Observation of X(6900) and evidence of X(7100) in the J/ψψ(2S) → $\mu^+\mu^-\mu^+\mu^-$ mass spectrum

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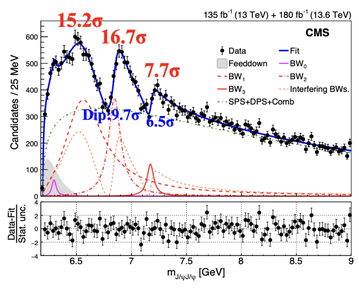
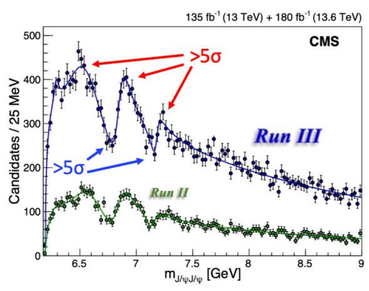
Introduction

- CMS have established candidates for all-charm tetra-quark family, each peak and each dip **well over 5σ** in complete dataset [1]:
  - X(6900) observed by 3 experiment [2-4],
  - X(6600) and X(7100) added by CMS [2].
- If seen in **J/ψ/J/ψ**, probably in **ψ(2S)J/ψ**?

- X(6600) is below the J/ψψ(2S) threshold, but both X(6900) and X(7100) are above it.
- ψ(2S)J/ψ's model defined: **2 peaks with interference**.





Data samples & Event selections

- **135 fb^{-1}** CMS data taken in 2016, 2017 and 2018 LHC runs
- **180 fb^{-1}** CMS data taken in 2022, 2023 and 2024 LHC runs

- Trigger:
  - HLT_Dimuon0_Jpsi_Muon
  - HLT_Dimuon0_Jpsi3p5_Muon2
  - HLT_DoubleMu4_3_LowMass

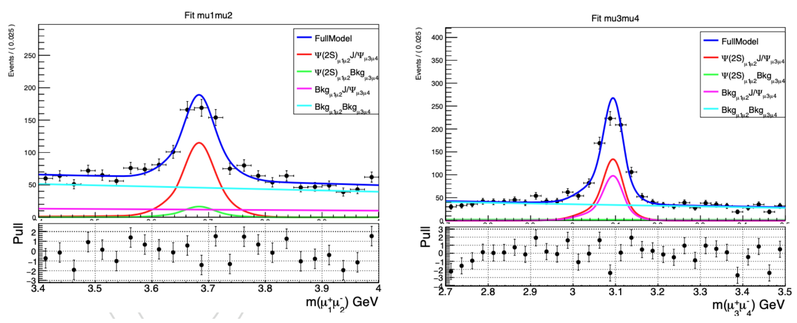
- Main selections:
  - Fire corresponding trigger in each year;
  - Single μ from J/ψ: **$p_T(\mu)$>=3.5 GeV; soft muon ID;**
  - Single μ from ψ(2S): **$p_T(\mu)$>=2.5 GeV; loose muon ID;**
  - Single J/ψ: p_T>=11 GeV; m($\mu^+\mu^-$) within 2.5σ; constraint to J/ψ mass;
  - Single ψ(2S): p_T>=13.5 GeV; m($\mu^+\mu^-$) within 2.5σ; constraint to ψ(2S) mass;
  - **|η(μ)|<=2.4;**
  - 4μ vertex probability > 0.005, total charge is 0;
  - Exclude events with wrong combination within 2σ of J/ψJ/ψ

- Multiple candidates treatment:
  - Select best combination of same 4μ with

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

  - Keep all candidates arising from more than 4μ

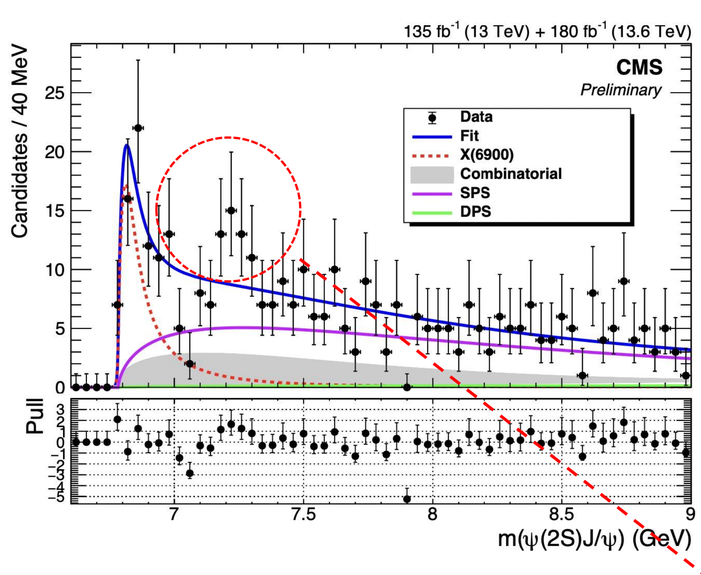
- Signal and background MC samples are produced by JHUGen and Pythia8



*Projections of di-muon mass from 2 dimensional fit

Independent measurement - 1BW - X(6900)

- The J/ψψ(2S) mass spectrum with the fit including **1BW**:



Signal shapes:
Relativistic **Breit-Wigner** functions convolved with **Gaussian resolution functions** (BW)

Background shapes:
Single-parton scattering (**NRSPS**, MC simulation)
Double-parton scattering (**DPS**, data event-mixing)
Combinatorial background (**Comb**, nine-tile method)

Fit model building:
- Based on J/ψJ/ψ analysis
- X(6600) under J/ψψ(2S) mass threshold

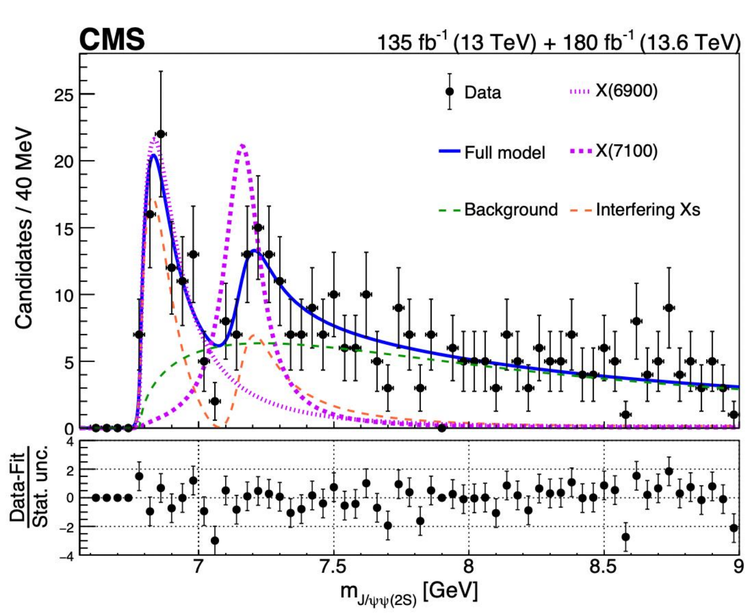
$$Pdf(m) = \sum N_{X_j} \cdot |BW(m, M_j, \Gamma_j)|^2 \otimes R(M_j) + N_{SPS} \cdot f_{SPS}(m) + N_{DPS} \cdot f_{DPS}(m) + N_{Combinatorial} \cdot f_{Combinatorial}(m)$$

For the 1BW model, it is evident that one additional peak need to be incorporated into consideration - X(7100)

Independent measurement - 2BW (Interference) - X(6900)&X(7100)

- Dips in the data show possible interference effects

- The J/ψψ(2S) mass spectrum with the fit including **2BW (interference)**:



- **Constrain** mass & width of both peaks within 1σ of J/ψJ/ψ values to calculate significances:
  - **Model I: 2BW interfered (NLL = -2056.83)**
  - **Model II: X(6900) only (NLL = -2045.87)**
  - **Model III: X(7100) only (NLL = -2021.63)**

- **Model I** vs **Model III** -> **X(6900)**
- **Model I** vs **Model II** -> **X(7100)**

- The floating parameters differ by two
  - **Degrees of freedom = 2**

- Significance of **X(6900)** = **8.1σ**
- Significance of **X(7100)** = **4.3σ**

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

Interf. term

Summary

CMS observed X(6900) and found evidence of X(7100) in J/ψψ(2S) using 315 fb^{-1} data.
- They **are consistent with** those observed in J/ψJ/ψ channel [1,2]
- A family of structures which are candidates for **all-charm tetra-quarks**

- Provide critical insights into non-perturbative QCD dynamics, particularly within heavy-quark systems
- Challenge traditional quark models and refine predictions from lattice QCD and effective theories
- Further searches in other decay modes will deepen our understanding of exotic hadrons

CMS has good sensitivity to all-muon final states in this mass region

		X(6600)	X(6900)	X(7100)
$J/\psi\,J/\psi$: Run 2 + 3	m (MeV)	$6593\,^{+15}_{-14} \pm 25$	$6847 \pm 10 \pm 15$	$7173\,^{+9}_{-10} \pm 13$
	Γ (MeV)	$446\,^{+66}_{-54} \pm 87$	$135\,^{+16}_{-14} \pm 14$	$73\,^{+18}_{-15} \pm 10$
$J/\psi\,\psi(2S)$: Run 2 + 3	m (MeV)	—	$6876\,^{+46}_{-29} \pm 110$	$7169\,^{+26}_{-52}\,^{+74}_{-70}$
	Γ (MeV)	—	$253\,^{+290}_{-100} \pm 120$	$154\,^{+110}_{-82}\,^{+140}_{-160}$
$J/\psi\,J/\psi$: Run 2 [14]	m (MeV)	$6638\,^{+43+16}_{-38-31}$	$6847\,^{+44+48}_{-28-20}$	$7134\,^{+48+41}_{-25-15}$
	Γ (MeV)	$440\,^{+230+110}_{-200-240}$	$191\,^{+66+25}_{-49-17}$	$97\,^{+40+29}_{-29-26}$

Bibliography

[1] CMS collaboration, "Observation of a family of all-charm tetraquark candidates at the LHC", CMS-PAS-BPH-24-003 (2024).

[2] CMS Collaboration, "New Structures in the J/ψJ/ψ Mass Spectrum in Proton-Proton Collisions at √s = 13TeV", Phys. Rev. Lett. 132 (2024), no. 11, 111901, doi:10.1103/PhysRevLett.132.111901, arXiv:2306.07164.

[3] LHCb Collaboration, "Observation of structure in the J/ψ-pair mass spectrum", Sci. Bull. 65 (2020) 1983, doi:10.1016/j.scib.2020.08.032, arXiv:2006.16957.

[4] ATLAS Collaboration, "Observation of an Excess of Dicharmonium Events in the Four-Muon Final State with the ATLAS Detector", Phys. Rev. Lett. 131 (2023), no. 15, 151902, doi:10.1103/PhysRevLett.131.151902, arXiv:2304.08962.

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