Determination of the spin and parity of all-charm tetraquarks

Xining Wang

Tsinghua University / Nanjing Normal University

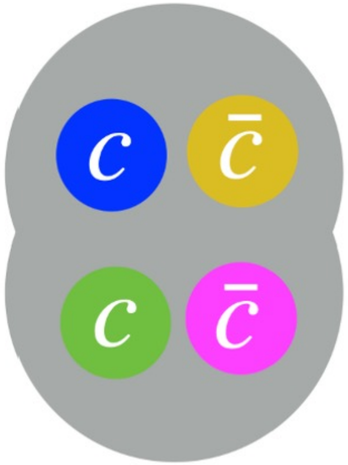
理论与实验联合研讨会--新粒子寻找

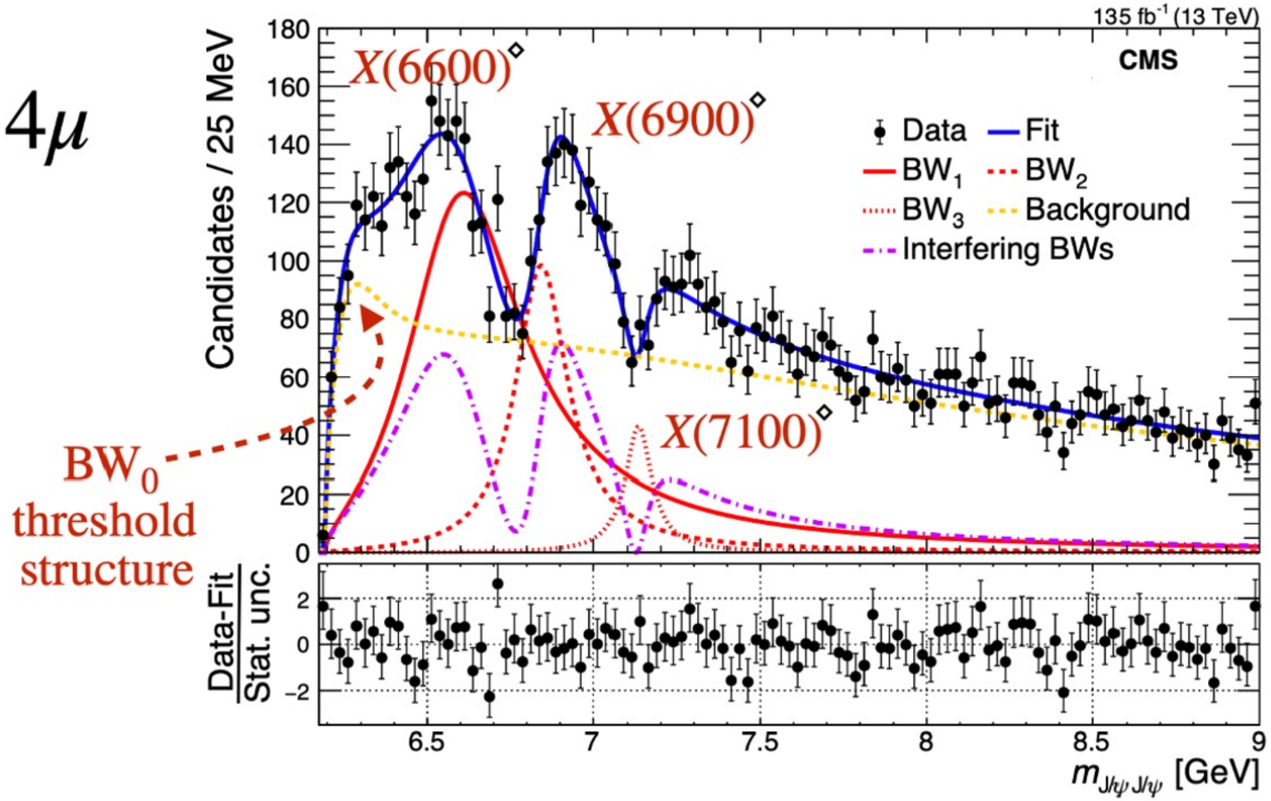
Sep 13, 2025

All-charm Tetraquarks on CMS

- CMS: family of 3 tetraquark candidates in 6 - 8 GeV range:

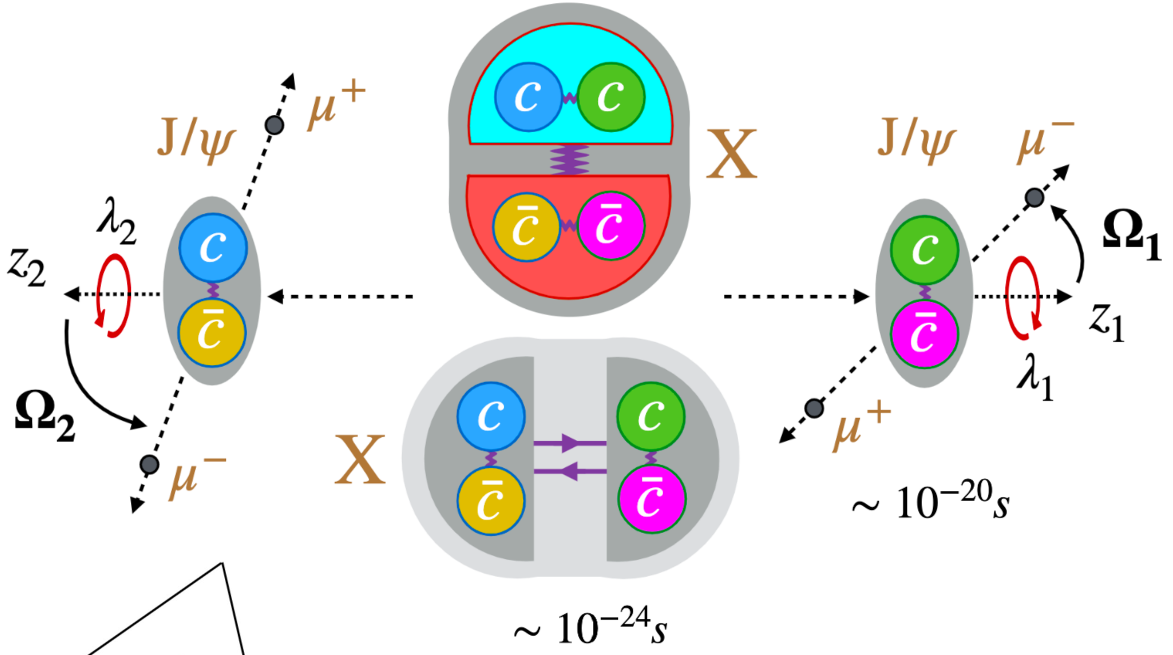
$$X \to J/\psi J/\psi \to 4\mu$$

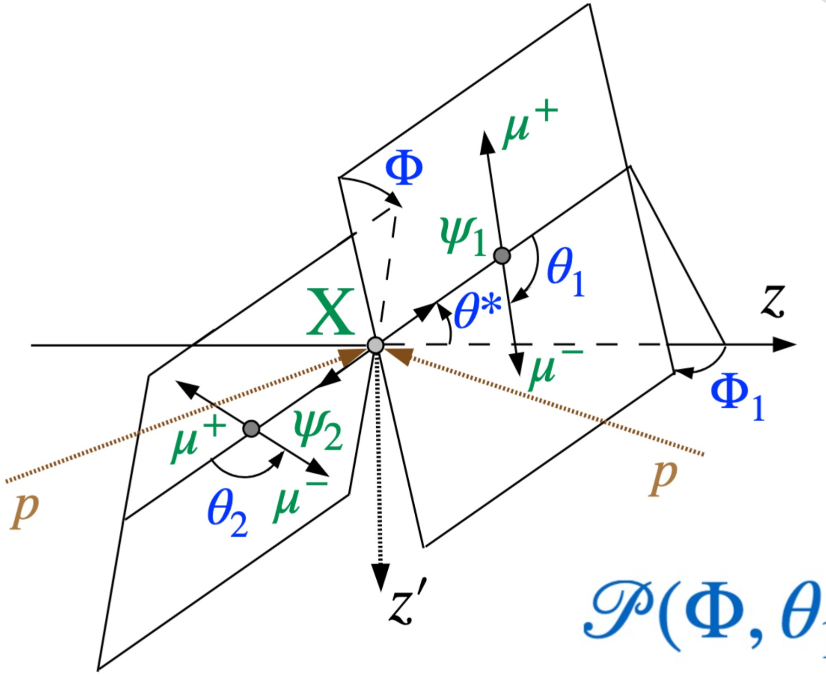




- Analysis with Run 2 data
- Interference among three resonances with same J^P — simplify
  - Strongly motivated by dips observed in data
  - Indicate coherent production process and share same J^P

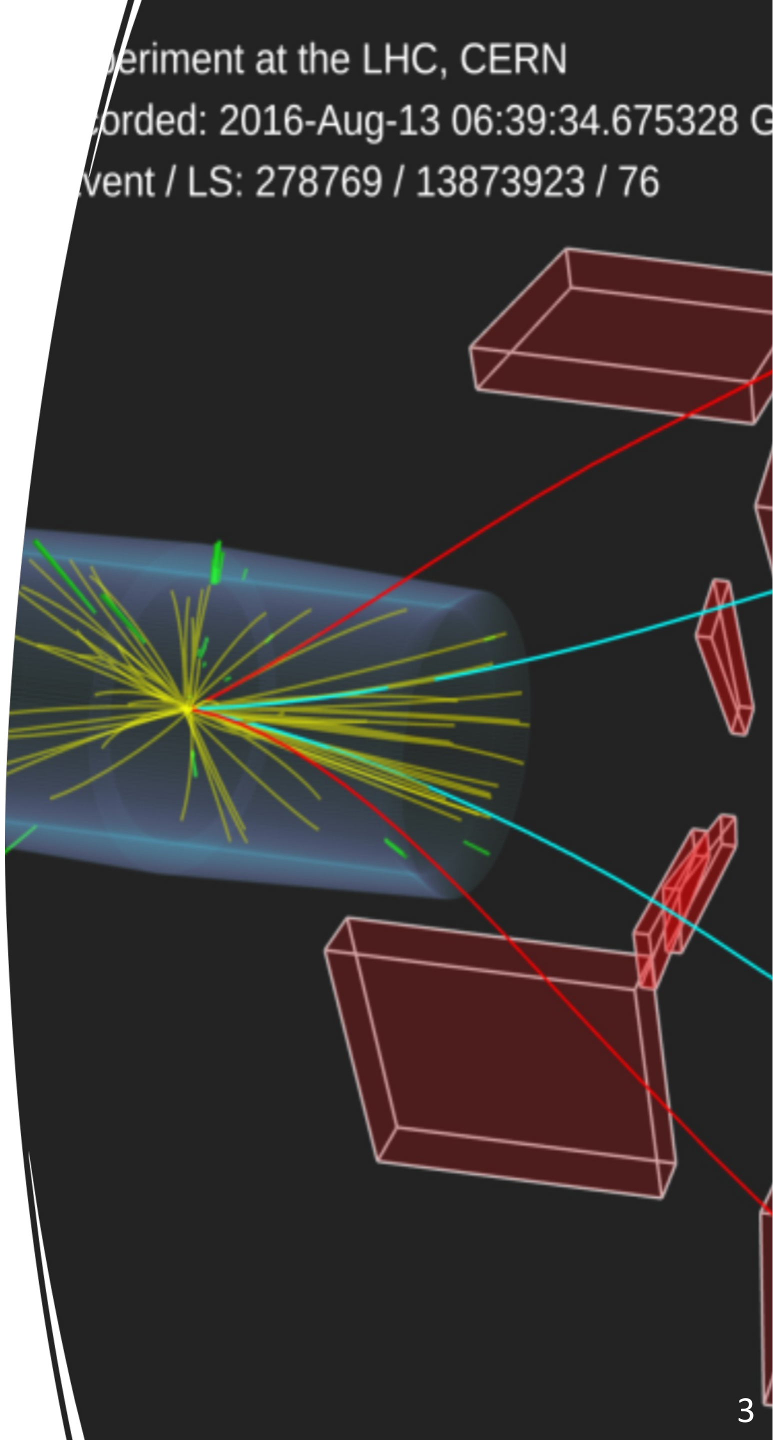
Spin parity analysis



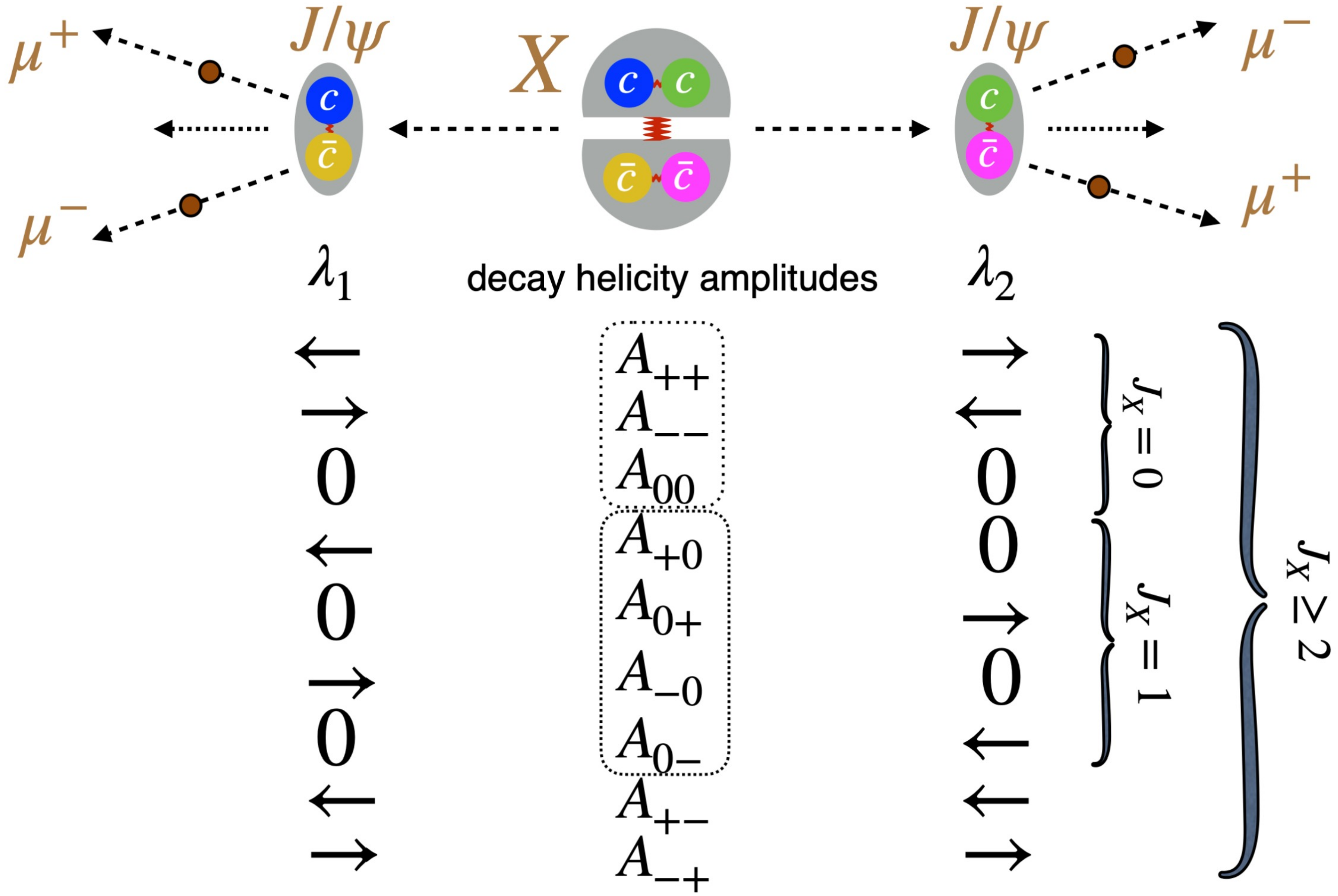


$$J^{PC} = ?$$

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



J/ψ polarizations



J/ψ polarizations

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

X with definite J^{PC}

$C = +1$

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

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

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

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

Test 8+ J_X^P models:

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

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

Angular Analysis

A_{++}
A_{--}
A_{00}
A_{+0}
A_{0+}
A_{-0}
A_{0-}
A_{+-}
A_{-+}

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

spin $= 0$ & ≥ 1

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

spin ≥ 1

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

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

spin ≥ 2

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

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:

$$A(X_{J=0} \to V_1V_2) = \left(a_1(q^2) m_V^2 \epsilon_1^* \epsilon_2^* + a_2(q^2) f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3(q^2) f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

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

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

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

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

arXiv:1001.3396

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

$$A(X_{J=1} \to V_1V_2) = \left(b_1(q^2) \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2(q^2) \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta \right)$$

1^- $\quad$ 1^+

more for spin-2

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

Lorentz-Invariant Amplitude

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

$$A(X_{J=2}\to V_1V_2) = 2c_1(q^2)t_{\mu\nu}f^{*1,\mu\alpha}f^{*2,\nu\alpha} + 2c_2(q^2)t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2}f^{*1,\mu\alpha}f^{*2,\nu,\beta}$$
$$+c_3(q^2)\frac{\tilde{q}^\beta\tilde{q}^\alpha}{\Lambda^2}t_{\beta\nu}(f^{*1,\mu\nu}f^{*2}_{\mu\alpha}+f^{*2,\mu\nu}f^{*1}_{\mu\alpha}) + c_4(q^2)\frac{\tilde{q}^\nu\tilde{q}^\mu}{\Lambda^2}t_{\mu\nu}f^{*1,\alpha\beta}f^{*(2)}_{\alpha\beta}$$
$$+m_V^2\left(2c_5(q^2)t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} + 2c_6(q^2)\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}t_{\mu\nu}\left(\epsilon_1^{*\nu}\epsilon_2^{*\alpha}-\epsilon_1^{*\alpha}\epsilon_2^{*\nu}\right) + c_7(q^2)\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right)$$
$$+c_8(q^2)\frac{\tilde{q}_\mu\tilde{q}_\nu}{\Lambda^2}t_{\mu\nu}f^{*1,\alpha\beta}\tilde{f}^{*(2)}_{\alpha\beta} + c_{10}(q^2)\frac{t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma}q^\rho\tilde{q}^\sigma\left(\epsilon_1^{*\nu}(q\epsilon_2^*)+\epsilon_2^{*\nu}(q\epsilon_1^*)\right),$$

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 $J \geq 2$)

Simplification in Angular Analysis

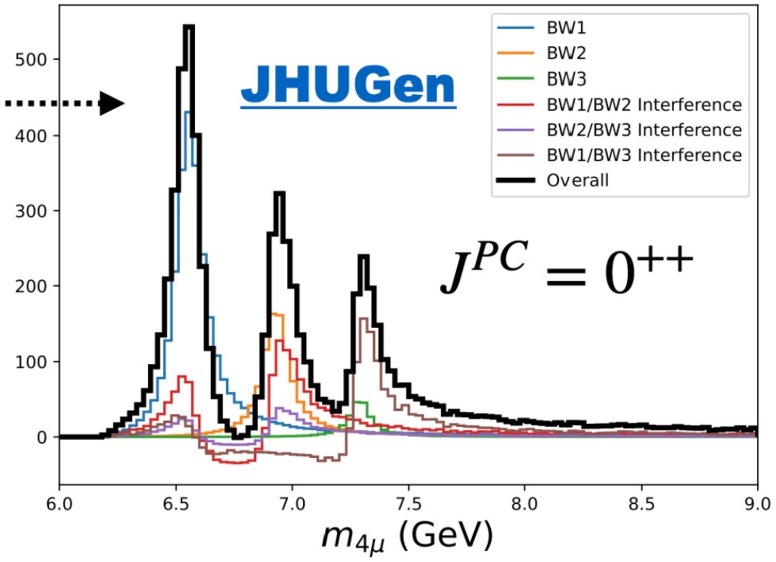
- Full model possible, but very complex

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

(1) Same properties of 3 resonances:

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

empirical angular



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

MELA

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

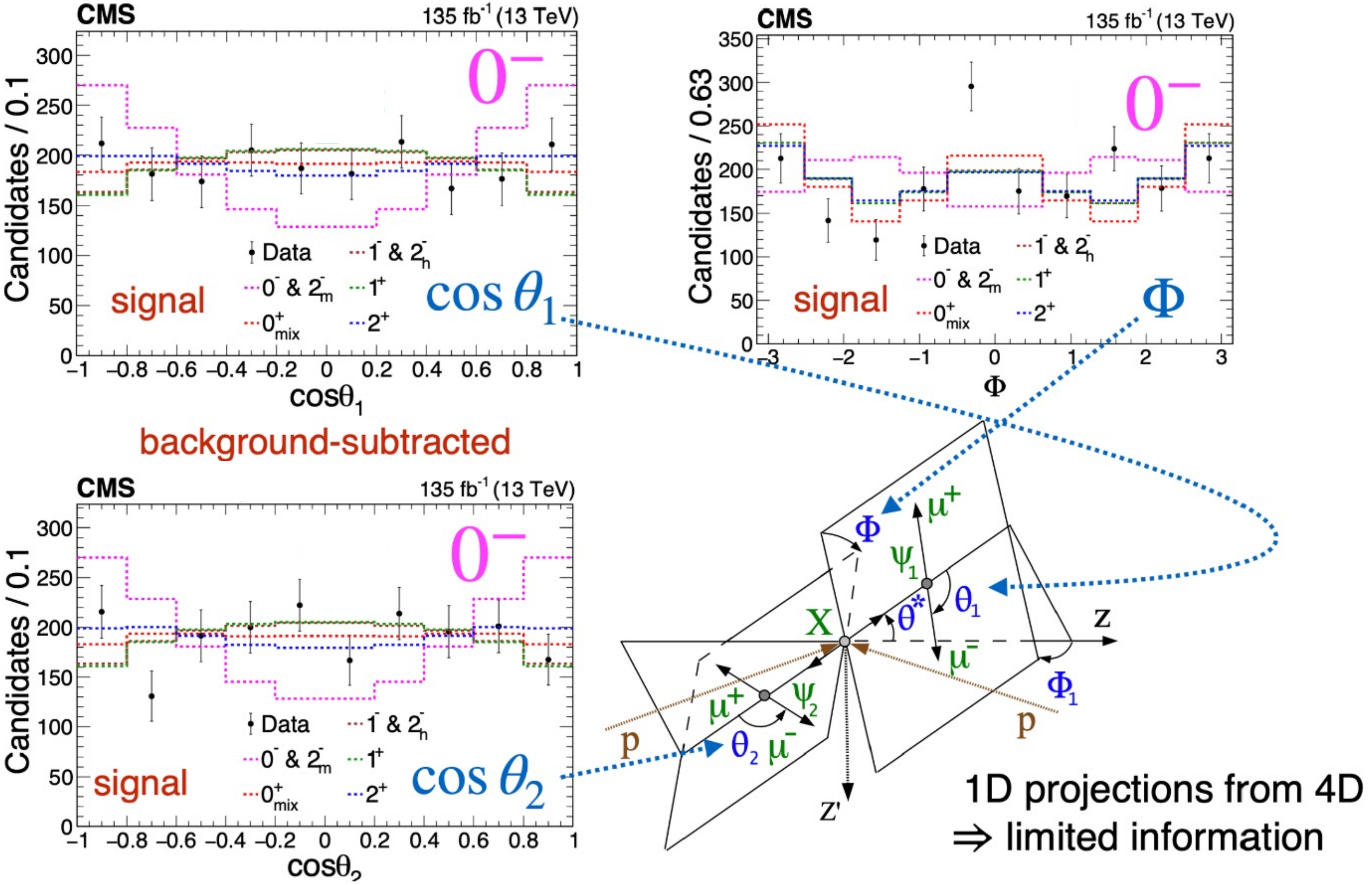
1 optimal observable

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

Decay Angles

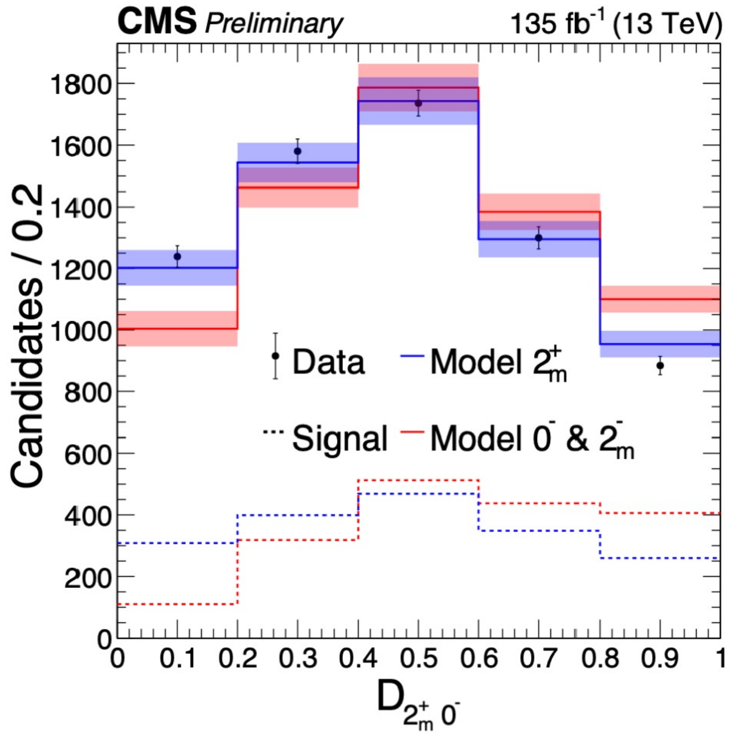
Production angles not use
Consistent with unpolarized (backup)

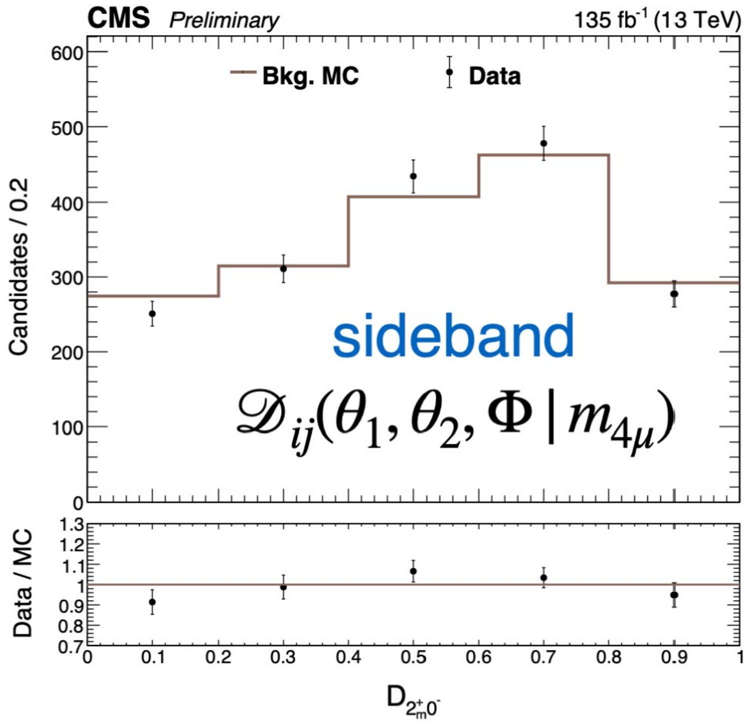
decay angles (consistency check): distinguish models



Optimal Observable

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





sideband

$\mathscr{D}_{ij}(\theta_1, \theta_2, \Phi \,|\, m_{4\mu})$

background model from MC

control in sidebands

systematic variations

optimal observable

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

1D projections from 2D
⇒ limited information

2D parameterization:

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

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:

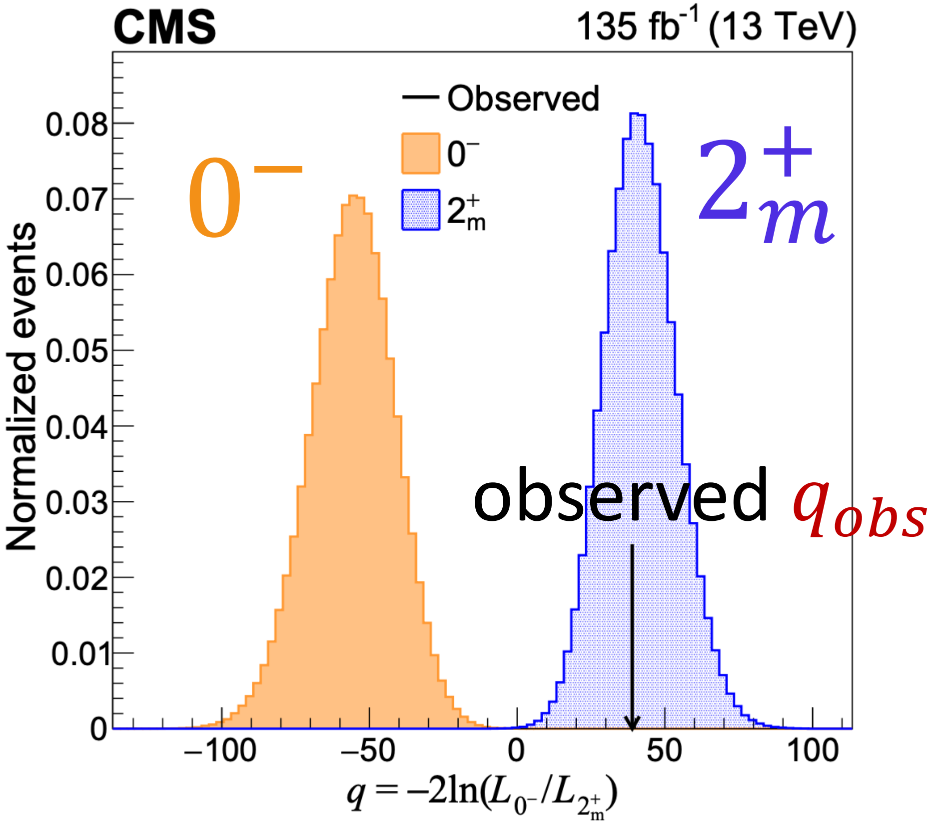
$$p = P(q \leq q_{obs}|J_1^P + bkg)$$
$$p = P(q \geq q_{obs}|J_2^P + bkg)$$

- Significance:

  Converted from p-value
  via Gaussian one-sided tail integral

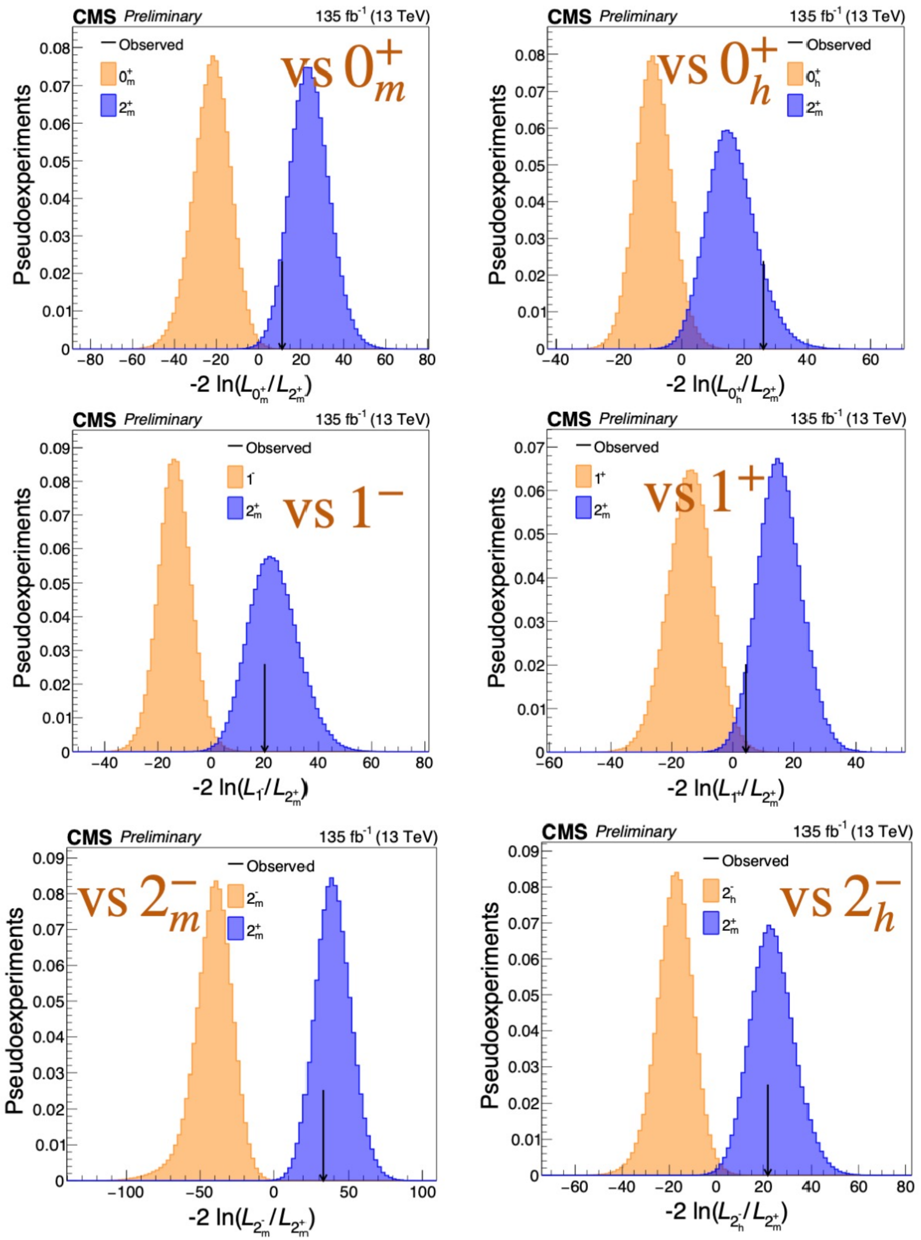
- Confidence level

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



		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

Hypothesis test



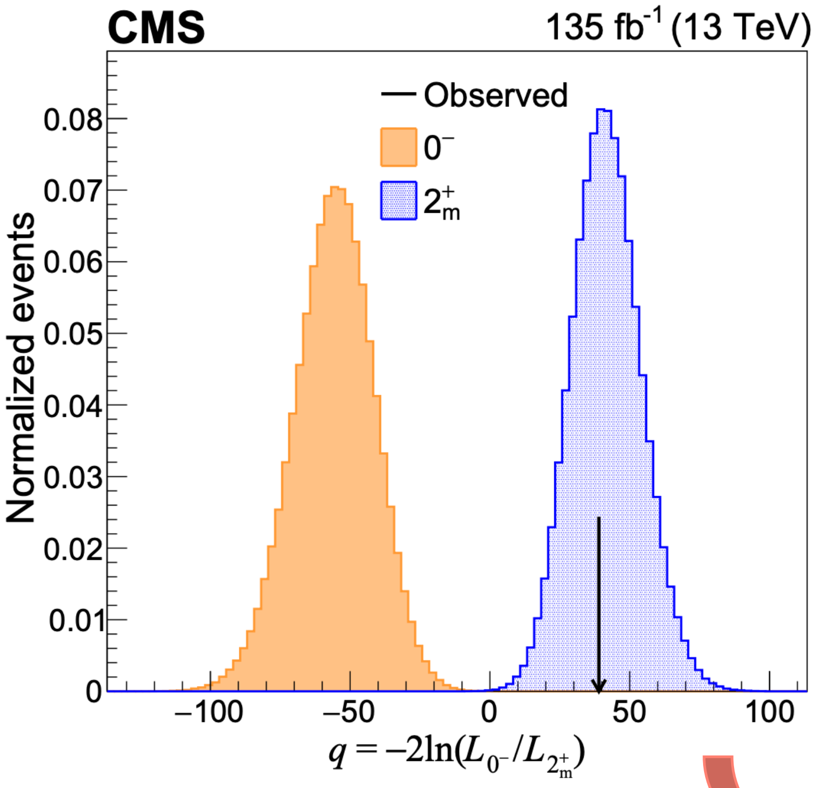
- Combine 2D fit: $\mathscr{P}_{ijk}(m_{4\mu}, \mathscr{D}_{ij})$
  - $J^P = 2_m^+$ model survives

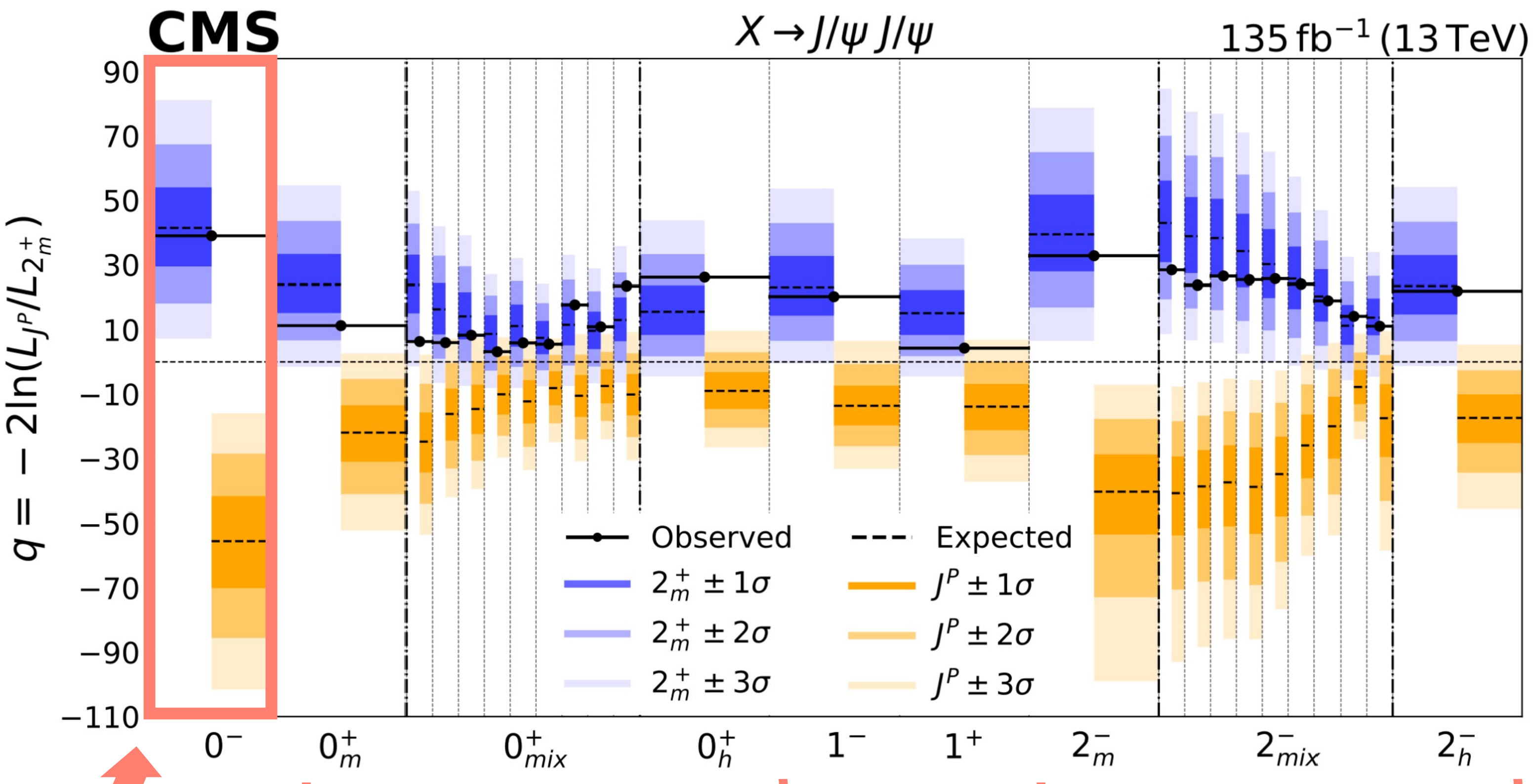
J_X^P	p-value	Z-score reject J_X^P
0^-	2.7×10^{-13}	7.2
0_m^+	4.3×10^{-5}	3.9
0_{mix}^+	1.4×10^{-2}	2.2
0_h^+	3.1×10^{-9}	5.8
1^-	8.0×10^{-8}	5.2
1^+	4.7×10^{-3}	2.6
2_m^-	4.1×10^{-12}	6.8
2_{mix}^-	6.5×10^{-4}	3.2
2_h^-	2.2×10^{-8}	5.5

mix

mix

Statistical Analysis

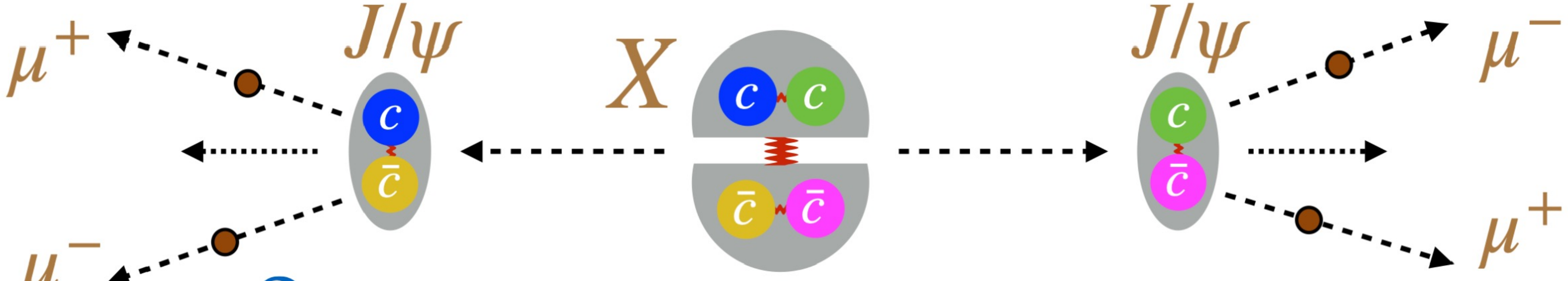




Scan mixture of 0^{++} amplitudes

Scan mixture of 2^{-+} amplitudes

Summary



? $(c\bar{c})_{s=1} + (c\bar{c})_{s=1}$

? $(cc)_{s=1} + (\bar{c}\bar{c})_{s=1} \Rightarrow L = 0\ (\mathrm{n}S):\ S = 2 \Rightarrow J^{PC} = 2^{++},\ n = (1,)2,3,4,...$

- J^{PC} analysis of exotic hadron decays at LHC (production-independent)
  - consistent picture: set of 3 exotic teraquark resonances with the same J^{PC}
  - $PC = ++$ very certain $n = (1,)2,3,4$
  - $J \neq 1$ at $> 99\,\%$ CL
  - $J \neq 0$ at $> 95\,\%$ CL
  - $J > 2$ possible, but highly unlikely, require $L \geq 2$
  - $J = 2$ consistent, rare in nature, naively expected $J = 0$

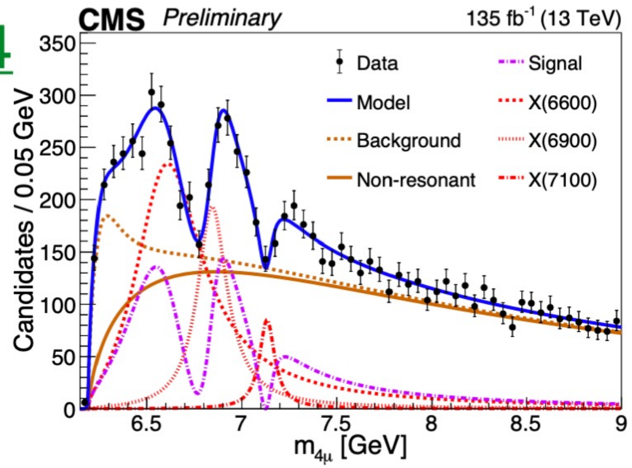
THANKS!

CMS is painting a coherent picture of $J/\psi J/\psi$ structures

BACKUP

J/ψ polarizations

(1) $m_{4\mu}$ spectrum $X \to 4\mu$ — arXiv:2306.07164



(2) p_T and p_Z of $X \to 4\mu$ — match to data

(3) polarization J_z or $J_{z'}$ of X — unpolarized

for $J = 0$ exact

for $J = 1,2,..$ depends on production mechanism

— vary J_z or $J_{z'}$ systematics or test

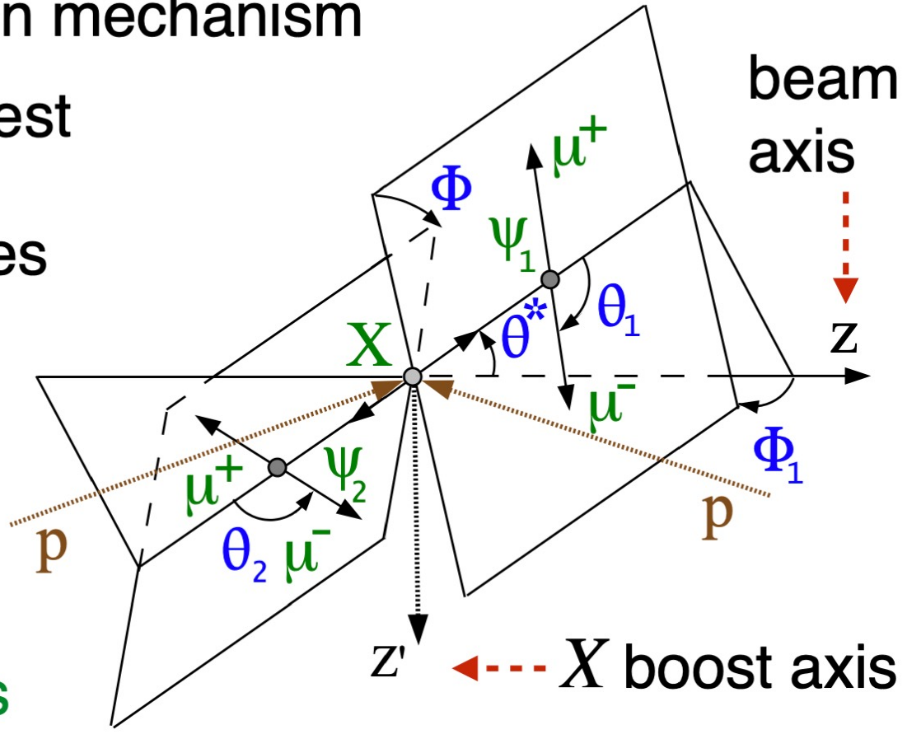
(4) Φ_1, θ^* or Φ_1', θ'^* production angles

flat for unpolarized — test in data

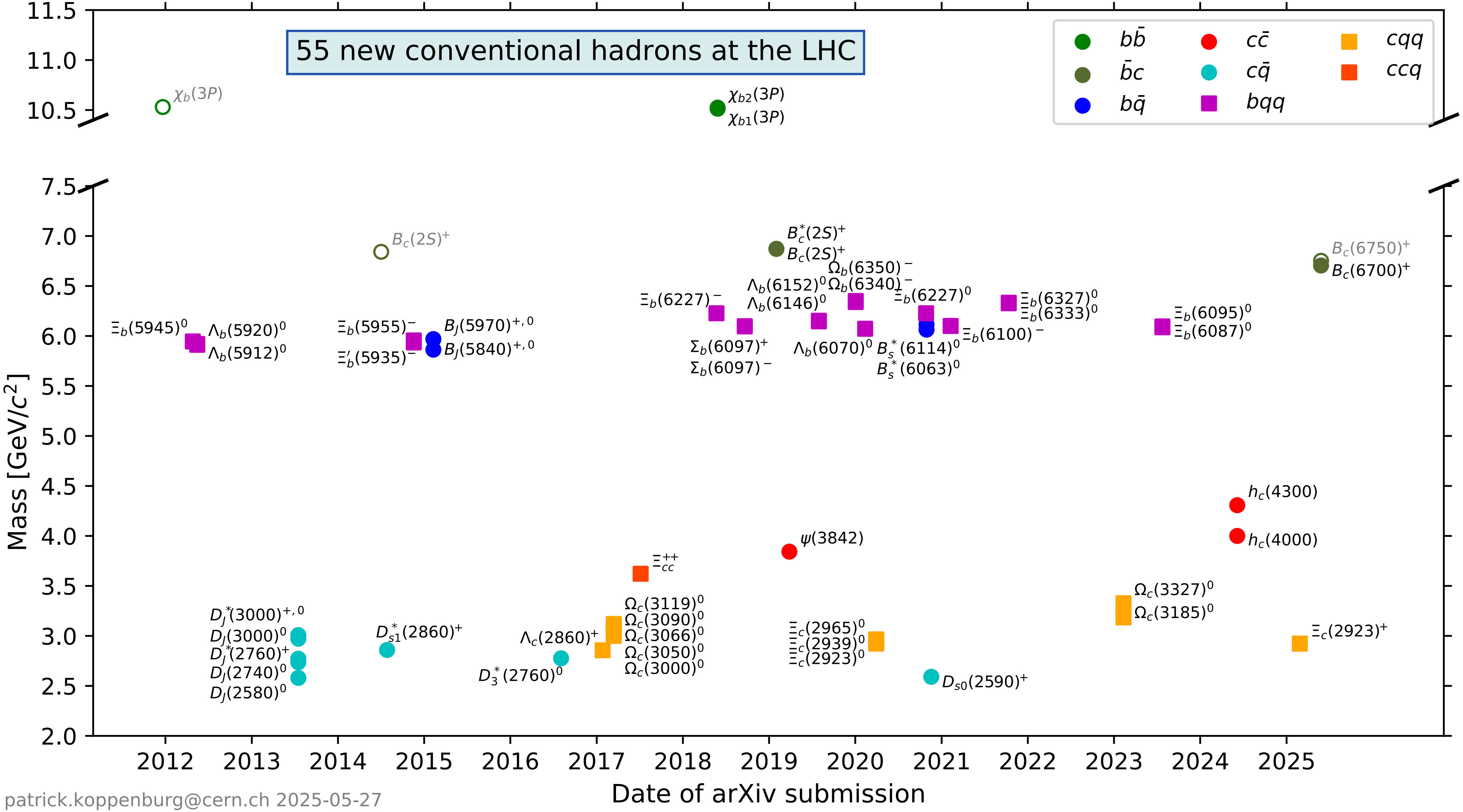
non-flat for polarized

do not use in the primary analysis

(5) Φ, θ_1, θ_2 decay angles — analysis

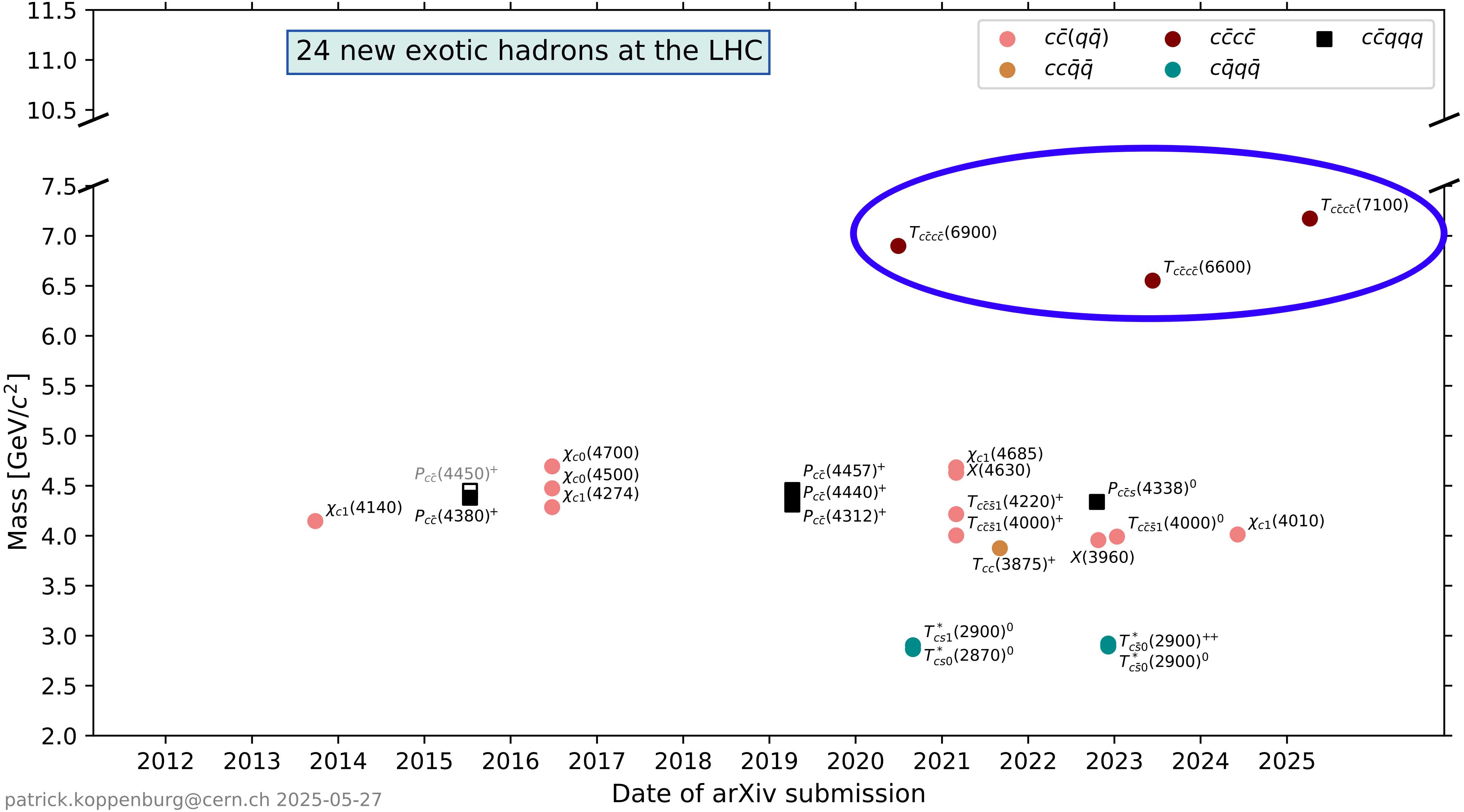


New conventional hadrons at LHC

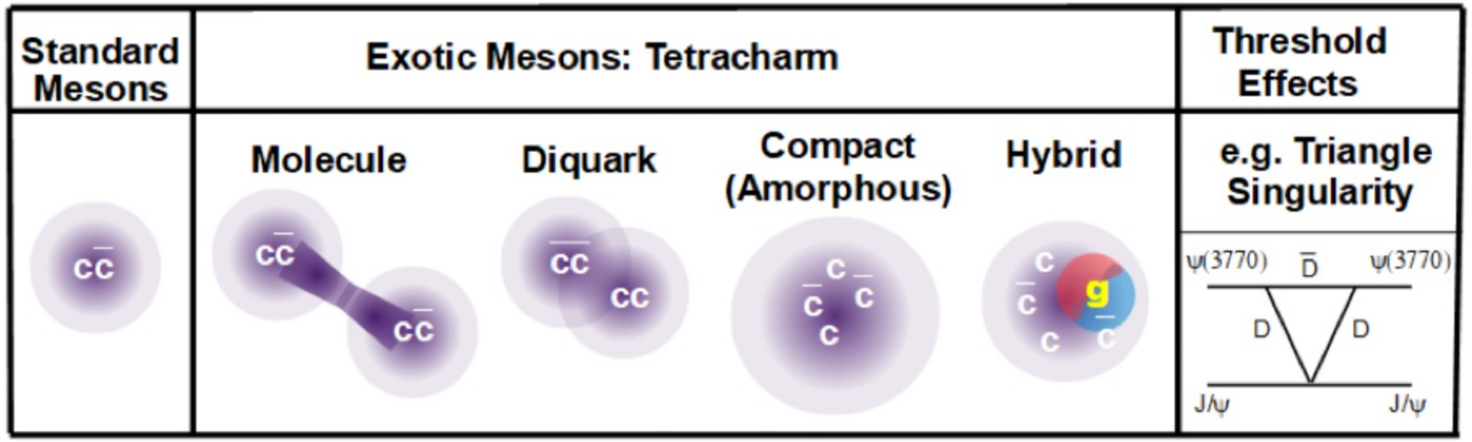


patrick.koppenburg@cern.ch 2025-05-27

New exotic hadrons at LHC



Status



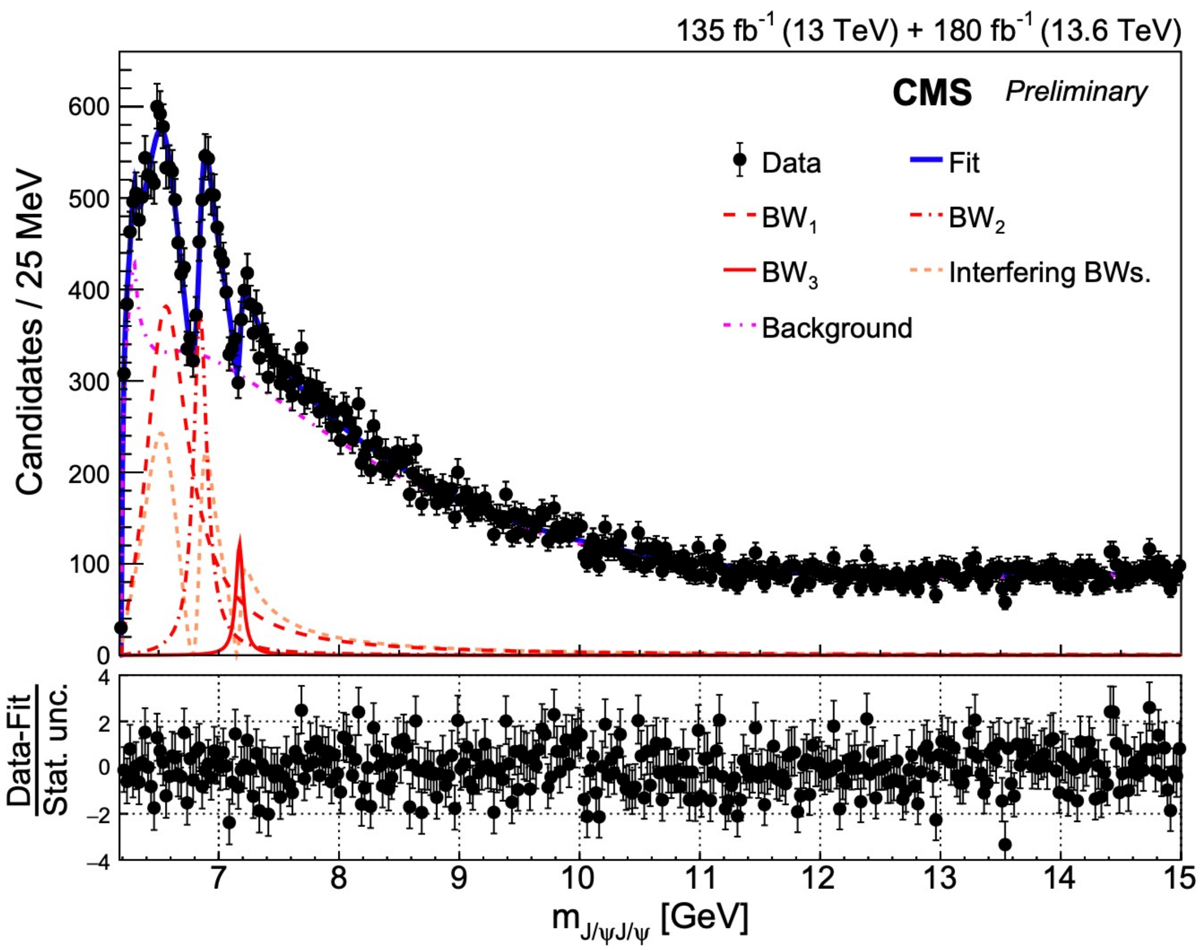
❖ Models of potential quark configurations for J/ψJ/ψ mesons.

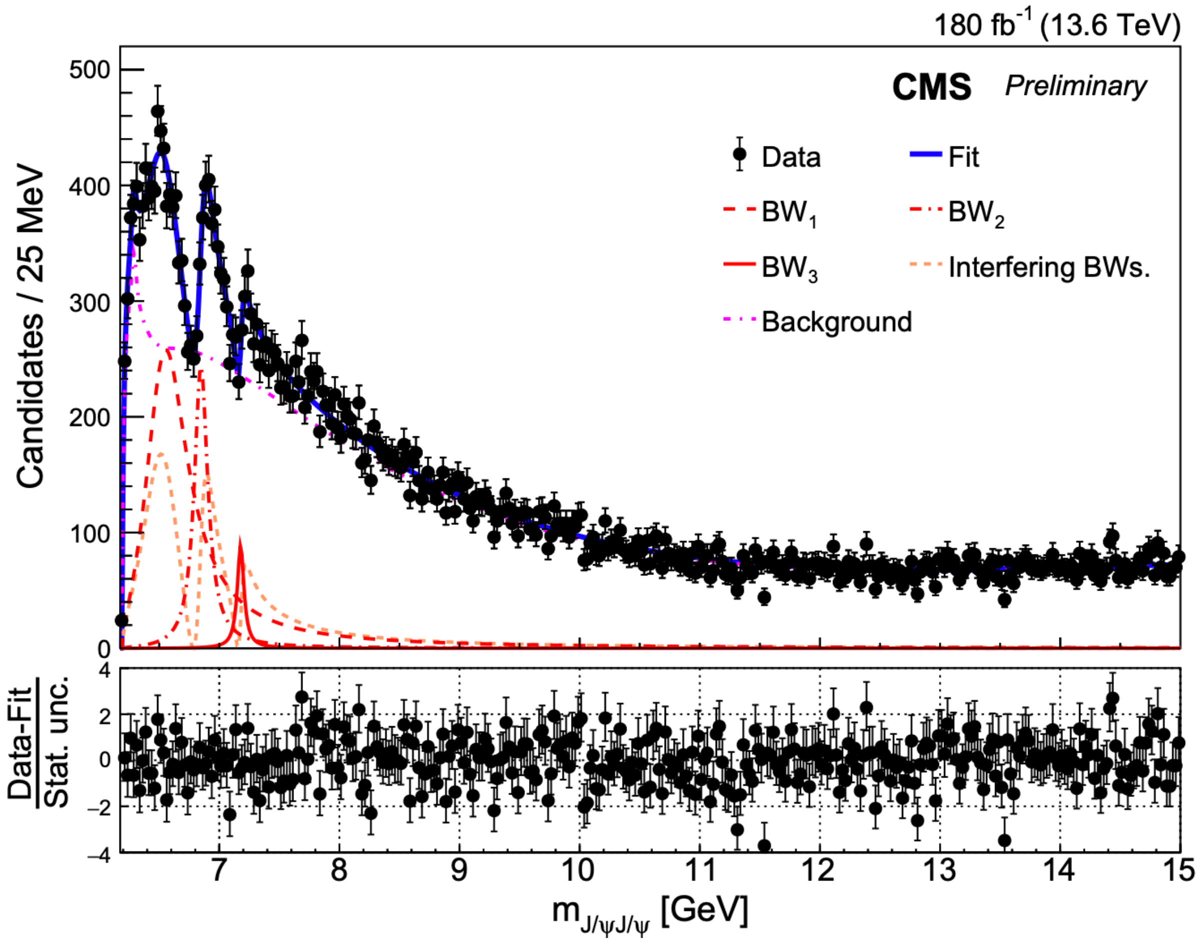
- Meson-meson "molecule" ($c\bar{c}$- $c\bar{c}$)
- Pair of diquarks (cc-$\bar{c}\bar{c}$)
- Hybrid with a valence gluon
- Peaks as artifact of dicharmonia production thresholds
- ……

Family of all-charm tetraquarks with same J^{PC}

offers new perspectives on interpretation for ***exotics***

$J/\psi J/\psi$: 6-15 GeV fits





Fit model

- **Final 2D fit model** $(0^+ \text{ vs. } 0^-)$:

$$P(m_X, D_{0^-}) = \ldots\ldots$$
$$+N_{(interf-BW1BW2BW3)} * \left[f_{0_m^+} * P_{0_m^+(interf-BW1BW2BW3)}(m_X, D_{0^-})\right.$$
$$\left.+\left(1 - f_{0_m^+}\right) * P_{0^-(interf-BW1BW2BW3)}(m_X, D_{0^-})\right]$$

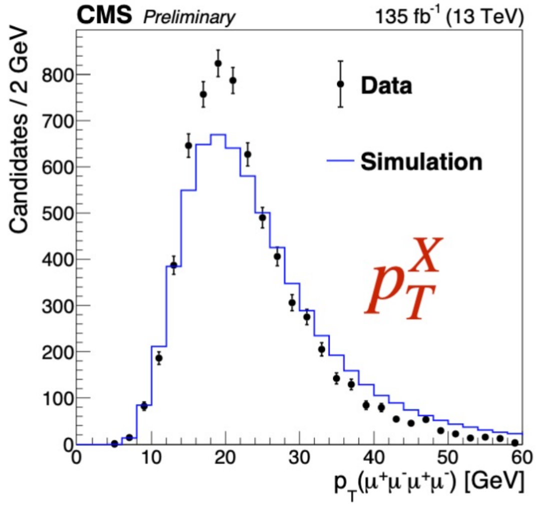
$f_{0_m^+}$: fraction of 0_m^+ signal component

Concept of Analysis: Production

- We do not know the production mechanism

— empirical model to reproduce p_T^X and p_z^X in data

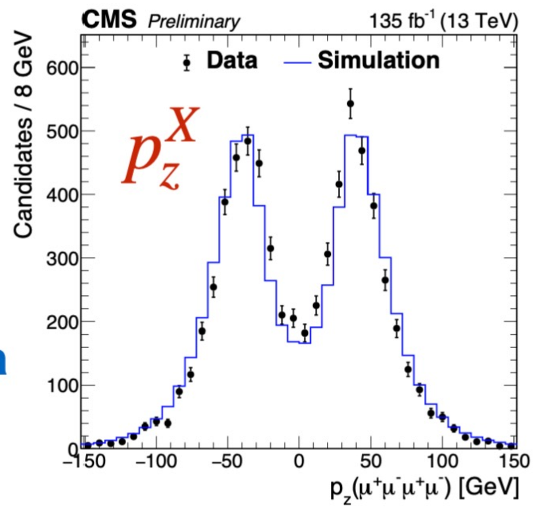
match p_z^X



— tune **Pythia** to match p_T^X in sideband and signal region

— fine-tune re-weighting p_T^X

match p_T^X



— residual p_T^X and p_z^X

consistency tests

coverage in systematics

Simulation

JHUGen + Pythia

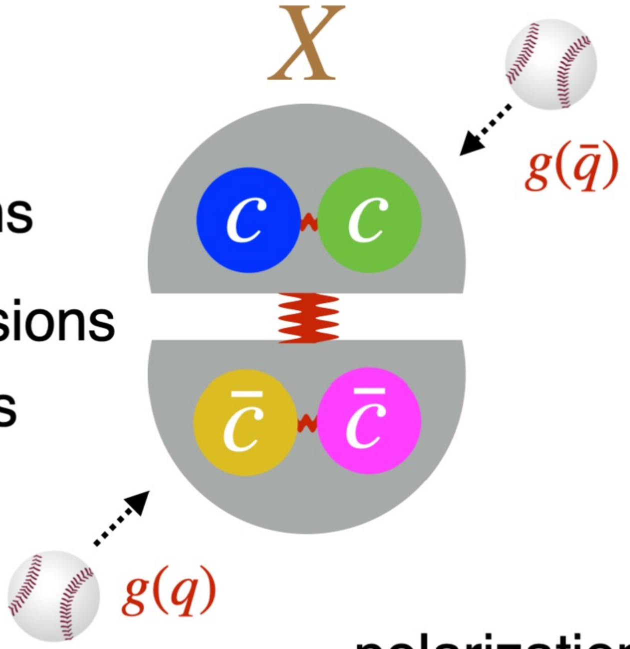
— essential to model detector acceptance

Concept of Analysis: Production

- We do not know the production mechanism

  — empirical model to reproduce p_T^X and p_z^X in data

- Monte Carlo tools:



JHUGen

to model spin correlations

(A) parton ($gg/q\bar{q}$) collisions

polarization J_z beam axis

arXiv:2109.13363

MELA

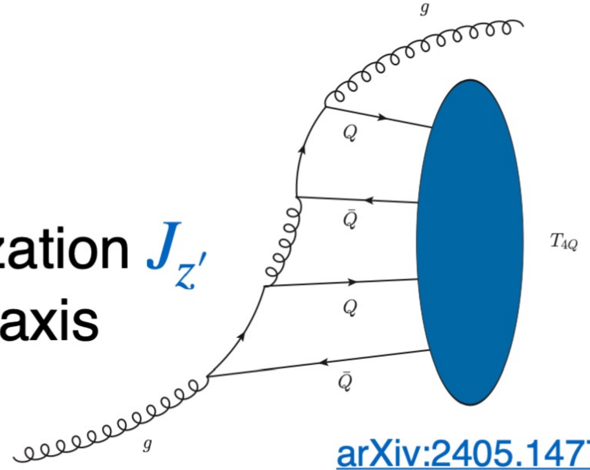
matrix elements

— re-weight $J = 1{,}2$ to unpolarized

— re-weight J_z or $J_{z'}$ for systematics

(B) gluon (quark) fragmentation

polarization $J_{z'}$ boost axis



arXiv:2405.14773

Angular Analysis

- Observations:
  - 1^+ & 1^- identical in 1D, differ in 3D
  - 0^+ & 1^+ cannot be distinguished from general 2^+
  - unique to 2^+ (or $J \geq 2$): A_{+-}, A_{-+}, "mixture" of 0^+ & 1^+
  - 0^- & 2^-_m identical
  - 1^- & 2^-_h identical
  - unique to 2^-: "mixture"
  - for $J \geq 3$

    $J^P \Leftrightarrow 2^P$
  - polarized $J \geq 1$

    unique Φ_1, θ^*

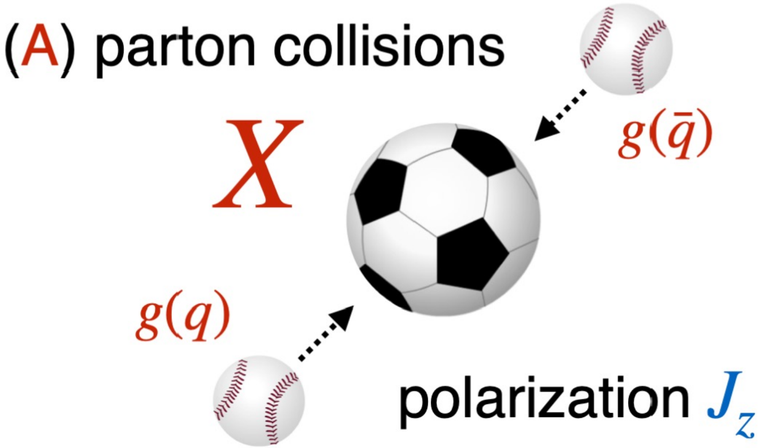
    not used here…

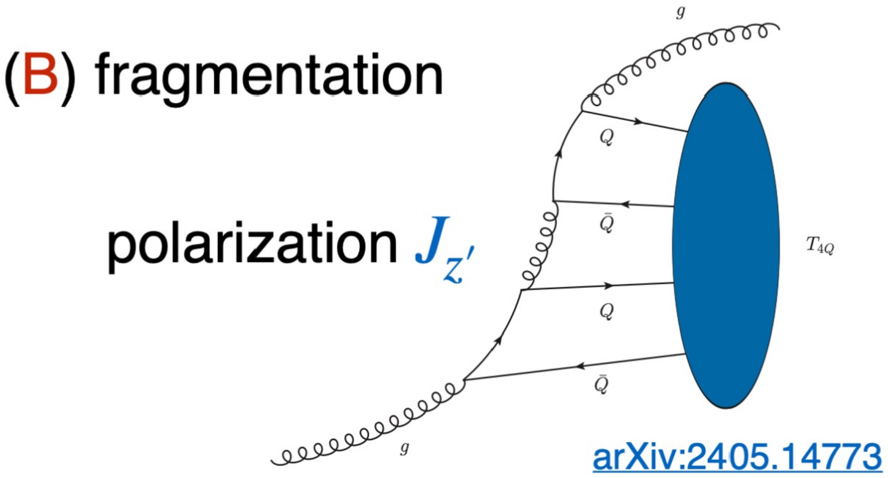
arXiv:1001.3396

$$F^J_{0,0}(\theta^*) \times \Big[4|A_{00}|^2 \sin^2\theta_1 \sin^2\theta_2 + 2|A_{++}||A_{--}|\sin^2\theta_1 \sin^2\theta_2 \cos(2\Phi - \phi_{--} + \phi_{++})\Big]$$
$$+ |A_{++}|^2 \left(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right)$$
$$+ |A_{--}|^2 \left(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \qquad \text{spin} = 0 \ \& \ \geq 1$$
$$+ 4|A_{00}||A_{++}|(A_{f_1} + \cos\theta_1)\sin\theta_1 (A_{f_2} + \cos\theta_2)\sin\theta_2 \cos(\Phi + \phi_{++})$$
$$+ 4|A_{00}||A_{--}|(A_{f_1} - \cos\theta_1)\sin\theta_1 (A_{f_2} - \cos\theta_2)\sin\theta_2 \cos(\Phi - \phi_{--})$$
$$+F^J_{1,1}(\theta^*) \times \Big[2|A_{+0}|^2(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)\sin^2\theta_2 + 2|A_{0-}|^2 \sin^2\theta_1 (1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)$$
$$+ 2|A_{-0}|^2(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)\sin^2\theta_2 + 2|A_{0+}|^2 \sin^2\theta_1 (1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)$$
$$+ 4|A_{+0}||A_{0-}|(A_{f_1} + \cos\theta_1)\sin\theta_1 (A_{f_2} - \cos\theta_2)\sin\theta_2 \cos(\Phi + \phi_{+0} - \phi_{0-})$$
$$+ 4|A_{0+}||A_{-0}|(A_{f_1} - \cos\theta_1)\sin\theta_1 (A_{f_2} + \cos\theta_2)\sin\theta_2 \cos(\Phi + \phi_{0+} - \phi_{-0})\Big] \qquad \text{spin} \geq 1$$
$$+F^J_{1,-1}(\theta^*) \times \Big[4|A_{+0}||A_{0+}|(A_{f_1} + \cos\theta_1)\sin\theta_1 (A_{f_2} + \cos\theta_2)\sin\theta_2 \cos(2\Psi - \phi_{+0} + \phi_{0+})$$
$$+ 4|A_{0-}||A_{-0}|(A_{f_1} - \cos\theta_1)\sin\theta_1 (A_{f_2} - \cos\theta_2)\sin\theta_2 \cos(2\Psi - \phi_{0-} + \phi_{-0})$$
$$+4|A_{+0}||A_{-0}|\sin^2\theta_1 \sin^2\theta_2 \cos(2\Psi - \Phi - \phi_{+0} + \phi_{-0}) + 4|A_{0-}||A_{0+}|\sin^2\theta_1 \sin^2\theta_2 \cos(2\Psi + \Phi - \phi_{0-} + \phi_{0+})\Big]$$
$$+F^J_{2,2}(\theta^*) \times \Big[|A_{+-}|^2(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)$$
$$+ |A_{-+}|^2(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)\Big] \qquad \text{spin} \geq 2$$
$$+F^J_{2,-2}(\theta^*) \times \Big[2|A_{+-}||A_{-+}|\sin^2\theta_1 \sin^2\theta_2 \cos(4\Psi - \phi_{+-} + \phi_{-+})\Big] + \text{other 26 interference terms for spin}$$

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

Polarization in Production





- Helicity amplitudes appear in production. For parton collision:
  - — spin-0: unpolarized in any case, e.g. $gg \to X$
  - — spin-1: $q\bar{q} \to X$ produce $J_z = \pm 1$ (not 0!)
  - — spin-2: $gg \to X$ produce $J_z = 0, \pm 2$, minimal coupling: $J_z = \pm 2$
    $q\bar{q} \to X$ produce $J_z = \pm 1$
- Similar ideas in fragmentation of g or Q
  - — re-weight MELA to any model: unpolarized, polarized z' or z

Lorentz-Invariant Amplitude

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

$$A(X_{J=0} \to V_1V_2) = \left(a_1(q^2) m_V^2 \epsilon_1^* \epsilon_2^* + a_2(q^2) f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3(q^2) f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

0_m^+ 0_h^+ 0^-

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

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

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

arXiv:1001.3396

Backup

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

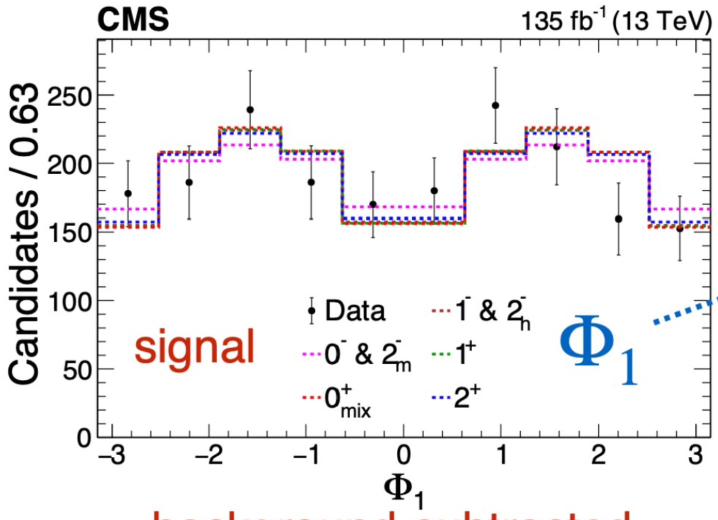
$$A(X_{J=1} \to V_1V_2) = \left(b_1(q^2) \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2(q^2) \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta \right)$$

1^- 1^+

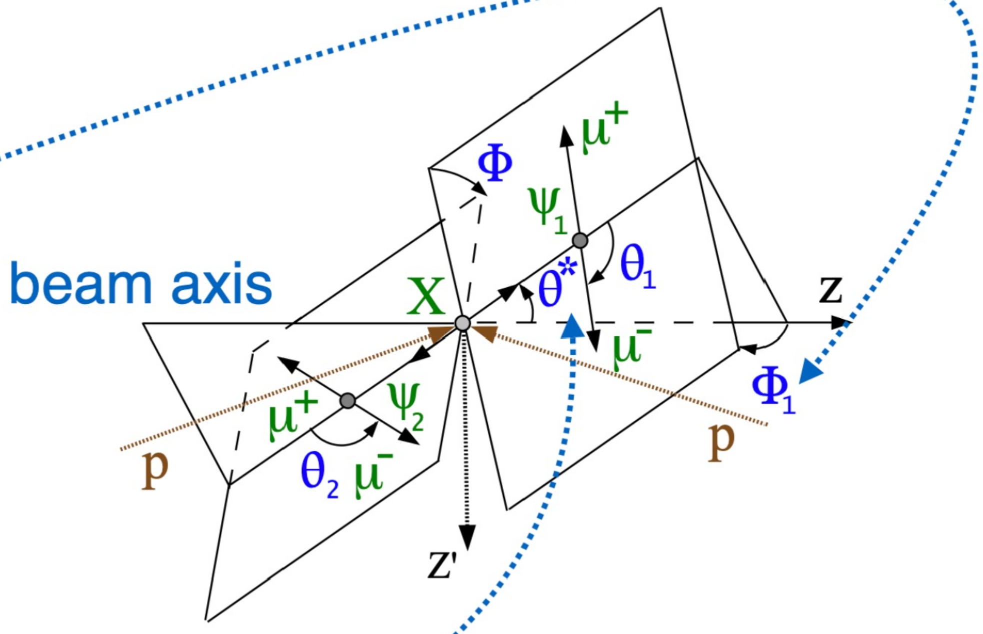
more for spin-2 $A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$ $A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$

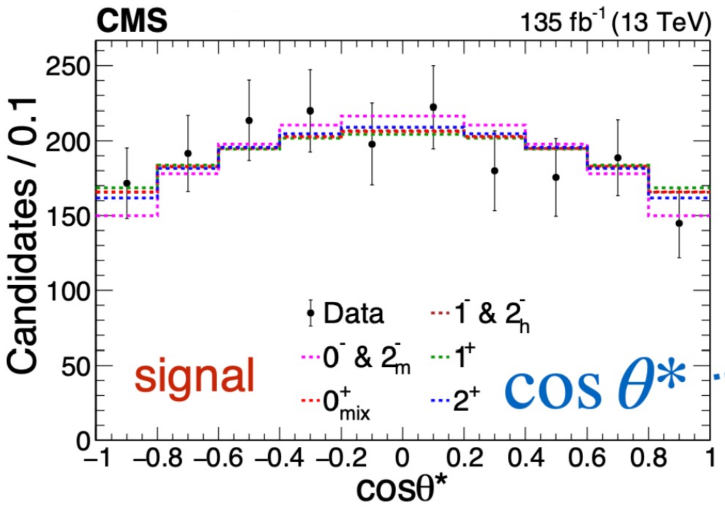
Production Angles

(4) production angles consistent with unpolarized resonances



with respect to the beam axis

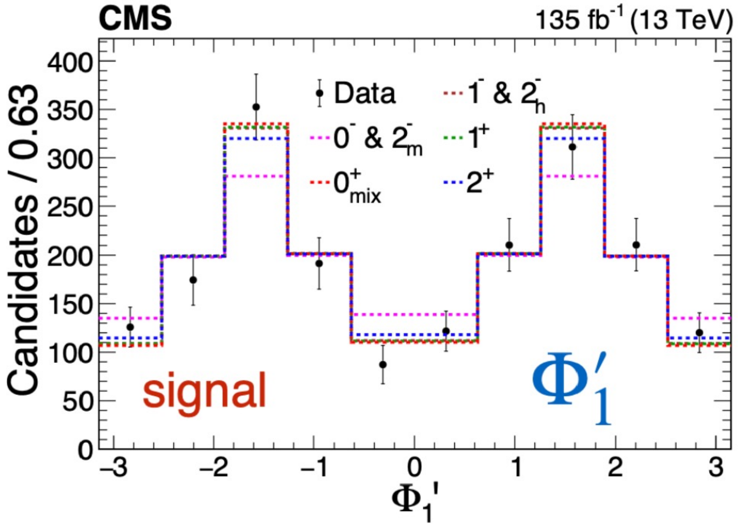




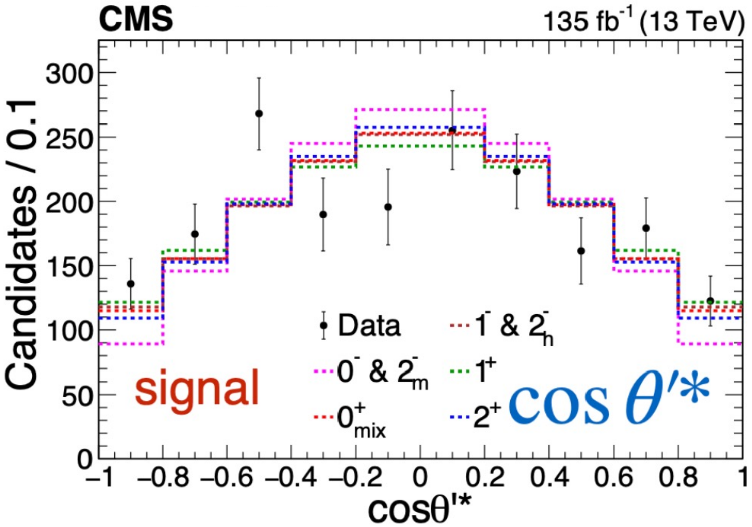
acceptance effects
⇒ distributions not flat

Production Angles

(4) production angles consistent with unpolarized resonances

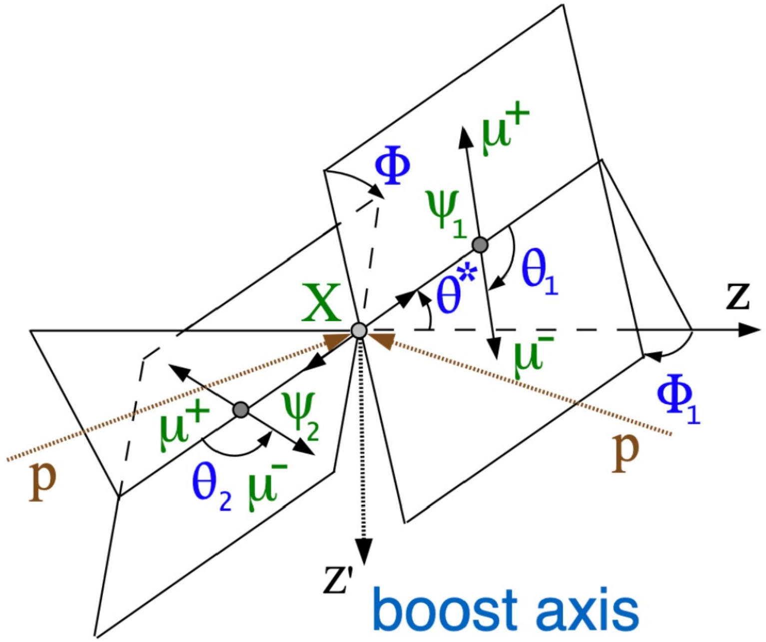


background-subtracted

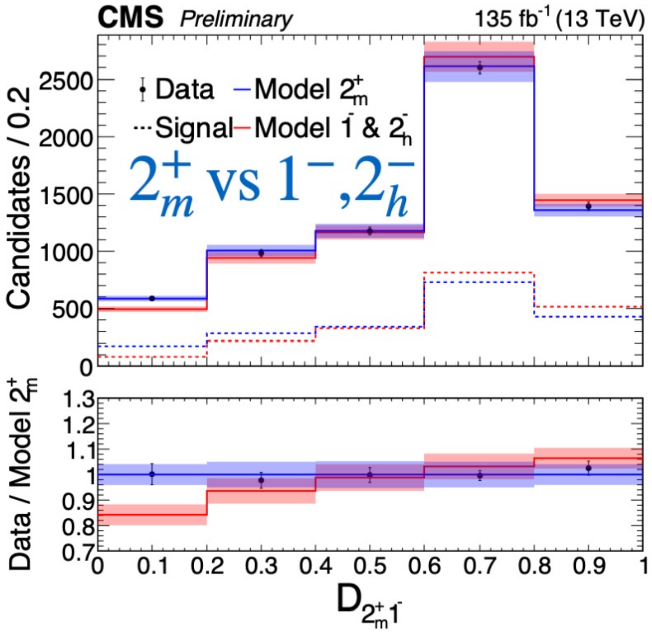


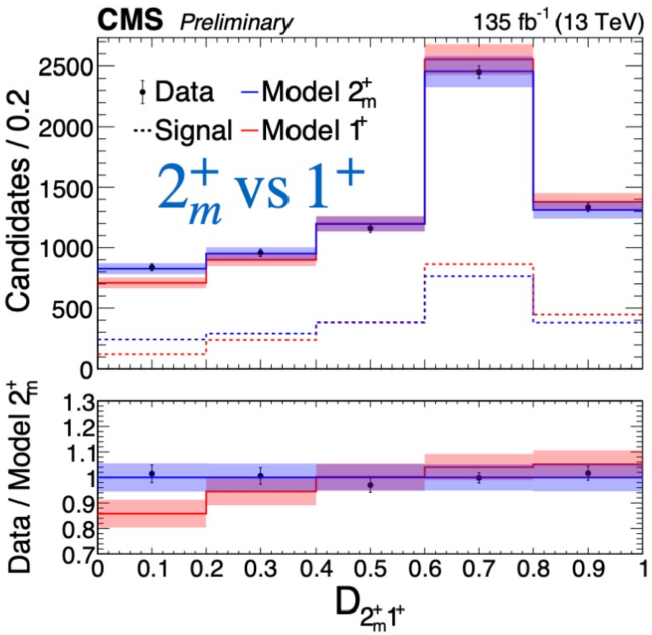
with respect to the boost axis

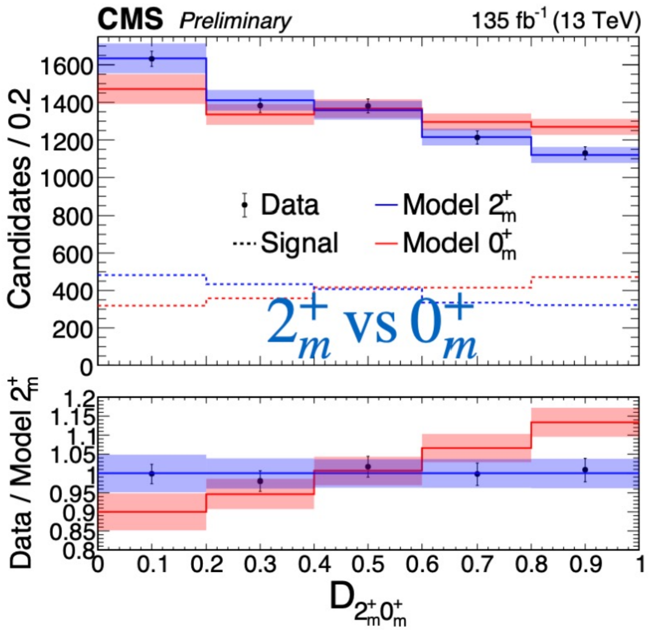
does not prove unpolarized

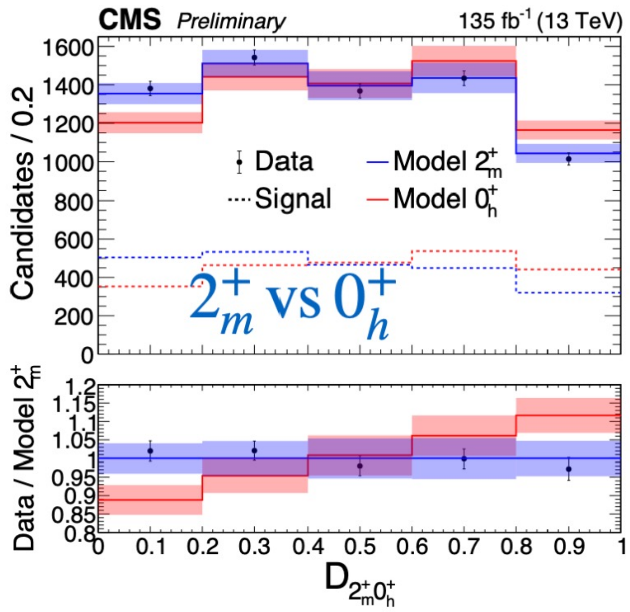


Discriminant Distributions

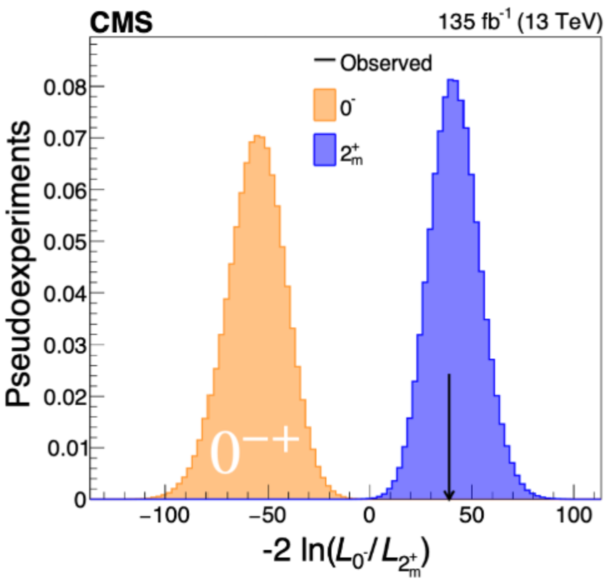


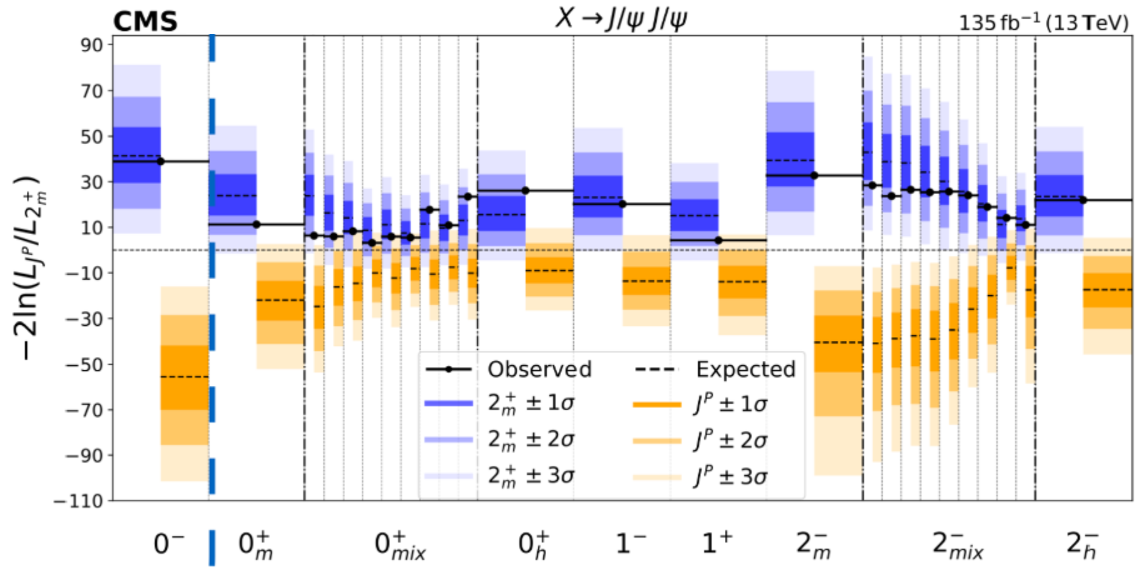






Hypothesis test





- Scan mixture of two 0^{++} amplitudes

- Scan mixture of two 2^{-+} amplitudes

- Data are consistent with a 2^{++} model, inconsistent with others

Summary of Results

- Full set of results, compared to 2^+_m

$P = -1$

		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
0^+_m vs 2^+_m	0^+_m	4.3×10^{-5}	3.9	5.6×10^{-9}	5.7
	2^+_m	7.2×10^{-2}	1.5	0.50	0.0
0^+_{mix} vs 2^+_m	0^+_{mix}	1.4×10^{-2}	2.2	8.4×10^{-4}	3.1
	2^+_m	1.7×10^{-1}	1.0	0.50	0.0
0^+_h vs 2^+_m	0^+_h	3.1×10^{-9}	5.8	8.5×10^{-5}	3.8
	2^+_m	9.0×10^{-1}	−1.3	0.50	0.0
1^- vs 2^+_m	1^-	8.0×10^{-8}	5.2	6.4×10^{-9}	5.7
	2^+_m	3.8×10^{-1}	0.3	0.50	0.0
1^+ vs 2^+_m	1^+	4.7×10^{-3}	2.6	2.7×10^{-5}	4.0
	2^+_m	5.2×10^{-2}	1.6	0.50	0.0
2^-_m vs 2^+_m	2^-_m	4.1×10^{-12}	6.8	3.9×10^{-14}	7.5
	2^+_m	2.8×10^{-1}	0.6	0.50	0.0
2^-_{mix} vs 2^+_m	2^-_{mix}	6.5×10^{-4}	3.2	1.5×10^{-4}	3.6
	2^+_m	3.1×10^{-1}	0.5	0.50	0.0
2^-_h vs 2^+_m	2^-_h	2.2×10^{-8}	5.5	6.3×10^{-9}	5.7
	2^+_m	4.3×10^{-1}	0.2	0.50	0.0

– $J^{PC} = 2^{++}$ most likely

– $J > 2$ possible but highly unlikely require $L \geq 2$

– $J \neq 0$ at $> 95\,\%$ CL

– confidence level:

$$CL_s = \frac{P(q \geq q_{\text{obs}} \mid J^P_j + \text{bkg})}{P(q \geq q_{\text{obs}} \mid J^P_i + \text{bkg})}$$

– $J \neq 1$ at $> 99\,\%$ CL

– $P \neq -1$ very certain (exclude J^{-+} including $J \geq 3$)

- Recall: 2^{++} can have a mixture of 2^+_m and look-alike of $0^+, 1^+$