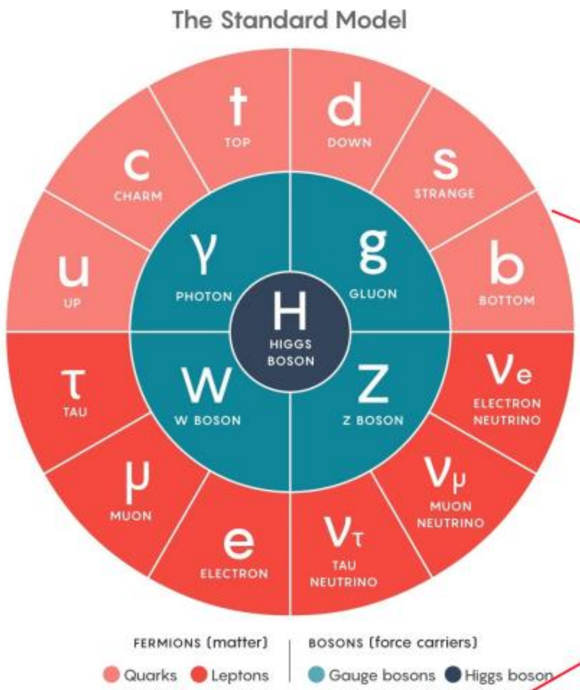
Observation of new structure in the J/ψJ/ψ mass spectrum in proton-proton collisions at $\sqrt{s}$ = 13 TeV

Petrov Nikita (on behalf of the CMS Collaboration)
MIPT, Moscow
nikita.petrov@cern.ch

Overview

- Motivation
- CMS experiment
- Selection procedure
- CMS non-interference model
- LHCb models
- CMS interference model
- Systematic uncertainties
- Results discussion
- Summary

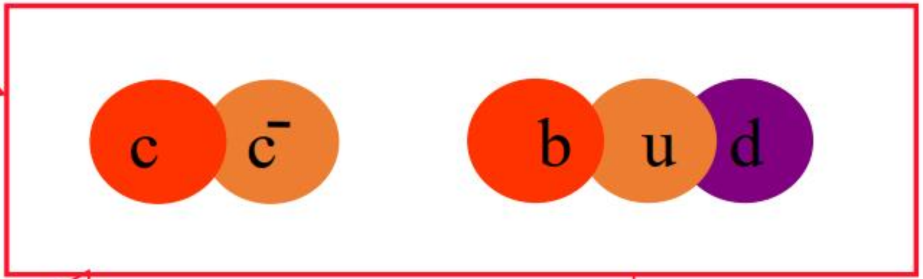
Theoretical motivation



QCD allows the possibility of exotic hadrons

Mesons

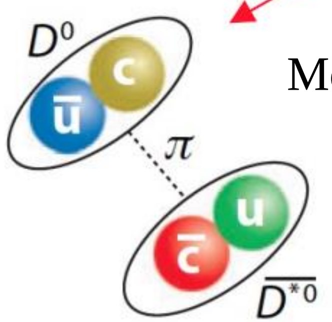
Baryons

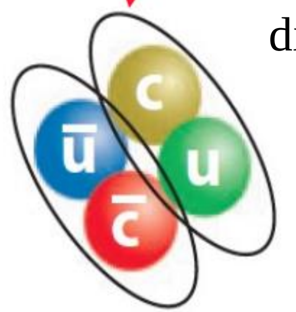


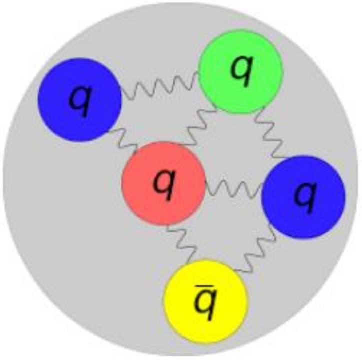
Multi-quark states

Bound states of diquarks

Molecules







Theoretical models consider different internal structures of the exotic states, like X(3872)

Theoretical motivation

- Theoretical studies of J/ψJ/ψ structures started since 1975

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	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

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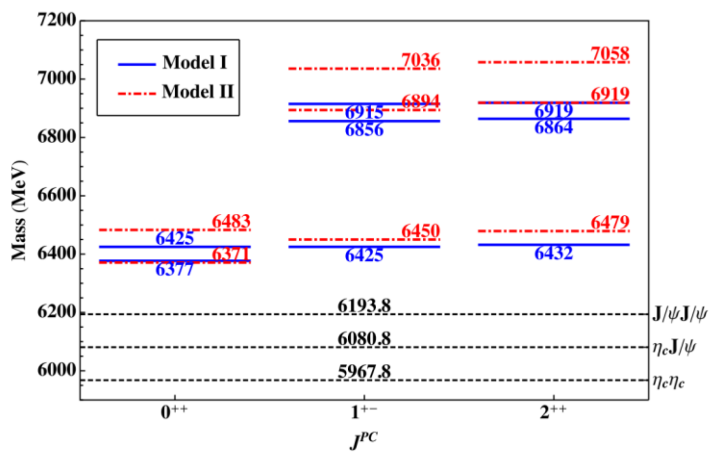
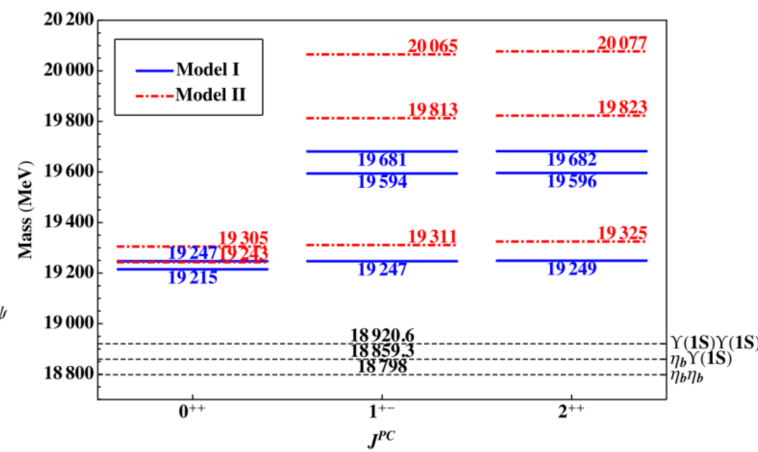
L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.82
2	0	2^{++}	7.15
3	0	3^{--}	7.41

- 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;
  - consistent on existence of resonant states.

PRD 100 (2019) 096013

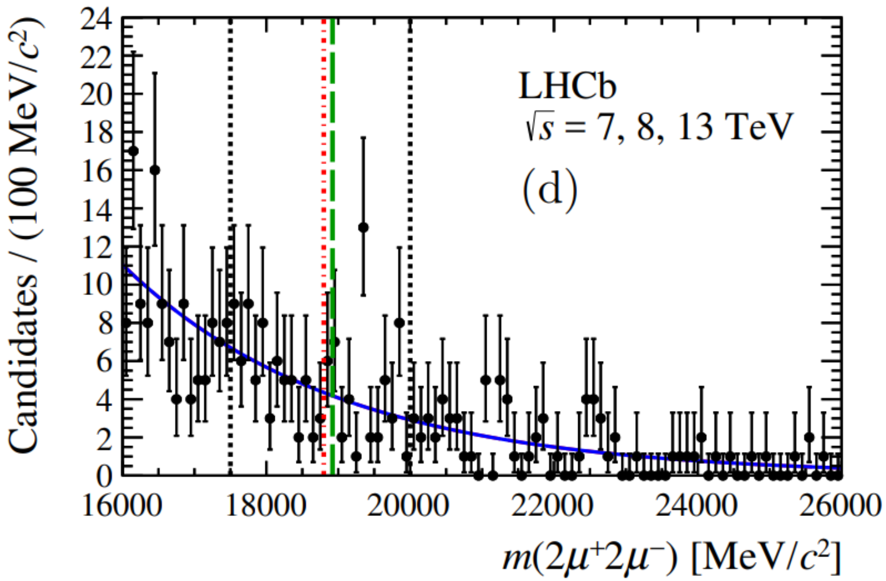




Experimental motivation

- Theoretical studies predict lots of $cc\overline{cc}$, $bc\overline{bc}$ and $bb\overline{bb}$ exotic states
- However various approaches provide different predictions, moreover majority of them don't say anything about production cross-sections of these states.
- CMS and LHCb Collaborations performed searches for heavy $bb\overline{bb}$ tetraquarks in $\Upsilon(1S)\mu^+\mu^-$ final state, but set only upper limits on production cross-sections times branching fractions depending on mass of searched state

JHEP 10 (2018) 086



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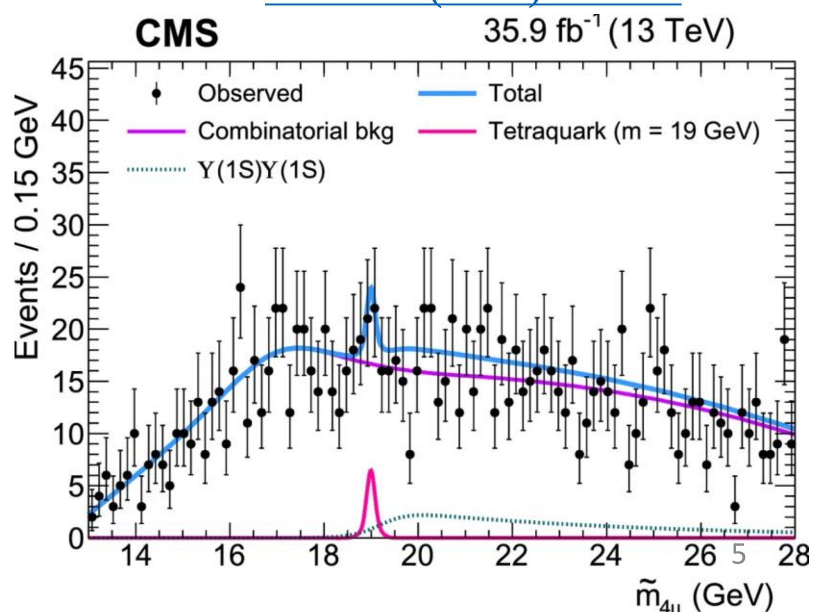

Experimental motivation

- In 2020, LHCb collaboration reported observation of X(6900) state decaying to J/ψJ/ψ final state using combination of Run I and Run II data
- A fit model without interference does not describe the dip at 6750 MeV

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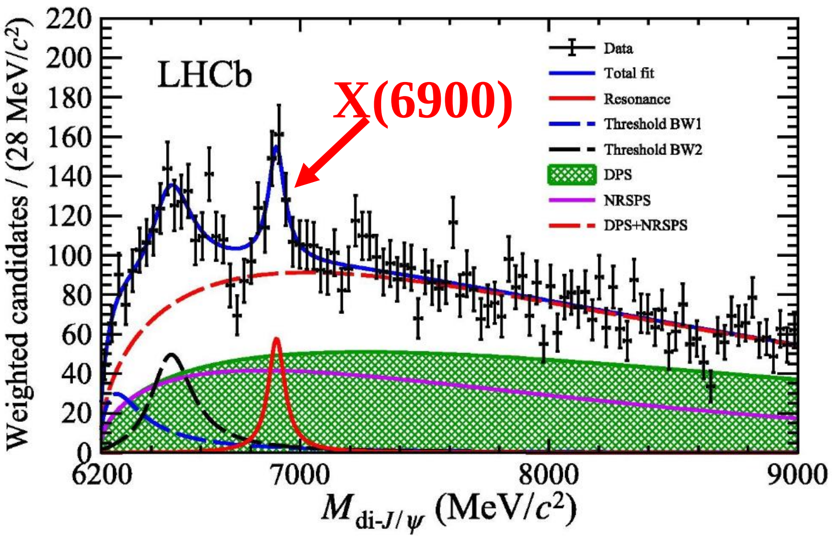
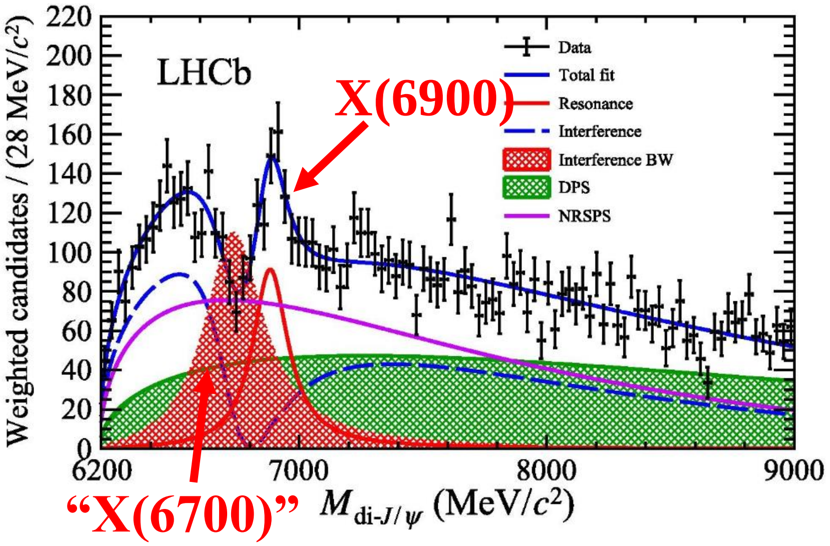
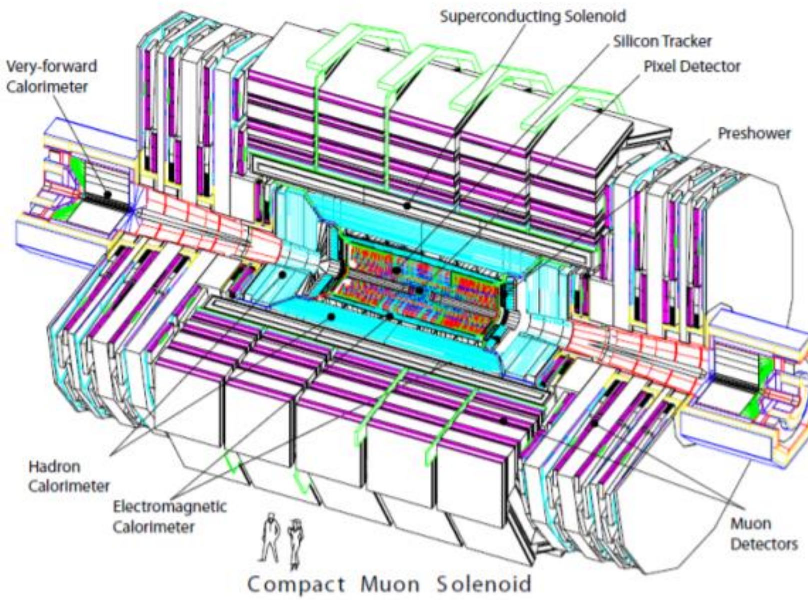
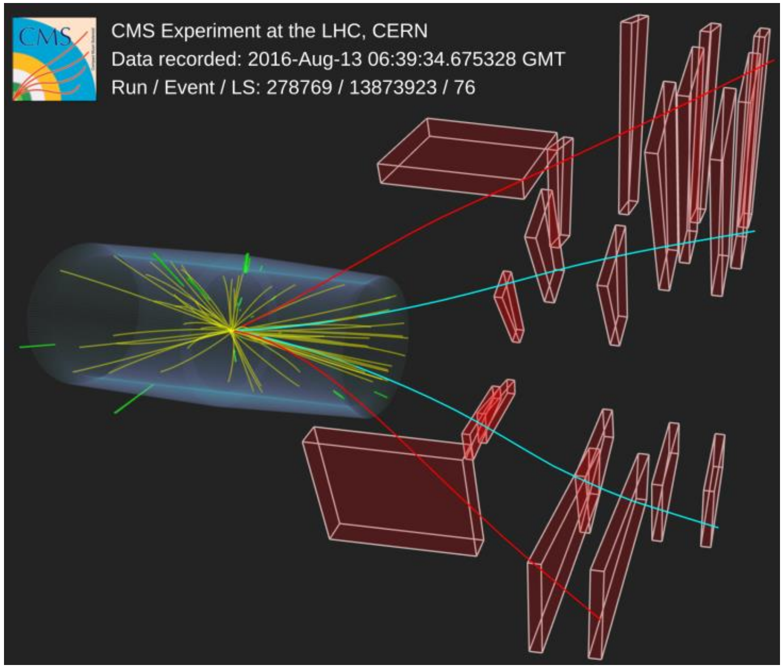


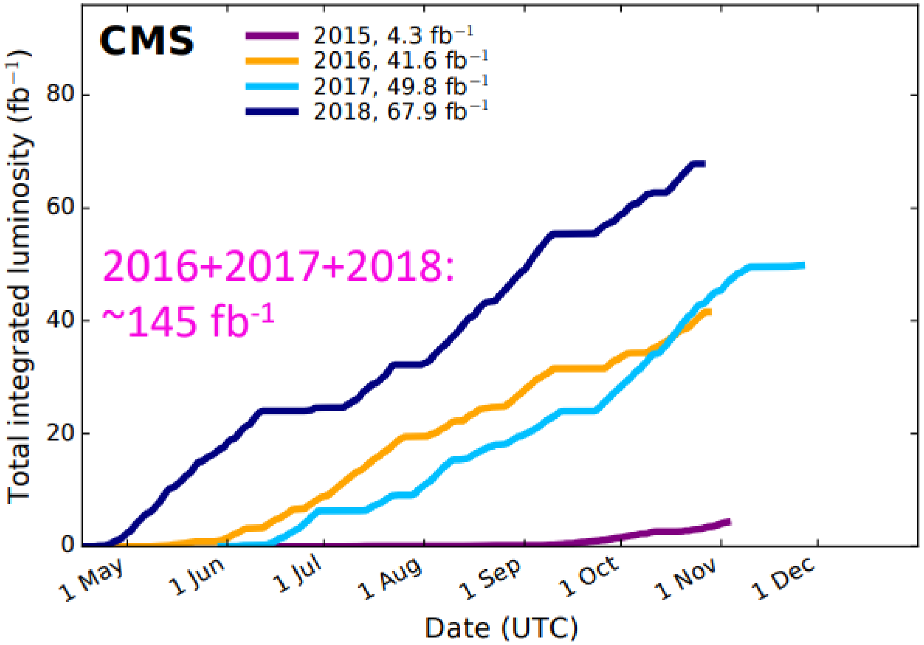


- Assuming interference between NRSPS component and X(6900) satisfactory description was achieved
- Structure at the very threshold was not understood, described by a sum of two BWs
- Decay into J/ψJ/ψ suggests fully-charm tetraquark nature of the X(6900) state

CMS experiment







- Excellent muon system with large rapidity coverage and high-purity muon ID
- Good resolution in $p_T \sim 1\%$ for central region of tracker
- Special muon triggers, including 3μ
- Large integrated luminosity

Event selection

Muon selection

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

J/ψ selection

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

J/ψJ/ψ selection

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

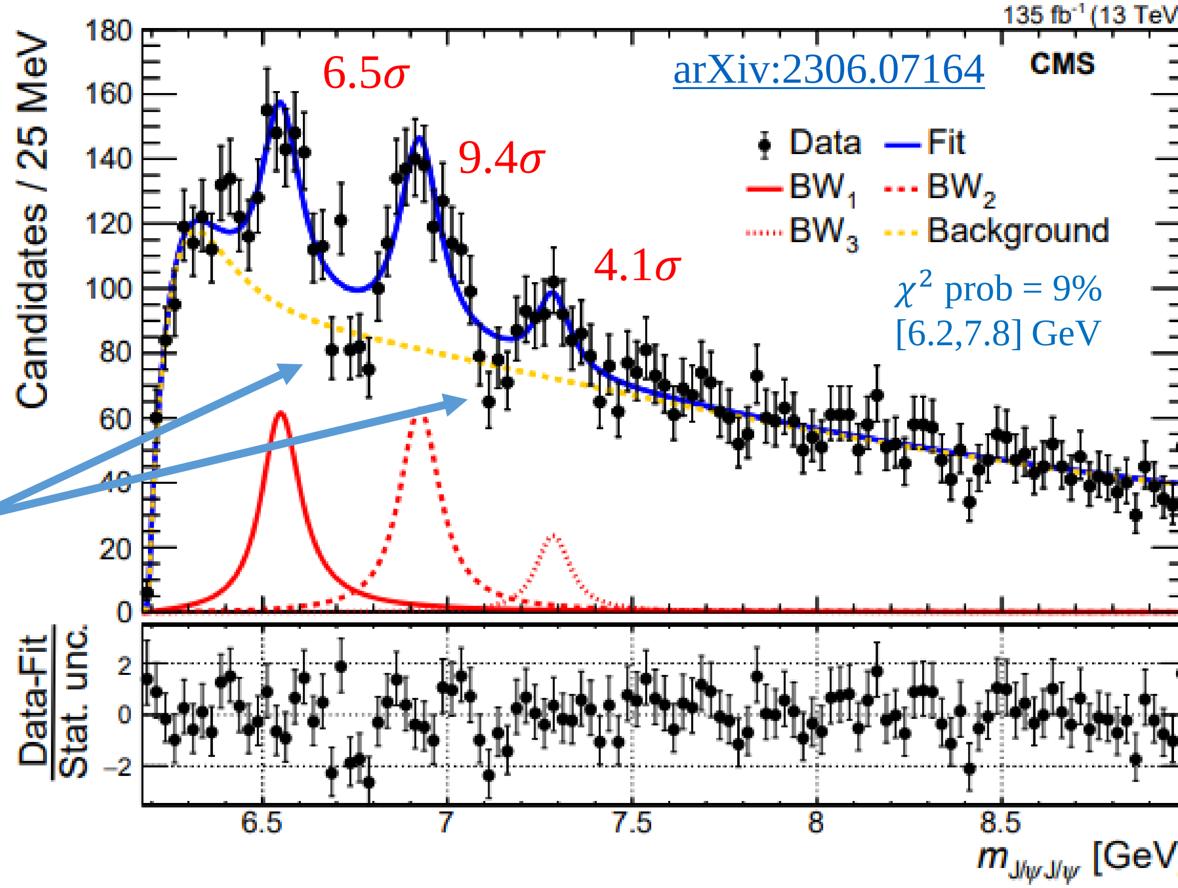
Multiple candidates

- Choose the best candidate with minimum $\left(\frac{M(J/\psi_1)-M(J/\psi_{PDG})}{\sigma(M(J/\psi_1))}\right)^2+\left(\frac{M(J/\psi_2)-M(J/\psi_{PDG})}{\sigma(M(J/\psi_2))}\right)^2$ value if there are 4 muons in event, but more than one candidate (~0.3%)
- Keep all candidates if there are more then 4 muons in event (~0.2%)

Non-interference CMS model: 3 BWs + Background

$$pdf(m) = \sum_i N_i(|BW_i(m; m_i, \Gamma_i)|^2 \otimes R(m_i)) + N_{NRSPS} \cdot pdf_{NRSPS}(m, p_2) + N_{DPS} \cdot pdf_{DPS}(m),$$

- Background component contains NRSPS, NRDPS and BW0 contributions
- Nature of BW0 is still unclear
- Two dips are described poorly

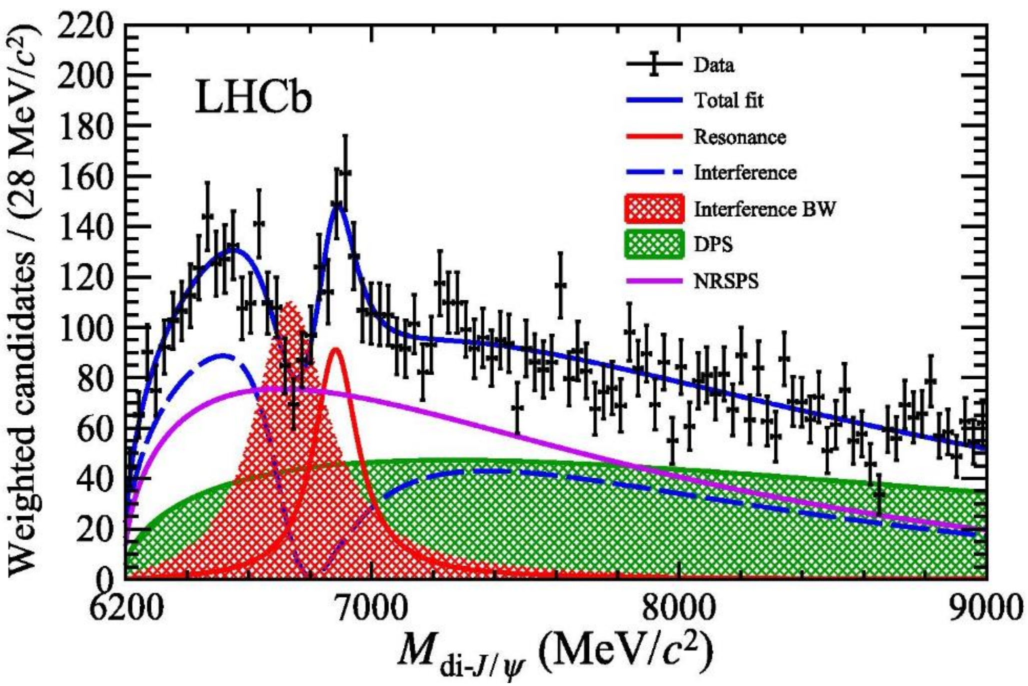


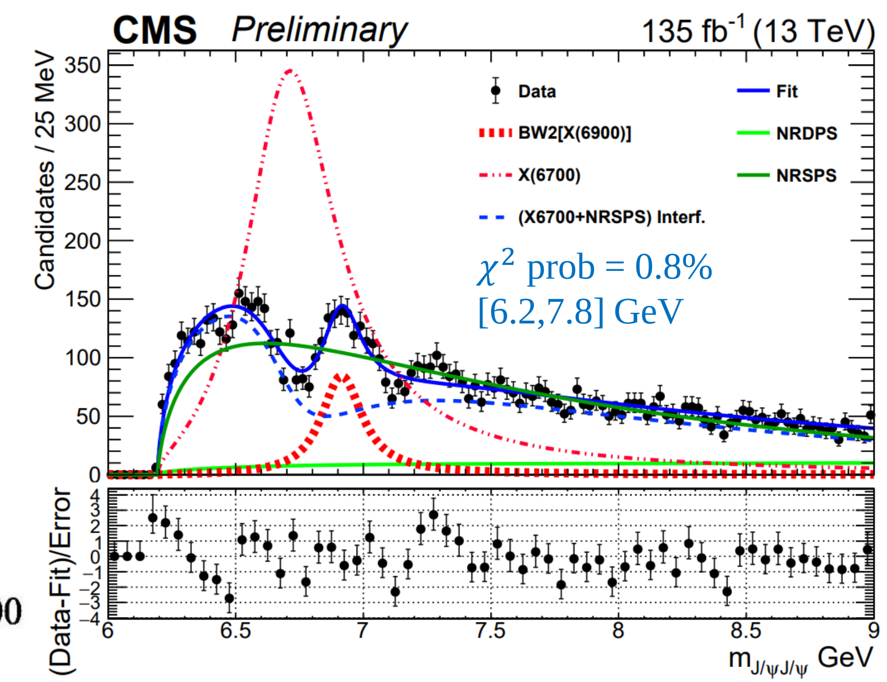
	BW_1	BW_2	BW_3
m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}

- Confirmation of BW2[X(6900)] (9.4σ, >9.7σ(syst.))
- Observation of BW1 (6.5σ, >5.7σ(syst.))
- Evidence for BW3 (4.1σ, >4.2σ(syst.))

LHCb model II (2 BW, “X(6700)” interferes with NRSPS)

$$pdf(m) = N_{inter.}(|Ae^{i\phi} \cdot BW_1(m; m_1, \Gamma_1) + \sqrt{pdf_{NRSPS}(m, p_2)}|)^2 +$$
$$+ N_2(|BW_2(m; m_2, \Gamma_2)|^2 \otimes R(m_2)) + N_{DPS} \cdot pdf_{DPS}(m),$$





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

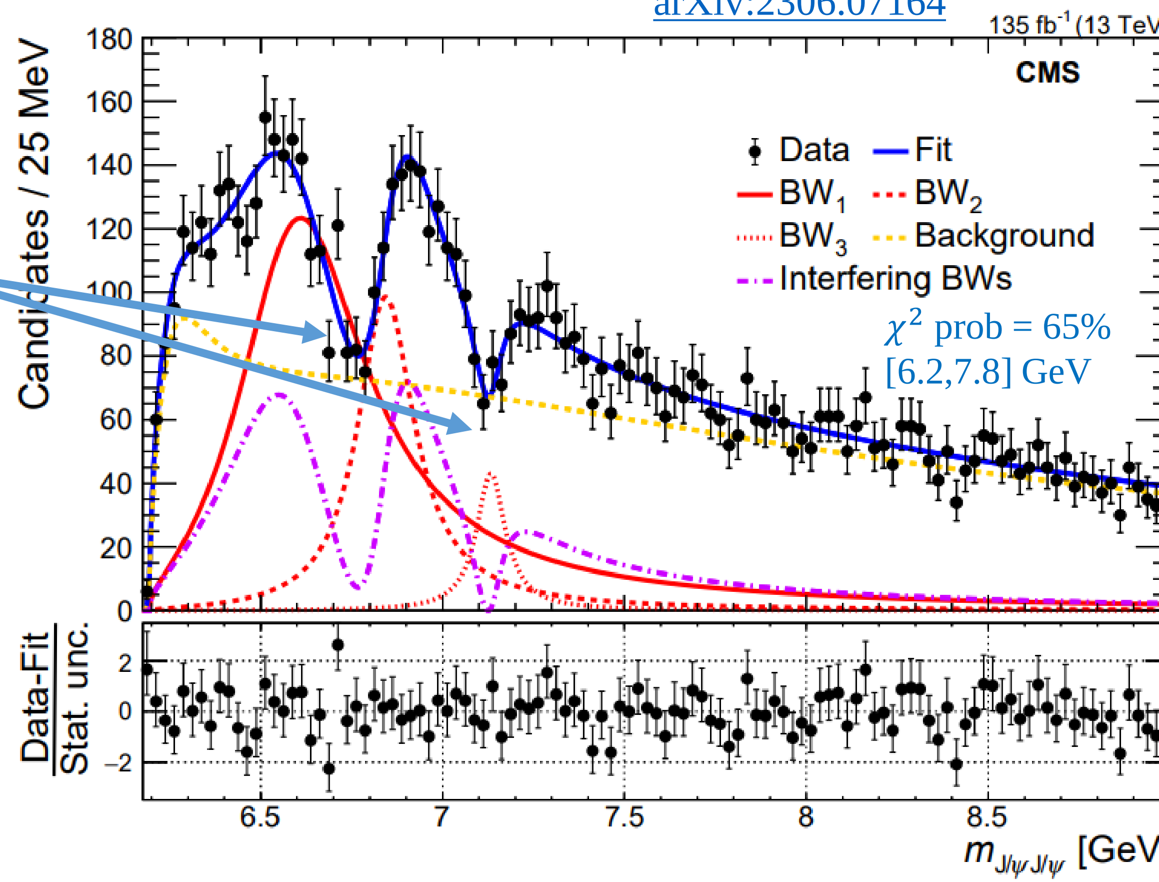
- X(6900) parameters are consistent
- CMS obtained larger amplitude and natural width for BW1
- The model poorly describes threshold and ~7300 MeV regions

Interference CMS model: 3 interfering BW + Background (null)

$$pdf(m) = N_{inter.}(|A_1 e^{i\phi_1} \cdot BW(m; m_1, \Gamma_1) + BW_2(m; m_2, \Gamma_2) + A_3 e^{i\phi_3} \cdot BW_3(m; m_3, \Gamma_3)|)^2 + N_{Th.} \cdot |BW_0(m; m_0, \Gamma_0)|^2 \otimes R(m_0) + N_{NRSPS} \cdot pdf_{NRSPS}(m, p_2) + N_{DPS} \cdot pdf_{DPS}(m)$$

arXiv:2306.07164

- A model with 3 interfering resonances significantly improves fit quality, both dips are well described
- Masses and width are shifted w.r.t. the non-interference fit
- However other interpretations of the observed structures are also possible



	BW_1	BW_2	BW_3
m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

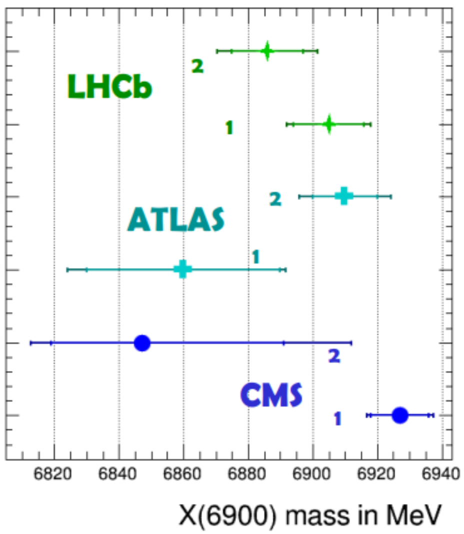
Parameters systematic summary

Fit	Dominant sources	M_{BW_1}	M_{BW_2}	M_{BW_3}	Γ_{BW_1}	Γ_{BW_2}	Γ_{BW_3}
No-interference	Signal shape	3	3	3	10	5	5
	NRSPS shape	3	1	1	18	15	17
	Feed-down	11	1	1	25	8	6
	Total uncertainty	12	4	5	33	18	19
Interference	Signal shape	7	12	7	56	8	7
	DPS shape	1	3	2	18	6	2
	NRSPS shape	9	14	13	85	9	20
	Mass resolution	8	4	1	24	7	13
	Combinatorial bkg.	7	2	<1	5	3	2
	Feed-down	$^{+0}_{-27}$	$^{+44}_{-0}$	$^{+38}_{-0}$	$^{+0}_{-210}$	$^{+19}_{-0}$	$^{+12}_{-0}$
	Total uncertainty	$^{+16}_{-31}$	$^{+48}_{-20}$	$^{+41}_{-15}$	$^{+110}_{-240}$	$^{+25}_{-17}$	$^{+29}_{-26}$

- Largest source of systematic uncertainties: NRSPS shape, feed-downs (X -> charm charm -> $J/\psi J/\psi$ + smth.)
- The effects of feed-down components in the interference model can produce large asymmetric uncertainties, so an asymmetric uncertainty is assigned for this source.

Comparison between LHC experiments

arXiv:2304.08962



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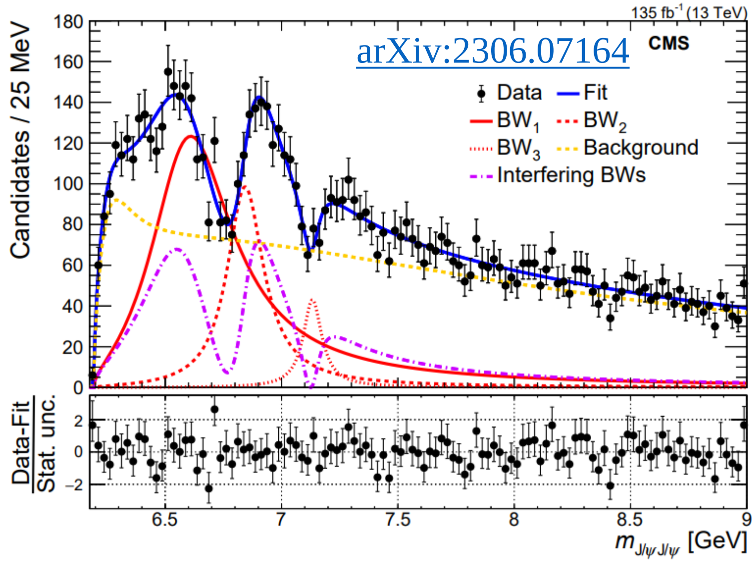

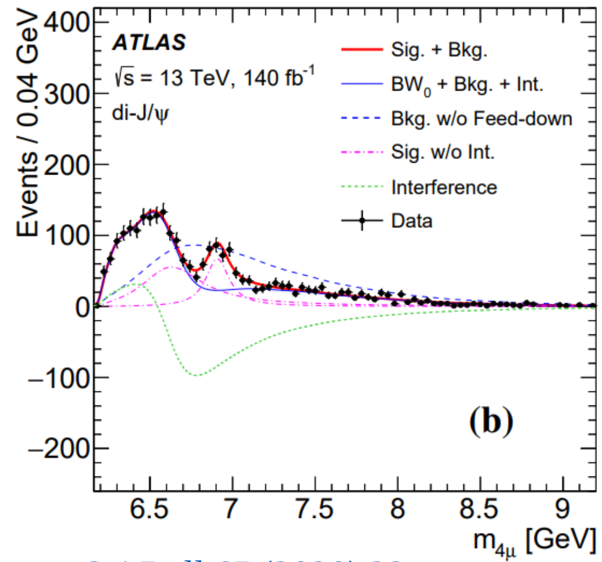

Table 17: Comparison of X(6900) mass in MeV

Model	LHCb	CMS	ATLAS
1	6905±11 ± 7	6927±9 ± 4	$6860\pm30^{+10}_{-20}$
2	6886±11 ± 11	6847^{+44+48}_{-28-20}	6910±10 ± 10

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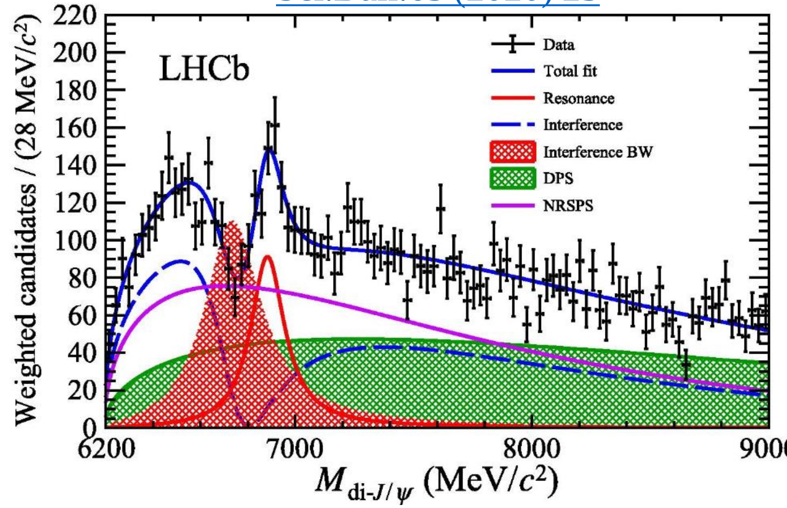
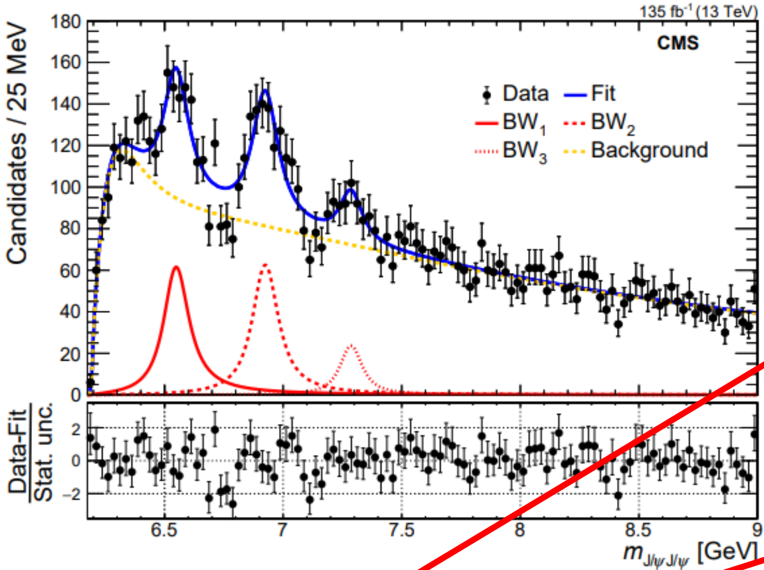


- Models are different between the experiments! Not exact comparison, but the masses are still agree with each other
- CMS experiment confirmed X(6900), observed X(6600) and found an evidence for X(7300)

Comparison with theoretical predictions



	BW$_1$	BW$_2$	BW$_3$
m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}

arXiv:2108.04017

$N^{2S+1}L_J$	J^{PC}	$\langle K.E.\rangle$	$E^{(0)}$	$\langle V_C^{(0)}\rangle$	$\langle V_L^{(0)}\rangle$	$\langle V_{SS}^{(1)}\rangle$	$\langle V_{LS}^{(1)}\rangle$	$\langle V_T^{(1)}\rangle$	$V^{(1)}(r)$	M_f	$\mathbf{M_{th}}$ [49]	**Threshold**
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	6459	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	6577	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	6849	-	-
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	-	-

- Some theoretical predictions match with our measurements
- However they predict a lot of another states
- Further steps
  - measure J^{PC} for better understanding
  - collect more data to observe and resolve (may be) new states
  - investigate another final states (ψ(2S)J/ψ, YY, J/ψY, to be continued …)

Summary

- Using a data sample corresponding to an integrated luminosity of 135 fb^{-1} of pp collisions collected by the CMS experiment at $\sqrt{s}$ = 13 TeV in 2016-2018, rich resonance structure was observed.

- Masses and widths in non-interference model were determined to be:

M[BW1] = $6552 \pm 10 \pm 12$ MeV; Γ[BW1] = $124^{+32}_{-26} \pm 33$ MeV Observation (>5.7σ)
M[BW2] = $6927 \pm 9 \pm 4$ MeV; Γ[BW2] = $122^{+24}_{-21} \pm 18$ MeV Observation (>9.4σ)
M[BW3] = $7287^{+20}_{-18} \pm 5$ MeV; Γ[BW3] = $95^{+59}_{-40} \pm 19$ MeV Evidence (>4.1σ)

- In interference case masses and widths were determined to be:

M[BW1] = 6638^{+43+16}_{-38-31} MeV; Γ[BW1] =$440^{+230+110}_{-200-240}$ MeV
M[BW2] = 6847^{+44+48}_{-28-20} MeV; Γ[BW2] =191^{+66+25}_{-49-17} MeV
M[BW3] = 7134^{+48+41}_{-25-15} MeV; Γ[BW3] =97^{+40+29}_{-29-26} MeV

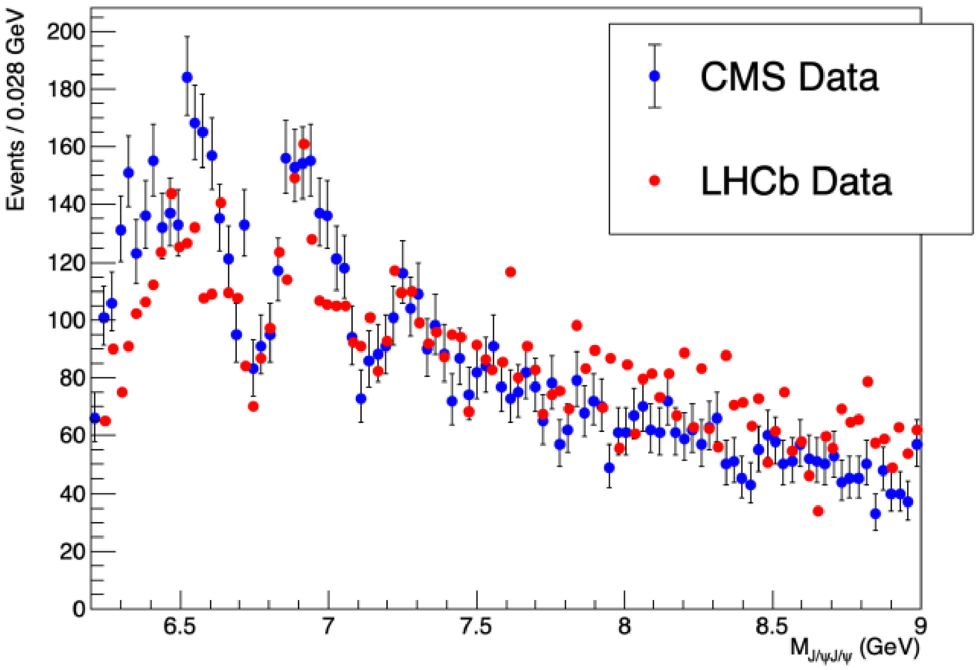
- All states are candidates in fully-charmed tetraquarks

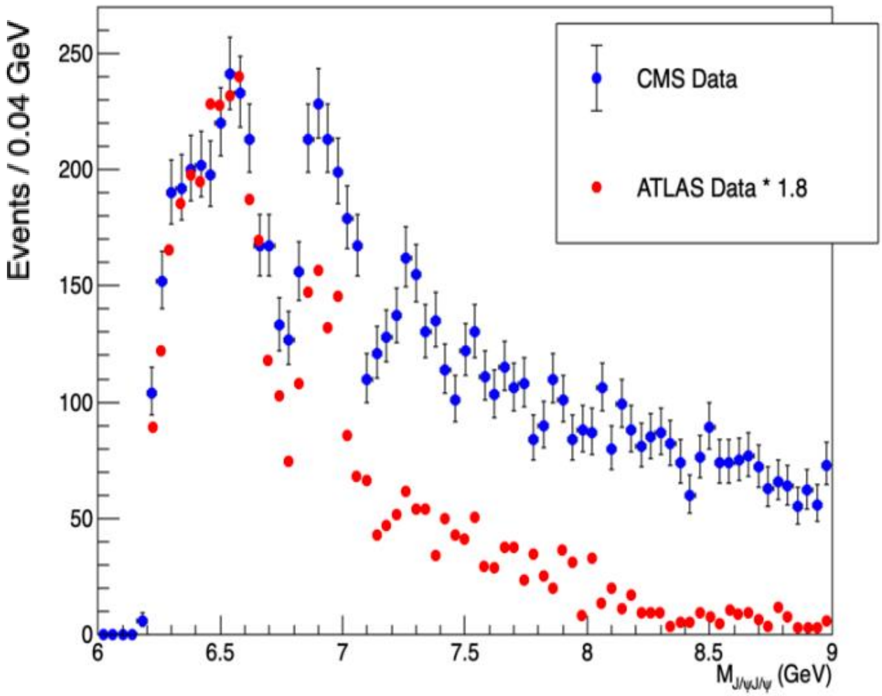
- Need more data and further studies for better understanding of exotic nature

Thank you for attention!

Back up

Comparison with LHCb and ATLAS





CMS vs LHCb

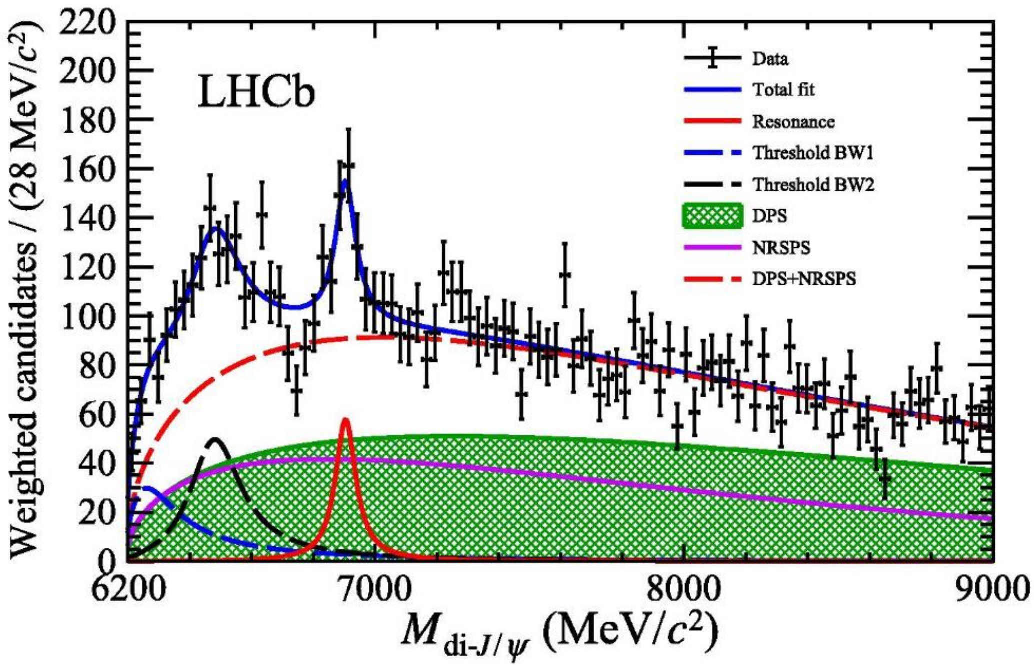
- 135/9 ~ 15X (int. luminosity)
- $(5/3)^4$ ~ 8X (muon acceptance)
- Higher muon p_T (> 3.5 or 2.0 GeV vs > 0.6 GeV)
- Similar number of J/ψJ/ψ candidates, but significantly less NRDPS yield
- 2X yield for X(6900)

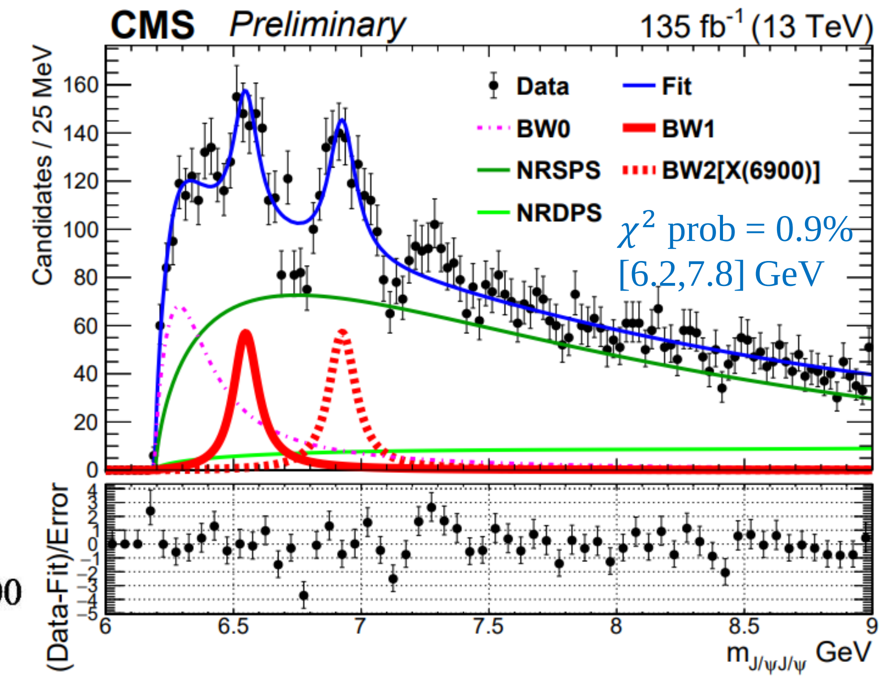
CMS vs ATLAS

- ATLAS has 1/3-1/2 of CMS data
- ATLAS used dR cut – removed higher mass region
- CMS has slightly better resolution

LHCb model I (3 BW, no interference)

$$pdf(m) = \sum_i N_i(|BW_i(m; m_i, \Gamma_i)|^2 \otimes R(m_i)) + N_{NRSPS} \cdot pdf_{NRSPS}(m, p_2) + N_{DPS} \cdot pdf_{DPS}(m),$$





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- X(6900) parameters are consistent
- The model poorly describes the dips and ~7300 MeV region