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

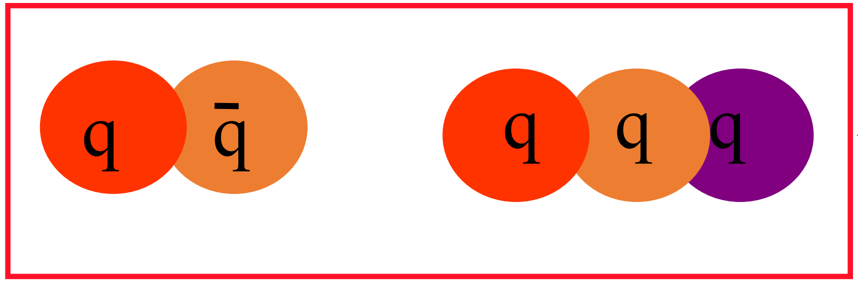
Xining WANG (Tsinghua University & Nanjing Normal University & Sun Yat-Sen University)

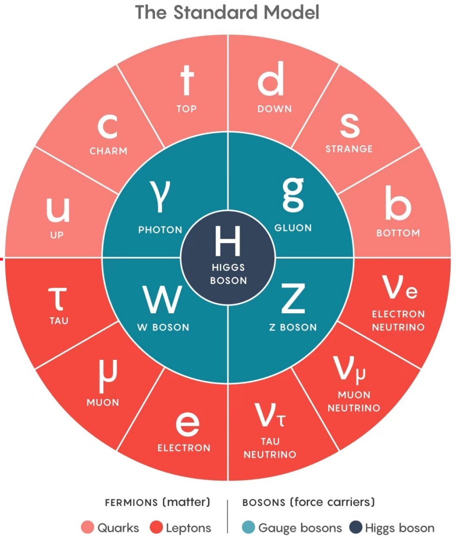
The 8th XYZ Particle Symposium
26 July 2023, Jilin, China

- **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**

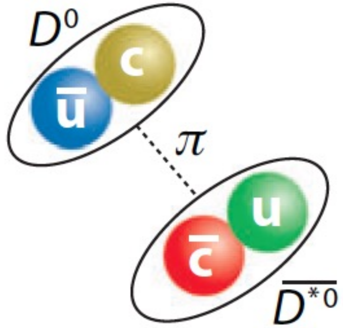
Quark model

Meson *Baryon*

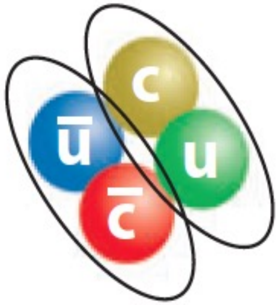




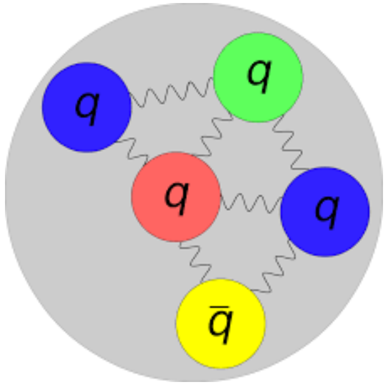
"exotic" hadron

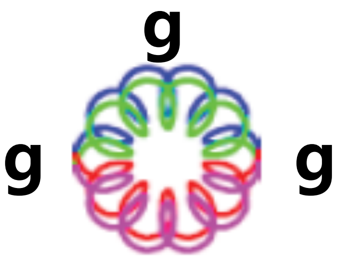


D^0–$\overline{D}^{*0}$ "molecule"



Diquark–diantiquark

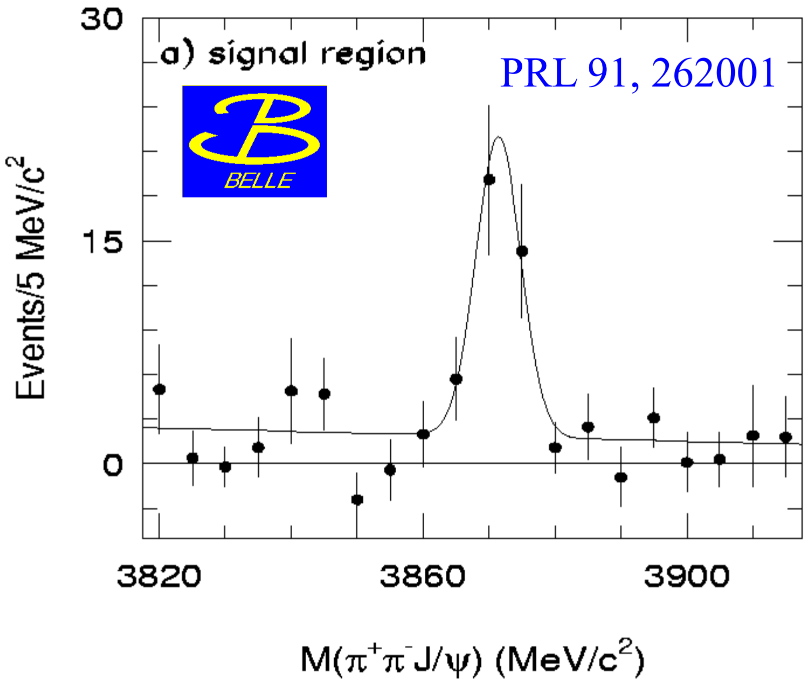




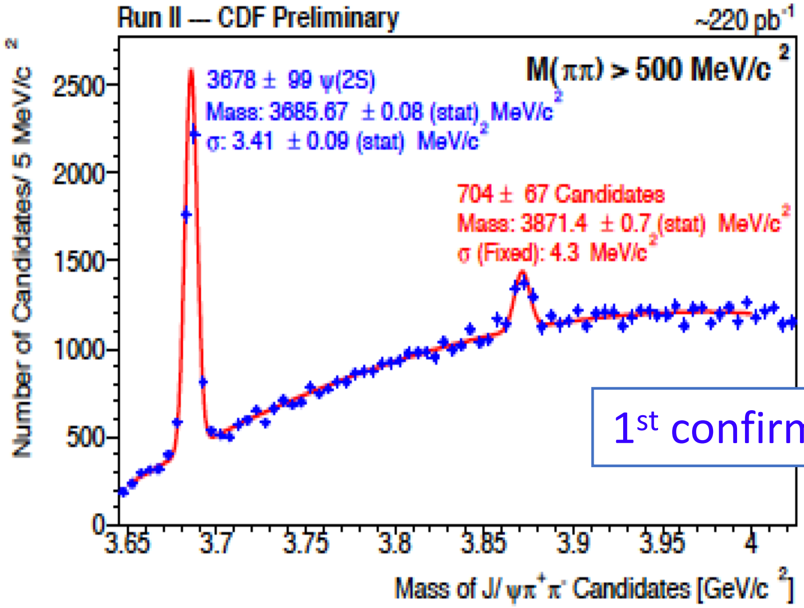
- *Glueball*

- *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



PRL 91, 262001



1st confirmation by CDF

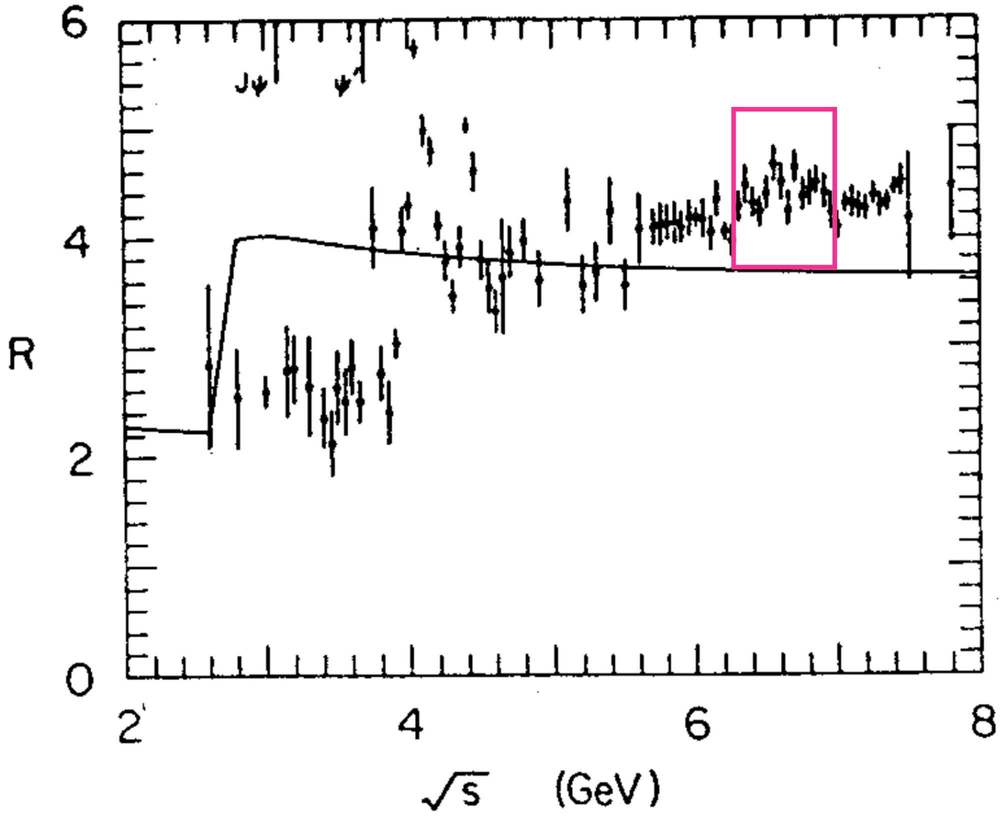
2017 Laureates

"…The X(3872) was discovered by Dr. Sookyung Choi and Dr. Stephen Olsen with their colleagues in the Belle experiment among the final states of the decay of B mesons. The X(3872) was confirmed by seven other experimental groups thereafter and is the first example of a new type of XYZ meson and the most well-established state among them. …"

2017 Korean Ho-Am Science Prize

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



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

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

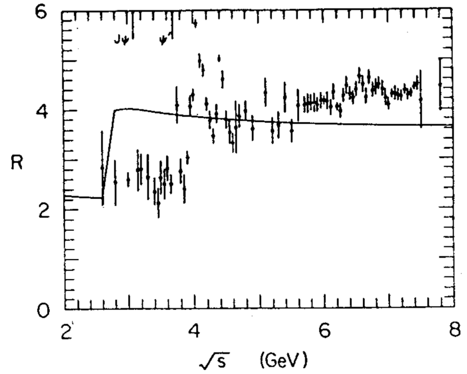
$(cc)_{\underline{3}^*} - (\overline{cc})_{\underline{3}}$

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

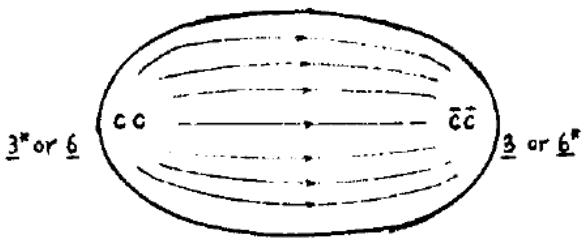
$(cc)_{\underline{6}} - (\overline{cc})_{\underline{6}^*}$

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

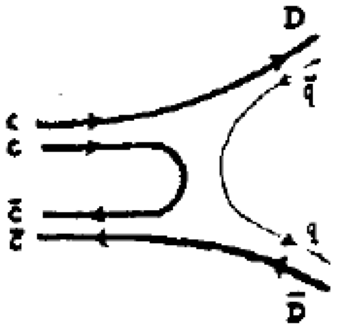
Data for R from SLAC-LBL collaboration. The curve is the QCD prediction for R.

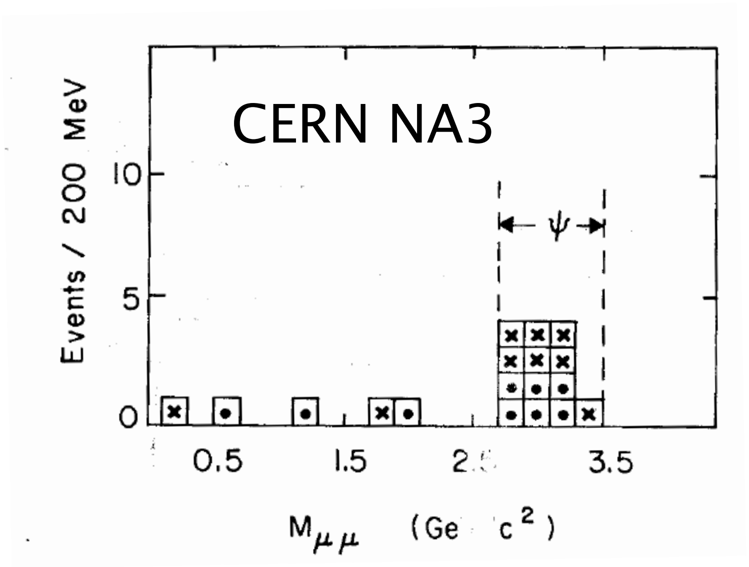


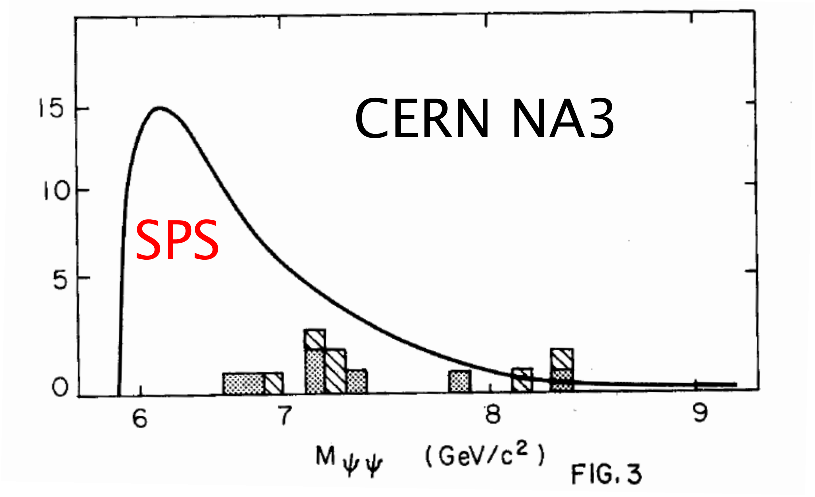
Linked by color electric flux in a bag



Possible two-body decays

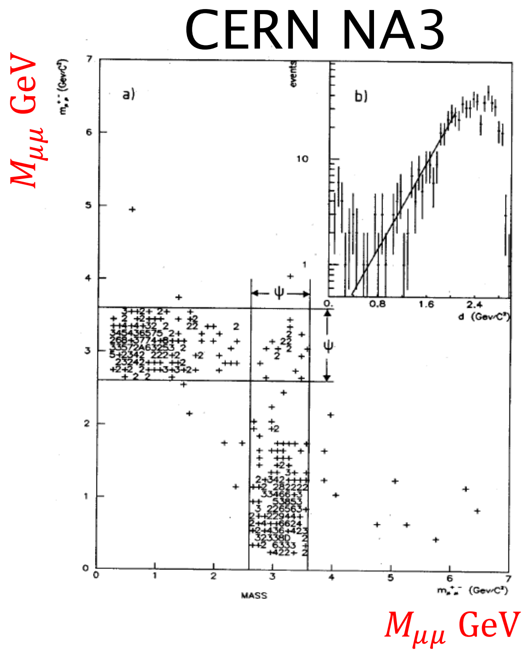


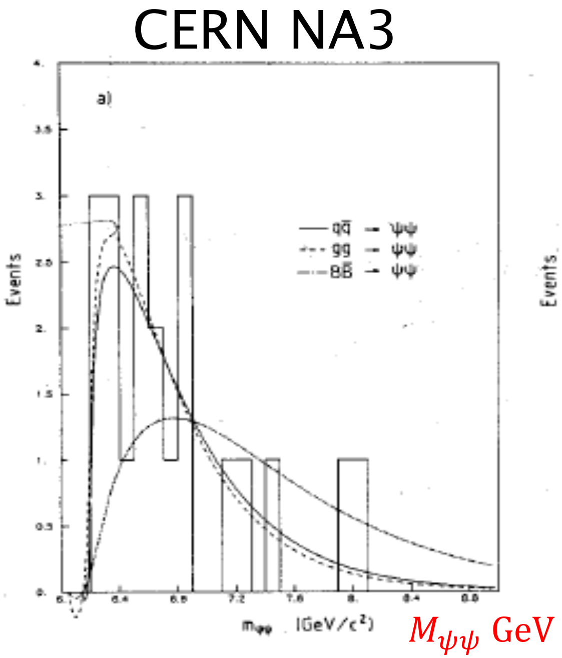


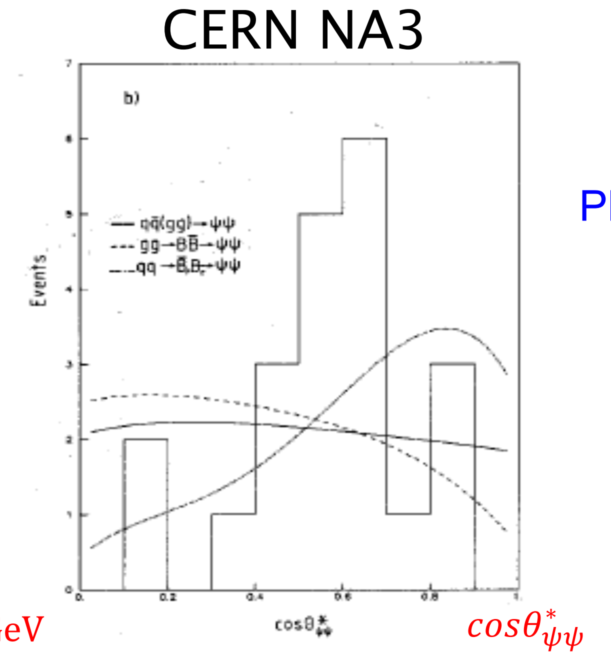


PLB114 (1982) 457

Was interpreted as 2^{++} 4-quark state







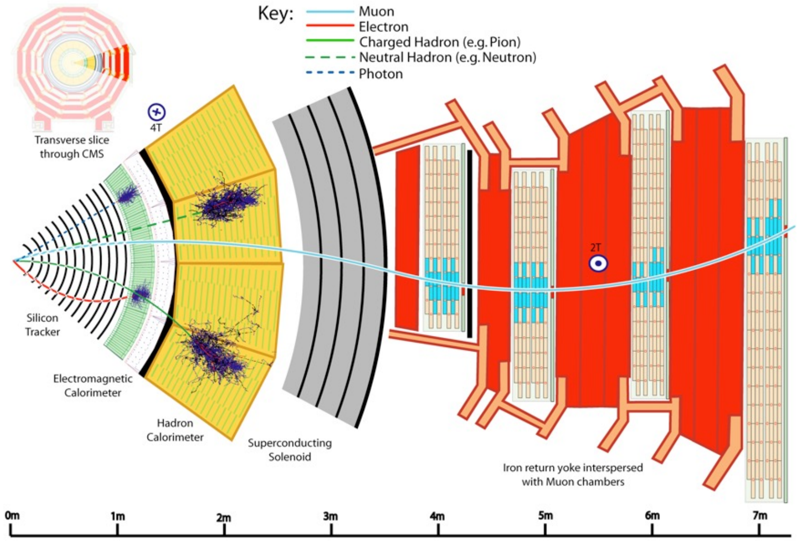
PLB158 (1985) 85

There were other attempts

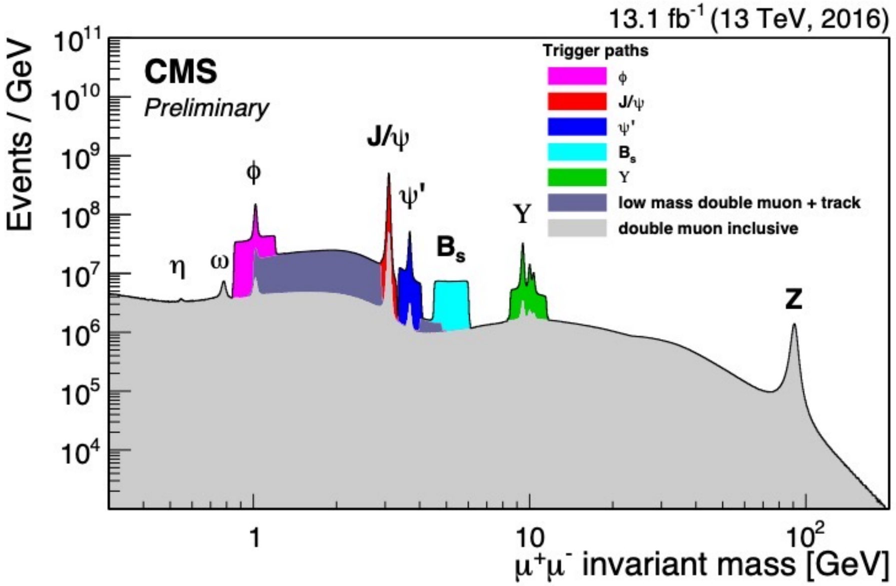
2++ four-quark states, PRD29 (1984) 426

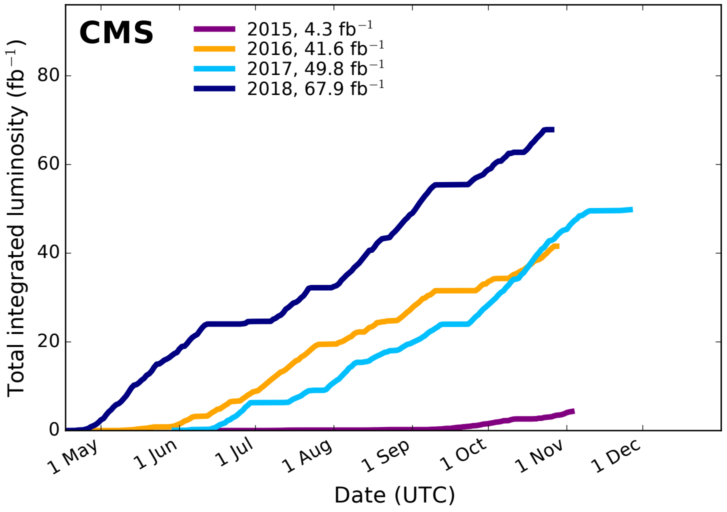
TABLE I. Parameters used in Eq. (8) to calculate the cross sections for vector-meson pair production. (+) and (−) denote two degenerate 2^{++} $Q^2\bar{Q}^2$ states. Except in the case of JJ, we take $4\pi/f_J^2=0.03$, due to the fact that the 2^{++} $Q^2\bar{Q}^2$ are expected to lie not far above the threshold. α_s is determined from Eq. (11).

V_1V_2	$a^j_{V_1V_2}/a$	$b^j_{\alpha\beta}\Big/\alpha_s\frac{a}{\sqrt{8}}\delta_{\alpha\beta}$	M_j (GeV)	α_s	m_1
JJ	$1/\sqrt{3}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_J^2}$	7.0	0.18	3.10
$J\omega^{(+)}$	$1/\sqrt{6}$	$\frac{-1}{\sqrt{3}}\frac{4\pi}{f_Jf_\omega}$	4.05	0.2	
$J\omega^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_Jf_\omega}$	4.05	0.2	
$\Upsilon J^{(+)}$	$1/\sqrt{6}$	$\frac{-1}{\sqrt{3}}\frac{4\pi}{f_\Upsilon f_J}$	13.5	0.167	
$\Upsilon J^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_\Upsilon f_J}$	13.5	0.167	
$B_c^*\bar{B}_c^{*(+)}$	$-1/\sqrt{6}$	$\frac{-1}{\sqrt{3}}\frac{4\pi}{f_\Upsilon f_J}$	13.5	0.167	6.60
$B_c^*\bar{B}_c^{*(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_\Upsilon f_J}$	13.5	0.167	



η coverage (track & muon): [-2.5,2.5]





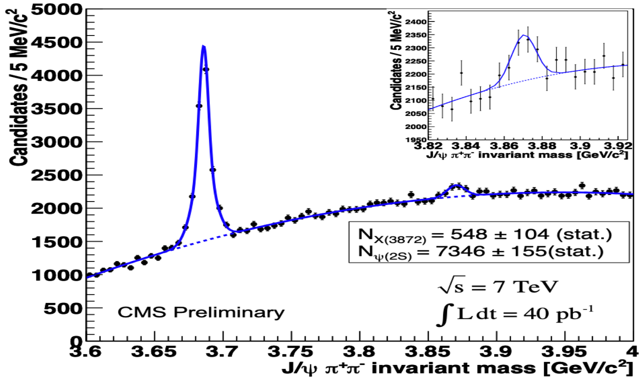
2016+2017+2018: ~145 fb^{-1}

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

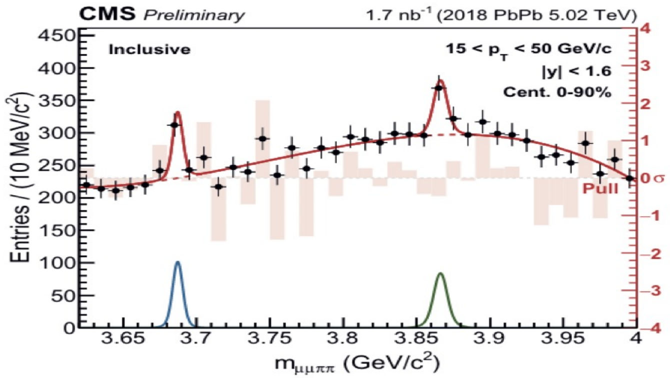
Re-discovered X(3872)

CMS PAS BPH-10-018



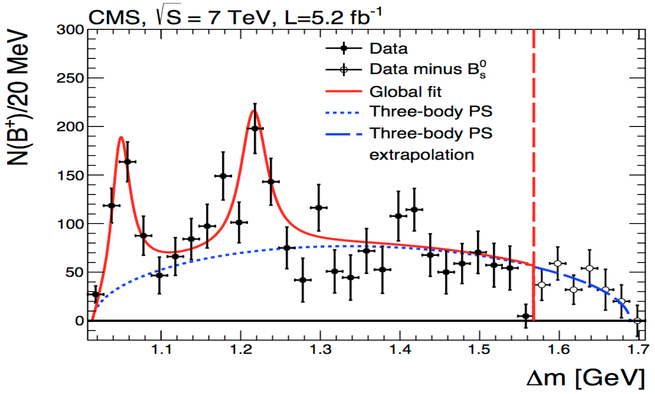
Observed X(3872) signal in PbPb

Nucl. Phys. Vol 1005 (2021)121781



Confirmation of Y(4140)

PLB 734 261 (2014)



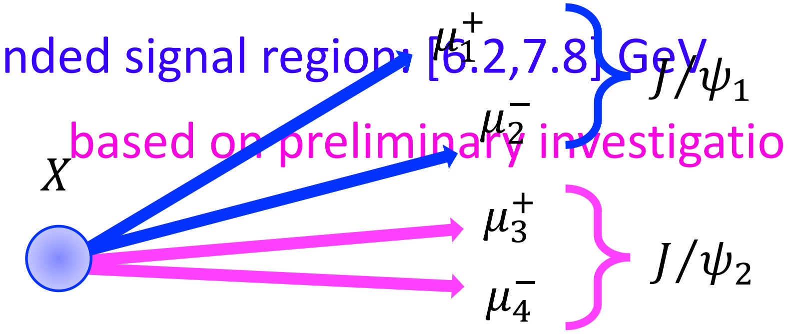
- Di-J/ψ cross section analysis was carried out in 2011
- CMS has large di-J/ψ sample
- Any surprise in di-J/ψ mass spectrum?

- 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**
- Discussion and summary

❖ 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/$\psi$ 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

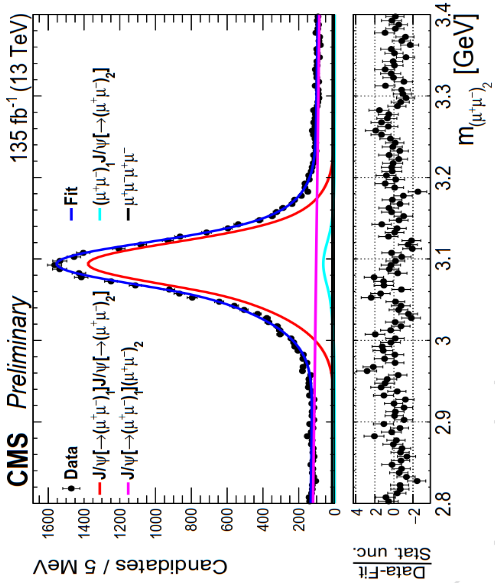
$$\chi_m^2 = \left(\frac{m_1(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

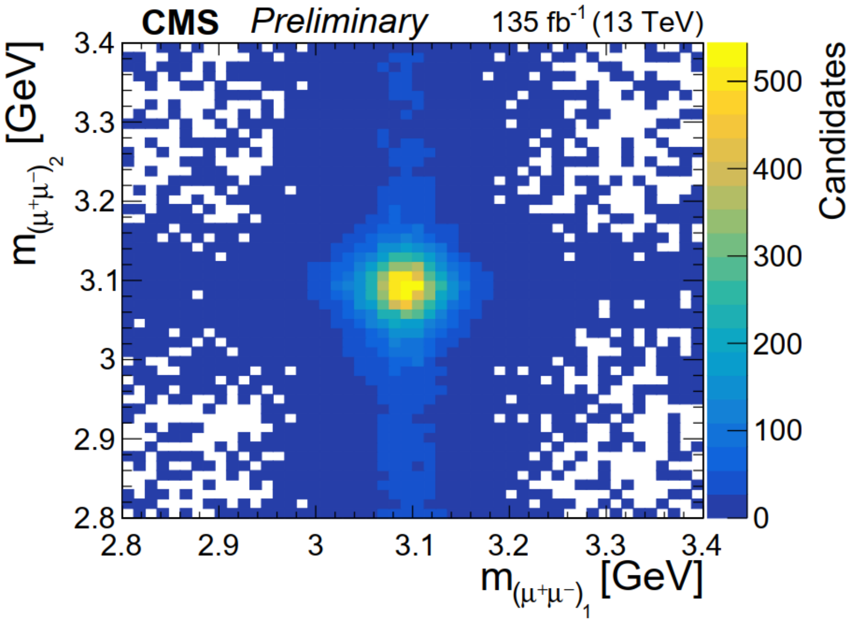
Keep all candidates arising from > 4μ (~0.2%)

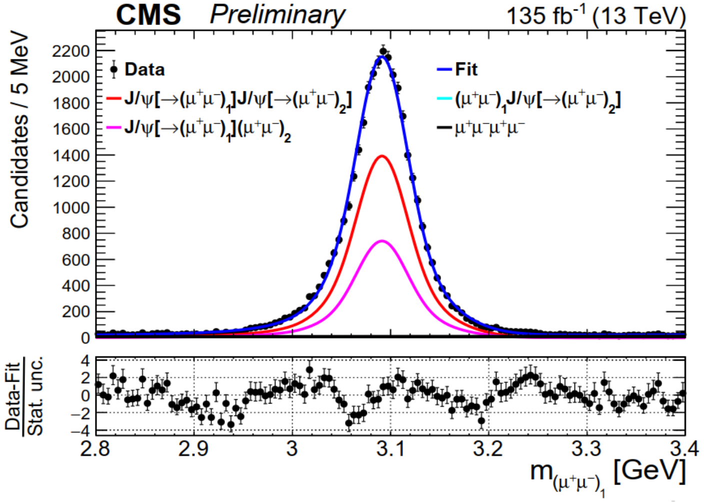
❖ Signal and background MC samples produced by Pythia8, JHUGen, HELAC-Onia…

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

J/ψ signal





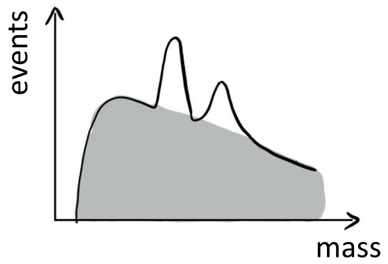


- Remove by J/ψ mass related cuts
- Clean J/ψ signal as seen

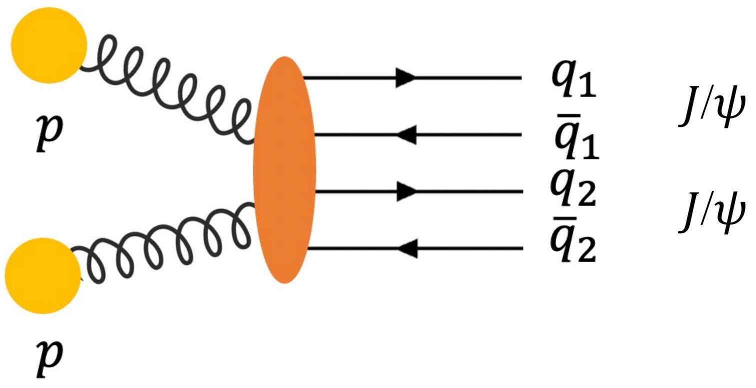
- ~15000 J/ψ pairs after final selection (m(J/ψ J/ψ) <15 GeV)

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

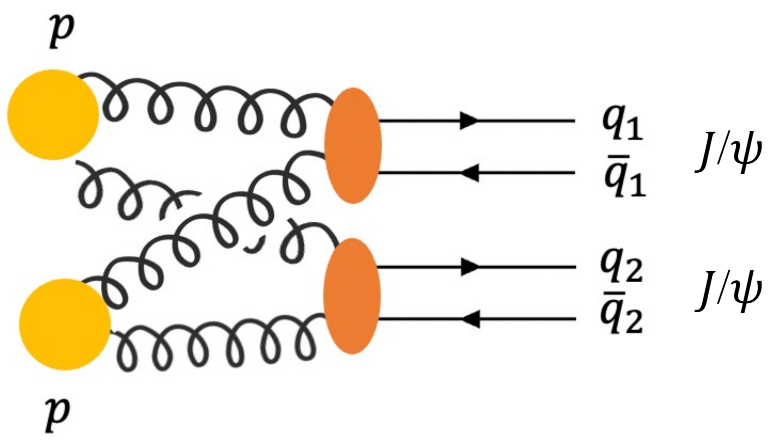
- Null-hypothesis (initial baseline model): NRSPS+NRDPS
  - NRSPS—Non-Resonant Single Parton Scattering
  - NRDPS—Non-Resonant Double Parton Scattering
  - Feed-down from possible heavier mass states
    - $X \rightarrow J/\psi\psi(2S) \rightarrow J/\psi J/\psi + \cdots$
  - Combinatorial backgrounds
    - $J/\psi\mu\mu$、$\mu\mu\mu\mu$
    - Misidentified hadrons
    - Shapes well modeled by NRSPS +NRDPS



❖ SPS：

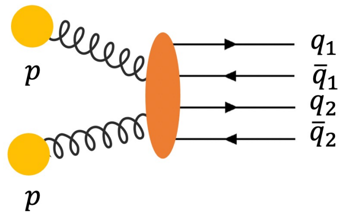


❖ NRDPS：

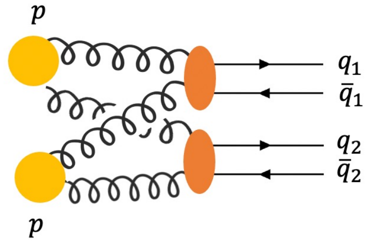


- Null-hypothesis (initial baseline model): NRSPS+NRDPS
  - NRSPS—Non-Resonant Single Parton Scattering
  - NRDPS—Non-Resonant Double Parton Scattering

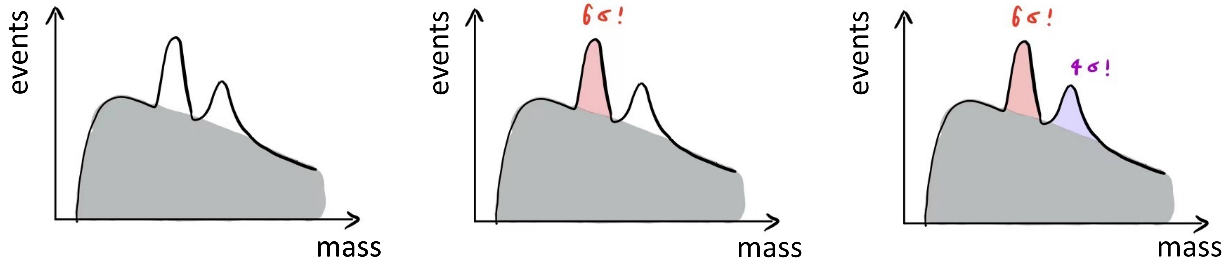
❖ SPS：

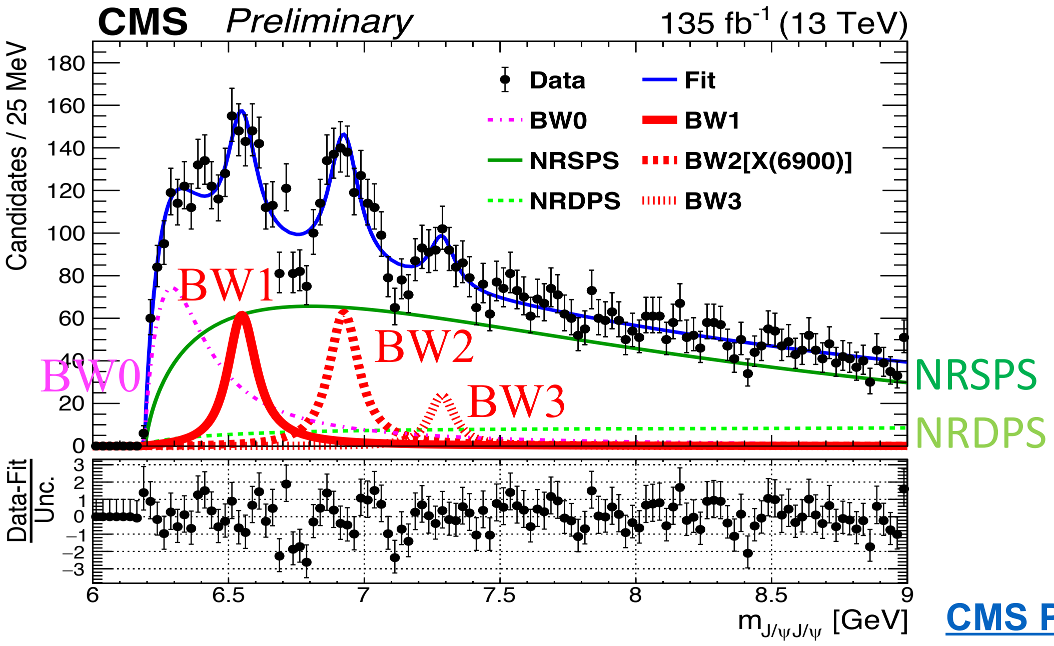


❖ NRDPS：



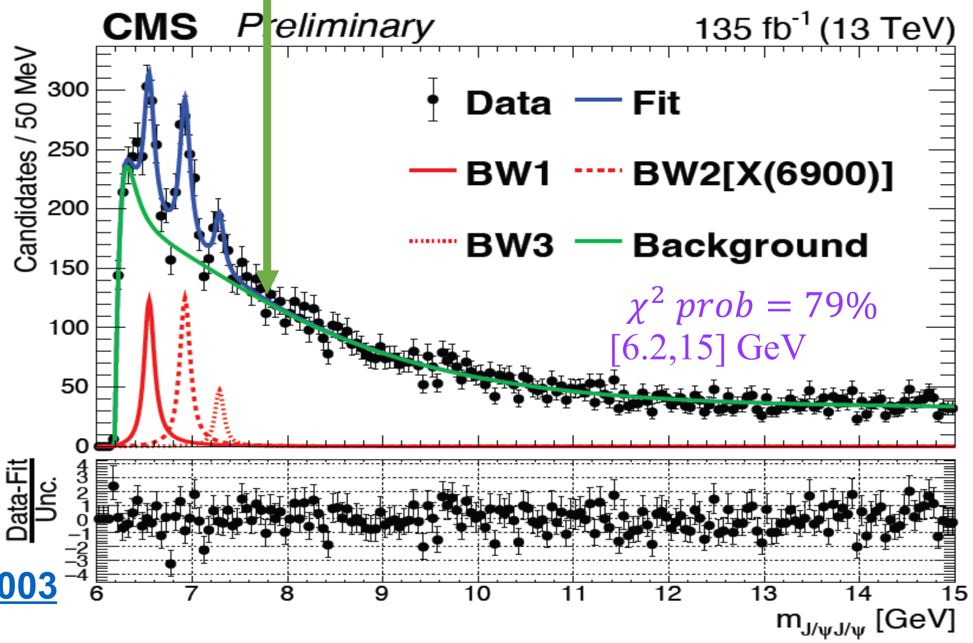
- Add potential structures to baseline model
  - Add the most prominent structure to baseline model
    - Relativistic S-wave Breit-Wigner (BW) convolved with double-Gaussian resolution function for each structure
  - Calculate its local significance
    - Local significance: standard likelihood ratio method
  - Keep it in baseline model only if $> 3\sigma$ significance
  - Repeat until no more $> 3\sigma$ structures





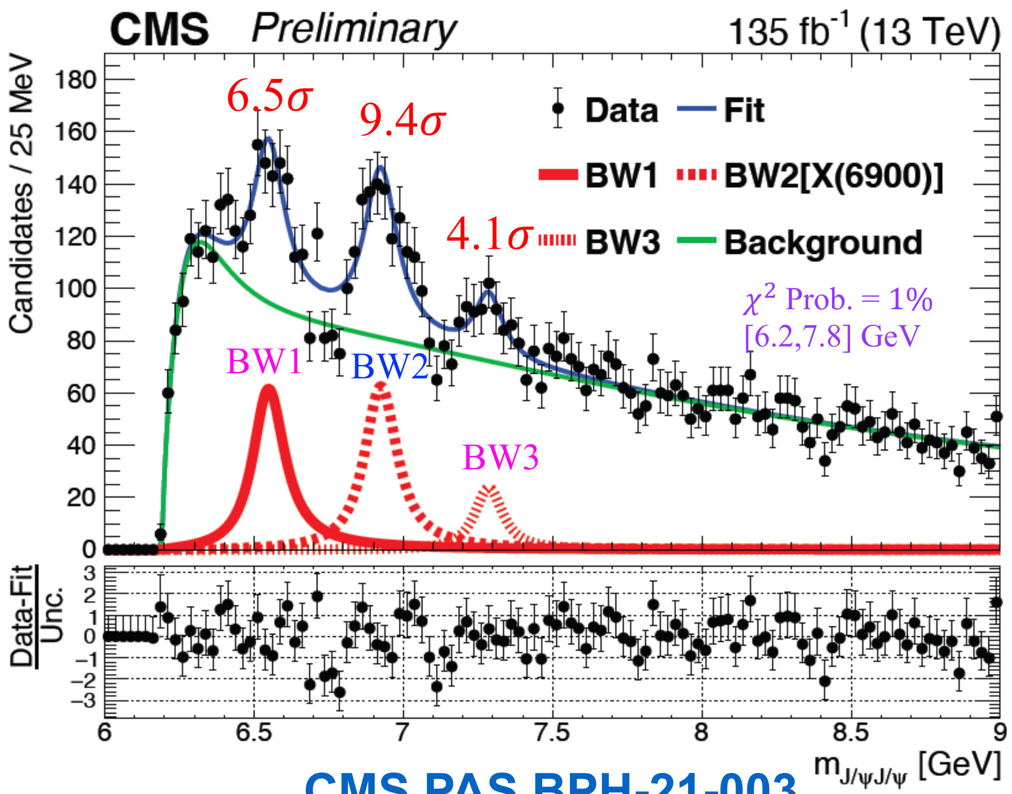
CMS PAS BPH-21-003

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 higher 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

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	>5.7**σ**
M[BW2] = 6927^{+9+4}_{-9-4} MeV	Γ[BW2] = 122^{+24+18}_{-21-18} MeV	>9.4**σ**
M[BW3] = 7287^{+20+5}_{-18-5} MeV	Γ[BW3] = 95^{+59+19}_{-40-19} MeV	>4.1**σ**

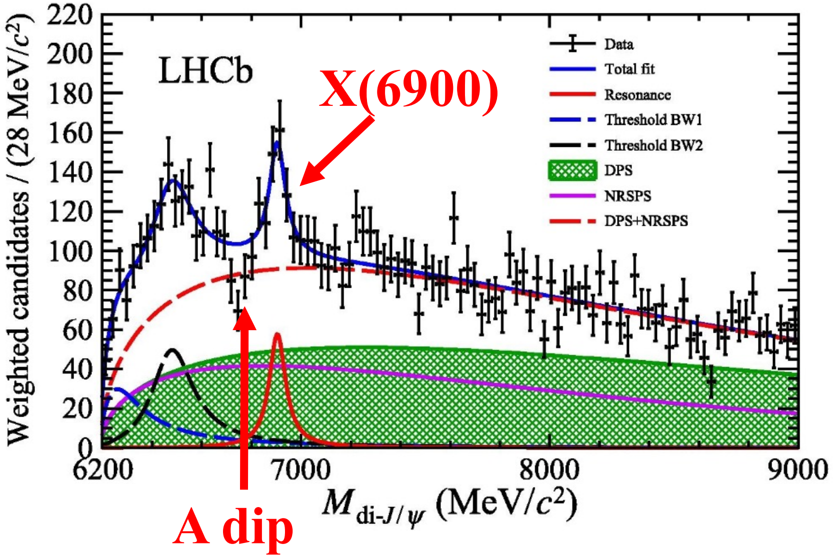
consistent →

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

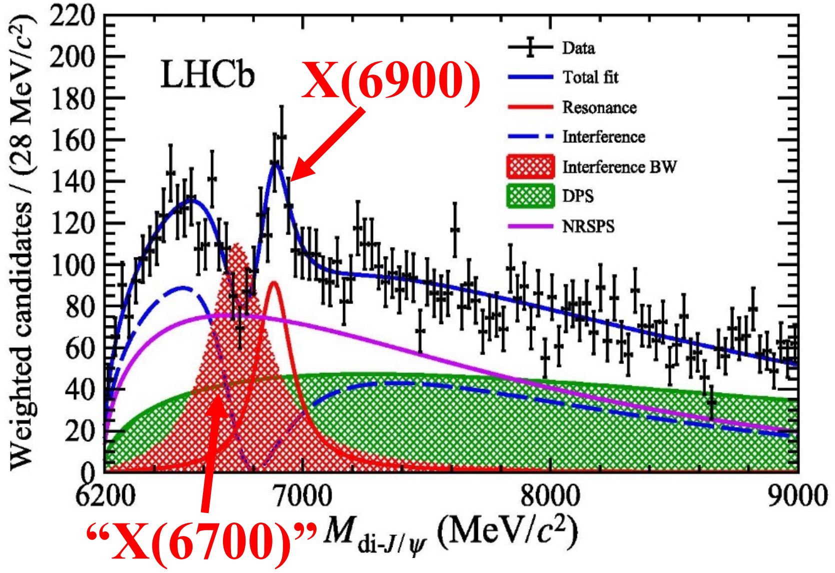
M[BW2]=6905±11±7 MeV
Γ[BW2] =80±19±33 MeV

- 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?

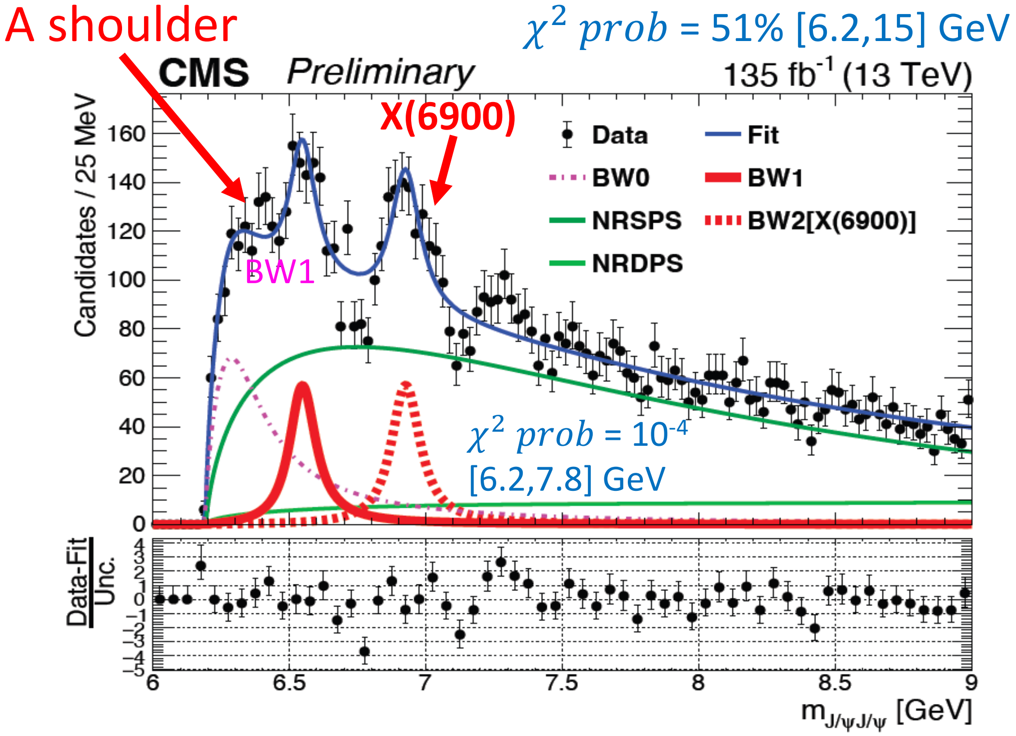
Model I

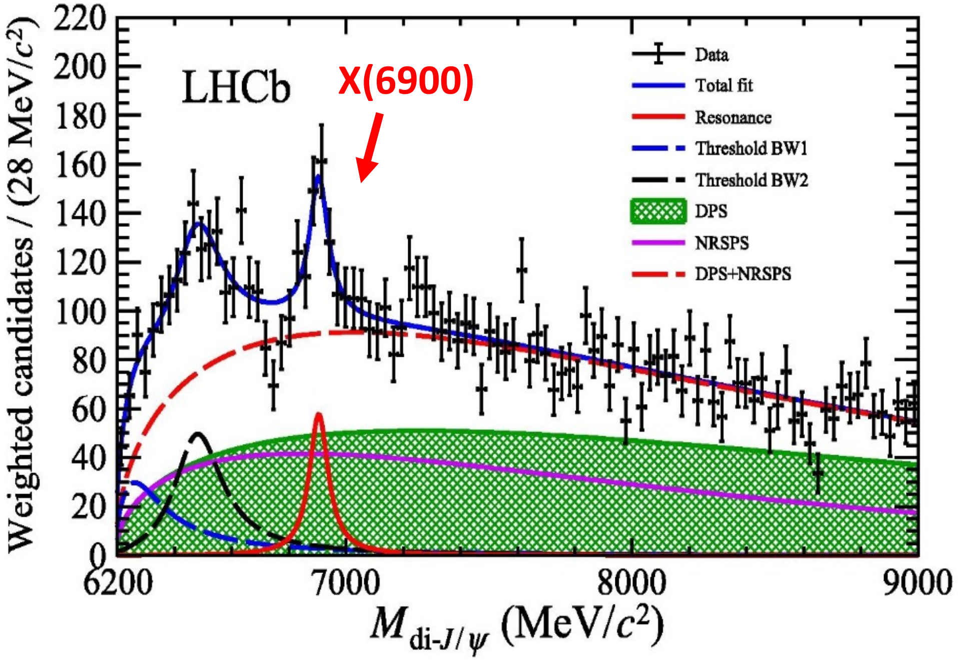


Model II



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





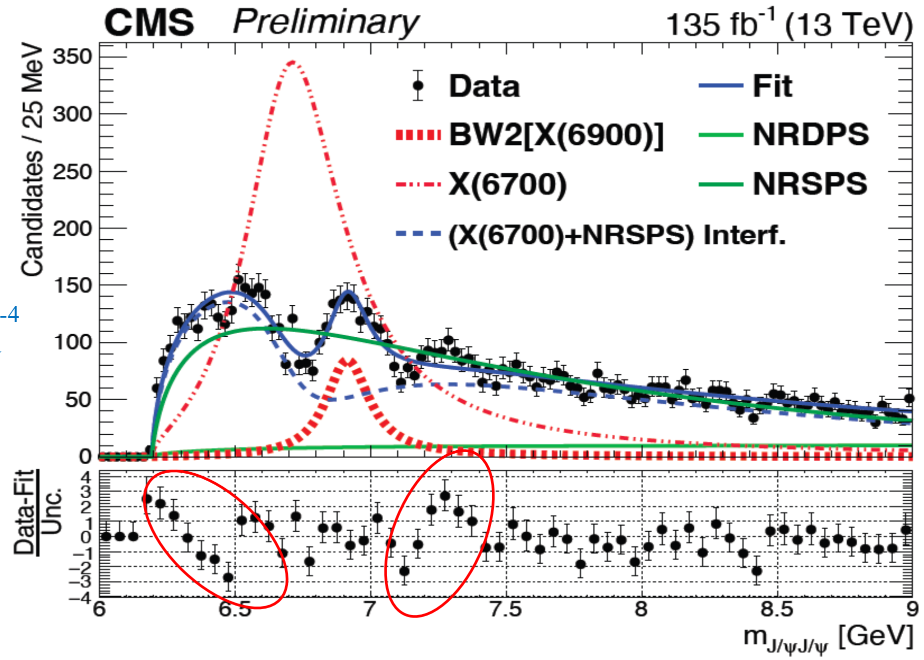
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

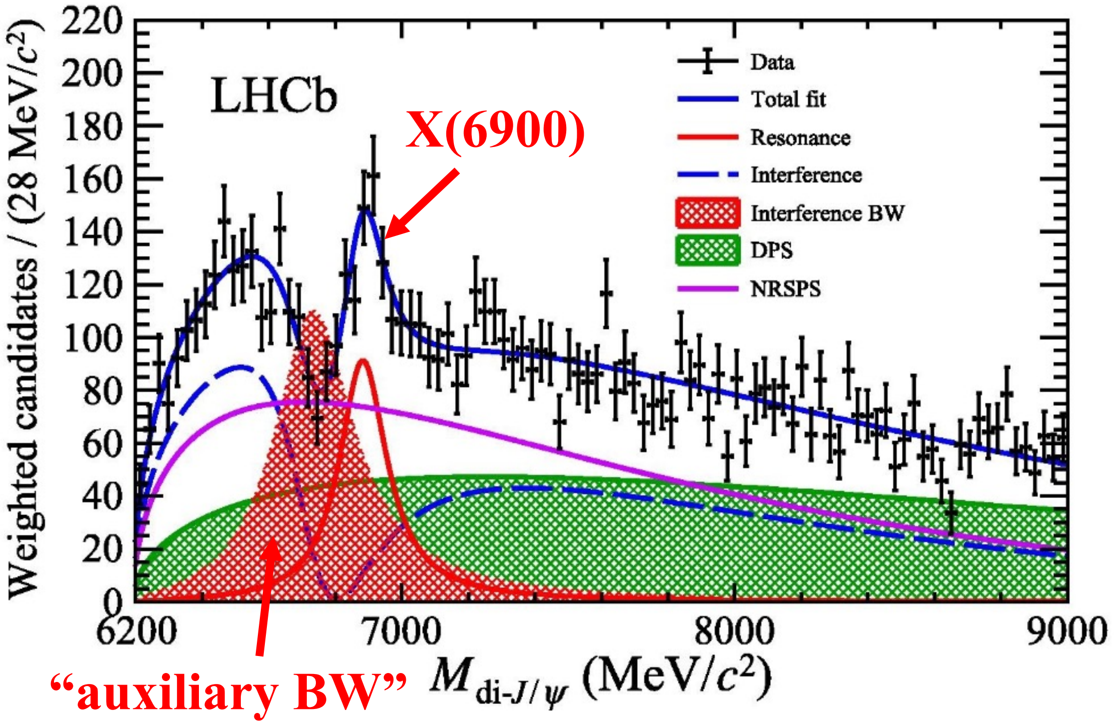
X(6900) parameters are in good agreement with LHCb
LHCb did not give parameters for another 2 BWs

- 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

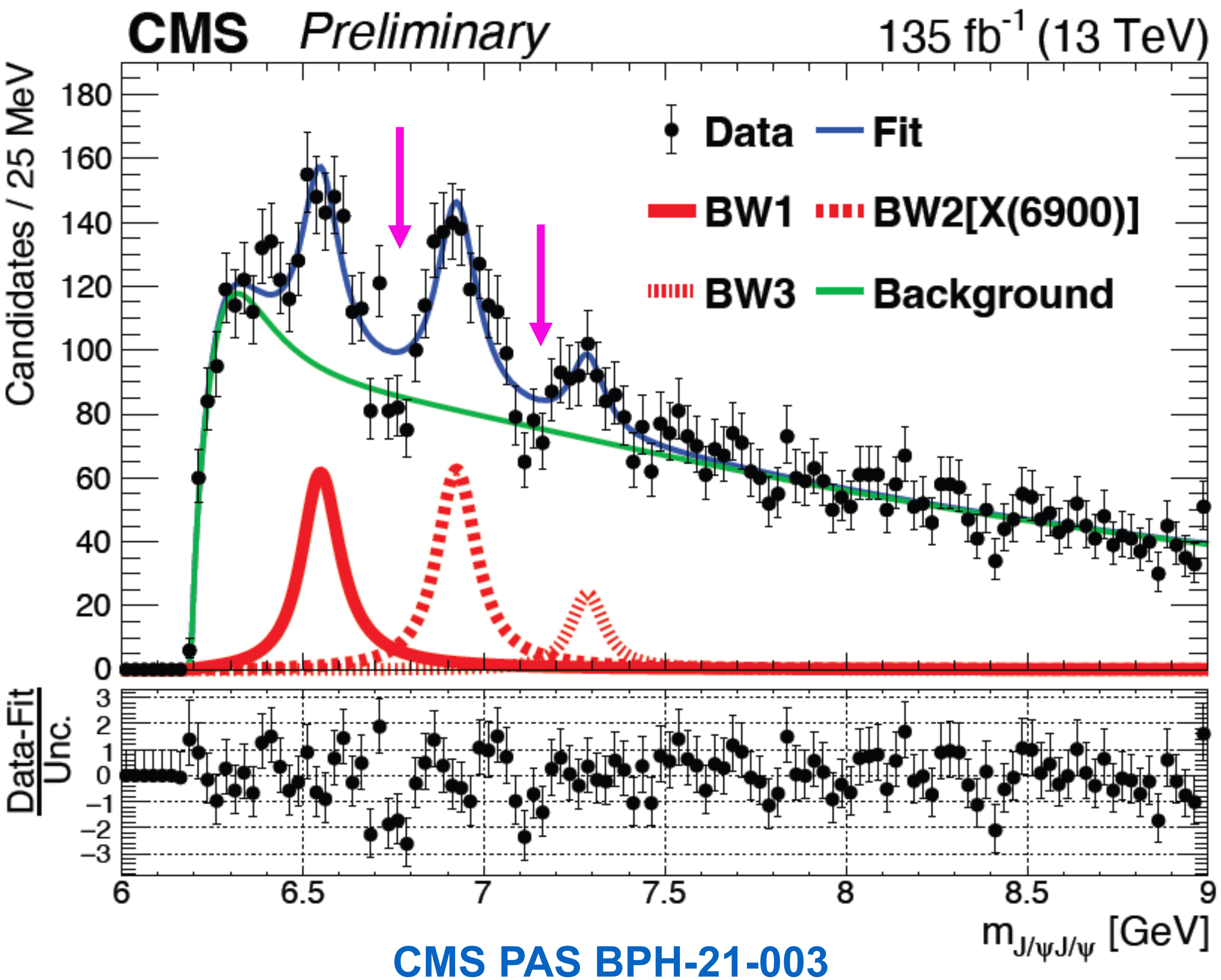




Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

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



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

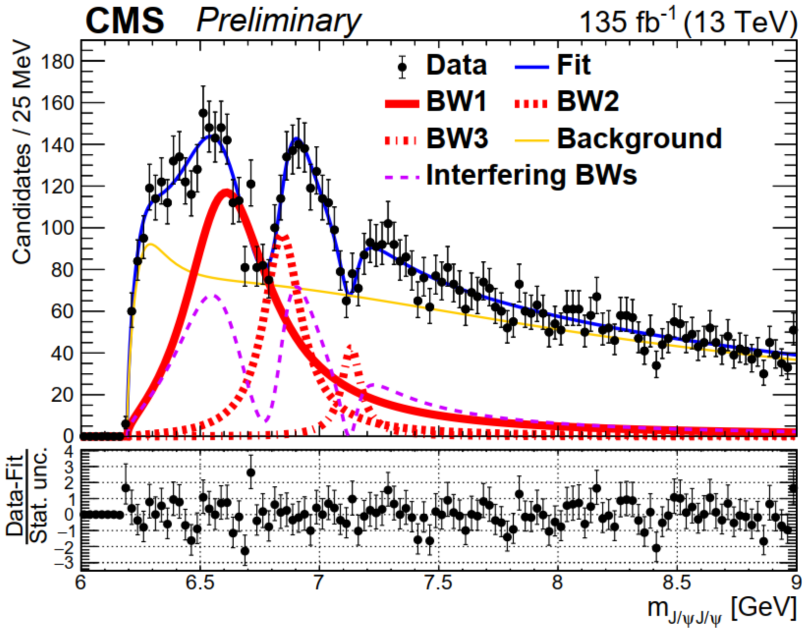
$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \bigotimes R(M_0)$$

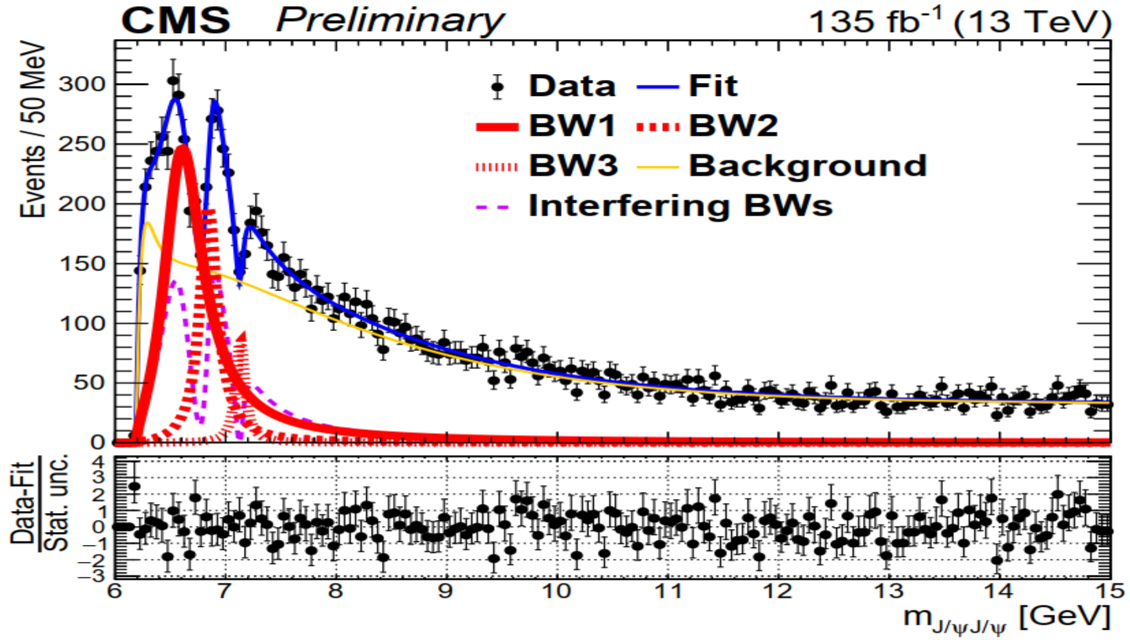
$$+N_{X\ and\ interf} \cdot \boxed{|r_1 \cdot e^{i\phi_1} \cdot BW_1 + BW_2 + r_3 \cdot e^{i\phi_3} \cdot BW_3|^2} \leftarrow \textbf{Interf. term}$$

$$+N_{NRSPS} \cdot f_{NRSPS}(m) + N_{NRDPS} \cdot f_{NRDPS}(m)$$

- 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





- Fit with interf. between BW1, BW2 and BW3 describes data well
- χ^2 probability in [6.2, 7.8] GeV is 65% (vs. 9% in no-interf. fit)
- Measured mass and width in the interference fit

	M(BW1)	M(BW2)	M(BW3)	Γ(BW1)	Γ(BW2)	Γ(BW3)
Interf. fit [MeV]	6638^{+43}_{-38}	6847^{+44}_{-28}	7134^{+48}_{-25}	440^{+230}_{-200}	191^{+66}_{-49}	97^{+40}_{-29}
Non-interf. fit [MeV]	6552^{+10}_{-10}	6927^{+9}_{-9}	7287^{+20}_{-18}	124^{+32}_{-26}	122^{+24}_{-21}	95^{+59}_{-40}

Summary of systematic uncertainties 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 fit

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

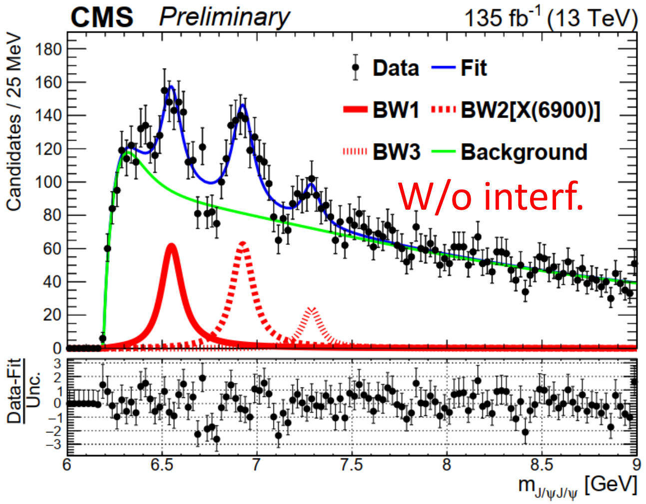
- Systematic uncertainty table (sources with minor effects suppressed)

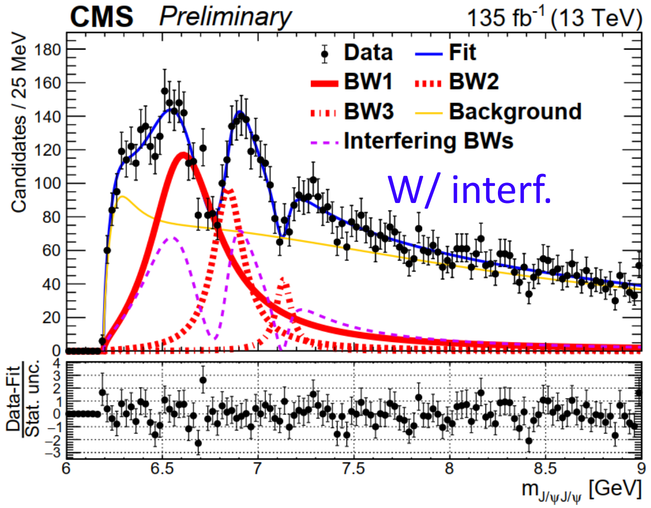
Fit	Dominant sources	M_{BW_1}	M_{BW_2}	M_{BW_3}	Γ_{BW_1}	Γ_{BW_2}	Γ_{BW_3}
No-interference	Signal shape	3	3	3	10	5	5
	NRSPS shape	3	1	1	18	15	17
	Feed-down	11	1	1	25	8	6
	Total uncertainty	12	4	5	33	18	19
Interference	Signal shape	7	12	7	56	8	7
	DPS shape	1	3	2	18	6	2
	NRSPS shape	9	14	13	85	9	20
	Mass 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?





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}

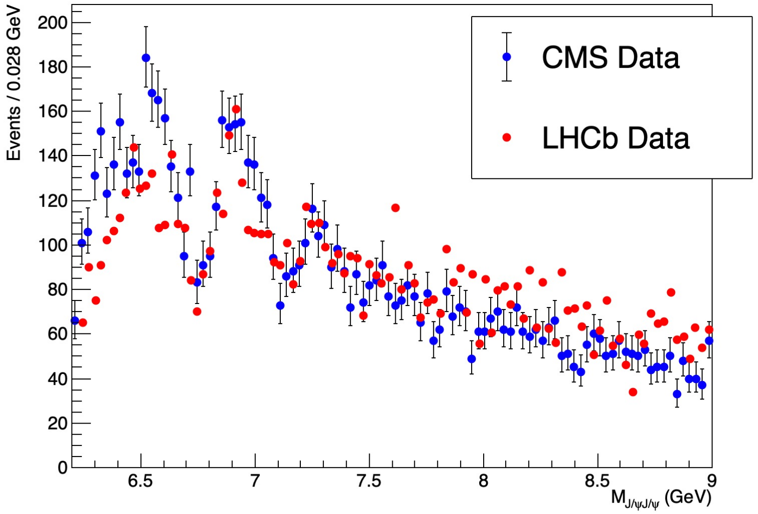
Nucl. Phys. B 966 (2021) 115393

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

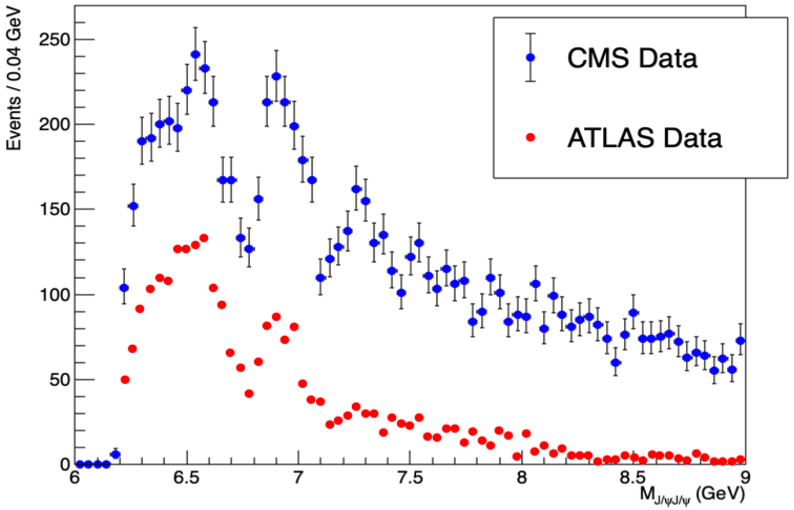
M[BW2] = 6847^{+44+48}_{-28-20} MeV

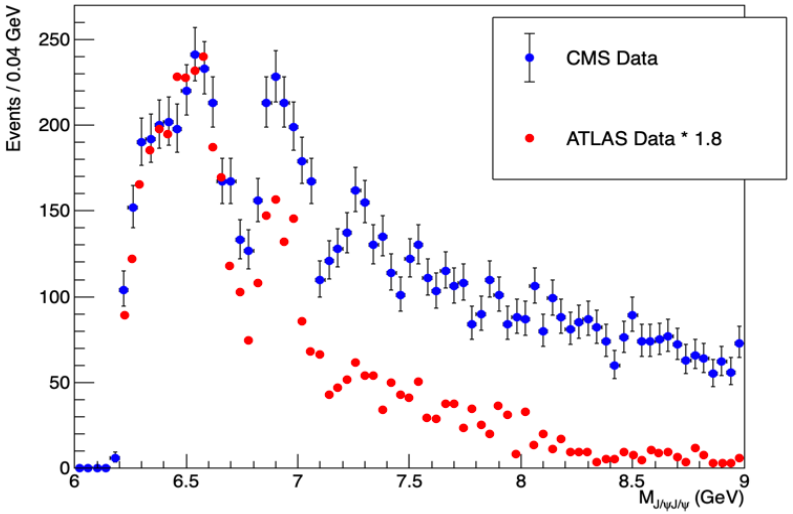
M[BW3] = 7134^{+48+41}_{-25-15} MeV

- 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?



Sci.Bull.65 (2020) 23





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

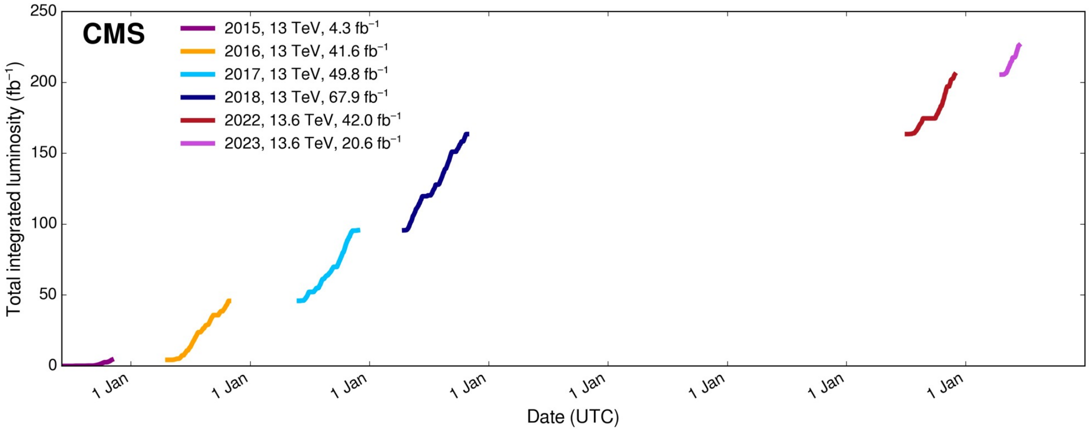
- **CMS has good sensitivity to all-muon final state in this mass region**

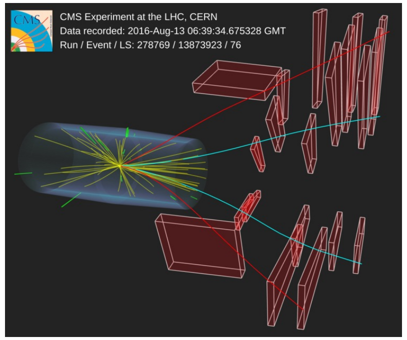
Summary

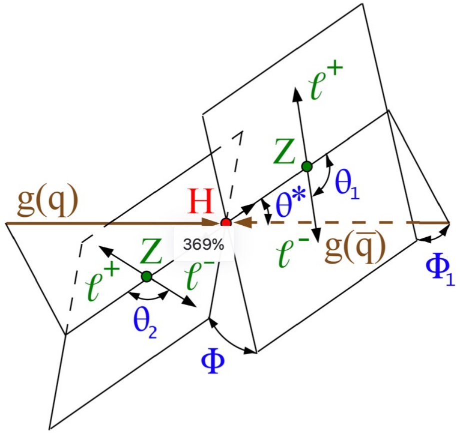
- CMS found 3 significant $J/\psi J/\psi$ structures using 135 fb^{-1} 13 TeV data arXiv:2306.07164
  - BW2 consistent with X(6900) reported by LHCb
  - CMS found two new structures, provisionally named as X(6600), X(7300)

- 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

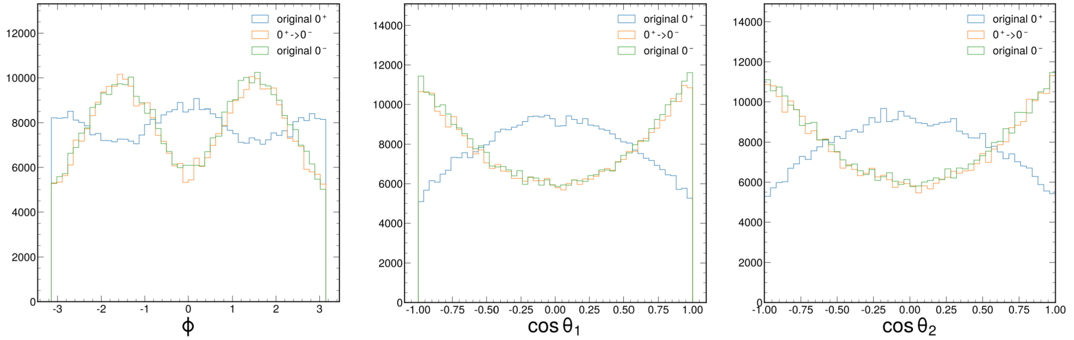
  - All-heavy quark exotic structures offer a system easier to understand
  - Mass differences from multiple structures can be better calculated
  - A new window for further research in strong interaction

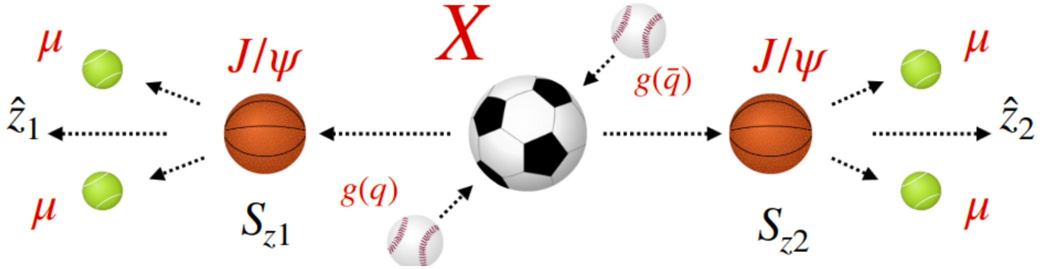






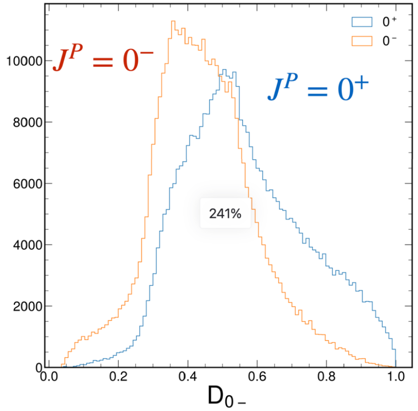
- Data in 2016 + 2017 + 2018: 41.6 + 49.8 + 67.9 = 159.3 fb^{-1}
- Updated data in 2022 + 2023: 42.0 + 20.6 = 62.6 fb^{-1}
  - Confirmation of X(6600), X(6900) with updated data?
  - Observation of X(7300)
- Spin parity analysis is going on





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

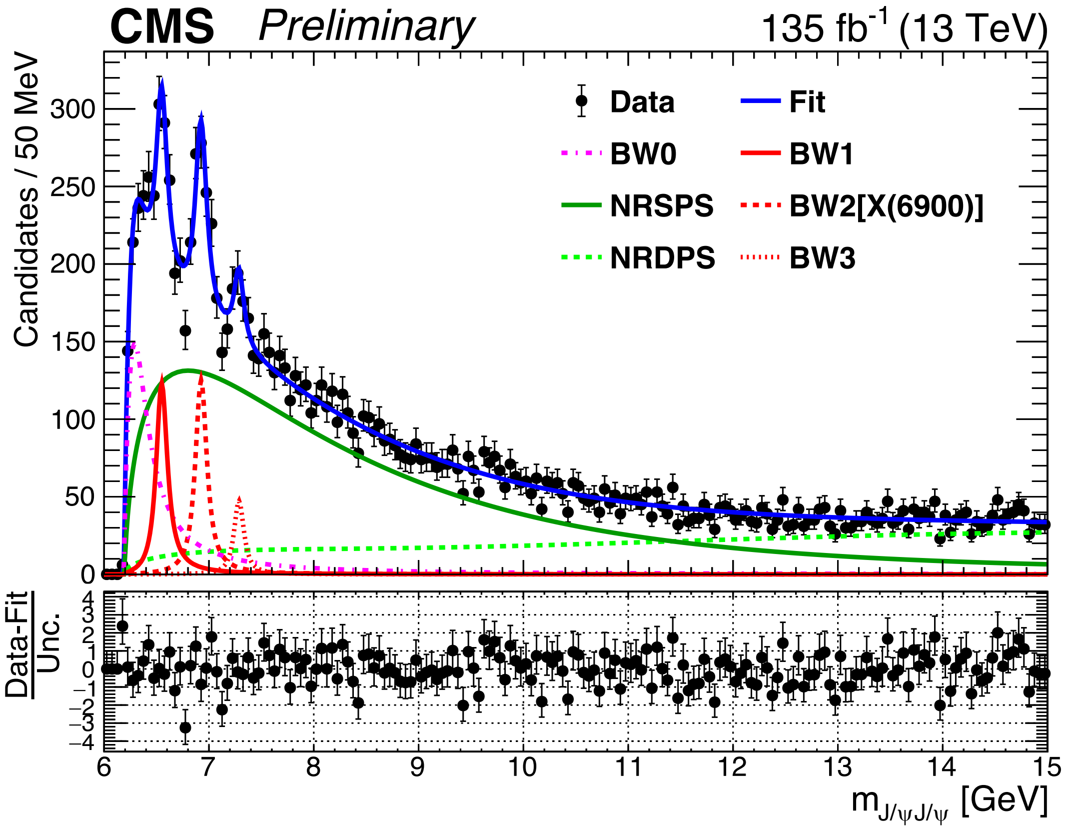
- BW2 consistent with X(6900) reported by LHCb
- CMS found two new structures, provisionally named as X(6600), X(7200)
- A family of structures which are candidates for all-charm tetra-quarks!
  - Large mass separations — 200+ MeV — suggest radial excitation
  - Possible interference effects suggest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

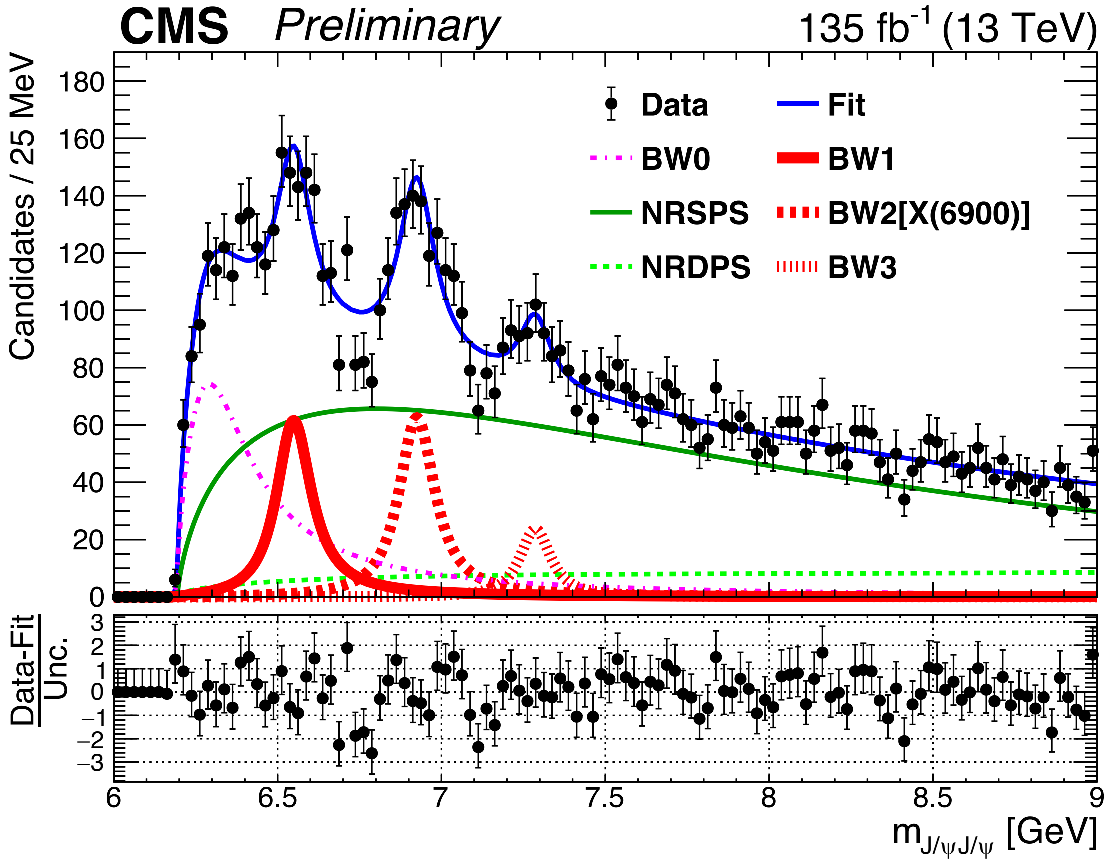
- All-heavy quark exotic structures offer system easier to understand
- Mass differences from multiple structures can be better calculated
- A new window to understand the strong interaction

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

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

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

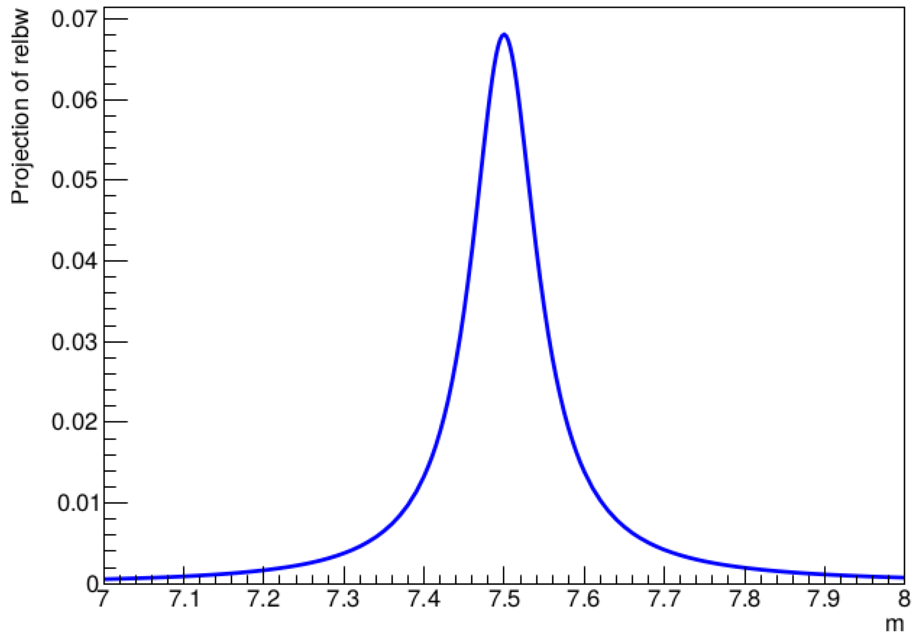
$$B_1(q,d) = \sqrt{\frac{2z}{z+1}},$$

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

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

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

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



- Default : L=0

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

Background PDF

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

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

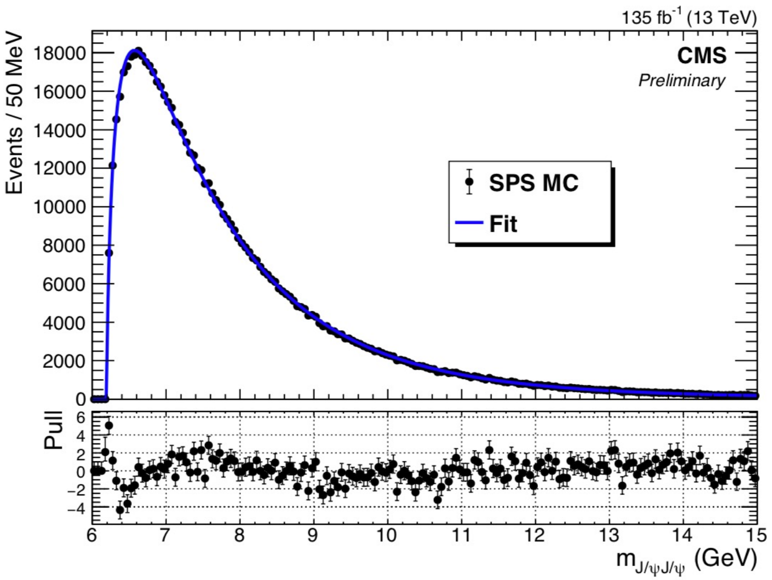
$$f_{DPS}(x) = \sqrt{x_t} \cdot \exp(-a \cdot x_t) \cdot (p_0 + p_1 \cdot x_t + p_2 \cdot x_t^2),$$

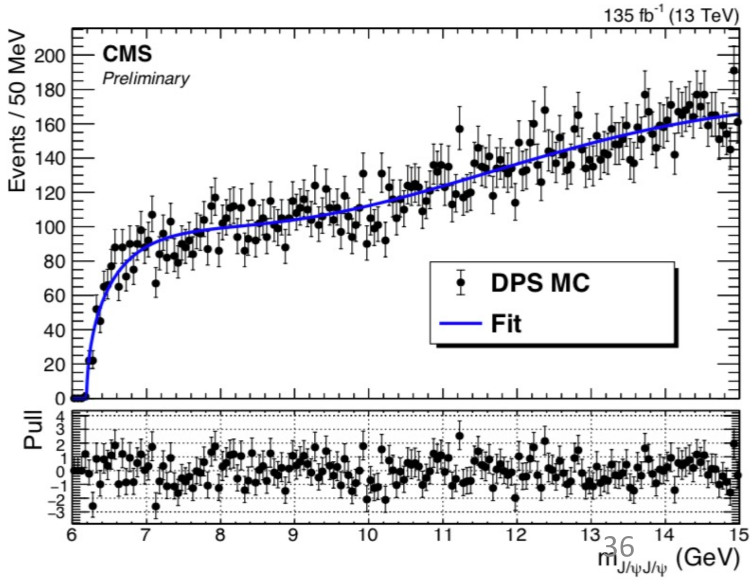
$$x_t = x - x_0, \quad x_0 = 2M_{J/\psi}.$$

3 float parameters:

p2 from NRSPS

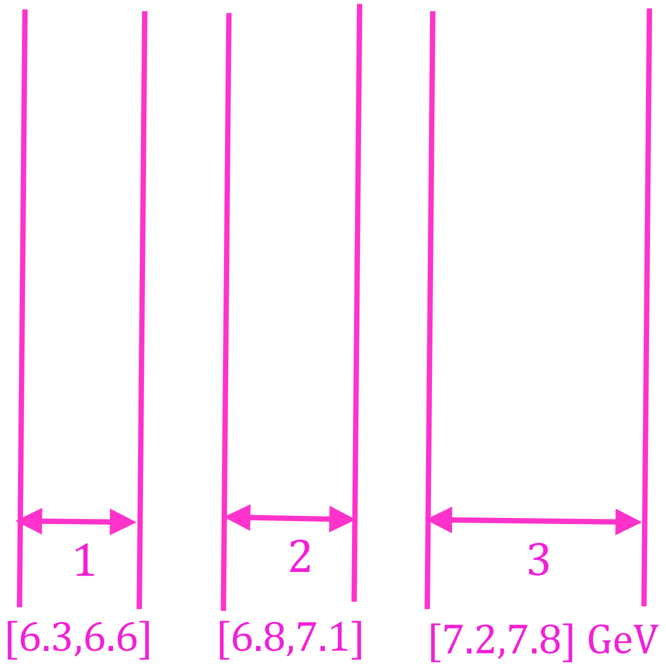
N(NRSPS), N(NRDPS)





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