

# Observation of multiple structures in the J/ $\psi$ J/ $\psi$ mass spectrum at CMS

<https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-003/index.html>

<https://cms.cern/news/cms-observes-potential-family-tetra-quark-states-composed-only-charm-quarks>



Zhen Hu  
on behalf of the CMS Collaboration

[Exotic Hadron Spectroscopy 2023@Durham University](#)



# the Compact Muon Solenoid detector

3.8T Superconducting Solenoid

Lead tungstate  
E/M Calorimeter (ECAL)

All Silicon Tracker  
(Pixels and Microstrips)

Redundant Muon System  
(RPCs, Drift Tubes,  
Cathode Strip Chambers)

Hermetic ( $|y| < 5.2$ )  
Hadron Calorimeter (HCAL)  
[scintillators & brass]

# the Compact Muon Solenoid detector

3.8T Superconducting Solenoid

Hermetic ( $|\eta| < 5.2$ )  
Hadron Calorimeter (HCAL)  
[scintillators & brass]

Lead tungstate  
E/M Calorimeter (ECAL)

$\eta$  coverage (track & muon): [-2.5, 2.5]

HCAL

ECAL

Hadron  
Calorimeter

Electromagnetic  
Calorimeter

Superconducting  
Solenoid

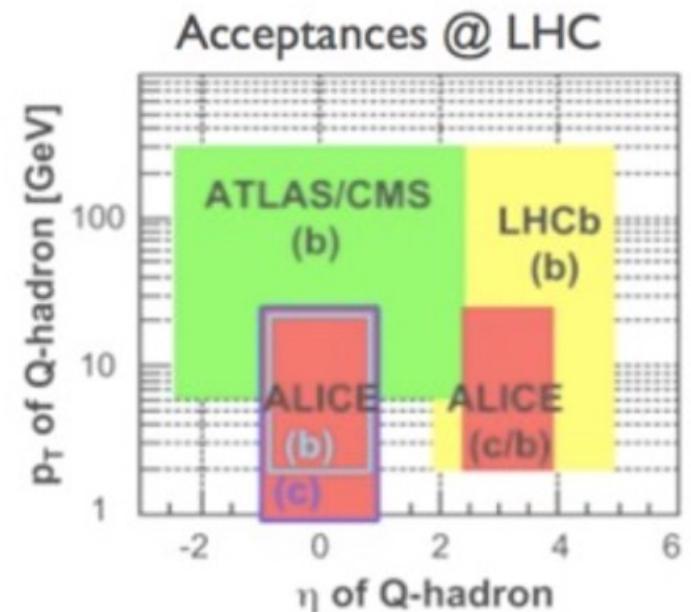
Iron return yoke intersected

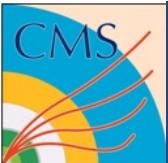
All Silicon Tracker  
(Pixels and Microstrips)

Redundant Muon System  
(RPCs, Drift Tubes,  
Cathode Strip Chambers)

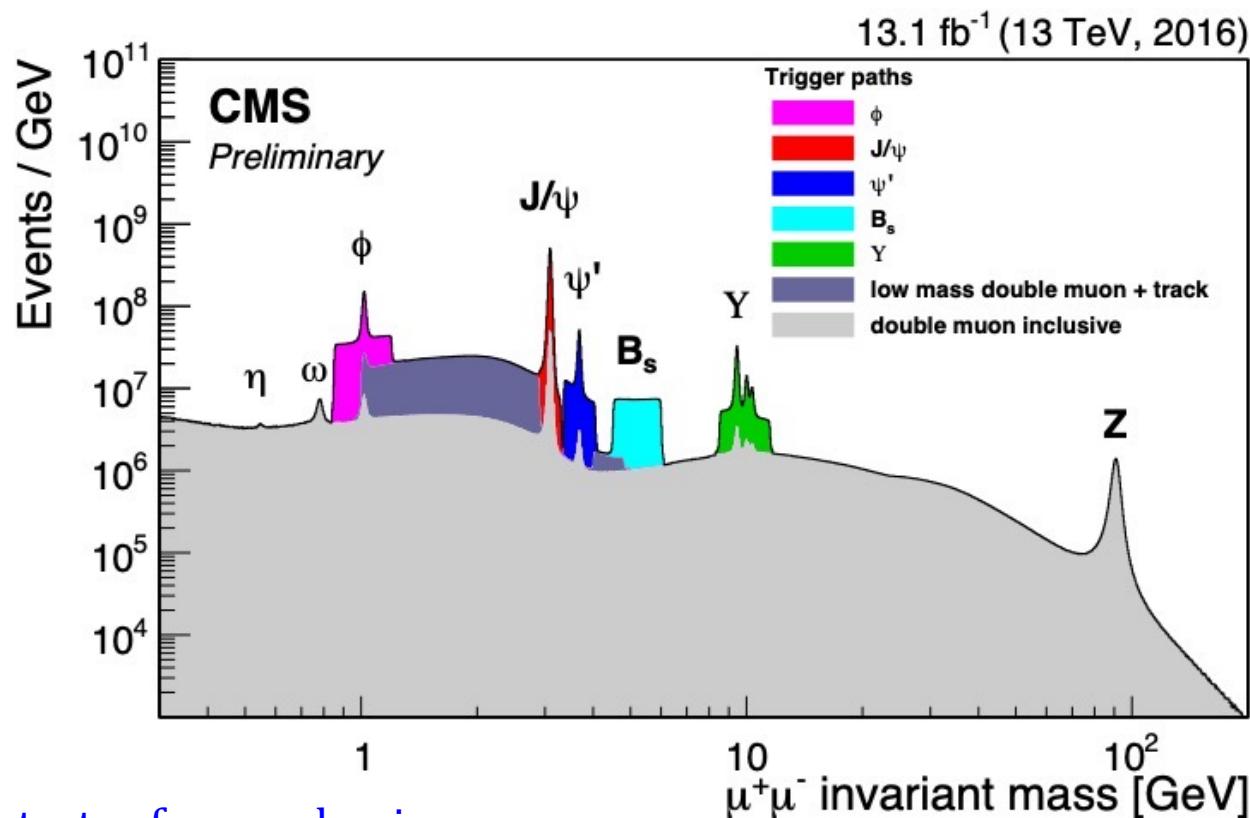
# B physics at CMS

- Better momentum resolution for charged particles, including muons
- vs RHIC
  - better resolution
    - CMS' 1st  $\Upsilon(1S,2S,3S)$  measurements in HI
  - additional detector capability
    - CMS' 1st secondary vertex meas. in HI (eg  $b \rightarrow J/\psi$ )
- vs ALICE
  - complementary acceptance (ALICE access low-pt)
  - CMS better resolution
- vs Tevatron experiments
  - extend kinematic ( $p_T, y$ ) acceptance
- vs ATLAS
  - more flexible trigger, lower  $p_T$  threshold
- vs LHCb
  - complementary acceptance, LHCb great particle ID
  - higher luminosity





# Dimuon at CMS & trigger



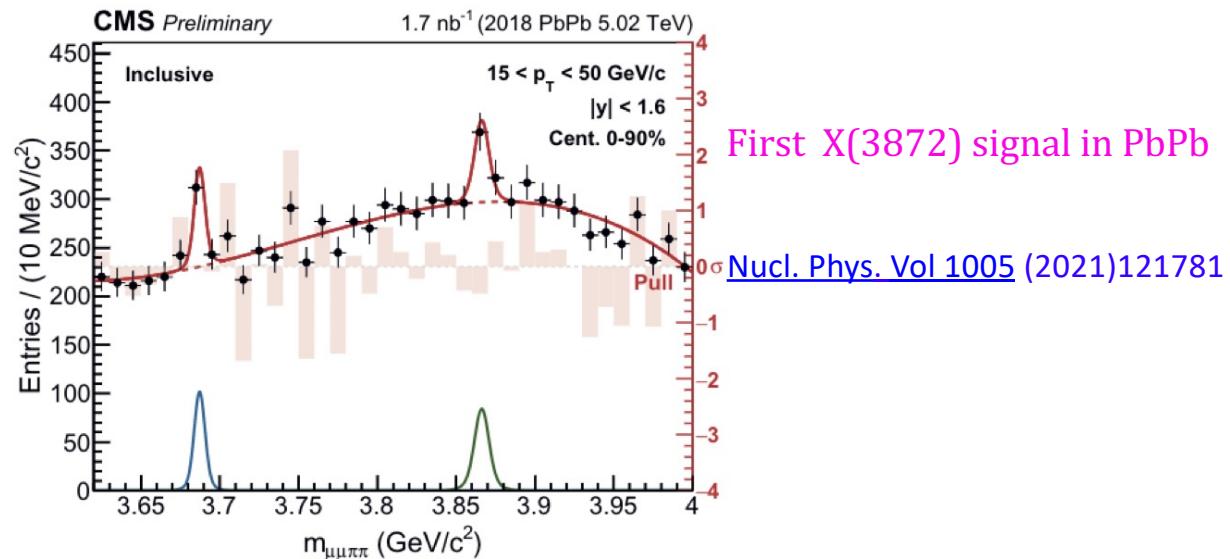
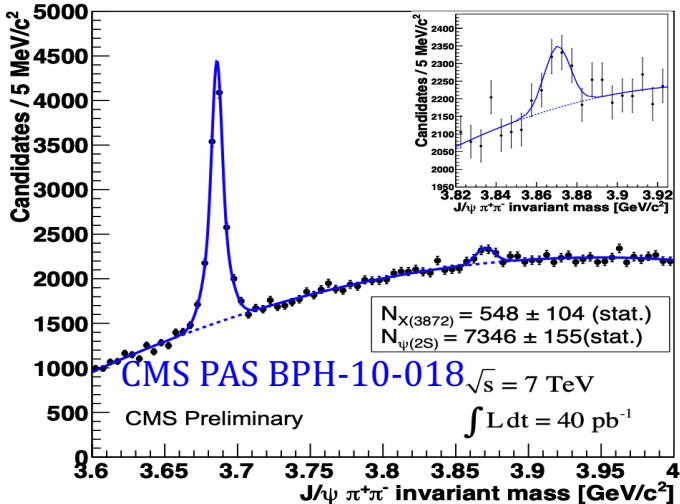
Excellent detector for quarkonium

- Muon system
  - High-purity muon ID,  $\Delta m/m \sim 0.6\%$  for  $J/\psi$
- Silicon Tracking detector,  $B=3.8\text{T}$ 
  - $\Delta p_T/p_T \sim 1\%$  & excellent vertex resolution
- Special triggers for different analyses at increasing Inst. Lumi.
  - $\mu p_T$ ,  $(\mu\mu) p_T$ ,  $(\mu\mu)$  mass,  $(\mu\mu)$  vertex, and additional  $\mu$

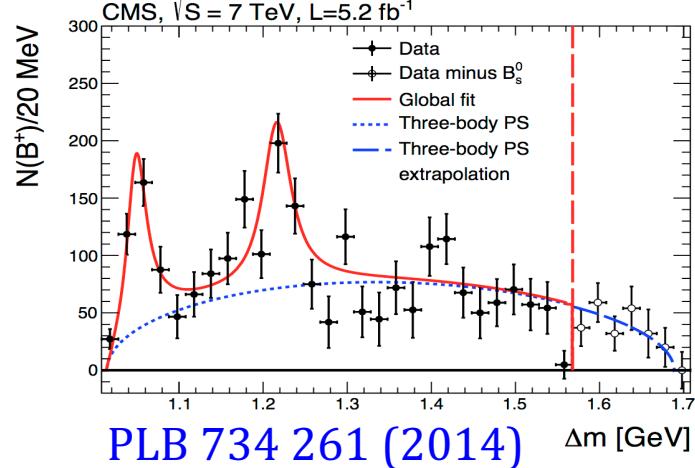


# Selected CMS contributions to heavy exotic states

First LHC experiment re-discovered X(3872)



First confirmation of Y(4140)



<https://www.nikhef.nl/~pkoppenb/particles.html>

CMS played the following leading roles:

- First LHC experiment to see X(3872)
- First experiment to see X(3872) in  $B_s^0$  decay
- First experiment to see X(3872) in PbPb data
- First LHC experiment to see new exotic hadrons (Y(4140))

# New Domain of Exotics: All-Heavy Tetra-quarks

- First mention of 4c states at 6.2 GeV (1975)
  - Just one year after the discovery of  $J/\psi$

We expect at least three exotic mesons with hidden charm,  $c\bar{c}(p\bar{p}-n\bar{n})$  [between  $3.7 \sim 4.1$  GeV],  $c\bar{c}\lambda\bar{\lambda}$  [ $\sim 4.1$  GeV] and  $c\bar{c}c\bar{c}$  [ $\sim 6.2$  GeV], to which we refer as  $\psi_1$ ,  $\psi_2$  and  $\psi_3$  respectively. [W. E. Casper et al., Phys. Rev. Lett. 30, 1261 (1973)]

Progress of Theoretical Physics, Vol. 54, No. 2, August 1975

## A Possible Model for New Resonances

—Exotics and Hidden Charm—

Yoichi IWASAKI

Research Institute for Fundamental Physics  
Kyoto University, Kyoto

(Received January 20, 1975)

- First calculation of 4c states (1981): Z. Phys. C 7 (1981) 317

$L$	$S$	$J^{PC}$	Mass (GeV)
1	0	$1^{--}$	6.55
	1	$0^{-+}, 1^{-+}, 2^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}$	
2	0	$2^{++}$	6.78
	1	$1^{+-}, 2^{+-}, 3^{+-}$	
	2	$0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}$	
3	0	$3^{--}$	6.98
	1	$2^{-+}, 3^{-+}, 4^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

$$(cc)_3^* - (\overline{cc})_3$$

$$(cc)_6 - (\overline{cc})_6^*$$

$L$	$S$	$J^{PC}$	Mass (GeV)
1	0	$1^{--}$	6.82
2	0	$2^{++}$	7.15
3	0	$3^{--}$	7.41

- A different exotic system compared to exotics with light quarks



# J/ $\psi$ J/ $\psi$ events—first evidence (1982)

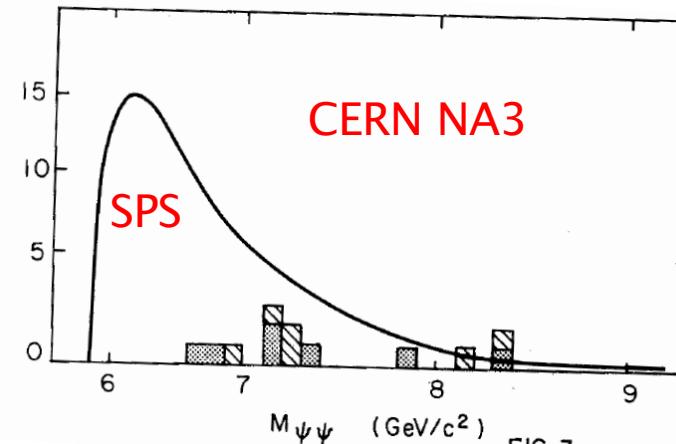
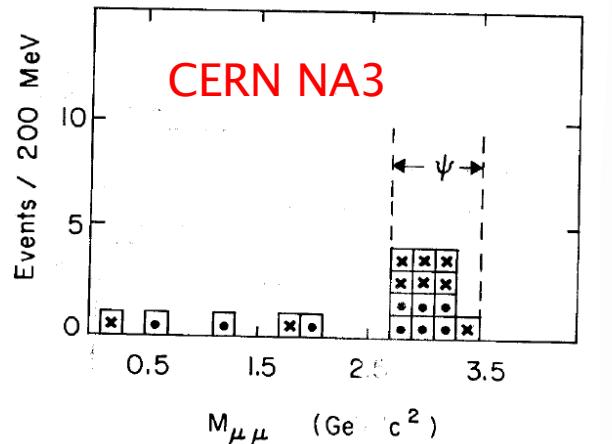
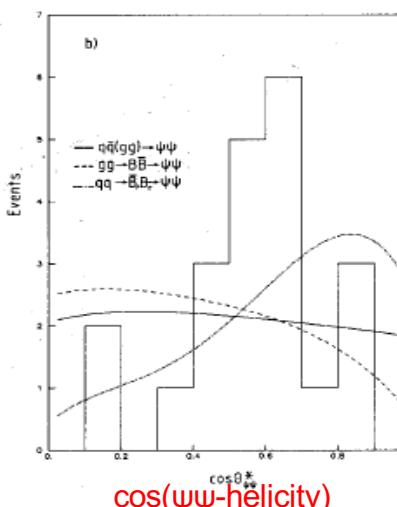
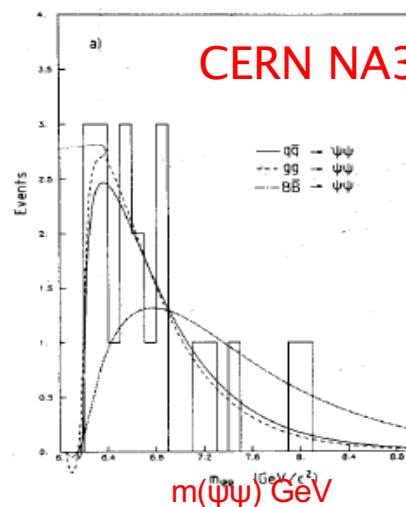
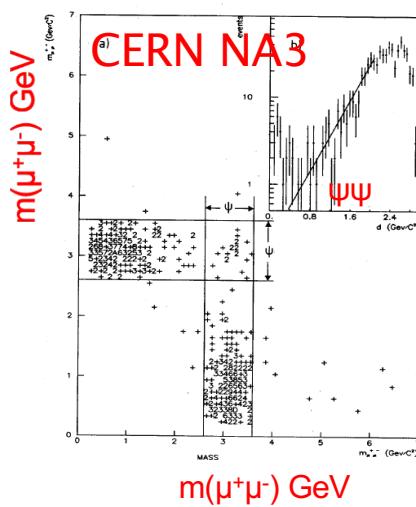


FIG. 3

PLB114 (1982) 457

Was interpreted  
as 2<sup>++</sup> 4-quark state



PLB158 (1985) 85

# Possible explanations of J/ $\psi$ J/ $\psi$ states

2<sup>++</sup> four-quark states, PRD29 (1984) 426

**TABLE I.** Parameters used in Eq. (8) to calculate the cross sections for vector-meson pair production. (+) and (−) denote two degenerate 2<sup>++</sup>  $Q^2\bar{Q}^2$  states. Except in the case of JJ, we take  $4\pi/f_L^2=0.03$ , due to the fact that the 2<sup>++</sup>  $Q^2\bar{Q}^2$  are expected to lie not far above the threshold.  $\alpha_s$  is determined from Eq. (11).

$V_1 V_2$	$a \vec{V}_1 \cdot \vec{V}_2 / a$	$b_{\alpha\beta}^J / \alpha_s \frac{a}{\sqrt{8}} \delta_{\alpha\beta}$	$M_J$ (GeV)	$\alpha_s$	$m_1$
JJ	$1/\sqrt{3}$	$\left[ \frac{2}{3} \right]^{1/2} \frac{4\pi}{f_L^2}$	7.0	0.18	3.10
$J\omega^{(+)}$	$1/\sqrt{6}$	$\frac{-1}{\sqrt{3}} \frac{4\pi}{f_L f_\omega}$	4.05	0.2	
$J\omega^{(-)}$	$1/\sqrt{12}$	$\left[ \frac{2}{3} \right]^{1/2} \frac{4\pi}{f_L f_\omega}$	4.05	0.2	
$\Upsilon J^{(+)}$	$1/\sqrt{6}$	$\frac{-1}{\sqrt{3}} \frac{4\pi}{f_X f_L}$	13.5	0.167	
$\Upsilon J^{(-)}$	$1/\sqrt{12}$	$\left[ \frac{2}{3} \right]^{1/2} \frac{4\pi}{f_X f_L}$	13.5	0.167	
$B_c^* \bar{B}_c^{*(+)}$	$-1/\sqrt{6}$	$\frac{-1}{\sqrt{3}} \frac{4\pi}{f_X f_L}$	13.5	0.167	6.60
$B_c^* \bar{B}_c^{*(-)}$	$1/\sqrt{12}$	$\left[ \frac{2}{3} \right]^{1/2} \frac{4\pi}{f_X f_L}$	13.5	0.167	

There were other attempts





# Possible explanations of J/ψJ/ψ states

(cccc) *Phys. Rev. D 86, 034004 (2012)*

$$\begin{aligned} 0^{++'} : \quad M &= 5.966 \text{ GeV}, & M - M_{\text{th}} &= -228. \text{ MeV}, \\ 1^{+-'} : \quad M &= 6.051 \text{ GeV}, & M - M_{\text{th}} &= -142. \text{ MeV}, \\ 2^{++} : \quad M &= 6.223 \text{ GeV}, & M - M_{\text{th}} &= 29.5 \text{ MeV}. \end{aligned}$$

*Below double J/ψ threshold*

*Search via  $J/\psi\mu^+\mu^-$ ,  $J/\psi^*$*

*Above double J/ψ threshold*

*Search via  $J/\psi J/\psi$*

(bbcc)

$$\begin{aligned} 0^{++a} : \quad M &= 12.359 \text{ GeV}, & M - M_{\text{th}} &= -191. \text{ MeV} \\ 0^{++b} : \quad M &= 12.471 \text{ GeV}, & M - M_{\text{th}} &= -78.7 \text{ MeV}, \\ |\!1^{+-a} : \quad M &= 12.424 \text{ GeV}, & M - M_{\text{th}} &= -126. \text{ MeV} \\ |\!1^{+-b} : \quad M &= 12.488 \text{ GeV}, & M - M_{\text{th}} &= -62.5 \text{ MeV}, \\ 1^{++} : \quad M &= 12.485 \text{ GeV}, & M - M_{\text{th}} &= -64.9 \text{ MeV}, \\ 2^{++} : \quad M &= 12.566 \text{ GeV}, & M - M_{\text{th}} &= 16.1 \text{ MeV}. \end{aligned}$$

*Below double  $B_c$  threshold*

*$J/\psi Y(1S)$  threshold*

? ...

(bbbb)

$$\begin{aligned} 0^{++'} : \quad M &= 18.754 \text{ GeV}, & M - M_{\text{th}} &= -544. \text{ MeV}, \\ 1^{+-'} : \quad M &= 18.808 \text{ GeV}, & M - M_{\text{th}} &= -490. \text{ MeV}, \\ 2^{++} : \quad M &= 18.916 \text{ GeV}, & M - M_{\text{th}} &= -382. \text{ MeV}. \end{aligned}$$

*Above double  $B_c$  threshold*

*$J/\psi Y(1S)$  threshold*

*Search via the above two channels*

*Below double  $Y(1S)$  threshold*

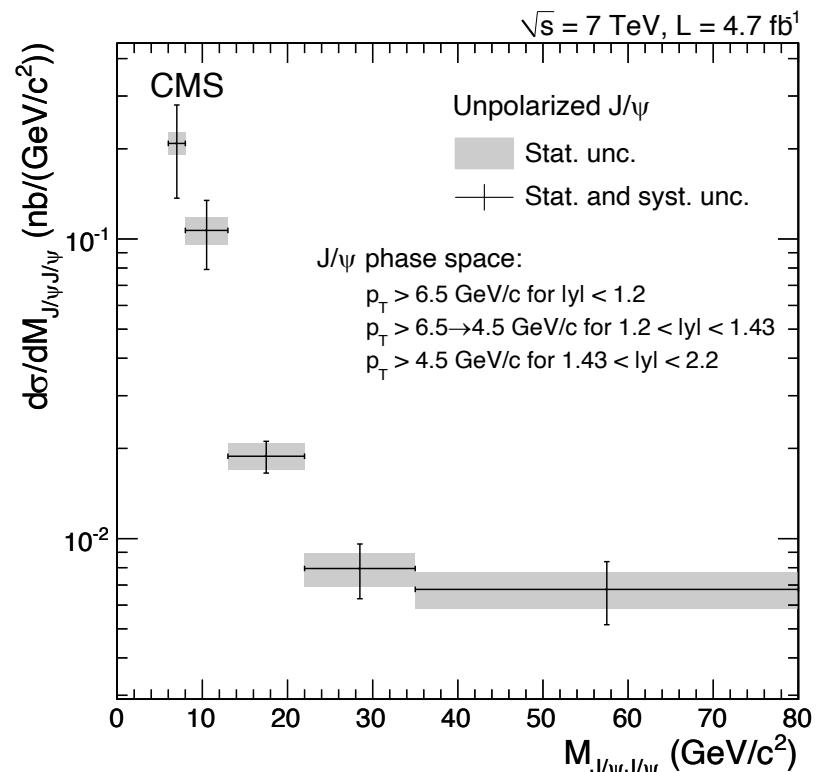
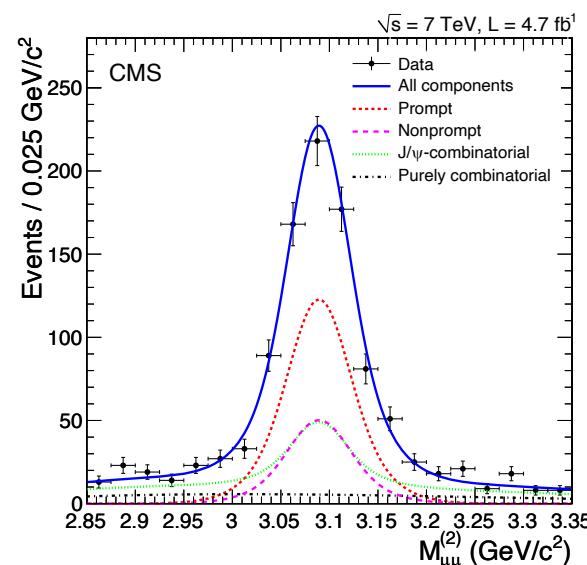
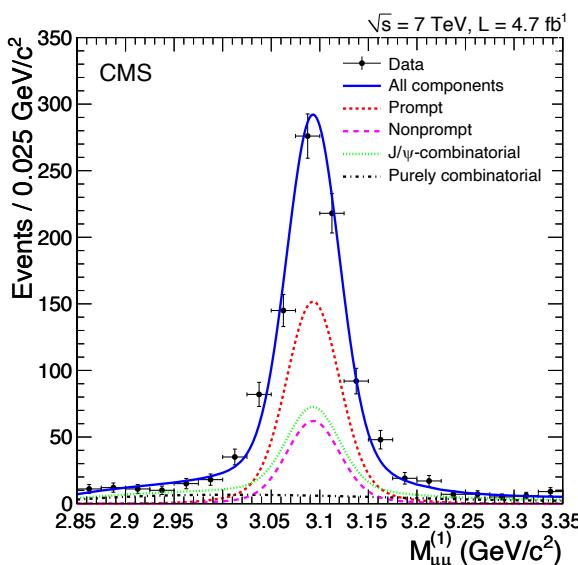
*Search via  $Y(1S)\mu^+\mu^-$*

- Many recent theoretical studies on  $(c\bar{c}c\bar{c})$ ,  $(b\bar{b}b\bar{b})$ ,  $(b\bar{b}c\bar{c})$ :
  - controversial on existence of bound states below  $\eta_b\eta_b$  (or  $\eta_c\eta_c$ ) threshold;
  - consistent on existence of resonant states above  $\eta_b\eta_b$  (or  $\eta_c\eta_c$ ) threshold.



# CMS J/ $\psi$ J/ $\psi$ cross section at 7 TeV

J. High Energy Phys. 09 (2014) 094



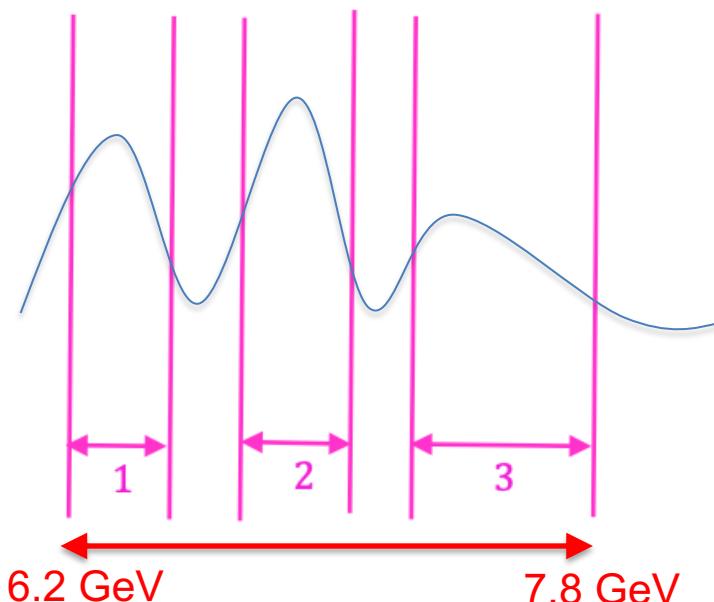
Total cross section, assuming unpolarized prompt J/ $\psi$ J/ $\psi$  pair production  
 $1.49 \pm 0.07 \text{ (stat.)} \pm 0.13 \text{ (syst.) nb}$

Different assumptions about the J/ $\psi$ J/ $\psi$  polarization imply modifications to the cross section ranging from -31% to +27%.

# Blind mass window for 13 TeV

We saw hints at Run I data (7 TeV & 8 TeV)  
Proposed **three** signal regions for Run II data

Signal:  $X \rightarrow J/\psi J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$



Blinded mass windows for Run II:

1. [6.3,6.6] GeV

2. [6.8,7.1] GeV

3. [7.2,7.8] GeV

(for potential wide structure)

These mass windows will be windows for LEE for potential structures

Run I data will be ignored for significance calculation

CMS eventually decide to blind the whole region: [6.2, 7.8] GeV after LHCb released their result (13 TeV, 2020)



# 13 TeV dataset and MC samples

- Signal:  $X \rightarrow J/\psi J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
- Data:  $135 \text{ } fb^{-1}$ , taken in 2016, 2017 and 2018 LHC runs
- Signal MC samples:
  - $J^P = 0^+$  resonance
    - Generator: Pythia8, JHUGen
- Background MC samples:
  - Nonresonant single-parton scattering (NRSPS)
    - Generator: Pythia8, HelacOnia (next-to-next-to-leading order), Cascade (next-to-leading order)
  - Nonresonant double-parton scattering (NRDPS)
    - Generator: Pythia8





# Event selections

## Muon selection

- $p_T(\mu^\pm) > 2.0 \text{ GeV}/c$
- $|\eta(\mu^\pm)| < 2.4$
- All muons are soft
- For 2017-18 years:  $p_T(\mu^\pm) > 3.5 \text{ GeV}/c$  for at least one  $\mu^+\mu^-$  pair, which has  $vtxprob(\mu^+\mu^-) > 0.5\%$  and  $2.95 < m_{\mu^+\mu^-} < 3.25 \text{ GeV}$

## J/ $\psi$ selection

- $2.95 < m_{J/\psi} < 3.25 \text{ GeV}$
- $p_T(J/\psi) > 3.5 \text{ GeV}/c$
- $vtxprob(J/\psi) > 0.5\%$
- Constrained  $vtxprob(J/\psi) > 0.1\%$

## J/ $\psi$ J/ $\psi$ selection

- $vtxprob(4\mu) > 0.5\%$
- $vtxprob(J/\psi J/\psi) > 0.1\%$
- Proper HLT is fired in event

## Multiple candidates

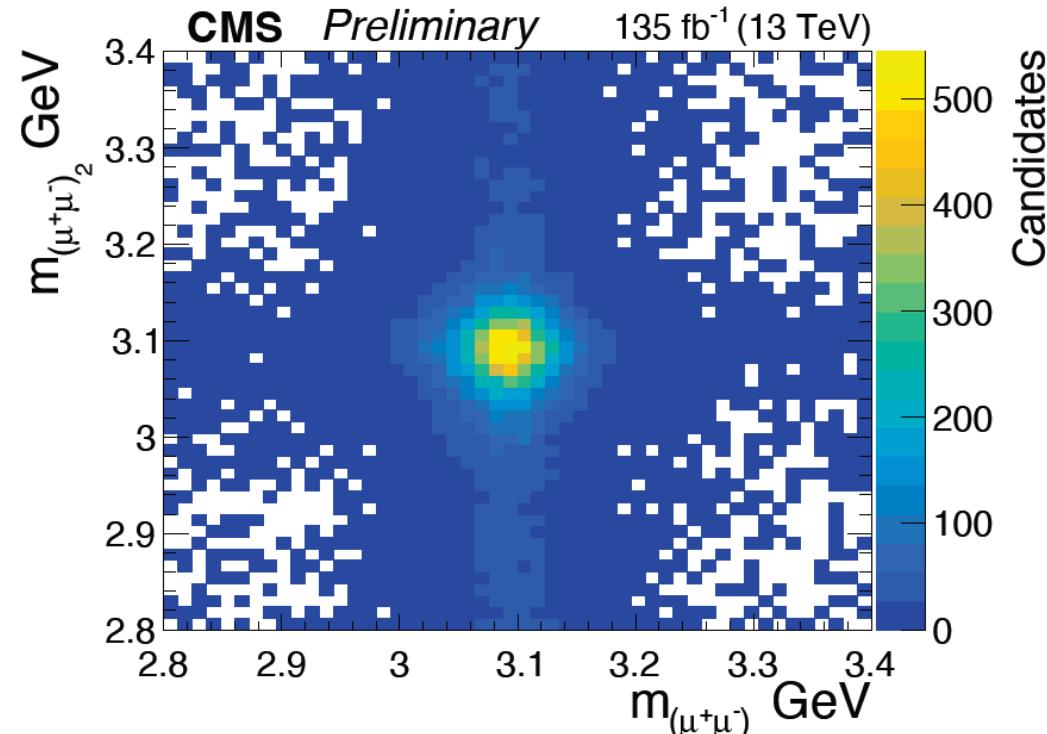
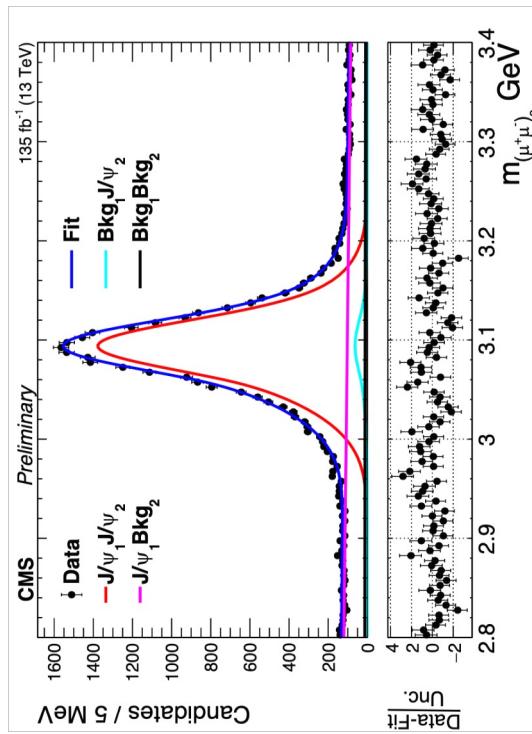
- Choose the best candidate with minimum  $(\frac{M(J/\psi_1) - M(J/\psi_{PDG})}{\sigma(M(J/\psi_1))})^2 + (\frac{M(J/\psi_2) - M(J/\psi_{PDG})}{\sigma(M(J/\psi_2))})^2$  value if there are 4 muons in event, but more than one candidate ( $\sim 0.2\%$ )
- Keep all candidates if there are more than 4 muons in event ( $\sim 0.2\%$ )

Baseline mass variable – invariant mass of two constrained J/ $\psi$  candidates



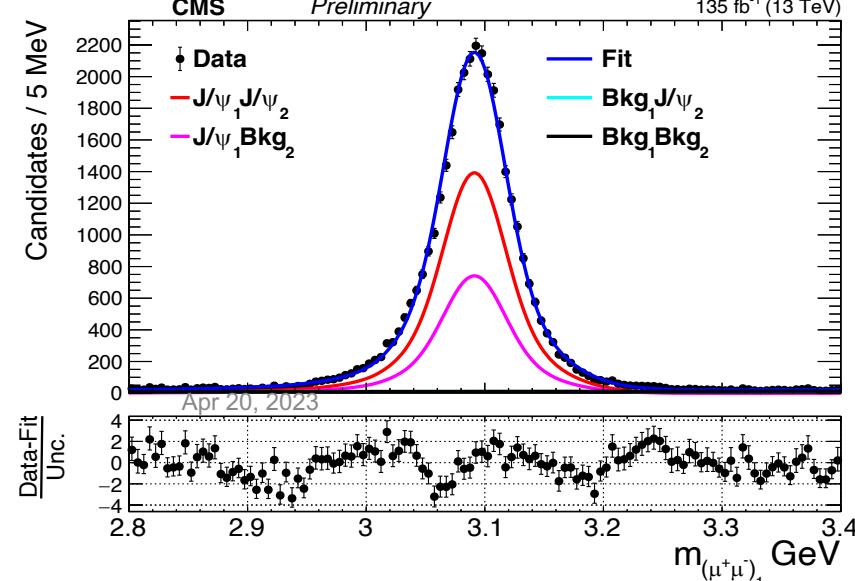


# J/ $\psi$ candidates at 13 TeV



- $J/\psi$  mass and vertex related cuts removed
- Clean  $J/\psi$  signals are seen

Zhen Hu



Zhen Hu

July 22, 2022



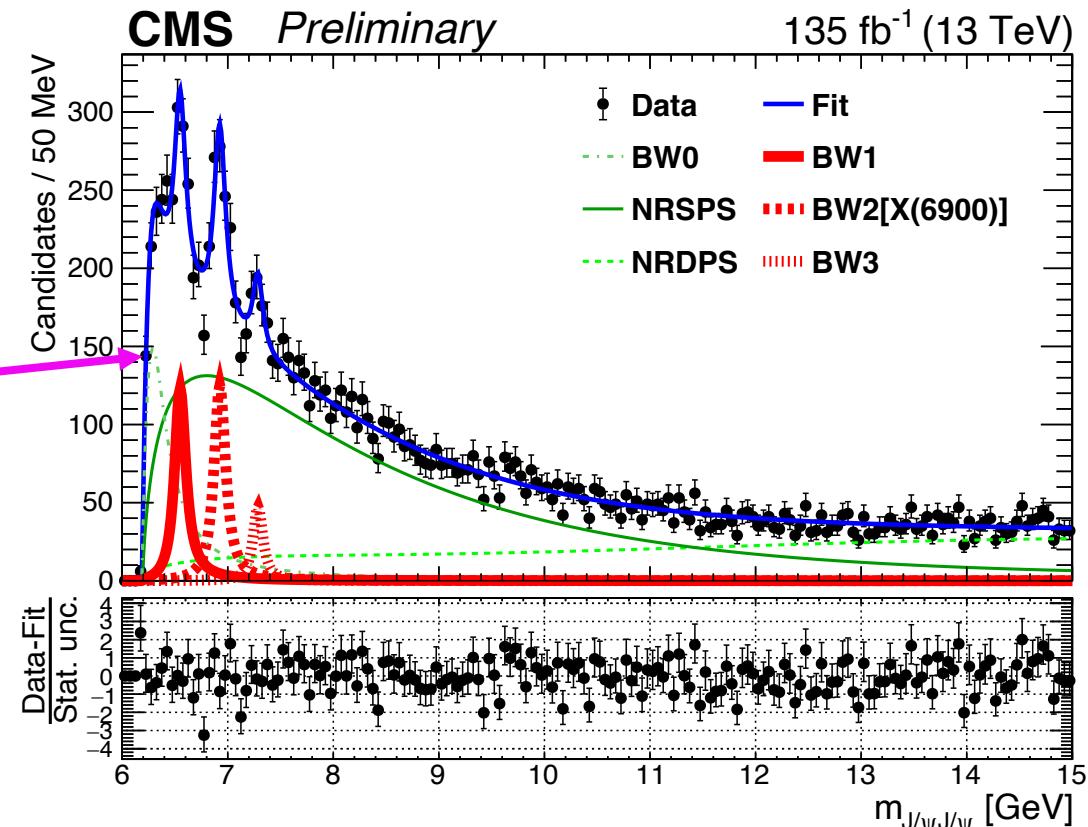


# CMS background (SPS + DPS + BW0)

CMS background (SPS + DPS + BW0)

$\chi^2$  prob = 79%

[6.2,15] GeV



- Most significant structure is a BW at threshold, **BW0**--what is its meaning?
- Treat **BW0** as part of background due to:
  - BW0 parameters very sensitive to SPS and DPS model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes...

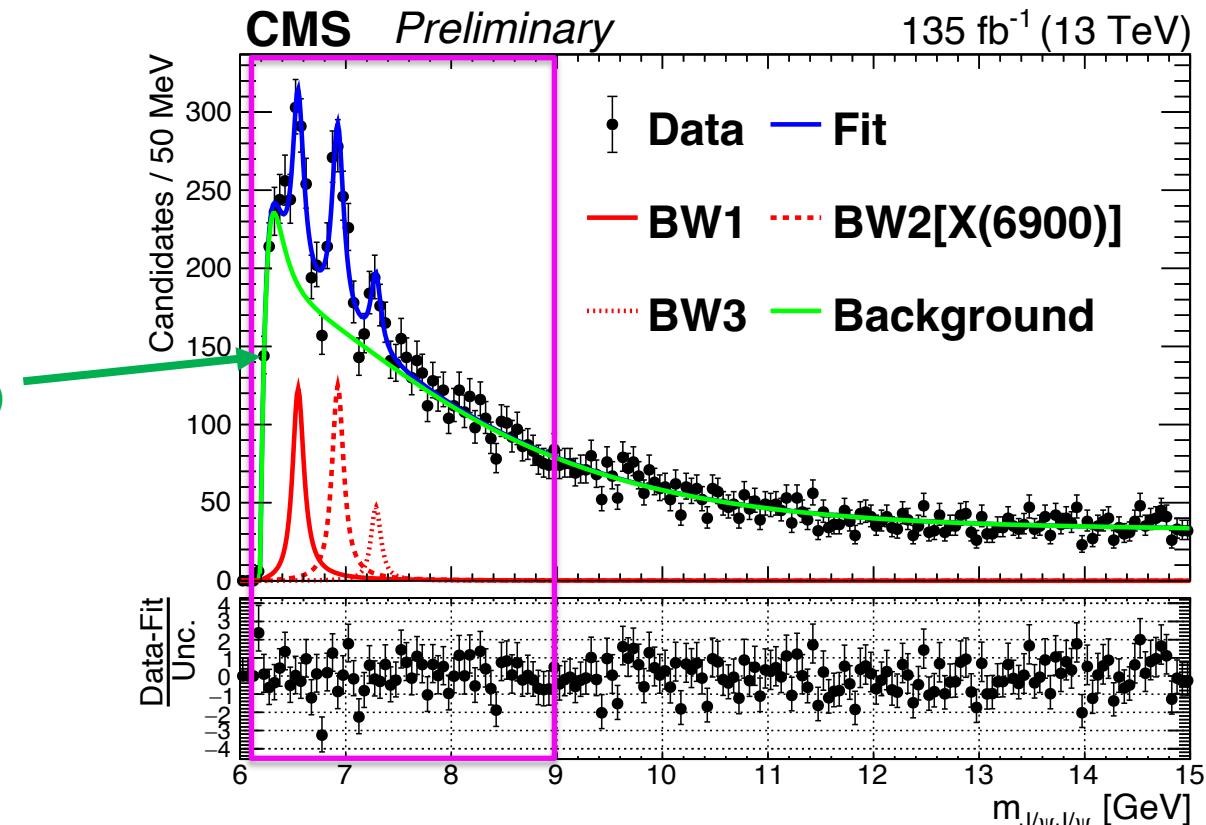


# CMS background (SPS + DPS + BW0)

CMS background (SPS + DPS + BW0)

$\chi^2 \text{ prob} = 79\%$

[6.2,15] GeV

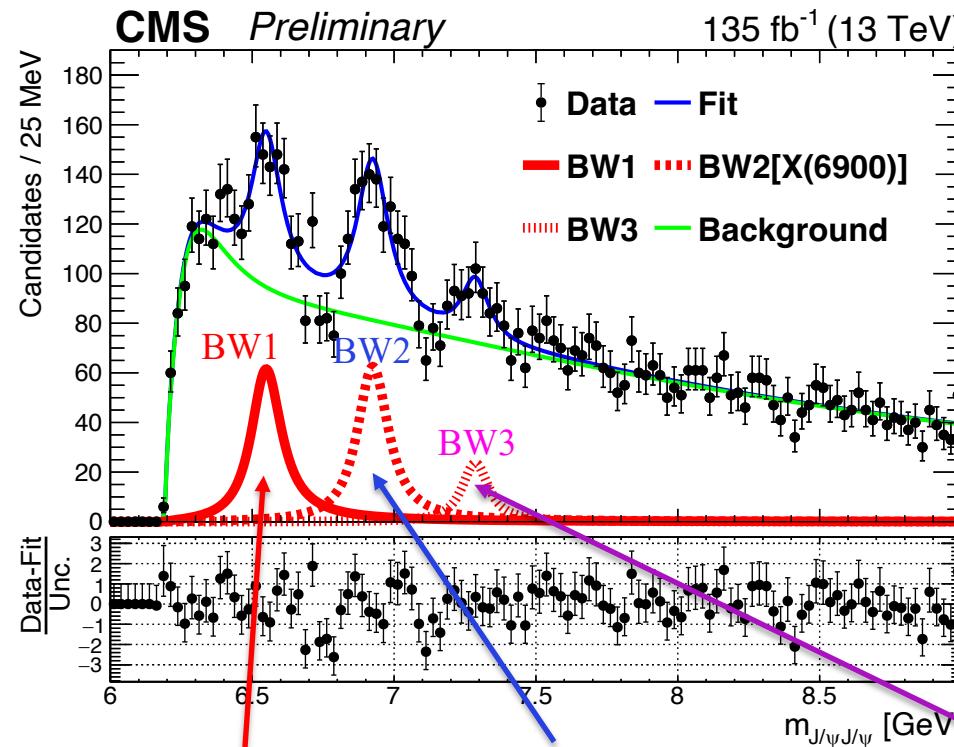


- Most significant structure is a BW at threshold, **BW0**--what is its meaning?
- Treat **BW0** as part of background due to:
  - BW0 parameters very sensitive to SPS and DPS model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes...
- SPS+DPS+BW0 as our background



# CMS model: 3 BWs + Background

$\chi^2$  Prob. = 1%  
[6.2,7.8] GeV



Statistical significance  
based on:

$$2 \ln(L_0/L_{\max})$$

	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	$6552 \pm 10$	$6927 \pm 9$	$7287 \pm 19$
$\Gamma$	$124 \pm 29$	$122 \pm 22$	$95 \pm 46$
N	$474 \pm 113$	$492 \pm 75$	$156 \pm 56$
$\sigma(\text{stat.})$	6.5	9.4	4.1
$\sigma(\text{stat. + syst.})$	5.7	9.4	4.1
	Observation	Confirmation of X(6900) from LHCb	Evidence



# Significance with systematics

Source	$\Delta M_{BW1}$	$\Delta M_{BW2}$	$\Delta M_{BW3}$	$\Delta \Gamma_{BW1}$	$\Delta \Gamma_{BW2}$	$\Delta \Gamma_{BW3}$
signal shape	3	4	3	14	7	7
NRDPS	1	< 1	< 1	3	3	4
NRSPS	3	1	1	18	15	17
momentum scaling	1	3	4	-	-	-
mass resolution	< 1	< 1	< 1	< 1	< 1	1
combinatorial background	< 1	< 1	< 1	2	3	3
efficiency	< 1	< 1	< 1	1	< 1	1
feeddown shape	11	1	1	25	8	6
total	12	5	5	34	19	20

- Investigated effects of systematics on local significance by a profiling procedure
- A discrete set of individual alternative signal and background hypotheses tested in minimization
  - Significant change: BW1 significance changed from  $6.5\sigma$  to  $>5.7\sigma$
  - No relative significance changes for BW2 and BW3

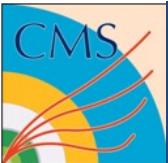
---


$$M[BW1] = 6552 \pm 10 \pm 12 \text{ MeV} \quad \Gamma[BW1] = 124 \pm 29 \pm 34 \text{ MeV} \quad >5.7\sigma$$

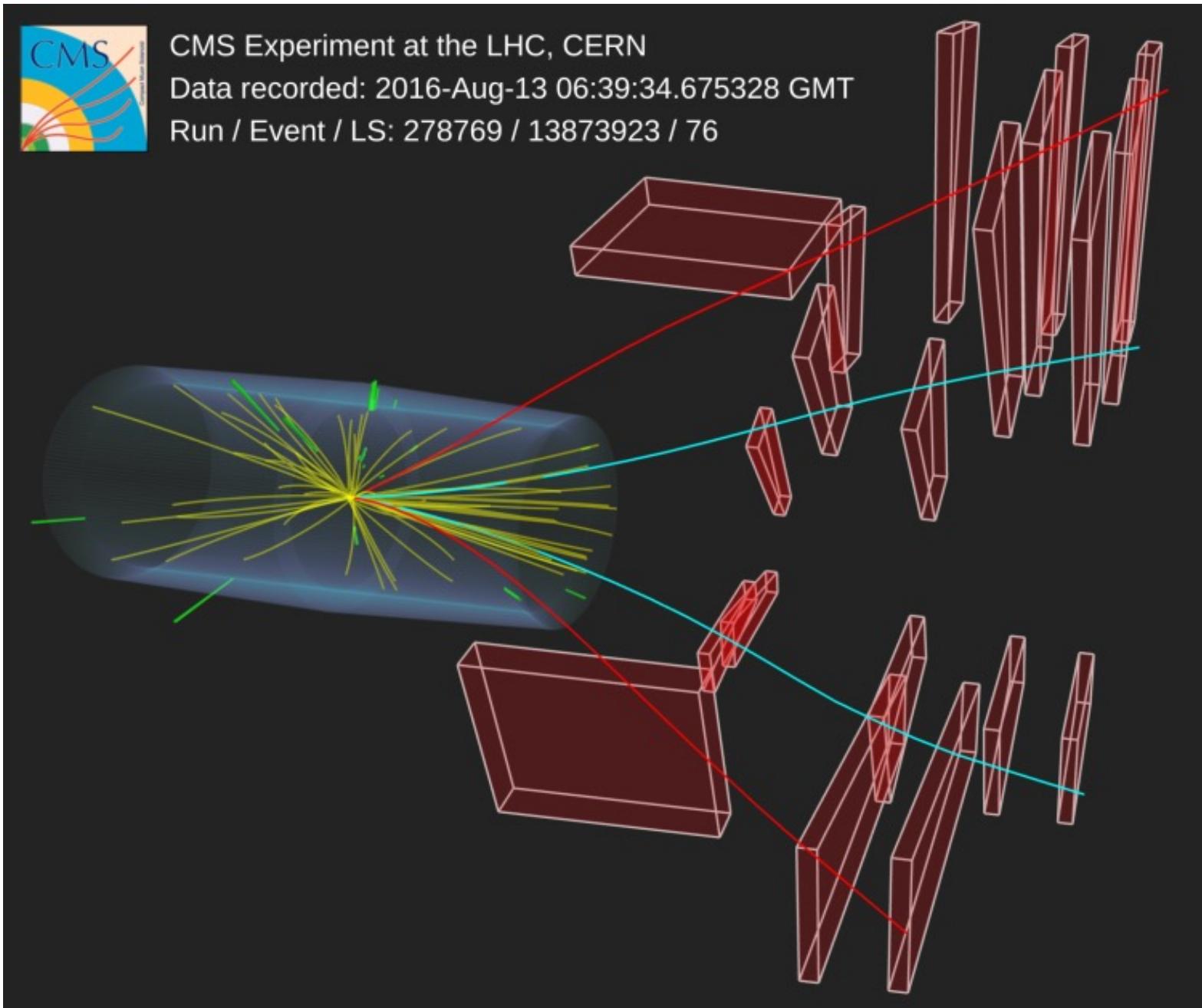
$M[BW2] = 6927 \pm 9 \pm 5 \text{ MeV}$	$\Gamma[BW2] = 122 \pm 22 \pm 19 \text{ MeV}$	$>9.4\sigma$
---	---	--------------

$M[BW3] = 7287 \pm 19 \pm 5 \text{ MeV}$	$\Gamma[BW3] = 95 \pm 46 \pm 20 \text{ MeV}$	$>4.1\sigma$
--	--	--------------

---

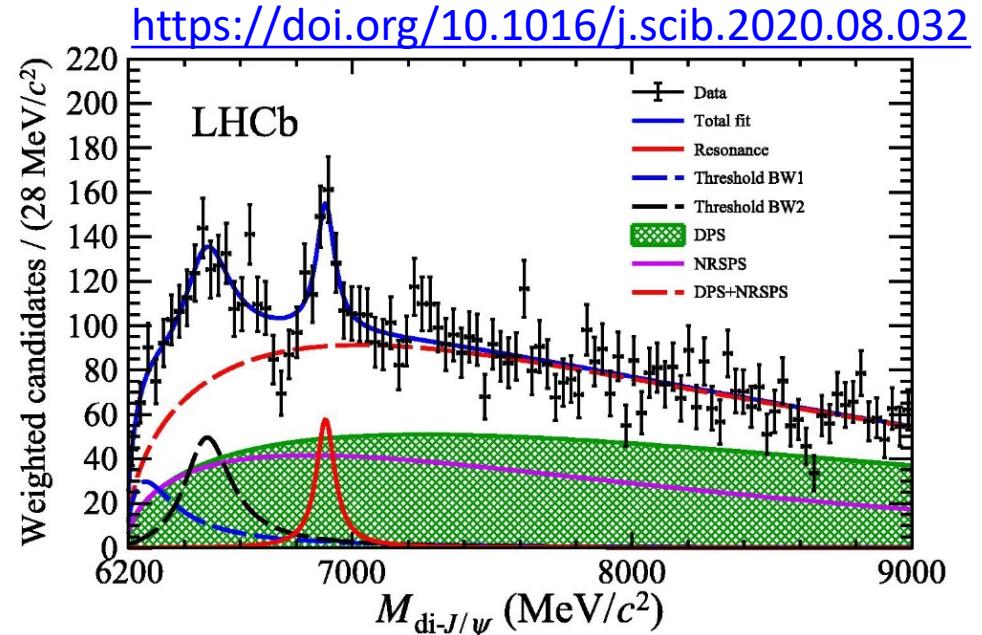
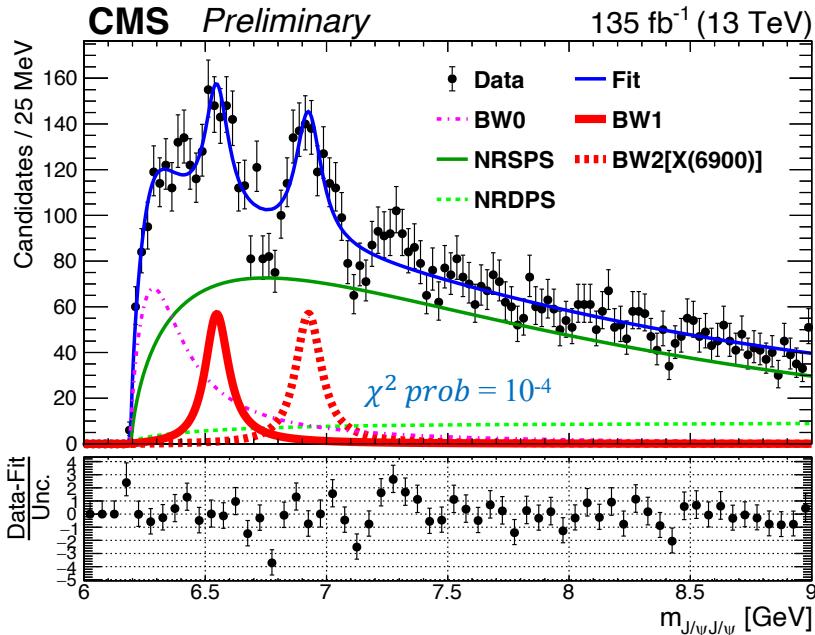


# An event display for X(6600)



# CMS and LHCb Comparison - 1

Fit CMS data with LHCb model I: 2 auxiliary BWs + X(6900) + bkg

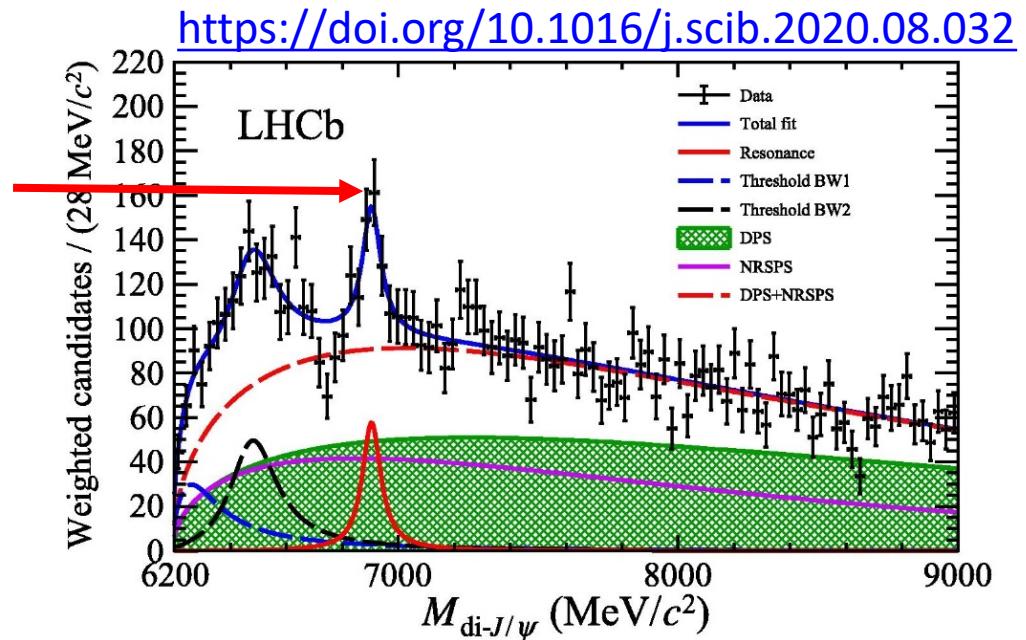
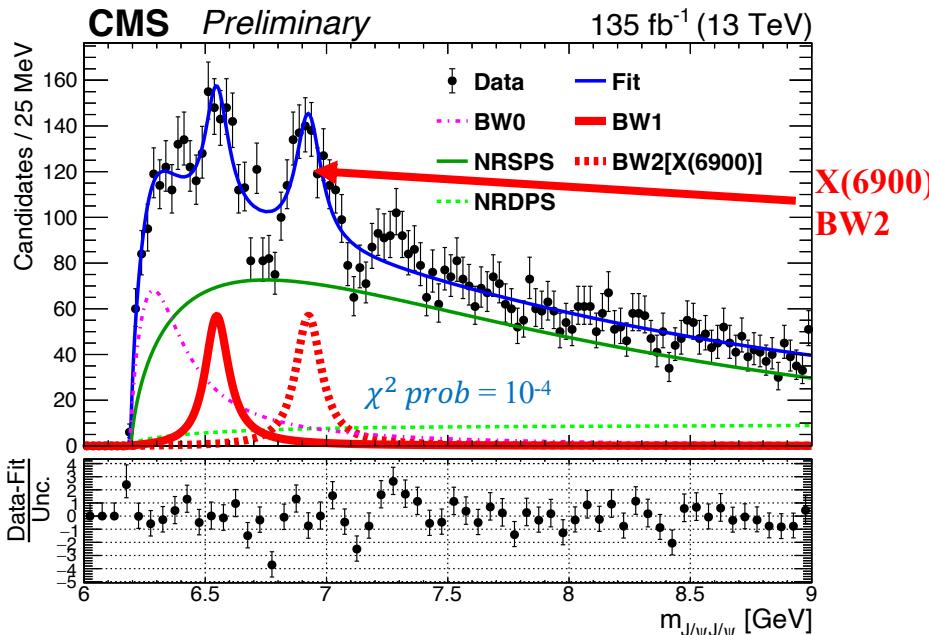


Exp.	Fit	$m(\text{BW1})$	$\Gamma(\text{BW1})$	$m(6900)$	$\Gamma(6900)$
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	$6550 \pm 10$	$112 \pm 27$	$6927 \pm 10$	$117 \pm 24$



# CMS and LHCb Comparison - 1

Fit CMS data with LHCb model I: 2 auxiliary BWs + X(6900) + bkg



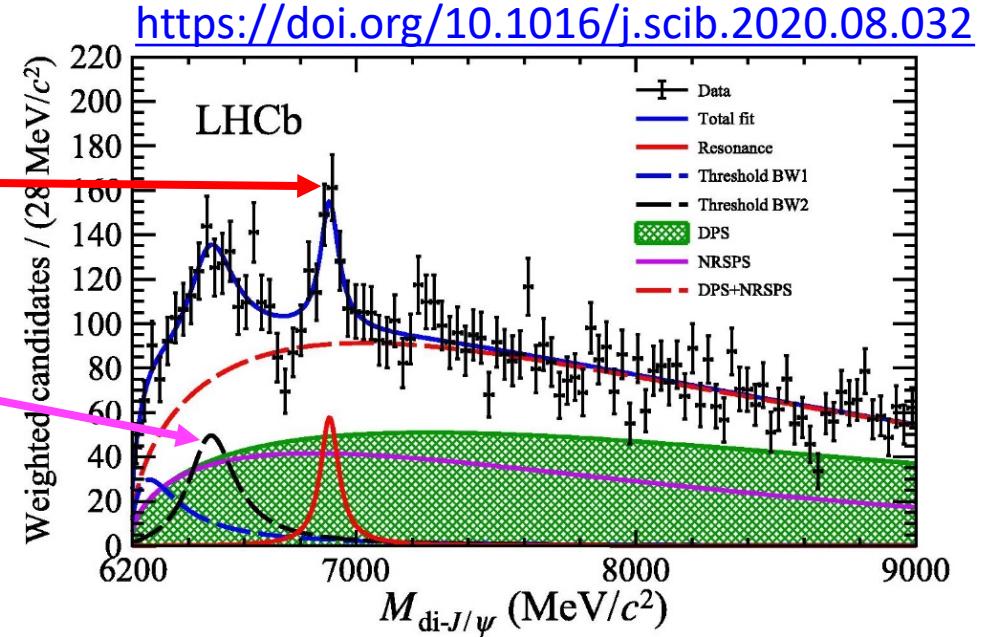
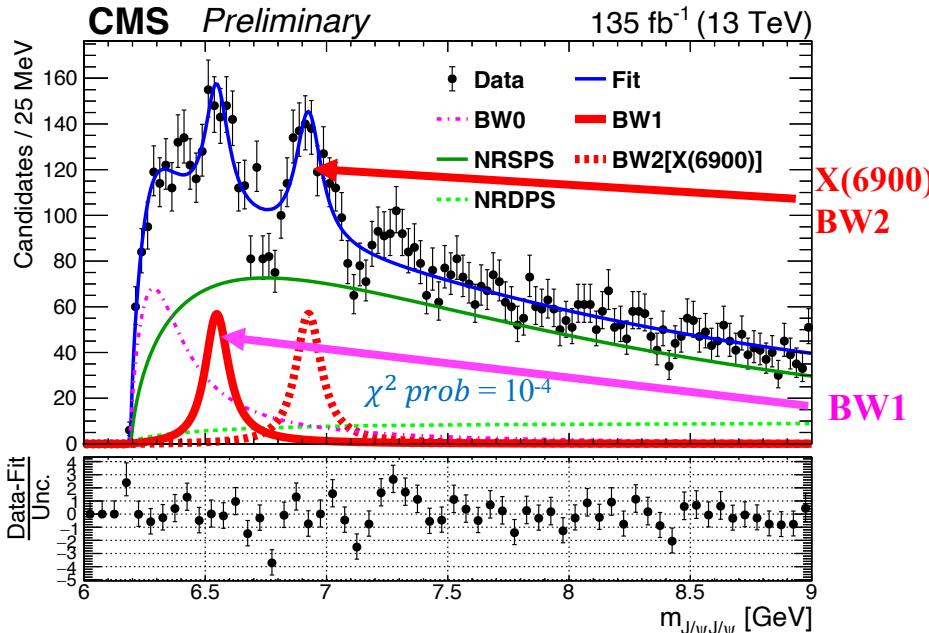
BW2 are in good agreement with LHCb X(6900)

Exp.	Fit	$m(\text{BW1})$	$\Gamma(\text{BW1})$	$m(6900)$	$\Gamma(6900)$
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	$6550 \pm 10$	$112 \pm 27$	$6927 \pm 10$	$117 \pm 24$



# CMS and LHCb Comparison - 1

Fit CMS data with LHCb model I: 2 auxiliary BWs + X(6900) + bkg

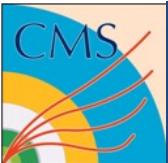


BW2 are in good agreement with LHCb X(6900)

Exp.	Fit	$m(\text{BW1})$	$\Gamma(\text{BW1})$	$m(6900)$	$\Gamma(6900)$
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	$6550 \pm 10$	$112 \pm 27$	$6927 \pm 10$	$117 \pm 24$

- LHCb did not give parameters for BW1
  - CMS has a shoulder before BW1
  - helps make BW1 distinct
- *Does not describe 2 dips well*

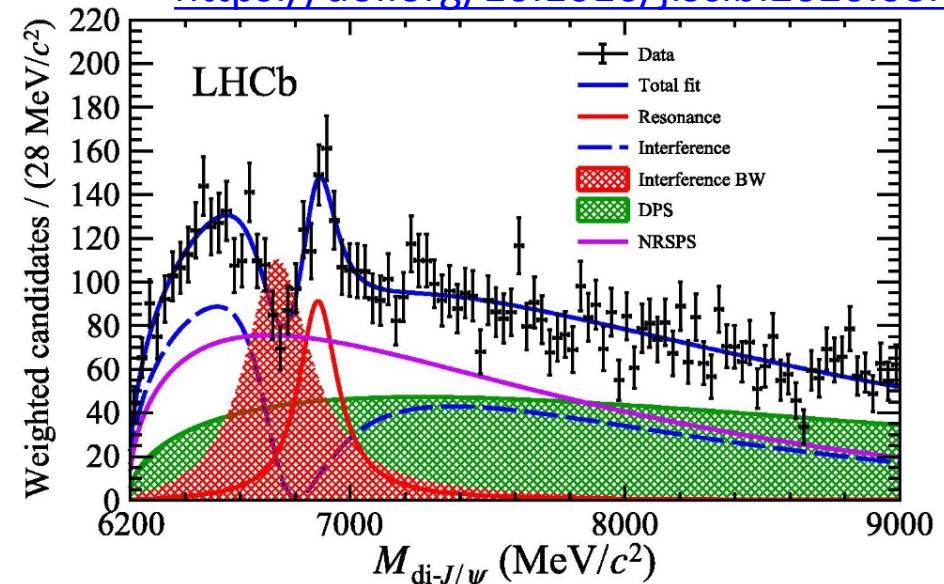
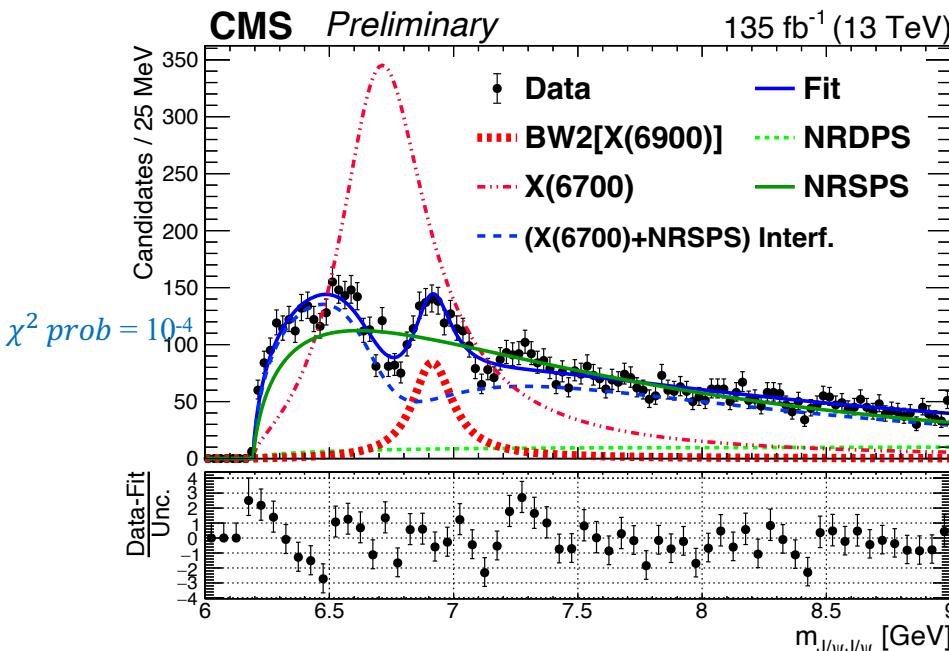




# CMS and LHCb Comparison - 2

Fit CMS data with LHCb model II : “X(6700)” interferes with NRSPS + X(6900) + Bkg

<https://doi.org/10.1016/j.scib.2020.08.032>



Exp.	Fit	$m(\text{BW1})$	$\Gamma(\text{BW1})$	$m(6900)$	$\Gamma(6900)$
LHCb [15]	Model II	$6741 \pm 6$	$288 \pm 16$	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	$6736 \pm 38$	$439 \pm 65$	$6918 \pm 10$	$187 \pm 40$



Zhen Hu

Apr 20, 2023

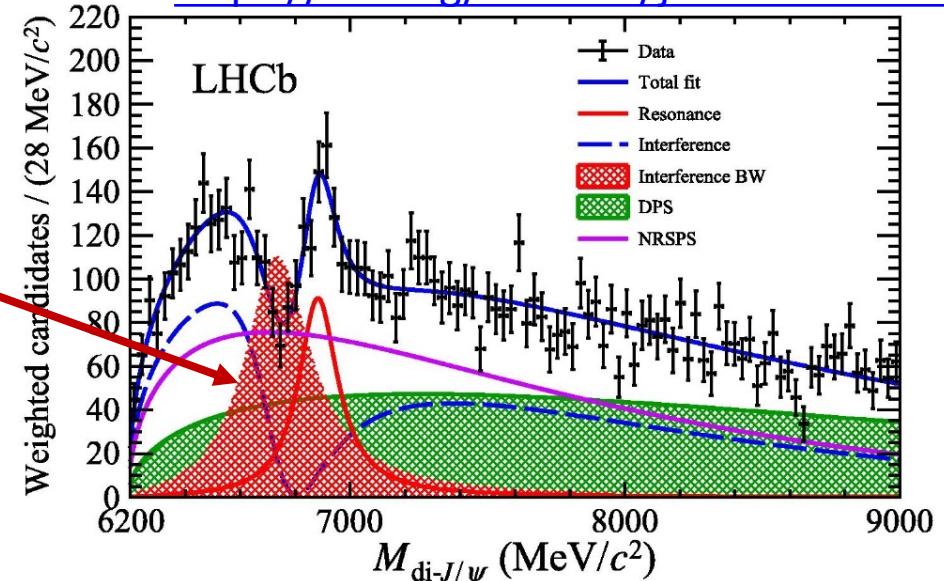
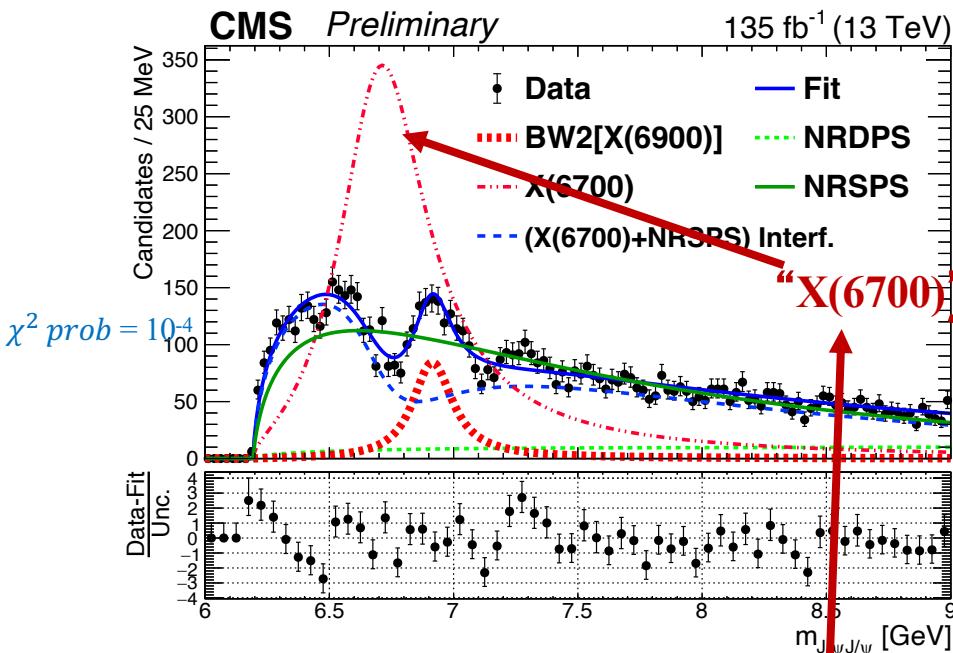
24



# CMS and LHCb Comparison - 2

## Fit CMS data with LHCb model II : “X(6700)” interferes with NRSPS + X(6900) + Bkg

<https://doi.org/10.1016/j.scib.2020.08.032>



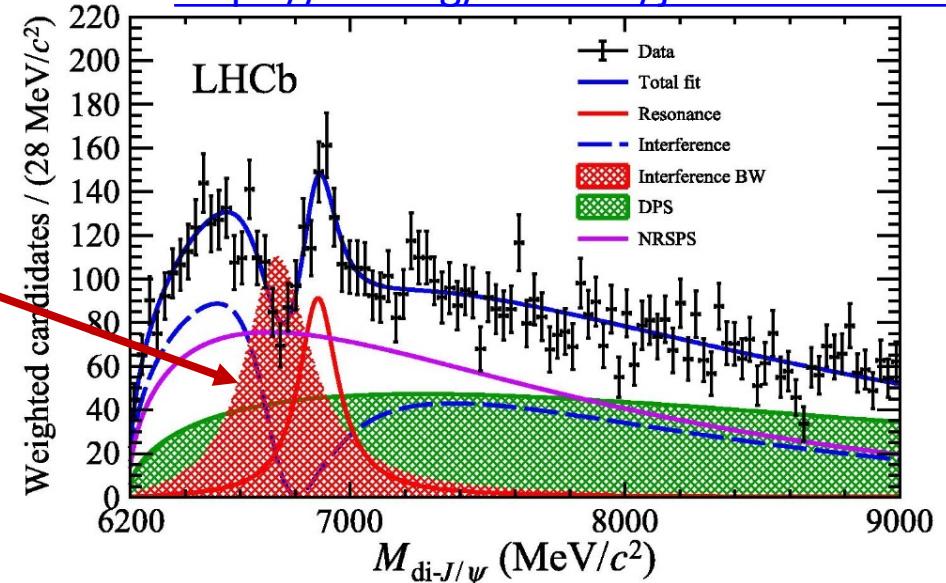
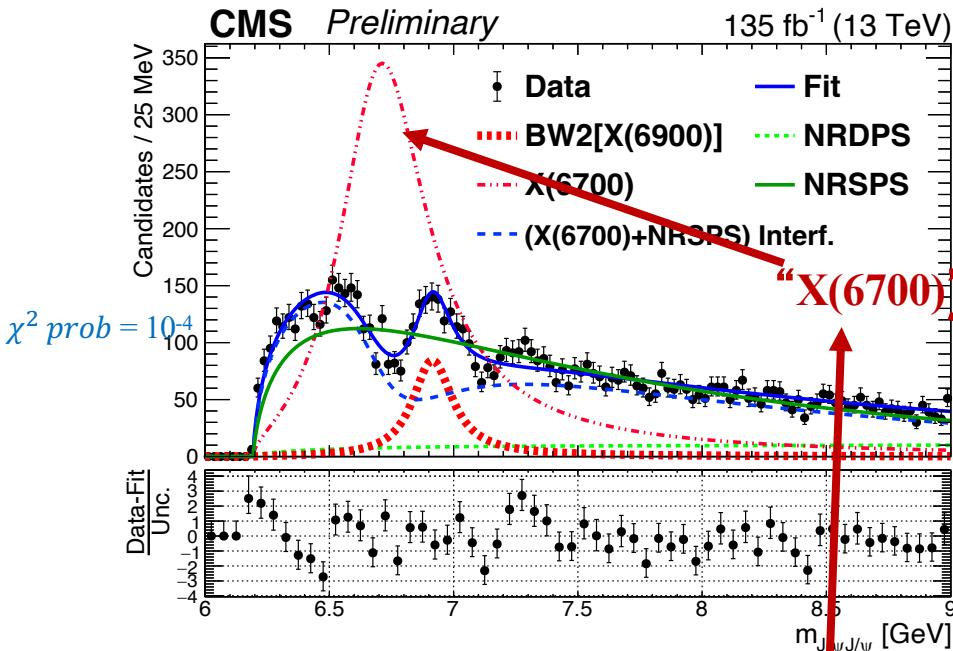
Exp.	Fit	$m(\text{BW1})$	$\Gamma(\text{BW1})$	$m(6900)$	$\Gamma(6900)$
LHCb [15]	Model II	$6741 \pm 6$	$288 \pm 16$	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	$6736 \pm 38$	$439 \pm 65$	$6918 \pm 10$	$187 \pm 40$

- CMS obtained larger amplitude and wider width for X(6700)

# CMS and LHCb Comparison - 2

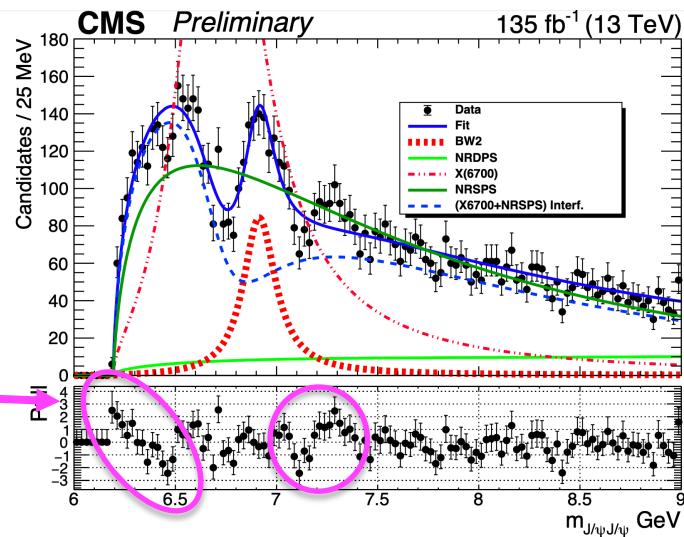
## Fit CMS data with LHCb model II : “X(6700)” interferes with NRSPS + X(6900) + Bkg

<https://doi.org/10.1016/j.scib.2020.08.032>

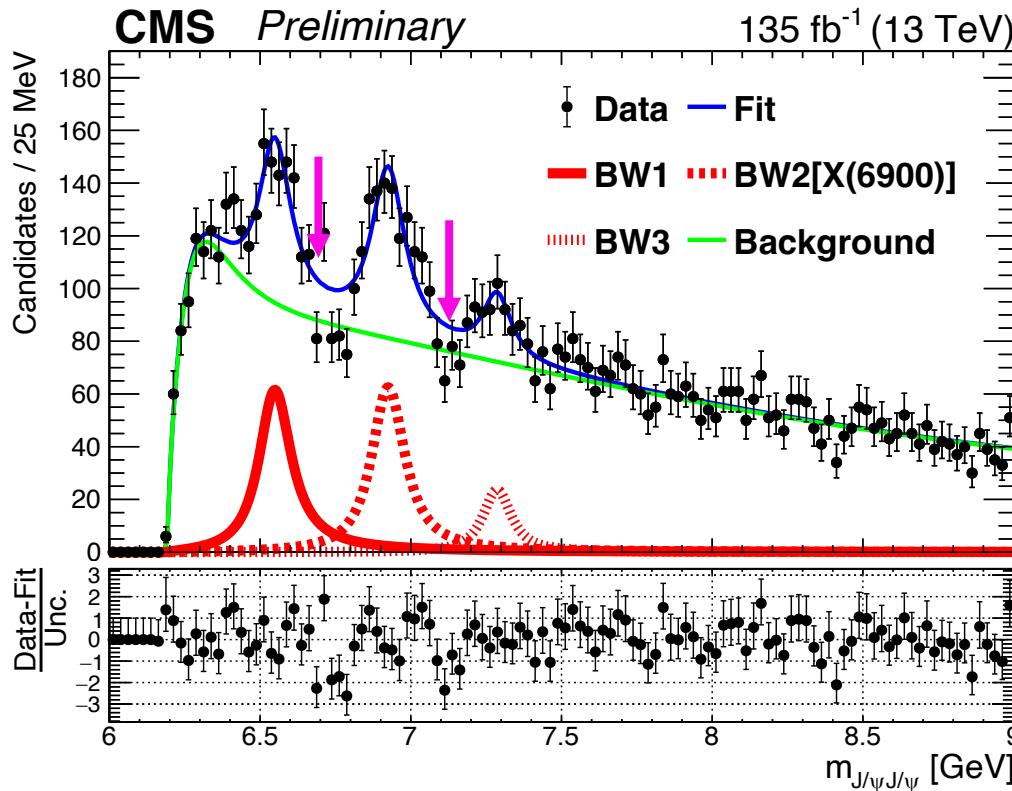


Exp.	Fit	$m(\text{BW1})$	$\Gamma(\text{BW1})$	$m(6900)$	$\Gamma(6900)$
LHCb [15]	Model II	$6741 \pm 6$	$288 \pm 16$	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	$6736 \pm 38$	$439 \pm 65$	$6918 \pm 10$	$187 \pm 40$

- CMS obtained larger amplitude and wider width for X(6700)
- Does not describe X(6600) and below
- Does not describe X(7200) region



# The dips



- Possibility #1:
    - Interference among structures?
    - Why no interference for  $Y(nS)$  peaks?
      - Width too narrow to overlap
    - More secrets to dig out
    - We explored possibility #1 in detail

- Possibility #2:
    - Multiple fine structures to reproduce the dips?
    - Mentioned in PAS



# Exploration of possible interference among BWs

- Explored fit with interference among various combinations of BWs
- Pdf for three BW interference

$$\begin{aligned} Pdf(m) = & N_{X_0} \cdot |BW_0|^2 \otimes R(M_0) \\ & + N_{X \text{ and interf}} \cdot |r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2 \\ & + N_{NRSPS} f_{SPS}(m) + N_{NRDPS} f_{DPS}(m). \end{aligned}$$

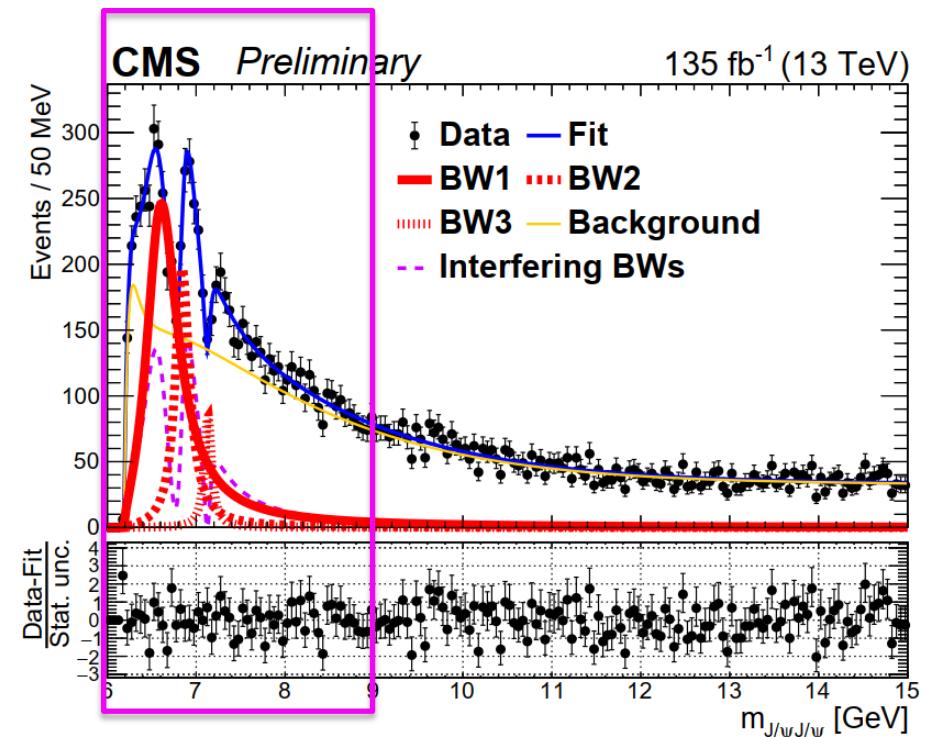
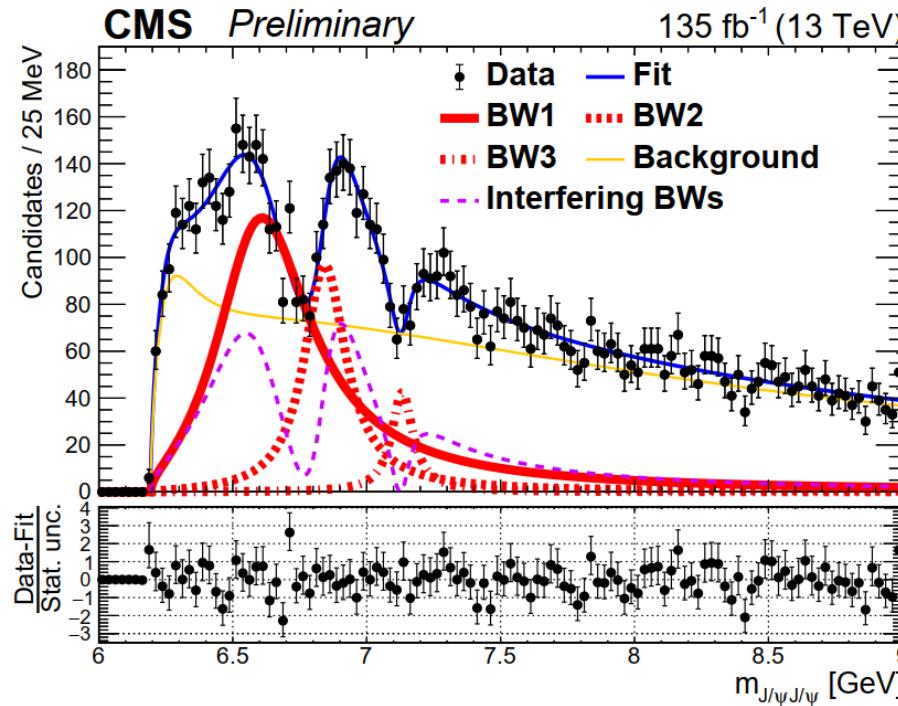
Interf. term

- Many ways interference due to possible  $J^{PC}$  and quantum coherence
  - 2-object-interference among BW0, BW1, BW2, BW3
  - 3-object-interference among BW0, BW1, BW2, BW3
  - 4-object-interference among BW0, BW1, BW2, BW3
- Our choice: interference among **BW1, BW2, BW3**



# CMS interference fit

[CMS PAS BPH-21-003](#)



- Fit with interf. among BW1, BW2 and BW3 describes data well
- Measured mass and width in the interference fit

		BW1	BW2	BW3
Interference	$m$ [MeV]	$6638^{+43+16}_{-38-31}$	$6847^{+44+48}_{-28-20}$	$7134^{+48+41}_{-25-15}$
	$\Gamma$ [MeV]	$444^{+226+109}_{-199-235}$	$191^{+66+25}_{-49-17}$	$97^{+40+29}_{-29-26}$

# Systematic uncertainties for interf. case

Fit	Dominant sources	$\Delta M_{BW1}$	$\Delta M_{BW2}$	$\Delta M_{BW3}$	$\Delta \Gamma_{BW1}$	$\Delta \Gamma_{BW2}$	$\Delta \Gamma_{BW3}$
Interference	Signal shape	7	12	7	56	8	7
	NRDPS	1	3	2	18	6	2
	NRSPS	9	14	13	85	9	20
	Resolution	8	4	1	24	7	13
	Combinatorial bkg.	7	2	< 1	5	3	2
	Feeddown shape	-27	+44	+38	-208	+19	+12
	Full uncertainty	+16 -31	+48 -20	+41 -15	+109 -235	+25 -17	+29 -26

- Total systematic uncertainty is quadrature sum of each source
- Systematic uncertainties from feeddown contribution are asymmetric
- Systematic uncertainties from other sources are symmetric



# Final result

- Measured mass and width

Non-interference fit

	BW1	BW2	BW3
$m$	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
$\Gamma$	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
$N$	$474 \pm 113$	$492 \pm 75$	$156 \pm 56$

Interference fit

	BW1	BW2	BW3
$m$ [ MeV]	$6638^{+43+16}_{-38-31}$	$6847^{+44+48}_{-28-20}$	$7134^{+48+41}_{-25-15}$
$\Gamma$ [ MeV]	$444^{+226+109}_{-199-235}$	$191^{+66+25}_{-49-17}$	$97^{+40+29}_{-29-26}$

- Systematic uncertainty table (sources with minor effects suppressed)

Non-interference fit

Source	$\Delta M_{BW1}$	$\Delta M_{BW2}$	$\Delta M_{BW3}$	$\Delta \Gamma_{BW1}$	$\Delta \Gamma_{BW2}$	$\Delta \Gamma_{BW3}$
signal shape	3	4	3	14	7	7
NRDPS	1	< 1	< 1	3	3	4
NRSPS	3	1	1	18	15	17
momentum scaling	1	3	4	-	-	-
mass resolution	< 1	< 1	< 1	< 1	< 1	1
combinatorial background	< 1	< 1	< 1	2	3	3
efficiency	< 1	< 1	< 1	1	< 1	1
feeddown shape	11	1	1	25	8	6
total	12	5	5	34	19	20

Interference fit

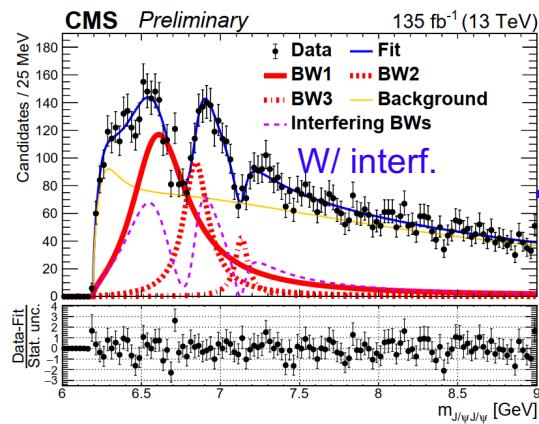
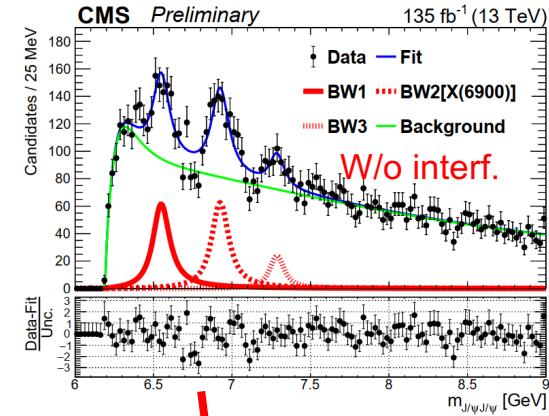
Dominant sources	$\Delta M_{BW1}$	$\Delta M_{BW2}$	$\Delta M_{BW3}$	$\Delta \Gamma_{BW1}$	$\Delta \Gamma_{BW2}$	$\Delta \Gamma_{BW3}$
Signal shape	7	12	7	56	8	7
NRDPS	1	3	2	18	6	2
NRSPS	9	14	13	85	9	20
Resolution	8	4	1	24	7	13
Combinatorial bkg.	7	2	< 1	5	3	2
Feeddown shape	-27	+44	+38	-208	+19	+12
Full uncertainty	+16	+48	+41	+109	+25	+29
	-31	-20	-15	-235	-17	-26

- Implication of interf. Result:
  - Same JPC
  - Large separation--200-300 MeV indicates radial excitation
  - Any theoretical predication?





# Comparison with some theoretical calculations



$1^1P_1$	$1^{--}$	363.9	320.3	-366.7	337.5	-14.4	0	0	-2.6	6553	-	-
$1^3P_0$	$0^+$	356.7	320.2	-366.7	337.5	-7.2	-56.9	-43.1	-2.6	6460	6398.1	$\eta_c(1S)\chi_{c0}(1P)$
$1^3P_1$	$1^+$	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554	6494.1	$\eta_c(1S)\chi_{c1}(1P)$
$1^3P_2$	$2^+$	356.6	320.2	-366.7	337.5	-7.2	28.4	-2.1	-2.4	6587	6539.6	$\eta_c(1S)\chi_{c2}(1P)$
$1^5P_1$	$1^{--}$	342.4	320.4	-366.7	337.5	7.2	-85.3	-30.2	-2.7	6449	6508.8	$\eta_c(1S)h_{c1}(1P)$
$1^5P_2$	$2^{--}$	342.2	320.2	-366.7	337.5	7.2	-28.4	30.2	-2.5	657	6607.6	$J/\psi(1S)\chi_{c1}(1P)$
$1^5P_3$	$3^{--}$	342.3	320.3	-366.7	337.5	7.2	56.9	-8.6	-2.5	6623	6653.1	$J/\psi(1S)\chi_{c2}(1P)$
$2^1P_1$	$1^{--}$	414.7	688.7	-263.4	548.6	-11.2	0	0	-1.6	6925	-	-
$2^3P_0$	$0^+$	410.0	689.6	-263.4	548.6	-5.6	-46.2	-34.5	-1.7	6851	-	-
$2^3P_1$	$1^+$	410.0	689.6	-263.4	548.6	-5.6	-23.1	17.2	-1.6	6926	-	-
$2^3P_2$	$2^+$	410.0	689.6	-263.4	548.7	-5.6	23.1	-3.4	-1.7	6951	-	-
$2^5P_1$	$1^{--}$	398.7	689.5	-263.4	548.6	-5.6	-69.3	-24.2	-1.7	6848	-	-
$2^5P_2$	$2^{--}$	398.7	689.5	-263.4	548.6	5.6	-23.1	24.2	-1.5	6944	-	-
$2^5P_3$	$3^{--}$	398.8	689.7	-263.4	548.6	5.6	46.2	-6.9	-1.6	6982	-	-
$3^1P_1$	$1^{--}$	479.8	982.2	-215.5	727.8	-9.3	0	0	-1.1	7221	-	-
$3^3P_0$	$0^+$	475.2	982.7	-215.5	727.7	-4.6	-41.9	-31.0	-1.2	7153	-	-
$3^3P_1$	$1^+$	475.1	982.6	-215.5	727.7	-4.6	-20.9	15.5	-1.2	7220	-	-
$3^3P_2$	$2^+$	475.1	982.6	-215.5	727.8	-4.6	20.9	-3.1	-1.0	7243	-	-
$3^5P_1$	$1^{--}$	465.9	982.8	-215.5	727.7	4.6	-62.8	-21.7	-1.2	7150	-	-
$3^5P_2$	$2^{--}$	465.7	982.6	-215.5	727.8	-4.6	-20.9	21.7	-1.1	7236	-	-
$3^5P_3$	$3^{--}$	465.8	982.6	-215.5	727.8	4.6	41.9	-6.2	-1.1	7271	-	-

arXiv:2108.04017 [hep-ph]

P-wave

$M[BW1]$	$= 6552 \pm 10 \pm 12$ MeV
$M[BW2]$	$= 6927 \pm 9 \pm 5$ MeV
$M[BW3]$	$= 7287 \pm 19 \pm 5$ MeV

Table 1. Predictions of the masses (MeV) of S-wave fully heavy  $T_{4Q}(nS)$  tetraquarks. Only  $0^{++}$  and  $2^{++}$  are considered for  $T_{bc\bar{b}\bar{c}}$ . The uncertainty is from the coupling constant  $\alpha_s = 0.35 \pm 0.05$ .

Nucl. Phys. B 966 (2021) 115393

$T_{4Q}(nS)$ states	$J^P$	Mass( $n=1$ )	Mass( $n=2$ )	Mass( $n=3$ )	Mass( $n=4$ )
$T_{cc\bar{c}\bar{c}}$	$0^{++}$	$6055^{+69}_{-74}$	$6555^{+36}_{-37}$	$6883^{+27}_{-27}$	$7154^{+22}_{-22}$
	$2^{++}$	$6090^{+62}_{-66}$	$6563^{+34}_{-35}$	$6886^{+27}_{-26}$	$7160^{+22}_{-22}$
$T_{cc\bar{c}\bar{c}}$	$0^{++}$	$5984^{+64}_{-67}$	$6468^{+25}_{-25}$	$6715^{+26}_{-26}$	$7166^{+21}_{-22}$
	$2^{++}$	$12387^{+109}_{-120}$	$12911^{+18}_{-18}$	$13200^{+35}_{-36}$	$13429^{+29}_{-30}$
$T_{bc\bar{b}\bar{c}}$	$0^{++}$	$12401^{+117}_{-106}$	$12914^{+49}_{-49}$	$13202^{+35}_{-36}$	$13430^{+29}_{-29}$
	$2^{++}$	$12300^{+106}_{-117}$	$12816^{+48}_{-50}$	$1304^{+35}_{-35}$	$13333^{+29}_{-29}$
$T_{bb\bar{b}\bar{b}}$	$0^{++}$	$18475^{+151}_{-169}$	$19073^{+59}_{-63}$	$1953^{+42}_{-42}$	$19566^{+33}_{-35}$
	$2^{++}$	$18483^{+149}_{-168}$	$19075^{+59}_{-62}$	$1955^{+41}_{-43}$	$19567^{+33}_{-35}$
$T_{bb\bar{b}\bar{b}}$	$0^{++}$	$18383^{+149}_{-167}$	$18976^{+59}_{-62}$	$1956^{+43}_{-42}$	$19468^{+34}_{-34}$
	$2^{++}$	$-$	$-$	$-$	$-$

$$M[BW1] = 6638 \pm 10 \pm 12 \text{ MeV}$$

$$M[BW2] = 6847 \pm 9 \pm 5 \text{ MeV}$$

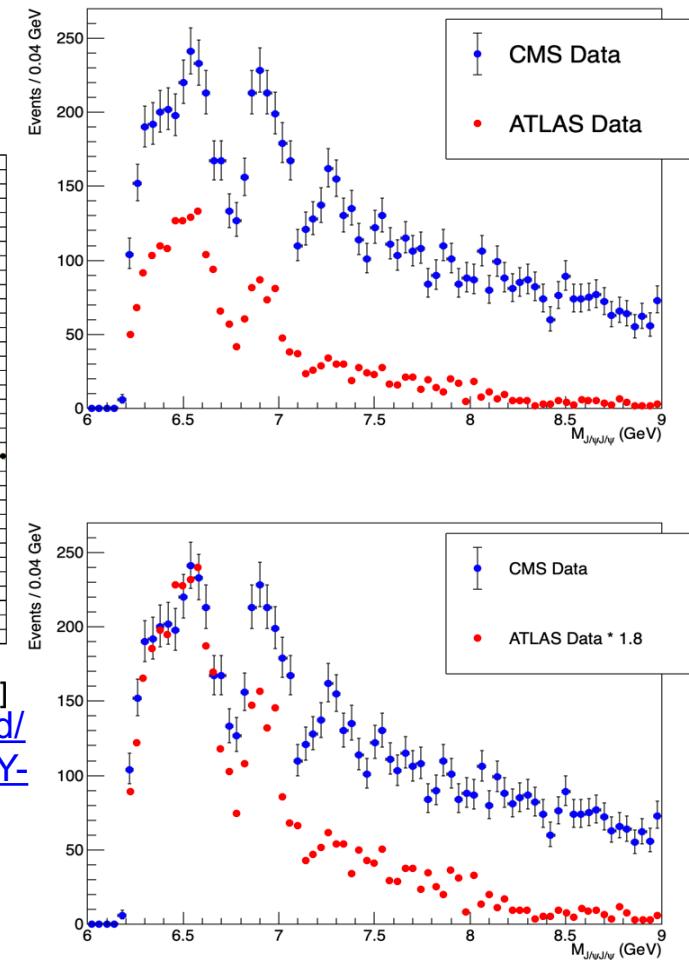
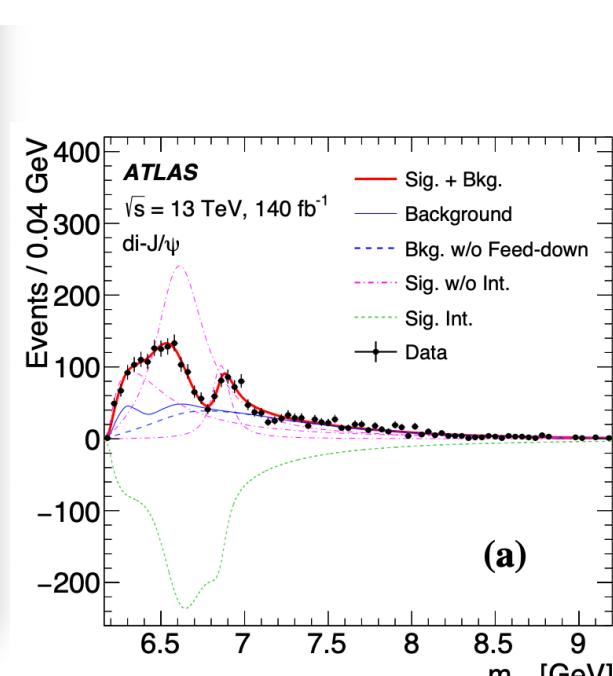
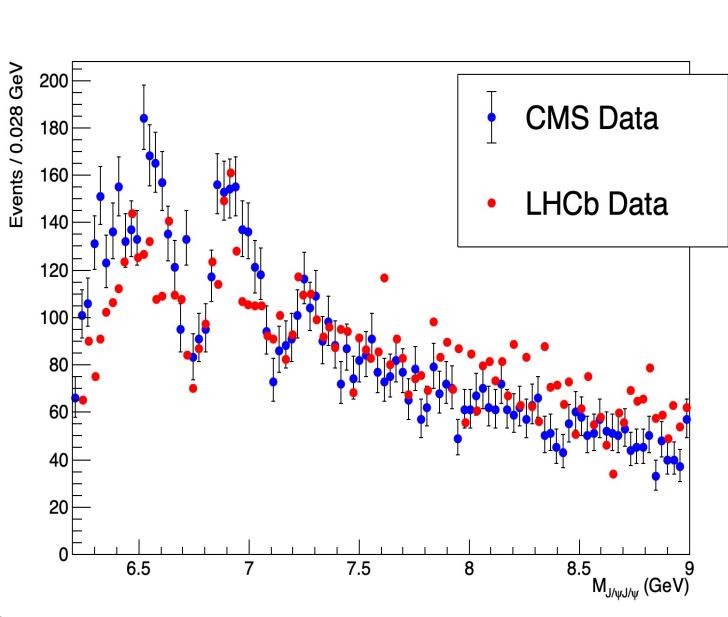
$$M[BW3] = 7134 \pm 19 \pm 5 \text{ MeV}$$

- Radial excited p-wave states (like  $J/\psi$  series)?
- Or Radial excited S-wave states?
- Theoretical situation difficulty & confusing
  - Important next step: measure  $J^{PC}$  to clarify
- Natural question: what about YY final state?



# Comparison with LHCb & ATLAS

Comparison plots in this page are not made by CMS  
 (taken from <https://indico.cern.ch/event/1158681/contributions/5162594/>)

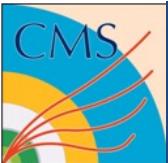


- CMS vs LHCb comparisons:

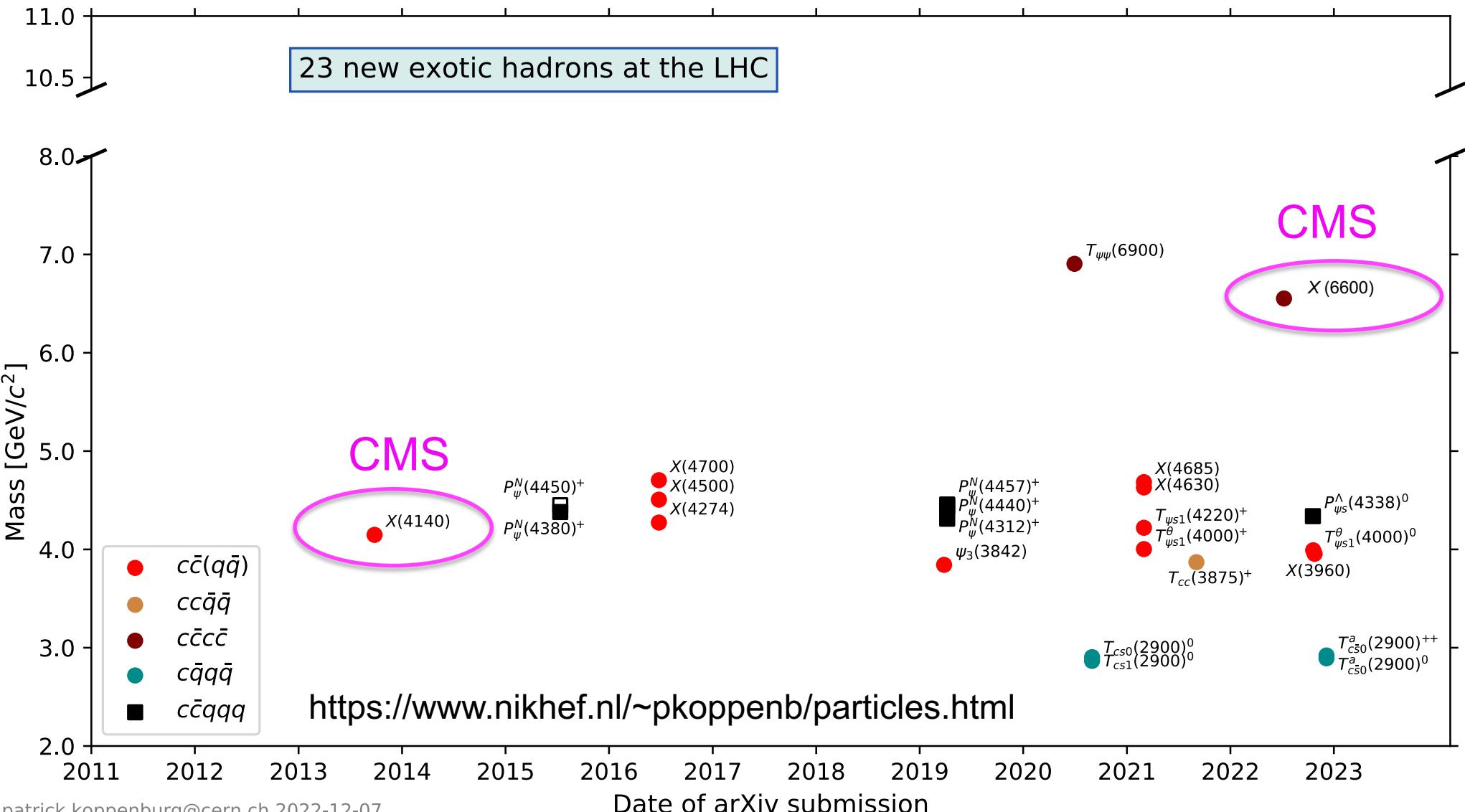
- $135/(3+6) \approx 15X$  (int. lum.)
- $(5/3)^4 \approx 8X$  (muon acceptance)
- Higher muon  $p_T$  ( $>3.5$  or  $2.0$  GeV vs  $>0.6$  GeV)
- Similar number of final events, but much less DPS
- 2X yield @CMS for X(6900)

- CMS vs ATLAS comparisons:

- ATLAS is  $1/3 - 1/2$  of CMS data (trigger?)
- ATLAS used dR cut—remove high mass events
- ATLAS has slightly worse resolution



# New exotic hadrons at LHC



Zhen Hu

Apr 20, 2023

34





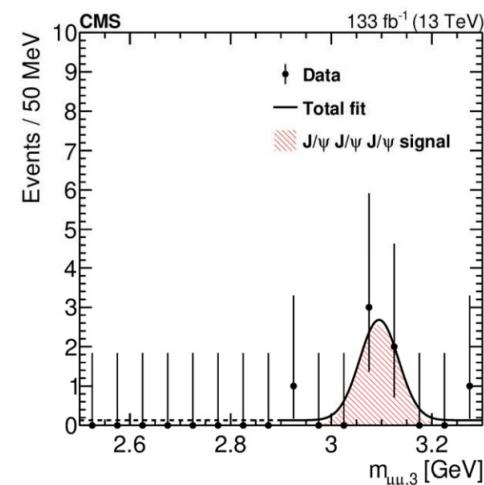
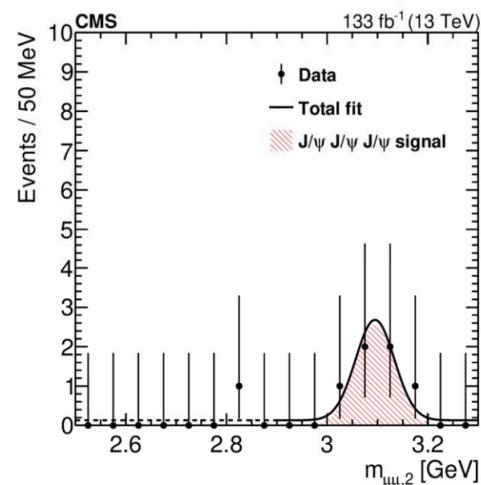
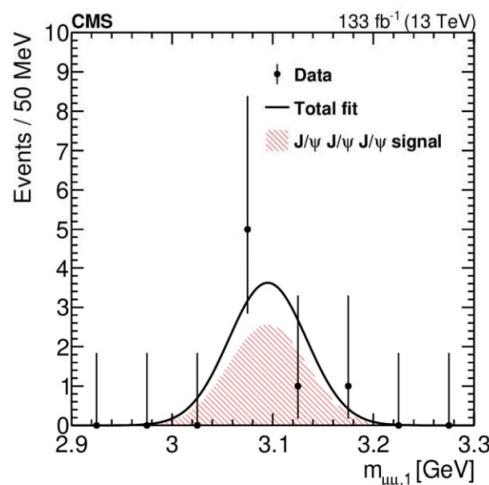
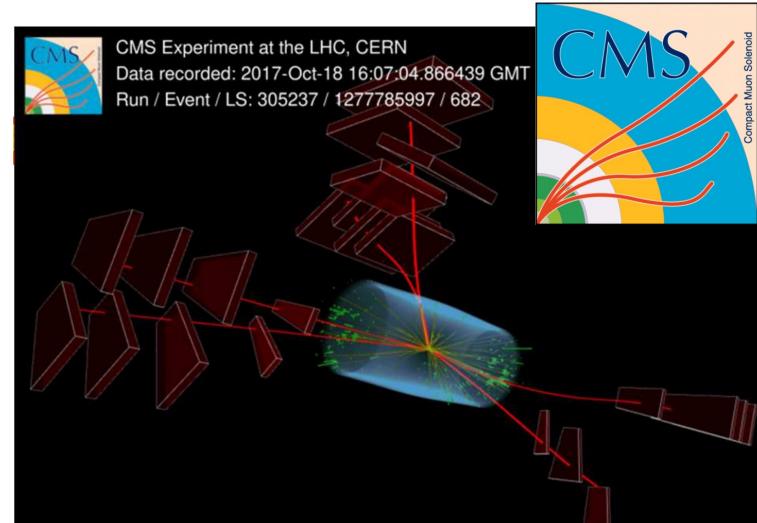
# First observation of triple J/ $\psi$ production

Signal yield:  $5^{+2.6}_{-1.9}$  events

Significance  $> 5\sigma$

$$\begin{aligned}\sigma(pp \rightarrow J/\psi J/\psi J/\psi X) \\ = 272 +141-104 \text{ (stat)} \pm 17 \text{ (syst)} \text{ fb}\end{aligned}$$

*Nature Physics* 19 (2023) 338



**“6c” search in future?**



Zhen Hu

Apr 20, 2023

35





# Summary

- Successful achievement of quarkonium measurements in the past ~10 years @ CMS
- Recently, CMS found 3 significant structures in double J/ $\psi$  mass spectrum
  - X(6900) consistent with LHCb
  - Two new structures seen for the first time, provisionally named as X(6600), X(7300)
  - **A family of structures which are candidates for all-charm tetra-quarks!**
  - Dips in data show possible interference effects
    - More data/knowledge needed to understand nature of near threshold region
- **All-heavy quark exotic structures offer a system easier to understand**
  - A new window to understand strong interaction
- Triple J/ $\psi$  production has also been observed for the first time by CMS





# Backup



Zhen Hu

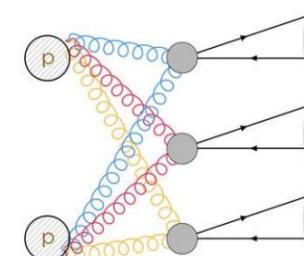
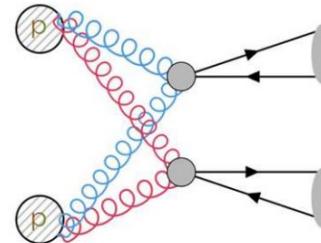
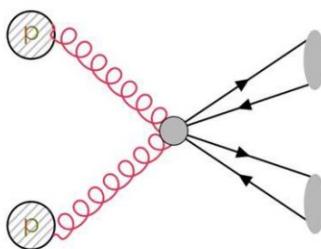
Apr 20, 2023

37



# Associated quarkonium production

- Study interplay of soft QCD with (semi)hard QCD and EW physics
- Sensitivity to perturbative heavy flavor generation and nonperturbative initial and final state effects
  - Initial state: e.g. sensitivity to the concepts of single (SPS), double (DPS) and triple (TPS) parton scattering



parameterized by  $\sigma_{\text{eff}}$

$$\sigma_{\text{DPS}}^{AB} = \frac{1}{1 + \delta_{AB}} \frac{\sigma^A \sigma^B}{\boxed{\sigma_{\text{eff}}}}$$

- Final state: e.g. sensitivity to heavy flavour hadron formation (colour singlet vs. colour octet), sensitivity to resonant multi-heavy-flavor states

# Significance with systematics

- To include systematics, alternative resonance/background shapes applied in the fit.
- Calculate signal- and null-hypothesis  $NLL_{syst}$  including systematic using:

$$NLL_{(syst-sig)} = \text{Min}\{NLL_{(nom-sig)}, NLL_{(alt-i-sig)} + 0.5 + 0.5 \cdot \Delta dof\}$$

- $NLL_{(nom-sig)}$ : the NLL of nominal ‘signal hypothesis’ fit.
- $NLL_{(alt-i-sig)}$ : the NLL of i-th alternative fit of ‘signal hypothesis’
- $\Delta dof$ : the additional free parameters comparing to the nominal ‘signal hypothesis’ fit.
- $NLL_{(syst-null)} = \text{Min}\{NLL_{(nom-null)}, NLL_{(alt-j-null)} + 0.5 + 0.5 \cdot \Delta dof\}$
- Significance including systematics as usual from  $NLL_{(syst-null)} - NLL_{(syst-sig)}$

	Significance with syst.
BW1	$5.7\sigma$
BW2	<i>no sensible changes</i>
BW3	<i>no sensible changes</i>



# Line shape

- S-wave relativistic Breit-Wigner (used in default fit):

$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)}, \text{ where } \Gamma(m) = \Gamma_0 \frac{qm_0}{q_0 m},$$

$q$  is the momentum of a daughter in the mother particle rest frame;  $q_0$  means the value at peak position ( $m = m_0$ ).

- NRSPS and NRDPS:

$$f_{NRSPS}(x, x_0, \alpha, p_1, p_2, p_3)$$

$$= (x - x_0)^\alpha \cdot \left( 1 - \left( \frac{1}{(15 - x_0)^2} - \frac{p_1}{10} \right) \cdot (15 - x)^2 \right) \cdot \exp \left( -\frac{(x - x_0)^{p_3}}{2 \cdot p_2^{p_3}} \right),$$

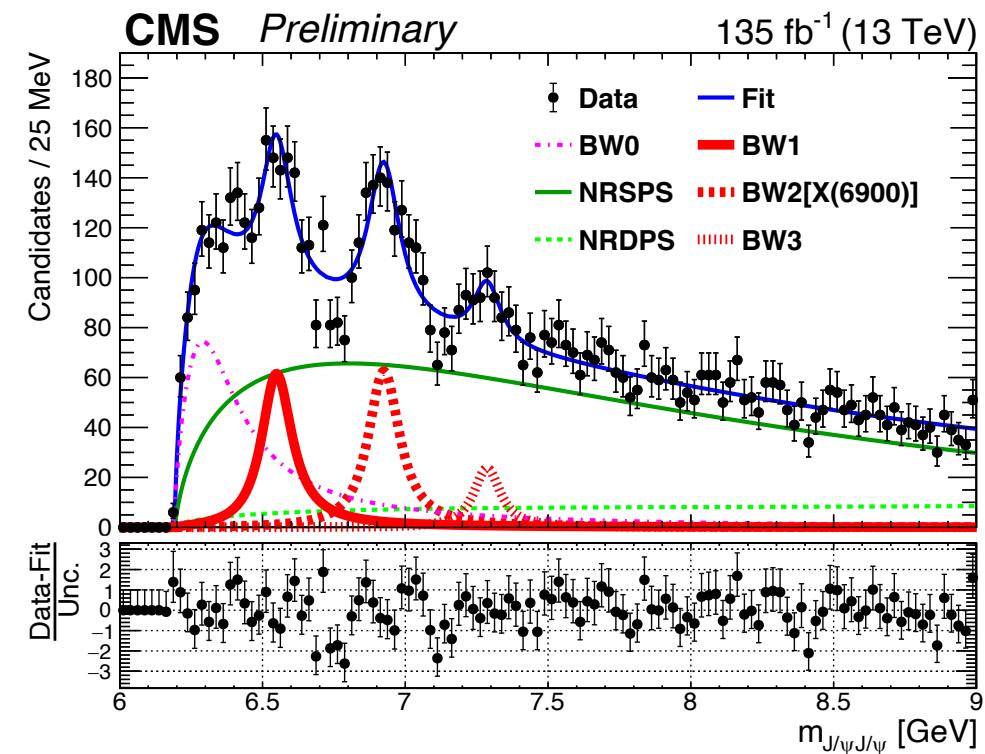
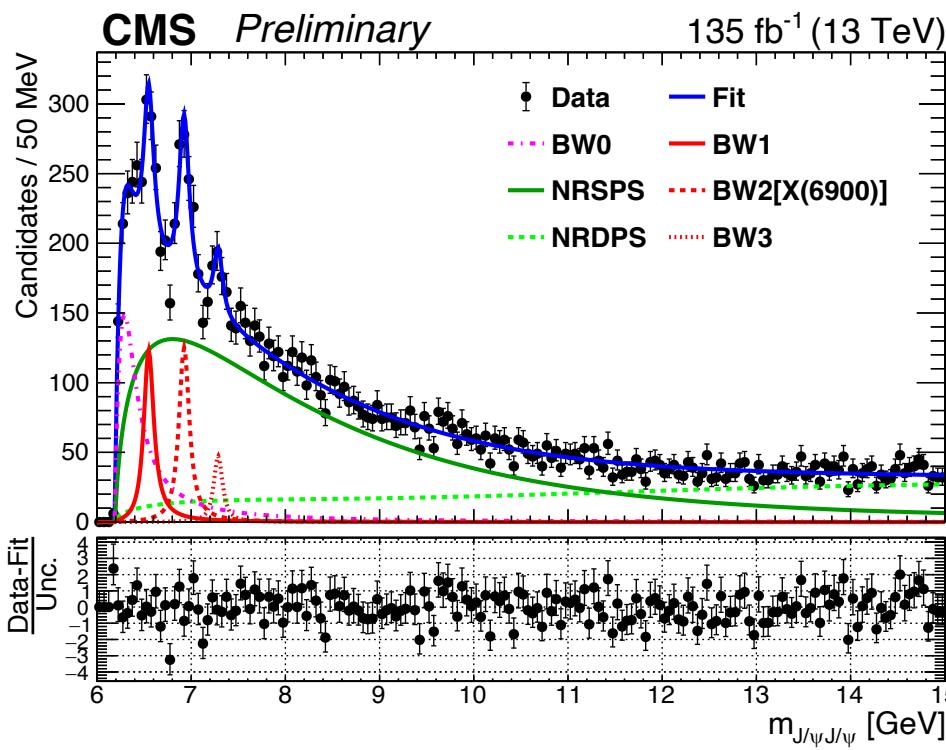
$$f_{NRDPS}(x, a, p_0, p_1, p_2) = \sqrt{x_t} \cdot \exp(-a \cdot x_t) \cdot (p_0 + p_1 \cdot x_t + p_2 \cdot x_t^2),$$

$$\text{where } x_0 = 2m_{J/\psi}, x_t = x - x_0$$





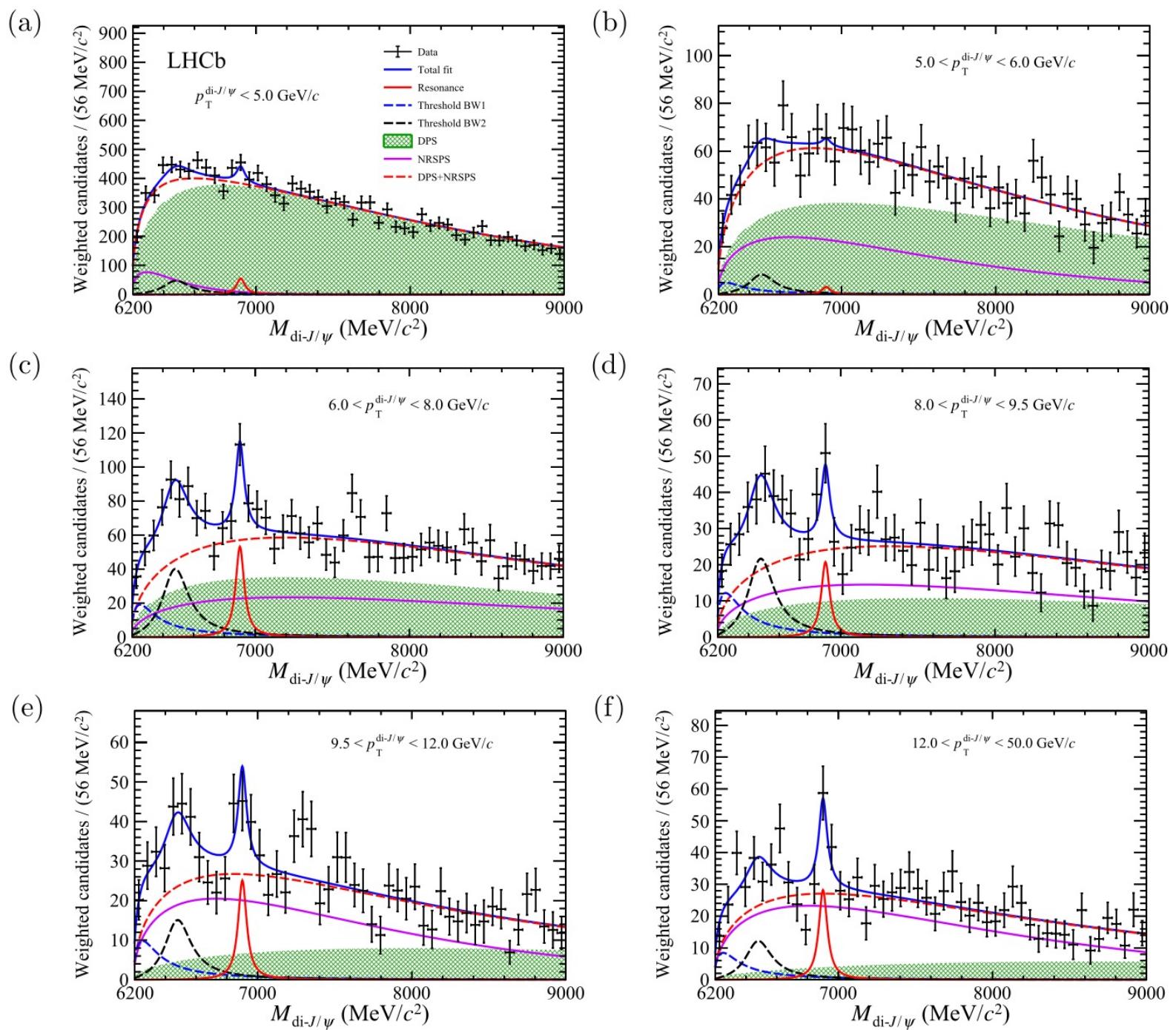
# CMS result with BW0 explicitly shown



Zhen Hu

Apr 20, 2023





**Fig. 4.** Invariant mass spectra of weighted di- $J/\psi$  candidates in bins of  $p_T^{\text{di-}J/\psi}$  and overlaid projections of the  $p_T^{\text{di-}J/\psi}$ -binned fit with model I.