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

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On behalf of the CMS collaboration

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New Domain of Exotics: All-Heavy Tetra-quarks

- Exotic hadrons (not $q\bar{q}$ or qqq) has been explored in theory since quark model proposed by Gell-Mann and Zweig, and they provide an unique environment to study the strong interaction and confinement
- First mention of 4c states at 6.2 Gev (1975): Prog. of Theo. Phys. Vol. 54, No. 2

  (Just one year after the discovery of J/ψ)
- 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	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

$(cc)_{\underline{3}}* - (\overline{cc})_{\underline{3}}$

$(cc)_{\underline{6}} - (\overline{cc})_{\underline{6}}*$

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

- 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 $\eta_b\eta_b$ threshold
  - Consistent on existence of resonant states above $\eta_b\eta_b$ threshold

Tetra-quark in four-muon final state

- LHCb observed X(6900) in di-J/ψ mass spectrum in 2020

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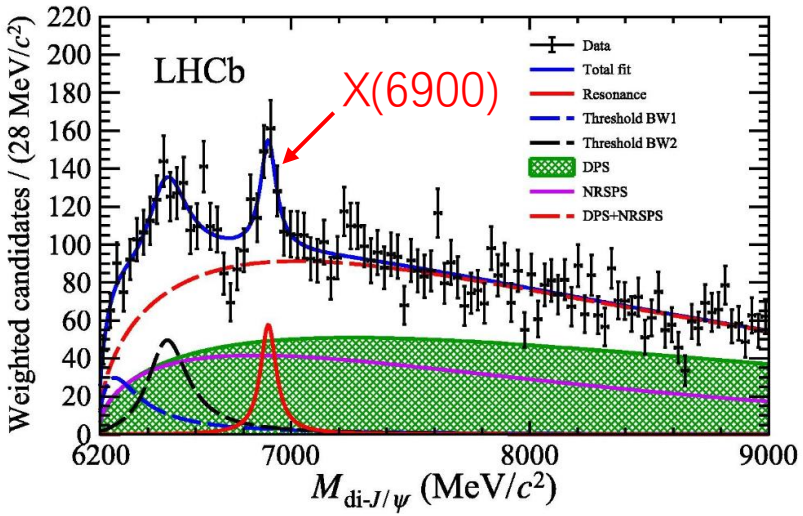
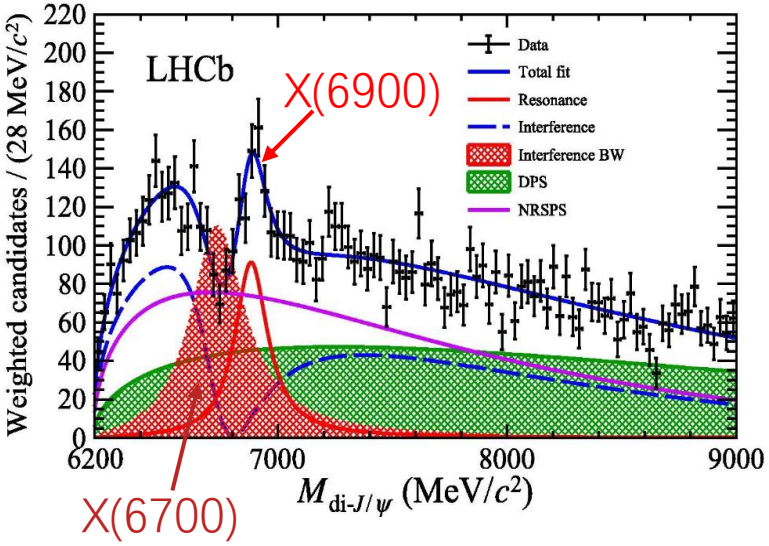
Model I: no interf.



Model II: X(6700) interf. with NRSPS



- This talk presents $J/\psi J/\psi$ mass spectrum study from CMS:

  Observation of new structures in the J/ψJ/ψ mass spectrum in pp collisions at $\sqrt{s}$ = 13 TeV (CMS-PAS-BPH-21-003)

Dataset and MC samples

- Signal: $J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$
- Data: 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs
- Signal MC samples:
  - $J^P = 0^+$ resonance

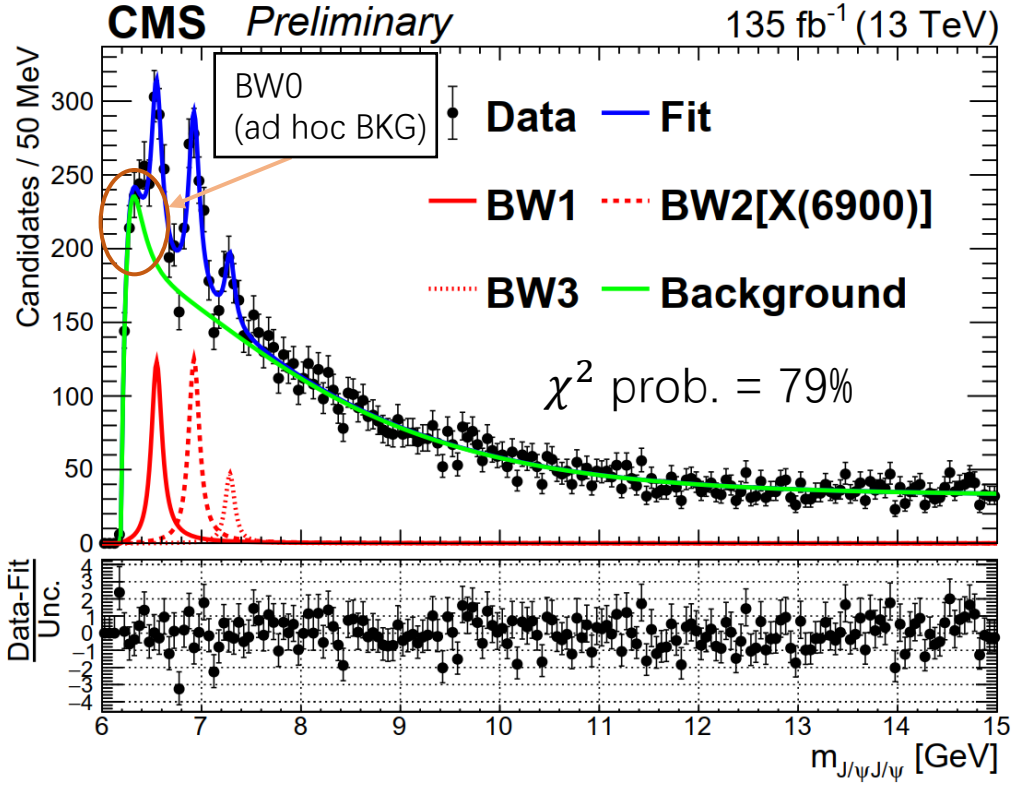
  -- Generator: Pythia8, JHUGen
- Background MC samples:
  - Nonresonant single-parton scattering (NRSPS)

  -- Generator: Pythia8, HelacOnia (next-to-next-to-leading order), Cascade (next-to-leading order)
  - Nonresonant double-parton scattering (NRDPS)

  -- Generator: Pythia8

CMS result

- Signal: S-wave BW convolved with resolution function
- Background: NRSPS, NRDPS, and near threshold BW (BW0)
- Fit always in [6, 15] GeV; also shown in zoomed range

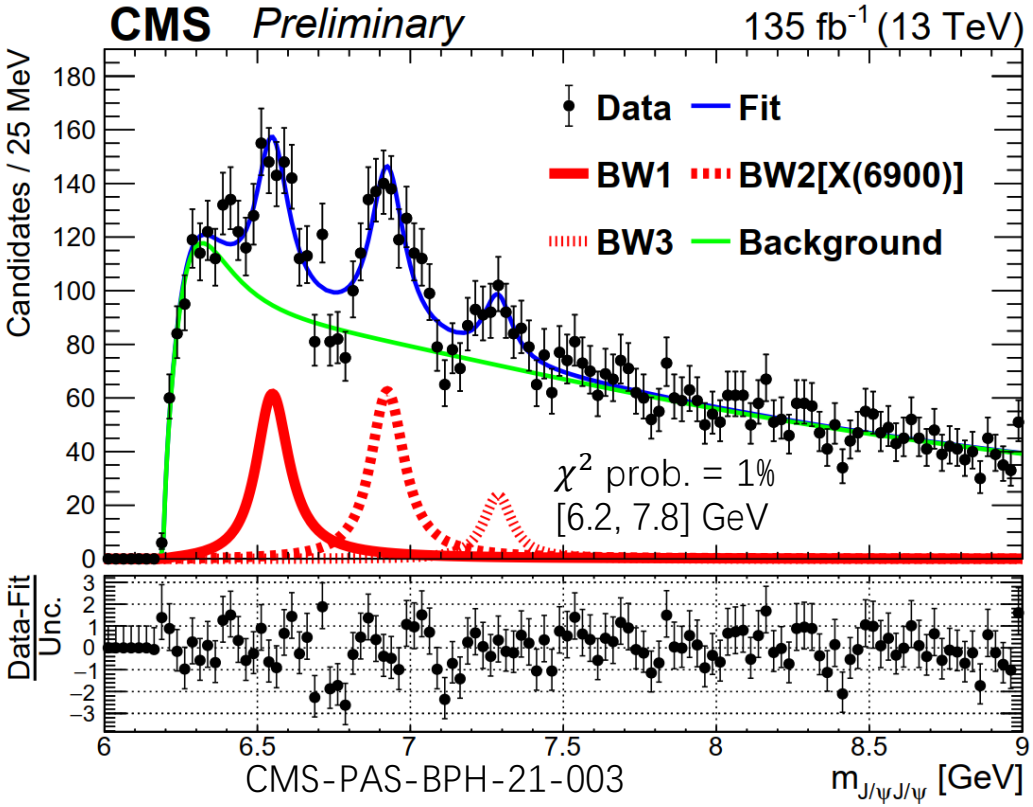


CMS-PAS-BPH-21-003

- BW0 near threshold:
- Significantly needed in the fit
- Various possibilities: resonance, coupled-channel interactions, pomeron exchange processes, inadequacy of our NRSPS model…
- Mass and width vary in a wide range under different situations.
- A region populated by feeddown from possible higher mass states.

➢ Regard BW0 as background

CMS result



Measured m, Γ (in MeV) of BWs

	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

Statistical significance (likelihood ratio test):

- Confirmation of BW2[X(6900)], 9.4σ
- Observation of BW1, 6.5σ
- Evidence of BW3, 4.1σ

- More BW2[X(6900)], CMS vs. LHCb: 492 ± 75 vs. 252 ± 63 (model I)

Systematic uncertainties

- Systematic uncertainties on mass and width

Table 2: Systematic uncertainties on masses and widths, in MeV.

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

- Local significance with syst. uncertainties by a profiling procedure:

  A discrete set of individual alternative signal and background hypotheses tested in minimization
  - BW1 significance: changed from 6.5σ to 5.7σ
  - BW2 and BW3 significance: no relative change

M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV

BW2 consistent with X(6900)

X(6900) in LHCb:

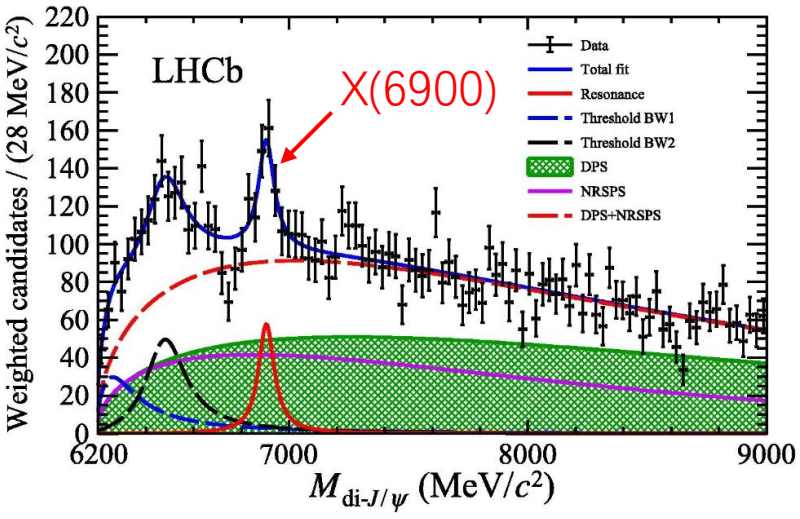
$\mathrm{M} = 6905 \pm 11 \pm 7$ MeV

$\Gamma = 80 \pm 19 \pm 33$ MeV

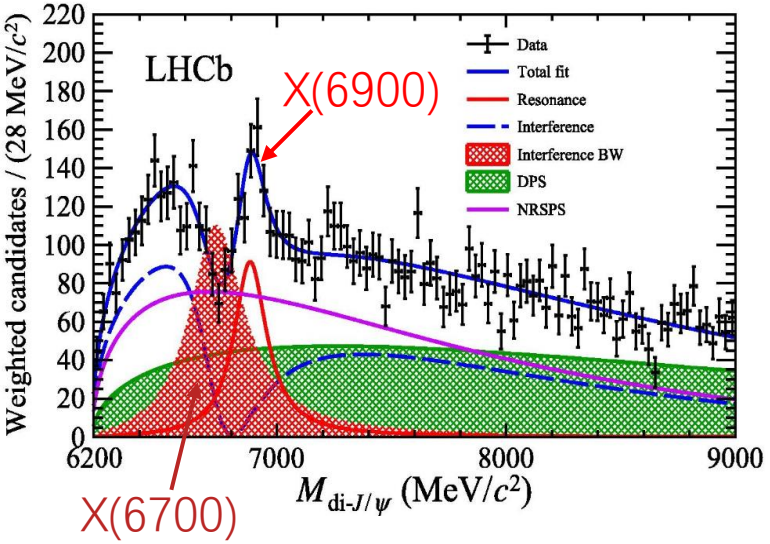
The LHCb models

- LHCb used two models to fit their data in Sci. Bull. 65 (2020) 23
  - Model I: background (NRSPS + NRDPS) + 2 auxiliary BWs + X(6900)
  - Model II: a 'invisible' X(6700) interferes with NRSPS + NRDPS + X(6900)
- We also explored the CMS data with these two LHCb models

Model I: no interf.

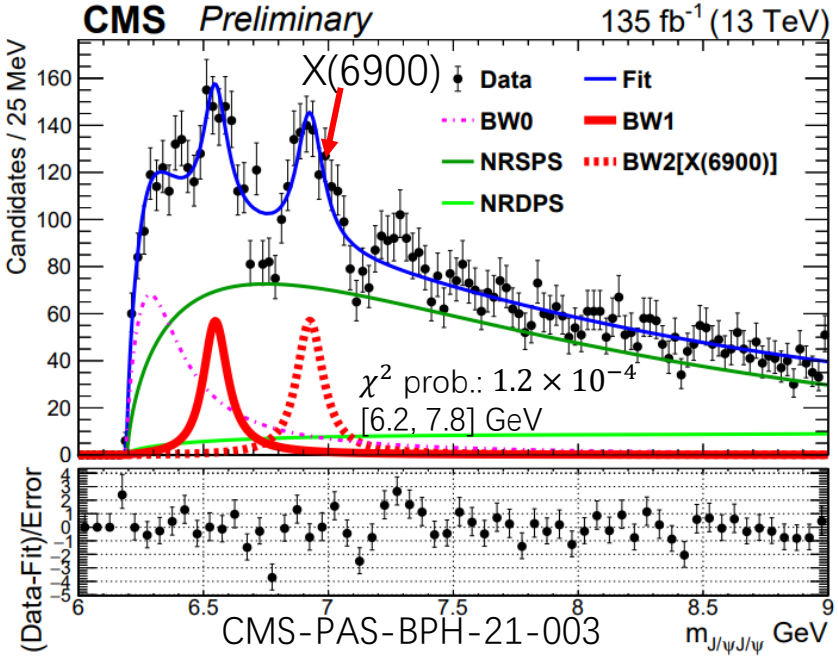


Model II: X(6700) interf. with NRSPS



Fit with LHCb Model I

- NRSPS + NRDPS + 2 auxiliary BWs + X(6900)



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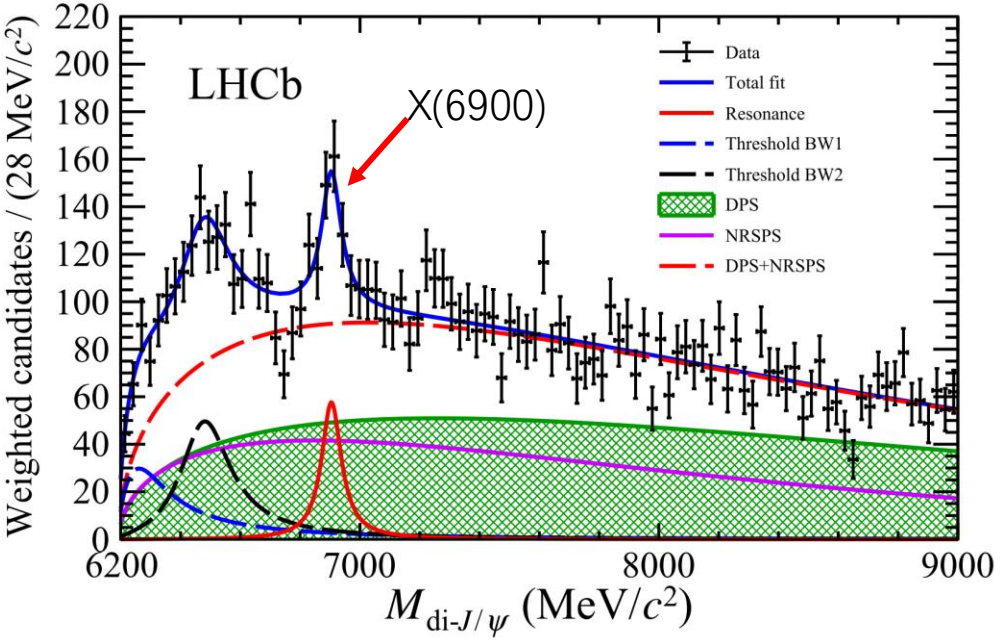


- Similar number of final states; CMS has higher muon pT (> 3.5, 2.0 GeV vs. > 0.6 GeV)

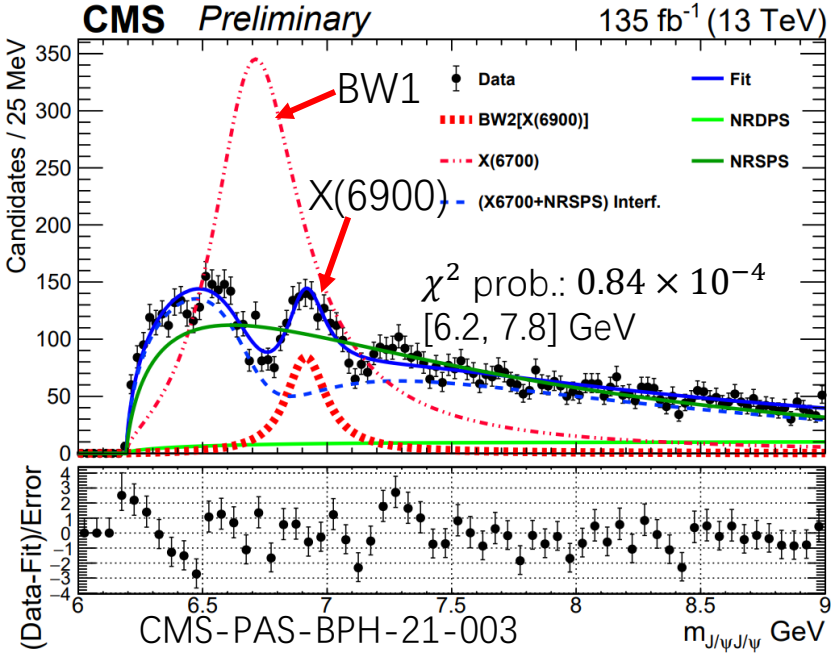
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

Consistent X(6900) mass and width

- CMS data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct
- Does NOT describe well dips

Fit with LHCb model II

- Incoherent sum of X(6900) and NRDPS + coherent sum of X(6700) and NRSPS



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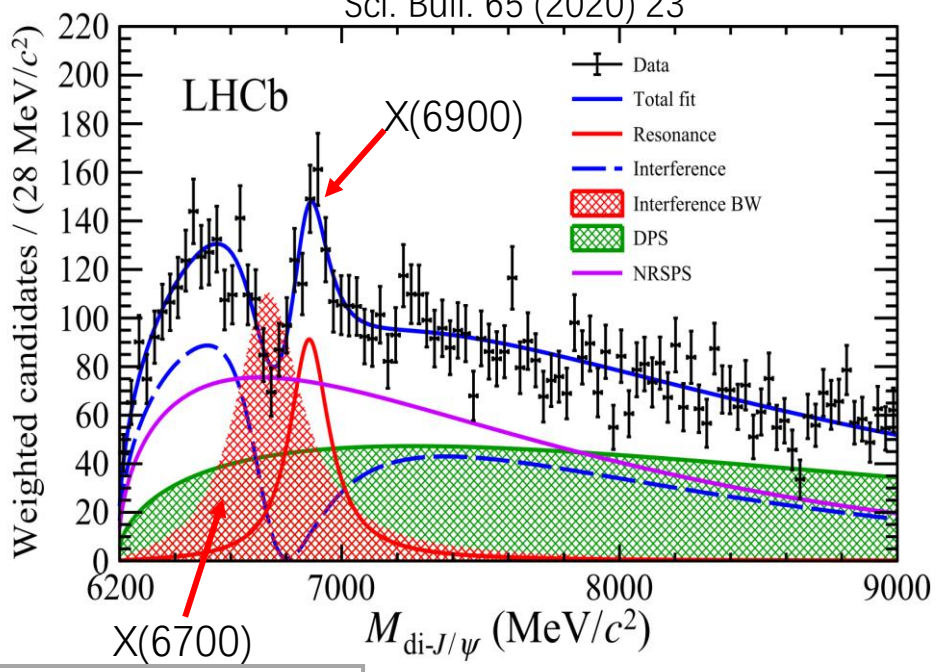

		Interfering BW		Non-interfering BW	
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

Consistent X(6900) mass and width

- CMS obtained larger amplitude and natural width for BW1
- CMS X(6600) is 'eaten' – does not describe X(6600) and below
- Does not describe X(7300) region

Summary

- CMS found 3 structures using 135 fb^{-1} 13 TeV data (CMS-PAS-BPH-21-003)
  https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-003/index.html

M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV	5.7**σ**
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV	9.4**σ**
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV	4.1**σ**

- BW2 consistent with X(6900) reported by LHCb
- Two new structures, provisionally named as X(6600) [BW1], X(7300) [BW3]
- A family of structures which are candidates for all-charm tetra-quarks!

- Dips in data show possible interference effects – under study
- More data/knowledge needed to understand nature of near threshold region

- All-heavy quark exotic structures offer system easier to understand, new window to understand strong interaction

Thank you for your attention