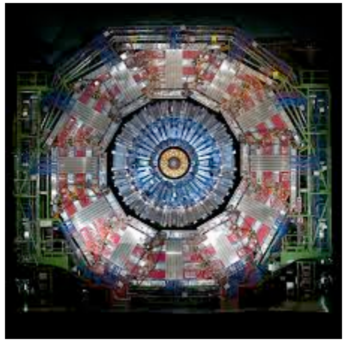


Observation of structures near $J/\psi J/\psi$ threshold at CMS

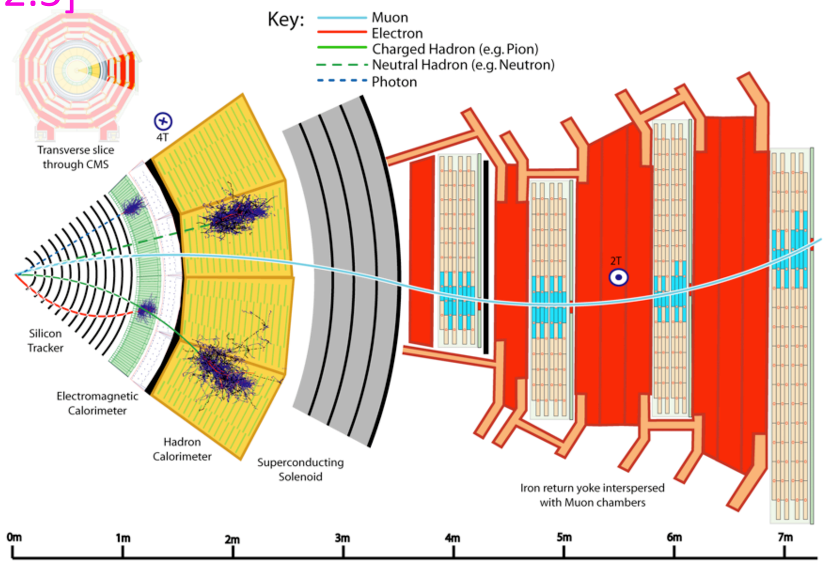
Kai Yi

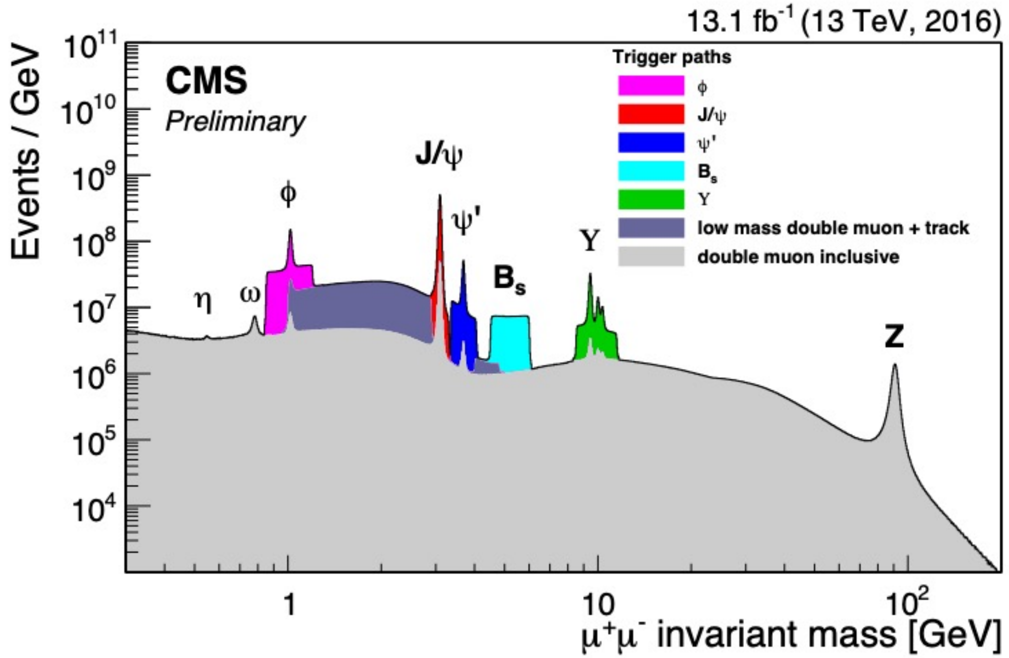
(Nanjing Normal University & Tsinghua University)

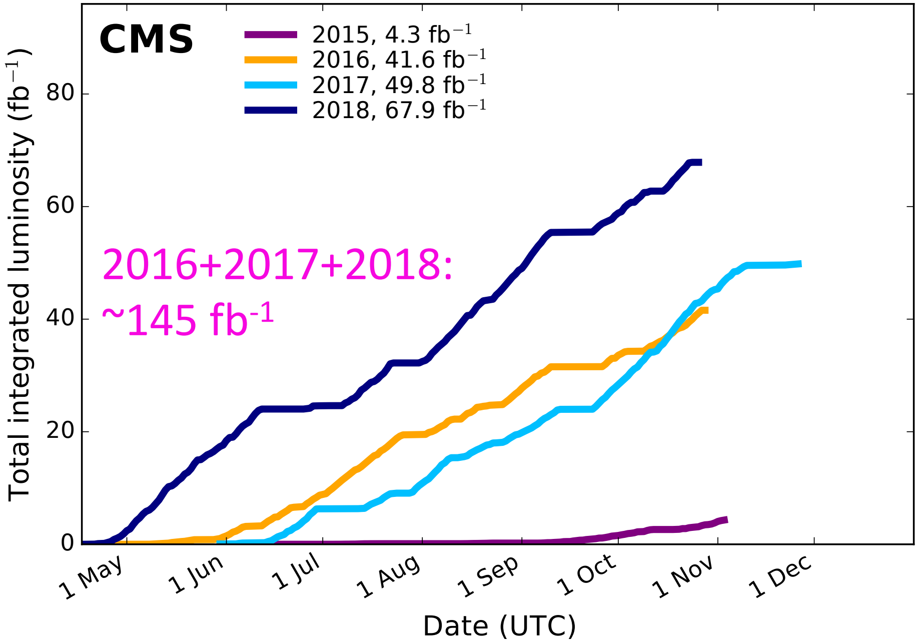
for the CMS Collaboration

η coverage (track & muon): [-2.5,2.5]

The CMS detector & trigger





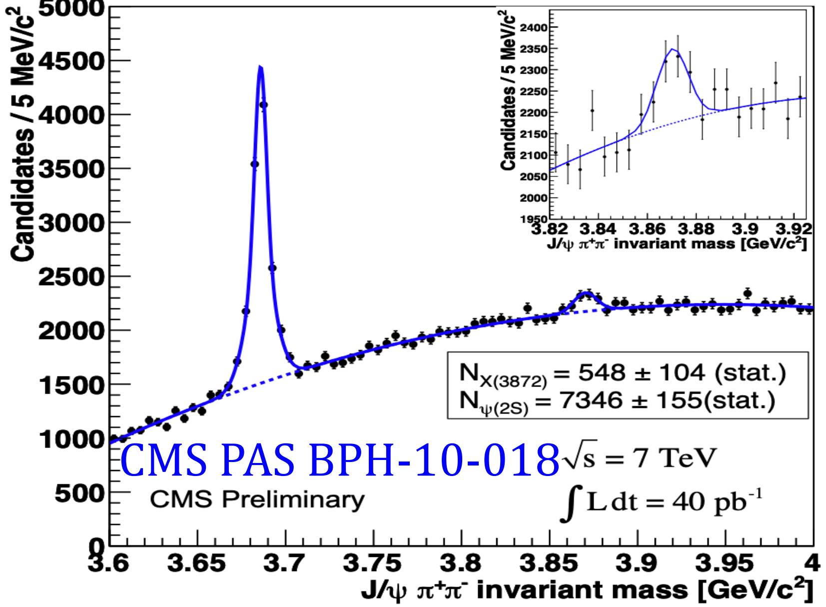


Excellent detectors for (exotic) quarkonium:

- Muon system
  - High-purity muon ID, Dm/m~0.6% for J/ψ
- Silicon Tracking detector, B=3.8T
  - Dp_T/p_T~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

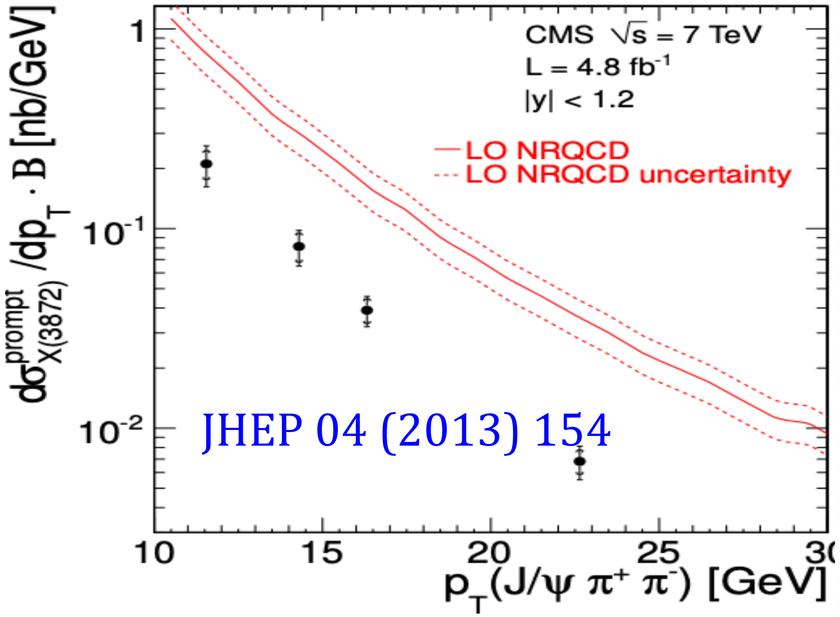
Selected CMS contributions to heavy exotic states

First LHC experiment re-discovered X(3872)



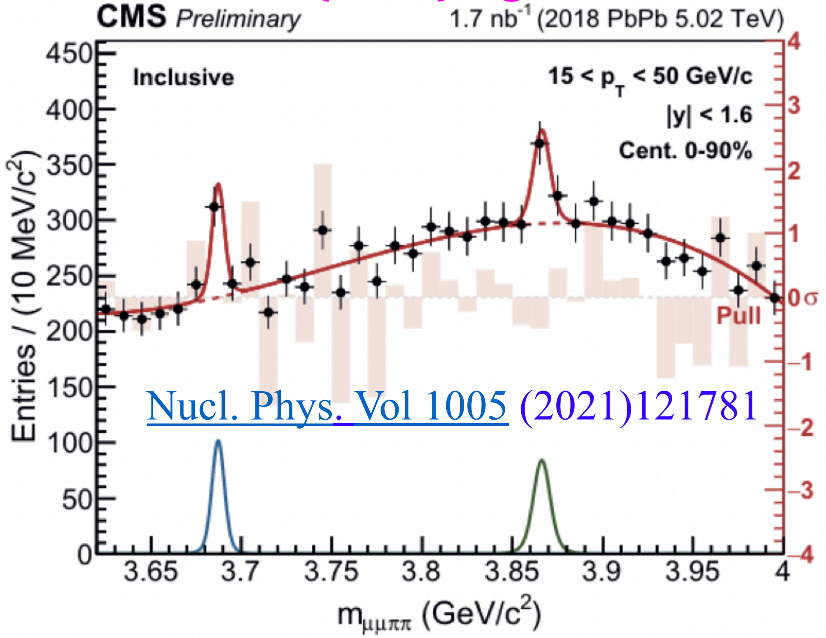
CMS PAS BPH-10-018

X(3872) measurement



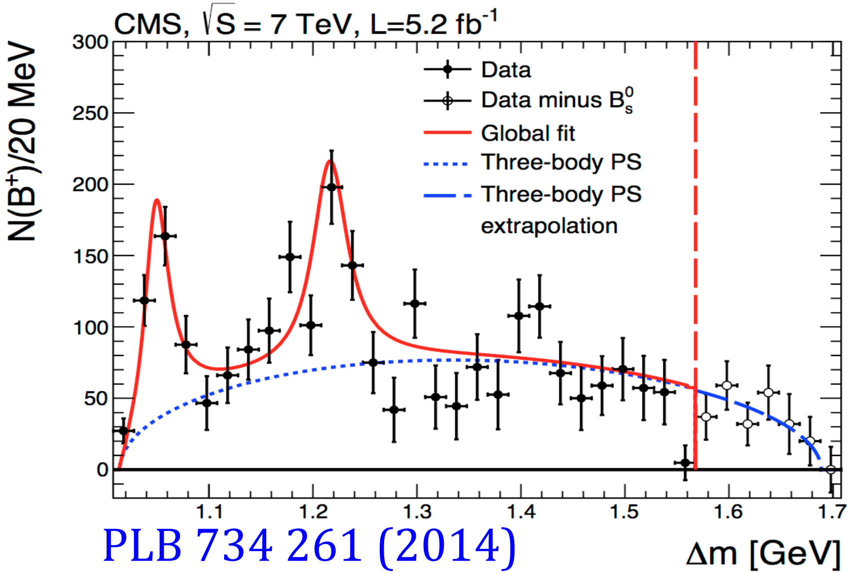
JHEP 04 (2013) 154

First X(3872) signal in PbPb



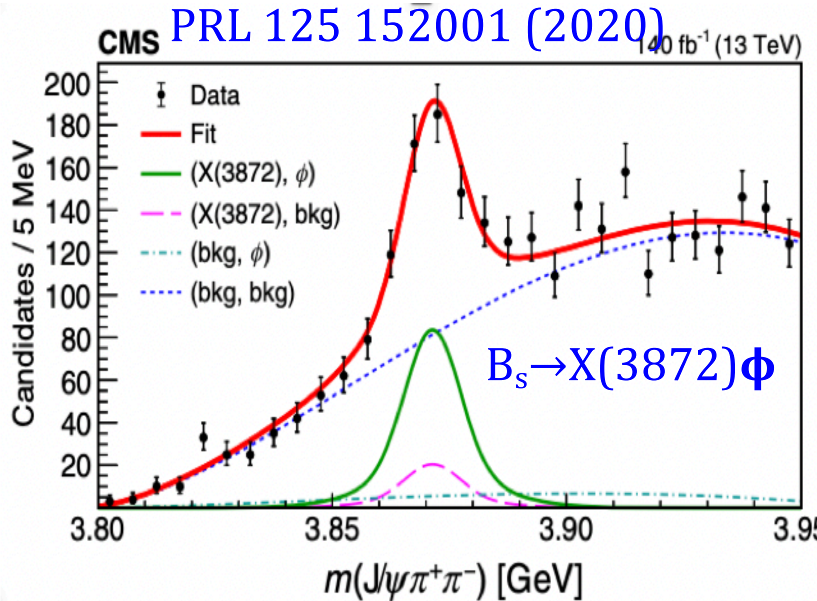
Nucl. Phys. Vol 1005 (2021)121781

First confirmation of Y(4140)



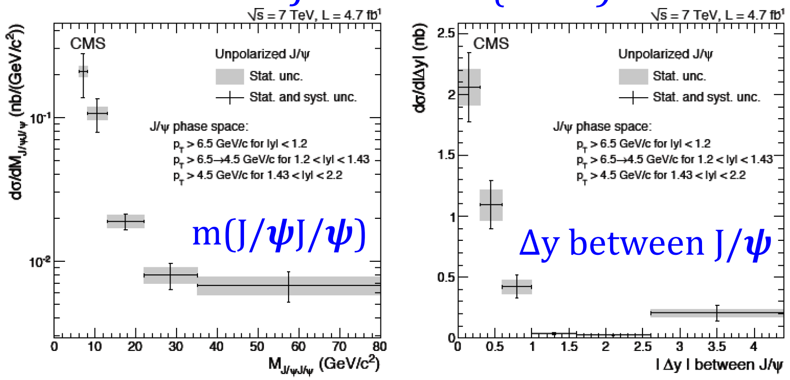
PLB 734 261 (2014)

PRL 125 152001 (2020)



$B_s \to X(3872)\phi$

JHEP 1409 (2014) 094



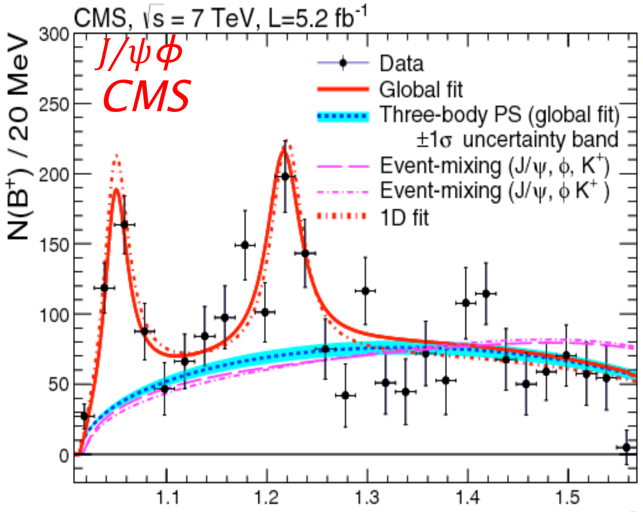
m(J/ψJ/ψ)

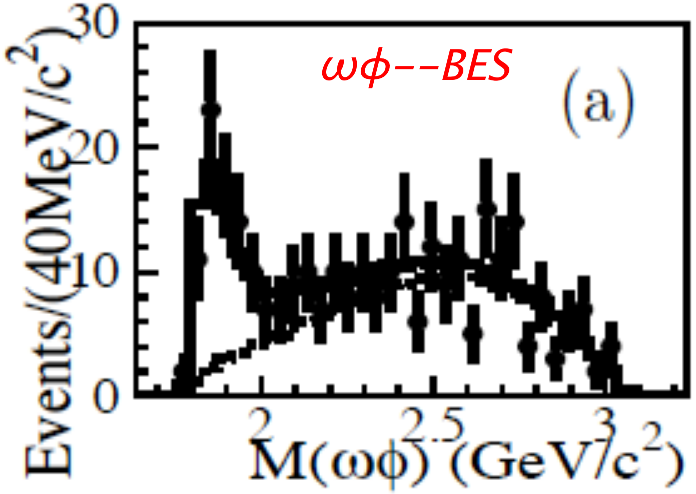
Δy between J/ψ

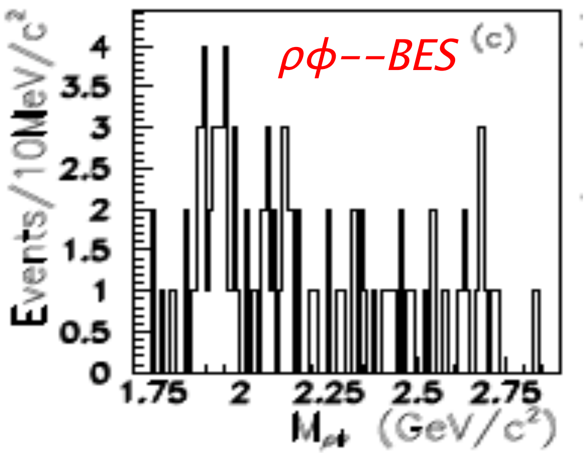
CMS has large di-J/ψ sample

Any surprises?

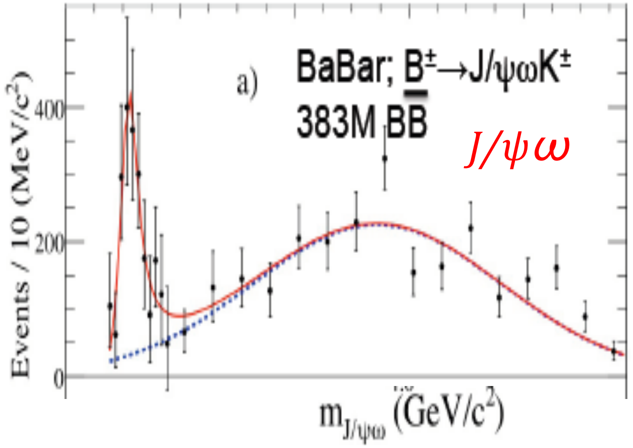
Near Threshold puzzle

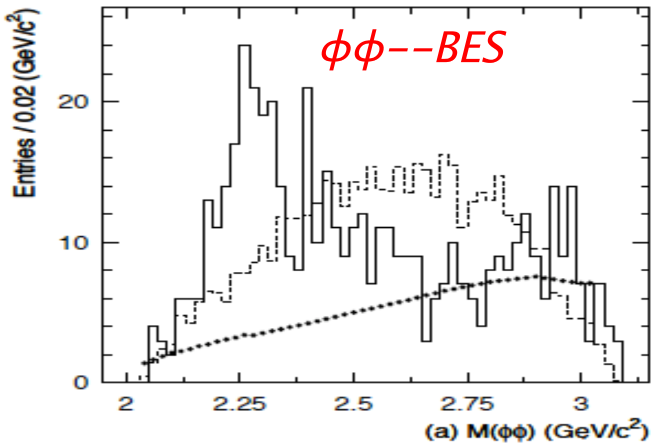


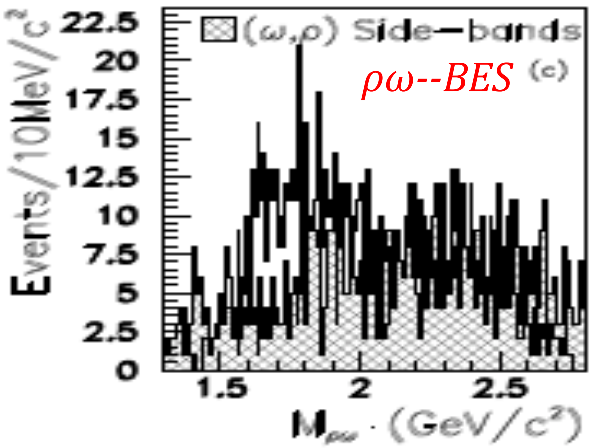




PRD 77, 012001(2008)







IJMPA Vol. 28, No. 18 (2013) 1330020

Clean vector-vector (VV) system:

--excesses when both V has no isospin

--not clear when one V has isospin

extend to other VV system, where V is composed of heavy quark?

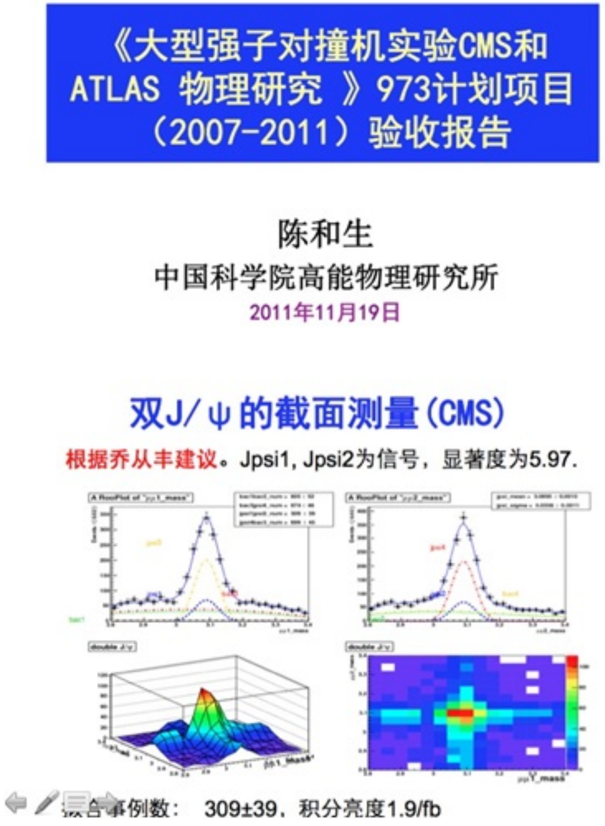
New Domain of Exotics: All-Heavy Tetra-quarks

- First mention of 4c states at 6.2 GeV (1975): Prog. of Theo. Phys. Vol. 54, No. 2

  (Just one year after the discovery of J/ψ)

- First calculation of 4c states (1981): Z. Phys. C 7 (1981) 317

- Many 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.



- **Jianguo Bian** initialized di-J/ψ cross section analysis @CMS

$J/\psi J/\psi$--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

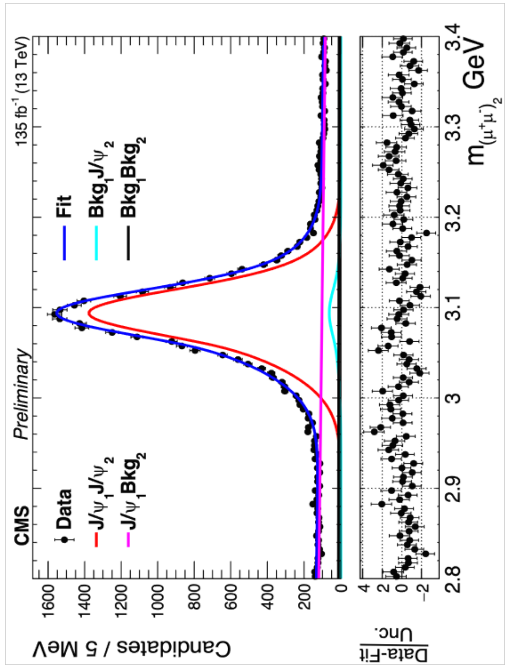
  based on preliminary investigation on data collected in 2011-2012

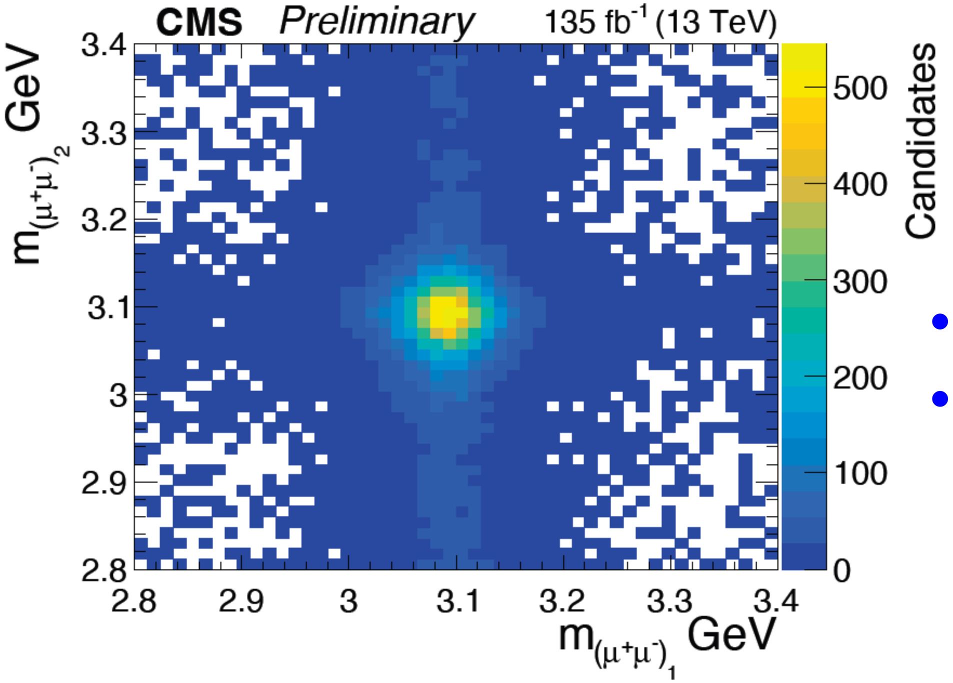
- Main selections:
  - Fire corresponding trigger in each year
  - $p_T(\mu)$>=2.0 GeV; $|\eta(\mu)|$<=2.4; $p_T(\mu)$ (J/ψ) >=3.5 GeV (2017&2018); $p_T(\mu^+\mu^-)$>=3.5 GeV;
  - $m(\mu^+\mu^-)$ in [2.95,3.25] GeV; then constrain $m(\mu^+\mu^-)$ to J/ψ mass
  - 4μ vertex probability >0.005

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

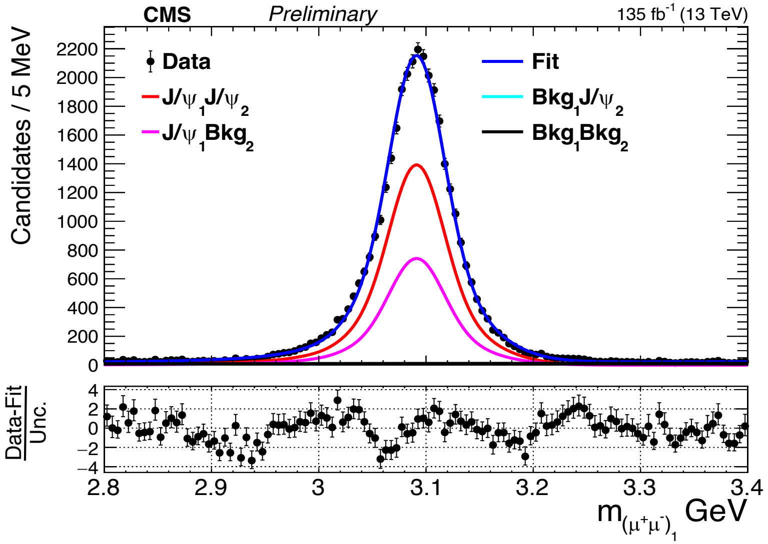
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-003/index.html

J/ψ signal





- Remove J/ψ mass related cuts
- Clean J/ψ signal is 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
- 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

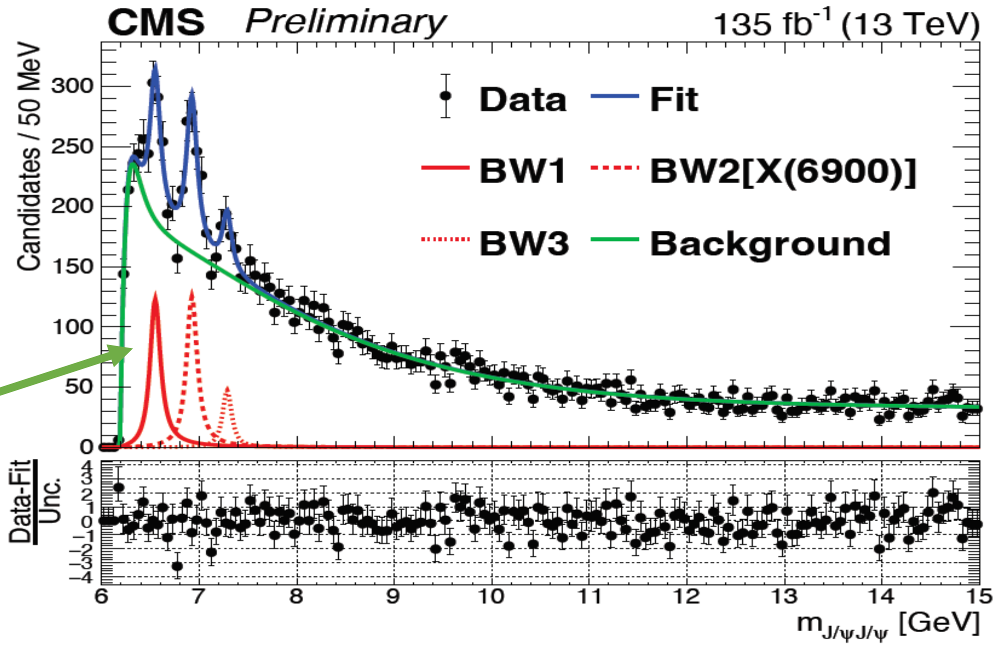
$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)}, \text{ where } \Gamma(m) = \Gamma_0 \frac{q m_0}{q_0 m},$$

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

CMS background (BW0 + NRSPS + DPS)

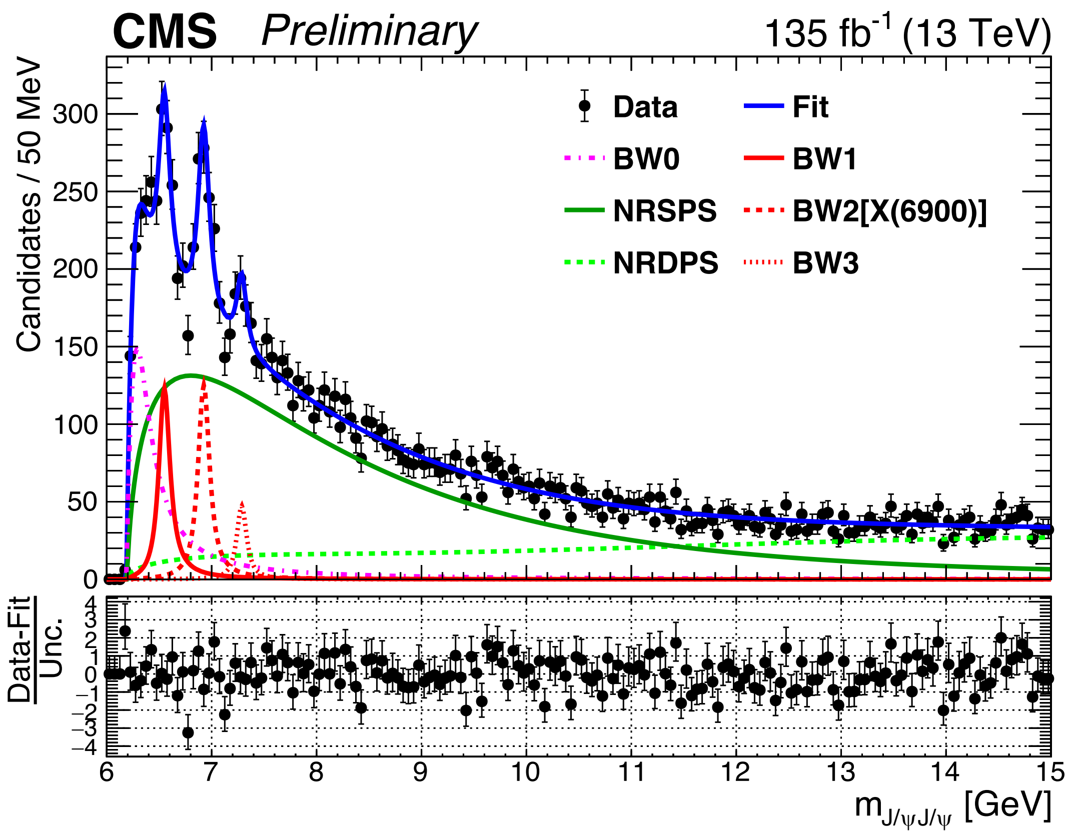
$\chi^2\ prob = 79\%$
[6.2,15] GeV

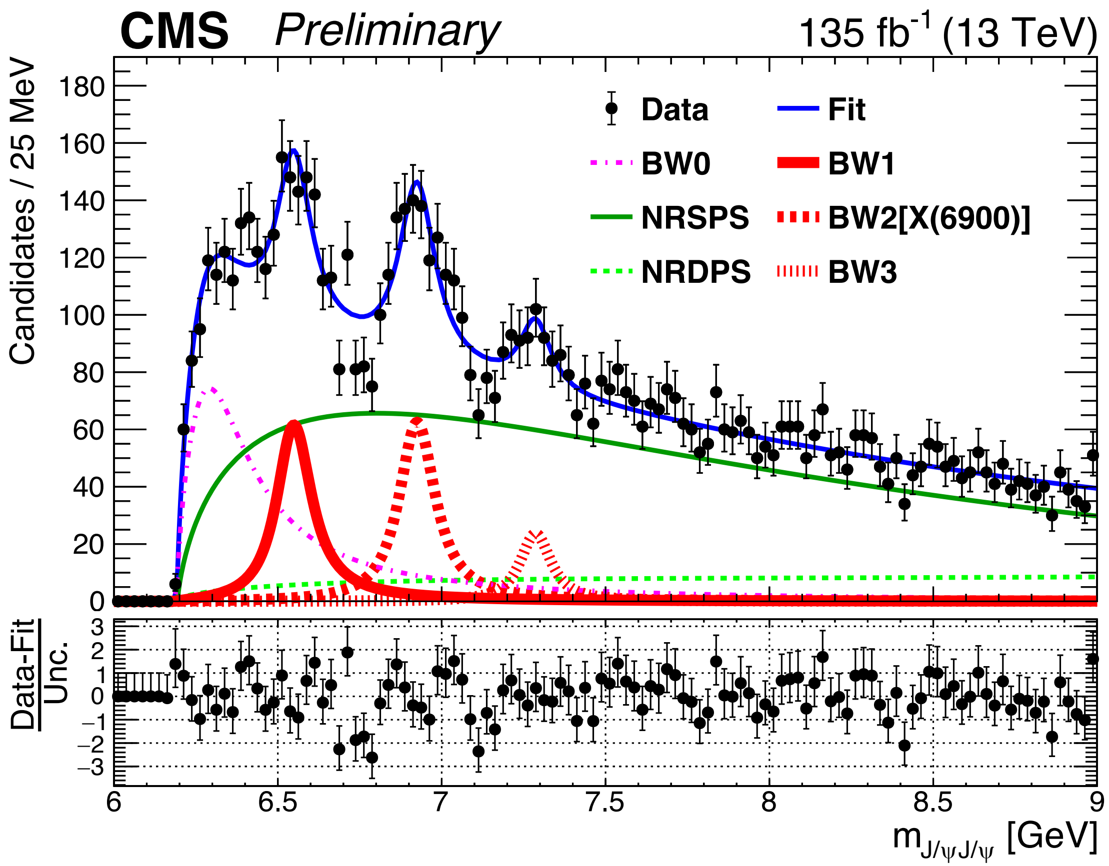
CMS background (BW0 + NRSPS + DPS)



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

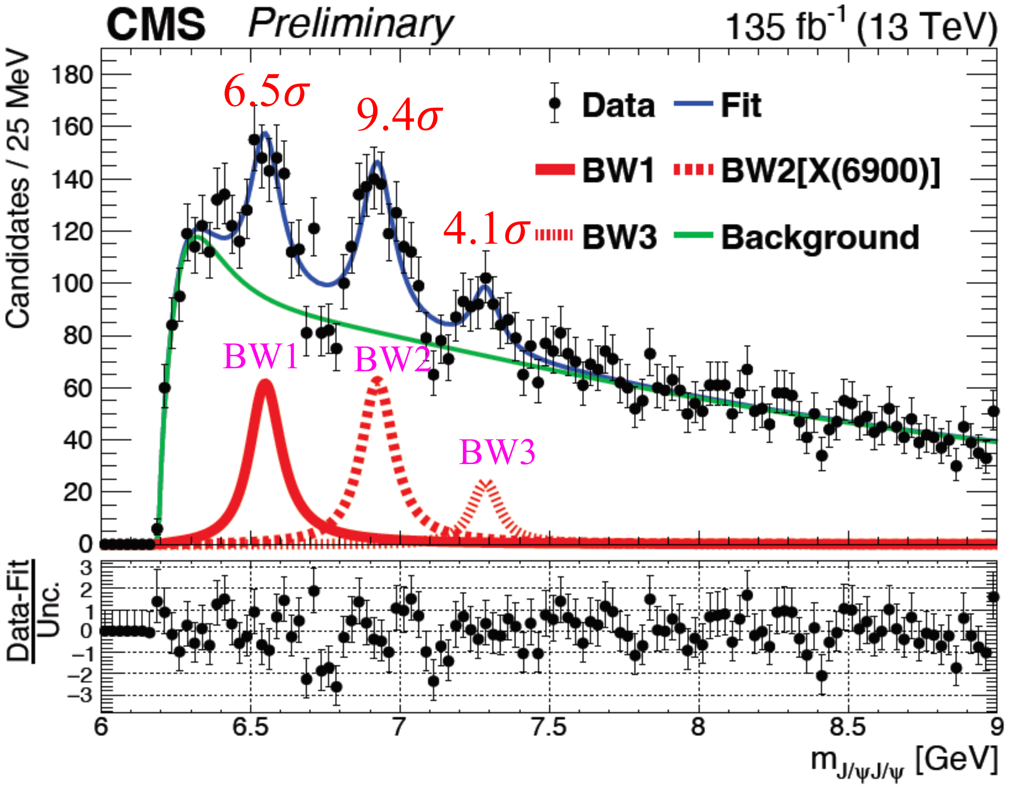
Final CMS model: 3 BWs + Backgrounds+ BW0





Final CMS model: 3 BWs + Background (null)

χ^2 Prob. = 1%
[6.2,7.8] GeV



Statistical significance based on:

$2\ln(L_0/L_{max})$

	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	6552 ± 10	6927± 9	7287± 19
Γ	124± 29	122± 22	95± 46
N	474± 113	492± 75	156± 56

Statistical uncertainties only

- BW2[X(6900)] (>9.4σ) – confirmation
- Observation of BW1 (>5.7σ)
- Evidence for BW3 (>4.1σ)

Statistical significance only

Significances including systematics

- To include systematics, alternative resonance/background shapes applied in the fit:
- Calculate signal- and null-hypothesis NLL_{syst} including systematic using:

$$NLL_{syst-sig} = \text{Min}\{NLL_{nom-sig}, NLL_{alt-i-sig} + 0.5 + 0.5 \cdot \Delta dof\}$$

  - $NLL_{nom-sig}$ 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.
- $NLL_{syst-null} = \text{Min}\{NLL_{nom-null}, NLL_{alt-j-null} + 0.5 + 0.5 \cdot \Delta dof\}$
- 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*

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

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

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

consistent →

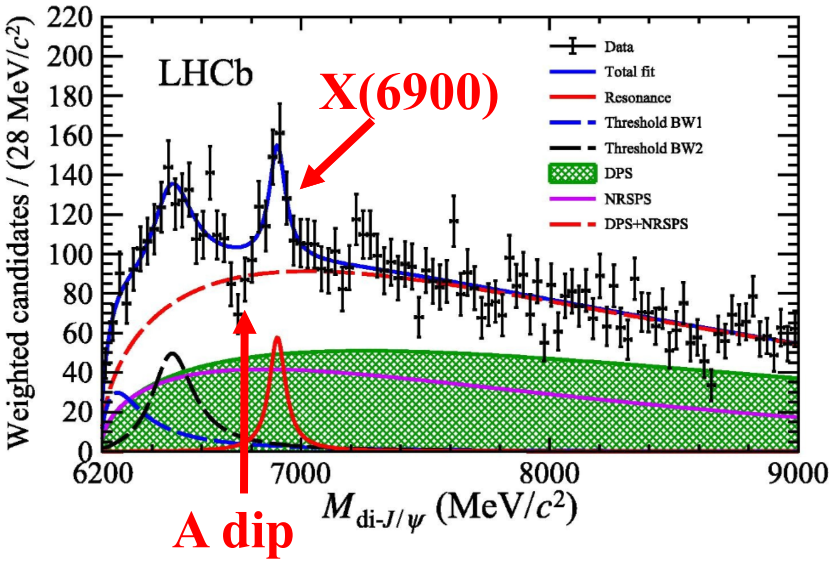
X(6900) [LHCb]
(somewhat different fit model)

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

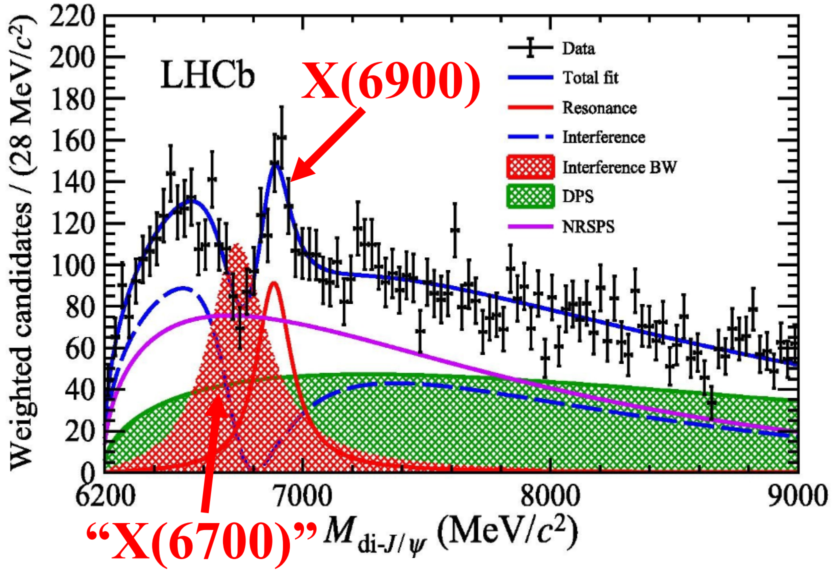
X(6900) reported by LHCb

- 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” X(6700) to interfere with NRSPS background to account for dip
- LHCb agnostic on which one is to be preferred
- What happens if fit CMS data using LHCb models?

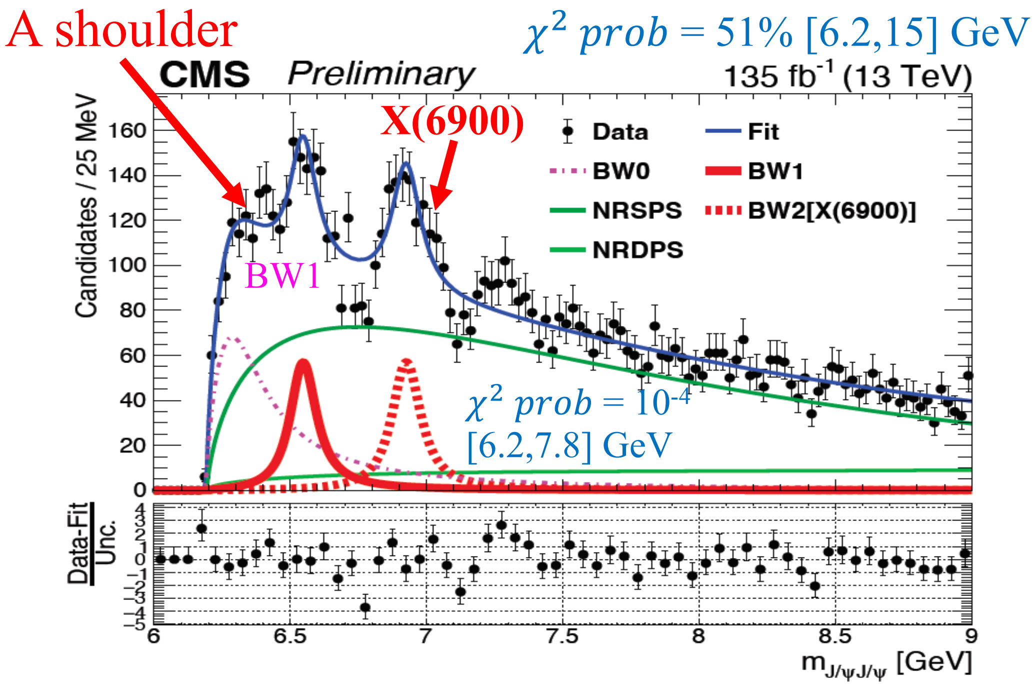
Model I

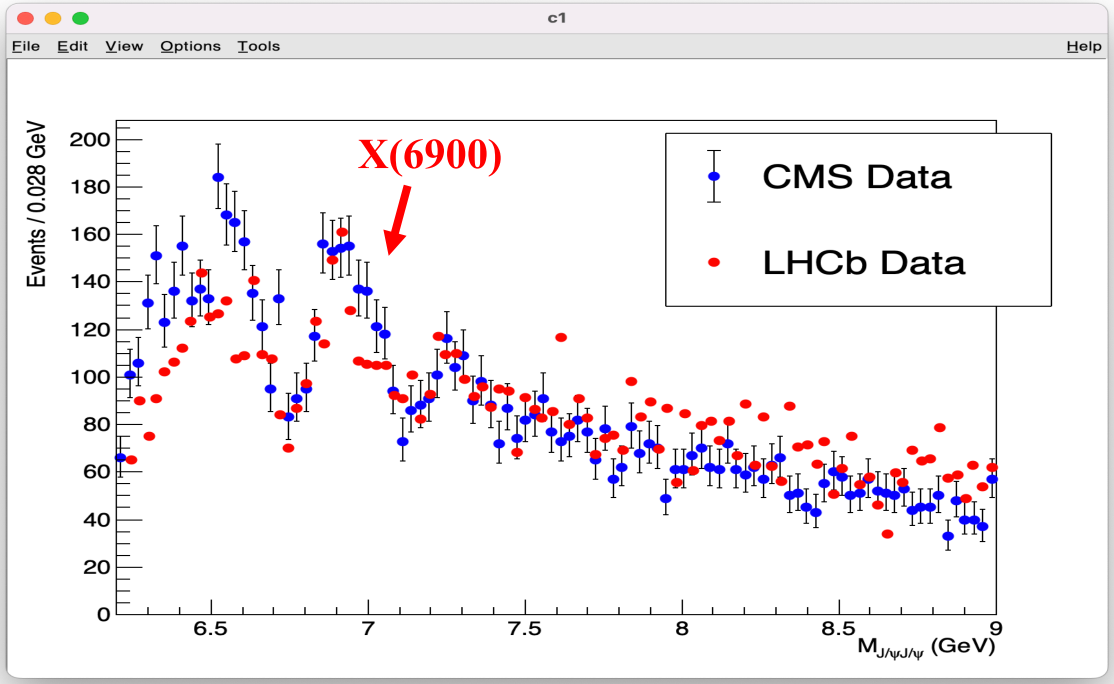


Model II



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

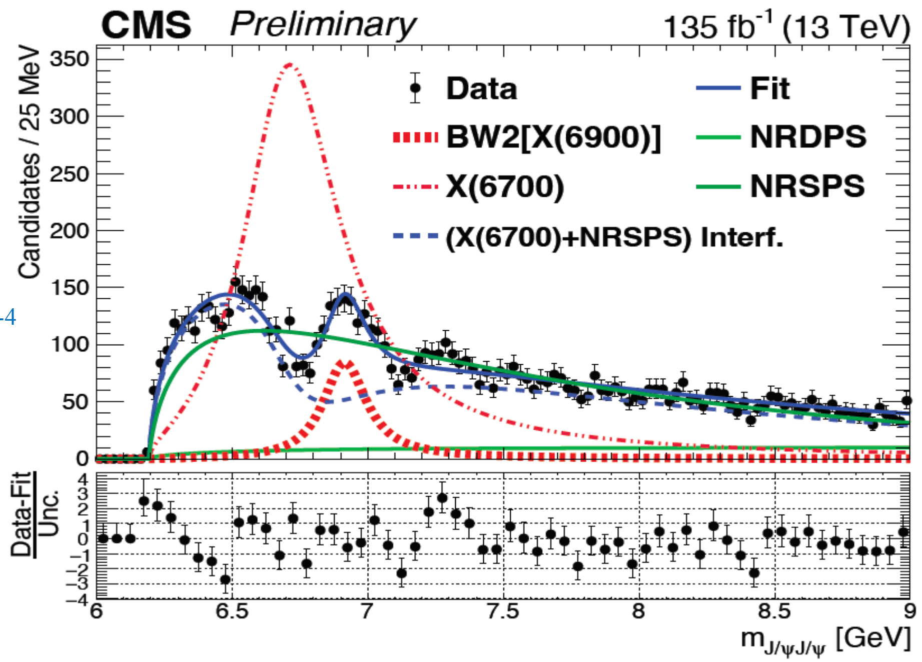
X(6900) parameters are in good agreement with LHCb
LHCb did not give parameters for another 2 BWs

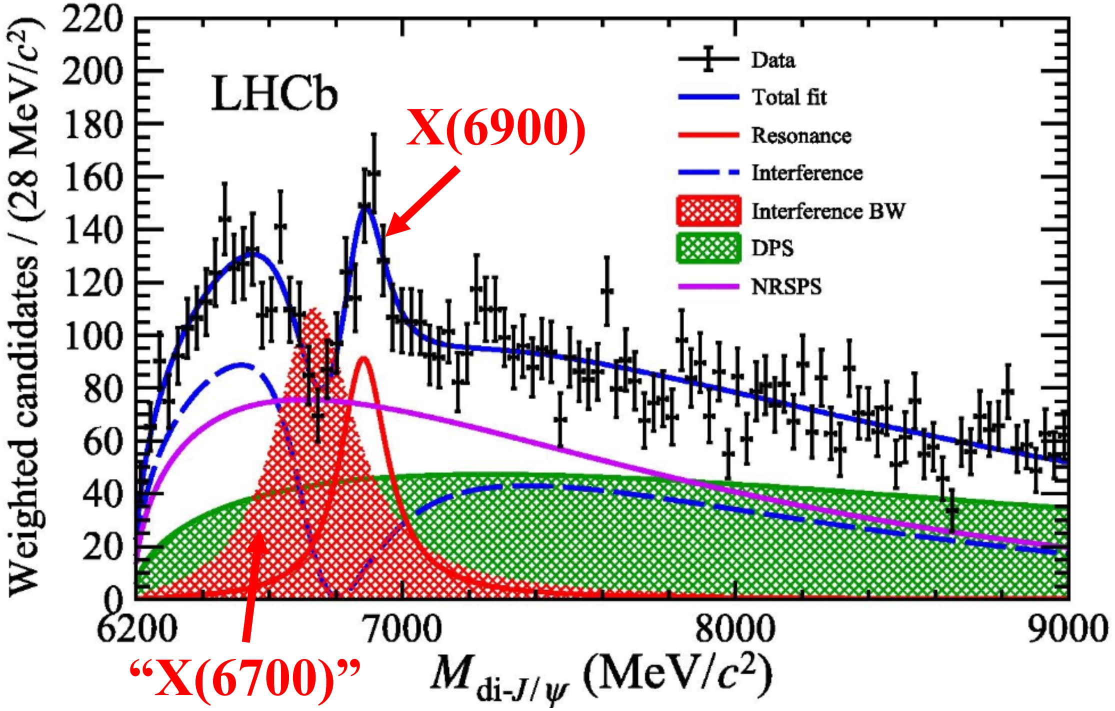
- CMS Data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct
- *Does not describe well dips*

- CMS vs LHCb comparisons:
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4$ ≈ 8X (muon acceptance due to pseudo-rapidity range)
  - Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
  - Similar number of final events
  - 2X yield @CMS for X(6900)

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

χ^2 $prob = 10^{-4}$
[6.2,7.8] GeV



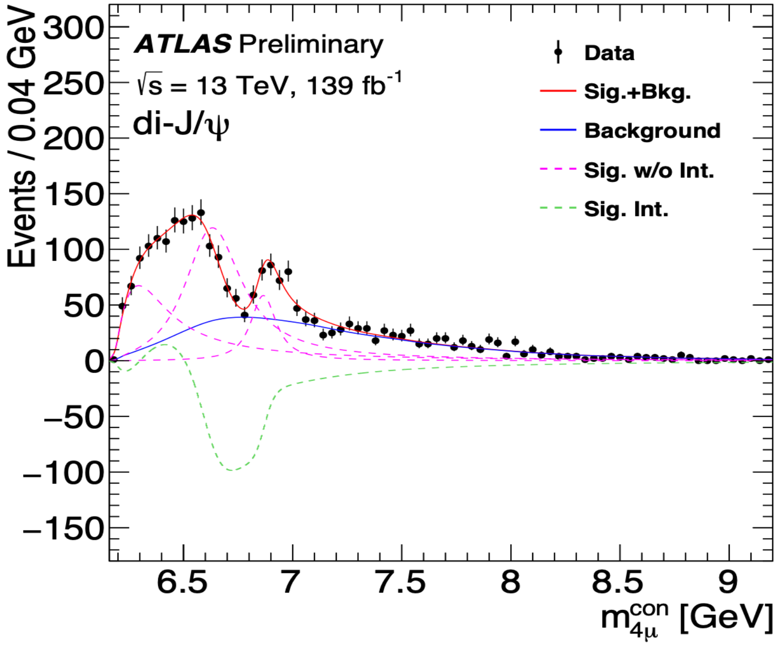


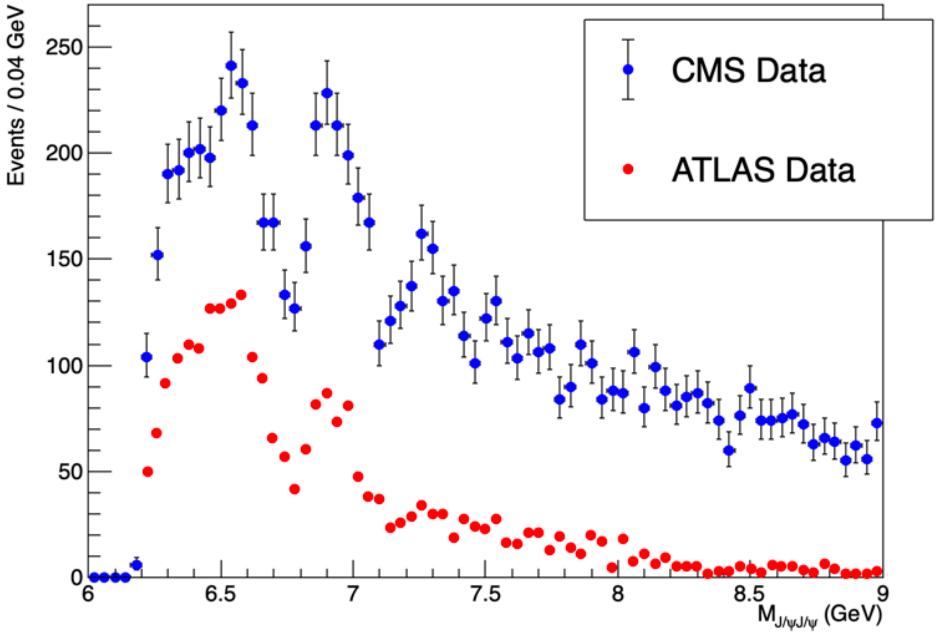
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

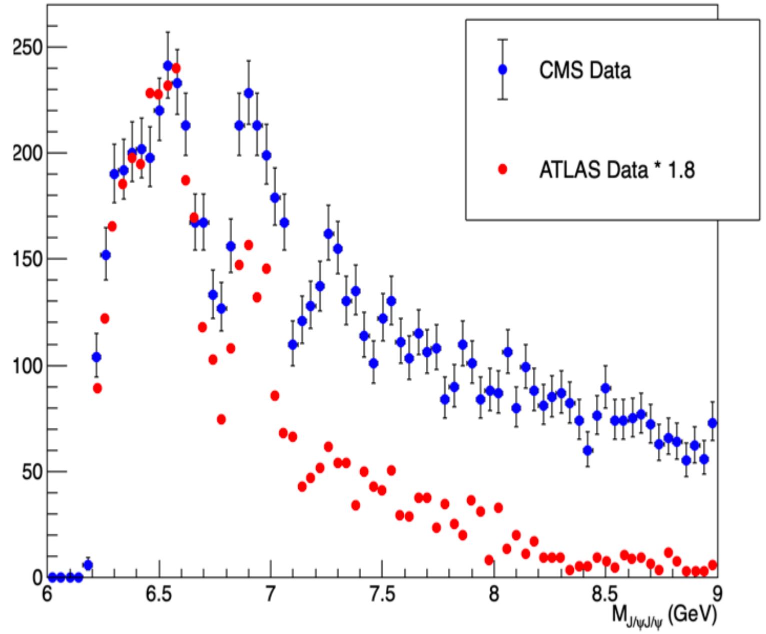
All CMS fits presented are not very good:
...other interference scenarios are under study in CMS

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

ATLAS result and comparison





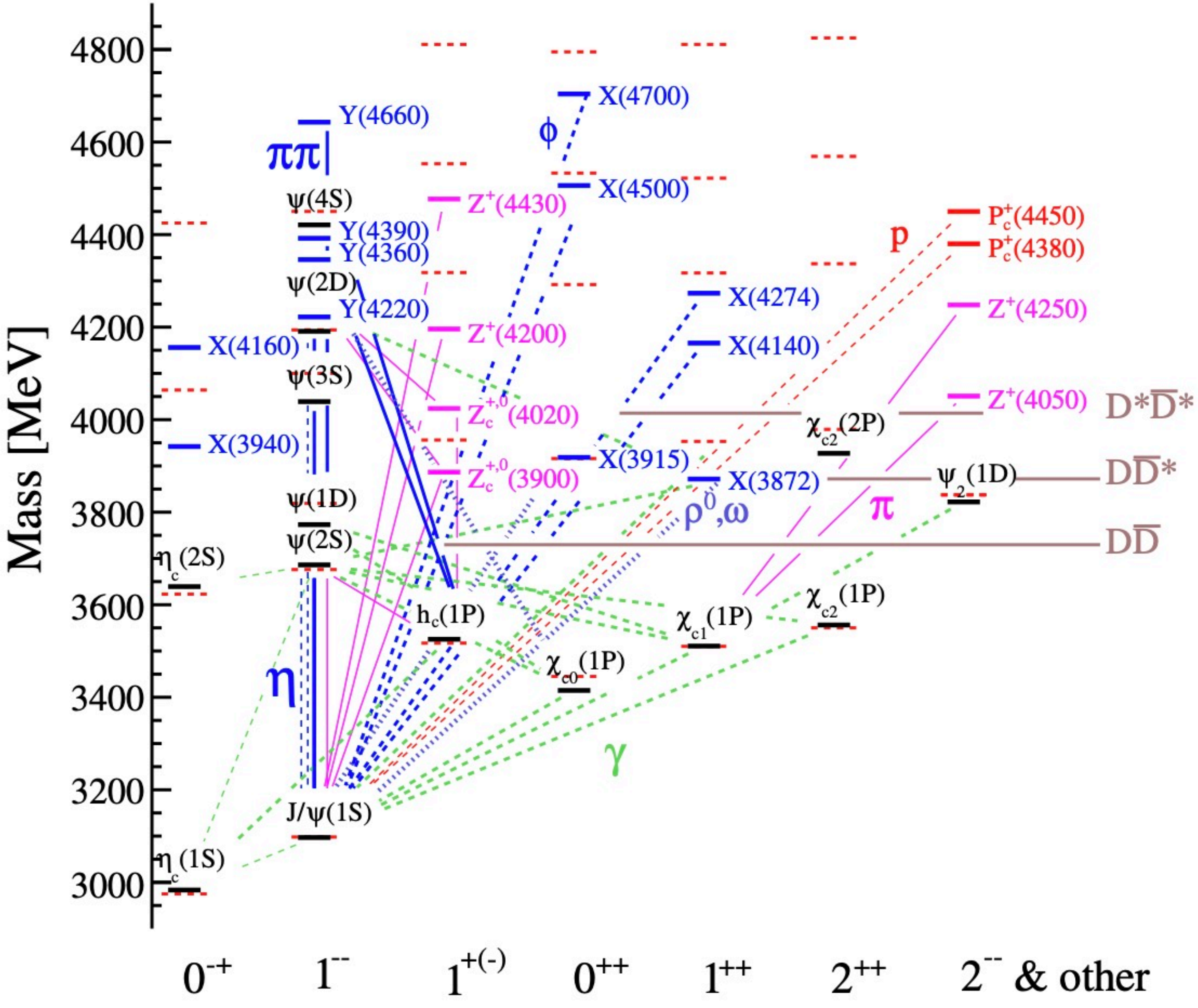


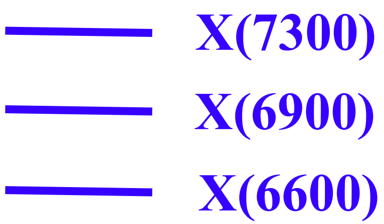
(GeV)	m_0	Γ_0	m_1	Γ_1
di-J/ψ	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2	—	
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	

- ATLAS assumed interference among BW0, BW1 and BW2
- Cannot compare numeric result yet
- Direct data point comparison seems consistent
- ATLAS has a dR cut that changes mass shape

Exotic zoo

Up to 2018, thanks to Liupan An





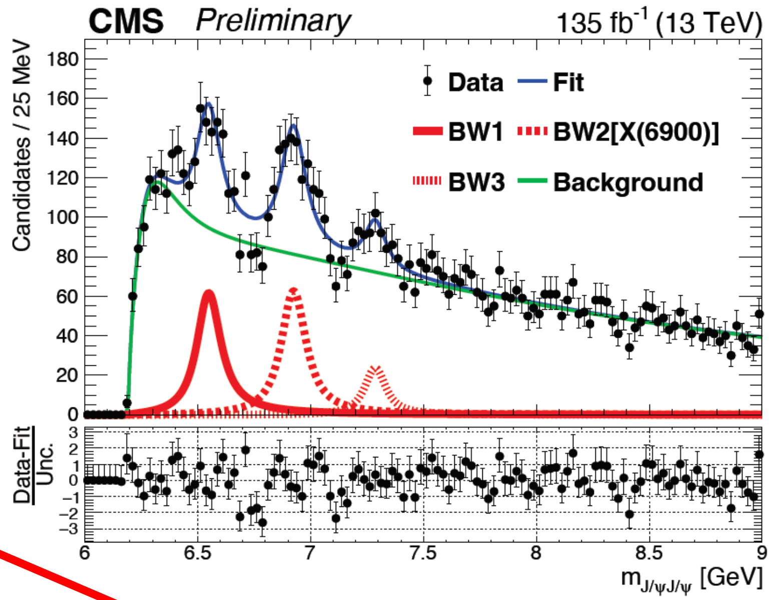
$J^{PC} = ??^+$

What are they—an accident?

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

TABLE 4: The mass-spectra of S and P-wave tetraquark T_{4c}, generated from our model. M_{th} [49] is threshold mass of two mesons. (Units are in MeV)

$N^{2S+1}L_J$	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	-	-



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?
- *$J^{PC}=1^{-+}$? An exotic quantum number!*
- Next important step: measure J^{PC}

What are they?

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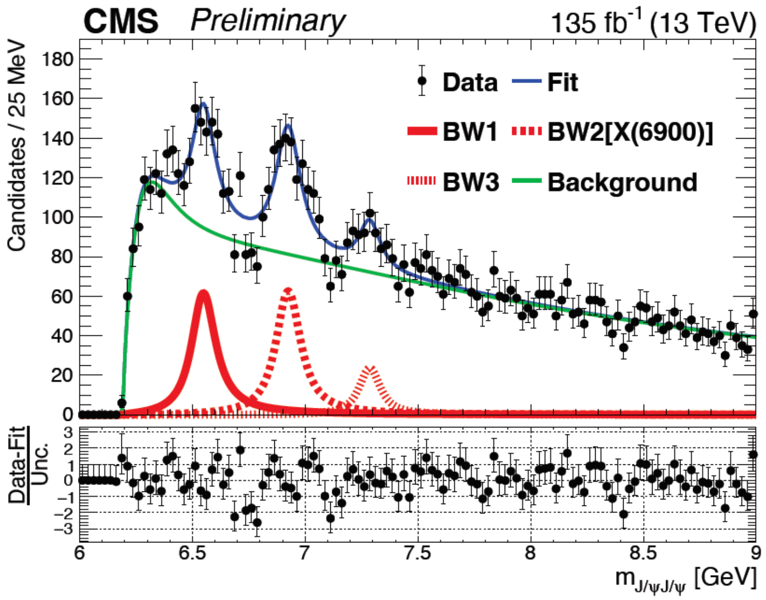
Table 1. Predictions of the masses (MeV) of S-wave fully heavy $T_{4Q}(nS)$ tetraquarks. Only 0^{++} and 2^{++} are considered for $T_{bc\bar{b}\bar{c}}$. The uncertainty is from the coupling constant $\alpha_s = 0.35 \pm 0.05$.

$T_{4Q}(nS)$ 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^{+35}_{-35}	6795^{+26}_{-26}	7066^{+21}_{-22}
$T_{bc\bar{b}\bar{c}}$	0^{++}	12387^{+109}_{-120}	12911^{+48}_{-51}	13200^{+35}_{-36}	13429^{+29}_{-30}
	2^{++}	12401^{+117}_{-106}	12914^{+49}_{-49}	13202^{+35}_{-36}	13430^{+29}_{-29}
$T'_{bc\bar{b}\bar{c}}$	0^{++}	12300^{+106}_{-117}	12816^{+48}_{-50}	13104^{+35}_{-35}	13333^{+29}_{-29}
$T_{bb\bar{b}\bar{b}}$	0^{++}	18475^{+151}_{-169}	19073^{+59}_{-63}	19353^{+42}_{-42}	19566^{+33}_{-35}
	2^{++}	18483^{+149}_{-168}	19075^{+59}_{-62}	19355^{+41}_{-43}	19567^{+33}_{-35}
$T'_{bb\bar{b}\bar{b}}$	0^{++}	18383^{+149}_{-167}	18976^{+59}_{-62}	19256^{+43}_{-42}	19468^{+34}_{-34}



M[BW1] = 6552 ± 10 ± 12 MeV
M[BW2] = 6927 ± 9 ± 5 MeV
M[BW3] = 7287 ± 19 ± 5 MeV

- Radial excited S-wave states?
- *$J^{PC}=0^{++}$ or 2^{++}?*
- **Next important step: measure J^{PC}**

- *Other possibilities exist! i.e. threshold effect…*

Summary

CMS found 3 significant structures using 135 fb^{-1} 13 TeV data

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

- 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!
- CMS data seems consistent with ATLAS data

- Dips in the data show possible interference effects --- Under study
- More data/knowledge needed to understand nature of near threshold region

- ***All-heavy quark exotic structures offer system easier to understand***
- ***A new window to understand strong interaction***

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

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

Backup