Observation of a family of all-charm tetraquarks at CMS

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强子谱和强子结构研讨会
July 13, 2025

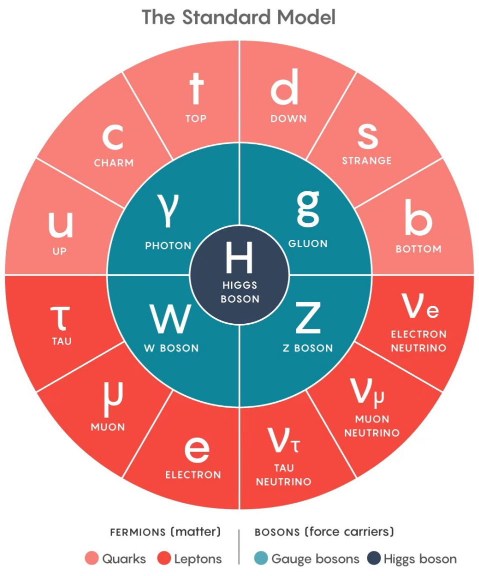
❑ Motivation

- Exotic hadron
- Tetraquark candidates

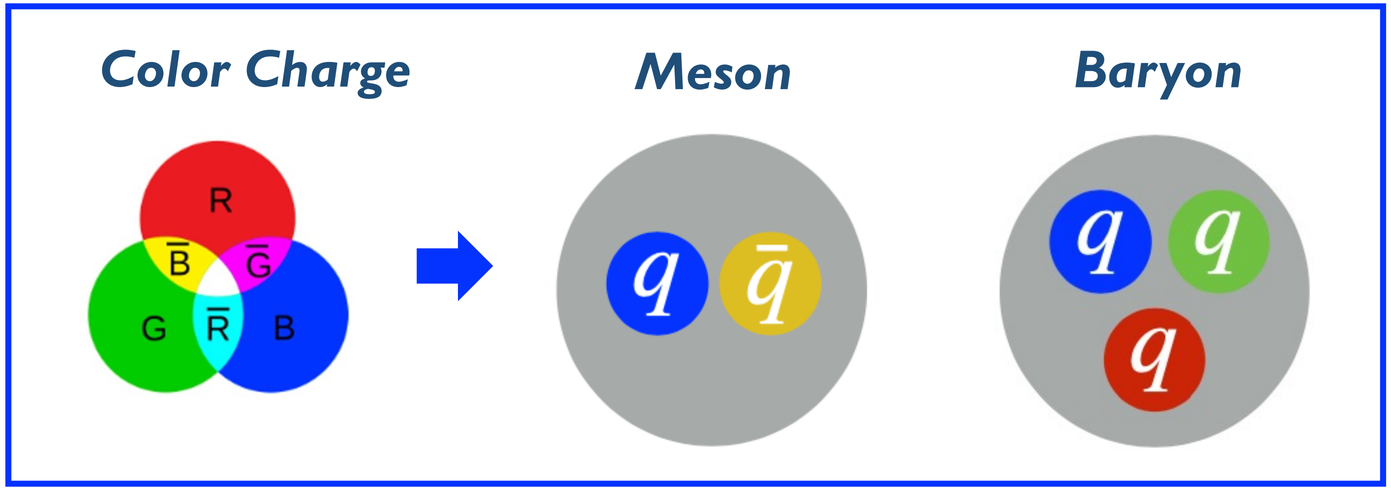
❑ Updated Analysis of $J/\psi J/\psi$ Channel

- Data sample and event selections
- $J/\psi J/\psi$ pairs signal in Run II+III data
- Fit model
- Run III && Run II+III result

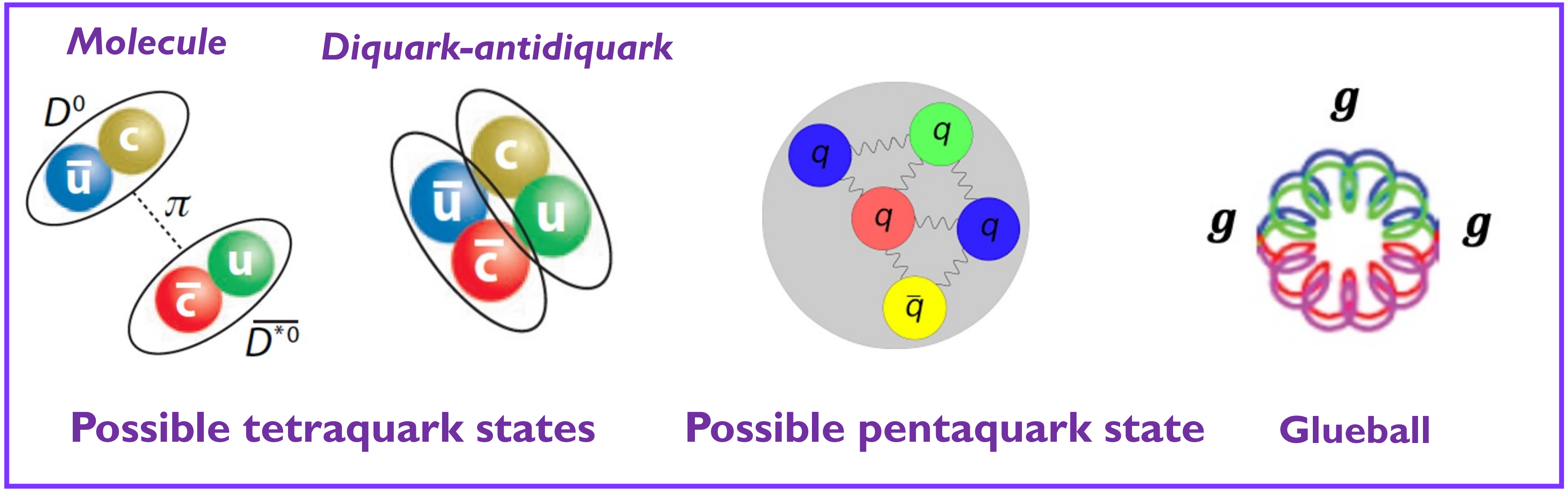
❑ Summary and Outlook



Quark model

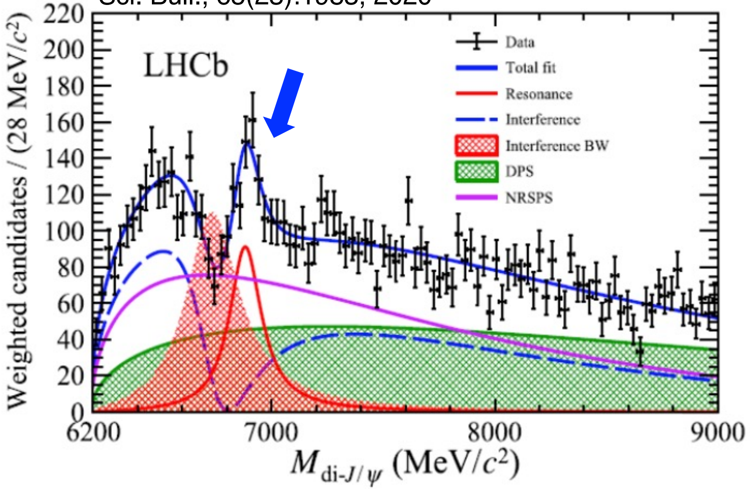


"Exotic" hadron

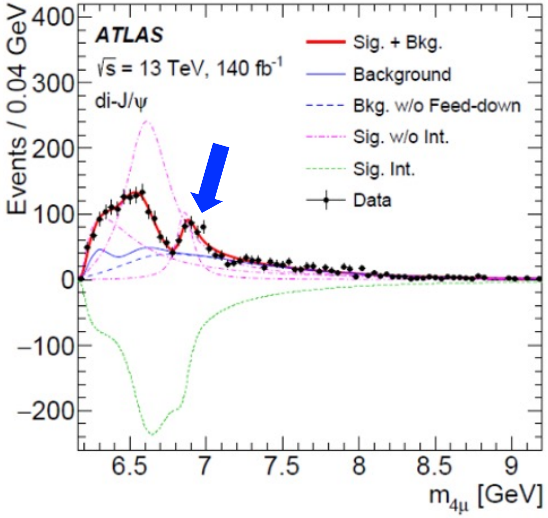


❖ All-charm Tetraquark on LHC in J/ψJ/ψ channel

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



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



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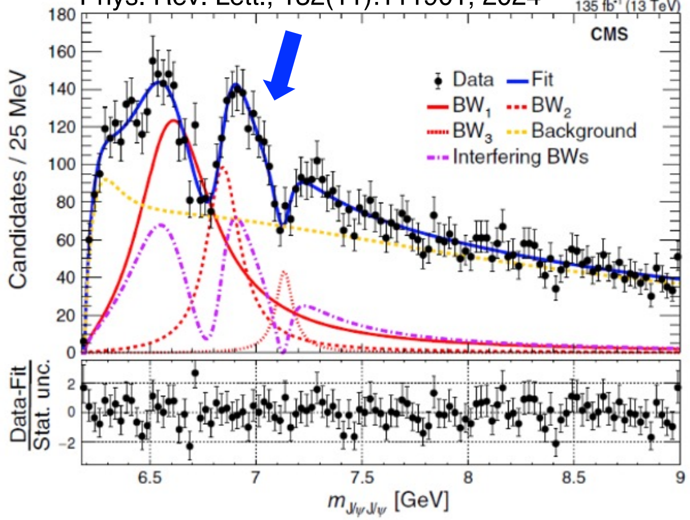

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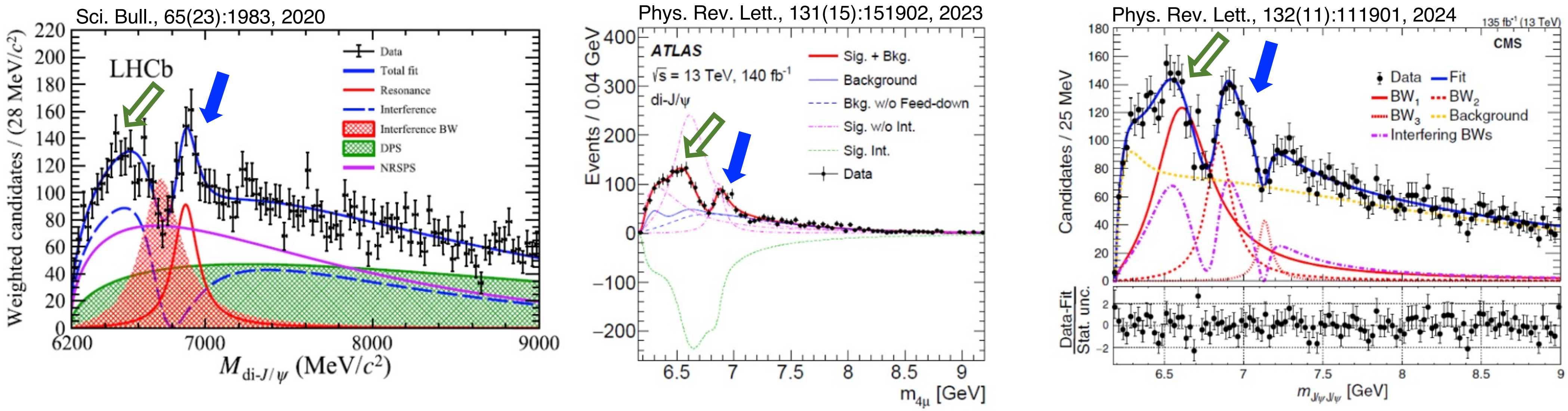

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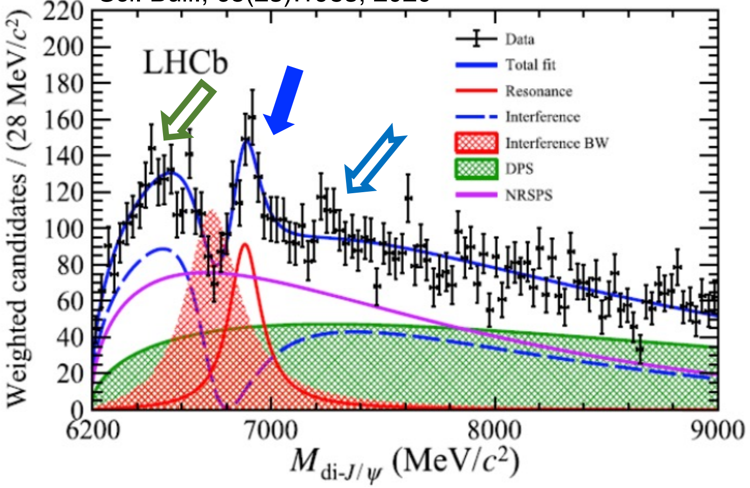

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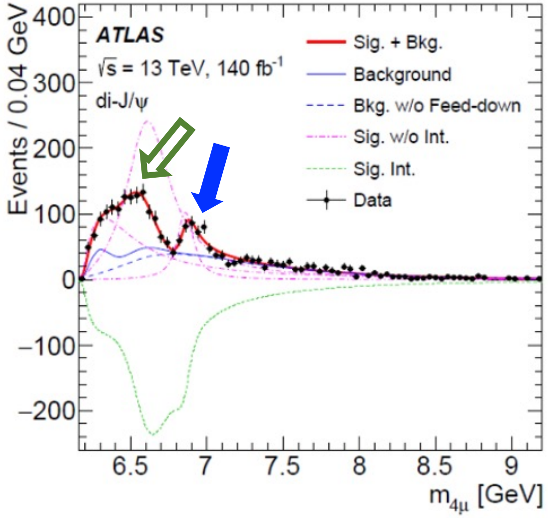

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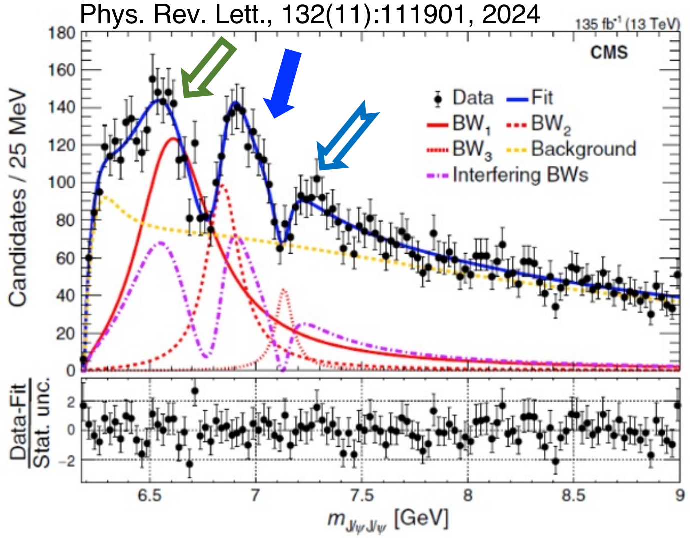

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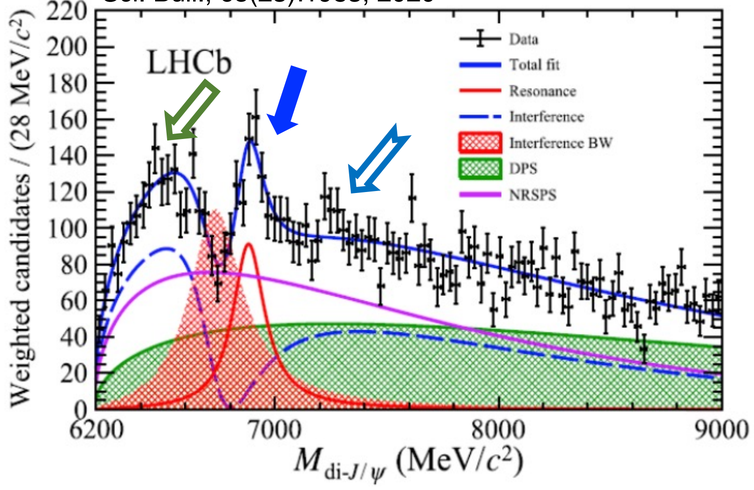

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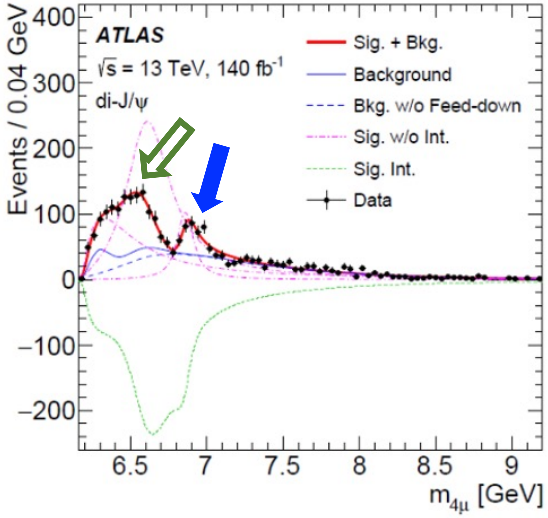

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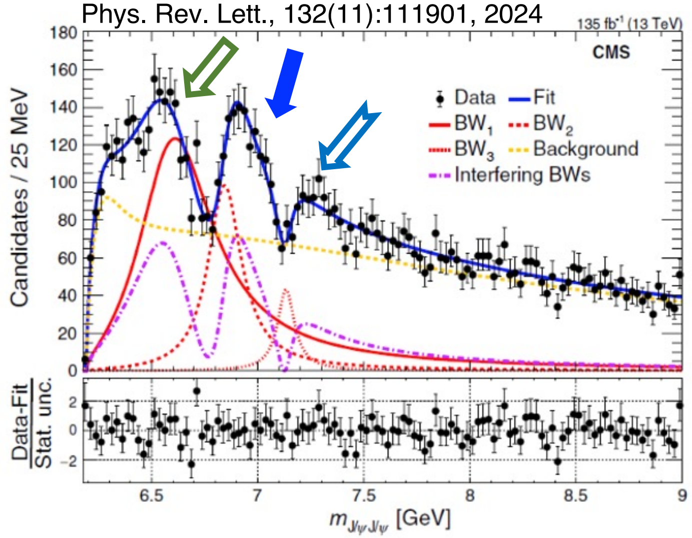

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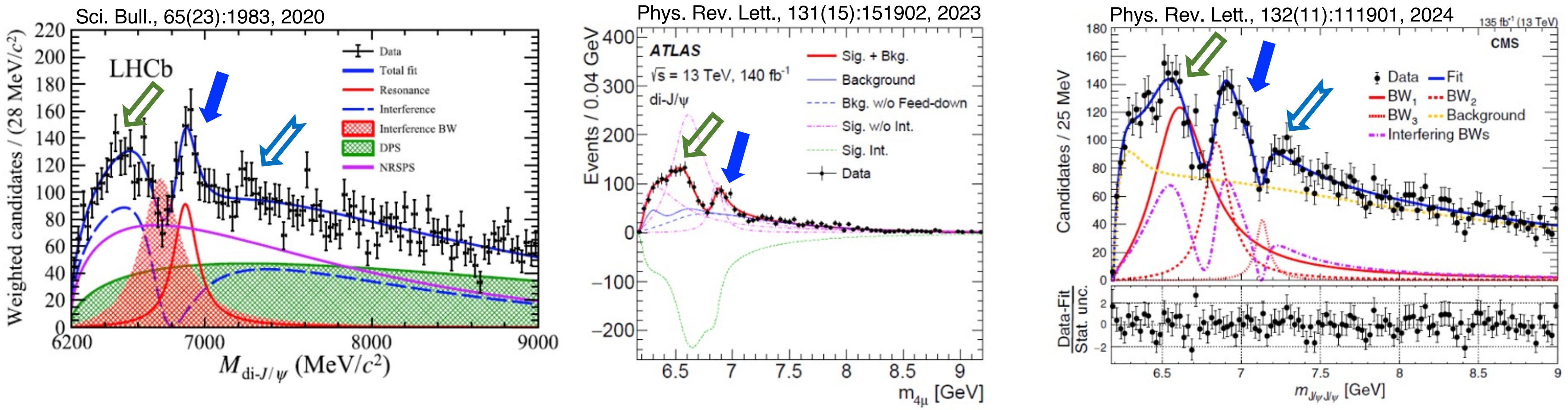

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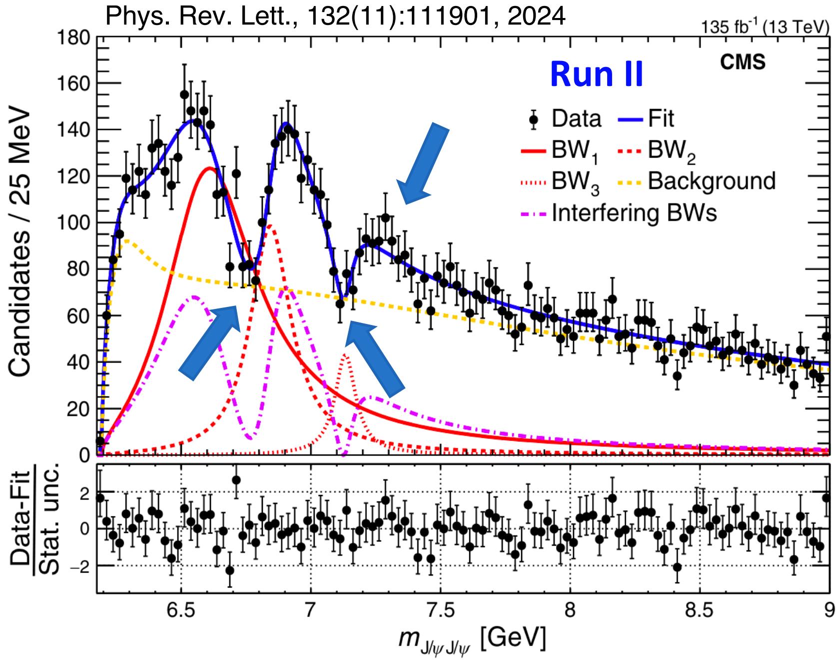
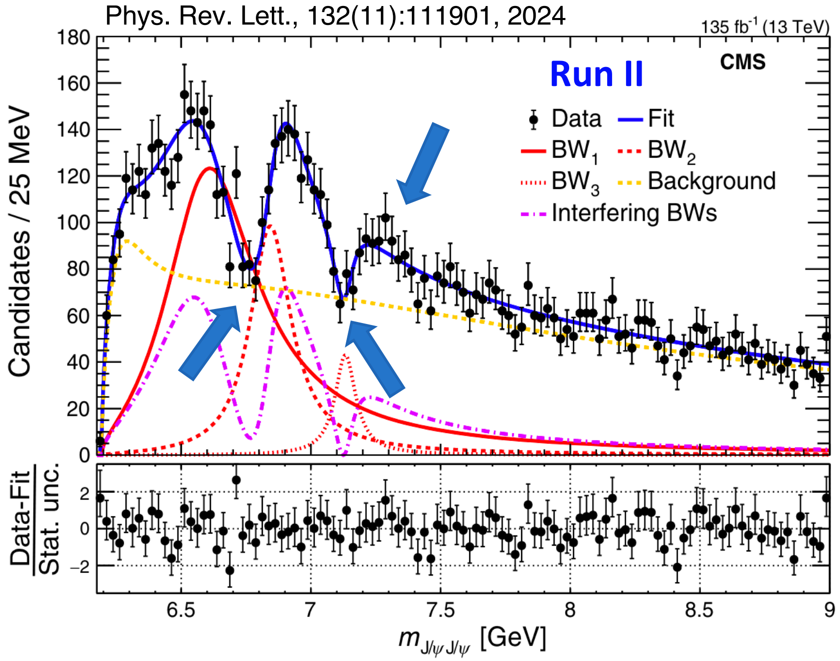
🔎 ***A number of unresolved questions !***

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



- **Run 2 result:**
  - **X(7100)**: 4.7σ
  - **Interference** < 4σ
- **With 3.6X statistics**:
  - ***ALL states*** over 5σ ?
  - ***Interferences*** over 5σ ?

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



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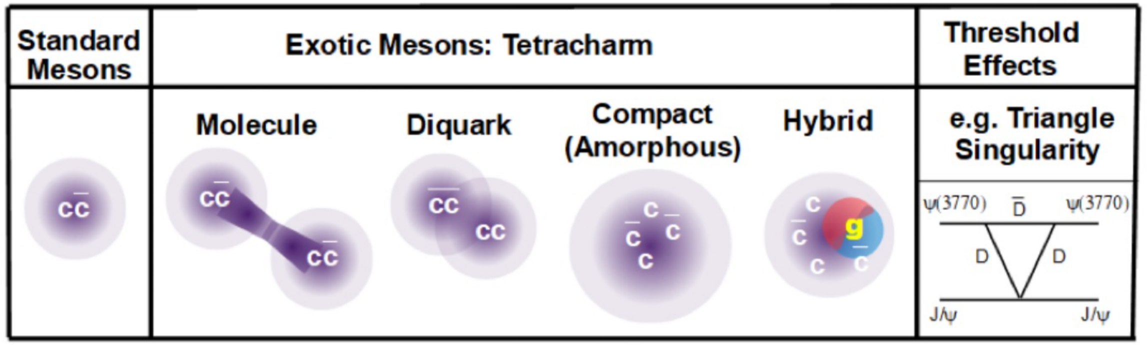
A family of all-charm tetraquarks with same J^{PC} ?

- **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
  - 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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  - Tetraquark candidates
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  - Data sample and event selections
  - $J/\psi J/\psi$ pairs signal in Run II+III data
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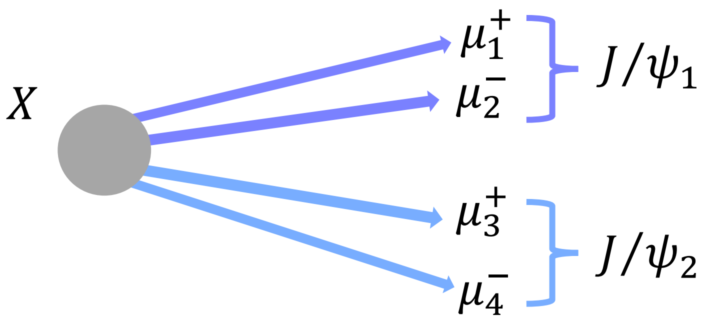
❖ Data samples [315 fb^{-1}]

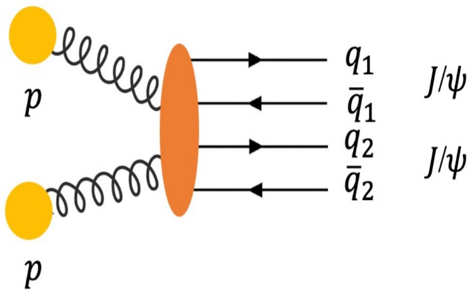
- Run II: 135 fb^{-1} data taken in 2016, 2017 and 2018.
- Run III: 180 fb^{-1} data taken in 2022, 2023 and 2024.

❖ Signal and Background simulated events:

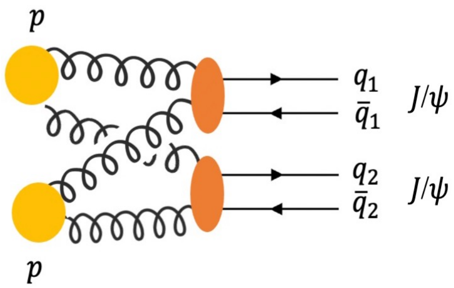
- Signal $X \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ by JHUGen



- NRSPS, DPS, and Feeddown by Pythia8 or event-mixing



SPS



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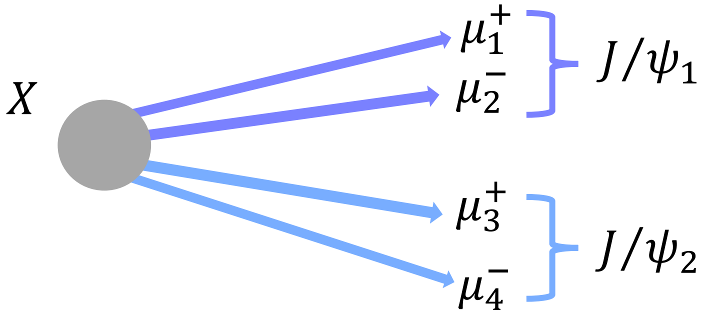

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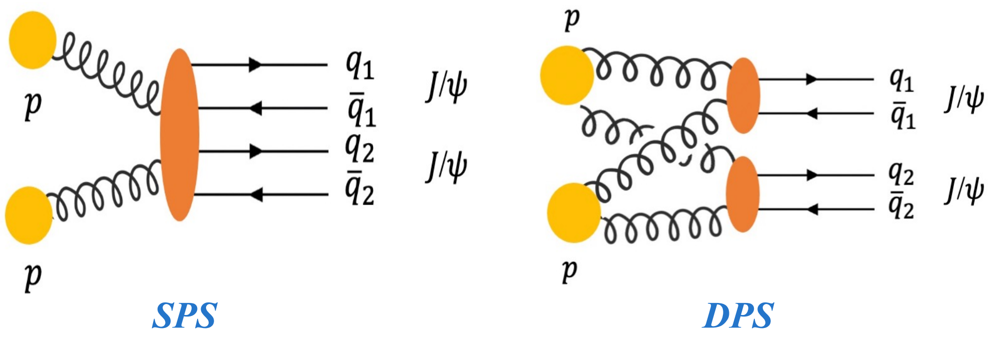

❖ Trigger of Run III

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 $p_T(\mu) > 3\ GeV$
- $p_T(\mu^+\mu^-) > 4.9\ GeV$

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

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**
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Baseline mass variable

– invariant mass of two constrained J/ψ candidates

❖ Two-dimensional fit

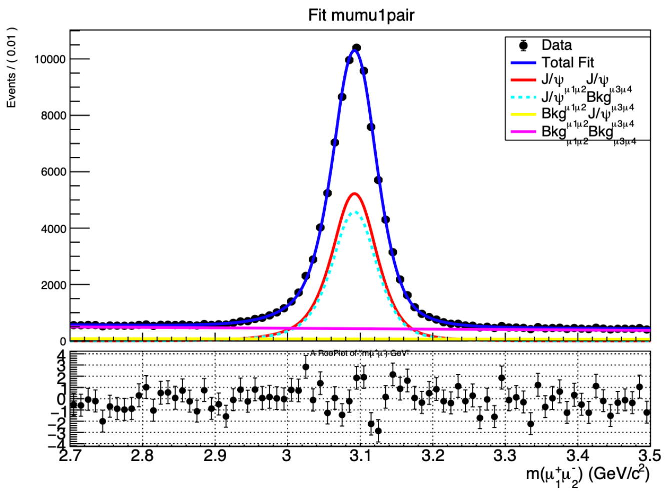
- J/ψ signal: Double Crystal Ball
- non-resonant: First-order Chebyshev polynomial

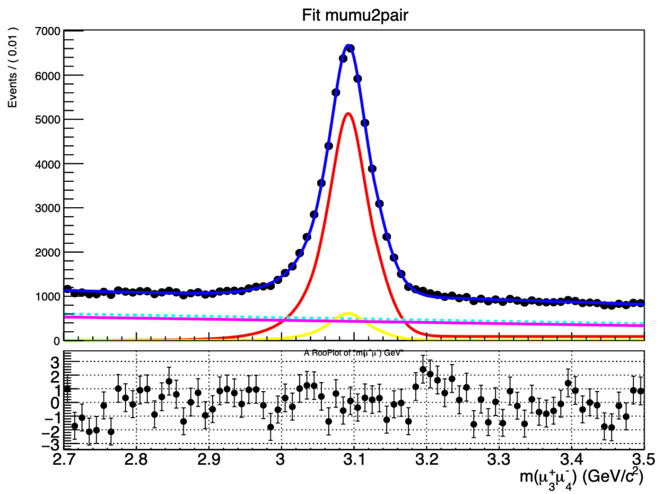
❖ J/ψJ/ψ yield statistics

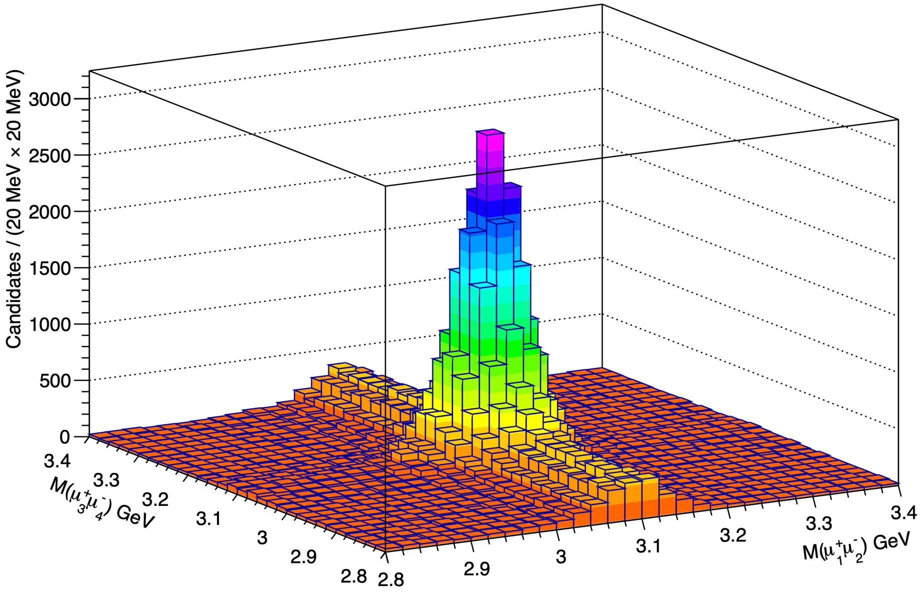
Run II : ~12622±165 / 135 fb^{-1} = 93 events / fb^{-1}

Run III : ~31802±476 / 180 fb^{-1} = 177 events / fb^{-1}

➢ **Run II+III J/ψJ/ψ yield is 3.6X of Run II, with luminosity is 2.3X of Run II**





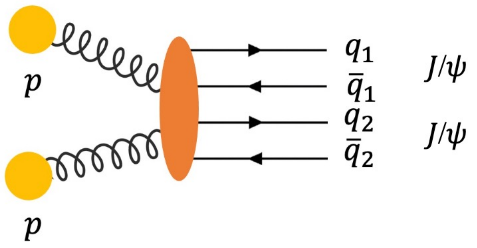


- **Signal shape:** Relativistic Breit-Wigner

$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)},$$
$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{m_0}{m} \left(B_L'(q, q_0, d)\right)^2,$$

- **Background component:** NRSPS+NRDPS+Comb+Feeddown+BW0

  - **NRSPS**
    Non-Resonant Single Parton Scattering



  - **NRDPS**
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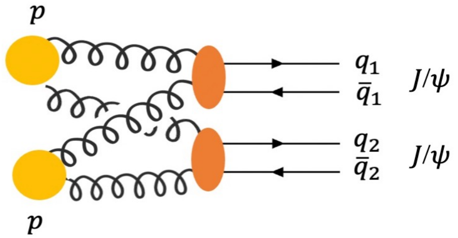

  - **Combinatorial background**

    $J/\psi\mu\mu$, $\mu\mu J/\psi$, and $\mu\mu\mu\mu$

    a Gaussian constraint of its yield

  - **Feed-down**

    From possible heavier mass states

    Here we consider: [BPH-22-004]

    $X(6900) \rightarrow J/\psi\psi(2S) \rightarrow J/\psi J/\psi$ + anything

  - **BW0**

    A significant structure at the threshold treated as background

    Inadequacy of NRSPS model at threshold.

    Parameters sensitive to model assumption;

    A region populated by feed-down;

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- **Background component:** NRSPS+NRDPS+Comb+Feeddown+BW0

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

$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m)$$
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- **Interference model:**
  - **Signal-hypothesis:** NRSPS+NRDPS+Comb+Feeddown+BW0**+BW123 Interf. Term**

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

❖ No-interference model:

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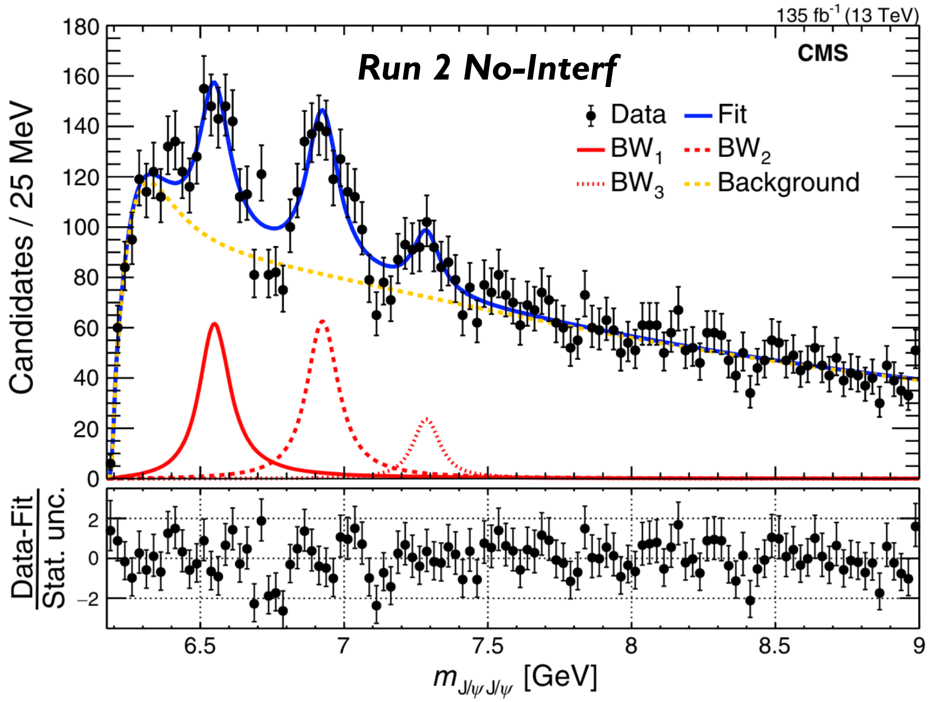

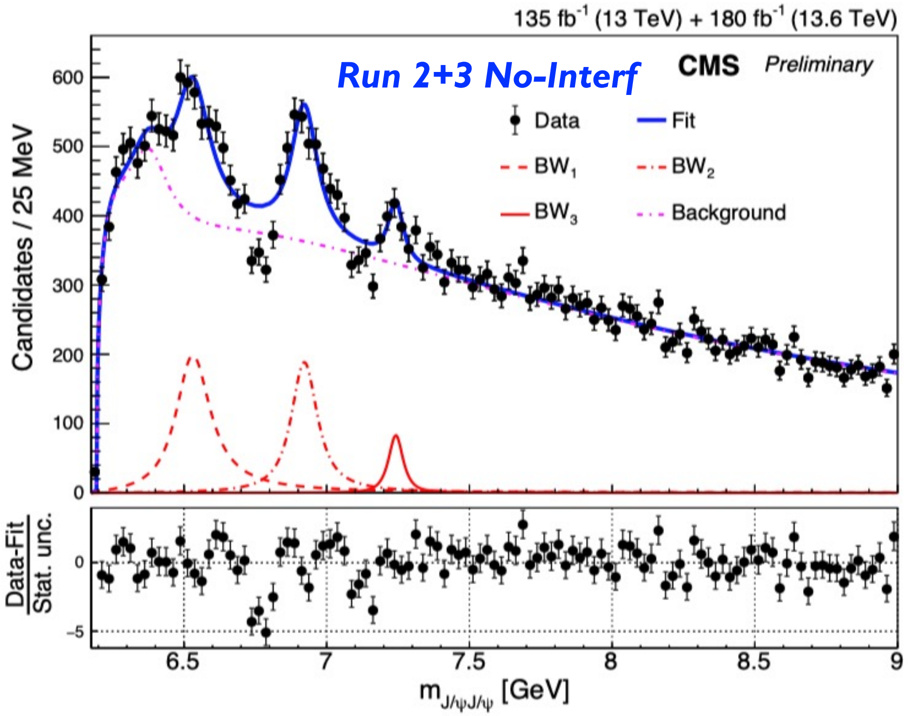

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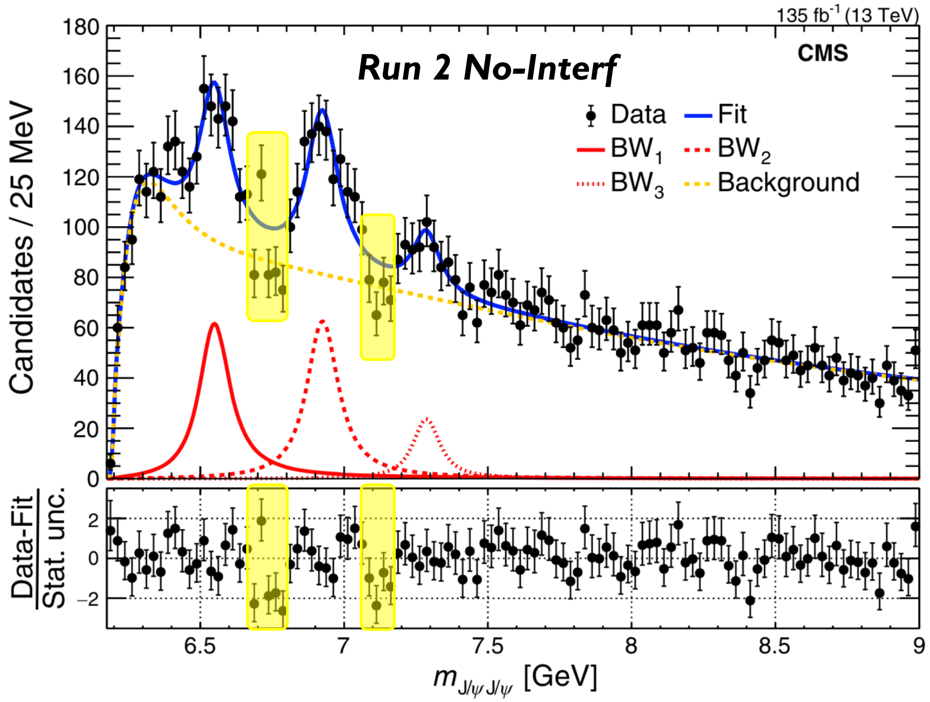
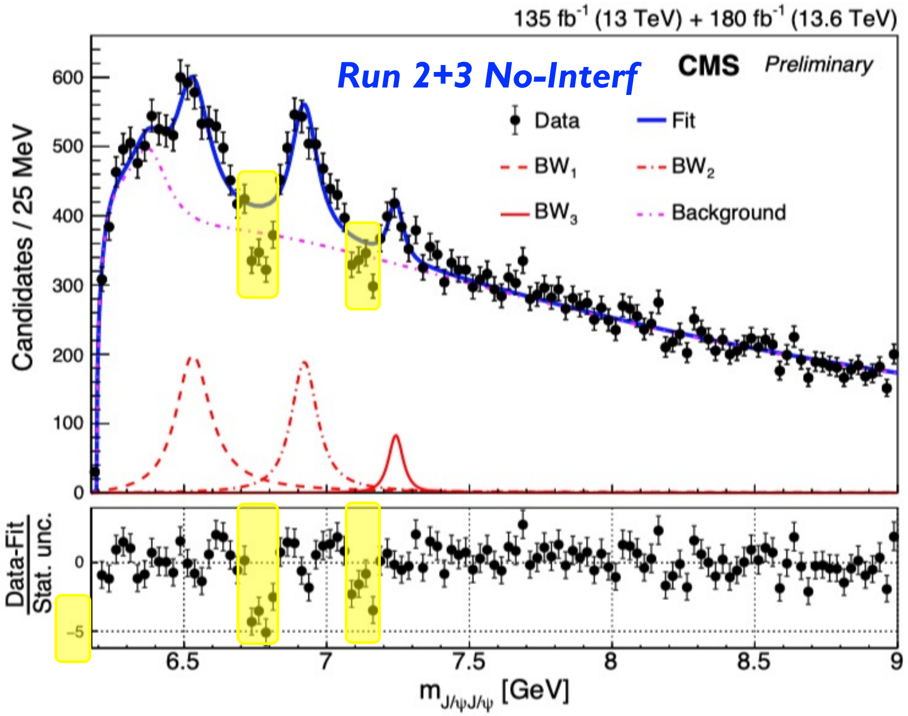
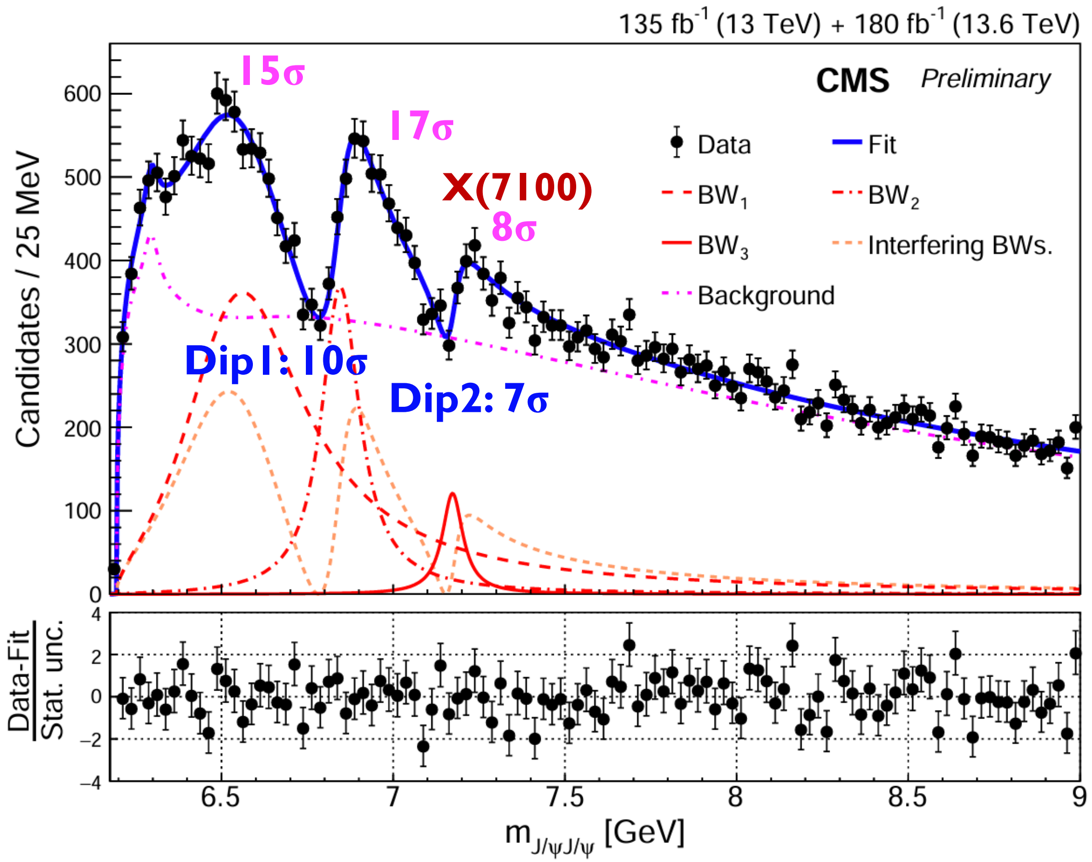
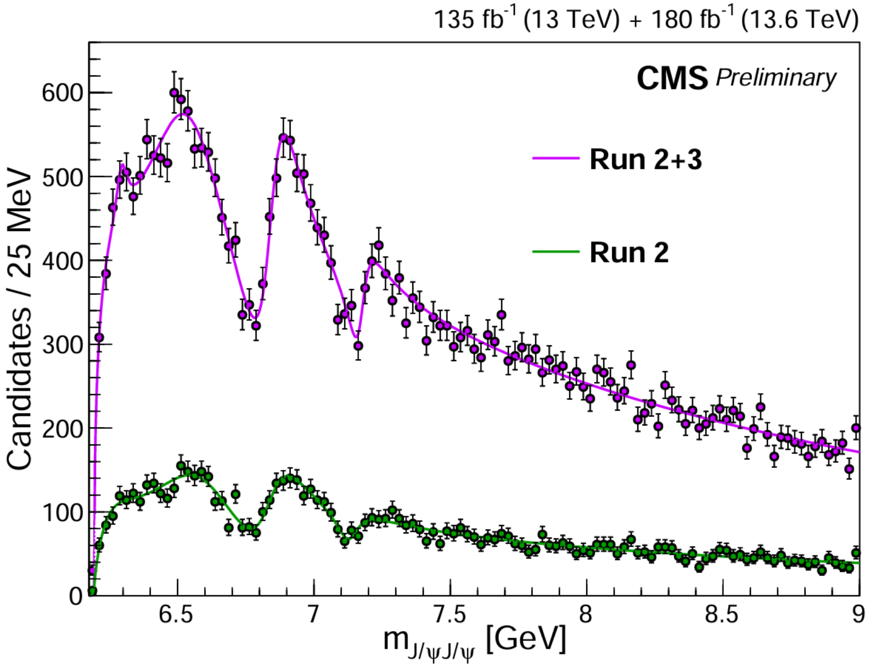




➢ **Dips poorly described — *no-Interf. model no longer sufficient !***

❖ Interference model with Run II + III:





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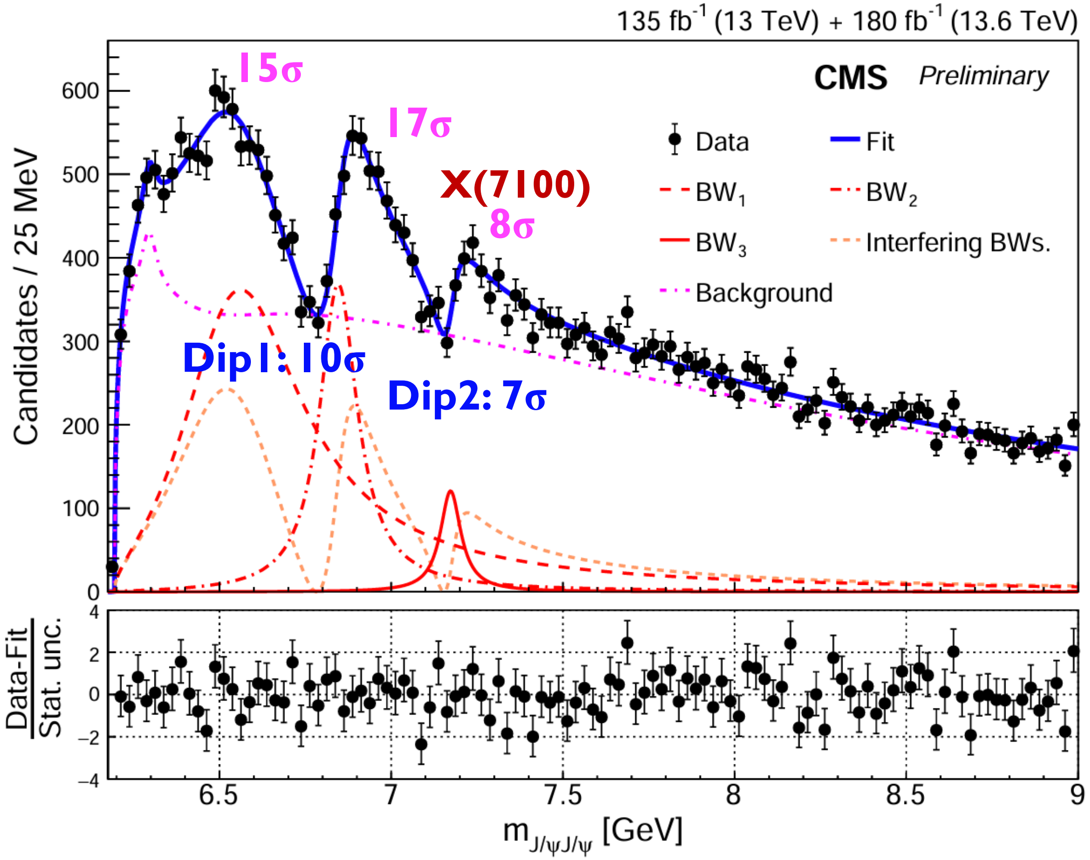

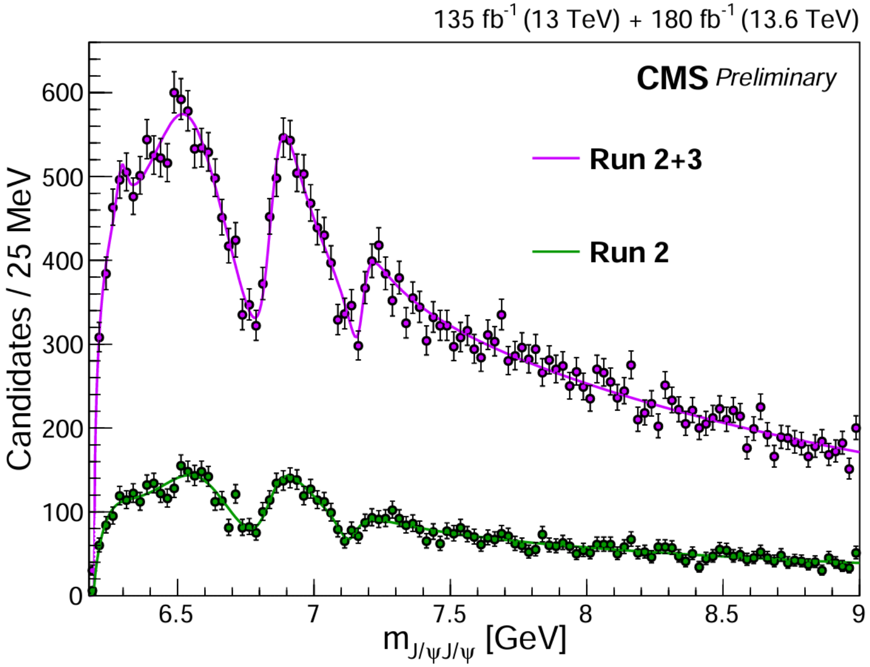

➢ **All states and dips well above 5σ !**

➢ **Quantum interference among structures validated!**

Strongly imply that they have same J^{PC}

❖ Interference model:

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

Params [MeV]	**Run II&III Interf.**	Run II Interf.
M(BW1)	$\mathbf{6593^{+15}_{-14} \pm 25}$	6638^{+43+16}_{-38-31}
Γ(BW1)	$\mathbf{446^{+66}_{-54} \pm 87}$	$440^{+230+110}_{-200-240}$
M(BW2)	$\mathbf{6847 \pm 10 \pm 15}$	6847^{+44+48}_{-28-20}
Γ(BW2)	$\mathbf{135^{+16}_{-14} \pm 14}$	191^{+66+25}_{-49-17}
M(BW3)	$\mathbf{7173^{+9}_{-10} \pm 13}$	7134^{+48+41}_{-25-15}
Γ(BW3)	$\mathbf{73^{+18}_{-15} \pm 10}$	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**
- ✓ **Large mass splittings (> 250MeV)** still exist, **with improved precision**

❖ Patterns among resonance mass

Regge trajectory for radially excited states defined as:

$$n_r = \beta \cdot m^2 + \beta_0$$

[Nucl. Phys. B, 966:115393, 2021, Zhu]

m^2: mass square

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

2, 3, 4 refers X(6600), X(6900), X(7100)

❖ Patterns among resonance mass

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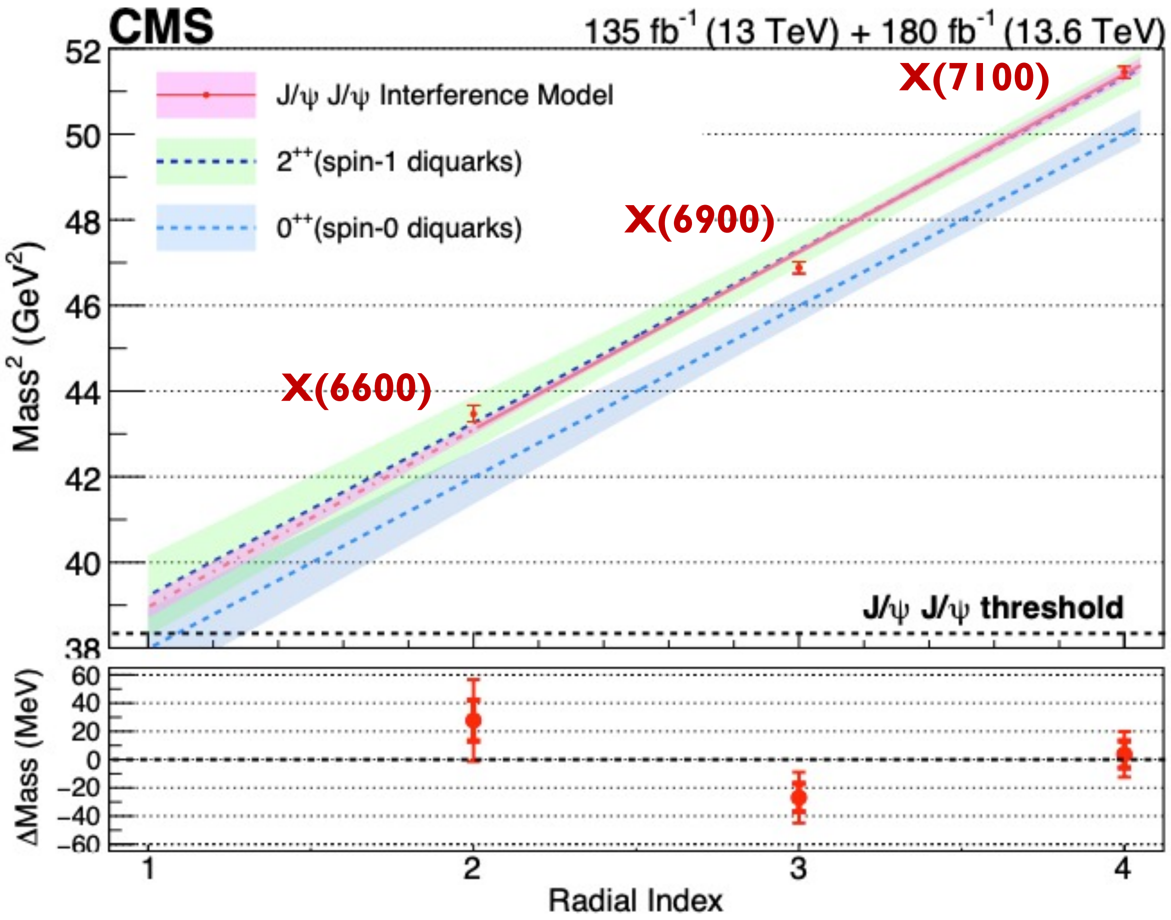

➢ ***Strongly suggests a radial excitation family !***

Well alignment with Regge trajectory !

+ same JPC and large mass splitting (>250 MeV)

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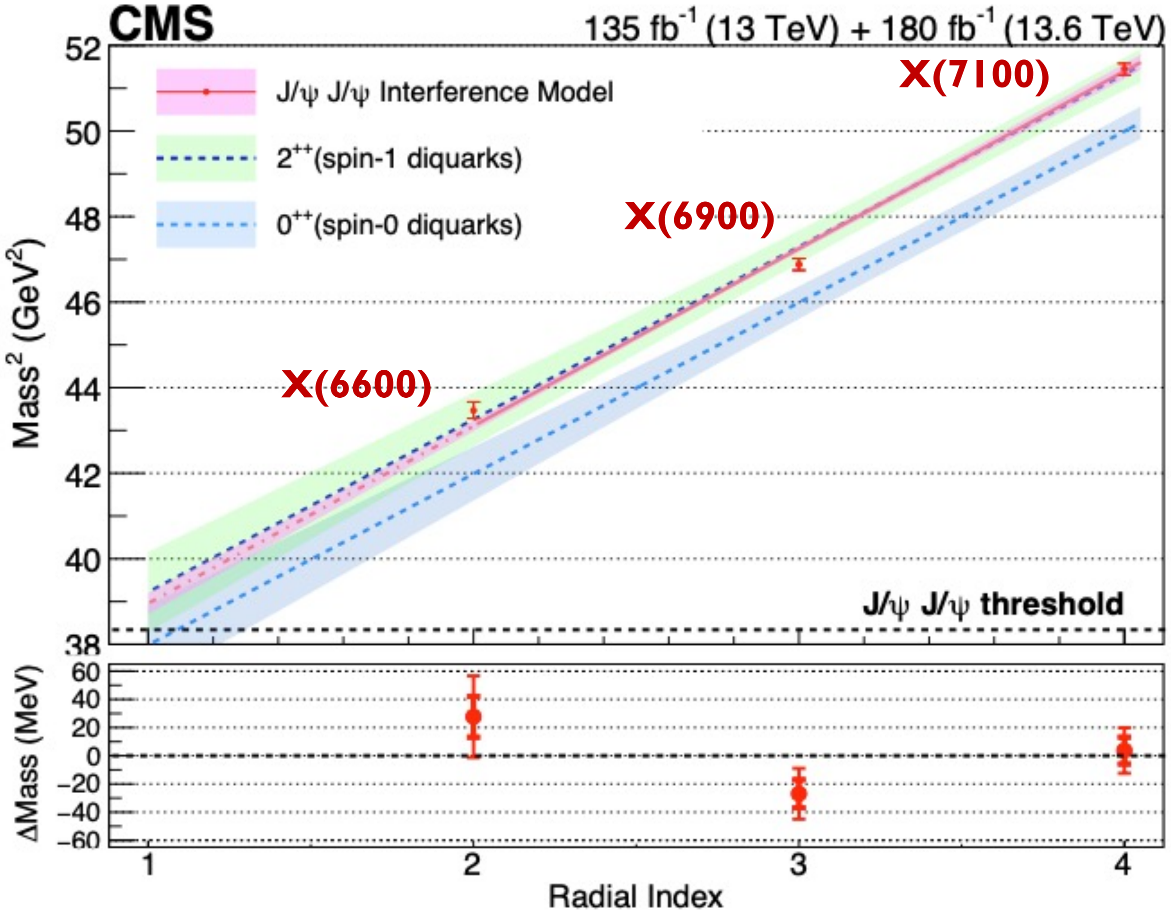

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Spin-0 diquarks: color-sextet, $J^{PC} = 0^{++}$

Spin-1 diquarks: color-triplet, $J^{PC} = 0^{++}, 2^{++}$

almost same, only plot one for clarity

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

- **Motivation**
  - Exotic hadron
  - Tetraquark candidates
- **Updated Analysis of $J/\psi J/\psi$ Channel**
  - Data sample and event selections
  - $J/\psi J/\psi$ pairs signal in Run II+III data
  - Fit model
  - Run III && Run II+III result
- **Summary and Outlook**

📝 **Update $J/\psi J/\psi$ result with the addition of Run III data**

- ✓ The **first** analysis including **2024 Data** among LHC 3 exps
- ✓ Include Feed-down and combinatorial background
- ✓ Update parameterization of Run 2&3 background

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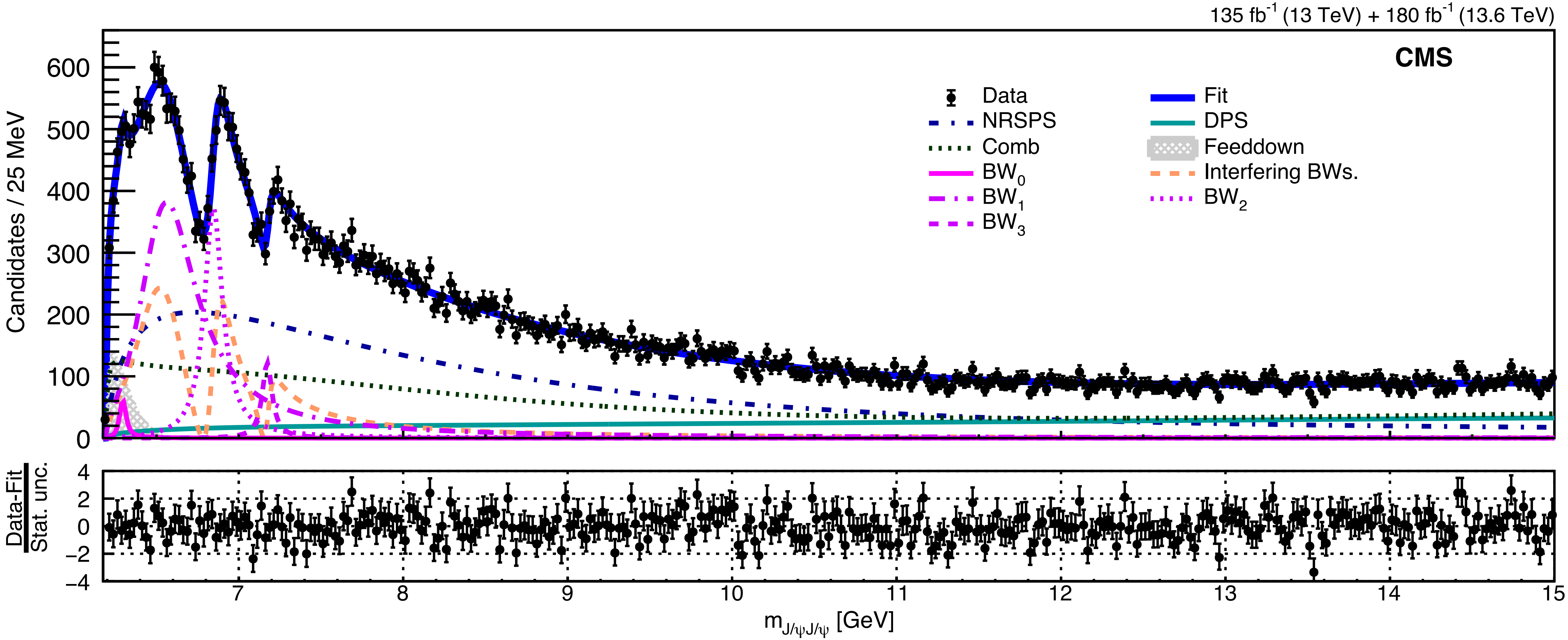
A family of all-charm tetraquarks !!!

- X(6600), X(6900), and X(7100) well above 5σ **==> Comparisons possible**
- Quantum interference among structures validated well above 5σ **==> States have common J^{PC}**
- Large mass splittings, more precisely **==> radial family of states**

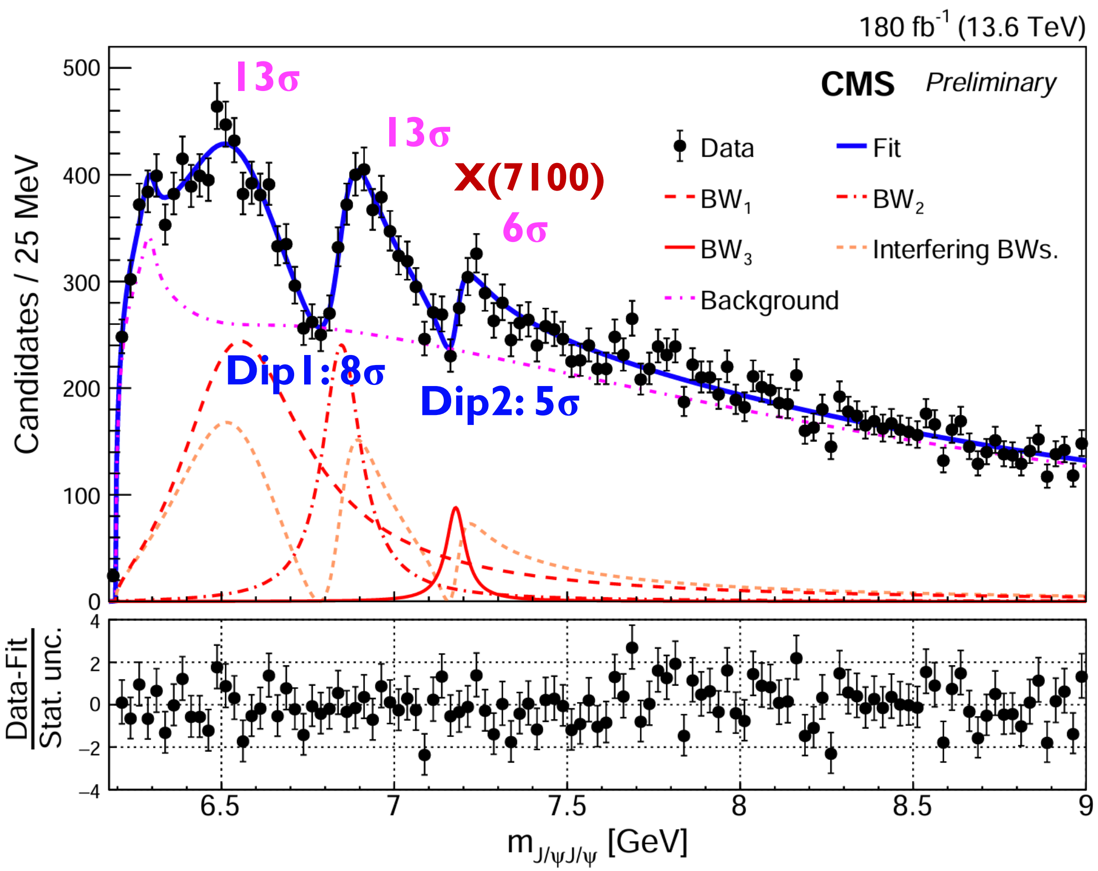
CMS is painting a coherent and compelling picture of J/ψ J/ψ structures!

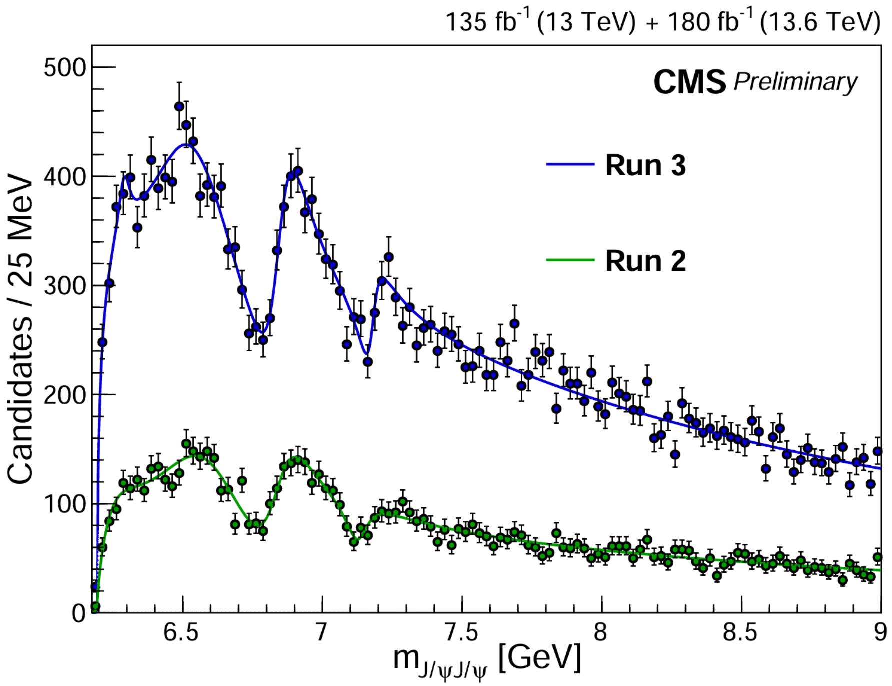
THANKS!

BACKUP


135 fb^{-1} (13 TeV) + 180 fb^{-1} (13.6 TeV)
CMS
Data
NRSPS
Comb
BW$_0$
BW$_1$
BW$_3$
Fit
DPS
Feeddown
Interfering BWs.
BW$_2$
Candidates / 25 MeV
Data-Fit / Stat. unc.
$m_{J/\psi J/\psi}$ [GeV]

❖ Interference model with Run III:





***All states and dips** above 5σ !*

---already achieve our goals!

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