Results on four-charm-quark states by ATLAS and CMS

https://arxiv.org/abs/2304.08962

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

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on behalf of the ATLAS & CMS Collaborations

Outline

- New domain of exotics: all-heavy tetra-quarks
- CMS fully-charmed exotic states
  - First observation of X(6600) and evidence of X(7300) in J/ψJ/ψ
  - Confirmation of X(6900) in J/ψJ/ψ
- ATLAS fully-charmed exotic states
  - Confirmation of X(6900) in J/ψJ/ψ
  - Evidence of structures in J/ψψ(2S)
- Comparison among ATLAS, CMS and LHCb
- Possible future: triple J/ψ
- Summary

New domain of exotics: all-heavy tetra-quarks

- First mention of 4c states at 6.2 GeV (1975)
  - Just one year after the discovery of J/ψ

We expect at least three exotic mesons with hidden charm, $c\bar{c}(p\bar{p}-n\bar{n})$ [between 3.7~4.1 GeV], $c\bar{c}\lambda\bar{\lambda}$ [~4.1 GeV] and $c\bar{c}c\bar{c}$ [~6.2 GeV], to which we refer

Progress of Theoretical Physics, Vol. 54, No. 2, August 1975

A Possible Model for New Resonances

——Exotics and Hidden Charm——

Yoichi IWASAKI

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received January 20, 1975)

- First calculation of 4c states (1981): 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	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

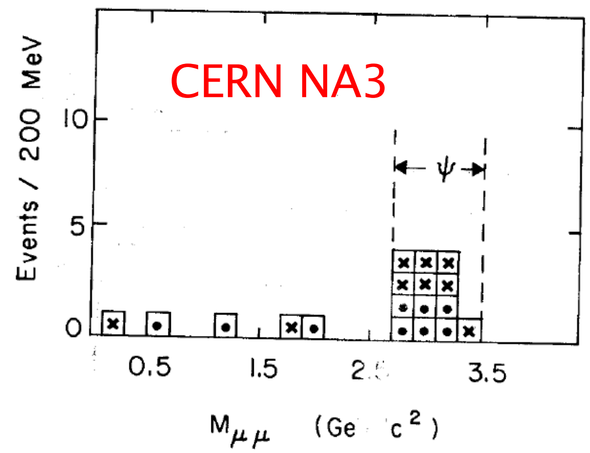
← $(cc)_{\underline{3}^*} - (\overline{cc})_{\underline{3}}$

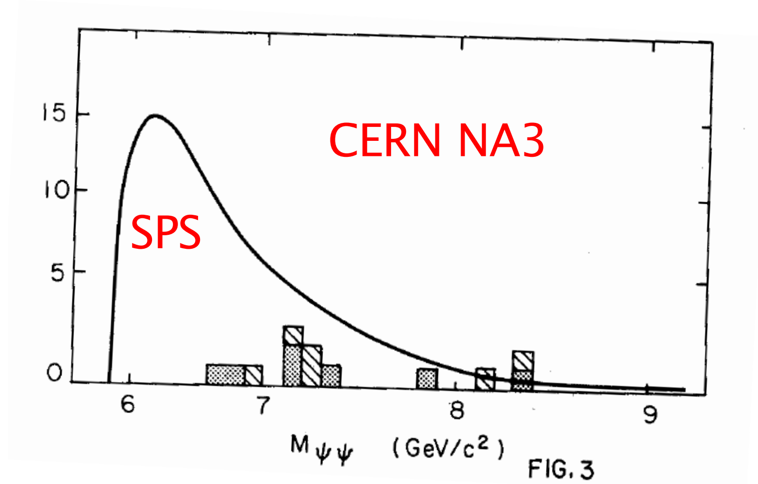
$(cc)_{\underline{6}} - (\overline{cc})_{\underline{6}^*}$ →

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

- A different exotic system compared to exotics with light quarks

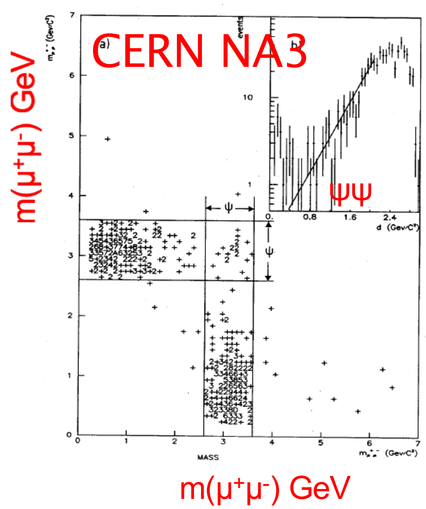
J/ψJ/ψ events—first evidence (1982)

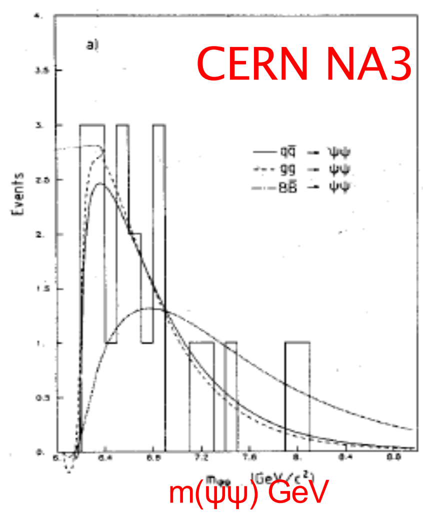


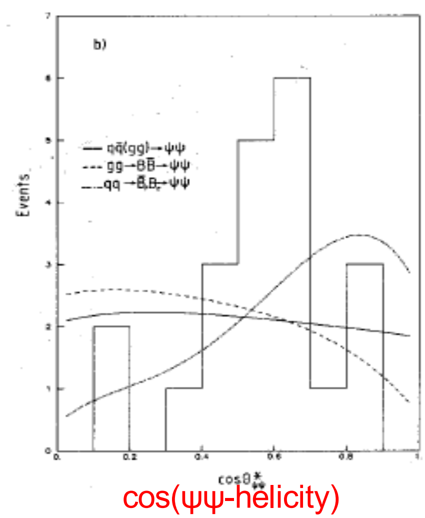


PLB114 (1982) 457

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







PLB158 (1985) 85

Possible explanations of J/ψJ/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
JJ	$1/\sqrt{3}$	$\left[\frac{2}{3}\right]^{1/2}\frac{4\pi}{f_J^2}$	7.0	0.18	3.10
$J\omega^{(+)}$	$1/\sqrt{6}$	$\frac{-1}{\sqrt{3}}\frac{4\pi}{f_J f_\omega}$	4.05	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

Possible explanations of J/ψJ/ψ states

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

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

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

Above double J/ψ threshold
Search via J/ψJ/ψ

(bbcc)

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

Below double B_c threshold
J/ψΥ(1S) threshold
? …

(bbbb)

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

Above double B_c threshold
J/ψΥ(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 $\eta_b\eta_b$ (or $\eta_c\eta_c$) threshold;
  - consistent on existence of resonant states above $\eta_b\eta_b$ (or $\eta_c\eta_c$) threshold.

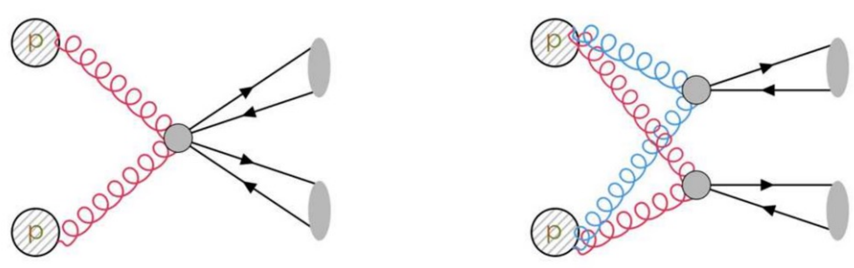
Signal and background

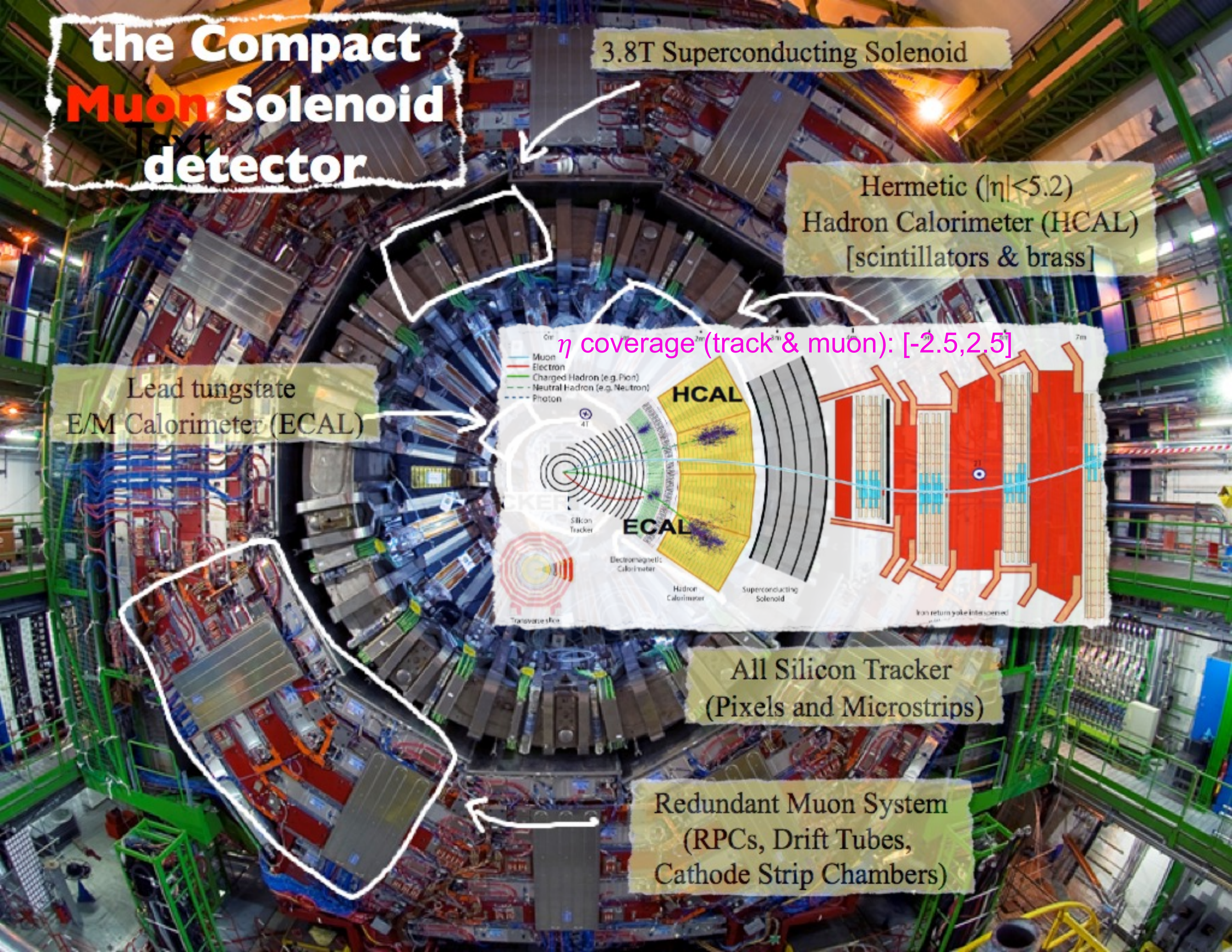
- Signal: $X \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$
- Signal MC samples:
  - $J^P = 0^+$ resonance

    Generator: Pythia8, JHUGen
- Main background:
  - Nonresonant single-parton scattering (NRSPS)

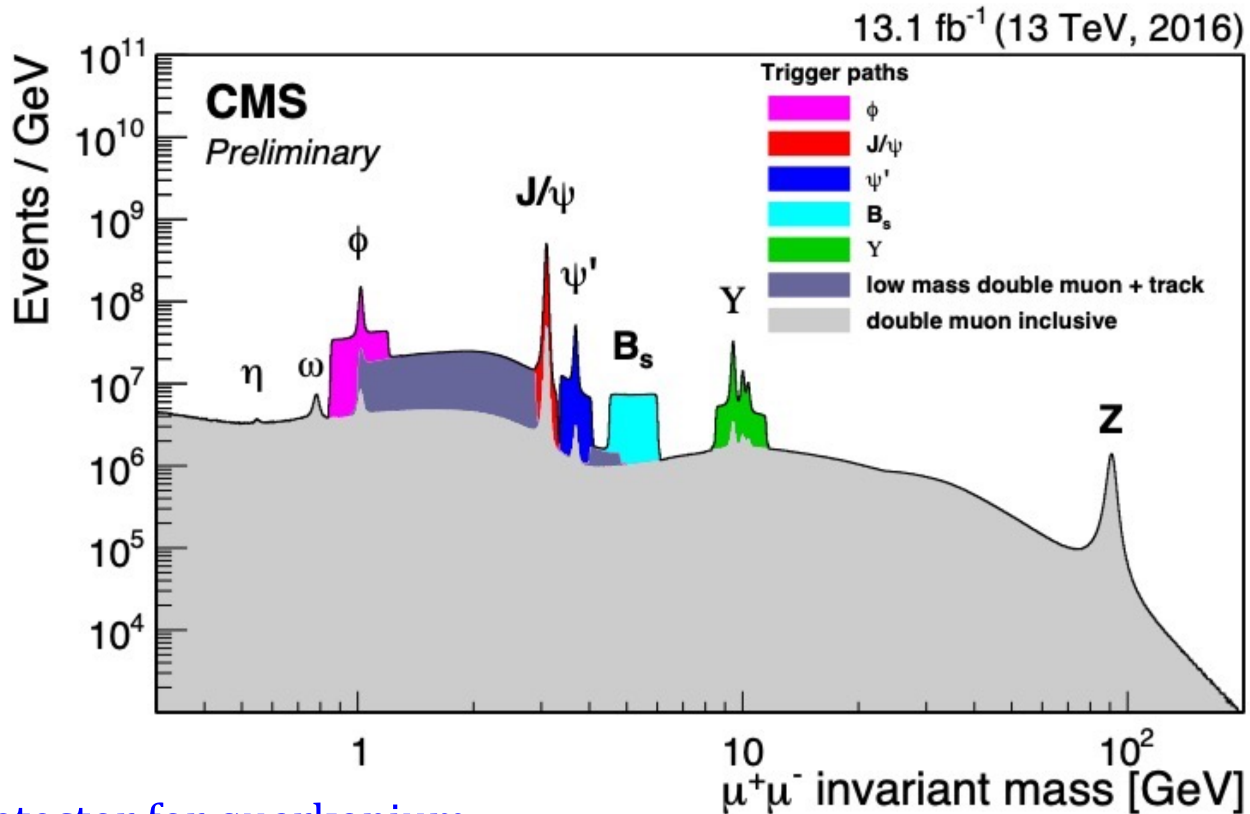
    Generator: Pythia8, HelacOnia (next-to-next-to-leading order), Cascade (next-to-leading order)
  - Nonresonant double-parton scattering (NRDPS)

    Generator: Pythia8
  - Combinatorial background




the Compact Muon Solenoid detector
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
η coverage (track & muon): [-2.5,2.5]
Lead tungstate
E/M Calorimeter (ECAL)
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
HCAL
ECAL
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Transverse slice
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

CMS dimuon & trigger

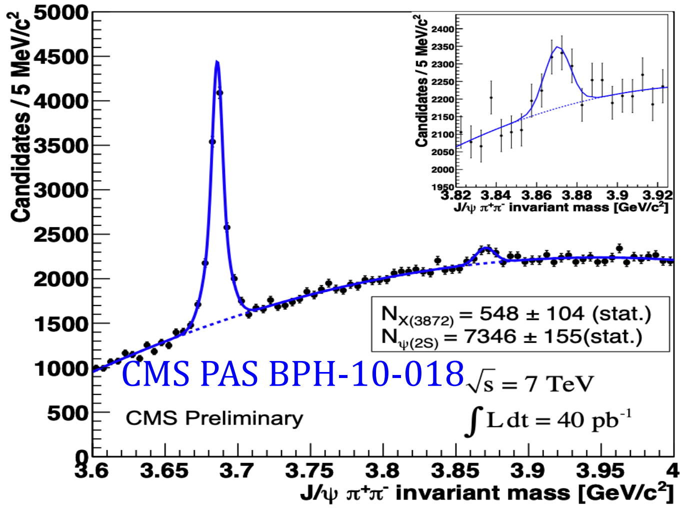


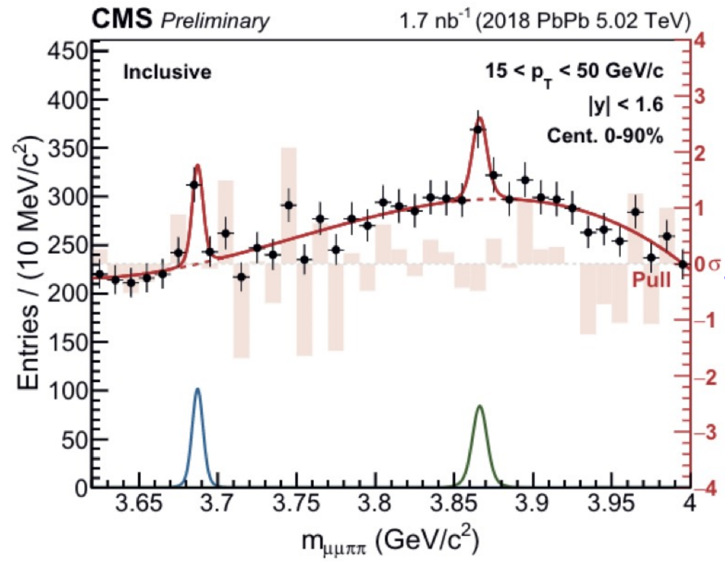
Excellent detector for quarkonium

- 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

Selected CMS contributions to heavy exotic states

First LHC experiment re-discovered X(3872)

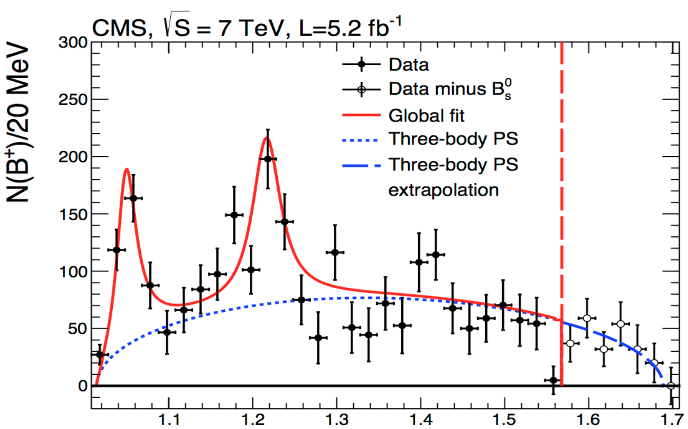




First X(3872) signal in PbPb

Nucl. Phys. Vol 1005 (2021)121781

First confirmation of Y(4140)



PLB 734 261 (2014)

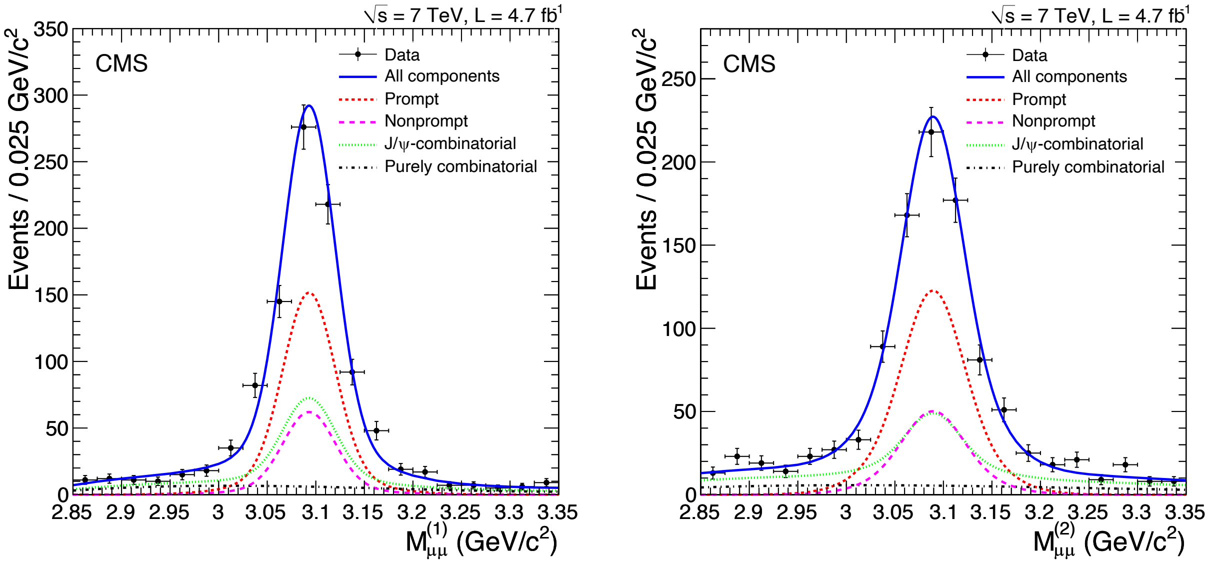
CMS played the following leading roles：

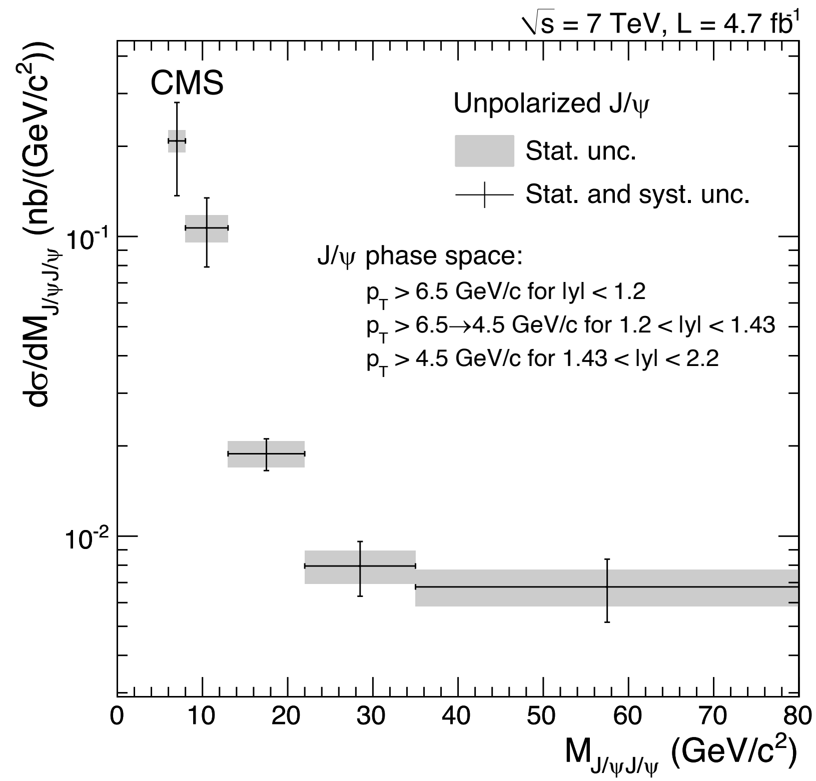
- First LHC experiment to see X(3872)
- First experiment to see X(3872) in B^0_S decay
- First experiment to see X(3872) in PbPb data
- First LHC experiment to see new exotic hadrons (Y(4140))

https://www.nikhef.nl/~pkoppenb/particles.html

CMS J/ψJ/ψ cross section at 7 TeV

[J. High Energy Phys. 09 (2014) 094]





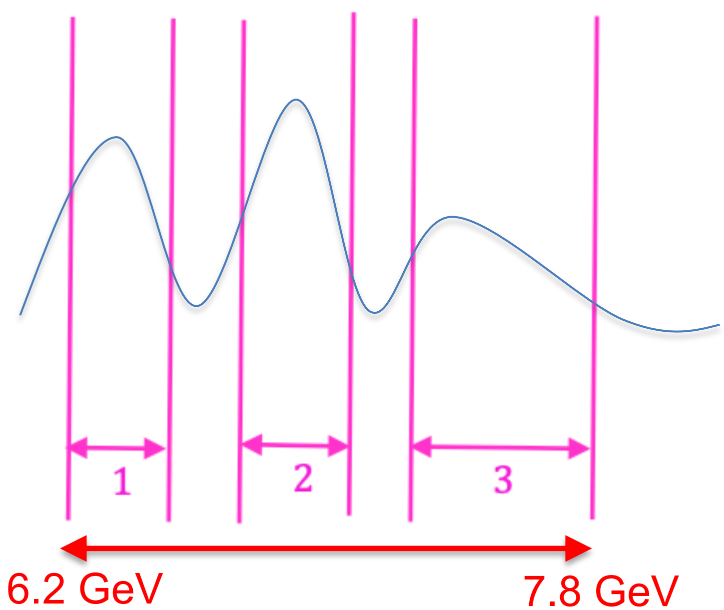
Total cross section, assuming unpolarized prompt J/ψJ/ψ pair production
1.49 ± 0.07 (stat.) ± 0.13 (syst.) nb

Different assumptions about the J/ψJ/ψ polarization imply modifications to the cross section ranging from -31% to +27%.

CMS blind mass window for 13 TeV

We saw hints at Run I data (7 TeV & 8 TeV)
Proposed three signal regions for Run II data

Signal: $X \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$



Blinded mass windows for Run II:

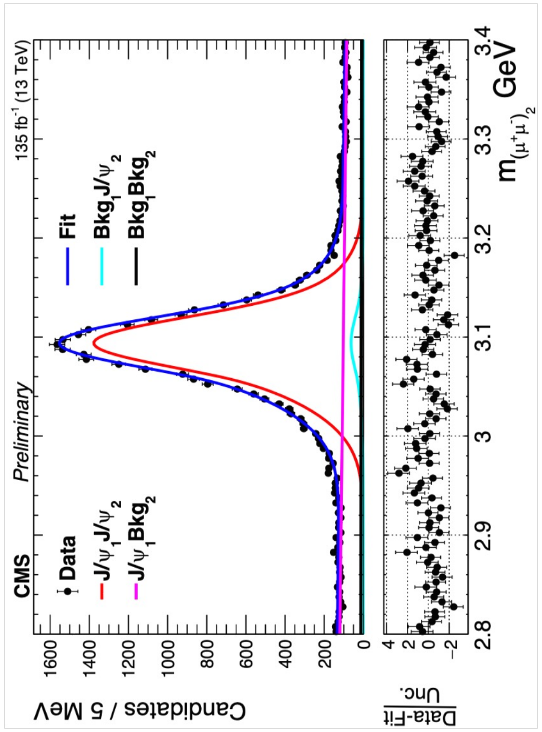
1. [6.3,6.6] GeV
2. [6.8,7.1] GeV
3. [7.2,7.8] GeV
   (for potential wide structure)

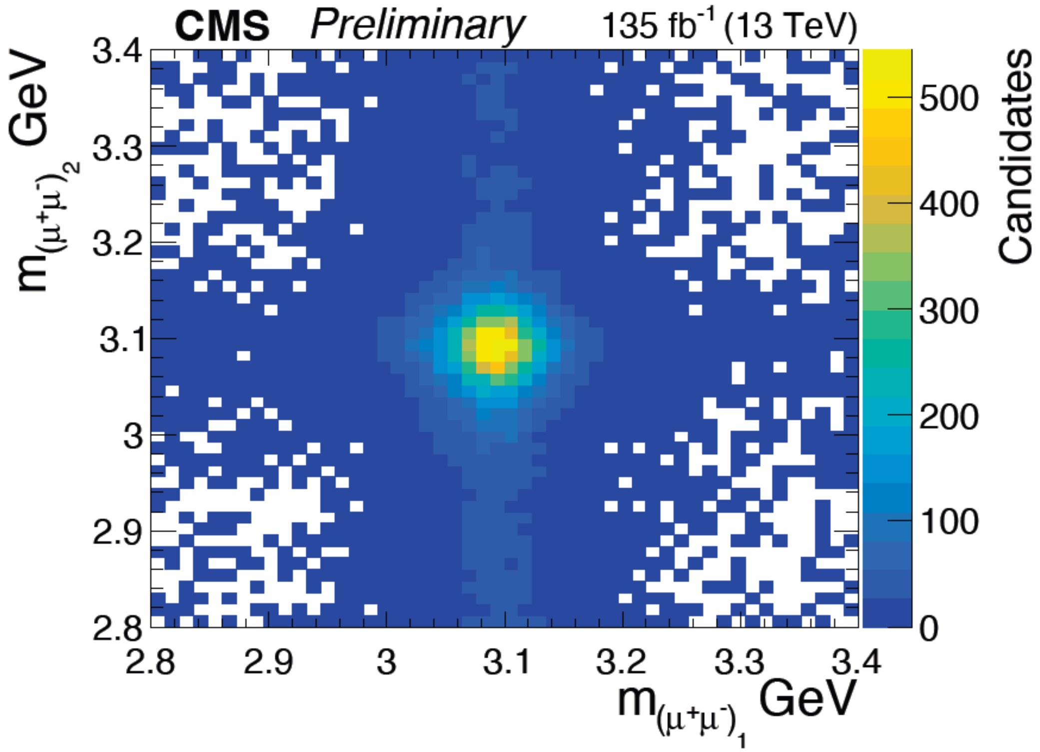
These mass windows will be windows for LEE for potential structures

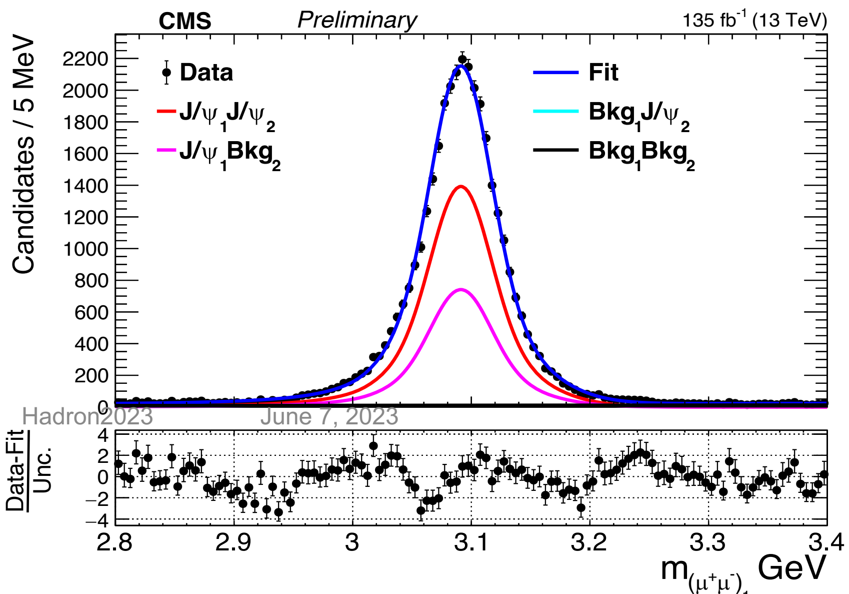
Run I data will be ignored for significance calculation

CMS eventually decide to blind the whole region: [6.2, 7.8] GeV after LHCb released their result (13 TeV, 2020)

CMS J/ψJ/ψ candidates at 13 TeV

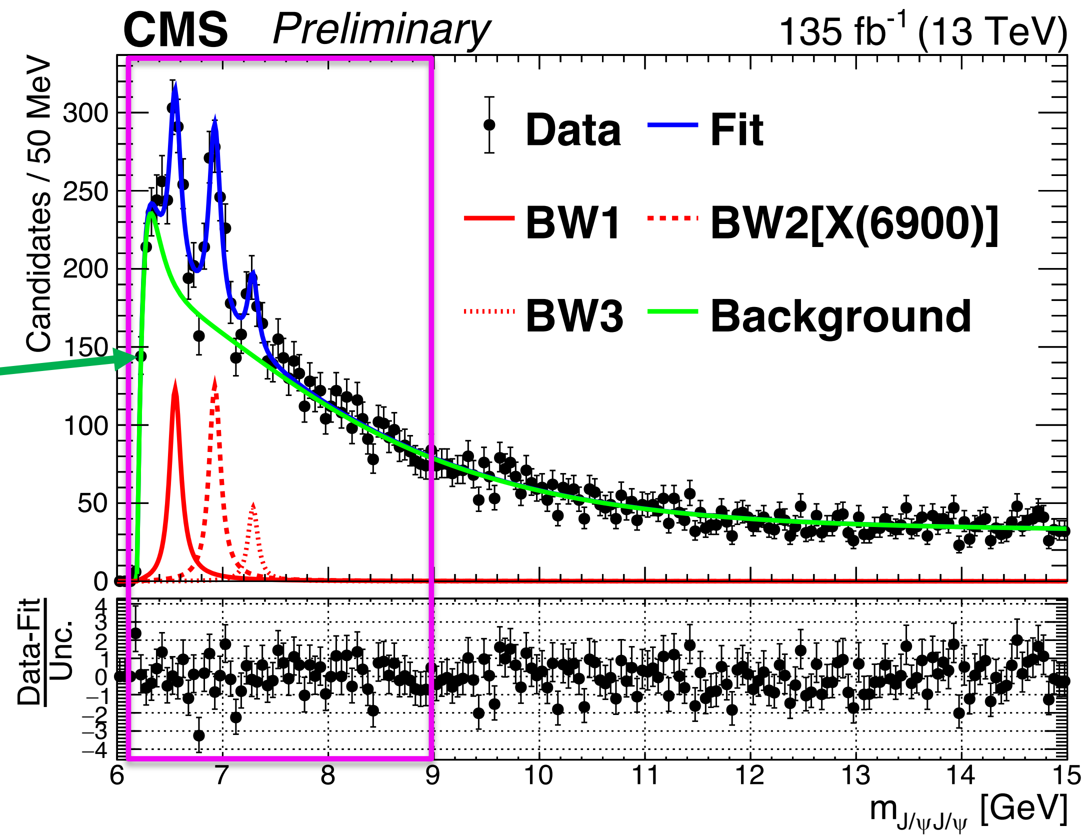






- CMS data: 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs
- J/ψ mass and vertex related cuts removed
- Clean J/ψ signals are seen

CMS background (SPS + DPS + BW0)



CMS background (SPS + DPS + BW0)

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

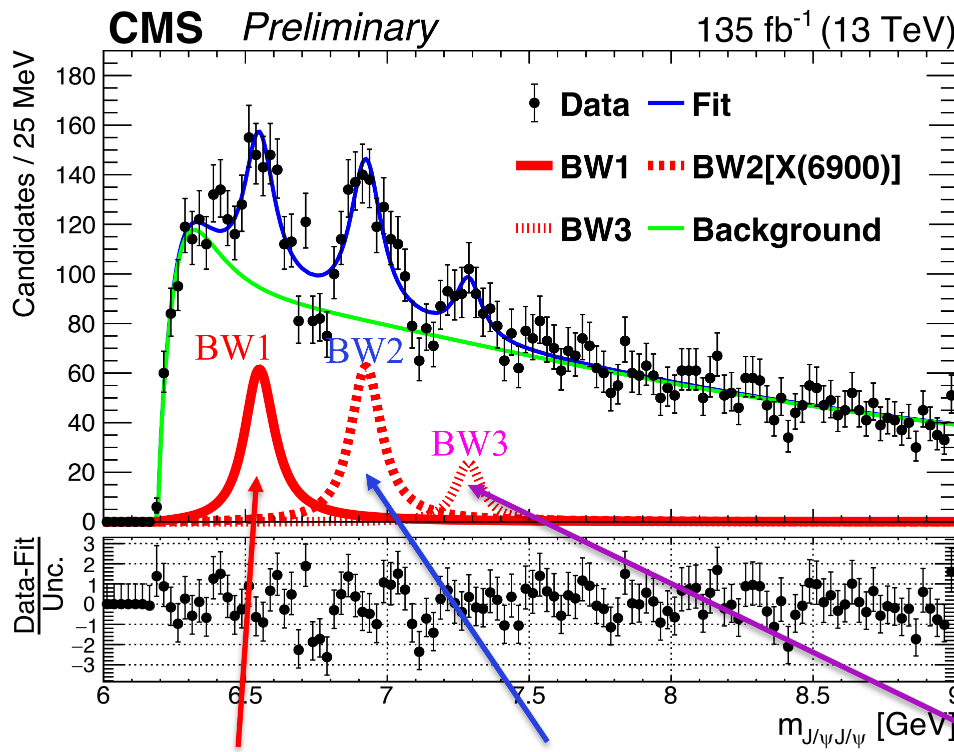
[6.2,15] GeV

- Most significant structure is a BW at threshold, BW0--what is its meaning?
- Treat BW0 as part of background due to:
  - BW0 parameters very sensitive to SPS and DPS model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…
- SPS+DPS+BW0 as our background

CMS model: 3 BWs + Background

χ^2 Prob. = 1%

[6.2,7.8] GeV

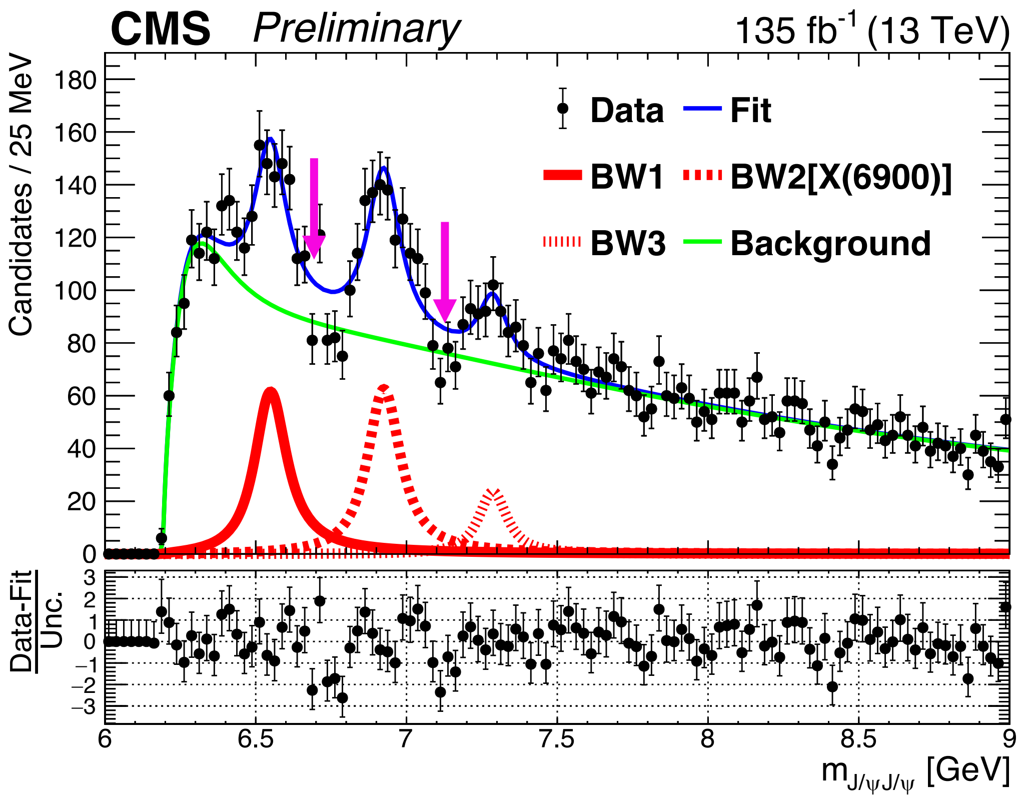


Statistical significance based on:

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

	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
σ(stat.)	6.5	9.4	4.1
σ(stat. + syst.)	5.7	9.4	4.1
	Observation	Confirmation of X(6900) from LHCb	Evidence

The dips



- ➢ Possibility #1:
- Interference among structures?

- ➢ 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

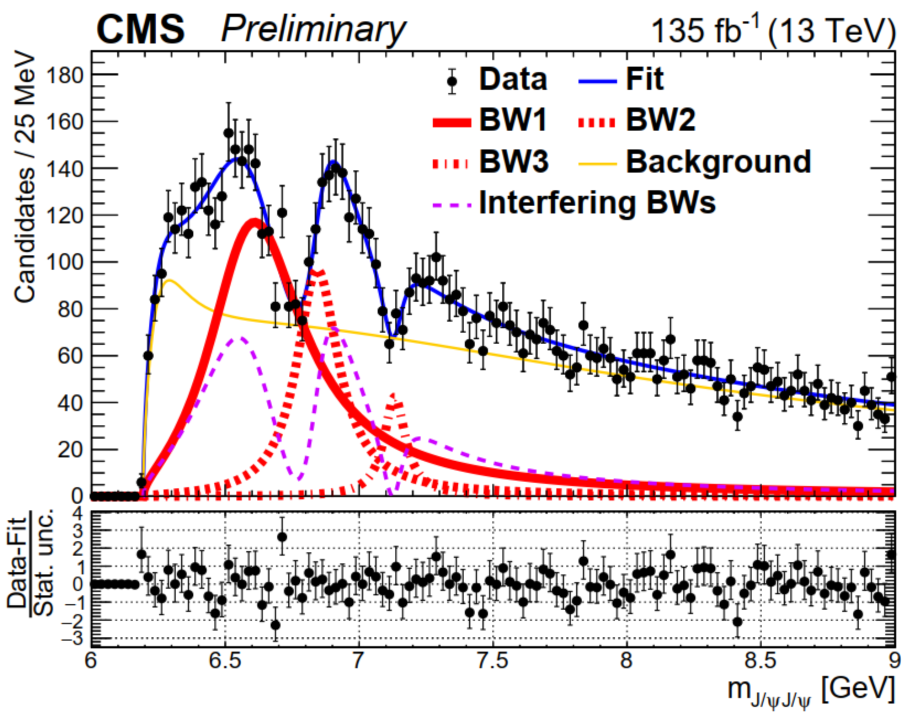
$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \otimes R(M_0)$$
$$+ N_{X\ and\ interf} \cdot \boxed{|r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2}$$
$$+ N_{NRSPS} \cdot f_{SPS}(m) + N_{NRDPS} \cdot f_{DPS}(m) \cdot$$

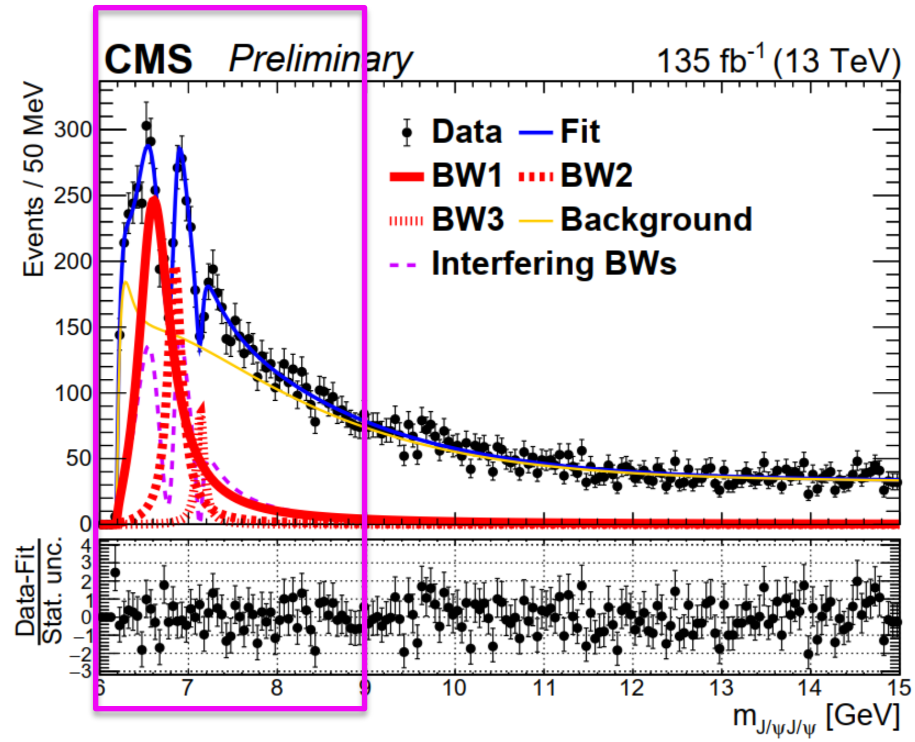
- Studied many ways interference due to possible J^{PC} and quantum coherence
  - 2-object-interference among BW0, BW1, BW2, BW3
  - 3-object-interference among BW0, BW1, BW2, BW3
  - 4-object-interference among BW0, BW1, BW2, BW3

Final CMS choice: interference among BW1, BW2, BW3

CMS interference fit

CMS PAS BPH-21-003



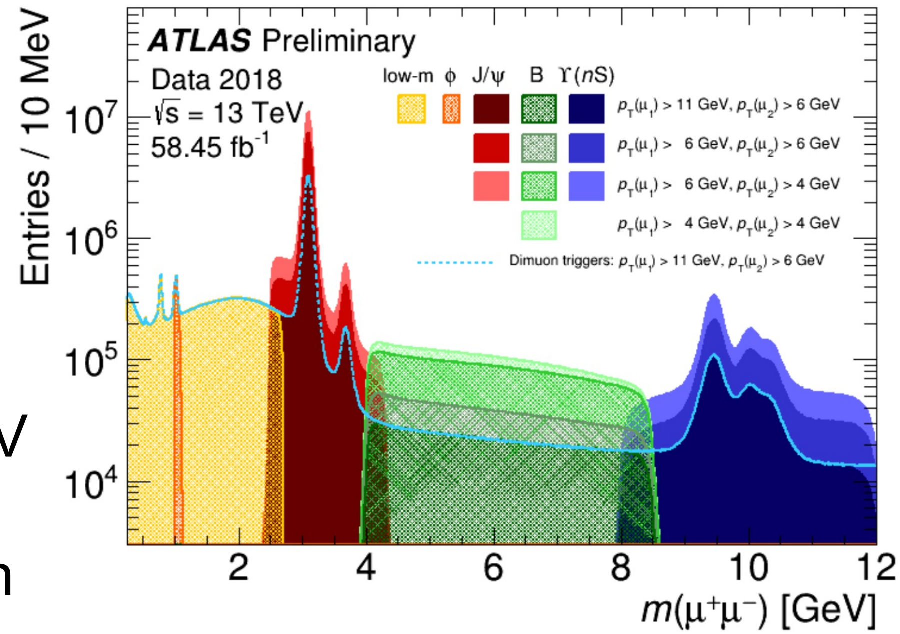


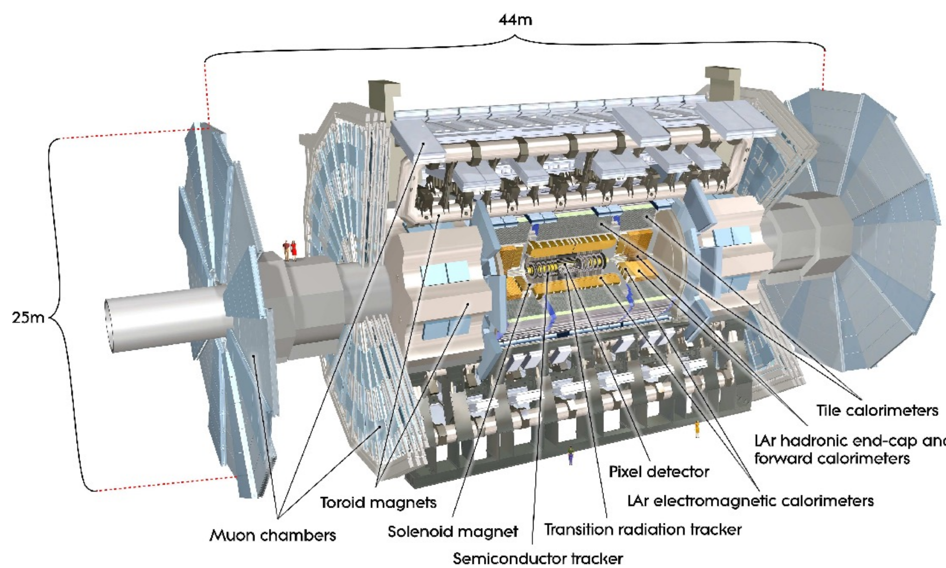
- Fit with interf. among BW1, BW2, and BW3 describes data well
- Measured mass and width in the interference fit

		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}

B physics at ATLAS

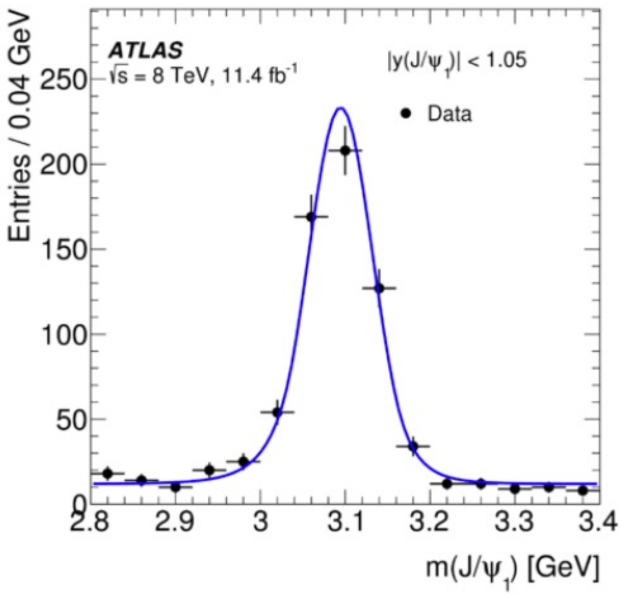
- ATLAS has collected a large set of data
  - Run 1 (2010-2013): $4.9fb^{-1}$ at 7 TeV and $20.3fb^{-1}$ at 8 TeV
  - Run 2 (2015-2018): $139fb^{-1}$ at 13 TeV
- Analysis focus mostly on final states with muons.
- Dedicated B-physics triggers.
- Excellent track and muon identification with the goodness of the inner detector and muon spectrometer.

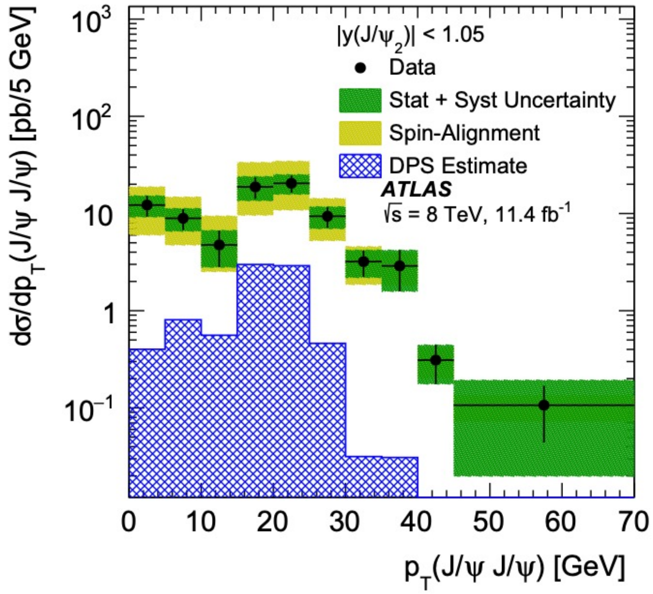


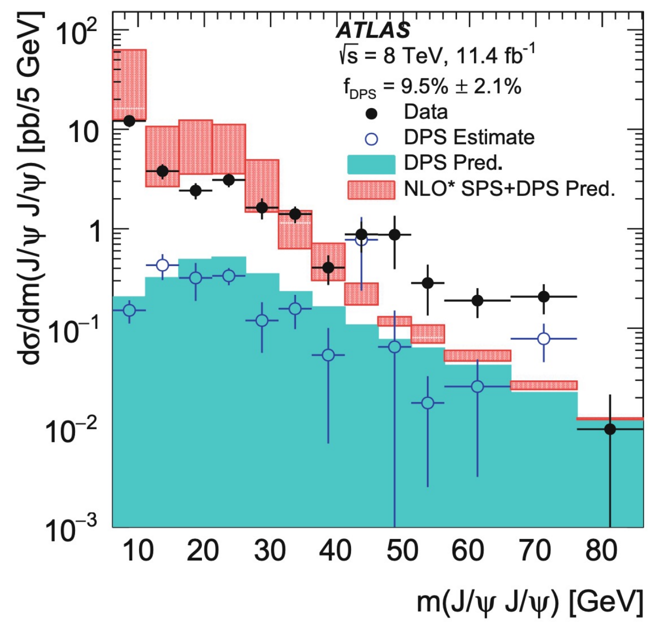


ATLAS J/ψJ/ψ measurement at 8 TeV

EPJC 77 (2017) 76







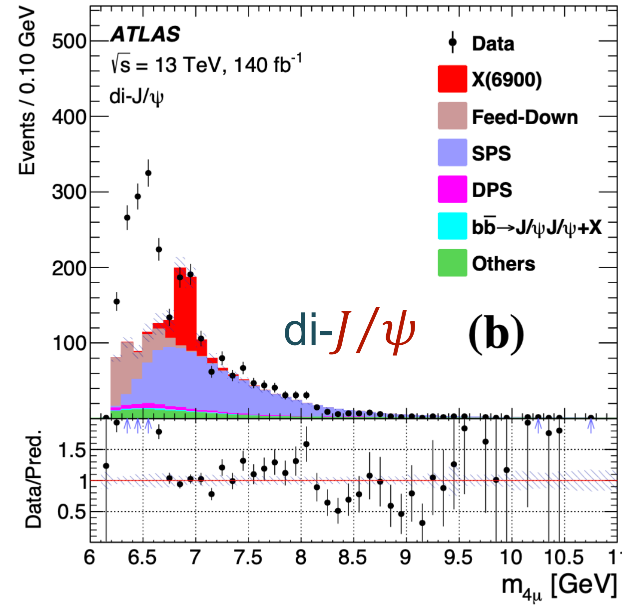
82.2 ± 8.3 (stat) ± 6.3 (syst) ± 0.9 (BF) ± 1.6 (lumi) pb in the central region and
78.3 ± 9.2 (stat) ± 6.6 (syst) ± 0.9 (BF) ± 1.5 (lumi) pb in the forward region
（assumes unpolarised *J*/ψ mesons and does not include the *J*/ψ spin-alignment systematic uncertainty）

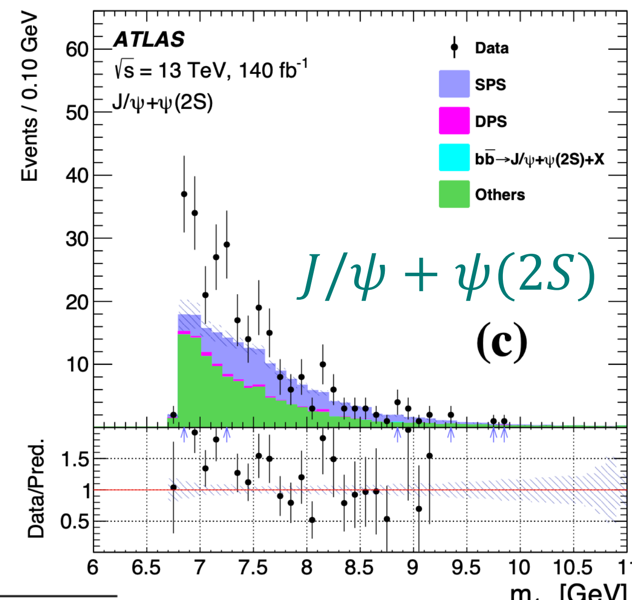
f_{DPS} = (9.2 ± 2.1 (stat) ± 0.5 (syst))%

σ_{eff} = 6.3±1.6(stat)±1.0(syst)±0.1(BF)± 0.1 (lumi) mb

Hunt for di-J/ψ resonances by ATLAS at 13 TeV

- Signal: $T_{cc\overline{cc}} \to J/\psi + J/\psi \quad or \quad J/\psi + \psi(2S) \to 4\mu$
- Backgrounds:
  - Prompt: SPS and DPS
  - Non-prompt: $b\bar{b} \to J/\psi + J/\psi/\psi(2S) + X \to 4\mu$
  - Others: Single J/ψ background and non-peaking background containing no real J/ψ candidate
- **Excess in both channels**
- The unbinned maximum likelihood fits are performed in the 4μ mass spectrum.
  - The signal pdf: several interfering BW multiplied with a phase space factor and convolved with a mass resolution function

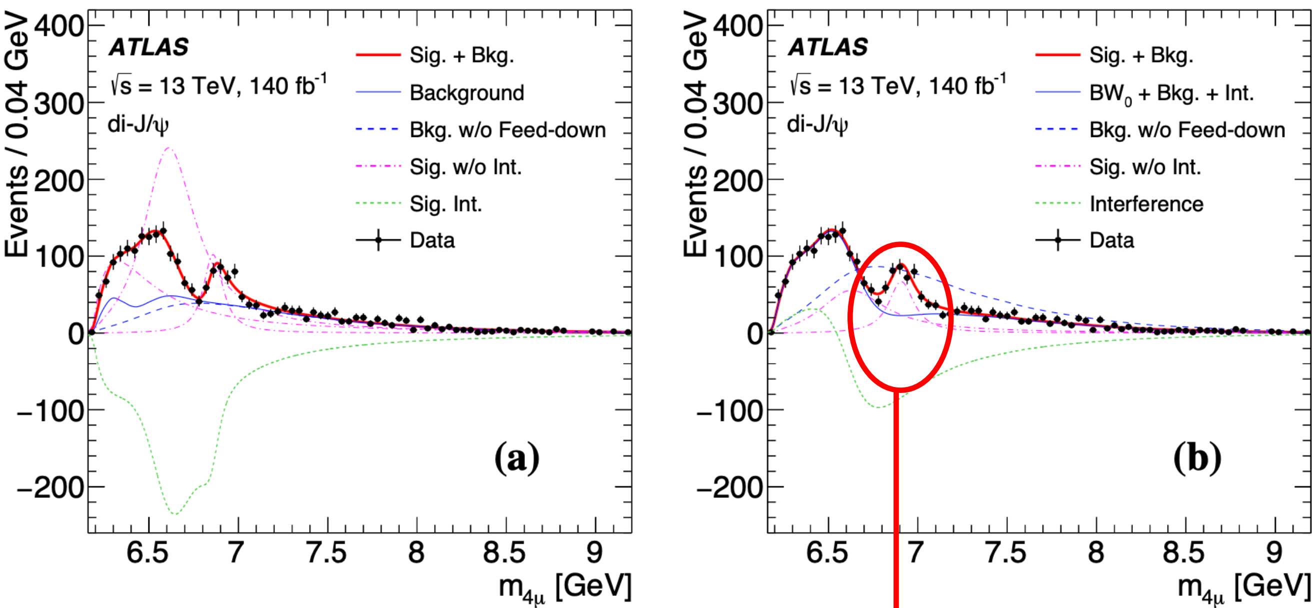




di-J/ψ : $$f_s(x) = \left|\sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i}\right|^2 \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\alpha)$$

$J/\psi + \psi(2S)$: $$f_s(x) = \left(\left|\sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i}\right|^2 + \left|\frac{z_3}{x^2 - m_3^2 + i m_3 \Gamma_3}\right|^2\right) \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x}\right)^2} \otimes R(\alpha)$$

ATLAS di-J/ψ channel



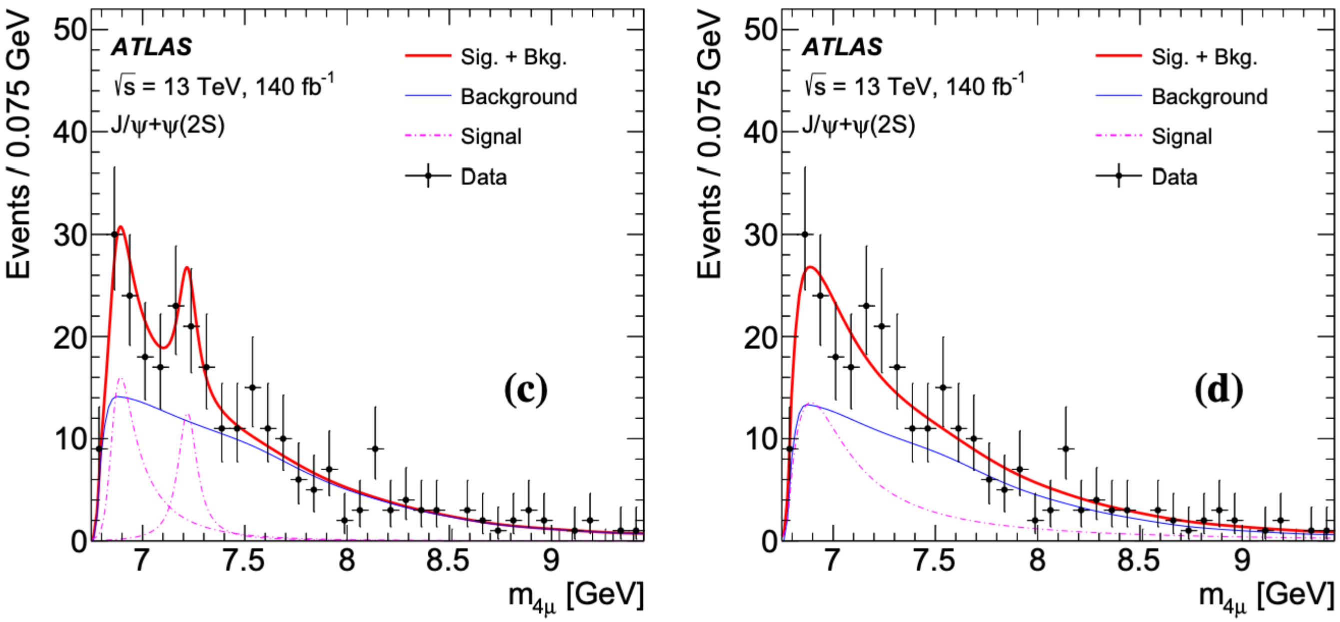
Extracted masses and widths (GeV)

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

X(6900) > 5σ

- Model A: analogous to LHCb model I, but 2 auxiliary BWs interfere with X(6900)
- Model B: analogous to LHCb model II, one auxiliary BW interferes with NRSPS
- Both models describe the data well
  - the broad structure at the lower mass could result from other physical effects, such as the feed-down
- The 3rd peak mass is consistent with the LHCb observed X(6900), with significance > 5σ

ATLAS $J/\psi + \psi(2S)$ channel



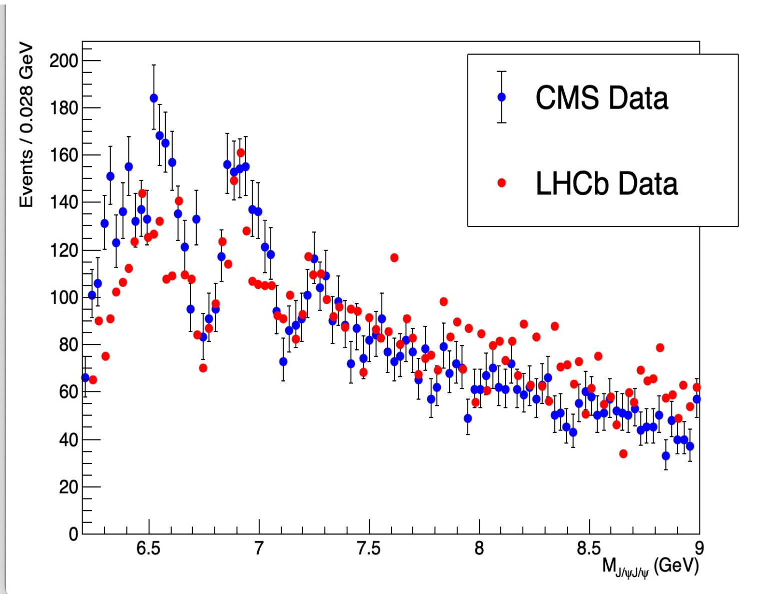
- Model α: X(6900)+2nd resonance
  - Two bumps together: 4.7 σ
  - 2nd bump alone: 3 σ
- Model β: a single resonance X(6900) in this channel
  - 4.3 σ

Extracted masses and widths (GeV)

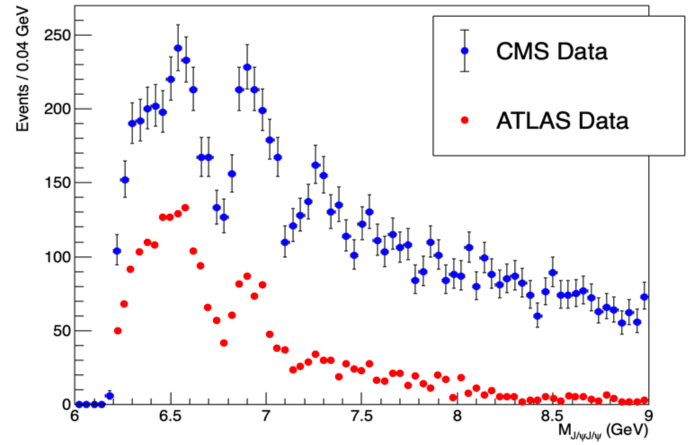
J/ψ+ψ(2S)	model α	model β
m_3 or m	$7.22 \pm 0.03^{+0.01}_{-0.03}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3 or Γ	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$

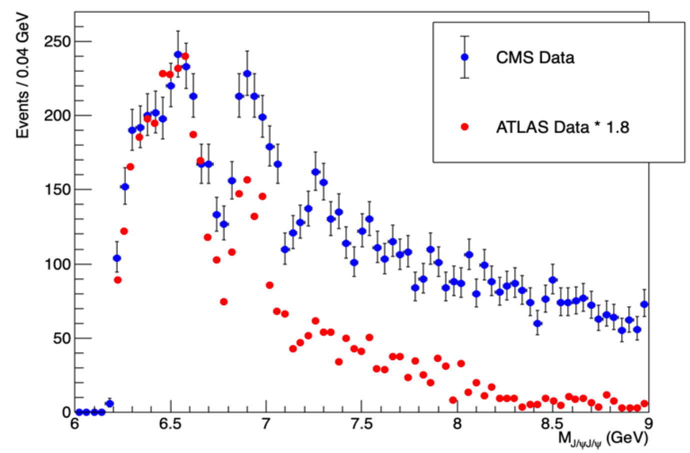
ATLAS-CMS-LHCb data comparison

Disclaimer: comparison plots in this page are not made by ATLAS/CMS/LHCb (taken from https://indico.cern.ch/event/1158681/contributions/5162594/)



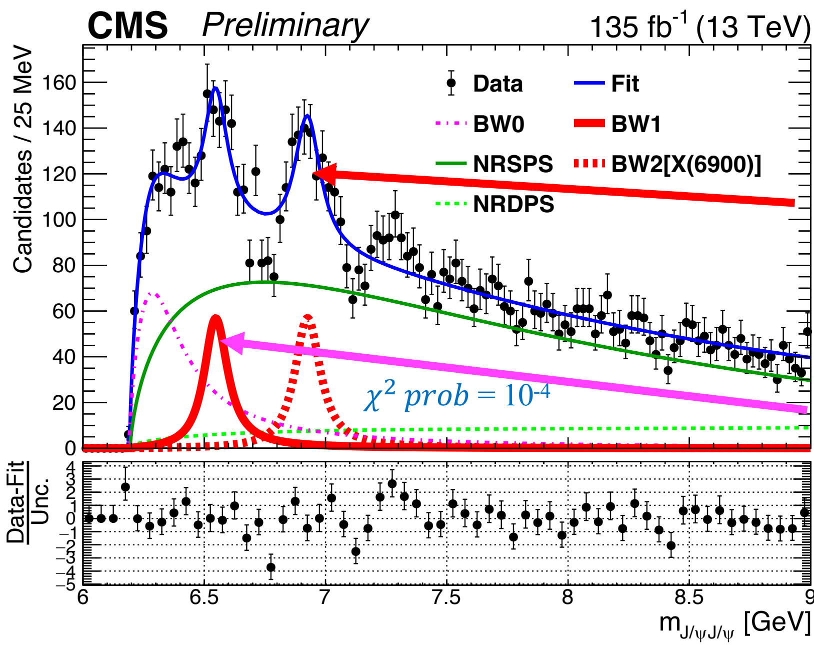
- Comparing with LHCb, CMS has:
  - 135/(3+6) ≈ 15X int. lum.
  - $(5/3)^4$ ≈ 8X muon acceptance
  - Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
  - Similar number of final events, but much less DPS
  - 2X yield @CMS for X(6900)



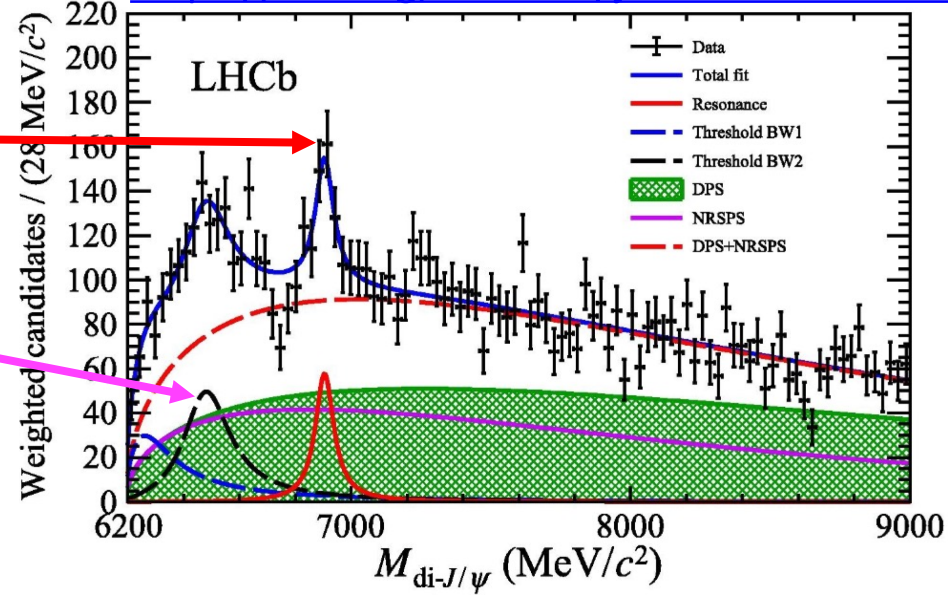


- Comparing with CMS, ATLAS has:
  - 1/3 –1/2 of CMS data (trigger?)
  - dR cut—remove high mass events

Fit CMS data with LHCb model I： 2 auxiliary BWs + X(6900) + bkg



https://doi.org/10.1016/j.scib.2020.08.032



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

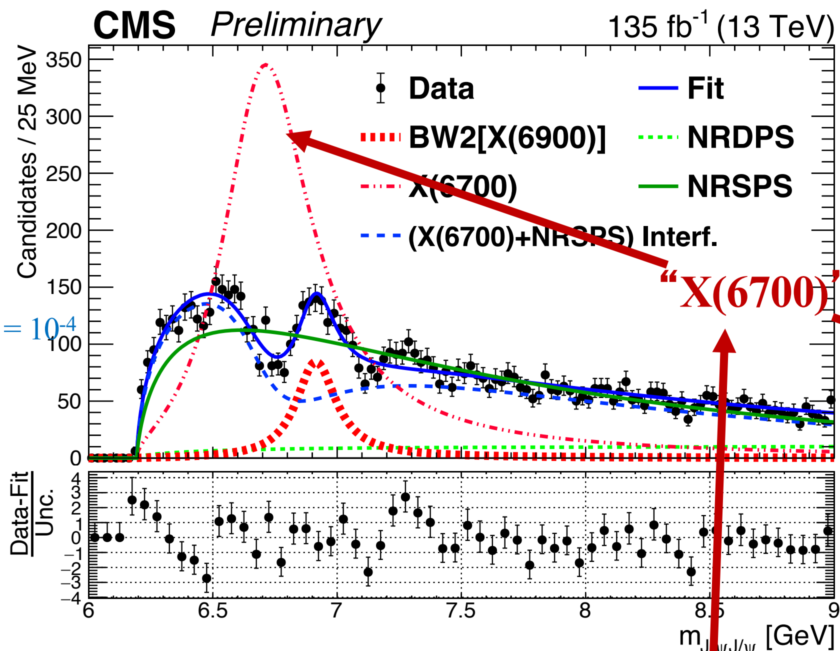
BW2 are in good agreement with LHCb X(6900)

- LHCb did not give parameters for BW1
  - CMS has a shoulder before BW1
  - helps make BW1 distinct
- ***Does not describe 2 dips well***

CMS and LHCb Fit Comparison - 2

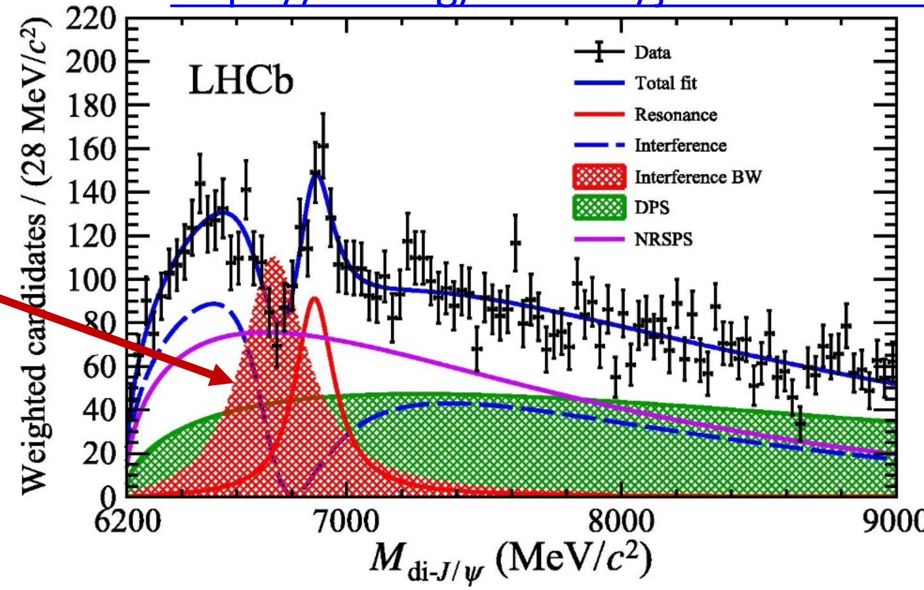
Fit CMS data with LHCb model II : "X(6700)" interferes with NRSPS + X(6900) + Bkg

https://doi.org/10.1016/j.scib.2020.08.032



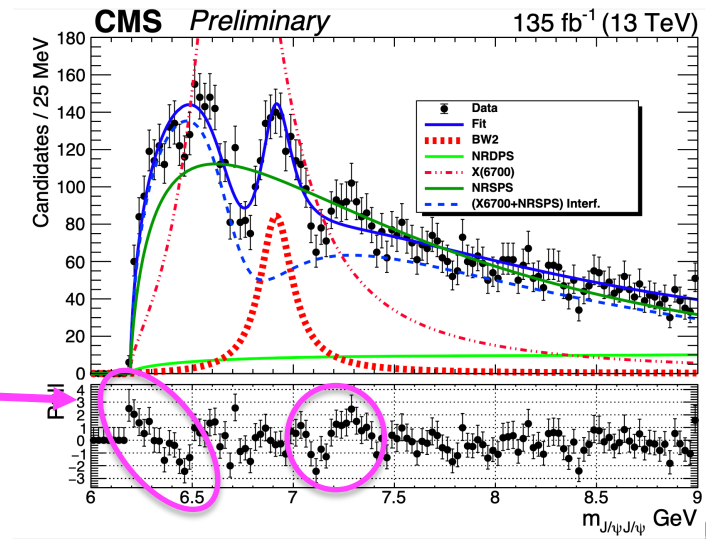
χ^2 prob = 10^{-4}

"X(6700)"

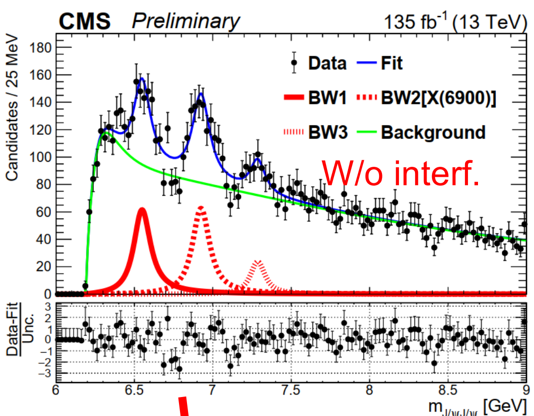


Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

- CMS obtained larger amplitude and wider width for X(6700)
- Does not describe X(6600) and below
- Does not describe X(7200) region



Comparison with some theoretical calculations



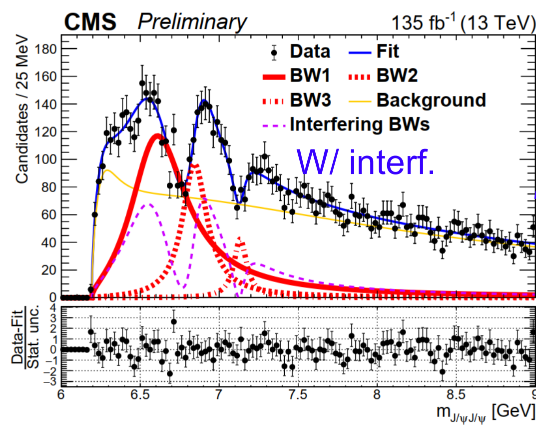


Table 1. Predictions of the masses (MeV) of S-wave fully heavy $T_{4Q}(nS)$ tetraquarks. Only 0^{++} and 2^{++} are considered for $T_{bc\bar{b}\bar{c}}$. The uncertainty is from the coupling constant $\alpha_s = 0.35 \pm 0.05$.

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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}	[illegible]$^{+34}_{-35}$	[illegible]$^{+27}_{-26}$	[illegible]$^{+21}_{-22}$
$T'_{cc\bar{c}\bar{c}}$	0^{++}	5984^{+64}_{-67}	6468[illegible]	6[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	64[illegible]9	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	657[illegible]	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	69[illegible]1	-	-
2^5P_1	1^{--}	398.7	689.5	-263.4	548.6	-5.6	-69.3	-24.2	-1.7	684[illegible]	-	-
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	-	-

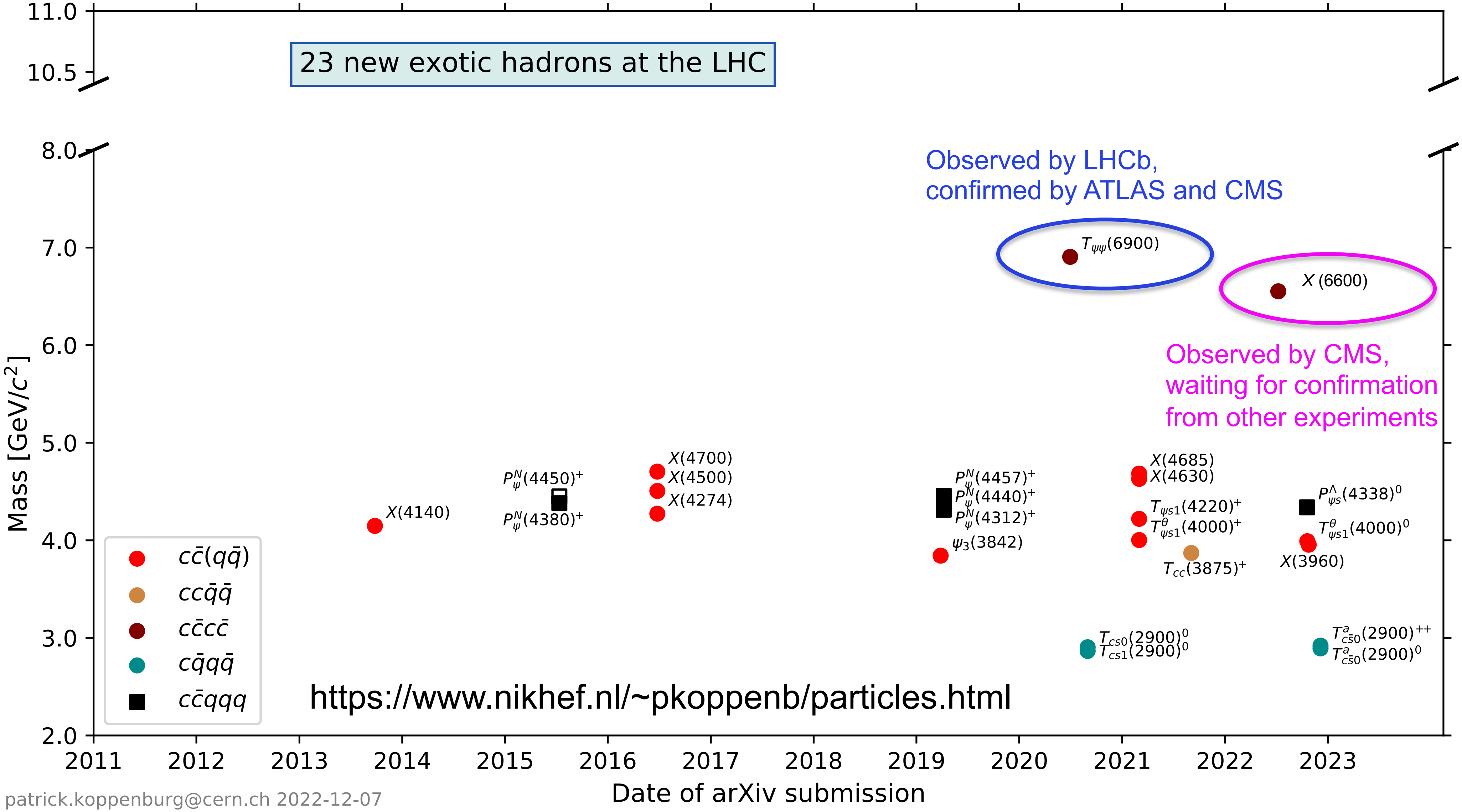
arXiv:2108.04017 **[hep-ph]**

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?

New exotic hadrons at LHC



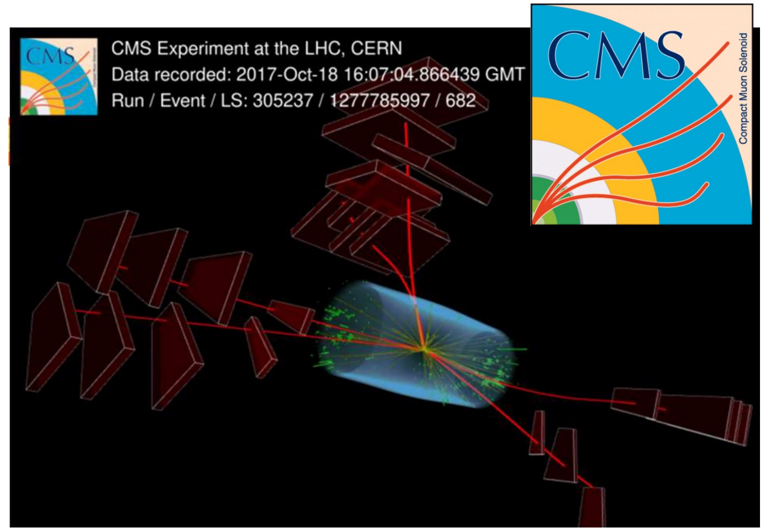
First observation of triple J/ψ production

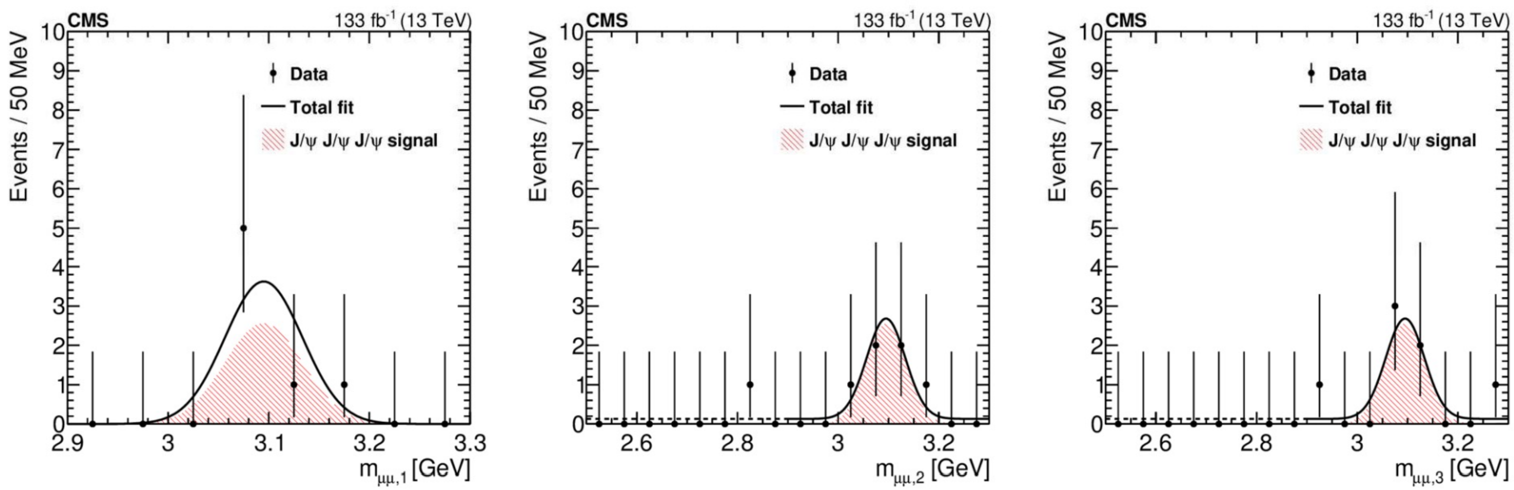
Signal yield: $5^{+2.6}_{-1.9}$events

Significance > 5σ

σ(pp→J/ψJ/ψJ/ψX)
= 272 +141−104 (stat) ± 17 (syst) fb

Nature Physics 19 (2023) 338

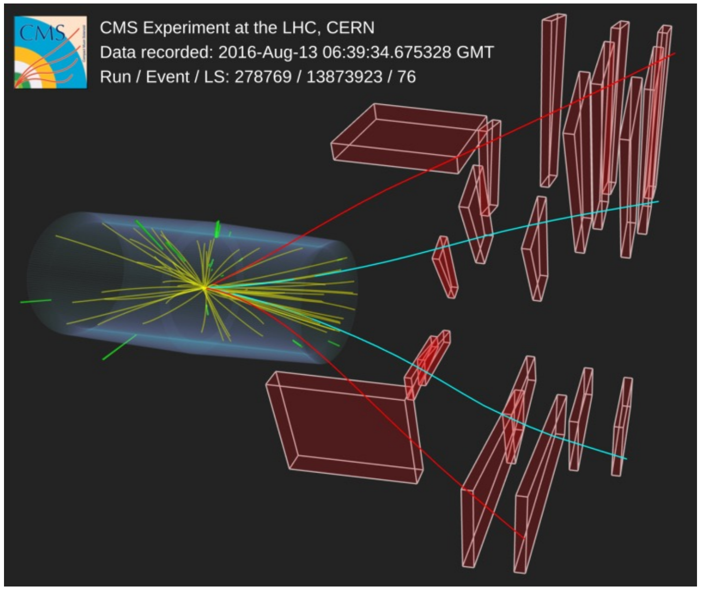




“6c” search in future?

Summary

- All-heavy quark exotic structures offer a system easier to understand
  - A new window to understand strong interaction
- CMS found 3 significant structures in di-J/ψ mass spectrum
  - X(6900) consistent with LHCb
  - **First observation of X(6600)** and evidence of X(7300) in di-J/ψ
  - Dips in data show possible interference effects
  - **A family of structures which are candidates for all-charm tetra-quarks!**



X(6600) event display

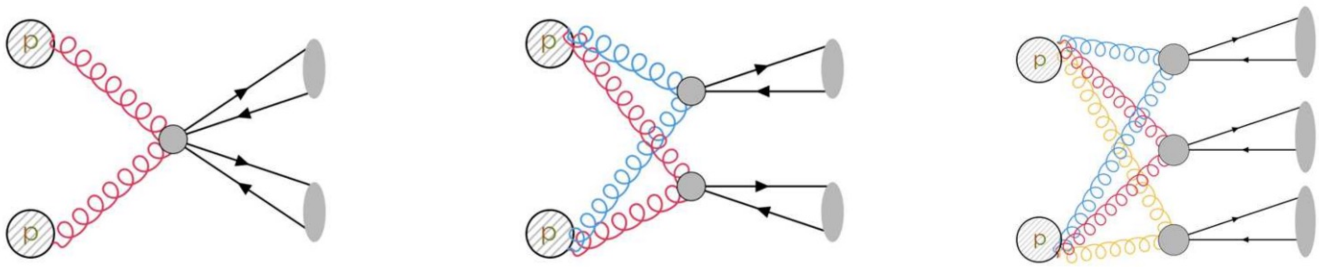
- ATLAS found significant excess in di-charmonium mass spectrum
  - X(6900) and low mass consistent with LHCb in di-J/ψ channel
  - Evidence of structures in the J/ψ+ψ(2S) channel
- Triple J/ψ production has also been observed for the first time
- First observation of J/ψ+Υ(1S) in pp collisions by LHCb last month (arXiv:2305.15580)

Backup

Associated quarkonium production

- Study interplay of soft QCD with (semi)hard QCD and EW physics
- Sensitivity to perturbative heavy flavor generation and nonperturbative initial and final state effects

  - Initial state: e.g. sensitivity to the concepts of single (SPS), double (DPS) and triple (TPS) parton scattering



parameterized by σ_{eff}

$$\sigma_{\rm DPS}^{AB} = \frac{1}{1+\delta_{AB}} \frac{\sigma^A \sigma^B}{\sigma_{\rm eff}}$$

  - Final state: e.g. sensitivity to heavy flavour hadron formation (colour singlet vs. colour octet), sensitivity to resonant multi-heavy-flavor states

Event selections

Muon selection

- $p_T(\mu^{\pm}) > 2.0$ GeV/c
- $|\eta(\mu^{\pm})| < 2.4$
- All muons are soft
- For 2017-18 years: $p_T(\mu^{\pm}) > 3.5$ GeV/c for at least one $\mu^+\mu^-$ pair, which has $vtxprob(\mu^+\mu^-) > 0.5\%$ and $2.95 < m_{\mu^+\mu^-} < 3.25$ GeV

J/ψ selection

- $2.95 < m_{J/\psi} < 3.25$ GeV
- $p_T(J/\psi) > 3.5$ GeV/c
- $vtxprob(J/\psi) > 0.5\%$
- Constrained $vtxprob(J/\psi) > 0.1\%$

J/ψJ/ψ selection

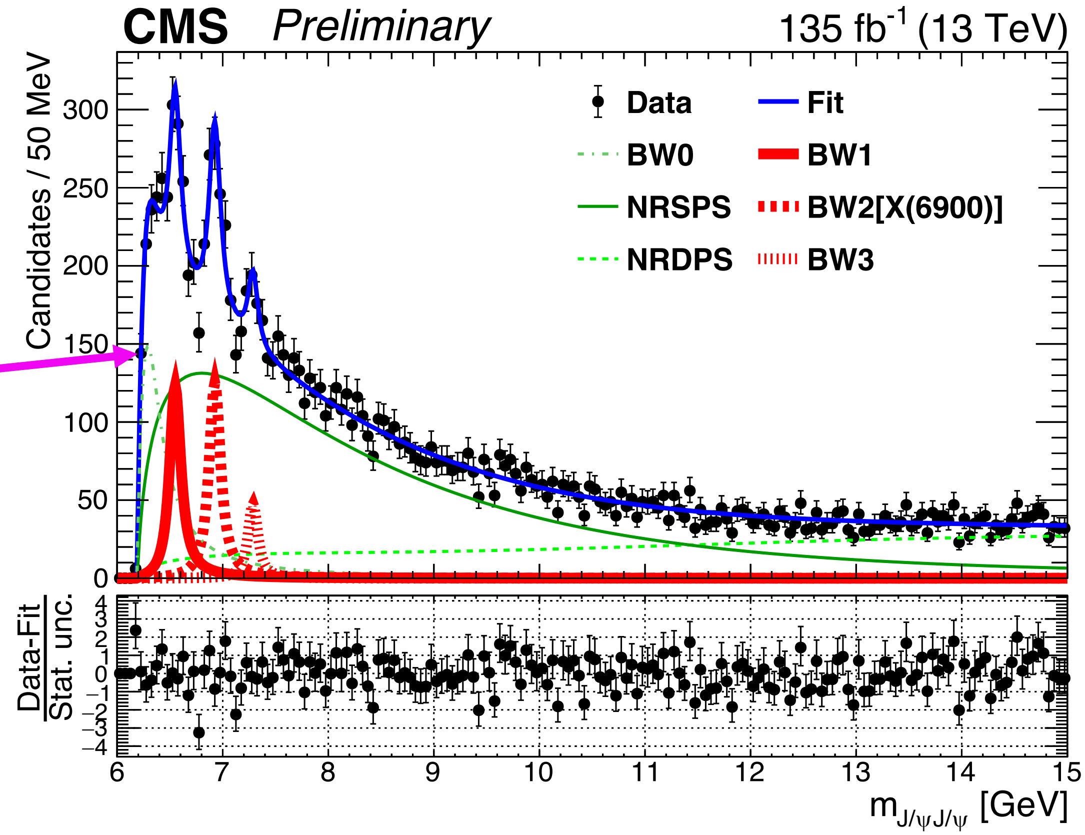
- $vtxprob(4\mu) > 0.5\%$
- $vtxprob(J/\psi J/\psi) > 0.1\%$
- Proper HLT is fired in event

Multiple candidates

- Choose the best candidate with minimum $\left(\frac{M(J/\psi_1)-M(J/\psi_{PDG})}{\sigma(M(J/\psi_1))}\right)^2+\left(\frac{M(J/\psi_2)-M(J/\psi_{PDG})}{\sigma(M(J/\psi_2))}\right)^2$ value if there are 4 muons in event, but more than one candidate (~0.2%)
- Keep all candidates if there are more then 4 muons in event (~0.2%)

Baseline mass variable – invariant mass of two constrained J/ψ candidates

CMS background (SPS + DPS + BW0)



CMS background (SPS + DPS + BW0)

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

[6.2,15] GeV

- Most significant structure is a BW at threshold, BW0--what is its meaning?
- Treat BW0 as part of background due to:
  - BW0 parameters very sensitive to SPS and DPS model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…

Significance with systematics

- To include systematics, alternative resonance/background shapes applied in the fit.
- Calculate signal- and null-hypothesis NLL_syst including systematic using:

$NLL\_(syst-sig)$ = Min{$NLL\_(nom-sig)$, $NLL\_(alt-i-sig)$+0.5+0.5·Δdof}

  - $NLL\_(nom-sig)$: the NLL of nominal 'signal hypothesis' fit.
  - $NLL\_(alt-i-sig)$: the NLL of i-th alternative fit of 'signal hypothesis'
  - Δdof: the additional free parameters comparing to the nominal 'signal hypothesis' fit.
- $NLL\_(syst-null)$ = Min{$NLL\_(nom-null)$, $NLL\_(alt-j-null)$+0.5+0.5·Δdof}
- 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*

Line shape

- S-wave relativistic Breit-Wigner (used in default fit):

$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)}, \text{where } \Gamma(m) = \Gamma_0 \frac{qm_0}{q_0 m},$$

q is the momentum of a daughter in the mother particle rest frame; q_0 means the value at peak position ($m = m_0$).

- NRSPS and NRDPS:

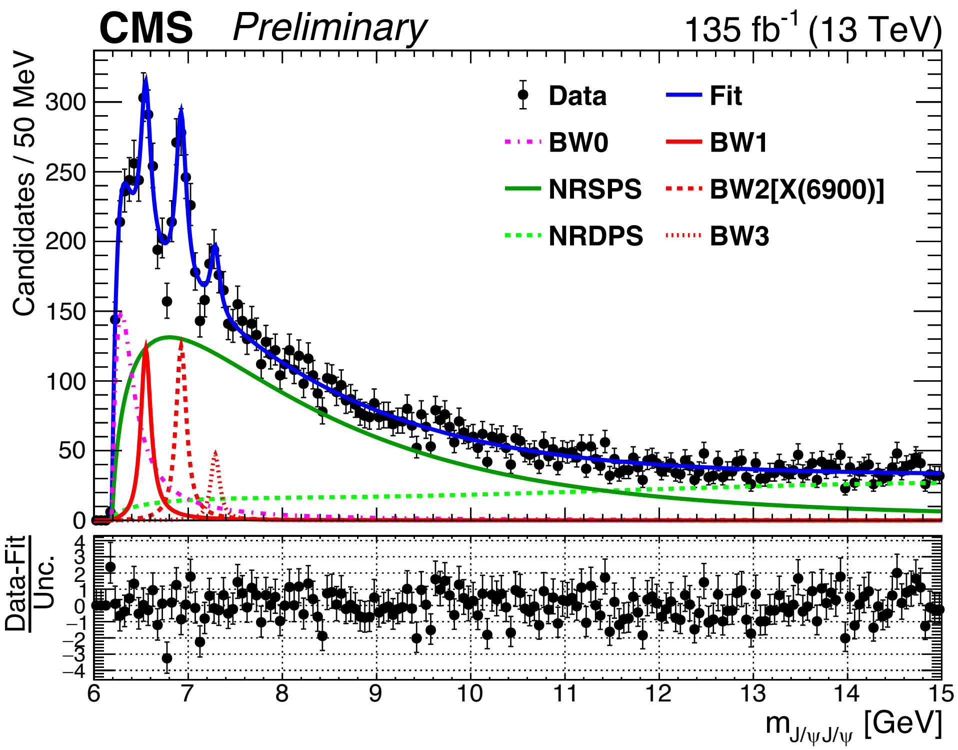
$$f_{NRSPS}(x, x_0, \alpha, p_1, p_2, p_3)$$

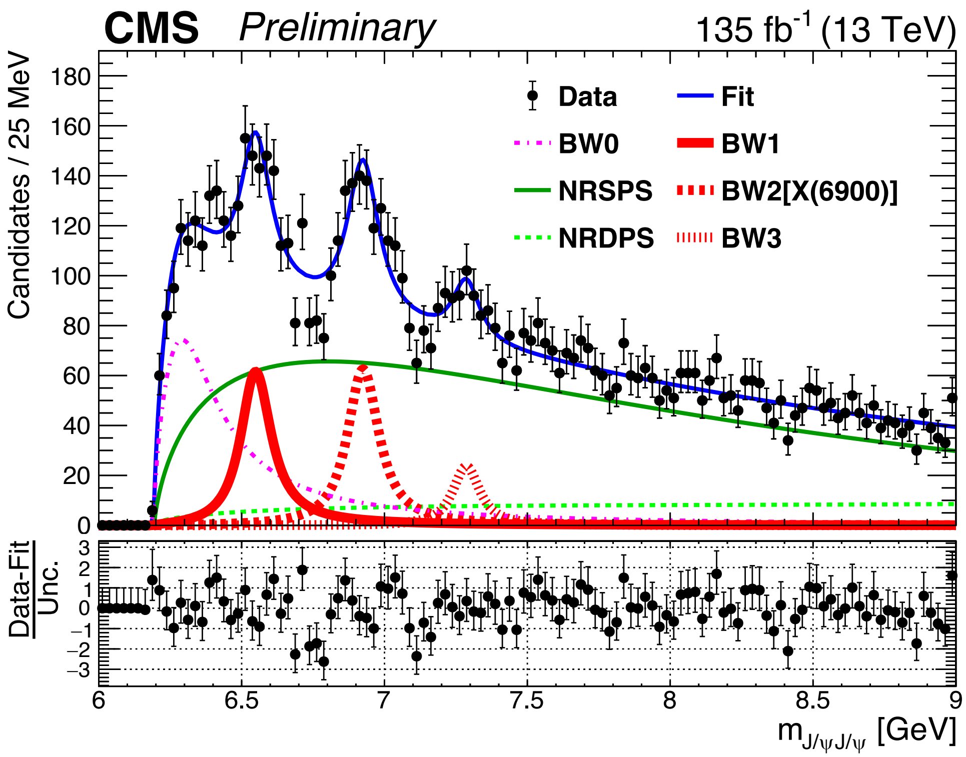
$$= (x - x_0)^{\alpha} \cdot \left(1 - \left(\frac{1}{(15 - x_0)^2} - \frac{p_1}{10}\right) \cdot (15 - x)^2\right) \cdot \exp\left(-\frac{(x - x_0)^{p_3}}{2 \cdot p_2^{p_3}}\right),$$

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

where $x_0 = 2m_{J/\psi}, x_t = x - x_0$

CMS result with BW0 explicitly shown





Significance with systematics

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

- 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

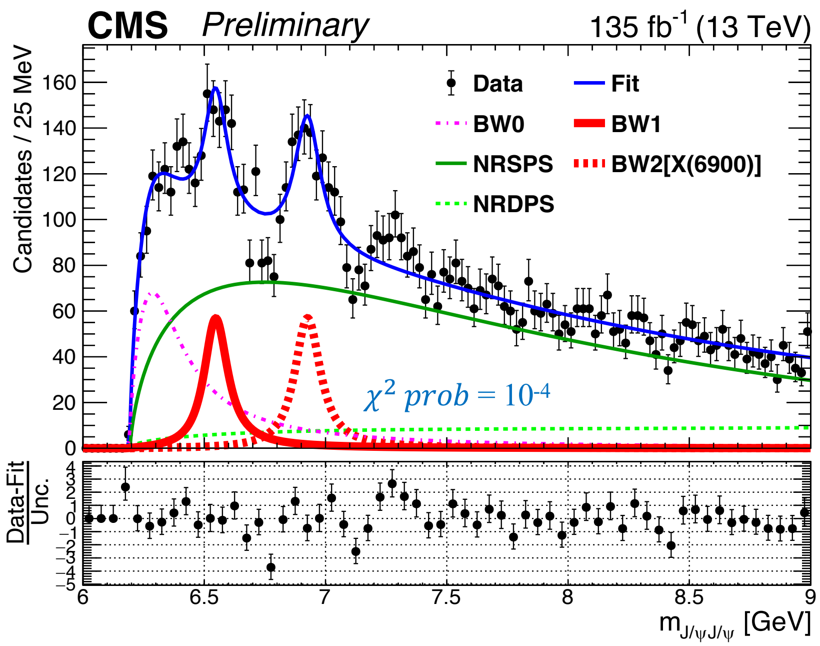
M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV	>5.7**σ**
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV	>9.4**σ**
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV	>4.1**σ**

Systematic uncertainties for interf. case

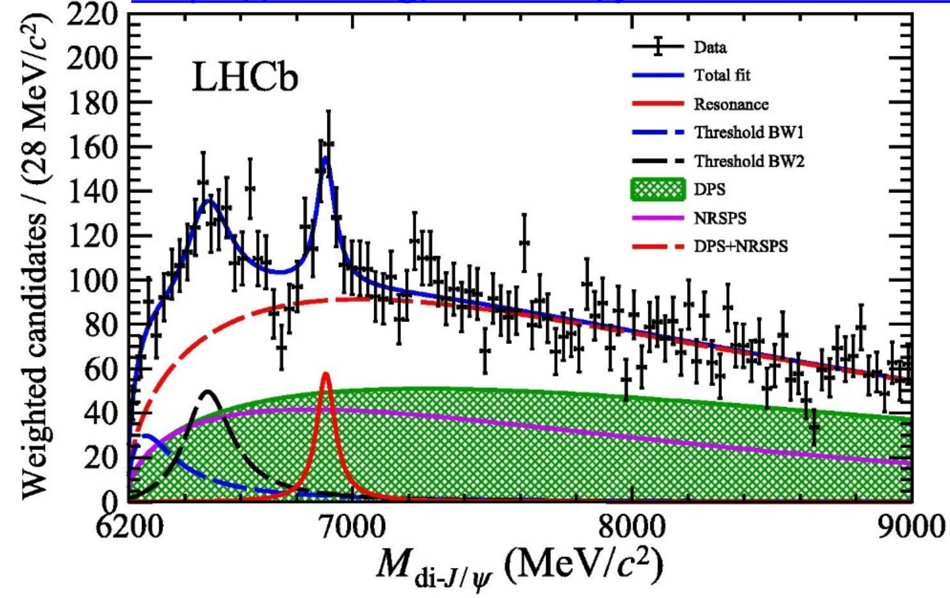
Fit	Dominant sources	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta\Gamma_{BW1}$	$\Delta\Gamma_{BW2}$	$\Delta\Gamma_{BW3}$
Interference	Signal shape	7	12	7	56	8	7
	NRDPS	1	3	2	18	6	2
	NRSPS	9	14	13	85	9	20
	Resolution	8	4	1	24	7	13
	Combinatorial bkg.	7	2	< 1	5	3	2
	Feeddown shape	-27	$+44$	$+38$	-208	$+19$	$+12$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

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

Fit CMS data with LHCb model I： 2 auxiliary BWs + X(6900) + bkg



https://doi.org/10.1016/j.scib.2020.08.032



Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
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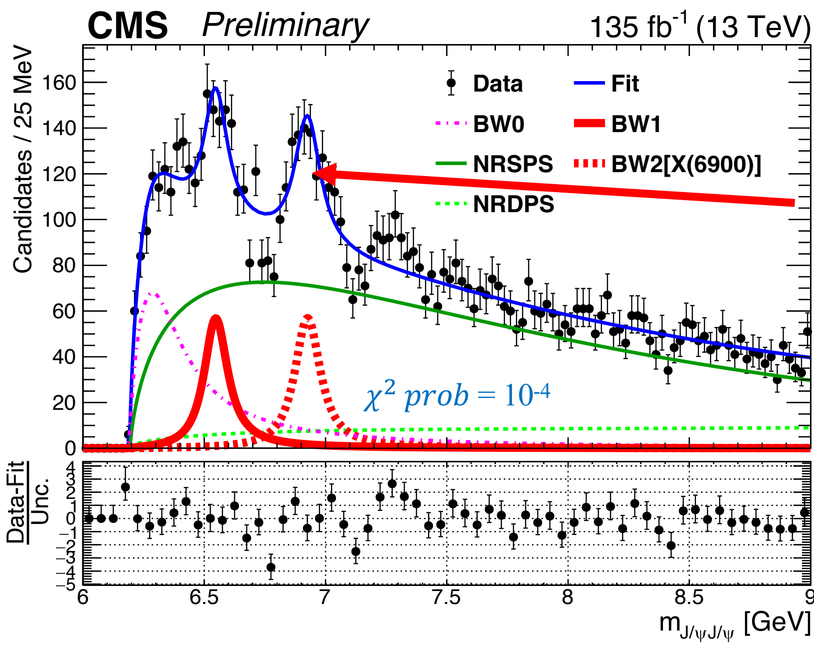
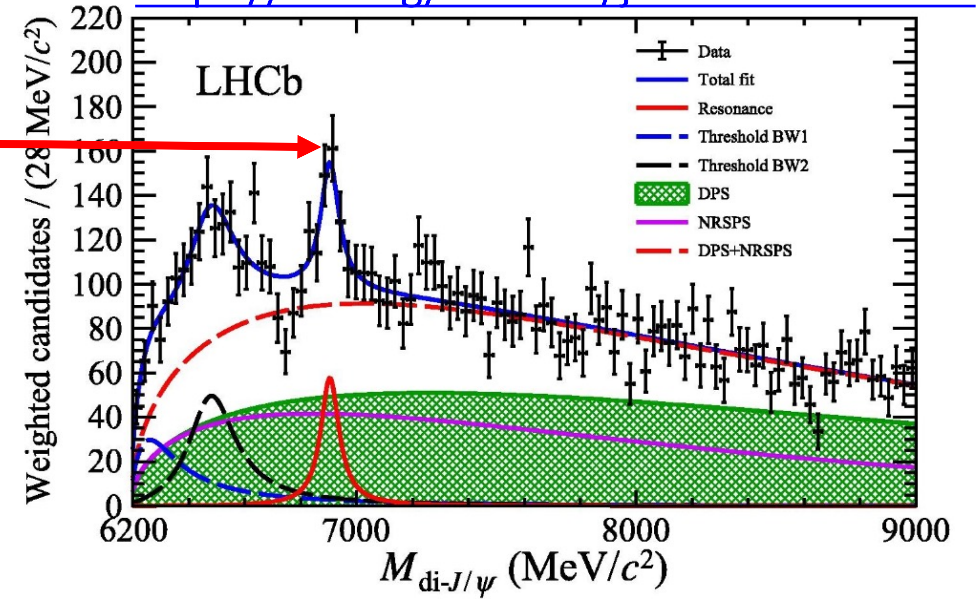
Fit CMS data with LHCb model I： 2 auxiliary BWs + X(6900) + bkg



X(6900)
BW2

https://doi.org/10.1016/j.scib.2020.08.032



Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
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CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

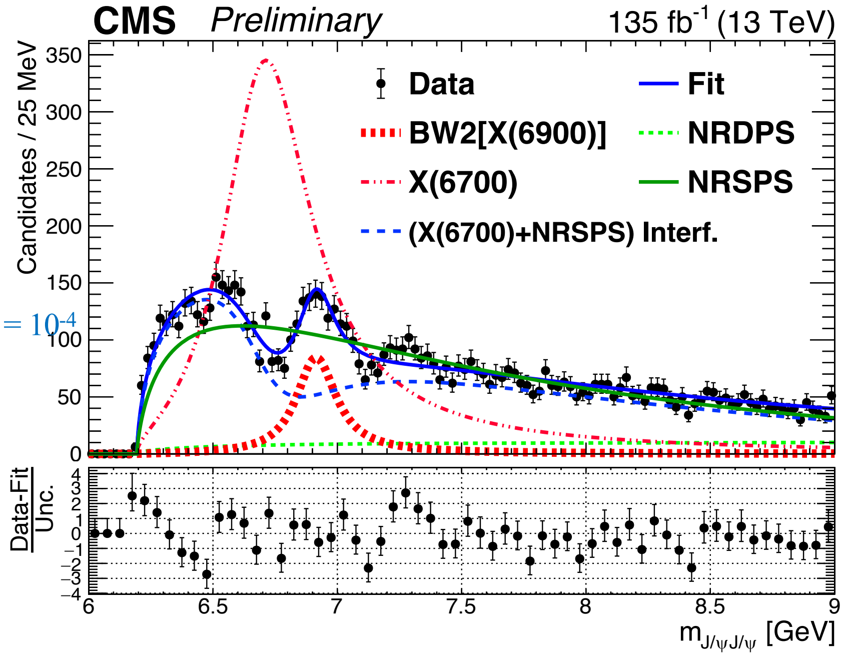
BW2 are in good agreement with LHCb X(6900)

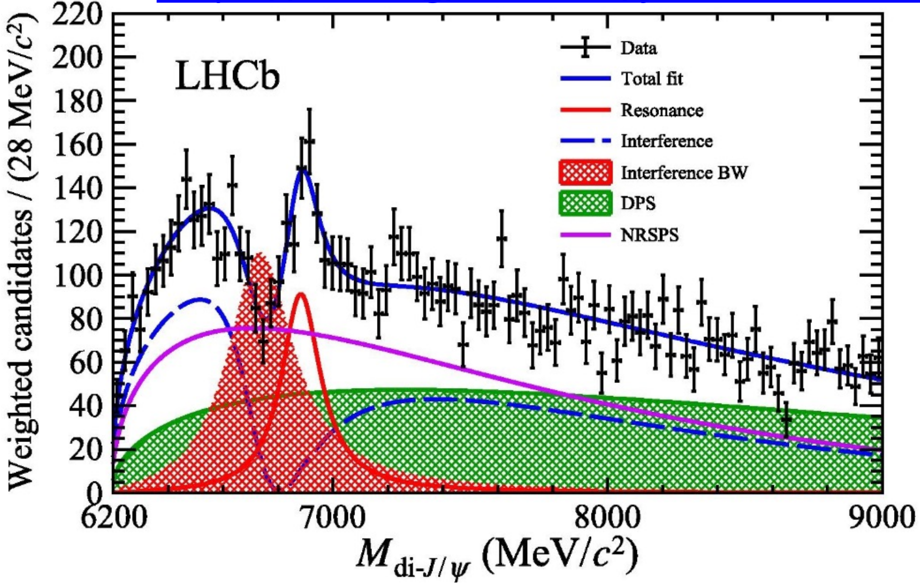
CMS and LHCb Fit Comparison - 2

Fit CMS data with LHCb model II : "X(6700)" interferes with NRSPS + X(6900) + Bkg

https://doi.org/10.1016/j.scib.2020.08.032

$\chi^2\ prob = 10^{-4}$



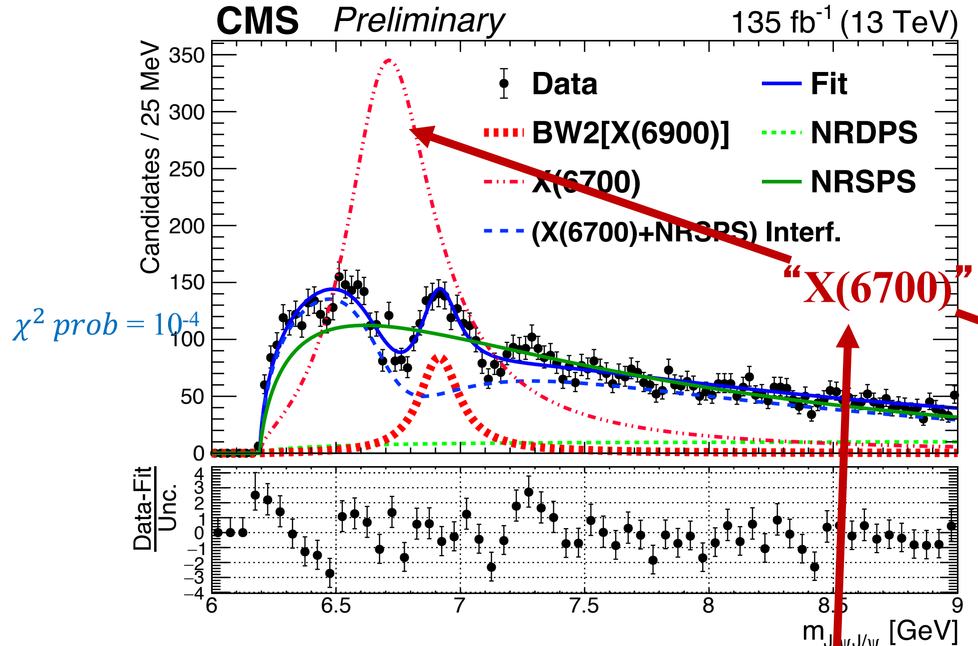


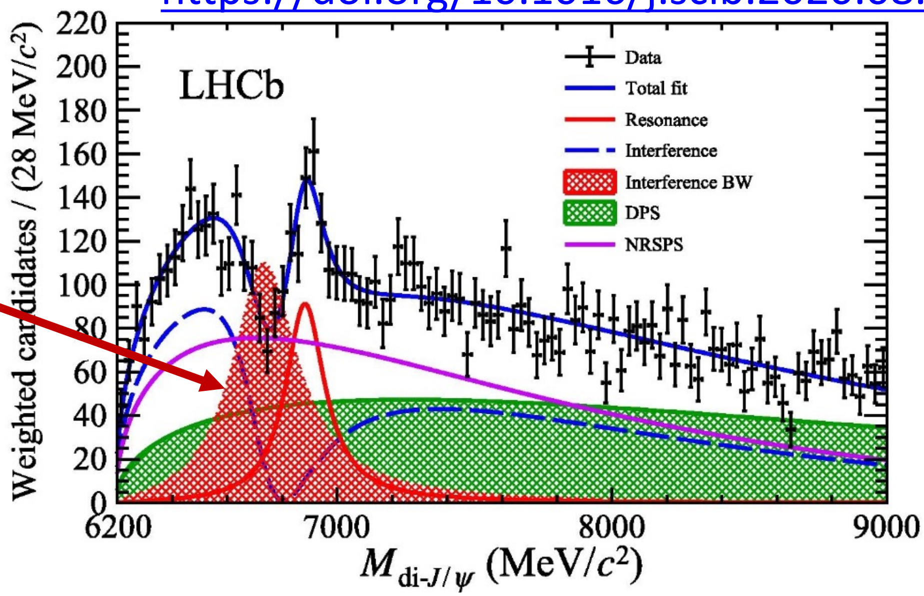
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

CMS and LHCb Fit Comparison - 2

Fit CMS data with LHCb model II : "X(6700)" interferes with NRSPS + X(6900) + Bkg

https://doi.org/10.1016/j.scib.2020.08.032





Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
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

- CMS obtained larger amplitude and wider width for X(6700)

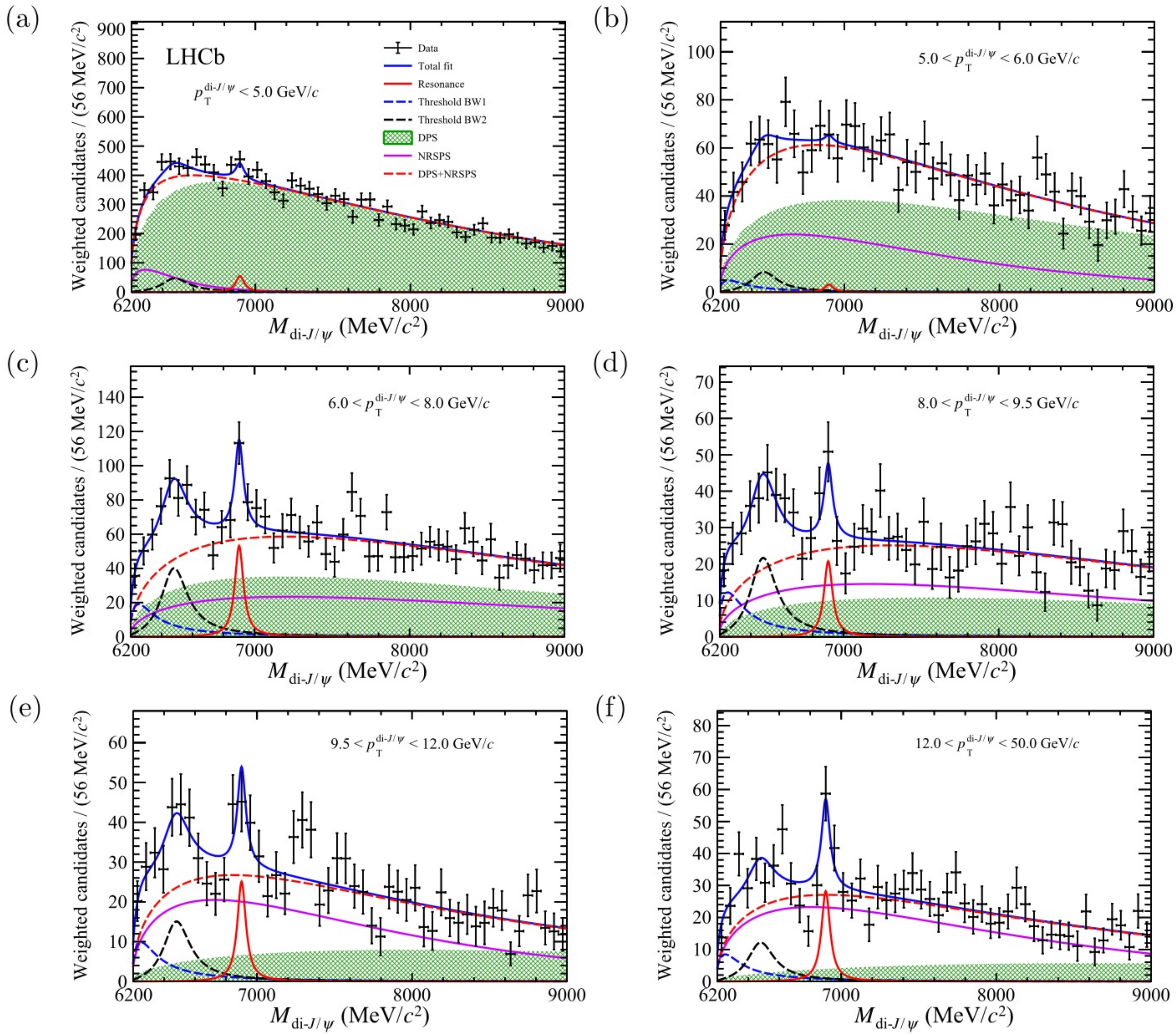


Fig. 4. Invariant mass spectra of weighted di-J/ψ candidates in bins of $p_T^{di-J/\psi}$ and overlaid projections of the $p_T^{di-J/\psi}$-binned fit with model I.