



Latest results on exotic hadrons from CMS

Nanjing Normal University & Tsinghua University

Jingqing Zhang

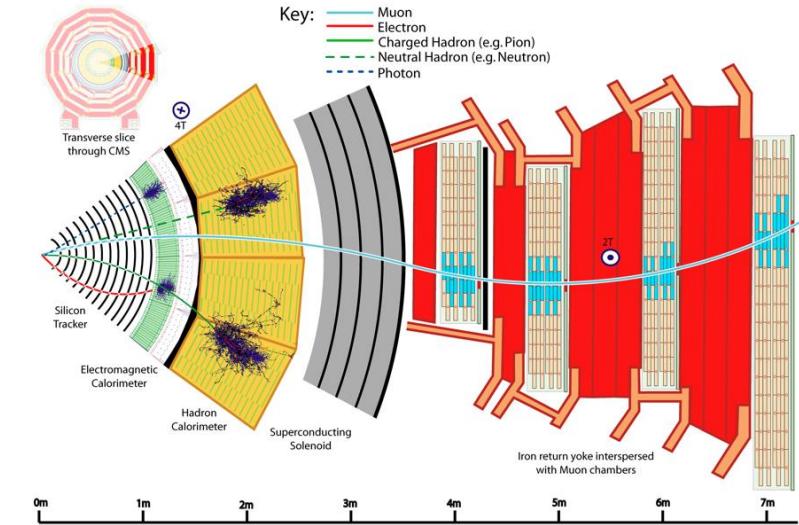
On behalf of CMS Collaboration



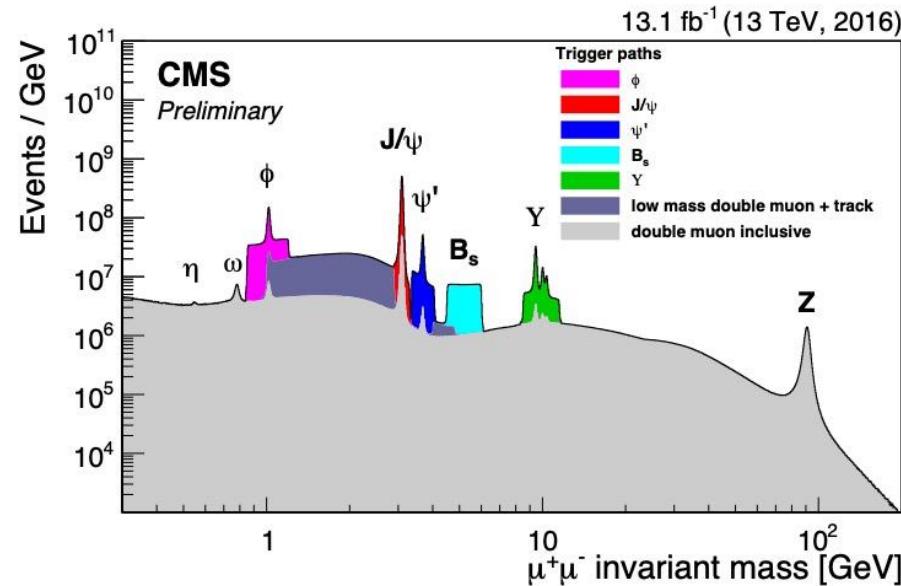
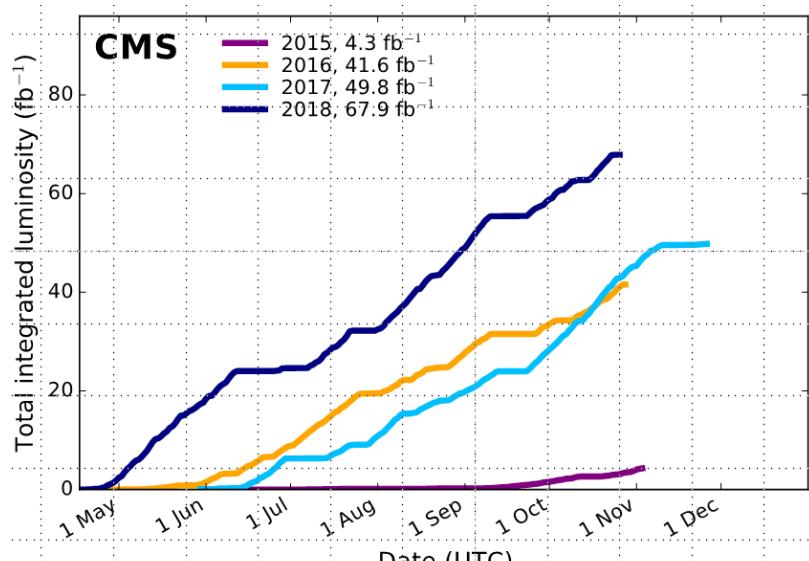
21st Conference on Flavor Physics and CP Violation (FPCP 2023)

Lyon, 2023.05.29 – 2023.06.02

CMS detector & trigger



η coverage (track & muon): [-2.5, 2.5]

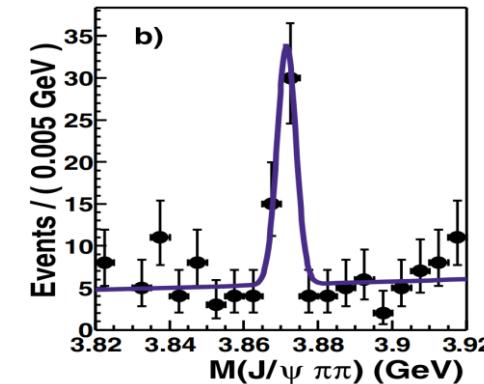


Excellent detector for (exotic) quarkonium

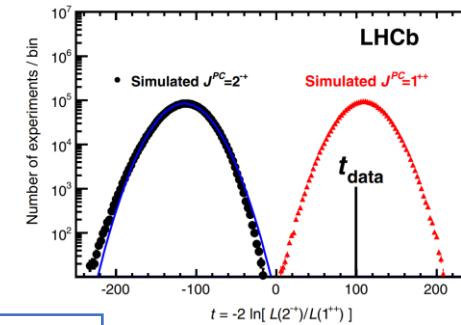
- Muon system
High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ
- Silicon tracking detector
 $B = 3.8$ T, $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution
- Special triggers for different analyses at increasing int. lumi
Requirements on μ & $\mu^+\mu^-$ pT, mass and vertex of $\mu^+\mu^-$, and addition muon

First observation of $B_S^0 \rightarrow X(3872)\phi$

- $X(3872)$ discovered in 2003 by Belle
- $J^{PC} = 1^{++}$
- $\pi^+\pi^-$ favors from ρ^0
- However, nature still not clear

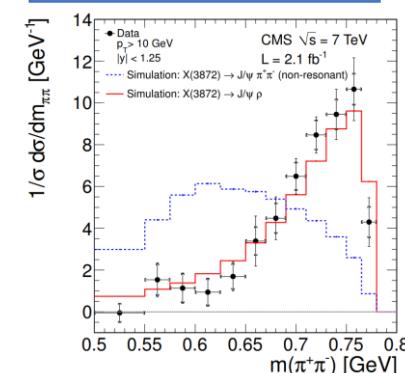


PRL91.262001(2003)

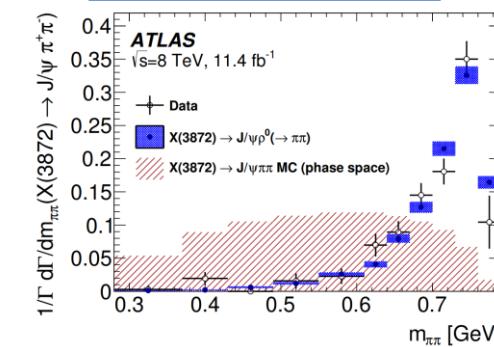


PRL110.222001(2013)

JHEP04.154(2013)



JHEP01.117(2017)



First observation of $B_s^0 \rightarrow X(3872)\phi$

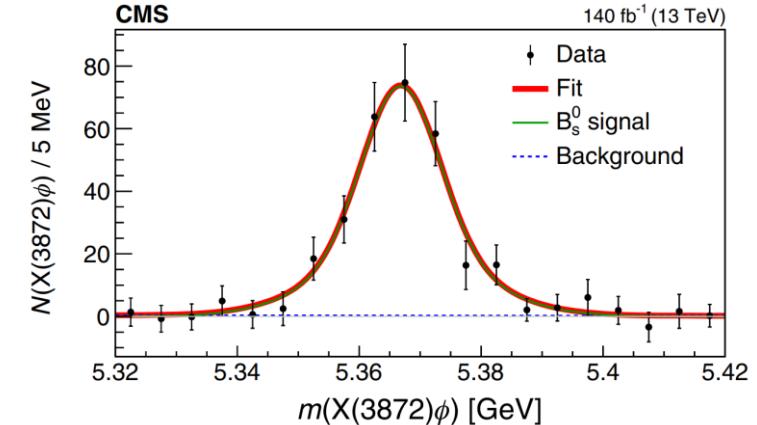
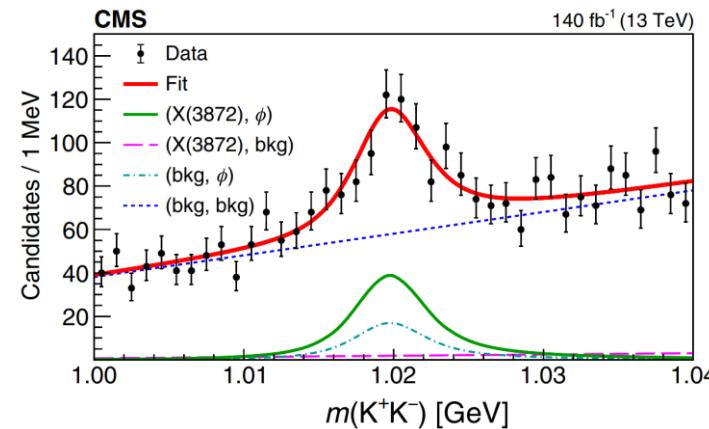
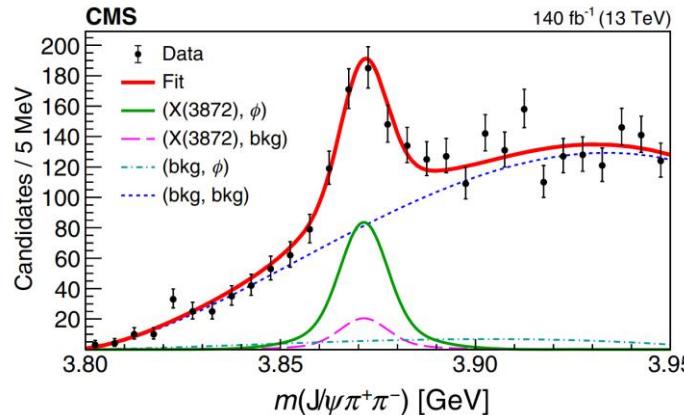
- CMS observed $B_s^0 \rightarrow X(3872)\phi$ decay for the first time PRL125.152001(2020)
 - 140 fb⁻¹ data collected in 2016-2018
 - $B_s^0 \rightarrow J/\psi\pi^+\pi^-\phi, J/\psi \rightarrow \mu^+\mu^-, \phi \rightarrow K^+K^-$
 - Branching fraction ratio is measured

$$\begin{aligned} R &\equiv \frac{\mathcal{B}[B_s^0 \rightarrow X(3872)\phi]\mathcal{B}[X(3872) \rightarrow J/\psi\pi^+\pi^-]}{\mathcal{B}[B_s^0 \rightarrow \psi(2S)\phi]\mathcal{B}[\psi(2S) \rightarrow J/\psi\pi^+\pi^-]} \\ &= \frac{N[B_s^0 \rightarrow X(3872)\phi]}{N[B_s^0 \rightarrow \psi(2S)\phi]} \frac{\epsilon_{B_s^0 \rightarrow \psi(2S)\phi}}{\epsilon_{B_s^0 \rightarrow X(3872)\phi}}. \end{aligned}$$

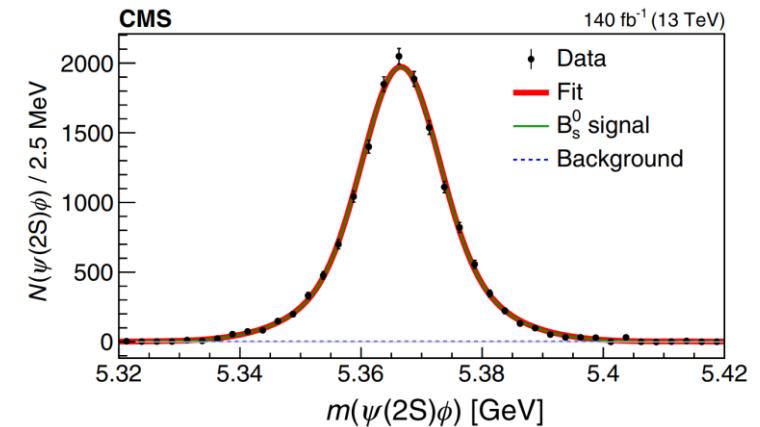
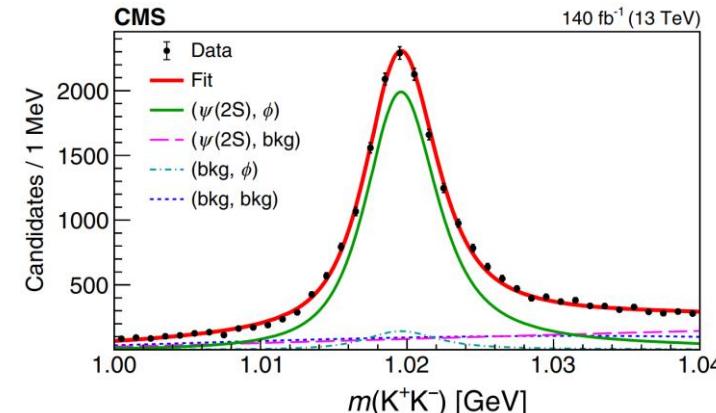
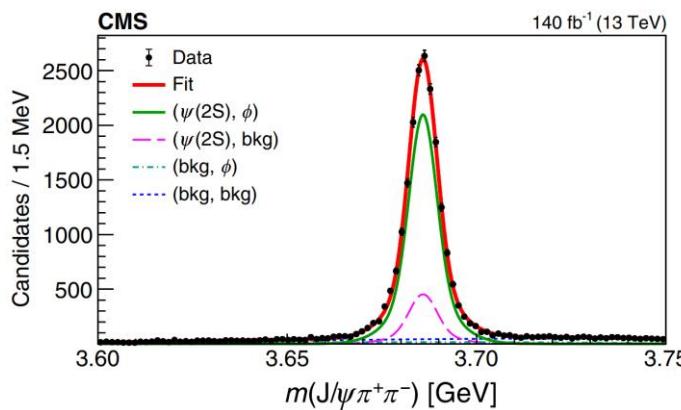
First observation of $B_s^0 \rightarrow X(3872)\phi$

PRL125.152001(2020)

- Yields of signal channel



- Yields of reference channel



First observation of $B_s^0 \rightarrow X(3872)\phi$

PRL125.152001(2020)

- BF ratio

$$R = [2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst})]\%$$

$$\begin{aligned} R &\equiv \frac{\mathcal{B}[B_s^0 \rightarrow X(3872)\phi] \mathcal{B}[X(3872) \rightarrow J/\psi\pi^+\pi^-]}{\mathcal{B}[B_s^0 \rightarrow \psi(2S)\phi] \mathcal{B}[\psi(2S) \rightarrow J/\psi\pi^+\pi^-]} \\ &= \frac{N[B_s^0 \rightarrow X(3872)\phi]}{N[B_s^0 \rightarrow \psi(2S)\phi]} \frac{\epsilon_{B_s^0 \rightarrow \psi(2S)\phi}}{\epsilon_{B_s^0 \rightarrow X(3872)\phi}}. \end{aligned}$$

- $\mathcal{B}[B_s^0 \rightarrow X(3872)\phi] \mathcal{B}[X(3872) \rightarrow J/\psi\pi^+\pi^-]$
 $= (4.14 \pm 0.54(\text{stat}) \pm 0.32(\text{syst}) \pm 0.46(\mathcal{B})) \times 10^{-6}$
 - Consistent with that for B^0
 - Two times smaller than that for B^+
- BF ratios of $B_s^0/B^0/B^+ \rightarrow X(3872)\phi/K$ different to those to $\psi(2S)\phi/K$
 - $X(3872)$ not a pure charmonium state

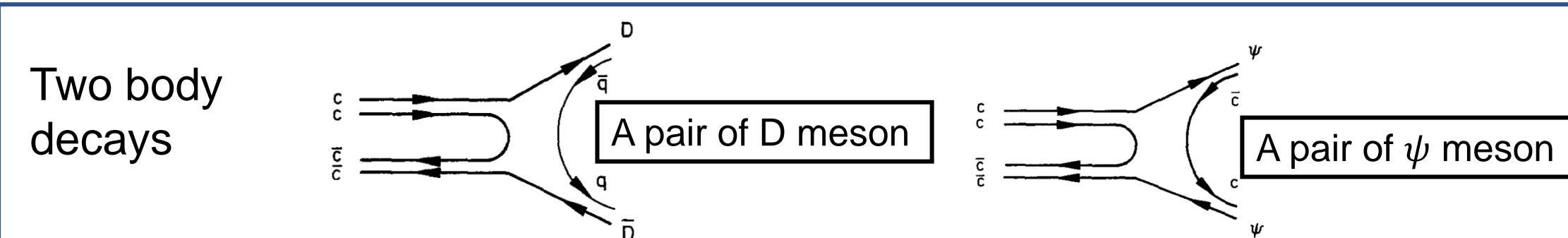
New Domain of Exotics: All-heavy Tetra-quarks

- First mention of 4c states: Y. Iwasaki, Prog. Theo. Phys. 54, 492 (1975)
- First calculation of 4c states: K.-T. Chao, Z. Phys. C 7, 317 (1981)

J^{PC} & mass

L	S	J^{PC}	$(cc)_{\underline{3}}^* - (\overline{cc})_{\underline{3}}$	Mass (GeV)
1	0	1^{--}	$(cc)_{\underline{3}}^* - (\overline{cc})_{\underline{3}}$	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	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$		

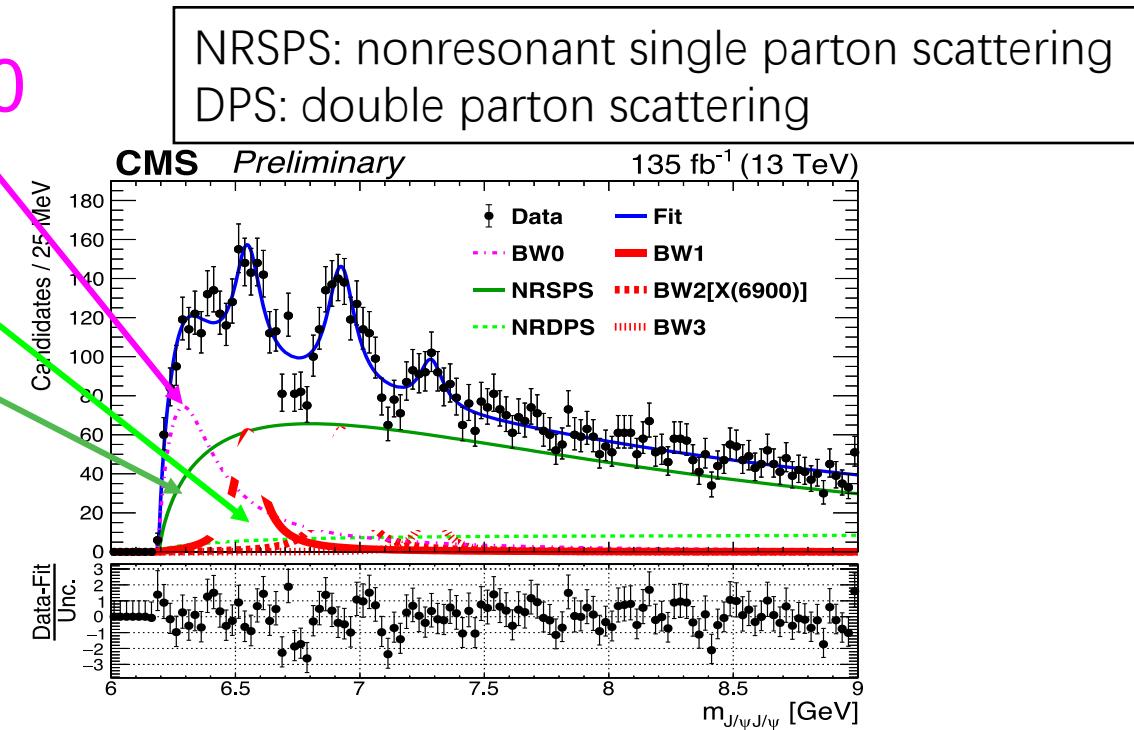
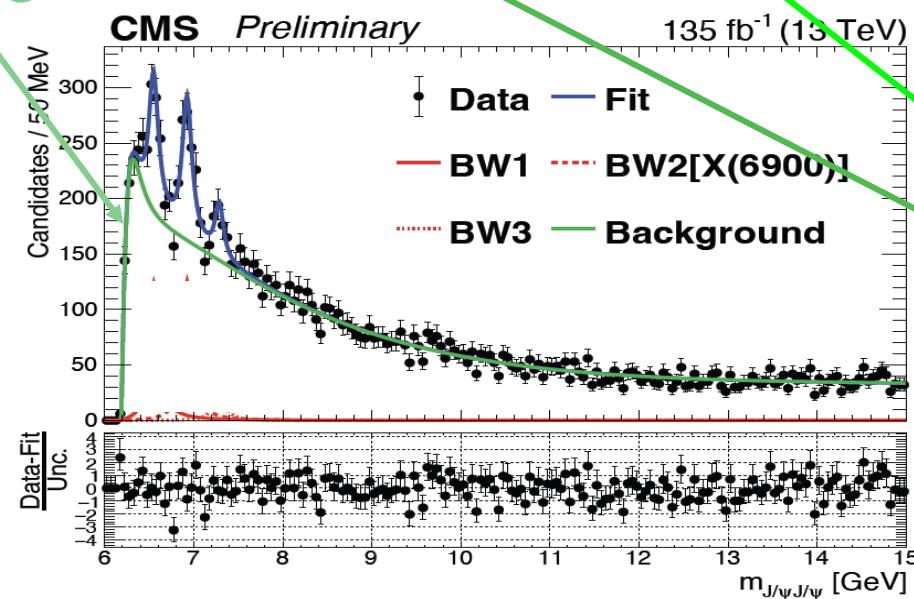
L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.82
2	0	2^{++}	7.15
3	0	3^{--}	7.41



Observation of structures in $J/\psi J/\psi$ mass spectrum

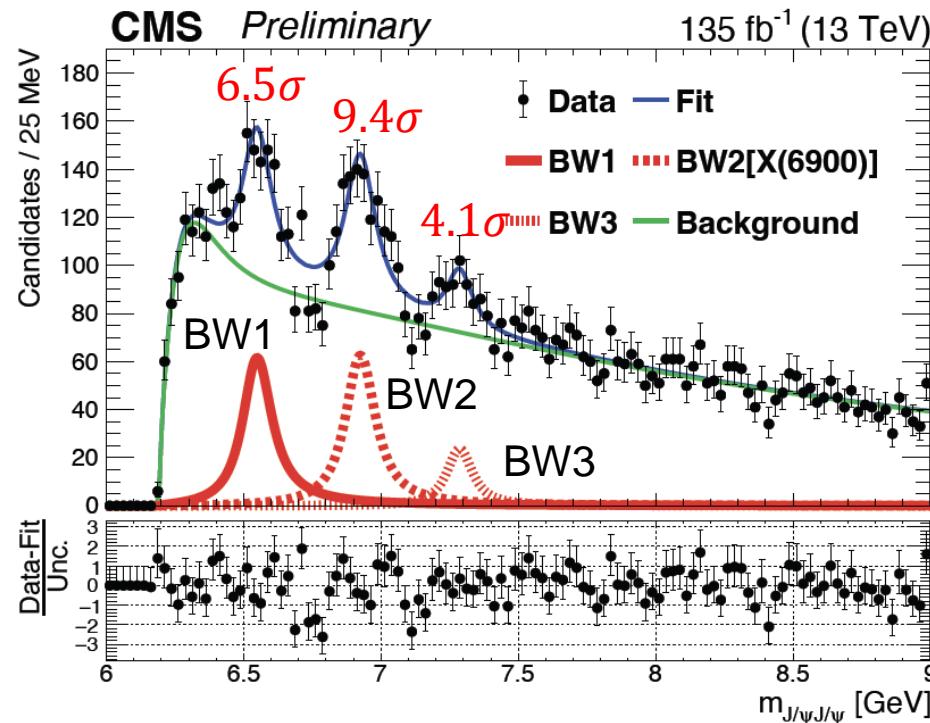
- 135 fb^{-1} data collected in 2016-2018
- Blind [6.2, 7.8] GeV when determine event selection
- Background = NRSPS + DPS + BW0

CMS-PAS-BPH-21-003



- Treat BW0 (significant structure) as part of background
 - Inadequacy of our NRSPS model at threshold
 - BW0 parameters are sensitive to other model assumptions
 - A region populated by feed-down, e.g., $X(6900) \rightarrow J/\psi J/\psi(2S) \rightarrow J/\psi J/\psi \pi\pi$

Fit result of $J/\psi J/\psi$ structures



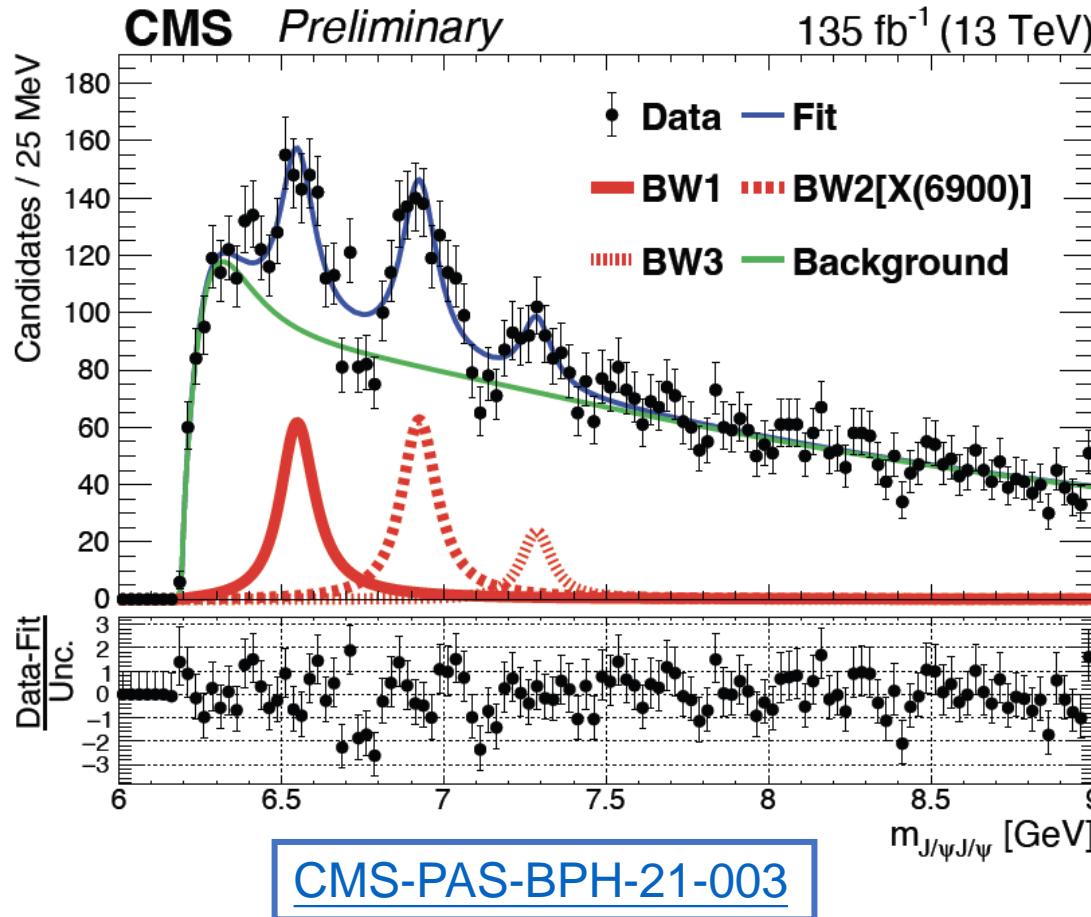
CMS-PAS-BPH-21-003

	BW1	BW2	BW3
M (MeV)	6552 ± 10	6927 ± 9	7287 ± 19
Γ (MeV)	124 ± 29	122 ± 22	95 ± 46
N	474 ± 113	492 ± 75	156 ± 56
Significance (Stat. only)	6.5σ	9.4σ	4.1σ

No-interference fit

- Confirmation of BW2 [X(6900)] -- 9.4σ
- Observation of BW1 -- 6.5σ
- Evidence of 4.1σ
- Significance base on likelihood ratio: $2\ln L_0/L_{\max}$

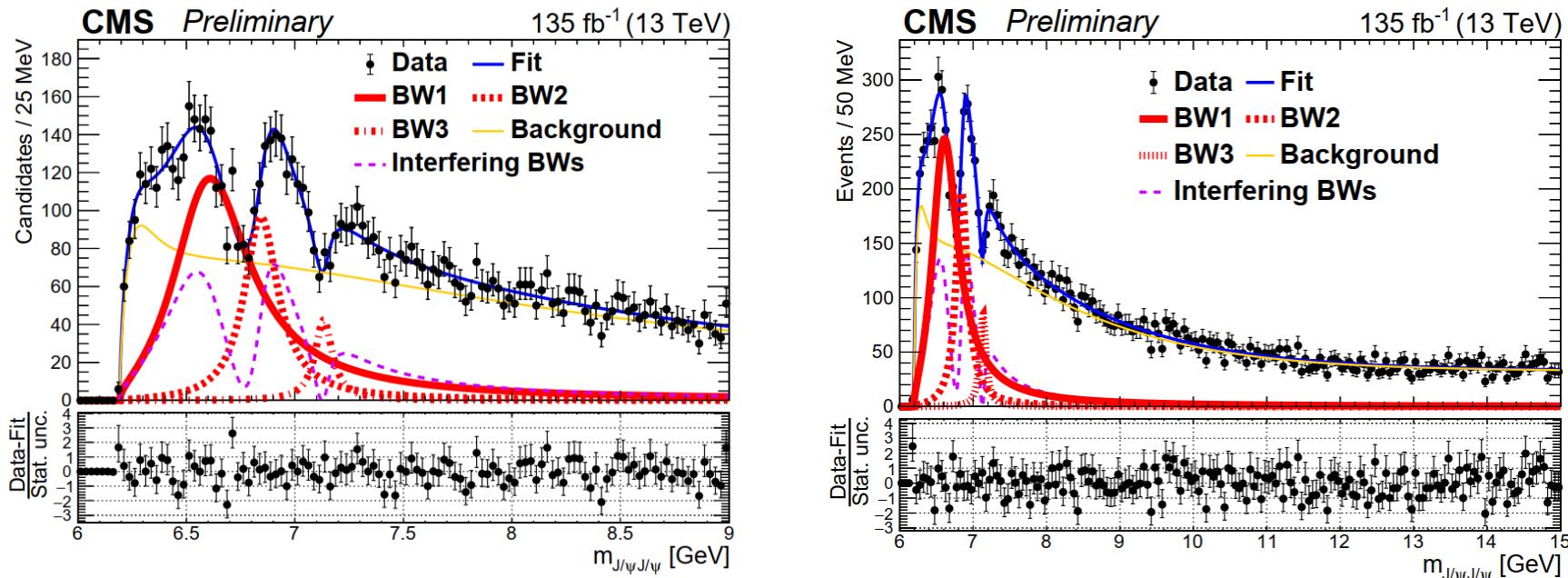
The dips in data



- Possibility #1
 - Interference among structures?
 - Possibility #2
 - Multiple fine structures to make dips?
 - Mentioned in PAS
 - More secrets to dig out
- ✓ We explored #1 in detail

Fit with interference

- Fit with interference among BW1, BW2, BW3 describes data well



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

CMS results of $J/\psi J/\psi$ structures

No-interference

CMS-PAS-BPH-21-003

Interference

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

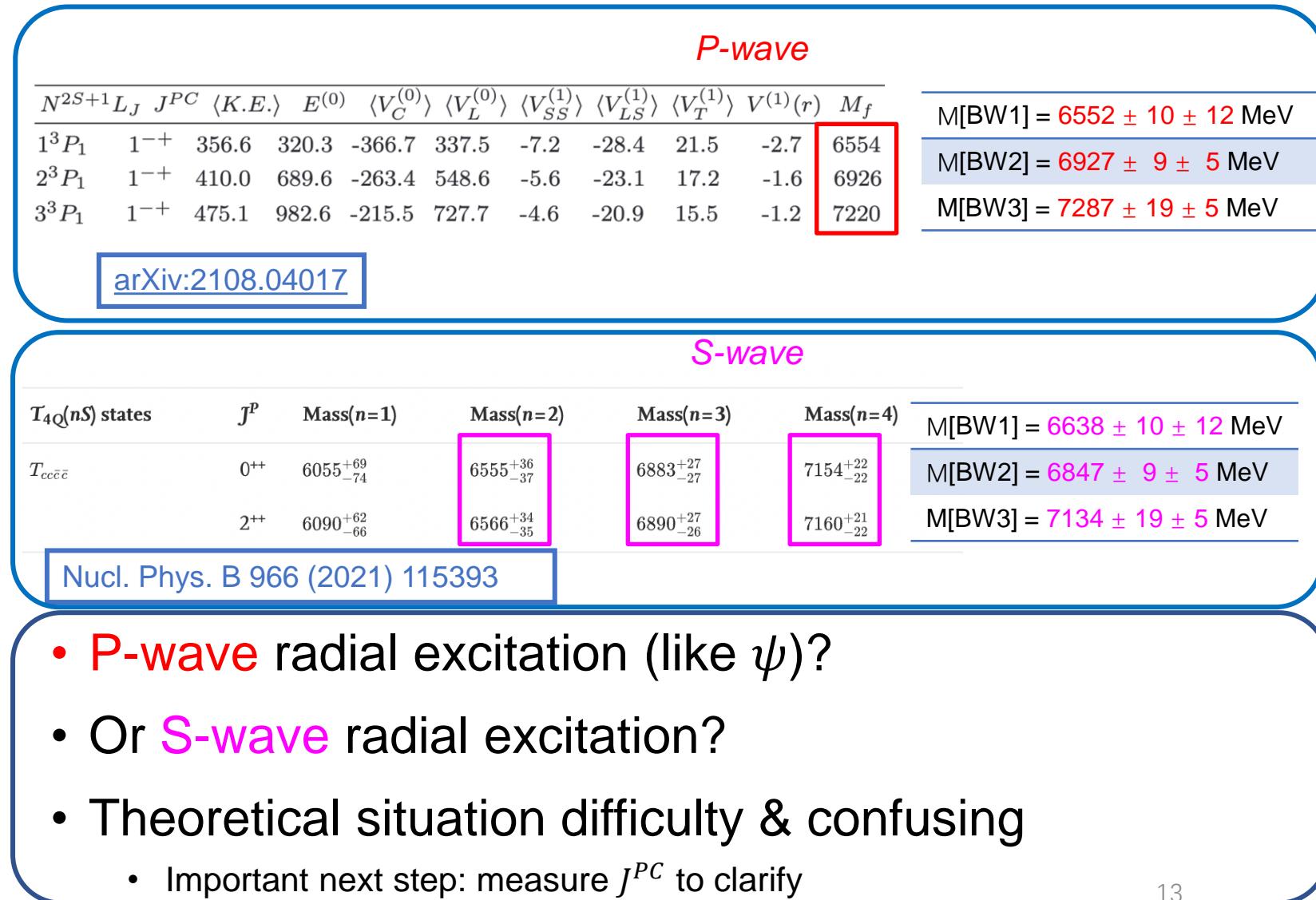
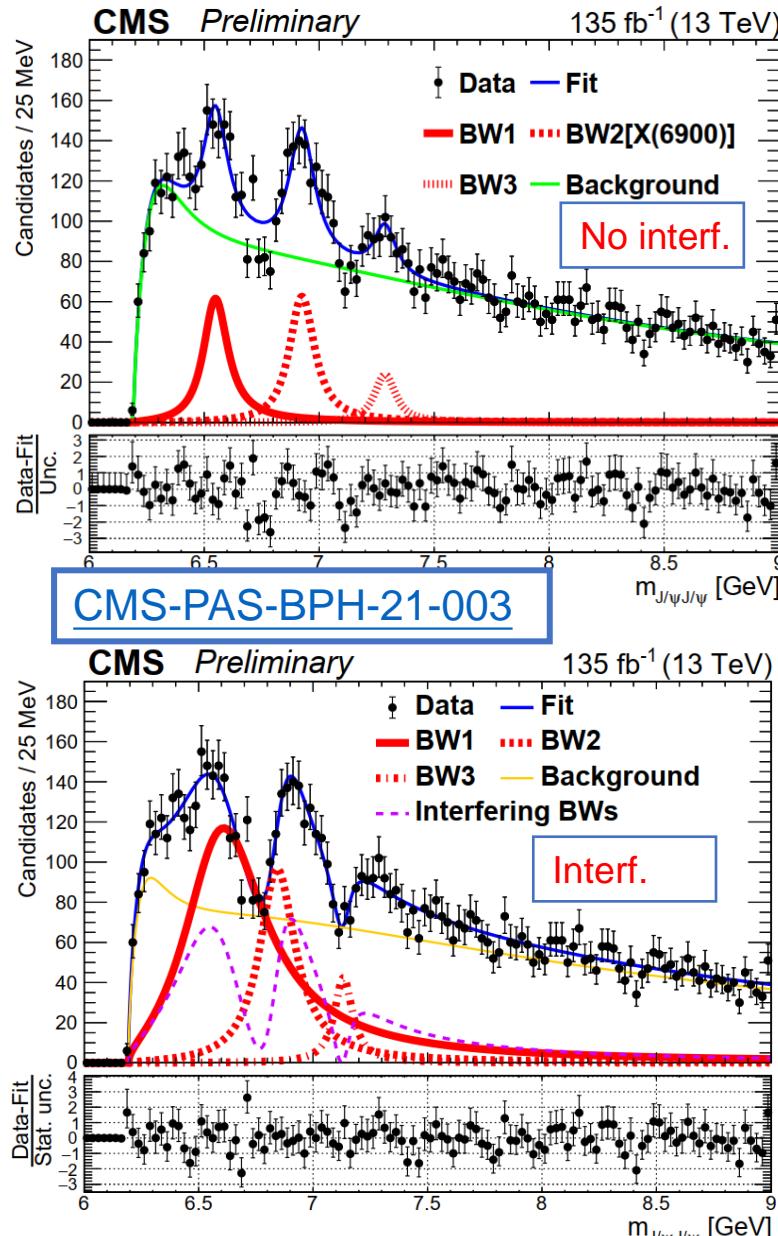
	BW1	BW2	BW3
m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
Γ [MeV]	$444^{+226+109}_{-199-235}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

Source	ΔM_{BW1}	ΔM_{BW2}	ΔM_{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

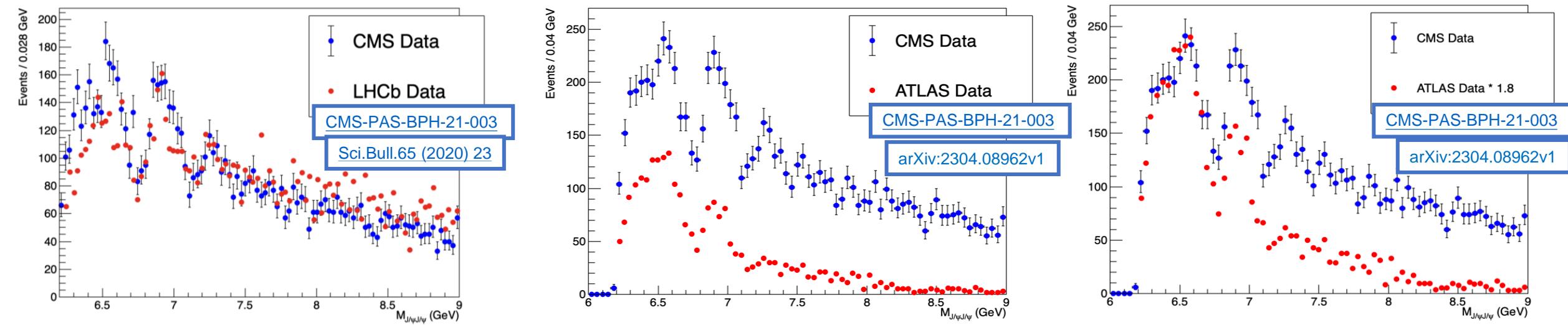
Dominant sources	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta \Gamma_{BW1}$	$\Delta \Gamma_{BW2}$	$\Delta \Gamma_{BW3}$
Signal shape	7	12	7	56	8	7
NRDPS	1	3	2	18	6	2
NRSPS	9	14	13	85	9	20
Resolution	8	4	1	24	7	13
Combinatorial bkg.	7	2	< 1	5	3	2
Feeddown shape	-27	+44	+38	-208	+19	+12
Full uncertainty	+16	+48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

- Large mass difference ($\sim 200\text{-}300$ MeV) indicates radial excitation
- Implication of interference fit
 - Same production mechanism
 - Same J^{PC}
- Any theoretical prediction?

Comparison with some theoretical predictions



Comparison with ATLAS & LHCb



- CMS vs. LHCb

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

[Sci.Bull.65 \(2020\) 23](#)

- $135/9 \approx 15X$ (Int. lumi.)
- $(5/3)^4 \approx 8 X$ (muon acceptance)
- Higher muon pT ($>3.5, 2.0$ GeV vs. > 0.6 GeV)
- Similar final events, but much less DPS
- $\sim 2X$ yield of X(6900) at CMS

- CMS vs. ATLAS

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

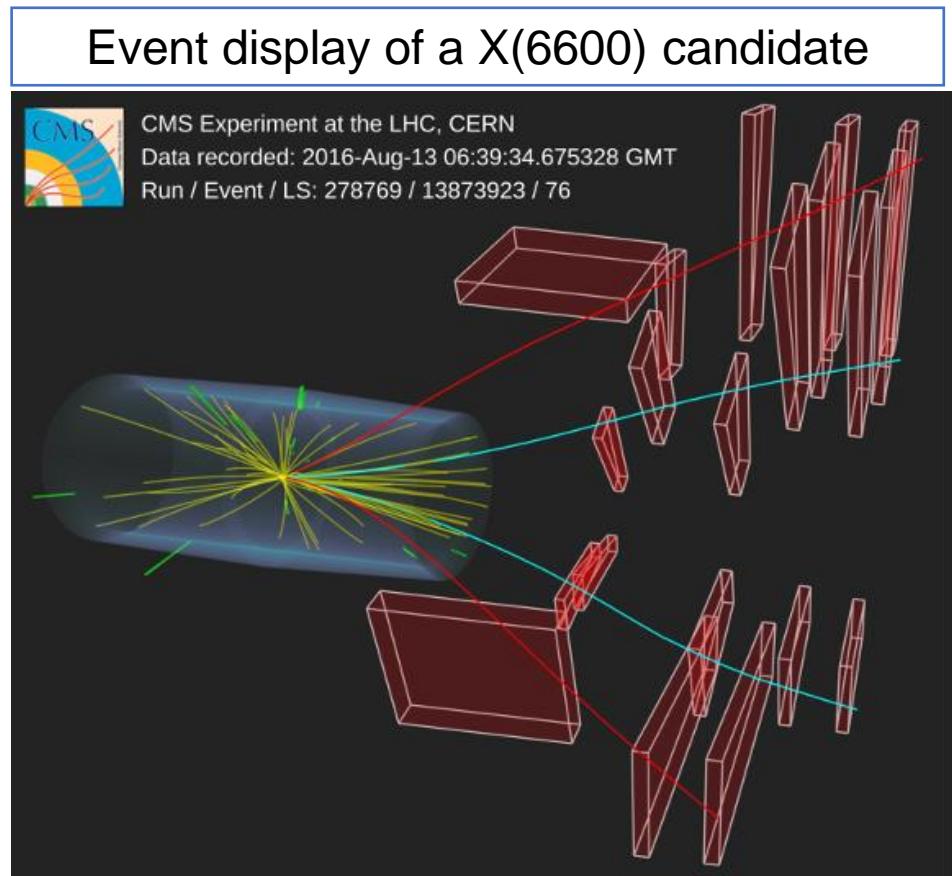
[arXiv:2304.08962v1](#)

- ATLAS is $1/3\sim 1/2$ of CMS data (trigger?)
- ATLAS applied ΔR cut, removed events in high mass
- CMS has slightly better mass resolution

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

Summary

- Observation of $B_S^0 \rightarrow X(3872)\phi$, first time!
- Observation of structures in $J/\psi J/\psi$, $X(6900)$ and new ones!

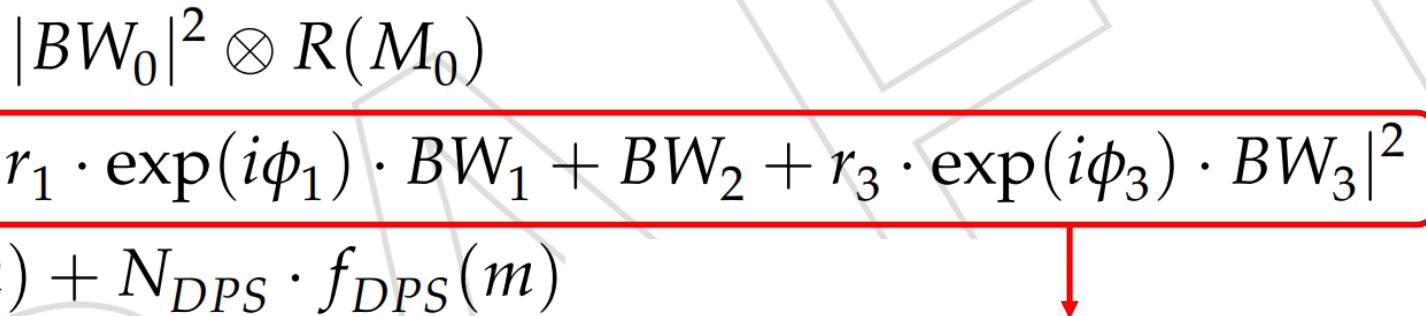


Thanks!

Backup

Interference PDF

- PDF of three interfering BWs

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


- Possible of interference with different J^{PC}
 - Two-way (two BWs) interference, three-way, four-way