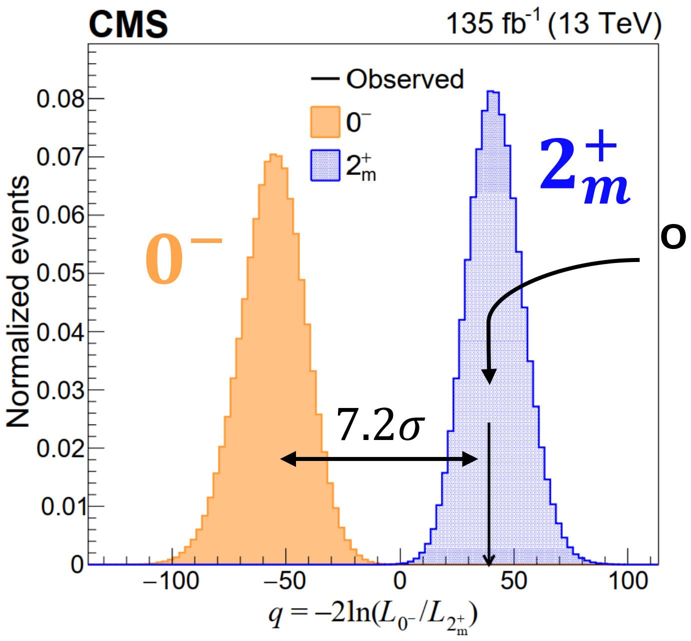
Hypothesis test of $\mathbf{0^-}$ vs. $\mathbf{2_m^+}$

arxiv:2506.07944

- Hypothesis test for $j = 0^-$ vs. $i = 2_m^+$

		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^+	0.42	0.2	0.5	0

- 2D parameterization:
$$\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})$$
- Test statistics:
$$q = -2\ln(\mathcal{L}_{J_i^P} / \mathcal{L}_{J_j^P})$$
- Confidence level:
$$CL_s = \frac{P(q \geq q_{\mathrm{obs}} \mid J_j^P + \mathrm{bkg})}{P(q \geq q_{\mathrm{obs}} \mid J_i^P + \mathrm{bkg})}$$



observed: q_{obs}

Hypothesis test of J_i^P vs. J_j^P

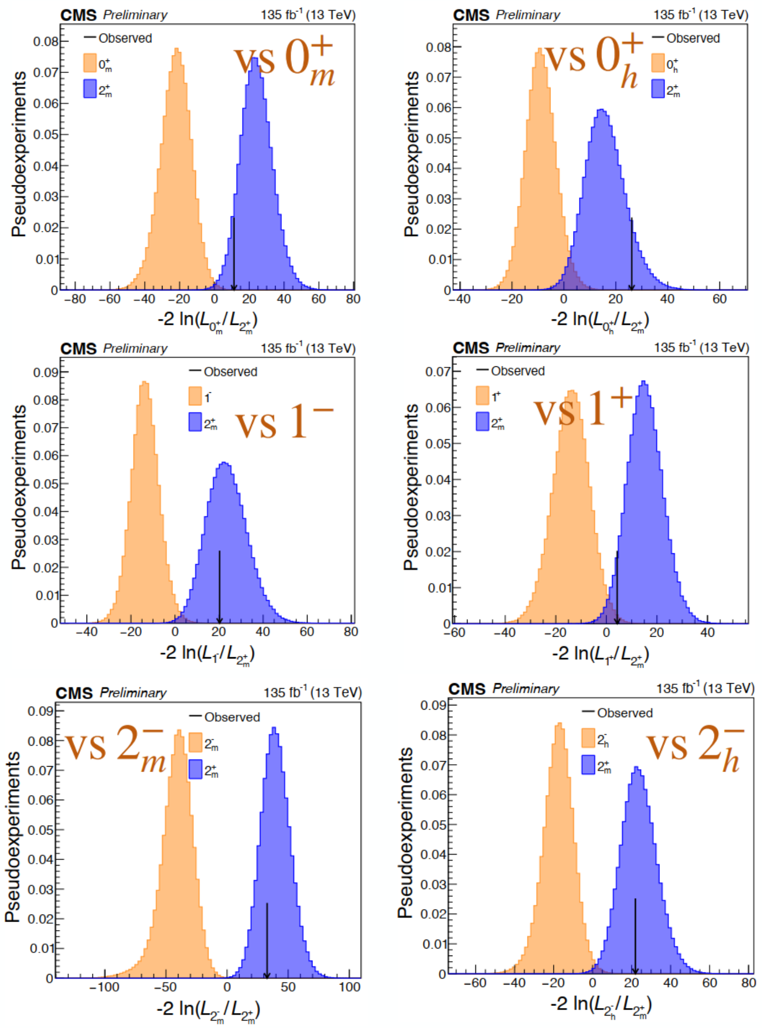
arxiv:2506.07944

- Combined 2D fit: $\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij})$
  - ➢ $J^P = 2_m^+$ model survives

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

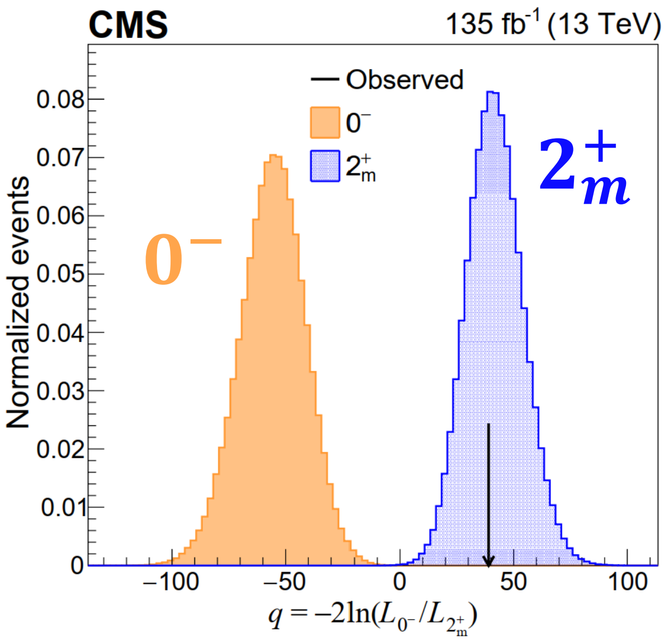
mix

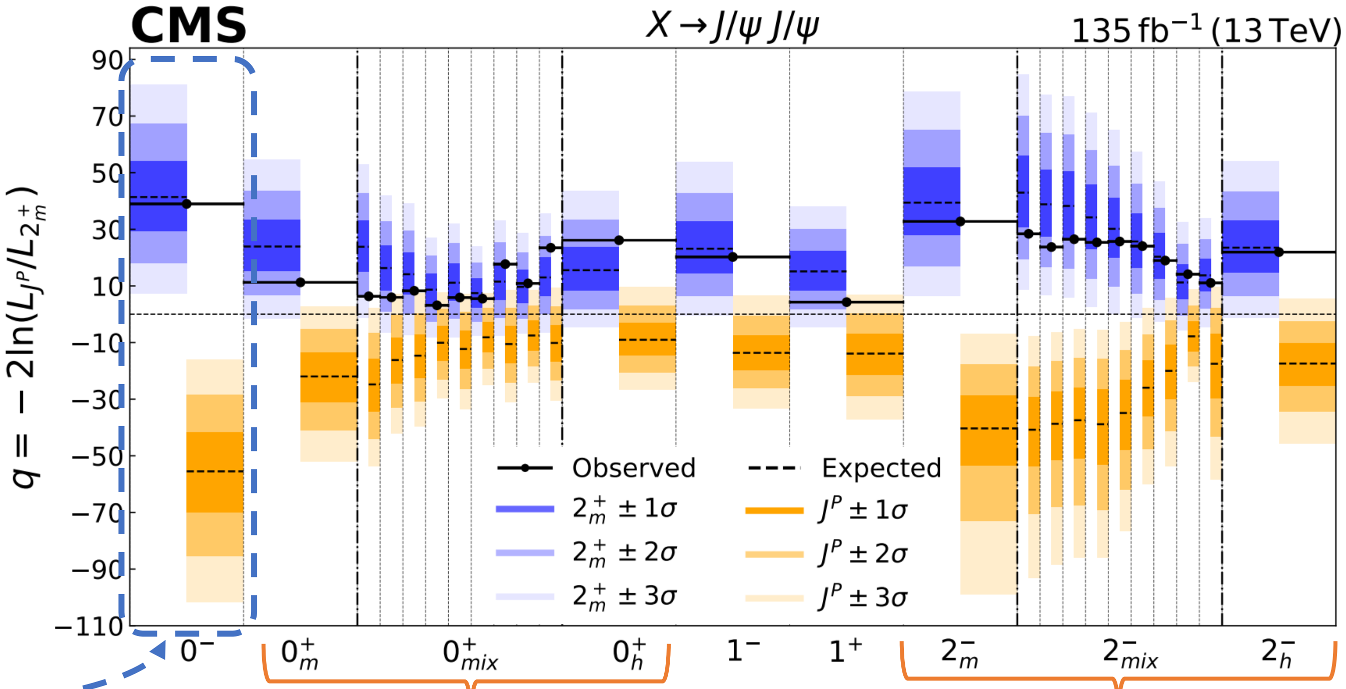
mix



Summary of results

arxiv:2506.07944





Scan of two 2^{-+} (11 steps)

--No interference (different spin projections)

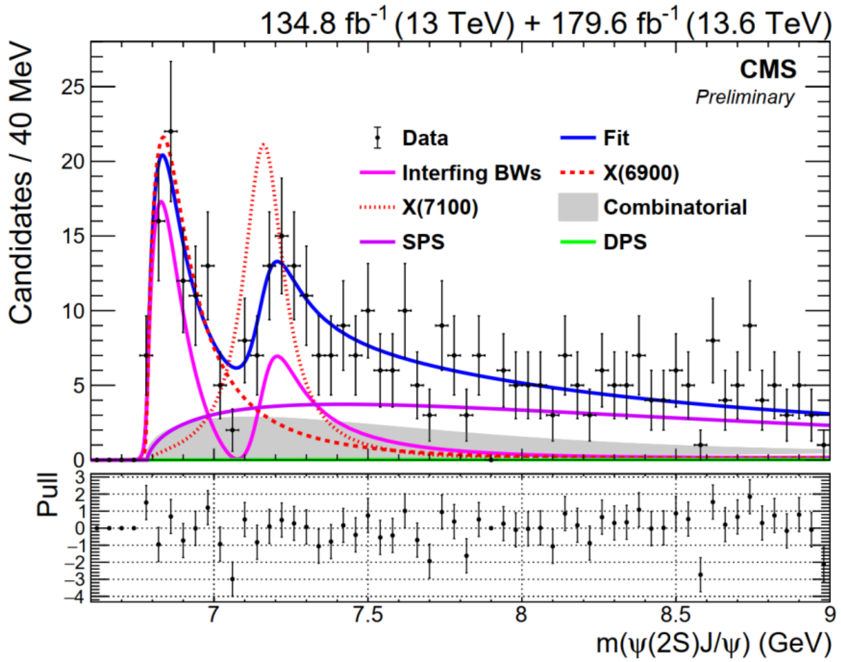
- Data consistent with $\mathbf{2^{++}}$, inconsistent with **others**
- JPC of the three tetraquark candidates X(6600), X(6900), X(7300)
  - $PC = ++$
  - $J \neq 1$ at > 99% CL; $J \neq 0$ at 95% CL
  - $J > 2$ possible, but highly unlikely, require $L \geq 2$
  - $\boldsymbol{J = 2}$ **consistent**, naively expected $J = 0$

Scan mixture of two 0^{++} amp. (11 steps)

-- Constructive interf. most conservative

X(6900) and X(7100) in $J/\psi\psi(2S)$ at CMS

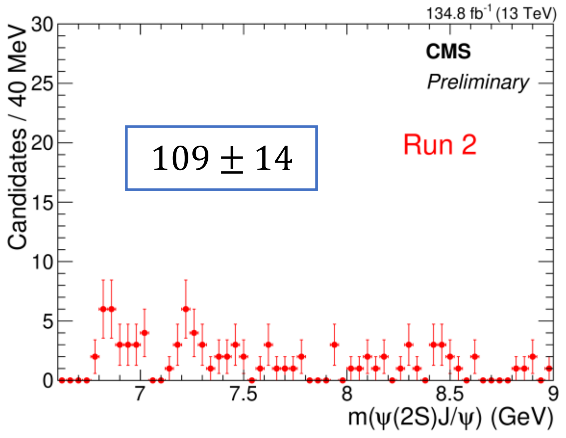
CMS-PAS-BPH-22-004

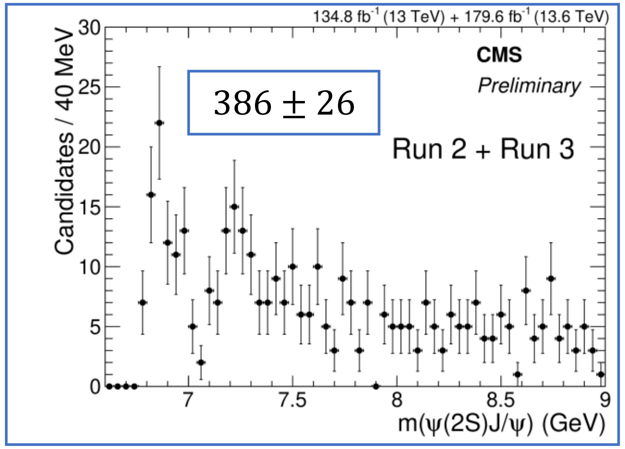


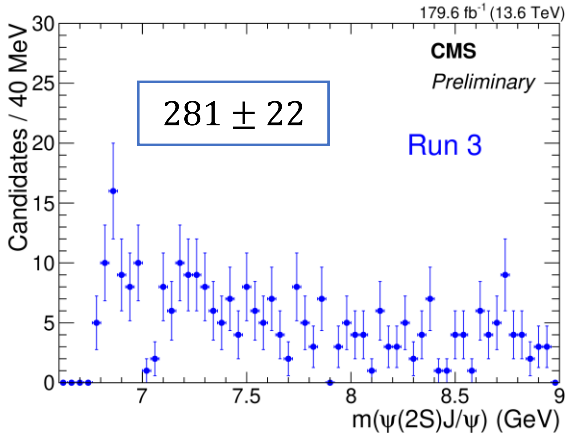
X(6900) and X(7100) in $J/\psi\psi(2S)$ at CMS

CMS-PAS-BPH-22-004

- J/ψ and $\psi(2S)$ reconstructed via $\mu^+\mu^-$
- Data (314 fb^{-1}):
  - 2016-2018 (run 2): 13 TeV, 134.8 fb^{-1}
  - 2022-2024 (run 3): 13.6 TeV, **179.6** fb^{-1}
- Trigger:
  - Run 2: 3 muons, pT > 5, 3, 3 GeV
  - Run 3: 2muons, pT > 4, 3 GeV



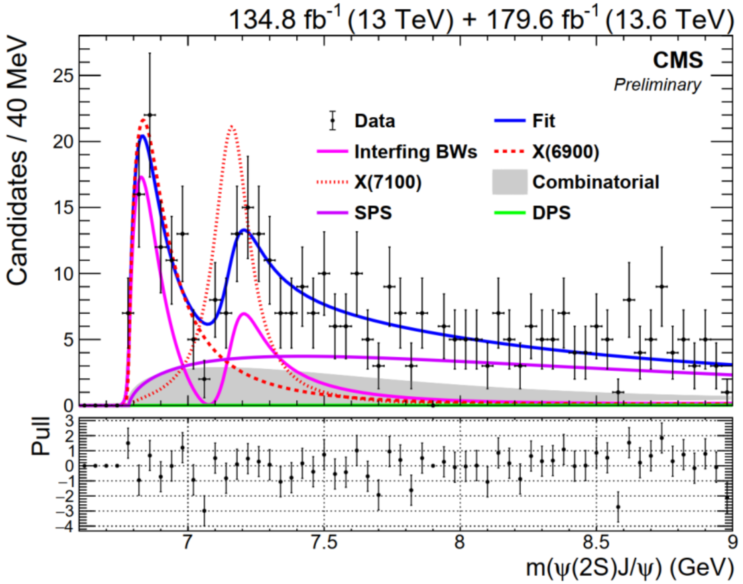




X(6900) and X(7100) in $J/\psi\psi(2S)$ at CMS

CMS-PAS-BPH-22-004

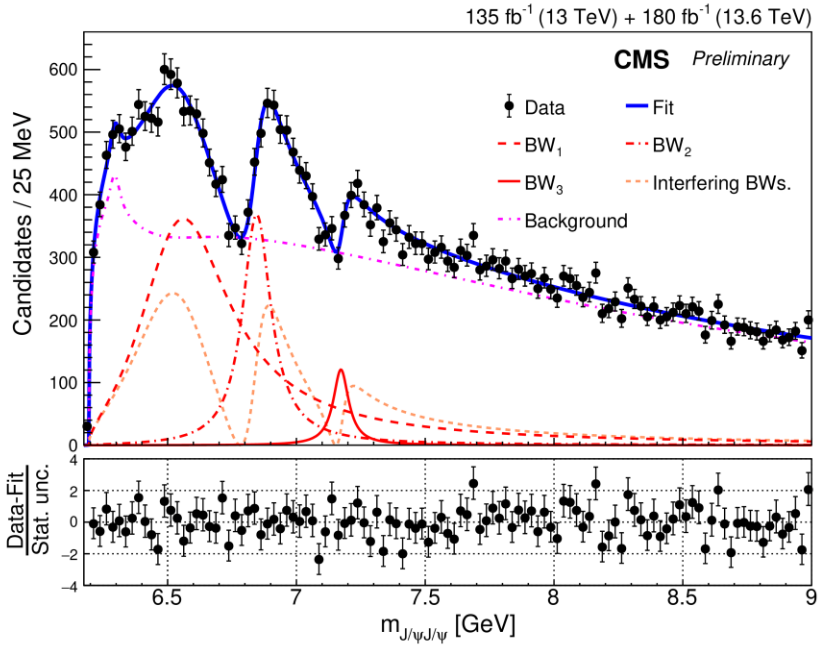
- X(6900) and X(7100) in $J/\psi\psi(2S)$
  - Data fit
    - Signal: X(6900), X(7100) and their interference
    - Background: NRSPS, DPS, combinatorial contribution
  - **$> 5\sigma$ for X(6900), 4.0σ for X(7100)**
  - Impact from X(6600) [below threshold] considered in systematic uncertainty



Fit	Sample	Interf.		$X(6600)$	$X(6900)$	$X(7100)$
f_{i23}	$J/\psi\psi(2S)$	BW_2, BW_3	m :	—	$6876^{+46+110}_{-29-110}$	7169^{+26+74}_{-52-70}
			Γ :	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
f_{JJ} [1]	$J/\psi J/\psi$	BW_1, BW_2, BW_3	m :	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
			Γ :	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

Observation of a family of all-charm tetraquarks candidates at the LHC

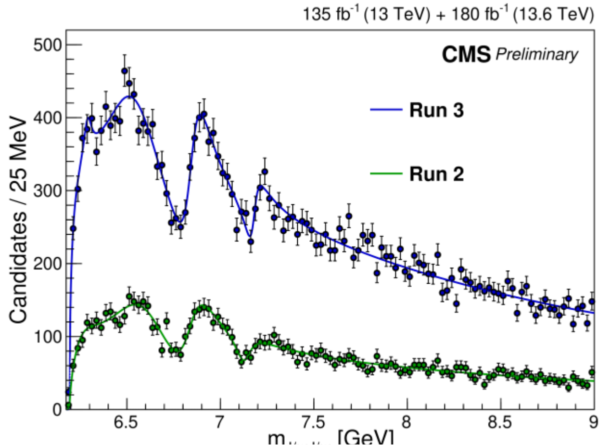
CMS-PAS-BPH-24-003

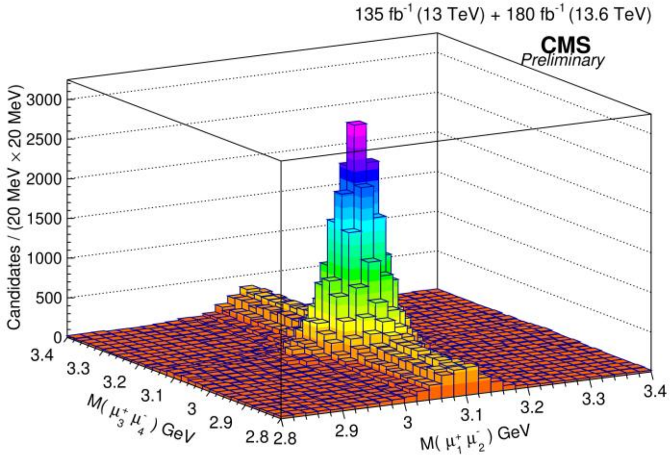


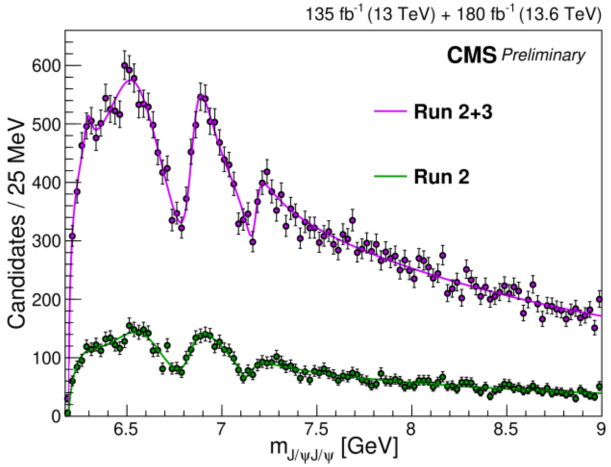
All-charm tetraquarks candidates at CMS

CMS-PAS-BPH-24-003

- Tetraquark candidates observed in $J/\psi J/\psi$ mass at CMS
  - J/ψ reconstructed via its $\mu^+\mu^-$ decays
- Data (314 fb^{-1})
  - 2016-2018 (run 2): 13 TeV, 134.8 fb^{-1}
  - 2022-2024 (run 3): 13.6 TeV, 179.6 fb^{-1}
- Trigger
  - Run 2: 3 muons, pT > 5, 3, 3 GeV
  - Run 3: 2muons, pT > 4, 3 GeV





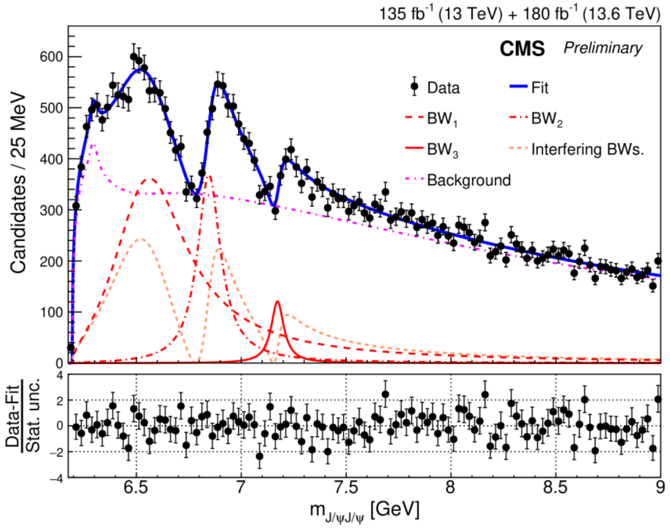


All-charm tetraquark candidates at CMS

CMS-PAS-BPH-24-003

- X(6600), X(6900), X(7100) in $J/\psi J/\psi$ at CMS
  - Data fit
    - Signal: Coherent sum of X(6600), X(6900), X(7100)
    - BKG: NRSPS, DPS, combinatorial contribution, feeddown
  - Significance
    - $>$ **5σ for each** of X(6600), X(6900), and **X(7100)**
    - $>$ **5σ for interference (two dips)**

      $>$ **5σ for each single dip**: 6750 MeV dip, and 7150 MeV dip



		X(6600)	X(6900)	X(7100)
		BW_1	BW_2	BW_3
Interference	m (MeV)	$6593\ ^{+15}_{-14} \pm 25$	$6847\ ^{+10}_{-10} \pm 15$	$7173\ ^{+9}_{-10} \pm 13$
(Run 2+Run 3)	Γ (MeV)	$446\ ^{+66}_{-54} \pm 87$	$135\ ^{+16}_{-14} \pm 14$	$73\ ^{+18}_{-15} \pm 10$
Interference	m (MeV)	$6638\ ^{+43+16}_{-38-31}$	$6847\ ^{+44+48}_{-28-20}$	$7134\ ^{+48+41}_{-25-15}$
(Run 2 [12])	Γ (MeV)	$440\ ^{+230+110}_{-200-240}$	$191\ ^{+66+25}_{-49-17}$	$97\ ^{+40+29}_{-29-26}$

Feeddown: e.g., $X \to J/\psi\psi(2S) \to J/\psi J/\psi\pi\pi$ is reconstructed as $J/\psi J/\psi$ instead of $J/\psi J/\psi\pi\pi$

Summary

- Spin parity of the tetraquarks decaying into $J/\psi J/\psi$ consistent with 2^{++}
- $X(6900)$ and $X(7100)$ in $J/\psi\psi(2S)$ using CMS run 2 + run 3 data
  - $X(6900)$ signifincance $> 5\sigma$
  - $X(7100)$ significance 4σ
- All tetraquark candidates using CMS run 2 + run 3 data
  - Obvious peaks of $X(6600), X(6900), X(7100)$
  - Significance of interference $> 5\sigma$
  - $X(7100)$ significance $> 5\sigma$ for the first time

Thanks!

Backup

Decay angles

- Production angles not use – consistent with unpolarized
- Decay angles (consistency check): distinguish models

arxiv:2506.07944