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

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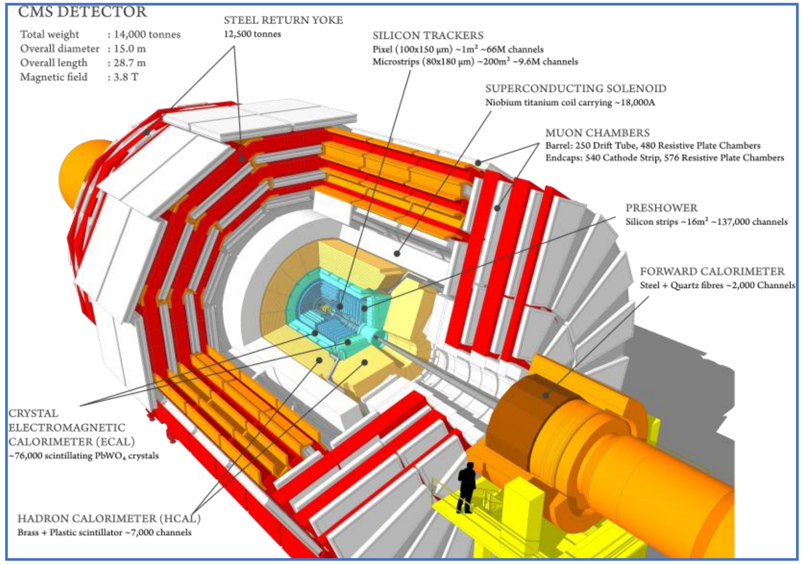
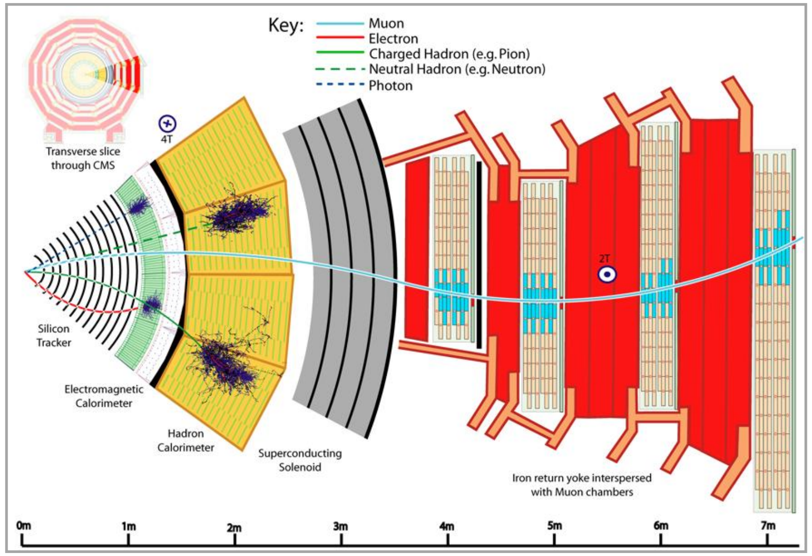
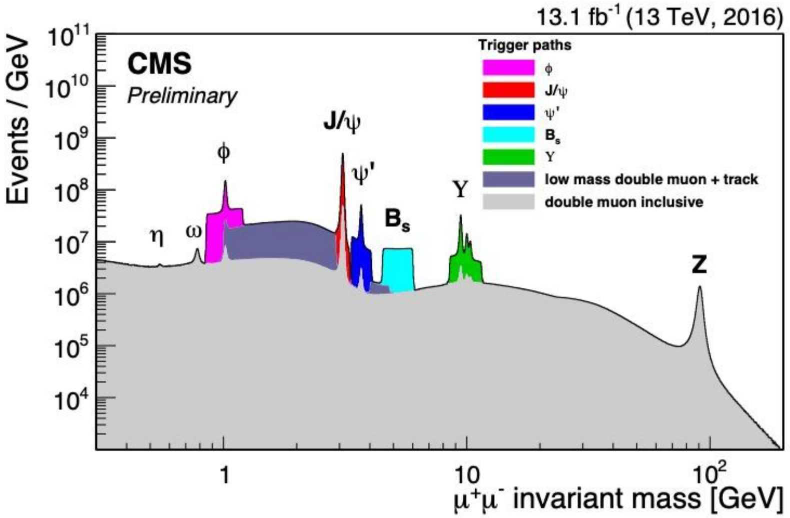
CMS detector



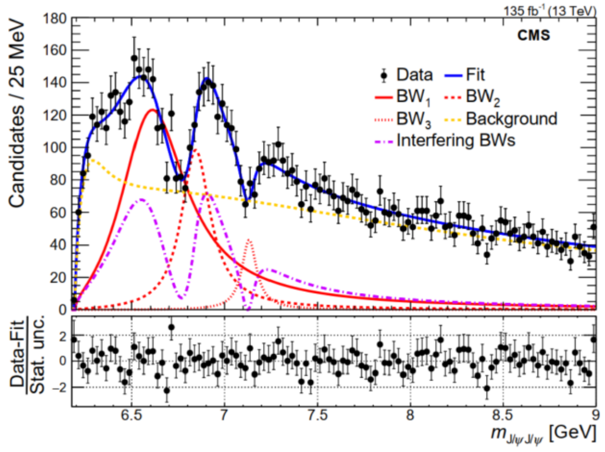




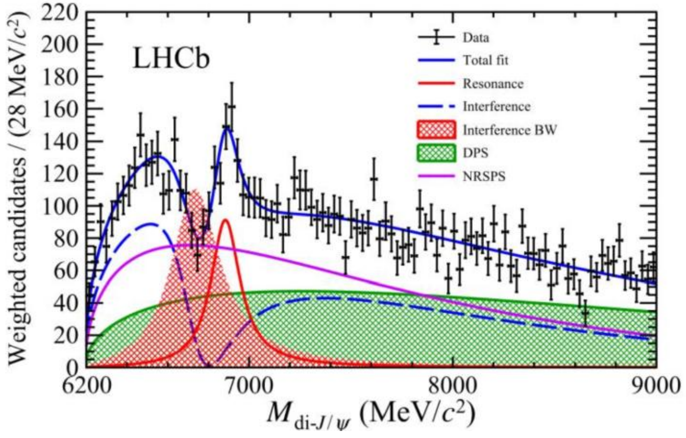
- ➢ Excellent detector for (exotic) quarkonium
- Good muon system
  - High-purity muon ID, $\frac{\Delta m}{m} \sim 0.6\%$ for J/ψ
- Silicon tracking detector
  - B = 3.8 T, $\frac{\Delta p_T}{p_T} \sim 1\%$ & good vertex resolution
- Different triggers for different physics programs/purposes

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)



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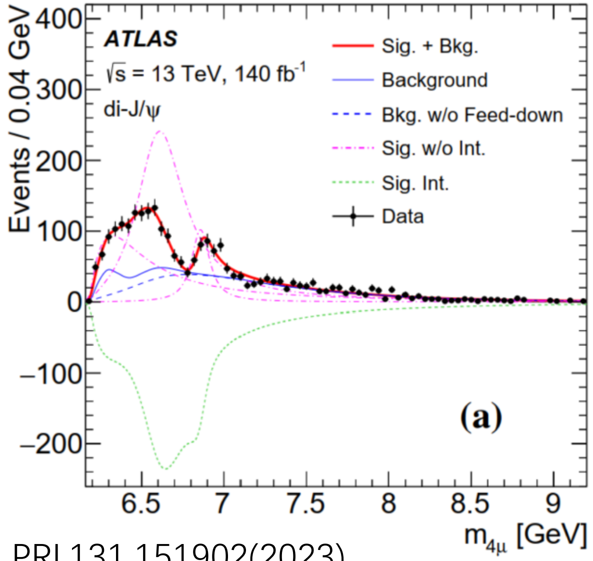
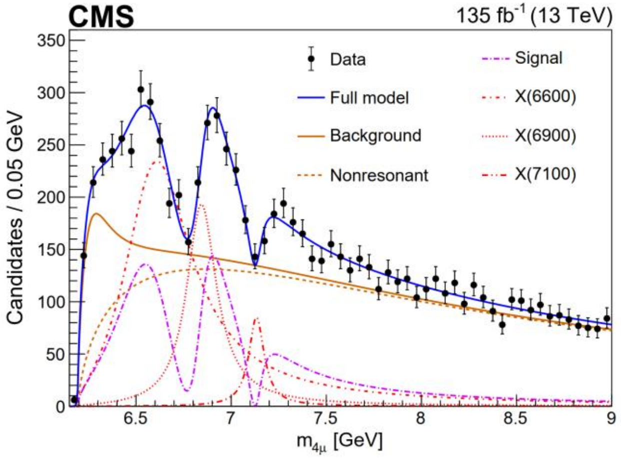


PRL131.151902(2023)

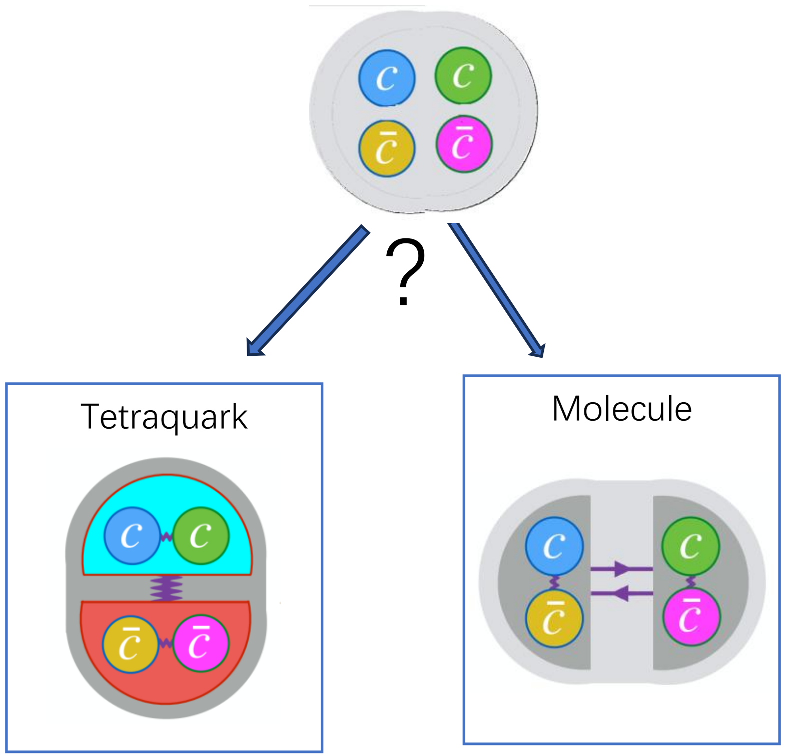
Internal Structure of the tetraquarks

arxiv:2506.07944

- Tetraquark candidates observed in experiments



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

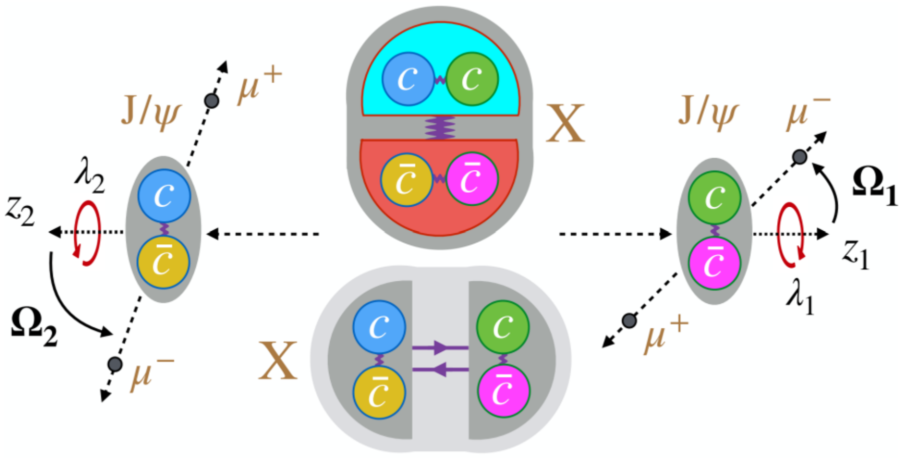


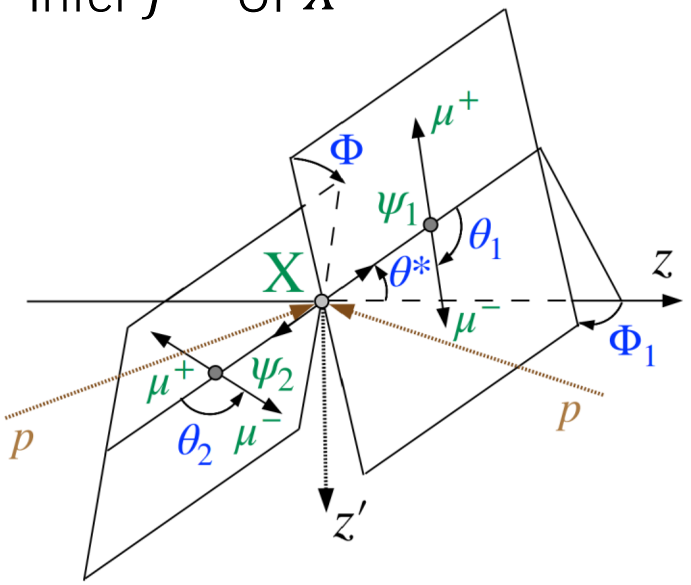
- Don't know internal structure
  - Tetraquark, molecule, ⋯?
- Don't know spin-parity either
  - How to study their spin-parity?

Infer spin-parity of X

arxiv:2506.07944

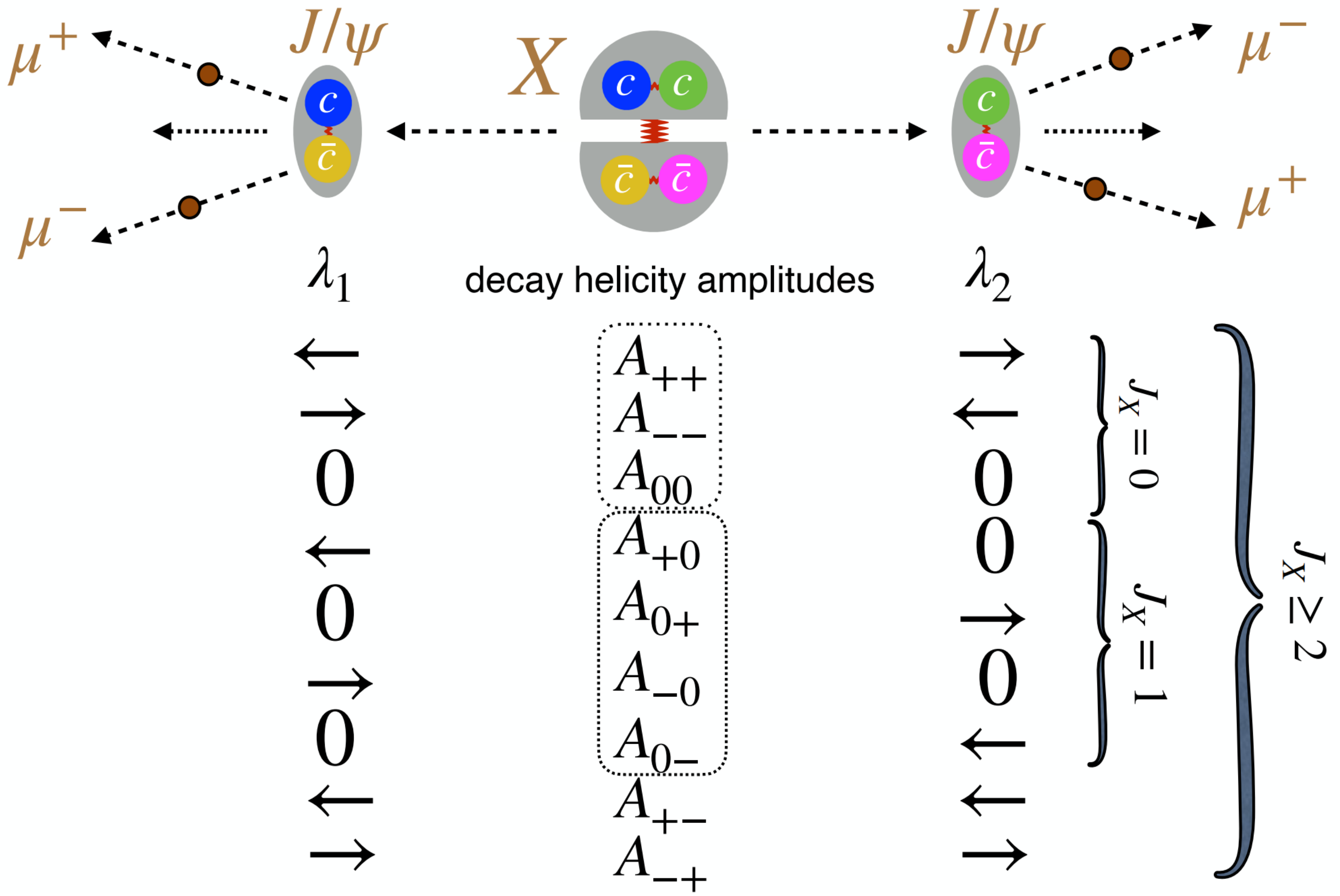
- Infer J^{PC} of X from angular distributions
  - Theory
    - $A(X \to VV)$ depends on J_X^{PC} polarization of J/ψ
    - $A(X \to VV)$ derermines angular distributions
  - Experiment
    - Measure angular distributions of $J/\psi, \mu$ etc.
    - Infer J^{PC} of X





J/ψ polarizations

arxiv:2506.07944



J/ψ polarizations

arxiv:2506.07944

- **Symmetries:**

— angular momentum: $|\lambda_1 - \lambda_2| \le J$

— 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^+ $\quad$ 0_h^+ $\quad$ 0^-

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

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

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

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^- $\quad$ 1^+

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

more for spin-2

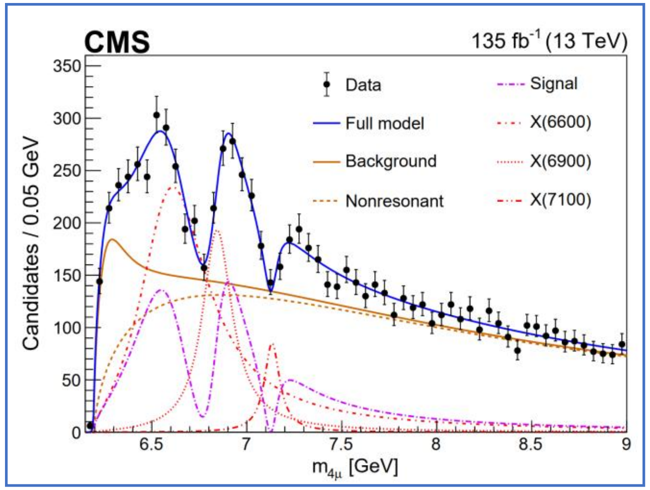
Helicities (0, -) of two J/ψ

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:

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

empirical   angular

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

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

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

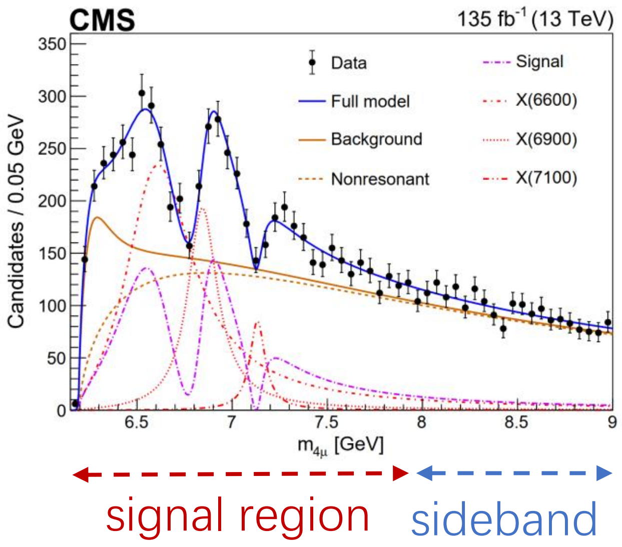
- Final 2D model: $$\mathscr{P}_{ijk}(m_{4\mu}, \mathscr{D}_{ij}) = \mathscr{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathscr{D}_{ij} \,|\, m_{4\mu})$$

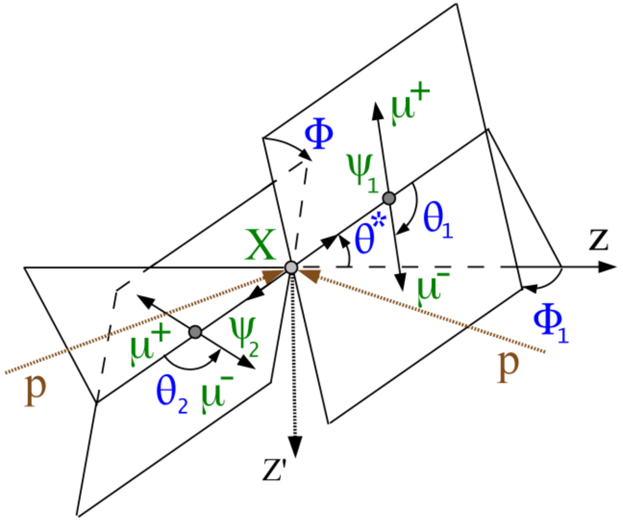
Analysis of data

[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

Decay angles

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

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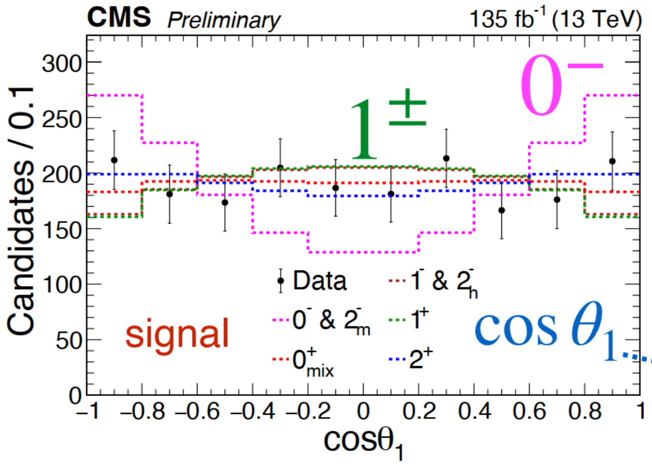

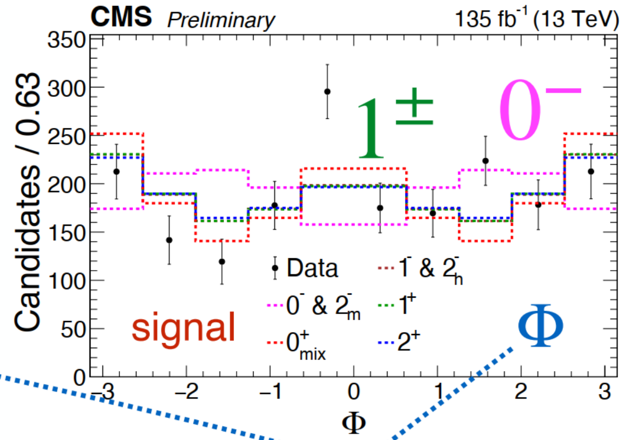

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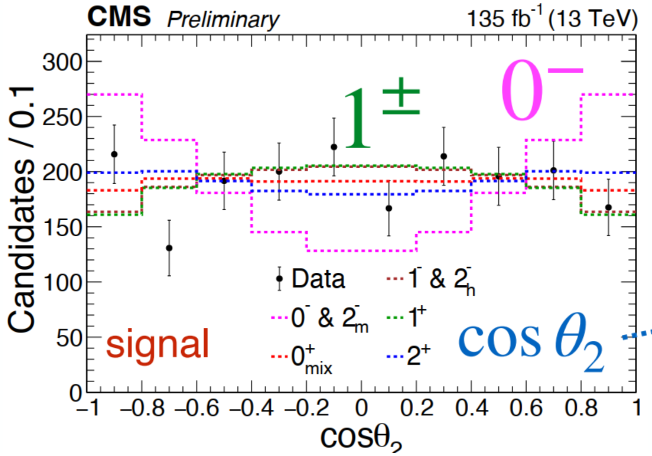
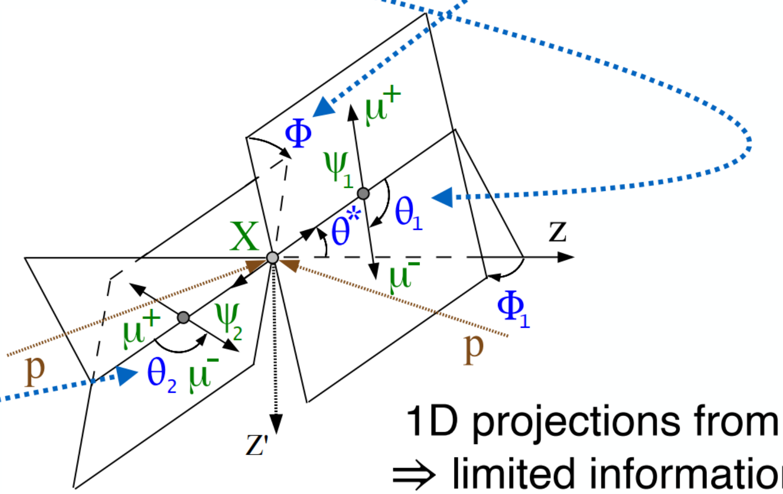


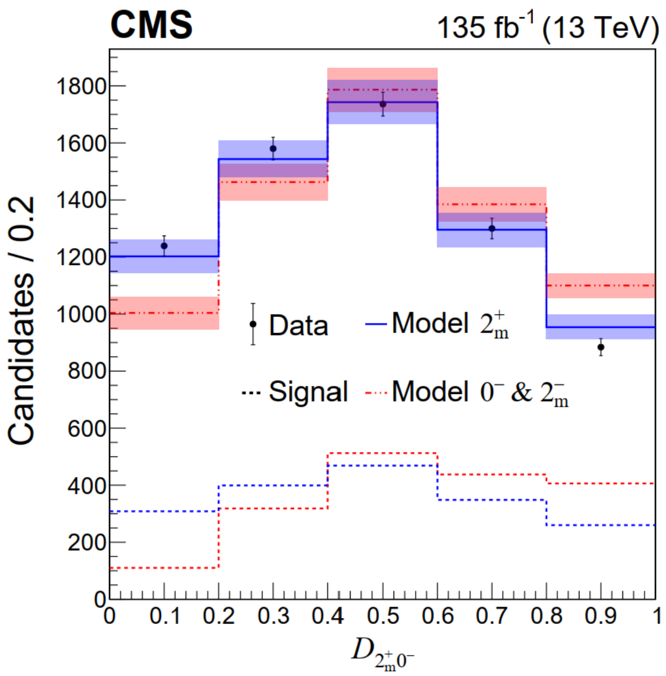


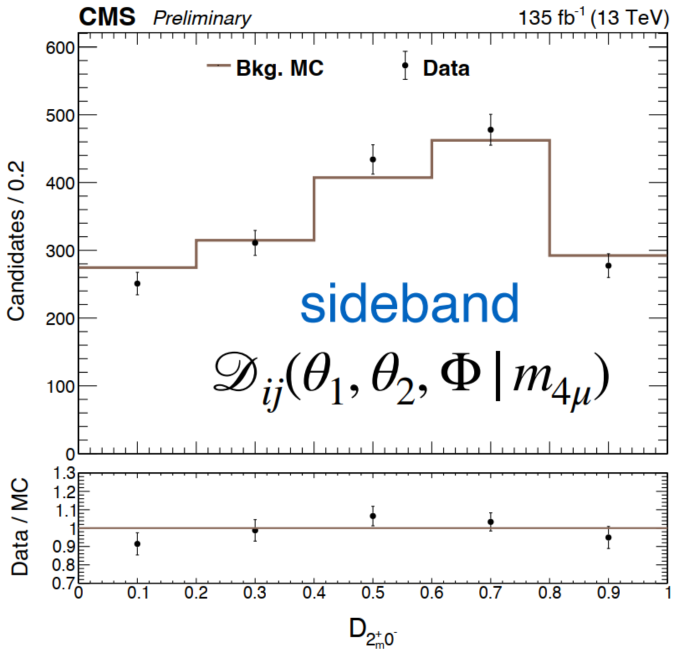
1D projections from 4D
⇒ limited information

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
⇒ limited information

background model from MC
control in sidebands
systematic variations

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

arxiv:2506.07944

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

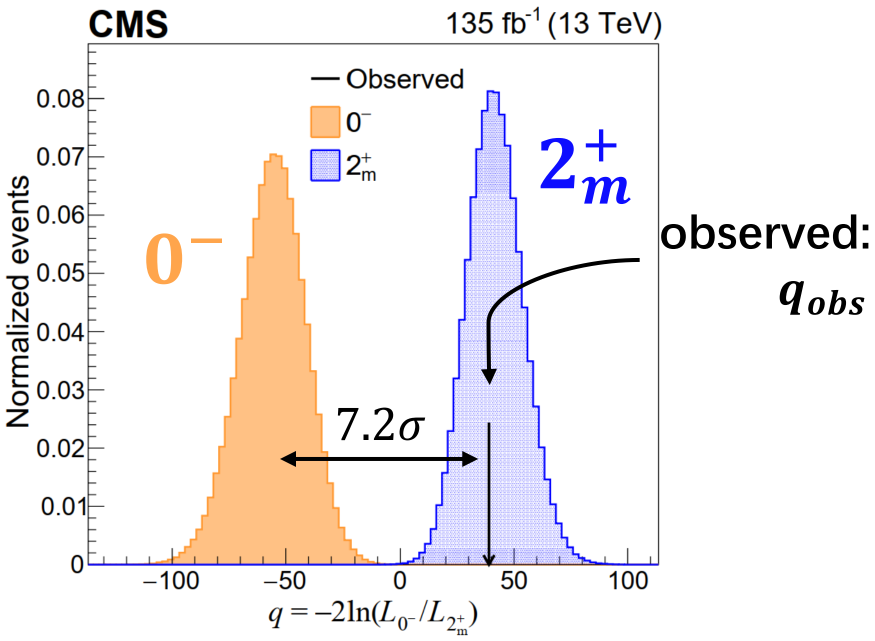
		Observed		Expected	
		p-value	Z-score	p-value	Z-score
0^- vs 2_m^+	0^-	2.7×10^{-13}	7.2	6.5×10^{-14}	7.4
	2_m^+	0.42	0.2	0.5	0

- 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:

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

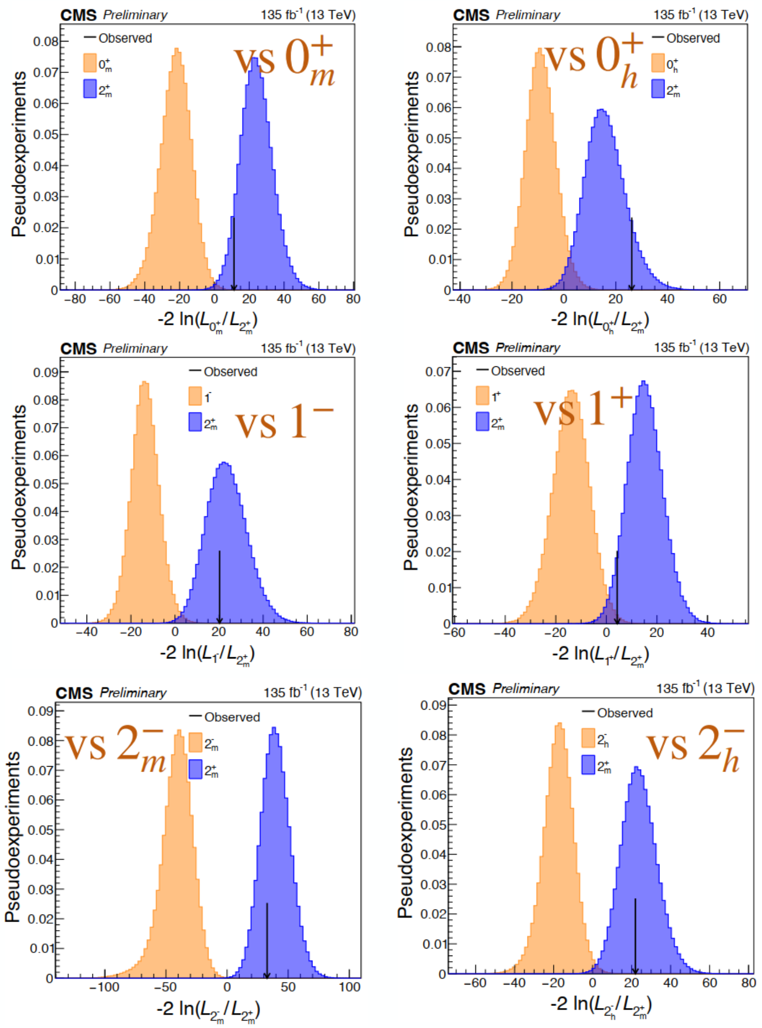


Hypothesis test of J_i^P vs. J_j^P

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	mix
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	mix
2^-_h	2.2×10^{-8}	5.5	



Summary of results

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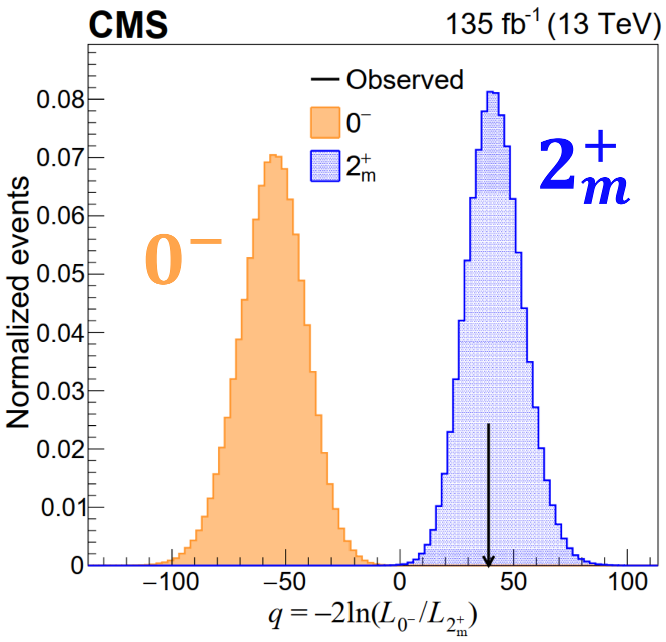
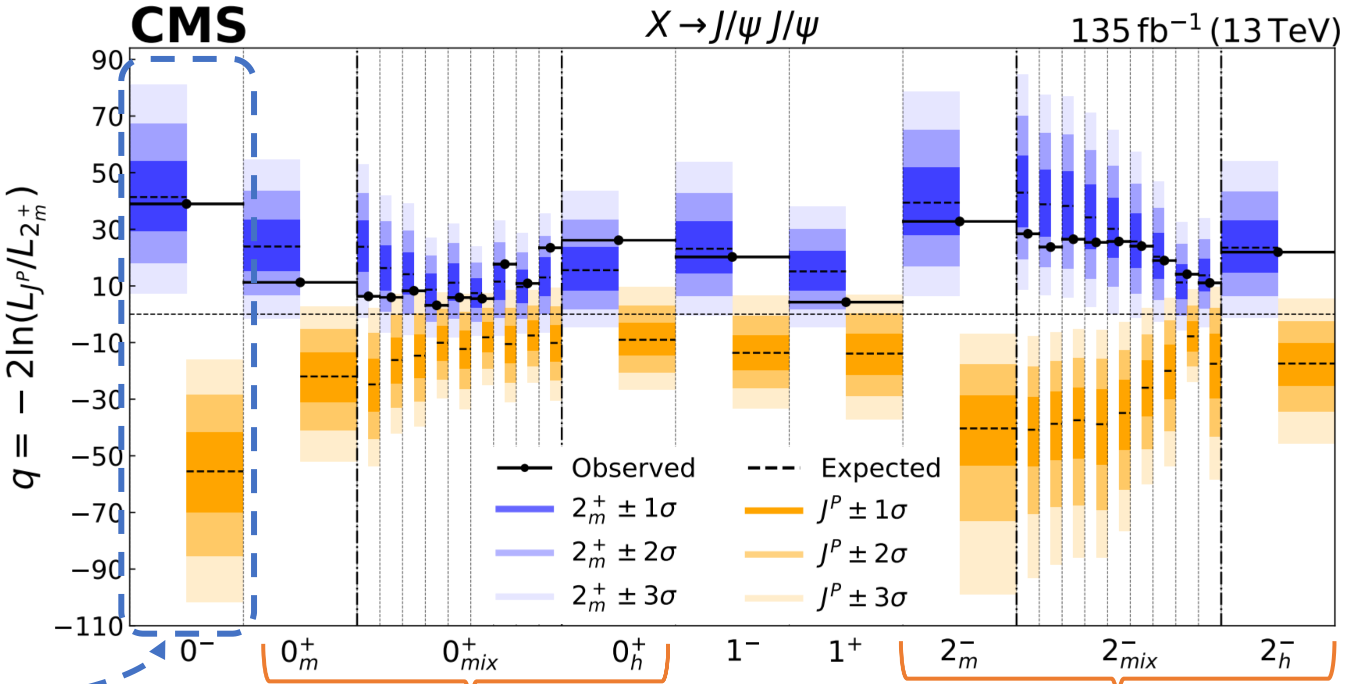




Scan of two 2^{-+} (11 steps)

--No interference (different spin projections)

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

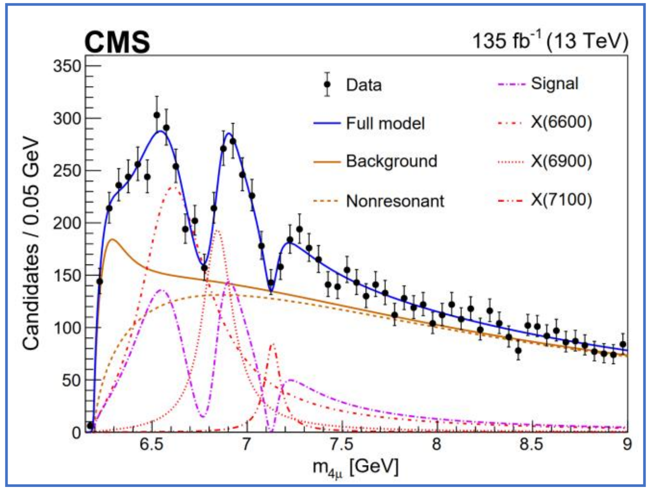
-- Constructive interf. most conservative

- 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 $J = 0$

Summary

- 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 $L \geq 2$
  - $\boldsymbol{J = 2}$ **consistent**, rare in nature,
    naively expected J = 0

arxiv:2506.07944



Thanks!

Backup

Production: p_T and p_z of X

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

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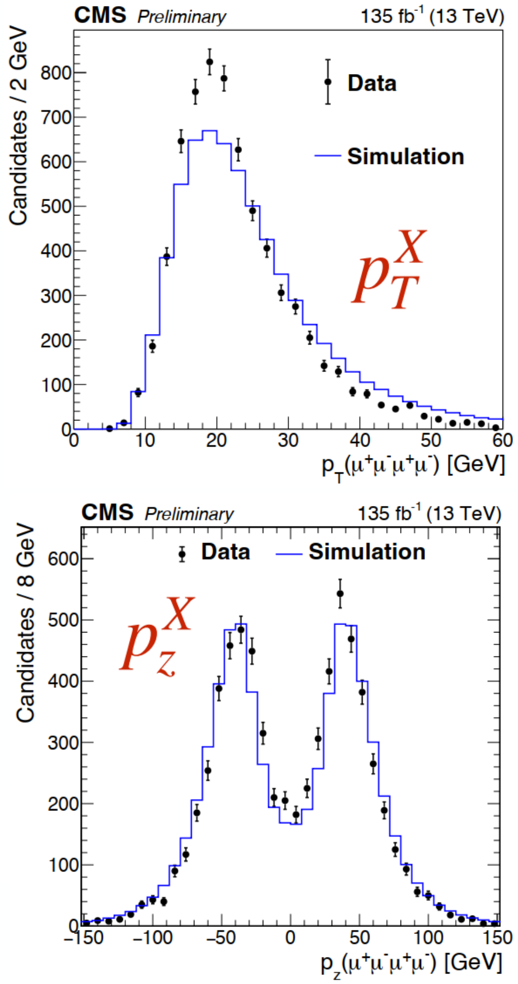


— tune **Pythia** to match p_T^X in sideband and signal region

— fine-tune re-weighting p_T^X

— residual p_T^X and p_z^X

consistency tests

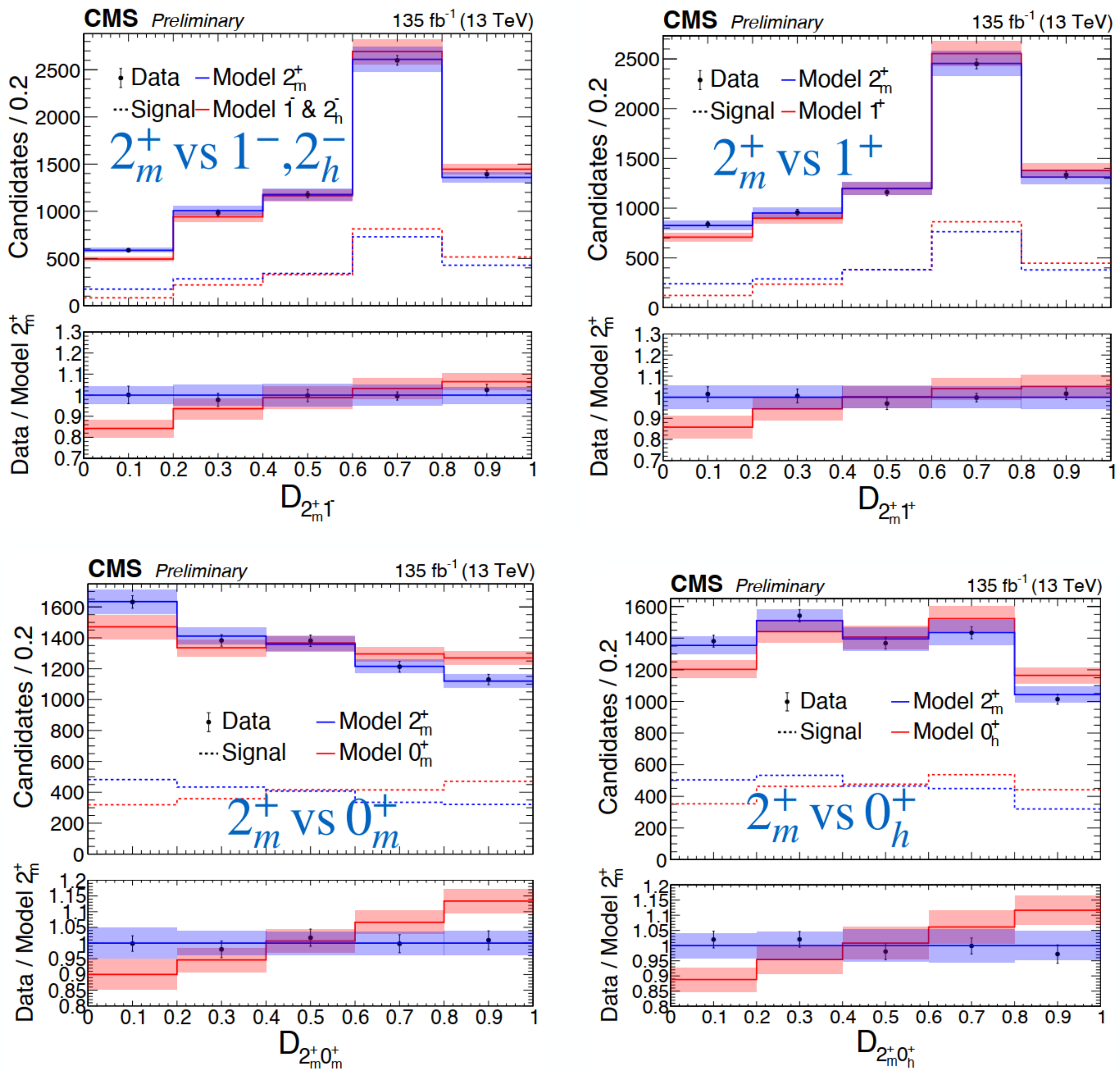
coverage in systematics

— essential to model detector acceptance

Simulation:
JHUGen + Pythia

Discriminant

arxiv:2506.07944

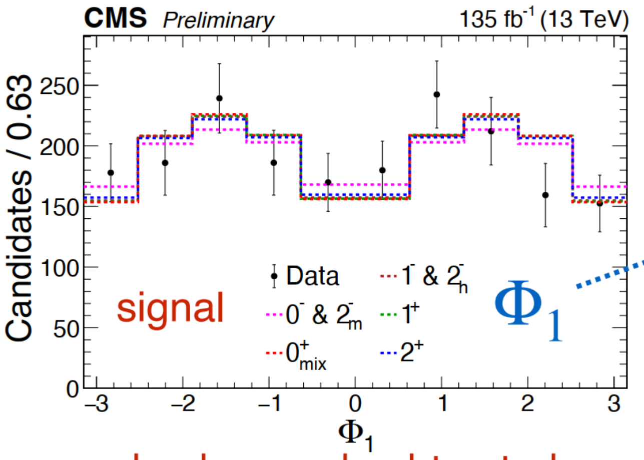


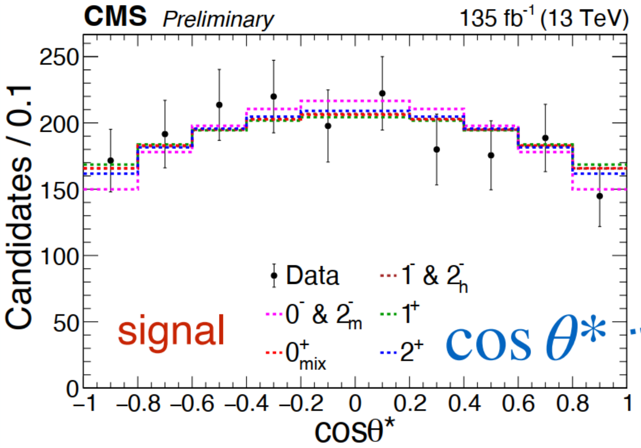
Production angles

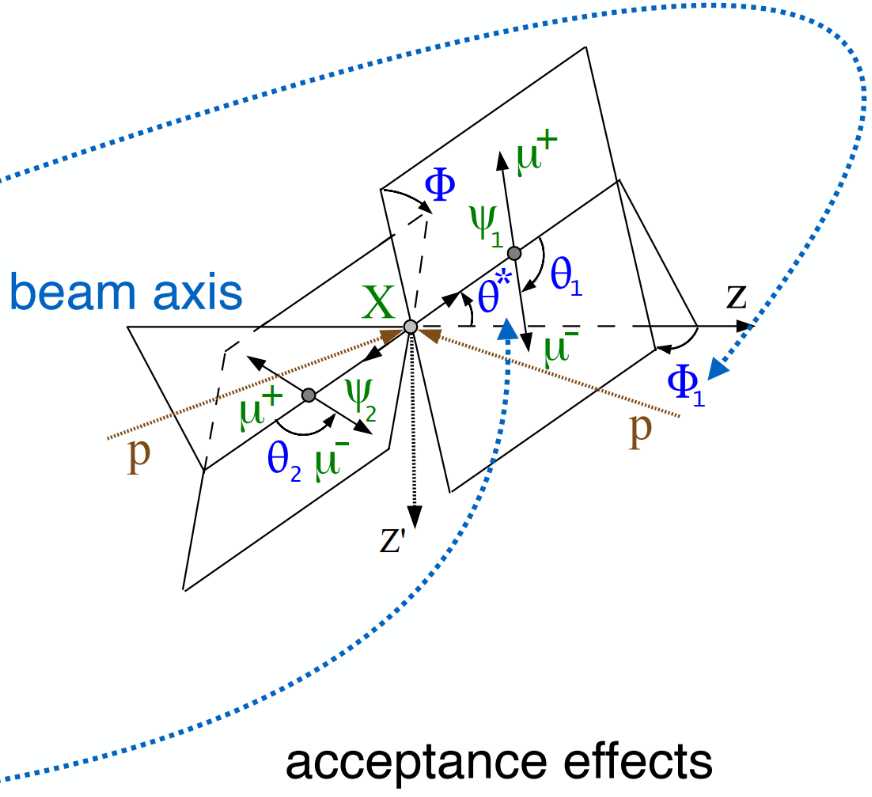
arxiv:2506.07944

(4) production angles consistent with unpolarized resonances

with respect to the beam axis







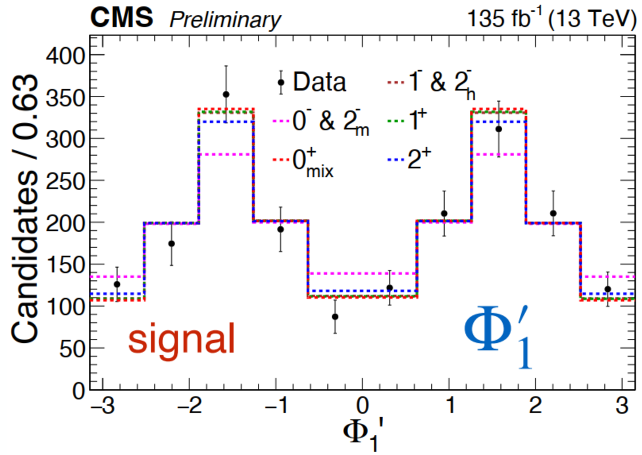
background-subtracted

acceptance effects
⇒ distributions not flat

Production angles

arxiv:2506.07944

(4) production angles consistent with unpolarized resonances



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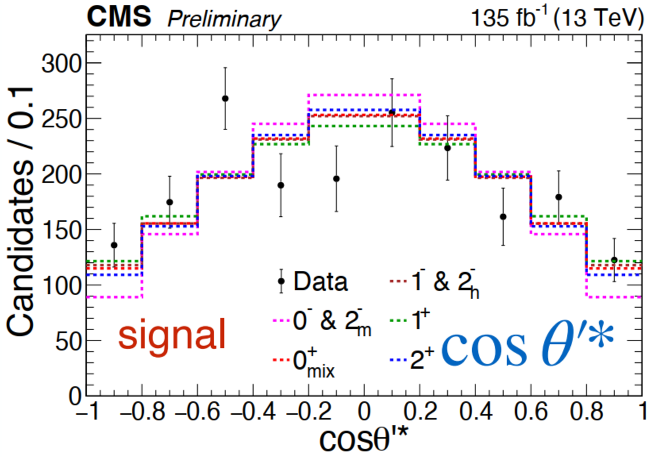
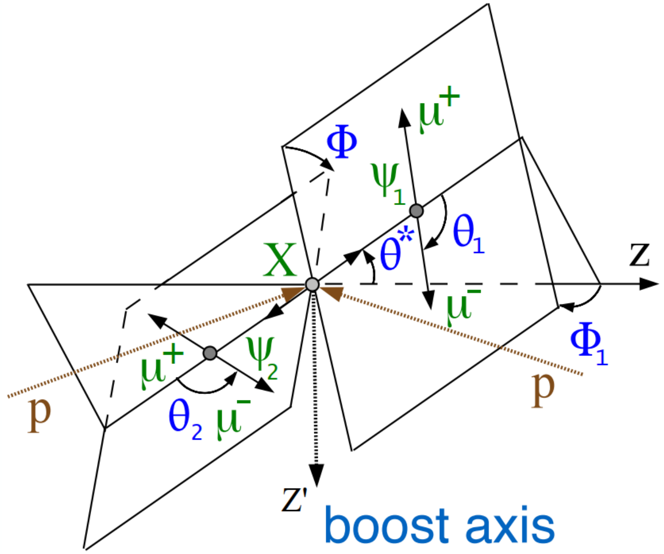


with respect to the boost axis

does not prove unpolarized



Lorentz invariant amplitude

arxiv:2506.07944

- 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 $\quad A_{++} = A_{--}$

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

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 $(m_{4\mu}^2)$

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

1^- $\quad$ 1^+

more for spin-2

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

Lorentz invariant amplitude

arxiv:2506.07944

- 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. $A_{00}, A_{++} = A_{--}; A_{+0} = A_{0+} = A_{-0} = A_{0-}; A_{+-} = A_{-+}$

21% 9% 47% 23%

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 $J \geq 2$)

Results of J^P $vs.$ 2_m^+

arxiv:2506.07944

- 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
$0_{\rm mix}^+$ vs 2_m^+	$0_{\rm mix}^+$	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
$2_{\rm mix}^-$ vs 2_m^+	$2_{\rm mix}^-$	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

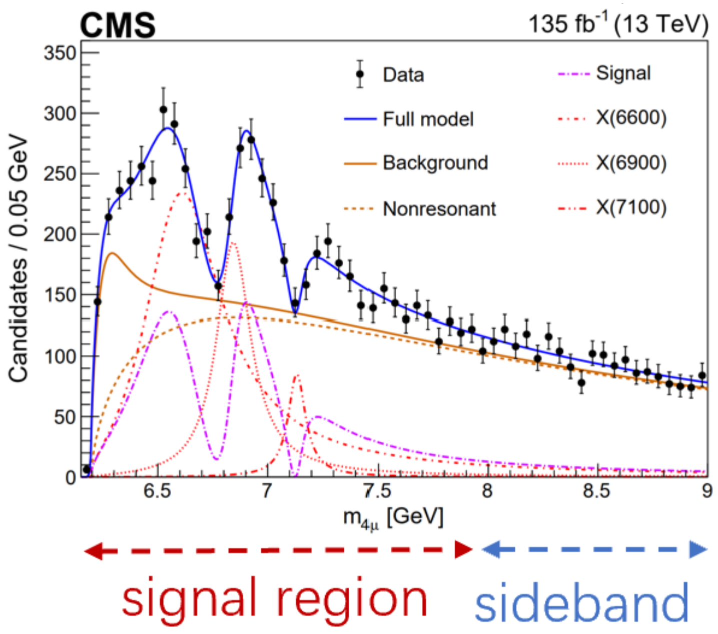
arxiv:2506.07944

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

— trigger $\mu^+\mu^-\mu^\pm$
$p_T > 3\,\mathrm{GeV},\, p_T > 5\,\mathrm{GeV}$

— reco $(\mu^+\mu^-)(\mu^+\mu^-)$
$p_T > 2\,\mathrm{GeV},\ |\eta| < 2.4$

— mass / vertex - constrained fit



- Background: sideband (data) & simulation (MC) with **Pythia**

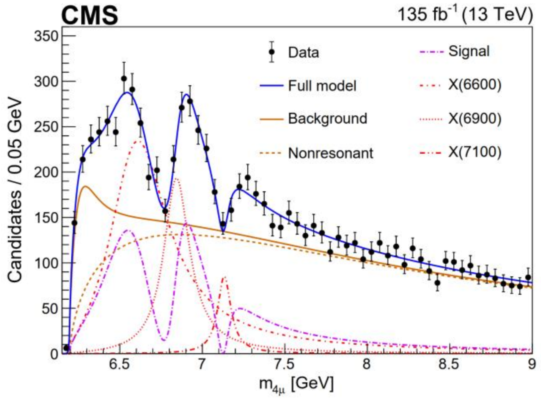
  — $J/\psi J/\psi$ single- and double-parton scattering

  — empirical threshold enhancement (signal-like MC)

Variables in the analysis

arxiv:2506.07944

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



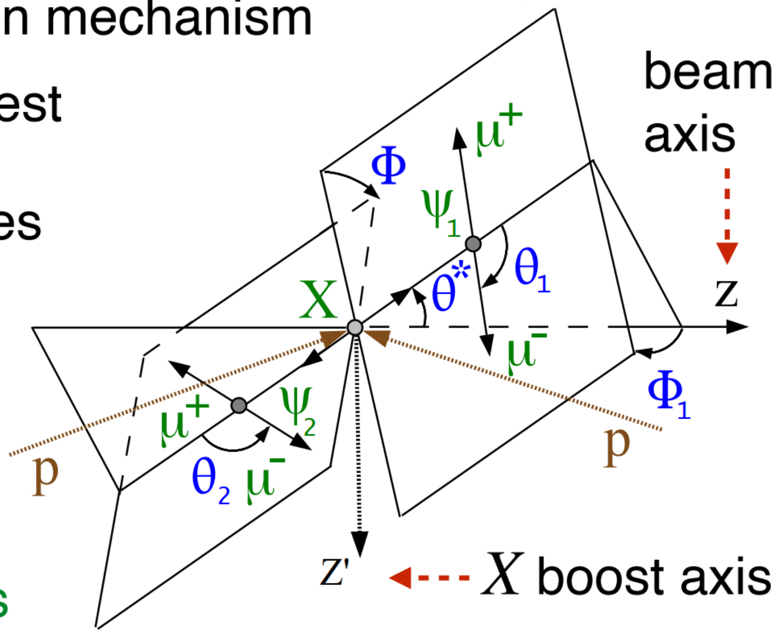
(2) p_T and p_Z of $X \to 4\mu$ — match to data

(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

All steps till here prepared blinded