Observation of a family of all-charm tetraquarks with spin-2 and positive parity at CMS

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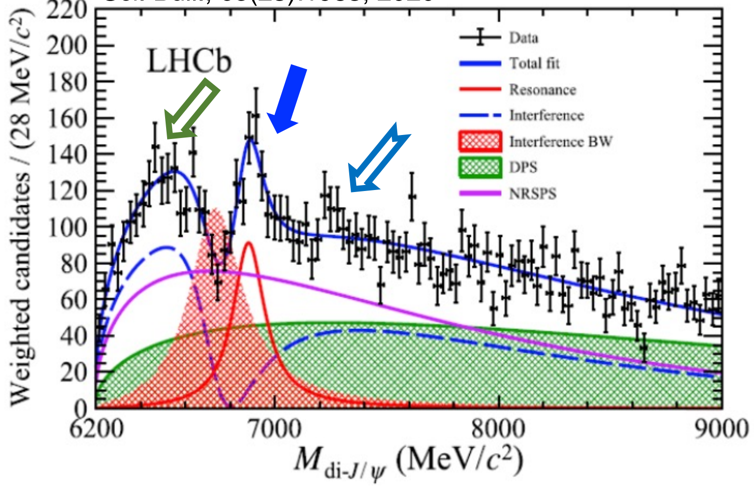
Outline

- **Motivation**
- ***J/ψJ/ψ* updated result**
- ***J/ψψ*(2S) result**
- **Spin-parity measurement**
- **Summary**

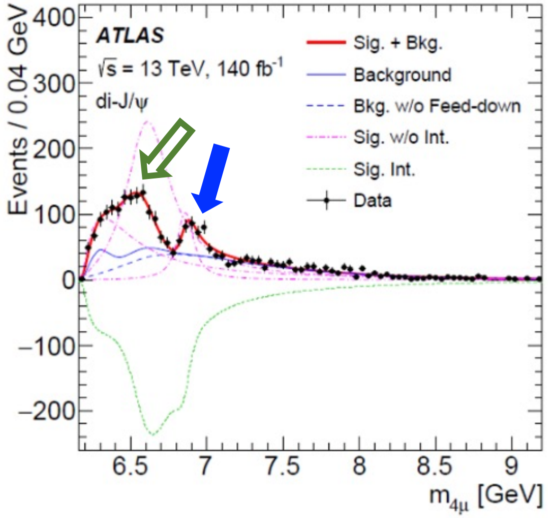
Status

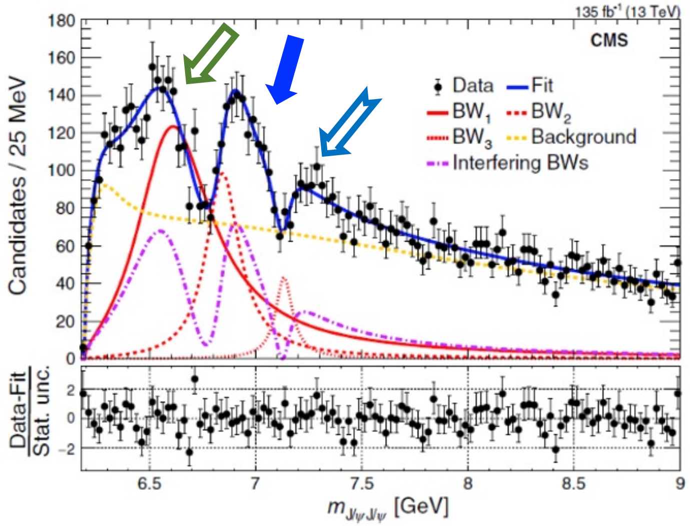
❖ **All-charm Tetraquark on LHC in J/ψJ/ψ channel**

Sci. Bull., 65(23):1983, 2020



Phys. Rev. Lett., 131(15):151902, 2023





❑ **ALL exp observe X(6900) + additional structure**

➢ **Only CMS claimed X(6600) & X(7100)**

- **Hump @ 6.6 GeV**: Different modeling
- **Hint @ 7.2 GeV**: LHCb not consider; ATLAS 3σ hint in $J/\psi\psi(2S)$

❑ **All exp use interference, but in diff ways**

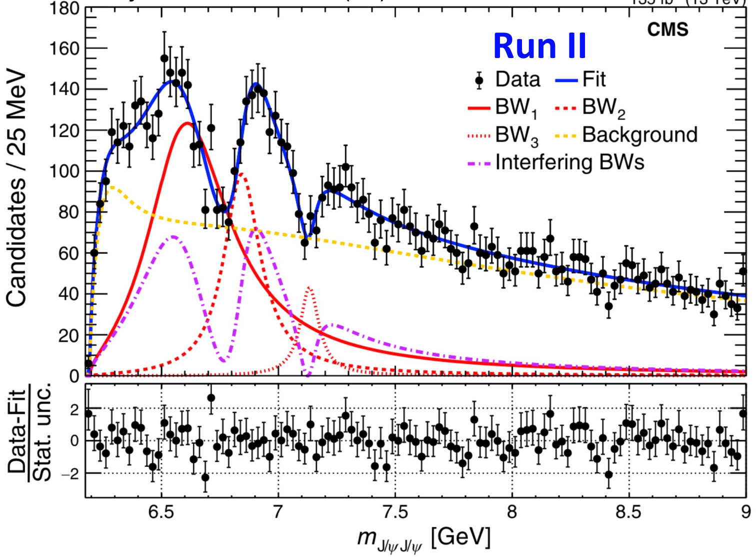
- LHCb: extra BW interfere with SPS, *X(6900) NOT interfering!*
- ATLAS and CMS: different multi-resonance interference

🔎 *A number of unresolved questions !*

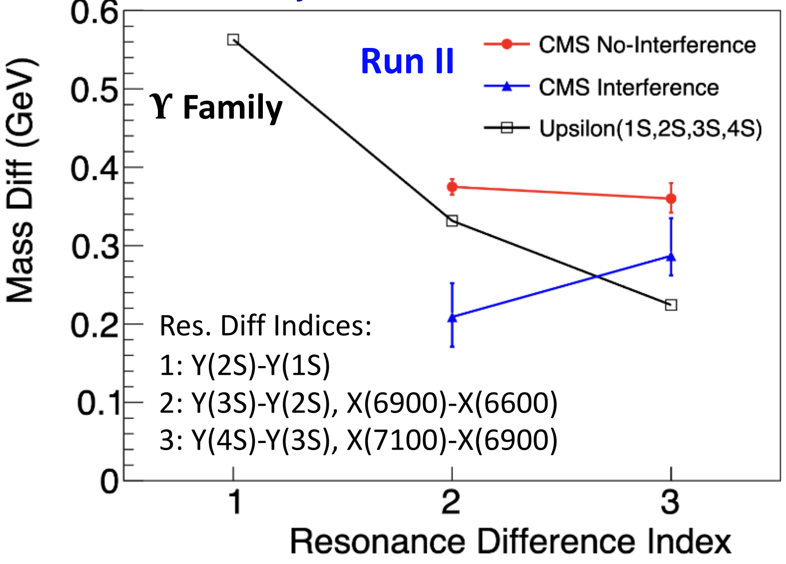
❑ **All exp see a threshold excess, NOT explained! Classified as background**

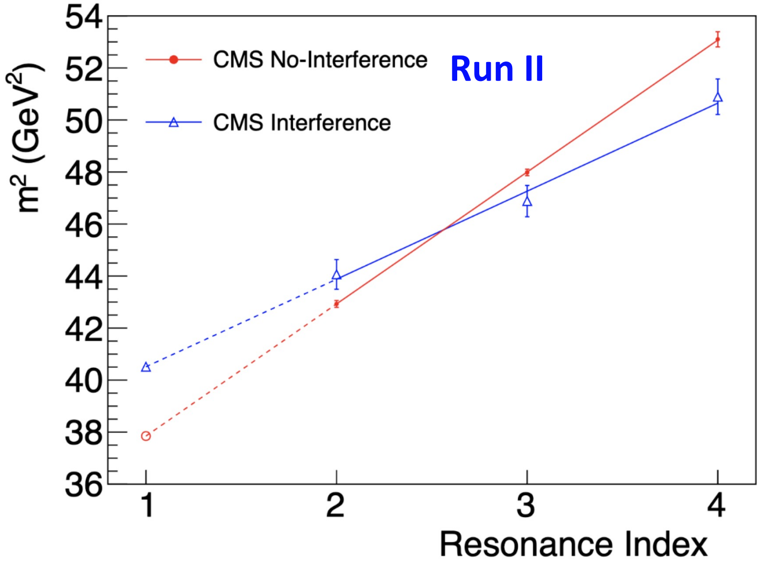
Status

Phys. Rev. Lett., 132(11):111901, 2024



Chinese Phys. Lett. 41 111201





Run 2 result:

- **X(7100)**: 4.7σ
- **Interference** < 4σ

With 3.6X statistics:

- ❑ Significance of ***ALL states*** over 5σ ?
- ❑ Significance of ***interference*** over 5σ ?

> ➢ Interference imply same J^{PC} quantum numbers
> ➢ > 200 MeV mass splittings ==> Radial excitations ?
> ➢ A **family** of all-charm tetraquarks ?

A FAMILY of all-charm tetraquark states with same J^{PC} ?

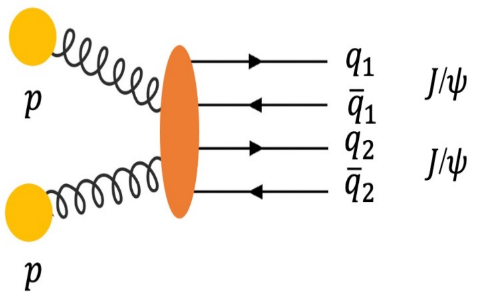
Datasets, MC, trigger, and event selection

❖ Data samples (315 fb^{-1})

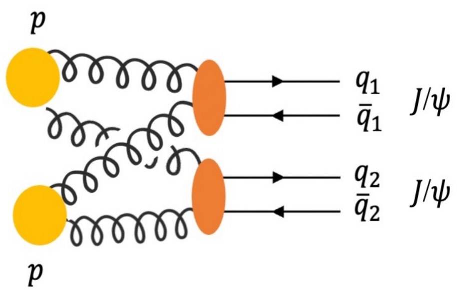
- Run 2: 135 fb^{-1} data taken in 2016, 2017 and 2018
- Run 3: 180 fb^{-1} data taken in 2022, 2023 and 2024

❖ Signal and Background simulated events:

- **Signal** $X \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ by JHUGen
- **NRSPS** and **Feeddown** by Pythia8
- **DPS** event-mixing
- **Feeddown**: $X(6900) \to J/\psi\psi(2S) \to J/\psi J/\psi + anything$



SPS



DPS

❖ Triggers

➢ **Run 2 trigger:**

- **Level 1 requirements: 3 muons**
- $2.95 < M(\mu^+\mu^-) < 3.25$ GeV
- $p_T(\mu) > 3.5$ GeV

➢ **Run3 trigger (new):**

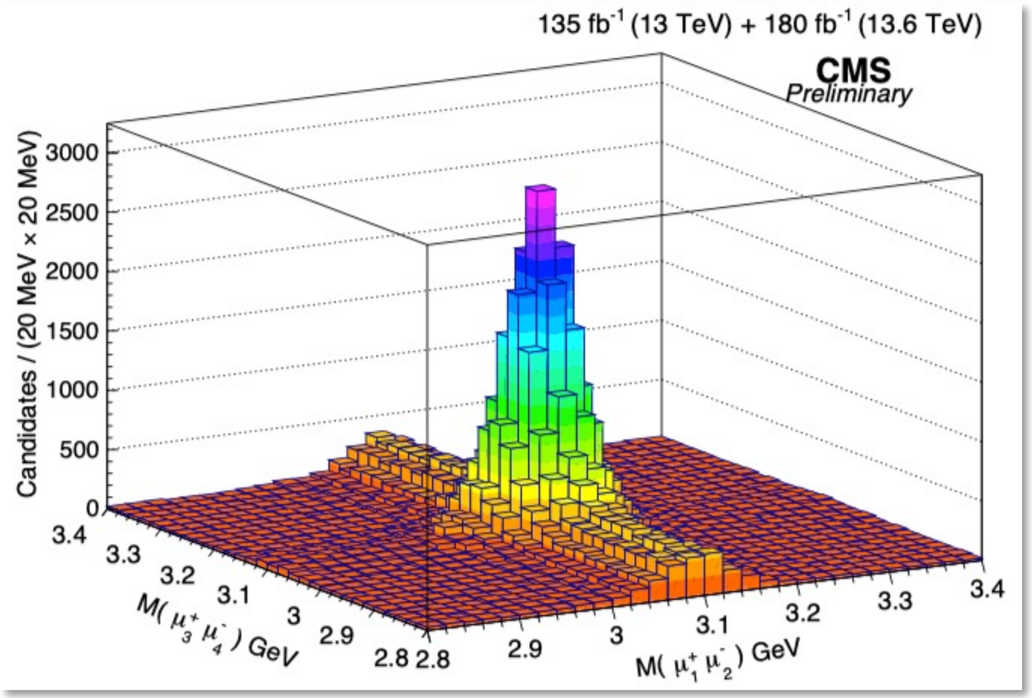
- **Level 1 requirements: 2 muons**
- $0.2 < M(\mu^+\mu^-) < 8.5$ GeV
- One muon $p_T(\mu) > 4$ GeV; The other $p_T(\mu) > 3$ GeV
- $p_T(\mu^+\mu^-) > 4.9$ GeV

➢ **increase 30% $J/\psi J/\psi$ statistics compared to old trigger**

❖ Event selection

- Follow Run 2 cuts + new trigger for Run 3

$J/\psi J/\psi$ yield: two-dimensional fit



- ***Luminosity***
  - Run 2 135 fb^{-1}
  - Run 3 180 fb^{-1}
- ***$J/\psi J/\psi$ yield***
  - Run 2: 12622 ± 165
  - Run 2+3 44936 ± 692
- ***$J/\psi J/\psi$ yield per unit luminosity***
  - Run 2 ~ 93 events / fb^{-1}
  - Run 3 ~ 177 events / fb^{-1}

➢ Run 2+3 ***$J/\psi J/\psi$ yield*** is *3.6X* of Run 2

➢ Run 2+3 ***luminosity*** is *2.3X* of Run 2

Signal and background models

- **Signal shape: Relativistic Breit-Wigner**
- **Background component:** NRSPS + NRDPS + Feeddown + Comb + BW0

$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)},$$

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{m_0}{m} \left(B'_L(q, q_0, d)\right)^2$$

❖ Non-interference model:

- **Signal-hypothesis:** NRSPS + NRDPS + Comb + Feeddown + BW0 + **BW1 + BW2 + BW3**

$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m)$$
$$+ N_{NRDPS} \cdot f_{NRDPS}(m) + N_{Comb} \cdot f_{Comb}(m) + N_{Feedown} \cdot f_{Feeddown}(m)$$

❖ Interference model:

- **Signal-hypothesis:** NRSPS + NRDPS + Comb + Feeddown + BW0 + **BW123 Interf. Term**

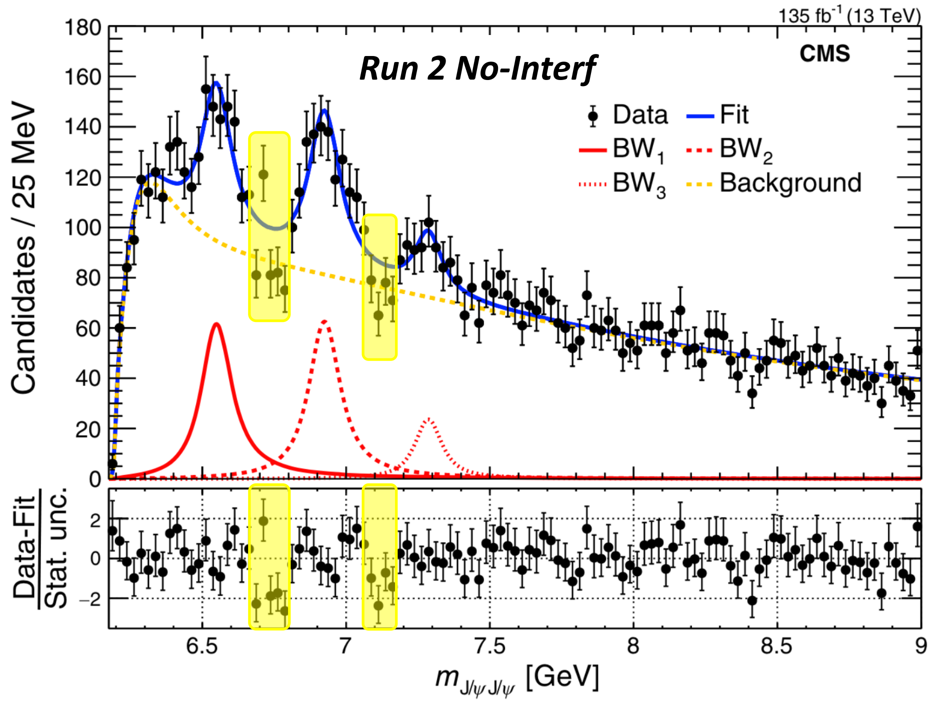
$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \otimes R(M_0)$$
$$+ N_{X\ and\ interf} \cdot |r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2$$
$$+ N_{NRSPS} \cdot f_{NRSPS}(m) + N_{DPS} \cdot f_{DPS}(m)$$
$$+ N_{Feeddown} \cdot f_{Feeddown}(m) + N_{Comb} \cdot f_{Comb}(m),$$

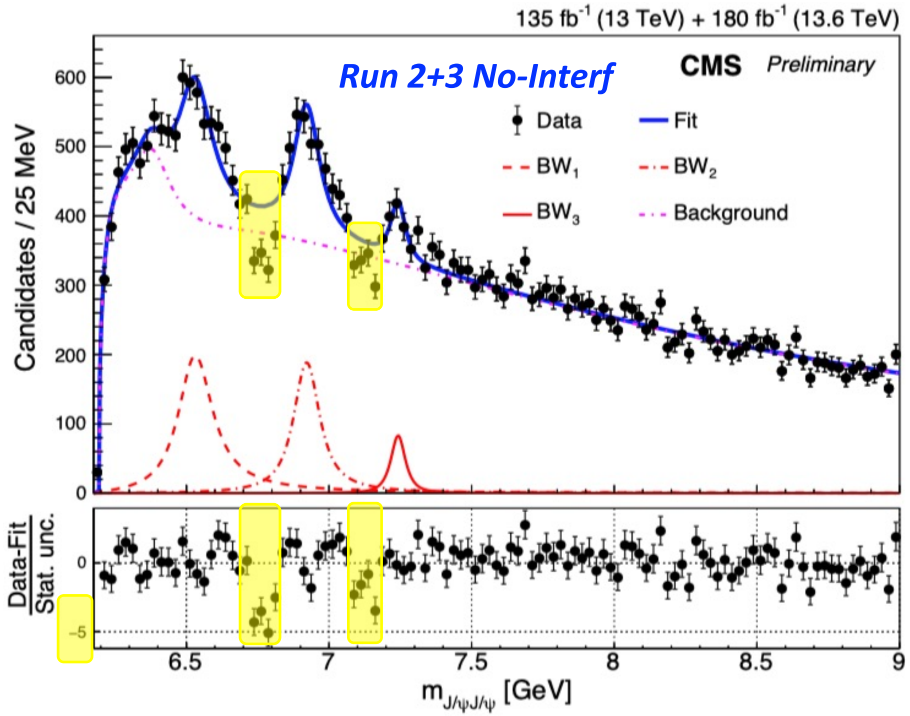
Run 2 & 3 no-interference fit result

❖ **No-interference model:**

- **Signal-hypothesis:** NRSPS + NRDPS + Comb + Feeddown + BW0 + **BW1 + BW2 + BW3**

$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m)$$
$$+N_{NRDPS} \cdot f_{NRDPS}(m) + N_{Comb} \cdot f_{Comb}(m) + N_{Feedown} \cdot f_{Feeddown}(m)$$

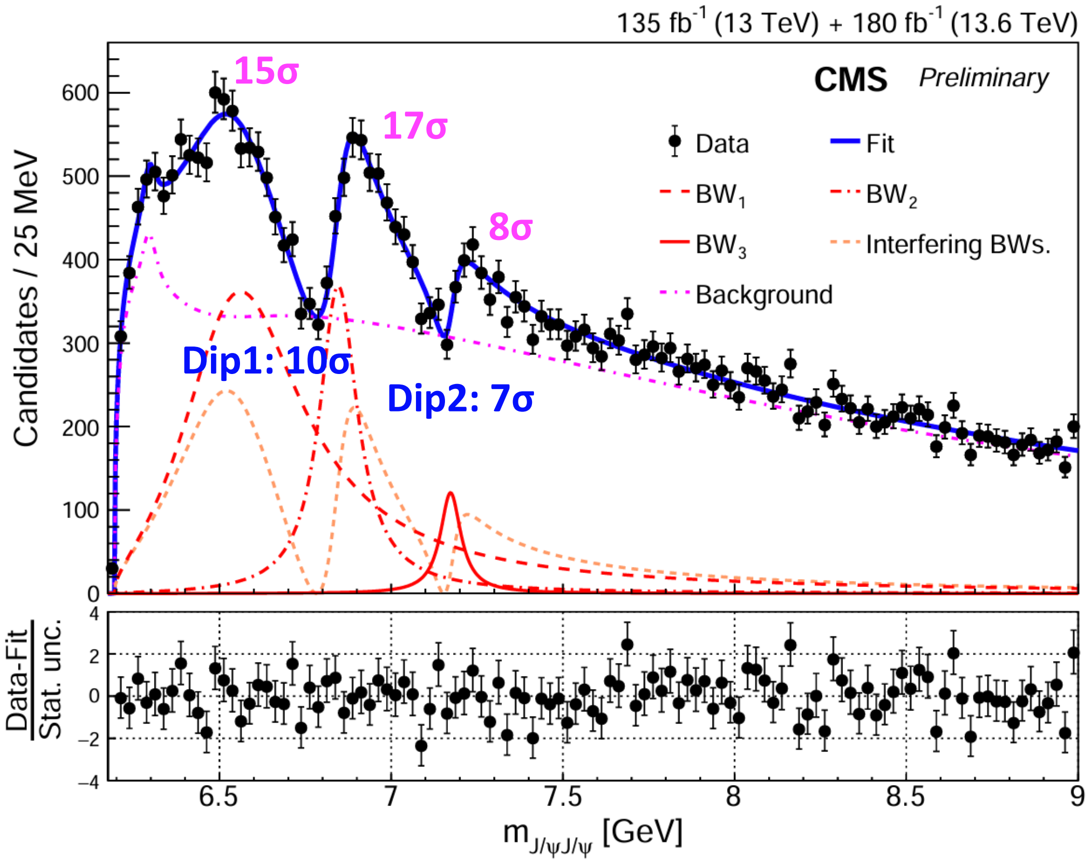


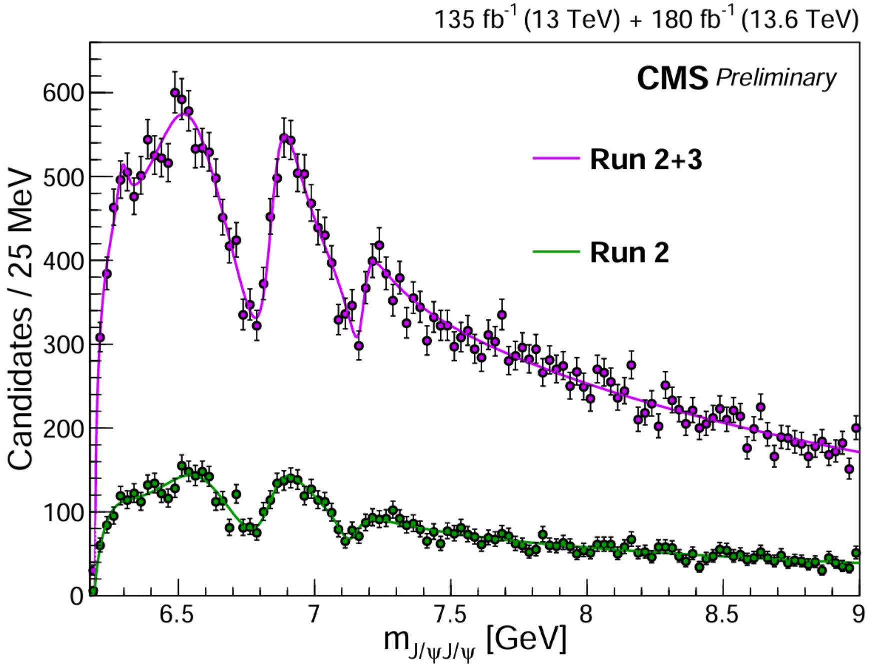


➢ **Dips poorly described —** ***no-Interf. model no longer sufficient !***

Run 2 & 3 interference fit result

❖ **Interference model with Run 2 + 3:**





➢ **All states and dips well above 5σ !**

➢ **Quantum interference among structures validated!**

Strongly imply that they have same J^{PC}

Run 2 & 3 interference fit result

Dominant sources	Δm_{BW_1}	$\Delta\Gamma_{\mathrm{BW}_1}$	Δm_{BW_2}	$\Delta\Gamma_{\mathrm{BW}_2}$	Δm_{BW_3}	$\Delta\Gamma_{\mathrm{BW}_3}$
Signal shape	25	52	2	11	3	5
NRSPS shape	3	7	<1	1	<1	5
DPS shape	<1	5	<1	<1	<1	1
Combinatorial bkg shape	<1	22	<1	2	<1	4
Feeddown	<1	1	<1	<1	<1	<1
Mass resolution	4	58	15	7	12	5
Efficiency	<1	4	<1	<1	<1	<1
Without BW_0	<1	29	2	3	2	1
Total uncertainty	25	87	15	14	13	10

Params	M(BW1)	Γ(BW1)	M(BW2)	Γ(BW2)	M(BW3)	Γ(BW3)
Run II & III Interf. [MeV]	$\mathbf{6593^{+15}_{-14} \pm 25}$	$\mathbf{446^{+66}_{-54} \pm 87}$	$\mathbf{6847 \pm 10 \pm 15}$	$\mathbf{135^{+16}_{-14} \pm 14}$	$\mathbf{7173^{+9}_{-10} \pm 13}$	$\mathbf{73^{+18}_{-15} \pm 10}$
Run II Interf. [MeV]	6638^{+43+16}_{-38-31}	$440^{+230+110}_{-200-240}$	6847^{+44+48}_{-28-20}	191^{+66+25}_{-49-17}	7134^{+48+41}_{-25-15}	97^{+40+29}_{-29-26}

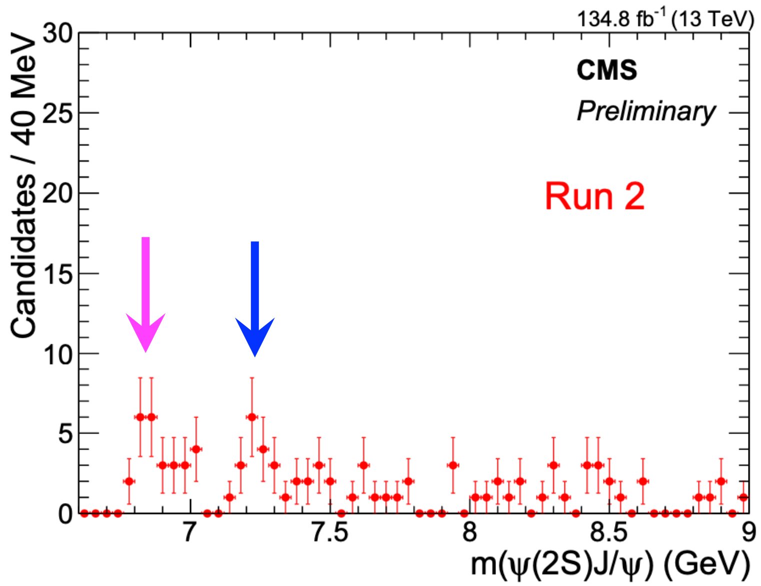
❖ ***VS. Run 2 result***

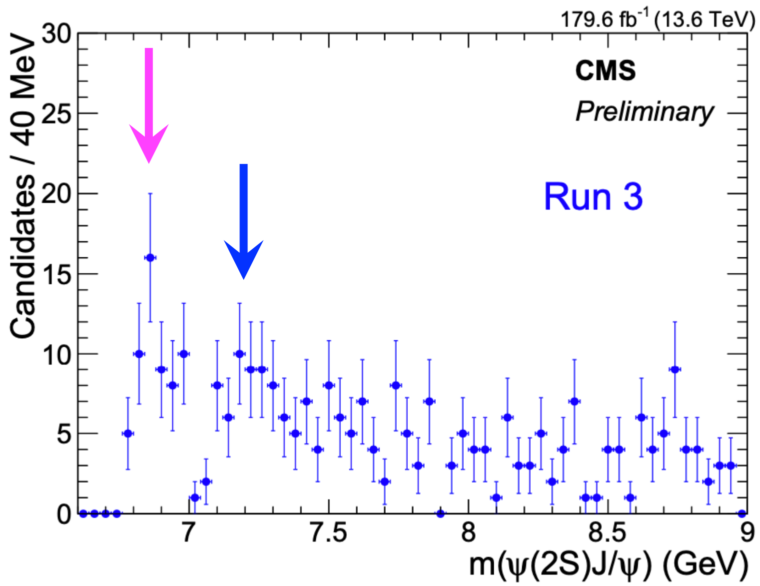
- ✓ **Statistical uncertainty** reduced by **a factor of 3**
- ✓ **Systematic uncertainty** reduced by about **a factor of 2**
- ✓ **Large mass splittings (> 200MeV)** still exist, **with improved precision**

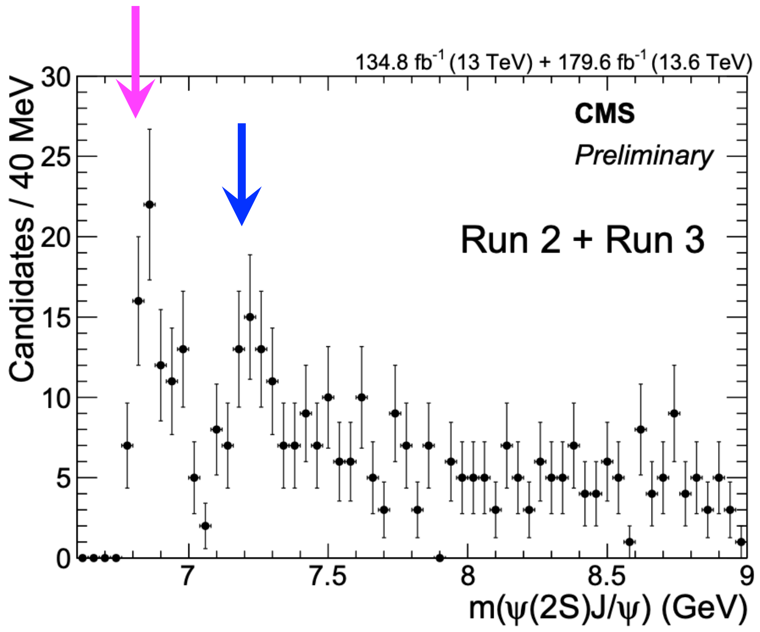
Explore $J/\psi\psi(2S)$ channel with Run 2 & 3 data

- X(6900) near threshold obvious
- X(7100) is visible
- According to $J/\psi J/\psi$ channel, should be an X(6900) and an X(7100)
- Signal dominated by Run 3
- Two dimensional fit for $\boldsymbol{J/\psi\psi(2S)}$ **yield** ***~2.6 X of Run 2***

Run 2 ~109 ± 14
Run 3 ~281 ± 22
Run 2+3 ~386 ± 26

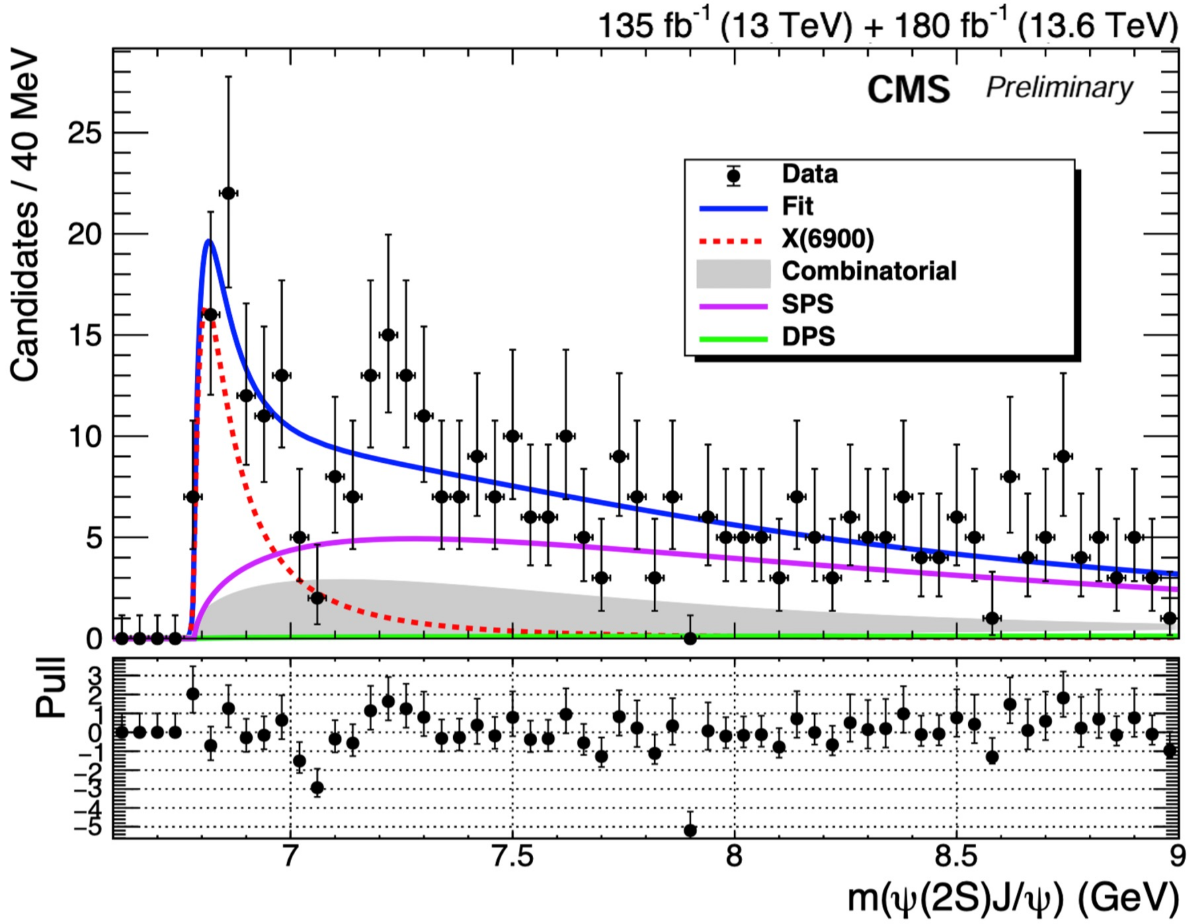






Explore $J/\psi\psi(2S)$ channel with Run 2 & 3 data

❖ **Only consider X6900 in $J/\psi\psi(2S)$ channel**

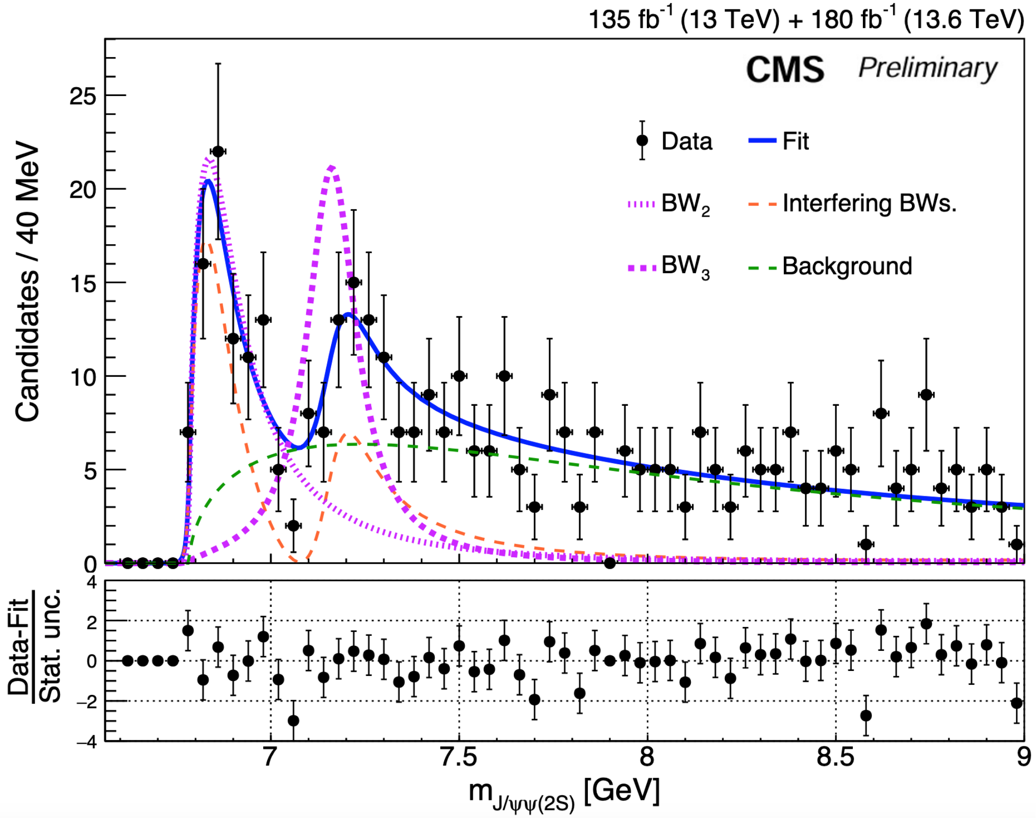


$$\mathbf{M(X(6900)) = 6841 \pm 14\ MeV}$$

$$\mathbf{\Gamma(X(6900)) = 150 \pm 28\ MeV}$$

Significance of **X(6900) = 7.5 σ**

Explore $J/\psi\psi(2S)$ channel with Run 2 & 3 data



Dominant sources	$M_{X(6900)}$	$\Gamma_{X(6900)}$	$M_{X(7100)}$	$\Gamma_{X(7100)}$
Signal shape	±29	±79	±22	±131
NRSPS shape	±14	±54	±14	±29
Combinatorial background shape	±15	±51	±15	±20
Mass resolution	±5	±7	±5	±9
Efficiency	±7	±27	±7	±10
Add X(6600) peak	±104	±14	±61	±31
Fitter bias	$^{+9}_{-11}$	$^{+43}_{-37}$	$^{+29}_{-14}$	$^{0}_{-80}$
Total	$^{+110}_{-110}$	$^{+120}_{-120}$	$^{+74}_{-70}$	$^{+140}_{-160}$

Params	$J/\psi\psi(2S)$ [MeV]	$J/\psi J/\psi$ [MeV]
M(BW2)	$6876^{+46+110}_{-29-110}$	$6847 \pm 10 \pm 15$
Γ(BW2)	$253^{+290+120}_{-100-120}$	$135^{+16}_{-14} \pm 14$
M(BW3)	7169^{+26+74}_{-52-70}	$7173^{+9}_{-10} \pm 13$
Γ(BW3)	$154^{+110+140}_{-82-160}$	$73^{+18}_{-15} \pm 10$

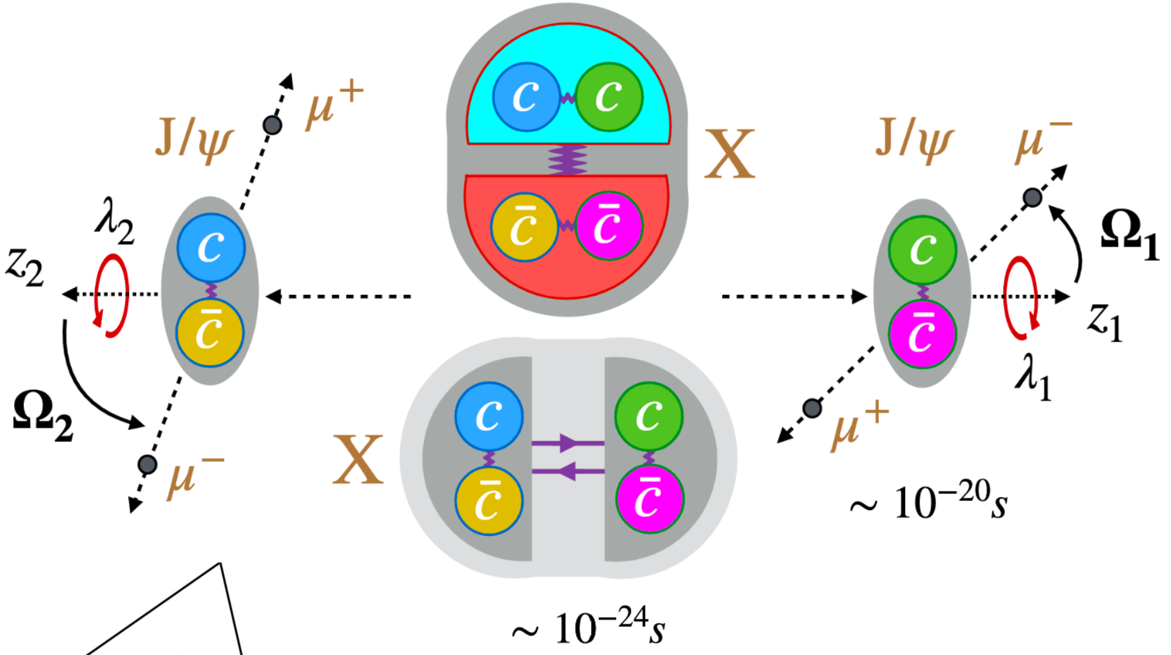
- Significance of **X(6900) = 7.9σ**
- Significance of **X(7100) = 4.0σ**

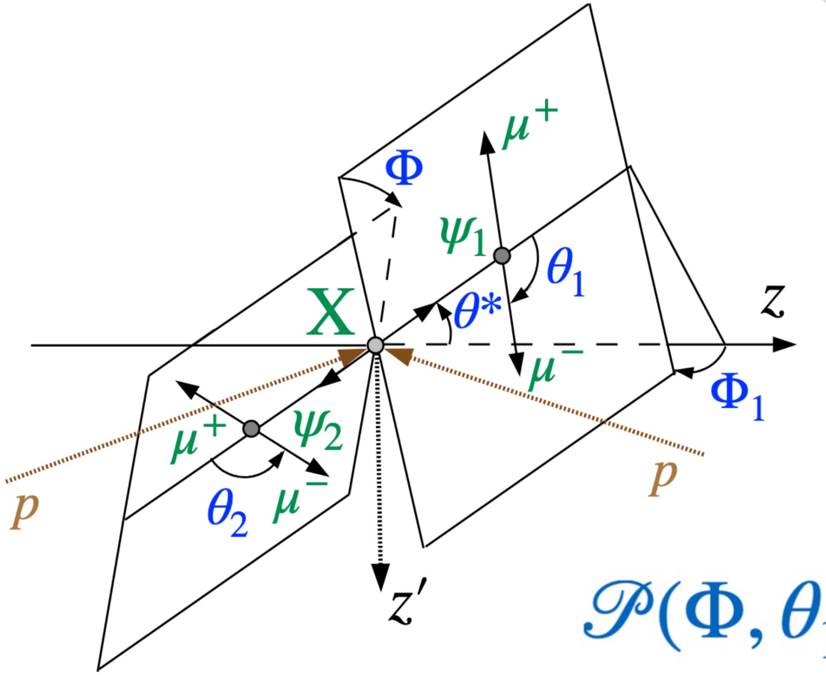
*ATLAS only claim X(6900) 4.7σ in J/ψψ(**2S**) channel*

✓ ***Consistent*** *with J/ψJ/ψ result!*

✓ ***Confirmed*** *in a different channel!*

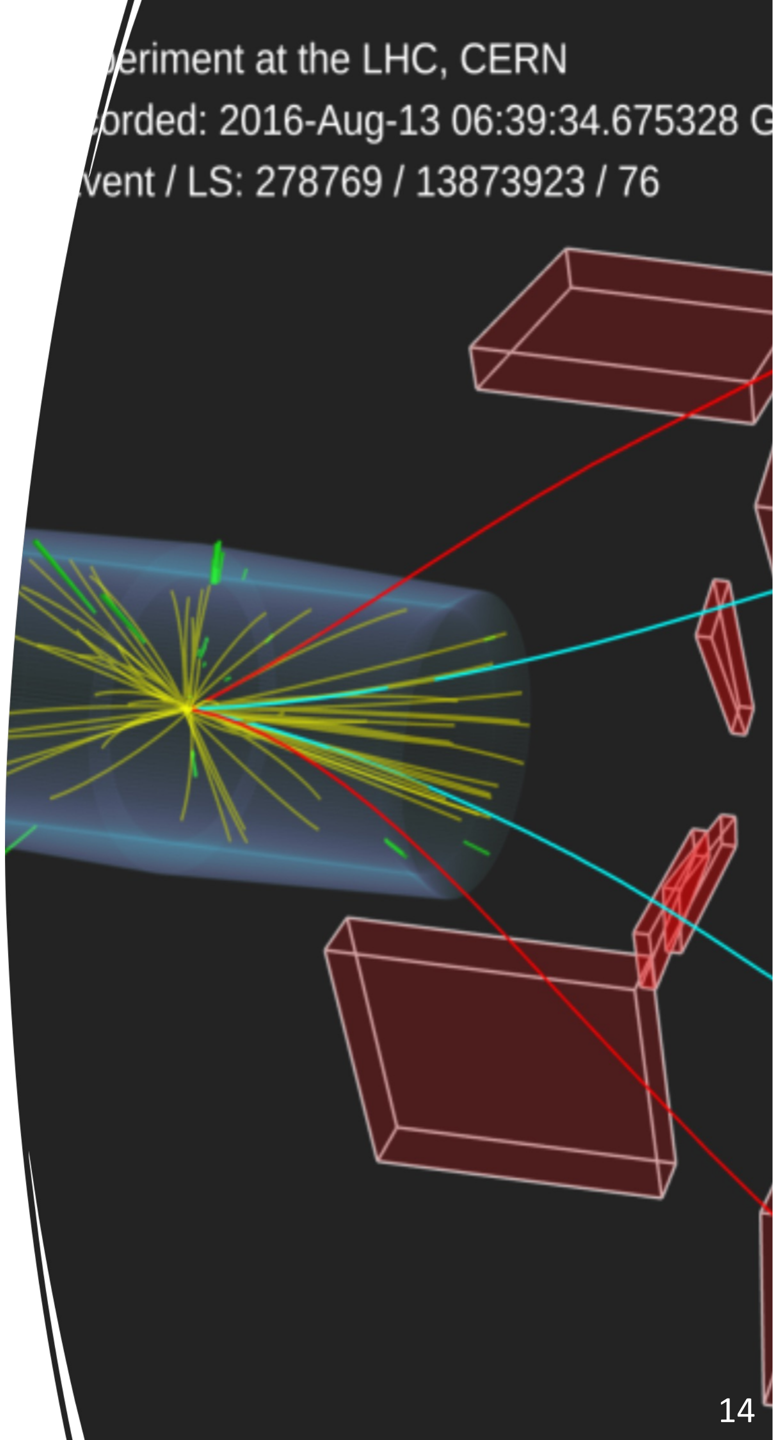
Spin parity analysis



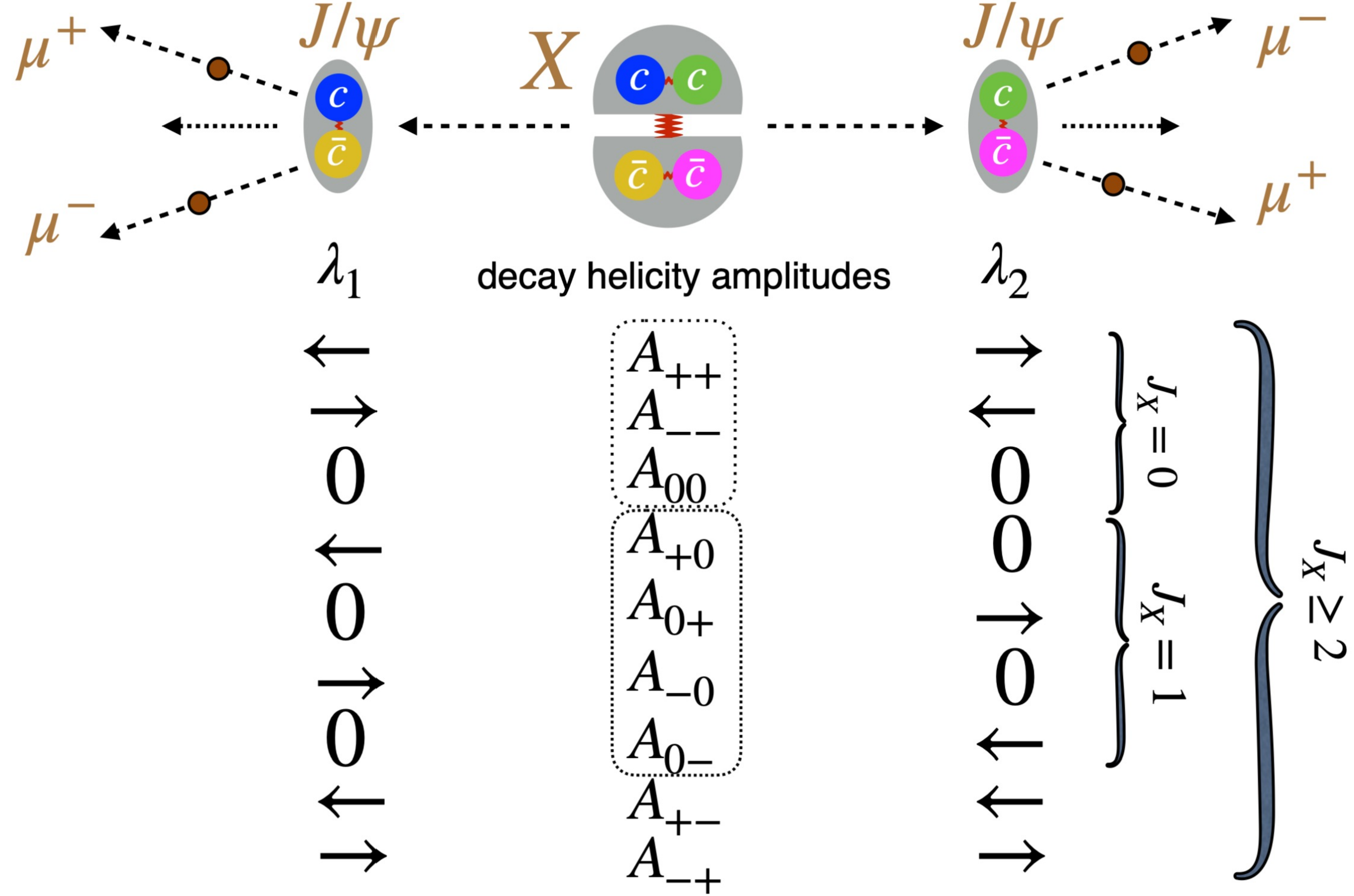


$$J^{PC} = ?$$

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



J/ψ polarizations



J/ψ polarizations

- Symmetries:

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

— 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-}

$J_X \ge 2$: 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

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

$$A(X_{J=2} \to V_1 V_2) = 2c_1(q^2) t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2(q^2) t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}$$

$$+c_3(q^2) \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + c_4(q^2) \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$

$$+m_V^2 \left(2c_5(q^2) t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2c_6(q^2) \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}) + c_7(q^2) \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$

$$+c_8(q^2) \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_{10}(q^2) \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)),$$

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. $A_{00}, A_{++} = A_{--}, A_{+0} = A_{0+} = A_{-0} = A_{0-}, A_{+-} = A_{-+}$ unique for 2^{++} (or $J \geq 2$)

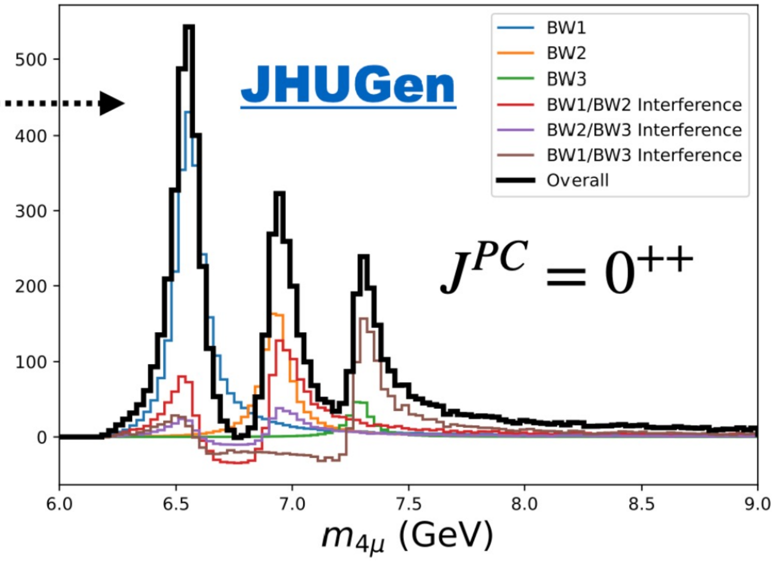
basis of 2^{++} could be equivalent to $2_m^+, 0_m^+, 0_h^+, 1^+$

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

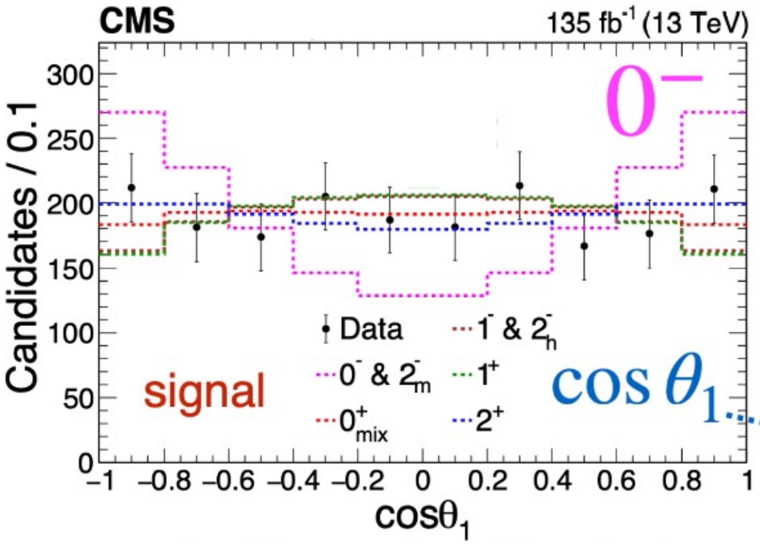
1 optimal observable

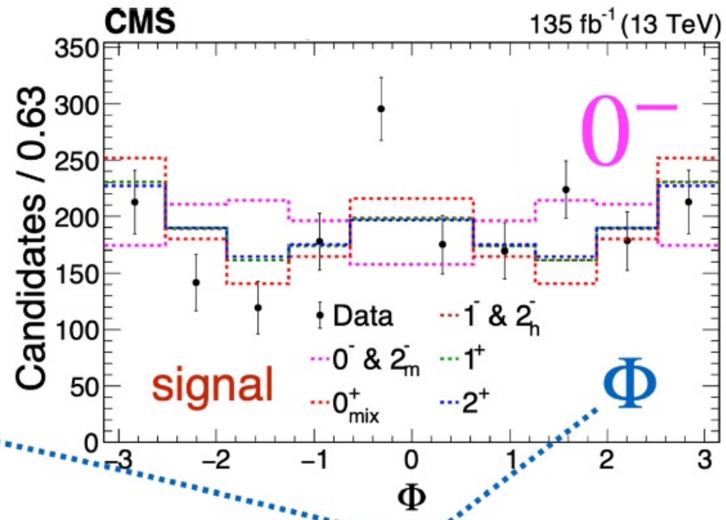
- Final 2D model: $$\mathscr{P}_{ijk}(m_{4\mu}, \mathscr{D}_{ij}) = \mathscr{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathscr{D}_{ij} \,|\, m_{4\mu})$$

Decay Angles

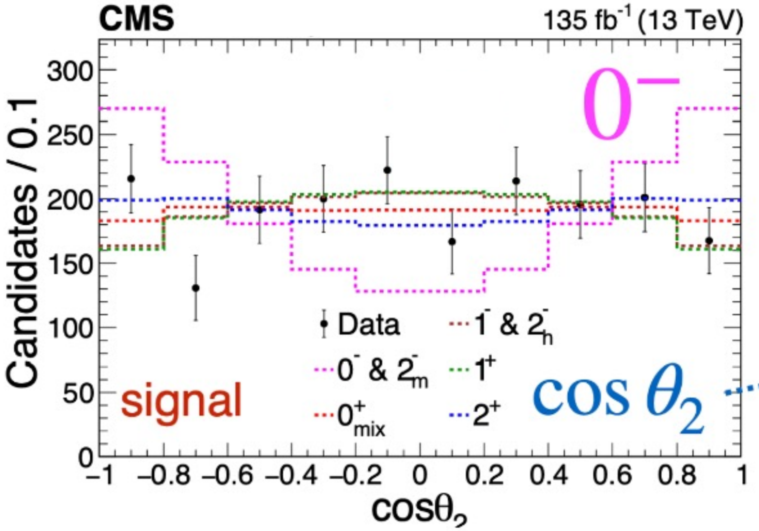
Production angles not use
Consistent with unpolarized (backup)

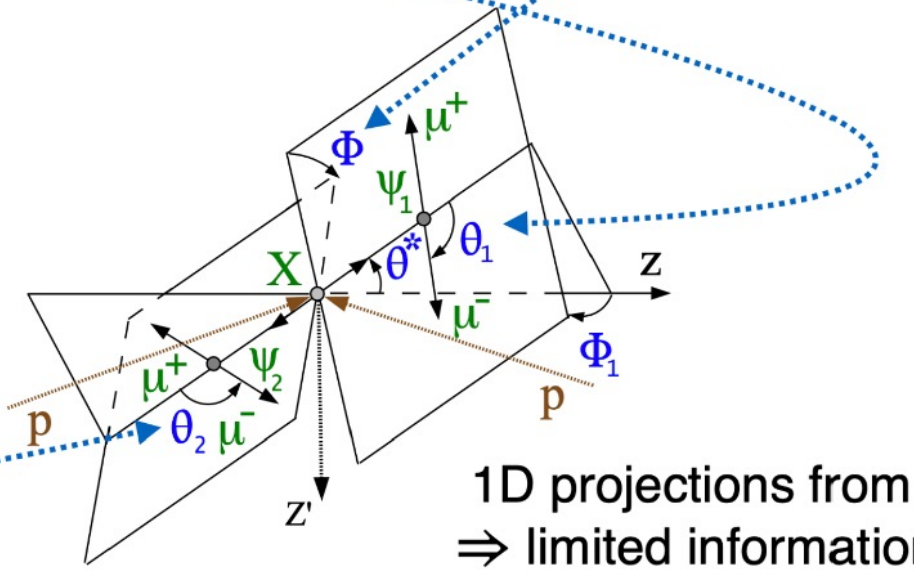
decay angles (consistency check): distinguish models





background-subtracted

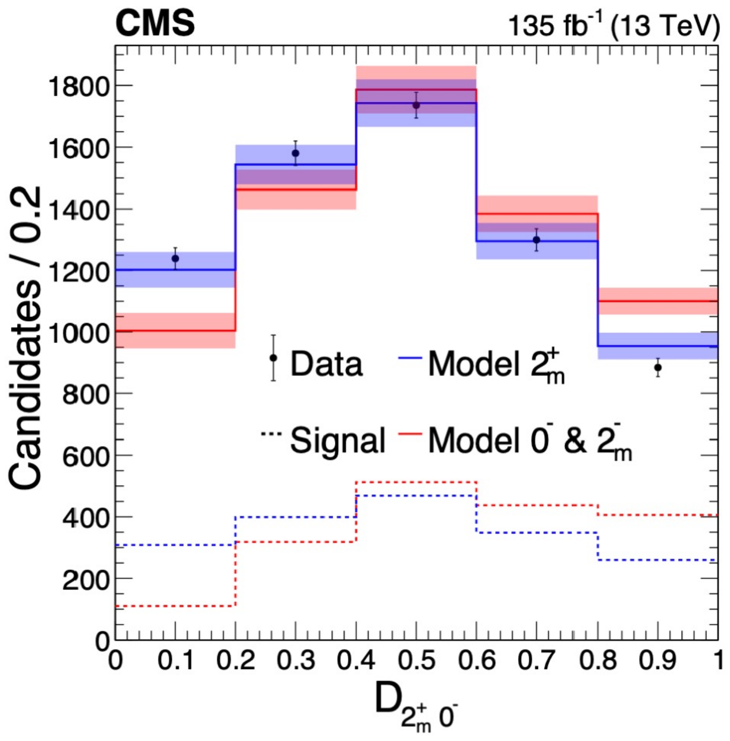


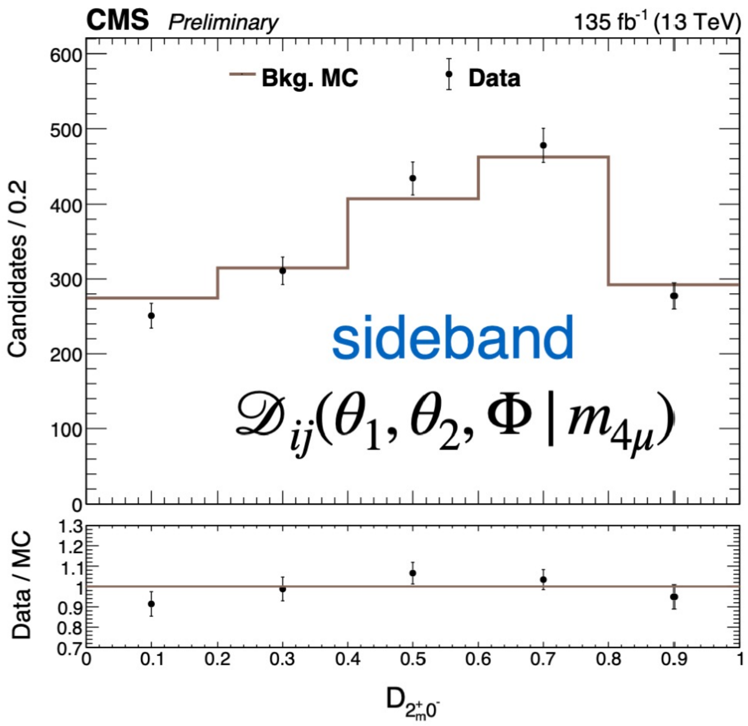


1D projections from 4D
⇒ limited information

Optimal Observable

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





optimal observable

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

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

background model from MC
control in sidebands
systematic variations

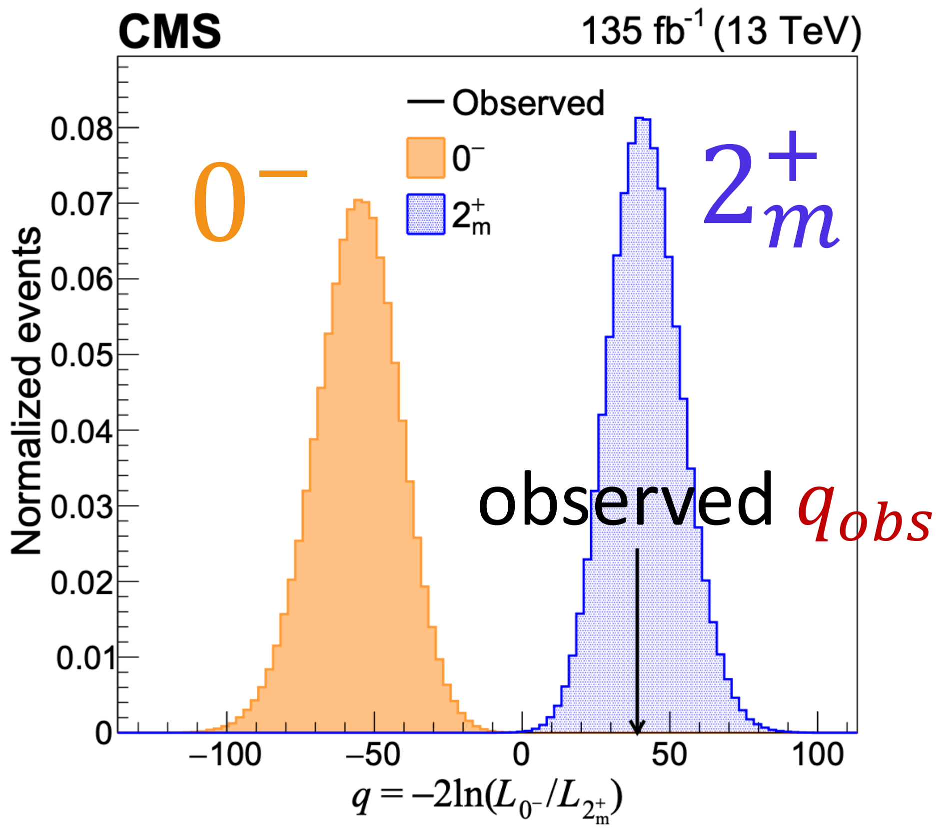
Statistical Analysis

- 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:

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

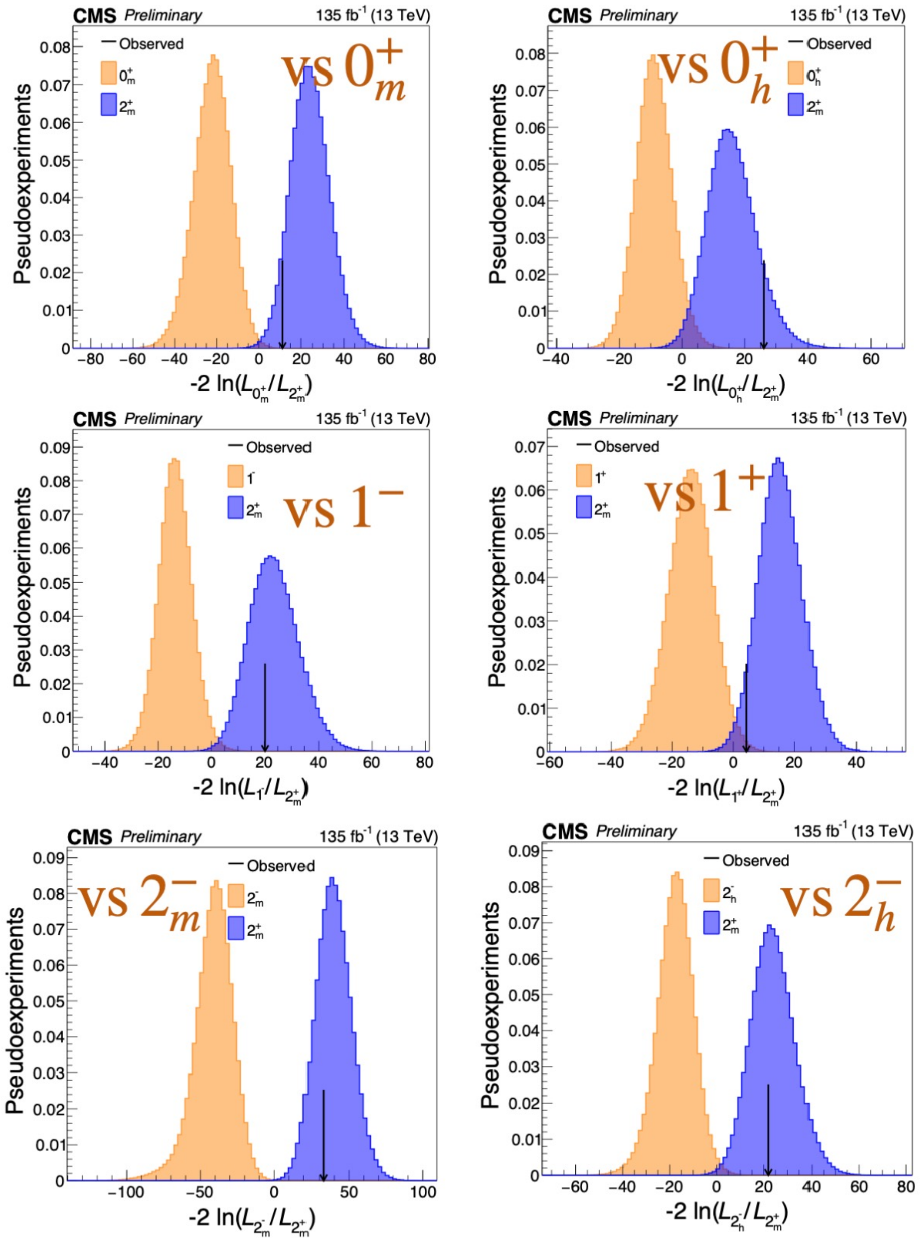
- Significance:
  Converted from p-value
  via Gaussian one-sided tail integral
- Confidence level

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



		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^P_X	p-value	Z-score reject J^P_X	
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	

***PC* $=++$ very certain**

$J \neq 1$ at $>99\%$ CL

$J \neq 0$ at $>95\%$ CL

$J > 2$ less likely

$J = 2$ consistent, rare

Summary

- A family of all-charm tetraquarks with $J^{PC} = 2^{++}$
  - Three structures X(6600), X(6900), X(7100) established *with significances* $> 5\sigma$
    - The first two analyses including 2024 data among LHC 3 exps
    - Precision improved by factor of 3
    - Multiple states makes comparisons possible
  - Quantum interference among structures validated *with significances* $> 5\sigma$

    ==> States have common J^{PC}, measured as 2^{++}
  - Large mass splittings, Regge trajectory

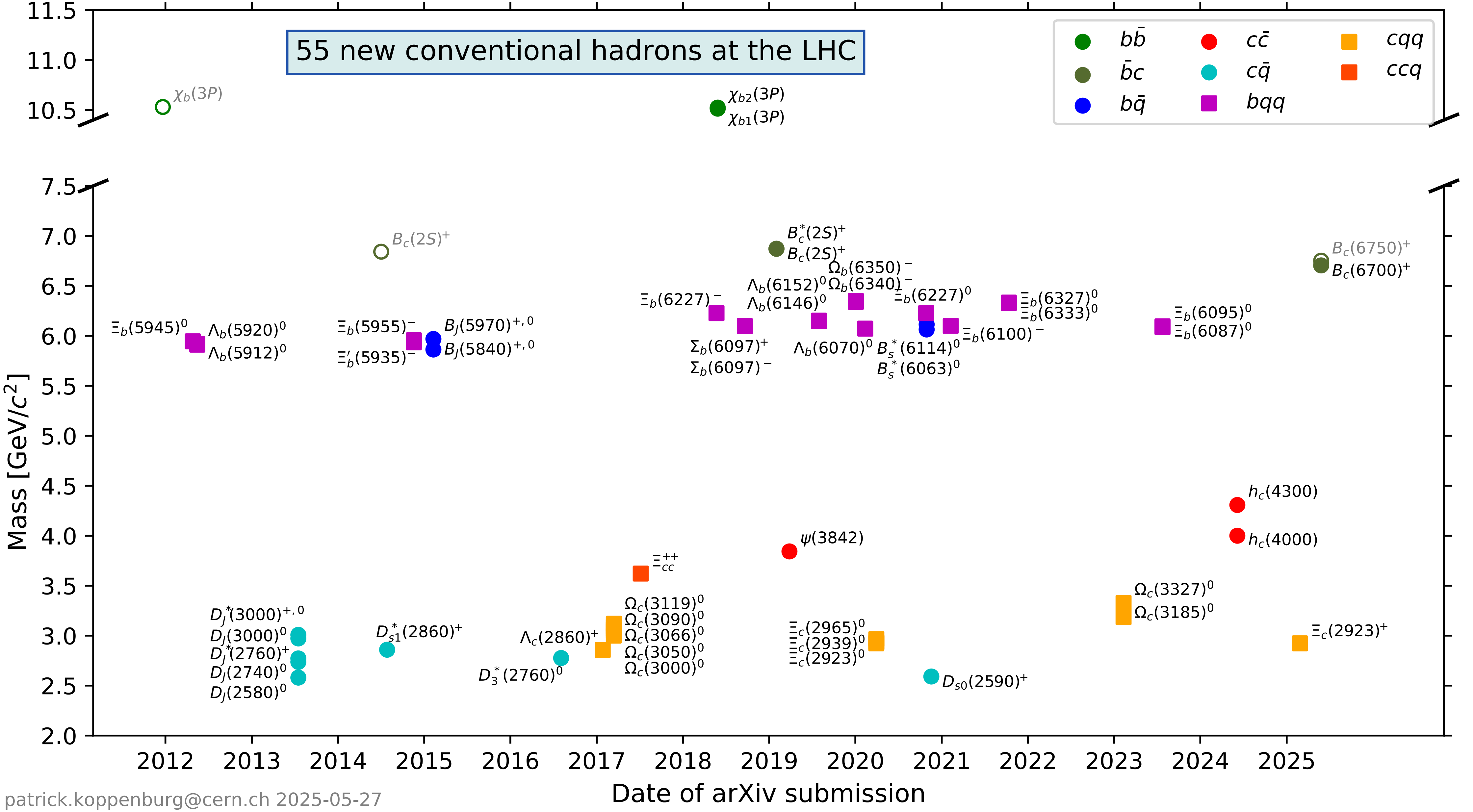
    ==> radial family of states

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

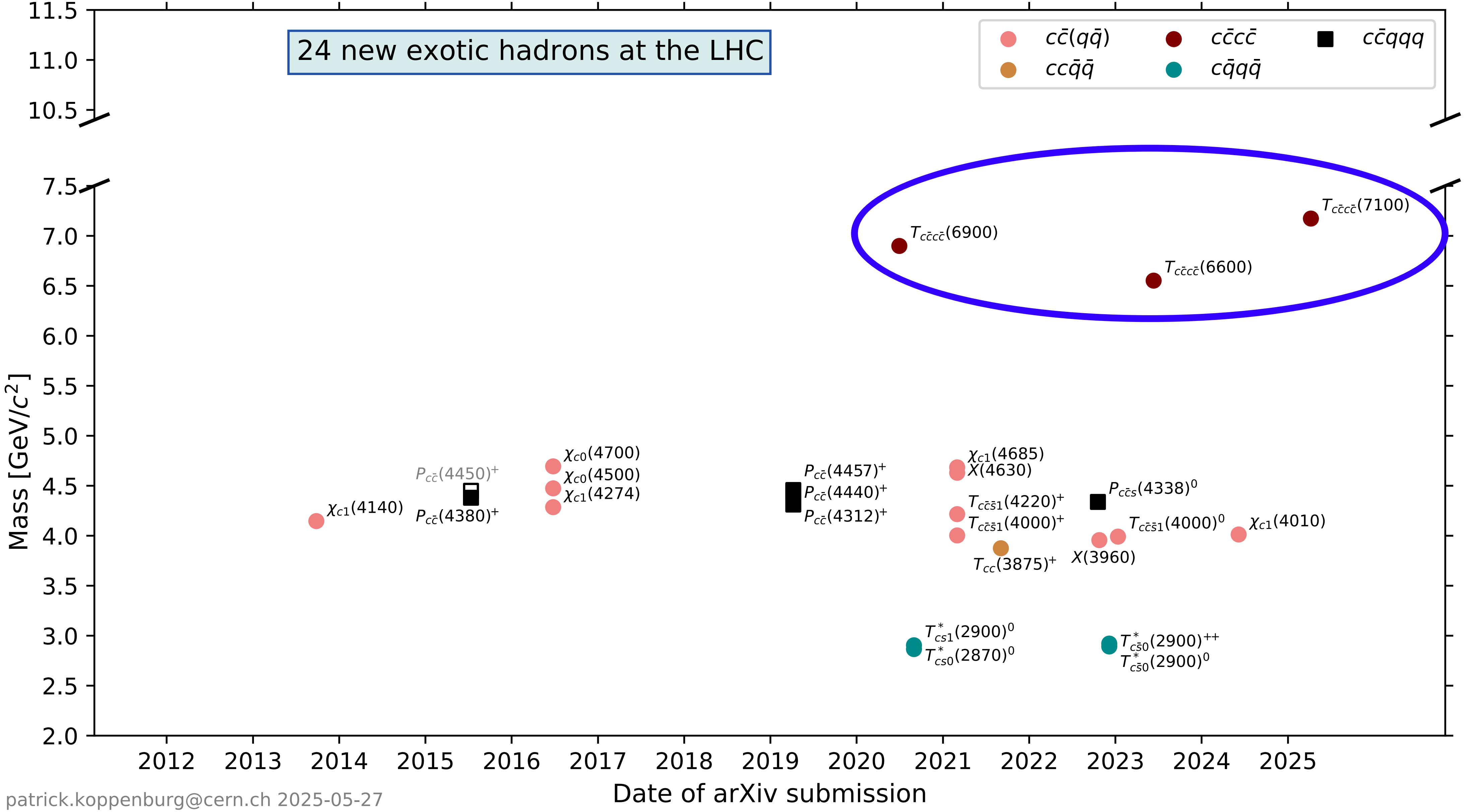
THANKS!

BACKUP

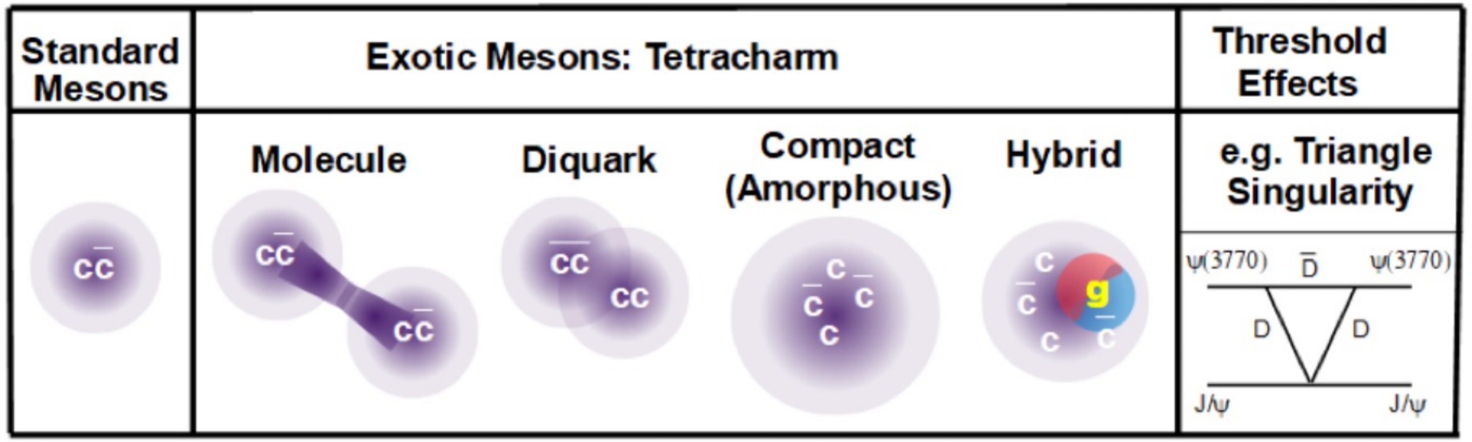
New conventional hadrons at LHC



New exotic hadrons at LHC



Status



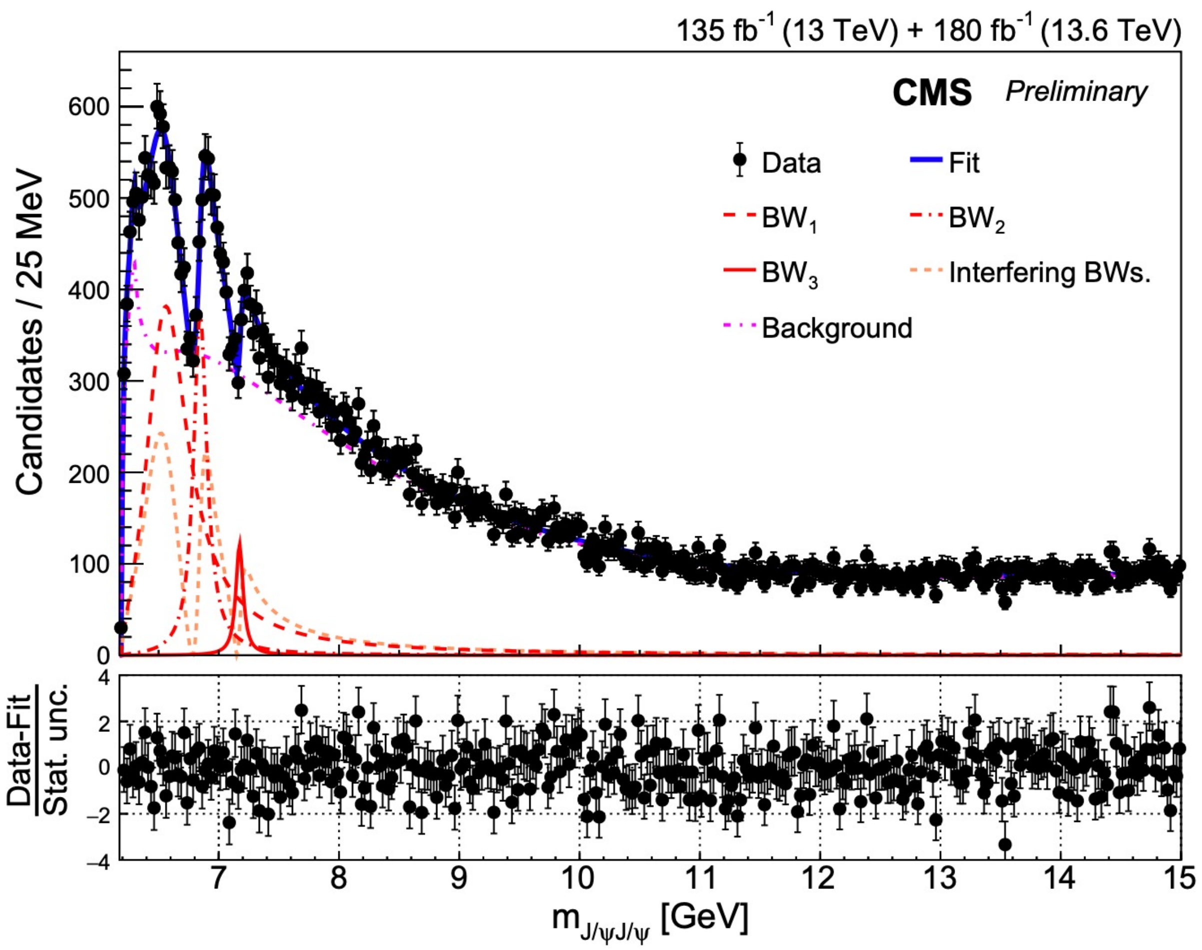
❖ Models of potential quark configurations for J/ψJ/ψ mesons.

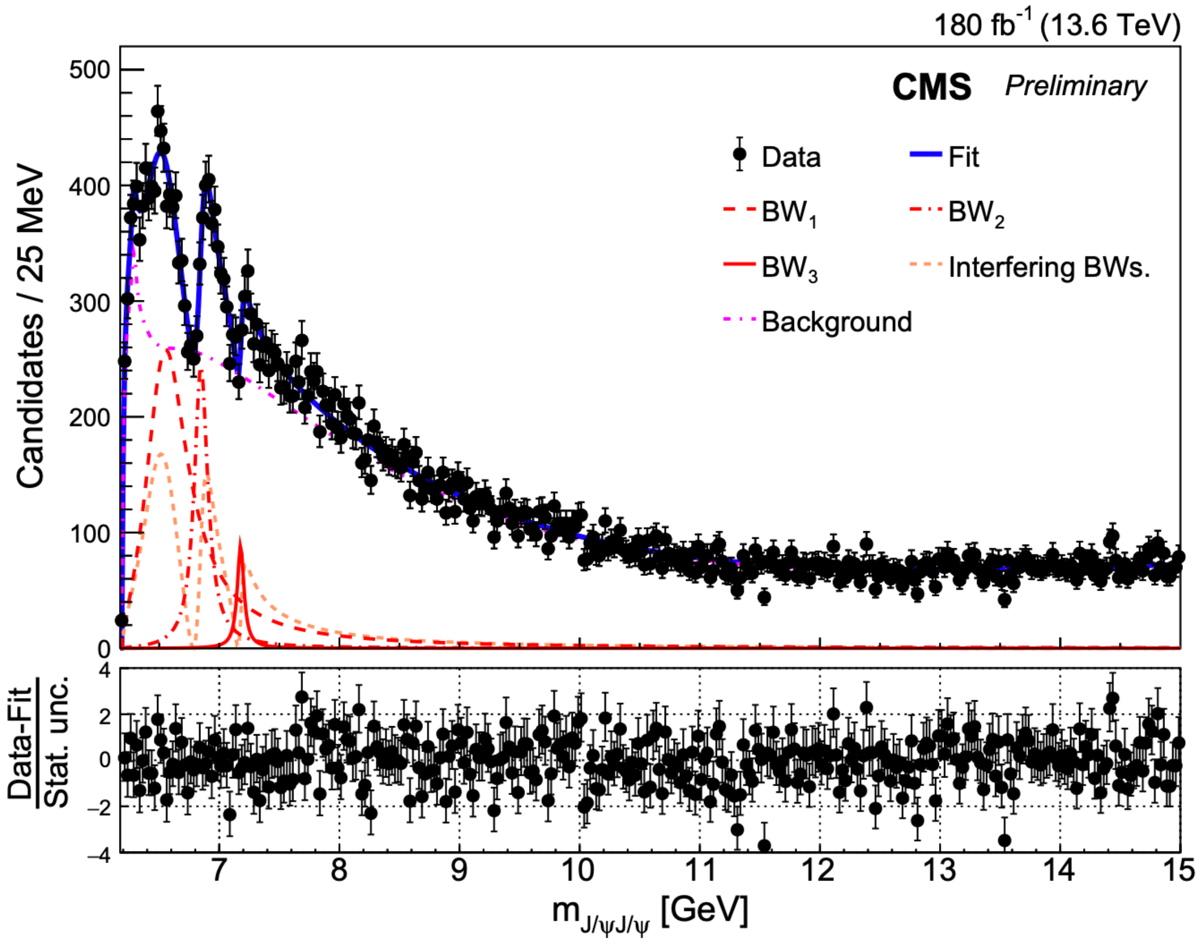
- Meson-meson "molecule" ($c\bar{c}$- $c\bar{c}$)
- Pair of diquarks (cc-$\bar{c}\bar{c}$)
- Hybrid with a valence gluon
- Peaks as artifact of dicharmonia production thresholds
- ……

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** $(0^+ \text{ vs. } 0^-)$:

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

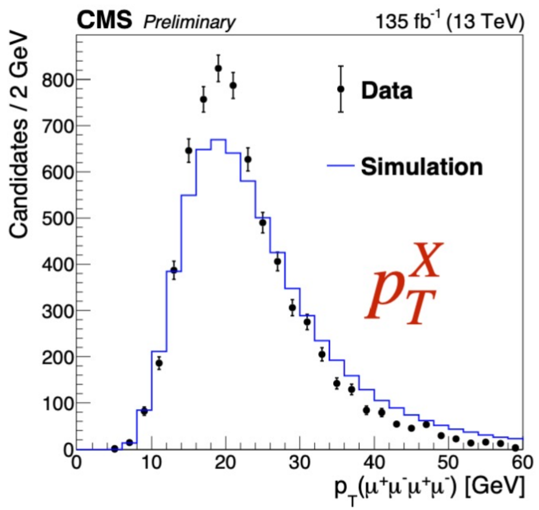
$f_{0_m^+}$: fraction of 0_m^+ signal component

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

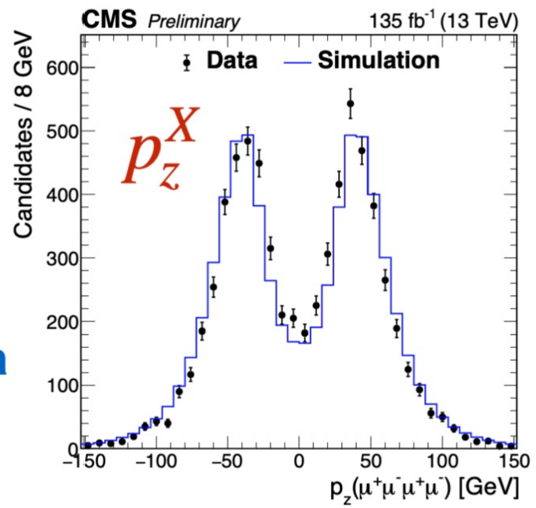


— tune **Pythia** to match p_T^X

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

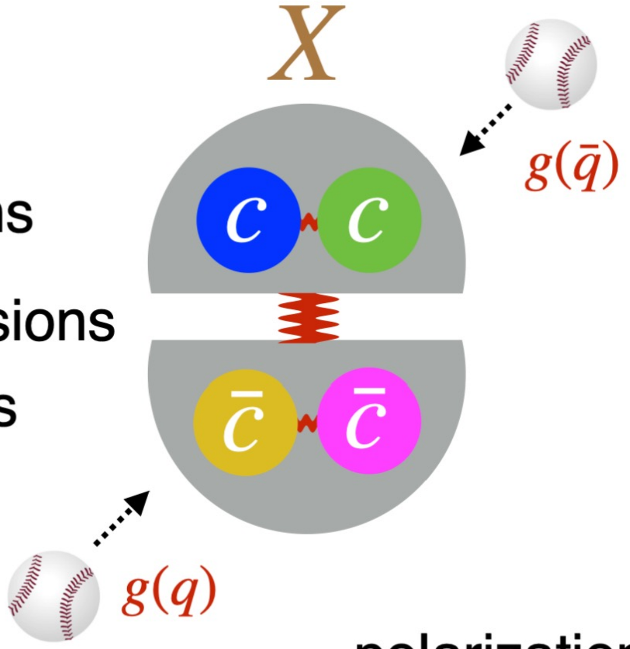
arXiv:2109.13363

MELA

matrix elements

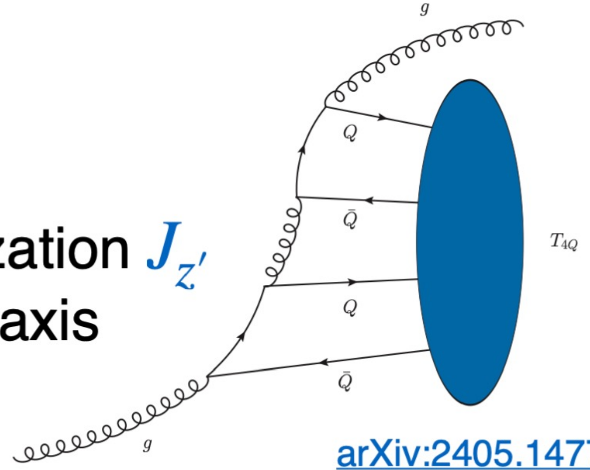
— re-weight $J = 1{,}2$ to unpolarized

— 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…

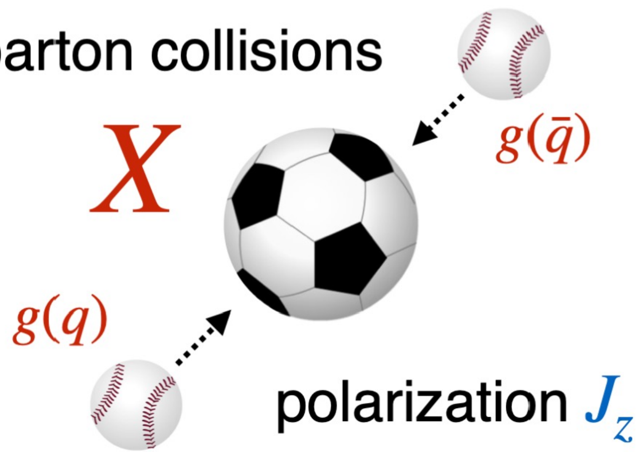
arXiv:1001.3396

$$
\begin{aligned}
& F^J_{0,0}(\theta^*) \times \left[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_{++})\right] \\
& \quad + |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) \\
& \quad + |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 \\
& \quad + 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_{++}) \\
& \quad + 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) \\
& \quad + 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) \\
& \quad + 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-}) \\
& \quad + 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+}) \\
& \quad + 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) \\
& \quad + |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 \left[2|A_{+-}||A_{-+}| \sin^2\theta_1 \sin^2\theta_2 \cos(4\Psi - \phi_{+-} + \phi_{-+})\right] + \text{other 26 interference terms for spin}
\end{aligned}
$$

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

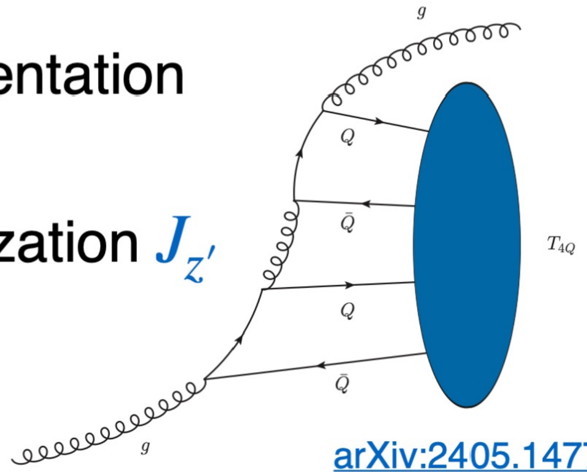
Polarization in Production

(A) parton collisions



(B) fragmentation

polarization $J_{z'}$



arXiv:2405.14773

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

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

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

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

Backup

arXiv:1001.3396

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

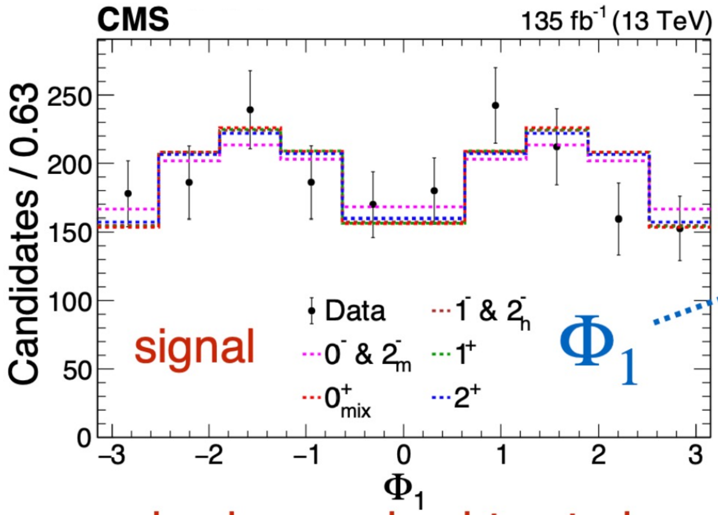
$$A(X_{J=1} \to V_1V_2) = \left(b_1(q^2) \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2(q^2) \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta \right)$$

1^- $\quad$ 1^+

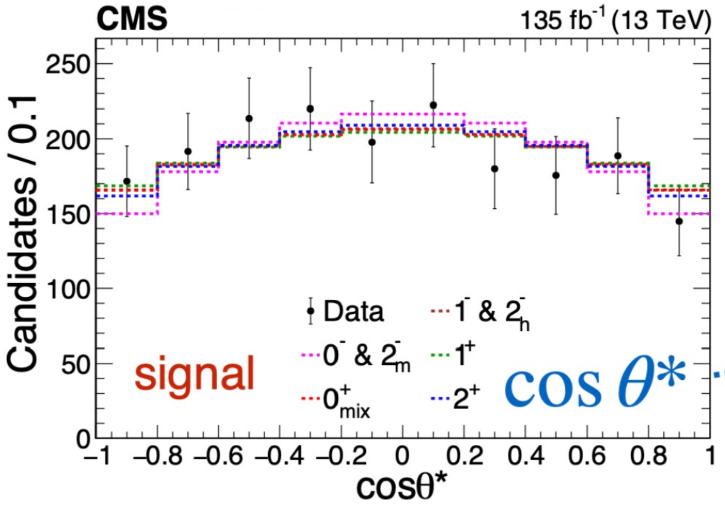
more for spin-2 $\quad A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$ $\quad A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$

Production Angles

(4) production angles consistent with unpolarized resonances

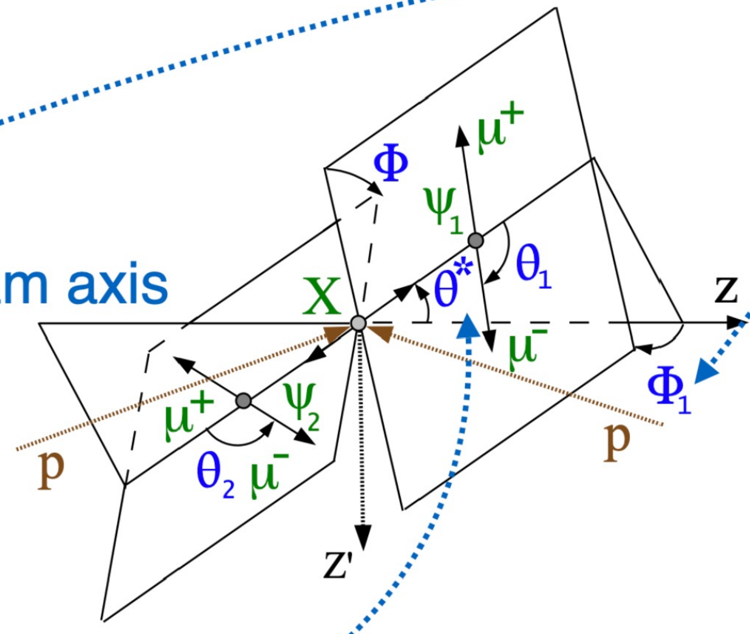


background-subtracted



with respect to the beam axis

beam axis

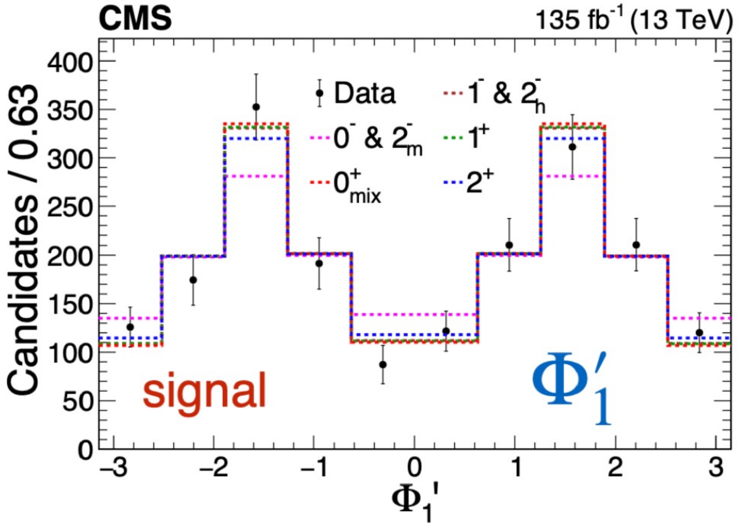


acceptance effects

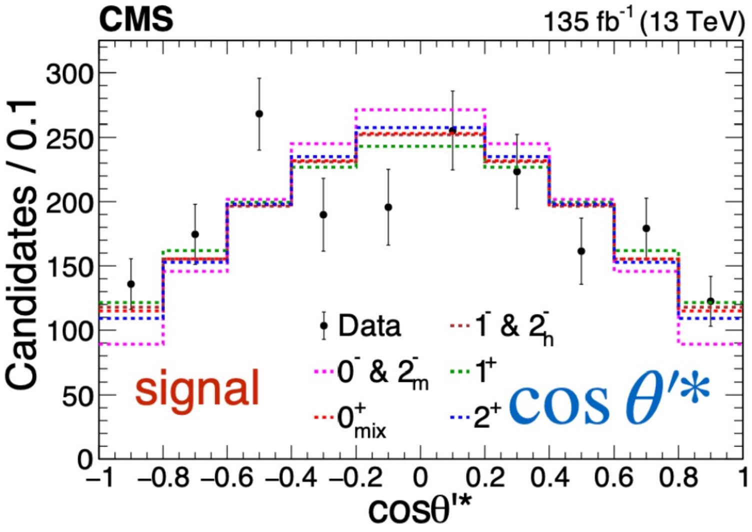
⇒ distributions not flat

Production Angles

(4) production angles consistent with unpolarized resonances

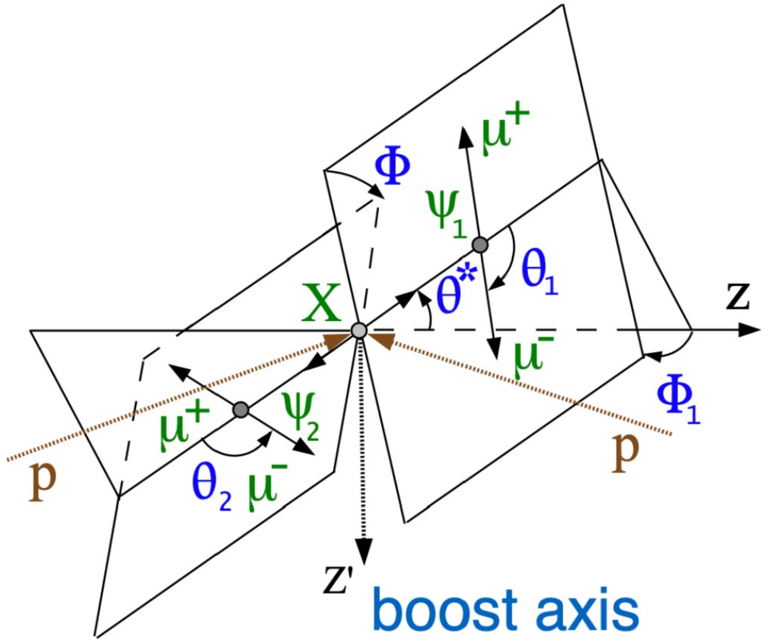


background-subtracted

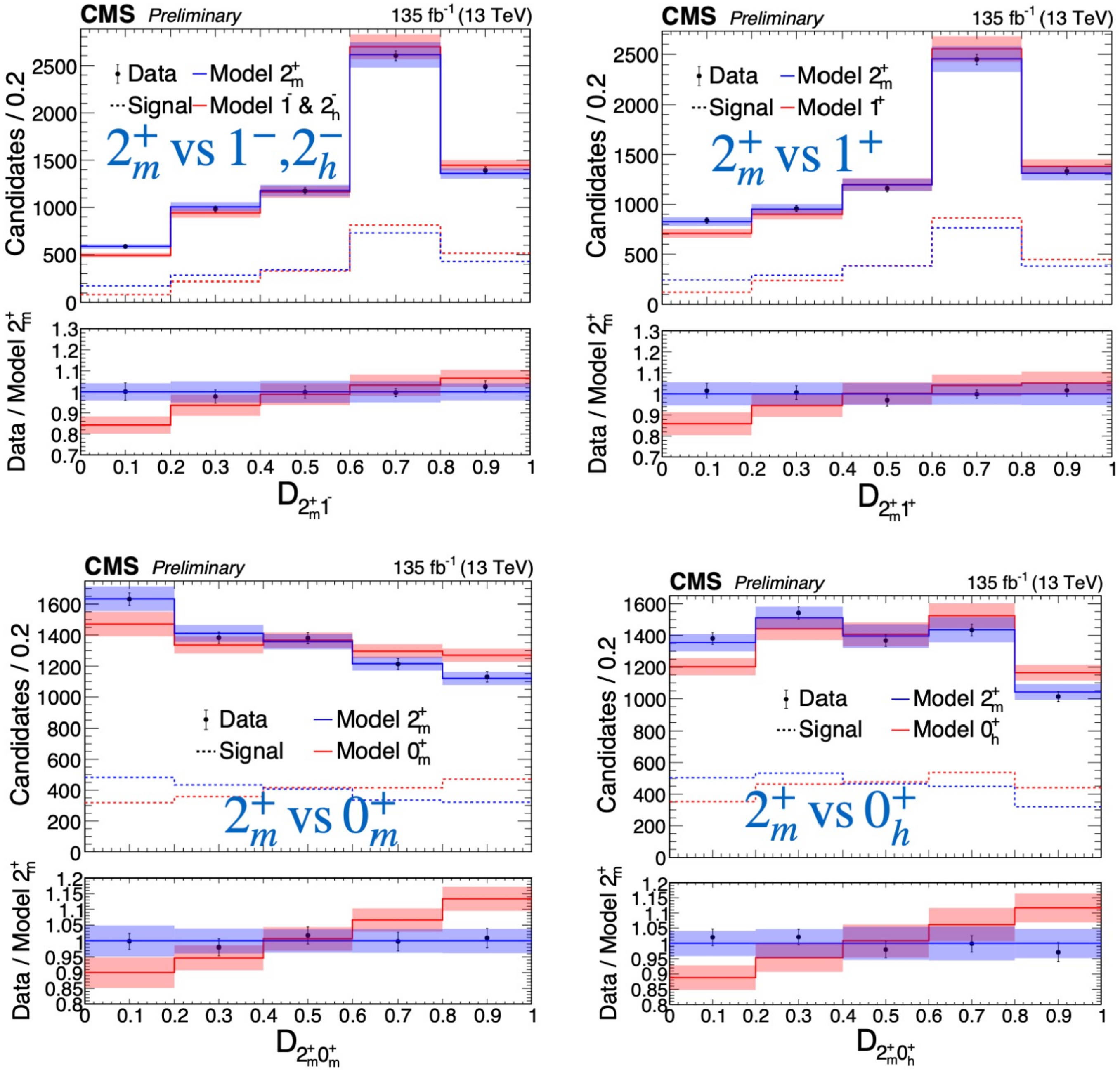


with respect to the boost axis

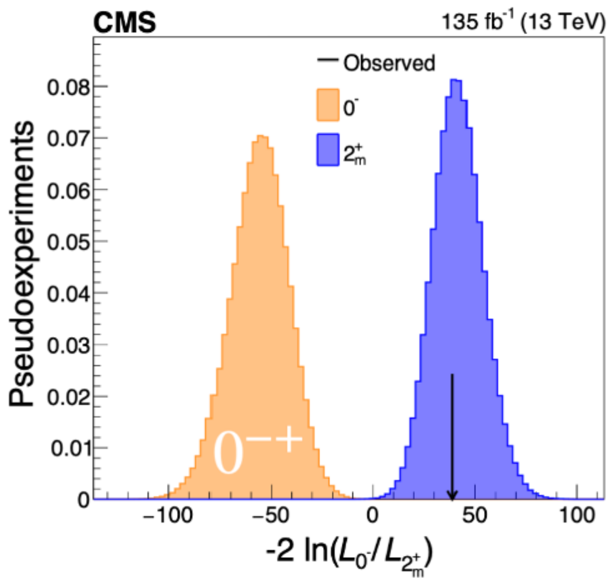
does not prove unpolarized

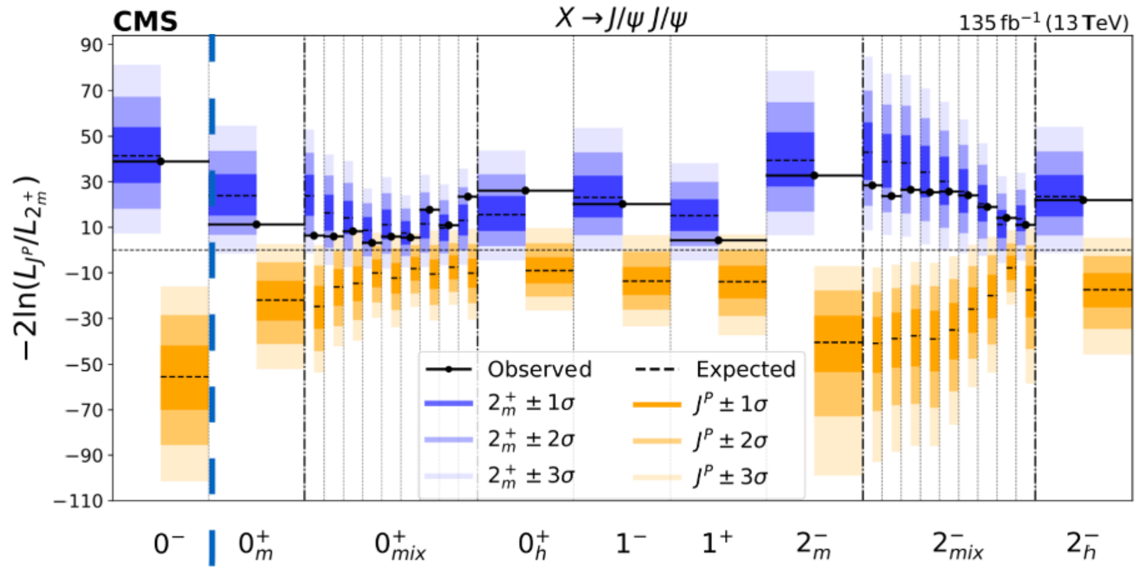


Discriminant Distributions



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:

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

– $J \neq 1$ 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 $0^+, 1^+$