Observations (evidence) of new structure in J/ψJ/ψ ($J/\psi\psi(2S)$) mass spectrum

Speaker:

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New Domain of Exotics: All-Heavy Tetra-quarks

- 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.

Introduction

- Exotic hadrons composed of four ($qq\bar{q}\bar{q}$) or five quarks ($qqq\bar{q}\bar{q}$) predicted by theory They provide an unique environment to study the strong interaction and confinement
- A series of states consistent with containing four quarks have been discovered
- The existence of pentaquark states and their interpretation is not well established so far

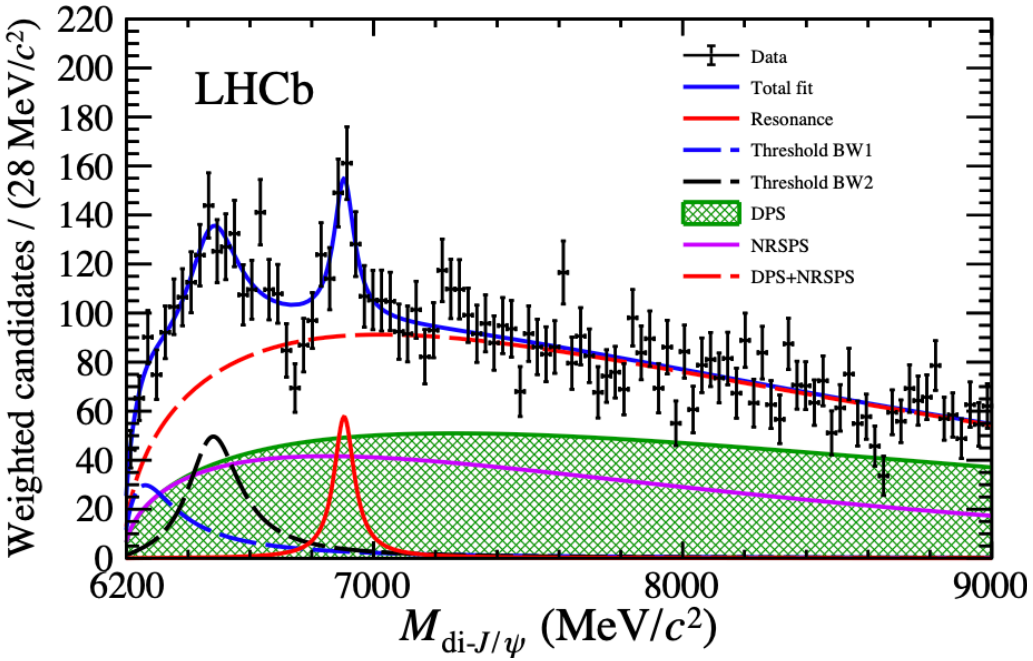
In this talk

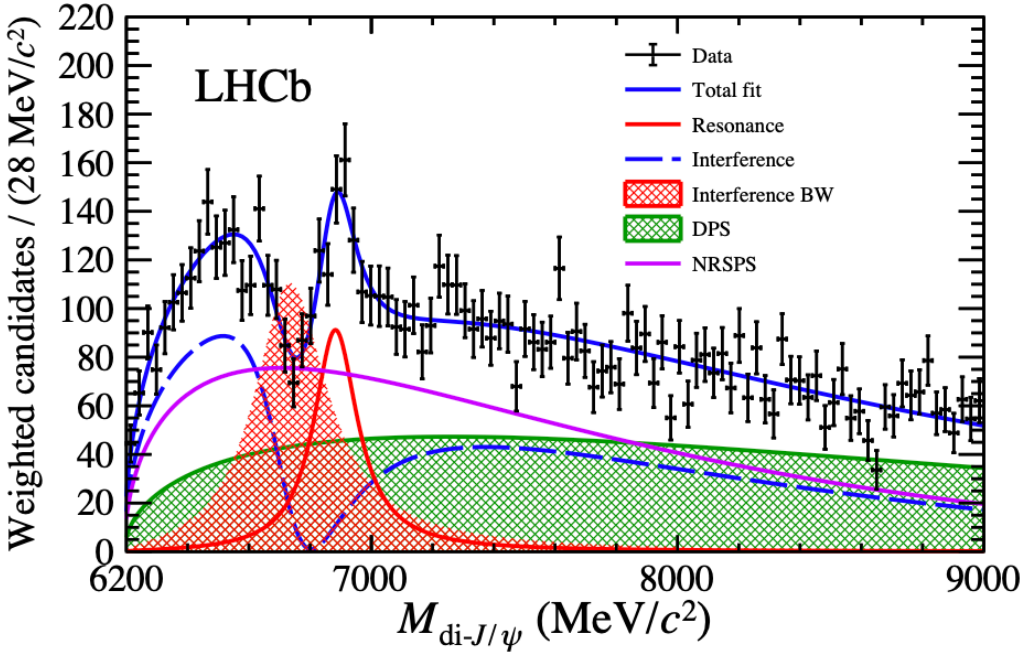
- Observation of di-charmonium excess in the four-muon final state with the ATLAS detector (**ATLAS-CONF-2022-040**)
- Observation of new structures in the $J/\psi J/\psi$ mass spectrum in PP collisions at $\sqrt{s} = 13$ TeV with CMS detector (**CMS-BPH-21-003**)

Tetra-quark in four-muon final state(LHCb)

- Observation of a narrow resonance at 6.9 GeV in J/ψJ/ψ $\rightarrow$ 4μ mass spectrum
- Near threshold enhancement
  - Mixture of multiple four-charm quarks states
  - Feed-down decays of four-charm states
  - Re-scattering of charmonium final states

arXiv:2006.16957





No interference model with NRSPS

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$

$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV}$$

Interference with NRSPS

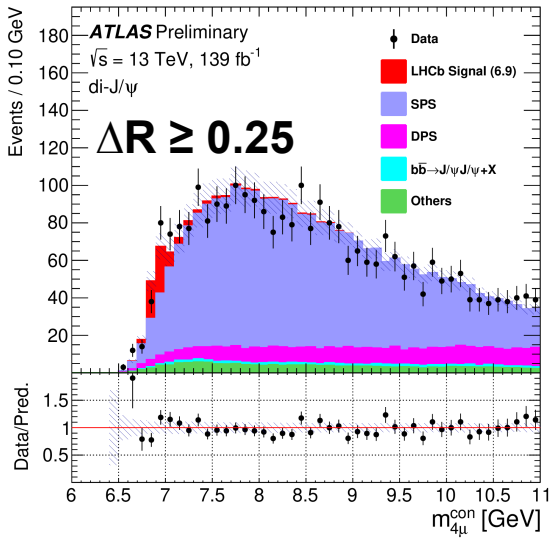
$$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$$

$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}$$

Observation in J/ψJ/ψ(ψ(2S)) → 4μ mass spectrum (ATLAS)

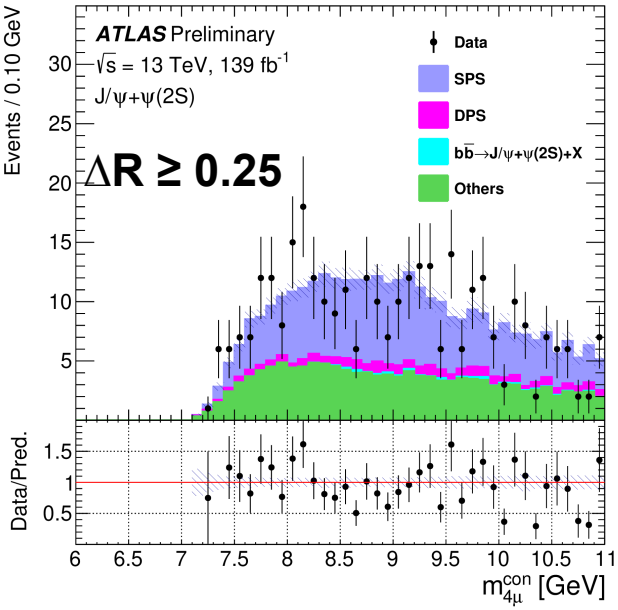
- Full RunII data (139 fb^{-1}) recorded by ATLAS(Blinded signal region)
- Background MC samples (simulated with Pythia8)
- Signal MC samples with JHU (m = 6.9 GeV, width =0.1, spin = 0)
- **Prompt:** *Single parton scattering (SPS), Double Parton scattering(DPS)*
- **Nonprompt:** $b\bar{b} \rightarrow$ J/ψJ/ψ
- **Others:** charmonium includes fake muons(data driven)

SPS shape validation



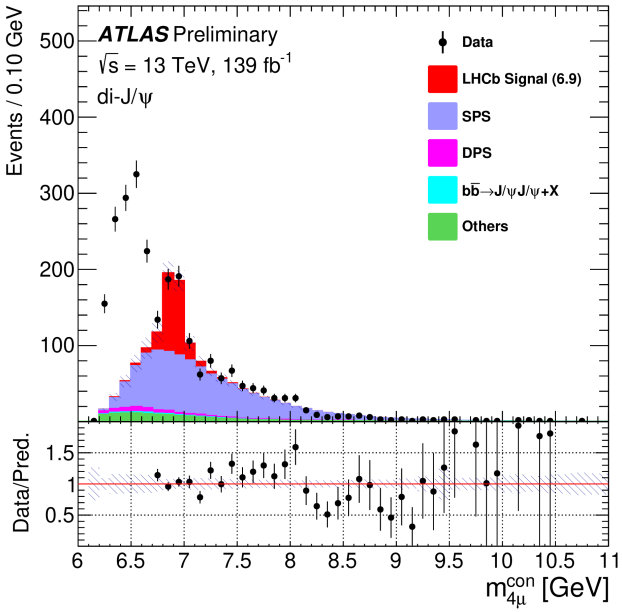
Signal (CR) region and event selection

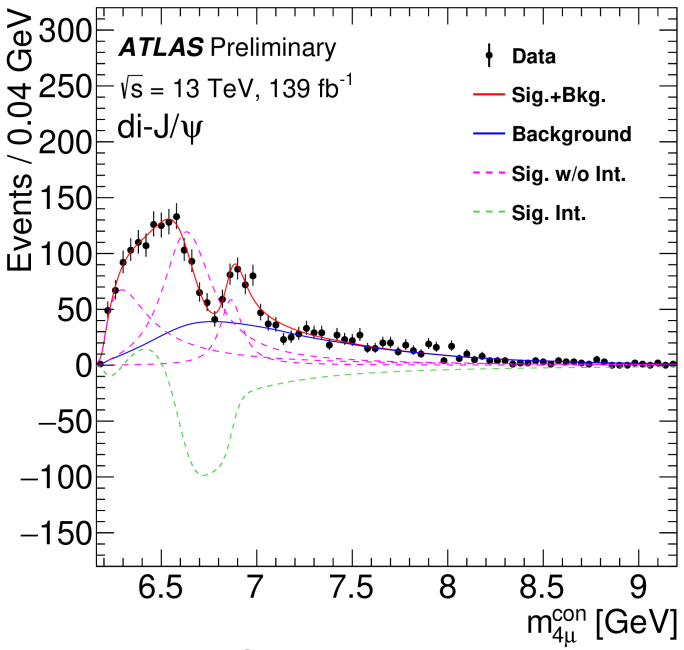
Signal region	SPS/DPS control region	non-prompt region
Di-muon or tri-muon triggers, Opposite charged muons from the same J/ψ or $\psi(2S)$ vertex, Loose muon ID, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons $m_{J/\psi} \in \{2.94, 3.25\}$ GeV, or $m_{\psi(2S)} \in \{3.56, 3.80\}$ GeV, Loose vertex cuts $\chi^2_{4\mu}/N < 40$ and $\chi^2_{\text{di-}\mu}/N < 100$,		
Vertex $\chi^2_{4\mu}/N < 3$, $L_{xy}^{4\mu} < 0.2$ mm, $\lvert L_{xy}^{\text{di-}\mu}\rvert < 0.3$ mm,		Vertex $\chi^2_{4\mu}/N > 6$,
$m_{4\mu} < 7.5$ GeV, $\Delta R < 0.25$ between charmonia	7.5 GeV$< m_{4\mu} <$ 12.0 GeV (SPS) 14.0 GeV$< m_{4\mu} <$ 25.0 GeV (DPS)	$\lvert L_{xy}^{\text{di-}\mu}\rvert > 0.4$ mm

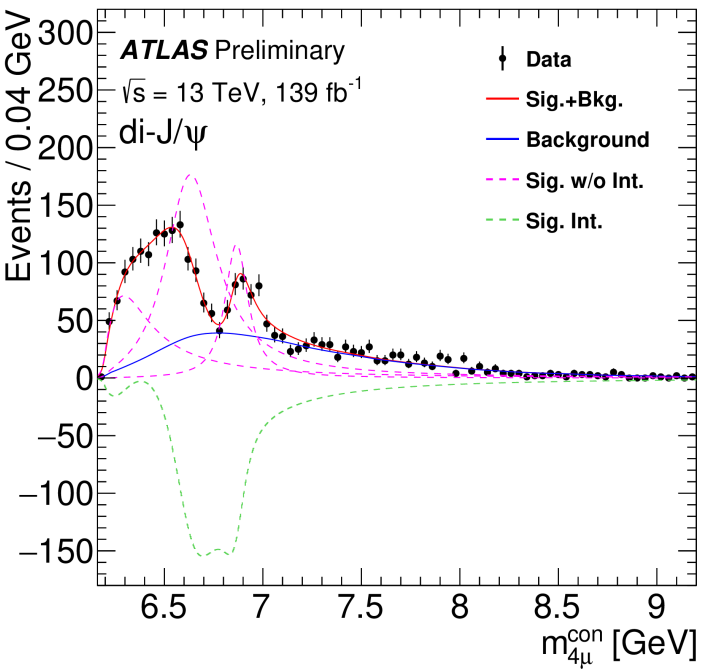


Observation in J/ψJ/ψ → 4μ mass spectrum (ATLAS)

3 resonance fit: 2 out of 4 degenerate solutions







- 70% worse fit quality for 2-resonance fit
- LHCb model II is disfavored due to bad fit quality

significance of 3rd resonance: 10σ

- Feed down from J/ψ+ψ(2S) included in systematics
- Other higher dicharmonium resonances not included

Fitted masses and widths

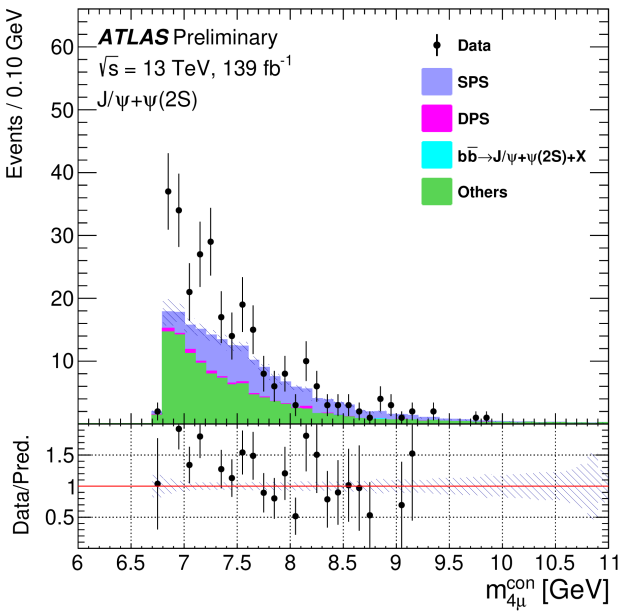
(GeV)	m_0	Γ_0	m_1	Γ_1
di-J/ψ	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2		
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.0}$	—	—

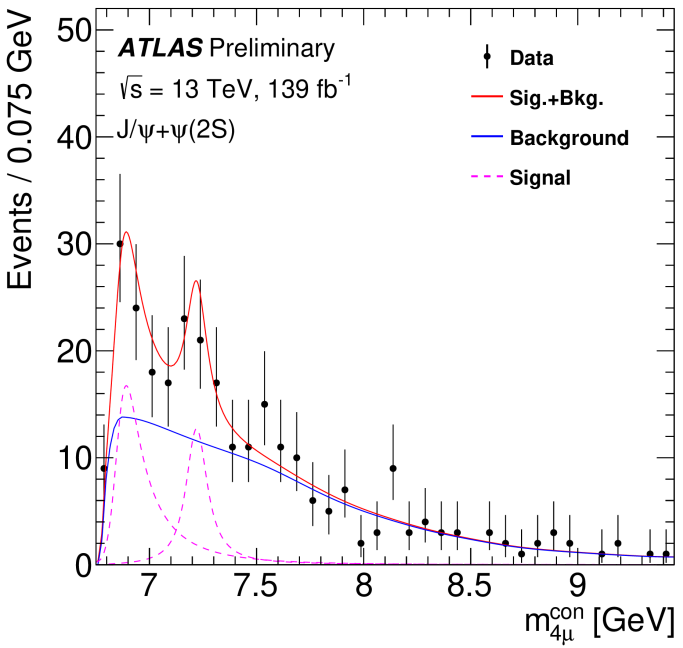
Consistent with LHCb model I (no interference with NRSPS)

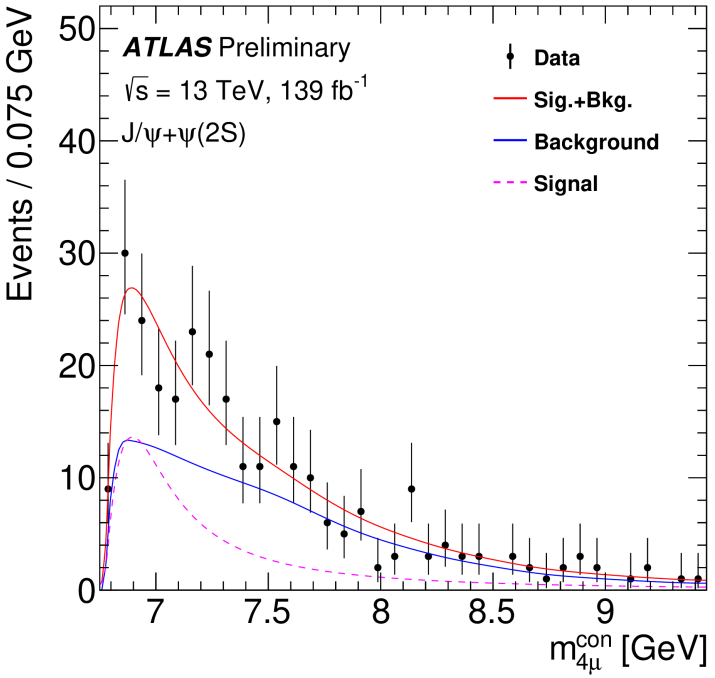
6.9 GeV confirmed, best fit with 3 interfering resonances, other explanations possible

Evidence in J/$\psi\psi$(2S) → 4μ mass spectrum (ATLAS)

Fitted mass in SR (Model A and Model B)







Model A:

- Significance (6.9 GeV) = 4.6σ
- Significance (7.2 GeV) = 3.2σ

Model B:

- Significance (6.9 GeV) = 4.3σ

(GeV)		m_3	Γ_3
$J/\psi+\psi(2S)$	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$

Evidence of 6.9 GeV, hints for 7.2 GeV. More data is needed to explore further

J/ψJ/ψ--Data samples & Event selections (CMS)

- 135 fb^{-1} CMS data taken in 2016, 2017 and 2018 LHC runs
- Trigger: 3μ with a J/ψ mass window, μ p_T from J/ψ>3.5 GeV for 2017&2018 data
- Blinded signal region: [6.2,7.8] GeV
  based on preliminary investigation on data collected in 2011-2012
- Main selections:
  - Fire corresponding trigger in each year
  - $p_T(\mu)$>=2.0 GeV; $|\eta(\mu)|$<=2.4; $p_T(\mu)$ (J/ψ) >=3.5 GeV (2017&2018); soft muon ID (very loose)
  - $p_T(\mu^+\mu^-)$>=3.5 GeV; m($\mu^+\mu^-$) in [2.95,3.25] GeV; then constrain m($\mu^+\mu^-$) to J/ψ mass
  - 4μ vertex probability >0.005
  - Multiple candidates treatment:
    - Select best combination of same 4μ (~0.2%) with

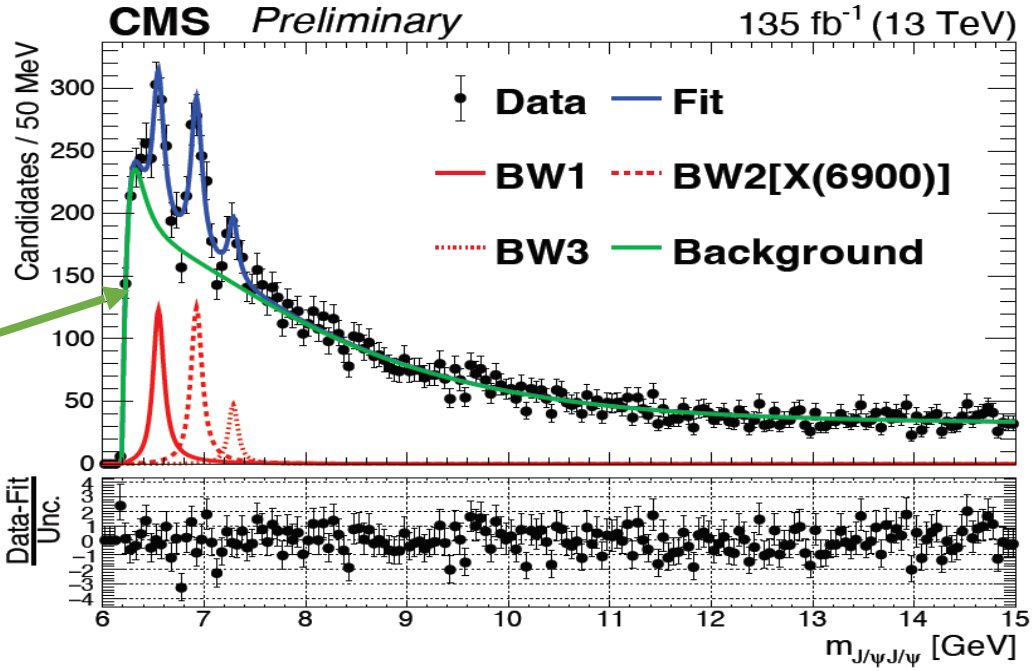
$$\chi^2_m = \left(\frac{m_1(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m2}}\right)^2$$

    - Keep all candidates arising from >=4μ (~0.2%)
- Signal and background samples produced by Pythia8, JHUGen, HELAC-Onia…

CMS background (BW0 + NRSPS + DPS)

$\chi^2\ prob = 79\%$
[6.2,15] GeV

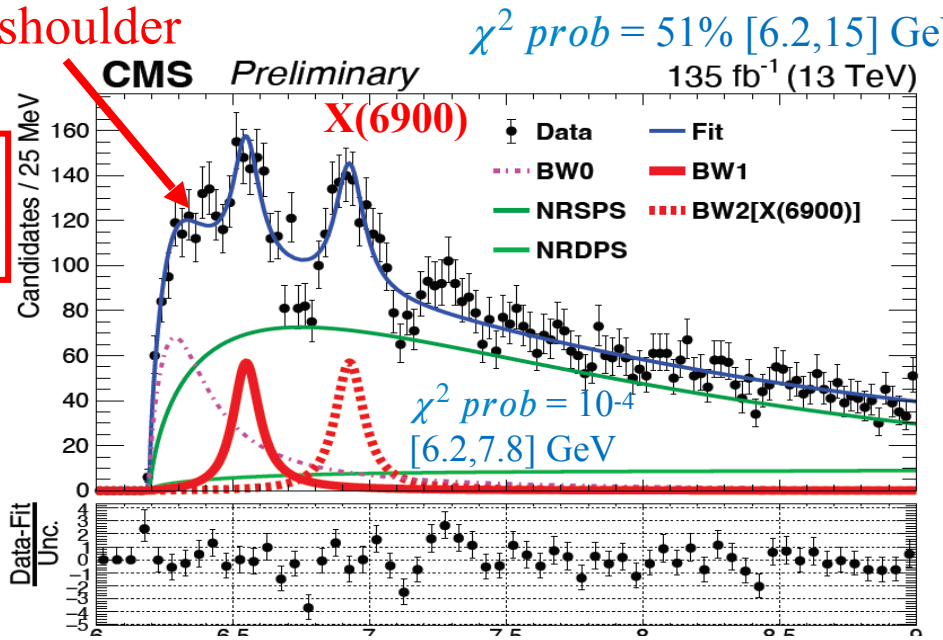
CMS background (BW0 + NRSPS + DPS)



- Most significant structure in first step is a BW at threshold, BW0--what is its meaning?
- Treat BW0 as part of background due to:
  - Inadequacy of our NRSPS model at threshold though one floating parameter?
  - BW0 parameters very sensitive to other model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…
- NRSPS+NRDPS+BW0 as our background

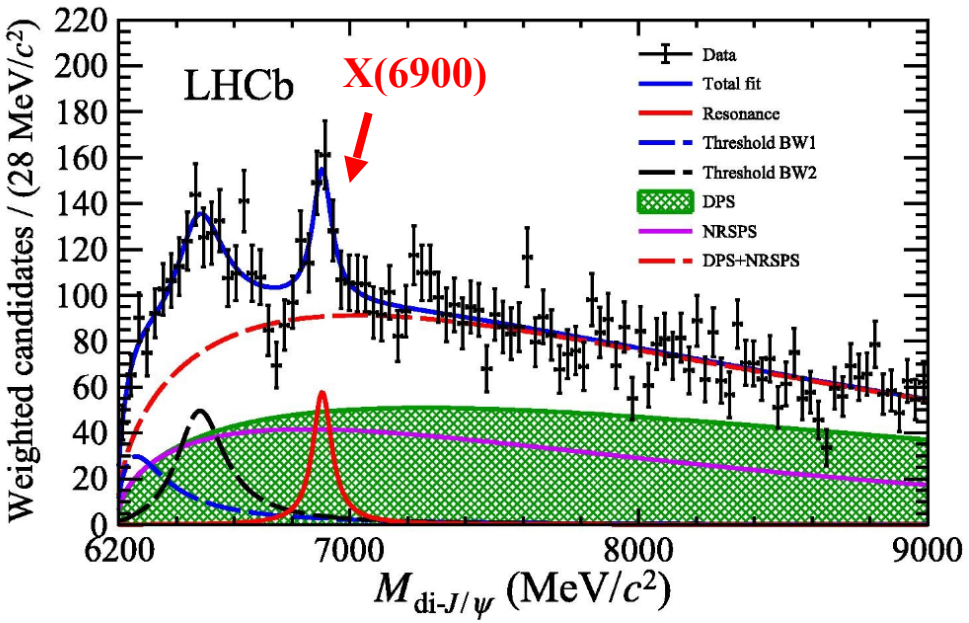
Fit with LHCb model I--background+2 auxiliary BWs+ X(6900)

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



- CMS Data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct
- *Does not describe well dips*

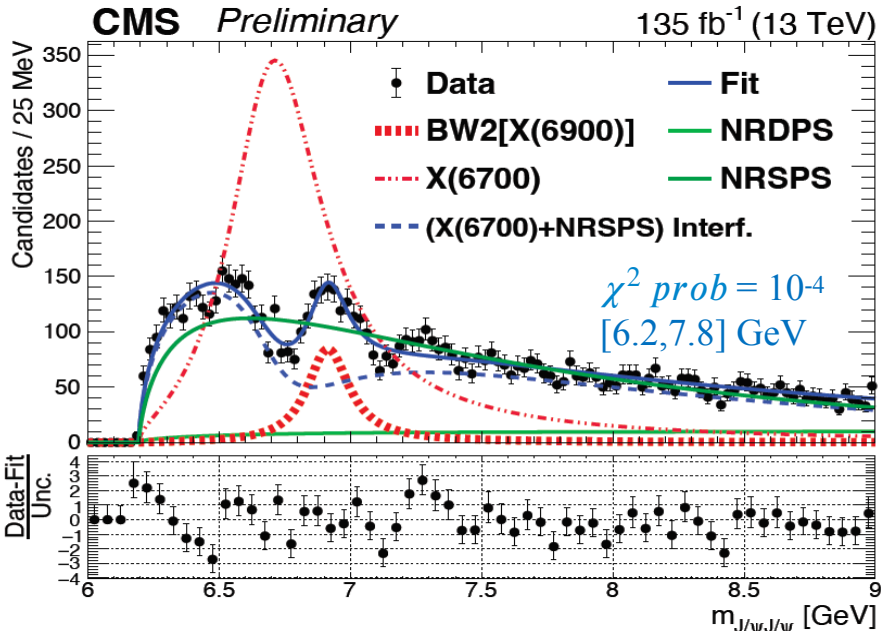
X(6900) parameters are in good agreement with LHCb



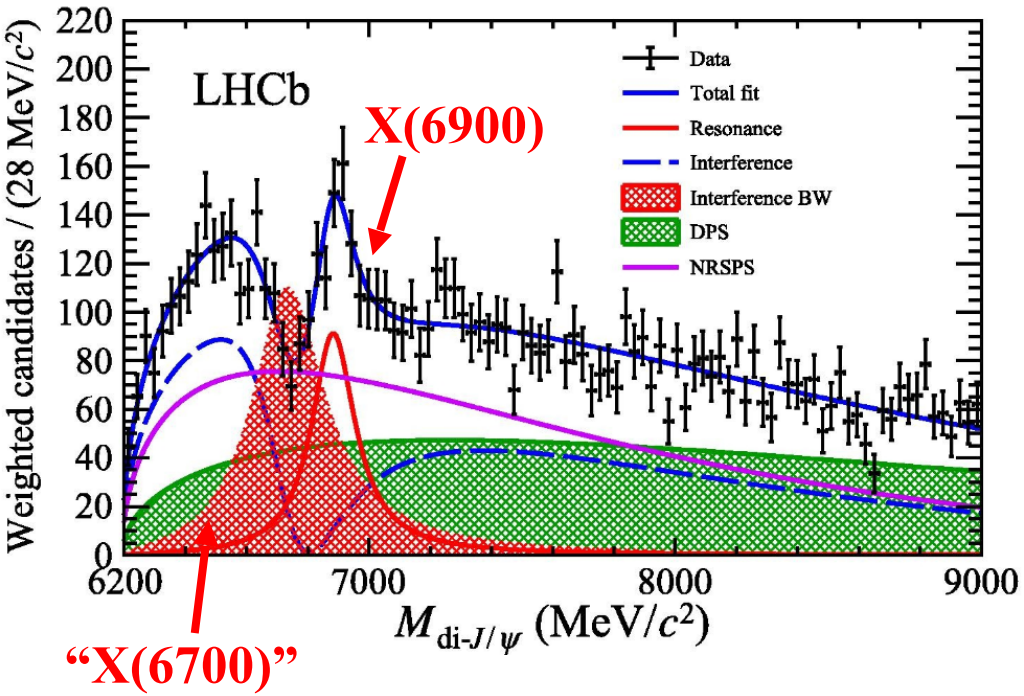
- CMS vs LHCb comparisons:
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4$ ≈ 8X (muon acceptance due to pseudo-rapidity range)
  - Higher muon p_T (>3.5 or 2.0 GeV vs > 0.6 GeV)
  - Similar number of final events

Fit with LHCb model I--background+2 auxiliary BWs+ X(6900)

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

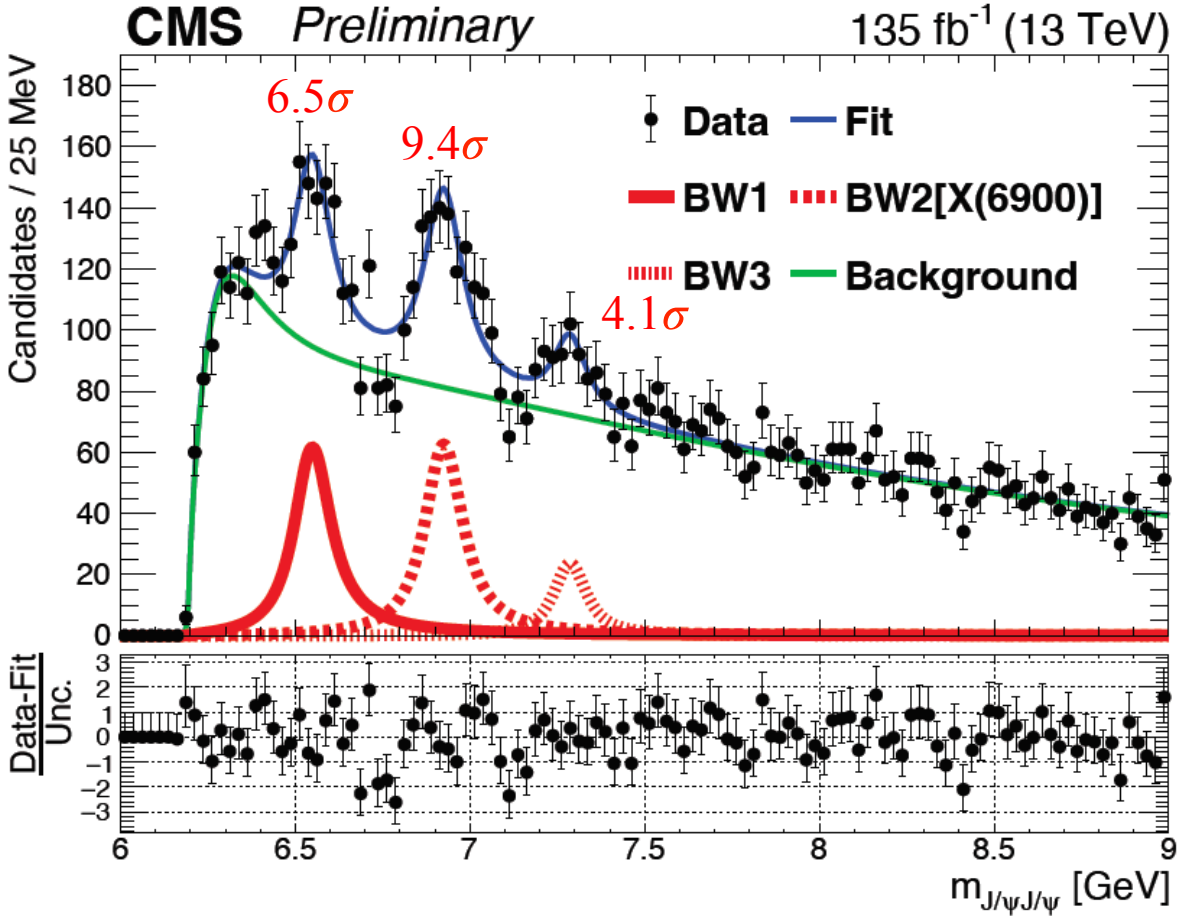


- X(6900) parameters are consistent
- CMS obtained larger amplitude and natural width for BW1
- CMS's X(6600) is 'eaten' –does not describe X6600 and below
- Does not describe X(7200) region



All CMS fits presented are not very good:
...other interference scenarios are under study in CMS

Final CMS model: 3 BWs + Background (null)



χ^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 ± 10	6927± 9	7287± 19
Γ	124± 29	122± 22	95± 46
N	474± 113	492± 75	156± 56

BW2[X(6900)] (>9.4σ) – confirmation

Observation of BW1 (>5.7σ)

Evidence for BW3 (>4.1σ)

Statistical significance only

Summary and Outlook

- Significant excess has been in $J/\psi J/\psi$ observed and a resonance at ~6.9 GeV is confirmed by both CMS and ATLAS, consistent with LHCb
- Best description of ATLAS given by a 3-resonance (2 near threshold) model with interference
- Excess observed in the ATLAS data in $J/\psi + \psi(2S)$ channel at 6.9 and 7.2 GeV, more data is needed to explore it further
- A family of structures, candidates for all-charm tetra-quarks!
- CMS found two new structures, provisionally named as X(6600), X(7200)
- 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

Thanking you for your attentions