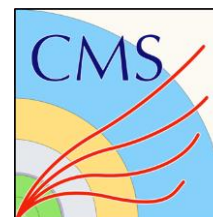


Spin parity of tetraquark candidates in $J/\psi J/\psi$ mass spectrum at CMS

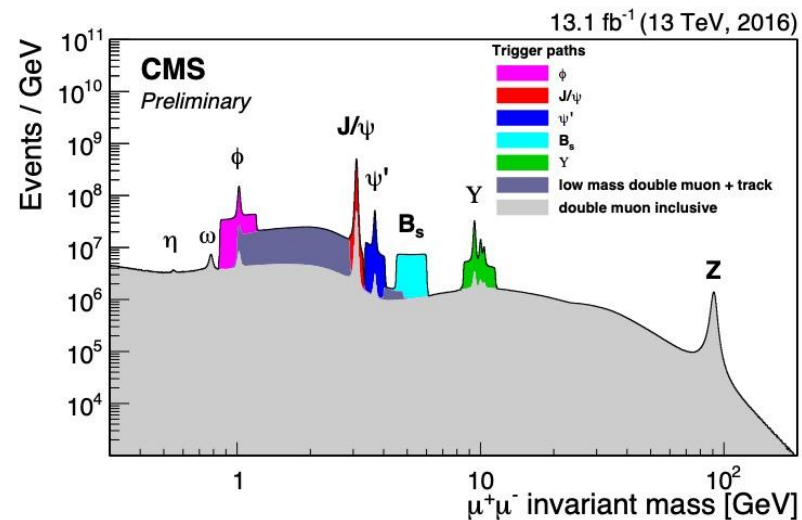
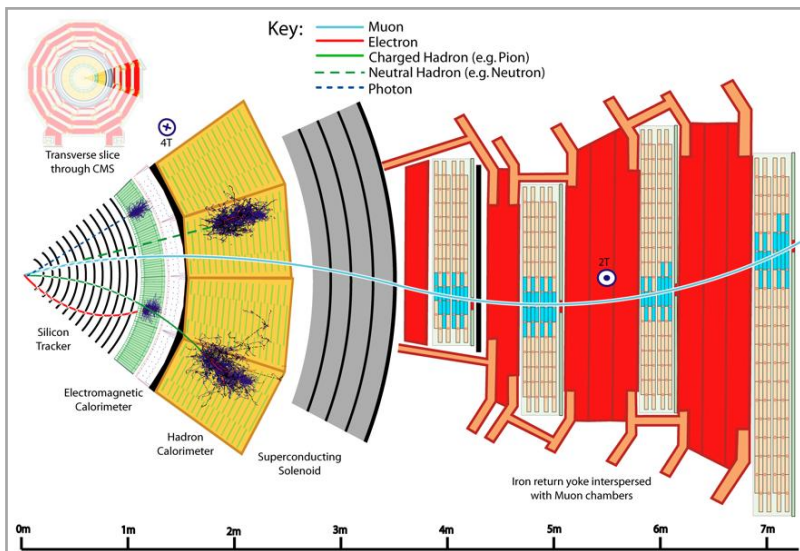
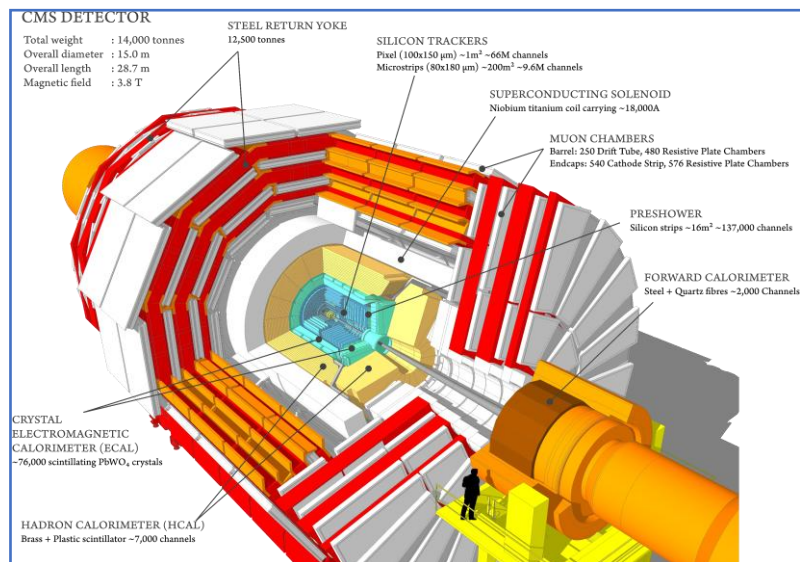
张敬庆

南京师范大学



第十一届XYZ研讨会
贵阳 2026.07.22-2026.07.27

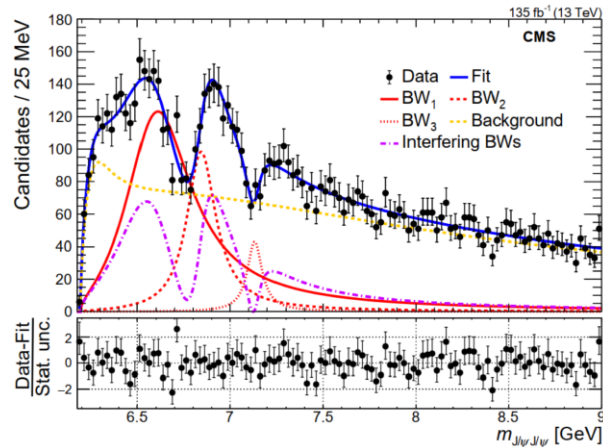
CMS detector



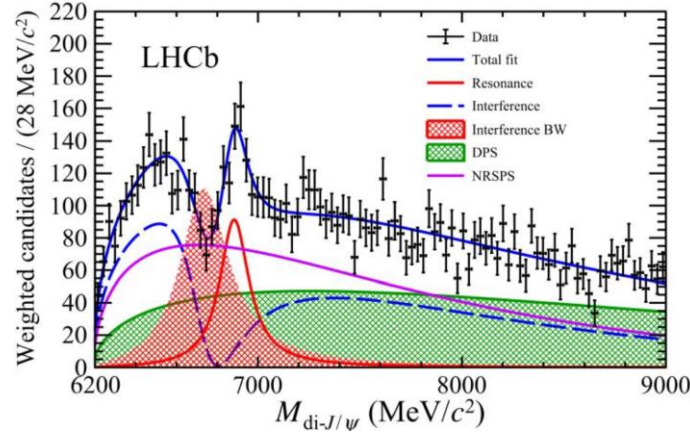
- Excellent detector for (exotic) quarkonium
- Good muon system
 - High-purity muon ID, $\frac{\Delta m}{m} \sim 0.6\%$ for J/ψ
- Silicon tracking detector
 - $B = 3.8\text{ T}$, $\frac{\Delta p_T}{p_T} \sim 1\%$ & good vertex resolution
- Different triggers for different physics programs/purposes

The tetraquark candidates at LHC

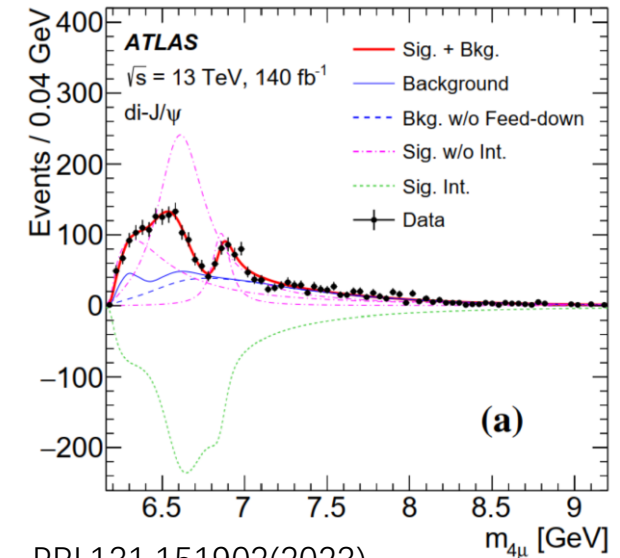
- Structures in $J/\psi J/\psi$ mass spectrum at CMS, LHCb and ATLAS from the LHC run 2 data
- Structures established but need more study to understand them



PRL132.111901(2024)



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

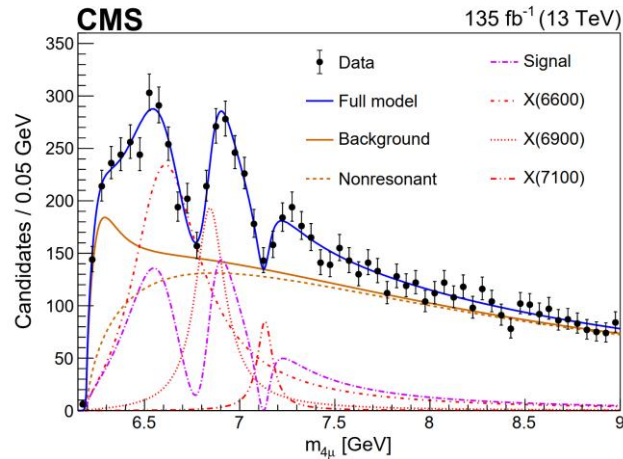


PRL131.151902(2023)

Internal Structure of the tetraquarks

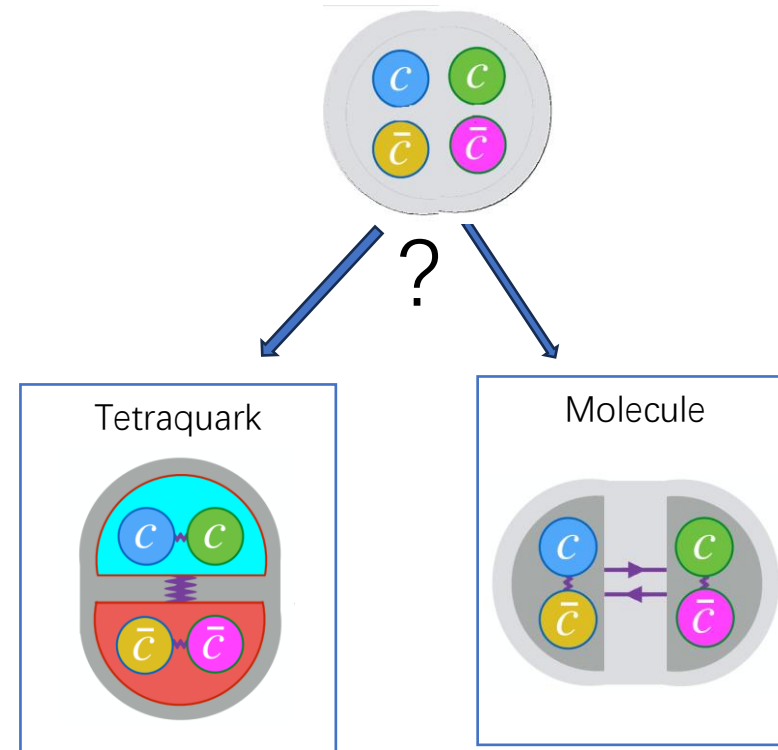
Nature 648 (2025) 58

- Tetraquark candidates observed in experiments



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

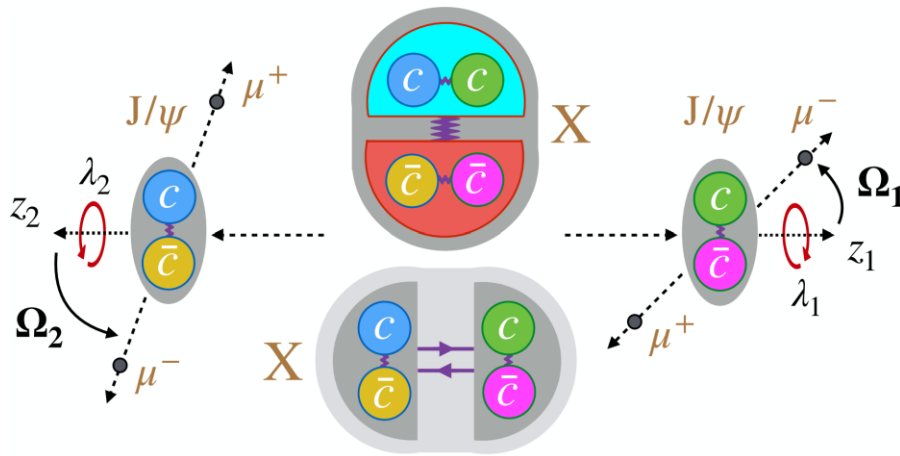
$$X \rightarrow J/\psi J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$



Infer spin-parity of X

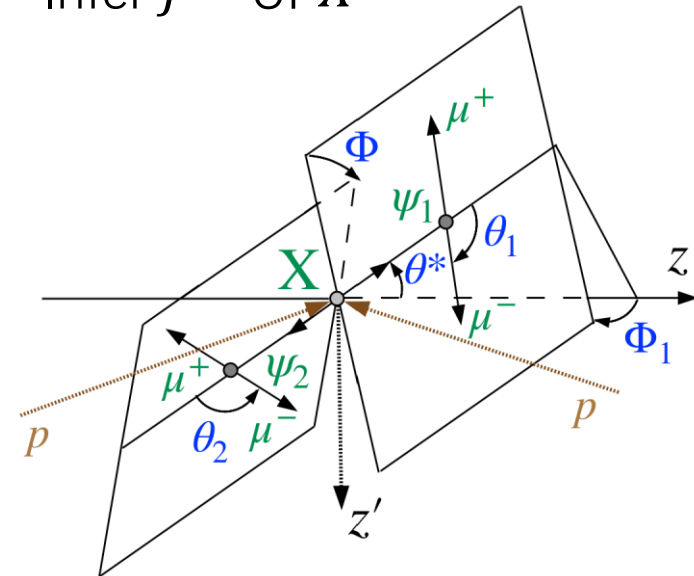
Nature 648 (2025) 58

- Infer J^{PC} of X from angular distributions
- Theory
 - $A(X \rightarrow VV)$ depends on J_X^{PC}
polarization of J/ψ
 - $A(X \rightarrow VV)$ determines angular distributions



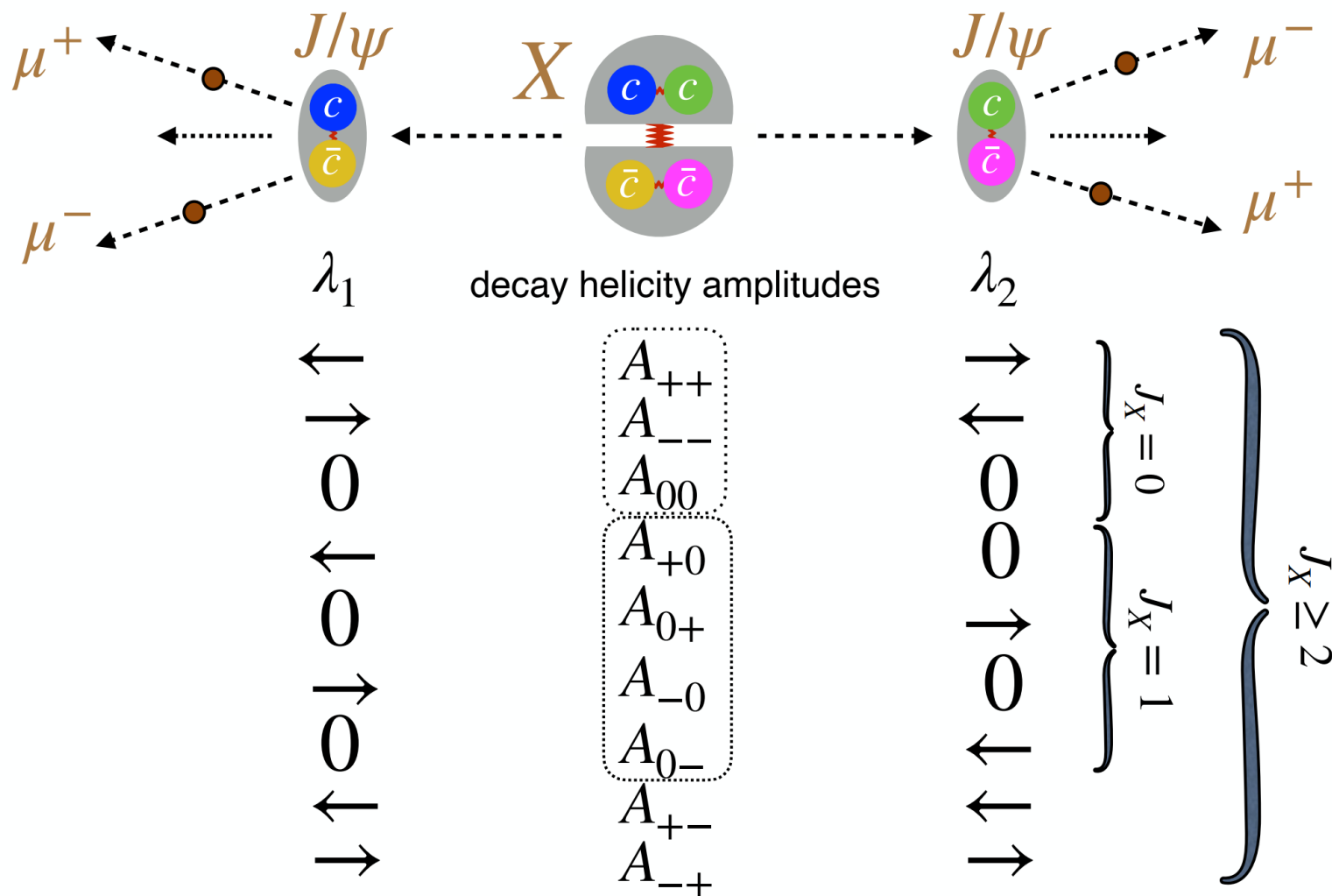
Experiment

- Measure angular distributions of $J/\psi, \mu$ etc.
- Infer J^{PC} of X



J/ψ polarizations

Nature 648 (2025) 58



J/ψ polarizations

Nature 648 (2025) 58

• 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

Nature 648 (2025) 58

- Expect three resonances to have the same tensor structure

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

recall (22 years):
 $B \rightarrow \varphi K^*$ expect A_{00}
 found ~50% A_{++}
 Higgs (12 years):
 $H \rightarrow 4\ell \Rightarrow 0_m^+$

0_m^+ 0_h^+ 0^-

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

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

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

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

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

more for spin-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^+

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

Helicities (0, -) of two J/ψ

Simplification in angular analysis

Nature 648 (2025) 58

- Full amplitude analysis possible, but very complex

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

- Simplification in angular analysis

(1) Same properties of **3 resonances**:

$$\mathcal{P}(m_{4\mu}, \vec{\Omega}) = \underbrace{\mathcal{P}(m_{4\mu})}_{\text{empirical}} \cdot \underbrace{T(\vec{\Omega} | m_{4\mu})}_{\text{angular}}$$

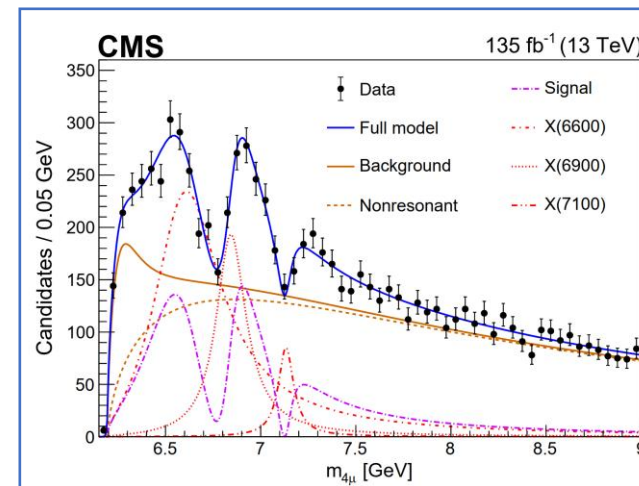
(2) Pairwise tests of J_X^P hypotheses i and j :

[arXiv:1208.4018](https://arxiv.org/abs/1208.4018)

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

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

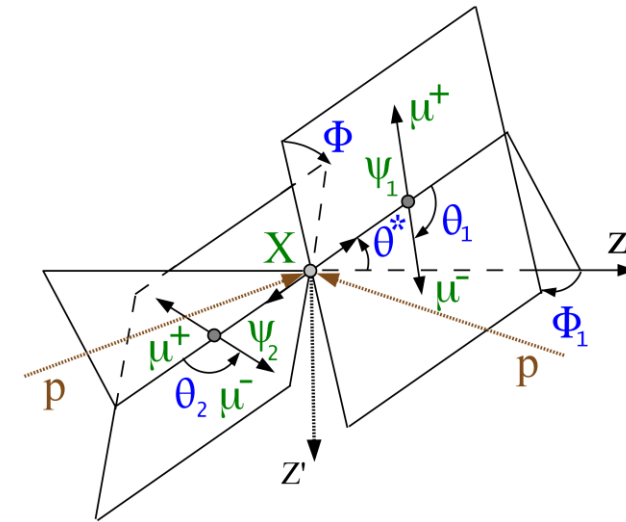
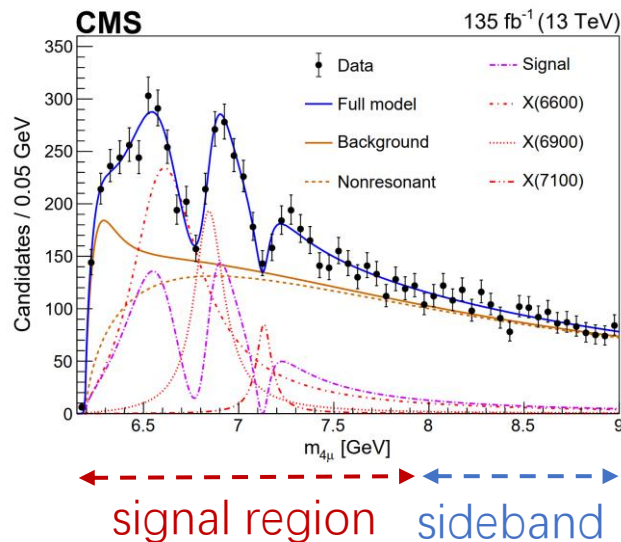
- Final 2D model: $\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})$



Analysis of data

Nature 648 (2025) 58

- Two dimensions ($m_{4\mu}, D_{ij}$) analysis: $\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})$
 - Event selection from observation paper [Phys. Rev. Lett. 132 \(2024\) 111901](#)
 - BKG: data sideband & MC simulation with Pythia
 - $m_{4\mu}$ shapes: [Phys. Rev. Lett. 132 \(2024\) 111901](#)
 - Decay angles Φ, θ_1, θ_2 to identify $D_{ij}(\Phi, \theta_1, \theta_2; m_{4\mu})$

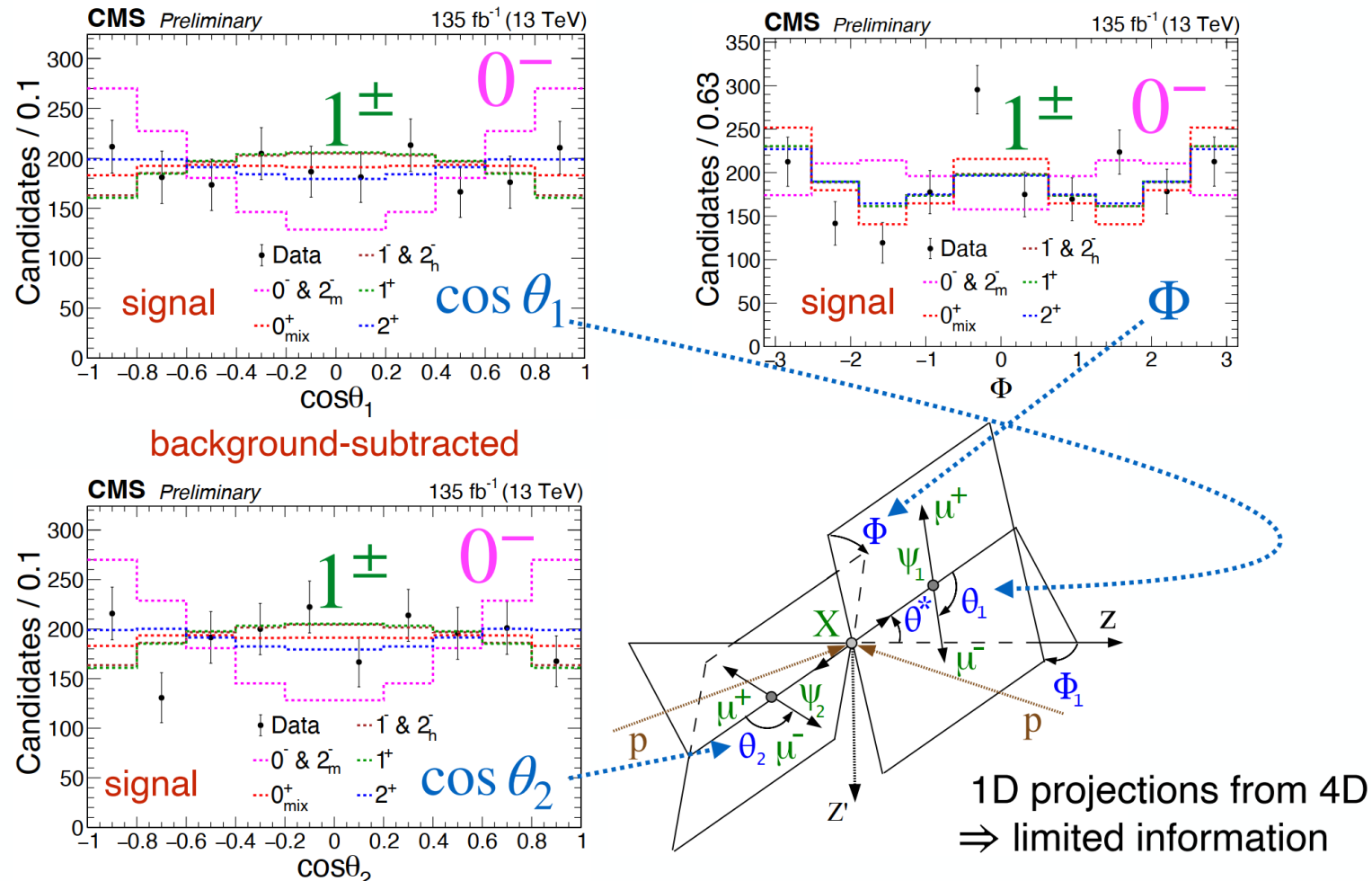


All steps till here prepared blinded

Decay angles

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

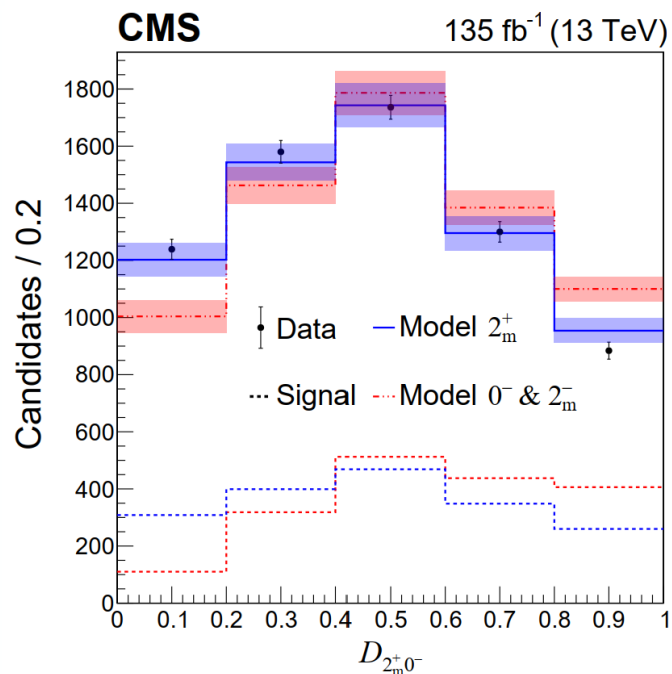
Nature 648 (2025) 58



Optimal Observables

Nature 648 (2025) 58

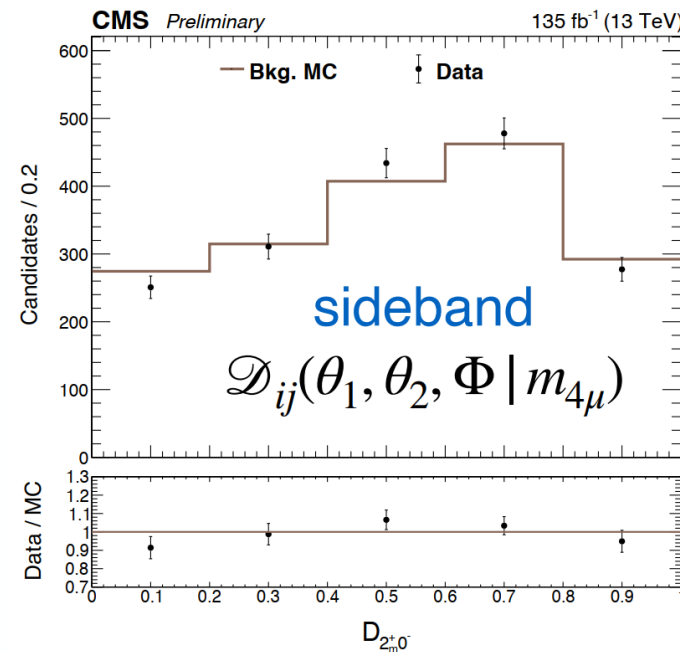
- 1D projection of data, optimal for $j = 0^-(2_m^-)$ vs $i = 2_m^+$



optimal observable

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

1D projections from 2D
⇒ limited information



background model from MC

control in sidebands

systematic variations

Hypothesis test of 0^- vs. 2_m^+

Nature 648 (2025) 58

- 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:

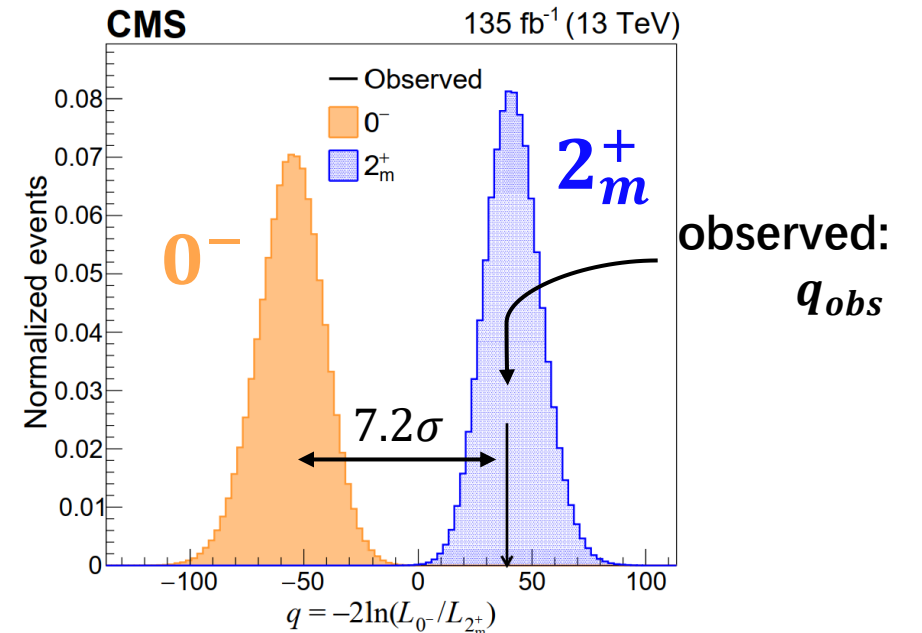
$$\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})$$

- Test statistics:

$$q = -2\ln(\mathcal{L}_{J_i^P} / \mathcal{L}_{J_j^P})$$

- Confidence level:

$$CL_s = \frac{P(q \geq q_{\text{obs}} | J_j^P + \text{bkg})}{P(q \geq q_{\text{obs}} | J_i^P + \text{bkg})}$$



Hypothesis test of J_i^P vs. J_j^P

Nature 648 (2025) 58

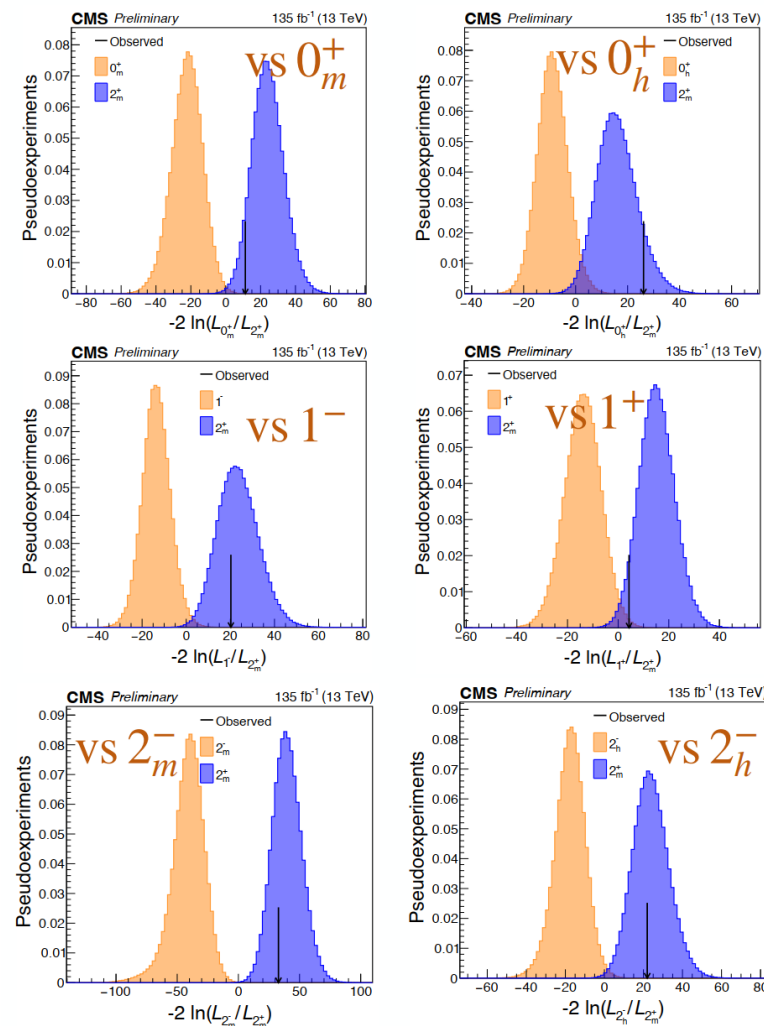
- Combined 2D fit: $\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij})$

➤ $J^P = 2_m^+$ 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

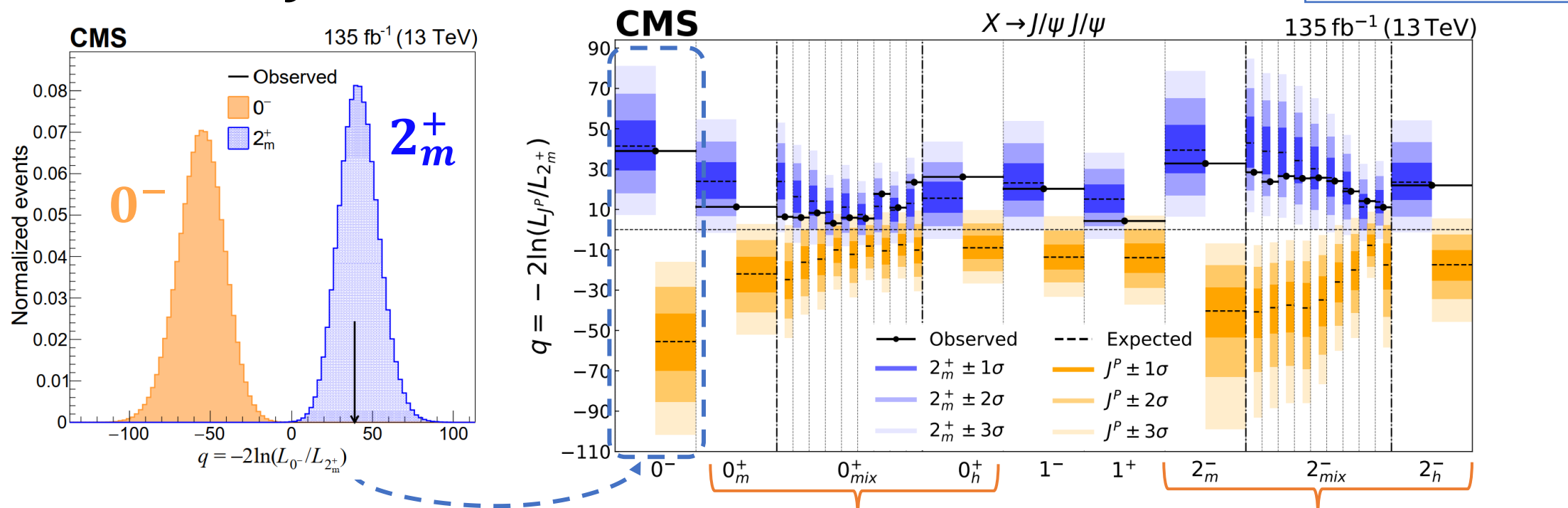
mix

mix



Summary of results

Nature 648 (2025) 58



- Data consistent with 2^{++} , inconsistent with others
 - $PC = ++$
 - $J \neq 1$ 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 $J = 0$

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

-- No interference (different spin projections)

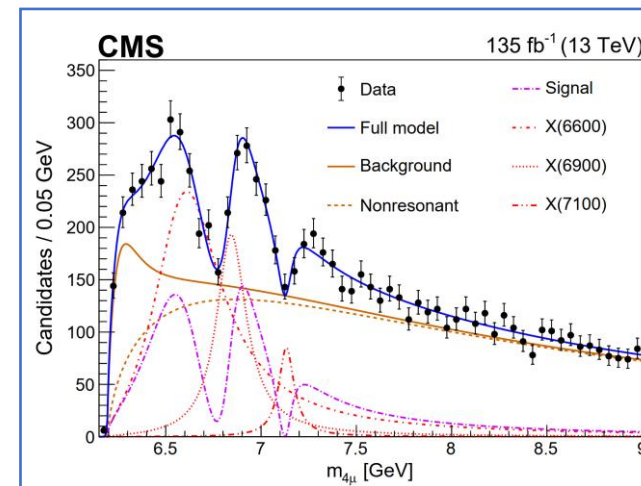
Scan mixture of two 0^{++} amp. (11 steps)

-- Constructive interf. most conservative

Summary

Nature 648 (2025) 58

- J^{PC} of the three resonances in $J/\psi J/\psi$ at CMS
 - $PC = ++$
 - $J \neq 1$ 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 $J = 0$



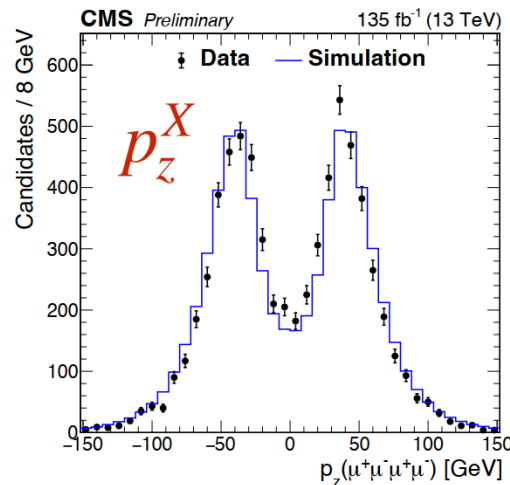
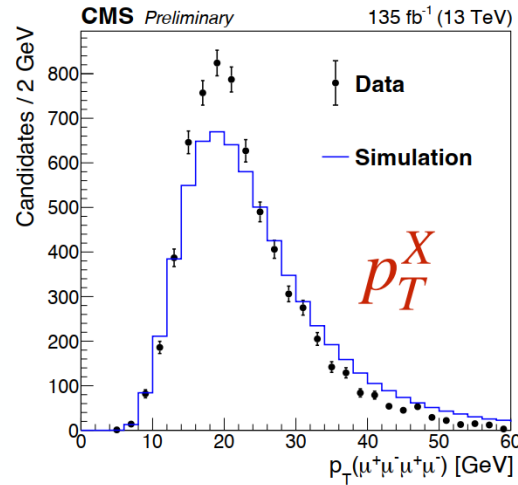
Thanks!

Backup

Production: p_T and p_z of X

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

Nature 648 (2025) 58



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

- fine-tune re-weighting p_T^X

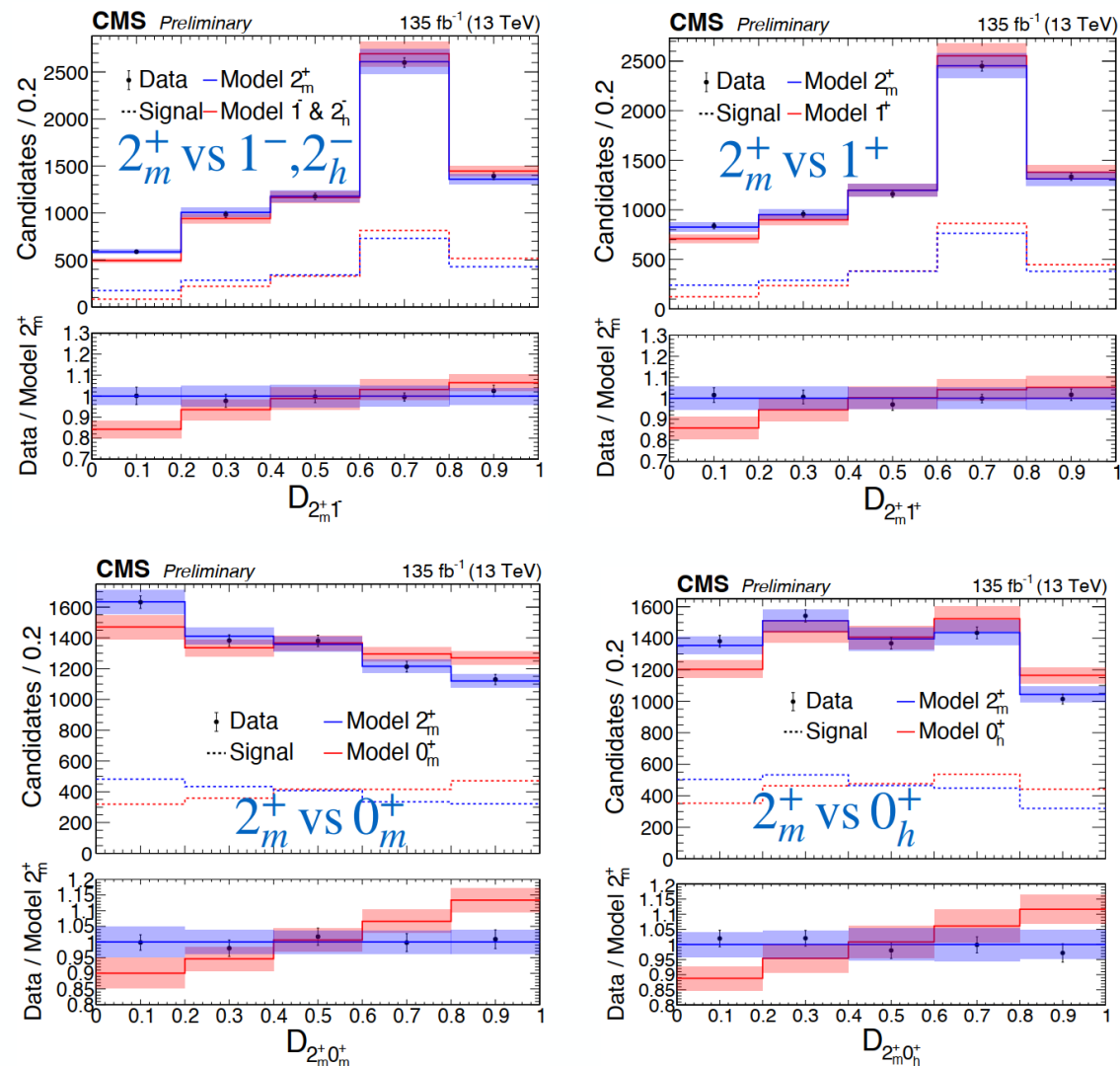
- residual p_T^X and p_z^X consistency tests coverage in systematics

- essential to model **detector acceptance**

Simulation:
JHUGen + Pythia

Discriminant

Nature 648 (2025) 58

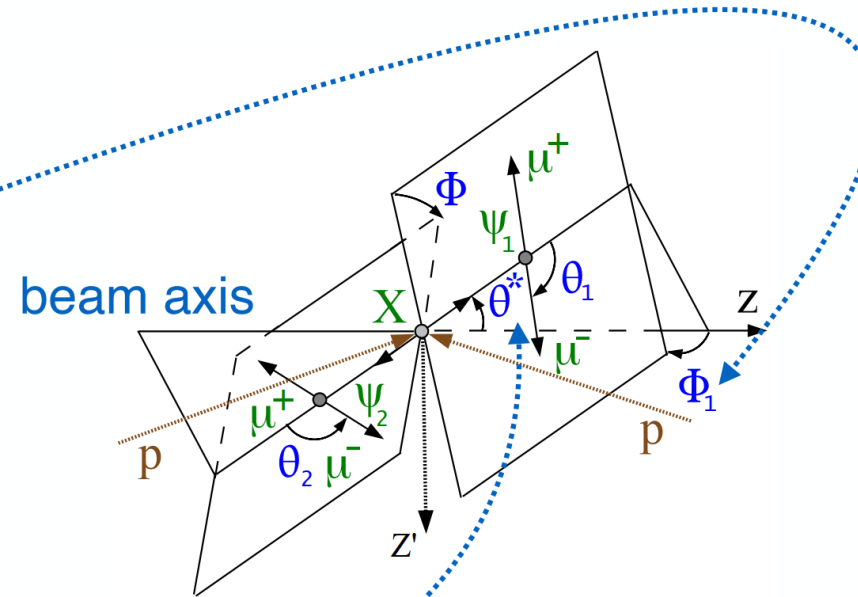
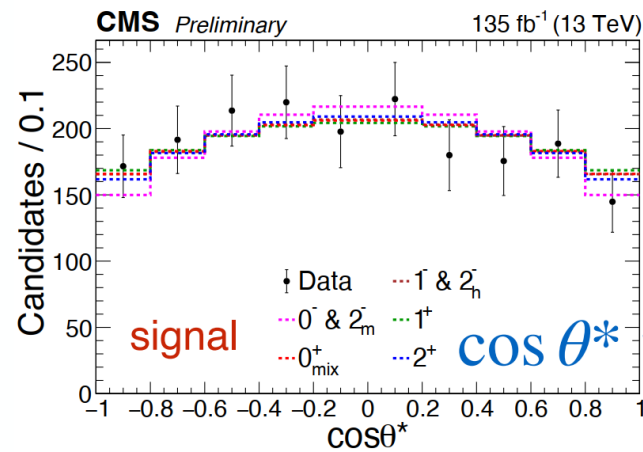
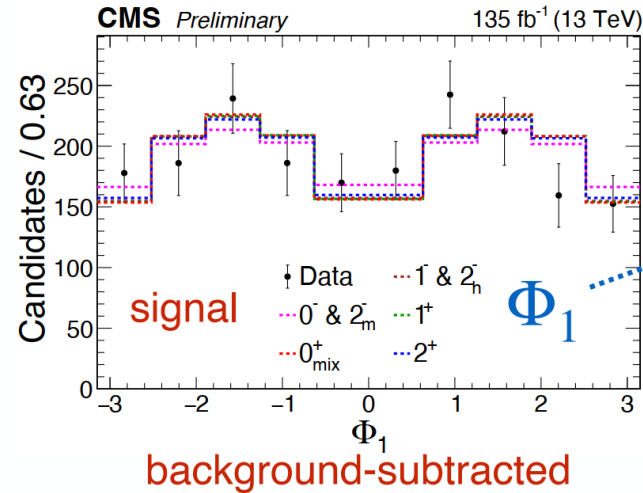


Production angles

Nature 648 (2025) 58

(4) production angles consistent with **unpolarized** resonances

with respect to the **beam axis**



acceptance effects
⇒ distributions not flat

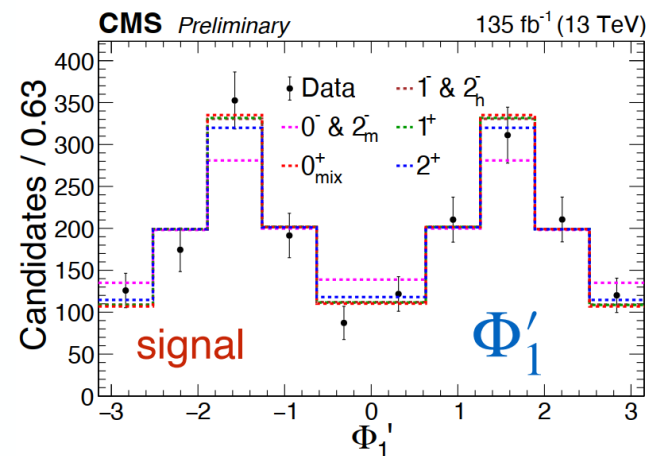
Production angles

Nature 648 (2025) 58

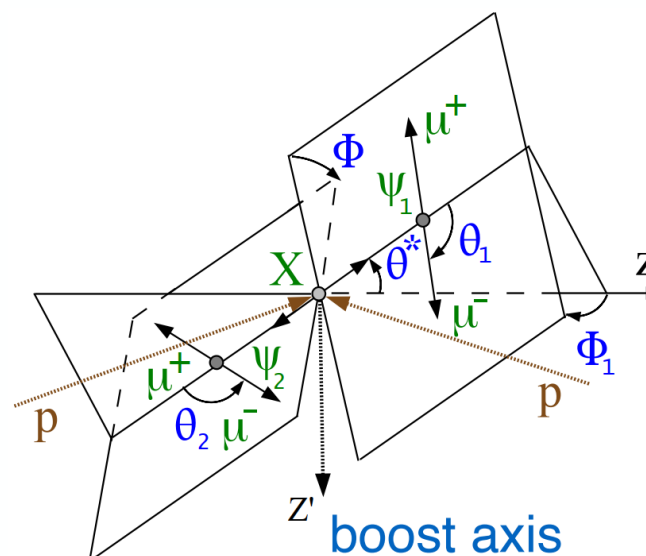
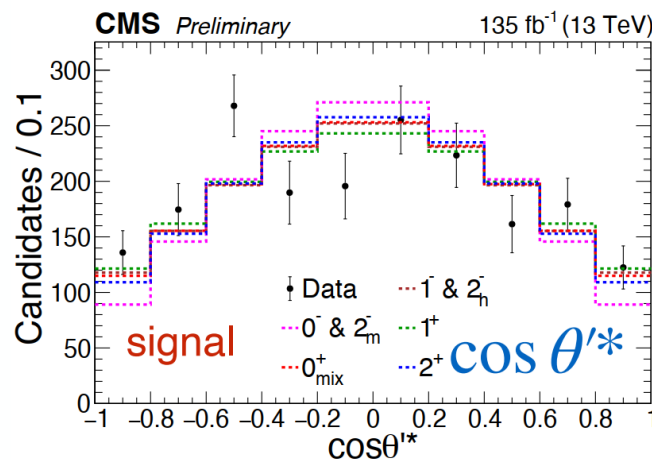
(4) production angles consistent with **unpolarized** resonances

with respect to the **boost axis**

does not prove **unpolarized**



background-subtracted



Lorentz invariant amplitude

Nature 648 (2025) 58

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

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

recall (22 years):
 $B \rightarrow \varphi K^*$ expect A_{00}
 found ~50% A_{++}
 Higgs (12 years):
 $H \rightarrow 4\ell \Rightarrow 0_m^+$

0_m^+

0_h^+

0^-

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

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

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

[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

Nature 648 (2025) 58

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

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

2_m^- (A₊₊ = -A₋₋) 2_h^- (A₊₀ = A₀₊ = -A₋₀ = -A₀₋)

arXiv:1001.3396

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 $J \geq 2$)

21% 9% 47% 23%

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 $J \geq 2$)

Results of J^P vs. 2_m^+

Nature 648 (2025) 58

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

$P = -1$

		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
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

– $J \neq 1$ at $> 99\%$ CL

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

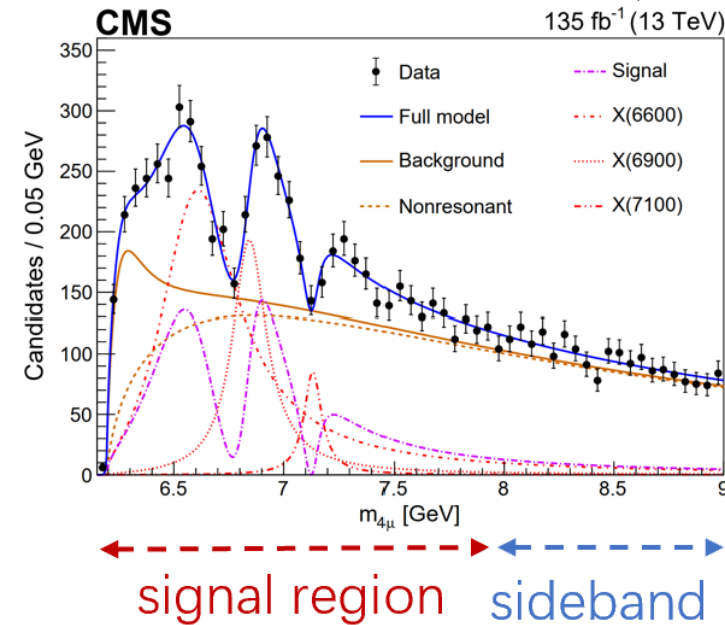
- Recall: 2^{++} can have a mixture of 2_m^+ and look-alike of $0^+, 1^+$

Data analysis

Nature 648 (2025) 58

(1) empirical $m_{4\mu}$ spectrum $\rightarrow$ for **signal** and **background**

- trigger $\mu^+\mu^-\mu^\pm$
 $p_T > 3 \text{ GeV}, p_T > 5 \text{ GeV}$
- reco $(\mu^+\mu^-)(\mu^+\mu^-)$
 $p_T > 2 \text{ GeV}, |\eta| < 2.4$
- mass / vertex - constrained fit



- Background: **data** **MC** **sideband** & **simulation** with **Pythia**
 - $J/\psi J/\psi$ single- and double-parton scattering
 - empirical threshold enhancement (signal-like MC)

Variables in the analysis

Nature 648 (2025) 58

(1) $m_{4\mu}$ spectrum $X \rightarrow 4\mu$ — [arXiv:2306.07164](https://arxiv.org/abs/2306.07164)

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

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

for $J = 0$ exact

for $J = 1, 2, \dots$ 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

All steps till here
prepared blinded

