Observation of a family of all-charm tetraquarks

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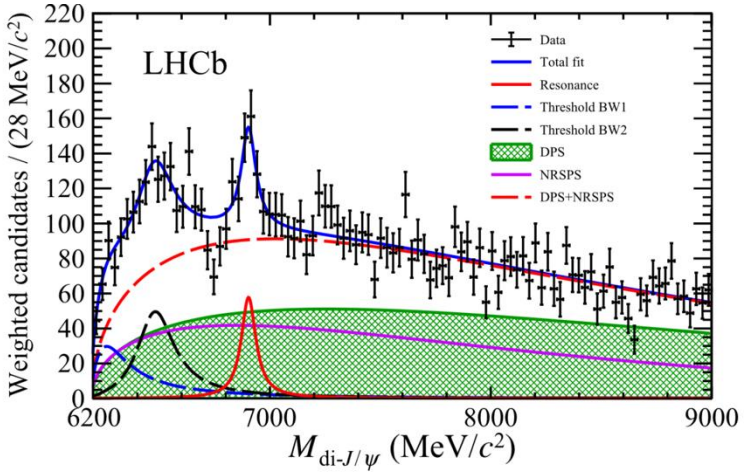
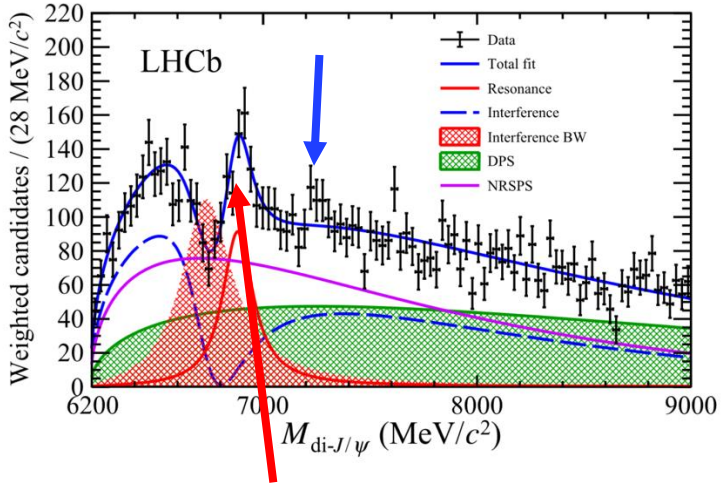
Outline

- Motivation
- J/ψJ/ψ updated result (Poster from Yilin Zhou)
- J/ψψ(2S) result (Poster from Liangliang Chen)
- Summary

Motivation

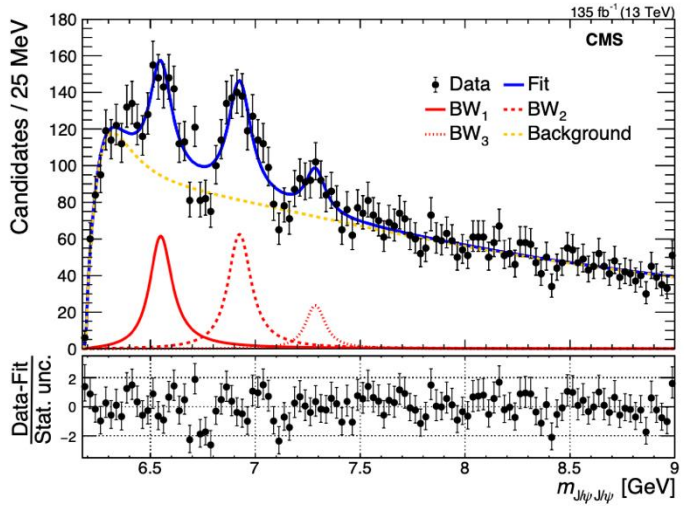
LHCb : Sci.Bull.65(2020)1983

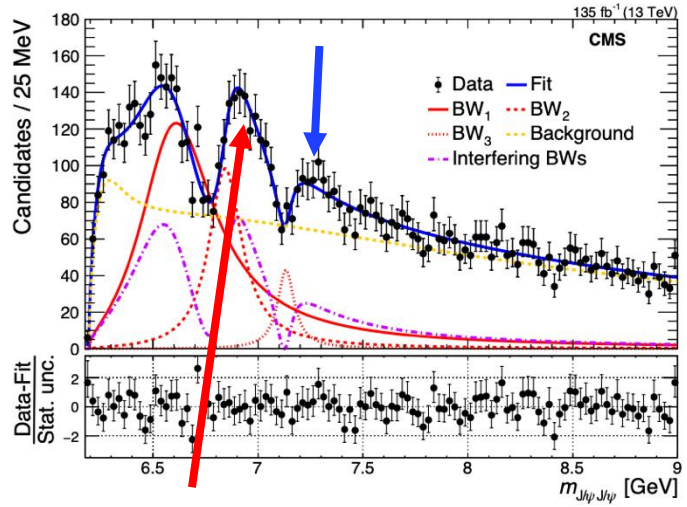




- Observed structure at 6.9 GeV, > 5σ
- M ~ 6900 MeV, Γ ~ 100 MeV

CMS : Phys. Rev. Lett. 132, 111901

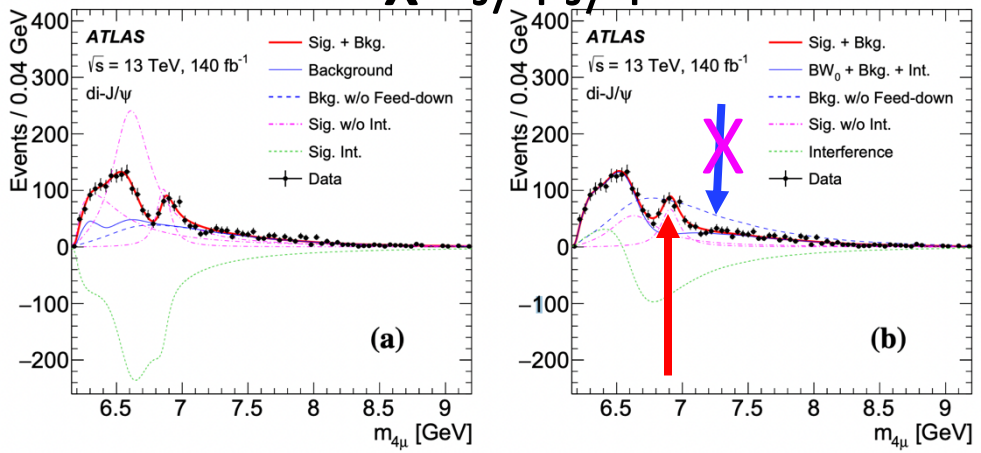




- X(6900) consistent with LHCb
- New state X(6600) with 6.5σ
- Evidence of X(7100) with 4.1σ

ATLAS : Phys. Rev. Lett. 131, 151902

X→J/ΨJ/Ψ



- X(6900) consistent with LHCb

- X(6900) observed by 3 experiment
- CMS adds X(6600) & X(7100)
  - X(6600) below J/ΨΨ(2S) threshold
  - X(6900)/X(7100) above threshold
- Debate: Tetraquark? Dynamical?
- Further studies vital:
  - More data? Other channels?

Datasets and trigger

- Charmonium dataset
- 135 fb-1 CMS data taken in 2016, 2017 and 2018 LHC runs (13 TeV)
  - 2017B excluded due to improper trigger
- 180 fb-1 CMS data taken in 2022, 2023 and 2024 LHC runs (13.6 TeV)

} 315 fb-1

Trigger

- HLT_Dimuon0_Jpsi_Muon (2016)
- HLT_Dimuon0_Jpsi3p5_Muon2 (2017 & 2018)
- **HLT_DoubleMu4_3_LowMass_v (2022 & 2023 & 2024)**

JSON

- Cert_271036-284044_13TeV_Legacy2016_Collisions16_JSON_MuonPhys.txt
- Cert_294927-306462_13TeV_UL2017_Collisions17_JSON_MuonJSON.txt
- Cert_314472-325175_13TeV_Legacy2018_Collision18_JSON_MuonPhys.txt
- Cert_Collisions2022_355100_362760_Muon.json
- Cert_Collisions2023_366442_370790_Muon.json
- Cert_Collisions2024_378981_386951_Muon.json

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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.

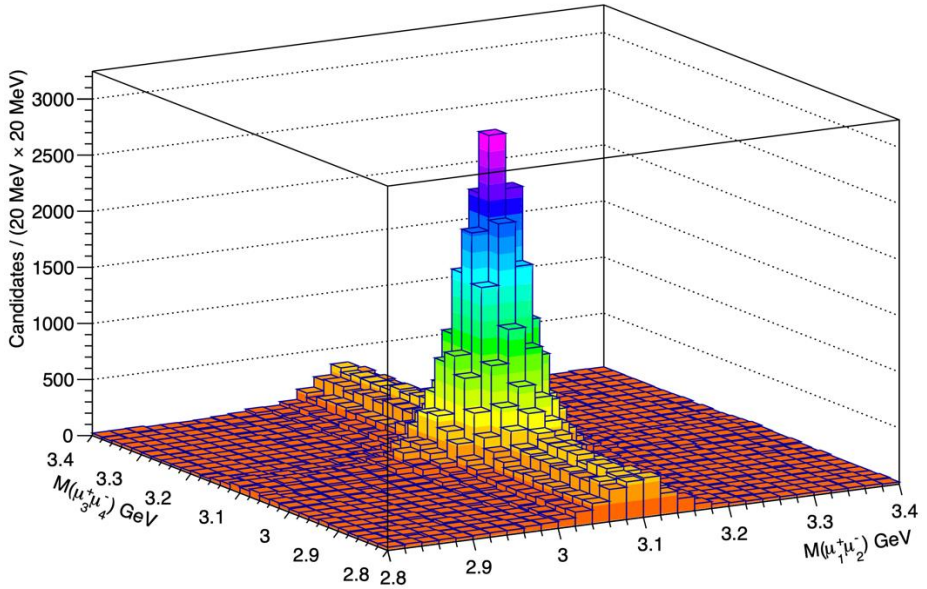
$$\chi^2_m = \left(\frac{m_1(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

- Keep duplicate combination if pairs have non-overlapping muons

❑ Trigger related (OR logic):

- **HLT_Dimuon0_Jpsi3p5_Muon2**
  - **Level 1 requirements: 3 muons**
  - $2.95 < M(\mu^+\mu^-) < 3.25\ GeV$
  - $p_T(\mu) > 3.5\ GeV$

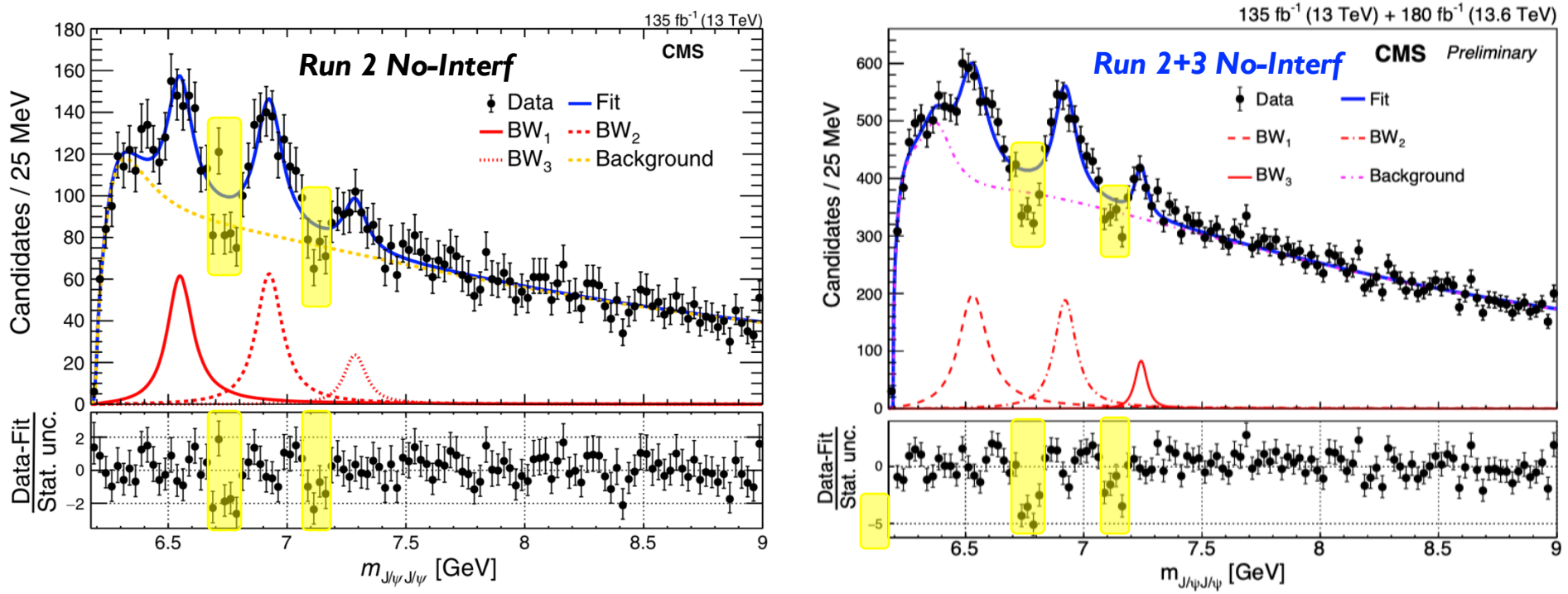
- **HLT_DoubleMu4_3_LowMass [new trigger for Run III]**
  - **Level 1 requirements: 2 muons**
  - $0.2 < M(\mu^+\mu^-) < 8.5\ GeV$
  - one muon $p_T(\mu) > 4\ GeV$ and the other $p_T(\mu) > 3\ GeV$
  - $p_T(\mu^+\mu^-) > 4.9\ GeV$



❖ No-interference model:

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

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

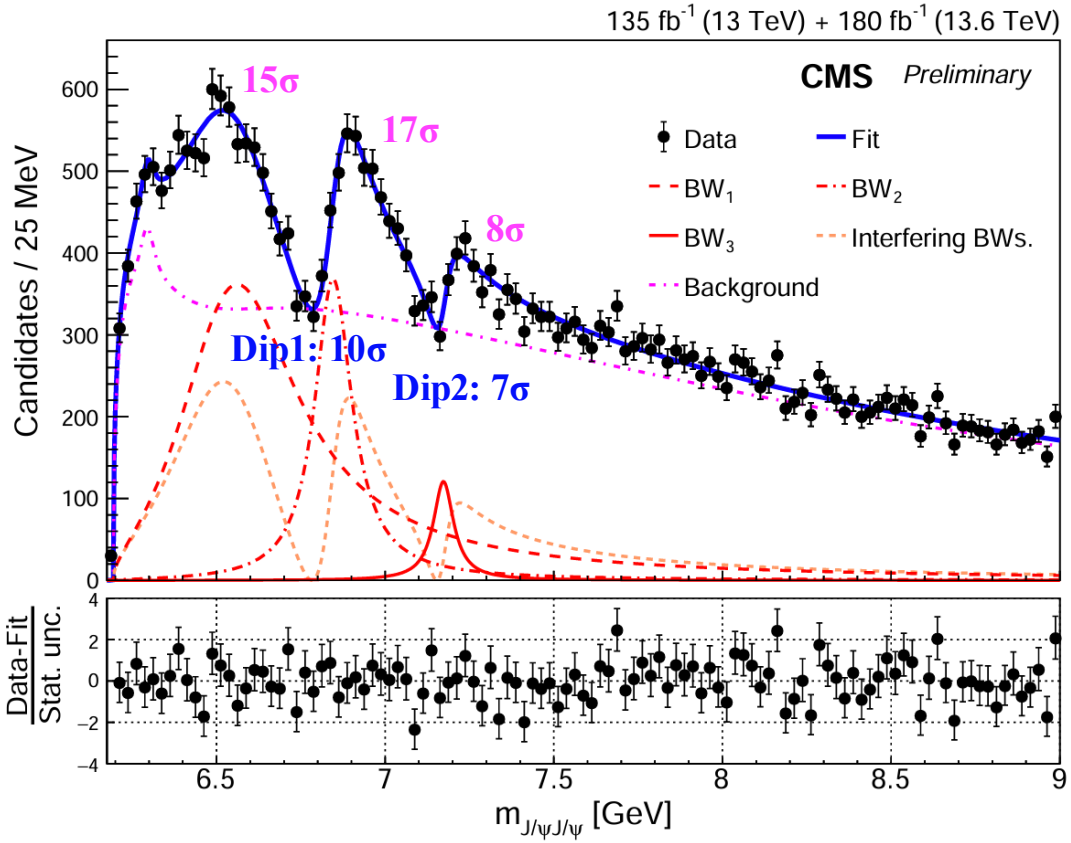


➢ **Dips poorly described — *no-Interf. model no longer sufficient !***

❖ Interference model:

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

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



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**

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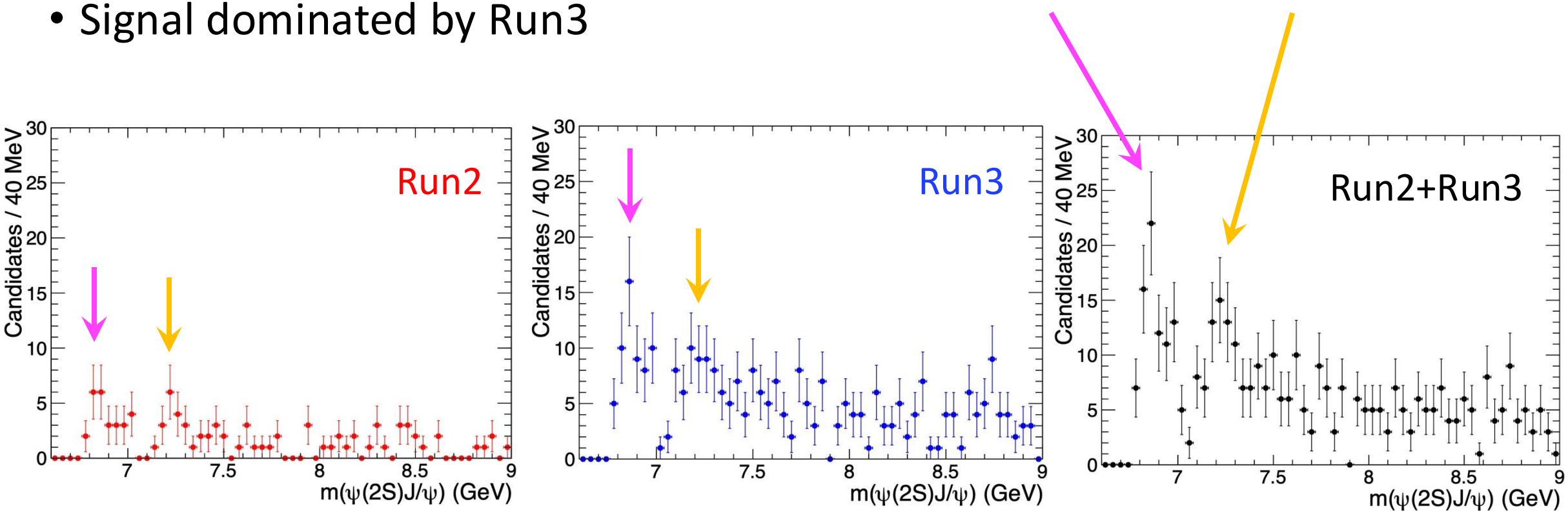
- Same cuts for Run2 and Run3 data except triggers

- Single muon from J/ψ:
  - Soft muon ID
  - $p_{T(muon\quad from\quad J/\psi)}$ >3.5 GeV
- Single muon from $\psi(2S)$:
  - Loose muon ID
  - $p_{T(muon\quad from\quad \psi(2S))}$ >2.5 GeV

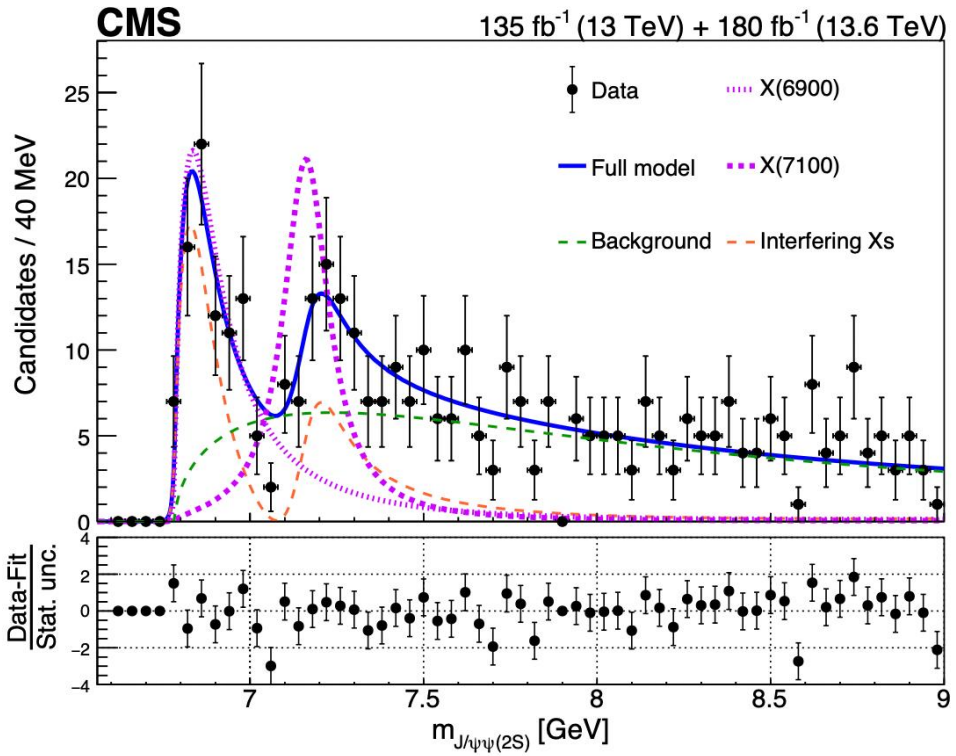
- Single J/ψ:
  - M(J/ψ) within 2.5σ
  - M(J/ψ) constraint to J/ψ mass
  - $p_T(J/\psi)$ >11 GeV
- Single $\psi(2S)$:
  - M($\psi(2S)$) within 2.5σ
  - M($\psi(2S)$) constraint to $\psi(2S)$ mass
  - $p_T(\psi(2S))$ >13.5 GeV

- Four muons:
  - $prob_{vtx}(4\mu)$ >0.5%
  - 4μ charge should be zero
  - Single muon from J/ψ: $p_{T(muon\quad from\quad J/\psi)}$ >3.5 GeV
  - Single muon from $\psi(2S)$: $p_{T(muon\quad from\quad \psi(2S))}$ >2.5 GeV
  - Pass η requirement: $|\eta^{\mu}| \leq 2.4$.
- Multiple candidate treatment:
  - Select best ('min. χ^2_m') combination from one $\mu_1^+\mu_2^-\mu_3^+\mu_4^-$ candidate if both $(\mu_1^+\mu_2^-, \mu_3^+\mu_4^-)$ and $(\mu_3^+\mu_2^-, \mu_1^+\mu_4^-)$ combinations pass final $\psi(2S)J/\psi$ selections based on: $\chi^2_m = \left[\frac{m(\mu^+\mu^-)_1 - m_{\psi(2S)}}{\sigma_{m(\mu^+\mu^-)}}\right]^2 + \left[\frac{m(\mu^+\mu^-)_2 - m_{J/\psi}}{\sigma_{m(\mu^+\mu^-)}}\right]^2$.
  - Keep all combinations if an event has multiple $\psi(2S)J/\psi$ candidates which are composed of more than four distinct muons, i.e. the candidates have one or more non-overlapping muons. There is no multiple candidate after final selection
- Exclude events with wrong combination making J/ψ-pair <2σ of PDG.

- Threshold peak is obvious
- X(7100) is visible
- According to J/ψJ/ψ channel, should be an X(6900) and an X(7100)
- Signal dominated by Run3



- Significance of X(6900) / X(7100) : 8.1σ / 4.3σ



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 :	—	$253\ ^{+290\ +120}_{-100\ -120}$	$154\ ^{+110\ +140}_{-82\ -160}$
$f_{JJ}[1]$	$J/\psi J/\psi$	BW_1, BW_2, BW_3	m :	$6638\ ^{+43\ +16}_{-38-31}$	$6847\ ^{+44\ +48}_{-28\ -20}$	$7134\ ^{+48\ +41}_{-25\ -15}$
(Run 2)			Γ :	$440\ ^{+230\ +110}_{-200\ -240}$	$191\ ^{+66\ +25}_{-49\ -17}$	$97\ ^{+40\ +29}_{-29\ -26}$
$f_{JJ}[2]$	$J/\psi J/\psi$	BW_1, BW_2, BW_3	m :	$6593\ ^{+15}_{-14} \pm 25$	$6847\ ^{+10}_{-10} \pm 15$	$7173\ ^{+9}_{-10} \pm 13$
(Run 2+Run 3)			Γ :	$446\ ^{+66}_{-54} \pm 87$	$135\ ^{+16}_{-14} \pm 14$	$73\ ^{+18}_{-15} \pm 10$

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	$^{+110}_{-110}$	$^{+120}_{-120}$	$^{+74}_{-70}$	$^{+140}_{-160}$

➢ Alternatives with no significant changes are not listed in the table, such as DPS shape

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Summary

- **About J/ψJ/ψ result**
- X(6600), X(6900), and X(7100) well above 5σ
- Quantum interference among structures validated well above 5σ
- Large mass splittings, more precisely
- **About J/ψψ(2S) result**
- CMS observed X(6900) and found evidence of X(7100) in J/ψψ(2S)
- They are consistent with those observed in J/ψJ/ψ channel

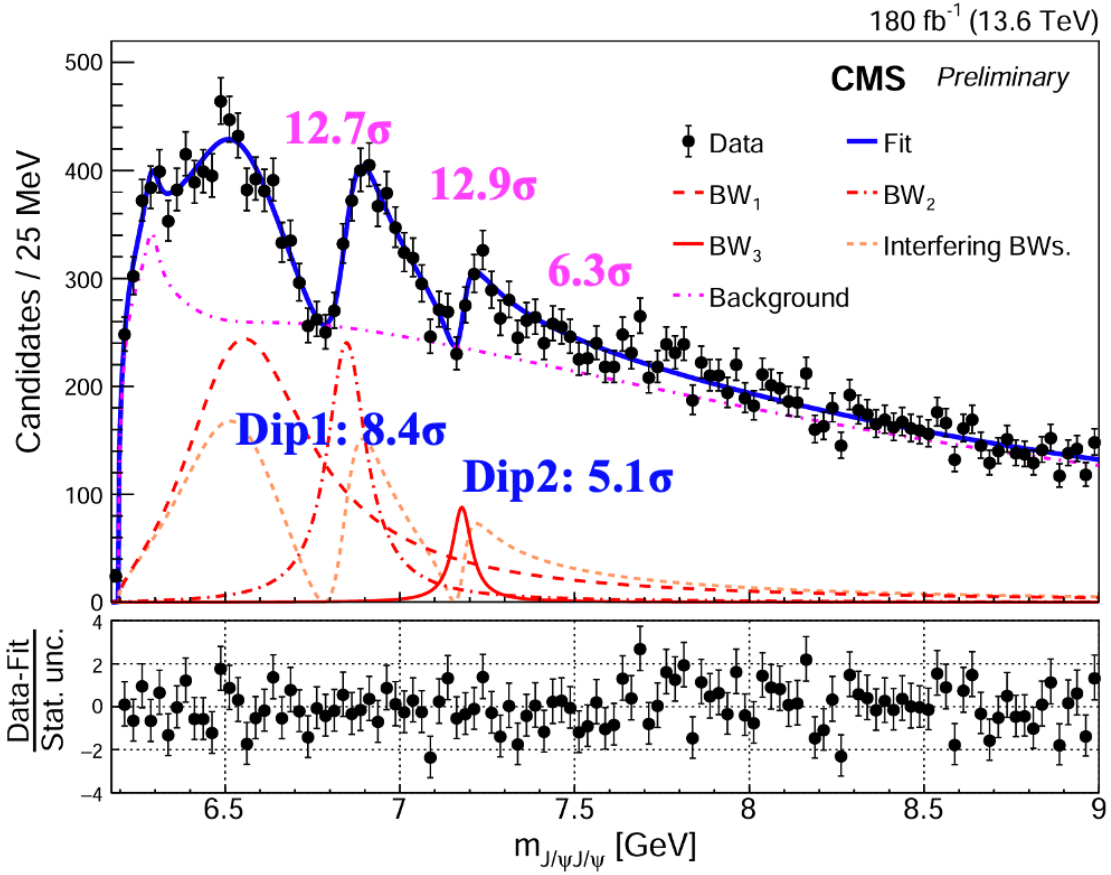
CMS is painting a coherent and compelling picture of J/ψ J/ψ structures!

Thank you!

Back up

❖ Interference model:

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

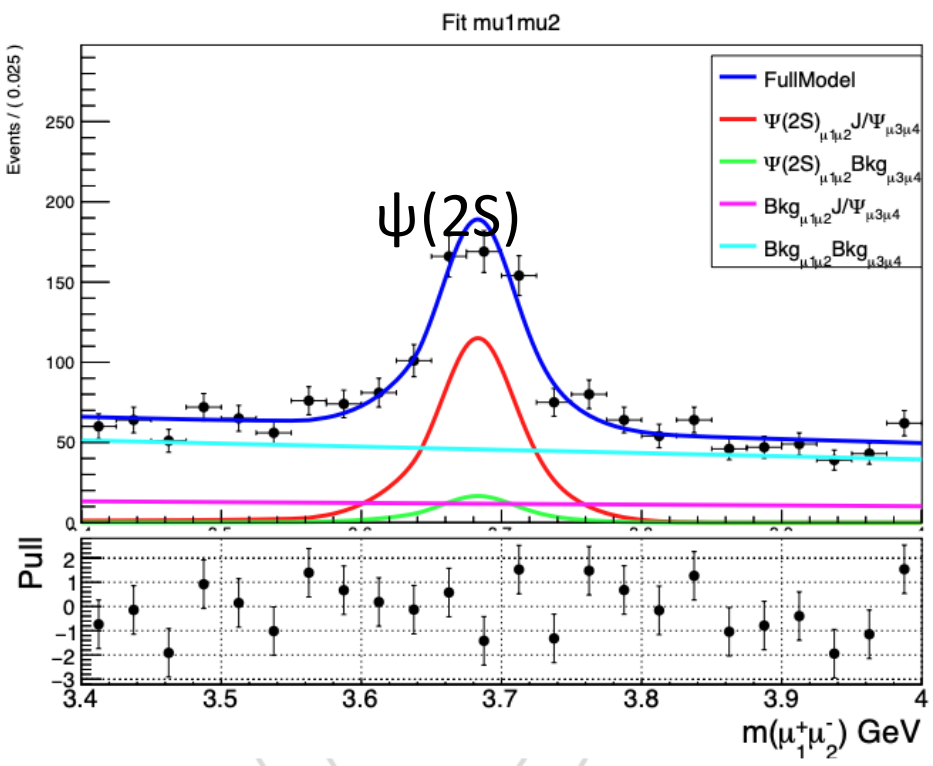


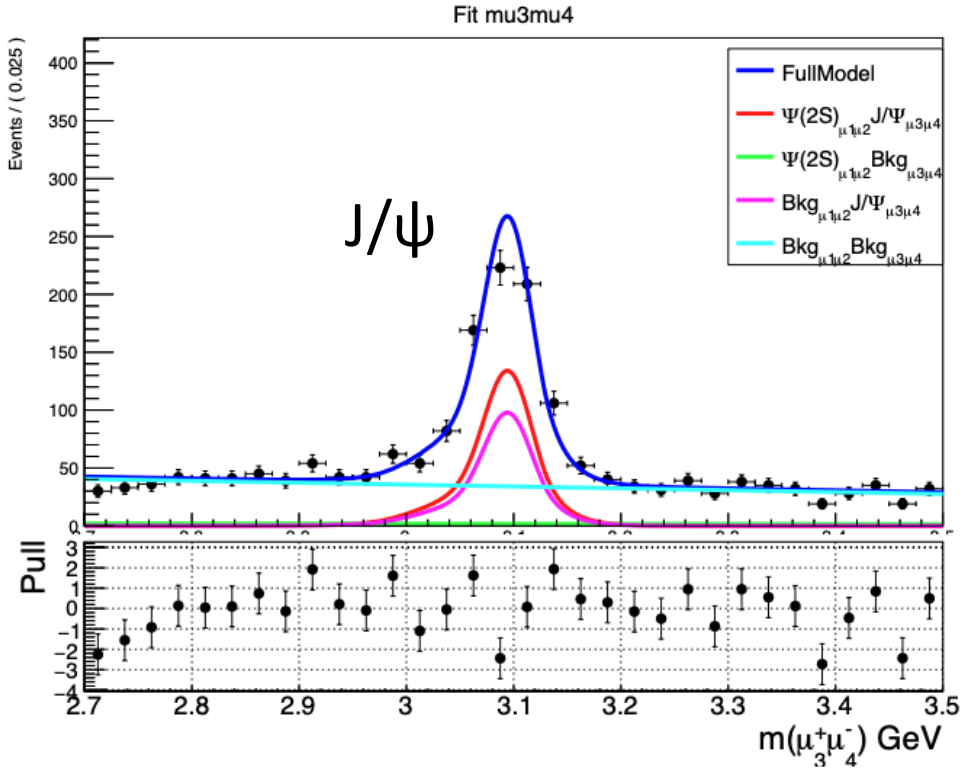
$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \otimes R(M_0)$$
$$+ N_{X\ and\ interf} \cdot |r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2$$
$$+ N_{NRSPS} \cdot f_{NRSPS}(m) + N_{DPS} \cdot f_{DPS}(m)$$
$$+ N_{Feeddown} \cdot f_{Feeddown}(m) + N_{Comb} \cdot f_{Comb}(m),$$

- ✓ **Confirm Run II results with Run III data only**
- ✓ **All states and dips above 5σ !**

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

Two dimensional fit for J/ΨΨ(2S) yield





Run2 + Run3

	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		

S : 3.5x of Run2

B : 6.9x of Run2

[m(J2s)<15 GeV]

Slight difference
if in signal mass window

- Constrain mass & width of both peaks within 1σ of J/ψJ/ψ values

Model I: X(6900) & X(7100) with interference (NLL = -2056.83):
Contents: X(6900) + X(7100) Interf. + Background
Floating Params (7) : Number of NRSPS, number of DPS, number of combinatorial bkg, number of X(6900)X(7100), amplitude of X(7100), phi angle of X(7100), p2 of NRSPS
Constrained Params (4, regarded as fixed) : Mass of X(6900) & X(7100), width of X(6900) & X(7100)

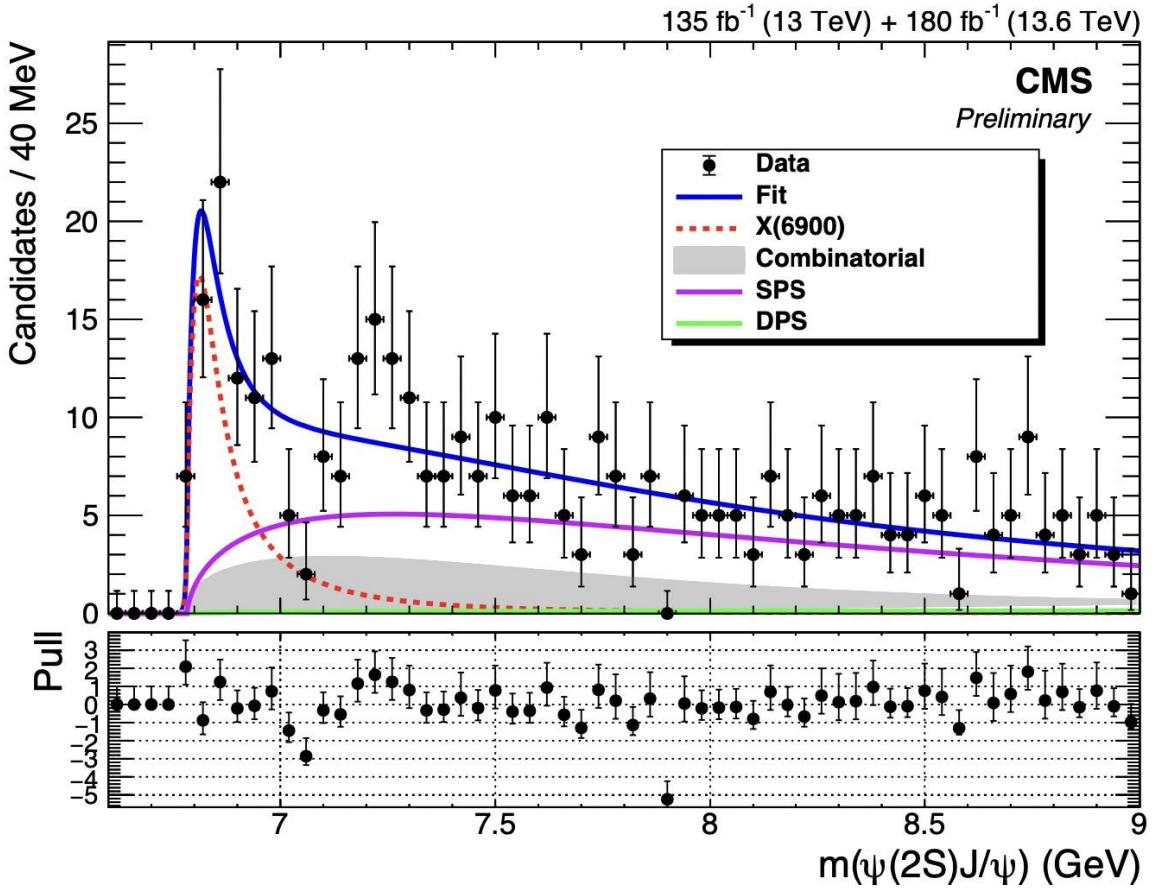
Model II: X(6900) only (NLL = -2045.87):
Contents: X(6900) + Background
Floating Params (5) : Number of NRSPS, number of DPS, number of combinatorial bkg, number of X(6900), p2 of NRSPS
Constrained Params (2, regarded as fixed) : Mass of X(6900), width of X(6900)

Model III: X(7100) only (NLL = -2021.63):
Contents: X(7100) + Background
Floating Params (5) : Number of NRSPS, number of DPS, number of combinatorial bkg, number of X(7100), p2 of NRSPS
Constrained Params (2, regarded as fixed) : Mass of X(7100), width of X(7100)

- Model I vs III
  - Degrees of freedom = 2
  - $\chi^2 = 2 * \Delta NLL$
  - Significance of X(6900) = 8.1 σ
- Model I vs II
  - Degrees of freedom = 2
  - $\chi^2 = 2 * \Delta NLL$
  - Significance of X(7100) = 4.3 σ

- Can use J/ψψ(2S) to make independent mass & width measurements?

- An independent measurement: 1BW - X(6900)

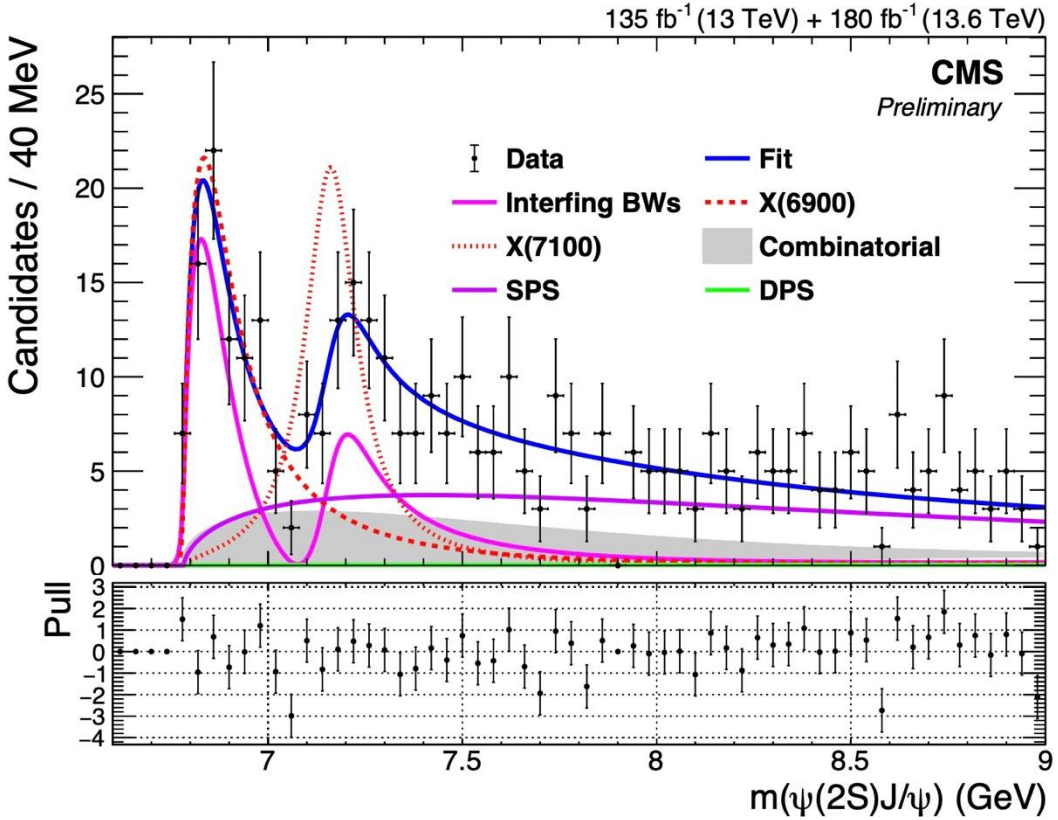


Parameter	Value
Mass of X(6900) (MeV)	6836^{+19}_{-15}
Width of X(6900) (MeV)	151^{+122}_{-52}

- NLL = -2040
- X(6900)
  + NRSPS + DPS + Comb.
- Fit range : 6.6 -- 15 GeV

(J/ψJ/ψ mass/width constraints removed)

- An independent measurement: 2BW (Interference) - X(6900)&X(7100)



Parameter	Value
Mass of X6900 (MeV)	6876^{+46}_{-29}
Mass of X7100 (MeV)	7169^{+26}_{-52}
Width of X6900 (MeV)	253^{+285}_{-101}
Width of X7100 (MeV)	154^{+112}_{-82}

- NLL = -2045.55
- Interfering X(6900) & X(7100)
  + NRSPS + DPS + Comb.
- Fit range : 6.6 -- 15 GeV

(J/ψJ/ψ mass/width constraints removed)