Observation of a family of all-charm tetraquarks at CMS

Speaker Yilin Zhou (Fudan University & Nanjing Normal University)

Beijing, October 26, 2025

Outline

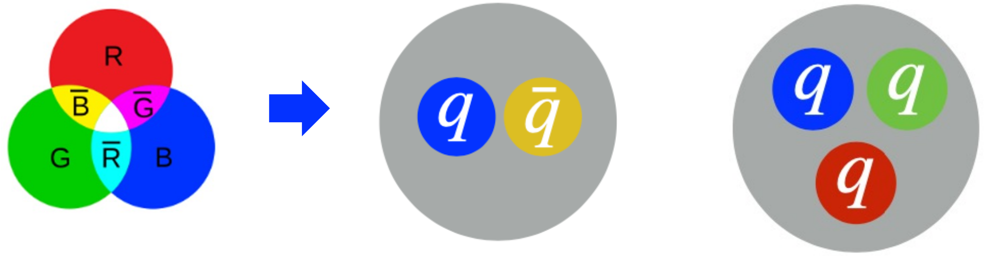
I. $J/\psi J/\psi$ spectroscopy in the four-muon final state using Run 3 data
PAS

II. Search for X(6900) in the $J/\psi\psi(2S)$ channel at CMS
PAS

III. Determination of the spin and parity of all-charm tetraquarks
PAS
PAPER

Classical quark model

Color Charge *Meson* *Baryon*

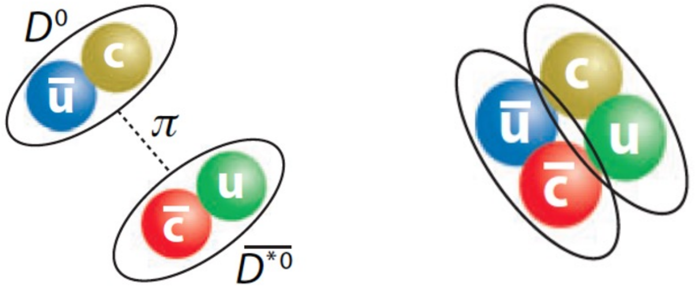


- **> 60 years of classical quark model**
  - **Experimentally tested at high energies; asymptotic freedom →Nobel Prize 2004**
  - **Success of Conventional Hadrons at low energies: non-perturbative quark model (confinement) →Nobel Prize 1969**
- **Exotic hadrons (Non-Conventional), no definitive conclusion yet**

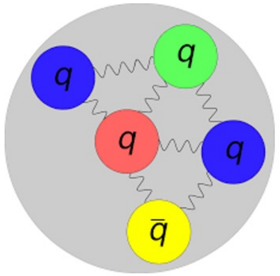
– currently a hot topic

"Exotic" hadron

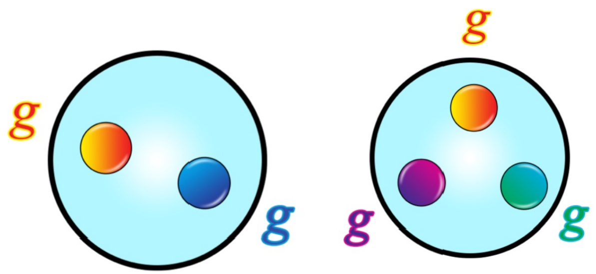
Molecule *Diquark-antidiquark*



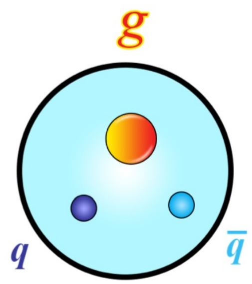
tetraquark



pentaquark

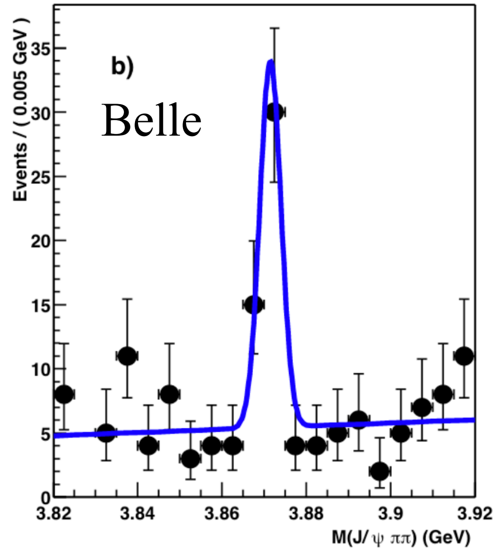


Glueball

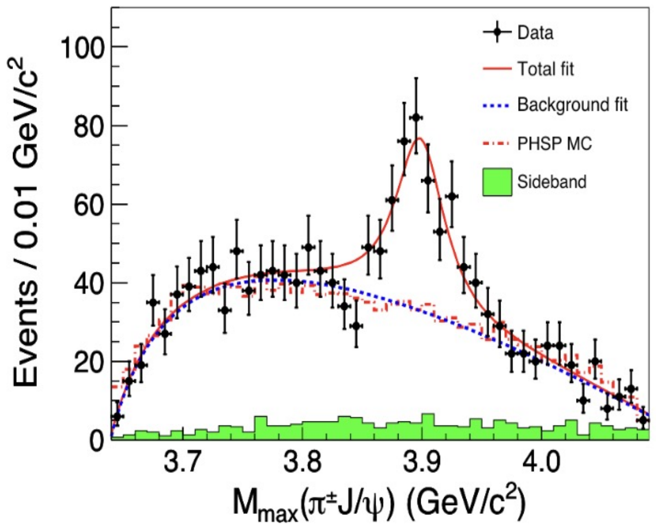


Hybrid

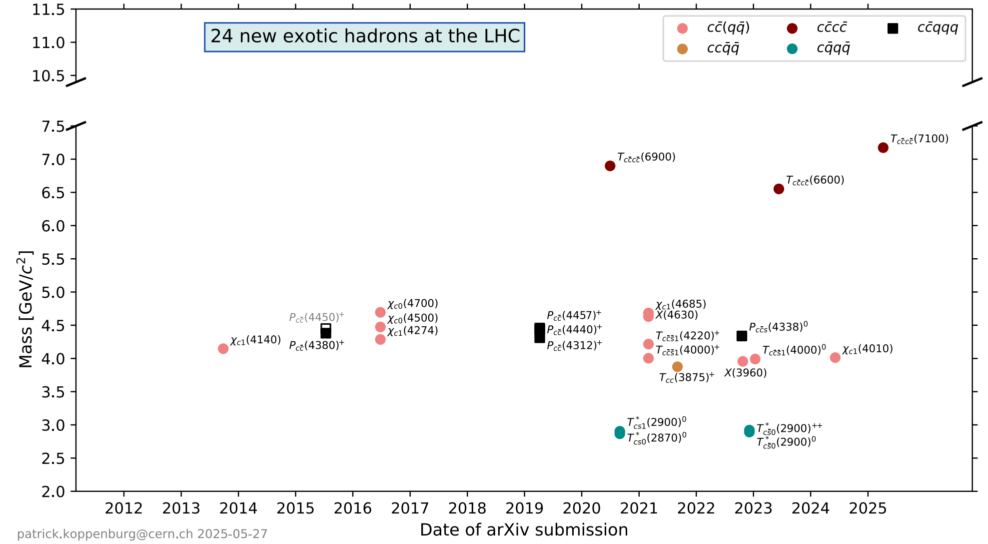
X(3872) [$uc\bar{u}\bar{c}$]



$Z_c^+(3900)$



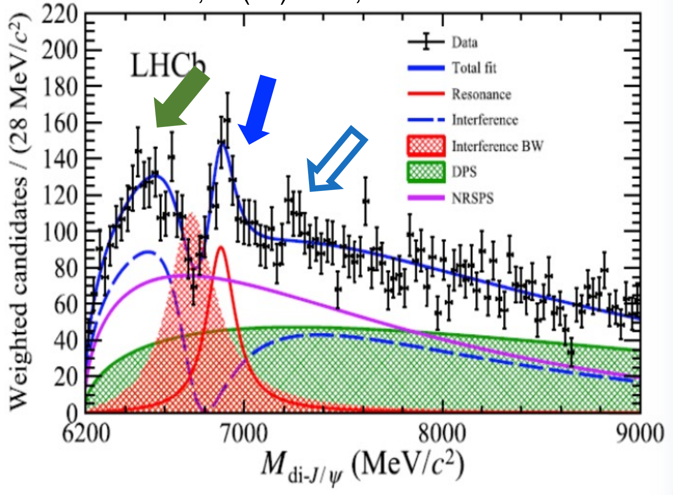
24 exotic hadrons at LHC

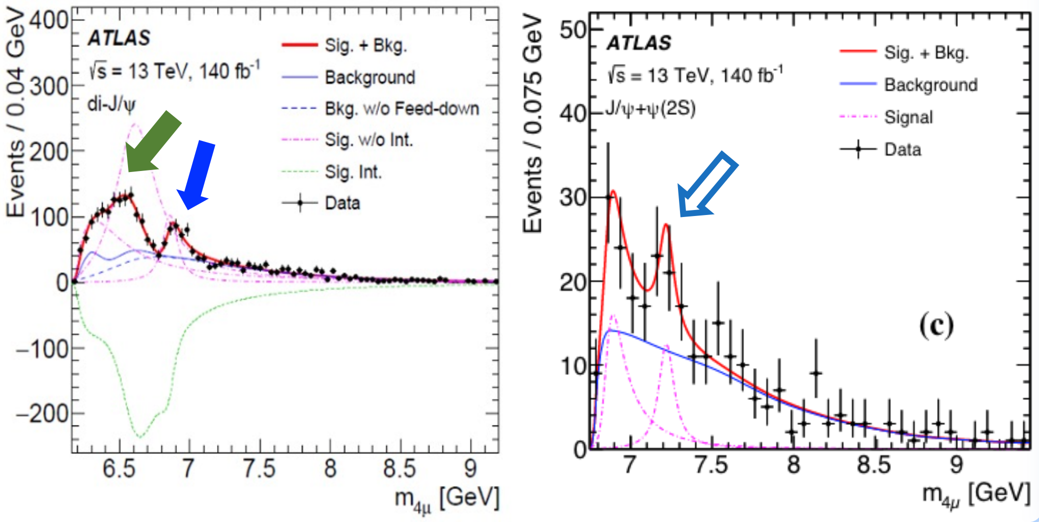


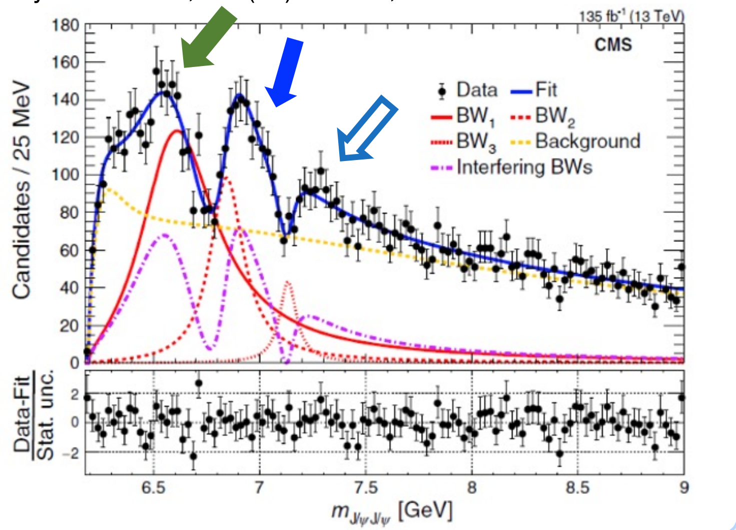
- **Light exotics** likely exist, but light-meson sector too messy for clear identification
- **Heavy-flavor exotics**: larger quark mass relative to Λ_{QCD}, theoretical treatments more reliable
- **X(3872),** kicked off a boom in **(heavy-flavor) exotic hadron,** dozens of XYZ found
- **Zc(3900),** carries charge and couples to charmonium
- **Fully-heavy exotic hadrons, promising and accessible for theoretical exploration**

Status of of all-charm tetraquark

LHCb	ATLAS	CMS
Sci. Bull., 65(23):1983, 2020	Phys. Rev. Lett., 131(15):151902, 2023	Phys. Rev. Lett., 132(11):111901, 2024







- ❖ **ALL exp observe X(6900)** **+ additional structure**

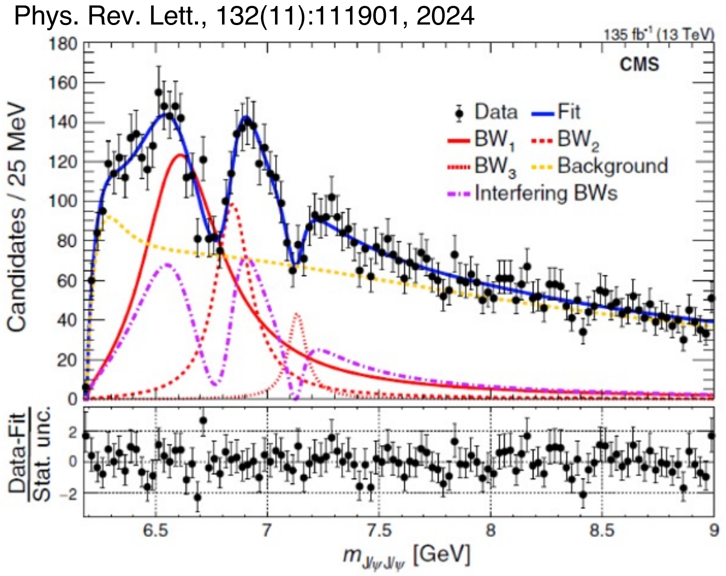
  Hump @ 6.6 GeV: Different modeling

  Hint @ 7.2 GeV: LHCb not consider; ATLAS 3σ hint in $J/\psi\psi(2S)$

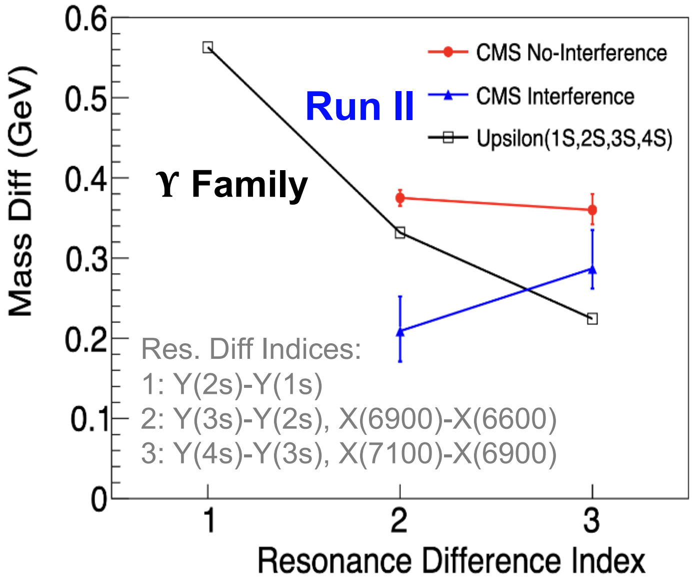
- ❖ **CMS first observed X(6600) & evidence of X(7100)**

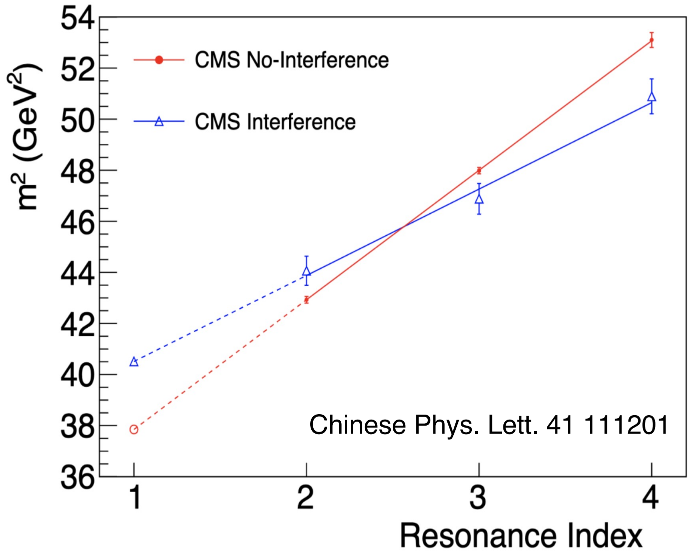
- ❖ **All exp use interference, but in diff ways**

CMS Run 2 mass spectrum



CMS Run 2 Regge plot





Run 2 result:

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

With 3.6X statistics:

- **ALL states over 5σ ?**
- **Interference over 5σ ?**

- Interference imply same J^{PC} quantum numbers
- > 200 MeV mass splittings ==> Radial excitations ?

Cornell Model: $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r + \ldots$

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

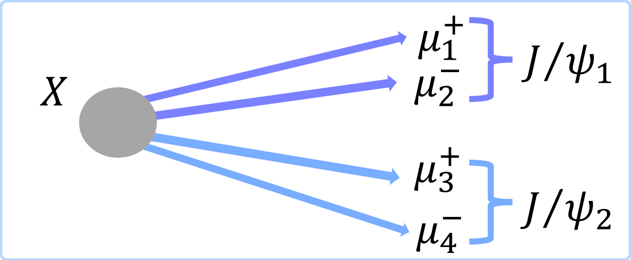
$J/\psi J/\psi$: Datasets, MC, trigger, and event selection

❖ Data samples [315 fb^{-1}]

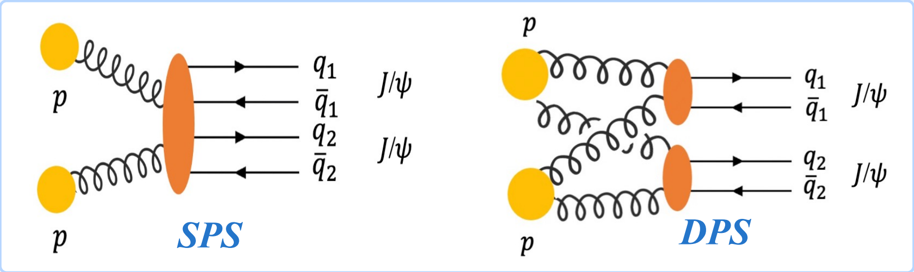
- Run 2: 135 fb^{-1} data taken in 2016, 2017 and 2018.
- Run 3: 180 fb^{-1} data taken in 2022, 2023 and 2024.

❖ Signal and Background simulated events:

- Signal $X \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ by **JHUGen**



- NRSPS, DPS by **Pythia8 or event-mixing**



- Feeddown by **Pythia8**: $X(6900) \to J/\psi\psi(2S) \to J/\psi J/\psi + anything$

Feeddown from X(7100) in systematics

❖ Trigger of Run 3

HLT_Dimuon0_Jpsi3p5_Muon2

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

HLT_DoubleMu4_3_LowMass [new trigger for Run 3 Parking data]

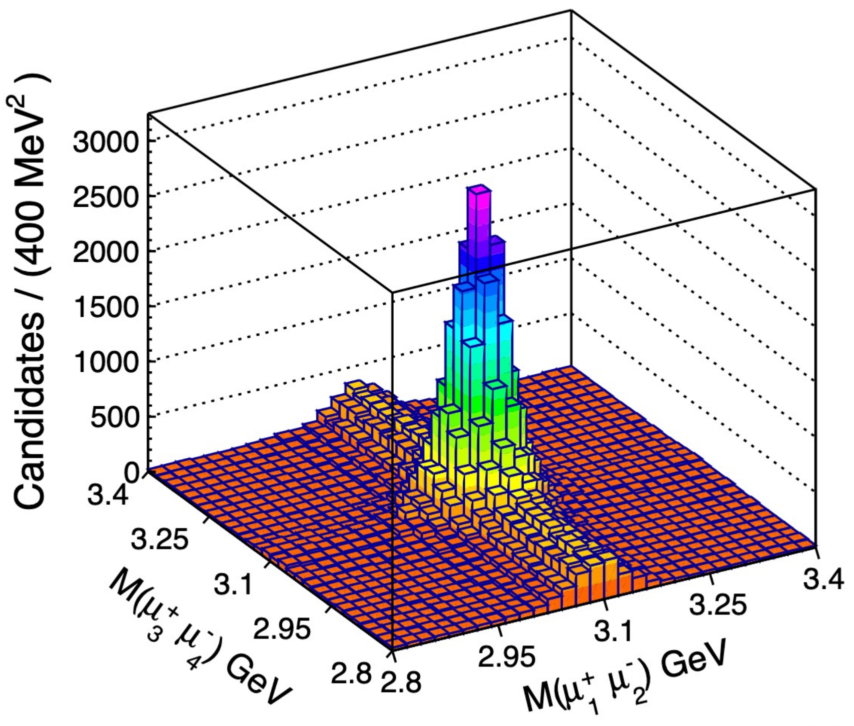
- **Level 1 requirements: 2 muons**
- $0.2 < M(\mu^+\mu^-) < 8.5\ GeV$
- one muon $p_T(\mu) > 4\ GeV$ and the other $p_T(\mu) > 3\ GeV$
- $p_T(\mu^+\mu^-) > 4.9\ GeV$

➢ Compared to only Dimuon trigger, LowMass trigger **increase 30% $J/\psi J/\psi$ statistics**

❖ Event selection of Run 3

Follow PRL cuts + A new trigger for Run 3

2D distributions of double-dimuon masses



- **Luminosity**

Run 2: 135 fb^{-1}

Run 3: 180 fb^{-1}

- **J/ψJ/ψ yield**

Run 2 ~12622 ± 165

Run 3 ~31802 ± 476

- **J/ψJ/ψ yield per unit luminosity**

Run 2 ~93 events / fb^{-1}

Run 3 ~177 events / fb^{-1}

➢ **Run 2+3 J/ψJ/ψ yield is 3.6X of Run 2**

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

Baseline mass variable

– invariant mass of two constrained J/ψ candidates

$J/\psi J/\psi$: Signal and Background models

- **Signal shape: Relativistic Breit-Wigner**
- **Background component:**

  NRSPS + NRDPS + Comb + Feeddown + 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**

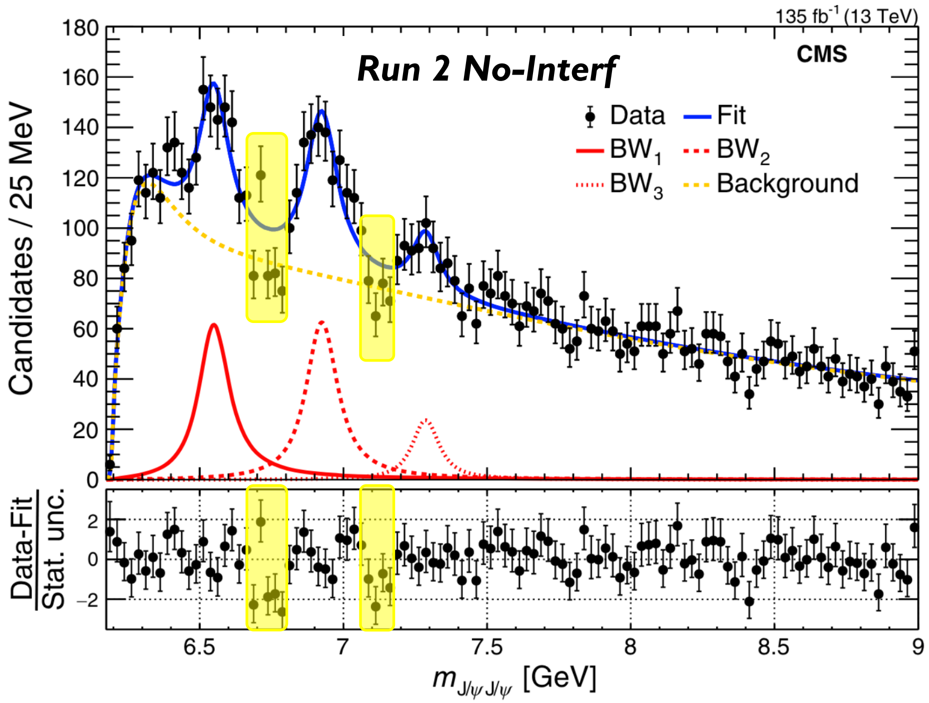
$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m)$$
$$+ N_{NRDPS} \cdot f_{NRDPS}(m) + N_{Comb} \cdot f_{Comb}(m) + N_{Feedown} \cdot f_{Feeddown}(m)$$

❖ Interference model:

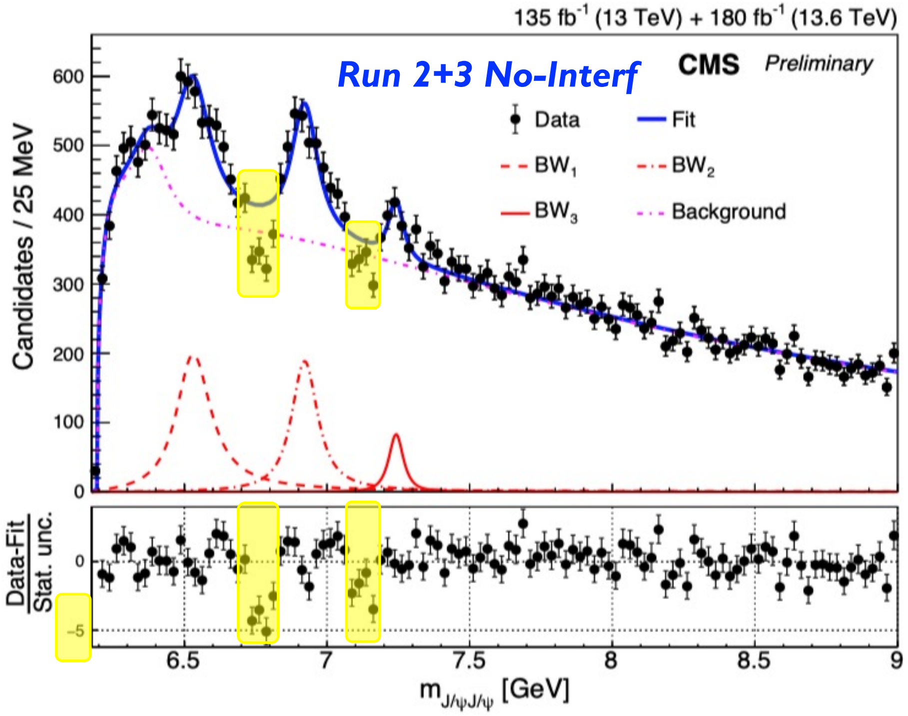
- **Signal-hypothesis:** NRSPS+NRDPS+Comb+Feeddown+BW0**+BW123 Interf. Term**

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

CMS Run 2 noninterference fit result



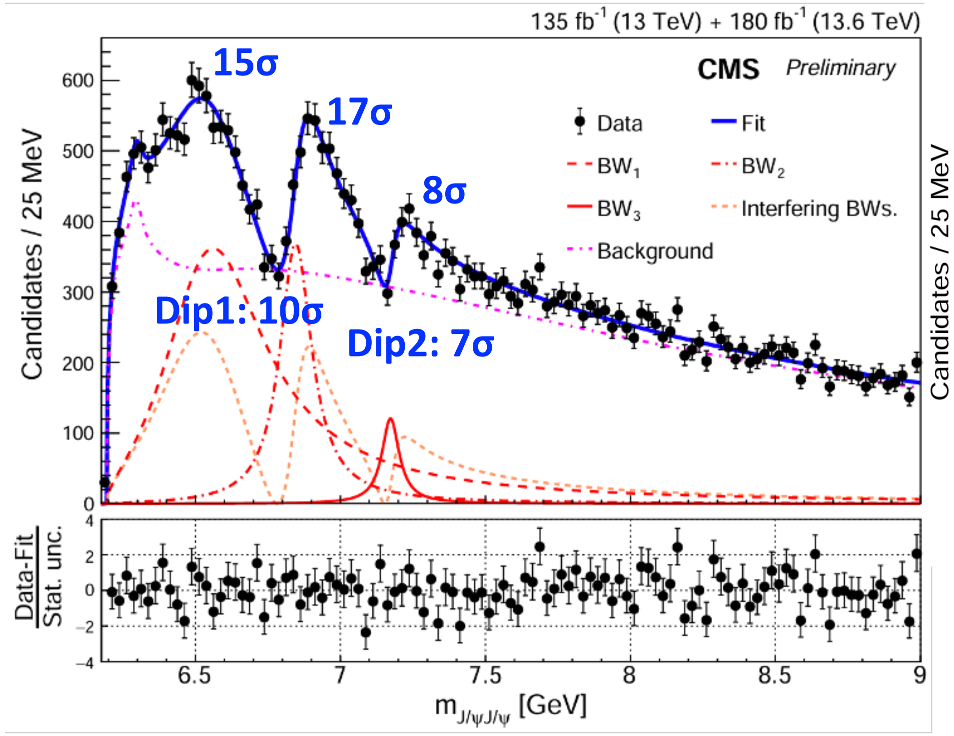
CMS Run 2+3 noninterference fit result

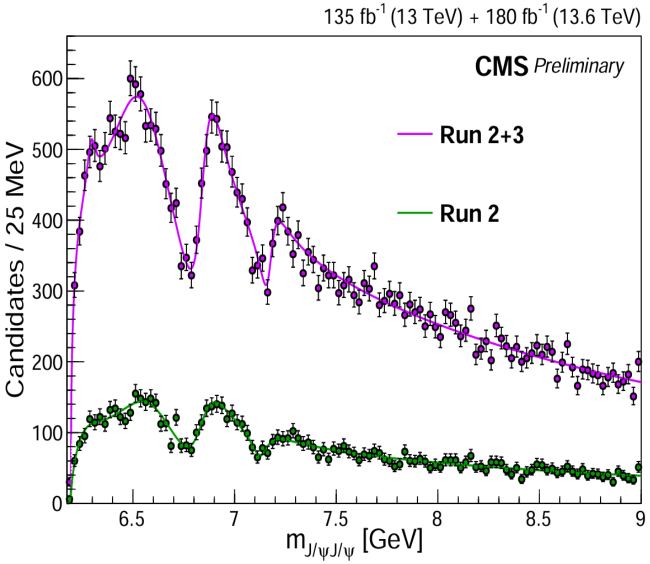


- **Dips poorly described — *no-Interf. model no longer sufficient !***

  ➢ **Let's now look at the fit results including interference**

CMS Run 2+3 interference fit result





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

❖ **VS. Run II result:**
- ✓ **Statistical uncertainty** reduced by **a factor of 3**
- ✓ **Systematic uncertainty** reduced by about **a factor of 2**

- ➢ **All states and dips well above 5σ !**
- ➢ **Quantum interference among structures validated!**
- ➢ **With improved precision, large mass splittings persist**

$J/\psi\psi(2S)$: Run 2+3 interference fit result

- **Motivation**
  - Seen in $J/\psi J/\psi$, probably in $J/\psi\psi(2S)$?
  - CMS $J/\psi\psi(2S)$ analysis started at the same time as $J/\psi J/\psi$ in 2020
- **A background suppression** with FOM value:

  S: number of X(6900) in signal MC   B: number of background in data

  $$S/\left(463/13 + 4\sqrt{B} + 5\sqrt{25 + 8\sqrt{B} + 4B}\right)$$

$p_T(J/\psi) > 11.0$ GeV

$p_T(\psi(2S)) > 13.5$ GeV

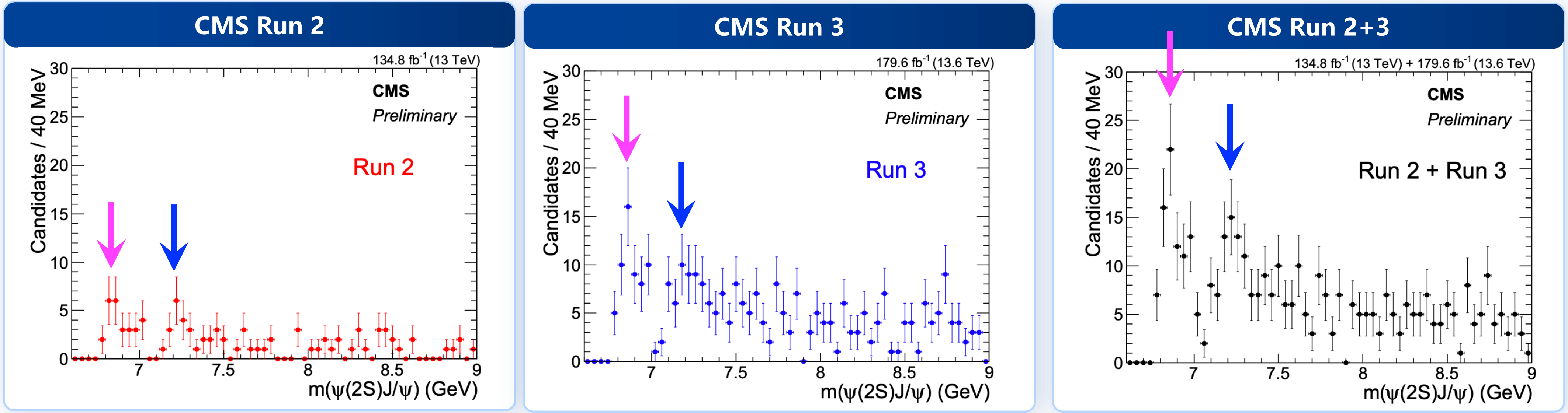
$p_T(\mu_{\text{in }\psi(2S)}) > 2.5$ GeV

$\mu_{\text{in }\psi(2S)}$ ID: Loose muon

Mass window for J/ψ and $\psi(2S)$: 2.5σ window

- **$J/\psi\psi(2S)$ yield:**

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



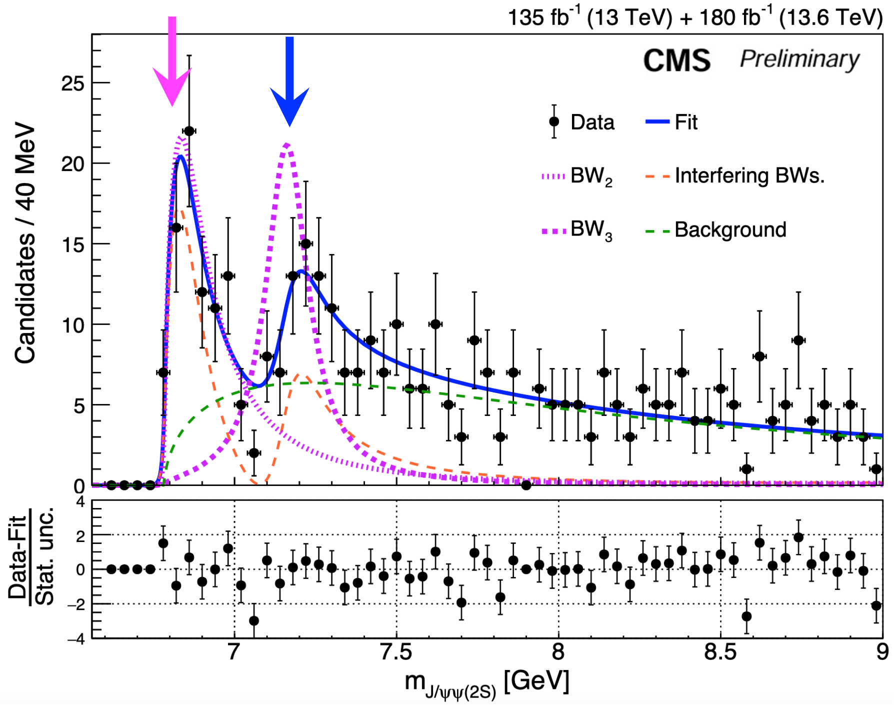
❖ Interference model:

Signal-hypothesis: NRSPS+NRDPS+Comb **+BW23 Interf. Term**

Consider resolution and efficiency

$$Pdf(m) = N_{X-\mathrm{interf}} \cdot \boxed{\left|\sum (r_k \cdot \exp(i\phi_k) \cdot BW(m, M_k, \Gamma_k))\right|^2 \otimes R(M_j) \cdot \epsilon(M_j)} + N_{SPS} \cdot f_{SPS}(m) + N_{DPS} \cdot f_{DPS}(m) + N_{\mathrm{Combinatorial}} \cdot f_{\mathrm{Combinatorial}}(m),$$

CMS Run 2+3 $J/\psi\psi(2S)$ fit result



- Constrain mass & width within 1σ of $J/\psi J/\psi$ values

X(6900) = 7.9σ

X(7100) = 4.0σ

Dip = 2.5σ

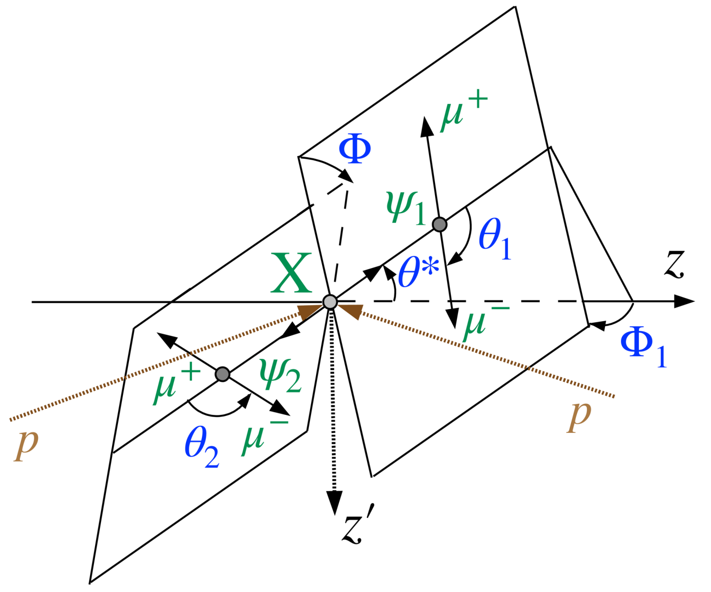
- An independent measurement with $J/\psi J/\psi$ mass/width constraints removed

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)	$154^{+110+140}_{-82-160}$	$73^{+18}_{-15} \pm 10$

❑ Framework

- $m_{4\mu}$ spectrum $X \to 4\mu$ — identical to Phys. Rev. Lett. 132 (2024) 111901
- p_T and p_Z of $X \to 4\mu$ — match MC to data
- Polarization of X — assume unpolarized

Angular observables



▪ Production angles *[for data test]*

- ϑ^* : angle between beam line and J/ψ momentum in X rest frame
- Φ_1: azimuthal angle between production plane and decay plane in X rest frame

▪ Decay angles *[for data analysis]*

- Φ : azimuthal angle between two l^+l^- decay planes defined in X rest frame
- ϑ_1 : helicity angle between opposite of J/ψ_2 momentum and l momentum defined in J/ψ_1 rest frame
- ϑ_2 : helicity angle between opposite of J/ψ_1 momentum and l momentum defined in J/ψ_2 rest frame

- After symmetries conditions, **8 models of J_x^P to test:**

$$0^-, 0_m^+, 0_h^+,\ 1^-, 1^+,\ 2_m^-, 2_h^-, 2_m^+$$

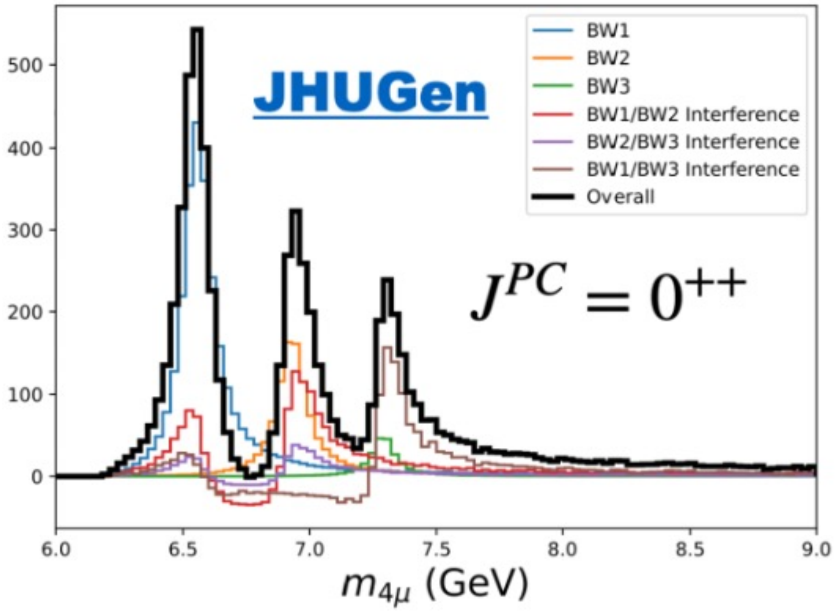
***m**: minimal dimension operators*
***h**: higher-dimension operators*

  - Full model possible, but complex

$$\mathcal{P}(\Phi, \vartheta_1, \vartheta_2; m_{4\mu})$$

  - Same properties of 3 resonances:

$$\mathcal{P}\left(m_{4\mu}, \vec{\Omega}\right) = \underbrace{\mathcal{P}\left(m_{4\mu}\right)}_{\textit{empirical}} \cdot \underbrace{T\left(\vec{\Omega} \,\middle|\, m_{4\mu}\right)}_{\textit{angular}},\ \vec{\Omega} = (\Phi, cos\theta_1, cos\theta_2)$$



  - **Pairwise test of J_x^P hypotheses i and j**

1 optimal observable

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

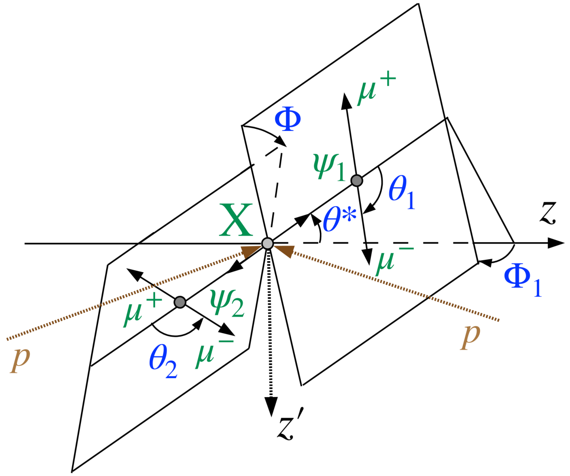
MELA *Higgs discovery and spin-parity*

  - **Final 2D model:**

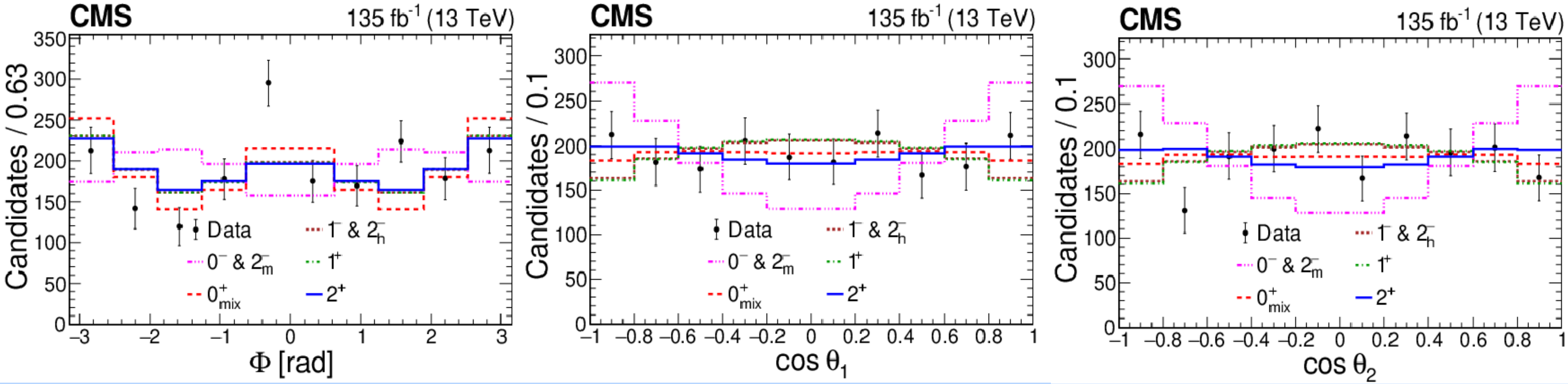
$$\mathcal{P}_{ijk}\left(m_{4\mu}, \mathcal{D}_{ij}\right) = \mathcal{P}_k\left(m_{4\mu}\right) \cdot T_{ijk}\left(\mathcal{D}_{ij} \,\middle|\, m_{4\mu}\right)$$

❖ Decay angles *background-subtracted*

- 1D projections
- **Limited information**
  - see 0^- not align
  - hard distinguish $1^\mp$



Distribution of the decay angles



❖ Optimal Observable

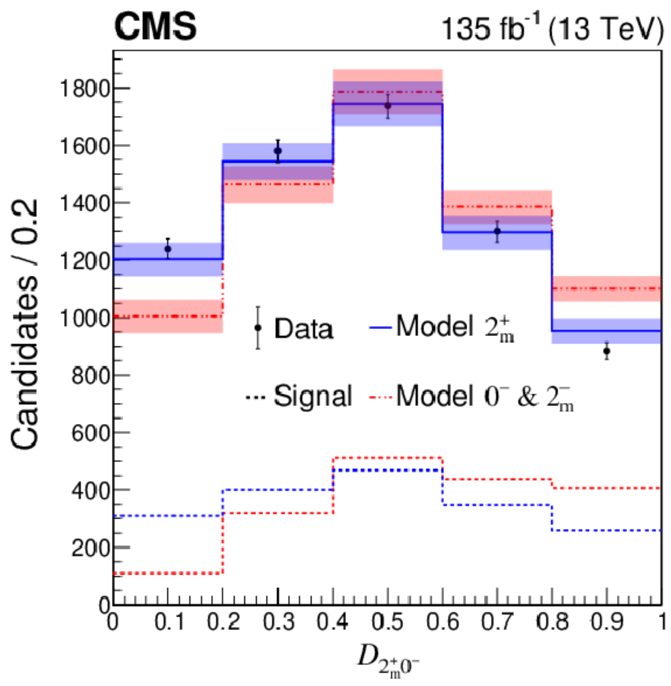
- **1D projection of data**

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

1 optimal observable

MELA *Higgs discovery and spin-parity*

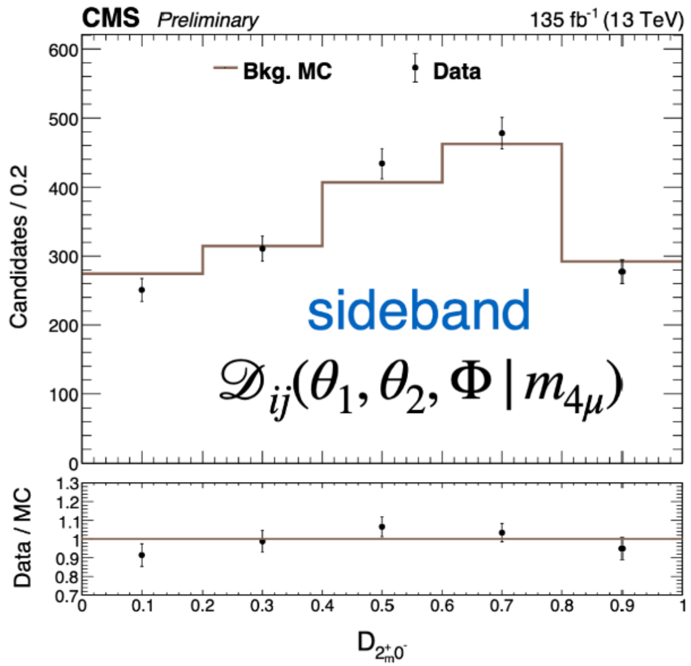
Distributions of discriminants



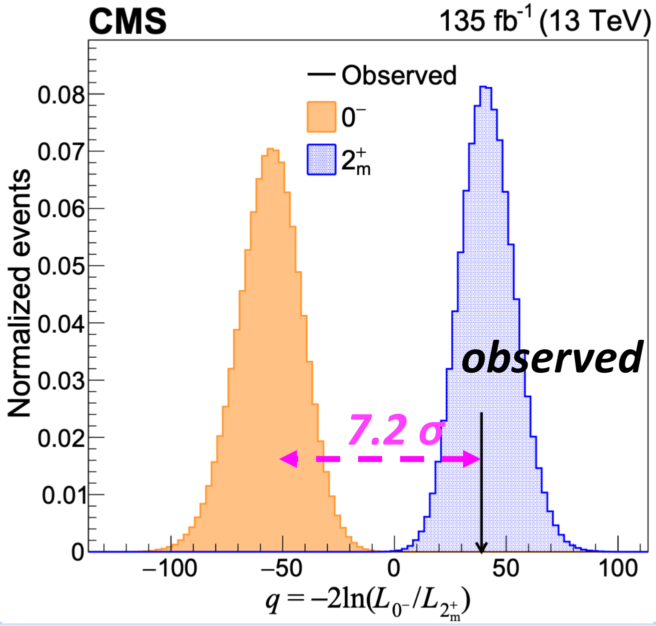
$j = 0^-(2^-_m)$ vs $i = 2^+_m$

- **Background 1D projection**

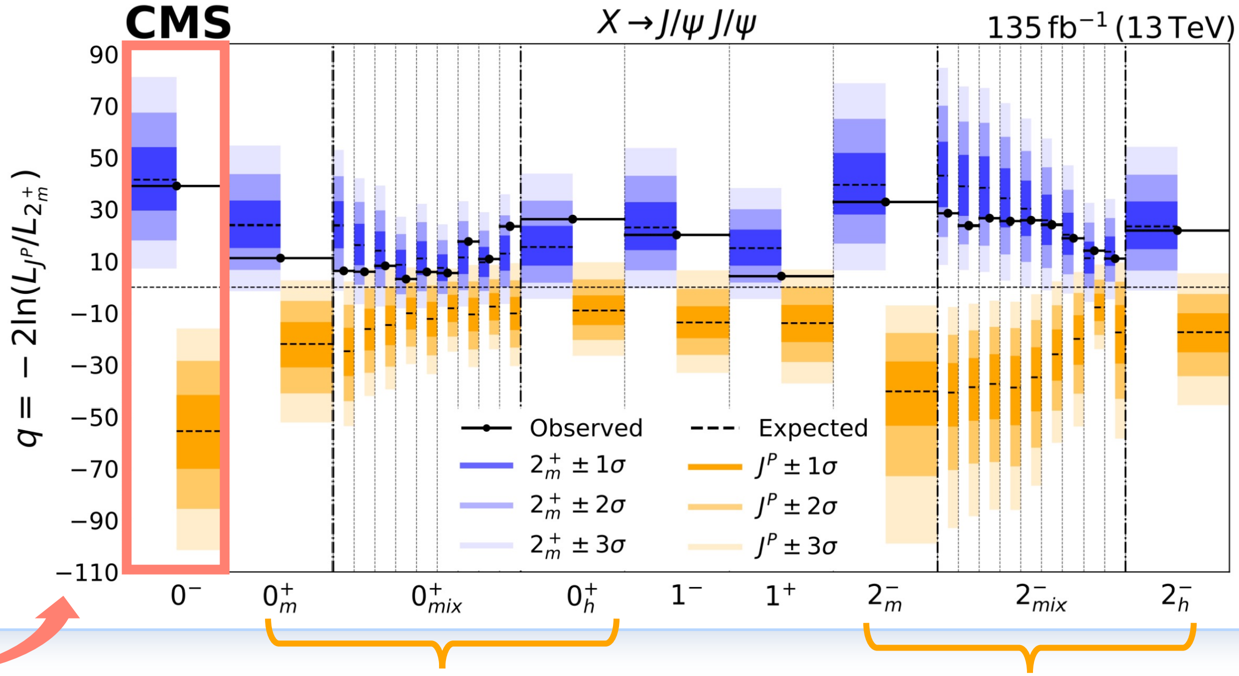
Control Background MC using Data sideband



Distributions of test statistic q



Summary of statistical tests



		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

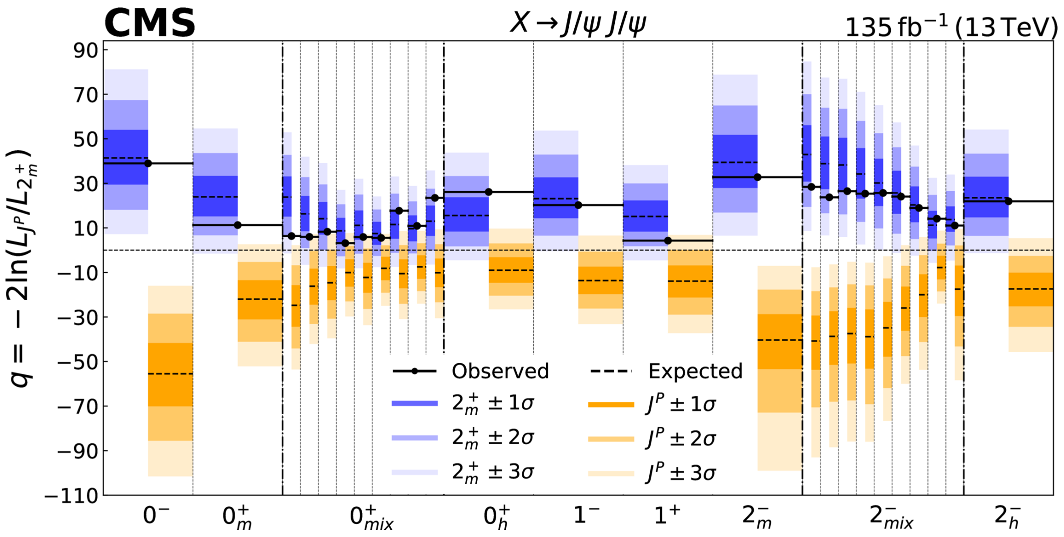
- Scan **mixture of two** 0^{++} , 2^{-+} amplitudes

✓ *Data are* **consistent with** 2^{++} *model, inconsistent with others*

❖ **Combine 2D fit** $\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij})$

- $PC = ++$ very certain, $P \neq -1$ **very certain =>** $L \neq 1$
- $J \neq 1$ at 99% CL
- $J \neq 0$ at 95% CL
- $J > 2$ unlikely, require $L \geq 2$, $L = 0$ **most likely**

➤ $J^P = 2^+_m$ ***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
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

arXiv:2506.07944 **[hep-ex]**

❖ A family of all-charm tetraquarks with $J^{PC} = 2^{++}$

- X(6600), X(6900), and X(7100) well above 5σ

  ==> Multiple states makes comparisons possible

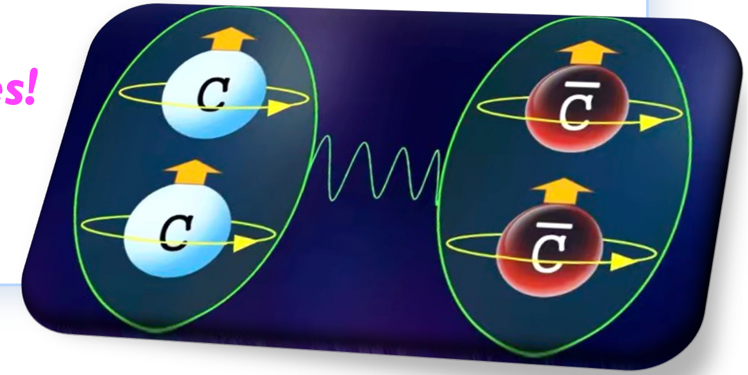
- Quantum interference among structures validated well above 5σ

  ==> States have common J^{PC}, measured as 2^{++}

- Large mass splittings, more precisely

  ==> radial family of states

CMS is painting a coherent picture of all-charm tetraquark structures!

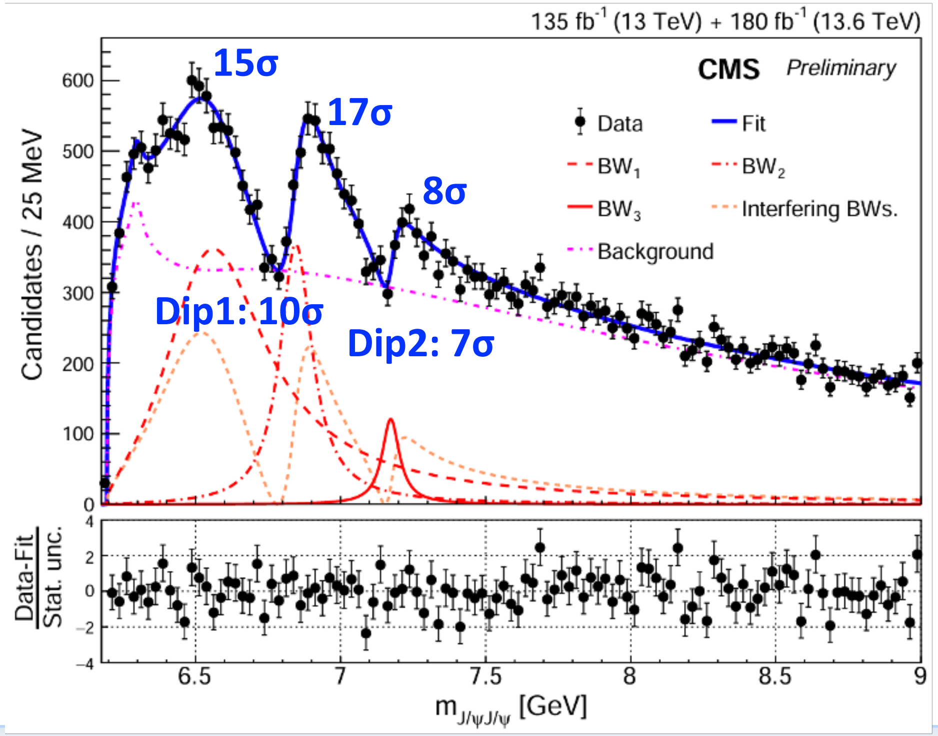


THANKS!

BACKUP

$J/\psi J/\psi$ Run II & III interference fit result

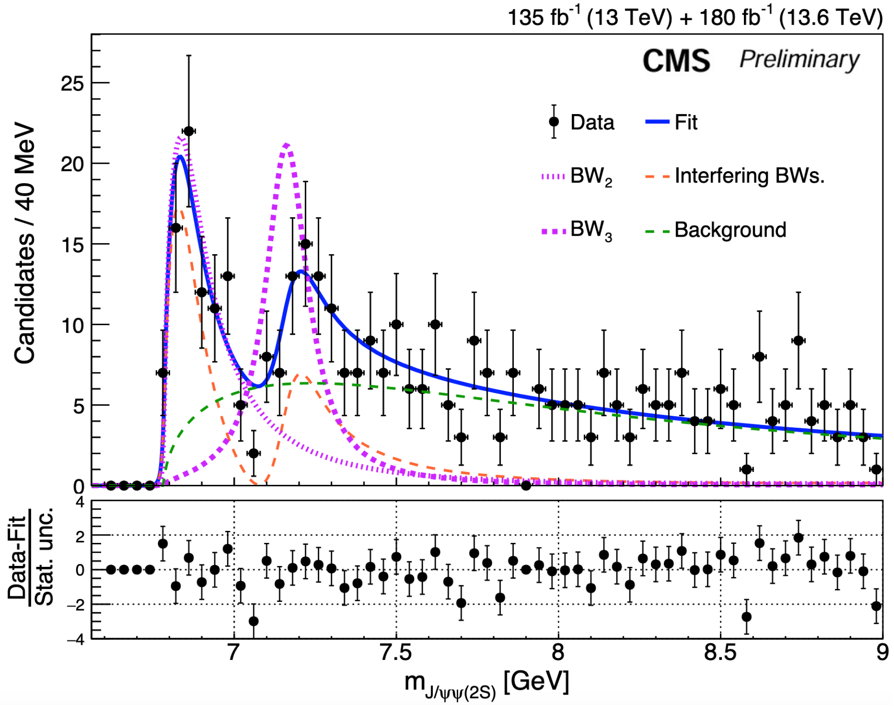
CMS Run 2+3



Dominant sources	Δm_{BW_1}	$\Delta\Gamma_{BW_1}$	Δm_{BW_2}	$\Delta\Gamma_{BW_2}$	Δm_{BW_3}	$\Delta\Gamma_{BW_3}$
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

$J/\psi\psi(2S)$ Run II & III interference fit result

CMS Run 2+3



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	$^{+110}_{-110}$	$^{+120}_{-120}$	$^{+74}_{-70}$	$^{+140}_{-160}$

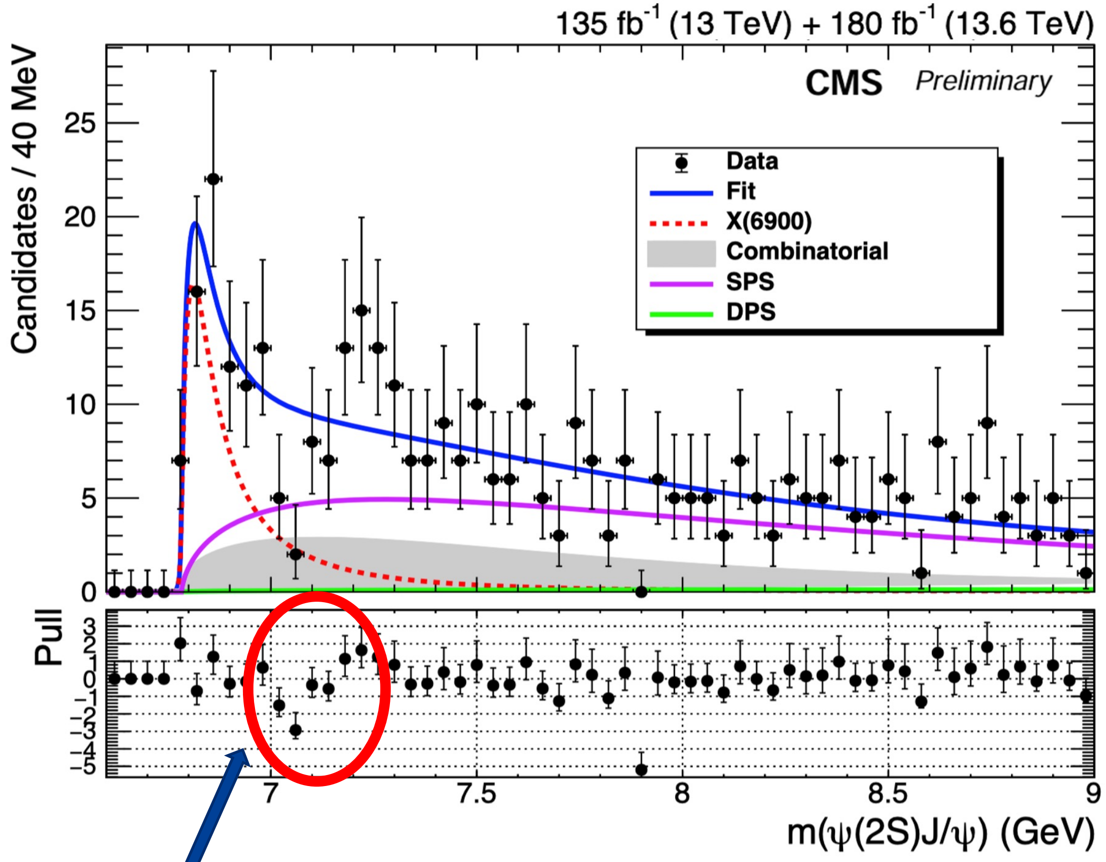
Params	$J/\psi\psi(2S)$ [MeV]	$J/\psi J/\psi$ [MeV]
M(BW2)	$6876^{+46+110}_{-29-110}$	$6847 \pm 10 \pm 15$
Γ(BW2)	$253^{+290+120}_{-100-120}$	$135^{+16}_{-14} \pm 14$
M(BW3)	7169^{+26+74}_{-52-70}	$7173^{+9}_{-10} \pm 13$
Γ(BW3)	$154^{+110+140}_{-82-160}$	$73^{+18}_{-15} \pm 10$

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

ATLAS only claim X(6900) 4.7σ in $J/\psi\psi(2S)$ channel

$J/\psi\psi(2S)$ Run II & III interference fit result

Only consider X6900



χ2/ndf = 0.82

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

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

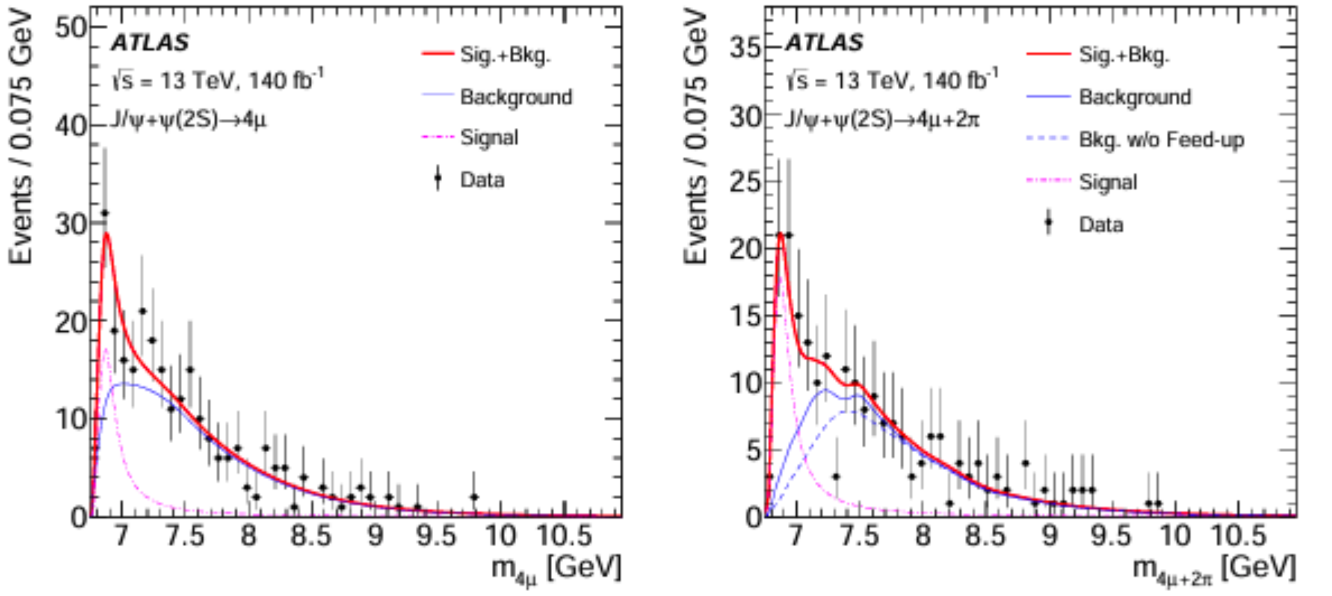
Significance of **X(6900) = 7.5 σ**

Deviations from fit: something more?

Update of $J/\psi\psi(2S)$ from ATLAS

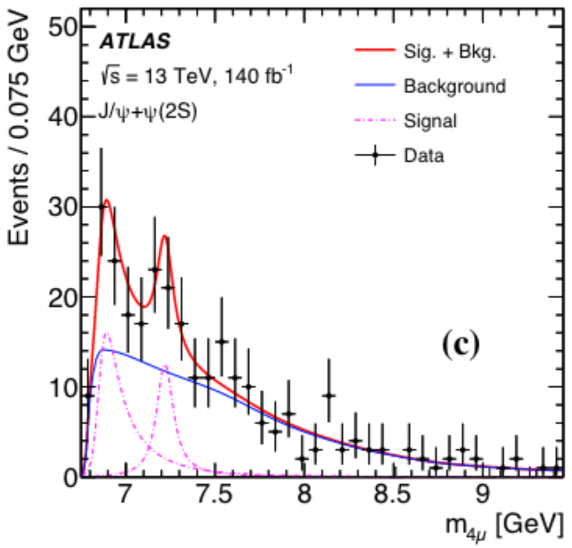
- **Simultaneous fit of 3 channels:** arXiv:2509.13101
  J/ψJ/ψ, J/ψψ(2S) [4μ], J/ψψ(2S) [4μ+2π]

Model C: Simultaneous fit for J/ψψ(2S) [4μ and 4μ+2π]



ATLAS 2023 paper

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



- **X(6900) 8.9σ** from model C
- Set a upper limit of **0.41 @95%CL** for X(7200)
- **In ATLAS 2023 paper, X(7200) 3σ in J/ψψ(2S) [4μ]**

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

_m : minimal
_h : high complexity

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