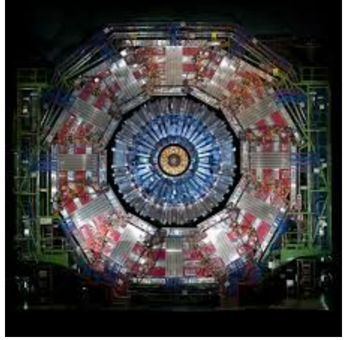
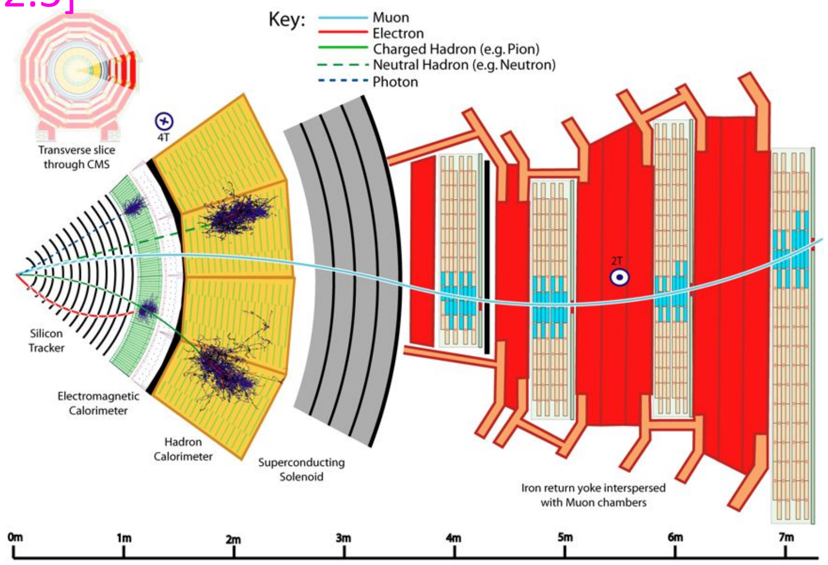


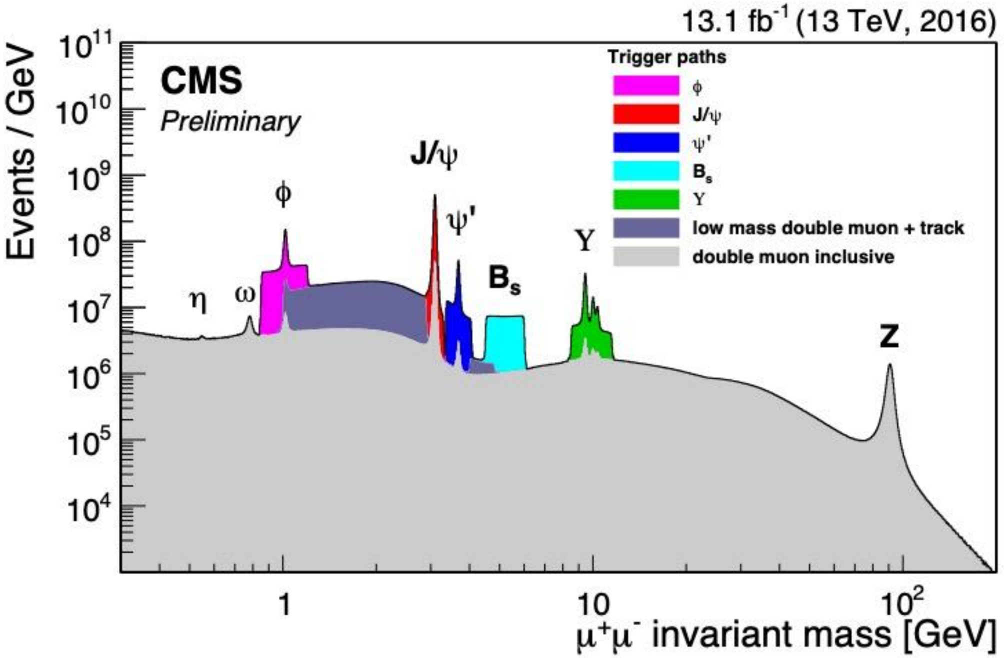
Observation of new structures in the J/Psi - J/Psi mass spectrum in pp collisions at sqrt(s)=13 TeV by CMS

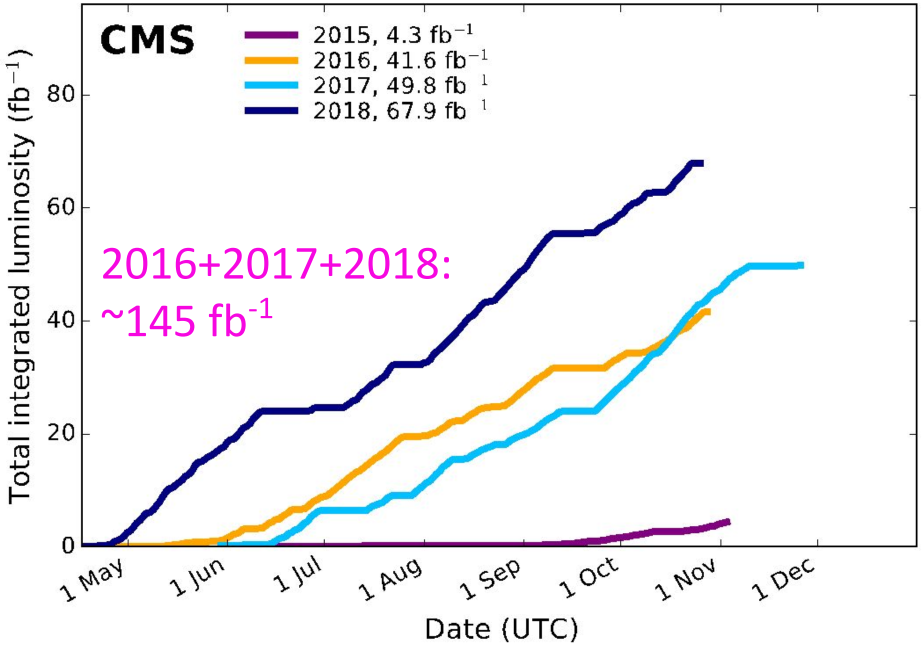
Jane Nachtman
(University of Iowa)
for the CMS Collaboration

The CMS detector & trigger

η coverage (track & muon): [-2.5,2.5]







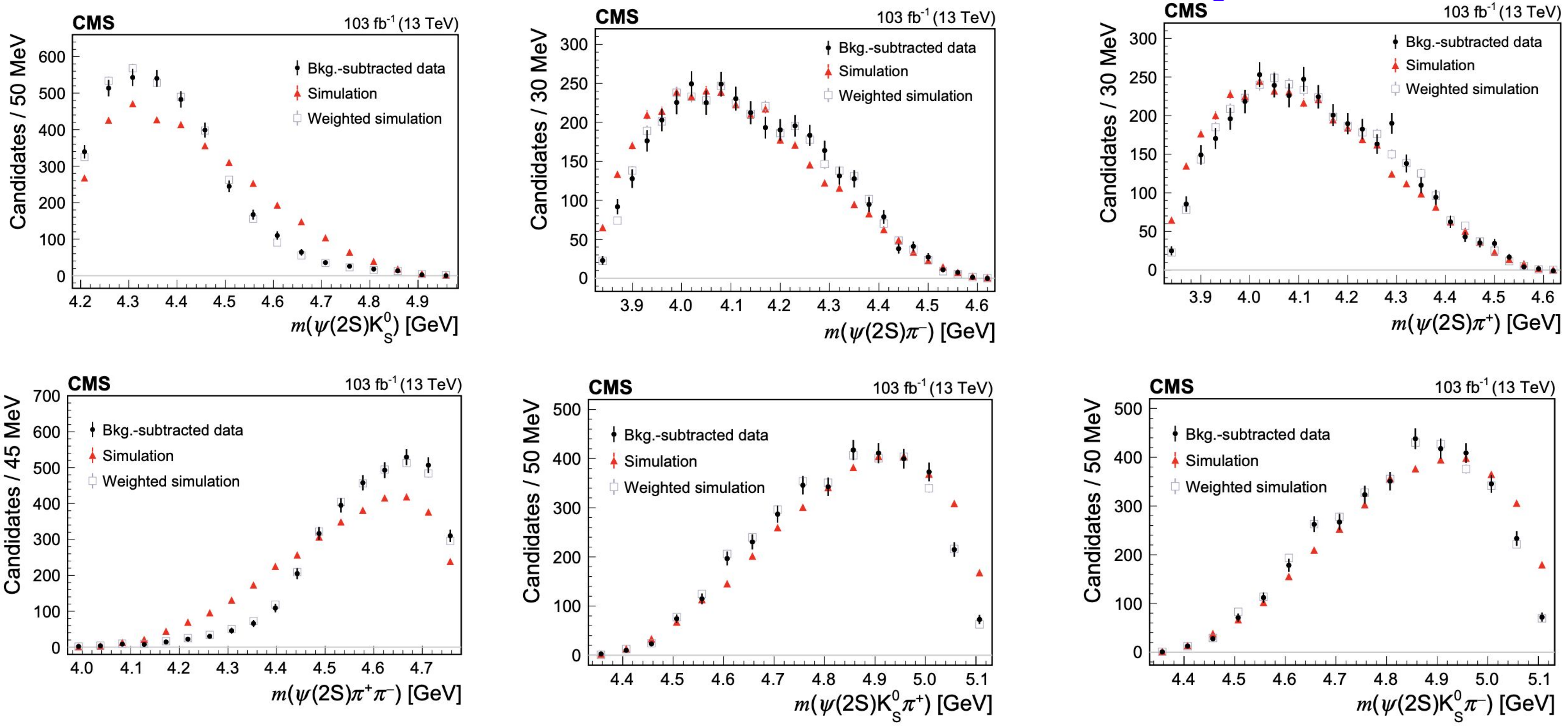
2016+2017+2018: ~145 fb^{-1}

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

Recent CMS contributions to heavy exotic states

--Search for exotics through $B^0 \to \psi(2S)K_s\,\pi^+\pi^-$ decays



Eur. Phys. J. C 82 (2022) 499

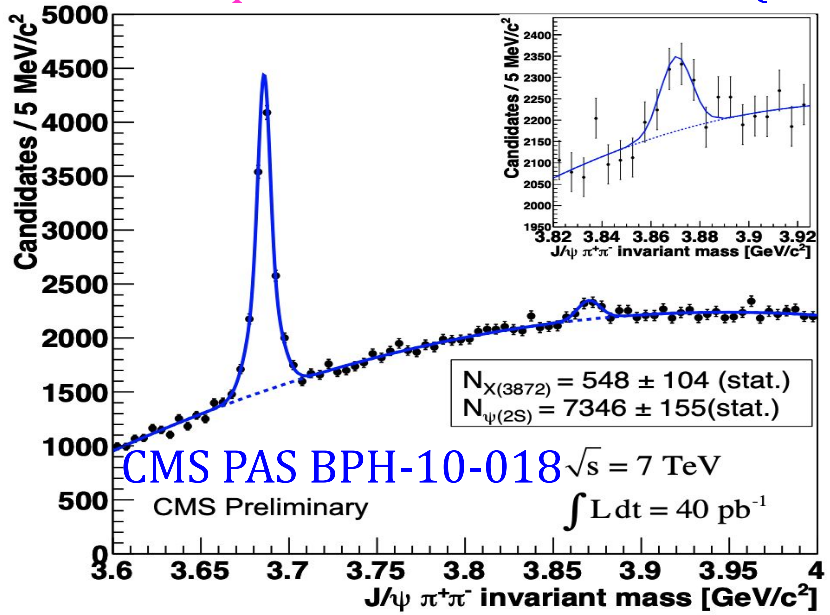
$$\mathcal{B}(\mathrm{B}^0 \to \psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}\pi^+\pi^-) = (13.9 \pm 0.4\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst}) \pm 1.2\,(\mathcal{B})) \times 10^{-5}$$

First observation

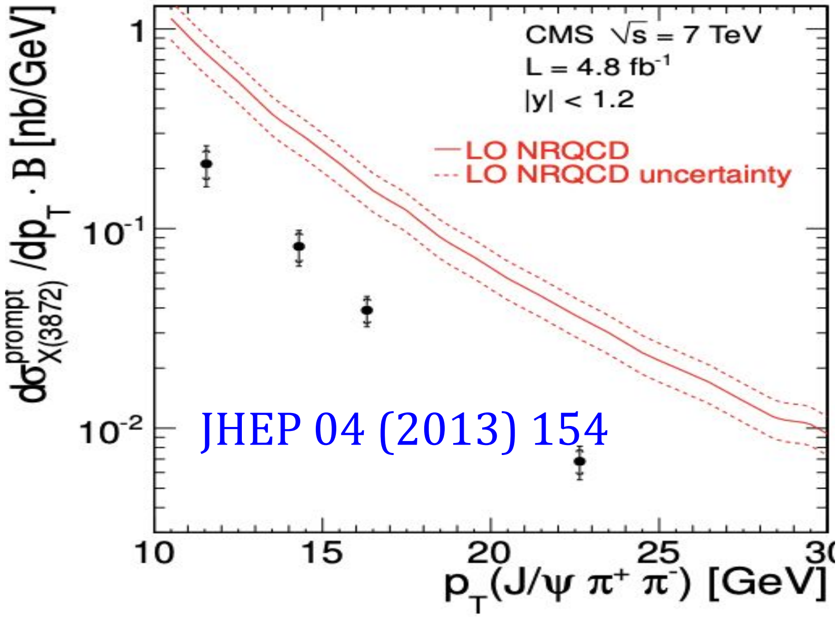
No significant charm related exotic states observed

Other selected CMS contributions to heavy exotic states

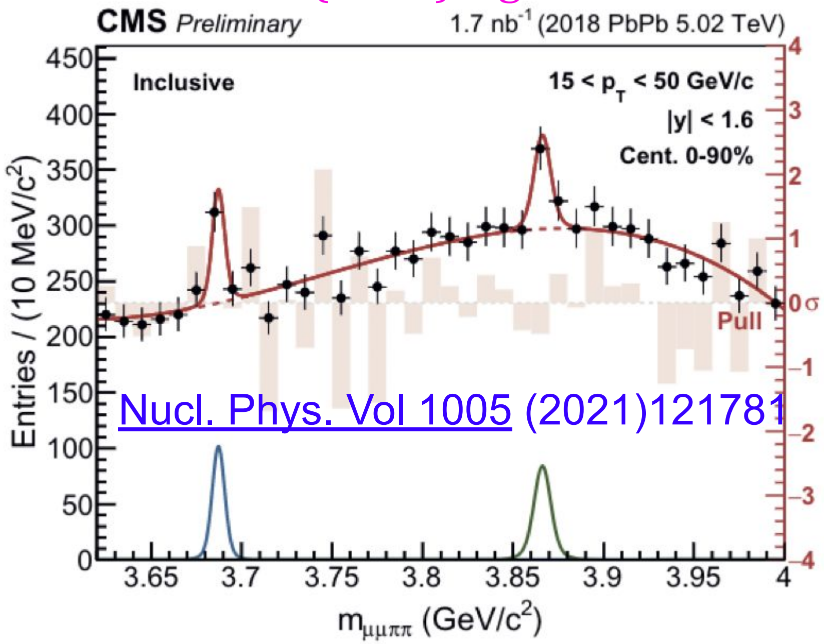
First LHC experiment re-discovered X(3872)



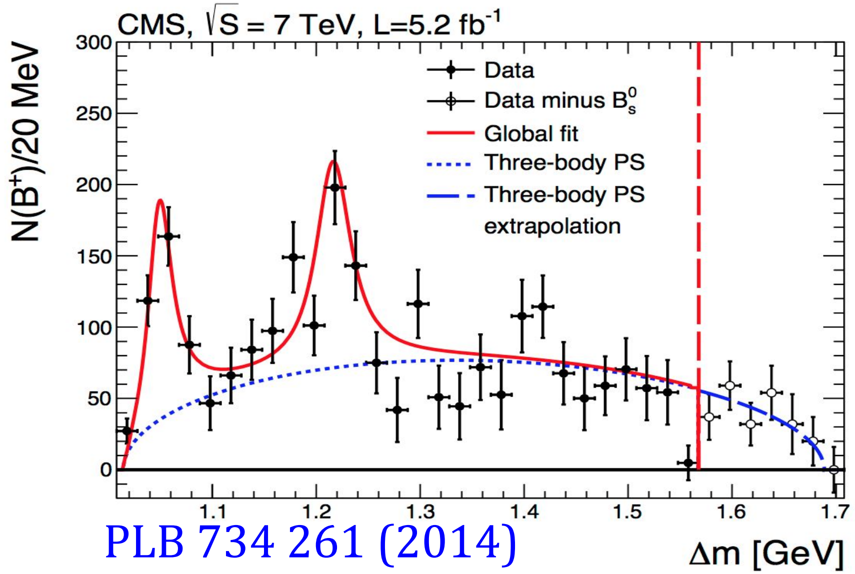
X(3872) measurement



First X(3872) signal in PbPb

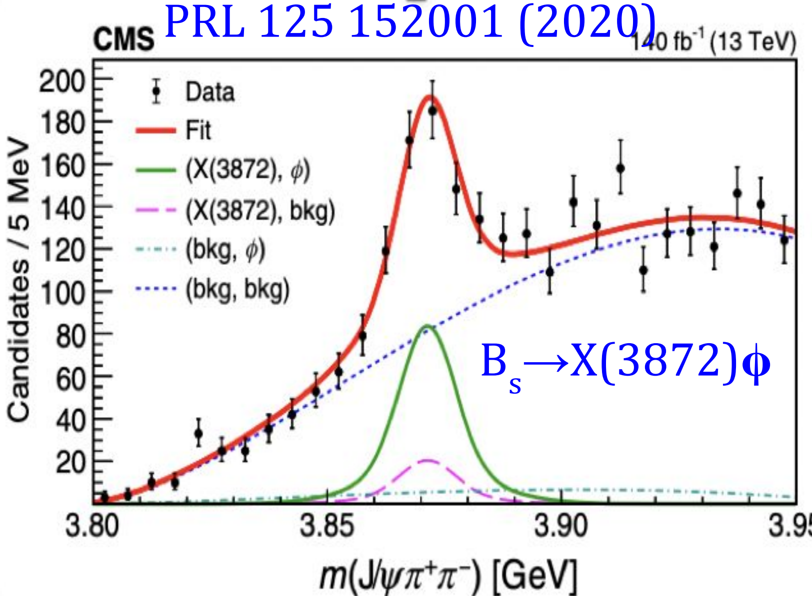


First confirmation of Y(4140)

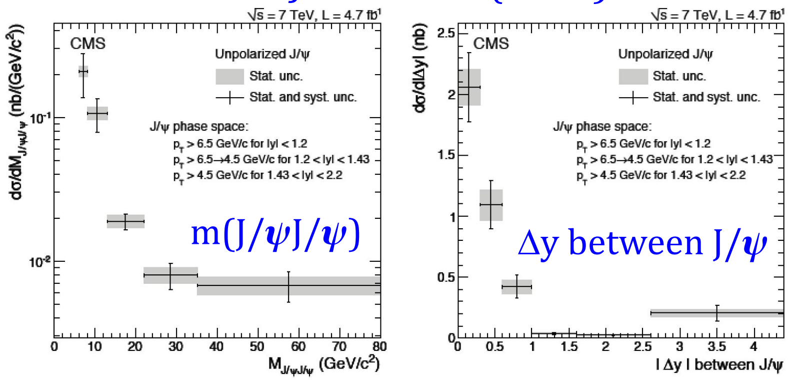


PLB 734 261 (2014)

PRL 125 152001 (2020)



JHEP 1409 (2014) 094



CMS has large di-J/ψ sample

Any surprises?

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

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

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

- 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.

CMS analysis of J/ψJ/ψ--Data samples & Event selections

- 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/ψ) >=3.5 GeV (2017&2018); 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 $J/\psi J/\psi$ 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

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

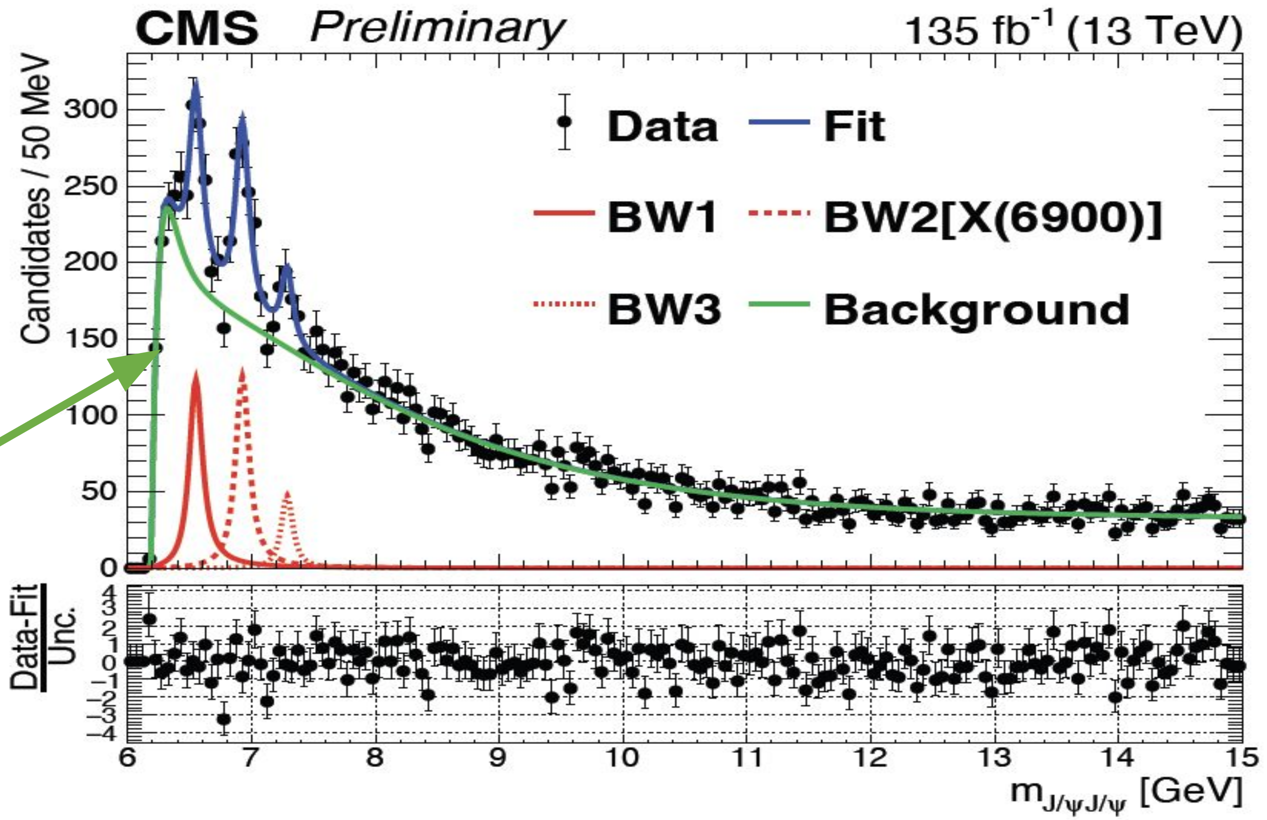
Relativistic S-wave Breit-Wigner (BW) for each structure convolved with resolution function

CMS background
(BW0 + NRSPS + DPS)

$$\chi^2\ prob = 79\%$$

[6.2,15] GeV

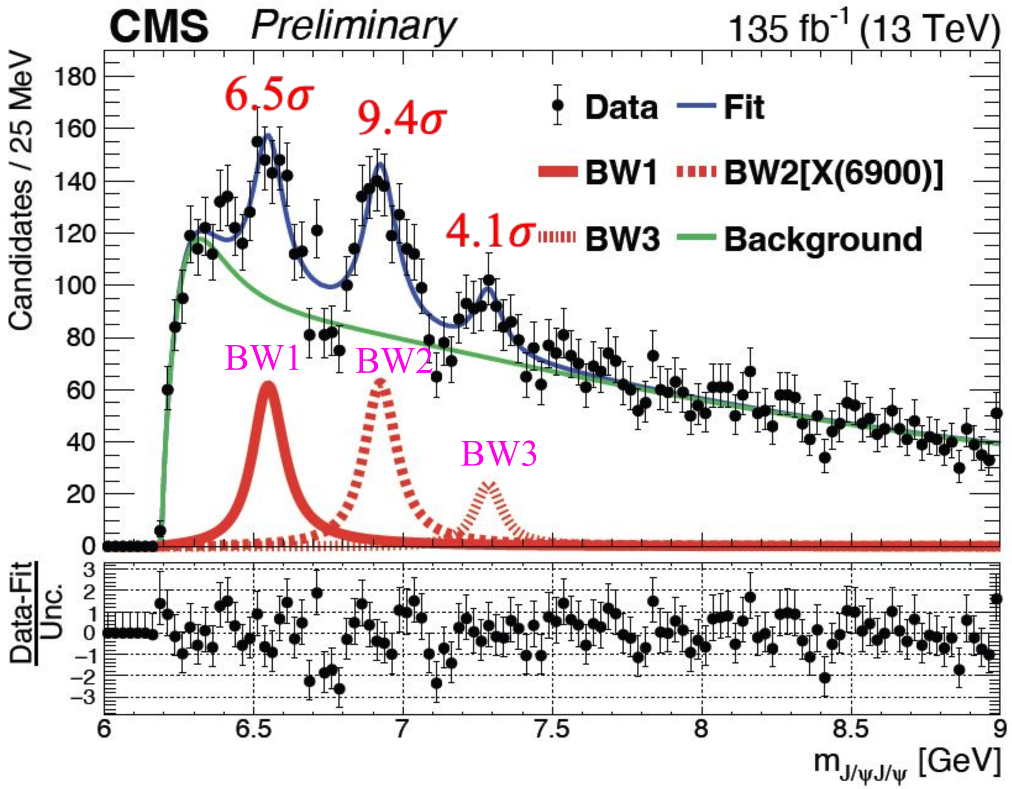
CMS background (BW0 + NRSPS + DPS)



- 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 + 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

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

Statistical significance only

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 6.5**σ** to >5.7**σ**
  - No relative significance changes for BW2 and BW3

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

consistent →

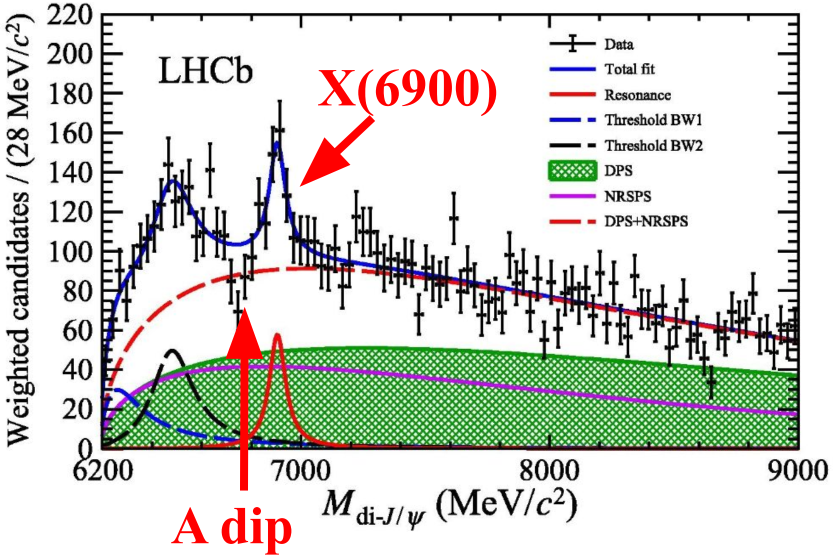
X(6900) [LHCb]
(somewhat different fit model)

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

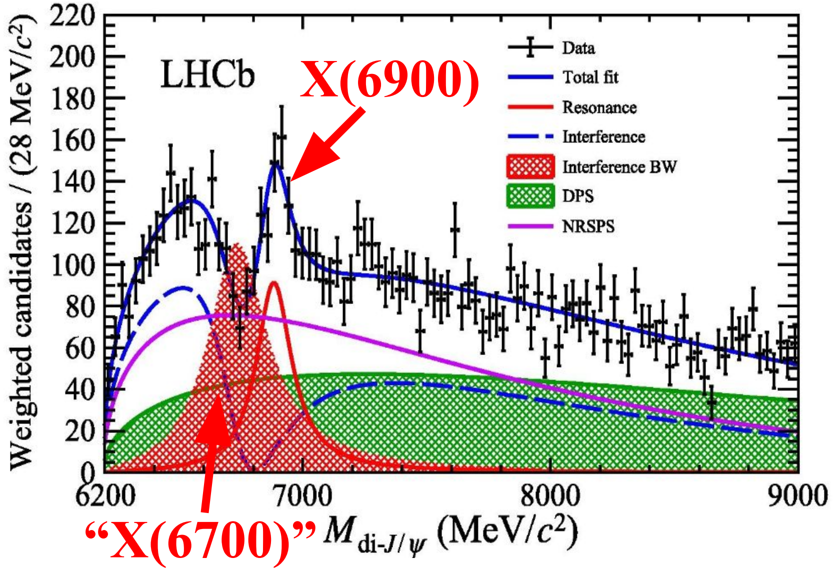
X(6900) reported by LHCb

- 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?

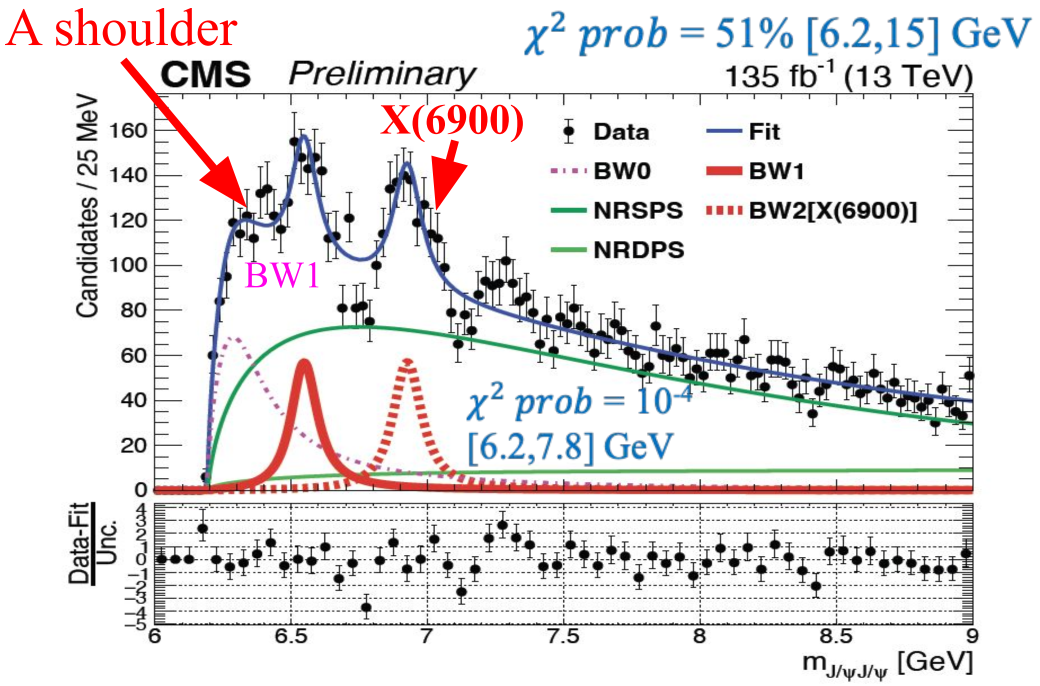
Model I

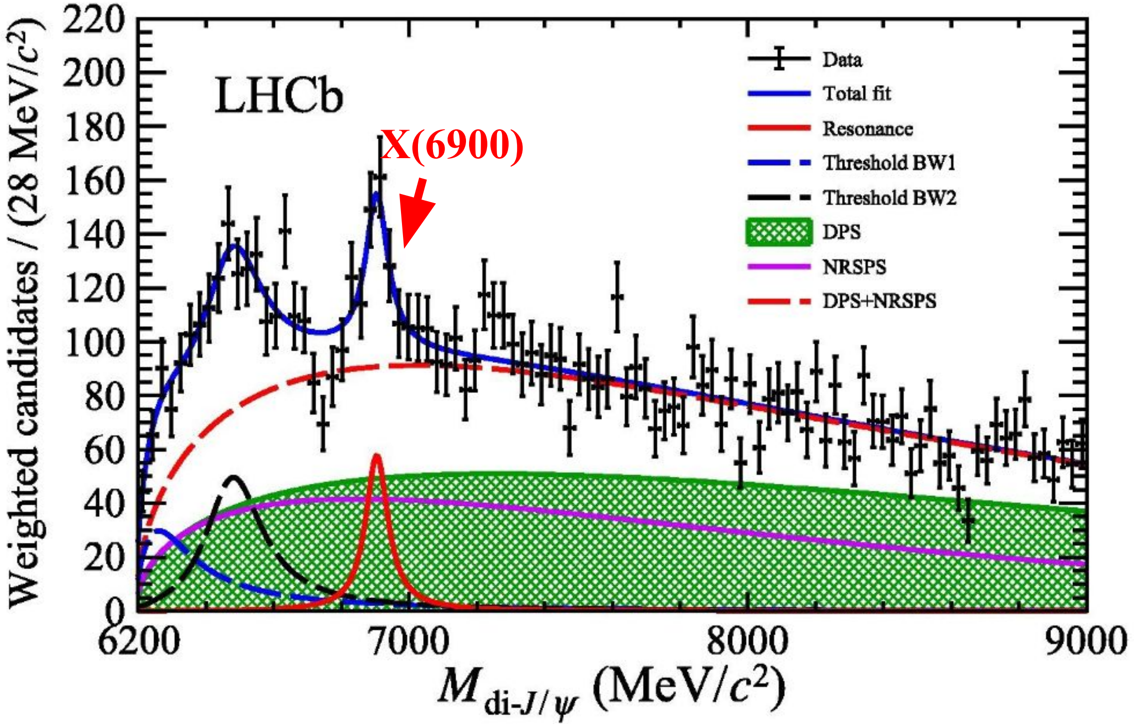


Model II



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

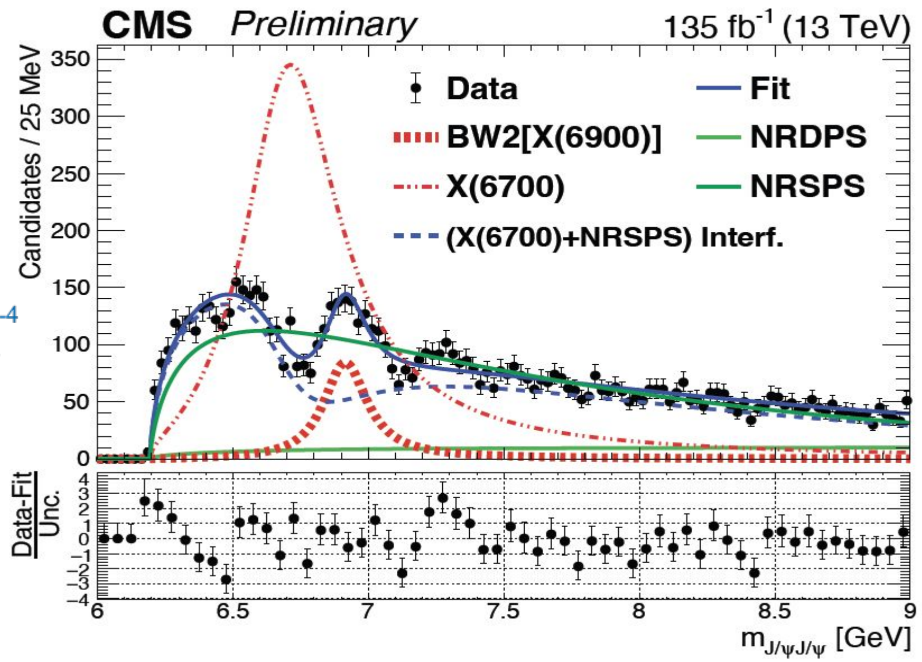
X(6900) parameters are in good agreement with LHCb
LHCb did not report parameters for another 2 BWs

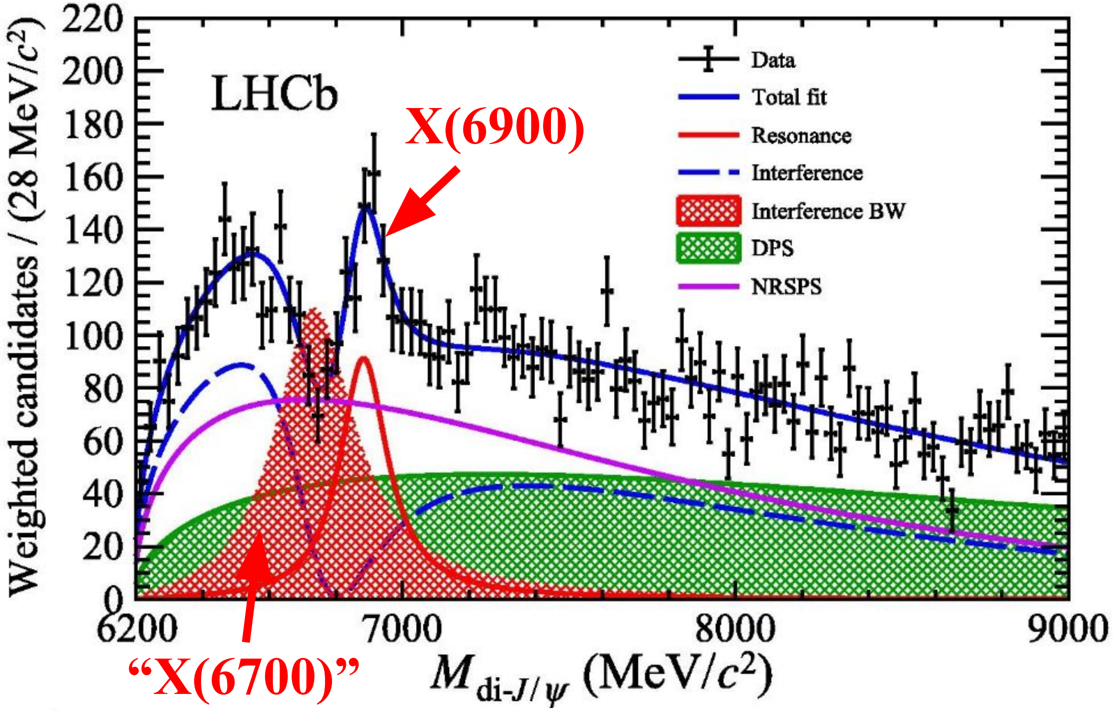
- CMS Data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct
- *Does not describe well dips*

- 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

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	$\boxed{6886 \pm 11 \pm 11}$	$\boxed{168 \pm 33 \pm 69}$
CMS	Model II	6736 ± 38	439 ± 65	$\boxed{6918 \pm 10}$	$\boxed{187 \pm 40}$

Models don't fit CMS data well…
...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

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!

- 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

Significances including systematics

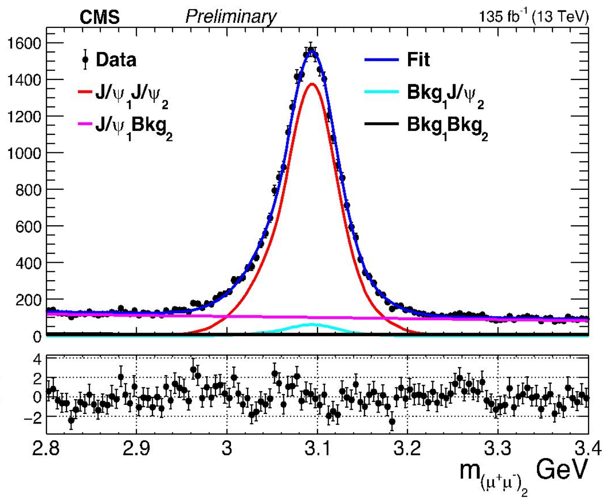
- To include systematics, alternative resonance/background shapes applied in the fit:
- Calculate signal- and null-hypothesis NLL_{syst} including systematic using:

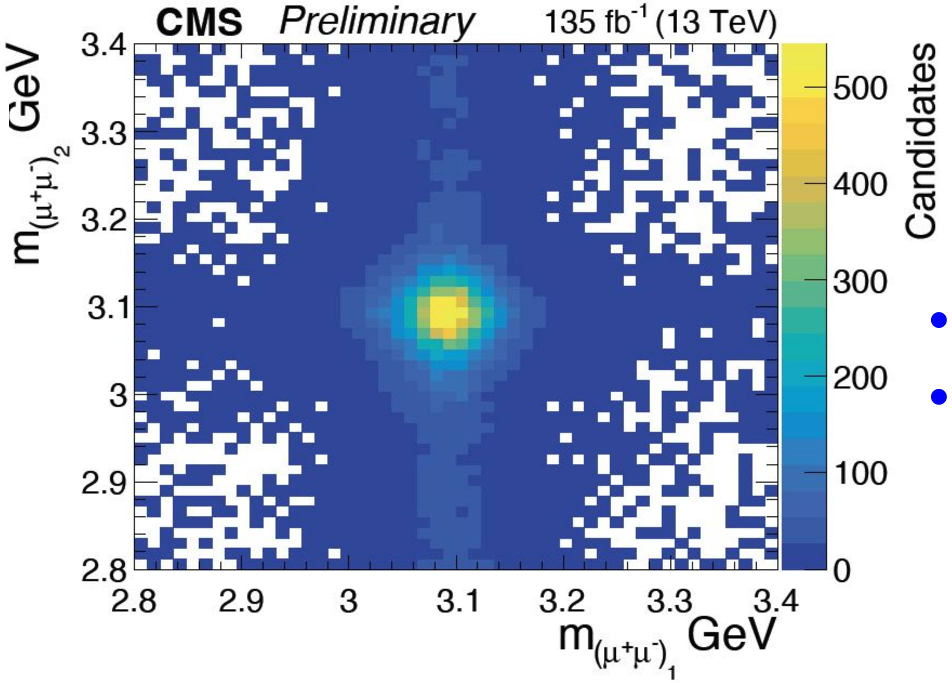
$$NLL_{syst-sig} = \mathrm{Min}\{NLL_{nom-sig}, NLL_{alt-i-sig} + 0.5 + 0.5 \cdot \Delta dof\}$$

  - $NLL_{nom-sig}$ 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 $NLL_{syst-null} - NLL_{syst-sig}$

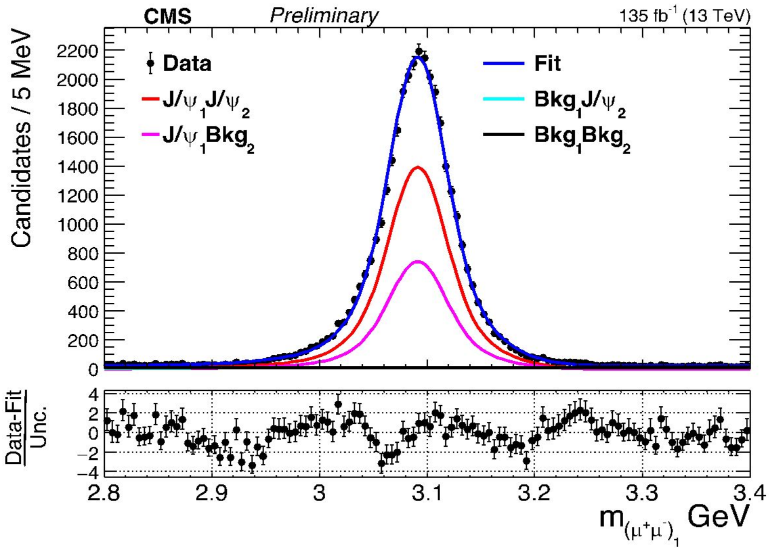
	Significance with syst.
BW1	
BW2	
BW3	

J/ψ signal





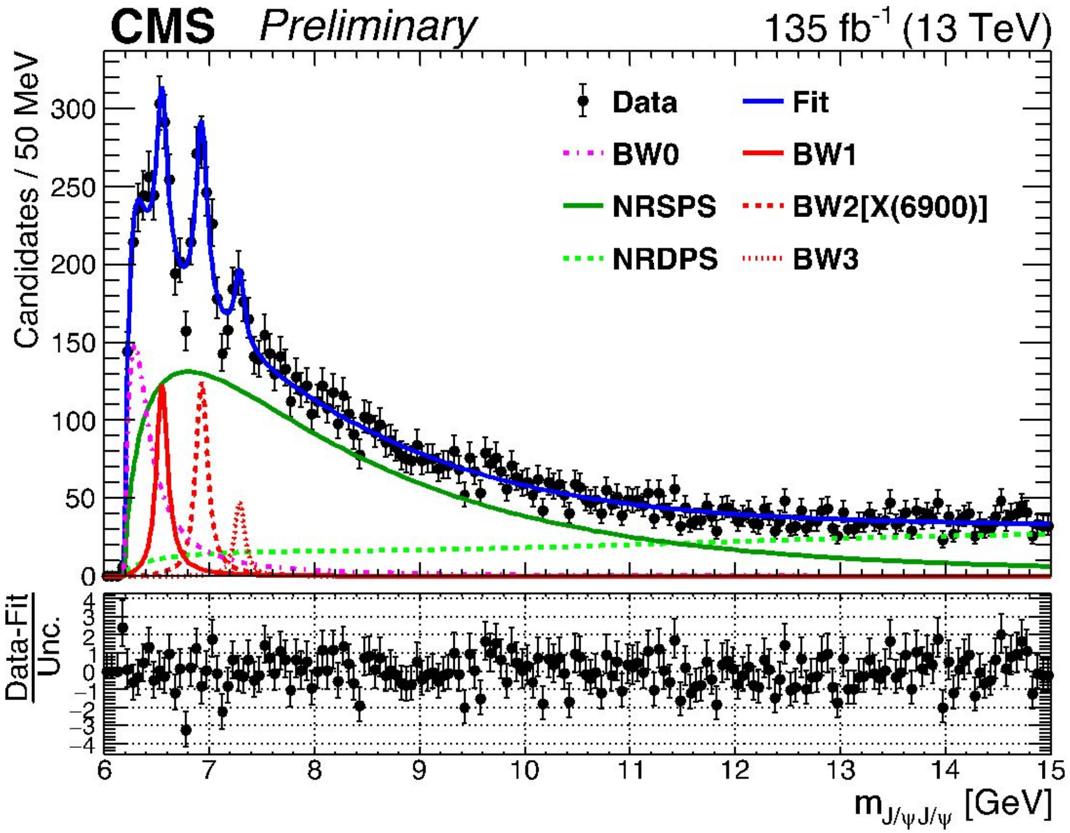
- Remove by J/ψ mass related cuts
- Clean J/ψ signal as seen

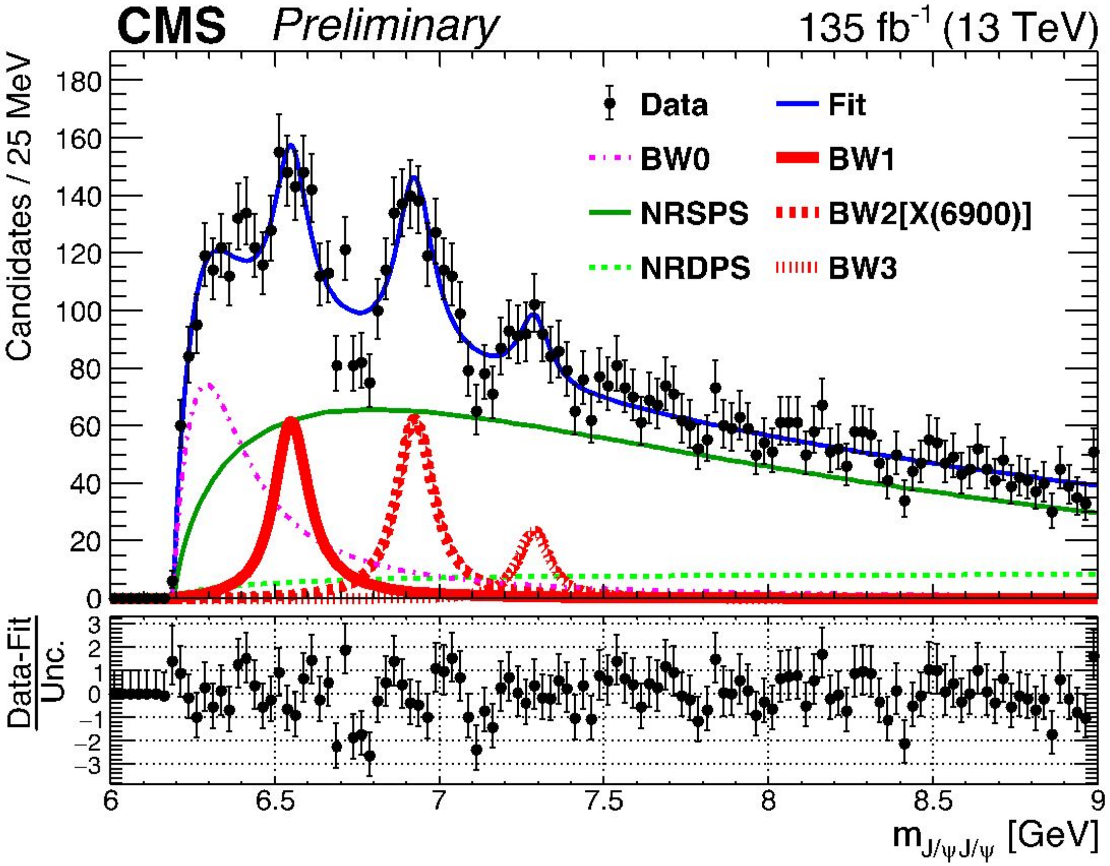


- ~15000 J/ψ pairs after final selection (m(J/ψ J/ψ <15 GeV)

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

Final CMS model: 3 BWs + Backgrounds+ BW0



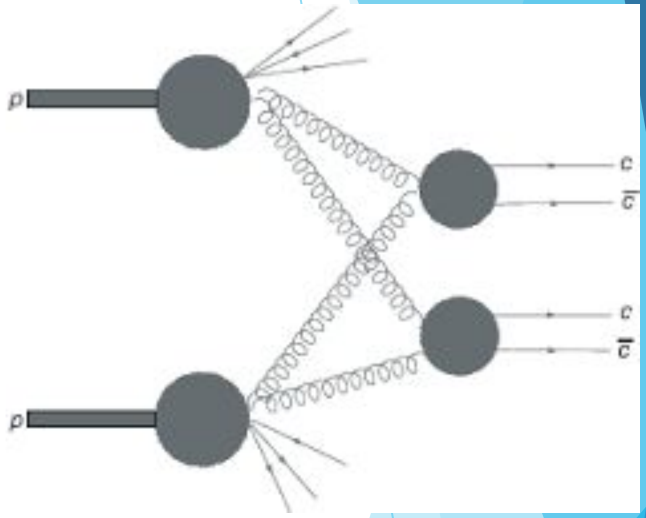


Introduction and Motivation

- Measurements of quarkonium production, including double quarkonium or simulataneous production with W/Z provides insight into particle production at LHC/Tevatron
  - Single particle interaction (Single Parton Scattering (SPS))
  - Multiple Particle Interaction (MPI or Double Parton Scattering (DPS))
    - Probable, given high flux at LHC
    - Difficult to calculate
      - Experimental observations needed!
    - Generally assume SPS dominant
      - SPS □ strongly correlated □small | Δy |
      - DPS □ less correlated □ large |Δy |
    - J/ψ Y W/Z clean signatures to probe Tevatron vs LHC

$q\bar{q}$ gg

Need high-statistics sample to measure angular distributions



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Introduction and Motivation: Quarkonium plus X to Search for Resonances

- Expect bottomonium ground state η_b □ J/ψ J/ψ (suppressed)
  - Measurements to test predictions
- Exotic tetraquark charm states
- Exotic states (eg, CP-odd Higgs in NMSSM mixes with η_b, alters rate
- Or something entirely unexpected??