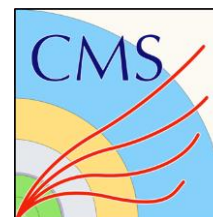


All-charm tetraquark candidates at CMS

张敬庆

南京师范大学



第十届手征有效场论研讨会
南京 2025.10.17-2025.10.21

Outline

- Introduction
- Spin-parity of all-charm tetraquarks
- $X(6900)$ and $X(7100)$ in $J/\psi\psi(2S)$
- All-charm tetraquarks using CMS run 2 + run 3 data
- Summary

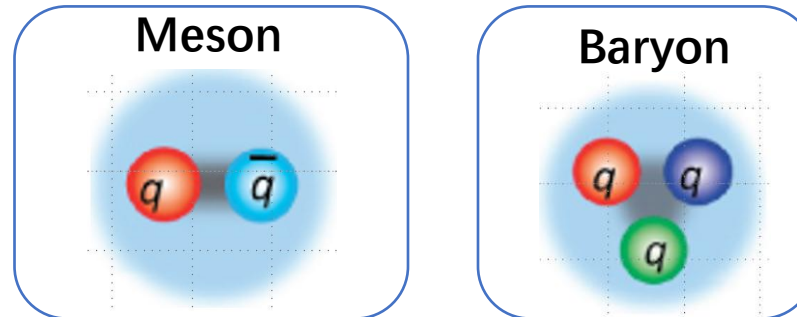
[arXiv:2506.07944](https://arxiv.org/abs/2506.07944)

[CMS-PAS-BPH-22-004](#)

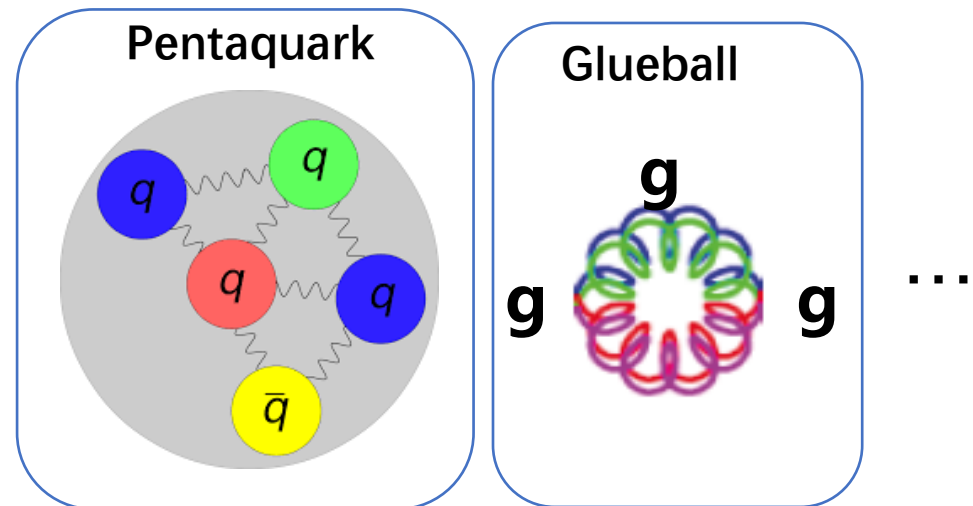
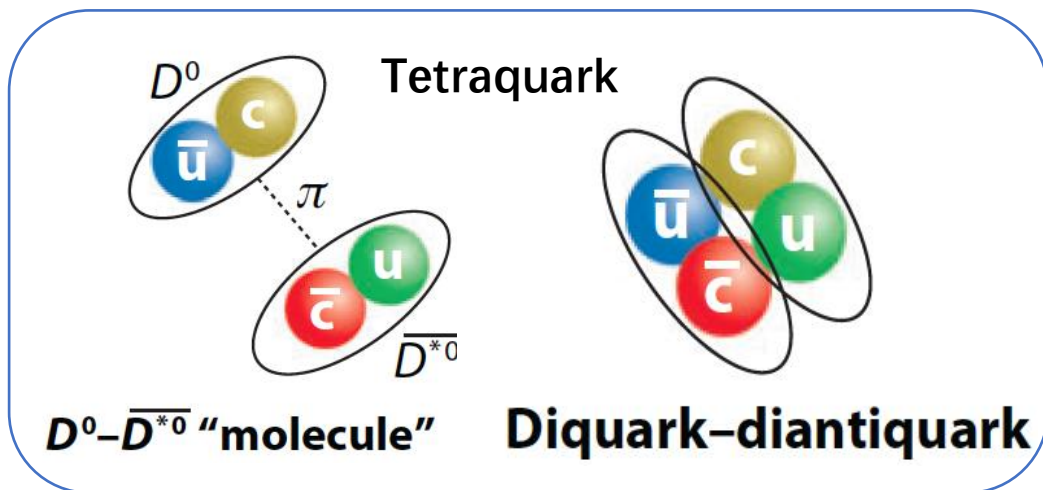
[CMS-PAS-BPH-24-003](#)

Exotic hadrons

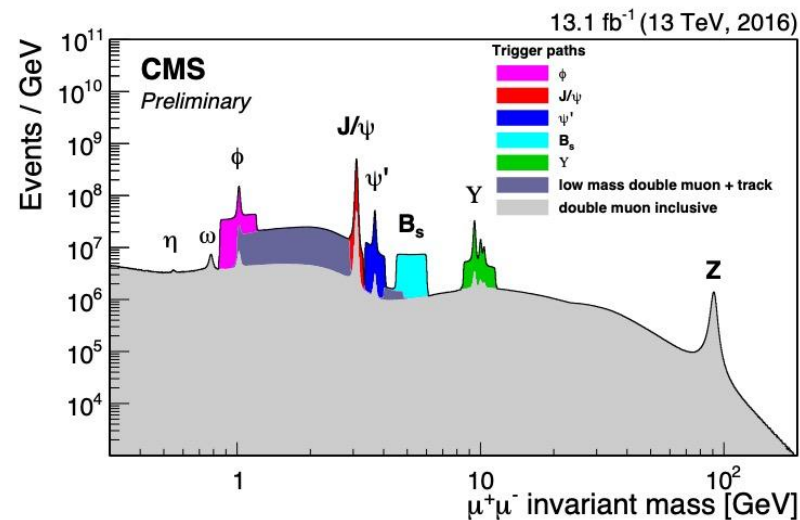
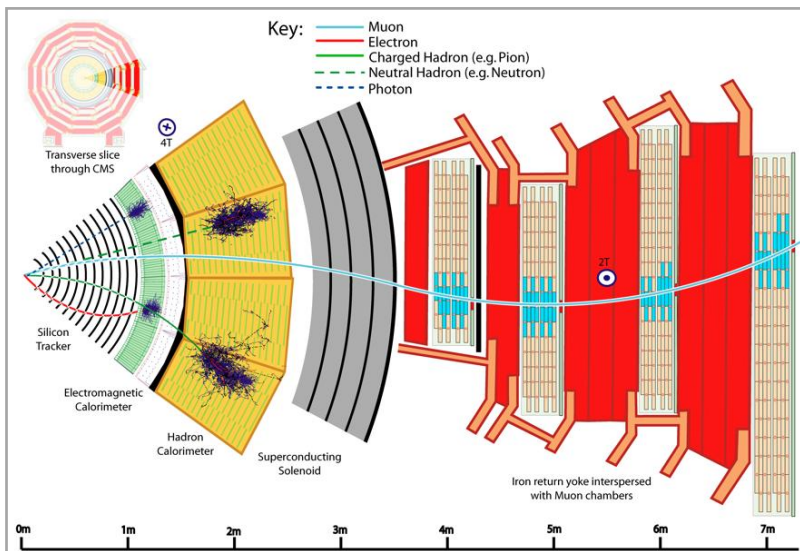
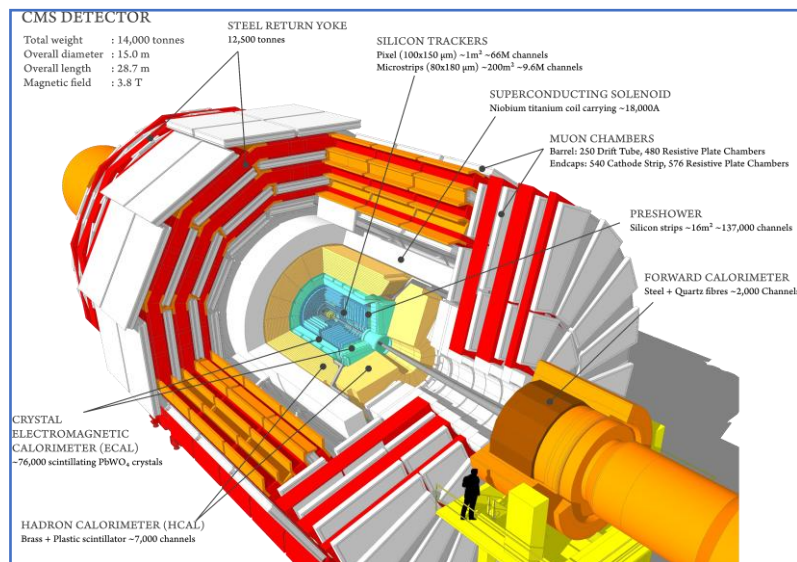
Conventional hadrons in quark model



Exotic hadrons in QCD



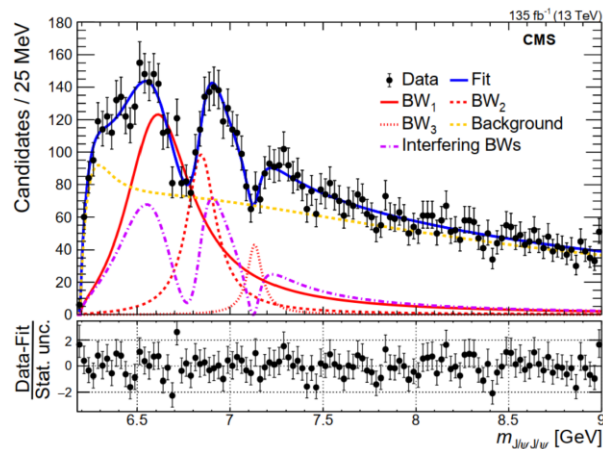
CMS detector



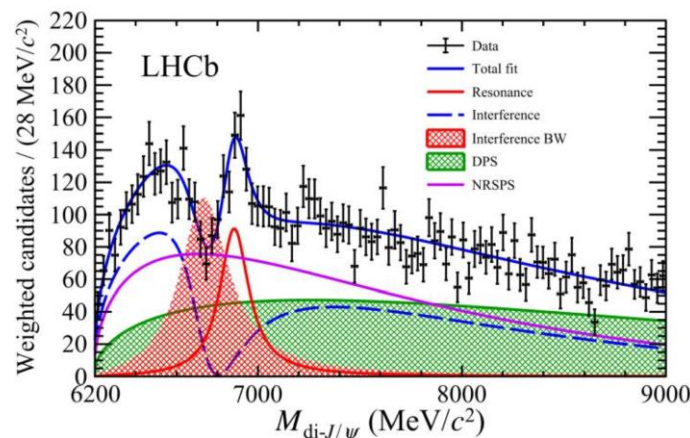
- Excellent detector for (exotic) quarkonium
- Good muon system
 - High-purity muon ID, $\frac{\Delta m}{m} \sim 0.6\%$ for J/ψ
- Silicon tracking detector
 - $B = 3.8\text{ T}$, $\frac{\Delta p_T}{p_T} \sim 1\%$ & good vertex resolution
- Different triggers for different physics programs/purposes

The tetraquark candidates at LHC

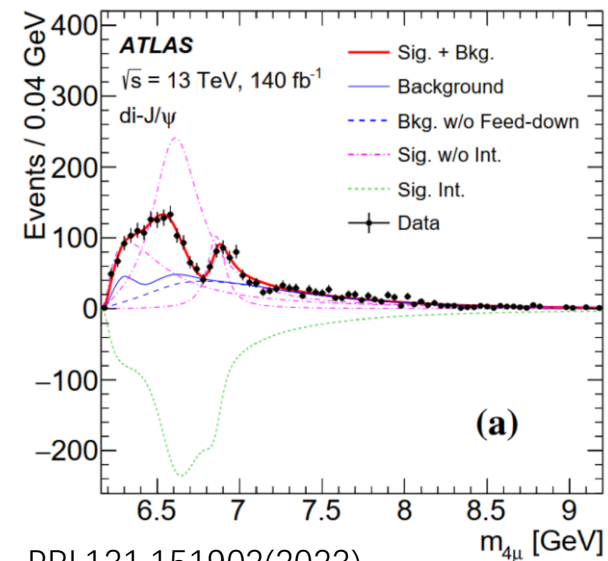
- Structures in $J/\psi J/\psi$ mass spectrum at CMS, LHCb and ATLAS from the LHC run 2 data
- Structures established but need more study to understand them



PRL132.111901(2024)



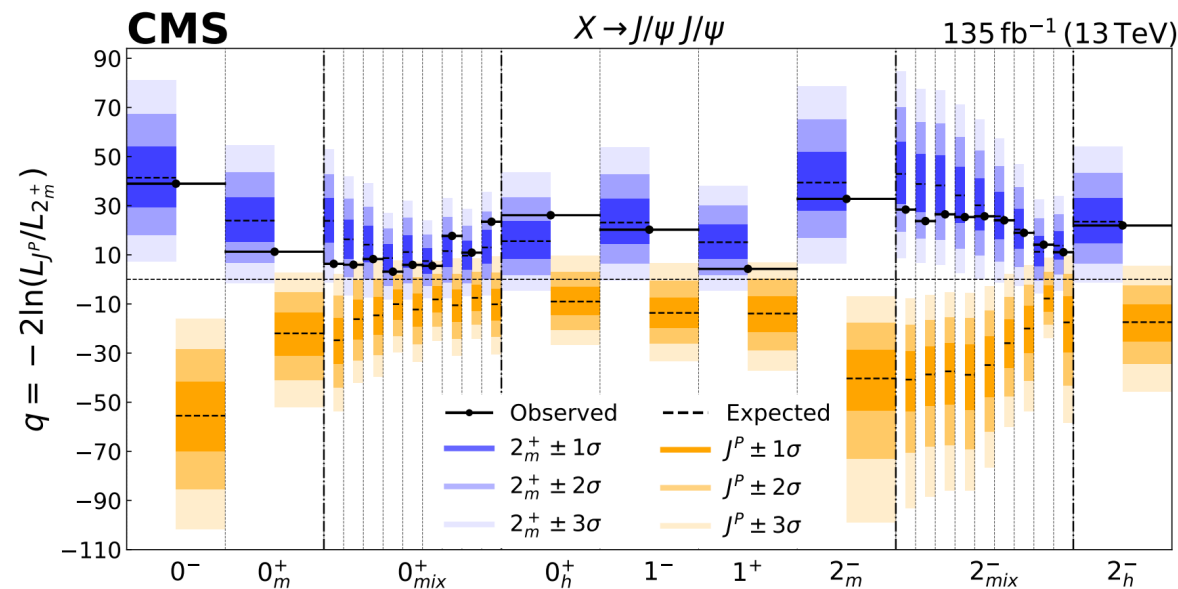
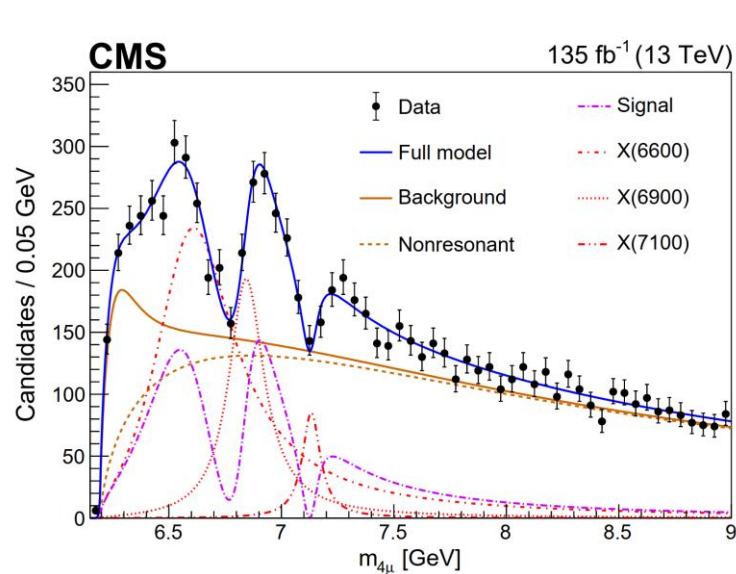
Sci.Bull.65(2020)23,1983-1993



PRL131.151902(2023)

Determination of the spin and parity of all-charm tetraquarks

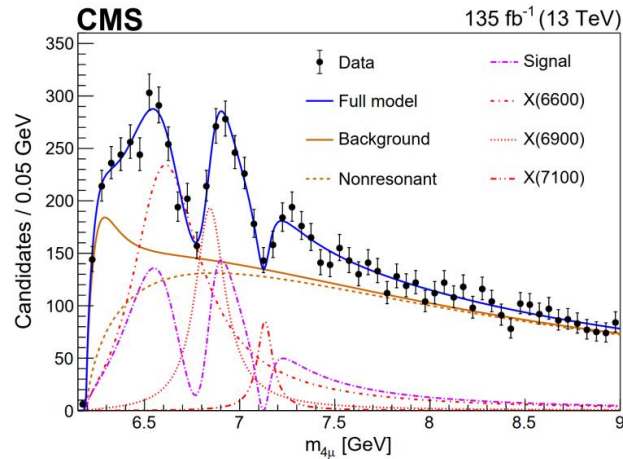
[arXiv:2506.07944](https://arxiv.org/abs/2506.07944)



Internal Structure of the tetraquarks

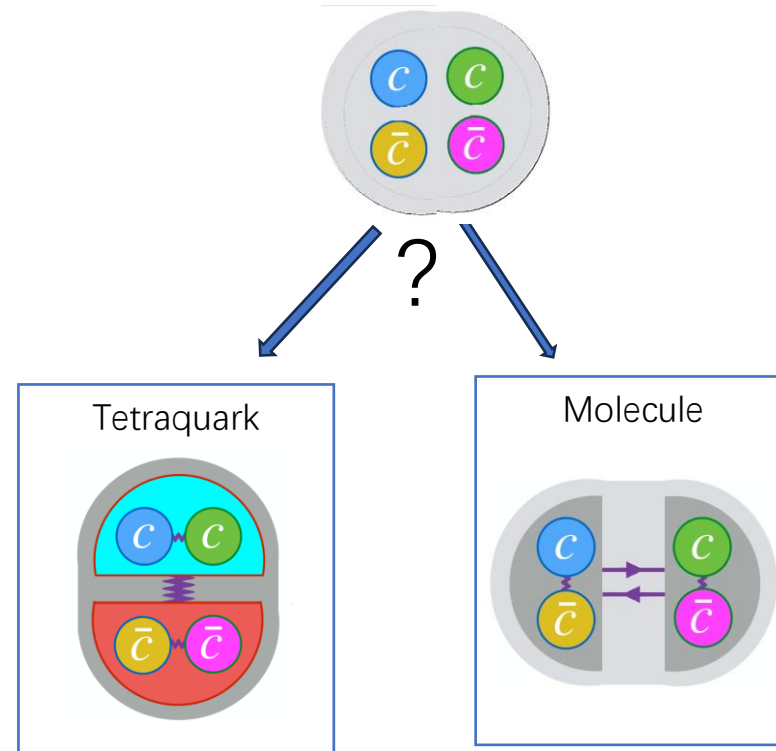
[arxiv:2506.07944](https://arxiv.org/abs/2506.07944)

- 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

[arxiv:2506.07944](https://arxiv.org/abs/2506.07944)

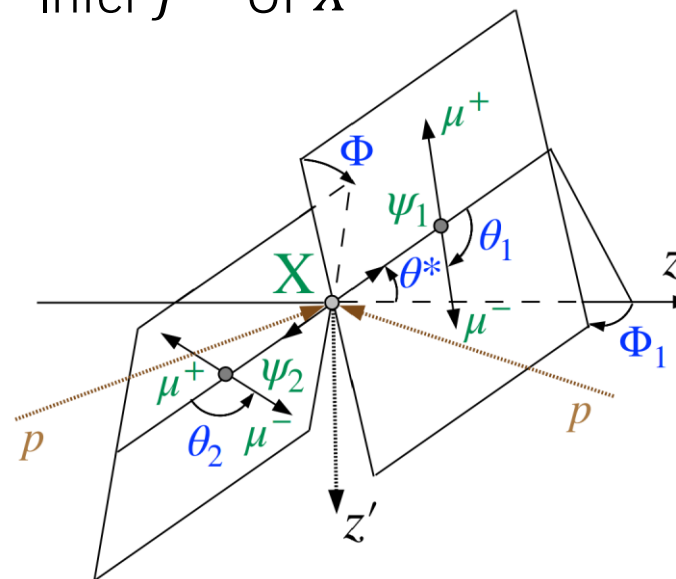
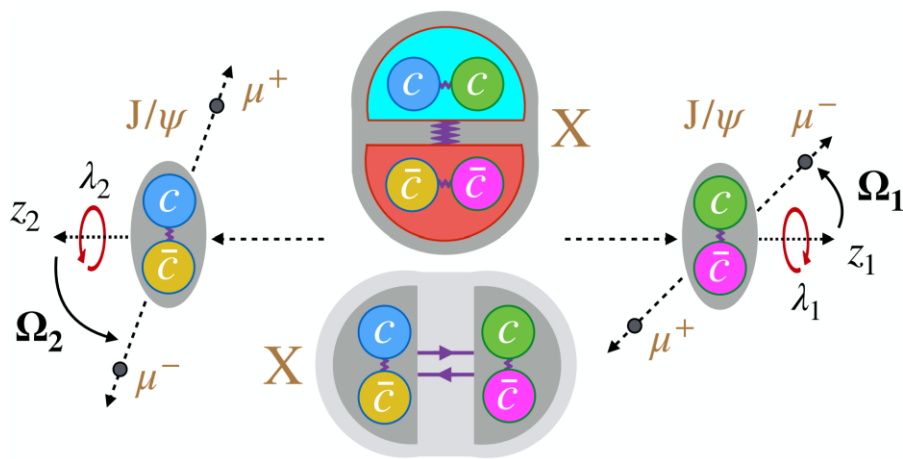
- Infer J^{PC} of X from angular distributions

- Theory

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

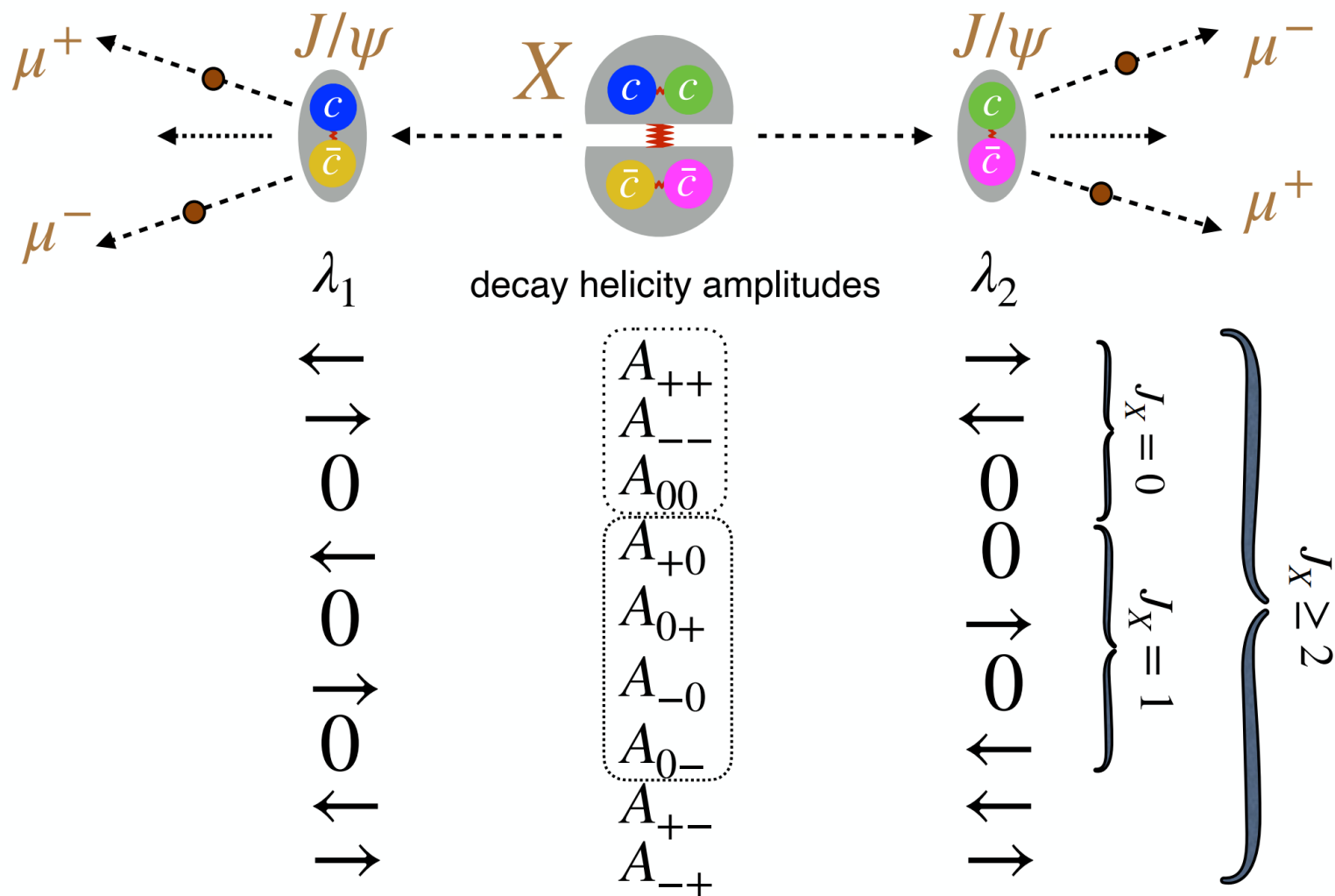
- Experiment

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



J/ψ polarizations

[arxiv:2506.07944](https://arxiv.org/abs/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

- Expect three resonances to have the same tensor structure

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

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

0_m^+ 0_h^+ 0^-

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

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

[arXiv: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^+

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

more for spin-2

Helicities (0, -) of two J/ψ

Simplification in angular analysis

[arxiv:2506.07944](https://arxiv.org/abs/2506.07944)

- 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**:

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

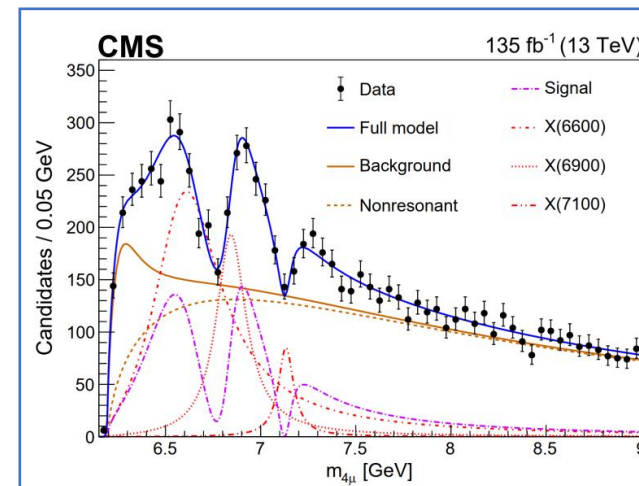
(2) Pairwise tests of J_X^P hypotheses i and j :

[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

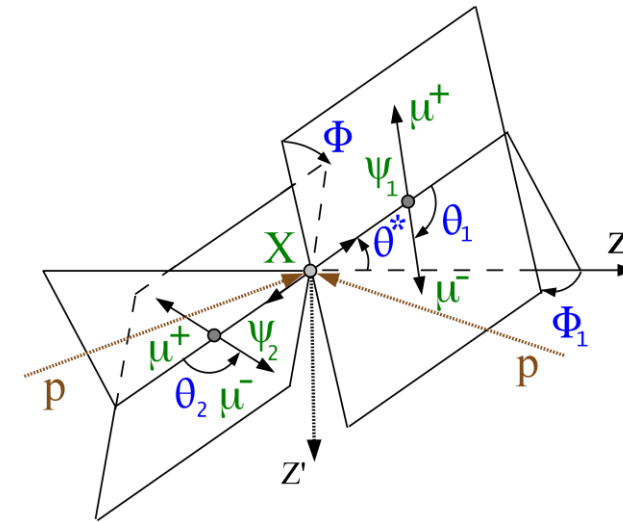
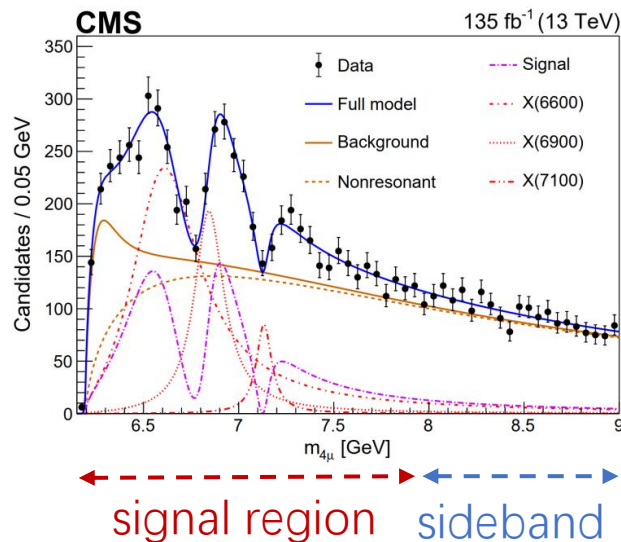
- Final 2D model: $\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})$



Analysis of data

arxiv:2506.07944

- 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 [arxiv:2306.07164](https://arxiv.org/abs/2306.07164)
 - BKG: data sideband & MC simulation with Pythia
 - $m_{4\mu}$ shapes: [arxiv:2306.07164](https://arxiv.org/abs/2306.07164)
 - Decay angles Φ, θ_1, θ_2 to identify $D_{ij}(\Phi, \theta_1, \theta_2; m_{4\mu})$

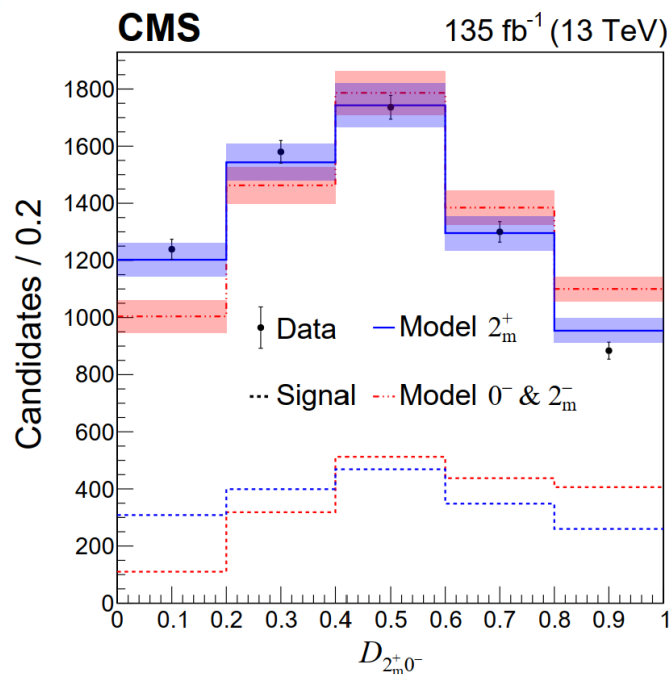


All steps till here prepared blinded

Optimal Observables

[arxiv:2506.07944](https://arxiv.org/abs/2506.07944)

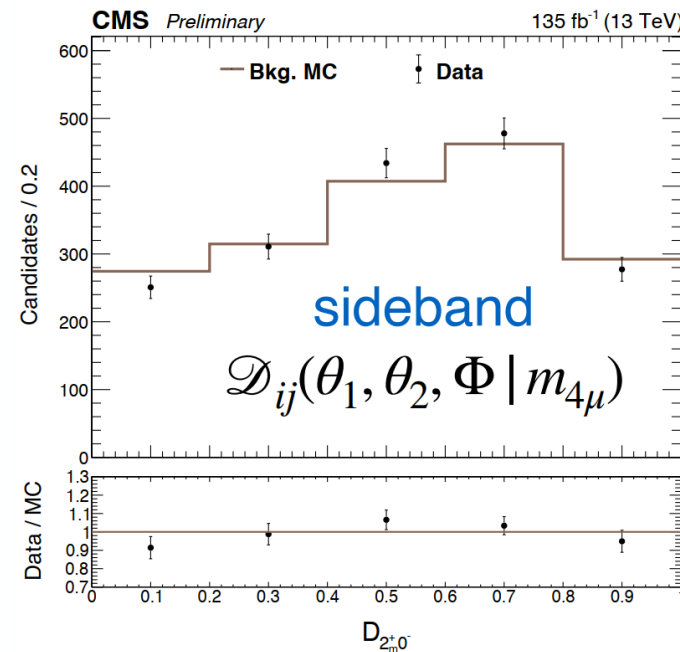
- 1D projection of data, optimal for $j = 0^-(2_m^-)$ vs $i = 2_m^+$



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^+

[arxiv:2506.07944](https://arxiv.org/abs/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:

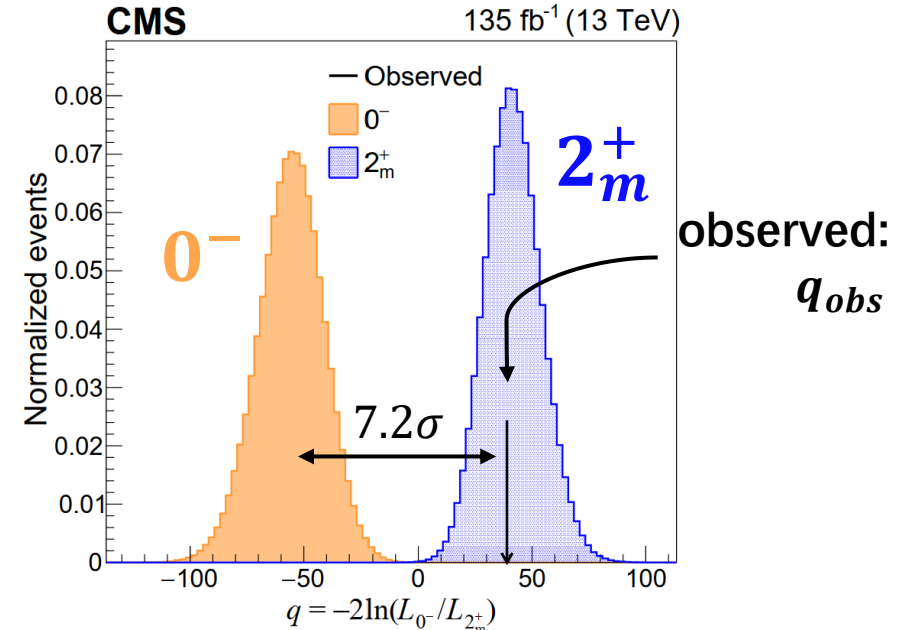
$$\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})$$

- Test statistics:

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

- Confidence level:

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



Hypothesis test of J_i^P vs. J_j^P

arxiv:2506.07944

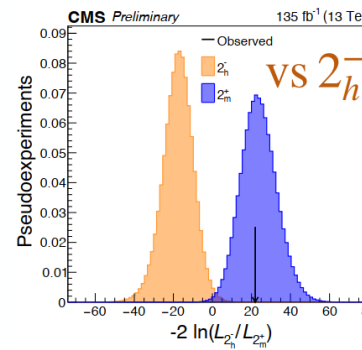
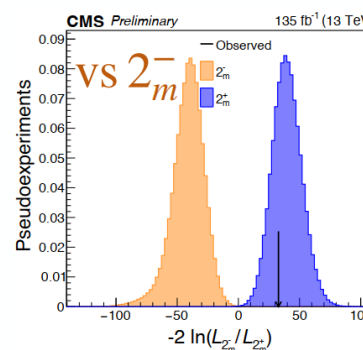
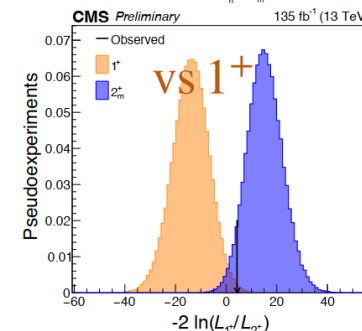
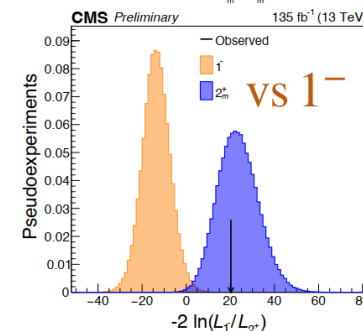
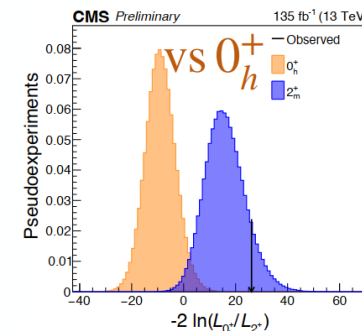
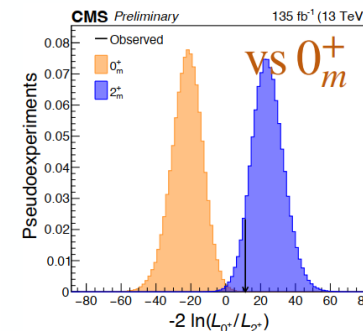
- Combined 2D fit: $\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij})$

➤ $J^P = 2_m^+$ 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

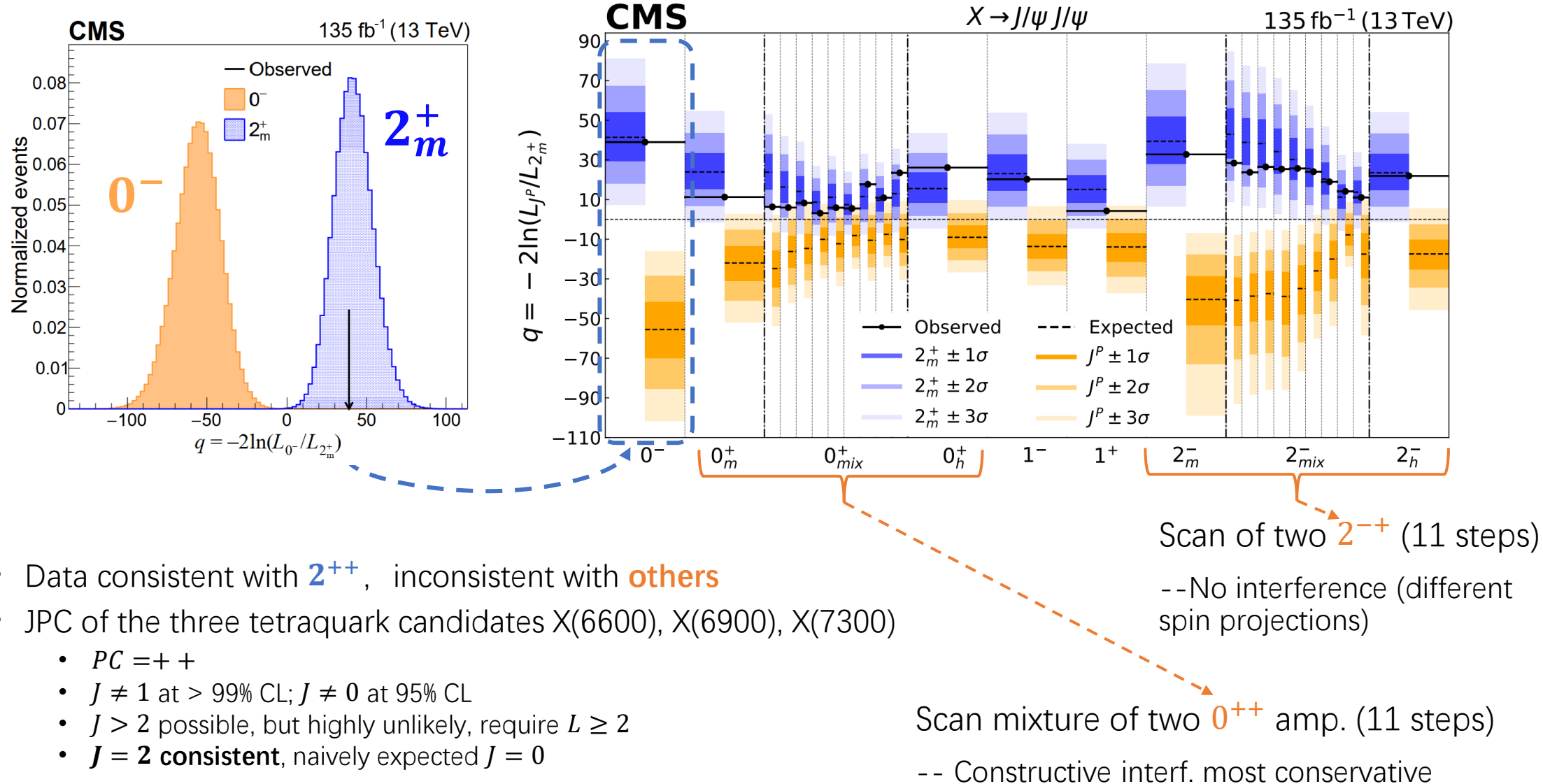
mix

mix



Summary of results

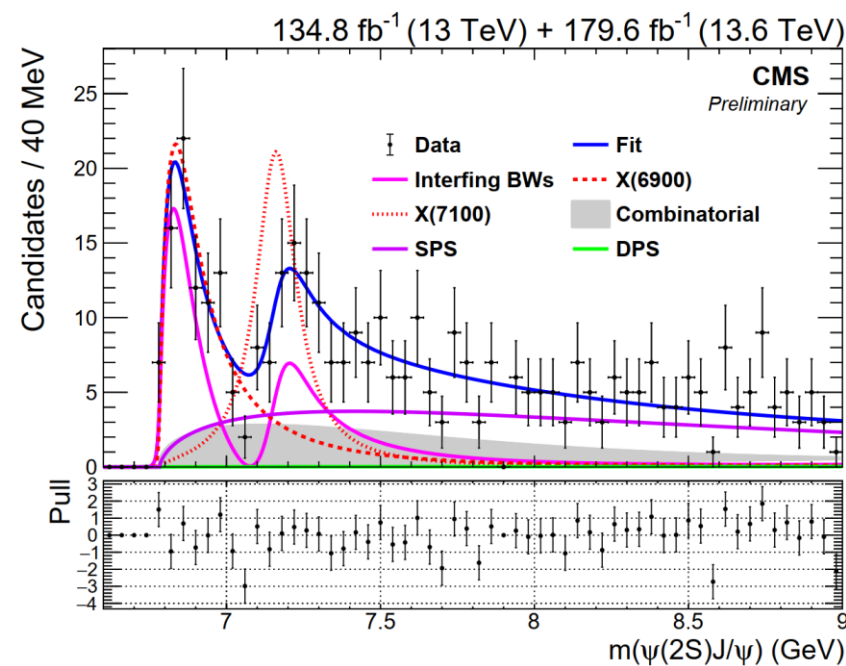
arxiv:2506.07944



- Data consistent with 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 $L \geq 2$
 - $J = 2$ consistent, naively expected $J = 0$

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

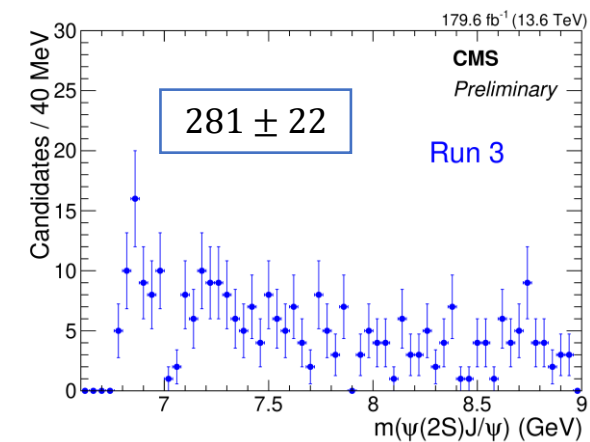
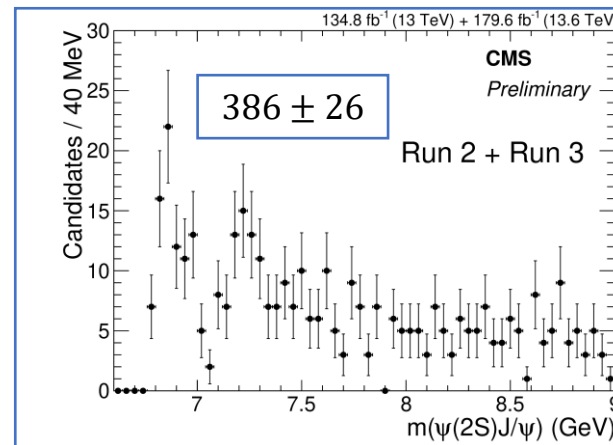
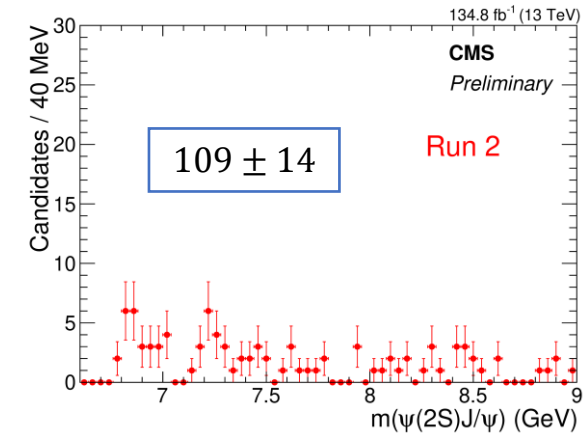
CMS-PAS-BPH-22-004



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

CMS-PAS-BPH-22-004

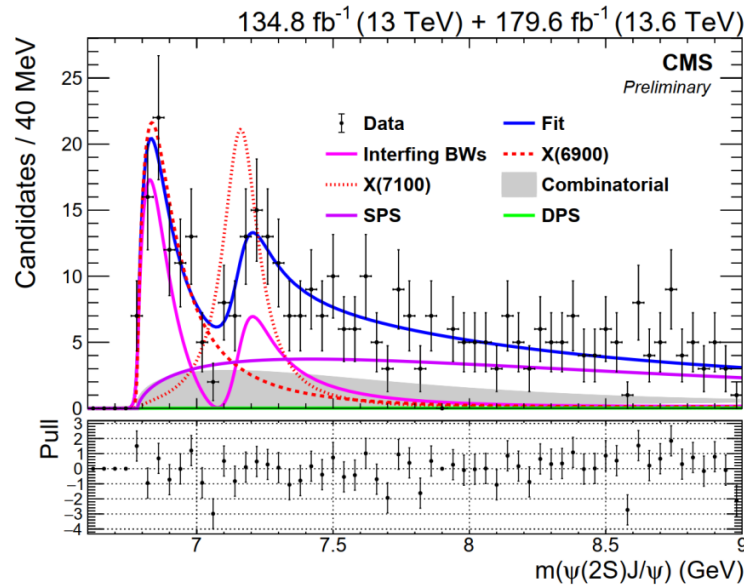
- J/ψ and $\psi(2S)$ reconstructed via $\mu^+\mu^-$
- Data (314 fb^{-1}):
 - 2016-2018 (run 2): 13 TeV, 134.8 fb^{-1}
 - 2022-2024 (run 3): 13.6 TeV, 179.6 fb^{-1}
- Trigger:
 - Run 2: 3 muons, $p_T > 5, 3, 3\text{ GeV}$
 - Run 3: 2muons, $p_T > 4, 3\text{ GeV}$



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

CMS-PAS-BPH-22-004

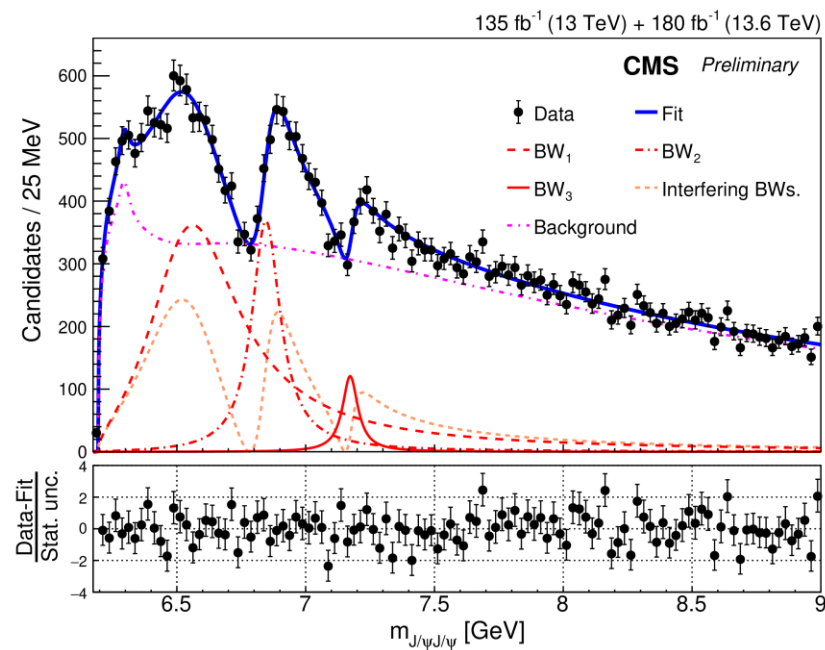
- X(6900) and X(7100) in $J/\psi\psi(2S)$
 - Data fit
 - Signal: X(6900), X(7100) and their interference
 - Background: NRSPS, DPS, combinatorial contribution
 - **$> 5\sigma$ for X(6900), 4.0σ for X(7100)**
 - Impact from X(6600) [below threshold] considered in systematic uncertainty



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}
			$\Gamma :$	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
$f_{JJ} [1]$	$J/\psi J/\psi$	BW_1, BW_2, BW_3	$m :$	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
			$\Gamma :$	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

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

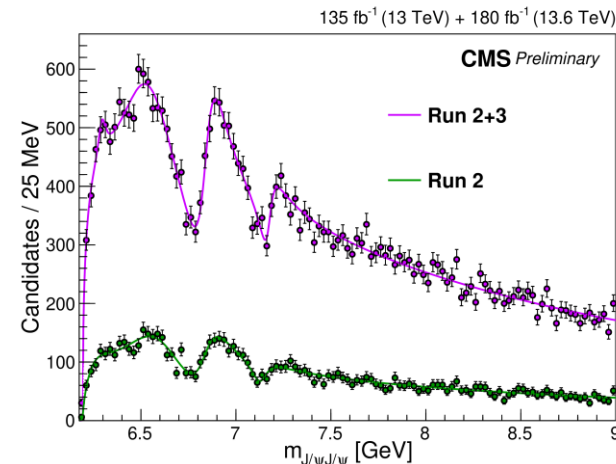
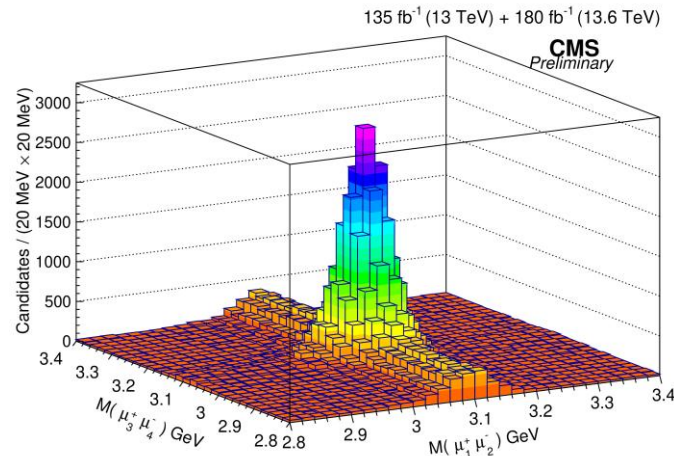
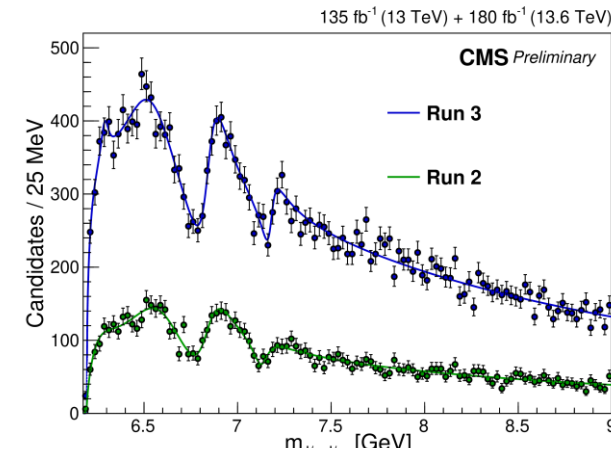
CMS-PAS-BPH-24-003



All-charm tetraquarks candidates at CMS

CMS-PAS-BPH-24-003

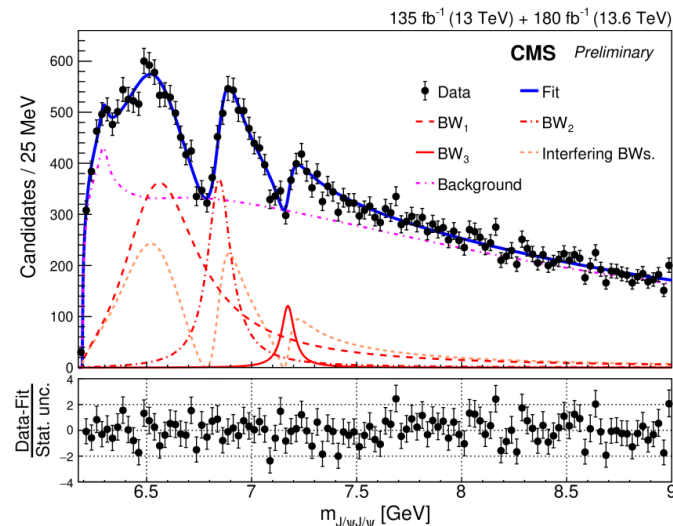
- Tetraquark candidates observed in $J/\psi J/\psi$ mass at CMS
 - J/ψ reconstructed via its $\mu^+ \mu^-$ decays
- Data (314 fb^{-1})
 - 2016-2018 (run 2): 13 TeV, 134.8 fb^{-1}
 - 2022-2024 (run 3): 13.6 TeV, 179.6 fb^{-1}
- Trigger
 - Run 2: 3 muons, $p_T > 5, 3, 3 \text{ GeV}$
 - Run 3: 2muons, $p_T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



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
 - $> 5\sigma$ for each of X(6600), X(6900), and **X(7100)**
 - $> 5\sigma$ for interference (two dips)
 - $> 5\sigma$ 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}

第十届手征有效场论研讨会

Feeddown: e.g., $X \rightarrow J/\psi\psi(2S) \rightarrow J/\psi J/\psi\pi\pi$ 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
 - $X(6900)$ significance $> 5\sigma$
 - $X(7100)$ 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](https://arxiv.org/abs/2506.07944)

