Recent results of XYZ studies at ATLAS & CMS

第十届XYZ研讨会

HUNAN NORMAL UNIVERSITY

Tsinghua University

胡 震

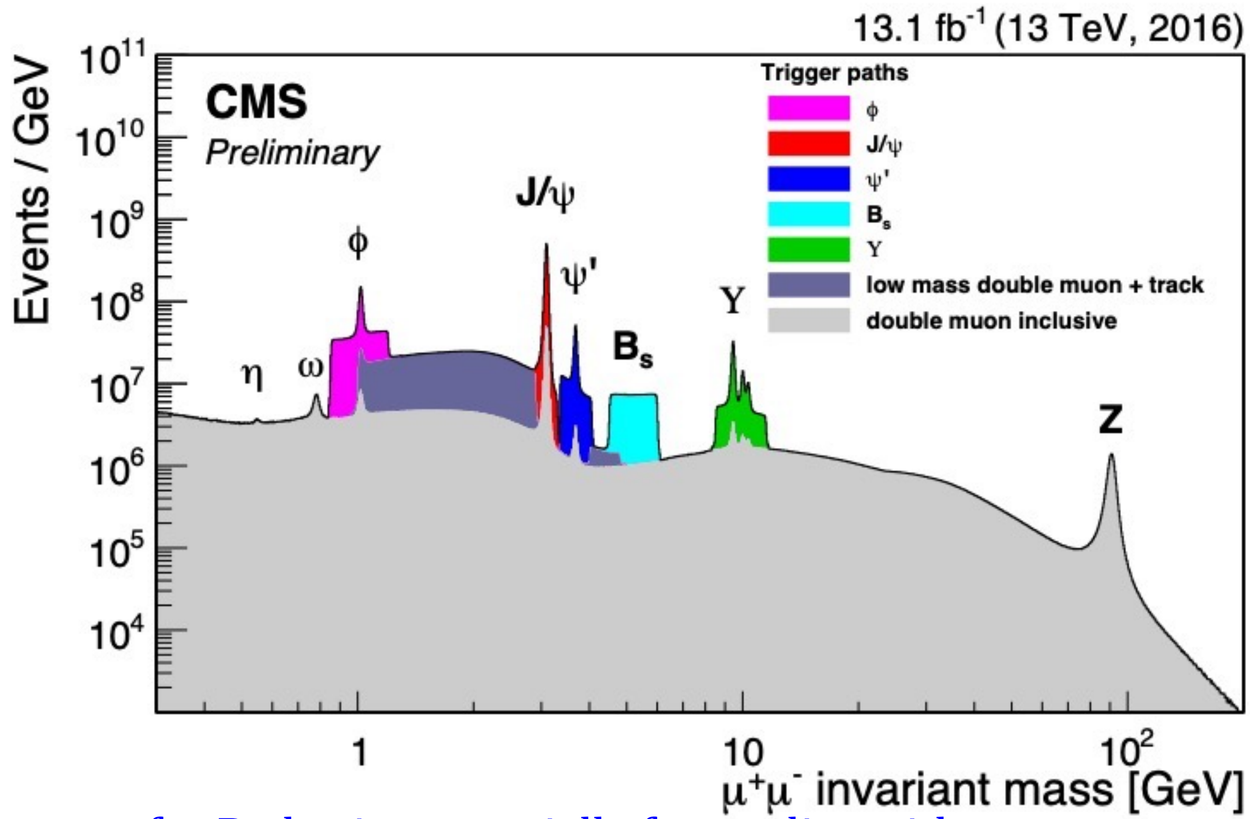
April 12, 2025

2025 Breakthrough Prize

The **ATLAS**, **CMS**, **ALICE** and **LHCb** Collaborations at **CERN's Large Hadron Collider.** April 5, 2025

For detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider.

CMS dimuon & trigger



Excellent detector for B physics, especially for studies with muons

- Muon system
  - High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ
- Silicon Tracking detector, B=3.8T
  - $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution
- Special triggers for different analyses at increasing Inst. Lumi.
  - μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ

CMS XYZ studies

- X(3872) studies (First LHC experiment to see X(3872))
  - Measurement of X(3872) to $J/\psi\pi^+\pi^-$ (2013)
  - Observation of $B_s^0 \to X(3872)\phi$ (2020)
  - Evidence of X(3872) in PbPb collisions (2022)
- Searches without showing significance structures
  - Upper limit for $X(5568)^\pm \to B_s^0\pi^\pm$ (2020)
  - Observation of $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ (2022)
  - Observation of $\Lambda_b^0 \to J/\psi\,\Xi^-K^+$ (2024)
- **Observations of new structures and decays**
  - Observation of X(4140) in $J/\psi\phi$ from $B^\pm \to J/\psi\phi K^\pm$ (2014)
  - Observation of X(6600) in $J/\psi\,J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (2023)
  - Observation of X(7100) in $J/\psi\,J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (2025.04.07)
  - Observation of X(6900) in $J/\psi\,\psi(2S) \to \mu^+\mu^-\mu^+\mu^-$ (2025.04.07)
  - Spin-parity measurement of X(6600),X(6900),X(7100) (2025.04.08)

New domain of exotics: all-heavy tetra-quarks

- First mention of 4c states at 6.2 GeV (1975)
  - Just one year after the discovery of J/ψ

We expect at least three exotic mesons with hidden charm, $c\bar{c}(p\bar{p}-n\bar{n})$ [between 3.7∼4.1 GeV], $c\bar{c}\lambda\bar{\lambda}$ [∼4.1 GeV] and $c\bar{c}c\bar{c}$ [∼6.2 GeV], to which we refer

Progress of Theoretical Physics, Vol. 54, No. 2, August 1975

A Possible Model for New Resonances

—Exotics and Hidden Charm—

Yoichi IWASAKI

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received January 20, 1975)

- First calculation of 4c states (1981): Z. Phys. C 7 (1981) 317

$(cc)_{\underline{3}^*} - (\bar{c}\bar{c})_{\underline{3}}$ ←

L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.55
	1	$0^{-+}, 1^{-+}, 2^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}$	
2	0	2^{++}	6.78
	1	$1^{+-}, 2^{+-}, 3^{+-}$	
	2	$0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}$	
3	0	3^{--}	6.98
	1	$2^{-+}, 3^{-+}, 4^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

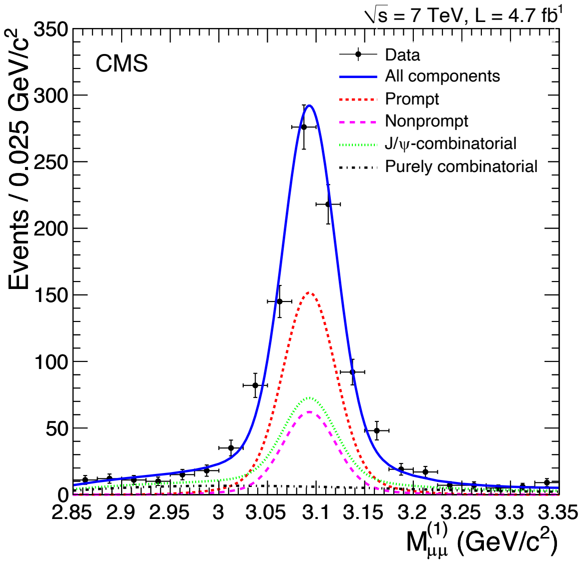
$(cc)_{\underline{6}} - (\bar{c}\bar{c})_{\underline{6}^*}$ →

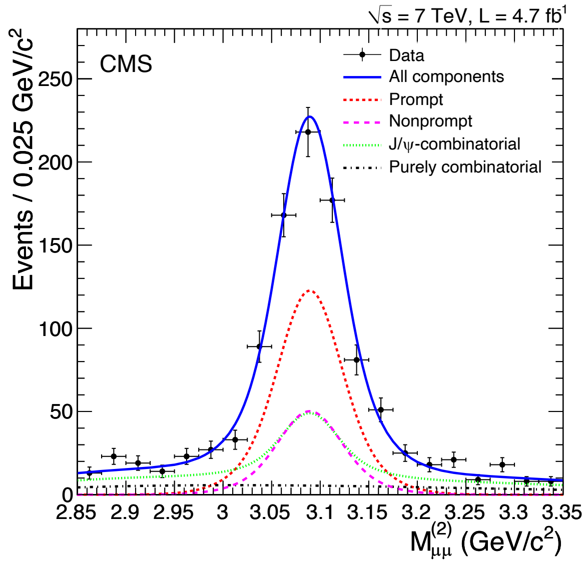
L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.82
2	0	2^{++}	7.15
3	0	3^{--}	7.41

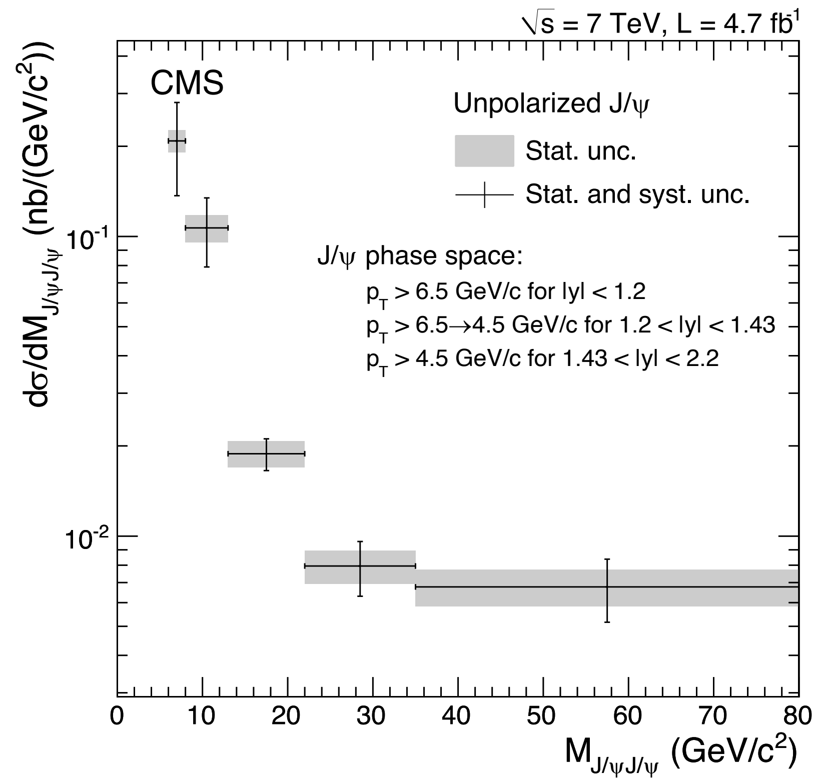
- A different exotic system compared to exotics with light quarks

J/ψJ/ψ cross section at 7 TeV

[*J. High Energy Phys. 09 (2014) 094*]







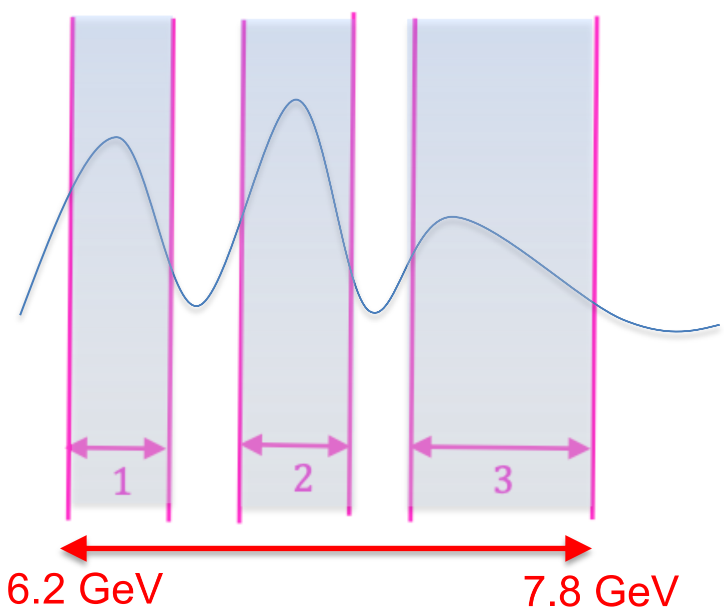
Total cross section, assuming unpolarized prompt J/ψJ/ψ pair production
1.49 ± 0.07 (stat.) ± 0.13 (syst.) nb

Different assumptions about the J/ψJ/ψ polarization imply modifications to the cross section ranging from -31% to +27%.

J/ψJ/ψ blind mass window for 13 TeV

We saw hints at Run I data (7 TeV & 8 TeV)
Proposed three signal regions for Run II data

Signal: $X \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$



Blinded mass windows for Run II:

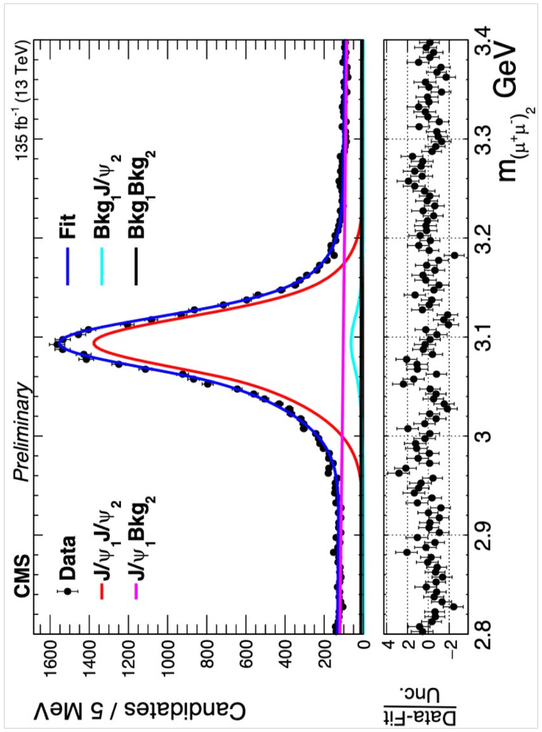
1. [6.3,6.6] GeV
2. [6.8,7.1] GeV
3. [7.2,7.8] GeV
   (for potential wide structure)

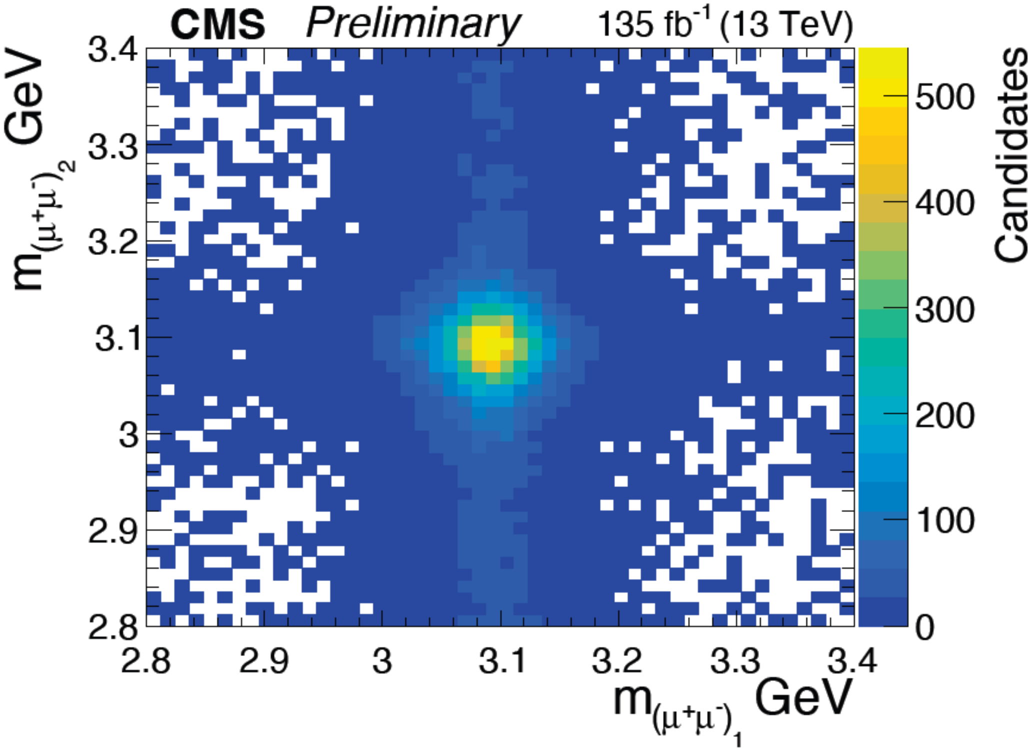
These mass windows will be windows for LEE for potential structures

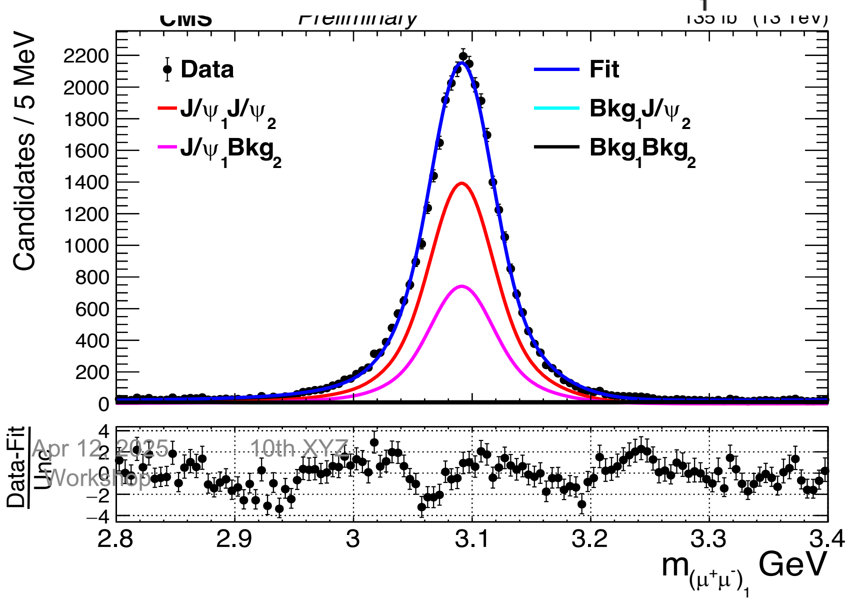
Run I data will be ignored for significance calculation

CMS eventually decide to blind the whole region: [6.2, 7.8] GeV after LHCb released their result (13 TeV, 2020)

J/ψJ/ψ candidates at 13 TeV







- CMS data: 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs
- J/ψ mass and vertex related cuts removed
- Clean J/ψ signals are seen

CMS background (SPS + DPS + BW0)

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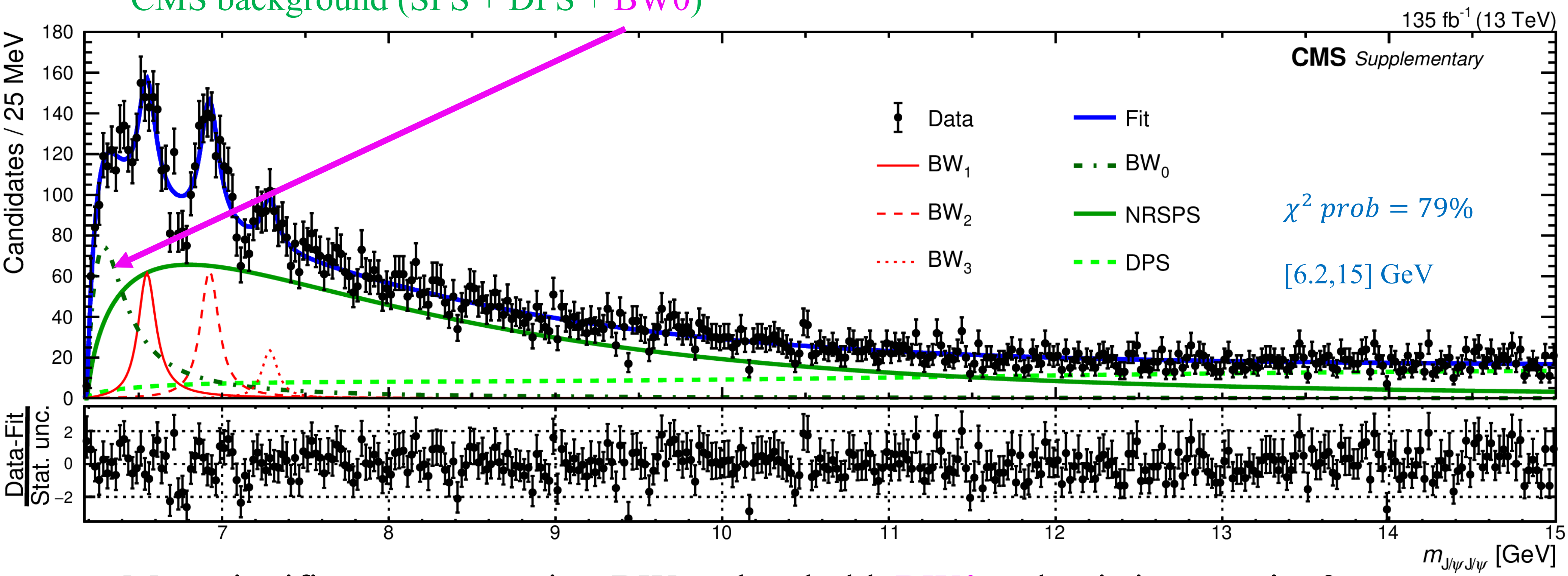

- Most significant structure is a BW at threshold, BW0--what is its meaning?
- Treat BW0 as part of background due to:
  - BW0 parameters very sensitive to SPS and DPS model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…

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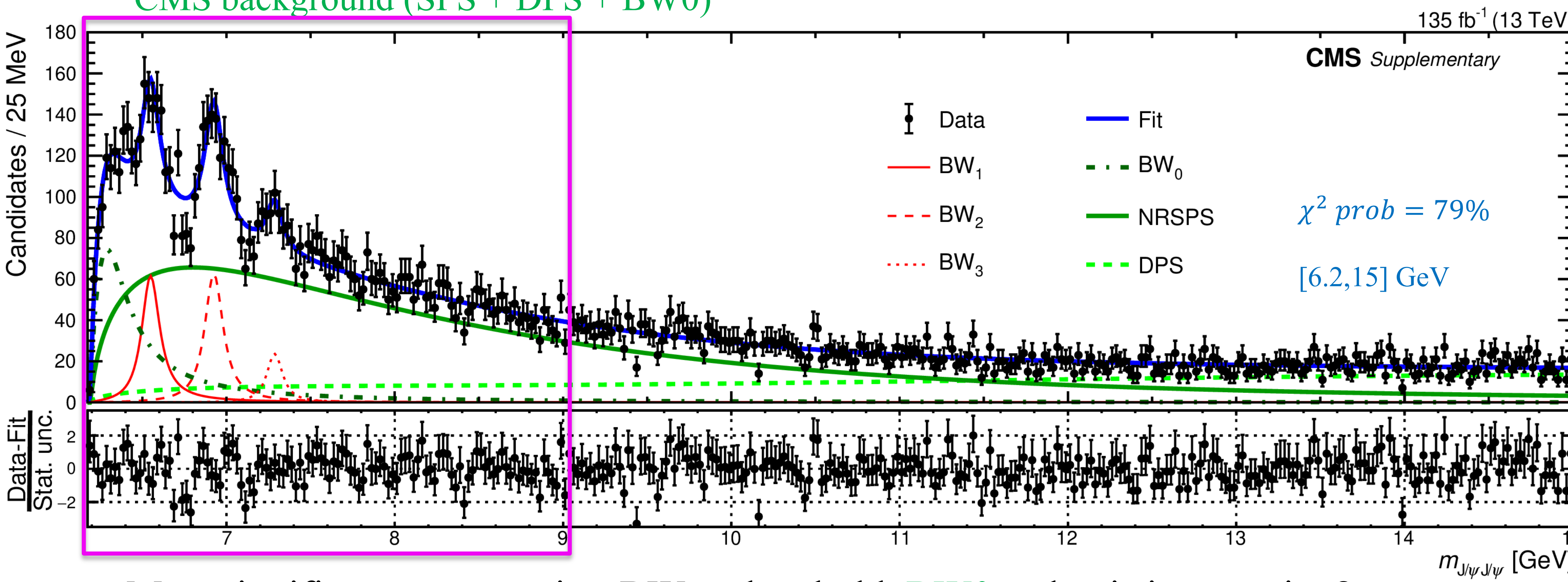

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  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…
- SPS+DPS+BW0 as our background

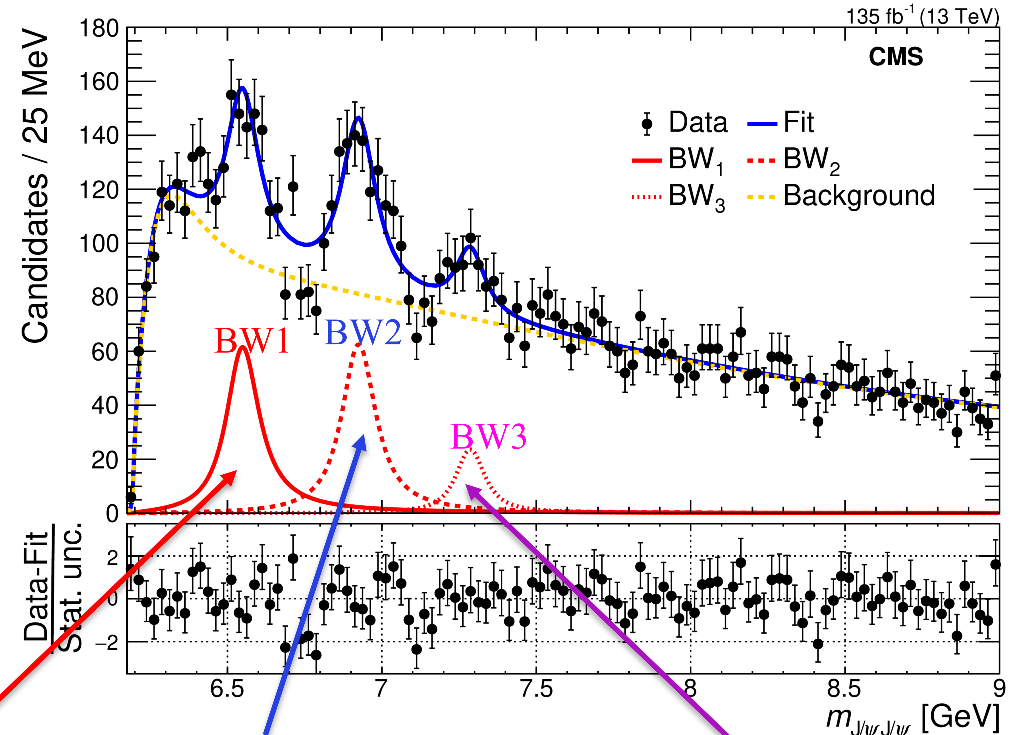
CMS J/ψJ/ψ fit: 3 BWs + Background

χ^2 Prob. = 1%

[6.2,7.8] GeV

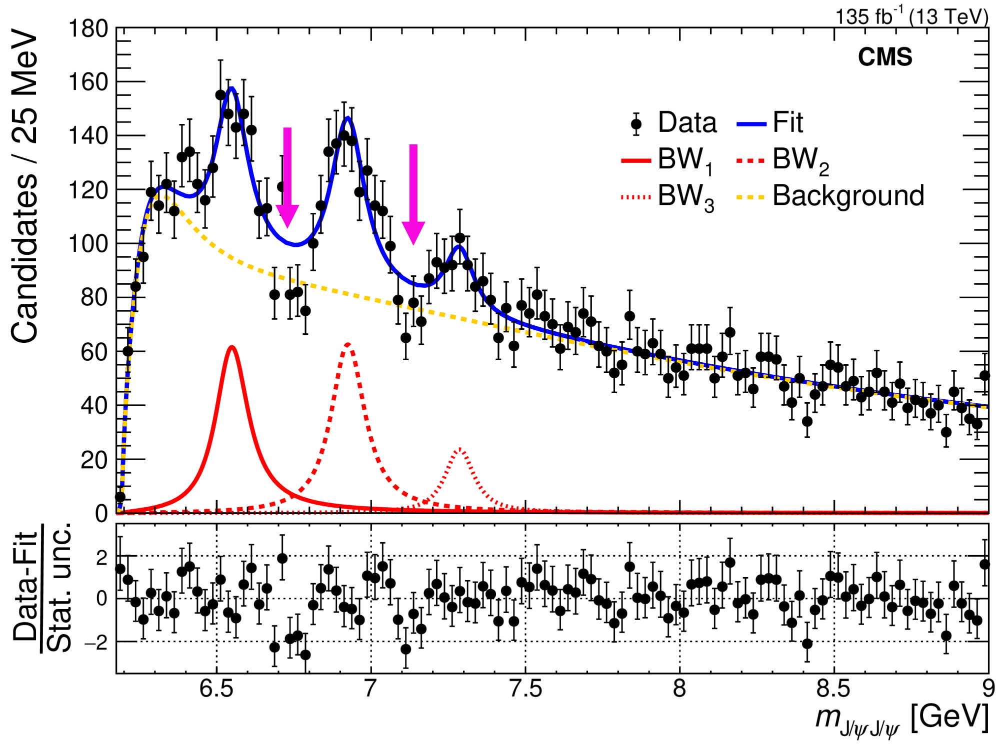
Statistical significance based on:

$2\ln(L_0/L_{max})$



	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	6552 ± 10 ± 12	6927 ± 9 ± 4	7287^{+20}_{-18} ± 5
Γ	124^{+32}_{-26} ± 33	122^{+24}_{-21} ± 18	95^{+59}_{-40} ± 19
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
σ(stat.)	6.5	9.4	4.1
σ(stat. + syst.)	5.7	9.4	4.1
	First Observation	Confirmation of X(6900) from LHCb	Evidence

The dips



- ➢ Possibility #1:
- Interference among structures?

- ➢ Possibility #2:
- Multiple fine structures to reproduce the dips?
- Mentioned in PAS

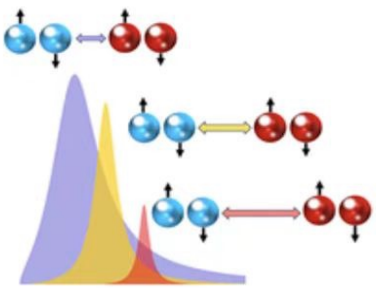
- More secrets to dig out
- We explored possibility #1 in detail

CMS J/ψJ/ψ interference fit

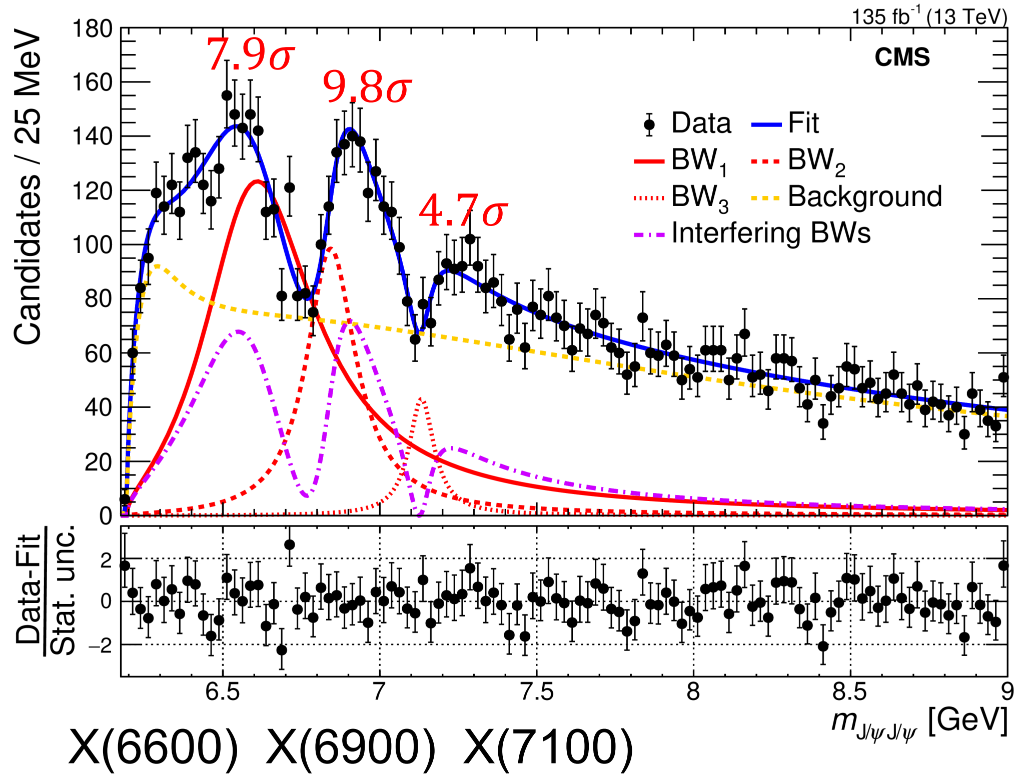
Editors' Suggestion

New Structures in the $J/\psi J/\psi$ Mass Spectrum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **132**, 111901 (2024) – Published 15 March 2024



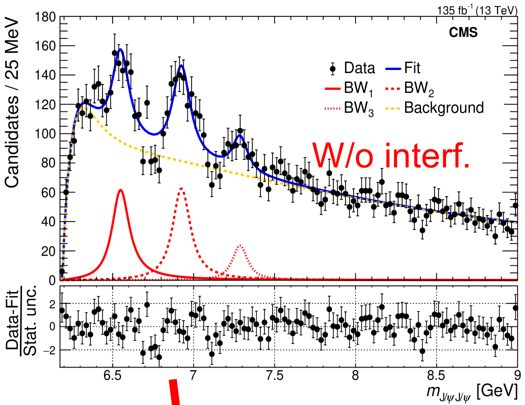
Three structures, $X(6900)$ and two new ones around 6.64 and 7.13 GeV, are seen in the $J/\psi J/\psi$ mass spectrum that are consistent with being part of a family of radial excitations.
Show Abstract +



- Fit with interf. among BW1, BW2, and BW3 describes data well
- Measured mass and width in the interference fit

		BW_1	BW_2	BW_3
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

Comparison with some theoretical calculations



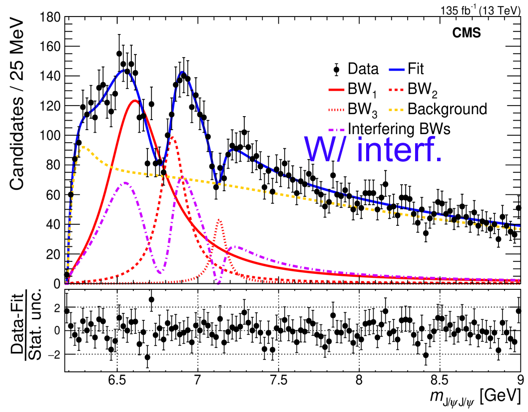


Table 1. Predictions of the masses (MeV) of S-wave fully heavy $T_{4Q}(nS)$ tetraquarks. Only 0^{++} and 2^{++} are considered for $T_{bc\bar{b}\bar{c}}$. The uncertainty is from the coupling constant $\alpha_s = 0.35 \pm 0.05$.

Nucl. Phys. B 966 (2021) 115393

$T_{4Q}(nS)$ states	J^P	Mass(n=1)	Mass(n=2)	Mass(n=3)	Mass(n=4)
$T_{cc\bar{c}\bar{c}}$	0^{++}	6055^{+69}_{-74}	6555^{+36}_{-37}	6883^{+27}_{-27}	7154^{+22}_{-22}
	2^{++}	6090^{+62}_{-66}	[illegible]	[illegible]	[illegible]
$T'_{cc\bar{c}\bar{c}}$	0^{++}	5984^{+64}_{-67}	[illegible]	[illegible]	[illegible]
$T_{bc\bar{b}\bar{c}}$	0^{++}	12387^{+109}_{-120}	[illegible]	[illegible]	13429^{+29}_{-30}
	2^{++}	12401^{+117}_{-106}	12914^{+49}_{-49}	[illegible]	13430^{+29}_{-29}
$T'_{bc\bar{b}\bar{c}}$	0^{++}	12300^{+106}_{-117}	12816^{+48}_{-50}	[illegible]	13333^{+29}_{-29}
$T_{bb\bar{b}\bar{b}}$	0^{++}	18475^{+151}_{-169}	19073^{+59}_{-63}	[illegible]	19566^{+33}_{-35}
	2^{++}	18483^{+149}_{-168}	19075^{+59}_{-62}	[illegible]	19567^{+33}_{-35}
$T'_{bb\bar{b}\bar{b}}$	0^{++}	18383^{+149}_{-167}	18976^{+59}_{-62}	[illegible]	19468^{+34}_{-34}

S-wave

M[BW1] = 6638 ± 10 ± 12 MeV

M[BW2] = 6847 ± 9 ± 5 MeV

M[BW3] = 7134 ± 19 ± 5 MeV

1^1P_1	1^{--}	363.9	320.3	-366.7	337.5	-14.4	0	0	-2.6	6553	-	-
1^3P_0	0^{-+}	356.7	320.2	-366.7	337.5	-7.2	-56.9	-43.1	-2.6	6460	6398.1	$\eta_c(1S)\chi_{c0}(1P)$
1^3P_1	1^{-+}	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554	6494.1	$\eta_c(1S)\chi_{c1}(1P)$
1^3P_2	2^{-+}	356.6	320.2	-366.7	337.5	-7.2	28.4	-2.1	-2.4	6587	6539.6	$\eta_c(1S)\chi_{c2}(1P)$
1^5P_1	1^{--}	342.4	320.4	-366.7	337.5	7.2	-85.3	-30.2	-2.7	[illegible]	6508.8	$\eta_c(1S)h_{c1}(1P)$
1^5P_2	2^{--}	342.2	320.2	-366.7	337.5	7.2	-28.4	30.2	-2.5	[illegible]	6607.6	$J/\psi(1S)\chi_{c1}(1P)$
1^5P_3	3^{--}	342.3	320.3	-366.7	337.5	7.2	56.9	-8.6	-2.5	6623	6653.1	$J/\psi(1S)\chi_{c2}(1P)$
2^1P_1	1^{--}	414.7	688.7	-263.4	548.6	-11.2	0	0	-1.6	6925	-	-
2^3P_0	0^{-+}	410.0	689.6	-263.4	548.6	-5.6	-46.2	-34.5	-1.7	6851	-	-
2^3P_1	1^{-+}	410.0	689.6	-263.4	548.6	-5.6	-23.1	17.2	-1.6	6926	-	-
2^3P_2	2^{-+}	410.0	689.6	-263.4	548.7	-5.6	23.1	-3.4	-1.7	[illegible]	-	-
2^5P_1	1^{--}	398.7	689.5	-263.4	548.6	-5.6	-69.3	-24.2	-1.7	[illegible]	-	-
2^5P_2	2^{--}	398.7	689.5	-263.4	548.6	5.6	-23.1	24.2	-1.5	6944	-	-
2^5P_3	3^{--}	398.8	689.7	-263.4	548.6	5.6	46.2	-6.9	-1.6	6982	-	-
3^1P_1	1^{--}	479.8	982.2	-215.5	727.8	-9.3	0	0	-1.1	7221	-	-
3^3P_0	0^{-+}	475.2	982.7	-215.5	727.7	-4.6	-41.9	-31.0	-1.2	7153	-	-
3^3P_1	1^{-+}	475.1	982.6	-215.5	727.7	-4.6	-20.9	15.5	-1.2	7220	-	-
3^3P_2	2^{-+}	475.1	982.6	-215.5	727.8	-4.6	20.9	-3.1	-1.0	7243	-	-
3^5P_1	1^{--}	465.9	982.8	-215.5	727.7	4.6	-62.8	-21.7	-1.2	7150	-	-
3^5P_2	2^{--}	465.7	982.6	-215.5	727.8	-4.6	-20.9	21.7	-1.1	7236	-	-
3^5P_3	3^{--}	465.8	982.6	-215.5	727.8	4.6	41.9	-6.2	-1.1	7271	-	-

arXiv:2108.04017 [hep-ph]

P-wave

M[BW1] = 6552 ± 10 ± 12 MeV

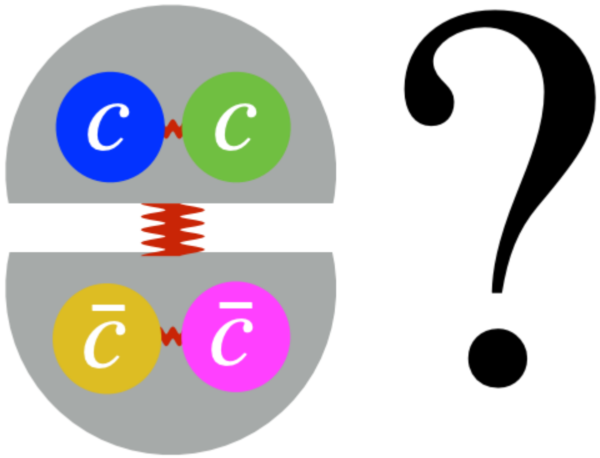
M[BW2] = 6927 ± 9 ± 5 MeV

M[BW3] = 7287 ± 19 ± 5 MeV

- Radial excited p-wave states (like J/ψ series)?
- Or Radial excited s-wave states?
- Theoretical situation difficulty & confusing
  - Important next step: measure J^{PC} to clarify

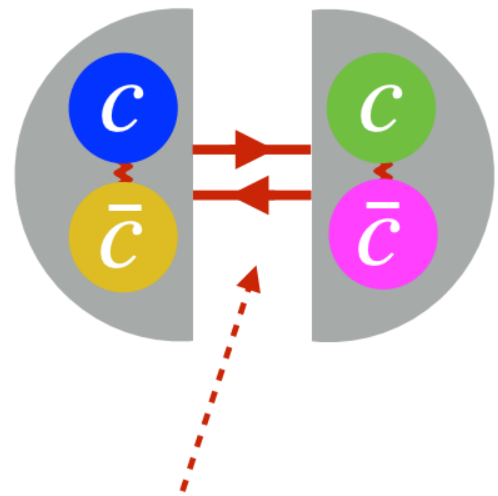
Spin Parity Analysis (2025)

CMS-PAS-BPH-24-002



"True" tetraquark
connects
two colored objects
(cc) and $(\bar{c}\bar{c})$
through direct strong
interactions
like quarks in a proton
or neutron

"Molecule"
a bound state
of two mesons
connected by
residual nuclear
force, like proton
and neutron in a
nucleus



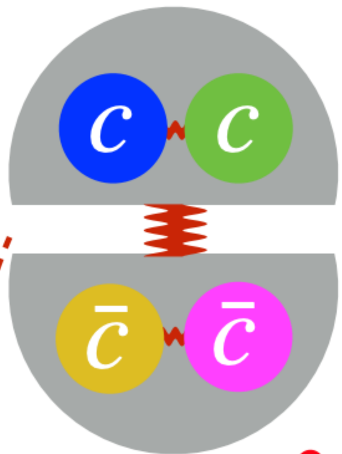
$$V(r) = g \cdot \frac{e^{-\frac{m_{\eta_c} c}{\hbar} r}}{r}$$

note $(c\bar{c})$ mass
$\times$ 22 heavier
than π

binding would be much weaker
than in a nucleus or light "tetraquarks"

other empirical interactions?

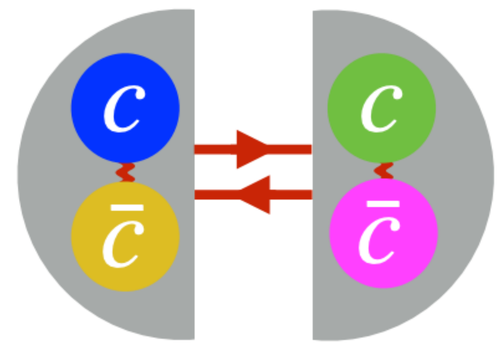
Spin Parity Analysis (2025)



- Fundamental study of matter at quark level…
  — unique all-heavy tetraquark states

  - Quantum numbers $J^{PC} = ?$

    directly related to structure:



- Tightly-bound tetraquark:

(cc) or $(\bar{c}\bar{c})$ identical ⇒ color anti-triplet (bg-gb,..) $L = 0$, axial vector $S_{1,2} = 1$

$(cc) + (\bar{c}\bar{c})$ ⇒ $L = 0\ (\mathrm{n}S):\ S = 0, 2 \ \Rightarrow J^P = 0^+, 2^+$ ← most likely for a tetraquark

$L = 1\ (\mathrm{n}P):\ S = 1 \ \Rightarrow J^P = 0^-, 1^-, 2^-$ ← less likely

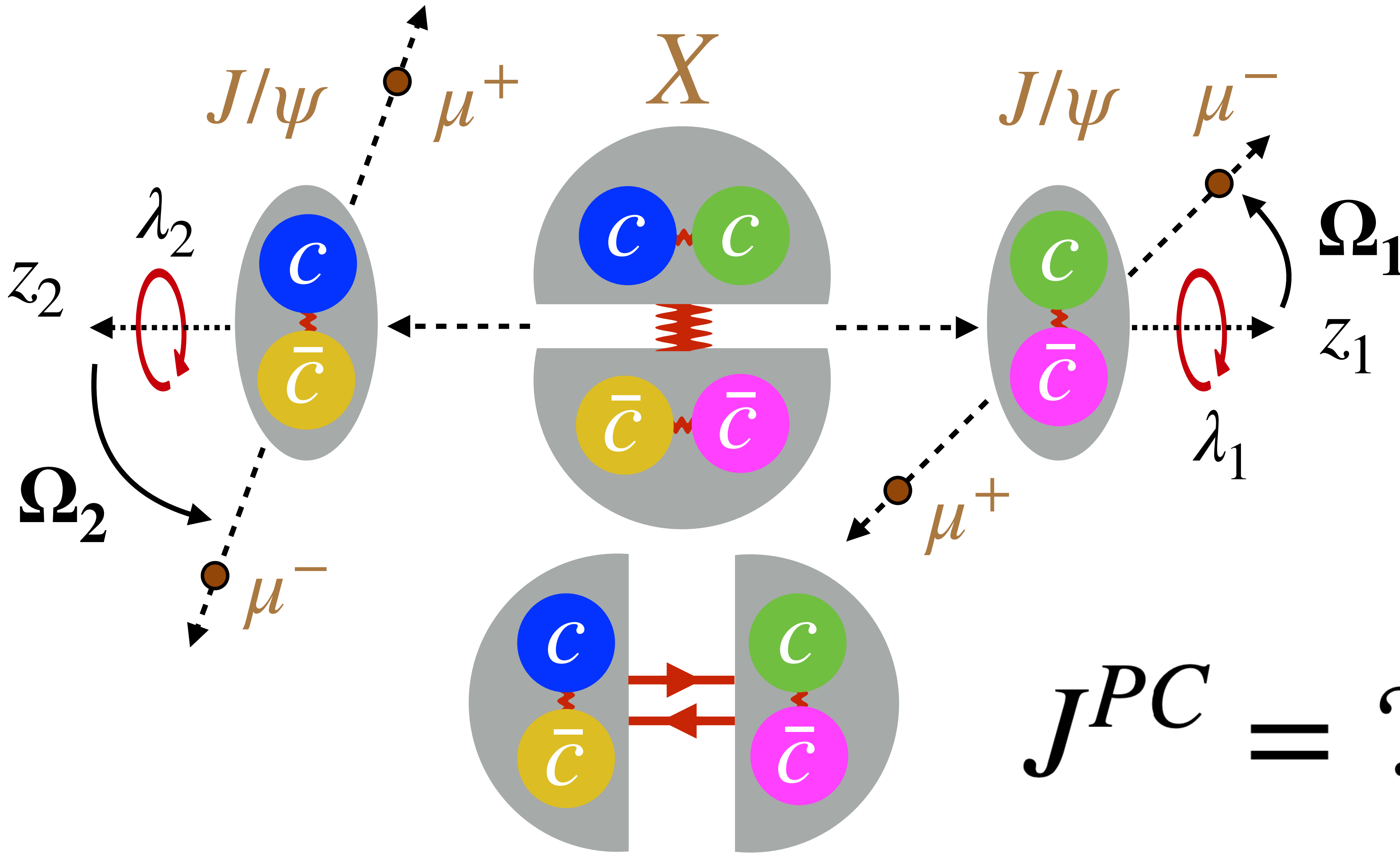
$n = 1,2,3,4,..$

$L = 2\ (\mathrm{n}D):\ S = 0 \ \Rightarrow J^P = 2^+$

$S = 2 \ \Rightarrow J^P = 0^+, 1^+, 2^+, 3^+, 4^+ \ \ldots$ (1^+ ← unlikely)

- Molecular: less restrictions (e.g. meson $S_{1,2} = 0,1$): recall $J^P = 1^+$

Data Analysis



$J^{PC} = ?$

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

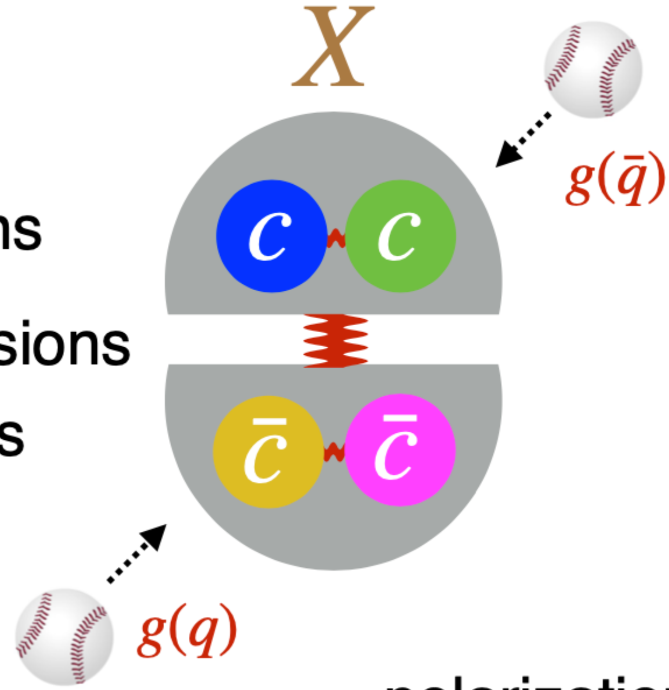
arXiv:2109.13363

MELA

matrix elements

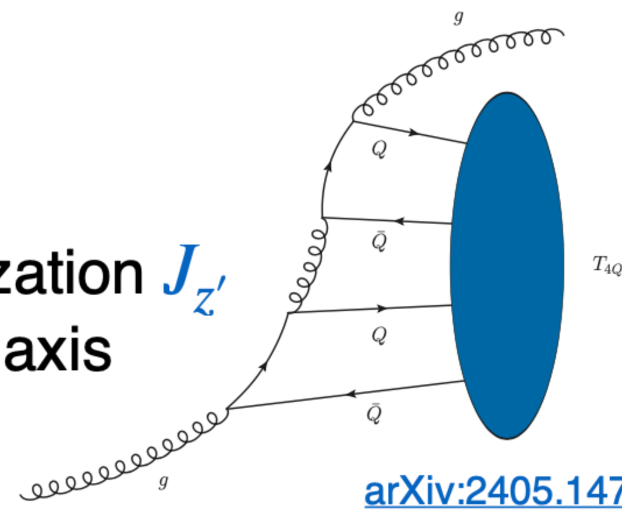
— re-weight $J = 1{,}2$ to unpolarized

— re-weight J_z or $J_{z'}$ for systematics



(B) gluon (quark) fragmentation

polarization $J_{z'}$ boost axis



arXiv:2405.14773

Concept of Analysis: All Input

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

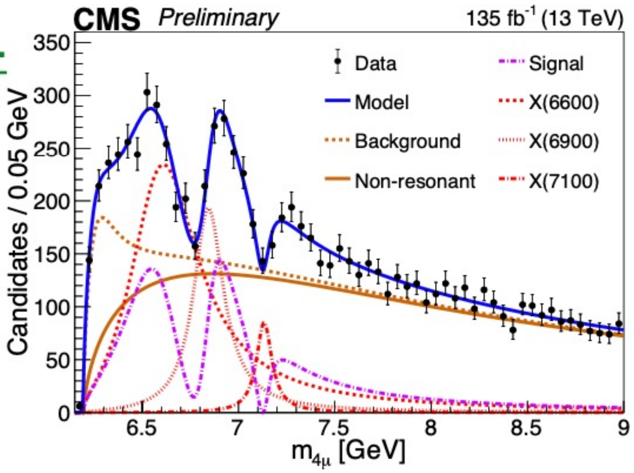
(2) p_T and p_Z of $X \to 4\mu$ — match to data

(3) polarization J_z or $J_{z'}$ of X — unpolarized

for $J = 0$ exact

for $J = 1,2,..$ depends on production mechanism

— vary J_z or $J_{z'}$ systematics or test

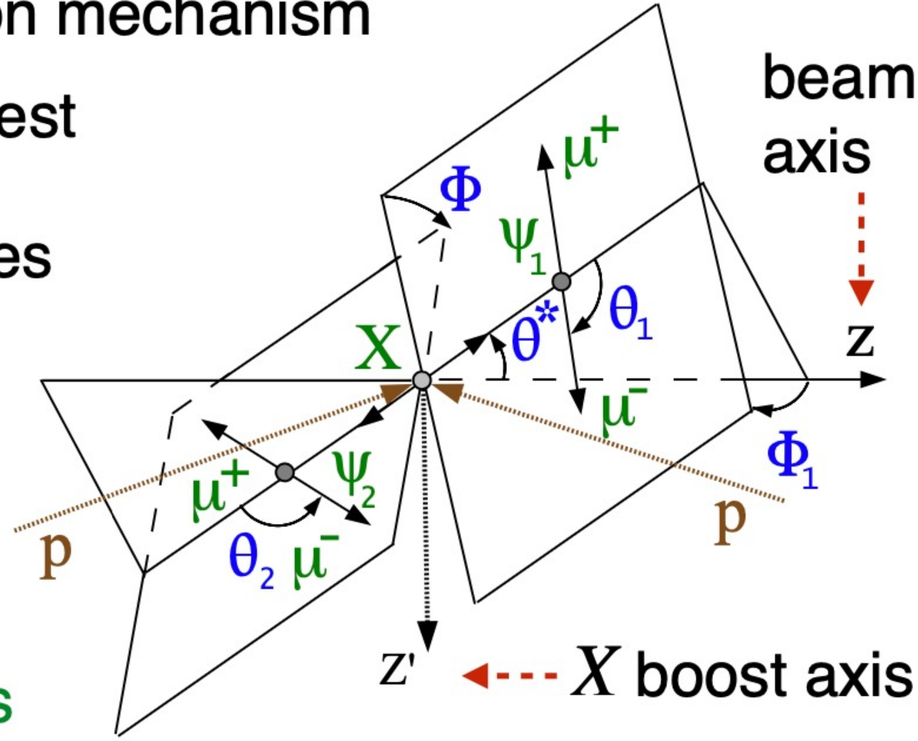


(4) Φ_1, θ^* or Φ'_1, θ'^* production angles

flat for unpolarized — test in data

non-flat for polarized

do not use in the primary analysis

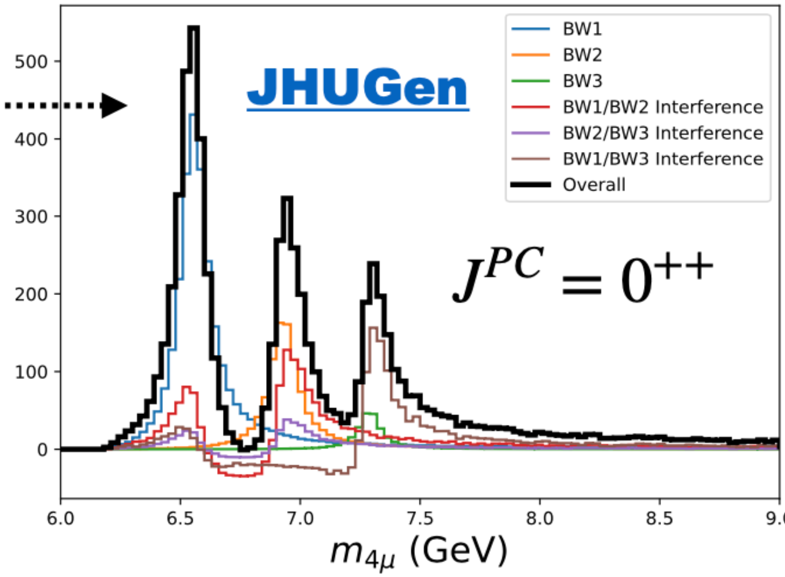


(5) Φ, θ_1, θ_2 decay angles — analysis

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:

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

empirical angular

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

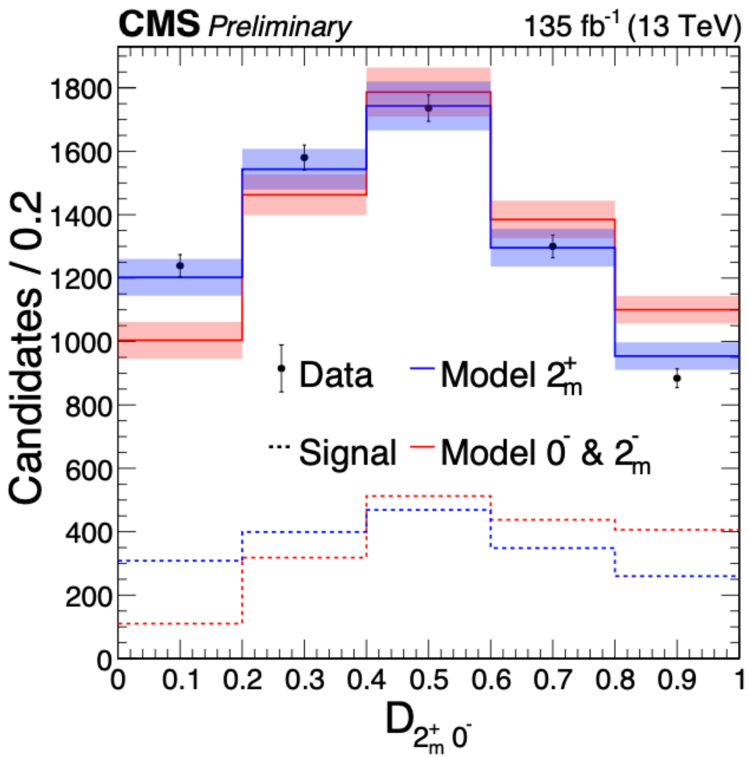
MELA $$\mathscr{D}_{ij}(\vec{\mathbf{\Omega}} \,|\, m_{4\mu}) = \frac{\mathscr{P}_i(\vec{\mathbf{\Omega}} \,|\, m_{4\mu})}{\mathscr{P}_i(\vec{\mathbf{\Omega}} \,|\, m_{4\mu}) + \mathscr{P}_j(\vec{\mathbf{\Omega}} \,|\, m_{4\mu})}$$

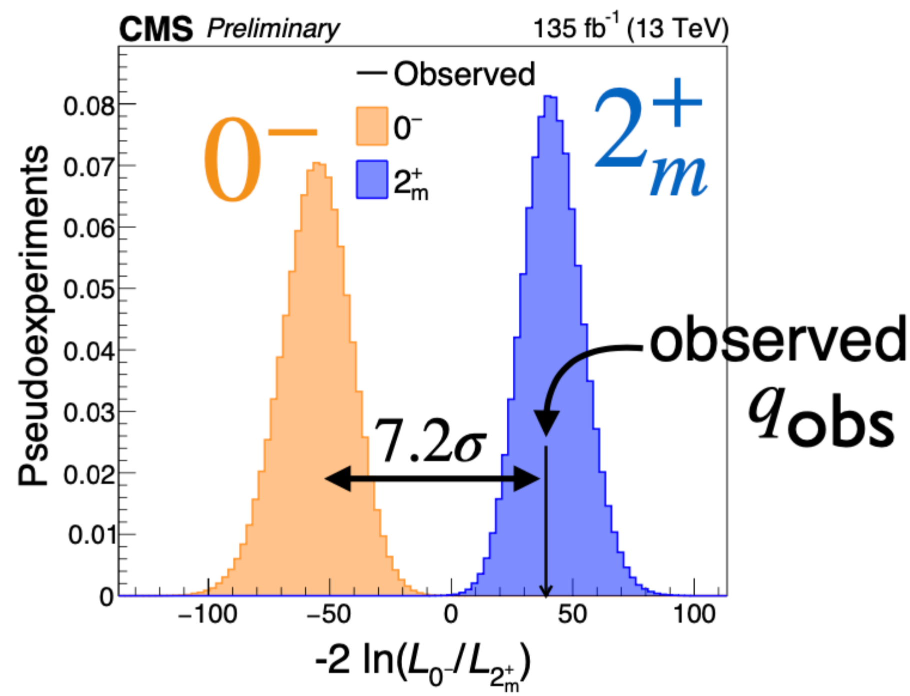
1 optimal observable ⇐ Higgs boson discovery and spin-parity

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

Optimal Observables and Statistical Analysis

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





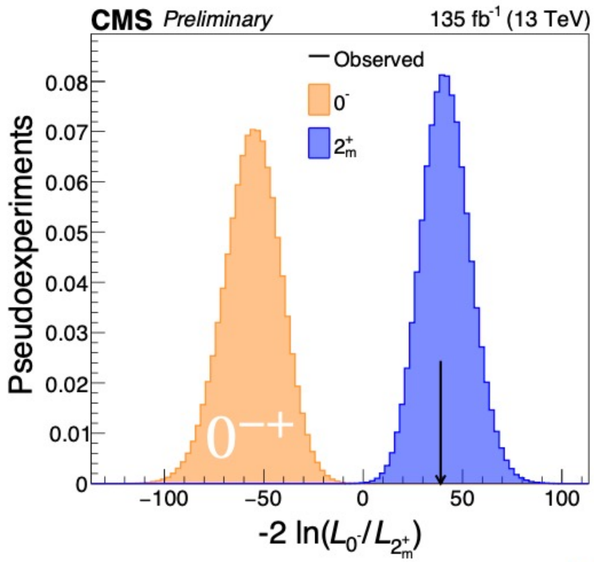
optimal observable

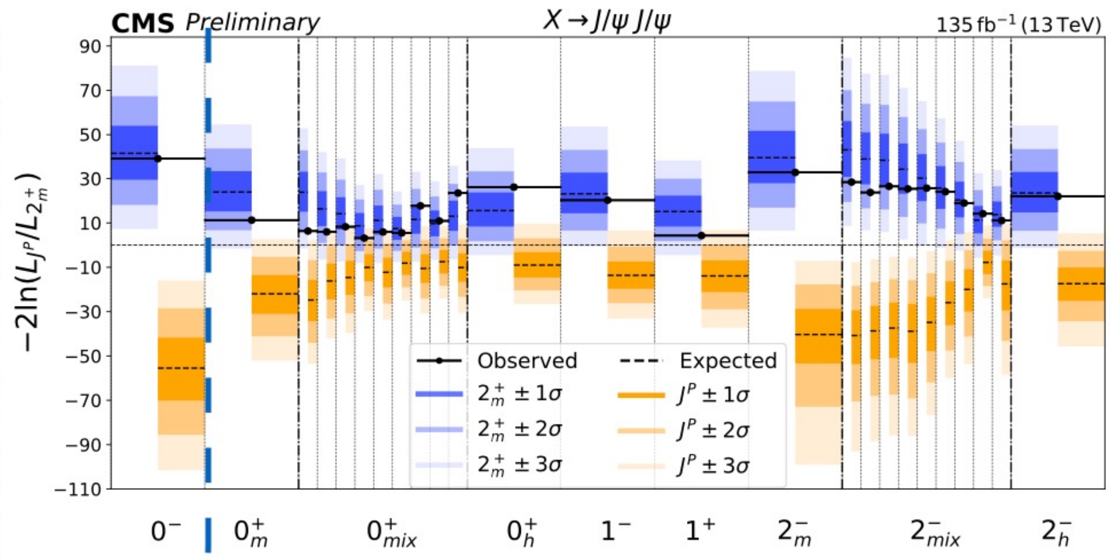
MELA $\mathscr{D}_{ij}(\vec{\Omega}\,|\,m_{4\mu}) = \dfrac{\mathscr{P}_i(\vec{\Omega}\,|\,m_{4\mu})}{\mathscr{P}_i(\vec{\Omega}\,|\,m_{4\mu}) + \mathscr{P}_j(\vec{\Omega}\,|\,m_{4\mu})}$

1D projections from 2D
⇒ limited information

	Observed		Expected	
	p-value	Z-score	p-value	Z-score
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

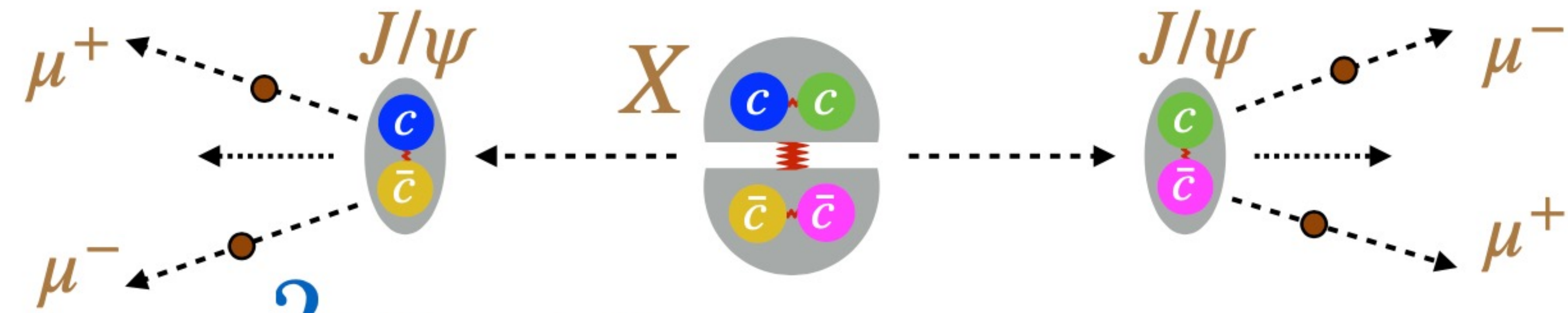
Summary of Statistical Analysis





- Scan mixture of two 0^{++} amplitudes (11 steps)
  - — constructive interference most conservative
- Scan mixture of two 2^{-+} amplitudes (11 steps)
  - — no interference (different spin projections)
- Data are consistent with a 2^{++} model, inconsistent with others

Summary of spin parity analysis



? $(c\bar{c})_{s=1} + (c\bar{c})_{s=1}$

most likely

? $(cc)_{s=1} + (\bar{c}\bar{c})_{s=1} \Rightarrow L = 0\ (\mathrm{n}S):\ S = 2 \Rightarrow J^{PC} = 2^{++},\ n = (1,)2,3,4,\ldots$

- J^{PC} analysis of exotic hadron decays at LHC (production-independent)
  - consistent picture: set of 3 exotic teraquark resonances with the same J^{PC}
  - $PC = ++$ very certain $\qquad n = (1,)2,3,4$
  - $J \neq 1$ at $> 99\,\%$ CL
  - $J \neq 0$ at $> 95\,\%$ CL
  - $J > 2$ possible, but highly unlikely, require $L \geq 2$
  - $J = 2$ consistent, rare in nature, naively expected $J = 0$

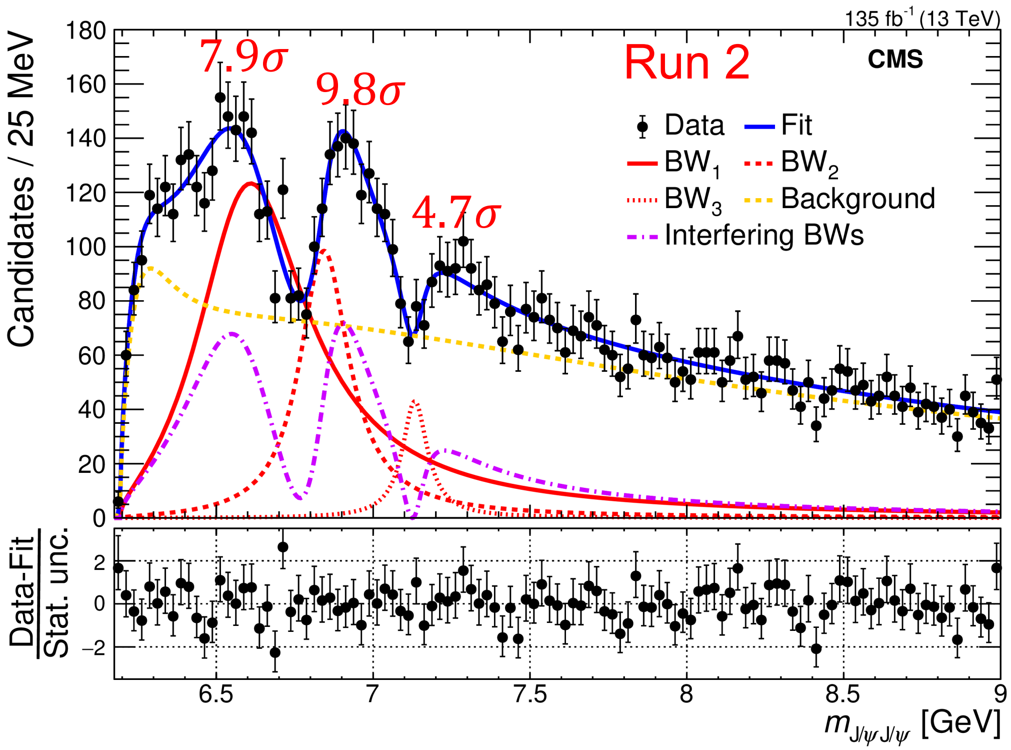
CMS J/ψJ/ψ Run 3

CMS-PAS-BPH-24-003

- 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

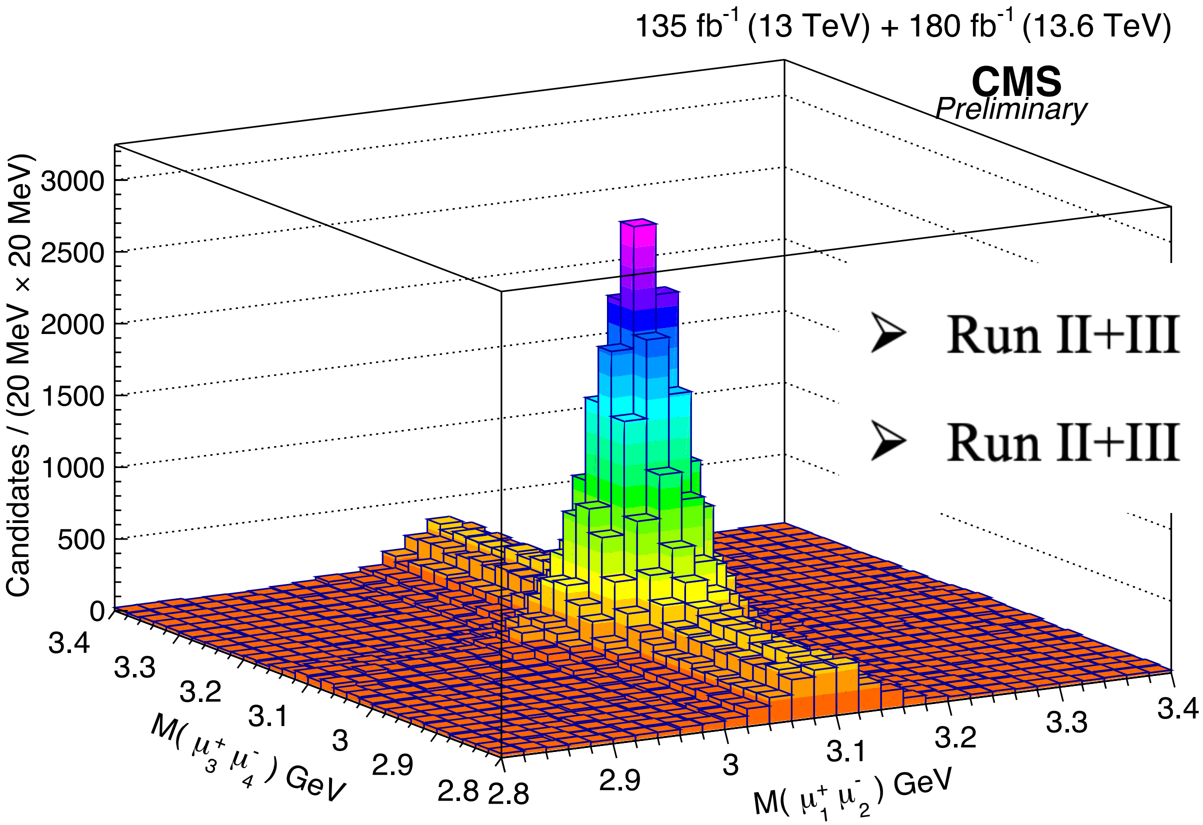
Trigger:

- Run II:
  - **HLT_Dimuon0_Jpsi_Muon (2016)**
  - **HLT_Dimuon0_Jpsi3p5_Muon2 (2017&2018)**
- Run III:
  - **HLT_Dimuon0_Jpsi3p5_Muon2**
  - **HLT_DoubleMu4_3_LowMass (new)**



- **X(7100)**: 4.7σ & Interference < 4σ
- Significance of **ALL** states over 5σ ?
- Significance of **interference** over 5σ ?

J/ψJ/ψ candidates Run 2+3



- Run II+III ***J/ψJ/ψ*** yield is **3.6X** of Run II
- Run II+III **Luminosity** is **2.3X** of Run II !

[6, 15] GeV	**N(*J/ψJ/ψ*)**	N(*J/ψμμ*)	N(*μμJ/ψ*)	N(*μμμμ*)
Run II	**12622 ± 165**	6451 ± 146	772 ± 52	1295 ± 60
Run III	**31802 ± 476**	33603 ± 491	4604 ± 166	33187 ± 267
Run II+III	**44936 ± 692**	39371 ± 698	5374 ± 181	34656 ± 278

CMS J/ψJ/ψ fit – Run 3

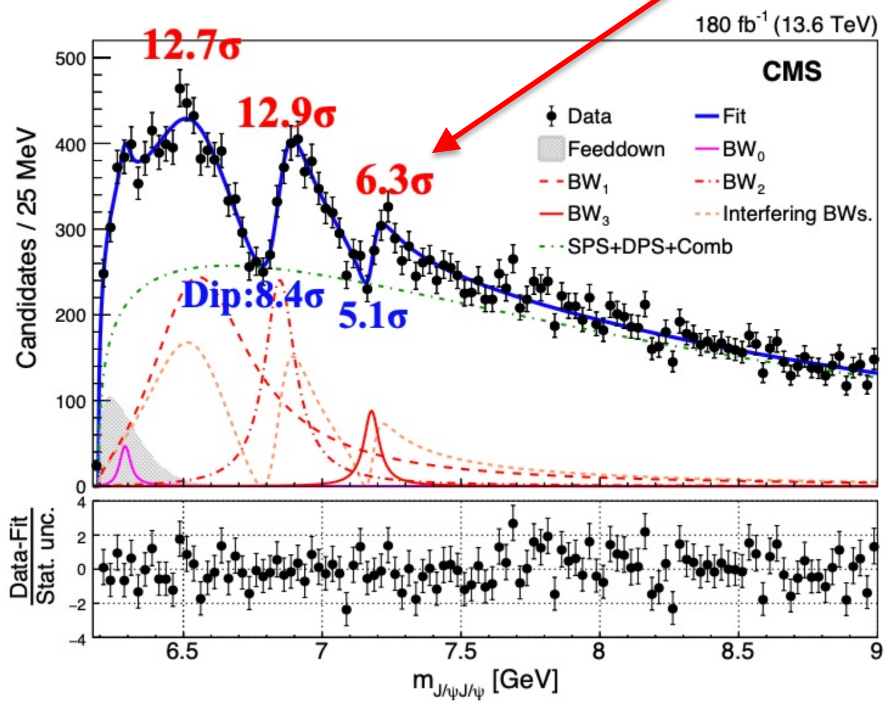
First observation of X(7100)

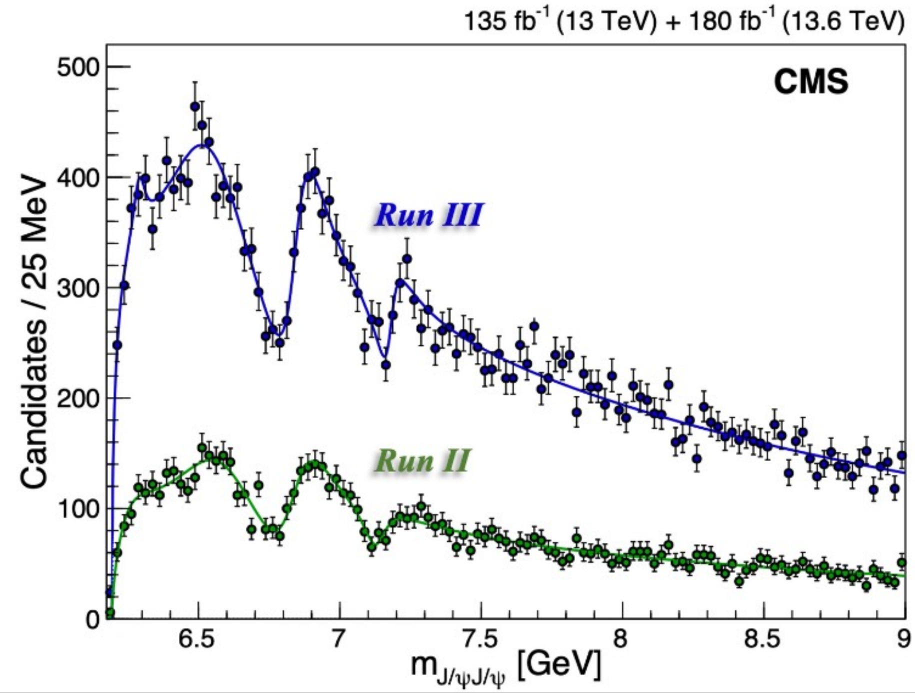
Chi2/nbins

[6, 15]: 363.20/353

[6, 9]: 117.33/113

[6.2, 7.8]: 56.66/64





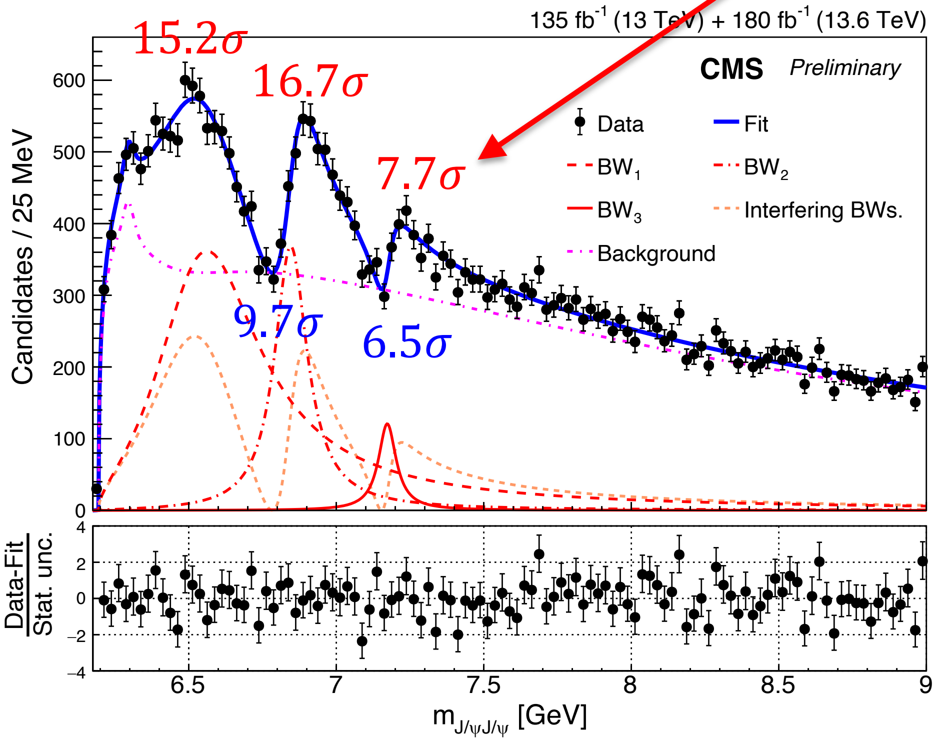
	BW1	BW2	BW3	Interf BW1-BW2	Interf BW2-BW3	Interf BW1-BW2-BW3
Significance (σ)	12.7	12.9	6.3	8.4	5.1	8.4

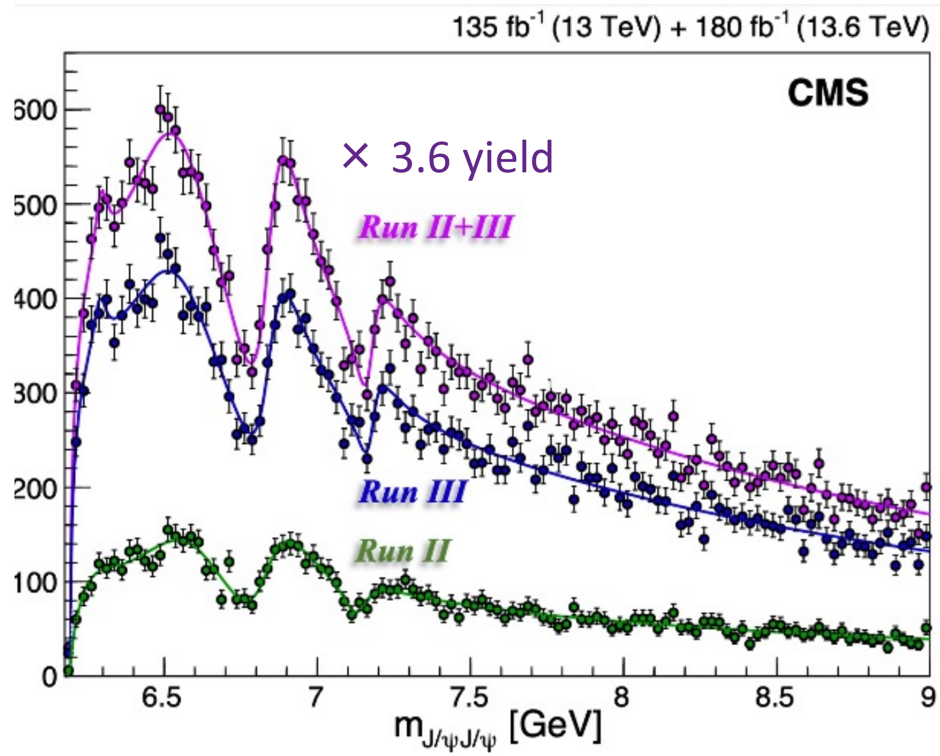
First observation of interferene

	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	6588 ± 19	6849 ± 12	7179 ± 10
Γ	454 ± 74	136 ± 18	67 ± 18

CMS J/ψJ/ψ fit – Run 2+3

First observation of X(7100)





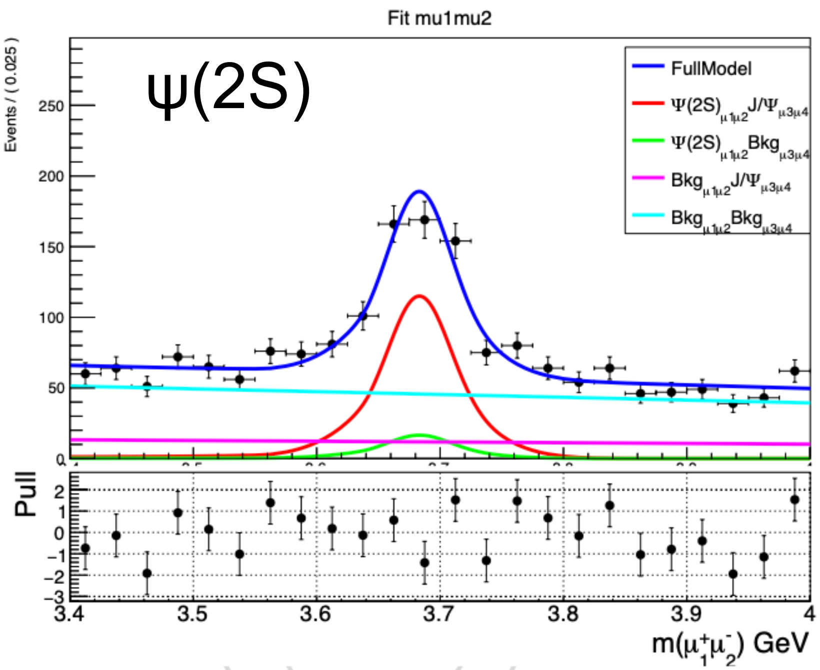
	BW1	BW2	BW3	Interf BW1-BW2	Interf BW2-BW3	Interf BW1-BW2-BW3
Significance (σ)	15.2	16.7	7.7	9.7	6.5	9.9

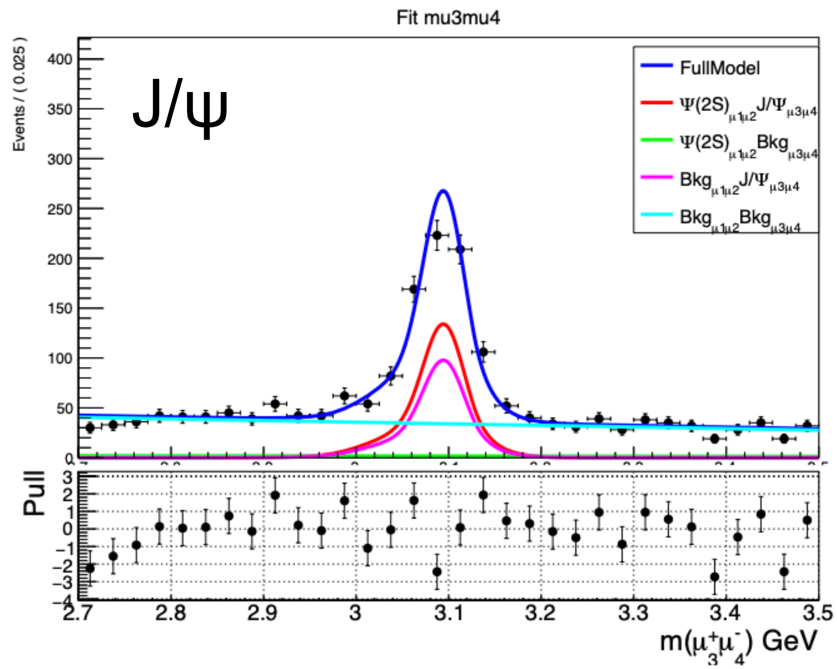
First observation of interferene

		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)	$440\,^{+230+110}_{-200-240}$	$191\,^{+66+25}_{-49-17}$	$97\,^{+40+29}_{-29-26}$

ψ(2S)J/ψ candidates Run 2+3

CMS-PAS-BPH-22-004

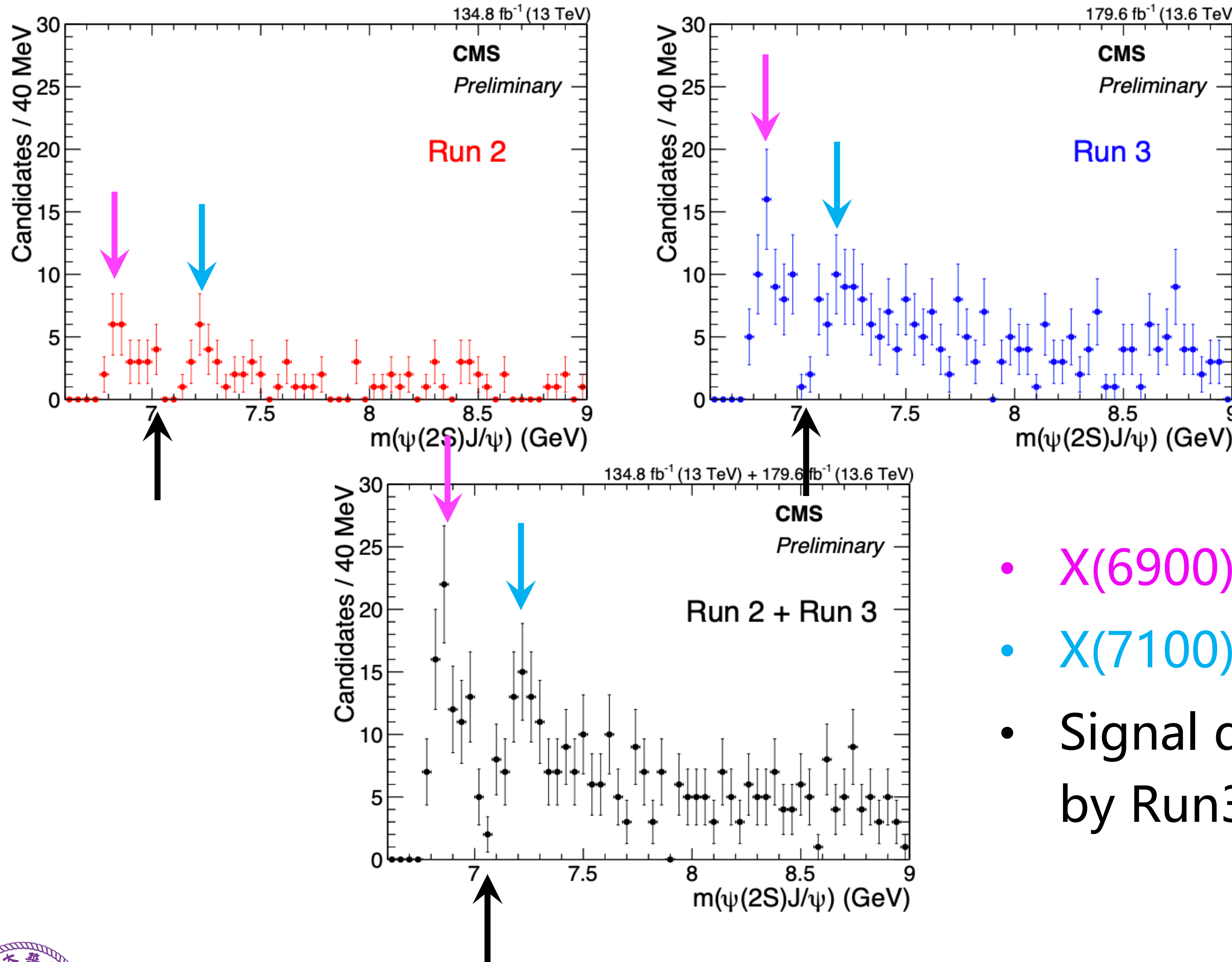




	Run2 + Run3 data		
$N(\psi(2S)\,J/\psi)$	386 ± 26	S	386 ± 26 (vs 109±14 in Run2)
$N(\psi(2S)Bkg_2)$	56 ± 24	B	1427 ± 57 (vs 208±22 in Run2)
$N(Bkg_1\,J/\psi)$	282 ± 28		
$N(Bkg_1\,Bkg_2)$	1089 ± 43		

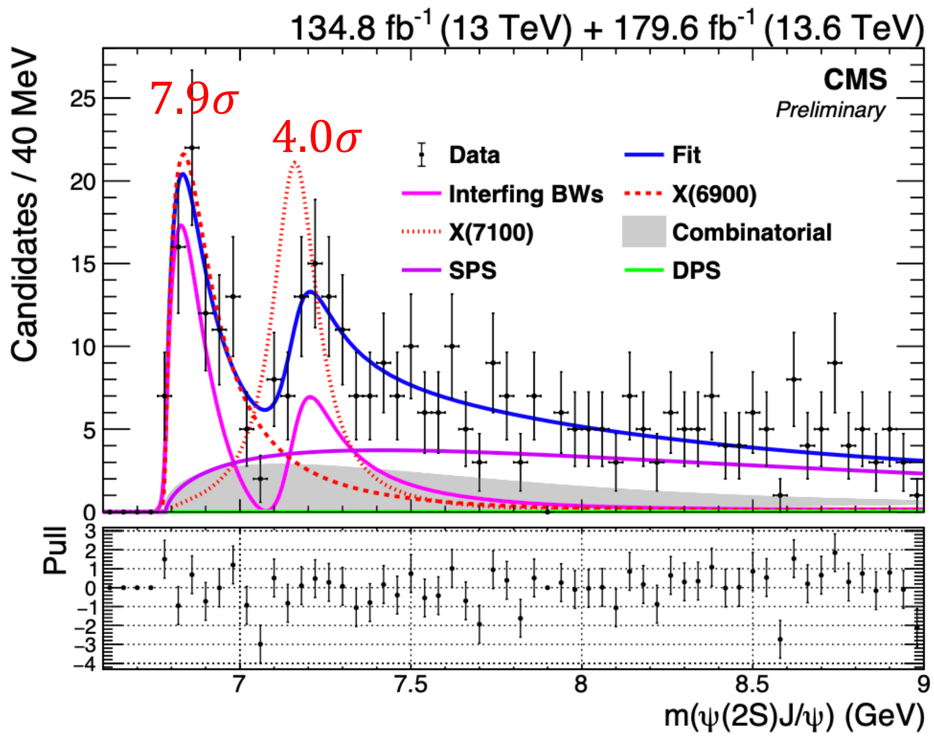
× 3.5 yield

CMS ψ(2S)J/ψ mass Run 2+3



- X(6900) is obvious
- X(7100) is visible
- Signal dominated by Run3

CMS ψ(2S)J/ψ fit Run 2+3



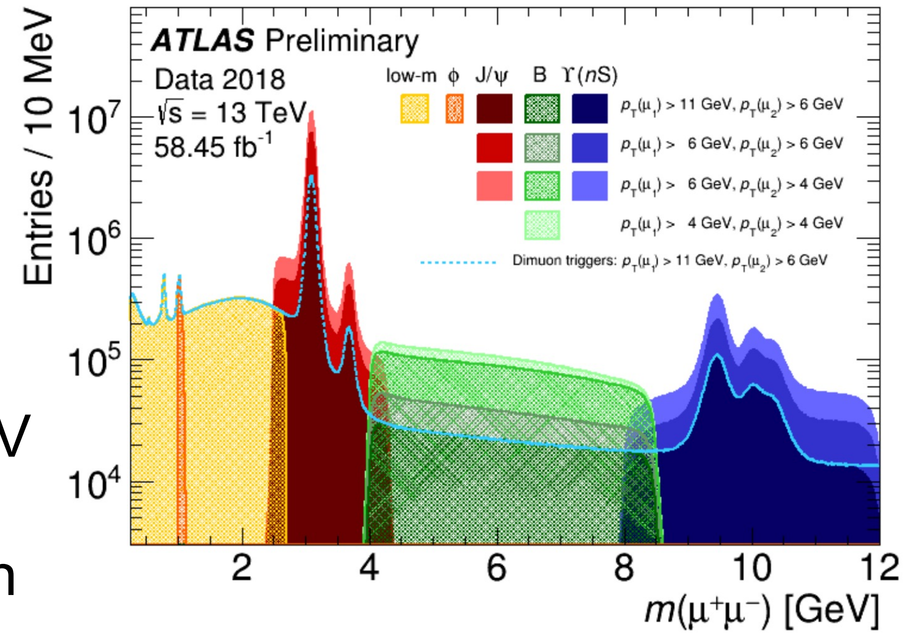
First observation of X(6900) → ψ(2S)J/ψ

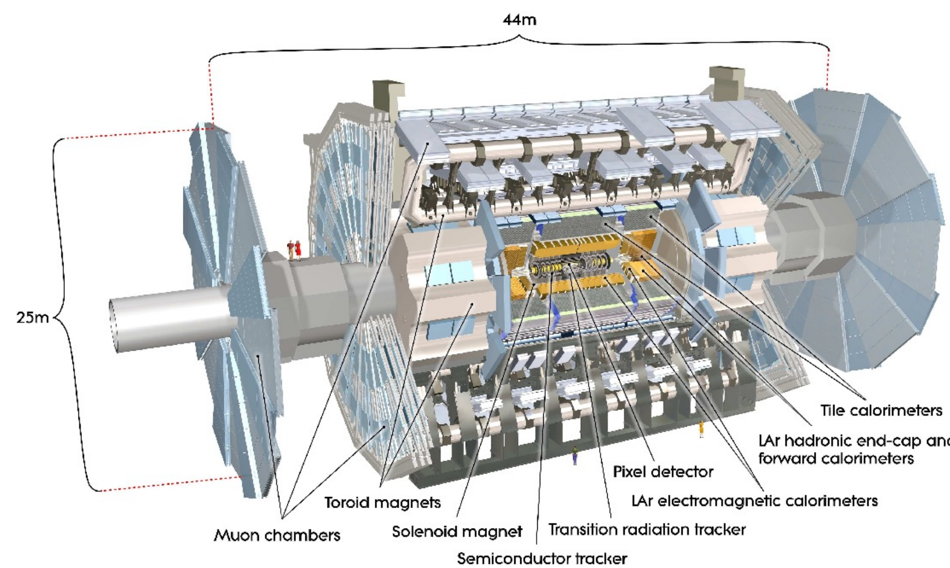
Evidence of X(7100) → ψ(2S)J/ψ

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}
			Γ :	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
f_{JJ} [1]	$J/\psi J/\psi$	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)	$440\ ^{+230+110}_{-200-240}$	$191\ ^{+66+25}_{-49-17}$	$97\ ^{+40+29}_{-29-26}$

B physics at ATLAS

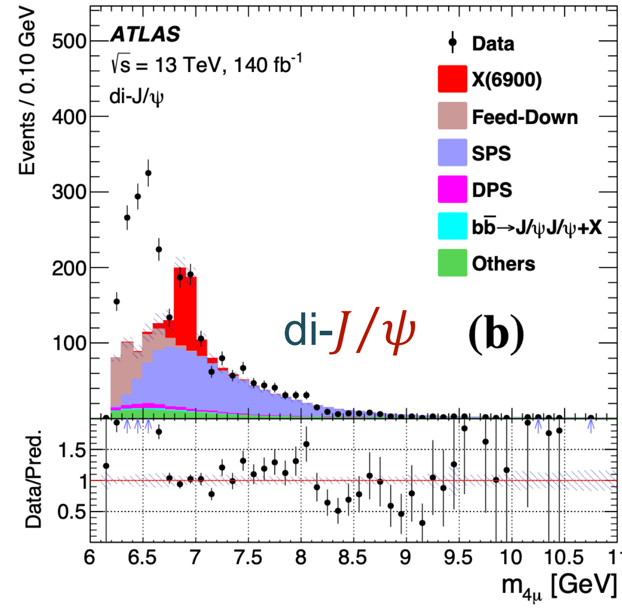
- ATLAS has collected a large set of data
  - Run 1 (2010-2013): $4.9 fb^{-1}$ at 7 TeV and $20.3 fb^{-1}$ at 8 TeV
  - Run 2 (2015-2018): $139 fb^{-1}$ at 13 TeV
- Analysis focus mostly on final states with muons.
- Dedicated B-physics triggers.
- Excellent track and muon identification with the goodness of the inner detector and muon spectrometer.

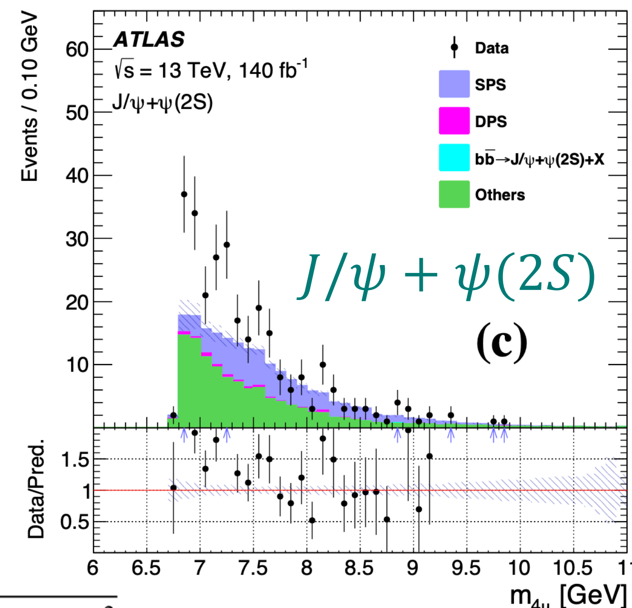




Hunt for di-J/ψ resonances by ATLAS at 13 TeV

- Signal: $T_{cc\overline{cc}} \to J/\psi + J/\psi \;\; or \;\; J/\psi + \psi(2S) \to 4\mu$
- Backgrounds:
  - Prompt: SPS and DPS
  - Non-prompt: $b\overline{b} \to J/\psi + J/\psi/\psi(2S) + X \to 4\mu$
  - Others: Single J/ψ background and non-peaking background containing no real J/ψ candidate
- **Excess in both channels**
- The unbinned maximum likelihood fits are performed in the 4μ mass spectrum.
  - The signal pdf: several interfering BW multiplied with a phase space factor and convolved with a mass resolution function



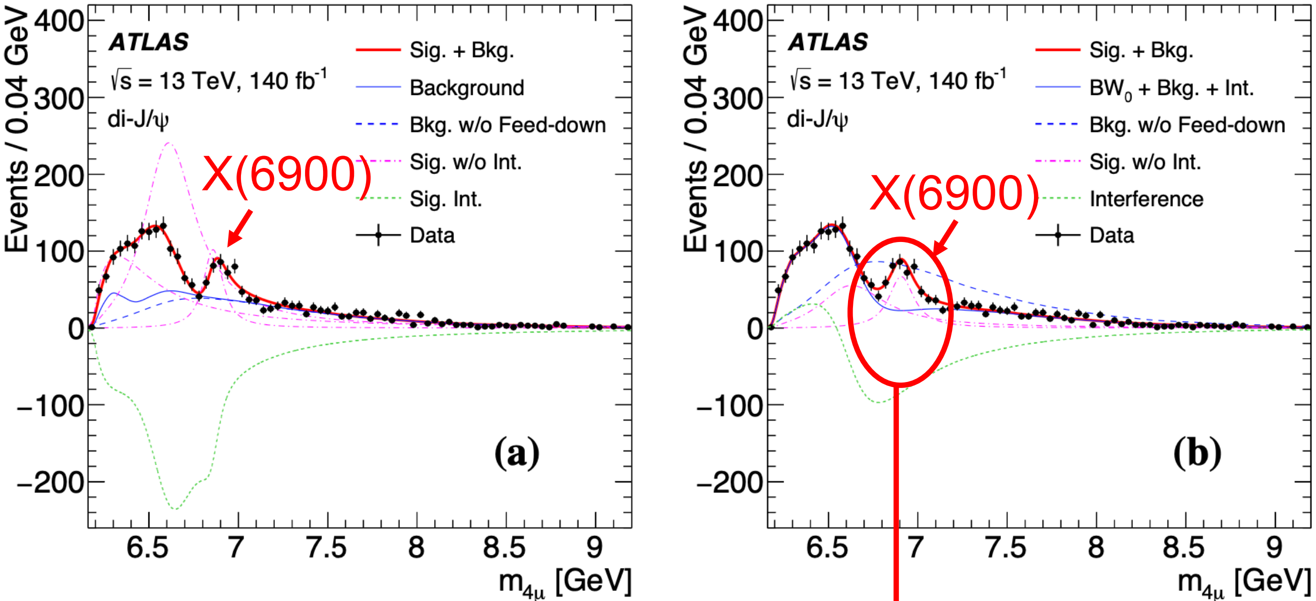


di-J/ψ : $$f_s(x) = \left|\sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i}\right|^2 \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\alpha)$$

$J/\psi + \psi(2S)$: $$f_s(x) = \left(\left|\sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i}\right|^2 + \left|\frac{z_3}{x^2 - m_3^2 + i m_3 \Gamma_3}\right|^2\right) \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x}\right)^2} \otimes R(\alpha)$$

ATLAS di-J/ψ channel

Model A | Model B



Extracted masses and widths (GeV)

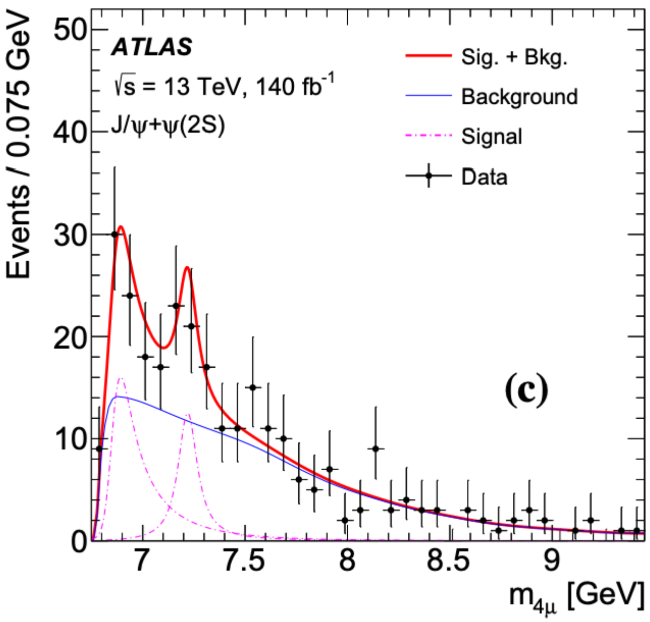
di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

X(6900) > 5σ

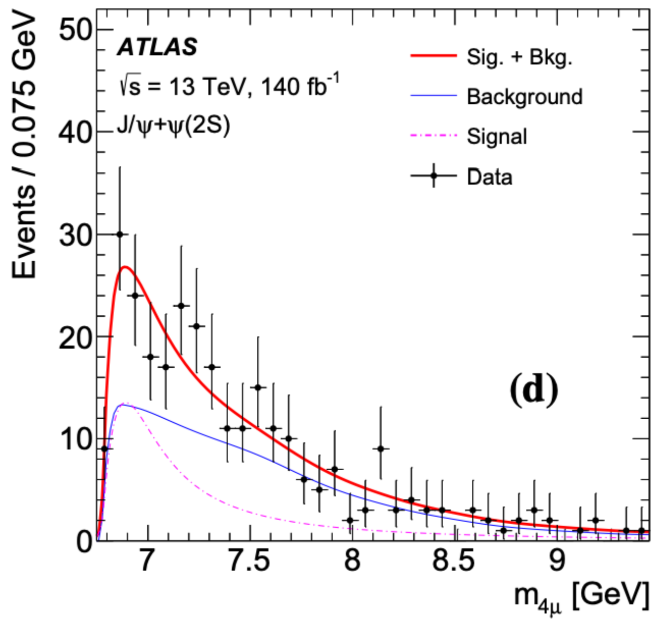
- Model A - similar to LHCb model I, but 2 auxiliary BWs interfere with X(6900)
- Model B - similar to LHCb model II: one auxiliary BW interferes with NRSPS
- Both models describe the data well
  - the broad structure at the lower mass could result from other physical effects, such as the feed-down
- The peak around 6.9 Gev is consistent with the LHCb observed X(6900), with significance > 5σ

ATLAS $J/\psi + \psi(2S)$ channel

Model α



Model β

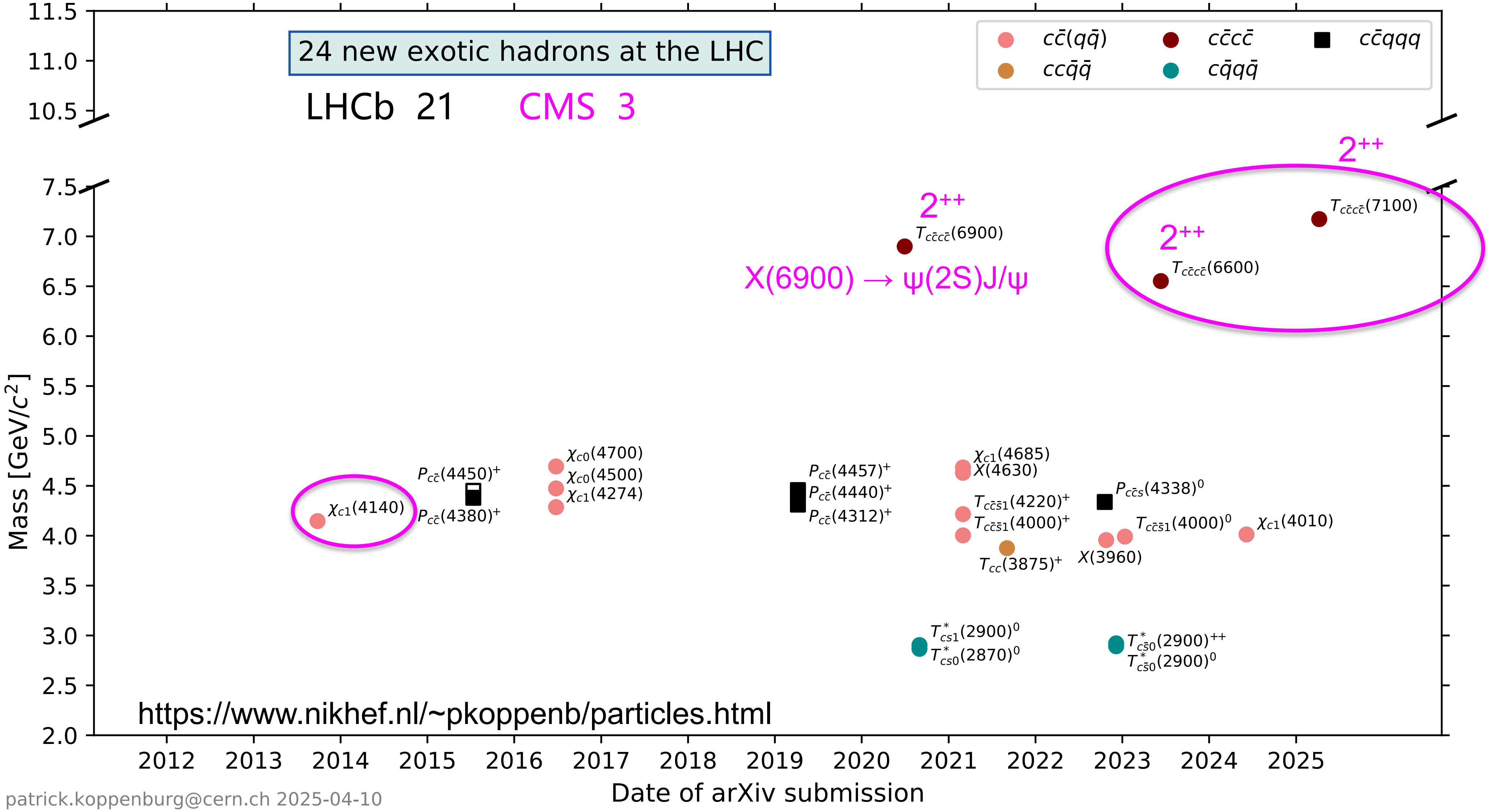


- Model α: X(6900)+2nd resonance
  - Two bumps together: 4.7 σ
  - 2nd bump alone: 3 σ
- Model β: a single resonance X(6900) in this channel
  - 4.3 σ

Extracted masses and widths (GeV)

$J/\psi+\psi(2S)$	model α	model β
m_3 or m	$7.22 \pm 0.03^{+0.01}_{-0.03}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3 or Γ	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$

Summary: new exotic hadrons at LHC



J/ψJ/ψ Run 2+3 http://cds.cern.ch/record/2929472 南师 复旦 清华 中山

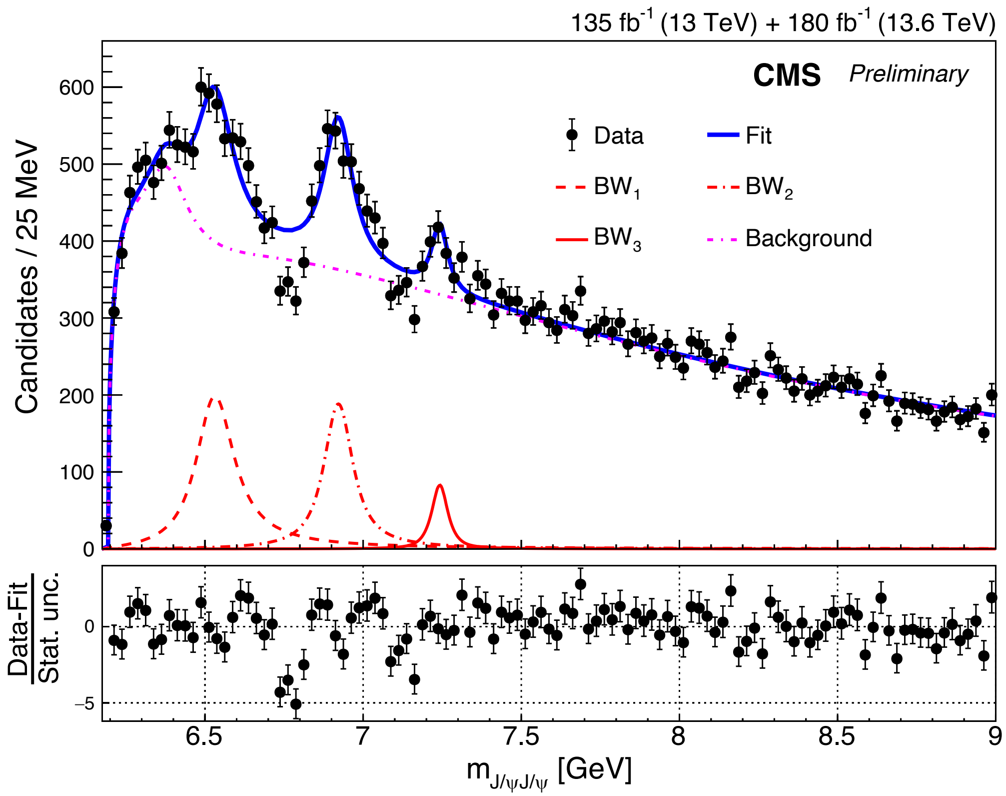
ψ(2S)J/ψ Run 2+3 http://cds.cern.ch/record/2929529 南师 清华 复旦

J/ψJ/ψ spin parity http://cds.cern.ch/record/2929695 南师 清华 JHU

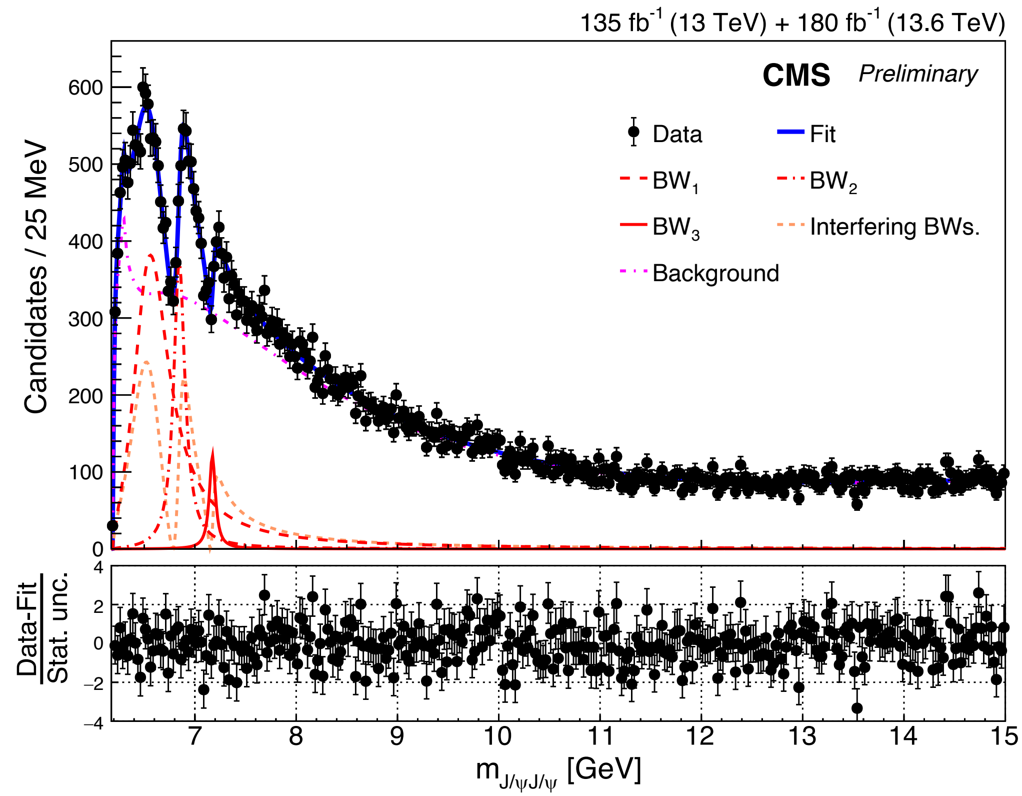
Backup

CMS J/ψJ/ψ fit – Run 2&3

No-interference fit



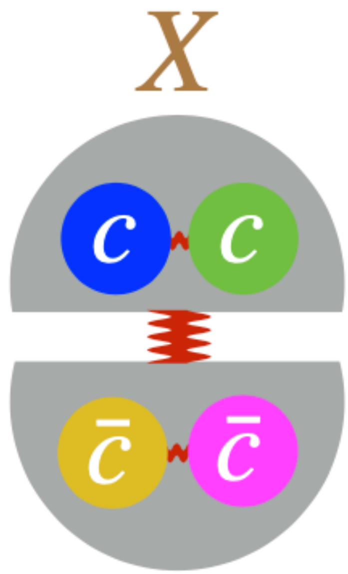
Wider region



Concept of Analysis: Production

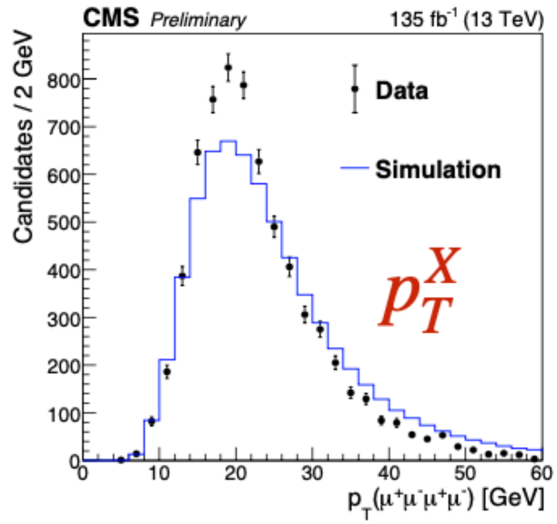
- We do not know the production mechanism

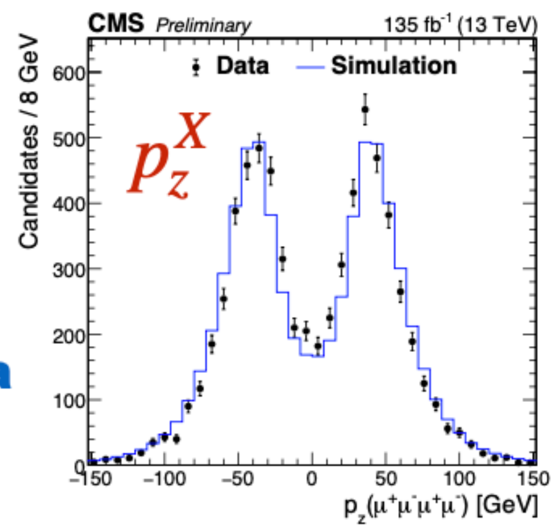
— empirical model to reproduce p_T^X and p_z^X in data



Simulation

JHUGen + Pythia





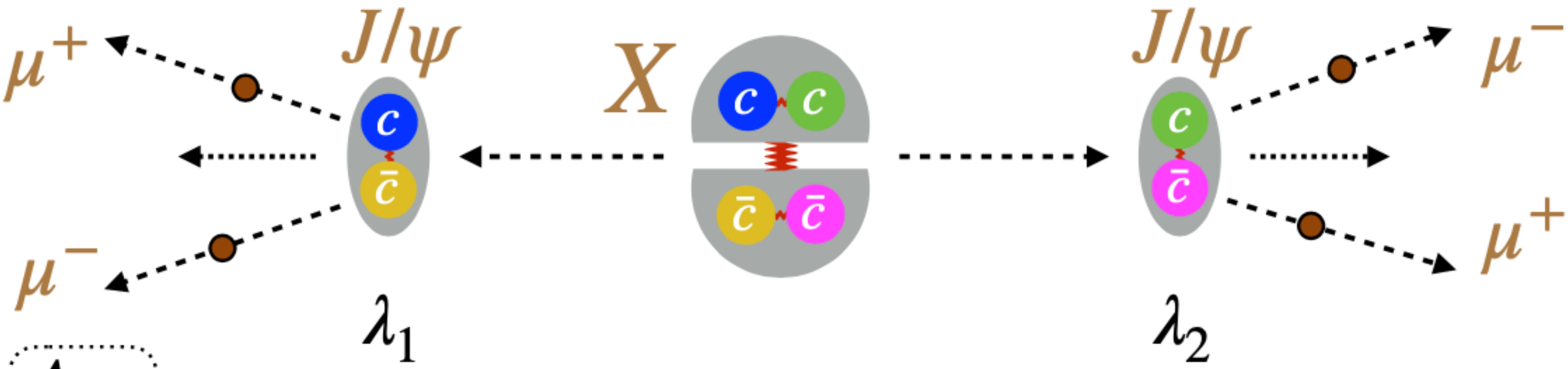
— tune **Pythia** to match p_T^X in sideband and signal region

— 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

J/ψ Polarization



A_{++}
A_{--}
A_{00}

A_{+0}
A_{0+}
A_{-0}
A_{0-}

A_{+-}
A_{-+}

- Symmetries:

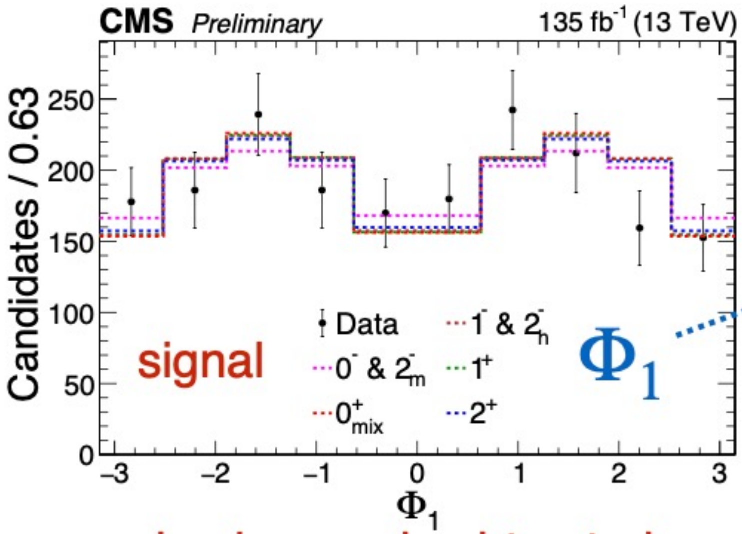
Test 8+ J_X^P models:

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

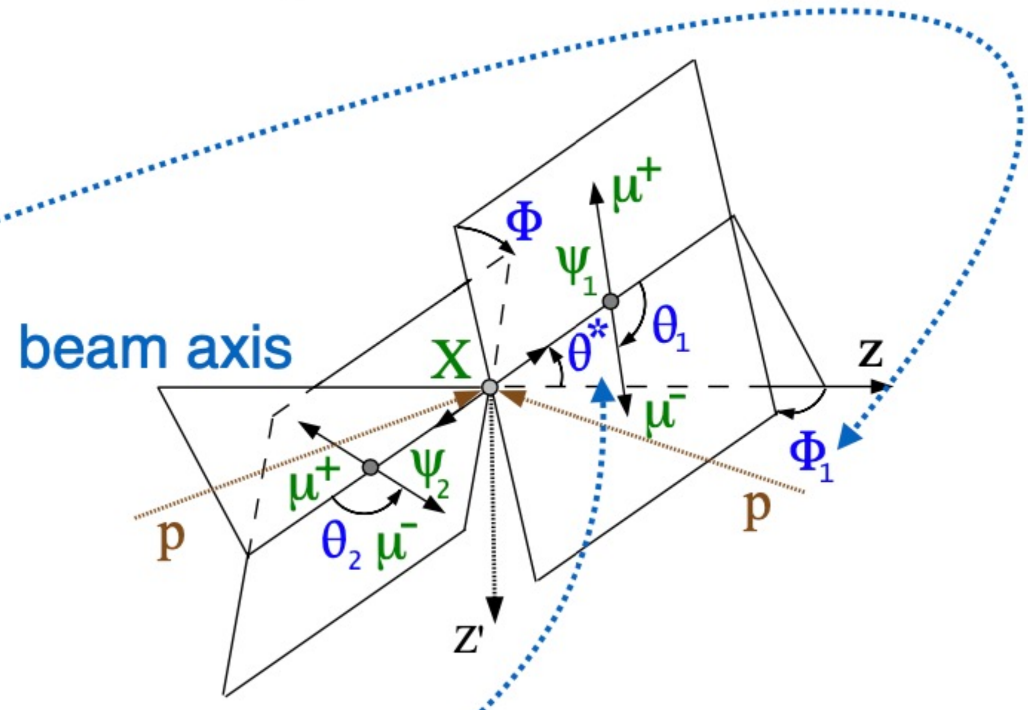
Production angles

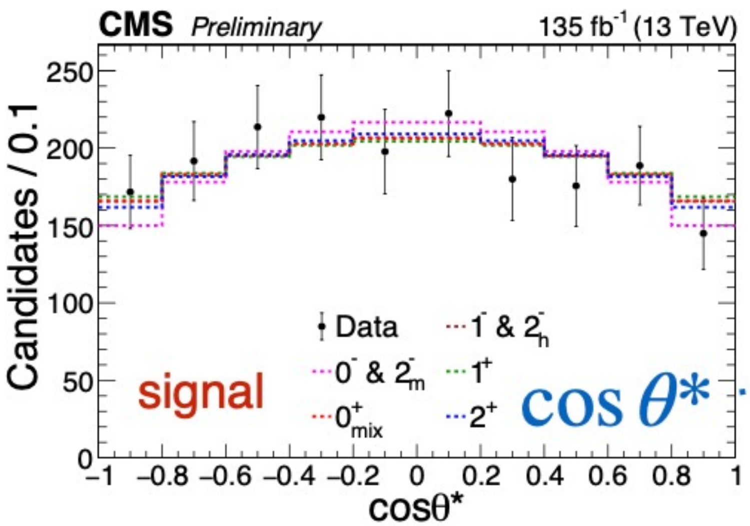
(4) production angles consistent with unpolarized resonances



background-subtracted

with respect to the beam axis

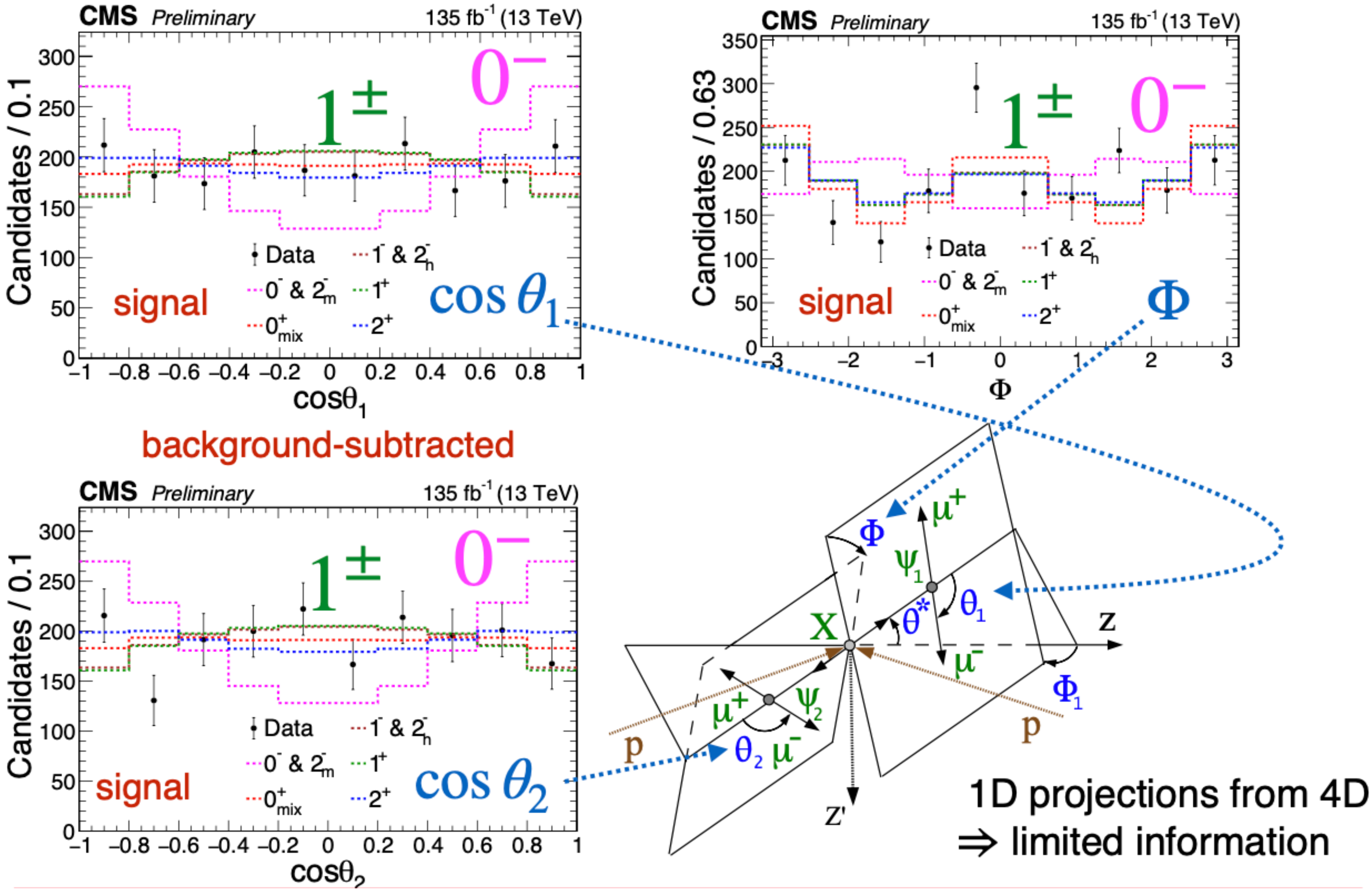




acceptance effects
⇒ distributions not flat

Decay angles

(5) decay angles (consistency check): distinguish models



Summary of Statistical Analysis

- 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 $L\geq2$

– $J\neq0$ at $>95\,\%$ CL

– $J\neq1$ at $>99\,\%$ CL

– $P\neq-1$ very certain (exclude J^{-+} including $J\geq3$)

- Recall: 2^{++} can have a mixture of 2^+_m and look-alike of 0^+, 1^+

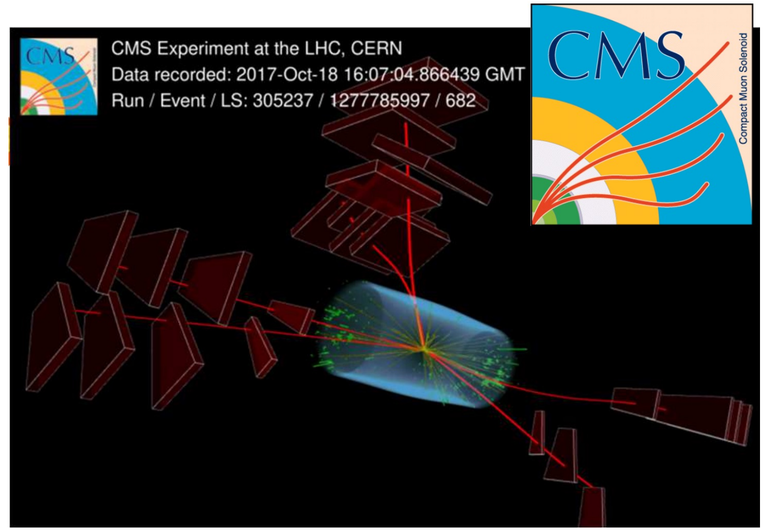
Observation of triple J/ψ

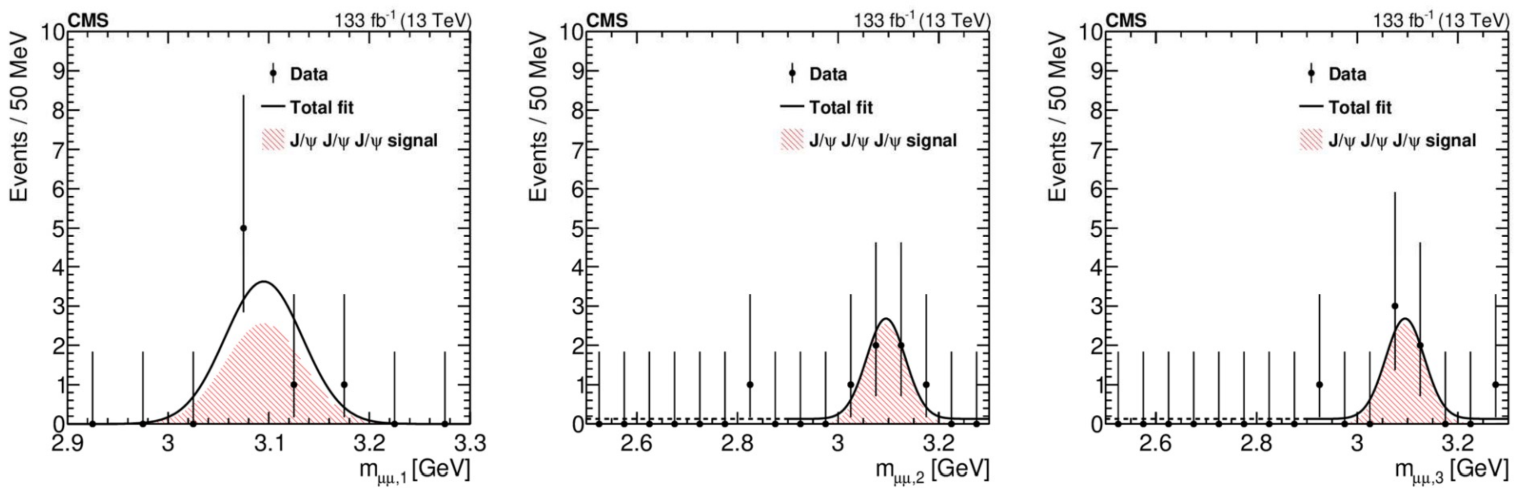
Signal yield: $5^{+2.6}_{-1.9}$events

Significance > 5σ

σ(pp→J/ψJ/ψJ/ψX)
= 272 +141−104 (stat) ± 17 (syst) fb

Nature Physics 19 (2023) 338

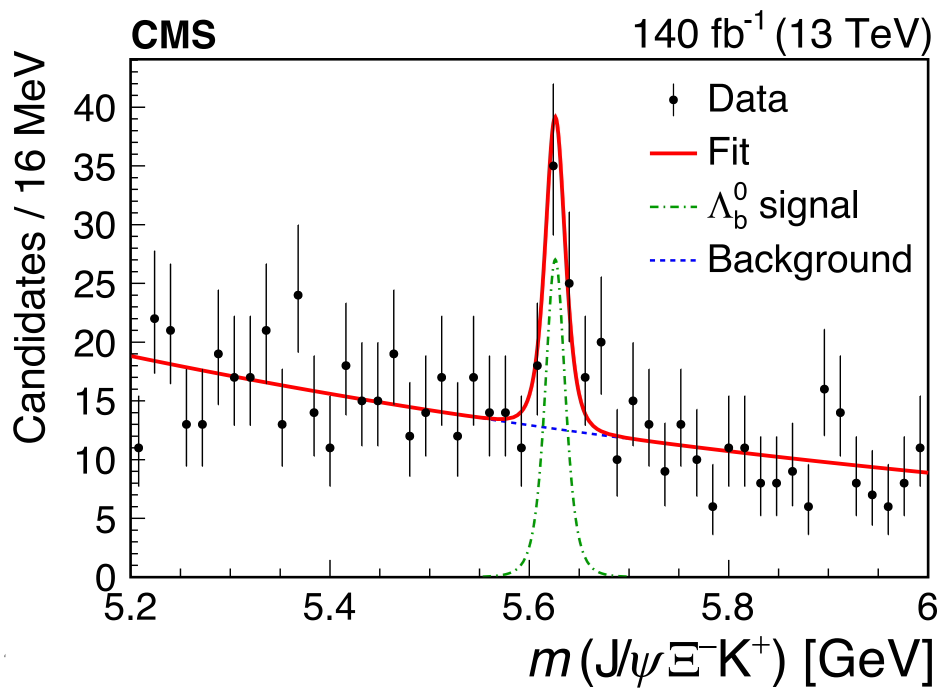


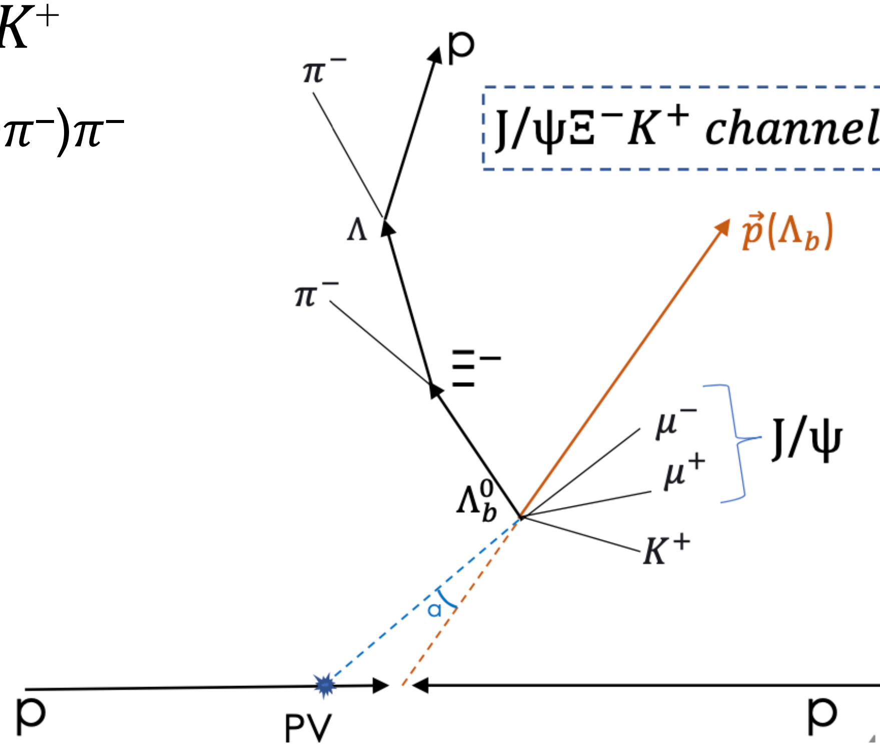


"6c" search in future?

Observation of $\Lambda_b \to J/\psi\, \Xi^- K^+$

- Multi-body decays of b-hadrons may proceed through exotic intermediate resonances
  - E. g. pentaquark $J/\psi\, p$ structure in $\Lambda_b \to J/\psi\, p\, K^-$ observed by LHCb
  - $\Lambda_b \to J/\psi\, \Xi^- K^+$ final state can unveil yet-unobserved (e. g. doubly-strange) pentaquarks
- First-time observation of $\Lambda_b \to J/\psi\, \Xi^- K^+$
  - In final states with $J/\psi \to \mu\mu$, $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$
  - **5.8** $\boldsymbol{\sigma}$ significance





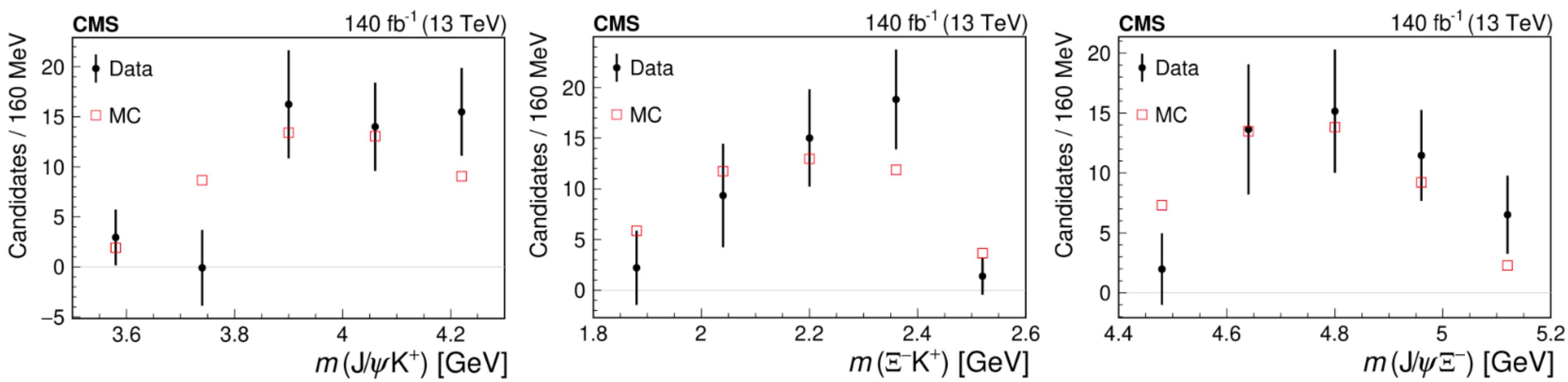
Observation of $\Lambda_b \to J/\psi\, \Xi^- K^+$

- $\Lambda_b \to J/\psi\, \Xi^- K^+$ branching fraction ratio measurement
  - Large systematics cancellation in the measured ratio R
  - Result dominated by low signal statistics

$$R = \frac{B(\Lambda_b \to J/\psi\, \Xi^- K^+)}{B(\Lambda_b \to \psi(2S)\Lambda)} = \frac{N_{signal}}{N_{ref.}} \times \frac{\epsilon_{signal}}{\epsilon_{ref.}} \times \frac{B(\psi(2S) \to J/\psi\, \pi^-\pi^+)}{B(\Xi^- \to \Lambda\pi^-)}$$

$$= [\mathbf{3.38 \pm 1.02\ (\mathit{stat.}) \pm 0.61 (\mathit{syst.}) \pm 0.03\ (\mathit{B})}]\ \%$$

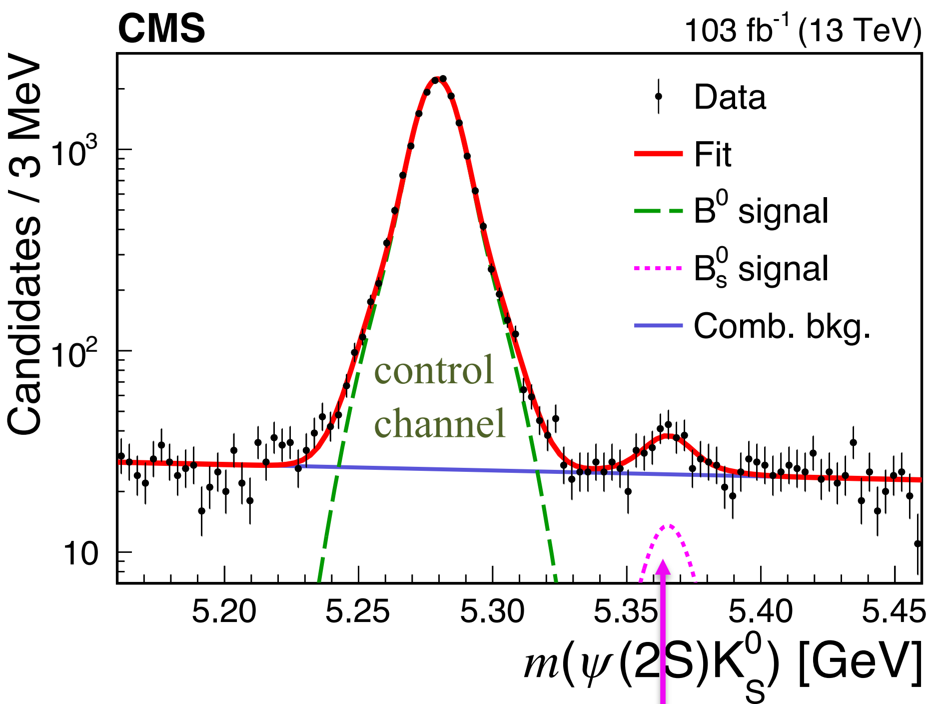
- Search for intermediate resonances

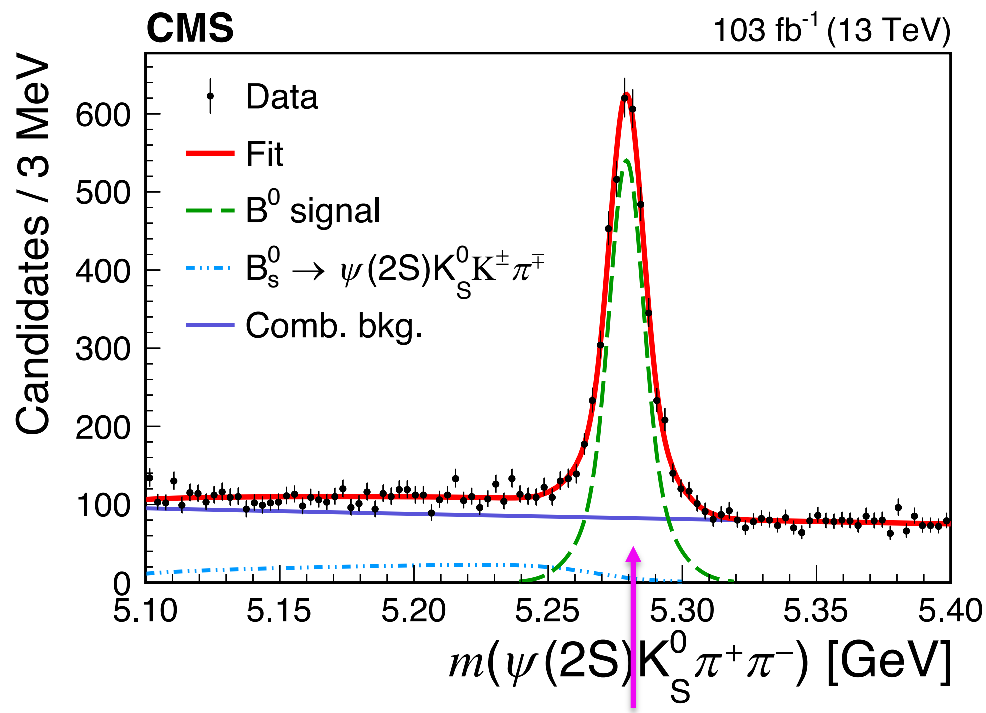


No evidence of resonant structures at this signal statistics

Observation of $B^0 \to \psi(2S) K_0^S \pi^+ \pi^-$

- 103 fb^{-1} @ 13 TeV pp collision data





Significance 5.2σ !
First observation of
$B_s^0 \to \psi(2S)K_S^0$!

Significance > 30
First observation

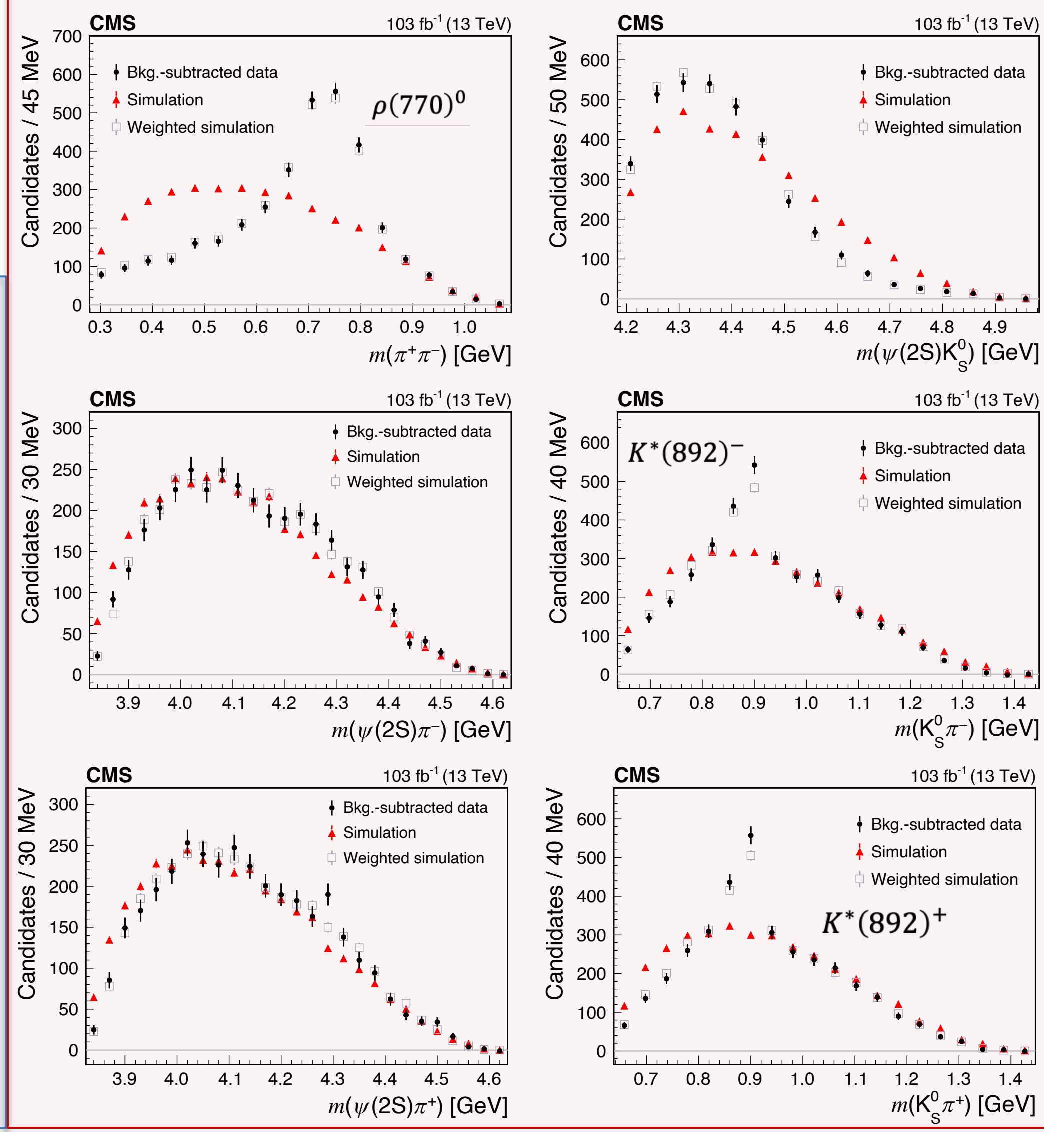
$$\mathcal{B}(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)/\mathcal{B}(B^0 \to \psi(2S)K_S^0) = 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst}),$$

$$\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)/\mathcal{B}(B^0 \to \psi(2S)K_S^0) = (3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2}$$

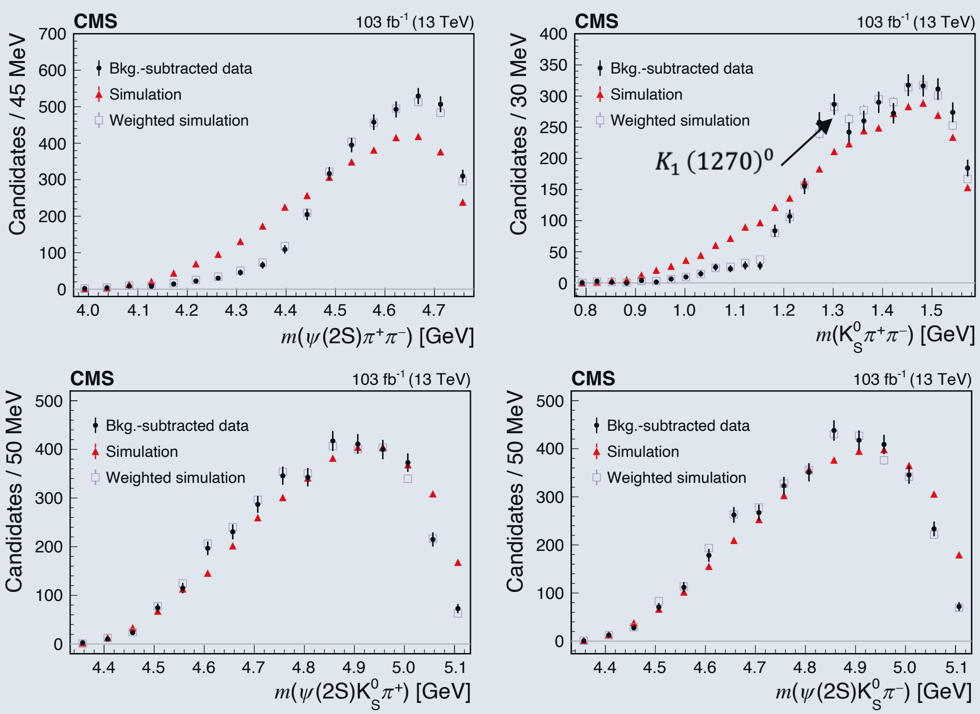
Observation of $B^0 \to \psi(2S) K_0^S \pi^+ \pi^-$

- No evidence of new resonant structures at this signal statistics

2-body intermediate invariant masses

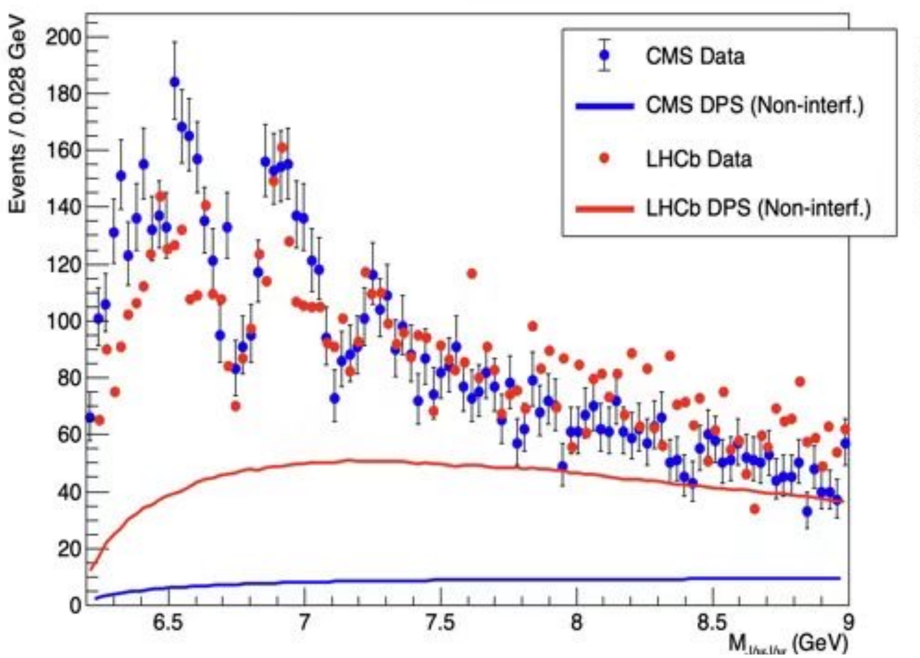


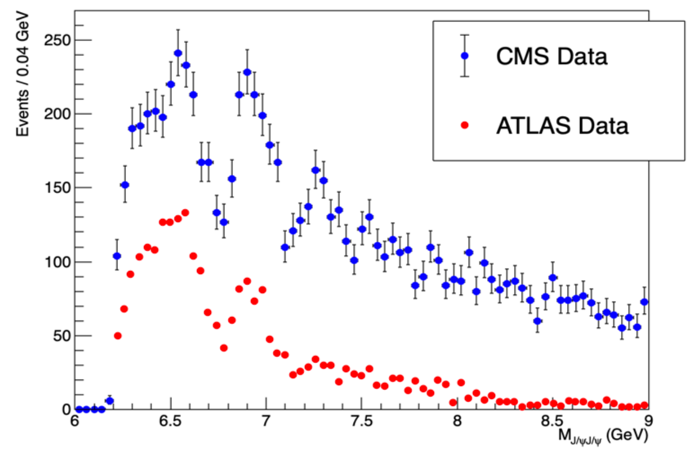
3-body intermediate invariant masses

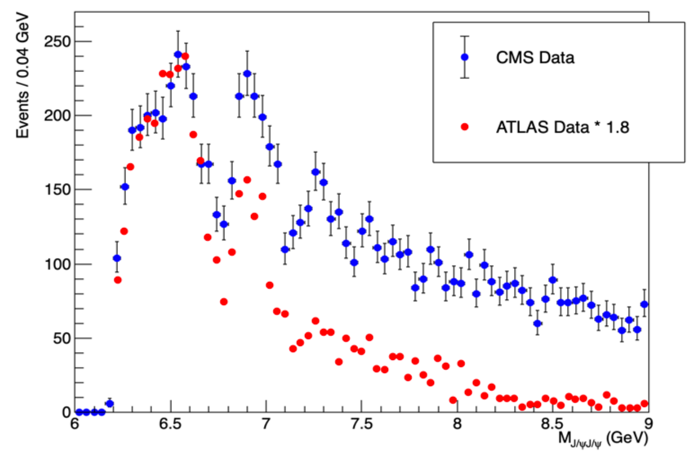


ATLAS-CMS-LHCb data comparison

Disclaimer: comparison plots in this page are not made by ATLAS/CMS/LHCb (taken from https://indico.cern.ch/event/1158681/contributions/5162594/)



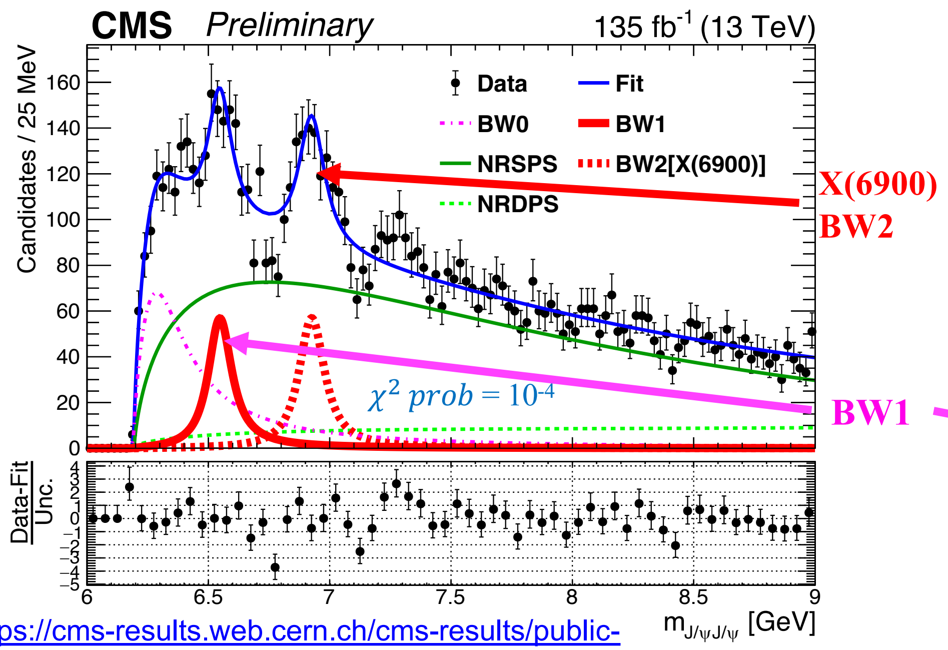




- Comparing with LHCb, CMS has:
  - 135/(3+6) ≈ 15X int. lum.
  - $(5/3)^4$ ≈ 8X muon acceptance
  - Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
  - Similar number of final events, but much less DPS
  - 2X yield @CMS for X(6900)

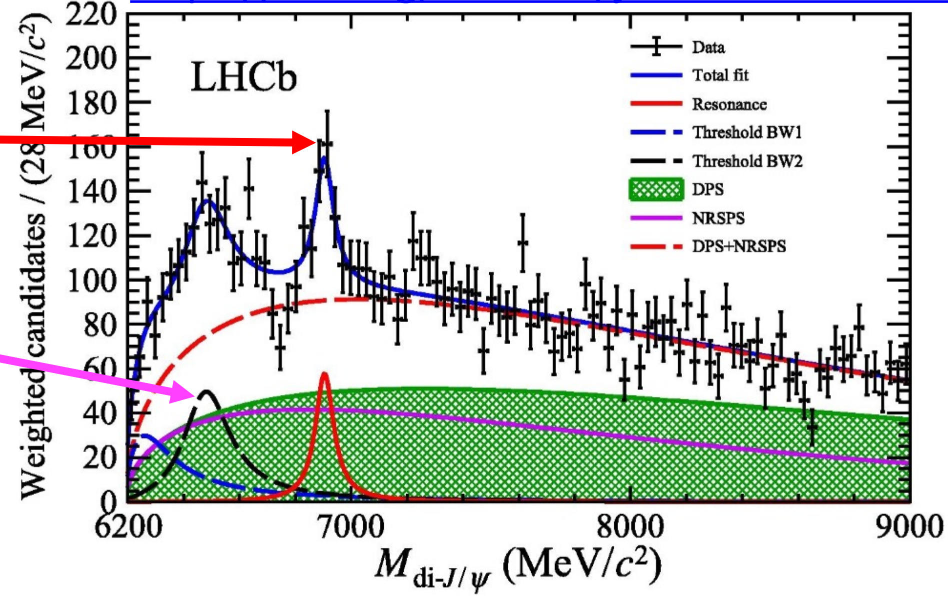
- Comparing with CMS, ATLAS has:
  - 1/3 –1/2 of CMS data (trigger?)
  - dR cut—remove high mass events

Fit CMS data with LHCb model I : 2 auxiliary BWs + X(6900) + bkg



https://cms-results.web.cern.ch/cms-results/public-results/superseded/BPH-21-003/index.html

https://doi.org/10.1016/j.scib.2020.08.032



Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

BW2 are in good agreement with LHCb X(6900)

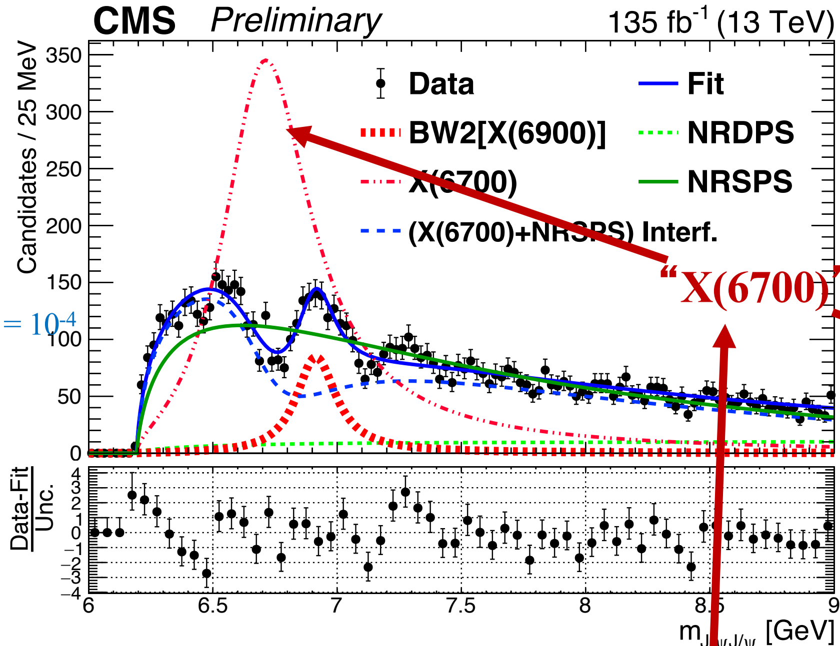
- LHCb did not give parameters for BW1
  - CMS has a shoulder before BW1
  - helps make BW1 distinct

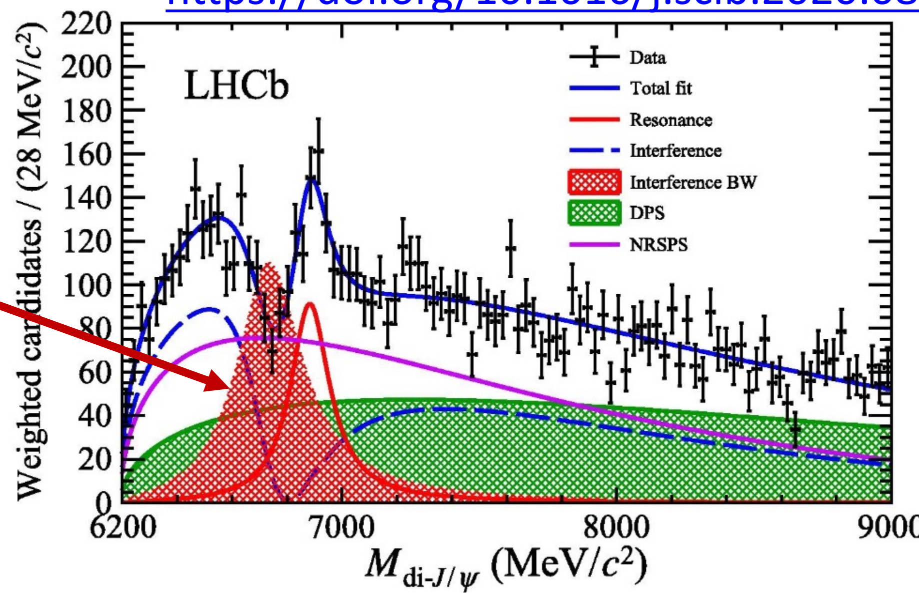
- ***Does not describe 2 dips well***

CMS and LHCb Fit Comparison - 2

Fit CMS data with LHCb model II : "X(6700)" interferes with NRSPS + X(6900) + Bkg

https://doi.org/10.1016/j.scib.2020.08.032

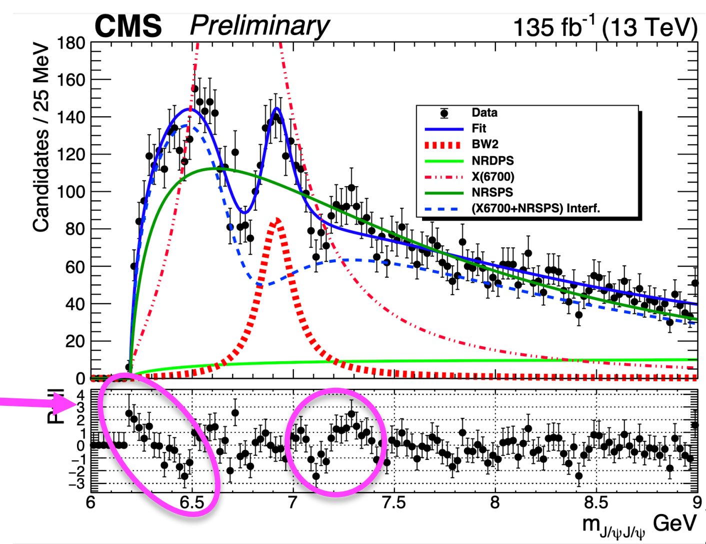




https://cms-results.web.cern.ch/cms-results/public-results/superseded/BPH-21-003/index.html

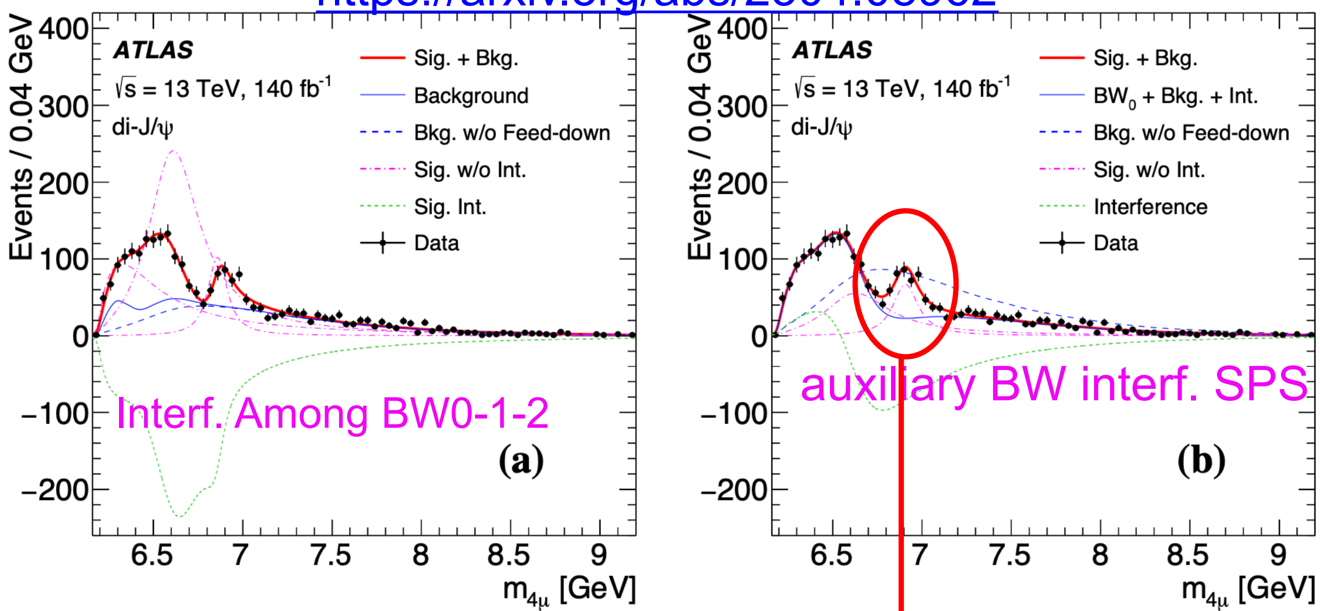
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

- CMS obtained larger amplitude and wider width for X(6700)
- Does not describe X(6600) and below
- Does not describe X(7200) region



CMS and ATLAS Fit Comparison

https://arxiv.org/abs/2304.08962



di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

X(6900) > 5σ

- ATLAS model A: analogous to LHCb model I, but 2 auxiliary BWs interfere with X(6900)
- ATLAS Model B: analogous to LHCb model II, one auxiliary BW interferes with NRSPS
- Both models describe the data well
  - the broad structure at the lower mass could result from other physical effects, such as the feed-down
- The 3rd peak mass is consistent with the LHCb observed X(6900), with significance > 5σ