

Study of a family of all-charm tetraquarks at CMS

Speaker

Yilin Zhou

(Fudan University & Nanjing Normal University)

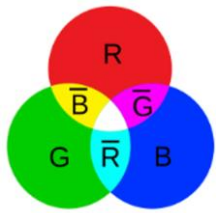
Wuhan, Oct 31

CLHCP2026 第十二届中国 LHC 物理会议
The 12th China LHC Physics Conference

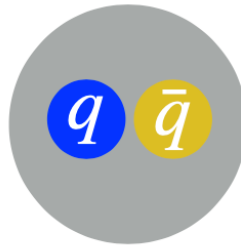
The quark model

Classical quark model

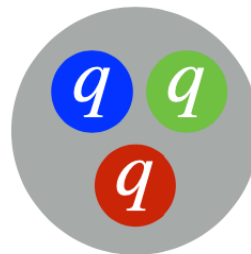
Color Charge



Meson



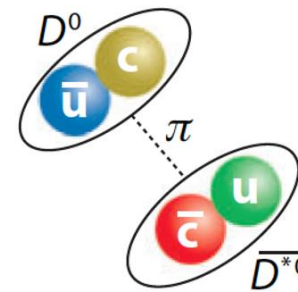
Baryon



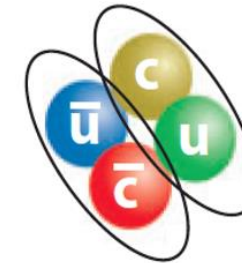
- > 60 years of classical quark model
 - Experimentally tested at high energies; asymptotic freedom → Nobel Prize 2004
 - Success of Conventional Hadrons at low energies: non-perturbative quark model (confinement) → Nobel Prize 1969
- Exotic hadrons (Non-Conventional), no definitive conclusion yet
 -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

"Exotic" hadron

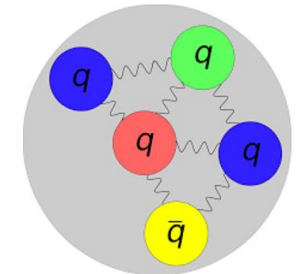
Molecule



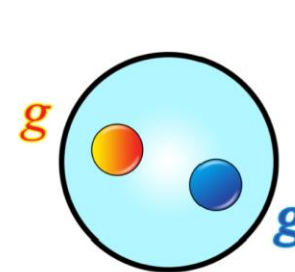
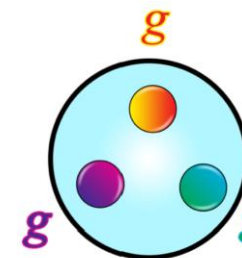
Diquark-antidiquark



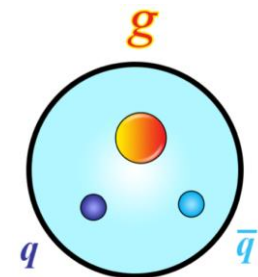
tetraquark



pentaquark



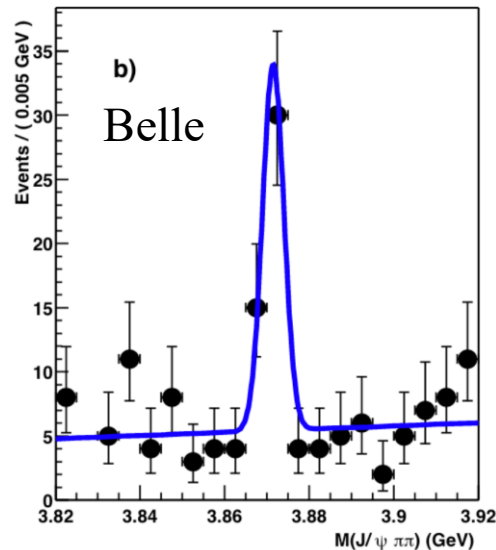
Glueball



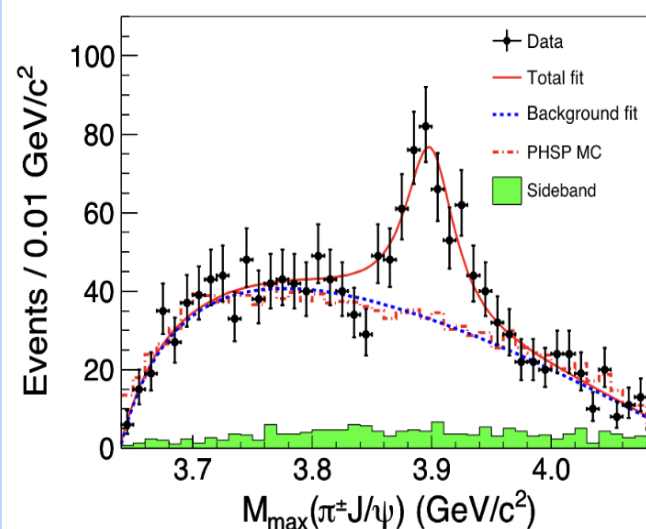
Hybrid

Heavy-Flavor Exotic Hadron States (XYZ Particles)

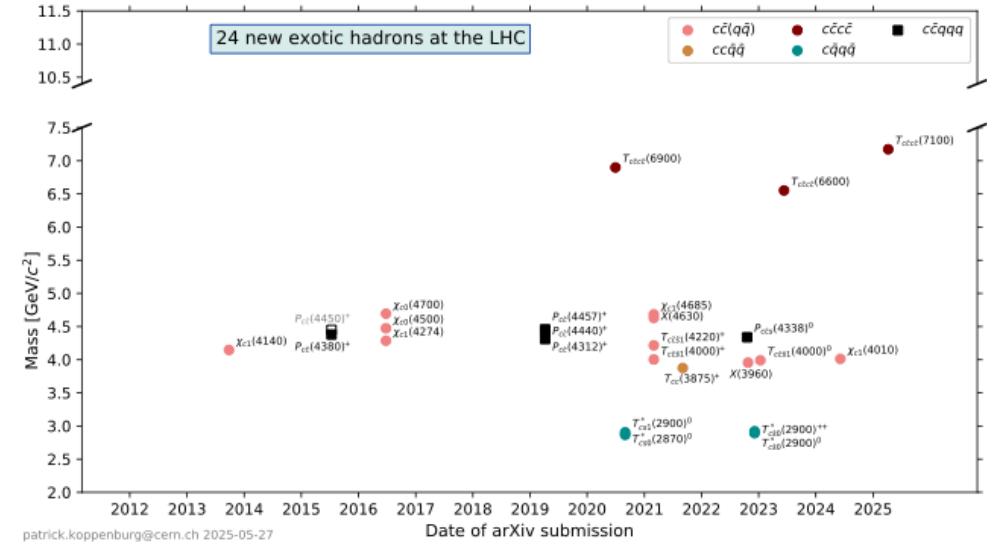
X(3872) [$uc\bar{u}\bar{c}$]



Z_c^+ (3900)



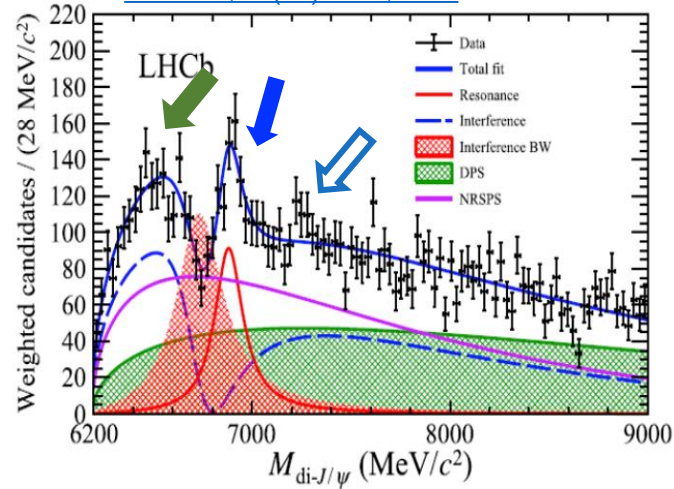
24 exotic hadrons at LHC



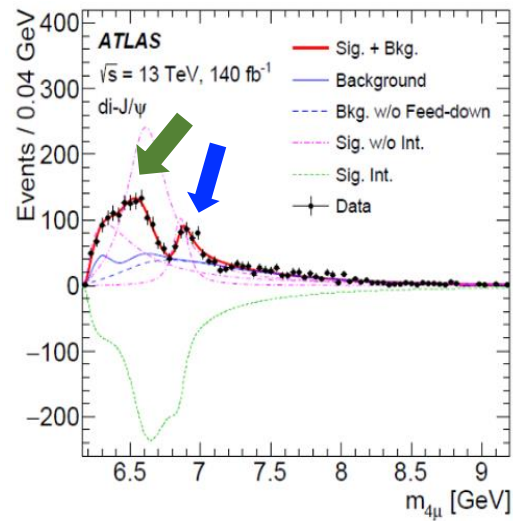
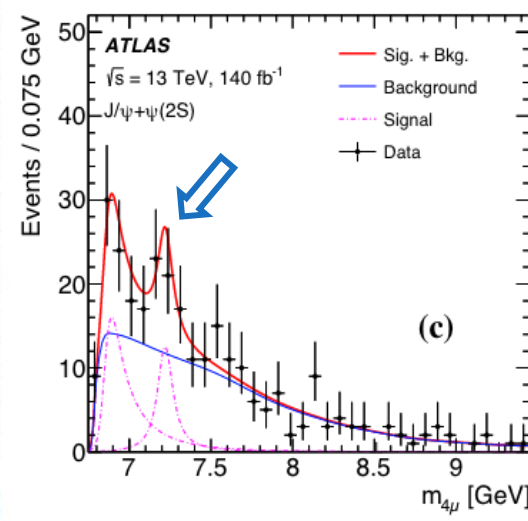
- Light exotics likely exist, but too messy for clear identification
- **Heavy-flavor exotics:** larger quark mass relative to Λ_{QCD} , theoretical treatments more reliable
 - X(3872), kicked off a boom in (heavy-flavor) exotic hadron, dozens of XYZ found
 - Z_c (3900), carries charge and couples to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

Status of of all-charm tetraquark

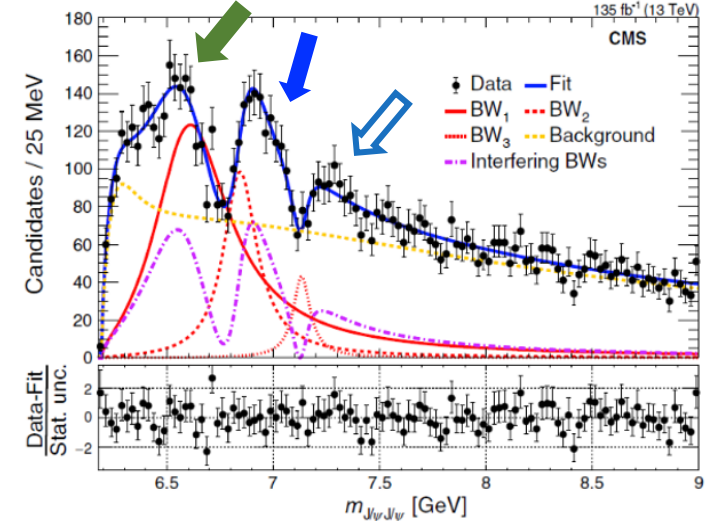
[Sci. Bull., 65\(23\):1983, 2020](#)



[Phys. Rev. Lett., 131\(15\):151902, 2023](#)



[Phys. Rev. Lett. 132:111901, 2024](#)



❖ All exp observe $X(6900)$

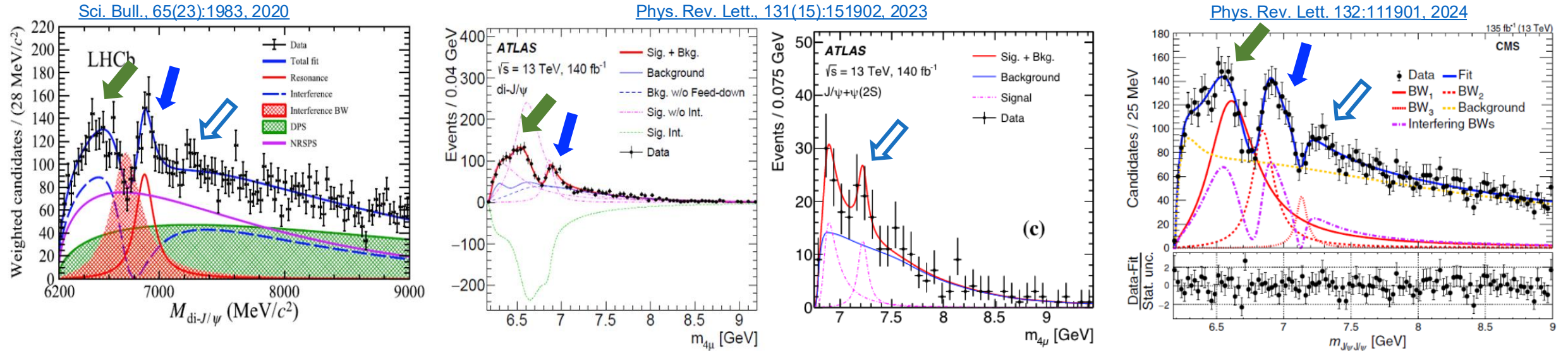
+ additional structures:

Hump @ 6.6 GeV: Different modeling

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

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

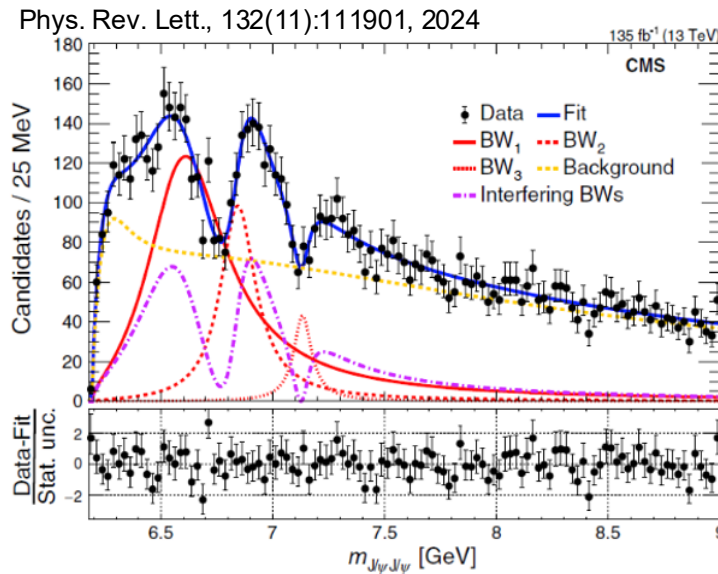
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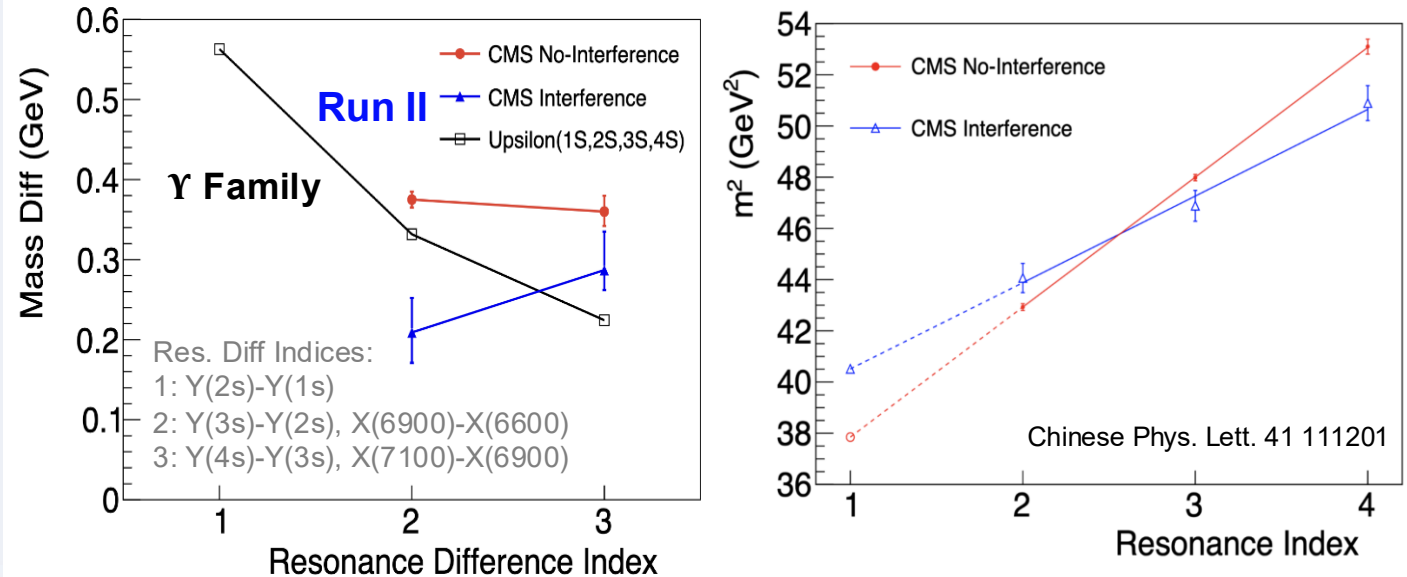
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- ❖ CMS first observed $X(6600)$ & evidence of $X(7100)$
- ❖ All exp use interference, but in diff ways:
LHCb: extra BW interfere with SPS, $X(6900)$ NOT interfering
ATLAS and CMS: different multi-resonance interference

A number of unresolved questions !

CMS Run 2 mass spectrum



CMS Run 2 Regge plot



Run 2 result:

- X(7100): 4.7 σ
- Interference < 4 σ

With 3.6X statistics:

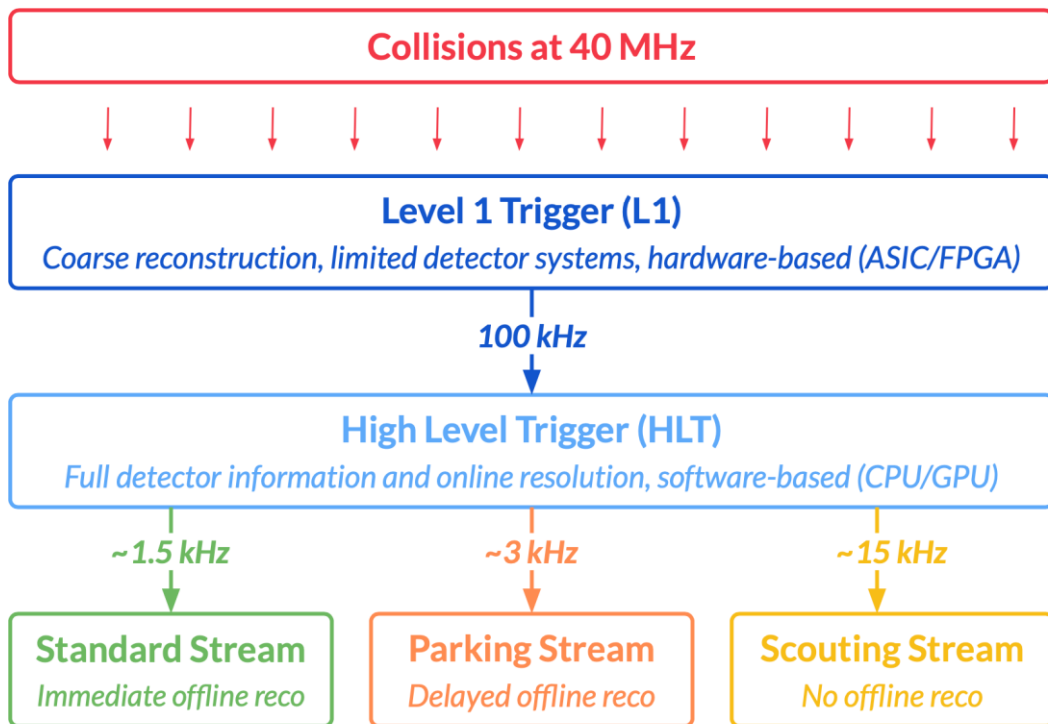
- ALL states over 5 σ ?
- Interference over 5 σ ?

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

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

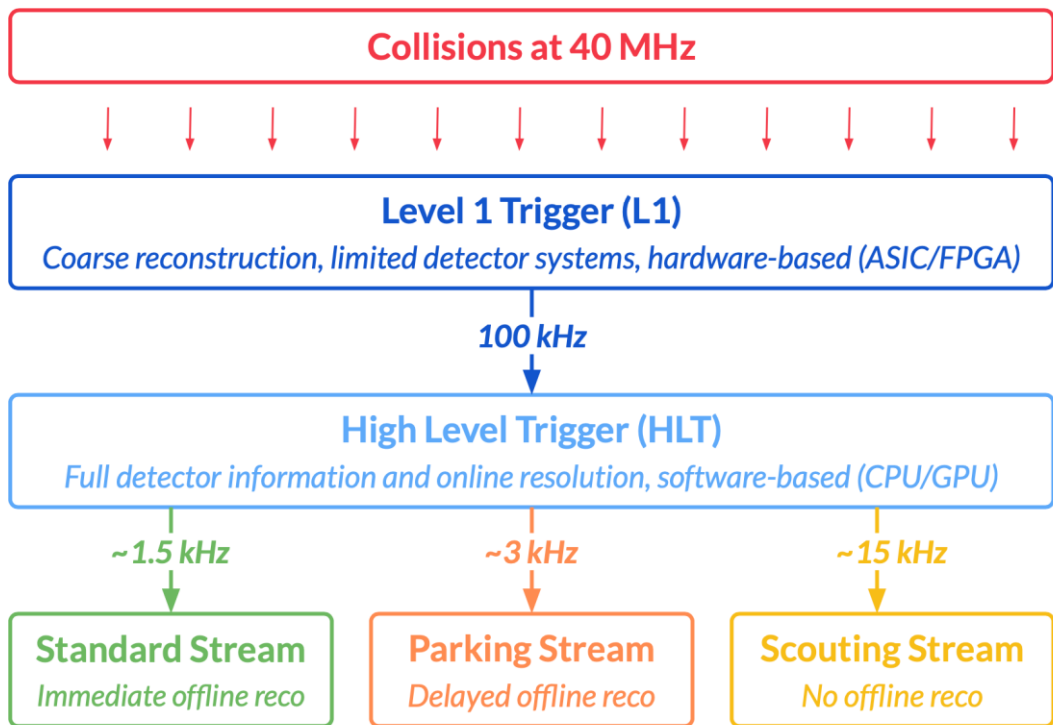
A radial FAMILY of all-charm tetraquark states with same J^{PC} ?

Overview of CMS Trigger System



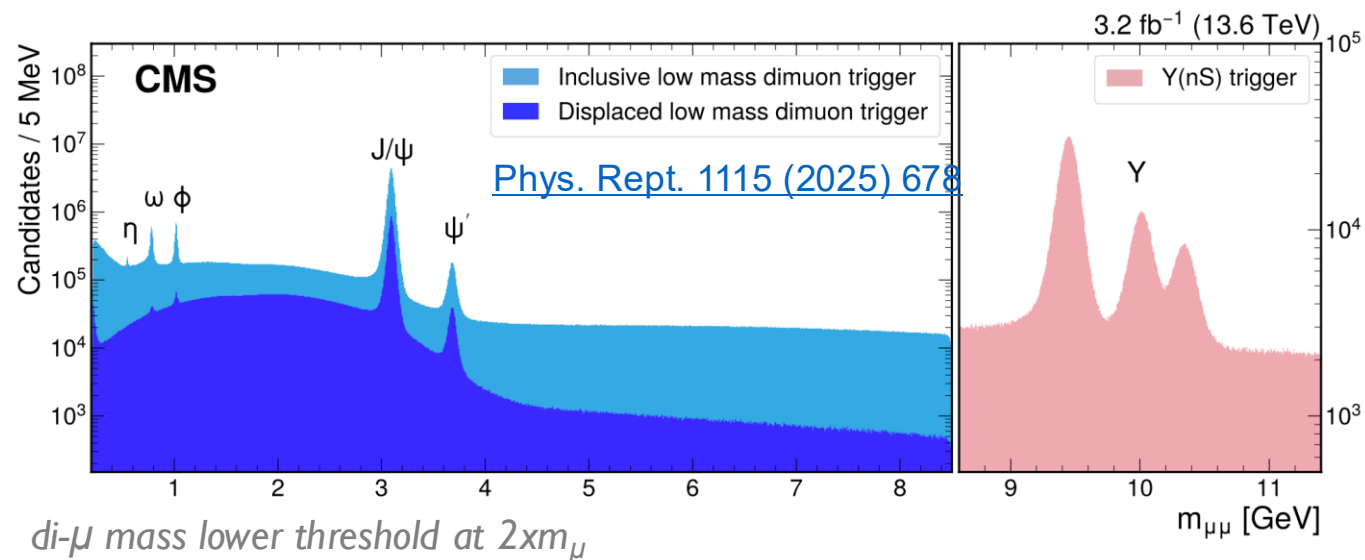
- Save RAW event, contains complete detector information, no reconstruction
- Uses less computational resources, enabling higher rates and lower kinematic thresholds

Overview of CMS Trigger System



- Save RAW event, contains complete detector information, no reconstruction
- Uses less computational resources, enabling higher rates and lower kinematic thresholds

- Majority of analyses rely on dimuon triggers
- Flexible trigger system for different analyses
- Parking streams are a game-changing effort for CMS flavour physics
- Expanded physics potential thanks to inclusive dimuon parking dataset



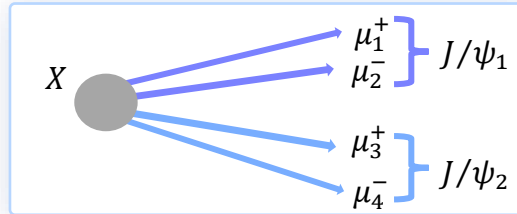
Open new opportunities in flavour physics!

❖ Data samples [315 fb⁻¹]

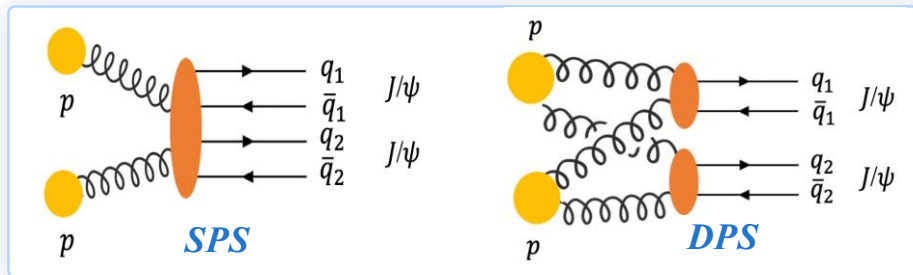
- Run 2: 135 fb⁻¹ data taken in 2016, 2017 and 2018.
- Run 3: 180 fb⁻¹ data taken in 2022, 2023 and 2024.

❖ Signal and Background simulated events:

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



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



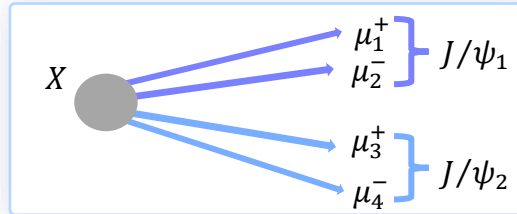
- Feaddown by **Pythia8**: $X(6900) \rightarrow J/\psi \psi(2S) \rightarrow J/\psi J/\psi + \text{anything}$
- Combinatorial background
- Enhancement near threshold, BW0

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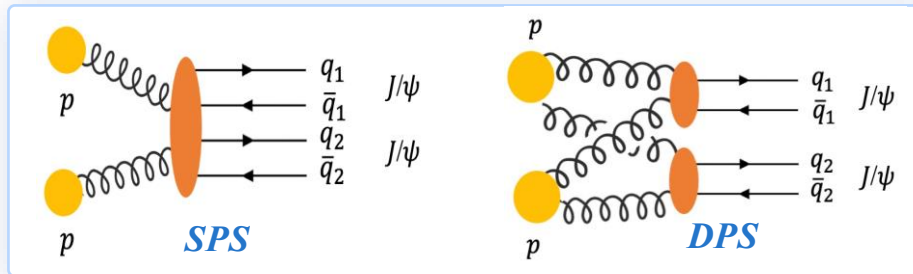
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❖ Trigger of Run 3

HLT_Dimuon0_Jpsi3p5_Muon2

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

HLT_DoubleMu4_3_LowMass [new trigger for Run III]

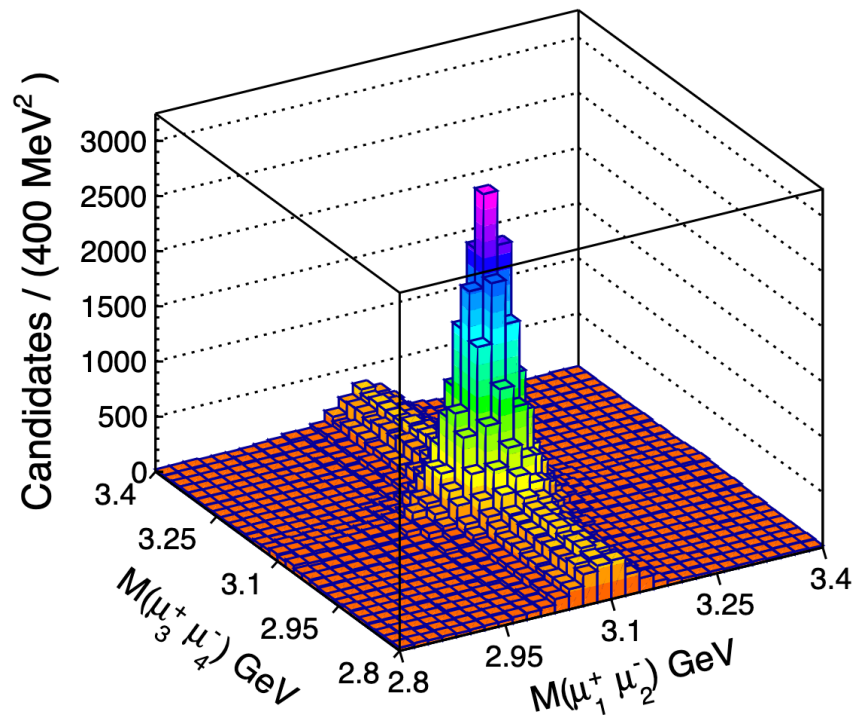
- **Level 1 requirements: 2 muons**
- $0.2 < M(\mu^+ \mu^-) < 8.5 \text{ GeV}$
- one muon $p_T(\mu) > 4 \text{ GeV}$ and the other $p_T(\mu) > 3 \text{ GeV}$
- $p_T(\mu^+ \mu^-) > 4.9 \text{ GeV}$

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

❖ Event selection of Run 3

Follow PRL cuts + A new trigger for Run 3

2D distributions of double-dimuon masses



- J/ψ signal: Double Crystal Ball
- non-resonant $\mu^+\mu^-$: 1st-order Chebyshev polynomial

- Luminosity

Run 2: 135 fb⁻¹

Run 3: 180 fb⁻¹

➤ $J/\psi J/\psi$ yield per unit luminosity

Run 2 ~93 events / fb⁻¹

Run 3 ~177 events / fb⁻¹

- $J/\psi J/\psi$ yield

Run 2 ~12622 ± 165

Run 3 ~31802 ± 476

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

➤ Run 2+3 luminosity is 2.3X of Run 2

Baseline mass variable

– invariant mass of two constrained J/ψ candidates

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

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

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

❖ Non-interference model:

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

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

❖ Interference model:

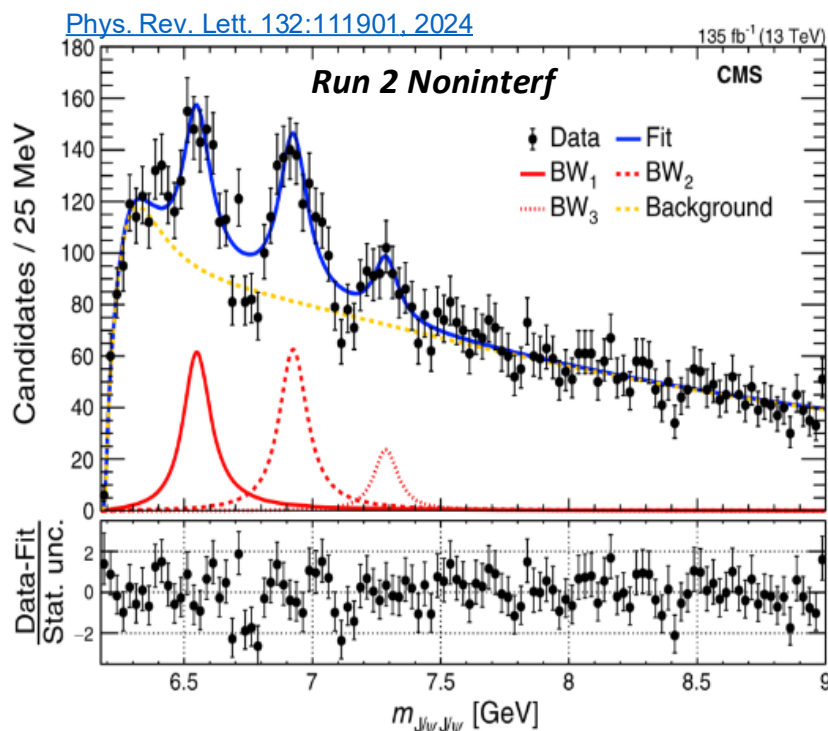
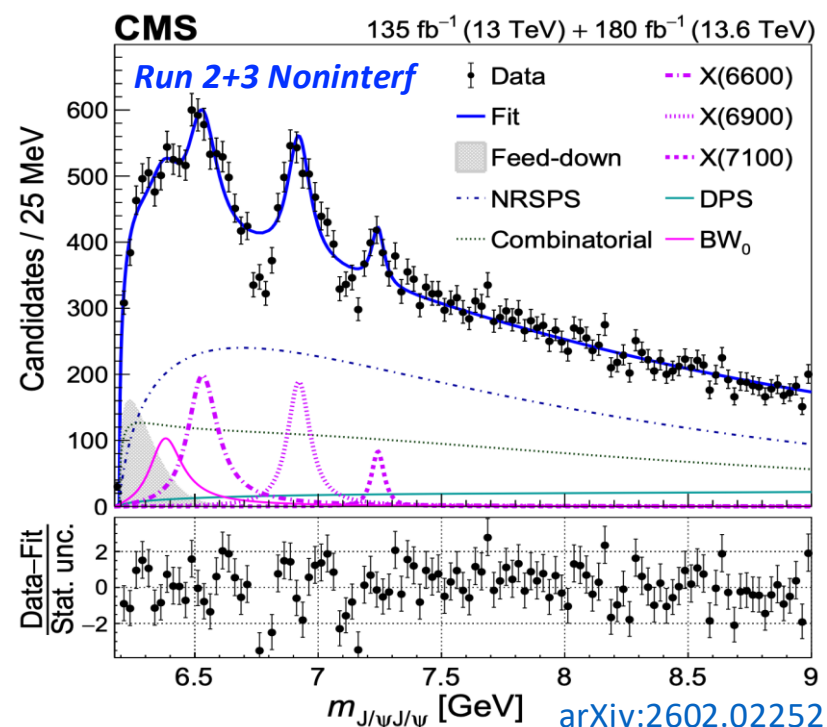
- Signal-hypothesis: NRSPS+NRDPS+Comb+Feeddown+BW0+BW123 Interf. Term

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

❖ Noninterference model

NRSPS + NRDPS + Comb + Feed-down + BW0 + BW1 + BW2 + BW3

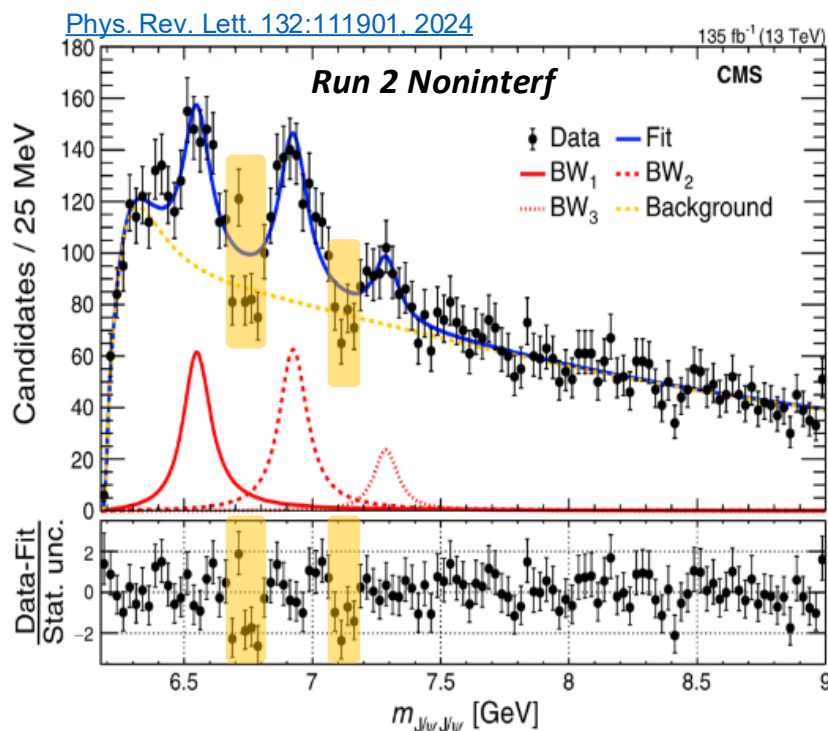
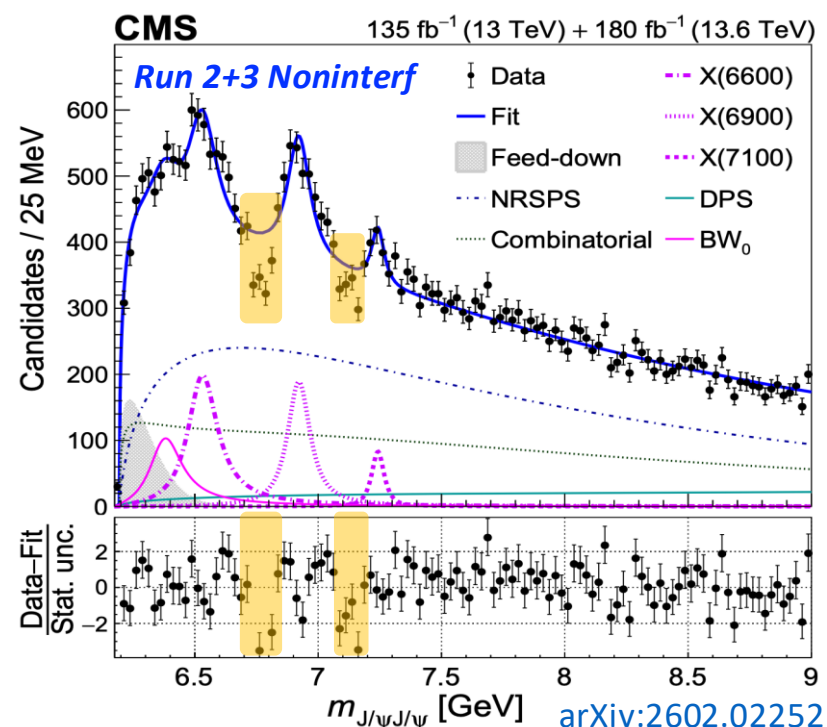
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❖ Noninterference model

NRSPS + NRDPS + Comb + Feed-down + BW0 + BW1 + BW2 + BW3

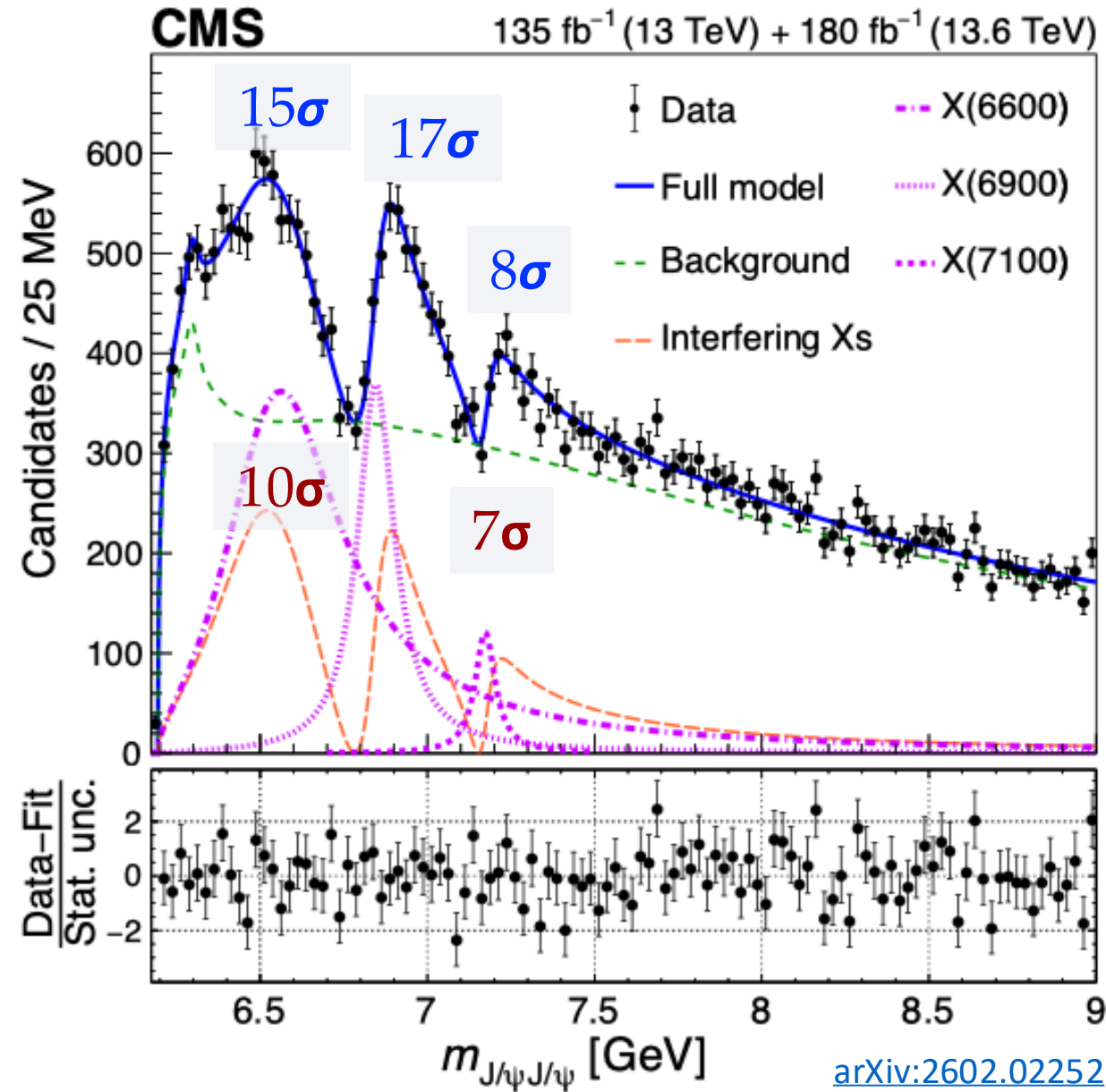
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[arXiv:2602.02252](#)

Dips poorly described --- Noninterference model no longer sufficient

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



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

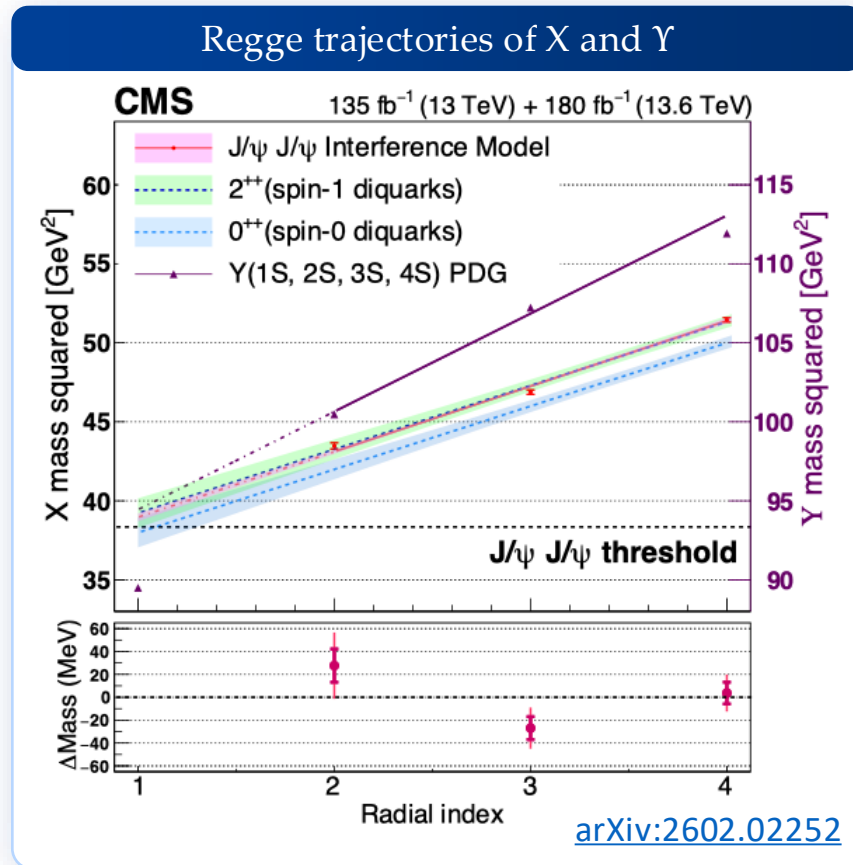
Precision improved by factor of 2~3

Large mass splittings, > 250 MeV

First observation of X(7100) in $J/\psi J/\psi$ channel

First observation of interference among X(6600), X(6900), and X(7100)

- ❖ In Regge theory: $n_r = \beta M^2 + \beta_0$
 $n_r = n - 1$, radial quantum number n



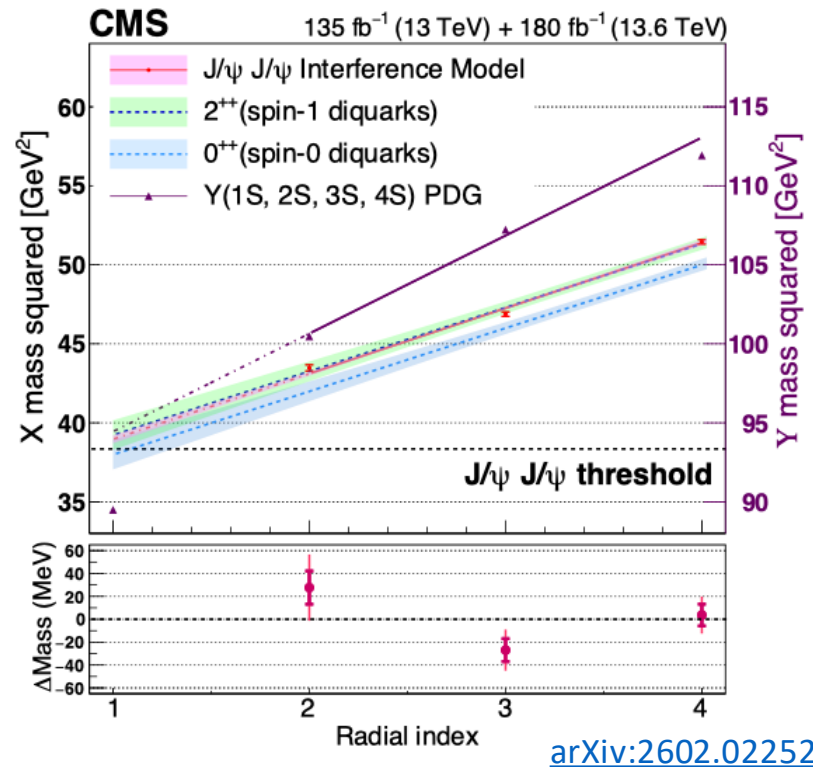
- 🔍 Good agreement with **spin-1 diquark**
 0⁺⁺ or 2⁺⁺ state [Nucl. Phys. B 966 \(2021\) 115393](https://arxiv.org/abs/2602.02252)

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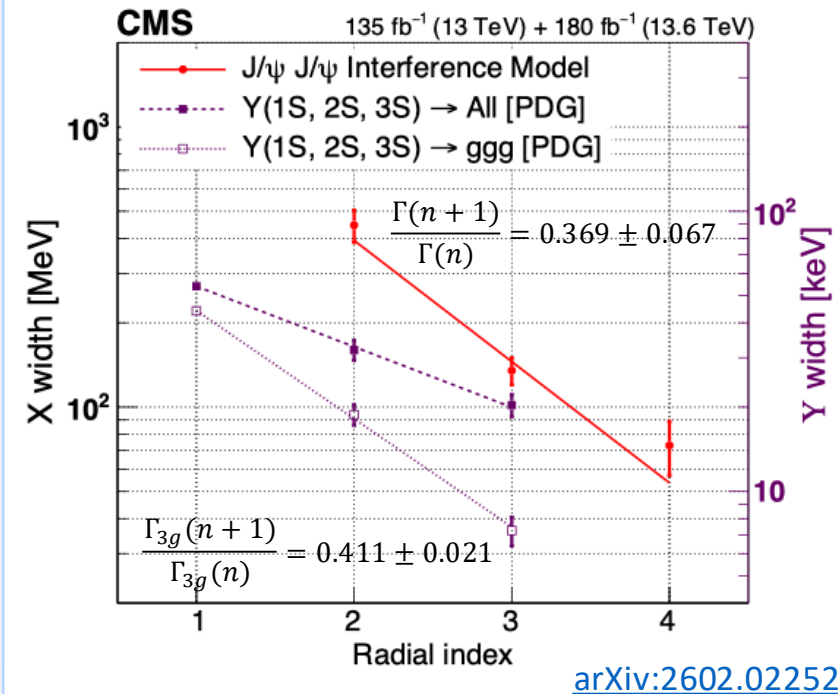
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❖ X widths decrease with radial excitation, exponentially

Regge trajectories of X and Y



Widths trend of X and Y



In Y family, $b\bar{b}$ quark-antiquark annihilation predominantly

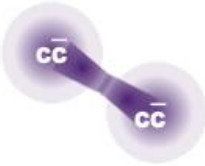
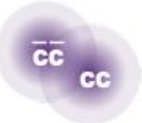
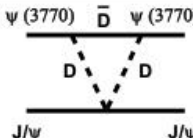
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🔍 Suggest **a similar decay mechanism** for X states
a sort of diquark-antidiquark “annihilation”

❖ Interpretation and discussion

★ Idealized models of all-charm structures theoretically

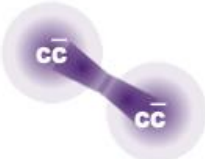
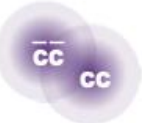
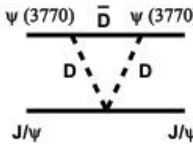
Molecular, Diquark-antidiquark, “amorphous” systems, hybrid, threshold effects

Standard meson	Exotic mesons: all-charm tetraquark				Threshold effects
	Molecule 	Diquark 	Compact (amorphous) 	Hybrid 	e.g., triangle singularity 

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- ★ Squared masses of triplet align Regge trajectory ==> Radial excitations

- ★ Regge match predictions for spin-1 (anti)diquarks with J^{PC} of 0^{++} or 2^{++}

0^{++} is less prominent in production than 2^{++} [arXiv:2006.14388](https://arxiv.org/abs/2006.14388)
[arXiv:2009.08376](https://arxiv.org/abs/2009.08376)

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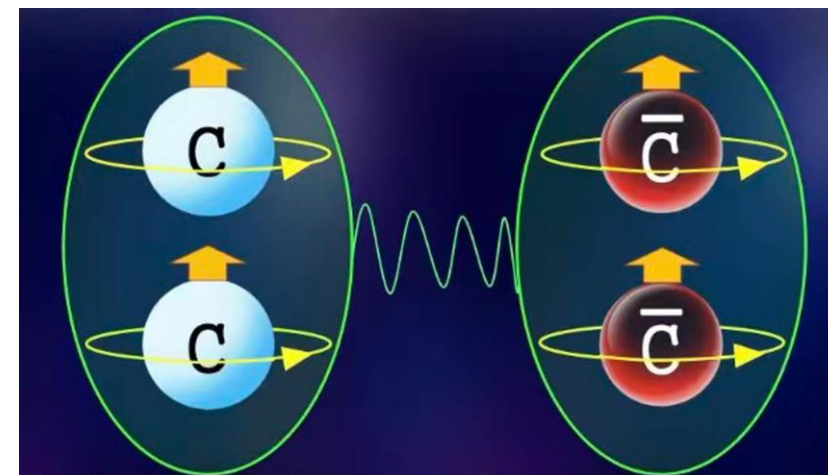
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- ★ CMS angular analysis favors $J^{PC} = 2^{++}$

- ★ No orbital angular momentum ($L_{[cc][\bar{c}\bar{c}]} = 0$)

high orbital less likely, difficult to produce



A system of aligned spin-1 diquarks forms a triplet of radially excited n^5S_2 states of $T_{cc\bar{c}\bar{c}}$

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

- Three structures X(6600), X(6900), X(7100) established with significances $> 5\sigma$
- Quantum interference among structures validated with significances $> 5\sigma$
- First preliminary picture of the internal structure of this family.

We are painting a coherent picture of Fully-heavy exotic hadrons

THANKS!

BACKUP