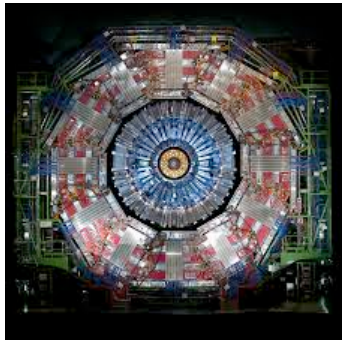


Recent Heavy Flavour Spectroscopy and Exotic Hadrons Results at CMS

Kai Yi (Tsinghua University & Nanjing Normal University)

On behalf of CMS Collaboration

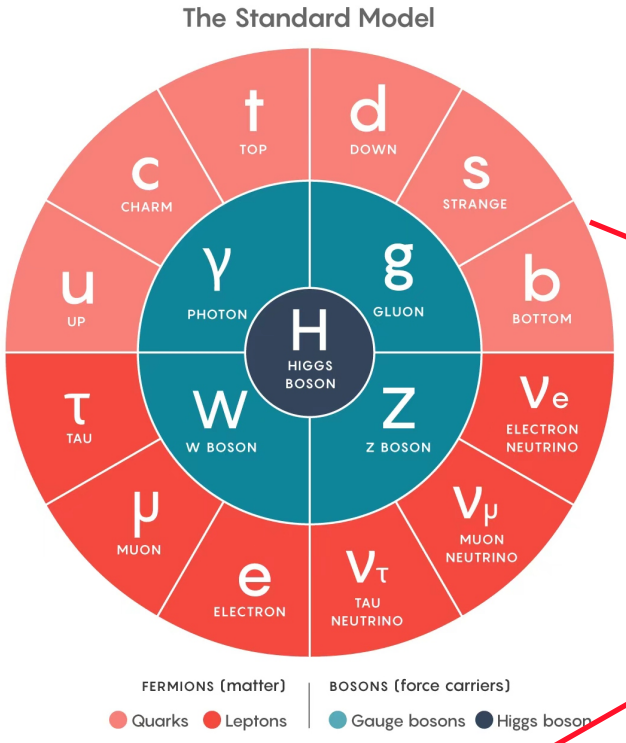
DIS2023

28 Mar 2023, Michigan State University, US

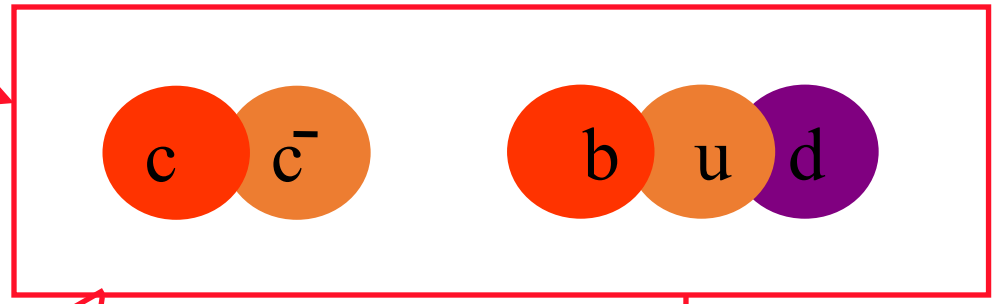
Outline

- **Observation of new structures in the $J/\psi J/\psi$ mass spectrum**
  - CMS preliminary result CMS PAS BPH-21-003 at CDS
- **Observation of a new excited beauty strange baryon $\Xi_b(6100)^-$ decaying to $\Xi_b^-\pi^+\pi^-$**
  - *Phys. Rev. Lett.* **126**, 252003 (2021)
- **Observation of $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_s^0$ decays**
  - *Eur. Phys. J. C* **82**, 499 (2022)

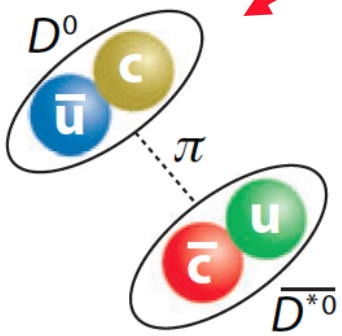
Quark model



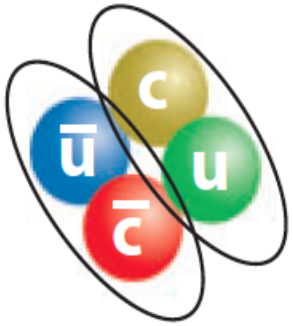
Meson *Baryon*



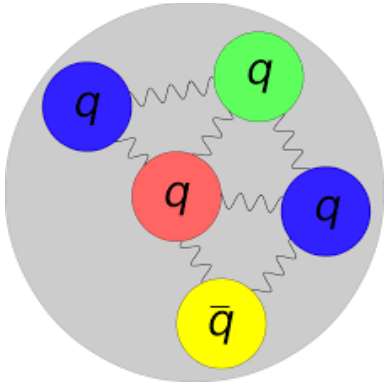
"exotic" hadron



D^0–$\overline{D^{*0}}$ "molecule"



Diquark–diantiquark

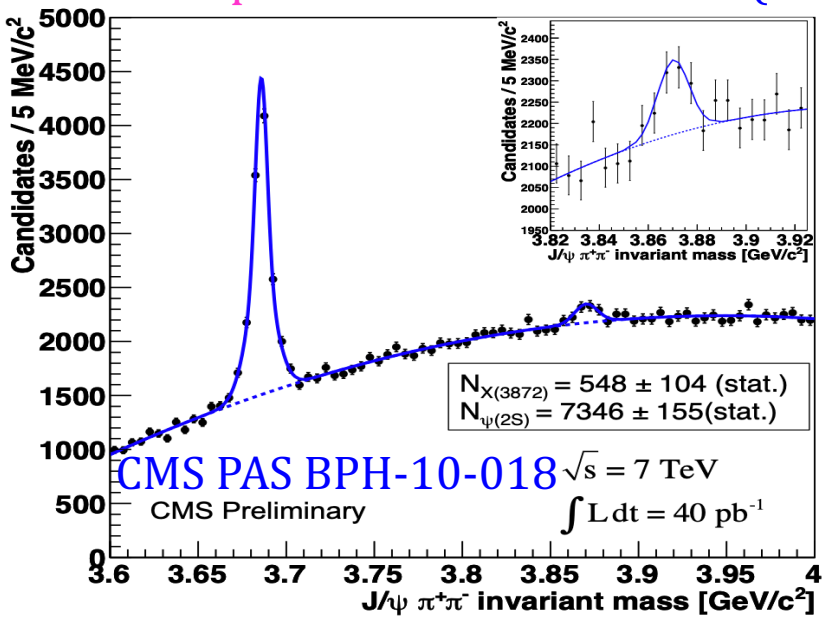


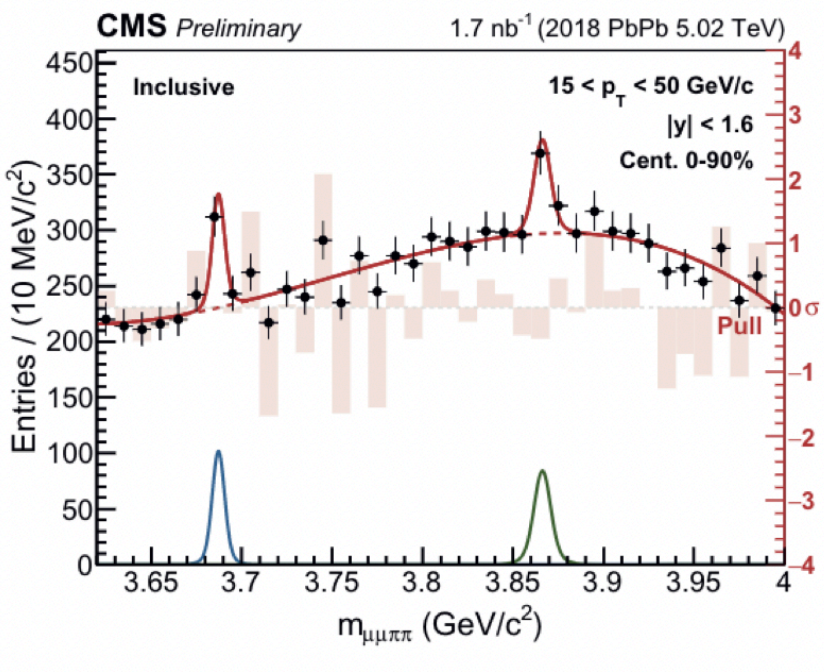
Two possible extensions of mesons to tetra-quark states *Possible penta-quark state*

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)

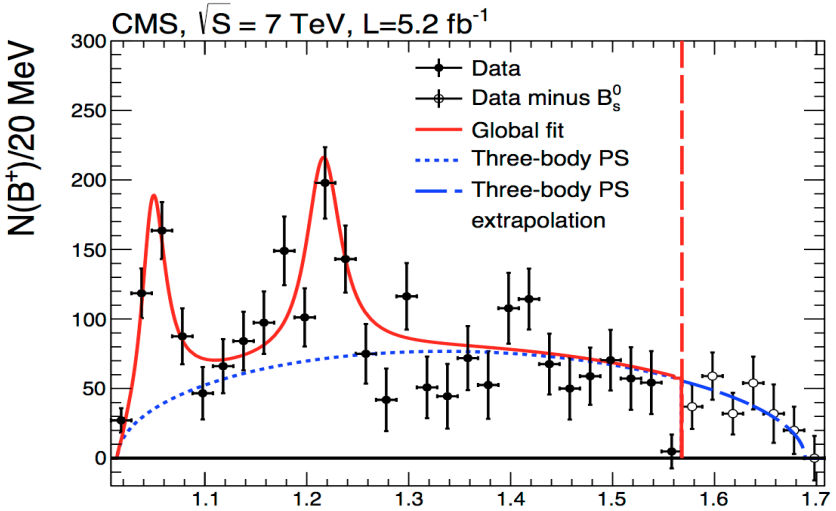




First X(3872) signal in PbPb

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

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

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

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

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

Linked by color electric flux in a bag

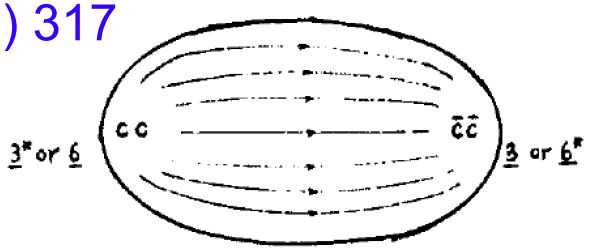


Fig. 2

Possible two-body decays

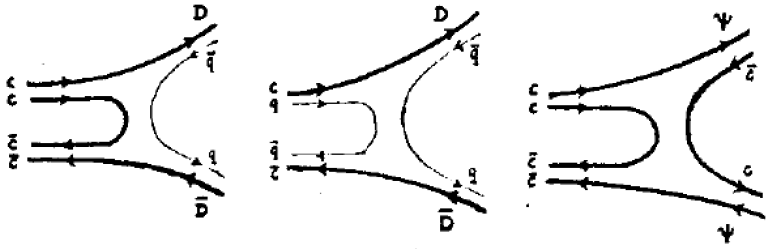


Fig.3(a) Fig.3(b) Fig.3(c)

Possible P-wave to S-wave decays

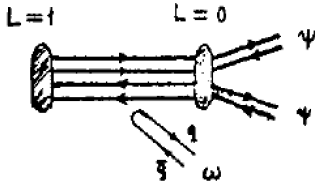
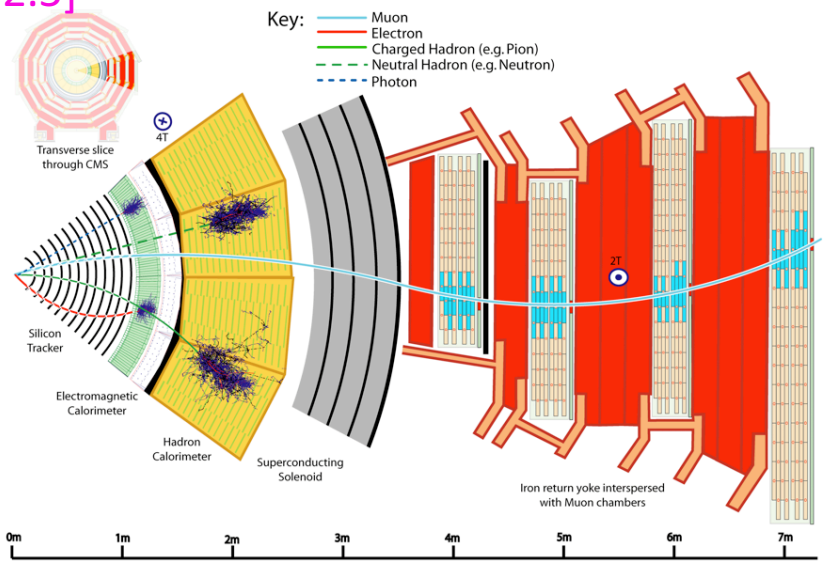


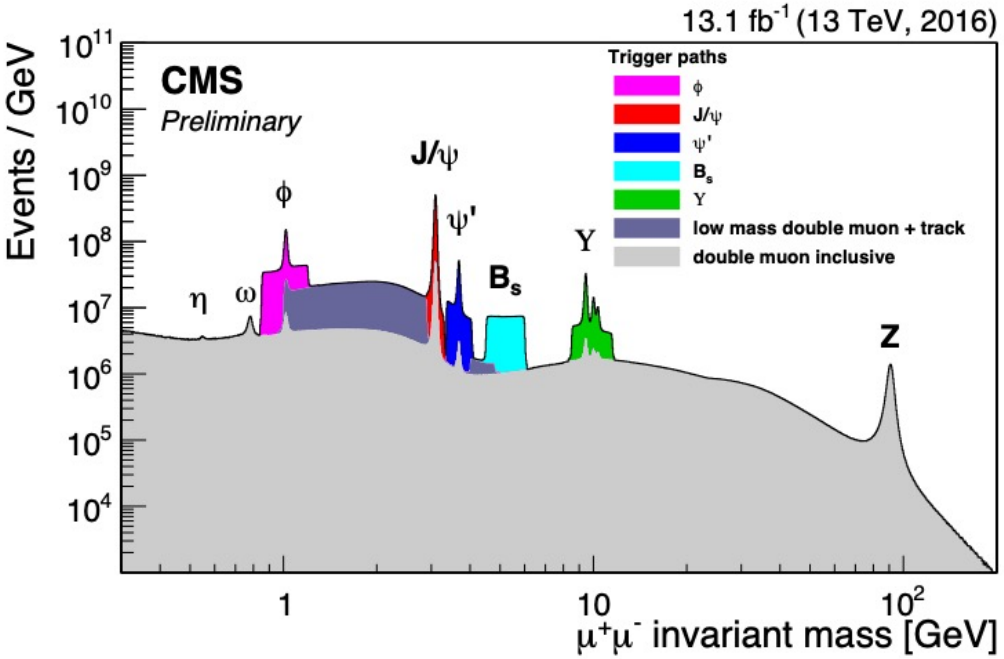
Fig.4

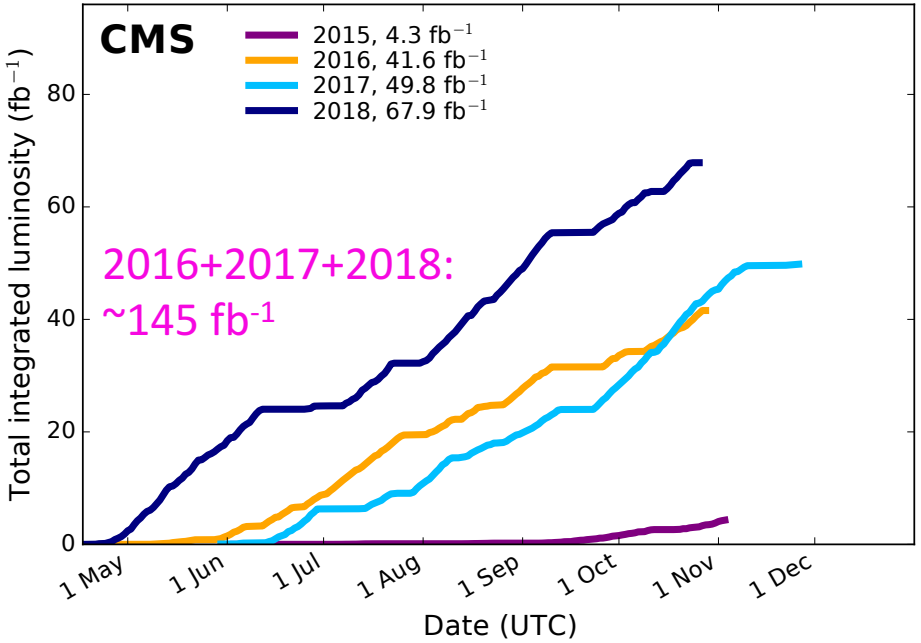
- A different exotic system compared to exotics with light quarks

The CMS detector & trigger

η coverage (track & muon): [-2.5,2.5]







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

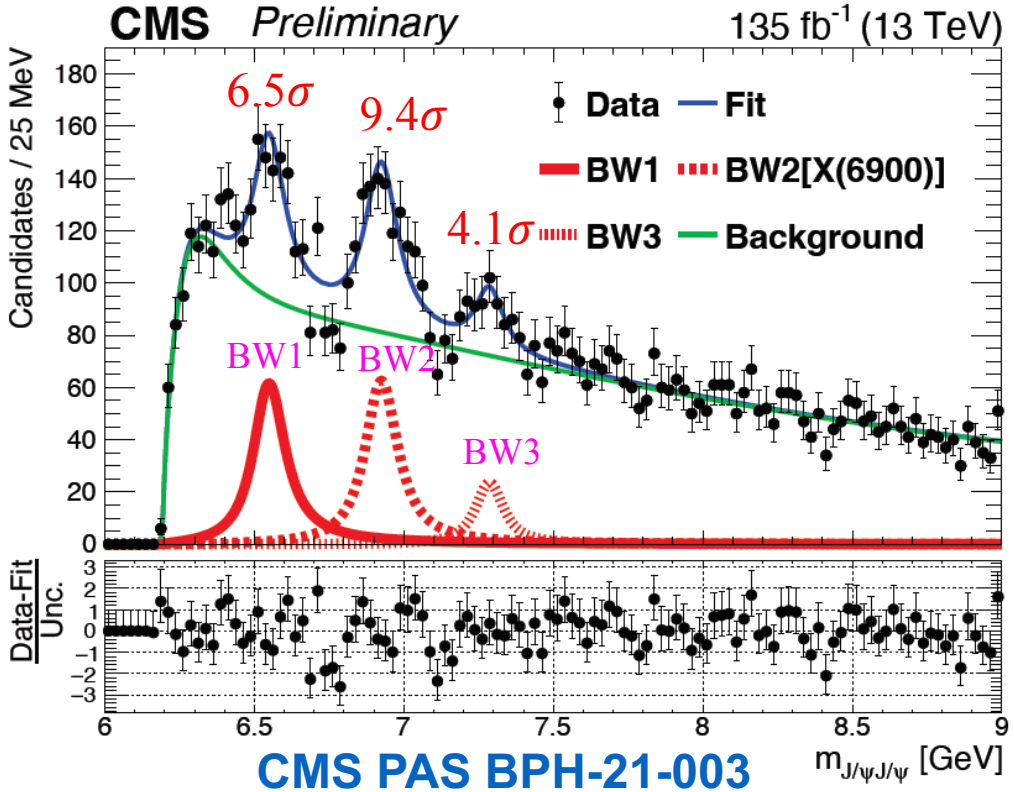
- 135 fb^{-1} CMS data taken in 2016, 2017 and 2018 LHC runs
- Trigger: 3μ with a J/ψ mass window, μ p_T from J/ψ>3.5 GeV for 2017&2018 data
- Blinded signal region: [6.2,7.8] GeV

  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

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

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

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 →

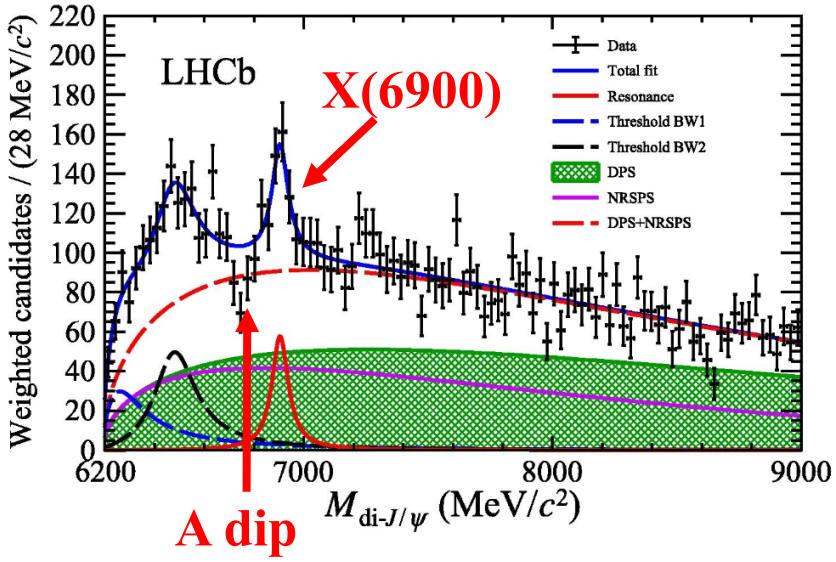
X(6900) [LHCb]
(somewhat different fit model)

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

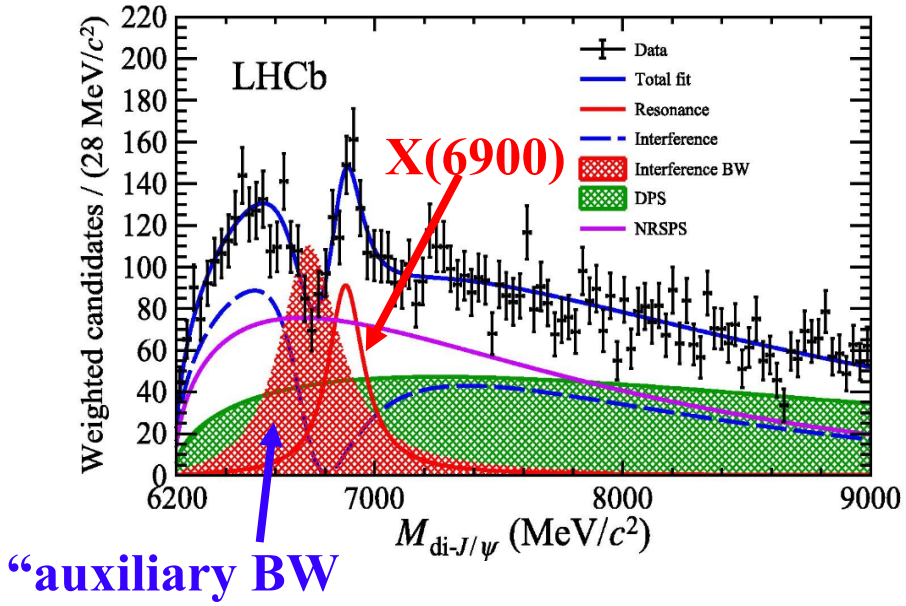
X(6900) reported by LHCb

- 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)

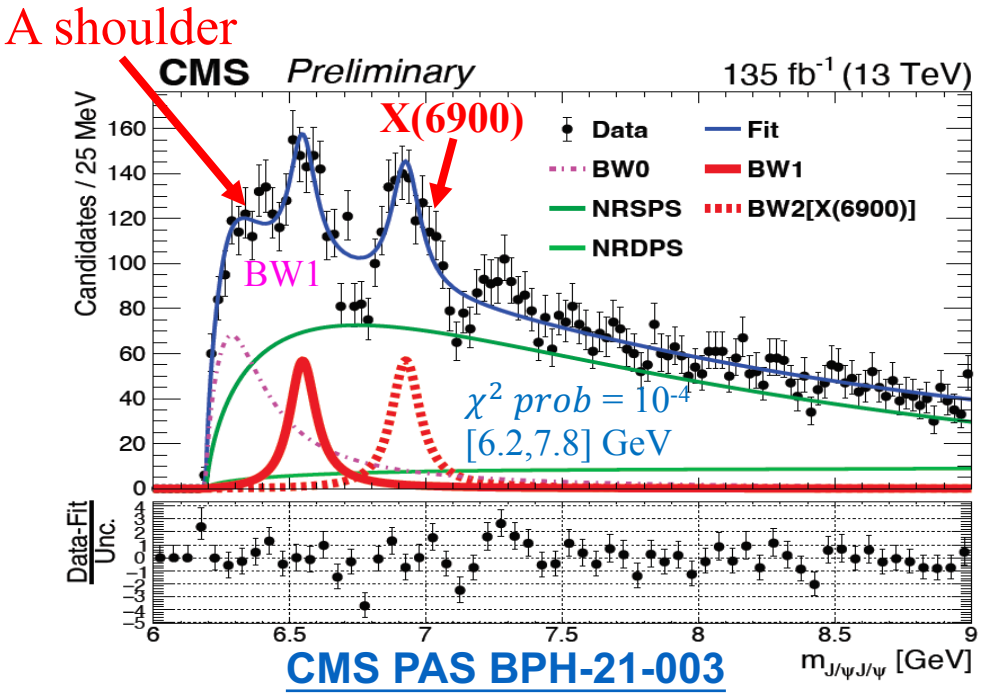


Model II (interference with an auxiliary BW)

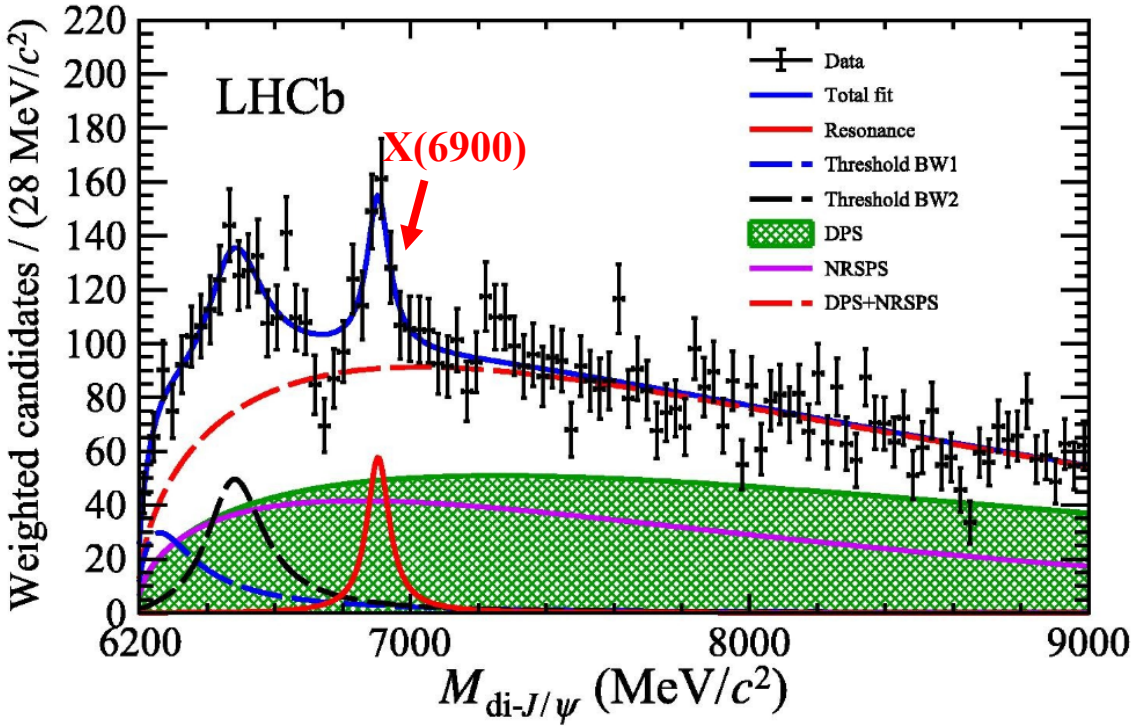


- What happens if fit CMS data using LHCb models?

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



CMS PAS BPH-21-003



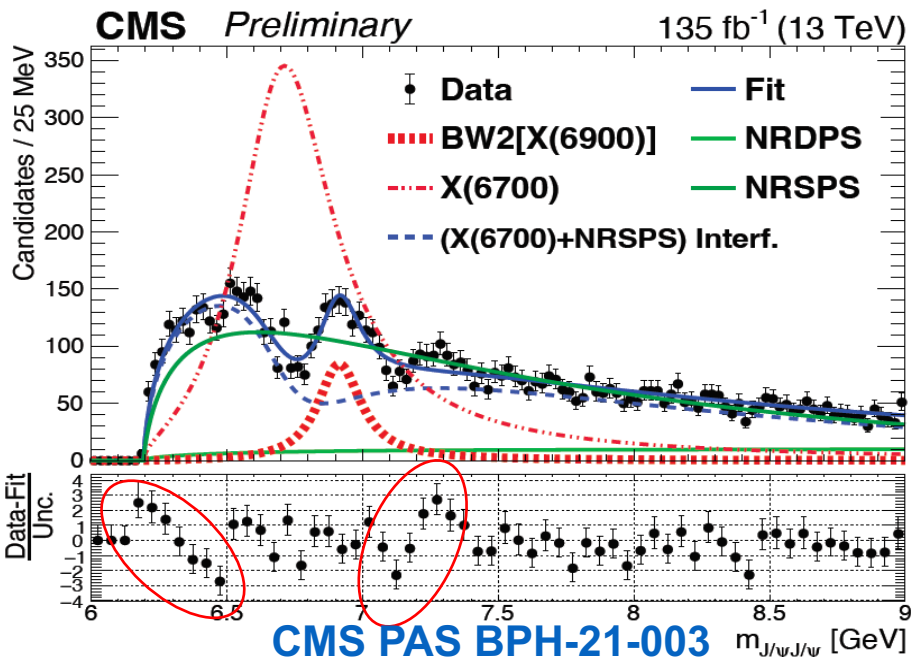
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

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

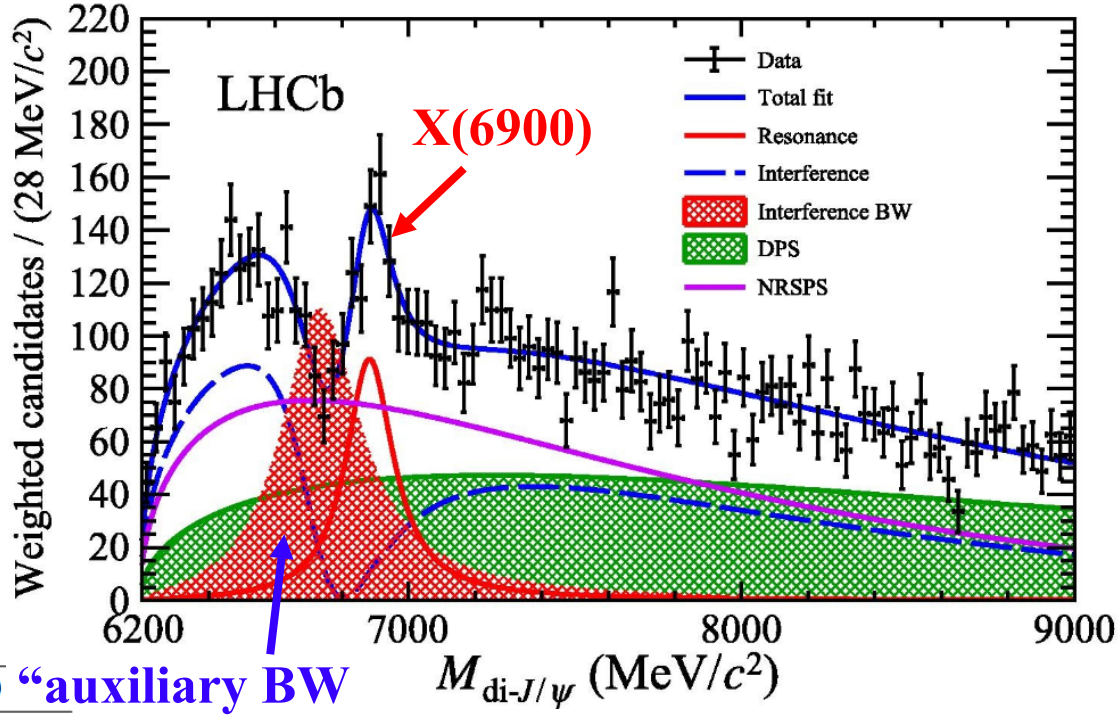
- CMS Data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct
- *Does not describe well dips*

- 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

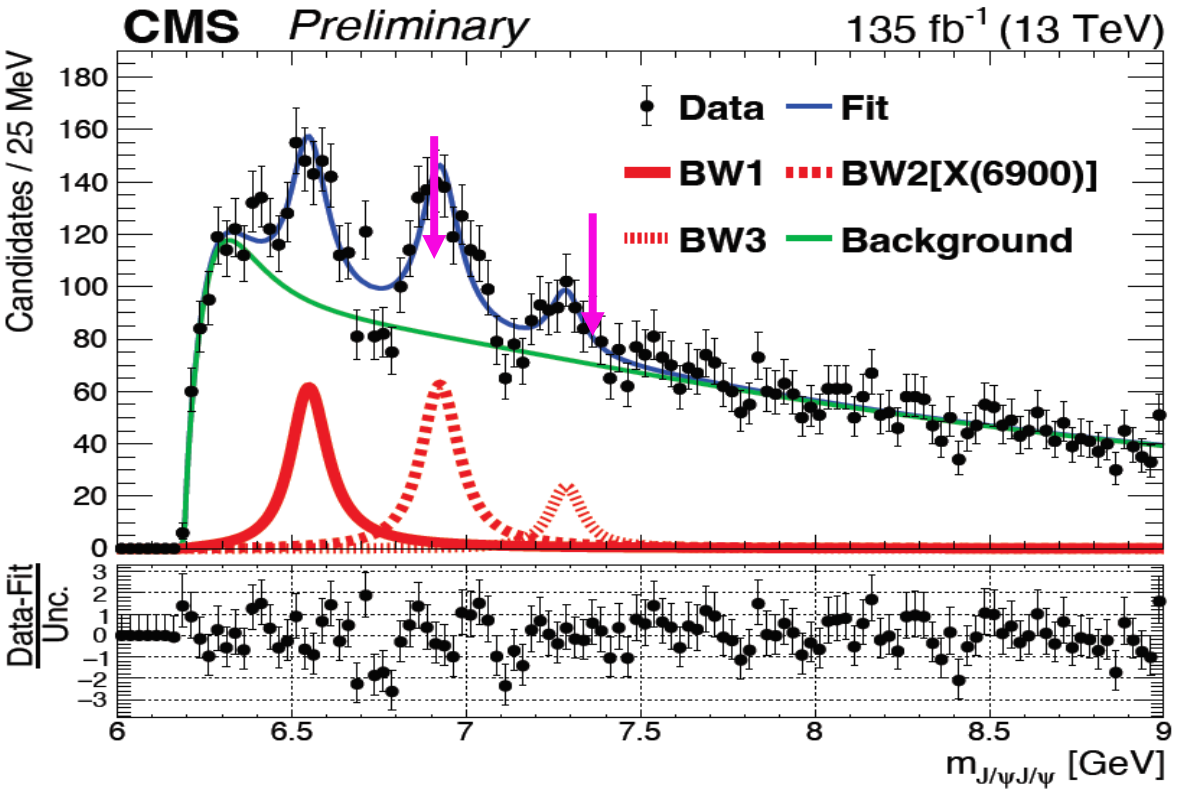


Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

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?

- 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

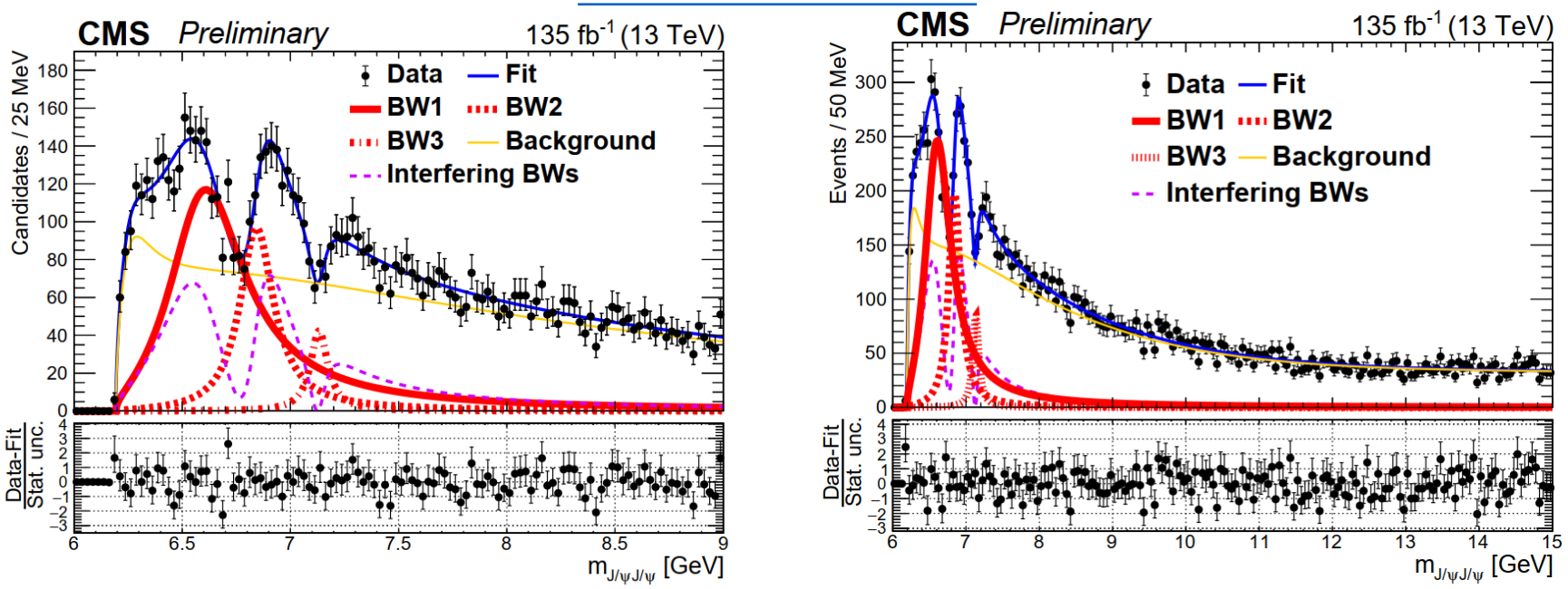
$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \otimes R(M_0)$$
$$+ N_{X\ and\ interf} \cdot \boxed{|r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2}$$
$$+ N_{NRSPS} \cdot f_{SPS}(m) + N_{NRDPS} \cdot f_{DPS}(m)$$

- 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

Feed down—partically reconstructed from higher mass states

Final result

- Measured mass and width

Non-interference fit

CMS PAS BPH-21-003

	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

Interference fit

	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

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

Interference fit

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?

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

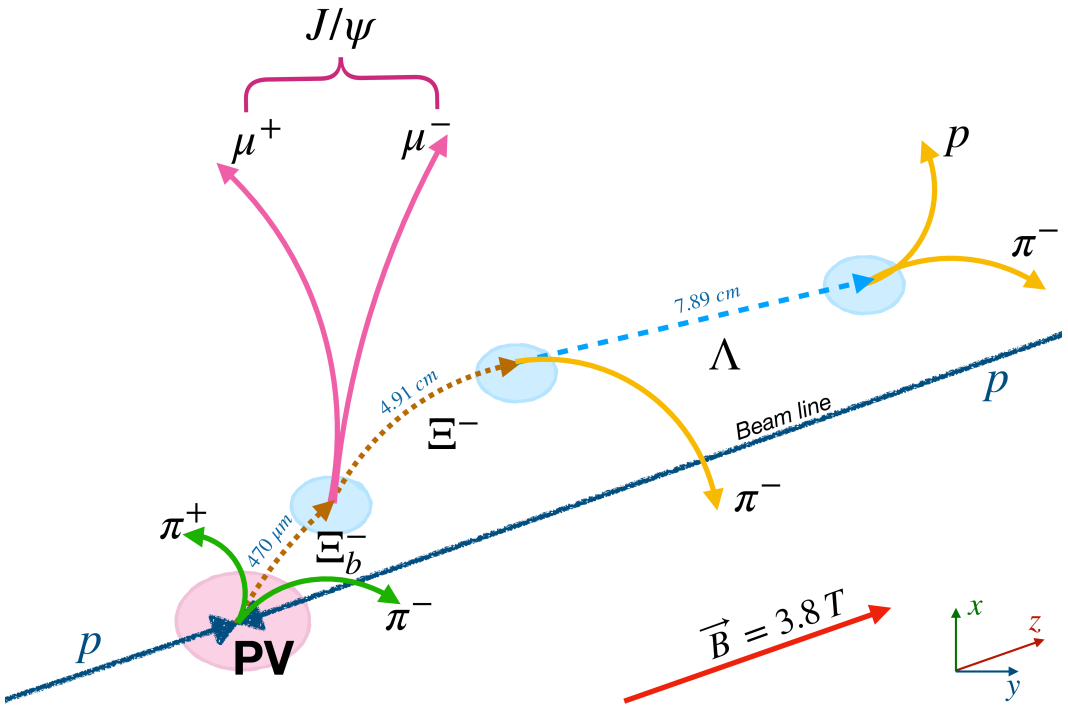
- All-heavy quark exotic states offer system easier to understand, i.e., ignore relativistic effect…
- Mass differences from multiple structures can be better calculated with a further measurement
- A new window to understand the strong interaction

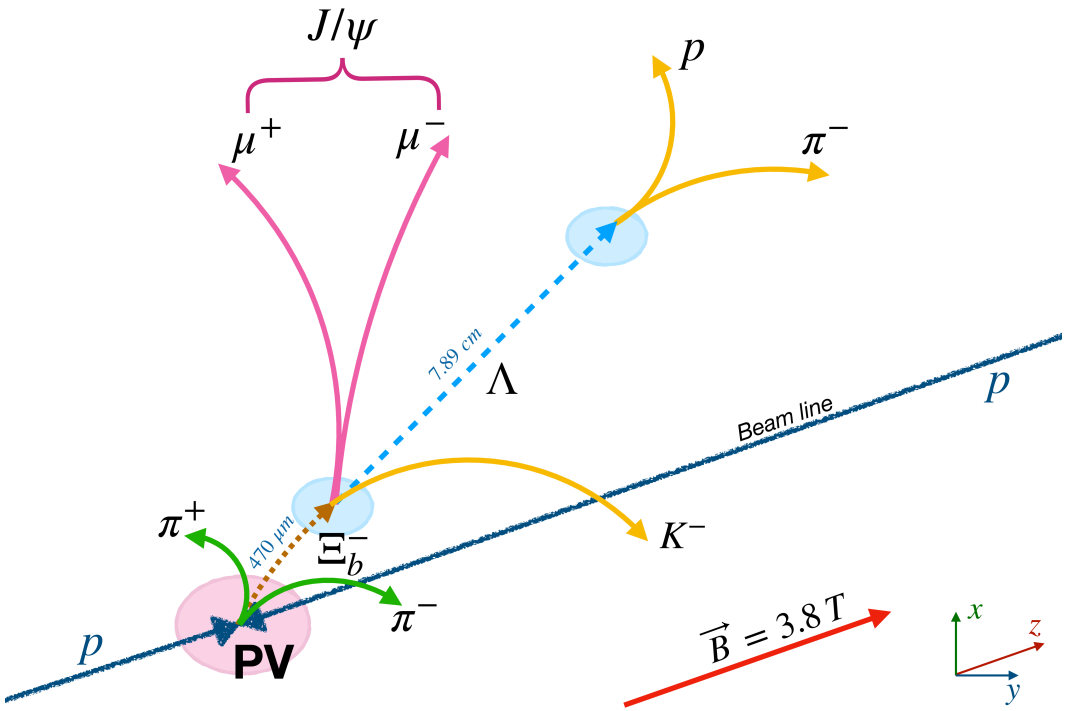
CMS has good sensitivity to all-muon final states in this mass region

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

Observation of a new excited beauty strange baryon $\Xi_b(6100)^-$ decaying to $\Xi_b^-\pi^+\pi^-$

Phys. Rev. Lett. **126**, 252003 (2021)





$\Xi_b(6100)^- \rightarrow \Xi_b^-\pi^+\pi^-$

Ξ_b^- decays to $J/\psi\,\Xi^-$

$\Xi_b(6100)^- \rightarrow \Xi_b^-\pi^+\pi^-$

Ξ_b^- decays to $J/\psi\,\Lambda K^-$

Ξ family and its spectroscopy

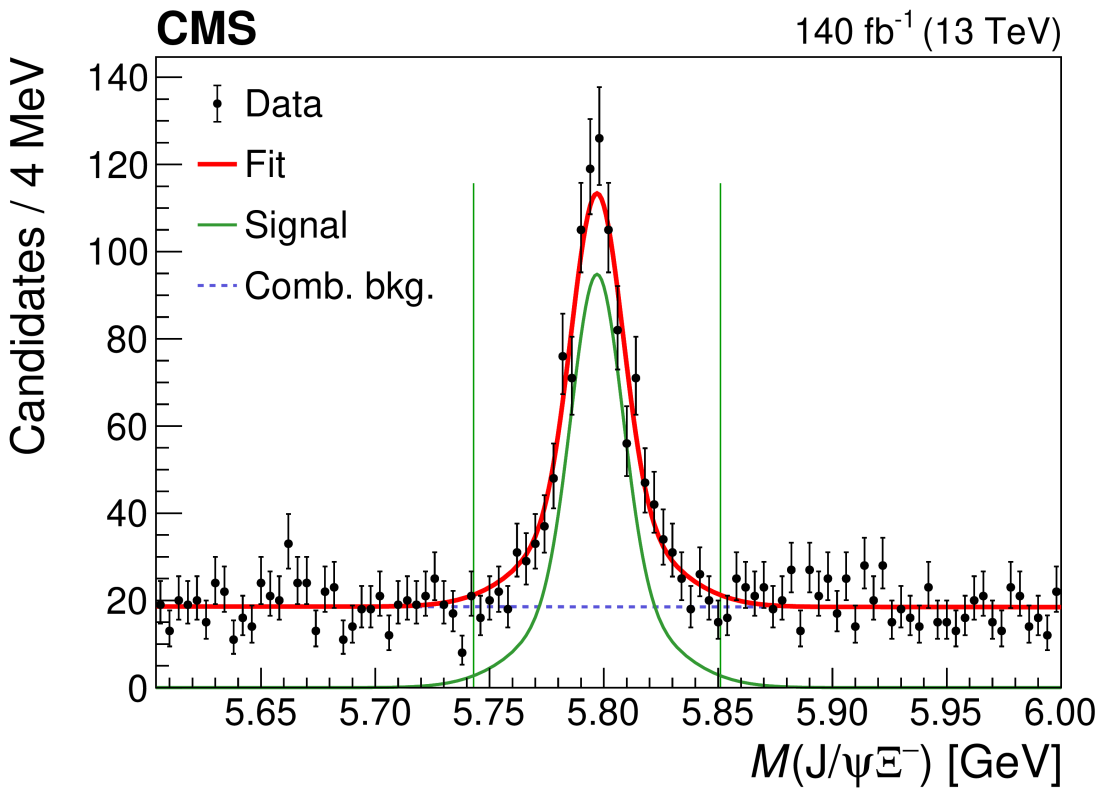
- The Ξ_b family are qsb isodoublets, their ground states have been observed at Tevatron.
  Now LHC' high energy and immense statistics provide a lot of opportunities for studying its resonances and rare decays, and several of such excited states have been observed recently

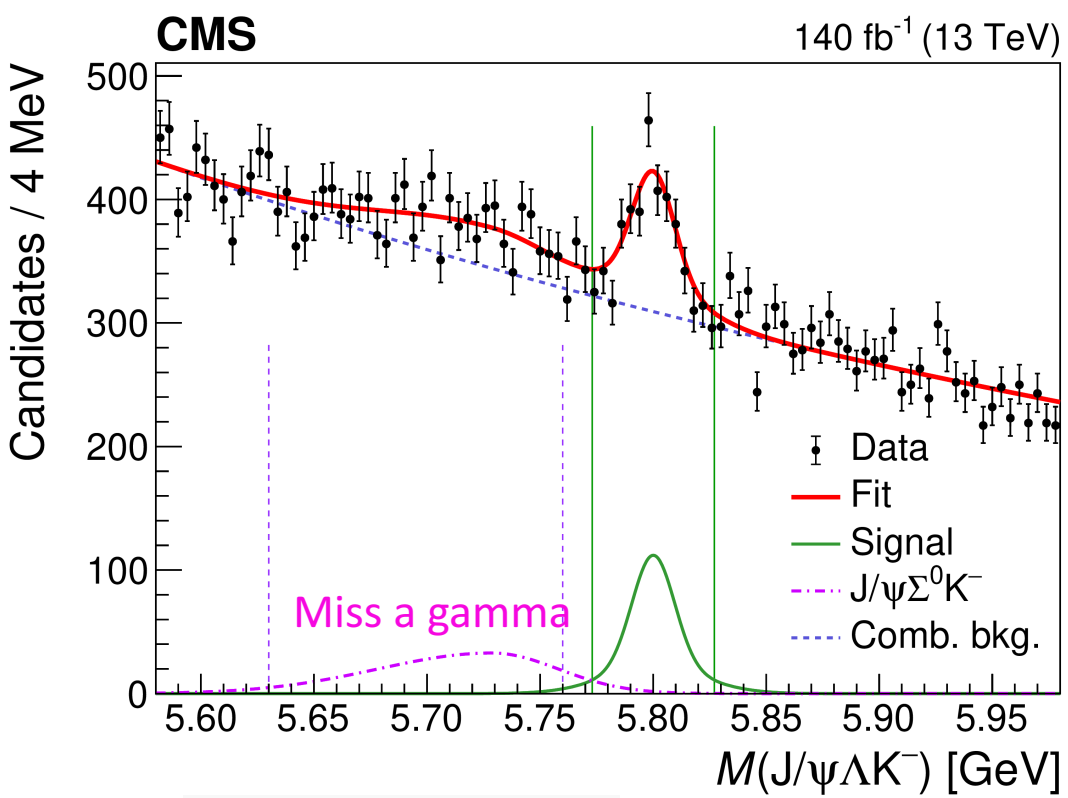
- There are predictions, based on $\Xi_c(2815) \to \Xi_c(2645)\pi \to \Xi_c\pi\pi$ analogues, for new Ξ_b^- resonance in near-threshold $\Xi_b^-\pi^+\pi^-$ mass spectrum, decaying with intermediate $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$.
  Ξ_b^{**-} is expected to have the mass about 6100-6130 MeV and non-neglible natural width.

State	j_{qs} , J^P	Quarks	Decay mode	Mass, MeV	Observation (with links)
Ξ_b^0	0 , $1/2^+$	$u\ s\ b$	$\Xi_c^+\pi^-$	5791.9 ± 0.5	D0, 2007 CDF, 2007
Ξ_b^-	0 , $1/2^+$	$d\ s\ b$	$J/\psi\Xi^-$	5797.0 ± 0.9	CDF, 2011
$\Xi_b^{\prime -}$ Ξ_b^{*-}	1 , $1/2^+$ 1 , $3/2^+$	$d\ s\ b$	$\Xi_b^0\pi^-$	5935.02 ± 0.05 5955.33 ± 0.13	LHCb, 2015, 7, 8 TeV
$\Xi_b^{\prime 0}$	1 , $1/2^+$	$u\ s\ b$	??? (radiational?)	$< m(\Xi_b^-) + m(\pi^+)$	:(
Ξ_b^{*0}	1 , $3/2^+$	$u\ s\ b$	$\Xi_b^-\pi^+$	5951.4 ± 1.2 5952.2 ± 0.9	**CMS, 2012, 7 TeV** LHCb, 2016, 7, 8 TeV
$\Xi_b(6227)^-$	???	$d\ s\ b$	$\Xi_b^0\pi^-$ $\Lambda_b K^-$	6226.9 ± 2.0	LHCb, 2018, 7, 8, 13 TeV
$\Xi_b(6227)^0$	???	$u\ s\ b$	$\Xi_b^-\pi^+$	6227.1 ± 1.5	LHCb, 2020 7, 8, 13 TeV

Ξ_b^- invariant mass

2016+2017+2018 data @13 TeV





Ξ_b^- decays to $J/\psi\,\Xi^-$

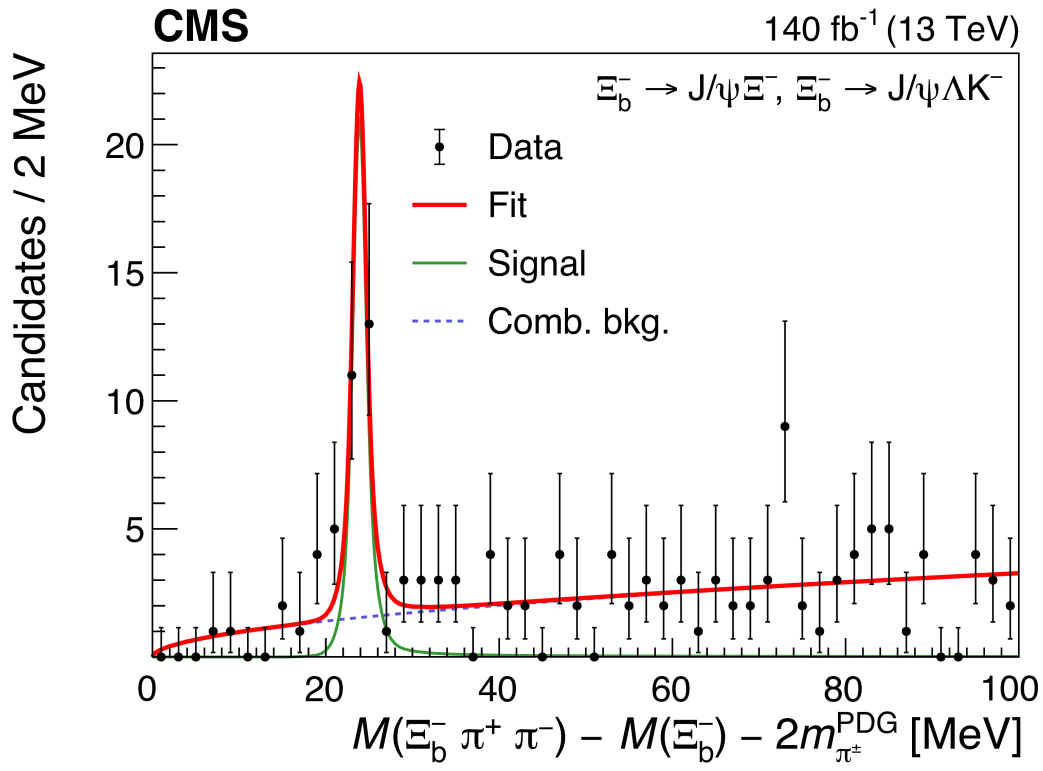
Yield: 859 ±36
Mass: 5797.0±0.7 MeV
Two gaussians for signal

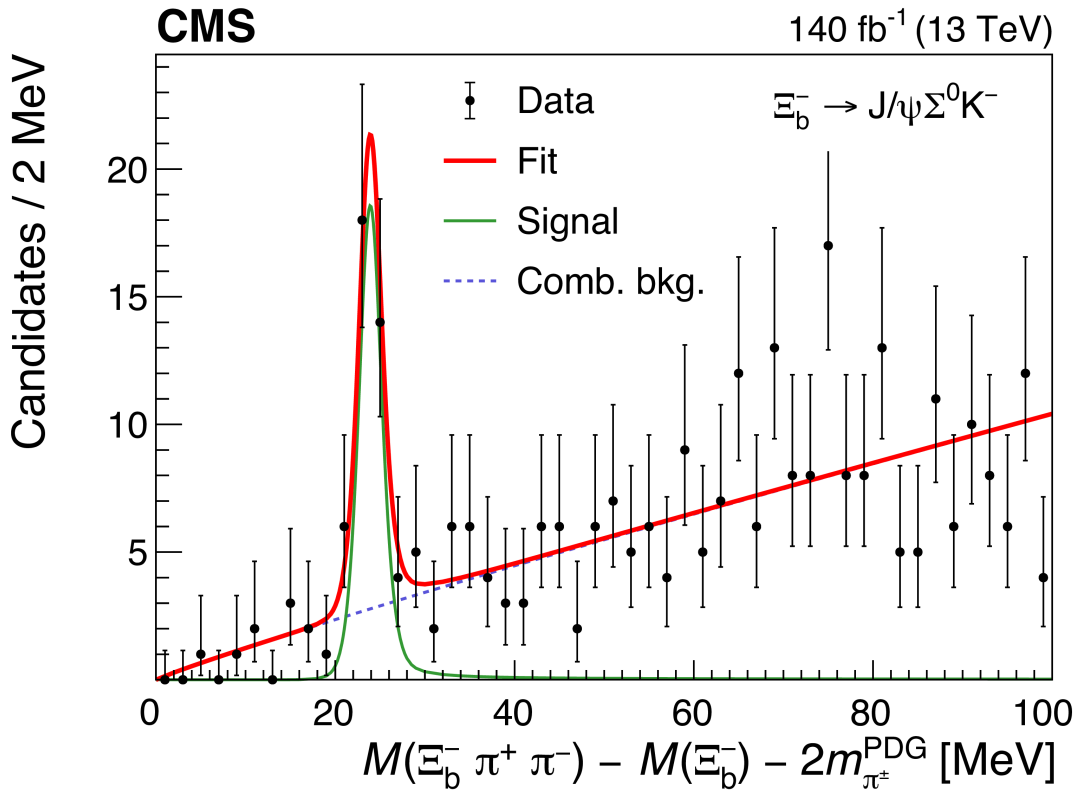
PDG: : 5797.0±0.6 MeV

Ξ_b^- decays to $J/\psi\,\Lambda K^-$

Yield: 815 ±74 for $J/\psi\Lambda K^-$, 820±158 for $J/\psi\,\Sigma^0K^-$
Mass: 5800.1±1.2 MeV (fully reconstructed channel)
Two gaussians for fully reconstructed signal
Asymetric Gaussian for particlly reconstructed signal

Invariant mass difference ΔM



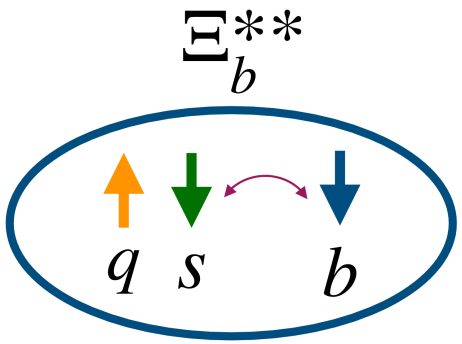


Yield: 26 ± 7 (fully reconstructed) and 34 ± 9

Mass difference: 5797.0±0.7 MeV

BW ⊕ Resolutoin for signal, where resolution (Gaus) parameters fixed to simulation

Summary



$j_{qs} = 1$

$J^P = \frac{1}{2}^-$ or $\frac{3}{2}^-$

$L = 1$

- The first observation of a new excited beauty strange baryon, supposing to be **Ξ_b (6100)$^-$** resonance with $J^P = 3/2^-$, with the following properties:

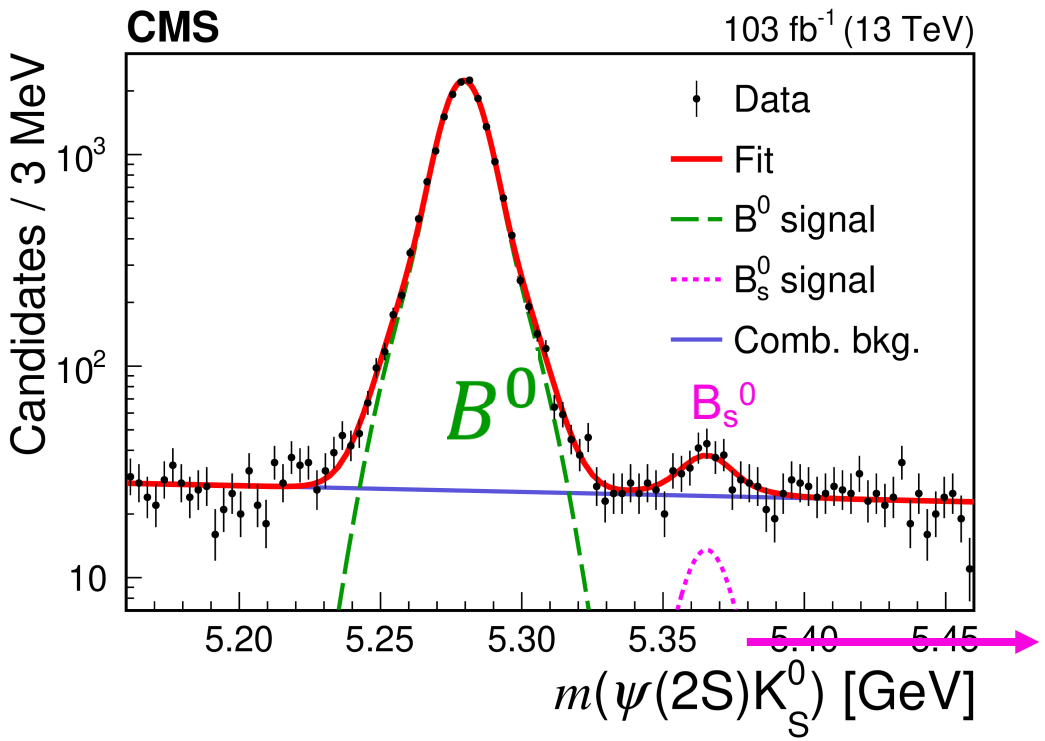
$$M(\Xi_b(6100)^-) - M(\Xi_b^-) - 2 \cdot m^{\mathrm{PDG}}(\pi^\pm) = 24.14 \pm 0.22 \pm 0.05\ MeV$$
$$M(\Xi_b(6100)^-) = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6\ MeV$$
$$\Gamma(\Xi_b(6100^-) < 1.9\ MeV\ @95\,\%\ CL$$

Recently confirmed by LHCb: https://moriond.in2p3.fr/QCD/2023/MondayAfternoon/Gandini.pdf

Observation of $B_s^0 \to \psi(2S)K_s^0$ decay

2017+2018 data @13 TeV

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



Background: exponential function

Signal: 2-x Gaus with common mean for both peaks.
$B^0 \to \psi(2S)K_S^0$ parameters are floating.
σ_1, σ_2 of $B_s^0 \to \psi(2S)K_S^0$ are fixed to $\sigma_{(12)}^{B^0} \cdot \sigma_{\text{eff.MC}}^{B_s^0} / \sigma_{\text{eff.MC}}^{B^0}$

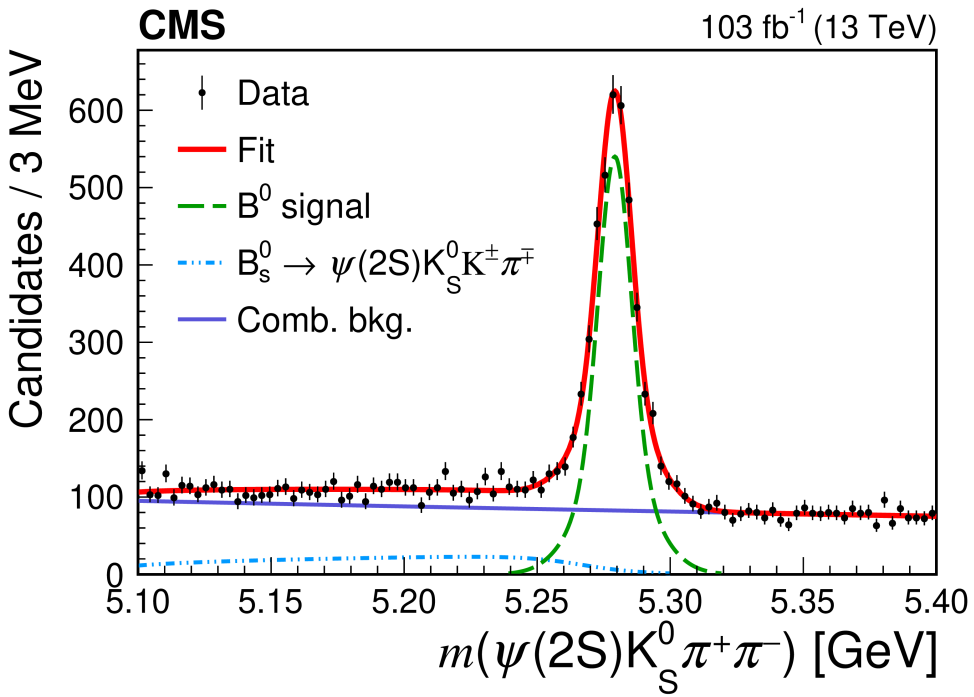
$N(B^0)$	16657 ± 135
$N(B_s^0)$	113 ± 23

Significance 5.2σ !

First observation of $B_s^0 \to \psi(2S)K_s^0$

Observation of $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ decays

2017+2018 data @13 TeV
Search for possible exotic states



Fit results

$m(B^0)$	5279.2 ± 0.2 MeV
$m_{PDG}(B^0)$	$5279.65 \pm 0.12\ MeV$
$\sigma_{eff}(B^0)$	$9.7 \pm 0.6\ MeV$
$\sigma_{effMC}(B^0)$	$9.17 \pm 0.10\ MeV$
χ^2/ndf	75.3 / 92

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

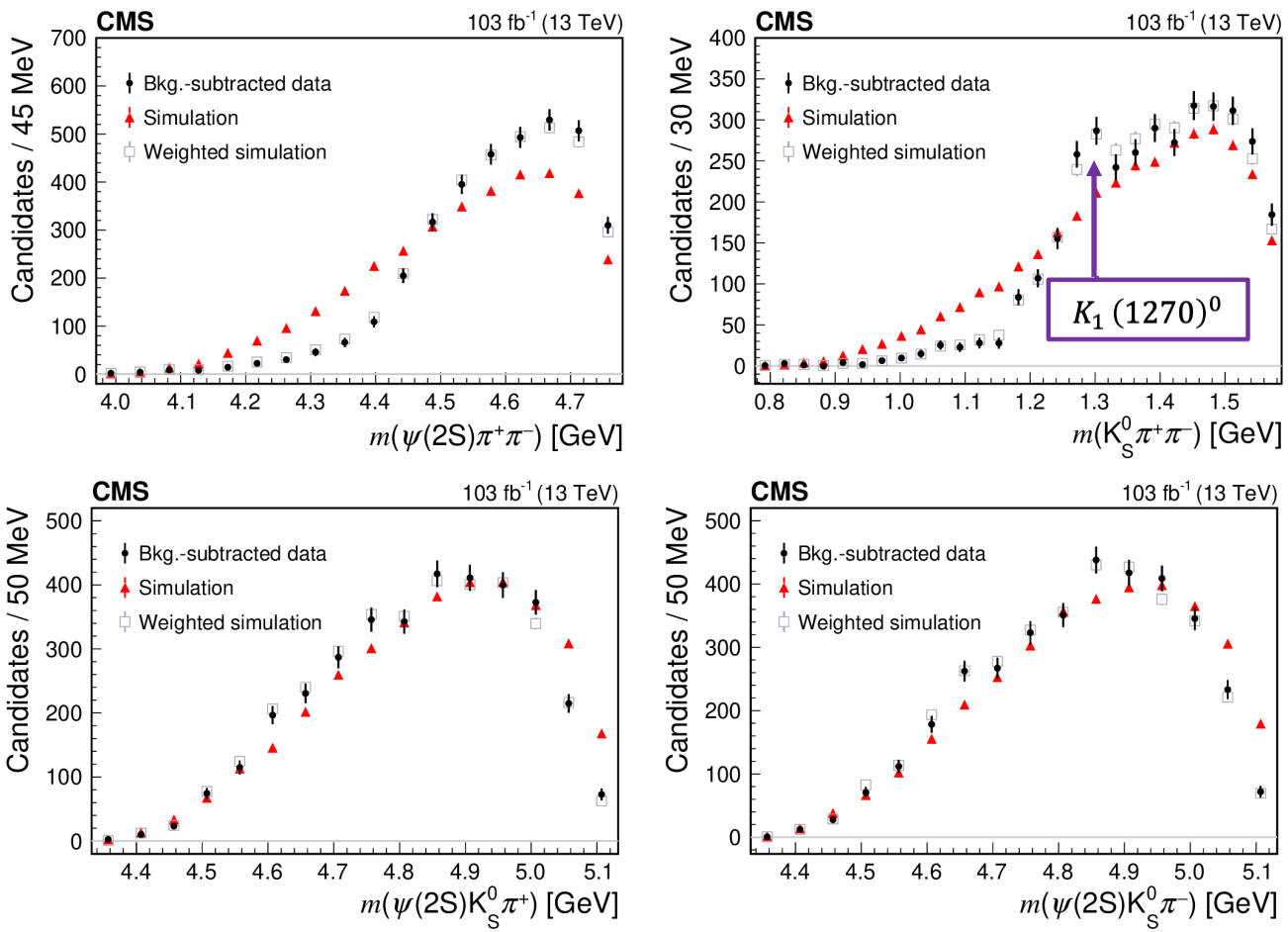
Significance > 30 σ

First observation!

$B^0 \to \psi\ (2S)K_s^0\pi^+\pi^-$

$N(B^0)$: 3498 ± 87

3-body intermediate invariant masses

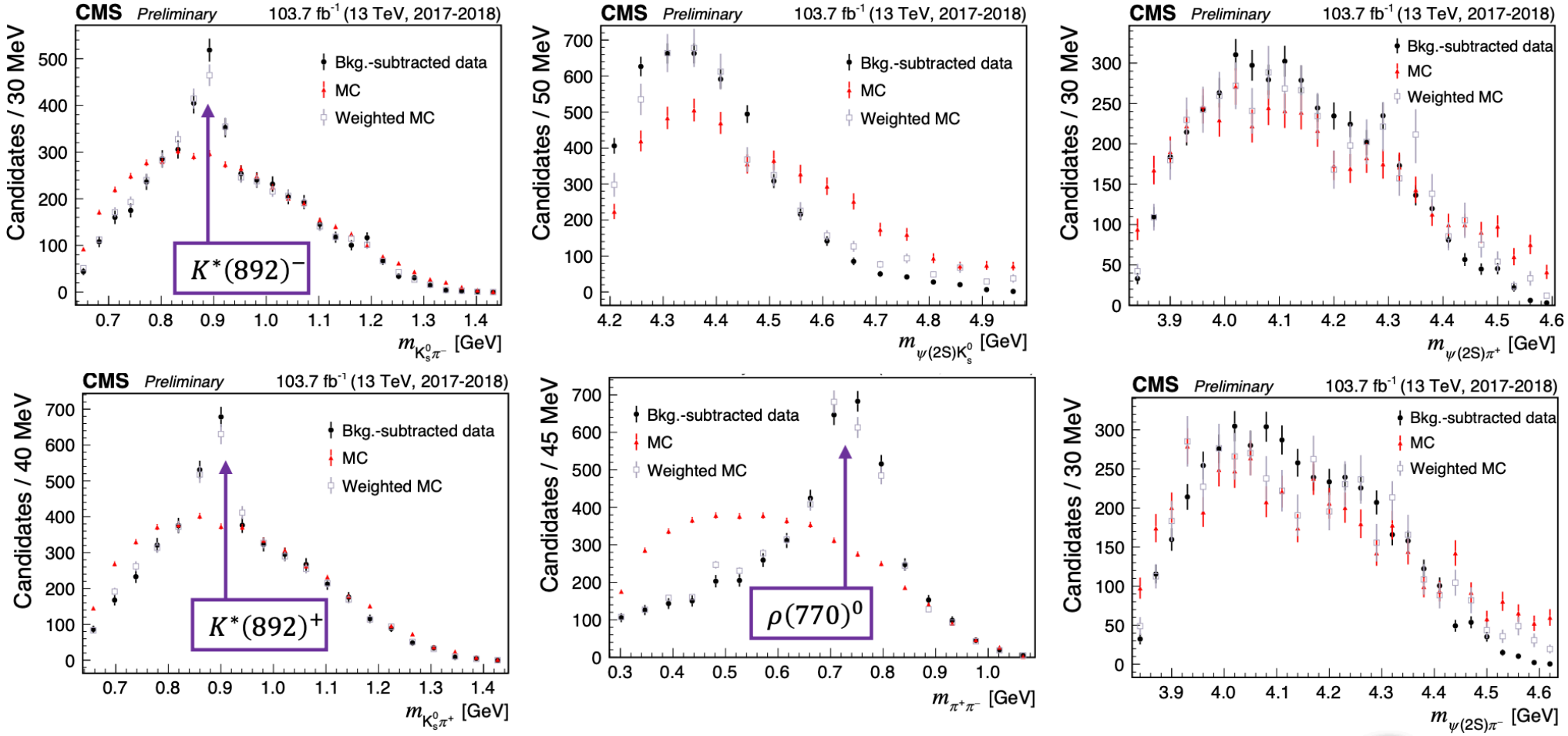


$$B^0 \to \psi(2S)K_S^0\pi^+\pi^-$$

The data (black) shows a hint of the $K_1(1270)^0 \to K_S^0\pi^+\pi^-$

Didn't see new exotic narrow structures

2-body intermediate invariant masses



Didn't see new exotic narrow structures

The data (black) shows clear signs of the known $K^*(892)^{\pm}$ and $\rho(770)^0$ resonances in $K_S^0\,\pi^{\pm}$ and $\pi^+\pi^-$ systems.

$$B^0 \to \psi(2S)K_S^0\pi^+\pi^-$$

Summary

- The first Observation of $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_s^0$ and estimation the branching fraction ratios

$$R_s = \frac{\mathcal{B}(\mathrm{B_s^0} \to \psi(2\mathrm{S})\mathrm{K_S^0})}{\mathcal{B}(\mathrm{B^0} \to \psi(2\mathrm{S})\mathrm{K_S^0})} = (3.33 \pm 0.69\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst}) \pm 0.74(f_s/f_d))\%,$$

$$R_{\pi^+\pi^-} = \frac{\mathcal{B}(\mathrm{B^0} \to \psi(2\mathrm{S})\mathrm{K_S^0}\pi^+\pi^-)}{\mathcal{B}(\mathrm{B^0} \to \psi(2\mathrm{S})\mathrm{K_S^0})} = (48.0 \pm 1.3\,(\mathrm{stat}) \pm 3.2\,(\mathrm{syst}))\%.$$

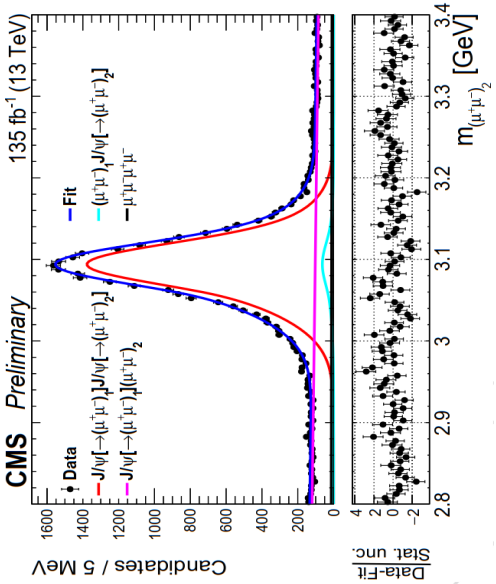
- Both ratios are compatible with their analogues in J/ψ channels.
- Inspection of the phase-space distributions of $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ does not reveal any additional exotic narrow structure.

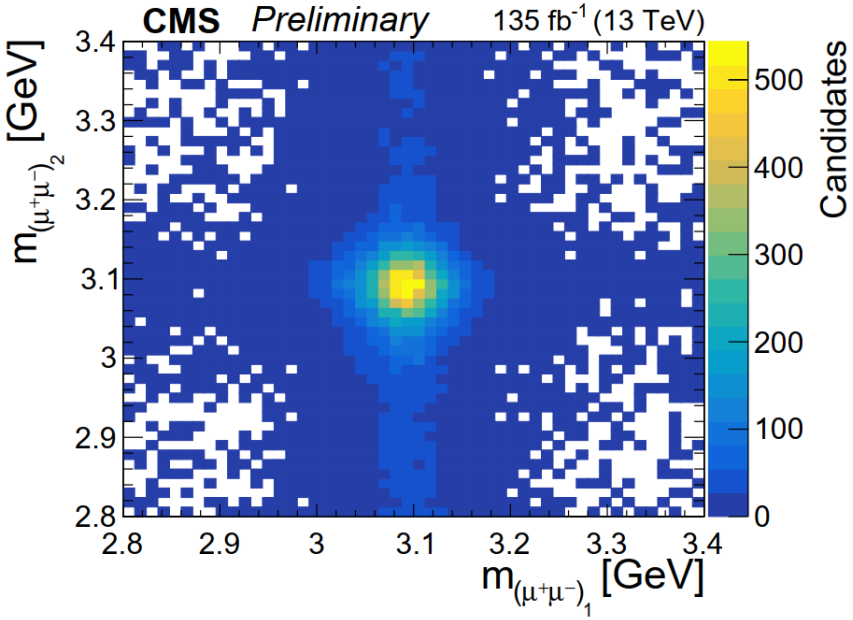
Overall Summary

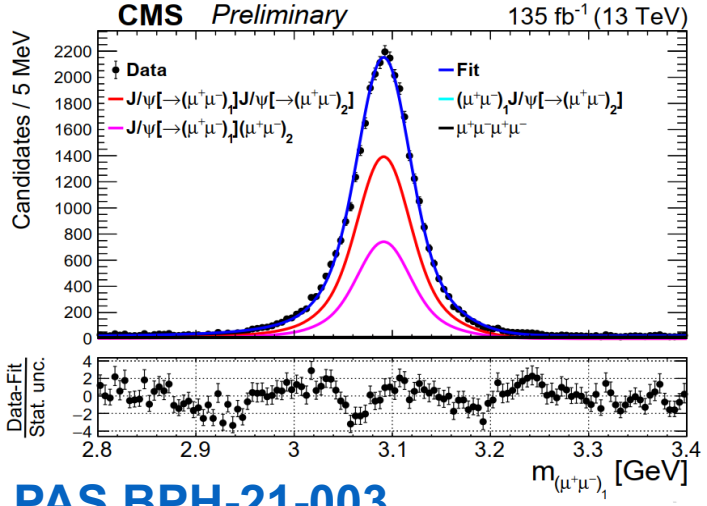
- CMS found 3 significant $J/\psi J/\psi$ structures using 135 fb^{-1} 13 TeV data
- First observation of a new excited beauty strange baryon, supposing to be Ξ_b **(6100)**$^-$
- First Observation of $B^0 \rightarrow \psi(2S)K_s^0\pi^+\pi^-$ and $B_s^0 \rightarrow \psi(2S)K_s^0$ and estimation the branching fraction ratios
- CMS continue make contributions to the this topic

Backup

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)

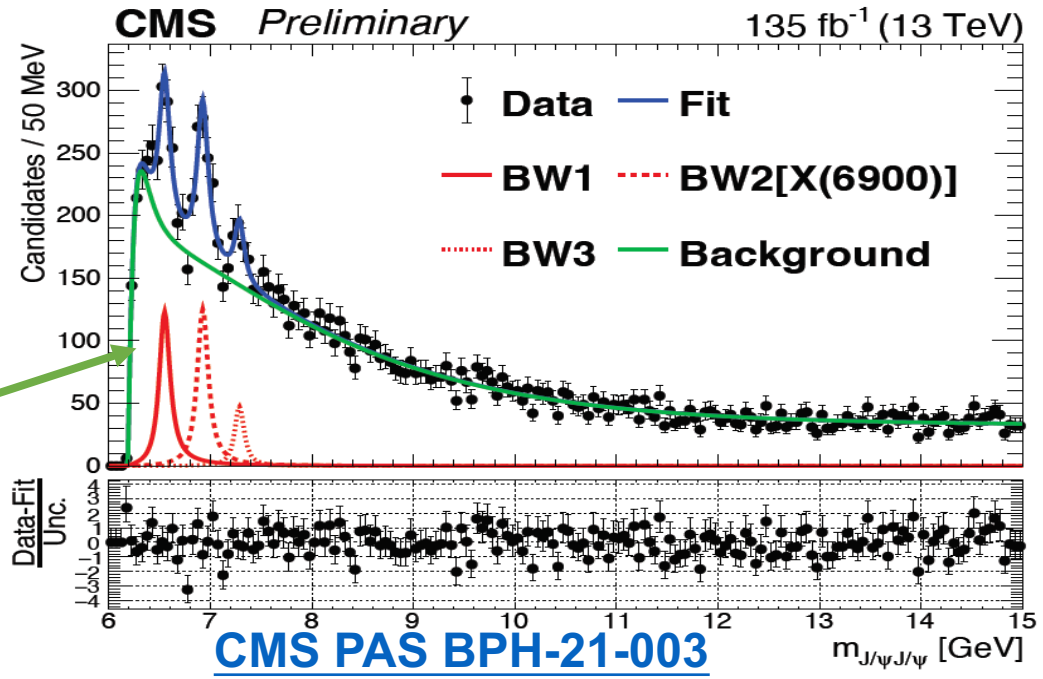
- ~9000 J/ψ pairs after final selection (m(J/ψ J/ψ) <9 GeV)

CMS PAS BPH-21-003

CMS background (BW0 + NRSPS + DPS)

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

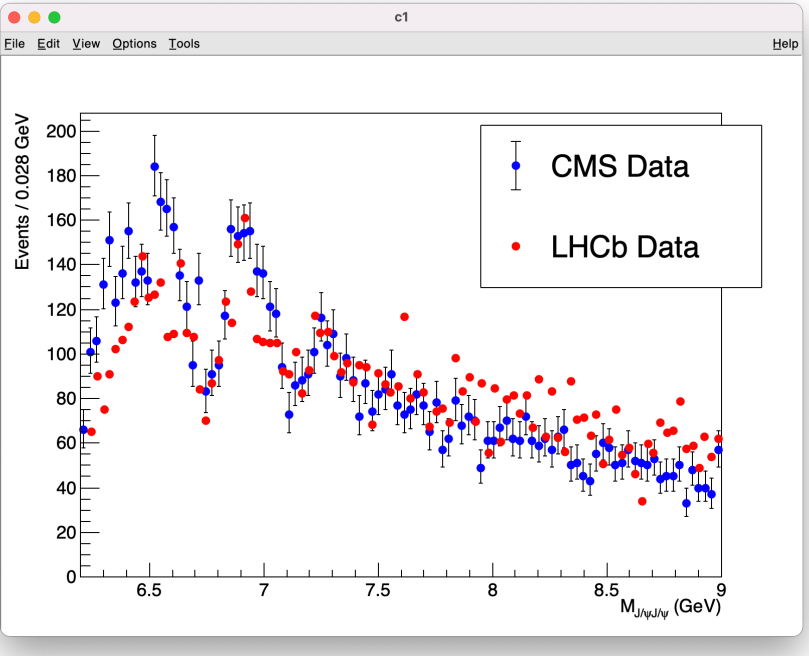
CMS background (BW0 + NRSPS + DPS)

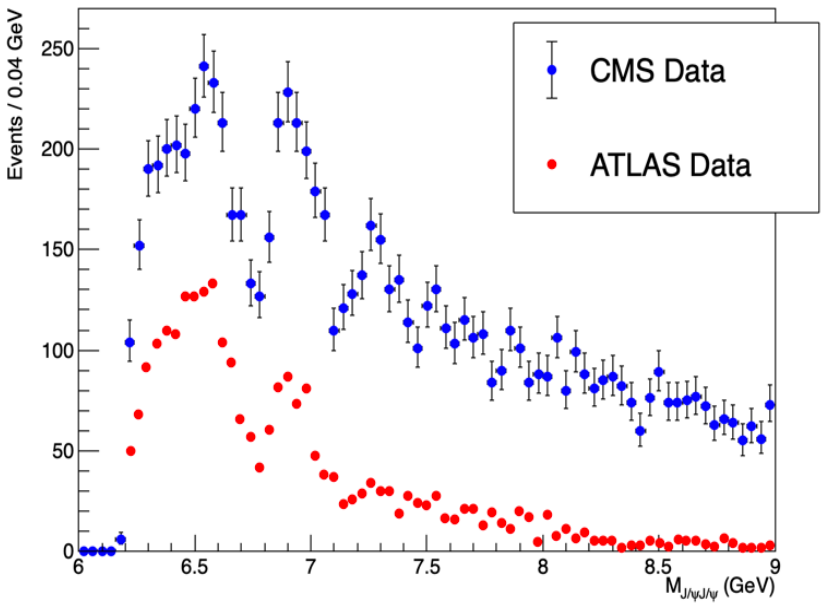


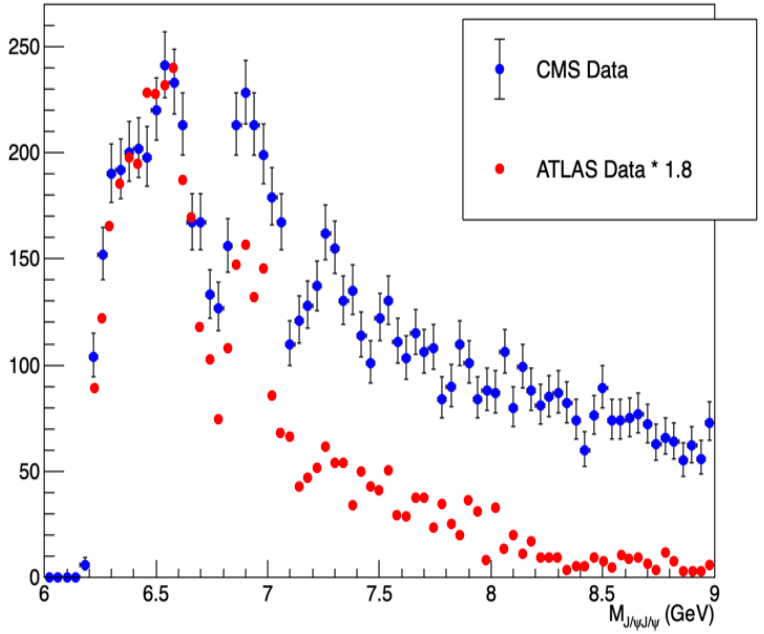
CMS PAS BPH-21-003

- 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

Comparison with LHCb & ATLAS





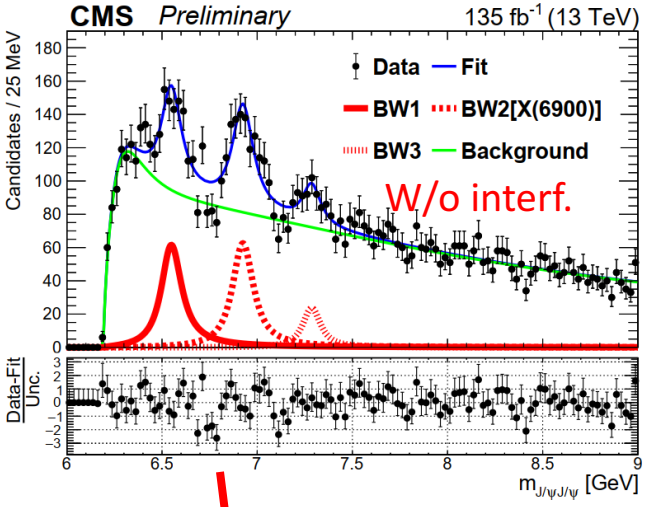


- CMS vs LHCb comparisons:
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4$ ≈ 8X (muon acceptance)
  - Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
  - Similar number of final events, but much less DPS
  - 2X yield @CMS for X(6900)

- CMS vs ATLAS comparisons:
  - ATLAS is 1/3 –1/2 of CMS data (trigger?)
  - ATLAS used dR cut—remove high mass events
  - ATLAS has slightly worse resolution

Comparison with some theoretical calculations

CMS PAS BPH-21-003



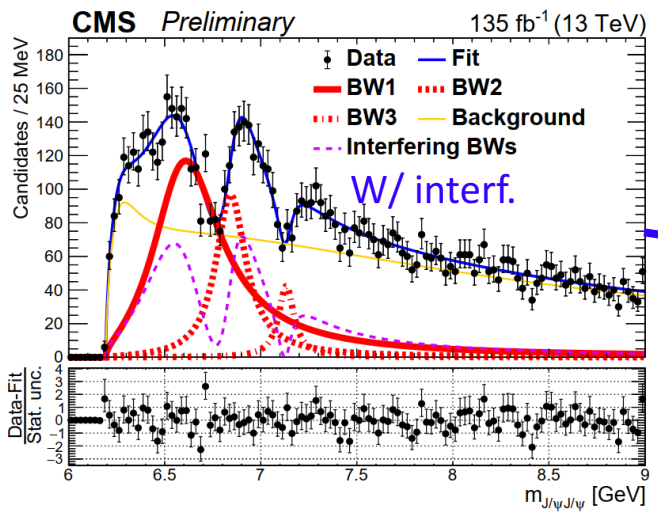


Table 1. Predictions of the masses (MeV) of S-wave fully heavy $T_{4Q}(nS)$ tetraquarks. Only 0^{++} and 2^{++} are considered for $T_{bc\bar{b}\bar{c}}$. The uncertainty is from the coupling constant $\alpha_s = 0.35 \pm 0.05$.

Nucl. Phys. B 966 (2021) 115393

$T_{4Q}(nS)$ 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}_{-36}	6795^{+26}_{-26}	7066^{+21}_{-22}
$T_{bc\bar{b}\bar{c}}$	0^{++}	12387^{+109}_{-120}	12911^{+48}_{-50}	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}	19453^{+42}_{-42}	19566^{+33}_{-35}
	2^{++}	18483^{+149}_{-168}	19075^{+59}_{-62}	19455^{+41}_{-43}	19567^{+33}_{-35}
$T'_{bb\bar{b}\bar{b}}$	0^{++}	18383^{+149}_{-167}	18976^{+59}_{-62}	19356^{+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