Observation of X(6900) and evidence of X(7100) in the J/ψψ(2S) → μ+μ−μ+μ− mass spectrum

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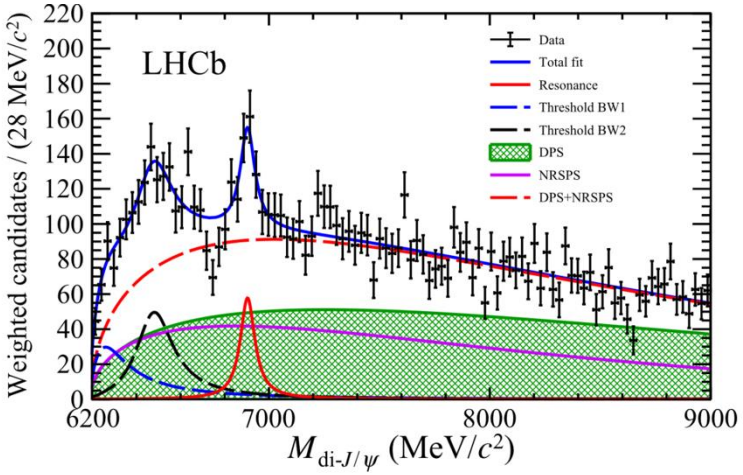
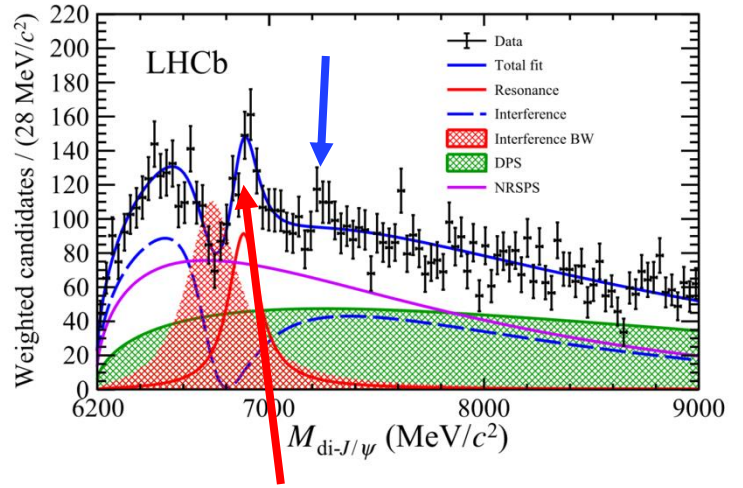
- Motivation
- Dataset samples
- Event selection
- Fitting models and results
- Summary

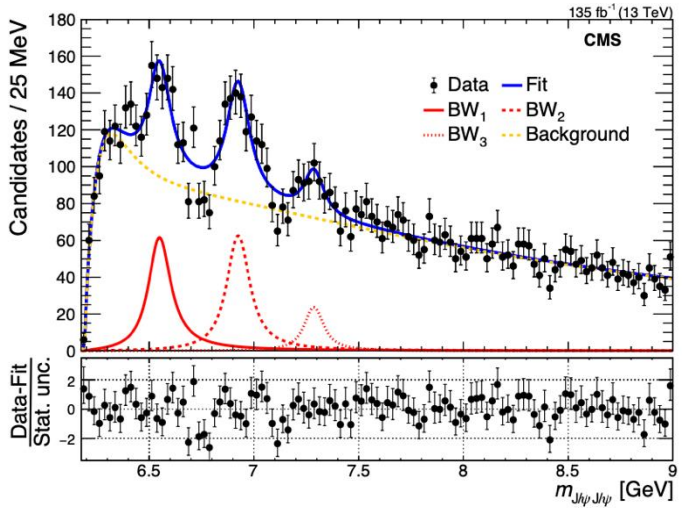
LHCb : Sci.Bull.65(2020)1983

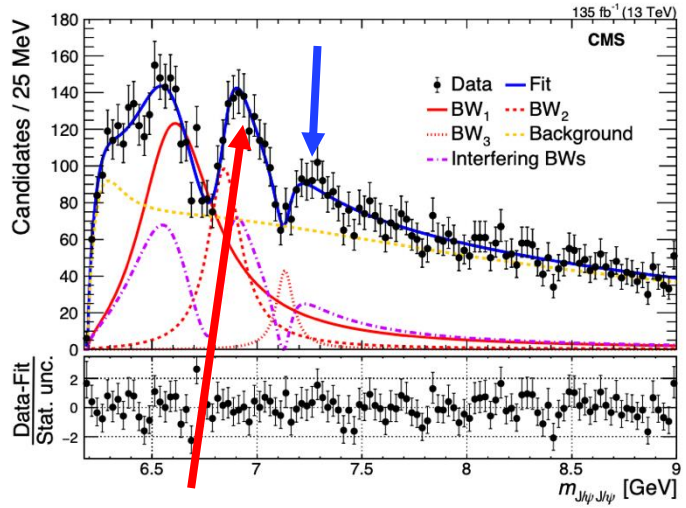




- Observed structure at 6.9 GeV, > 5σ
- M ~ 6900 MeV, Γ ~ 100 MeV

CMS : Phys. Rev. Lett. 132, 111901

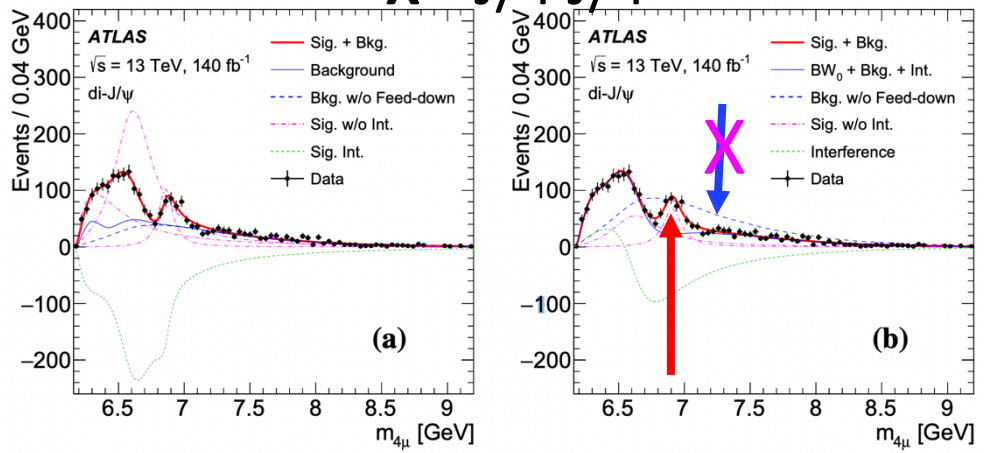




- X(6900) consistent with LHCb
- New state X(6600) with 6.5σ
- Evidence of X(7100) with 4.1σ

ATLAS : Phys. Rev. Lett. 131, 151902

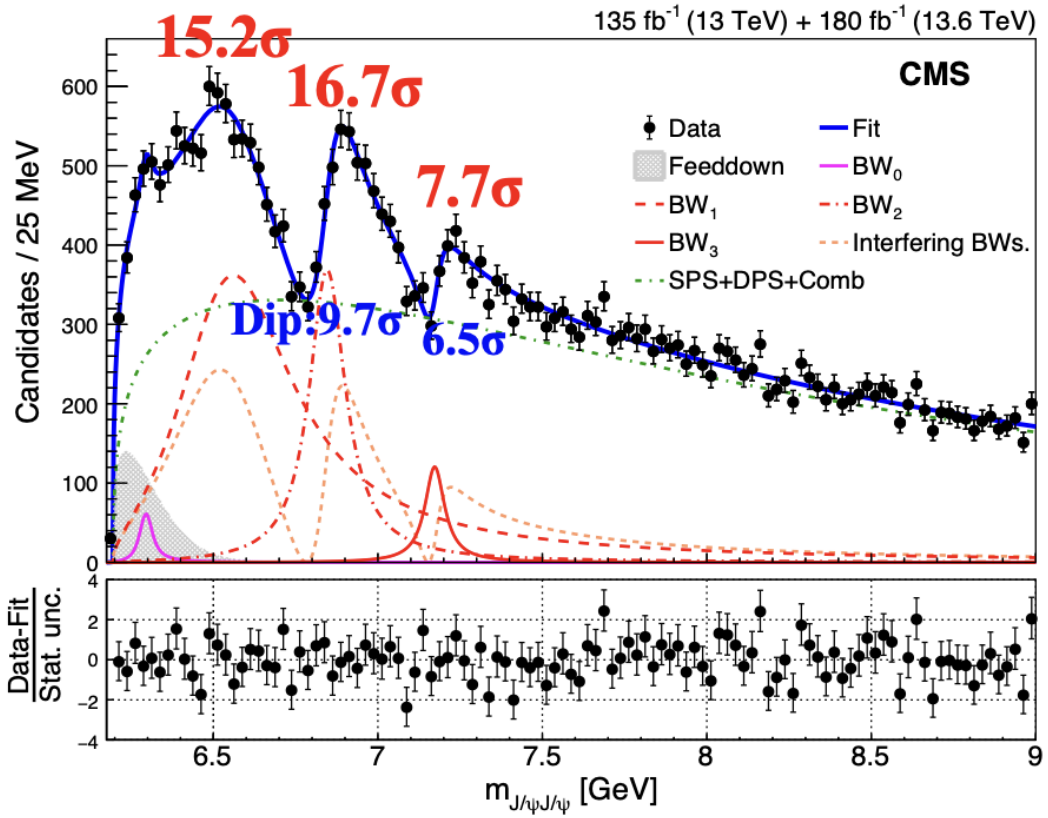
X→J/ΨJ/Ψ

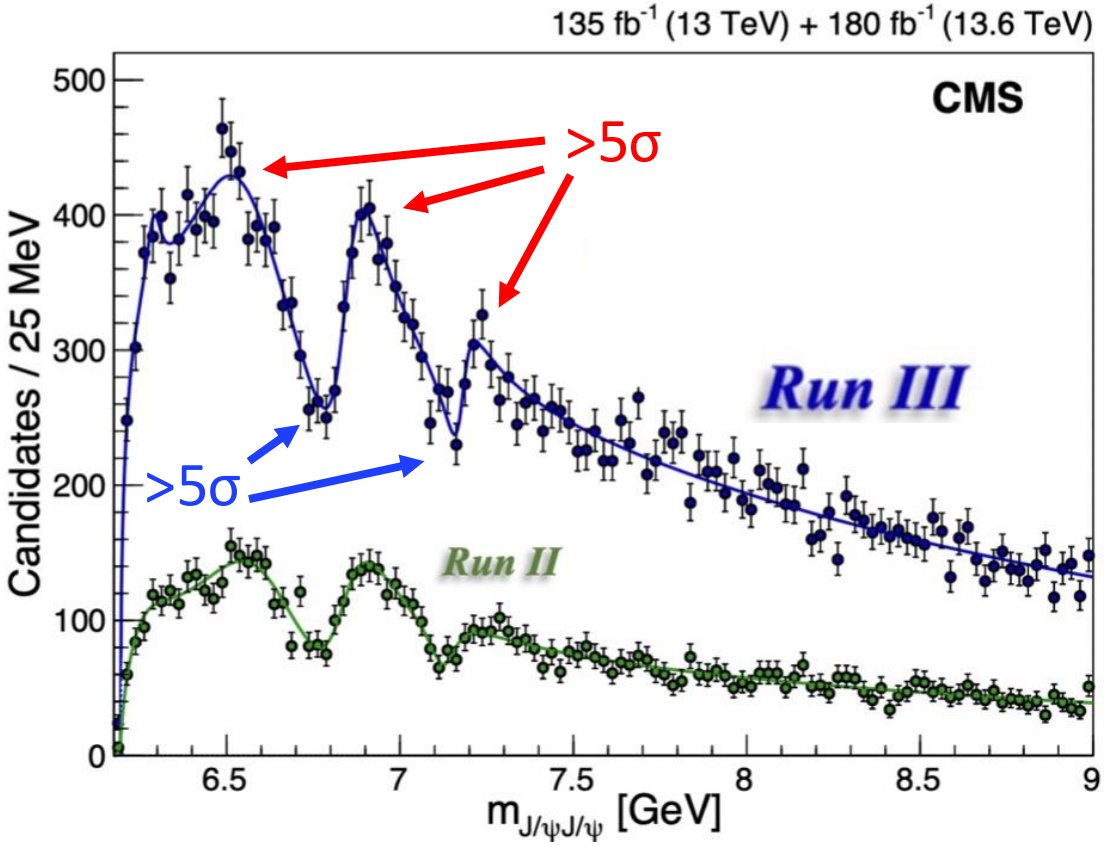


- X(6900) consistent with LHCb

- 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: other channels?

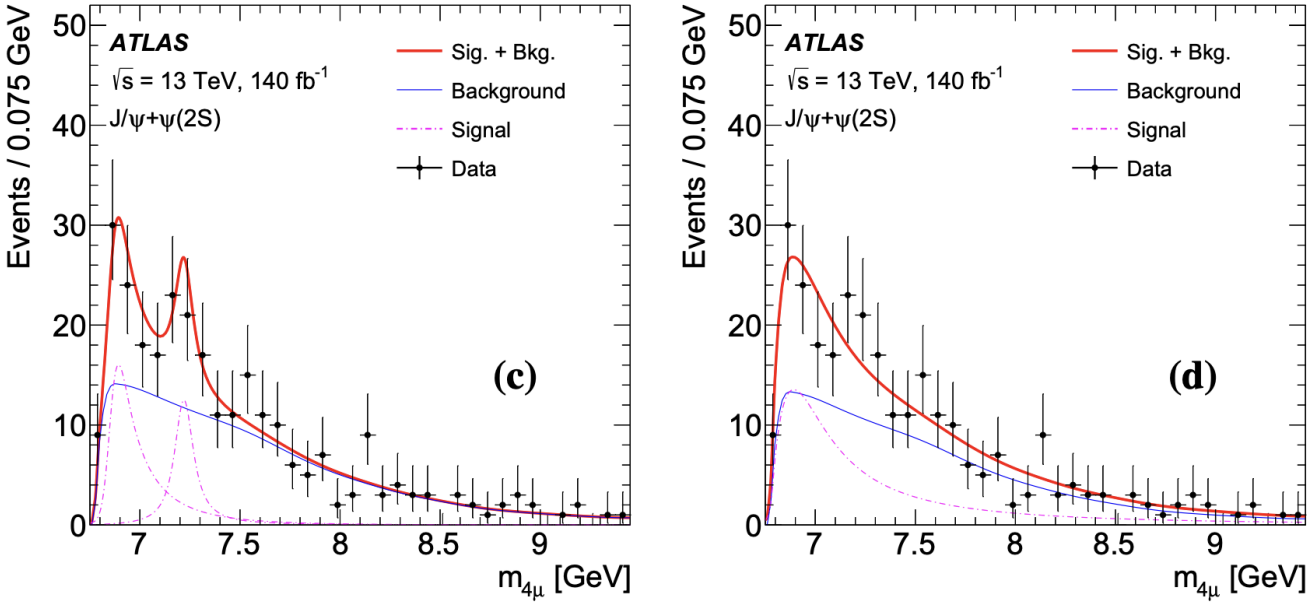
CMS : BPH-24-003





- CMS established candidates for all-charm tetra-quark family
- Each peak and each dip is well over 5σ in complete dataset
- This defines our model: two peaks with interference

X→J/ΨΨ(2S)



ATLAS : Phys. Rev. Lett. 131, 151902

- If seen in J/ψ/J/ψ, probably in ψ(2S)J/ψ?
- Possibility of non-resonant "threshold effects"?
- X(6900) is just above threshold

- ATLAS has published spectrum
- They do see excess
  - LEFT: Assumed X(6900) with J/ψ/J/ψ values (4.7σ) & find weak X(7100) signal (3σ local)
  - ATLAS compatible with CMS no-interf fit
  - RIGHT: One BW fit -- very fat!
    NOT very consistent with X(6900) (4.3σ)
- ***Is excess X(6900)?*** ATLAS doesn't actually claim it!

- ***Can we see it? Can CMS clarify??***

Dataset samples

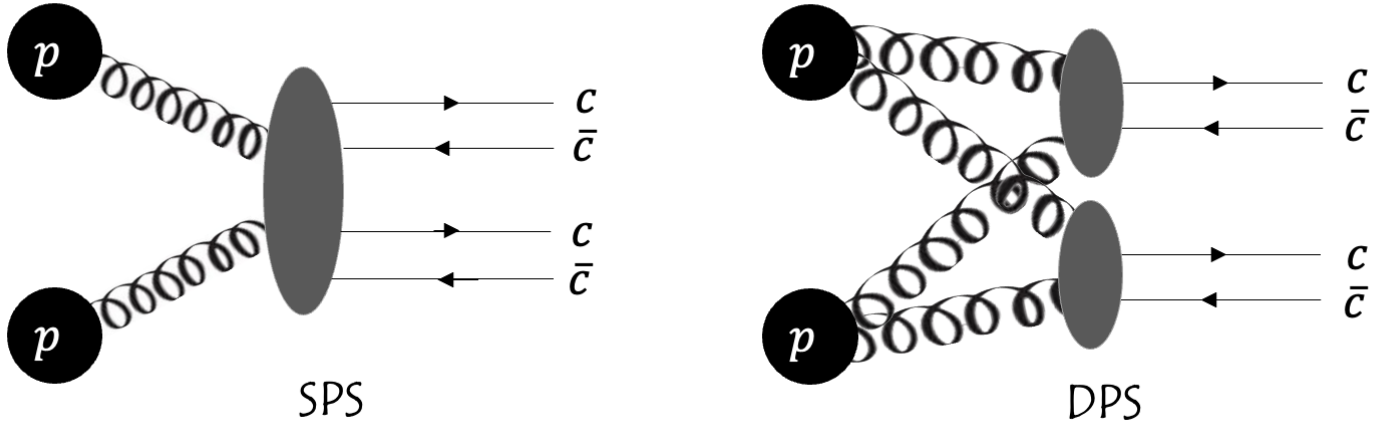
- Charmonium dataset
- 135 fb^{-1} CMS data taken in 2016, 2017 and 2018 LHC runs (13 TeV)
  - 2017B excluded due to improper trigger
- 180 fb^{-1} CMS data taken 2022, 2023 and 2024 LHC runs (13.6 TeV)

} 315 fb^{-1}

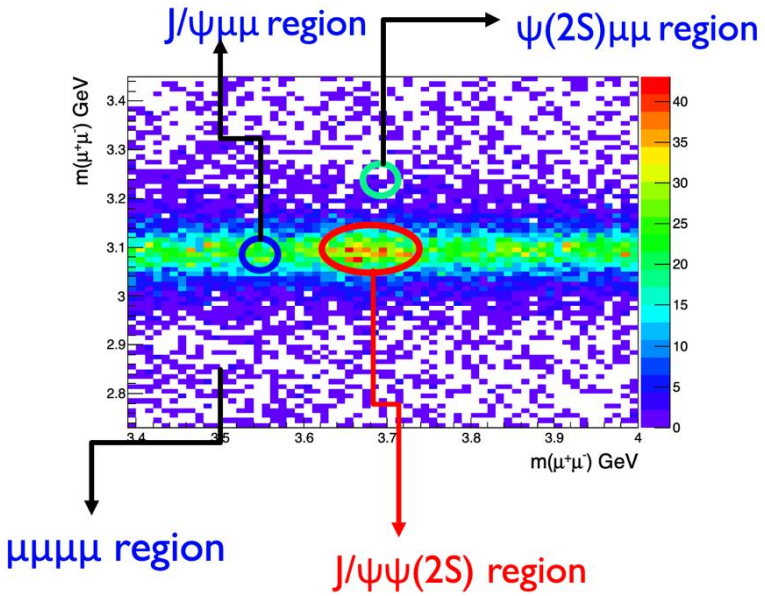
- Using J/ψJ/ψ selection as first step
- Preliminary event selections:
  - Fire trigger
  - Standard soft muon ID
  - pT(μ) ≥2.0 GeV
  - |η（μ）| ≤2.4
  - 4μ total charge = 0
  - Vtx(4μ) ≥ 0.5%
  - Vtx(μ+μ-)≥ 0.5% (HLT)
  - m(μ+μ-) within 3σ (EBE) of J/ψ or ψ (2S),scale factor 1.16
  - m(μ+μ-) constraited to J/ψ or ψ (2S) mass
  - Resolve pairing confusion using mass chisq

- Background
  - Single Parton Scattering (NRSPS) to $J/\psi\psi(2S)$ sample by Pythia8
  - Double Parton Scattering (DPS) to $J/\psi\psi(2S)$ sample by Pythia8

- Signal
  - $gg \rightarrow X \rightarrow J/\psi\psi(2S)$ by JHUGen - Default
  - $gg \rightarrow X \rightarrow J/\psi\psi(2S)$ by Higgs model in Pythia - Systematic



Two-dimensional fit



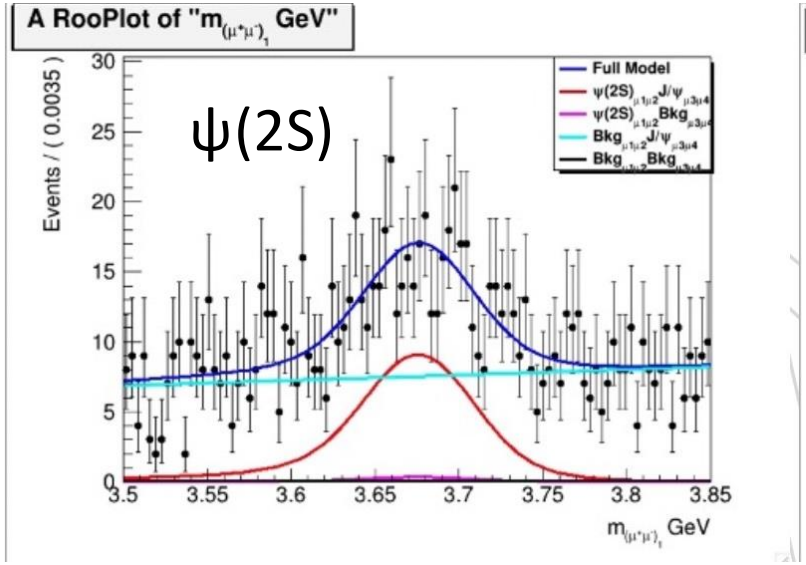
4 components for 2D fit:

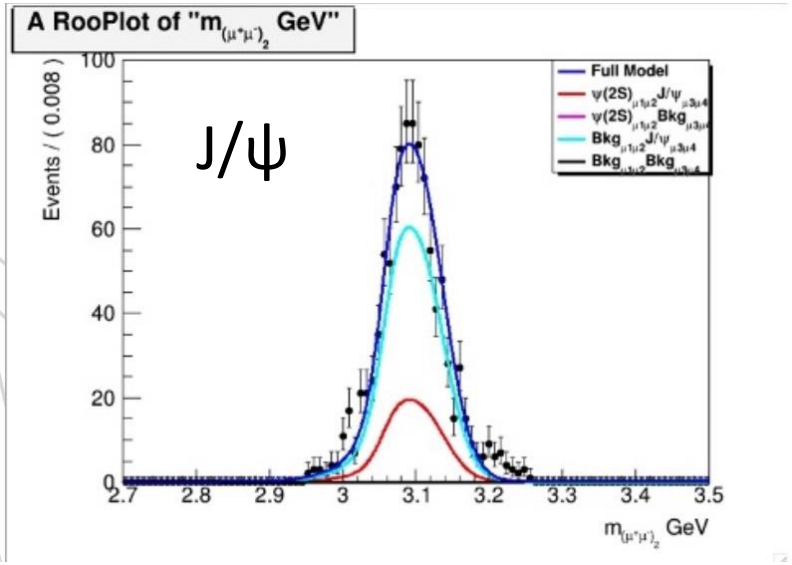
J/ψ+ψ(2S) : product of 2 Crystal-Ball functions for each resonance

J/ψ+$\mu^+\mu^-$: product of 2 Crystal-Ball functions and 1st order polynomial

ψ(2S)+$\mu^+\mu^-$: product of 2 Crystal-Ball functions and 1st order polynomial

Nonresonant: $\mu^+\mu^-\mu^+\mu^-$: product of 2x 1st order polynomial





Optimization procedure

Optimize X(6900) signal (JHUgen) (though model dependent)

- Defined signal mass window (6.7 ~ 7.1 GeV)
- Use $f = S/(463/13 + 4\sqrt{B} + 5\sqrt{25 + 8\sqrt{B} + 4B})$ as FOM
- S from X(6900) MC
- B from data
- Not need to do normalization

Variables	Previous cuts	Optimized cuts
$p_T(\psi(2S))$	-	> 13.5 GeV
$p_T(J/\psi)$	-	> 11 GeV
p_T (μ) from $\psi(2S)$	> 2 GeV	> 2.5 GeV
Muon ID of $\psi(2S)$	2 soft μ	2 loose μ
$\psi(2S)$ mass window	-	$< 2.5\sigma$
J/ψ mass window	-	$< 2.5\sigma$

Procedure:

- Optimize one variable at a time
- Cycle through all variables
- From "optimal point" iterate new optimization cycle
- Iterate until stable
- To avoid over-optimizing on fluctuations:

  try to round final optimum to 0.5 GeV increments

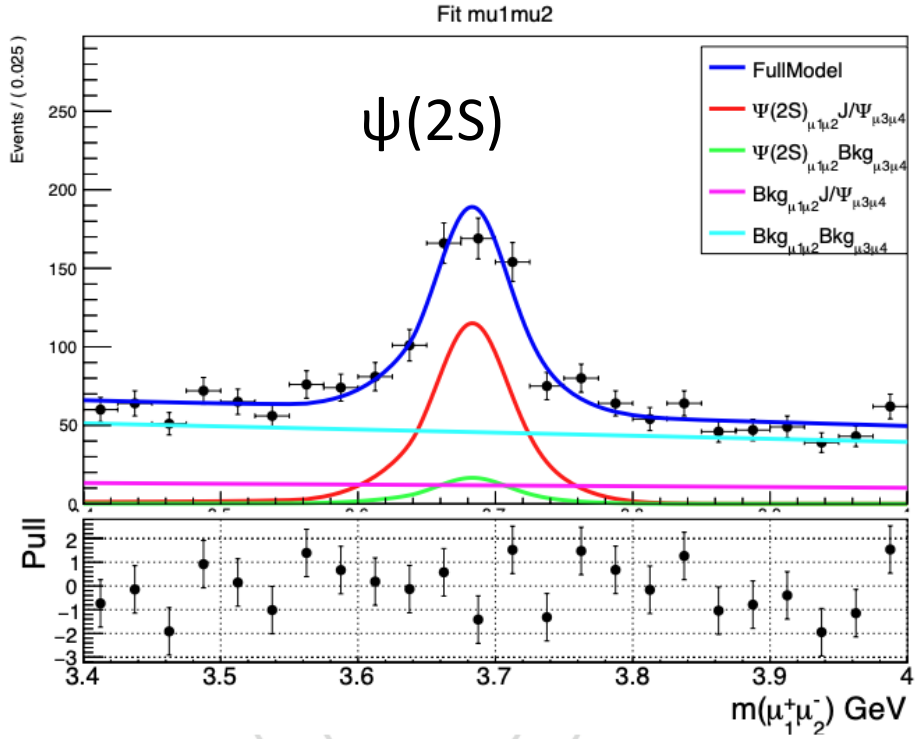
- Same cuts for Run2 and Run3 data except triggers

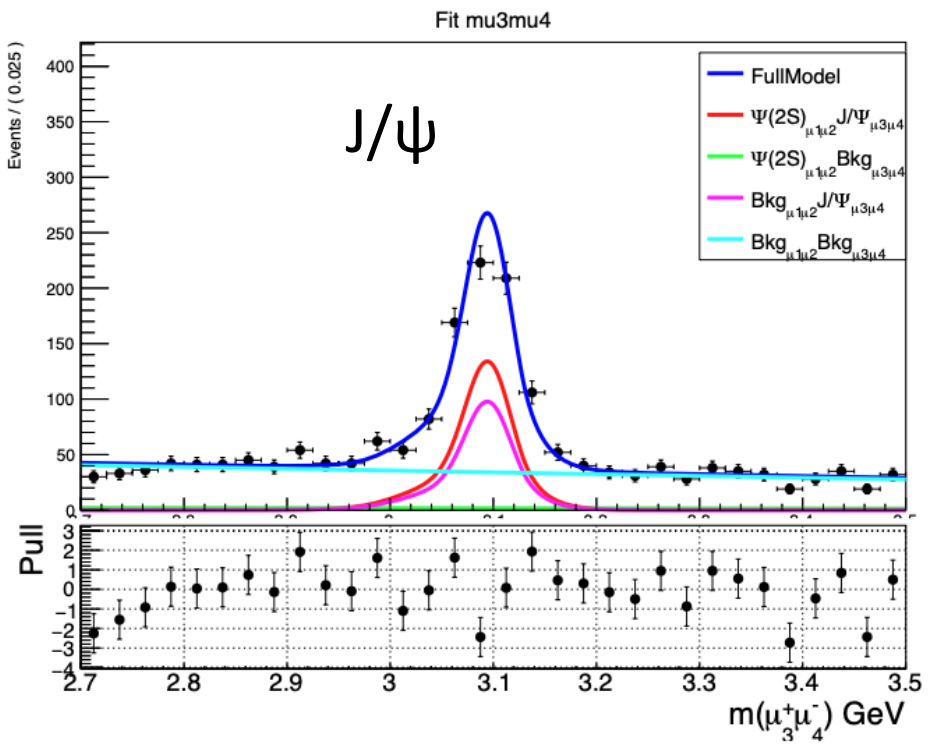
- Single muon from J/ψ:
  - Soft muon ID
  - $p_{T(muon\quad from\quad J/\psi)}$ >3.5 GeV
- Single muon from $\psi(2S)$:
  - Loose muon ID
  - $p_{T(muon\quad from\quad \psi(2S))}$ >2.5 GeV

- 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.

Two-dimensional fit





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 [m(J2s)<15 GeV]

B : 6.9x of Run2

Slight difference
if in signal mass window

- Same signal function as $J/\psi J/\psi$ analysis (Relativistic Breit-Wigner)

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

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

✓ Non-interference model:

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

✓ Interference model:

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

- $R(M_j)$ & $\epsilon(M_j)$: resolution & efficiency at M_j
- $f_{SPS}, f_{DPS}, f_{combinatorial}$: shapes of SPS, DPS and combinatorial background
- BW: relativistic Breit-Wigner
- r_k, ϕ_k: coupling magnitude and relative phase of interfering Breit-Wigner
- Resolution and efficiency included in the default model

Significance calculation

- 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)

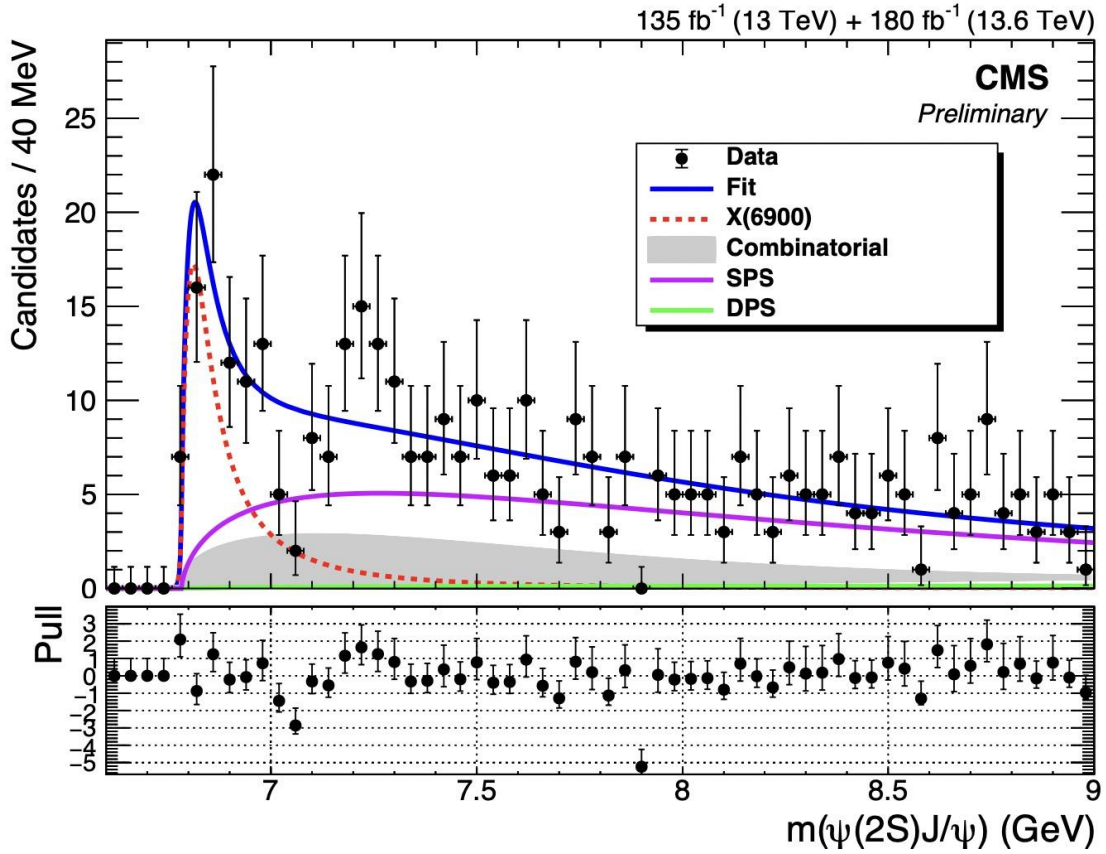
Model II: X(6900) only (NLL = -2045.87):
Contents: X(6900) + Background
Floating Params (5) : Number of NRSPS, number of DPS, number of combinatorial bkg, number of X(6900), p2 of NRSPS
Constrained Params (2, regarded as fixed) : Mass of X(6900), width of X(6900)

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
  - χ^2 = 2 * ΔNLL
  - Significance of X(6900) = 8.1 σ
- Model I vs II
  - Degrees of freedom = 2
  - χ^2 = 2 * ΔNLL
  - Significance of X(7100) = 4.3 σ

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

Independent measurement - 1BW - X(6900)

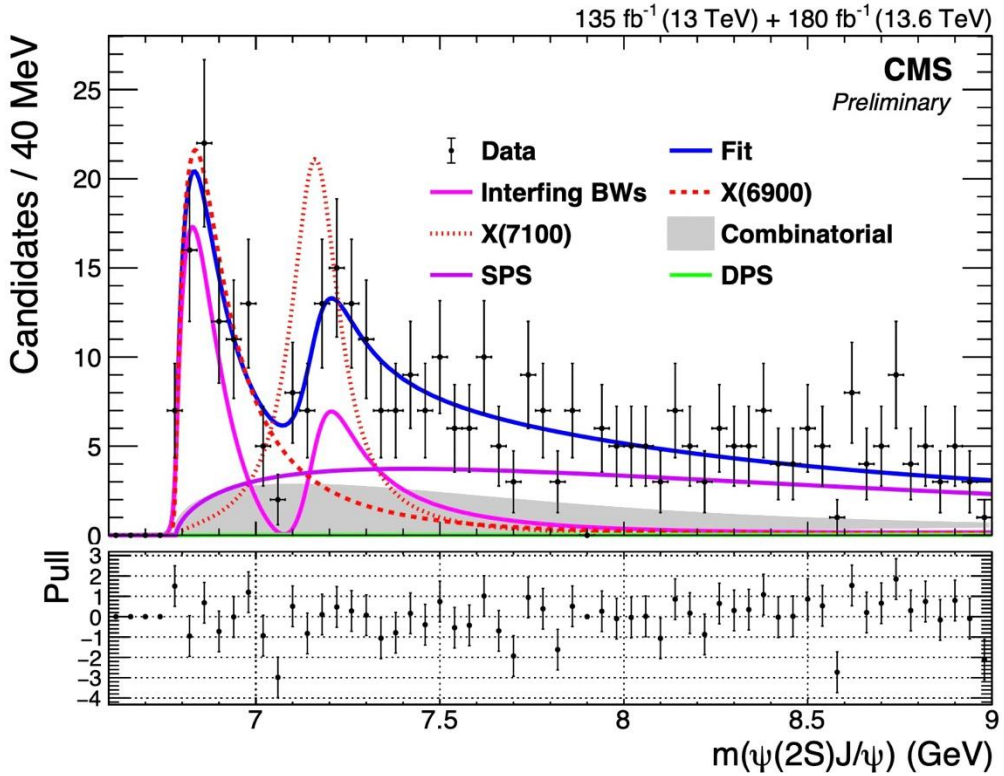


Parameter	X(6900) Mass (MeV)	X(6900) Width (MeV)
Value	6836^{+19}_{-15}	151^{+122}_{-52}

- NLL = -2040
- Signal: X(6900)
- Background: NRSPS, DPS, Comb bkg
- Fit range : 6.6 - 15 GeV

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

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



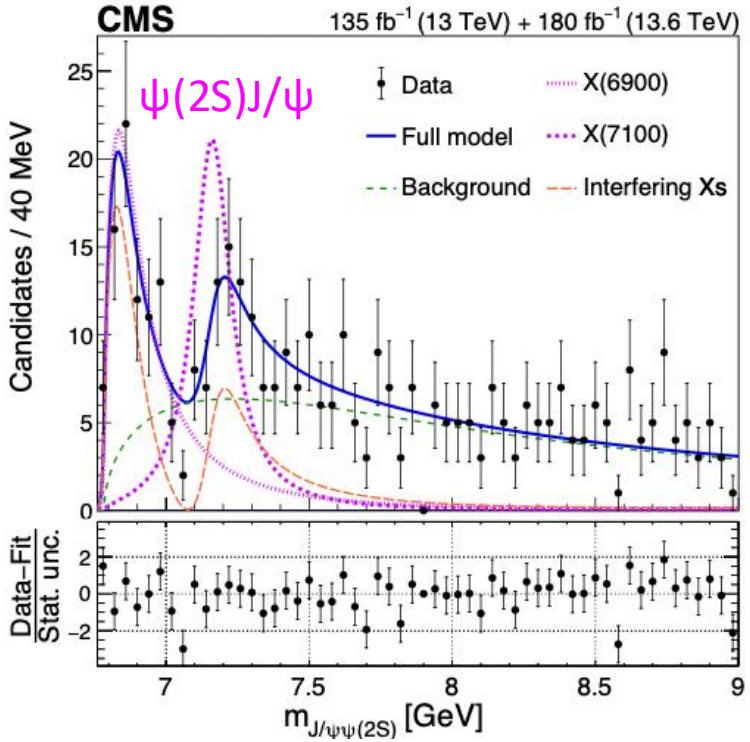
(J/ψJ/ψ mass/width constraints removed)

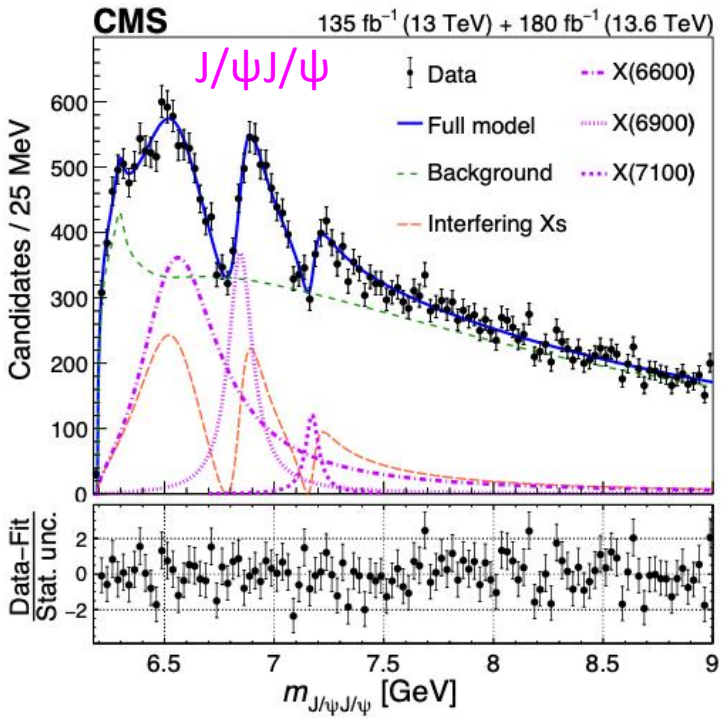
Parameter	X(6900) Mass (MeV)	X(6900) Width (MeV)
Value	6876^{+46}_{-29}	253^{+285}_{-101}

Parameter	X(7100) Mass (MeV)	X(7100) Width (MeV)
Value	7169^{+26}_{-52}	154^{+112}_{-82}

- NLL = -2045.55
- Signal: X(6900) & X(7100)
- Background: NRSPS, DPS, Comb bkg
- Fit range : 6.6 - 15 GeV

Comparison to J/ψJ/ψ analysis





		X(6600)	X(6900)	X(7100)
J/ψ J/ψ: Run 2 [15]	Mass	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Width	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}
J/ψ J/ψ: Run 2+3	Mass	$6593^{+15}_{-14} \pm 25$	$6847 \pm 10 \pm 15$	$7173^{+9}_{-10} \pm 13$
	Width	$446^{+66}_{-54} \pm 87$	$135^{+16}_{-14} \pm 14$	$73^{+18}_{-15} \pm 10$
J/ψ ψ(2S): Run 2+3	Mass	—	$6876^{+46+111}_{-29-112}$	7169^{+26+80}_{-52-72}
	Width	—	$253^{+290+140}_{-100-134}$	$154^{+110+140}_{-82\ -181}$

- Mass of both peaks consistent
- Width of both peaks consistent

- Do systematic for interference model with X(6900) & X(7100)
- Variations are below

❑ Signal Shape

- Default: BW function with L=0
- Alternative:
  - L=1/2, d=2/3/4
  - Flatte

❑ SPS shape

- $func_{default}(SPS) \rightarrow func_{default}(DPS)$

❑ DPS shape

- $func_{default}(DPS) \rightarrow func_{default}(SPS)$

❑ Combinatorial backgroud shape

- Nine-tile -> sPlot

❑ Mass resolution

- Take extremes of mass resolution dependence

❑ Efficiency

- Increase/Decrease the weight of Run3 efficiency

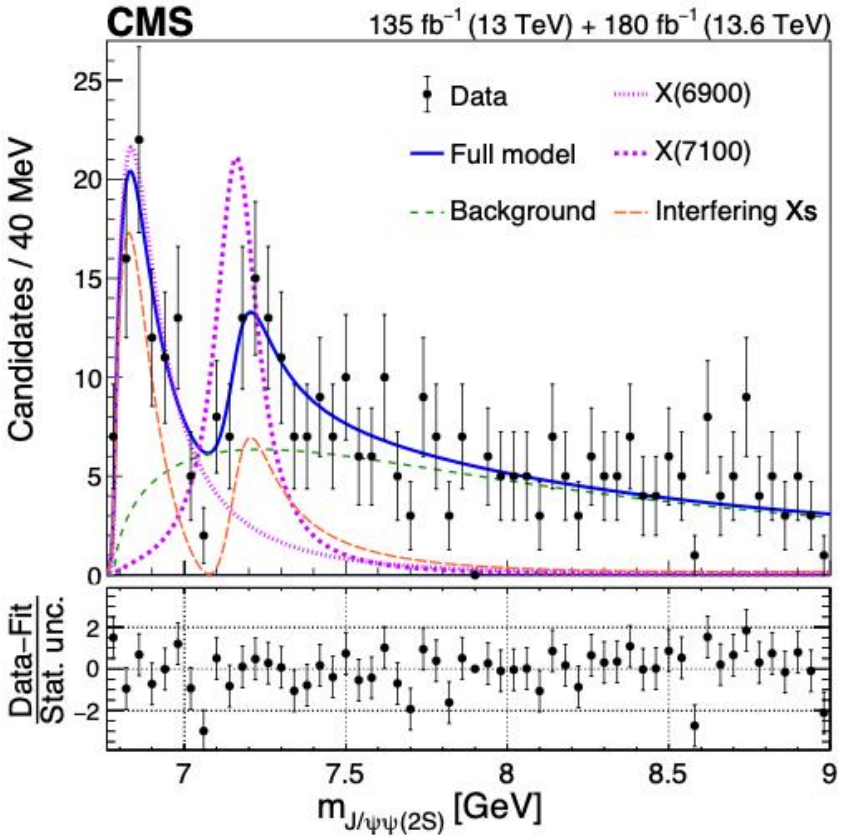
❑ Add X(6600) tail

- X(6600) mass/width/coef fixed to J/ψJ/ψ fit values

❑ Fitter bias

- Toy MC

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



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	Width	$446^{+66}_{-54} \pm 87$	$135^{+16}_{-14} \pm 14$	$73^{+18}_{-15} \pm 10$
$J/\psi\,\psi(2S)$: Run 2+3	Mass	—	$6876^{+46+111}_{-29-112}$	7169^{+26+80}_{-52-72}
	Width	—	$253^{+290+140}_{-100-134}$	$154^{+110+140}_{-82-181}$

	X(6900)		X(7100)	
Source	Δm	$\Delta\Gamma$	Δm	$\Delta\Gamma$
Signal shape	29	79	22	131
NRSPS shape	14	54	14	29
Comb. bkg. shape	15	51	15	20
Mass resolution	5	7	5	9
Efficiency	7	27	7	10
Fitter bias	$^{+16}_{-17}$	$^{+83}_{-72}$	$^{+41}_{-22}$	$^{+3}_{-115}$
X(6600) addition	104	14	61	31
Total uncertainty	$^{+111}_{-112}$	$^{+140}_{-134}$	$^{+80}_{-72}$	$^{+140}_{-181}$

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

- An excess observed in $\psi(2S)J/\psi$ channel [Significance: BW2 (8.1σ), BW3 (4.3σ)]

With interference:

$$\mathrm{BW2}: m = 6876\,^{+46}_{-29}(stat)\,^{+111}_{-112}(syst)\ MeV, \Gamma = 253\,^{+290}_{-100}(stat)\,^{+140}_{-134}(syst)\ MeV$$

$$\mathrm{BW3}: m = 7169\,^{+26}_{-52}(stat)\,^{+80}_{-72}(syst)\ MeV,\ \ \Gamma = 154\,^{+110}_{-82}(stat)\,^{+140}_{-181}(syst)\ MeV$$

- Consistent with interfering X(6900) and X(7100) as observed in $J/\psi J/\psi$ analysis

THANKS!

BACKUP