Observation of a family of all-charm tetraquarks in J/ψJ/ψ channel at CMS

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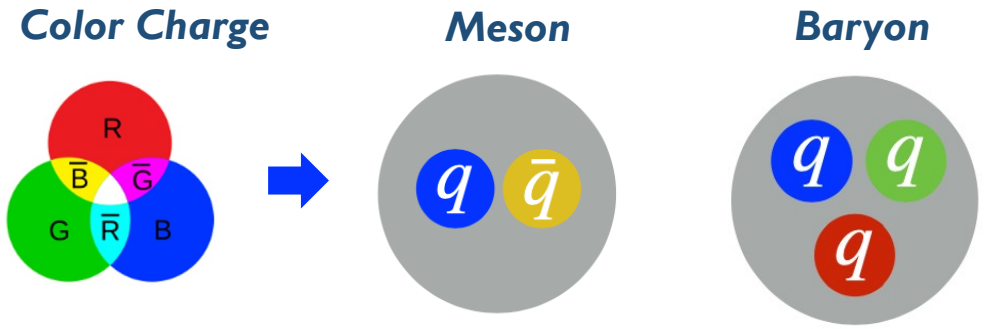
March 29, 2026

Outline

- Introduction
- $J/\psi J/\psi$ updated result
- Summary

The quark model

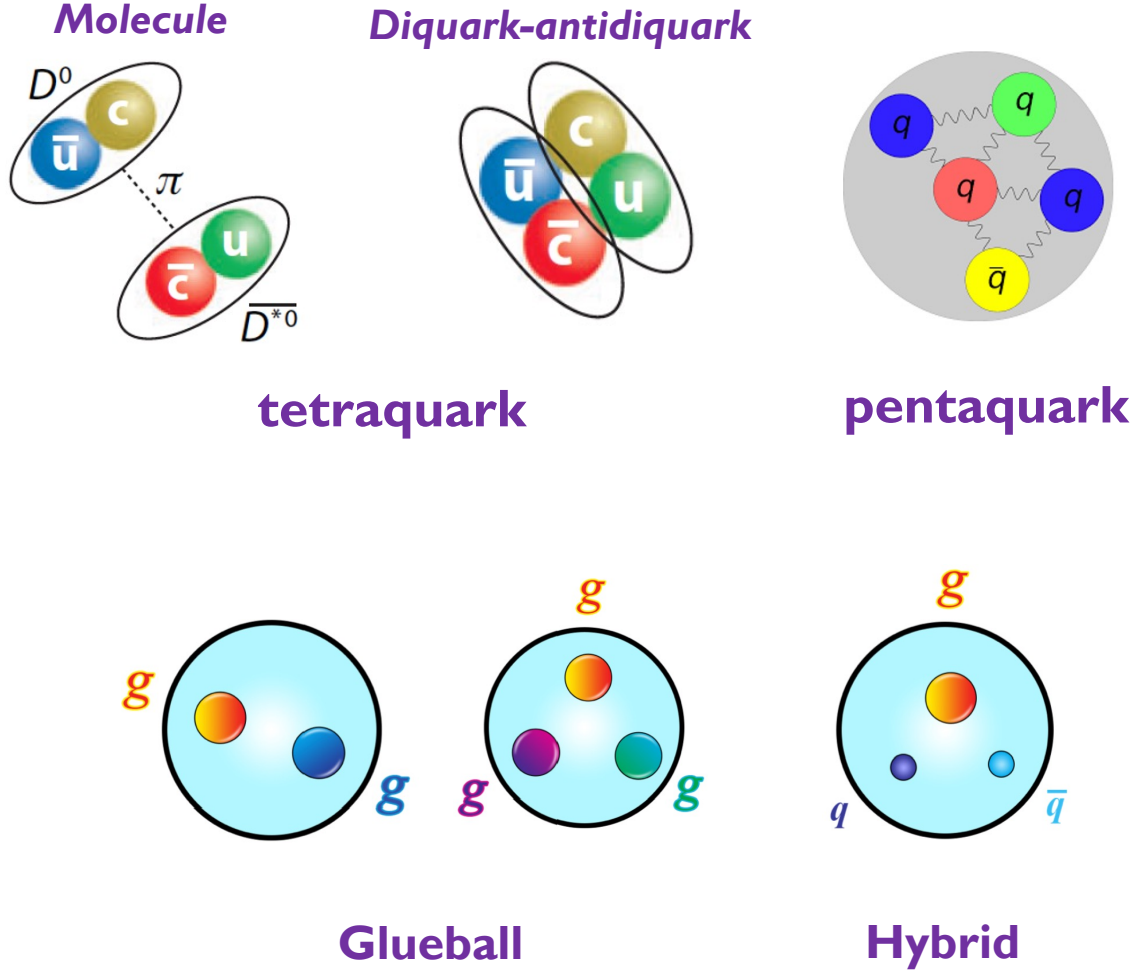
Classical quark model



- **> 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**

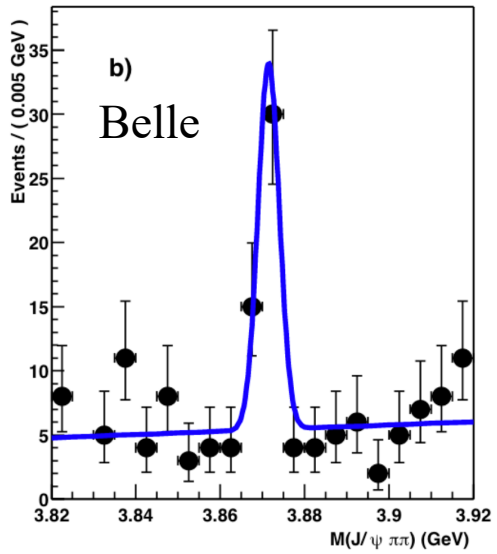
  – currently a hot topic

"Exotic" hadron

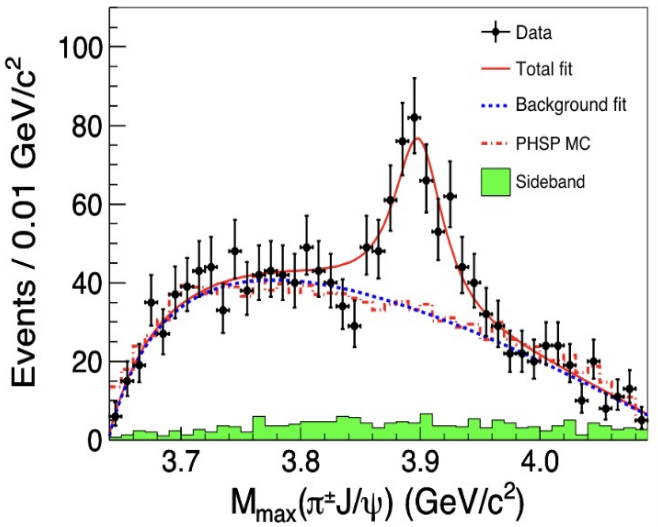


Heavy-Flavor Exotic Hadron States (XYZ Particles)

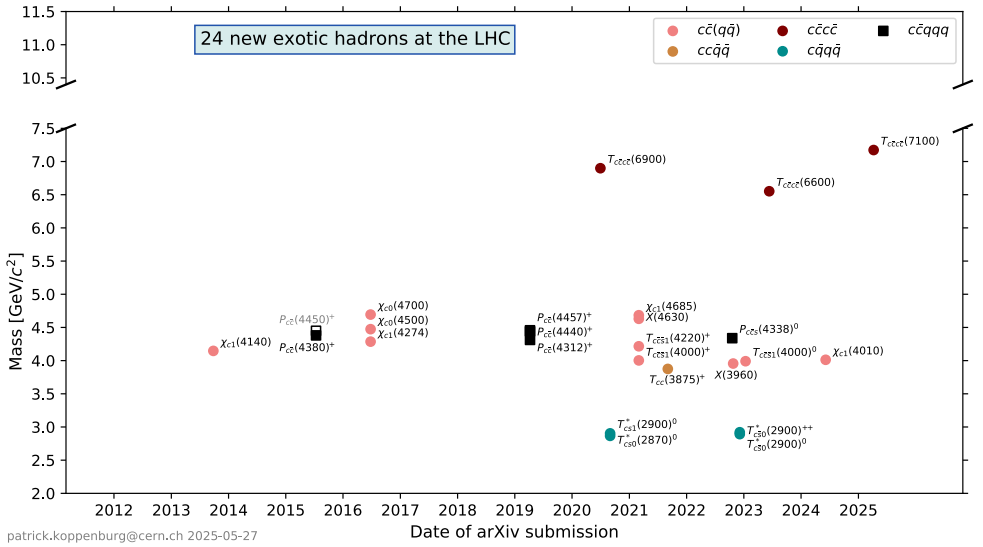
X(3872) [ucūc̄]



$Z_c^+(3900)$



24 exotic hadrons at LHC

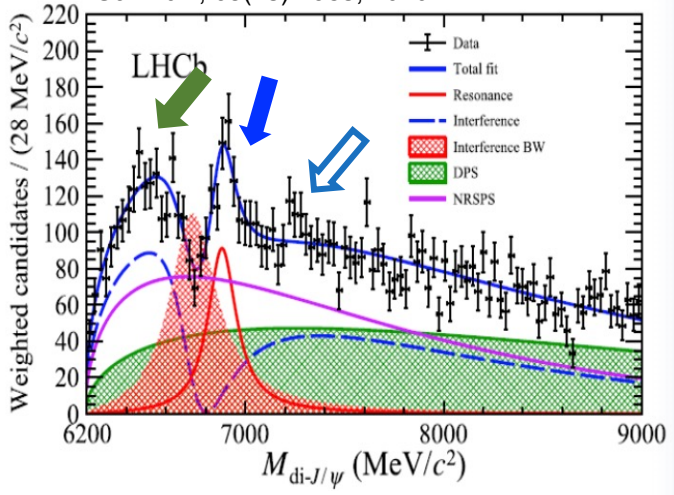


- **Light exotics** likely exist, but light-meson sector too messy for clear identification
- **Heavy-flavor exotics**: larger quark mass relative to Λ_{QCD}, theoretical treatments more reliable
- **X(3872),** kicked off a boom in **(heavy-flavor) exotic hadron,** dozens of XYZ found
- **Zc(3900),**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

Status of of all-charm tetraquark

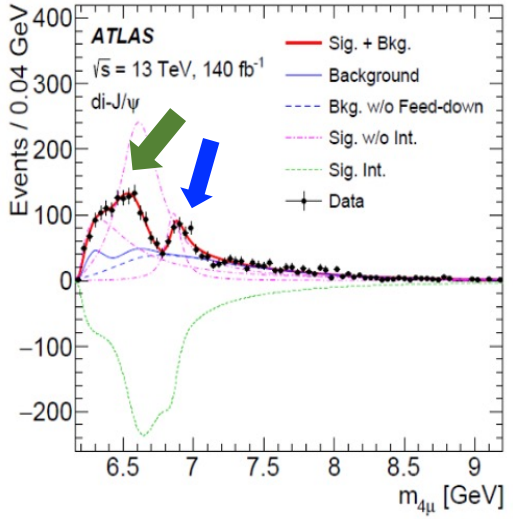
LHCb

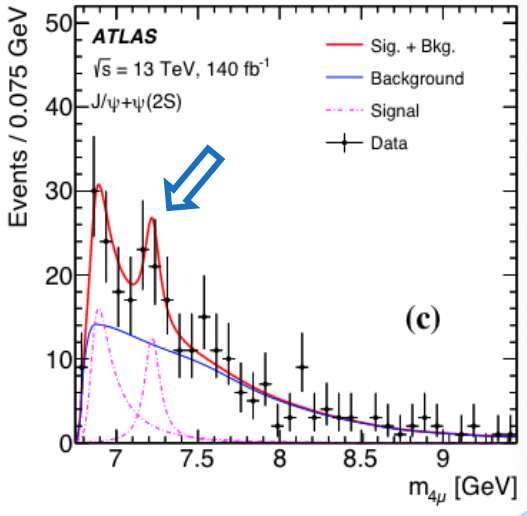
Sci. Bull., 65(23):1983, 2020



ATLAS

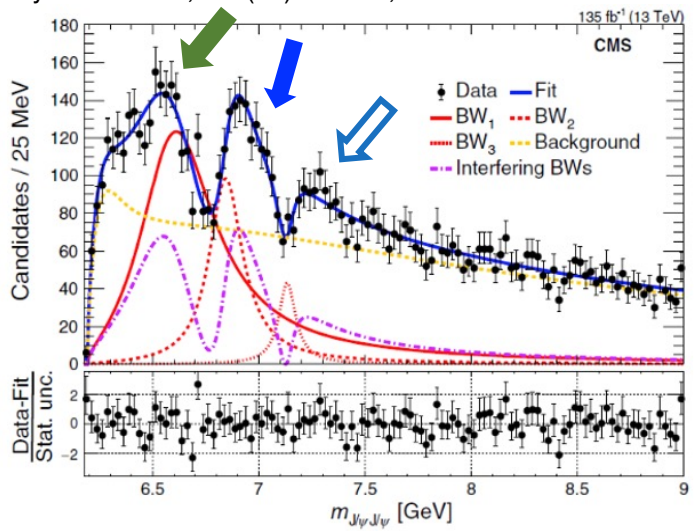
Phys. Rev. Lett., 131(15):151902, 2023





CMS

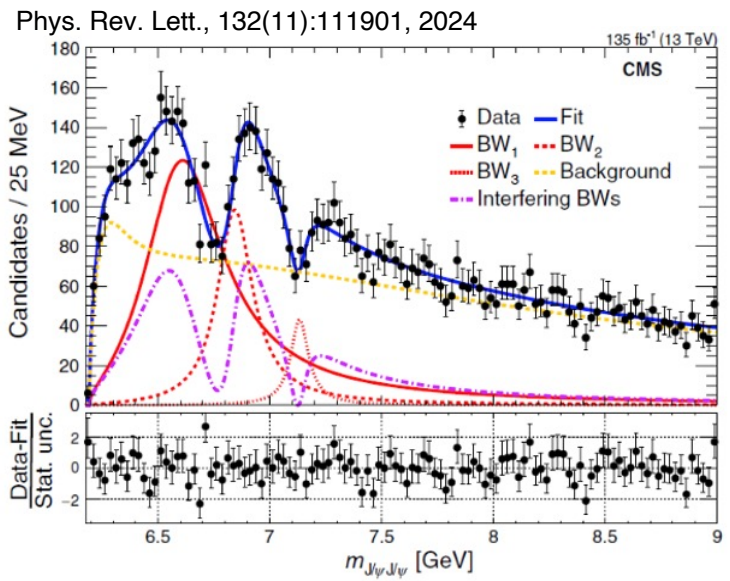
Phys. Rev. Lett., 132(11):111901, 2024



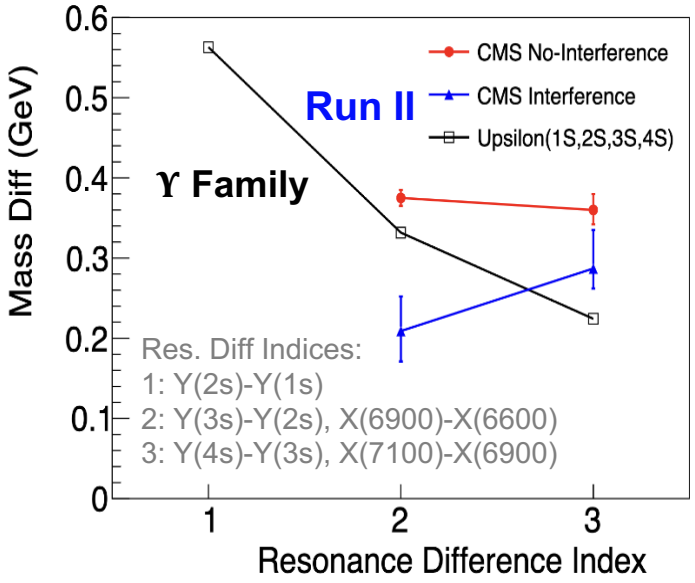
- **ALL exp observe X(6900)** **+ additional structure**
  - **Hump @ 6.6 GeV**: Different modeling
  - **Hint @ 7.2 GeV**: LHCb not consider; ATLAS 3σ hint in $J/\psi\psi(2S)$
- **CMS first observed X(6600) & evidence of X(7100)**
- **All exp use interference, but in diff ways**

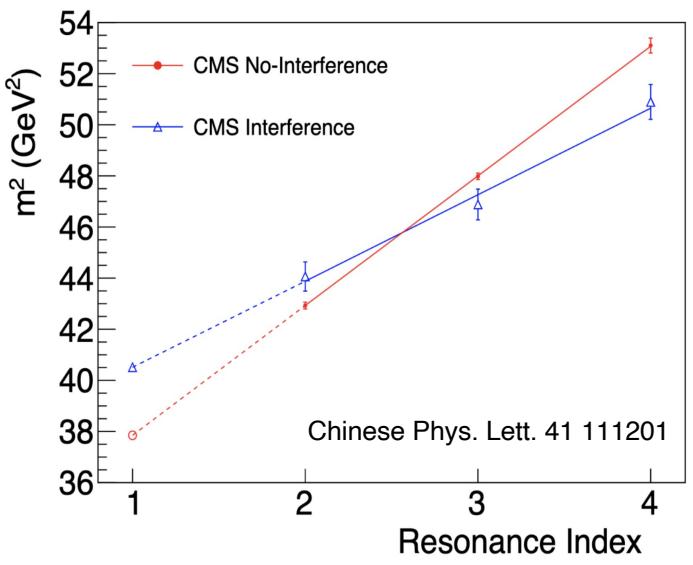
CMS Run 2 Result

CMS Run 2 mass spectrum



CMS Run 2 Regge plot





Run 2 result:

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

With 3.6X statistics:

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

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

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

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

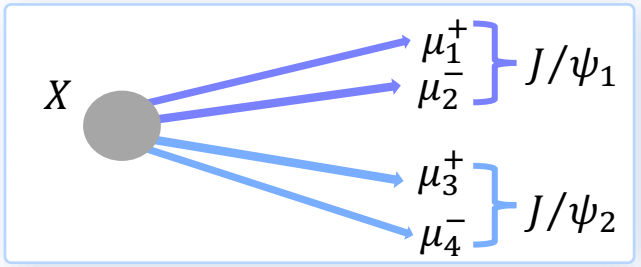
$J/\psi J/\psi$: Datasets, MC, trigger, and event selection

❖ Data samples [315 fb^{-1}]

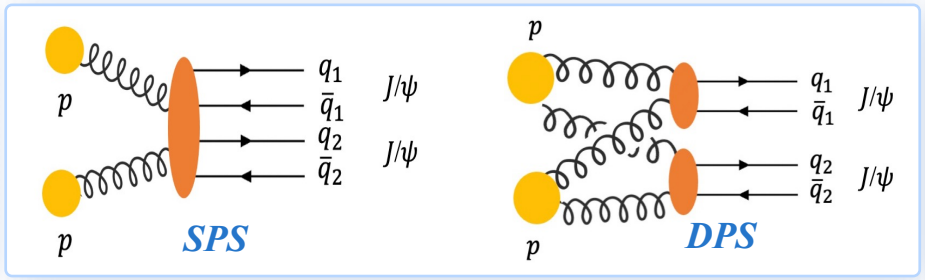
- Run 2: 135 fb^{-1} data taken in 2016, 2017 and 2018.
- Run 3: 180 fb^{-1} data taken in 2022, 2023 and 2024.

❖ Signal and Background simulated events:

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



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



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

Feeddown from X(7100) in systematics

❖ Trigger of Run 3

HLT_Dimuon0_Jpsi3p5_Muon2

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

HLT_DoubleMu4_3_LowMass [new trigger for Run III]

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

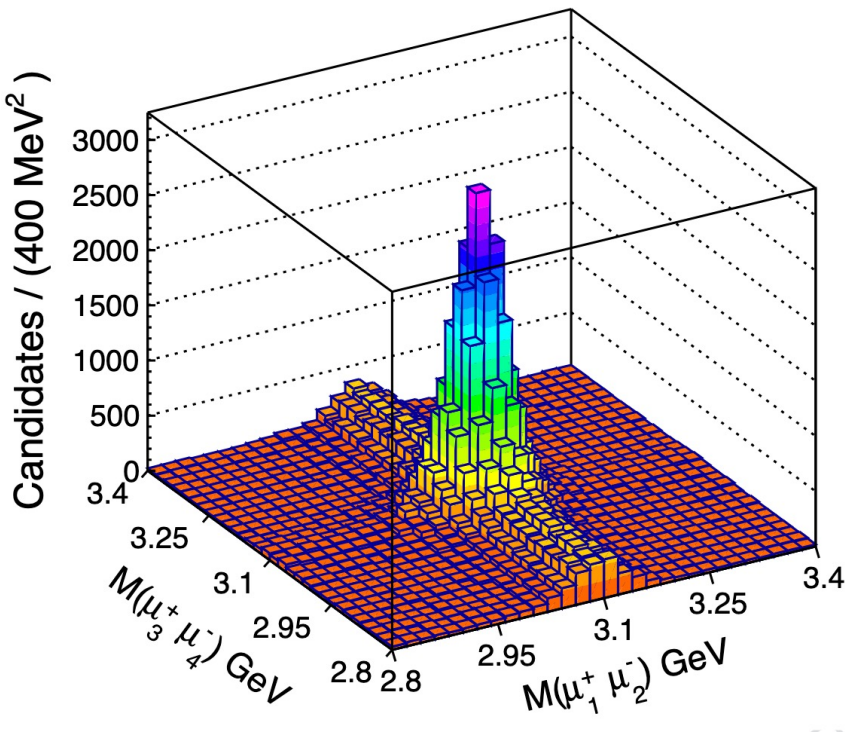
➢ Compared to only Dimuon trigger, LowMass trigger **increase 30% $J/\psi J/\psi$ statistics**

❖ Event selection of Run 3

Follow PRL cuts + A new trigger for Run 3

$J/\psi J/\psi$: Statistics of CMS Run 2+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**

Run 2 ~12622 ± 165

Run 3 ~31802 ± 476

➢ **$J/\psi J/\psi$ yield per unit luminosity**

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

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

➢ **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

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

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

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

❖ Non-interference model:

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

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

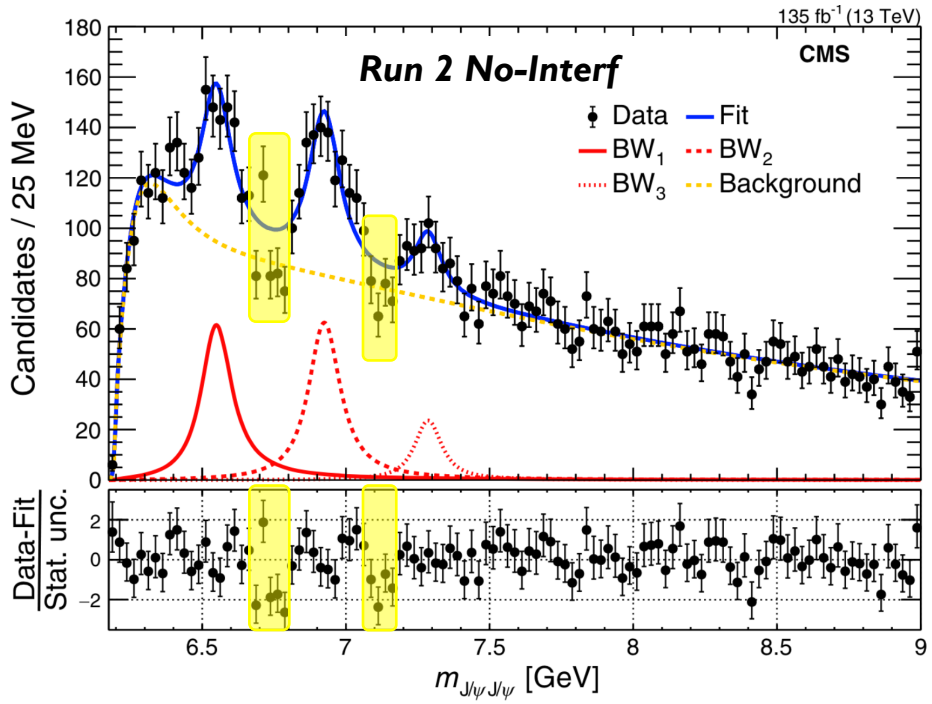
❖ Interference model:

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

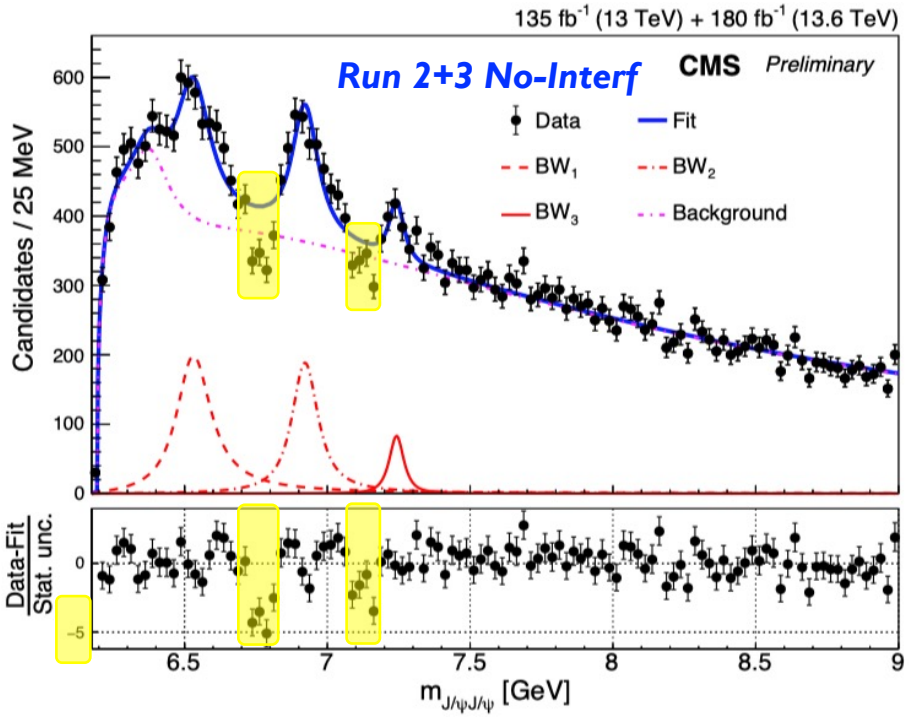
$$Pdf(m)=N_{X_0}\cdot|BW_0|^2\otimes R(M_0)$$
$$+N_{X\ and\ interf}\cdot|r_1\cdot\exp(i\phi_1)\cdot BW_1+BW_2+r_3\cdot\exp(i\phi_3)\cdot BW_3|^2$$
$$+N_{NRSPS}\cdot f_{NRSPS}(m)+N_{DPS}\cdot f_{DPS}(m)$$
$$+N_{Feeddown}\cdot f_{Feeddown}(m)+N_{Comb}\cdot f_{Comb}(m),$$

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

CMS Run 2 noninterference fit result



CMS Run 2+3 noninterference fit result

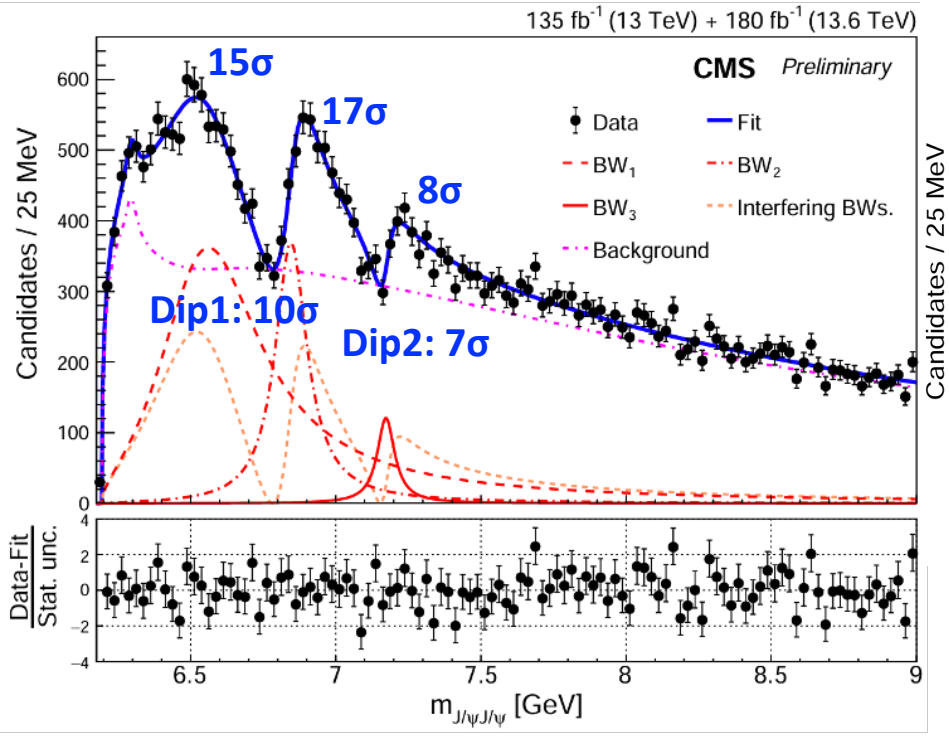


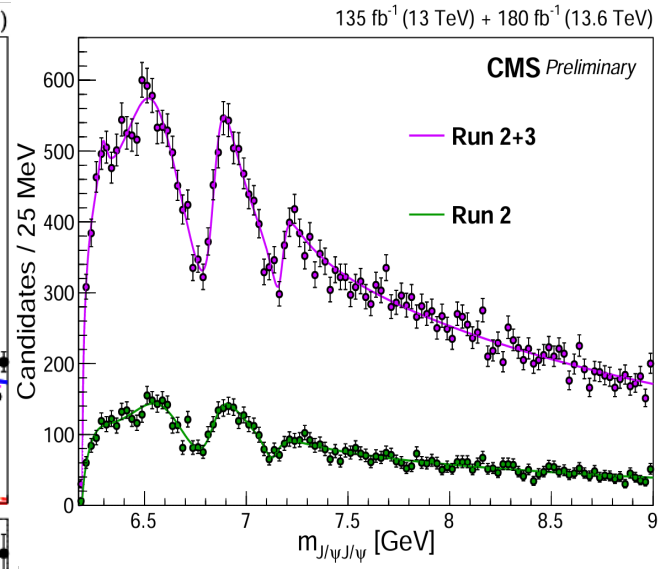
- **Dips poorly described — *no-Interf. model no longer sufficient !***

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

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

CMS Run 2+3 interference fit result





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

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

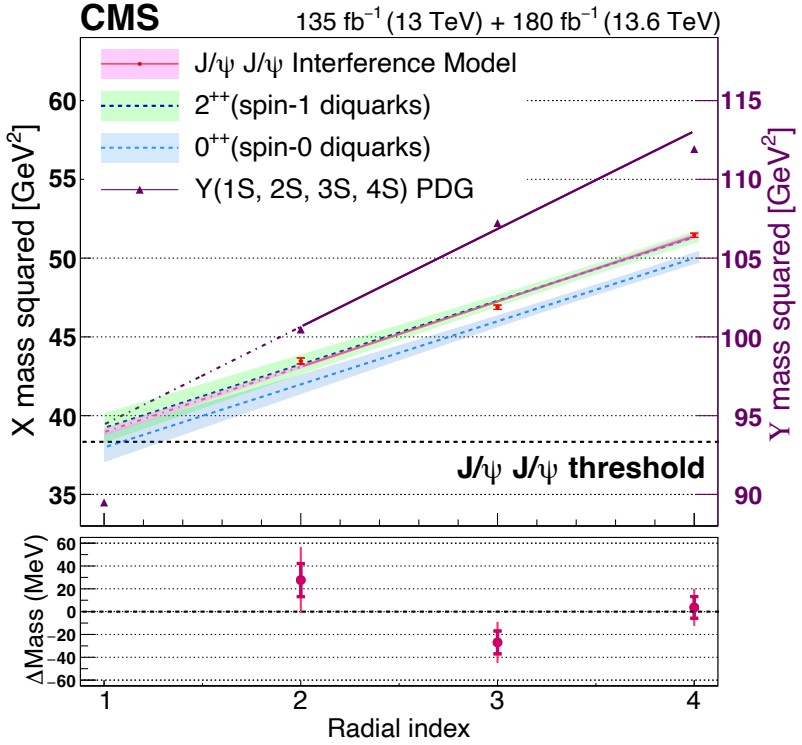
- **All states and dips well above 5σ !**
- **Quantum interference among structures validated!**
- **With improved precision, large mass splittings persist**

Patterns among the triplets

❖ In Regge theory : $n_r = \beta M^2 + \beta_0$

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

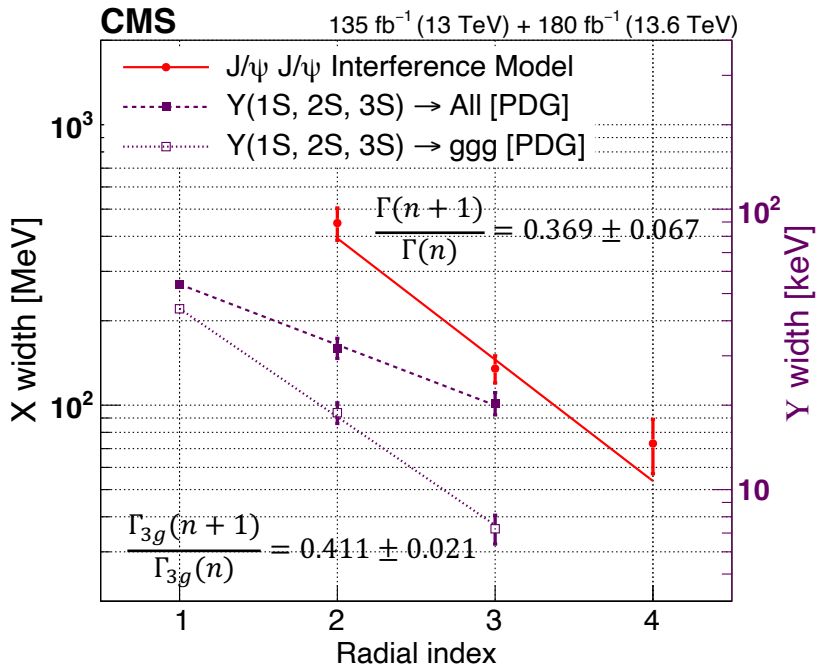
Regge trajectories of X and ϒ



🔎 Good agreement with **spin-1 diquark** 0++ or 2++ state

❖ X widths decrease with radial excitation, exponentially

Widths trend of X and ϒ



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

🔎 **A similar exponential width trend** with annihilation partial width of ϒ family

❖ A family of all-charm tetraquarks

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

  ==> Multiple states makes comparisons possible

- Quantum interference among structures validated well above 5σ

  ==> States have common J^{PC}

- Large mass splittings, more precisely

  ==> radial family of states

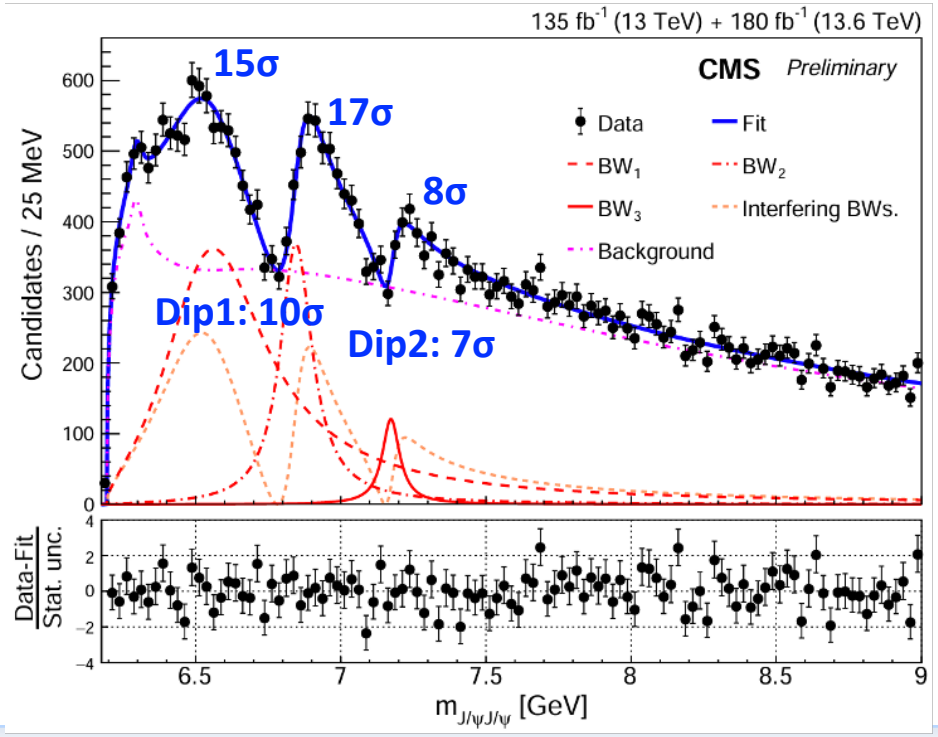
CMS is painting a coherent picture of all-charm tetraquark structures!

THANKS!

BACKUP

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

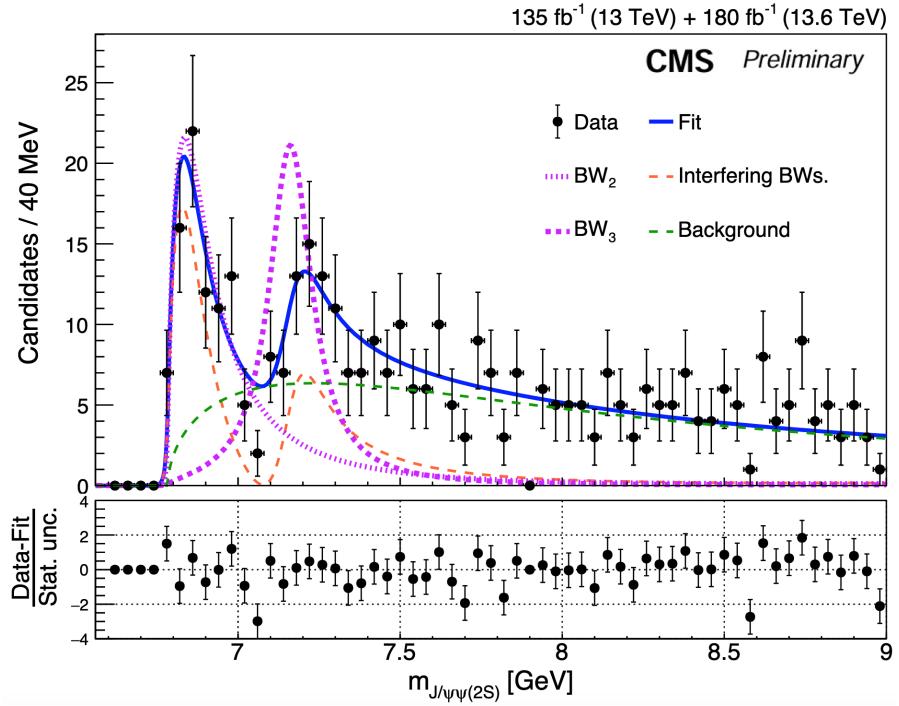
CMS Run 2+3



Dominant sources	Δm_{BW_1}	$\Delta\Gamma_{BW_1}$	Δm_{BW_2}	$\Delta\Gamma_{BW_2}$	Δm_{BW_3}	$\Delta\Gamma_{BW_3}$
Signal shape	25	52	2	11	3	5
NRSPS shape	3	7	<1	1	<1	5
DPS shape	<1	5	<1	<1	<1	1
Combinatorial bkg shape	<1	22	<1	2	<1	4
Feeddown	<1	1	<1	<1	<1	<1
Mass resolution	4	58	15	7	12	5
Efficiency	<1	4	<1	<1	<1	<1
Without BW$_0$	<1	29	2	3	2	1
Total uncertainty	25	87	15	14	13	10

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

CMS Run 2+3



Dominant sources	$M_{X(6900)}$	$\Gamma_{X(6900)}$	$M_{X(7100)}$	$\Gamma_{X(7100)}$
Signal shape	± 29	± 79	± 22	± 131
NRSPS shape	± 14	± 54	± 14	± 29
Combinatorial background shape	± 15	± 51	± 15	± 20
Mass resolution	± 5	± 7	± 5	± 9
Efficiency	± 7	± 27	± 7	± 10
Add X(6600) peak	± 104	± 14	± 61	± 31
Fitter bias	$^{+9}_{-11}$	$^{+43}_{-37}$	$^{+29}_{-14}$	$^{0}_{-80}$
Total	$^{+110}_{-110}$	$^{+120}_{-120}$	$^{+74}_{-70}$	$^{+140}_{-160}$

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

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

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