Observation of a family of all-charm tetraquarks

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Overview—Three new results based on the following CMS Physics Analysis Summary

- **1). *J/ψJ/ψ* updated result:** ***Led by NNU-FDU-THU*** **南京师范大学、复旦大学等单位**
  J/ψJ/ψ spectroscopy in the four-muon final state using Run 3 data

- **2). Spin-parity measurement:** ***Led by NNU-JHU-THU*** **南京师范大学、霍普金斯大学、清华大学等单位**
  Spin-parity analysis of the J/ψJ/ψ structure in the four-muon invariant mass spectrum

- **3). *J/ψψ*(2S) result:** ***Led by NNU-THU*** **南京师范大学、清华大学等单位**
  Search for X(6900) in the ψ(2S)J/ψ channel at CMS

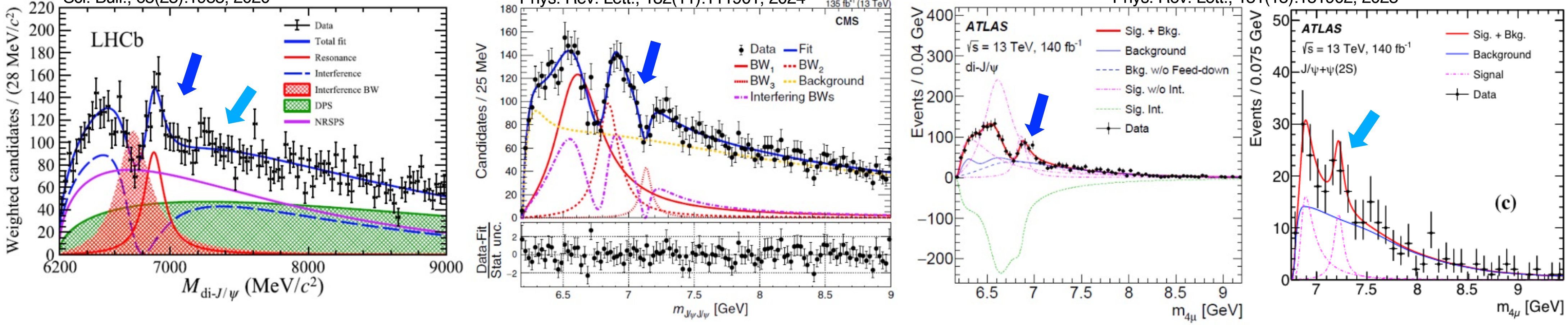
1) and 3) are the first two LHC analyses used 2024 data

Outline

- **Motivation**
- **Spin-parity measurement**
- $J/\psi\psi(2S)$ **result**
- $J/\psi J/\psi$ **updated result**
- **Interpretations and summary**

Status

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



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

- Only CMS claimed X(6600) & X(7100)
- Different modeling of “hump” **@6.6 GeV**
- **Hint @ 7.2 GeV**: LHCb not considered; ATLAS 3σ (local) hint in $J/\psi\psi(2S)$

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

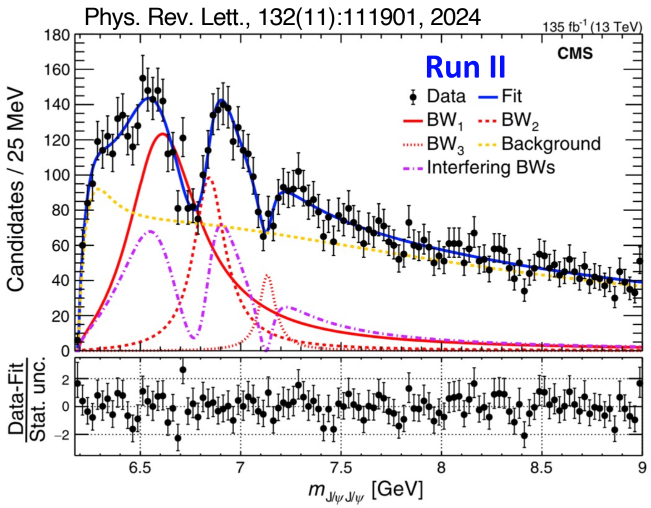
- LHCb: extra BW interfere with SPS, *X(6900) NOT interfering!*
- ATLAS: interference among three resonances, two for the threshold hump, one for X(6900).
- CMS: multi-resonance interference

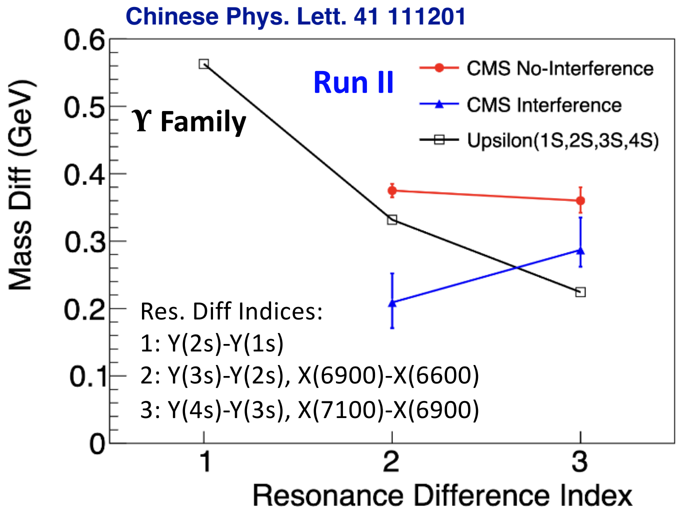
➢ **All exp see a threshold excess, NOT explained! Classified as background**

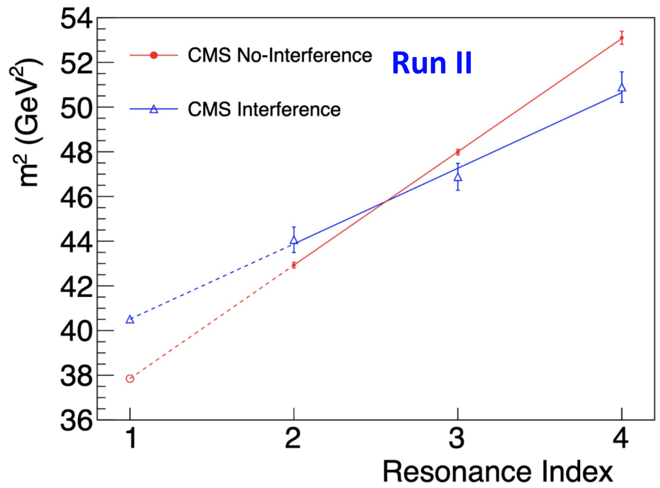
DOI: 10.1103/PhysRevD.111.034038

A number of unresolved questions!

Status







Run 2 result:

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

With 3.6X statistics:

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

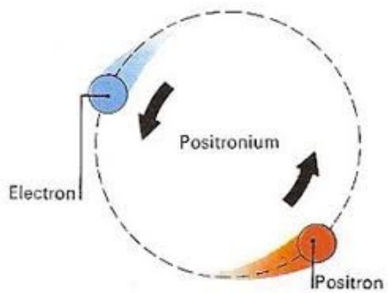
Cornell Model: $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r + \ldots$

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

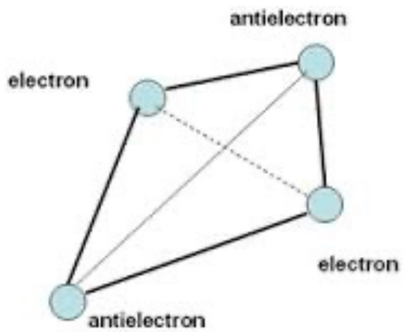
A FAMILY of all-charm tetraquark states with same J^{PC} ?

Status—example in lepton sector

Positronium (1951)



positronium molecule (2007)



Vol 449 | 13 September 2007 | doi:10.1038/nature06094 nature

Nature letter LETTERS

The production of molecular positronium

D. B. Cassidy[1] & A. P. Mills Jr[1]

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Mirror particles form new matter

By Jonathan Fildes
Science and technology reporter, BBC News

Fragile particles rarely seen in our Universe have been merged with ordinary electrons to make a new form of matter.

Antiparticles are the mirror image of ordinary particles

Di-positronium, as the new molecule is known, was predicted to exist in 1946 but has remained elusive to science.

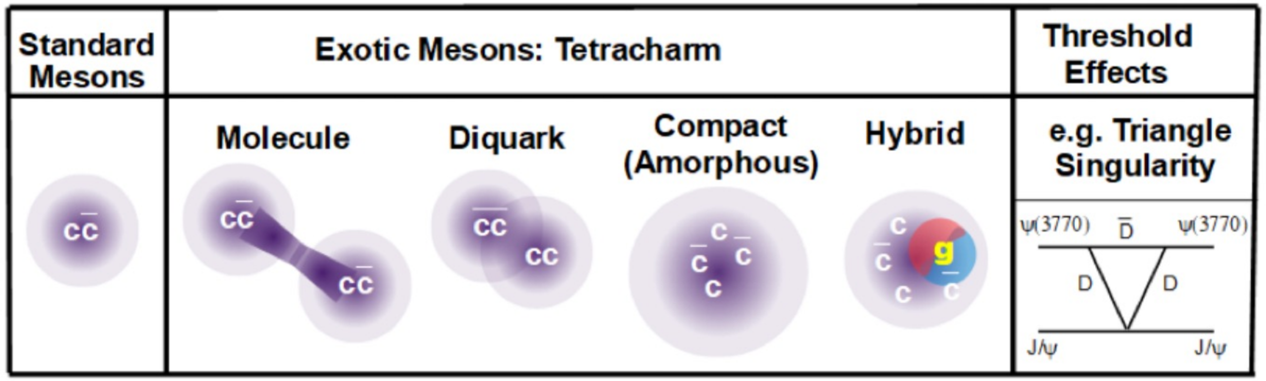
Now, a US team has created thousands of the molecules by merging electrons with their antimatter equivalent: positrons.

The discovery, reported in the journal Nature, is a key step in the creation of ultra-powerful lasers known as gamma-ray annihilation lasers.

Positronium molecule in lepton sector
Both c and b quark are many magnitude heavier than electron, so what?

6

Status



Lattice QCD:
2411.11533 [hep-lat]

Found repulsive between two charmoniums

❖ 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***

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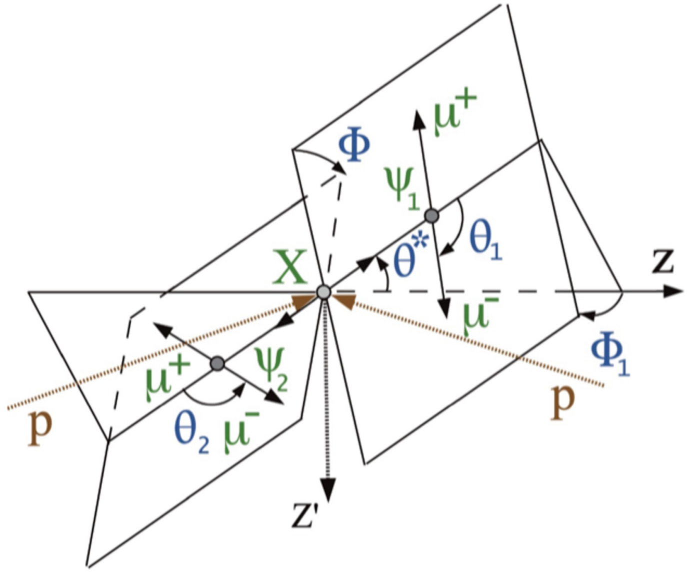
- ❑ Motivation
- ❑ **Spin-parity measurement**
- ❑ $J/\psi\psi(2S)$ result
- ❑ $J/\psi J/\psi$ updated result
- ❑ Interpretations and summary

Concept of Analysis: All Input

- 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



- **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 J/ψ_1 momentum and l momentum defined in J/ψ_1 rest frame
  - ϑ_2 : helicity angle between J/ψ_2 momentum and l momentum defined in J/ψ_2 rest frame

Simplification in Angular Analysis

❖ 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*

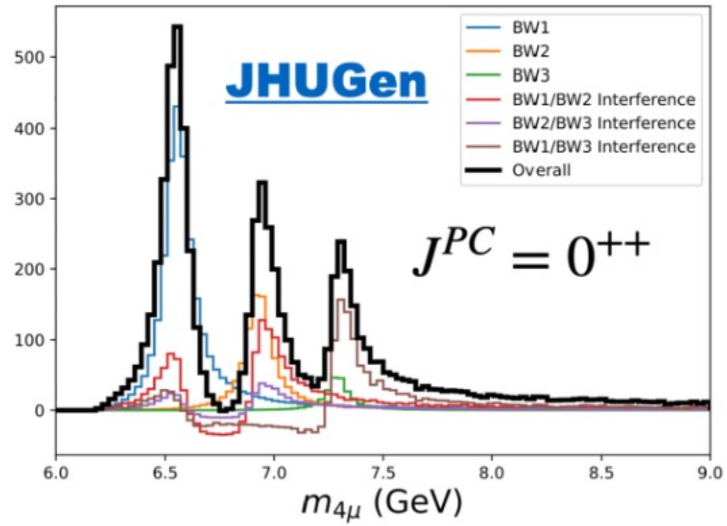
- Full model possible, but complex

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

- Same properties of 3 resonances:

$$\mathcal{P}\left(m_{4\mu}, \vec{\Omega}\right) = \mathcal{P}\left(m_{4\mu}\right) \cdot T\left(\vec{\Omega} \,\middle|\, m_{4\mu}\right)$$

empirical ***angular***



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

1 optimal observable

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

Higgs discovery and spin-parity

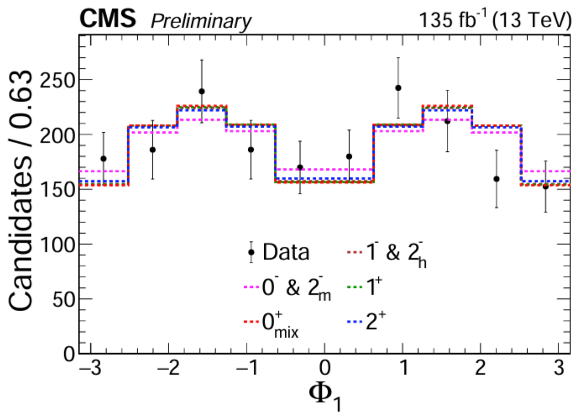
- Final 2D model:

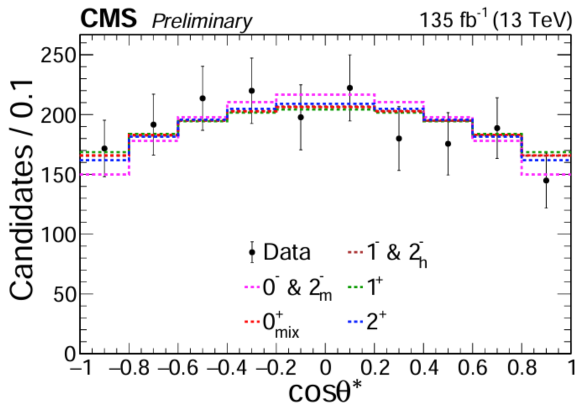
$$\mathcal{P}_{ijk}\left(m_{4\mu}, \mathcal{D}_{ij}\right) = \mathcal{P}_k\left(m_{4\mu}\right) \cdot T_{ijk}\left(\mathcal{D}_{ij} \,\middle|\, m_{4\mu}\right)$$

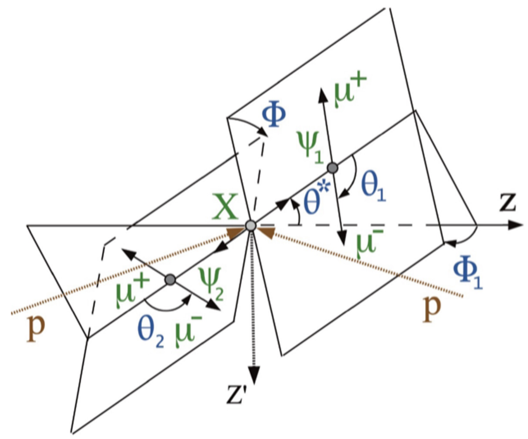
Production angles

❖ Production angles *background-subtracted*

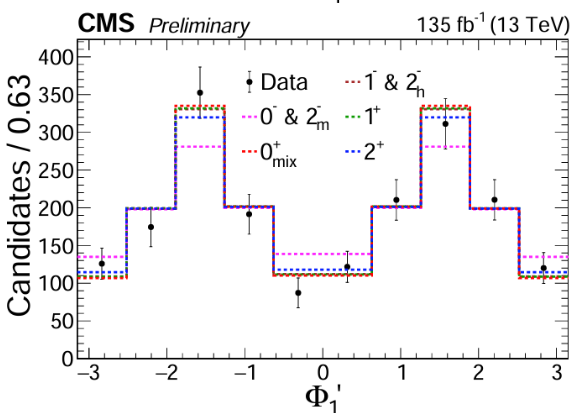
- Not used in analysis, for consistency check
- Data consistent with unpolarized

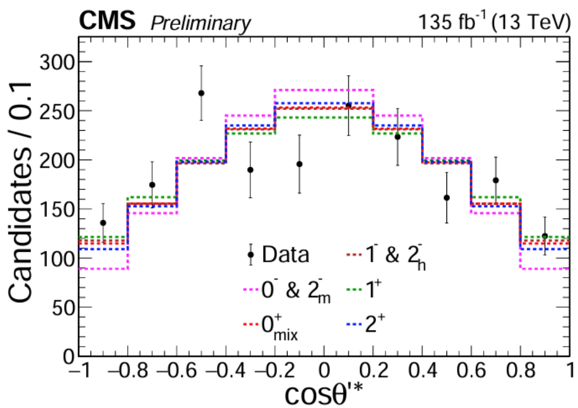






with respect ***the beam axis***

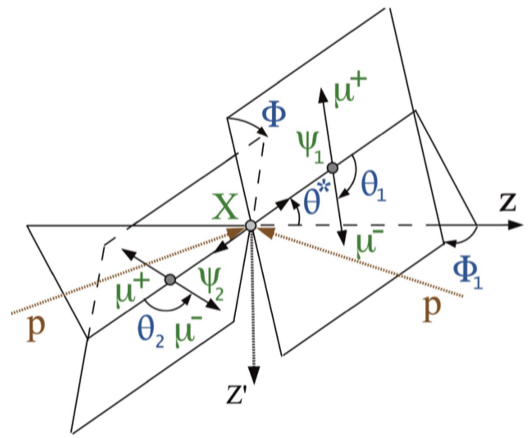




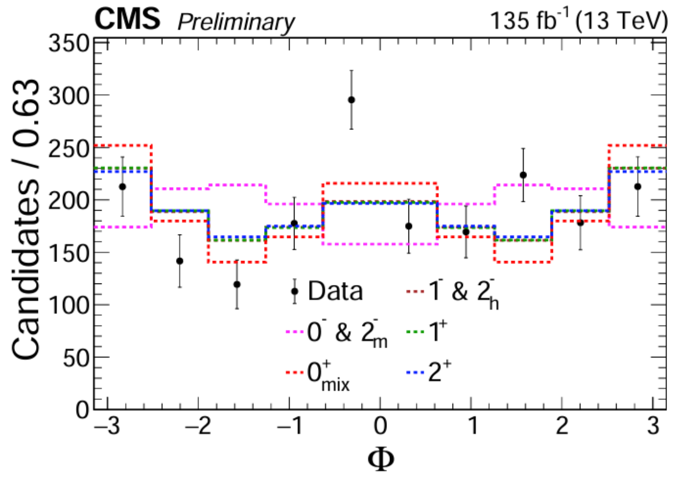
with respect ***the boost axis***

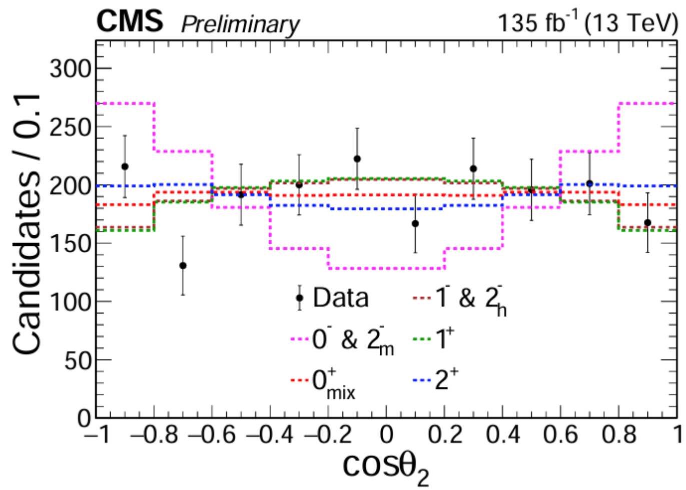
Results of spin-parity measurement

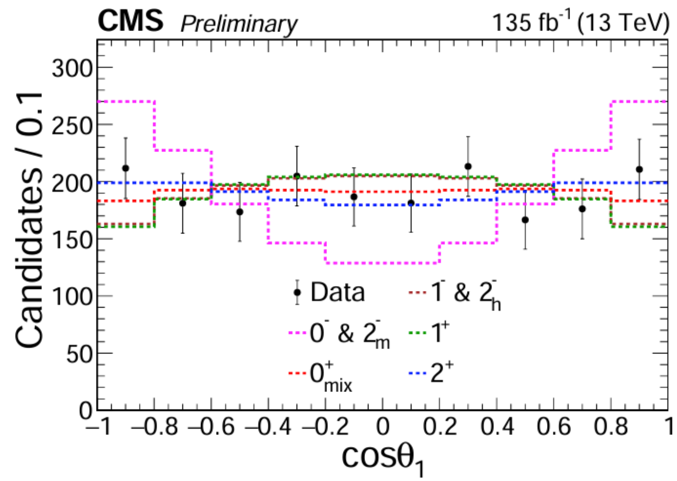
❖ Decay angles *background-subtracted*



- 1D projections from 4D
- Limited information





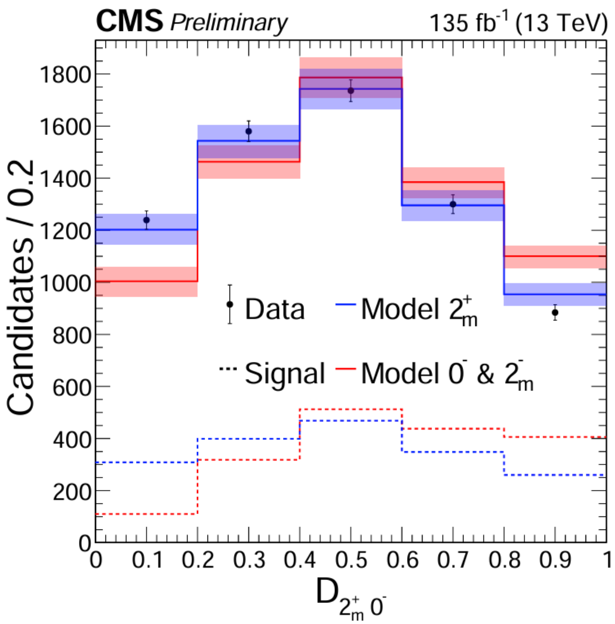


Results of spin-parity measurement

❖ Optimal Observable

- 1D projection of data

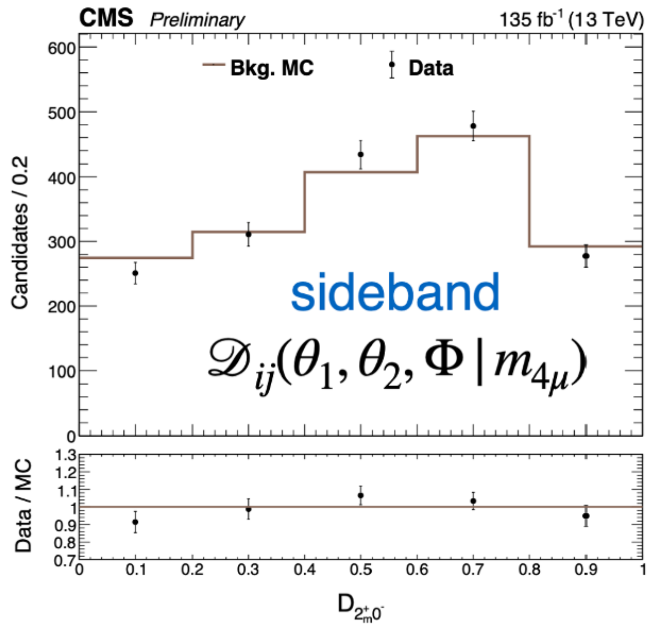
$$\mathcal{D}_{ij}(\vec{\Omega}\,|\,m_{4\mu}) = \frac{\mathcal{P}_i(\vec{\Omega}\,|\,m_{4\mu})}{\mathcal{P}_i(\vec{\Omega}\,|\,m_{4\mu}) + \mathcal{P}_j(\vec{\Omega}\,|\,m_{4\mu})}$$

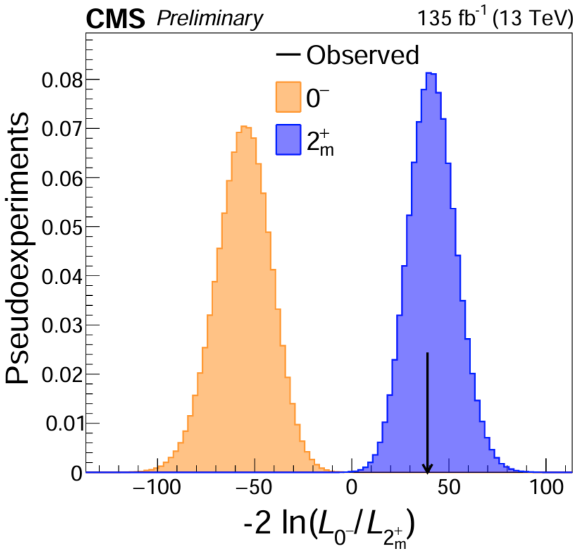


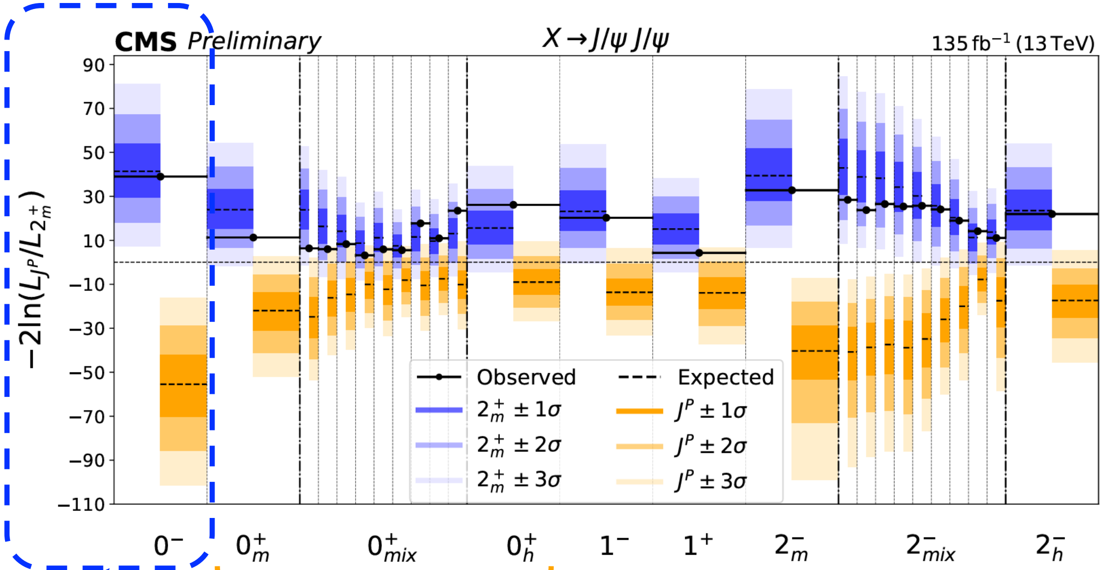
$j = 0^-(2^-_m)\ vs\ i = 2^+_m$

- Background 1D projection

Control Background MC using Data sideband







- Scan mixture of two $\mathbf{0^{++}}$ amplitudes
- Scan mixture of two $\mathbf{2^{-+}}$ amplitudes

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

Results of spin-parity measurement

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

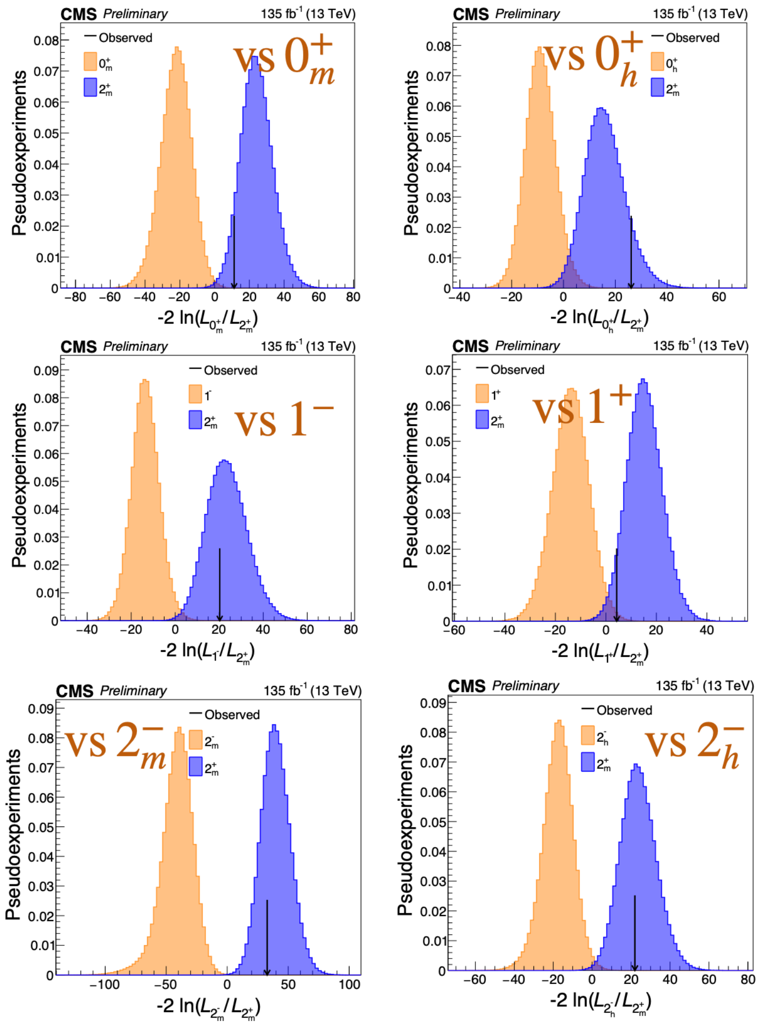
- $PC = ++$ very certain
- $P \neq -1$ very certain
- $J \neq 1$ at 99% CL
- $J \neq 0$ at 95% CL
- $J > 2$ unlikely, require $L \geq 2$
- Rule out P=-1, L=0 most likely

➢ $J^P = 2^+_m$ *model survives*

J_X^P	p-value	Z-score reject J_X^P
0^-	2.7×10^{-13}	7.2
0^+_m	4.3×10^{-5}	3.9
$0^+_{\rm mix}$	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
$2^-_{\rm mix}$	6.5×10^{-4}	3.2
2^-_h	2.2×10^{-8}	5.5

mix

mix

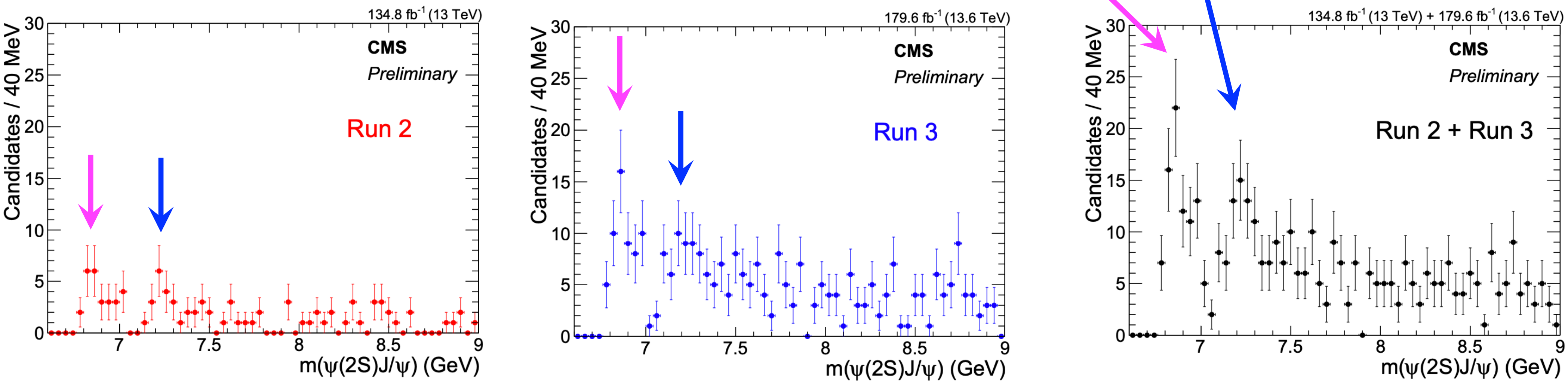


Outline

- ❑ **Motivation**
- ❑ **Spin-parity measurement**
- ❑ **$J/\psi\psi$(2S) result**
- ❑ **$J/\psi J/\psi$ updated result**
- ❑ **Interpretations and summary**

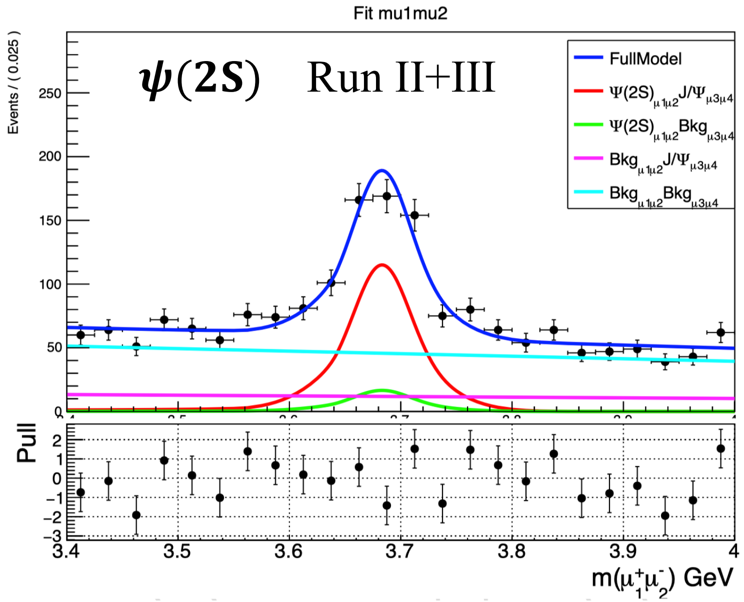
Explore $J/\psi\psi(\mathbf{2S})$ channel with Run II and Run III data

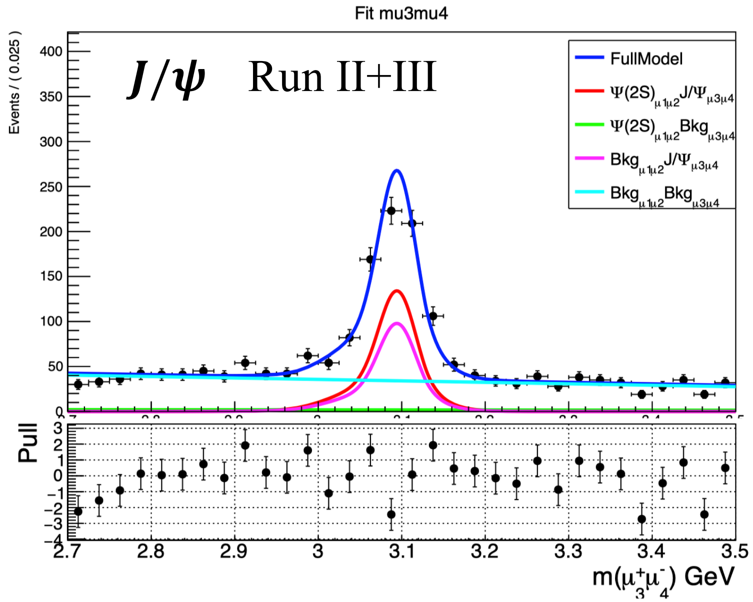
- X(6900) @ Threshold obvious
- X(7100) is visible
- According to $J/\psi J/\psi$ channel, should be an X(6900) and an X(7100)
- Signal dominated by Run III



Two dimensional fit for $J/\psi\psi(2S)$ yield

❖ $J/\psi\psi(2S)$ yield

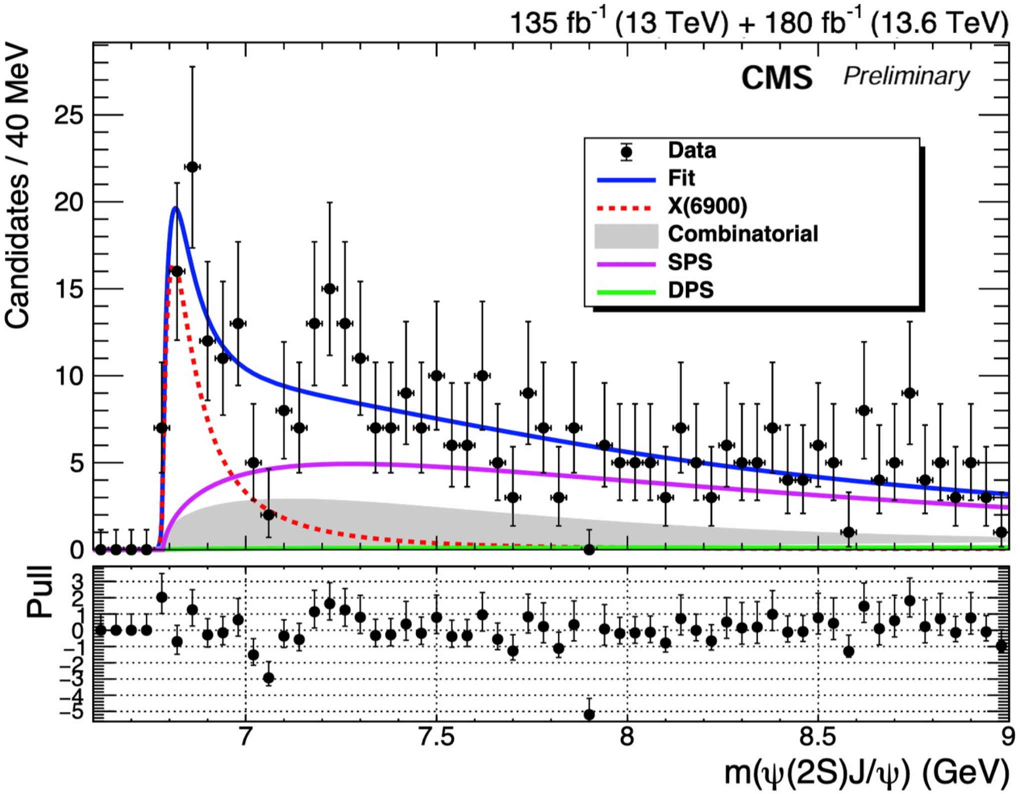




- Run II ~109 ± 14
- Run III ~281 ± 22 ***~2.6 X of Run II***
- Run II+III ~386 ± 26

Explore $J/\psi\psi(2S)$ channel with Run II and Run III data

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

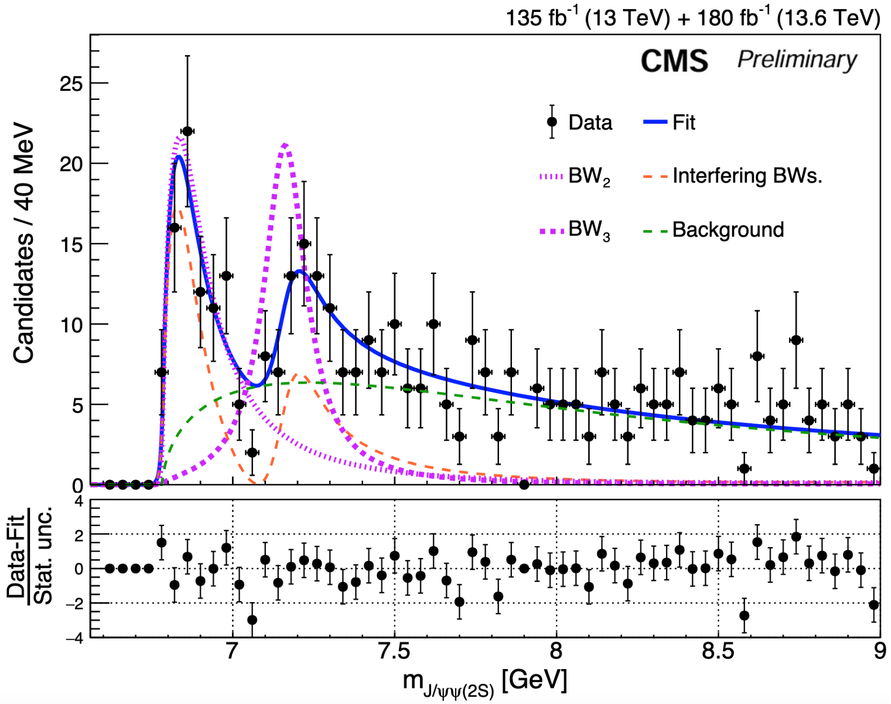


$$\mathbf{M(X6900) = 6841 \pm 14\ MeV}$$

$$\mathbf{\Gamma(X6900) = 150 \pm 28\ MeV}$$

Significance of **X(6900) = 7.5 σ**

Explore $J/\psi\psi(\mathbf{2S})$ channel with Run II and Run III 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 $J/\psi\psi(\mathbf{2S})$ channel

✓ ***Confirmed*** *in a different channel !*
✓ ***Consistent*** *with $J/\psi J/\psi$ result !*

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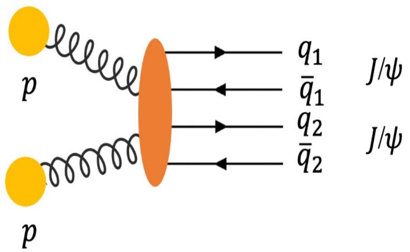
Datasets, MC, trigger, and event selection

❖ Data samples [315 fb^{-1}]

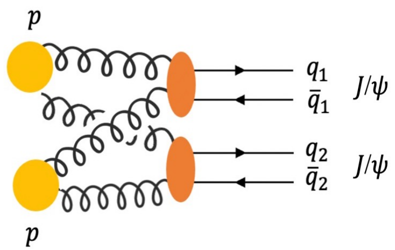
- Run II: 135 fb^{-1} data taken in 2016, 2017 and 2018.
- Run III: 180 fb^{-1} data taken in 2022, 2023 and 2024.

❖ 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

❖ Trigger of Run III

HLT_Dimuon0_Jpsi3p5_Muon2

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

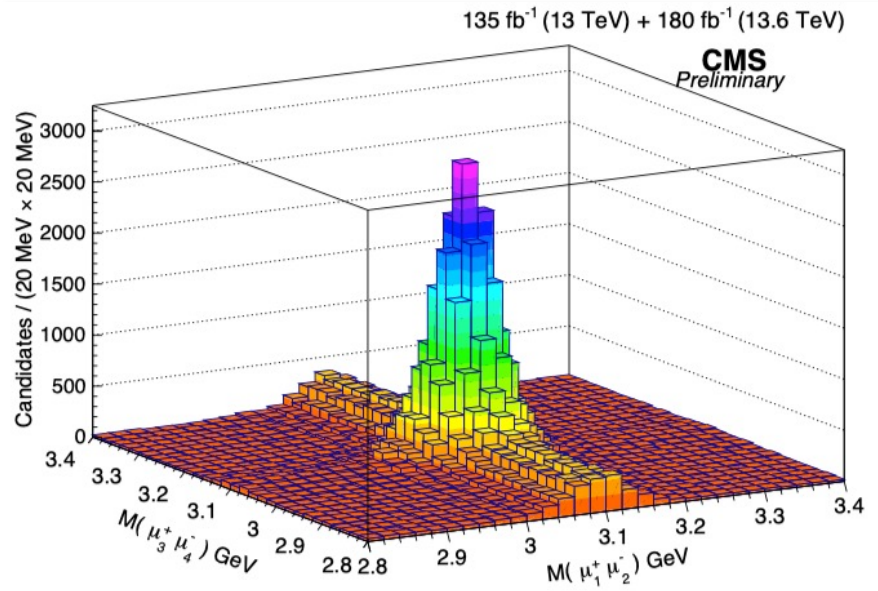
HLT_DoubleMu4_3_LowMass ***[new trigger for Run III]***

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

❖ Event selection

Follow Run II cuts + A new trigger for Run III

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



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

➢ Run II+III ***$J/\psi J/\psi$ yield*** is *3.6X* of Run II

➢ Run II+III ***luminosity*** is *2.3X* of Run II

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**

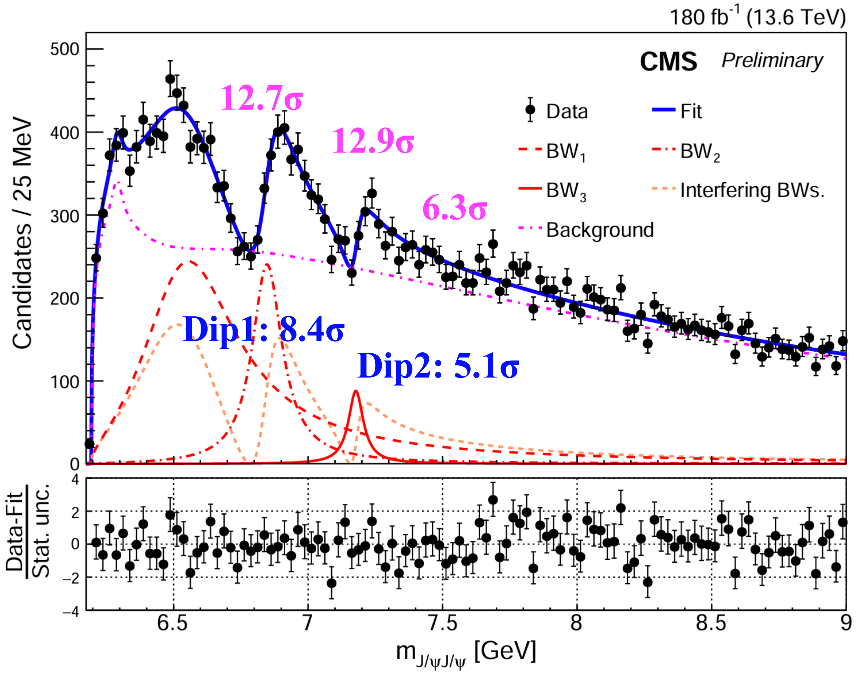
$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m)$$
$$+ N_{NRDPS} \cdot f_{NRDPS}(m) + N_{Comb} \cdot f_{Comb}(m) + N_{Feedown} \cdot f_{Feeddown}(m)$$

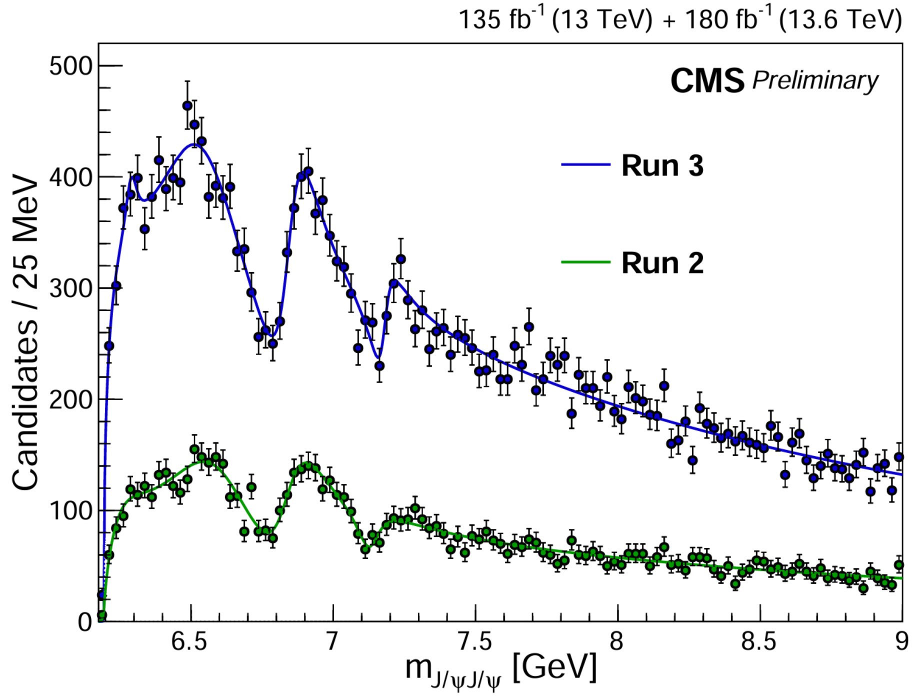
❖ **Interference model:**

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

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

Run III interference fit result

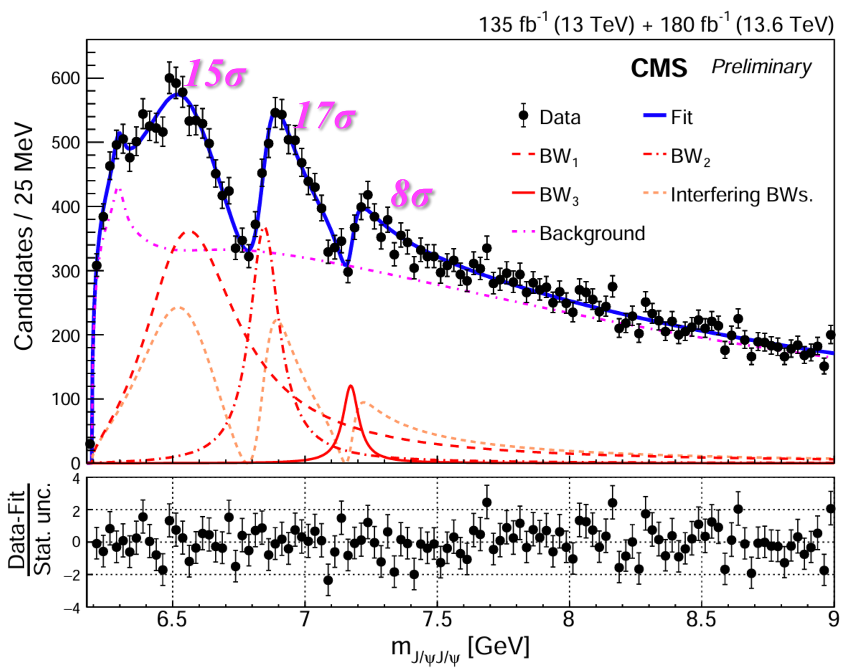


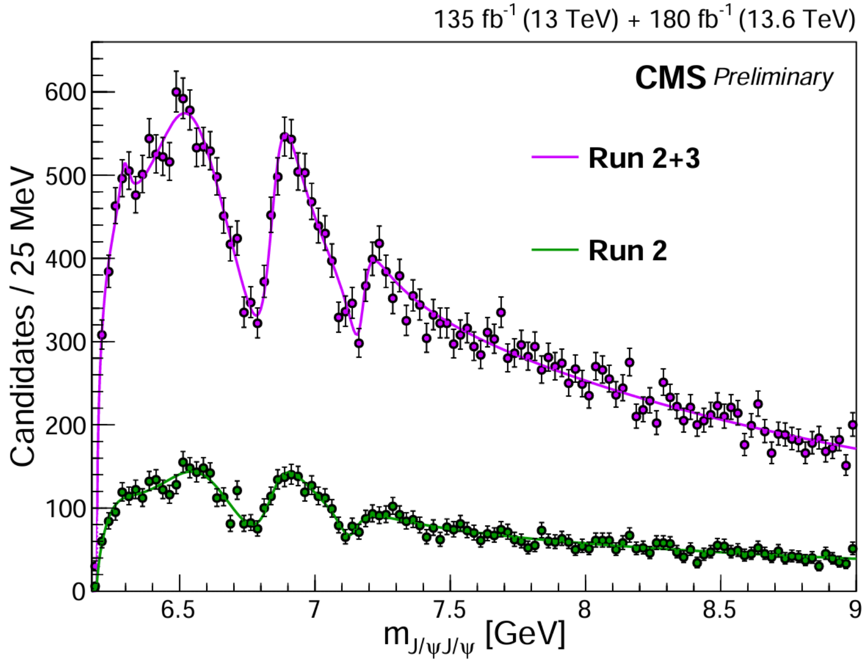


Params [MeV]	M(BW1)	Γ(BW1)	M(BW2)	Γ(BW2)	M(BW3)	Γ(BW3)
Run III Interf.	6588 ± 19	454 ± 74	6849 ± 12	136 ± 18	7179 ± 10	67 ± 18

✓ ***Confirm*** *Run II results with Run III data only---and with* ***better precision!***

Run II & III interference fit result

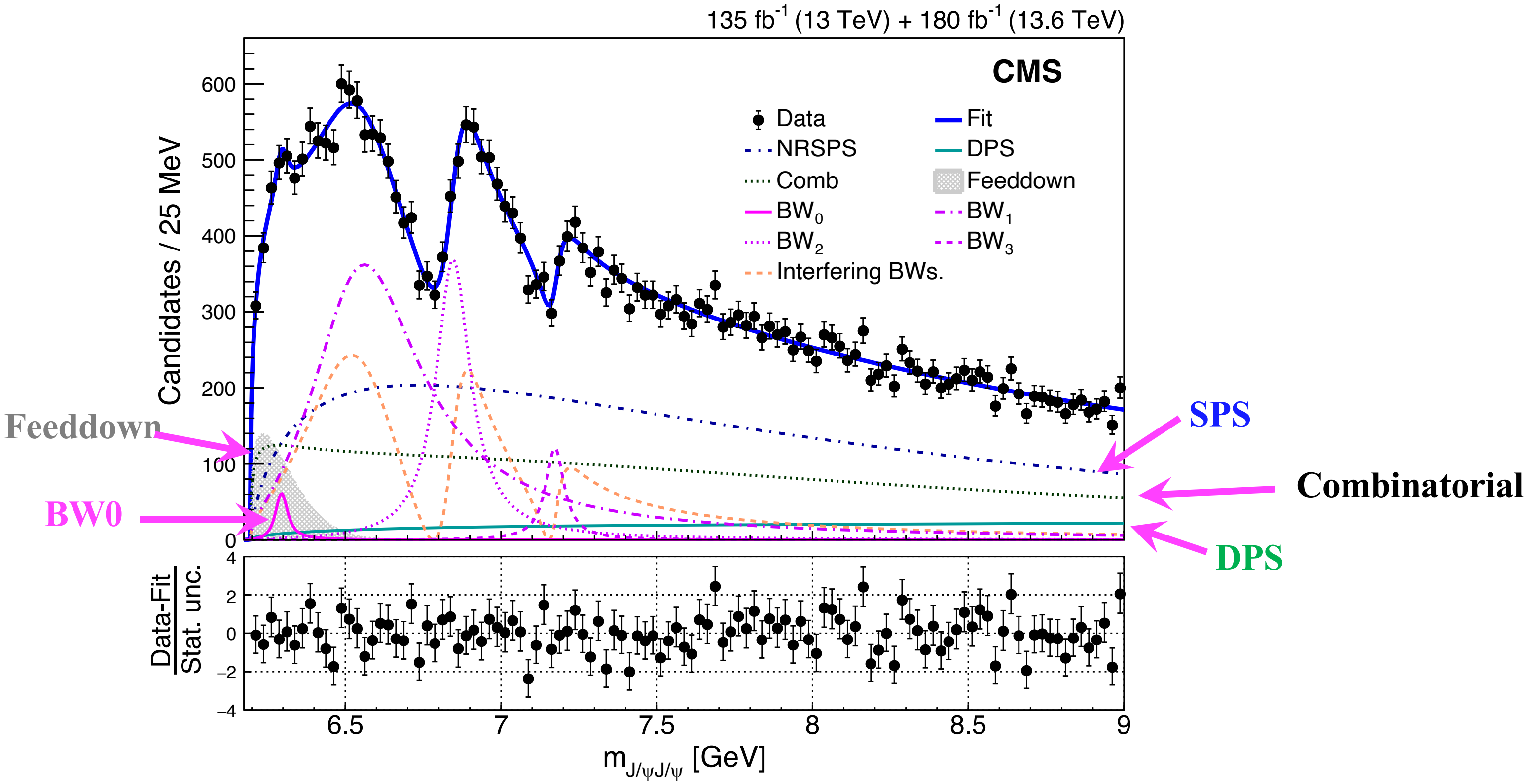




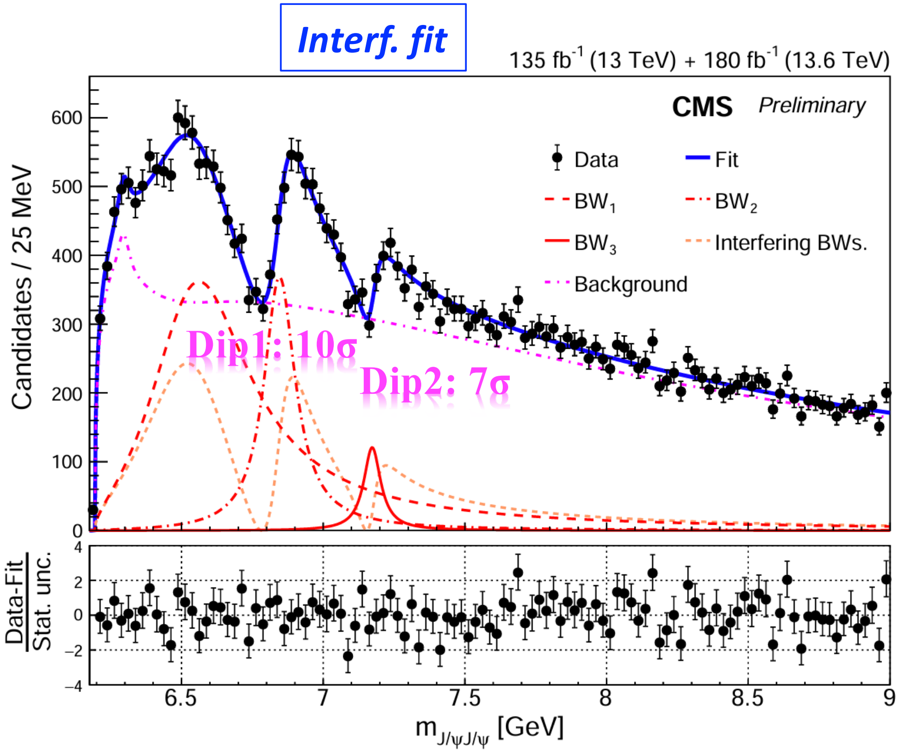
Params [MeV]	M(BW1)	Γ(BW1)	M(BW2)	Γ(BW2)	M(BW3)	Γ(BW3)
Run II & III Interf.	6593^{+15}_{-14}	446^{+66}_{-54}	6847^{+10}_{-10}	135^{+16}_{-14}	7173^{+9}_{-10}	73^{+18}_{-15}

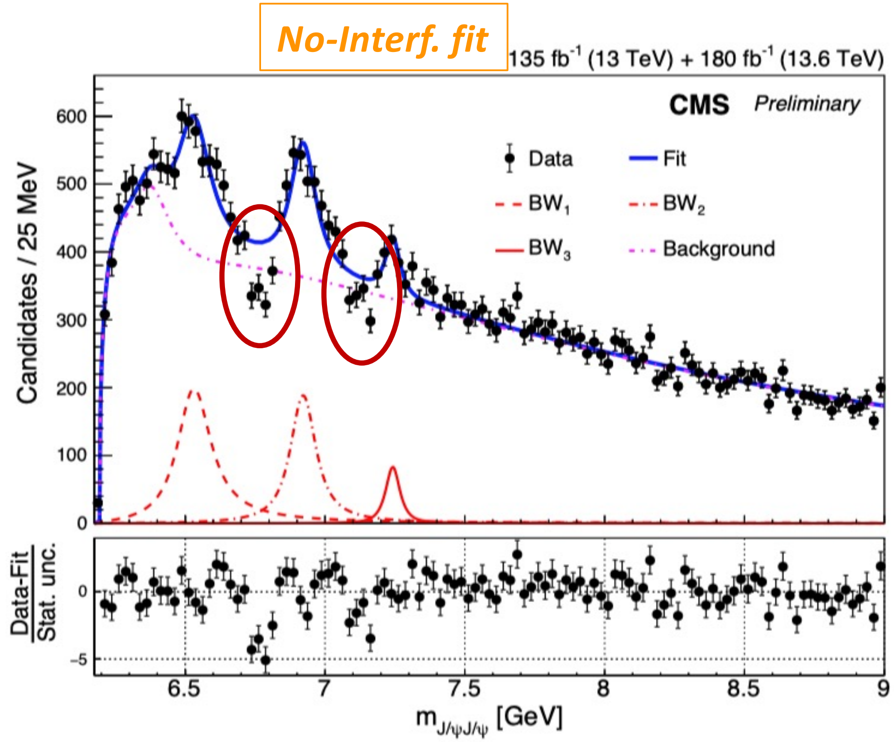
✓ *X(6600), X(6900), X(7100) well above 5σ !*

Run II & III interference fit result—detailed background components



Run II & III interference fit result





✓ *Quantum interference among structures validated!*

✓ *Strongly imply that they have* ***same JPC***

Run II & III 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 II result***

- ✓ **Statistical uncertainty** reduced by **a factor of 3**
- ✓ **Systematic uncertainty** reduced by about **a factor of 2**

Outline

- ❑ **Motivation**
- ❑ **Spin-parity measurement**
- ❑ $J/\psi\psi(2S)$ **result**
- ❑ $J/\psi J/\psi$ **updated result**
- ❑ **Interpretations and summary**

Mass trend: a radial family

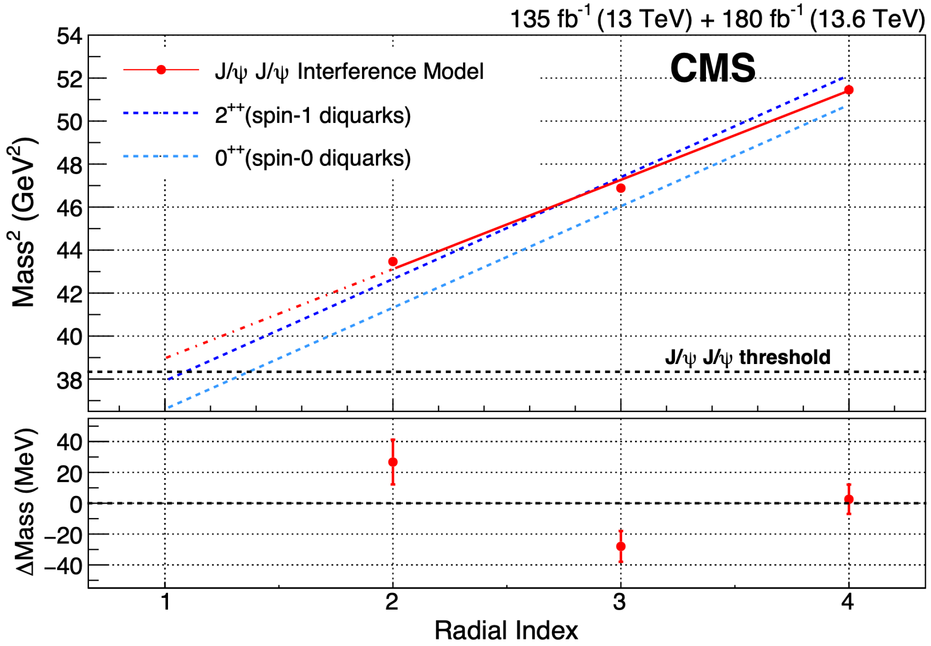
❖ **Patterns among resonance mass**

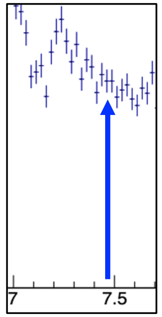
Regge trajectory for radially excited states defined as: $\boldsymbol{n_r = \beta \cdot m^2 + \beta_0}$

m^2: mass square

$n_r = n - 1, n$ is radial quantum number

Nucl. Phys. B, 966:115393, 2021,





❑ **Projection**

$n_r = 1: 6241 \pm 20$ MeV

$n_r = 5: 7453 \pm 21$ MeV (no hint in data)

❑ **Estimations by some diquark models:**

2++ production **dominates over 0++** by more than **two orders of magnitude**.

➢ ***Closer to the spin-1 diquark trajectory***

Additional trends

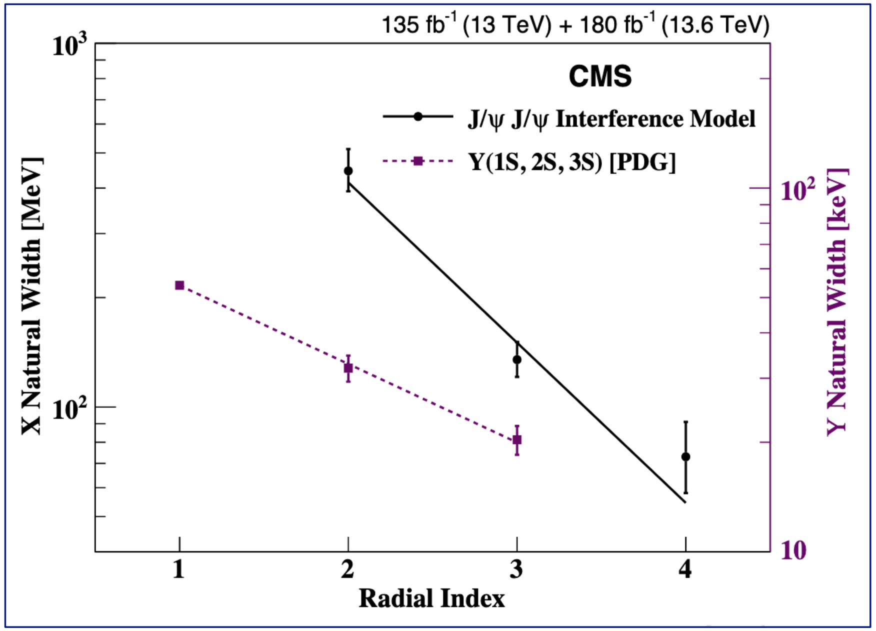
❖ Patterns among other resonance parameters

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

Interf. pdf

- Widths of three X states **show an exponential decrease**
- Similar pattern **in Υ(1S, 2S, 3S) radial family**
- Different magnitude and steeper slope,

  may NOT a good example to compare



Width pattern

Exhibit compatibility with ***a multiplicative scaling pattern among neighboring states***

Interpretations and summary

- Three structures X(6600), X(6900), X(7100) established *with significances > 5σ*
  - Precision improved by factor of 3
  - Having multiple states

    ==> Comparisons possible
- Quantum interference among structures validated *with significances > 5σ*

    ==> States have common J^{PC}
- Large mass splittings, more precisely, Regge trajectory

    ==> radial family of states

Interpretation and Summary

❖ Implications:

- **Production threshold effects** (triang. sing.; coupled chan.; pomeron;...) creating "fake" peaks generally not expected to follow Regge trajectory
- **Molecules** not expected to form Regge trajectory
- **Diquark-antidiquark** in **linear potential** expected to follow **Regge** ...

Nucl. Phys. B, 966:115393, 2021, Zhu did this--**CMS close to spin-1 diquark** case for 0^{++} and 2^{++}

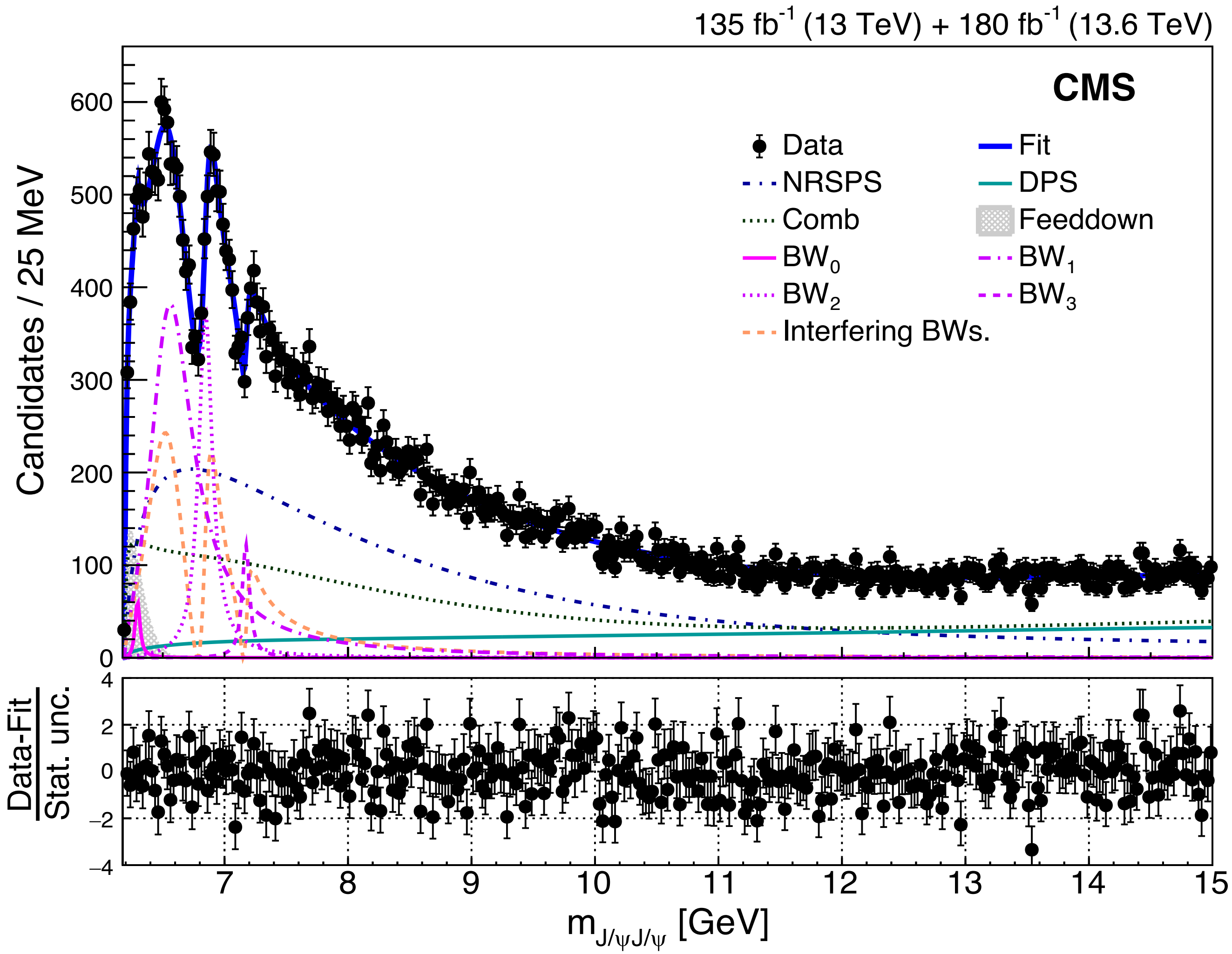
- **Diquarks** may also explain decreasing widths:

  wave function overlap decreases with radial excitation, tending to reduce widths?

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

BACK UP

BACKUP

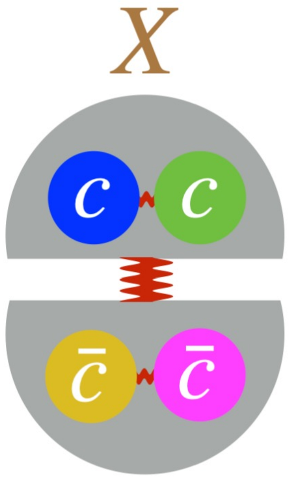


135 fb-1 (13 TeV) + 180 fb-1 (13.6 TeV)
CMS
Data
Fit
NRSPS
DPS
Comb
Feeddown
BW0
BW1
BW2
BW3
Interfering BWs.
Candidates / 25 MeV
Data-Fit / Stat. unc.
mJ/ψJ/ψ [GeV]

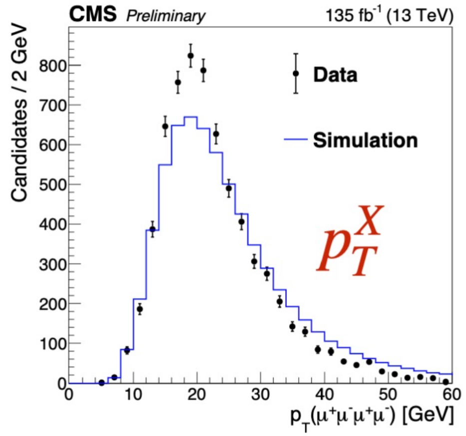
Spin-parity: MC Tune

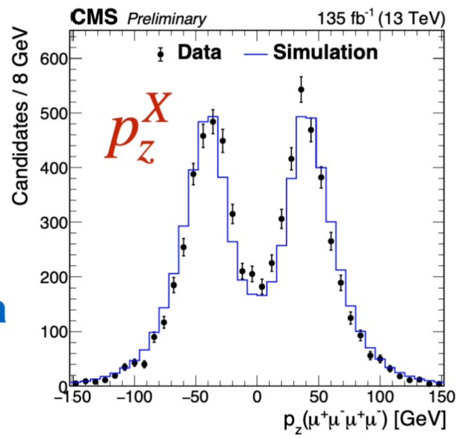
- We do not know the production mechanism

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



Simulation
JHUGen + Pythia





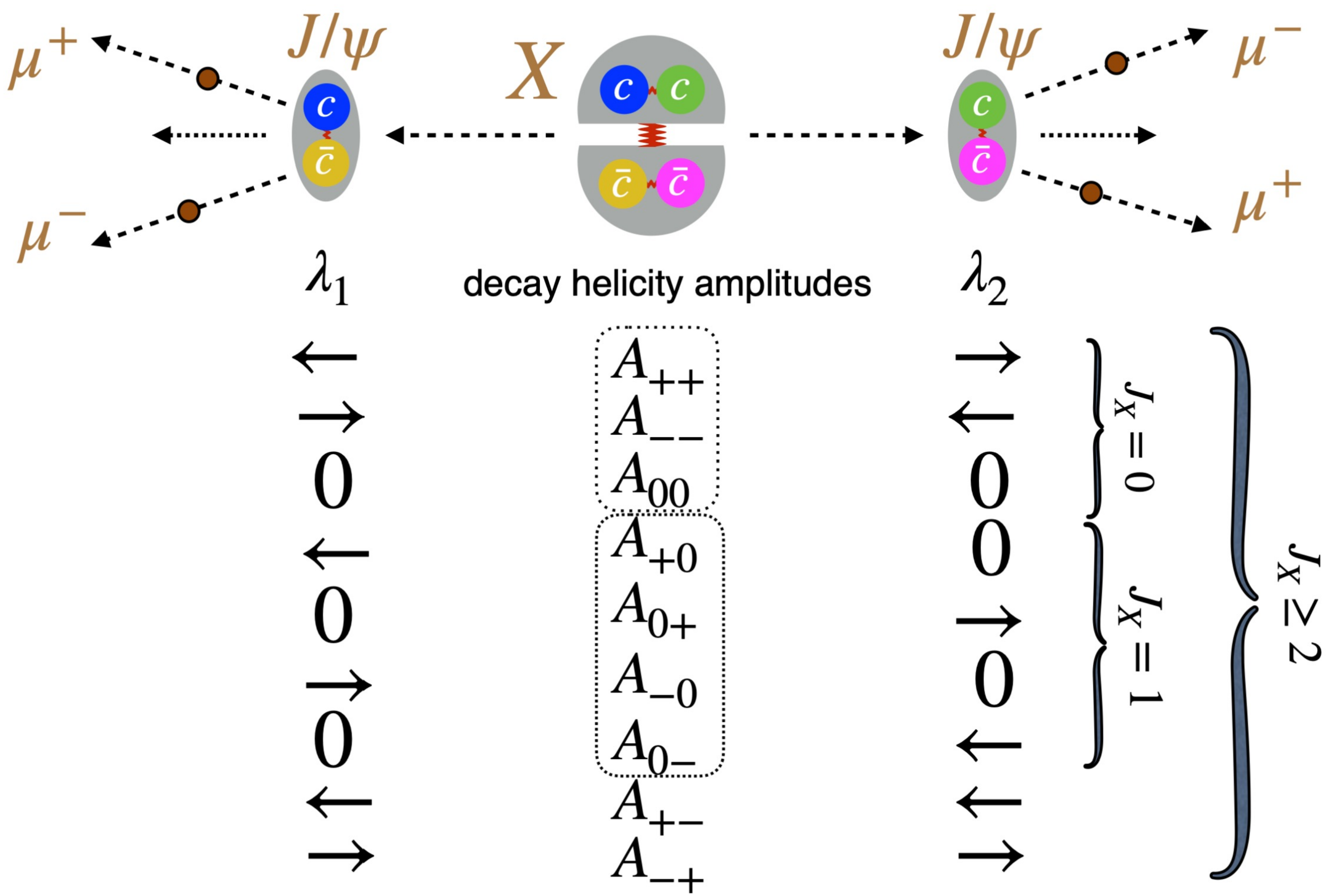
— tune **Pythia** to match p_T^X in sideband and signal region

— 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

Spin-parity: J/ψ polarizations



Spin-parity: J/ψ polarizations

- 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

Spin-parity: Lorentz-Invariant Amplitude

- Expect three X 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^+ $\qquad$ 0_h^+ $\qquad$ 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^- $\qquad$ 1^+

more for spin-2

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

Spin-parity: Lorentz-Invariant Amplitude

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

arXiv:1001.3396

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

2_m^- $(A_{++} = -A_{--})$

2_h^- $(A_{+0} = A_{0+} = -A_{-0} = -A_{0-})$

2_m^+ — minimal representative model including all amplitudes:

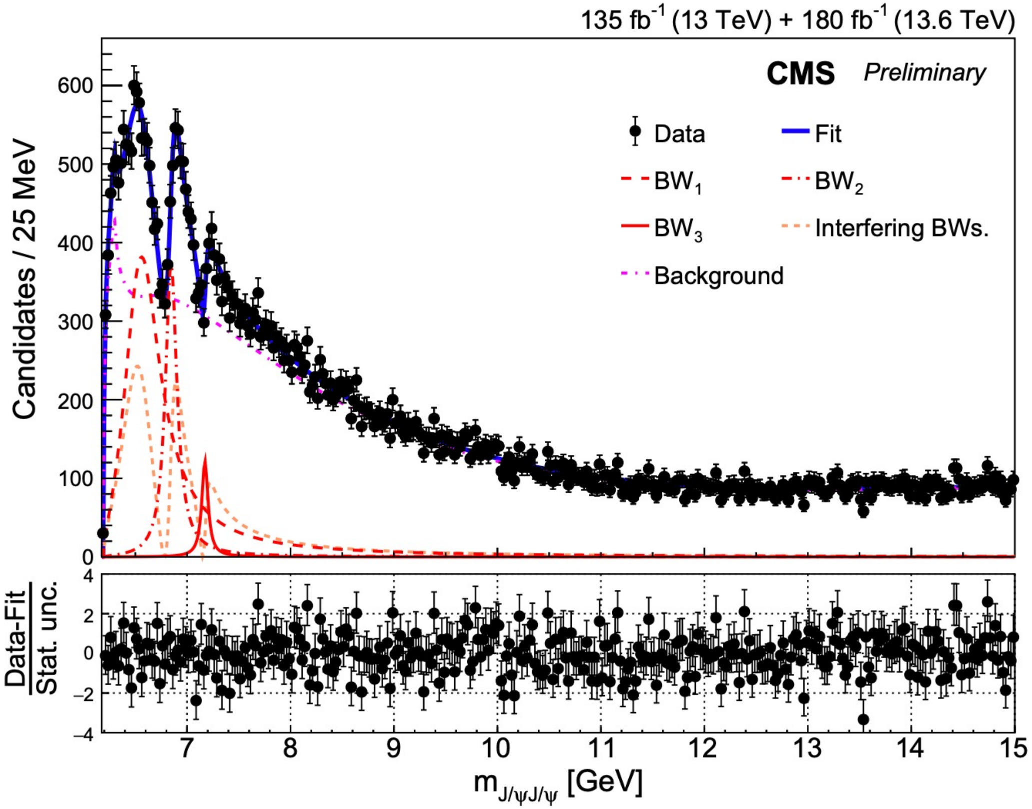
4 d.o.f. A_{00}, $A_{++} = A_{--}$, $A_{+0} = A_{0+} = A_{-0} = A_{0-}$, $A_{+-} = A_{-+}$ unique for 2^{++} (or $J \geq 2$)

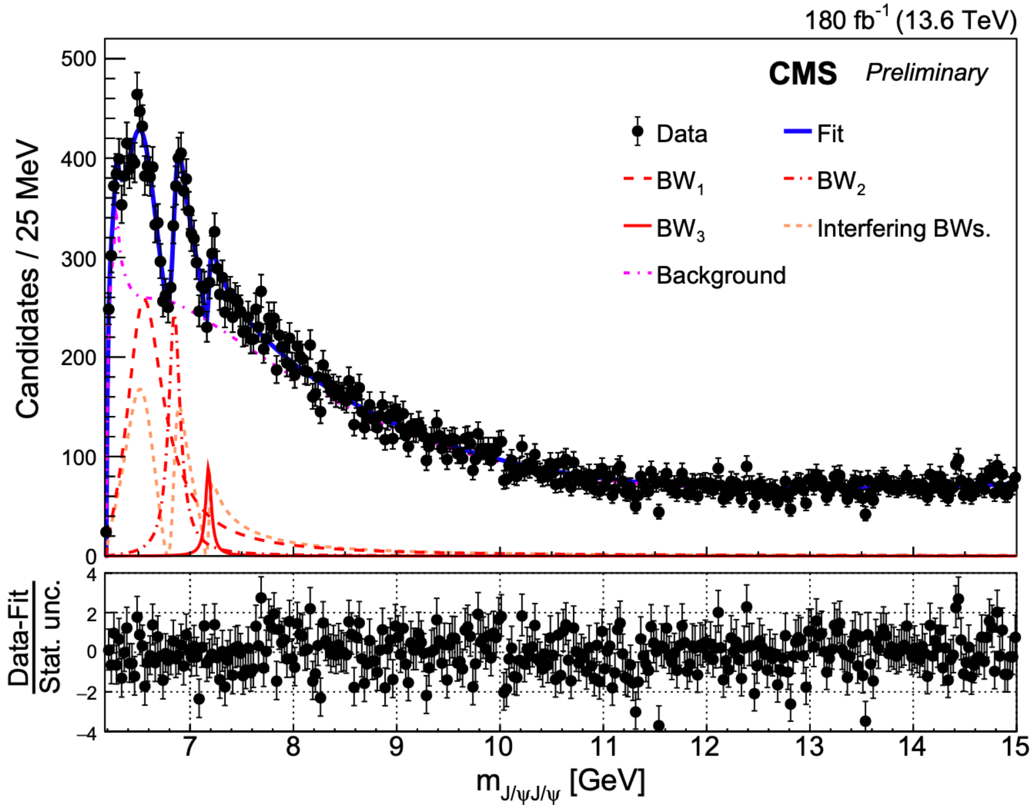
21% 9% 47% 23%

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

if data consistent with 2_m^+ $\Rightarrow$ unambiguously 2^{++} (or $J \geq 2$)

$J/\psi J/\psi$: 6-15 GeV fits





$J/\psi J/\psi$: Event selection for Run III data

Follow PRL cuts + A new trigger for Run III

- **Single muon:**
  - Soft muon ID
  - $|\eta(\mu)| \leq 2.4$

- **Single J/ψ:**
  - $2.95 < M(J/\psi) < 3.25\ GeV$
  - $prob_{vtx}(J/\psi) > 0.1\%$ $M(\mu^+\mu^-)$ *constrained to* $M(J/\psi)$
  - Final mass window cut for J/ψ candidate:

$$|M(\mu^+\mu^-) - M(J/\psi)| < 3\rho\sigma$$

- **Four muons:**
  - 4μ charge should be zero
  - $prob_{vtx}(4\mu) > 0.5\%$
  - $prob_{vtx}(J/\psi J/\psi) > 0.1\%$

- **Multiple candidates treatment:**
  - Select best combination from one 4μ candidate based on min.

$$\chi_m^2 = \left(\frac{m_1(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

  - Keep duplicate combination if pairs have non-overlapping muons

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

Baseline mass variable

– invariant mass of two constrained J/ψ candidates

$J/\psi\psi(2S)$

$p_T(J/\psi) > 11.0$ 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

- **A background suppression** with FOM value:

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

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

- $\boldsymbol{J/\psi\psi(2S)}$ **yield：** Run II ~109 ± 14

  Run III ~281 ± 22 ***~2.6 X of Run II***

  Run II+III ~386 ± 26

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

Consider resolution and efficiency

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

Results of spin-parity measurement

❖ Hypothesis test for $j = 0^- \; vs \; i = 2^+_m$

- 2D parameterization:

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

- Test statistic:

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

- Confidence level:

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

		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