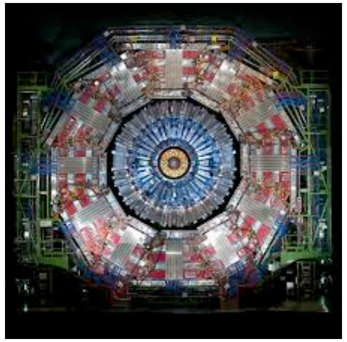


Observation of structures near $J/\psi J/\psi$ threshold at CMS

Kai Yi (Tsinghua University & Nanjing Normal University)

On behalf of CMS Collaboration

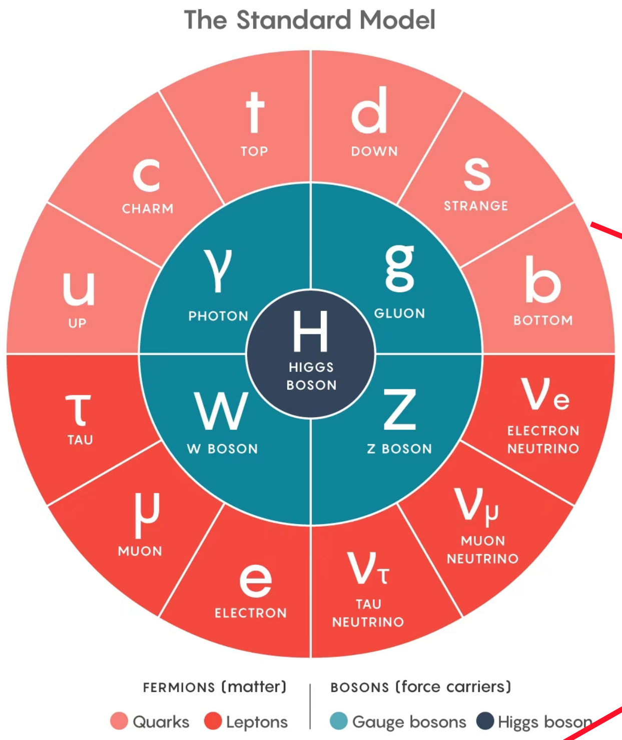
10th workshop of the APS Topical Group on Hadronic Physics

13 April 2023, Minneapolis, Minnesota

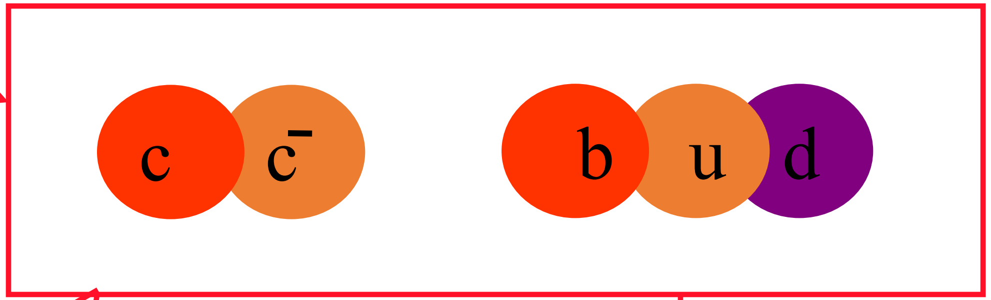
Outline

- **History**
  - About exotic hadron
  - CMS contribution to heavy exotic hadron CMS publications
  - New Domain of Exotics: All-Heavy Tetra-quarks
- **CMS $J/\psi J/\psi$ study** CMS preliminary result CMS PAS BPH-21-003 at CDS
  - Data sample and event selections
  - Steps to identify structures
  - Result and systematics
  - Interpretation through interference models
- **Discussion and summary**

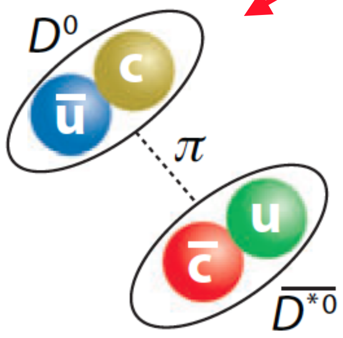
Quark model



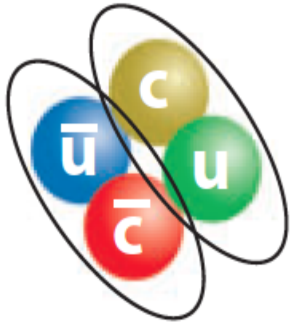
Meson *Baryon*



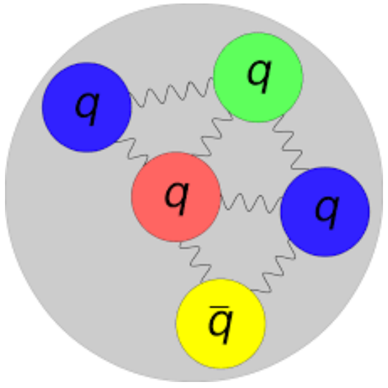
"exotic" hadron



D^0–$\overline{D}^{*0}$ "molecule"



Diquark–diantiquark

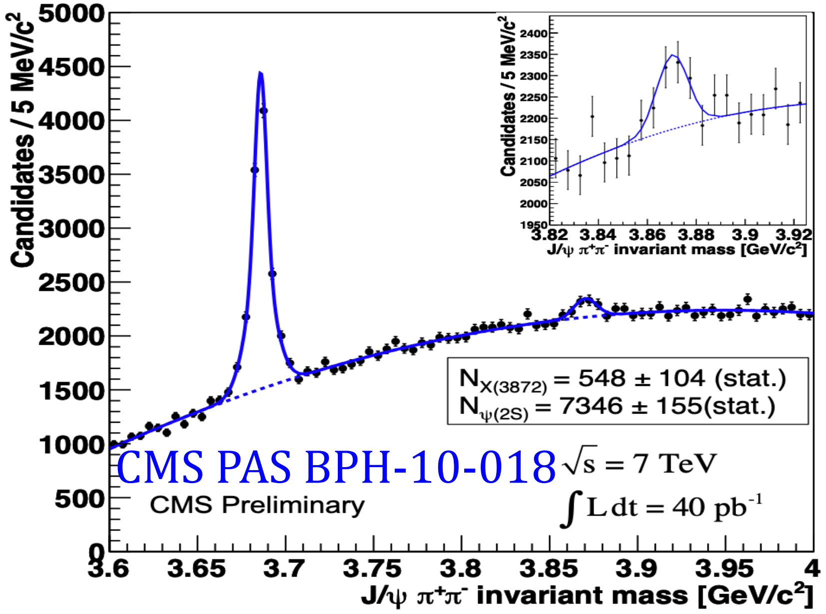


Two possible extensions of mesons to tetra-quark states *Possible penta-quark state*

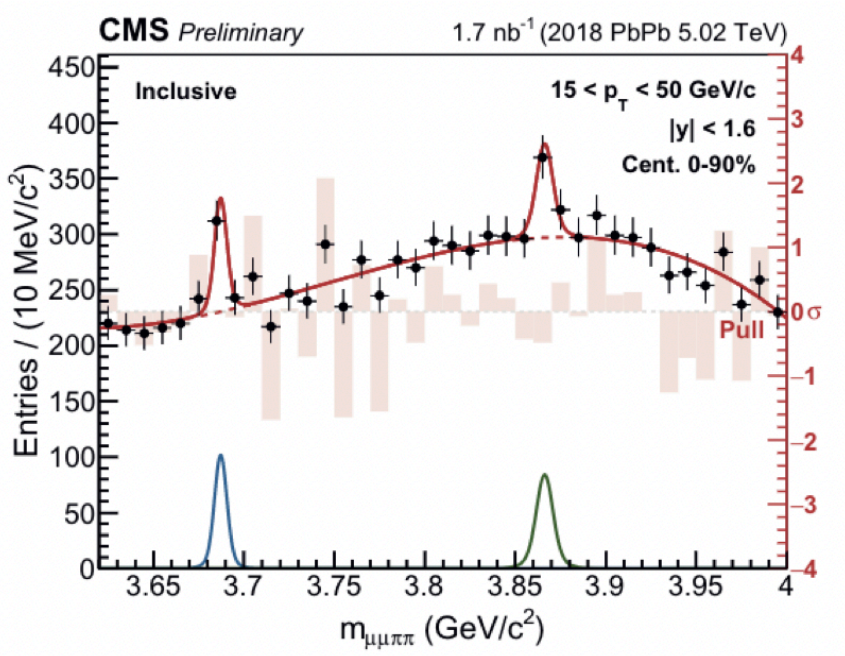
Gell-mann noted the possibility of "exotic" hadrons in classic 1964 paper

Selected CMS contributions to heavy exotic states

First LHC experiment re-discovered X(3872)



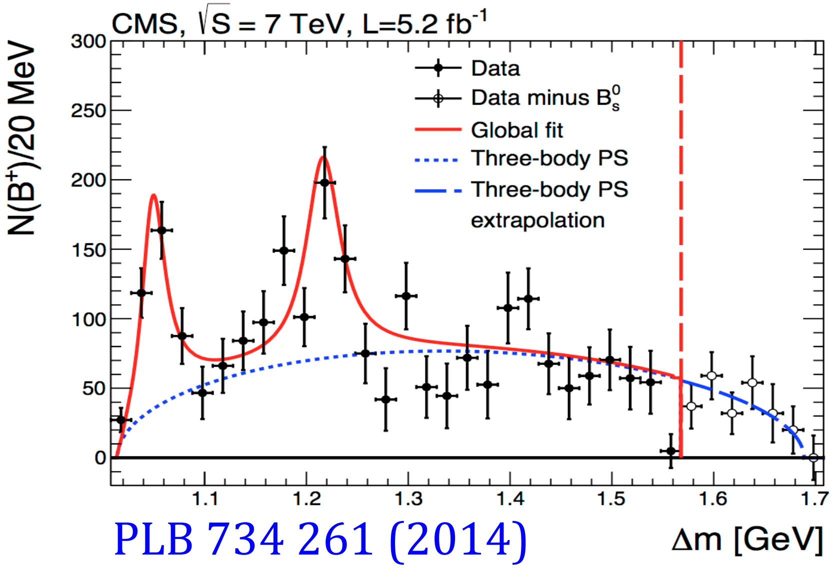
CMS PAS BPH-10-018



First X(3872) signal in PbPb

Nucl. Phys. Vol 1005 (2021)121781

First confirmation of Y(4140)



PLB 734 261 (2014)

CMS played the following leading roles

- First LHC experiment to see X(3872)
- First LHC experiment to see exotic hadron
- First LHC experiment to see X(3872) in PbPb data

New Domain of Exotics: All-Heavy Tetra-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

Linked by color electric flux in a bag

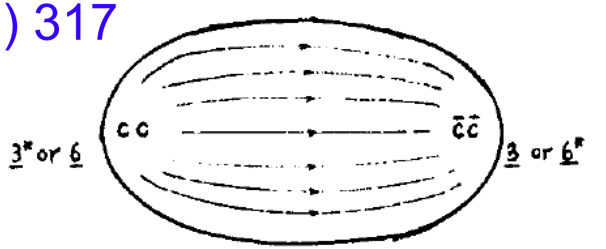
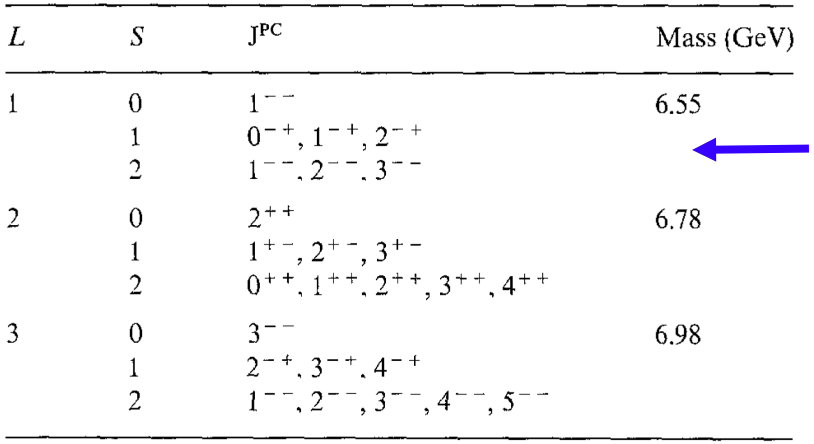


Fig.2



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

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

Possible two-body decays

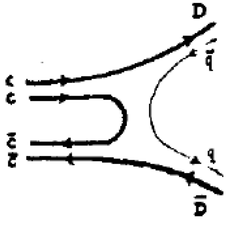


Fig.3(a)

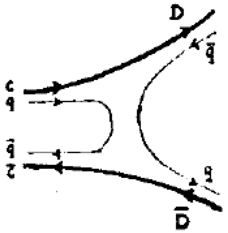


Fig.3(b)

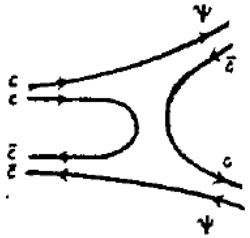
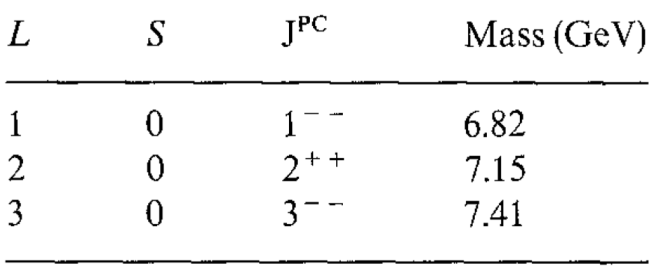


Fig.3(c)

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



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

Possible P-wave to S-wave decays

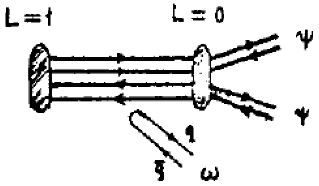
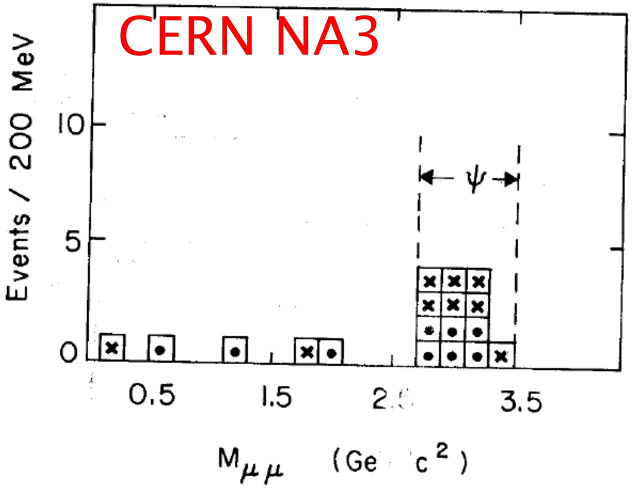
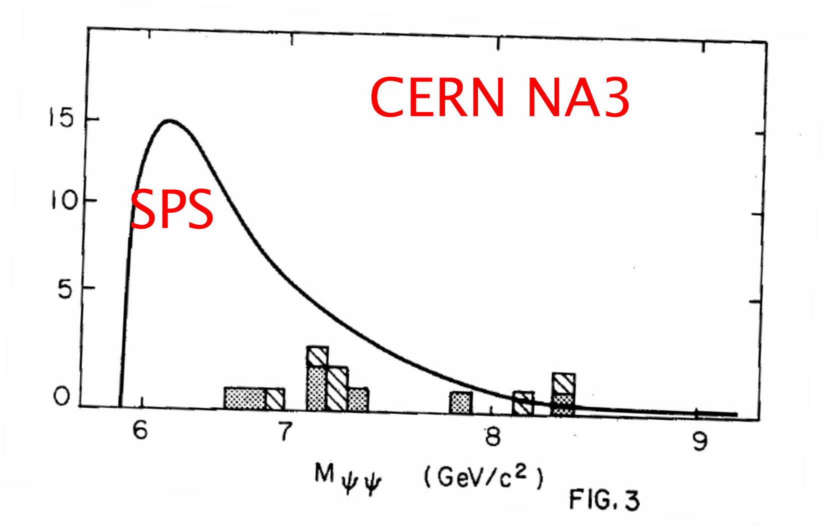


Fig.4

- A different exotic system compared to exotics with light quarks

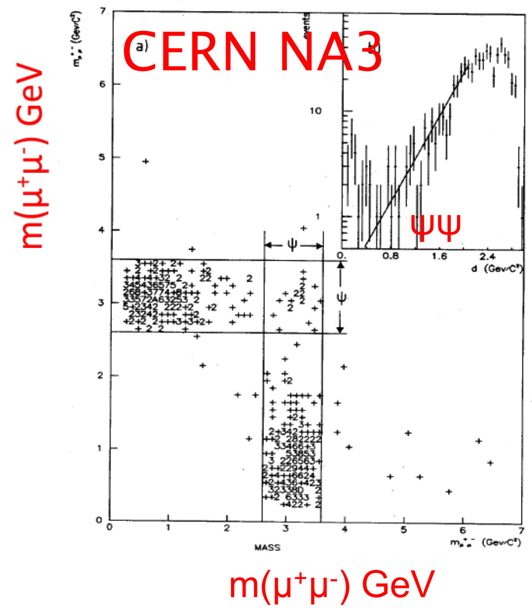
J/ψJ/ψ events—first evidence (1982)

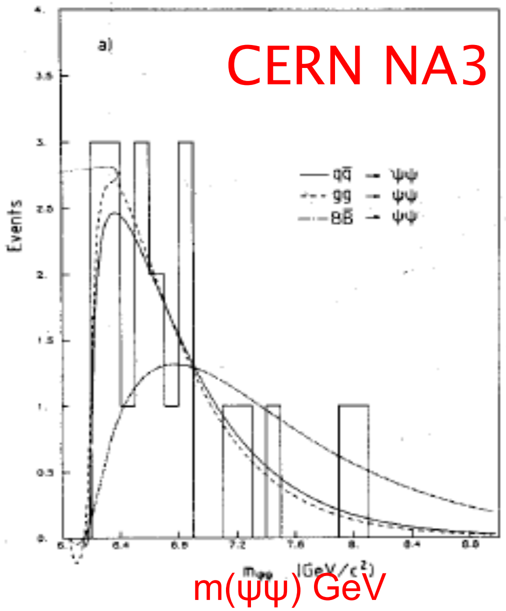


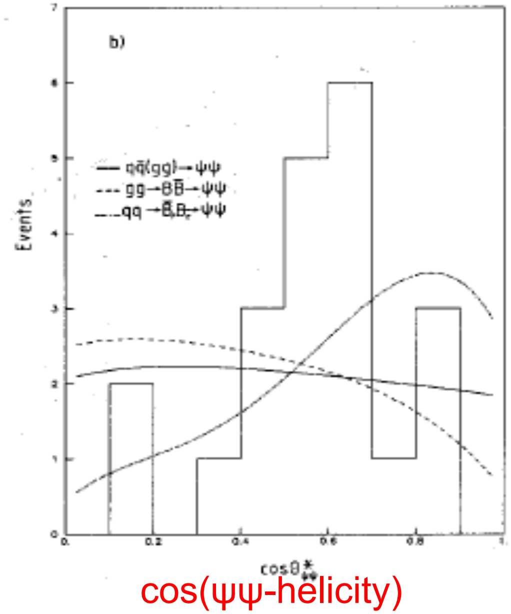


PLB114 (1982) 457

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







PLB158 (1985) 85

Possible explanations of J/ψ-J/ψ states

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

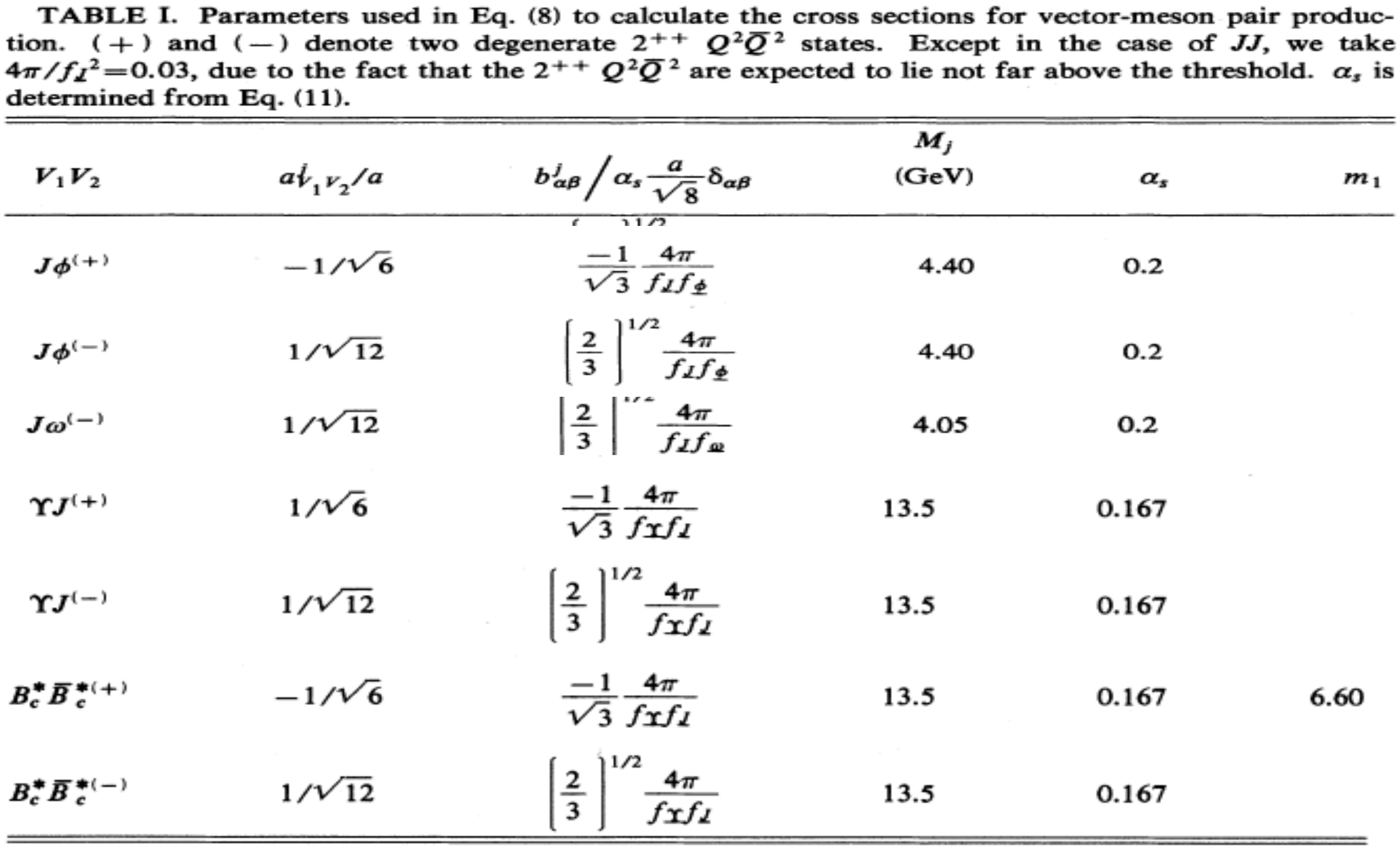


TABLE I. Parameters used in Eq. (8) to calculate the cross sections for vector-meson pair production. $(+)$ and $(-)$ denote two degenerate 2^{++} $Q^2\bar{Q}^2$ states. Except in the case of JJ, we take $4\pi/f_J{}^2=0.03$, due to the fact that the 2^{++} $Q^2\bar{Q}^2$ are expected to lie not far above 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
$J\phi^{(+)}$	$-1/\sqrt{6}$	$\frac{-1}{\sqrt{3}}\frac{4\pi}{f_J f_\phi}$	4.40	0.2	
$J\phi^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_J f_\phi}$	4.40	0.2	
$J\omega^{(-)}$	$1/\sqrt{12}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_J f_\omega}$	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	

There were other attempts

New Domain of Exotics: All-Heavy Tetra-quarks

(cccc) *Phys. Rev. D 86, 034004 (2012)*

$$0^{++\prime}: \quad M = 5.966\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -228.\,\mathrm{MeV},$$
$$1^{+-\prime}: \quad M = 6.051\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -142.\,\mathrm{MeV},$$
$$2^{++}: \quad M = 6.223\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = 29.5\,\mathrm{MeV}.$$

Below double J/ψ threshold
Search via $J/\psi\mu^+\mu^-$, J/ψ^*

Above double J/ψ threshold
Search via $J/\psi J/\psi$

(bbcc)

$$0^{++}a: \quad M = 12.359\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -191.\,\mathrm{MeV}$$
$$0^{++}b: \quad M = 12.471\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -78.7\,\mathrm{MeV},$$
$$1^{+-}a: \quad M = 12.424\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -126.\,\mathrm{MeV}$$
$$1^{+-}b: \quad M = 12.488\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -62.5\,\mathrm{MeV},$$
$$1^{++}: \quad M = 12.485\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -64.9\,\mathrm{MeV},$$
$$2^{++}: \quad M = 12.566\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = 16.1\,\mathrm{MeV}.$$

Below double B_c threshold
$J/\psi\Upsilon(1S)$ threshold
? …

(bbbb)

$$0^{++\prime}: \quad M = 18.754\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -544.\,\mathrm{MeV},$$
$$1^{+-\prime}: \quad M = 18.808\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -490.\,\mathrm{MeV},$$
$$2^{++}: \quad M = 18.916\,\mathrm{GeV}, \quad M - M_{\mathrm{th}} = -382.\,\mathrm{MeV}.$$

Above double B_c threshold
$J/\psi\Upsilon(1S)$ threshold
Search via the above two channels

Below double Υ(1S) threshold
Search via $\Upsilon(1S)\mu^+\mu^-$

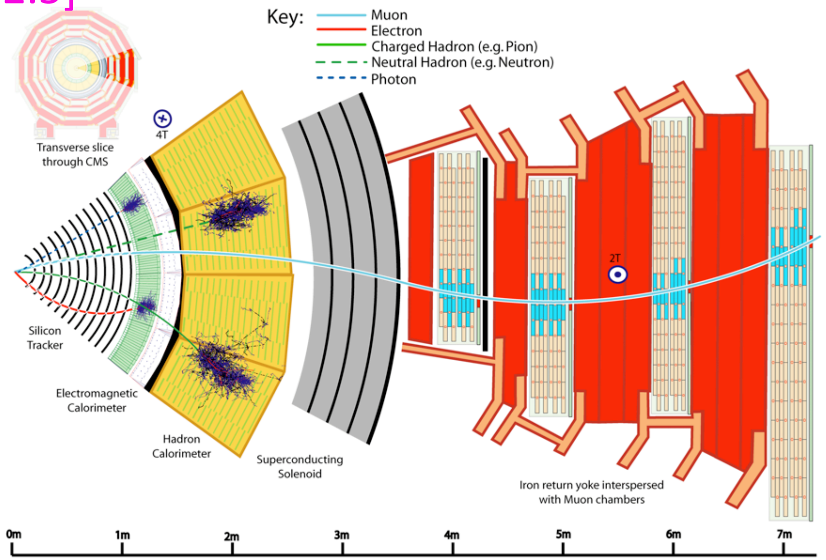
Many recent theoretical studies on $(c\bar{c}c\bar{c})$, $(b\bar{b}b\bar{b})$, $(b\bar{b}c\bar{c})$:

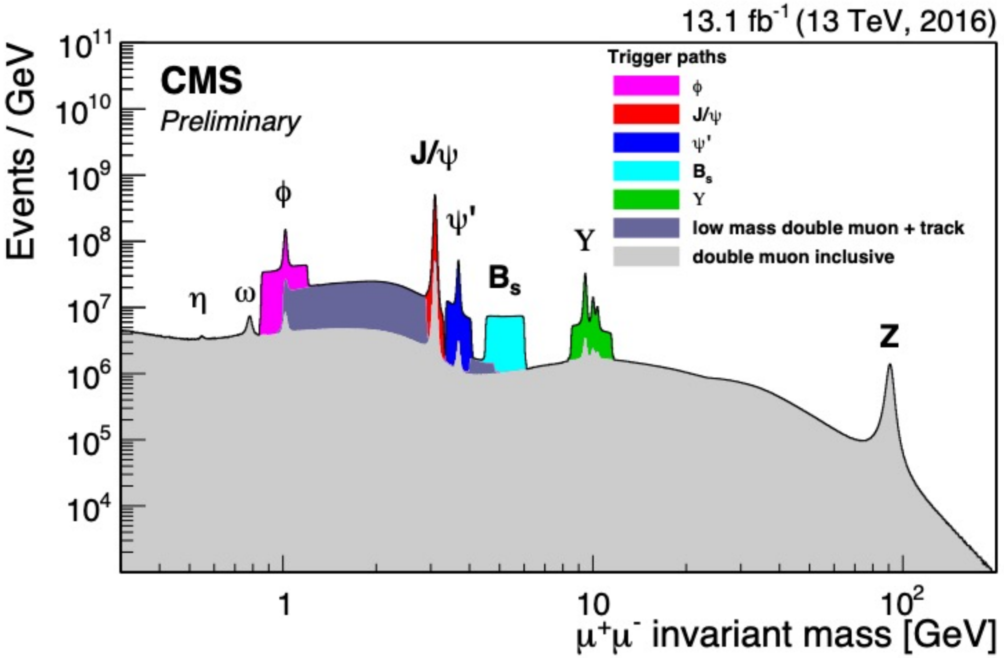
controversial on existence of bound states below $\eta_b\eta_b$ threshold;

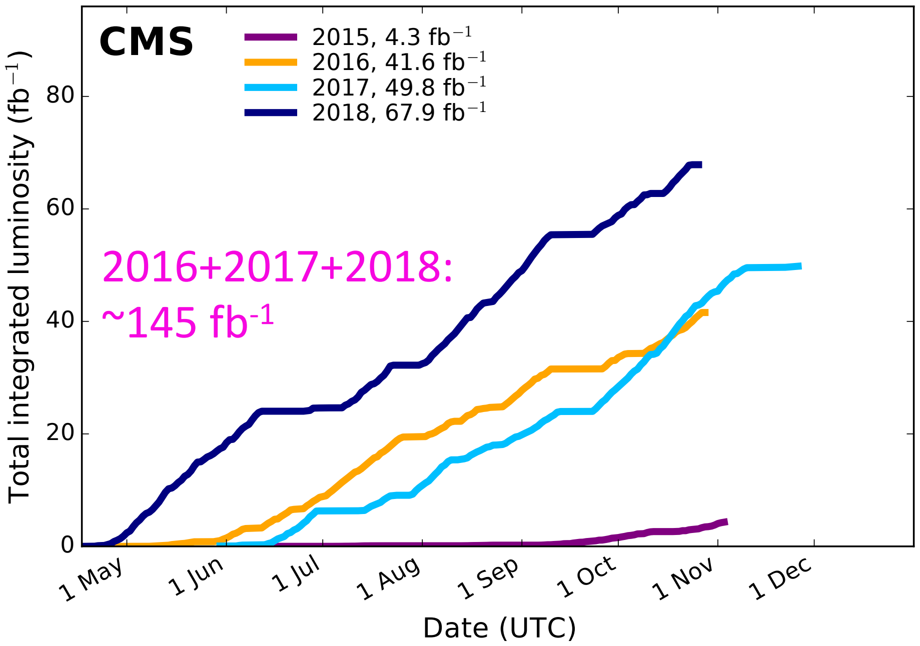
consistent on existence of resonant states above $\eta_b\eta_b$ threshold.

η coverage (track & muon): [-2.5,2.5]

The CMS detector & trigger







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

Excellent detectors for mulit-muon (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 analyses at increasing Inst. Lumi.
  - μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ

$J/\psi J/\psi$--Data samples & event selections at 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; $p_T(\mu)_{(J/\psi)}$ >=3.5 GeV; 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

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

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

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

Steps to identify structures in J/ψJ/ψ mass spectrum

- Null-hypothesis (initial baseline model): NRSPS+NRDPS backgrounds
- Add potential structures to baseline model
  - Add most prominent structure to baseline model
  - Calculate its local significance
  - Keep in baseline only if $> 3\sigma$ significance
  - Repeat until no more $> 3\sigma$ structures

NRSPS—Non-Resonant Single Parton Scattering

NRDPS—Non-Resonant Double Parton Scattering

Local significance: standard likelihood ratio method

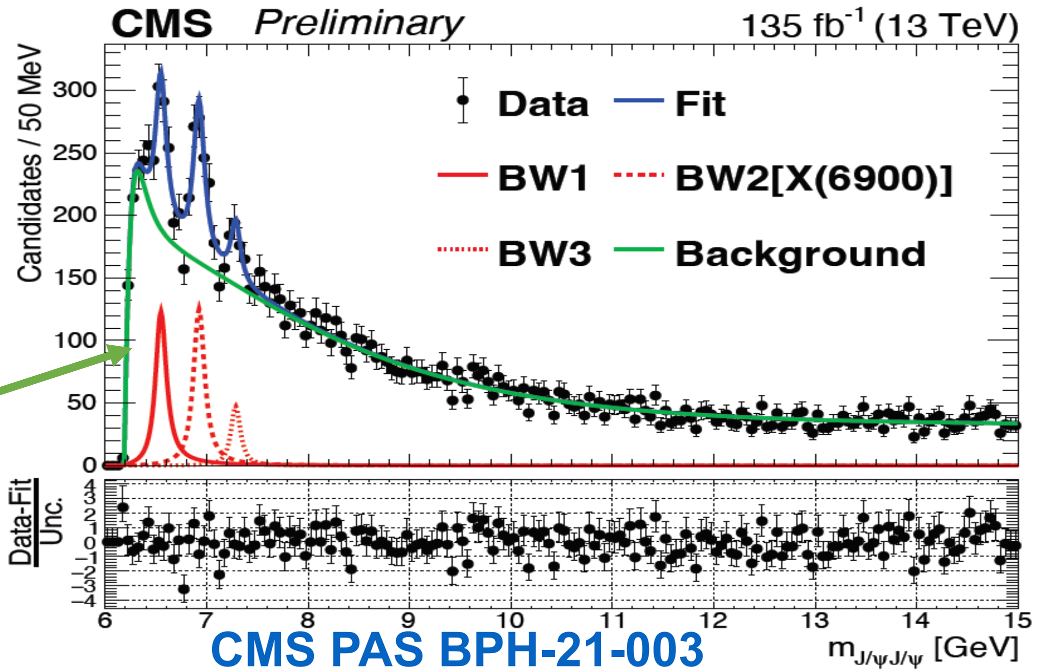
$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)}, \text{ where } \Gamma(m) = \Gamma_0 \frac{q m_0}{q_0 m},$$

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

CMS background (BW0 + NRSPS + DPS)

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

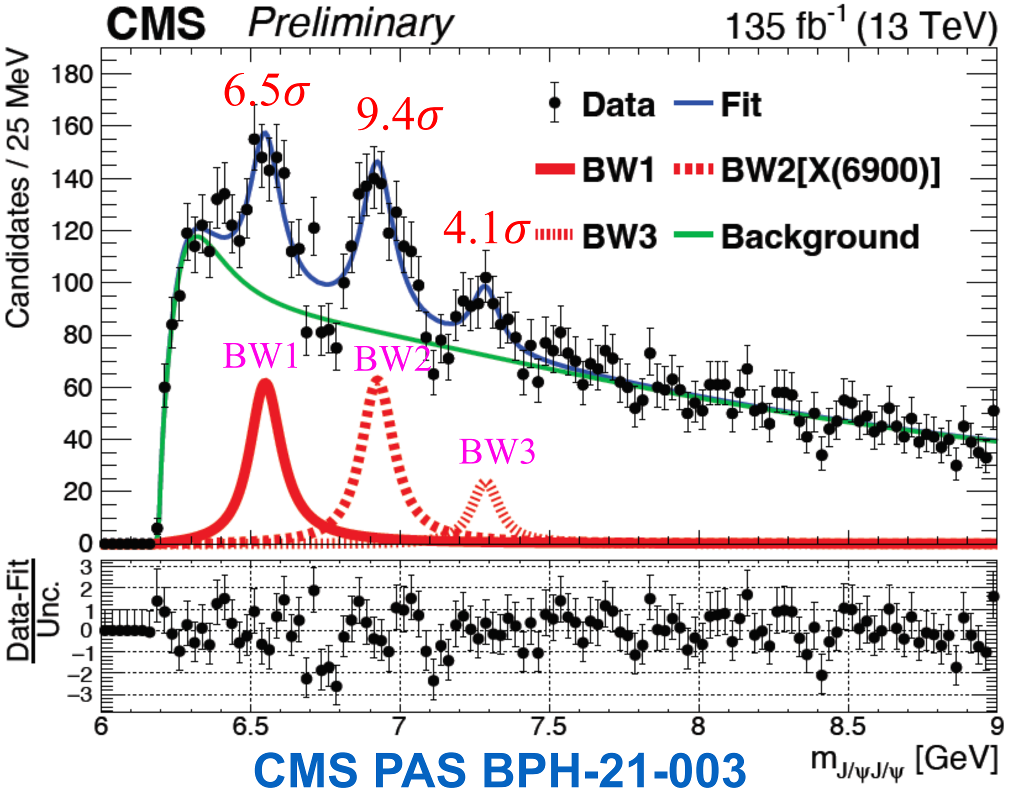
CMS background (BW0 + NRSPS + DPS)



CMS PAS BPH-21-003

- 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 NRSPS model at threshold (only 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

Final CMS model: 3 BWs + Background (null)



CMS PAS BPH-21-003

Statistical significance based on:

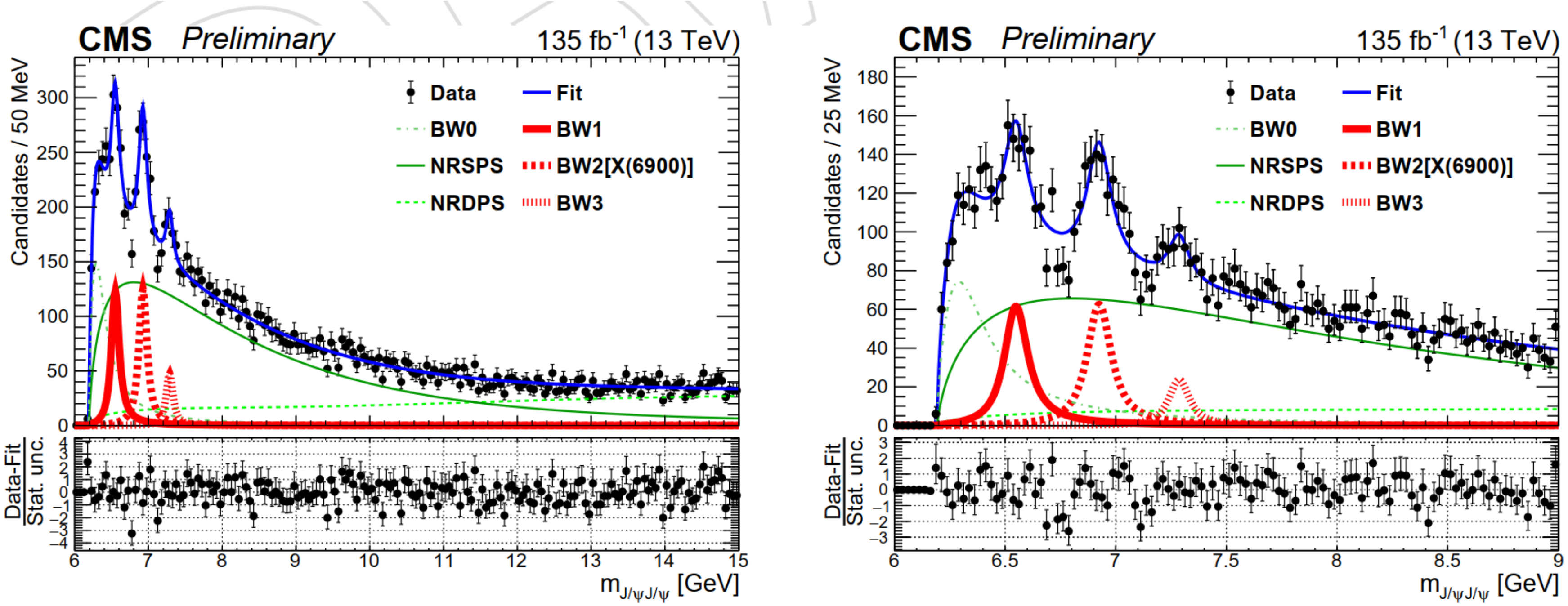
2 ln(L_0/L_{max})

	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 (6.5 σ)
- Evidence for BW3 (4.1σ)

Statistical significance only

Final CMS model: 3 BWs + Backgrounds+ BW0



CMS PAS BPH-21-003

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	$no\ sensible\ changes$

- Significances with systematics do not alter picture

Summary of systematic uncertainties and CMS result

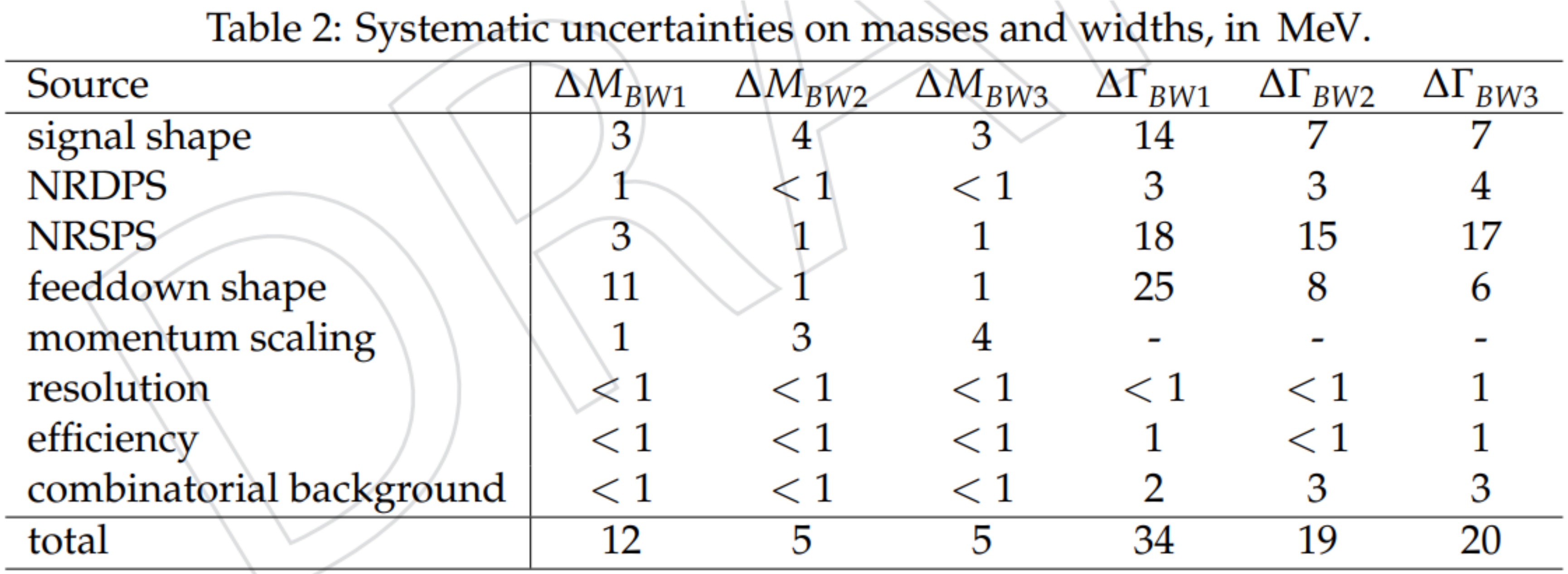


Table 2: Systematic uncertainties on masses and widths, in MeV.

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
feeddown shape	11	1	1	25	8	6
momentum scaling	1	3	4	-	-	-
resolution	< 1	< 1	< 1	< 1	< 1	1
efficiency	< 1	< 1	< 1	1	< 1	1
combinatorial background	< 1	< 1	< 1	2	3	3
total	12	5	5	34	19	20

CMS PAS BPH-21-003

- Investigated effects of systematics on local significance by a profiling procedure
  a discrete set of individual alternative signal and background hypotheses tested in minimization
  - Only noticeable change: BW1 significance changed from 6.5σ to >5.7σ
  - No relative significance changes for BW2 and BW3

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

CMS PAS BPH-21-003

(Non-interference fit results)

consistent →

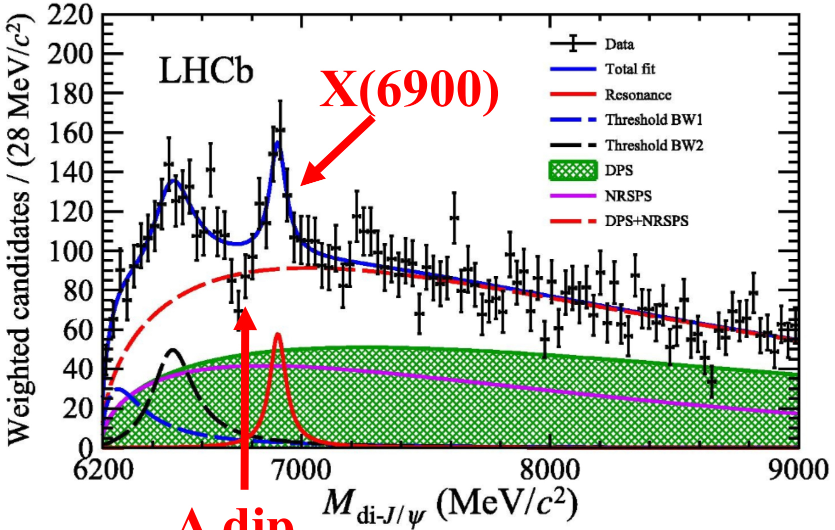
X(6900) [LHCb]
(somewhat different fit model)

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

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” auxiliary BWs to interfere with NRSPS background to account for dip
- LHCb agnostic on which one is to be preferred

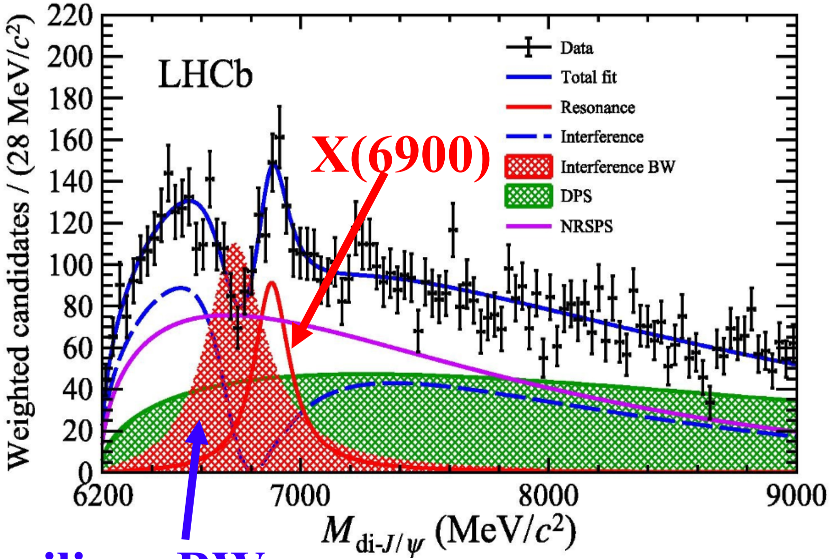
Model I (non-interference)



X(6900)

A dip

Model II (interference with an auxiliary BW)

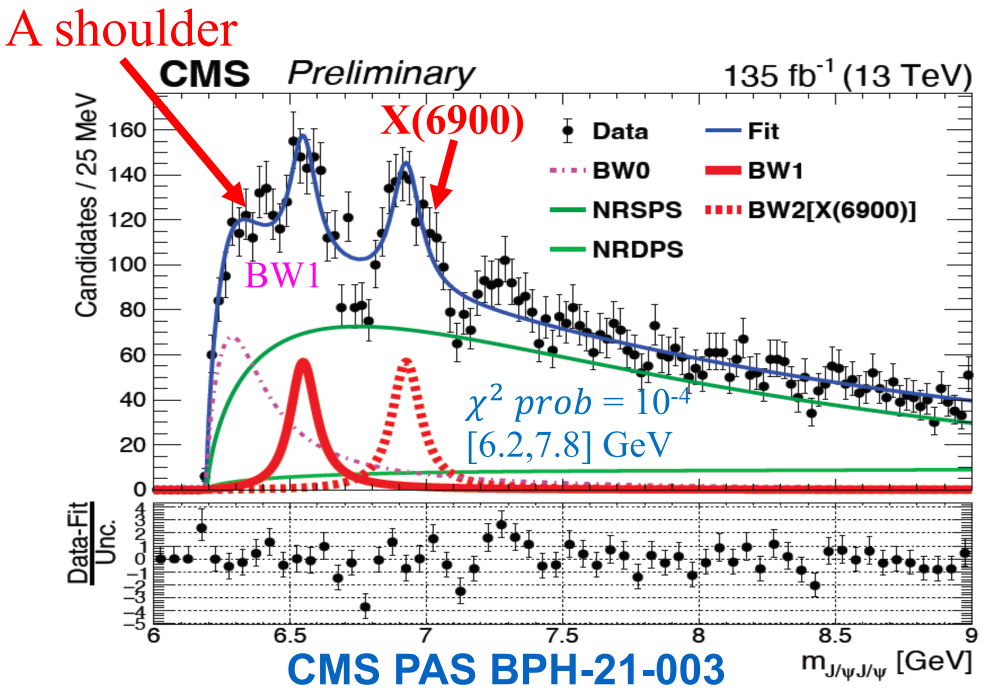


X(6900)

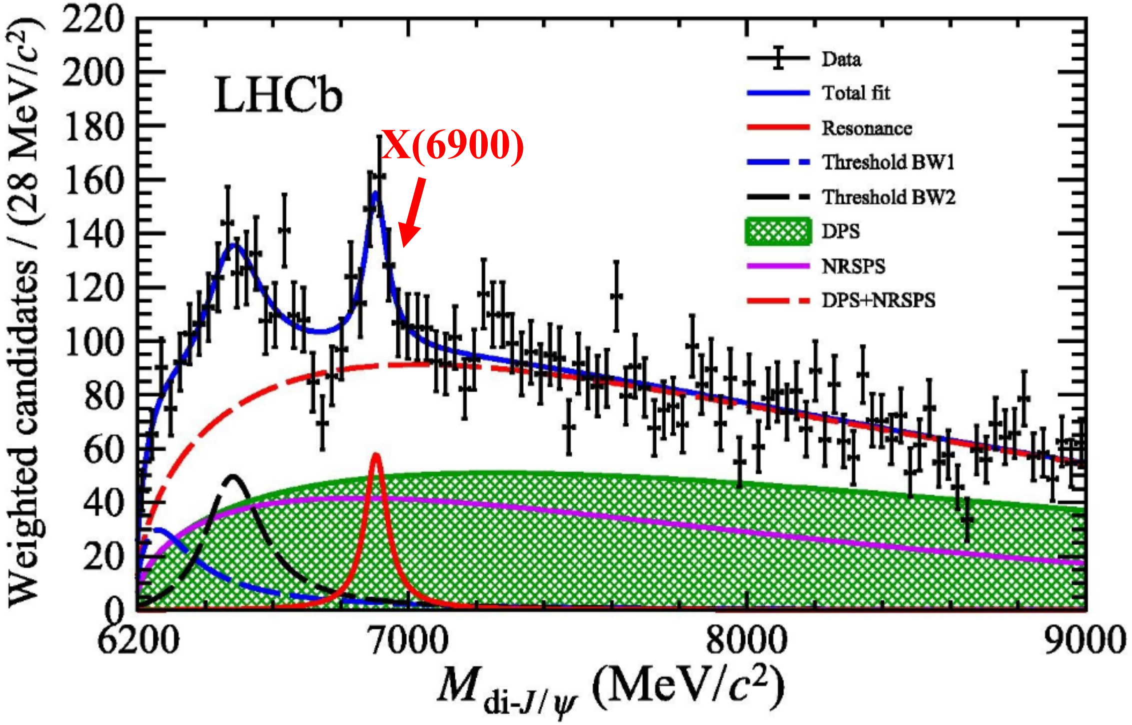
“auxiliary BW

- What happens if fit CMS data using LHCb models?

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



CMS PAS BPH-21-003



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

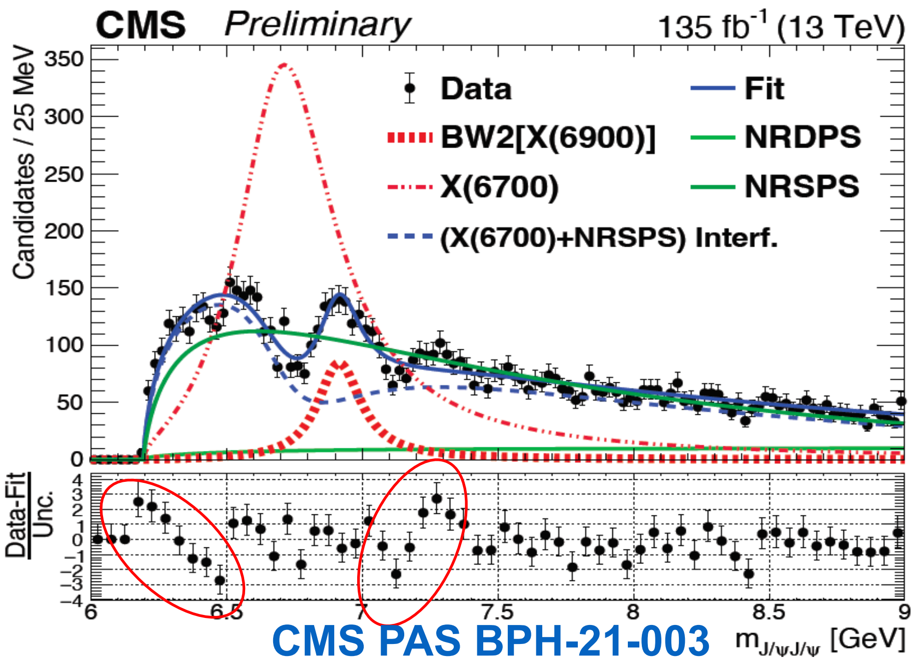
X(6900) parameters are in good agreement with LHCb
LHCb did not give parameters for another 2 BWs

- CMS Data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct

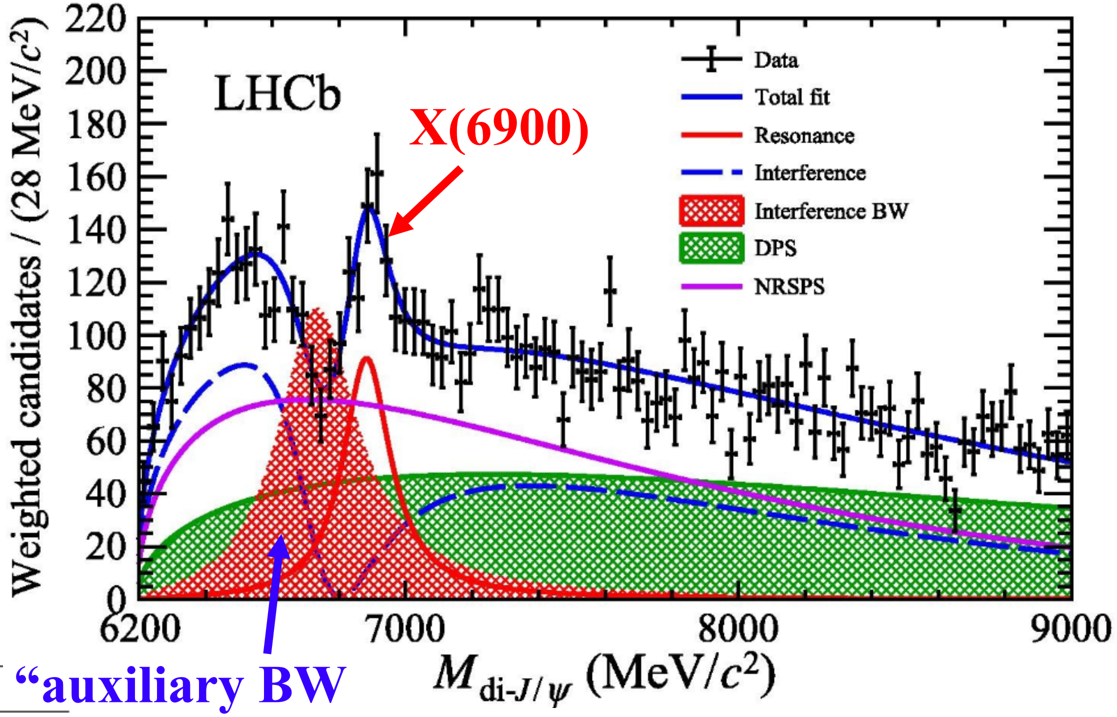
- *Does not describe well dips*

- CMS vs LHCb comparisons:
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4 \approx$ 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, but much less DPS
  - 2X yield @CMS for X(6900)

Fit with LHCb model II: DPS + X(6900) + auxiliary BW interferes with NRSPS



CMS PAS BPH-21-003

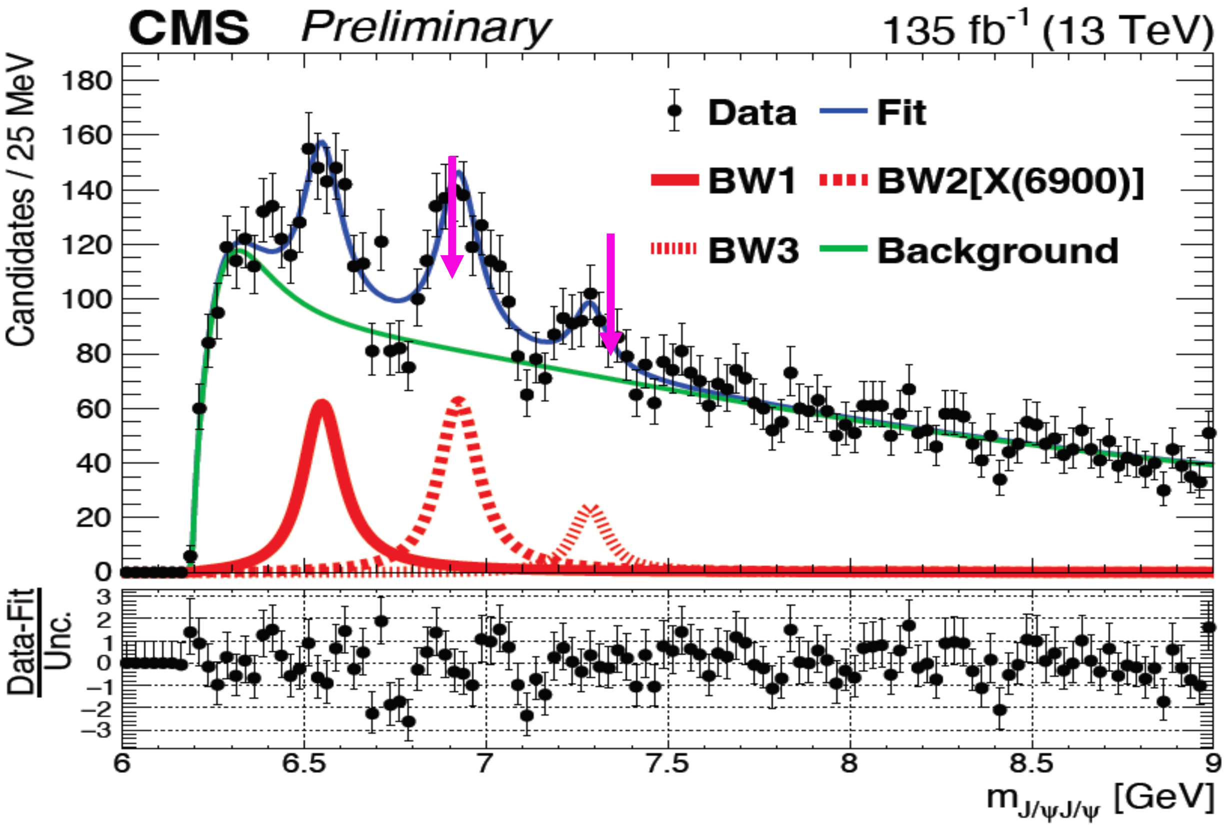


Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

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 BW1
  - 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(7200) region

The dips



CMS PAS BPH-21-003

- ➢ Possibility #1:
- Interference among structures?
- Why no interference between J/ψ and ψ(2S)?
  - 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 among various combinations of BWs
- Pdf for three BW interference

Interf. term

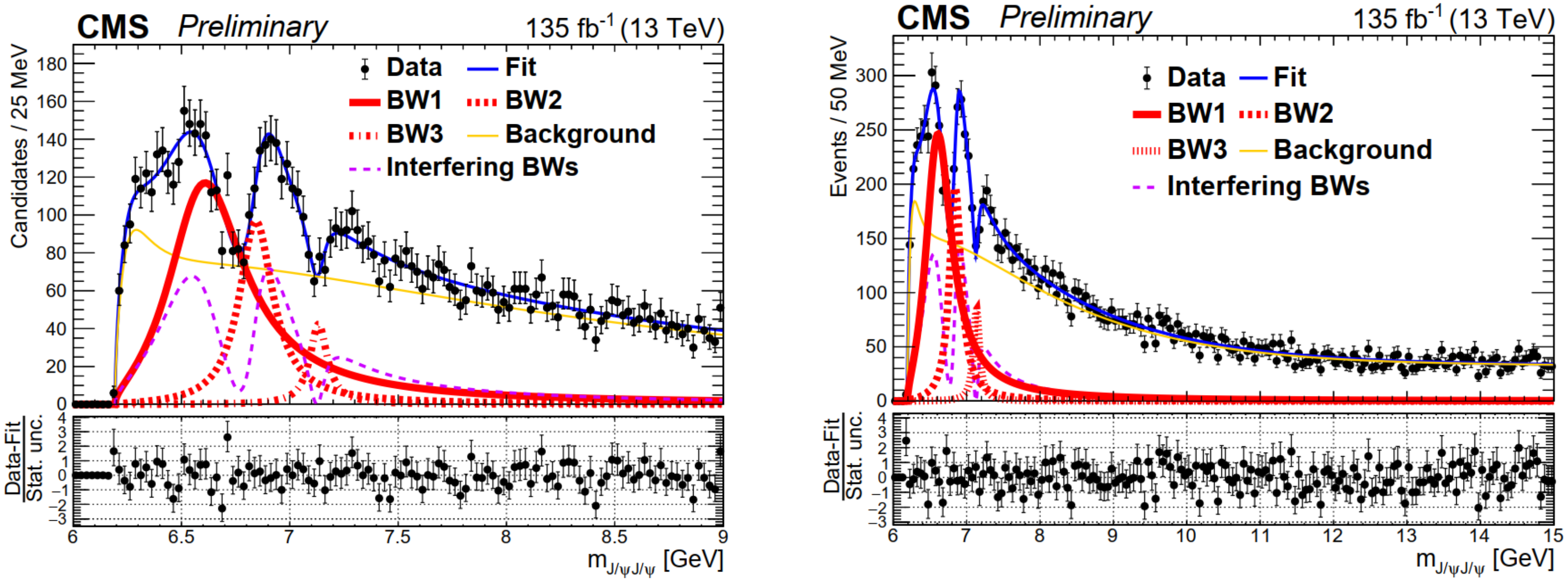
$$
\begin{aligned}
Pdf(m) &= N_{X_0} \cdot |BW_0|^2 \otimes R(M_0) \\
&+ N_{X\ and\ interf} \cdot \boxed{|r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2} \\
&+ N_{NRSPS} \cdot f_{SPS}(m) + N_{NRDPS} \cdot f_{DPS}(m) \cdot
\end{aligned}
$$

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

- Our choice: interference among BW1, BW2, BW3

CMS interference fit

CMS PAS BPH-21-003



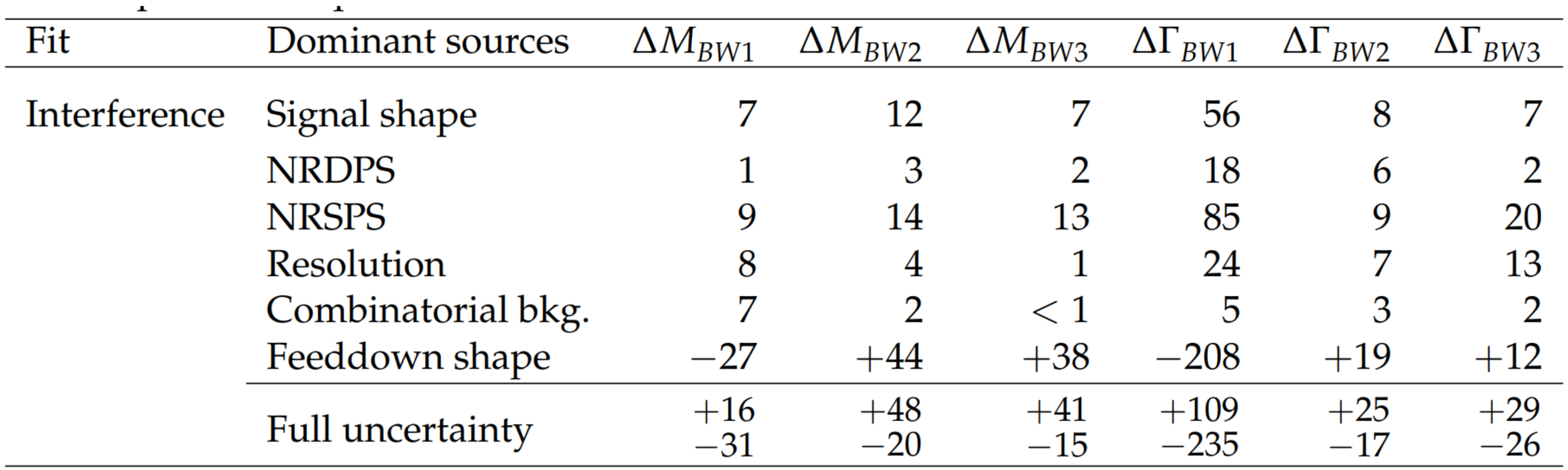
- Fit with interf. among BW1, BW2 and BW3 describes data well
- Measured mass and width in the interference fit

		BW1	BW2	BW3
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ [MeV]	$444^{+226+109}_{-199-235}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

CMS PAS BPH-21-003

Summary of systematic uncertainties for interf. case

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



Fit	Dominant sources	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta\Gamma_{BW1}$	$\Delta\Gamma_{BW2}$	$\Delta\Gamma_{BW3}$
Interference	Signal shape	7	12	7	56	8	7
	NRDPS	1	3	2	18	6	2
	NRSPS	9	14	13	85	9	20
	Resolution	8	4	1	24	7	13
	Combinatorial bkg.	7	2	< 1	5	3	2
	Feeddown shape	-27	$+44$	$+38$	-208	$+19$	$+12$
	Full uncertainty	$^{+16}_{-31}$	$^{+48}_{-20}$	$^{+41}_{-15}$	$^{+109}_{-235}$	$^{+25}_{-17}$	$^{+29}_{-26}$

CMS PAS BPH-21-003

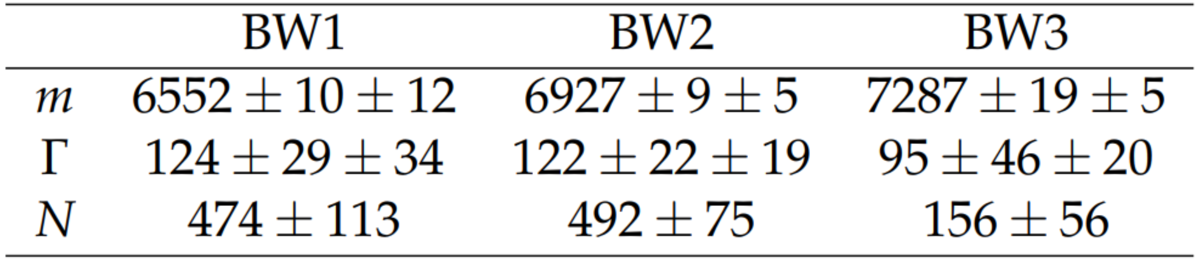
Final result

- Measured mass and width

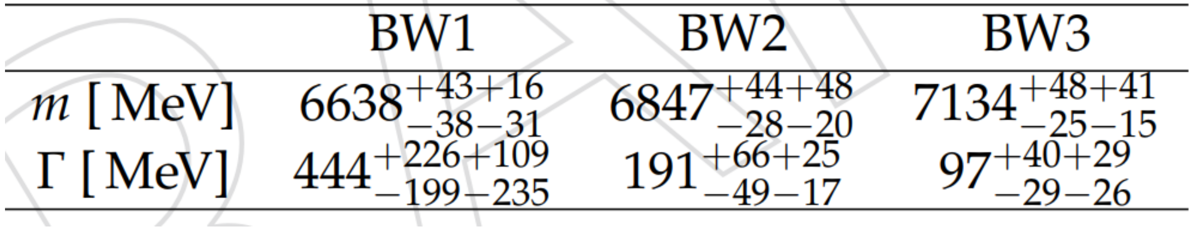
Non-interference fit

CMS PAS BPH-21-003

Interference fit



	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



	BW1	BW2	BW3
m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
Γ [MeV]	$444^{+226+109}_{-199-235}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

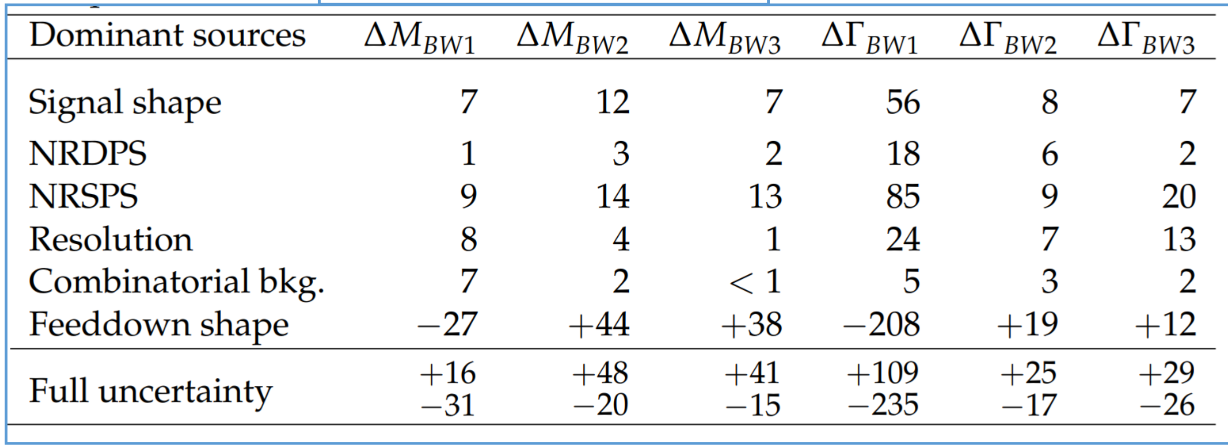
- Systematic uncertainty table (sources with minor effects suppressed)

Non-interference fit

CMS PAS BPH-21-003

Interference fit

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

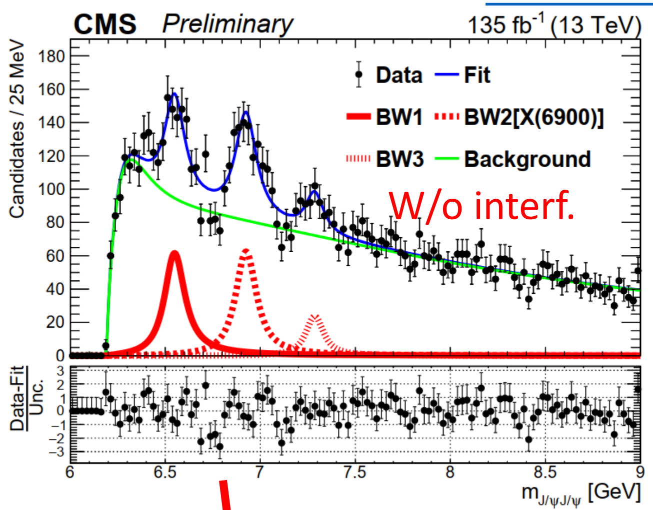


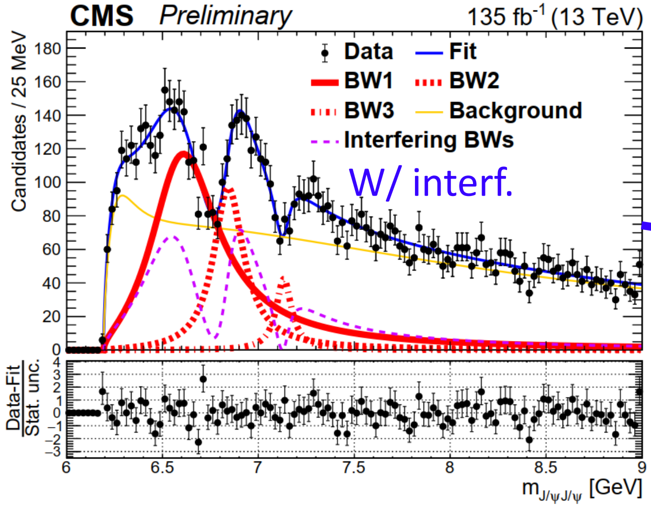
Dominant sources	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta\Gamma_{BW1}$	$\Delta\Gamma_{BW2}$	$\Delta\Gamma_{BW3}$
Signal shape	7	12	7	56	8	7
NRDPS	1	3	2	18	6	2
NRSPS	9	14	13	85	9	20
Resolution	8	4	1	24	7	13
Combinatorial bkg.	7	2	< 1	5	3	2
Feeddown shape	-27	$+44$	$+38$	-208	$+19$	$+12$
Full uncertainty	$+16$ -31	$+48$ -20	$+41$ -15	$+109$ -235	$+25$ -17	$+29$ -26

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

Comparison with some theoretical calculations

CMS PAS BPH-21-003





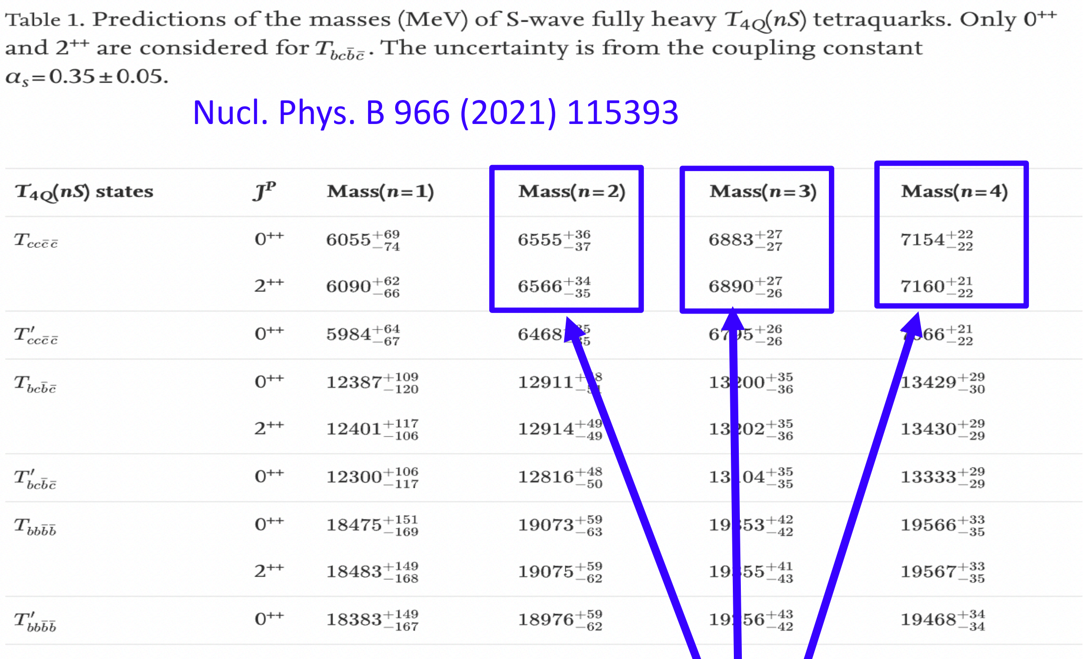


Table 1. Predictions of the masses (MeV) of S-wave fully heavy $T_{4Q}(nS)$ tetraquarks. Only 0^{++} and 2^{++} are considered for $T_{bc\bar{b}\bar{c}}$. The uncertainty is from the coupling constant $\alpha_s = 0.35 \pm 0.05$.

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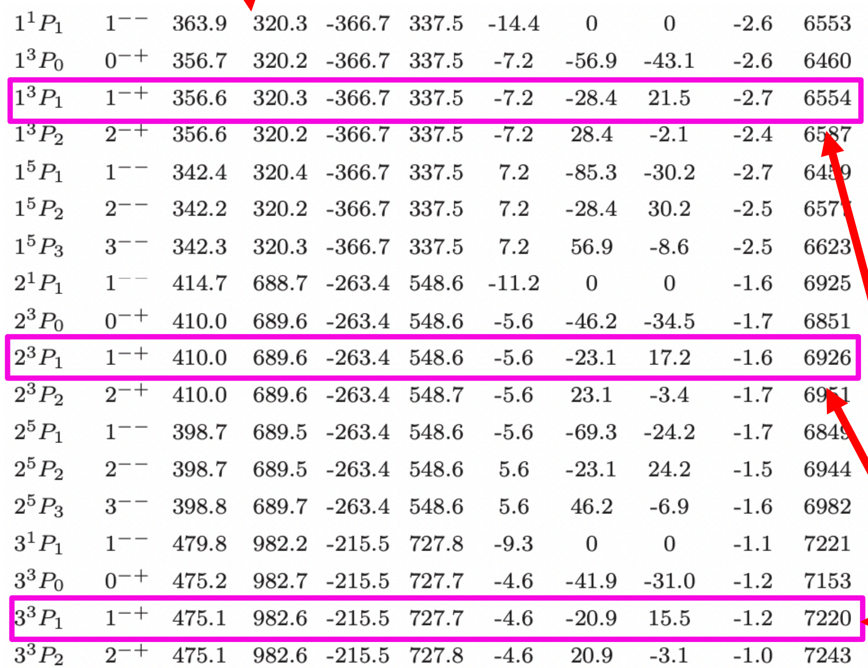
$T_{4Q}(nS)$ states	J^P	Mass($n=1$)	Mass($n=2$)	Mass($n=3$)	Mass($n=4$)
$T_{cc\bar{c}\bar{c}}$	0^{++}	6055^{+69}_{-74}	6555^{+36}_{-37}	6883^{+27}_{-27}	7154^{+22}_{-22}
	2^{++}	6090^{+62}_{-66}	6566^{+34}_{-35}	6890^{+27}_{-26}	7160^{+21}_{-22}
$T'_{cc\bar{c}\bar{c}}$	0^{++}	5984^{+64}_{-67}	6468[illegible]	67[illegible]5$^{+26}_{-26}$	[illegible]66$^{+21}_{-22}$
$T_{bc\bar{b}\bar{c}}$	0^{++}	12387^{+109}_{-120}	12911[illegible]	13[illegible]00$^{+35}_{-36}$	13429^{+29}_{-30}
	2^{++}	12401^{+117}_{-106}	12914^{+49}_{-49}	13[illegible]02$^{+35}_{-36}$	13430^{+29}_{-29}
$T'_{bc\bar{b}\bar{c}}$	0^{++}	12300^{+106}_{-117}	12816^{+48}_{-50}	13[illegible]04$^{+35}_{-35}$	13333^{+29}_{-29}
$T_{bb\bar{b}\bar{b}}$	0^{++}	18475^{+151}_{-169}	19073^{+59}_{-63}	19[illegible]53$^{+42}_{-42}$	19566^{+33}_{-35}
	2^{++}	18483^{+149}_{-168}	19075^{+59}_{-62}	19[illegible]55$^{+41}_{-43}$	19567^{+33}_{-35}
$T'_{bb\bar{b}\bar{b}}$	0^{++}	18383^{+149}_{-167}	18976^{+59}_{-62}	19[illegible]56$^{+43}_{-42}$	19468^{+34}_{-34}

S-wave

M[BW1] = 6638 ± 10 ± 12 MeV

M[BW2] = 6847 ± 9 ± 5 MeV

M[BW3] = 7134 ± 19 ± 5 MeV



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	-	-

arXiv:2108.04017 **[hep-ph]**

P-wave

M[BW1] = 6552 ± 10 ± 12 MeV

M[BW2] = 6927 ± 9 ± 5 MeV

M[BW3] = 7287 ± 19 ± 5 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?

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 states offer system easier to understand, i.e., ignore relativistic effect…
- Mass differences from multiple structures can be better calculated with a further measurement
- A new window to understand the strong interaction

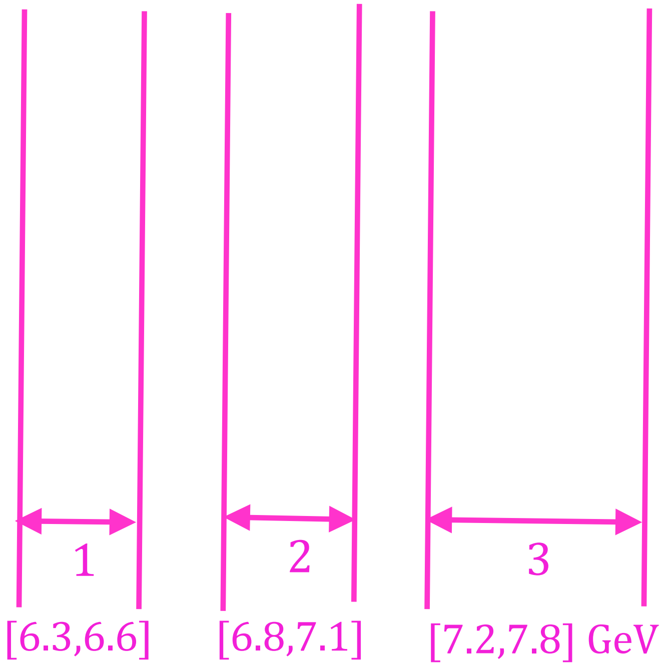
CMS has good sensitivity to all-muon final states in this mass region

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

Backup

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