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

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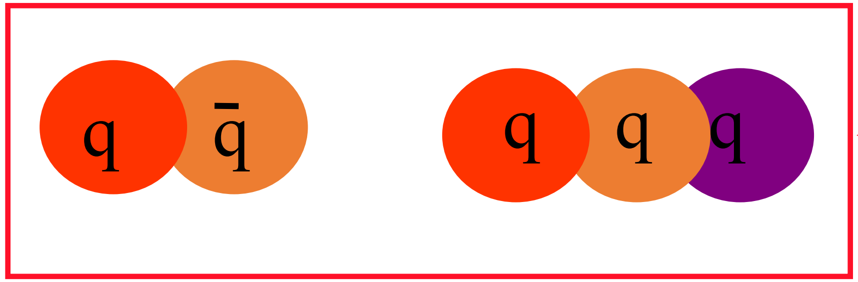
Outline

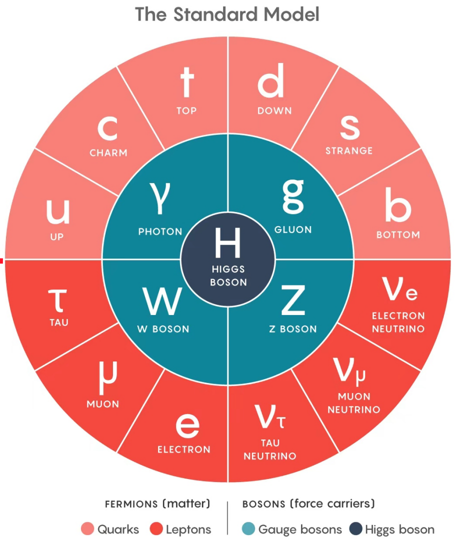
- History
  - About exotic hadron
  - New Domain of Exotics: All-Heavy Tetra-quarks
- CMS $J/\psi J/\psi$ study arXiv:2306.07164
  - Data sample and event selections
  - Steps to identify structures
  - Result and systematics
  - Interpretation through interference models
- Summary
- Outlook

Exotic hadron

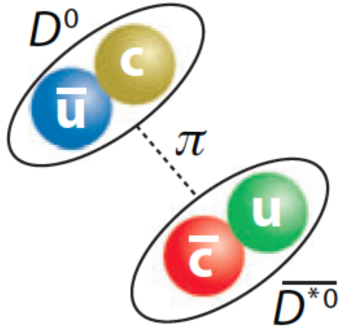
Quark model

Meson *Baryon*

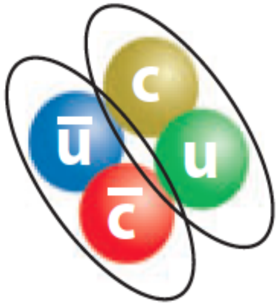




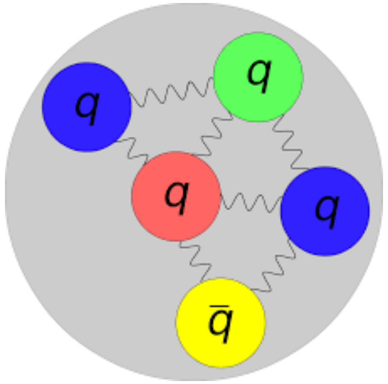
"exotic" hadron

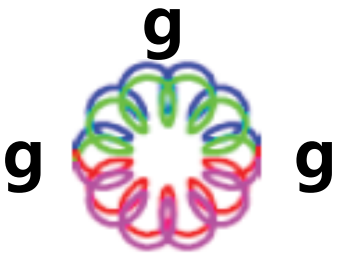


D^0–$\overline{D}^{*0}$ "molecule"



Diquark–diantiquark





- *Glueball*

- *Two possible extensions of mesons to tetra-quark states*
- *Possible penta-quark state*

Gell-mann noted the possibility of "exotic" hadrons in classic 1964 paper

New Domain of Exotics: All-Heavy Tetra-quarks

- A different exotic system compared to exotics with light quarks
- First mention of 4c states at 6.2 GeV (1975): Y. Iwasaki, Prog. of Theo. Phys. Vol. 54, No. 2

  (Just one year after the discovery of J/ψ)
- First calculation of 4c states (1981): K.-T. Chao, Z. Phys. C 7 (1981) 317

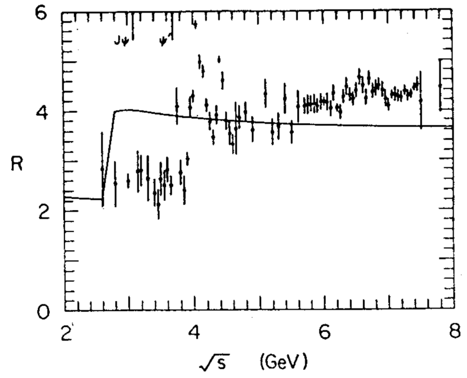
$(cc)_{\underline{3}^*} - (\overline{cc})_{\underline{3}}$

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

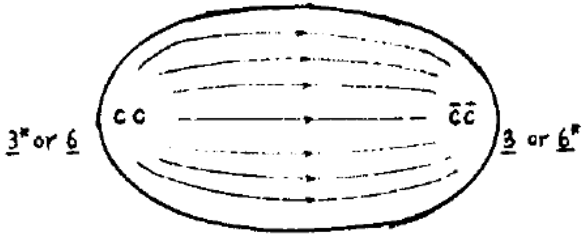
$(cc)_{\underline{6}} - (\overline{cc})_{\underline{6}^*}$

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

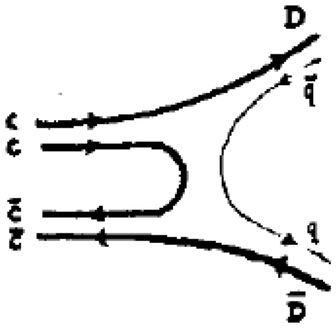
Data for R from SLAC-LBL collaboration. The curve is the QCD prediction for R.



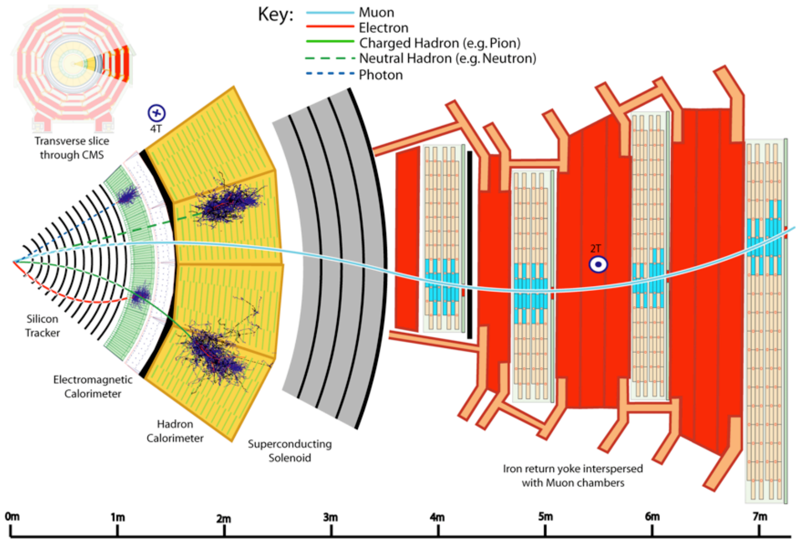
Linked by color electric flux in a bag



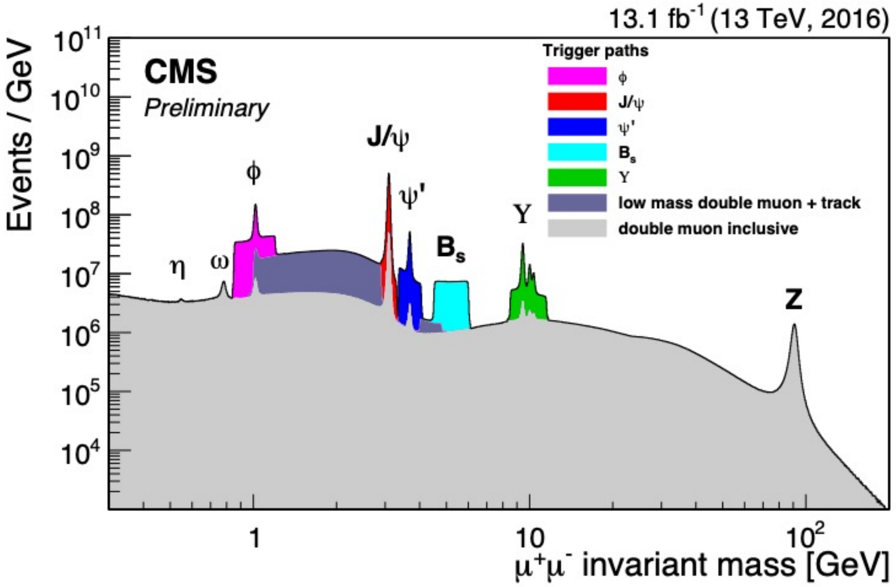
Possible two-body decays

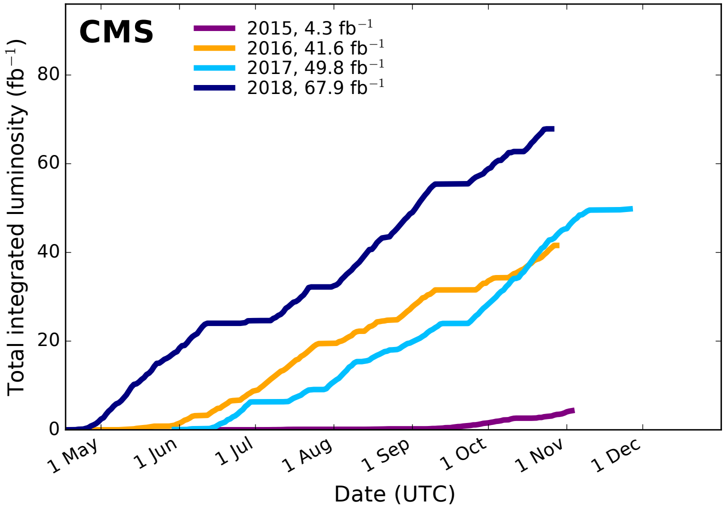


The CMS detector & trigger



η coverage (track & muon): [-2.5,2.5]





2016+2017+2018: ~145 fb^{-1}

Excellent detector for (exotic) quarkonium:

- Muon system

  High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ

- Silicon Tracking detector, B=3.8T

  $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution

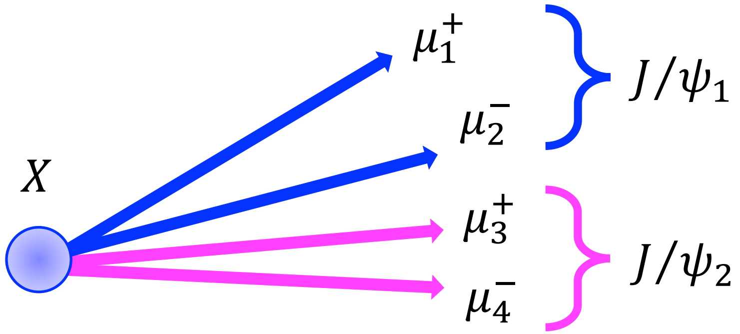
- Special triggers for different analysis at increasing Inst. Lumi.

  μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ

Data samples & Event selections

- 135 fb^{-1} CMS data taken in 2016, 2017 and 2018 LHC runs
- Blinded signal region: [6.2,7.8] GeV

  based on preliminary investigation on data collected in 2011-2012



$p_T(\mu) > 2$ GeV (2016) & $p_T(\mu) > 3.5$ GeV (2017, 2018)
$|\eta(\mu)| < 2.4$
$2.95\ GeV \leq M(\mu^+\mu^-) \leq 3.25\ GeV$, then constrain to J/ψ mass
$p_T(J/\psi) > 3.5$ GeV
Soft Muon ID (very loose)
$Vertex\ Probability(\mu^+\mu^-\mu^+\mu^-) > 0.5\%$

- Main selections:
  - Fire corresponding trigger in each year & offline selection
  - Multiple candidates' treatment:

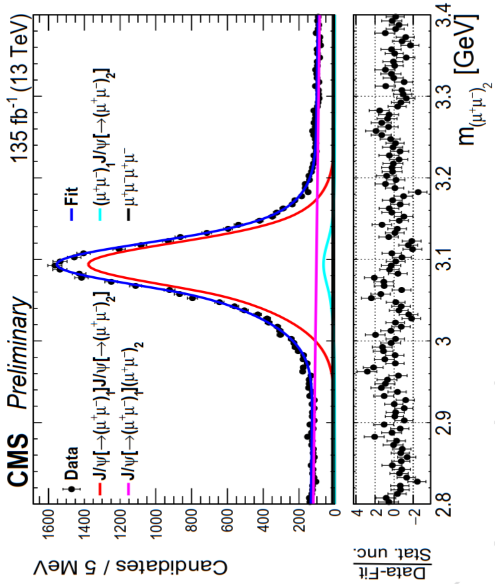
    Select best combination of same 4μ (~0.2%) with

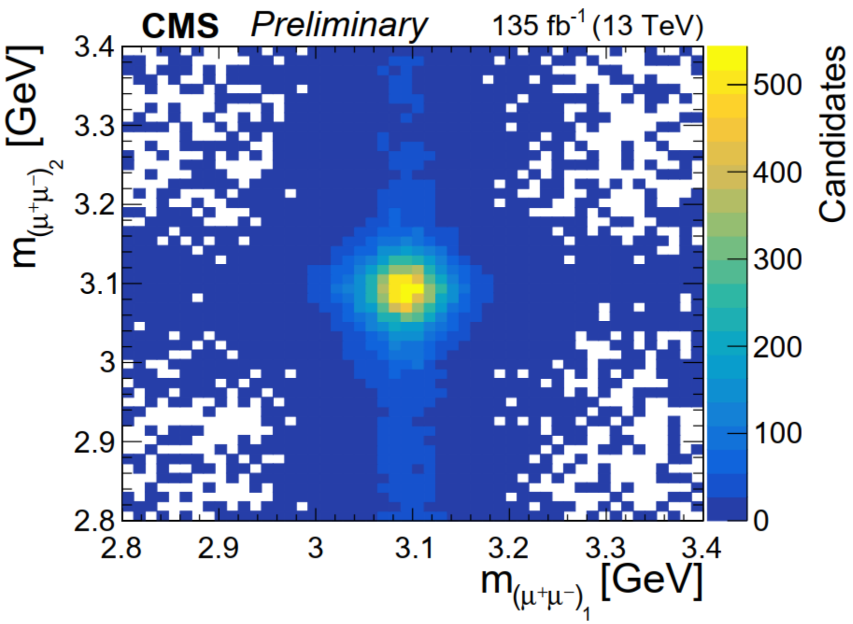
$$\chi_m^2 = \left(\frac{m_1(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

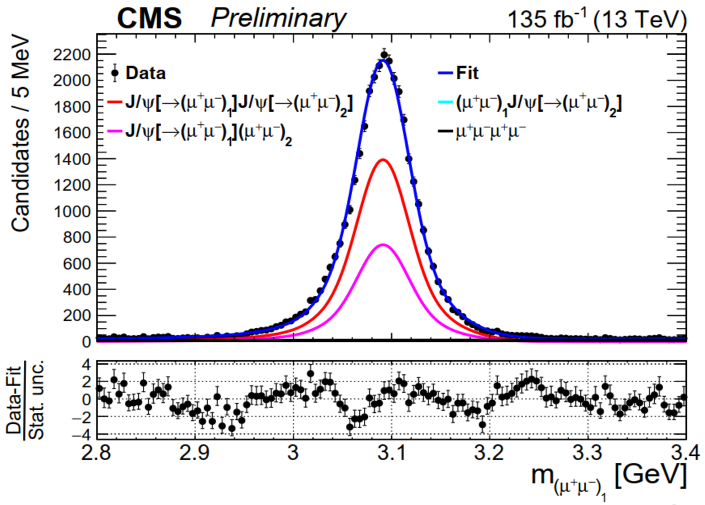
    Keep all candidates arising from > 4μ (~0.2%)

- Signal and background MC samples produced by Pythia8, JHUGen, HELAC-Onia…

J/ψ signal







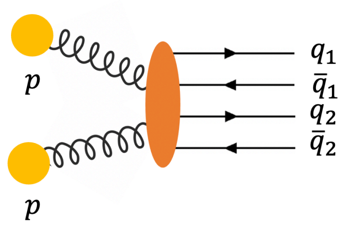
- Remove by J/ψ mass related cuts
- Clean J/ψ signal as seen

- ~15000 J/ψ pairs after final selection (m(J/ψ J/ψ) <15 GeV)
- ~9000 J/ψ pairs after final selection (m(J/ψ J/ψ) <9 GeV)

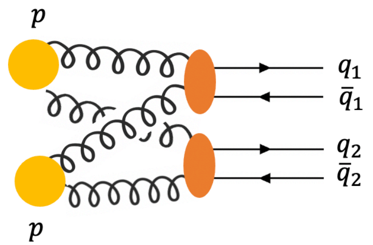
Steps to identify structures in $J/\psi J/\psi$ mass spectrum

- Null-hypothesis (initial baseline model): NRSPS+NRDPS
  - NRSPS—Non-Resonant Single Parton Scattering
  - NRDPS—Non-Resonant Double Parton Scattering

❖ SPS：



❖ NRDPS：



- Add potential structures to baseline model

  Add the most prominent structure to baseline model

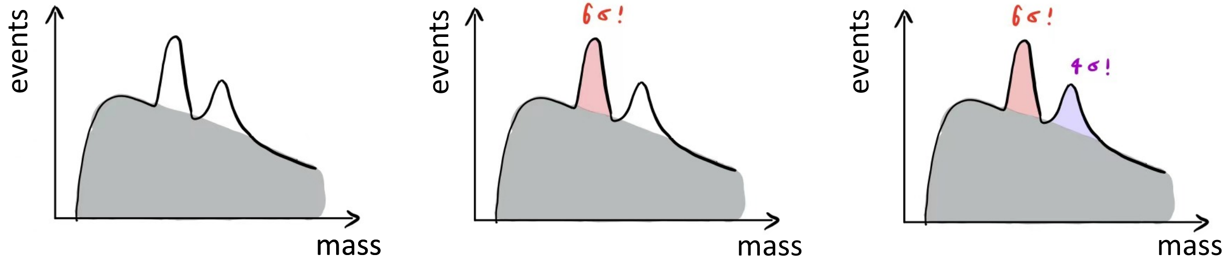
  Relativistic S-wave Breit-Wigner (BW) convolved with double-Gaussian resolution function for each structure

  Calculate its local significance

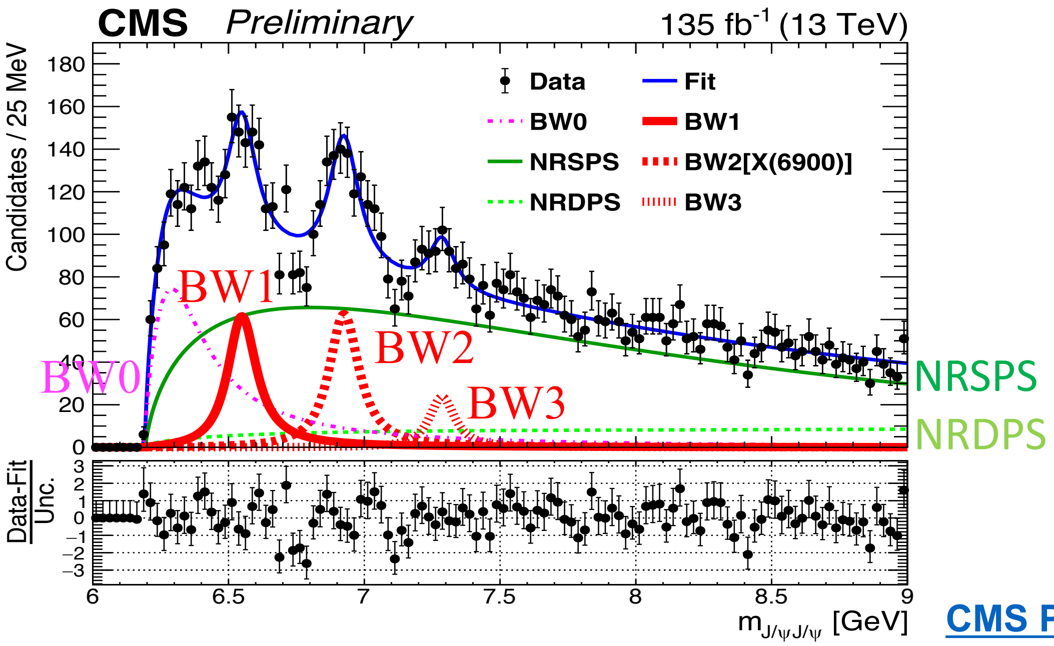
  Local significance: standard likelihood ratio method

  Keep it in baseline model only if $> 3\sigma$ significance

  Repeat until no more $> 3\sigma$ structures

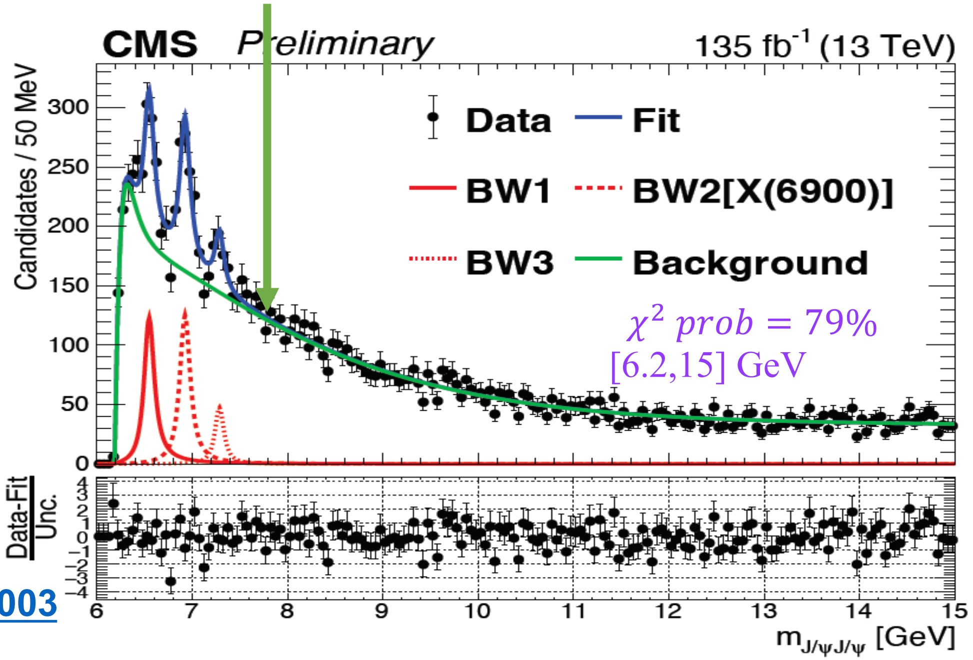


CMS background (BW0 + NRSPS + NRDPS)



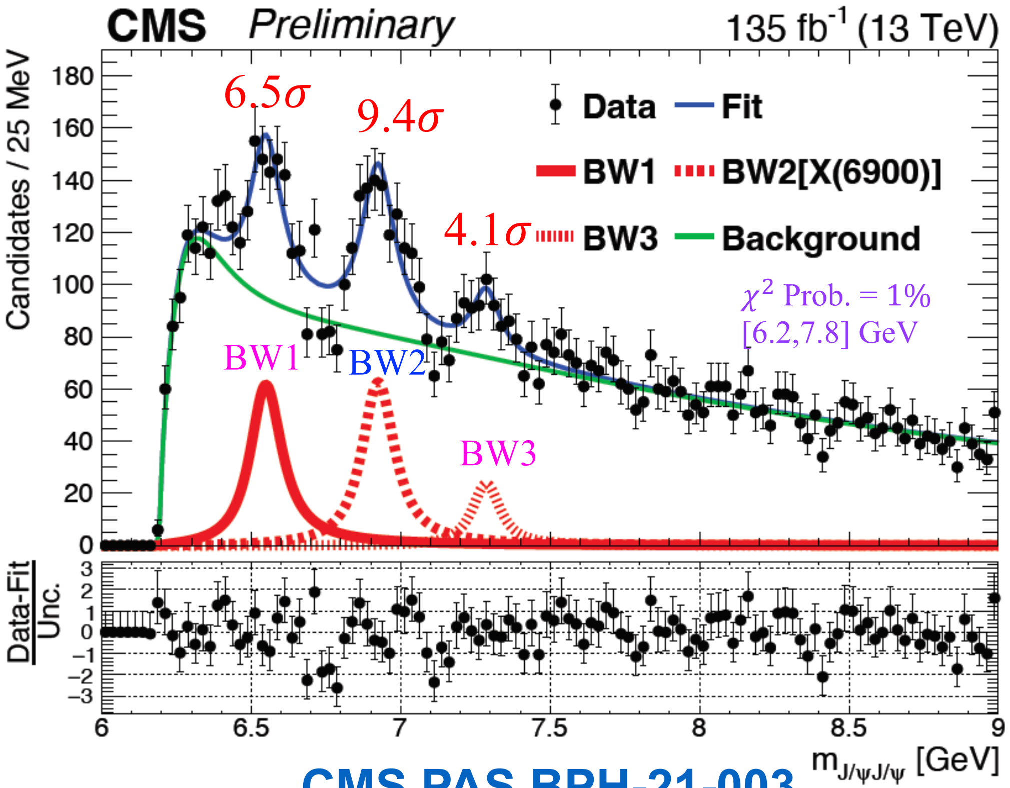
CMS PAS BPH-21-003

CMS background (BW0 + NRSPS + NRDPS)



- 4 significant structures: BW0, BW1, BW2, BW3
- Most significant structure in first step is BW0 at the threshold, what is its meaning?
- Treat BW0 as part of background due to:
  - Inadequacy of our NRSPS model at threshold
  - BW0 parameters are very sensitive to other model assumptions
  - A region populated by feed-down from possible heavier mass states
    - $X \to J/\psi\psi(2S) \to J/\psi J/\psi + \cdots$
- BW0+NRSPS+NRDPS as our background

Final CMS model: 3 BWs + Background (null)



CMS PAS BPH-21-003

- BW2[X(6900)] (9.4σ) – confirmation
- Observation of BW1 (6.5σ)
- Evidence for BW3 (4.1σ)

	BW1	BW2	BW3
M [MeV]	6552^{+10}_{-10}	6927^{+9}_{-9}	7287^{+20}_{-18}
Γ [MeV]	124^{+32}_{-26}	122^{+24}_{-21}	95^{+59}_{-40}
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}

Statistical significance only

Statistical significance based on: 2 ln(L_0/L_{max})

Significances including systematics

- To include systematics, alternative resonance/background shapes applied in the fit:
- Calculate signal- and null-hypothesis NLL_{syst} including systematic using:
  - $NLL_{syst-sig}$ = $\mathrm{Min}\{NLL_{nom-sig}, NLL_{alt-i-sig} + 0.5 + 0.5 \cdot \Delta dof\}$
    - $NLL_{nom-sig}$ means the NLL of nominal 'signal hypothesis' fit.
    - $NLL_{alt-i-sig}$ means the NLL of i-th alternative fit of 'signal hypothesis'
    - Δdof means the additional free parameters comparing to the nominal 'signal hypothesis' fit
  - $NLL_{syst-null}$ = $\mathrm{Min}\{NLL_{nom-null}, NLL_{alt-j-null} + 0.5 + 0.5 \cdot \Delta dof\}$
  - Significance including systematics as usual from $NLL_{syst-null} - NLL_{syst-sig}$

	Significance with syst.
BW1	5.7σ
BW2	*no sensible changes*
BW3	*no sensible changes*

- Investigated effects of systematics on local significance
  - Change: BW1 significance changed from 6.5**σ** to >5.7**σ**
  - No relative significance changes for BW2 and BW3

Summary of systematic uncertainties and CMS result

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: sum in quadrature

CMS PAS BPH-21-003

CMS PAS BPH-21-003

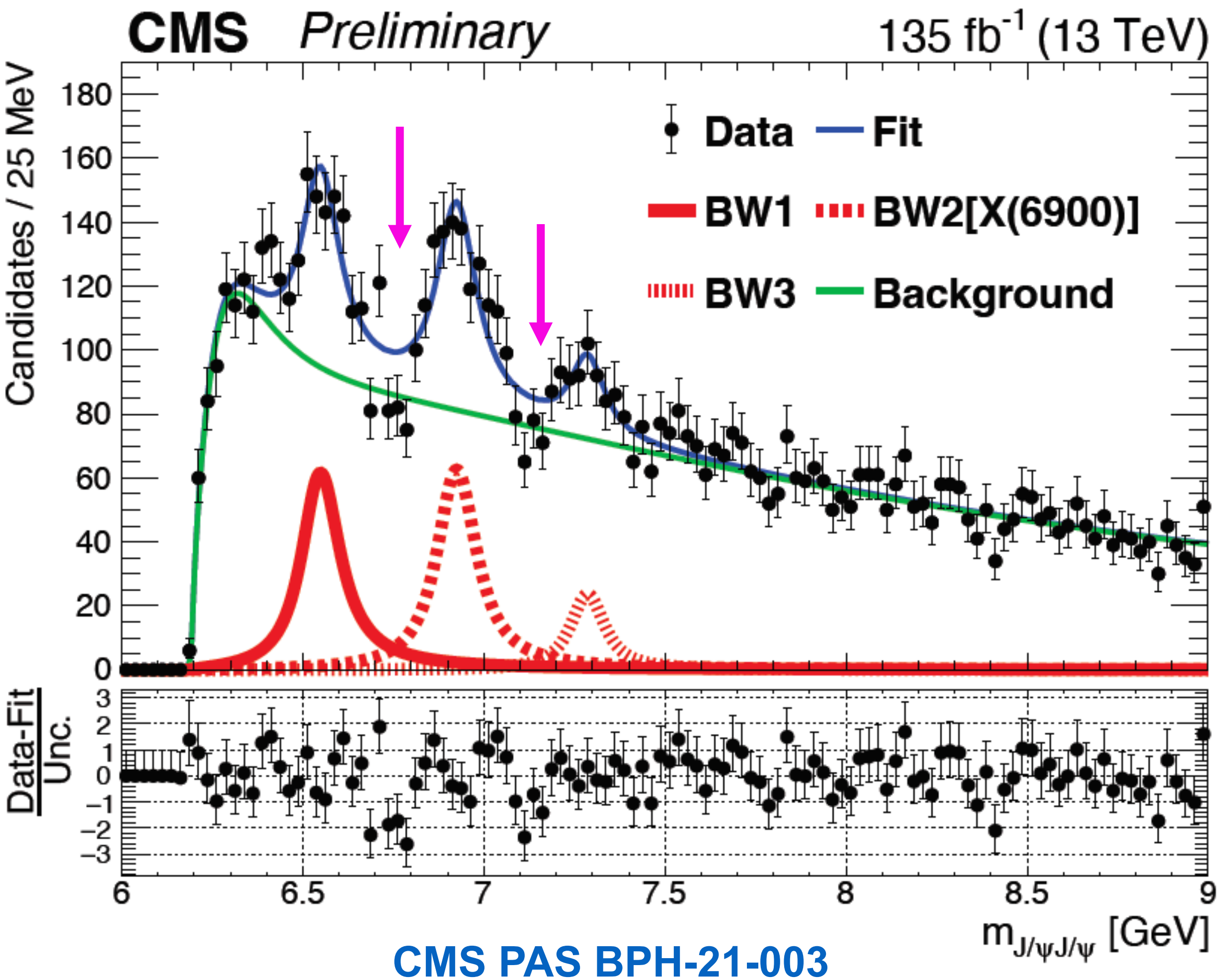
M[BW1] = 6552^{+10+12}_{-10-12} MeV	Γ[BW1] = 124^{+32+33}_{-26-33} MeV	>5.7σ
M[BW2] = 6927^{+9+4}_{-9-4} MeV	Γ[BW2] = 122^{+24+18}_{-21-18} MeV	>9.4σ
M[BW3] = 7287^{+20+5}_{-18-5} MeV	Γ[BW3] = 95^{+59+19}_{-40-19} MeV	>4.1σ

consistent →

X(6900) [LHCb]
(somewhat different fit model)

M[BW2]=6905±11±7 MeV
Γ[BW2] =80±19±33 MeV

The dips



CMS PAS BPH-21-003

- Possibility #1:
  - Interference between structures?
  - Why no interference for Y(nS) peaks?
    - Width too narrow to overlap
- Possibility #2:
  - Multiple fine structures to reproduce the dips?
  - Mentioned in PAS

- More secrets to dig out
- We explored possibility #1 in detail

Exploration of possible interference among BWs

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

$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \bigotimes R(M_0)$$
$$+N_{X\ and\ interf} \cdot \boxed{|r_1 \cdot e^{i\phi_1} \cdot BW_1 + BW_2 + r_3 \cdot e^{i\phi_3} \cdot BW_3|^2} \longleftarrow \textbf{Interf. term}$$
$$+N_{NRSPS} \cdot f_{NRSPS}(m) + N_{NRDPS} \cdot f_{NRDPS}(m)$$

- Many ways of interference due to possible J^{PC} and quantum coherence
  - 2-object-interference between BW0, BW1, BW2, BW3
  - 3-object-interference between BW0, BW1, BW2, BW3
  - 4-object-interference between BW0, BW1, BW2, BW3

- Our choice: interference between BW1, BW2, BW3
  - $\chi^2\ prob$ < 30% for 2-body
  - No significant better description for 4-body
  - BW0 – background-like

Summary of systematic for interf. case

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

Fit	Dominant sources	M_{BW_1}	M_{BW_2}	M_{BW_3}	Γ_{BW_1}	Γ_{BW_2}	Γ_{BW_3}
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	$^{+16}_{-31}$	$^{+48}_{-20}$	$^{+41}_{-15}$	$^{+110}_{-240}$	$^{+25}_{-17}$	$^{+29}_{-26}$

- Lager systematic uncertainties:
  - Greater complexity & increased parameters correlation of the model

Final result

- Measured mass and width

		BW_1	BW_2	BW_3
No-interference	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}
Interference	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}

Non-interference fit

Interference fit

- Systematic uncertainty table (sources with minor effects suppressed)

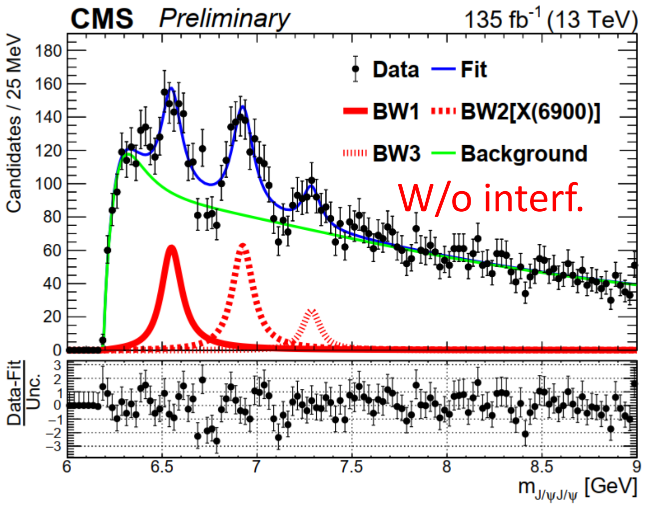
Fit	Dominant sources	M_{BW_1}	M_{BW_2}	M_{BW_3}	Γ_{BW_1}	Γ_{BW_2}	Γ_{BW_3}
No-interference	Signal shape	3	3	3	10	5	5
	NRSPS shape	3	1	1	18	15	17
	Feed-down	11	1	1	25	8	6
	Total uncertainty	12	4	5	33	18	19
Interference	Signal shape	7	12	7	56	8	7
	DPS shape	1	3	2	18	6	2
	NRSPS shape	9	14	13	85	9	20
	Mass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

Non-interference fit

Interference fit

- Implication of interf. Result:
  - Same J^{PC}
  - Large separation--200-300 MeV indicates radial excitation
- Any theoretical predication?

Comparison with some theoretical calculations



P-wave

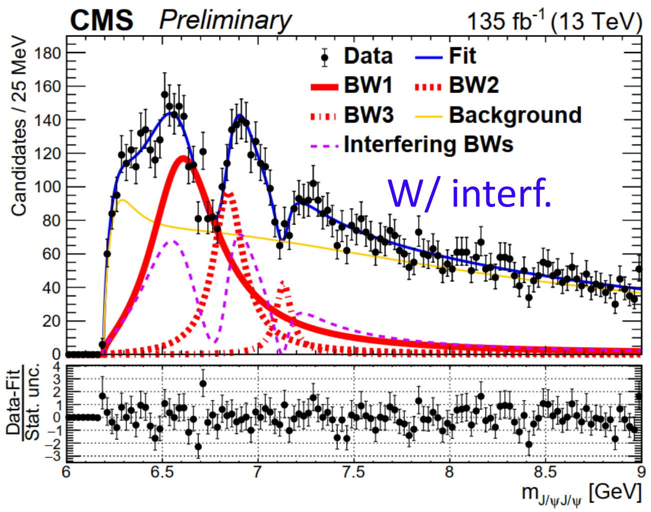
$N^{2S+1}L_J$	J^{PC}	$\langle K.E.\rangle$	$E^{(0)}$	$\langle V_C^{(0)}\rangle$	$\langle V_L^{(0)}\rangle$	$\langle V_{SS}^{(1)}\rangle$	$\langle V_{LS}^{(1)}\rangle$	$\langle V_T^{(1)}\rangle$	$V^{(1)}(r)$	M_f
1^3P_1	1^{-+}	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554
2^3P_1	1^{-+}	410.0	689.6	-263.4	548.6	-5.6	-23.1	17.2	-1.6	6926
3^3P_1	1^{-+}	475.1	982.6	-215.5	727.7	-4.6	-20.9	15.5	-1.2	7220

arXiv:2108.04017 [hep-ph]

M[BW1] = 6552^{+10+12}_{-10-12} MeV

M[BW2] = 6927^{+9+4}_{-9-4} MeV

M[BW3] = 7287^{+20+5}_{-18-5} MeV



S-wave

$T_{4Q}(nS)$ 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}	6566^{+34}_{-35}	6890^{+27}_{-26}	7160^{+21}_{-22}

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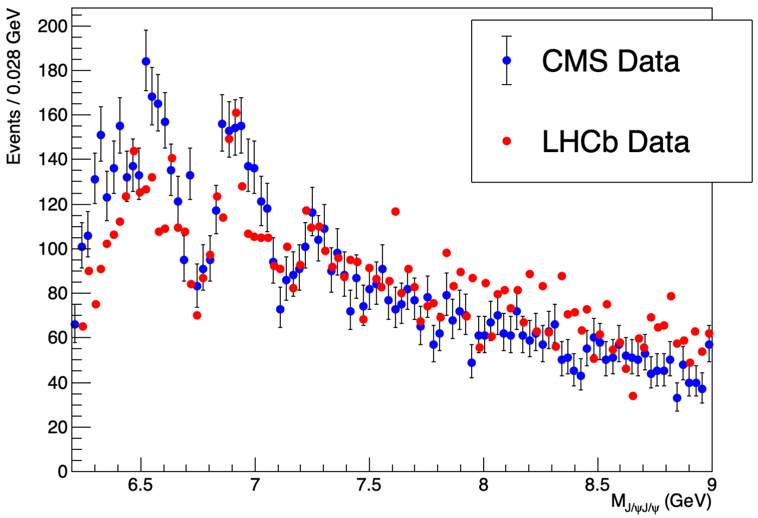
M[BW1] = 6638^{+43+16}_{-38-31} MeV

M[BW2] = 6847^{+44+48}_{-28-20} MeV

M[BW3] = 7134^{+48+41}_{-25-15} MeV

- Radial excited p-wave states (like J/ψ 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



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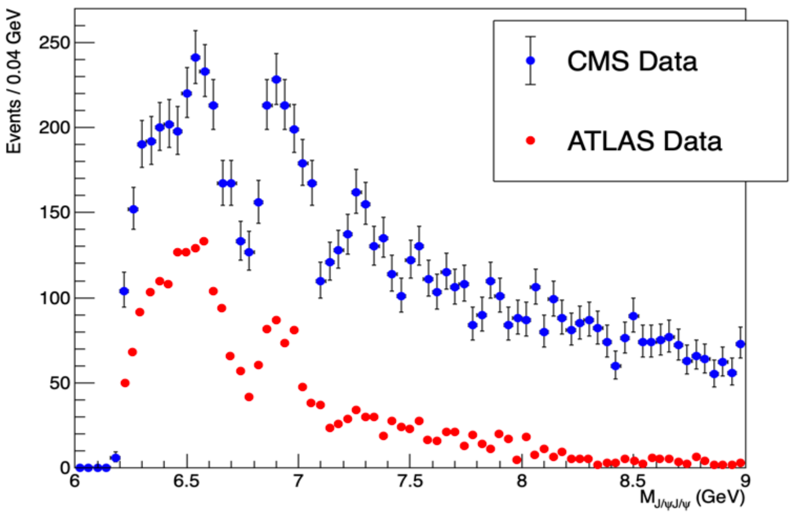
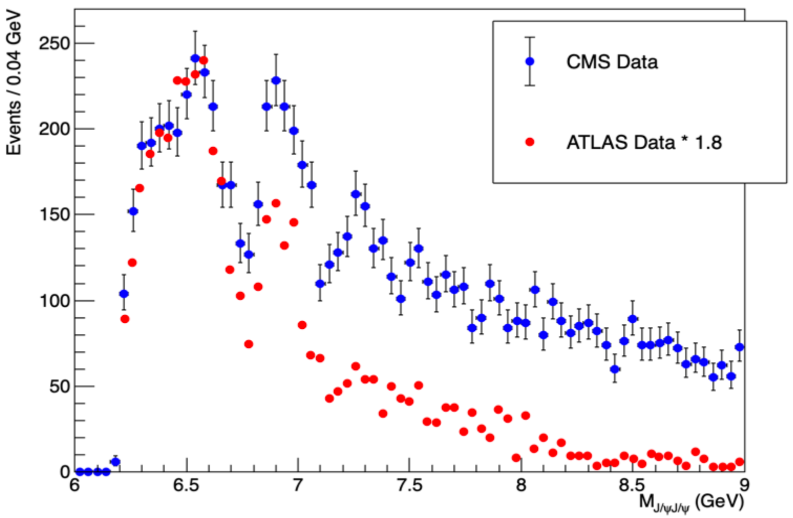




arXiv:2304.08962v1

- **CMS vs LHCb comparisons:**
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4$ ≈ 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
  - CMS has slightly better resolution

- **CMS has good sensitivity to all-muon final state in this mass region**

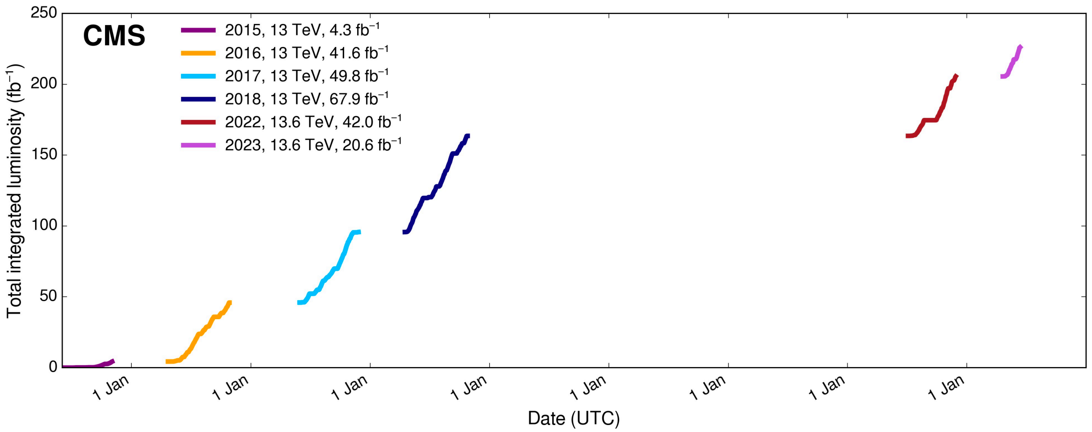
Summary

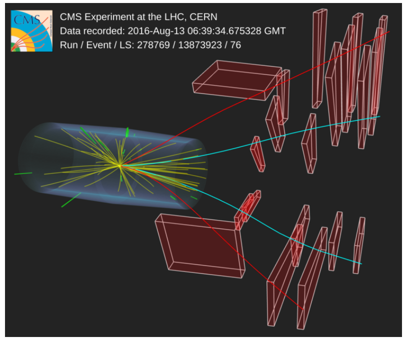
- CMS found 3 significant $J/\psi J/\psi$ structures using 135 fb^{-1} 13 TeV data arXiv:2306.07164
  - BW2 consistent with X(6900) reported by LHCb
  - CMS found two new structures, provisionally named as X(6600), X(7300)

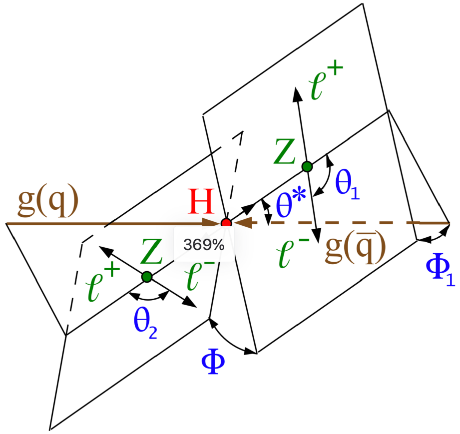
- A family of structures which are candidates for all-charm tetra-quarks!
  - Large mass separations — 200+ MeV — suggest radial excitation
  - Possible interference effects suggest the same J^{PC} and coherent production

  - All-heavy quark exotic structures offer a system easier to understand
  - Mass differences from multiple structures can be better calculated
  - A new window for further research in strong interaction

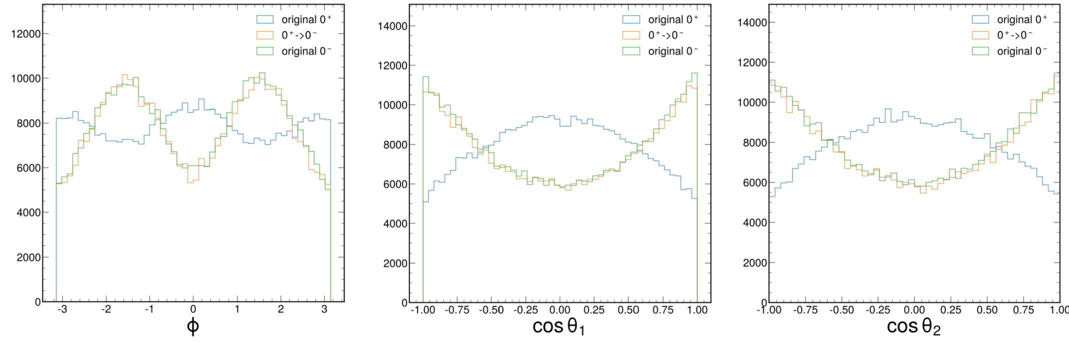
Outlook



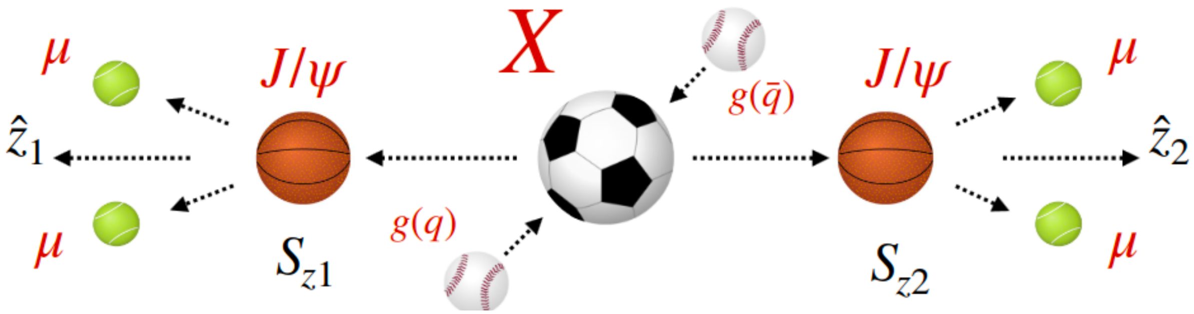




- Data in 2016 + 2017 + 2018: 41.6 + 49.8 + 67.9 = 159.3 fb^{-1}
- Updated data in 2022 + 2023: 42.0 + 20.6 = 62.6 fb^{-1}
  - Confirmation of X(6600), X(6900) with updated data?
  - Observation of X(7300)

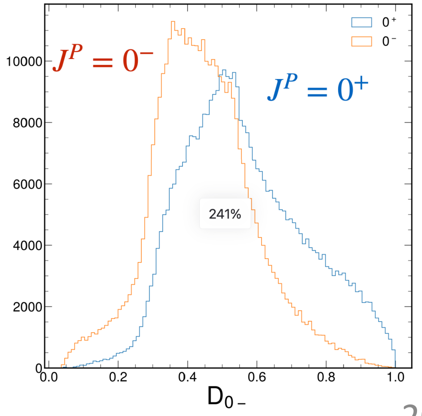


- Spin parity analysis is going on



Create an optimal observable (MELA) to separate spin parity

$$\mathcal{R}_{\text{opt},2} = \frac{\mathcal{P}_1(\vec{x}^{\text{full}}_{\text{reco}})}{\mathcal{P}_0(\vec{x}^{\text{full}}_{\text{reco}}) + c \cdot \mathcal{P}_1(\vec{x}^{\text{full}}_{\text{reco}})}$$



Backup

Summary

CMS found 3 significant $J/\psi J/\psi$ structures using 135 fb^{-1} 13 TeV data

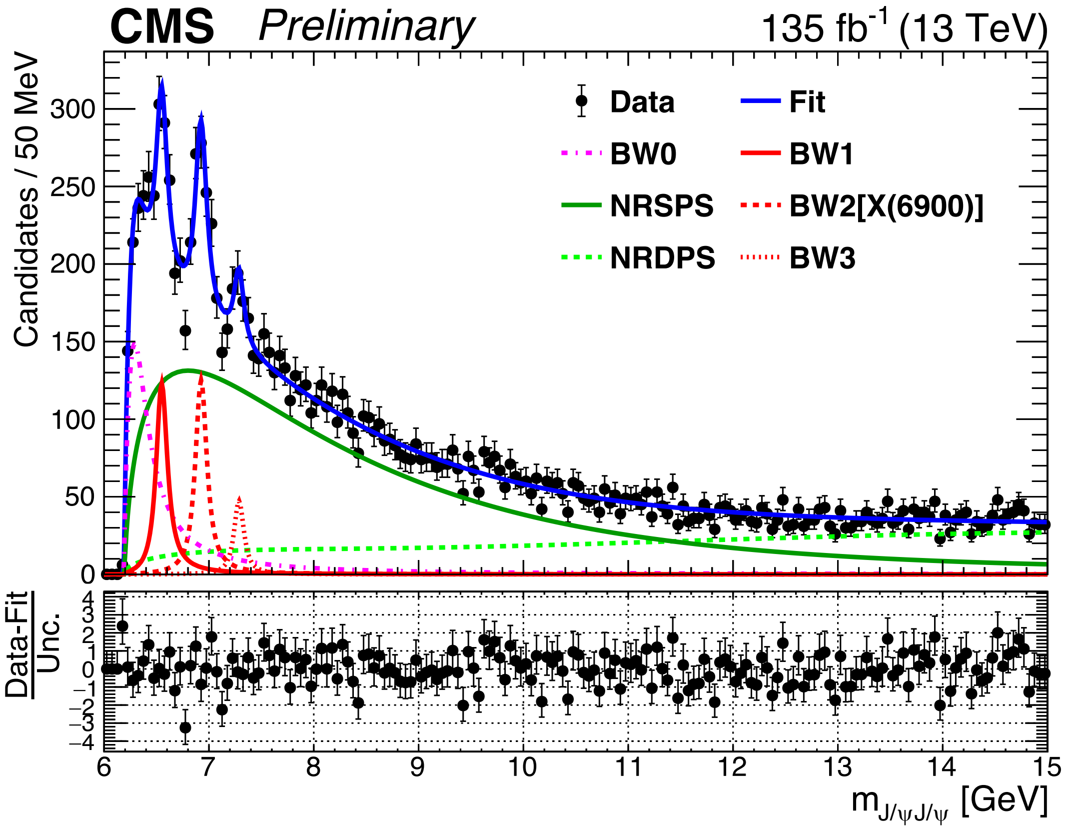
- BW2 consistent with X(6900) reported by LHCb
- CMS found two new structures, provisionally named as X(6600), X(7200)
- A family of structures which are candidates for all-charm tetra-quarks!
  - Large mass separations — 200+ MeV — suggest radial excitation
  - Possible interference effects suggest same J^{PC} and coherent production

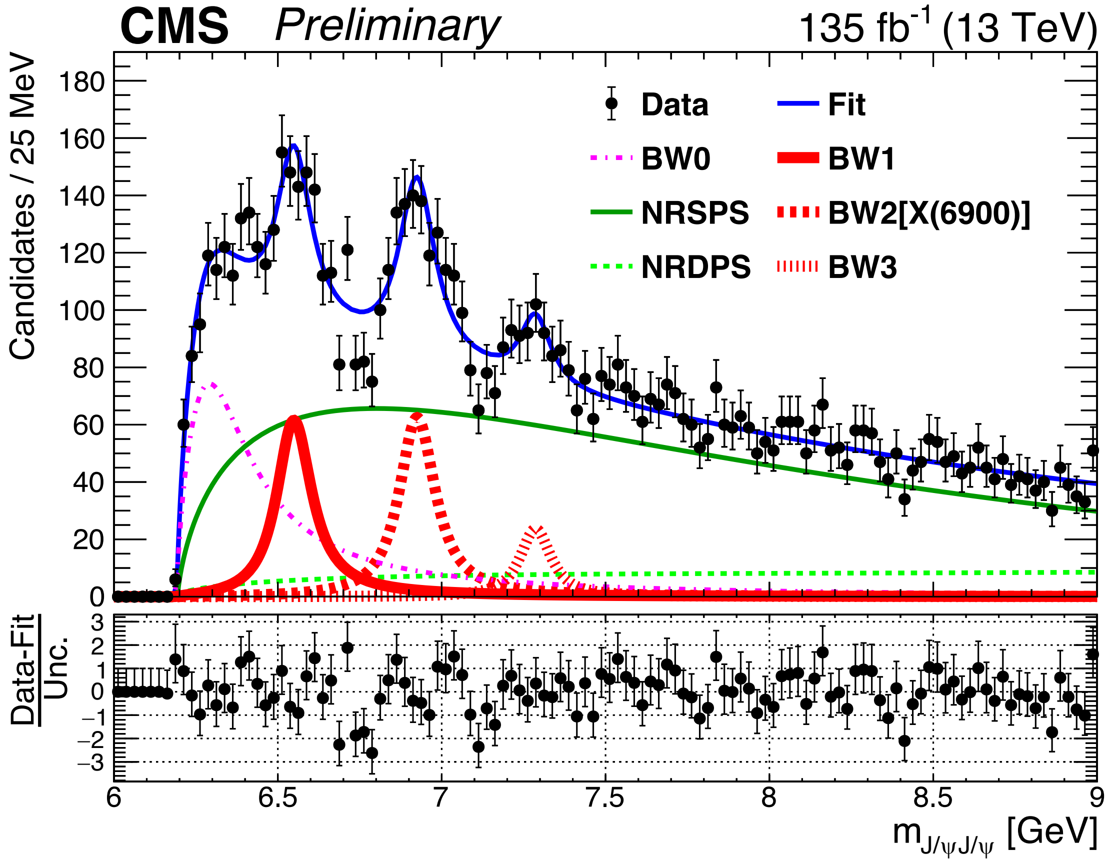
- All-heavy quark exotic structures offer system easier to understand
- Mass differences from multiple structures can be better calculated
- A new window to understand the strong interaction

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

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

Final CMS model: 3 BWs + Backgrounds+ BW0





Signal PDF

$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - i m_0 \Gamma(m)},$$

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{m_0}{m} \left(B'_L(q, q_0, d)\right)^2,$$

Phase space

$$B'_L(q, q_0, d) = \frac{q^{-L} B_L(q, d)}{q_0^{-L} B_L(q_0, d)} = \left(\frac{q_0}{q}\right)^L \frac{B_L(q, d)}{B_L(q_0, d)},$$

$$B_0(q, d) = 1,$$

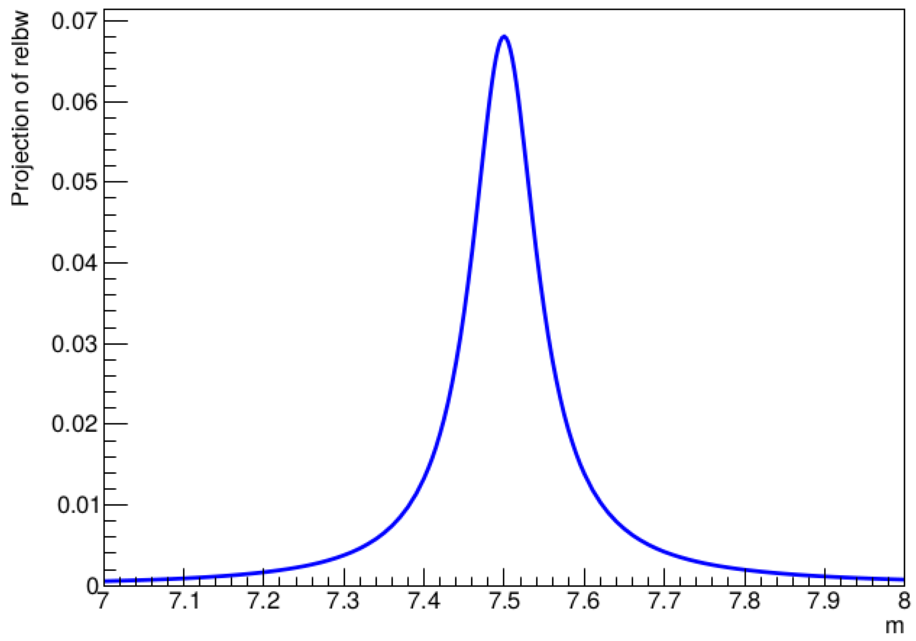
$$B_1(q, d) = \sqrt{\frac{2z}{z+1}},$$

$$B_2(q, d) = \sqrt{\frac{13z^2}{(z-3)^2 + 9z}},$$

$$B_3(q, d) = \sqrt{\frac{277z^3}{z(z-15)^2 + 9(2z-5)^2}},$$

$$B_4(q, d) = \sqrt{\frac{12746z^4}{(z^2 - 45z + 105)^2 + 25z(2z-21)^2}},$$

$$z = (|q|d)^2, z_0 = (|q_0|d)^2$$



- Default : L=0

$$\sum N_{X_j} \cdot |BW(m, M_j, \Gamma_j)|^2 \otimes R(M_j)$$

Background PDF

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

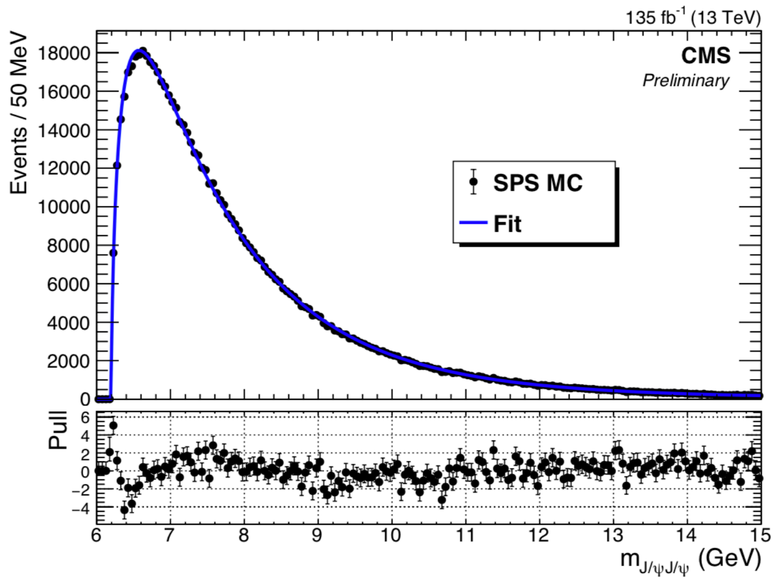
$$x_t = x - x_0, \quad x_0 = 2M_{J/\psi},$$

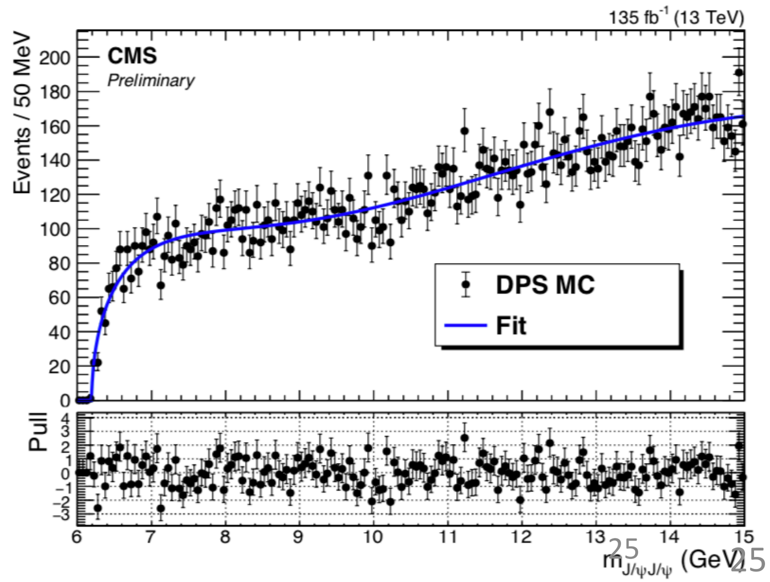
$$f_{DPS}(x) = \sqrt{x_t} \cdot \exp(-a \cdot x_t) \cdot (p_0 + p_1 \cdot x_t + p_2 \cdot x_t^2),$$

$$x_t = x - x_0, \quad x_0 = 2M_{J/\psi}.$$

3 float parameters:

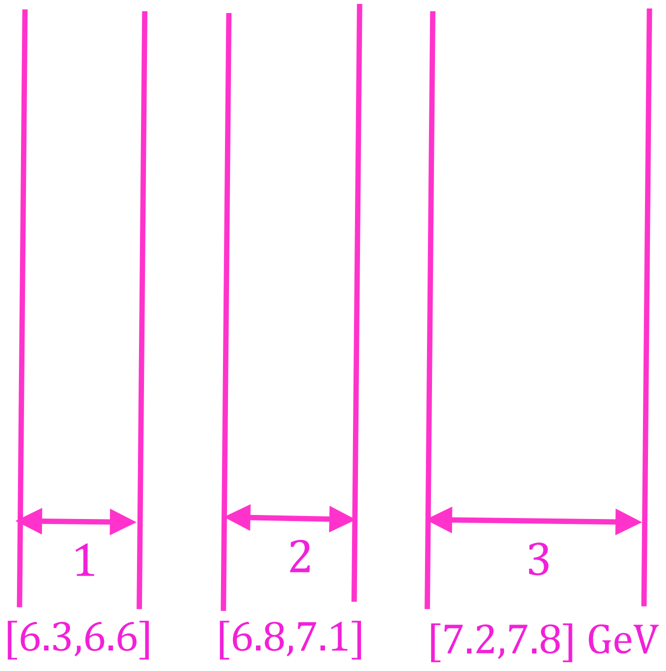
- p2 from NRSPS
- N(NRSPS), N(NRDPS)





Blinded mass windows for Run II $J/\psi J/\psi$ at CMS

We saw hints of structue at Run I data
Proposed three signal regions for Run II data



Blinded mass windows for Run II $J/\psi J/\psi$:

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

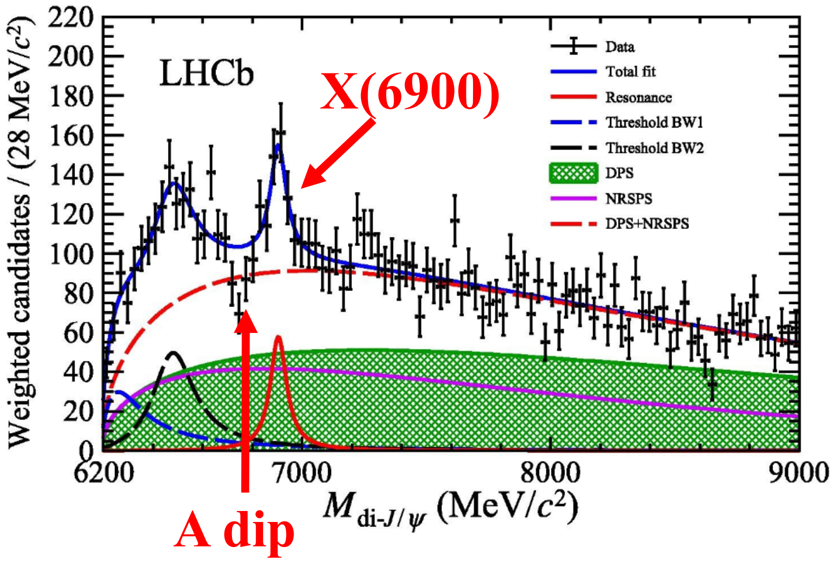
Run I data will be ignored for significance calculation

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

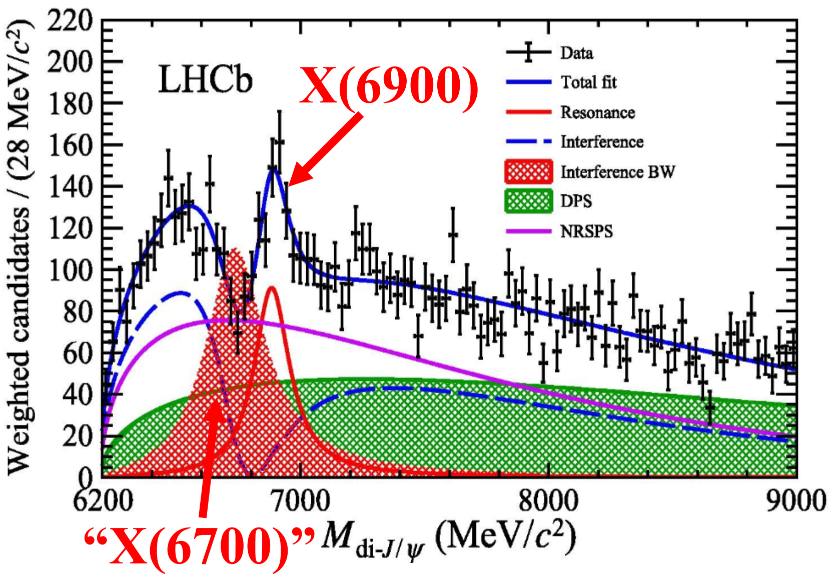
X(6900) reported by LHCb

- In 2020, LHCb reported X(6900) state in J/ψJ/ψ final state, Sci.Bull.65 (2020) 23
- Tried two different models
  - Model I: background+2 auxiliary BWs+ X(6900) → poor description of 'dip' around 6.7 GeV
  - Model II: a “virtual” X(6700) to interfere with NRSPS background to account for dip
- What happens if fit CMS data using LHCb models?

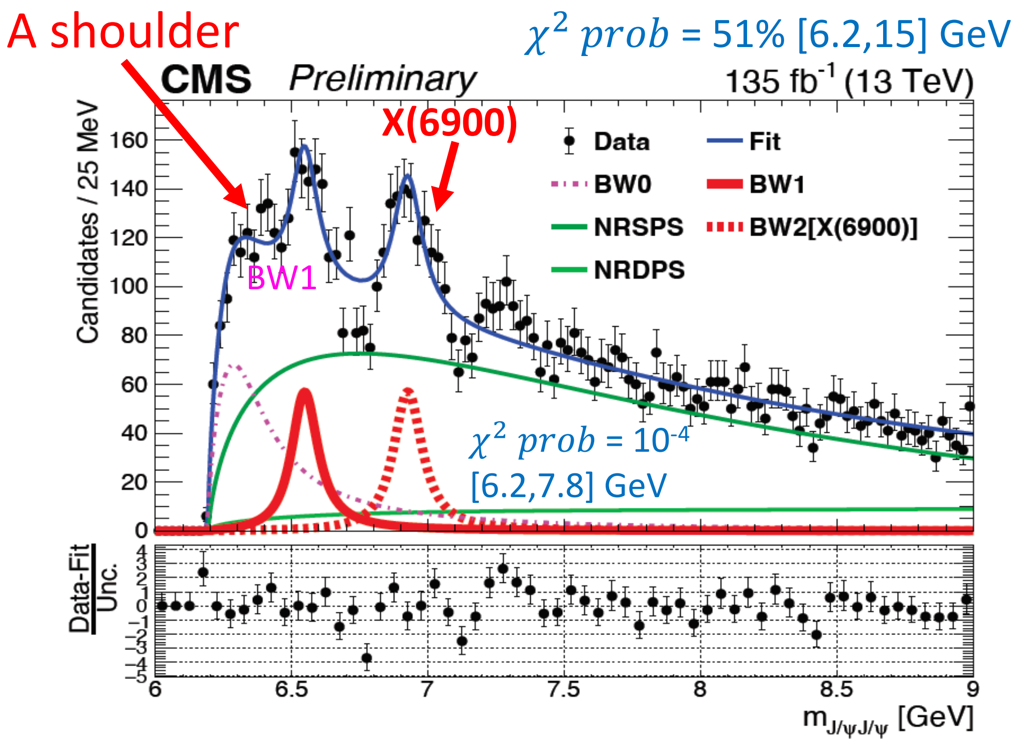
Model I

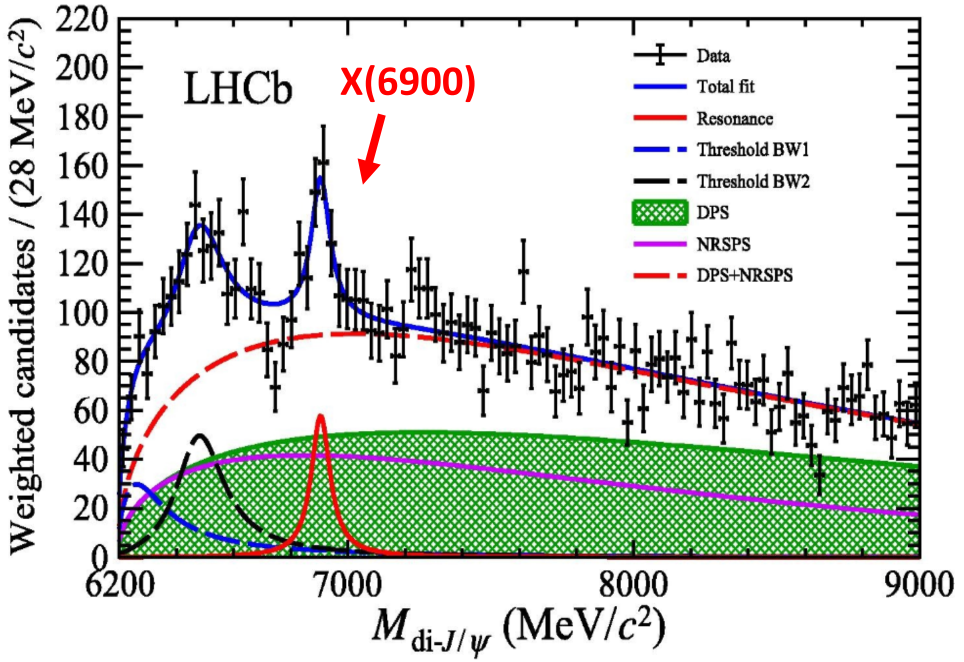


Model II



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

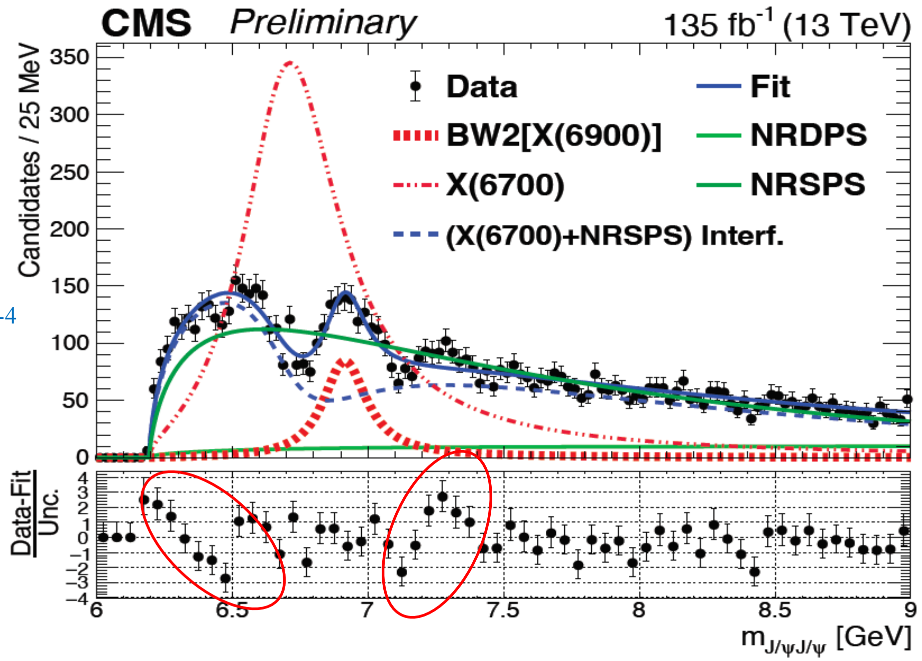
X(6900) parameters are in good agreement with LHCb
LHCb did not give parameters for another 2 BWs

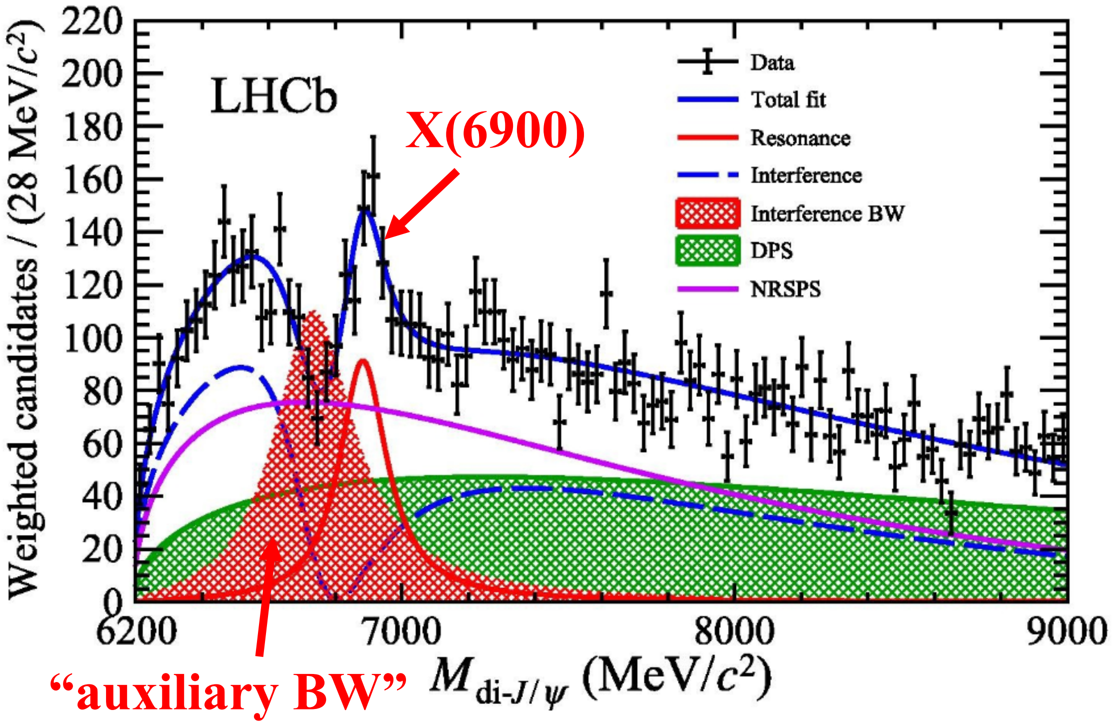
- CMS Data shows a shoulder before BW1
- CMS shoulder makes BW1 distinct

- *Does not describe well dips*

Fit with LHCb model II—DPS+X(6900)+“X(6700)” interferes with NRSPS

χ^2 $prob = 10^{-4}$
[6.2,7.8] GeV





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

All CMS fits presented are not very good:
…need other interference scenarios

- X(6900) parameters are consistent
- CMS obtained larger amplitude and natural width for X(6700)
  - Fast CMS threshold turn-on drives NRSPS high, which drives large aux. BW
- CMS's X(6600) is 'eaten' –does not describe X6600 and below
- Does not describe X(7300) region