New Structures in the J/ψ J/ψ Mass Spectrum at CMS

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on behalf of CMS Collaboration

FPCP2024

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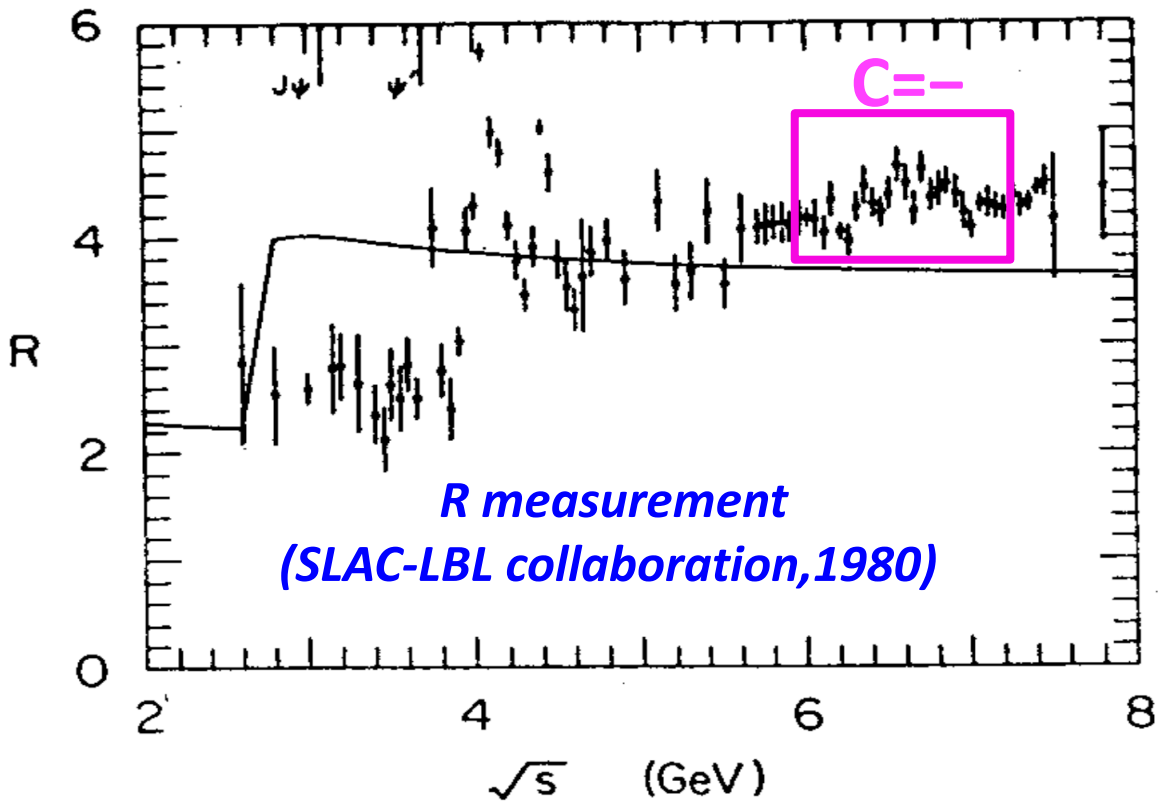
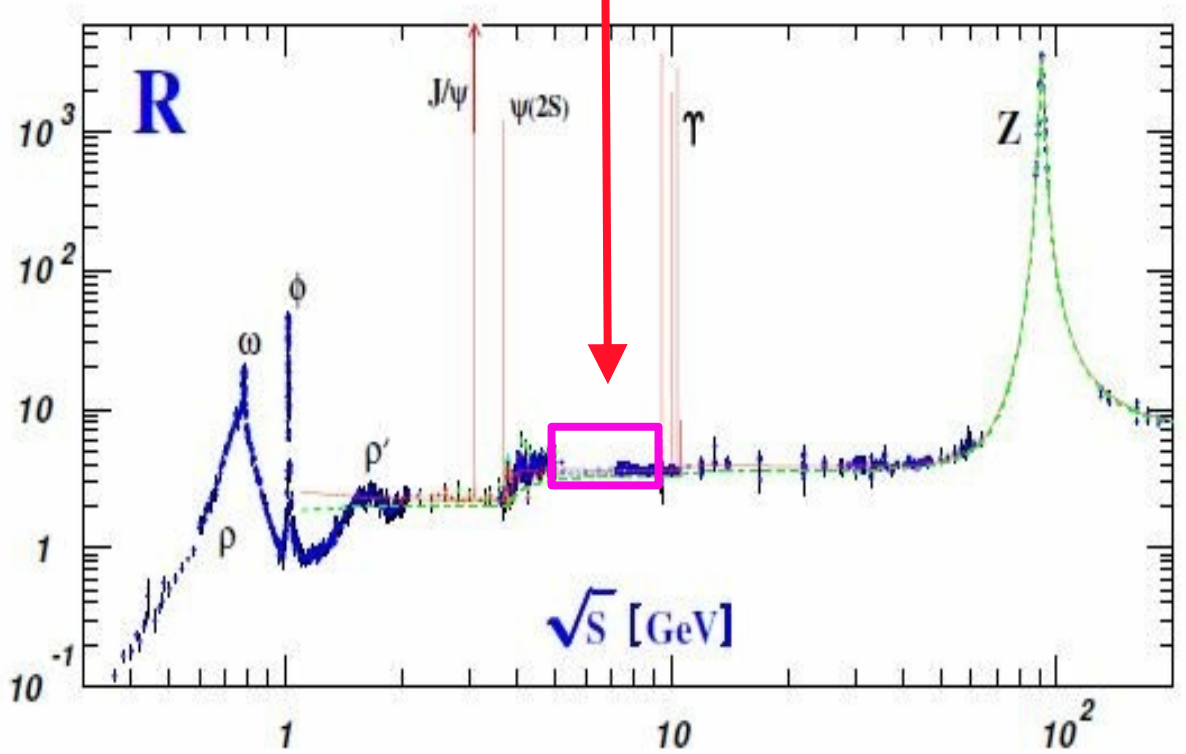
All-charm Tetra-quarks

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

STCF interested?

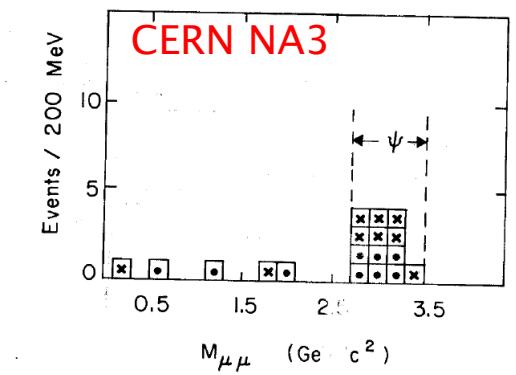


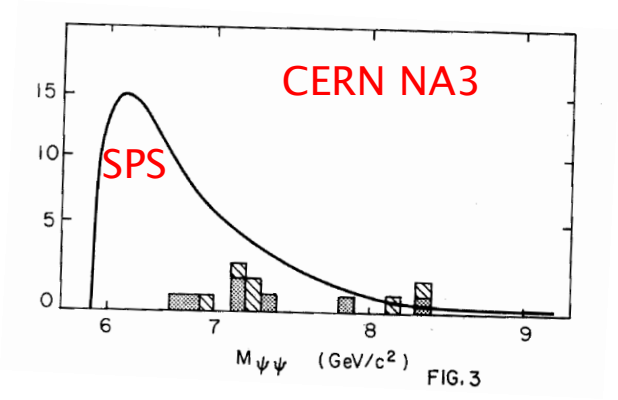
R measurement
(SLAC-LBL collaboration,1980)



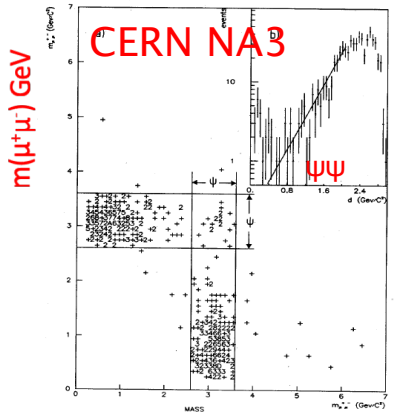
- Inspired by 1980 R curve, first calculation of 4c states (1981):
  K.-T. Chao, Z. Phys. C 7 (1981) 317

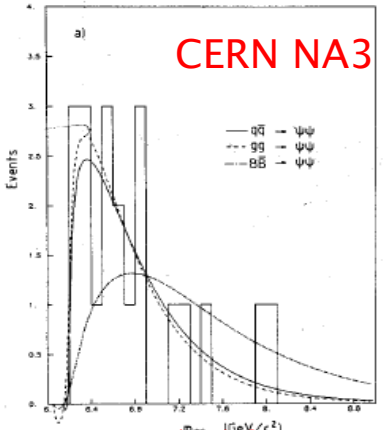
J/ψJ/ψ events—first evidence (1982)

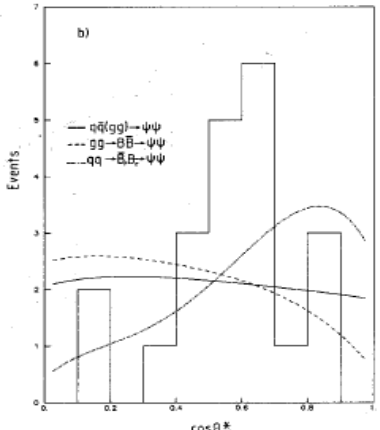




PLB114 (1982) 457

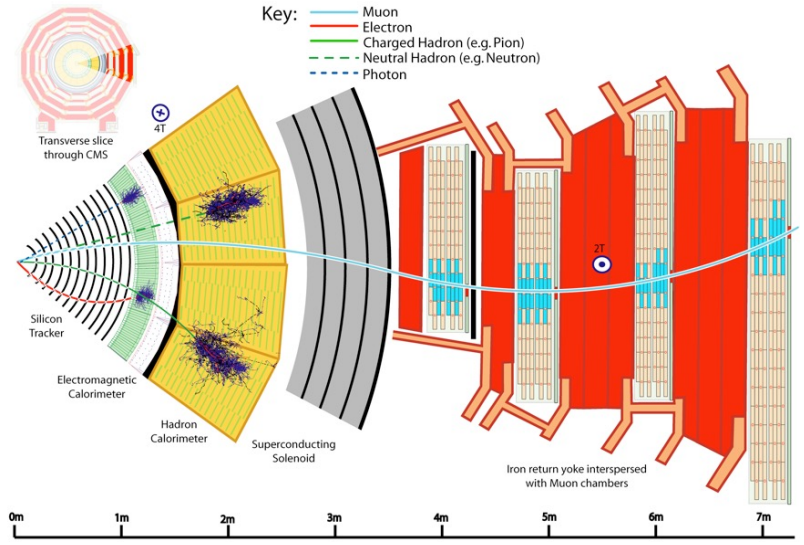




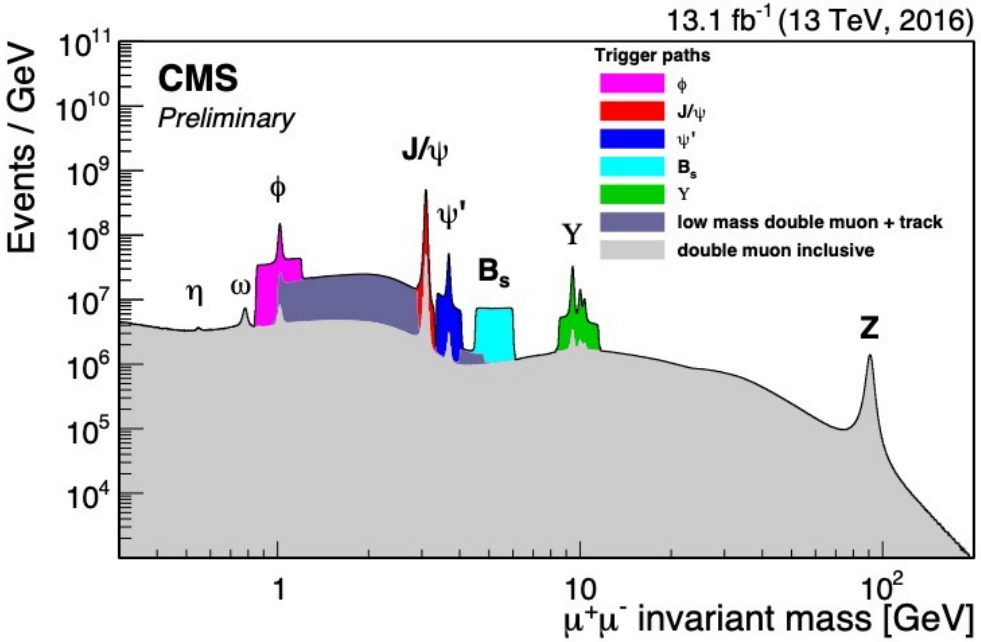


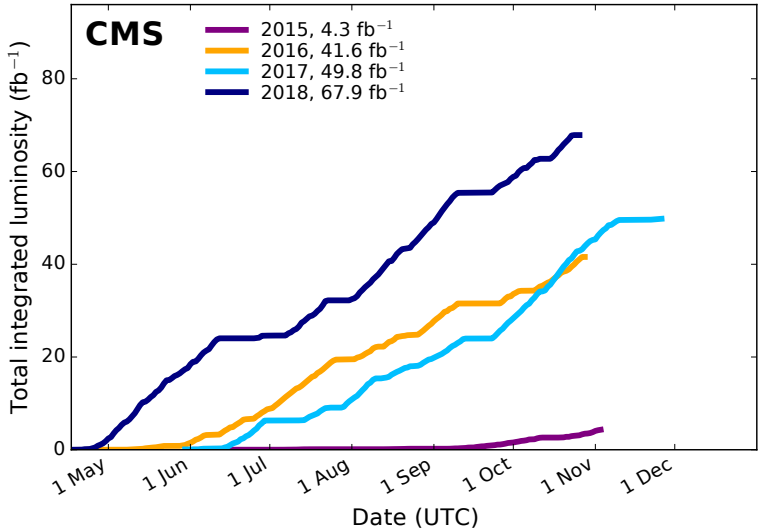
PLB158 (1985) 85

The CMS detector & trigger



η coverage (track & muon): [-2.5,2.5]





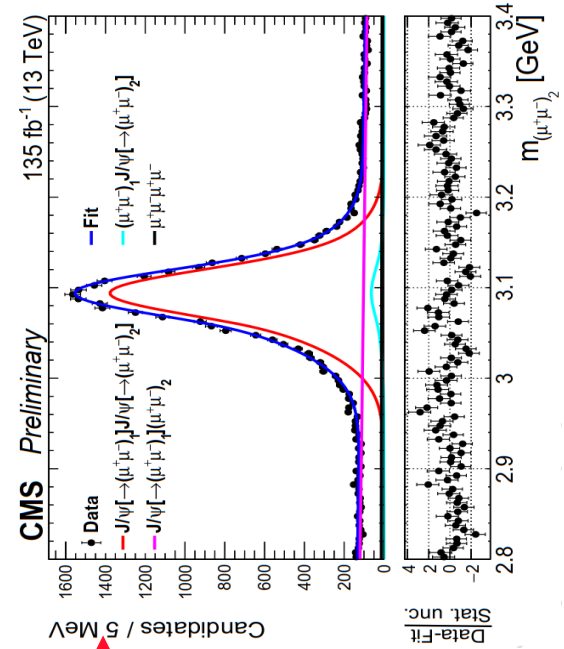
2016+2017+2018: ~145 fb^{-1}

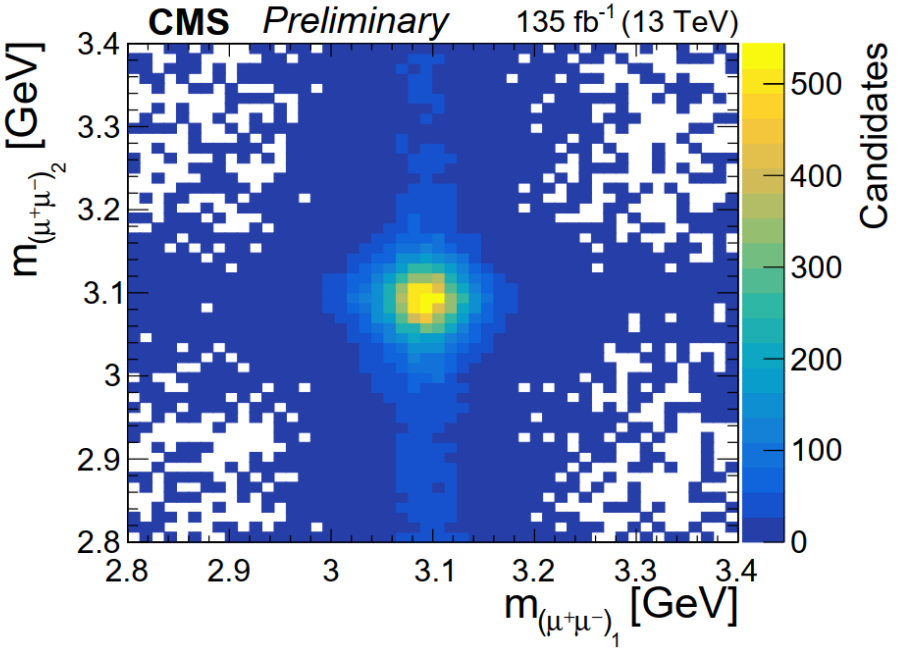
Excellent detector for (exotic) quarkonium:

- High-purity muon ID
- Excellent mass resolution, $\Delta m/m \sim 0.6\%$ for J/ψ
- Excellent vertex resolution
- Special triggers based on muon:
  μ pT, $(\mu\mu)$ pT, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ

CMS clean J/ψ signal

PRL 132 (2024), 111901

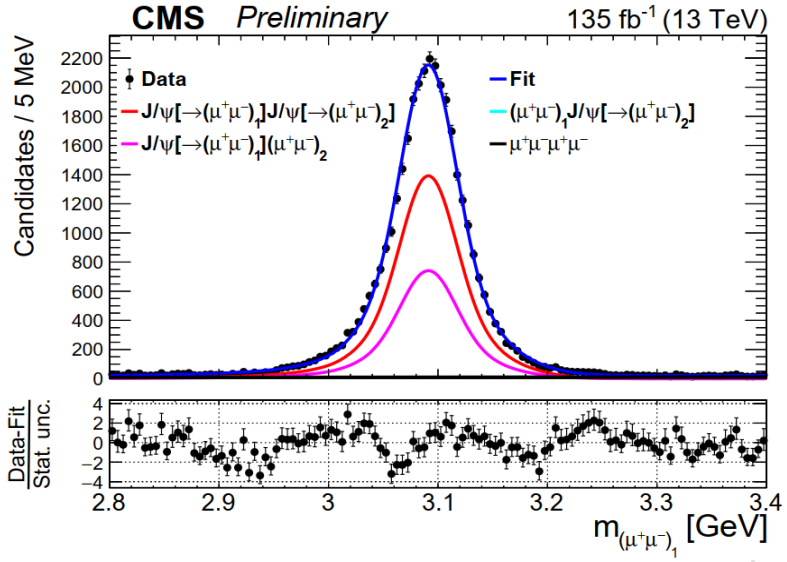




Low p_T

High p_T

J/ψ



- ~15000 J/ψ pairs after ($m(J/\psi\ J/\psi)$ <15 GeV)
- ~9000 J/ψ pairs ($m(J/\psi\ J/\psi)$ <9 GeV)

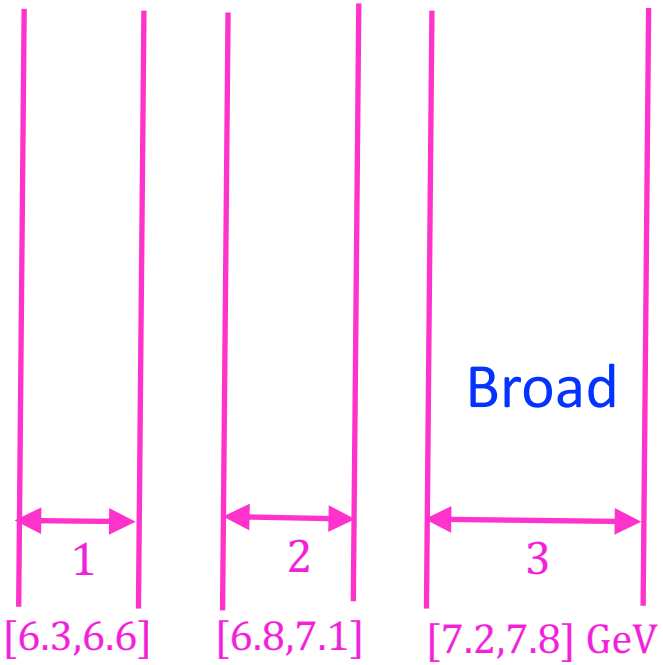
Large high p_T clean J/ψ pairs

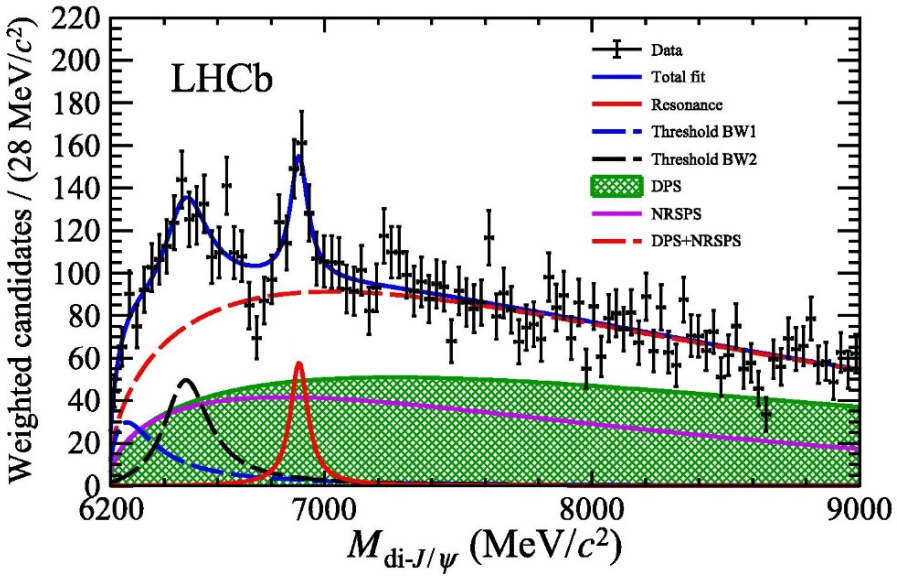
A blinded CMS analysis

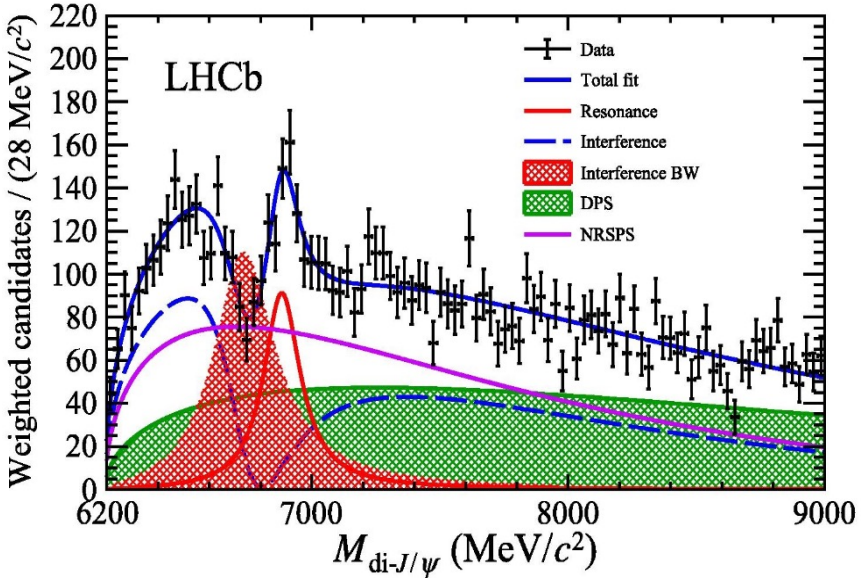
Designed 3 signal regions based on Run I hints

LHCb first got X(6900) out of the door! Congrats !

Sci.Bull.65 (2020) 23



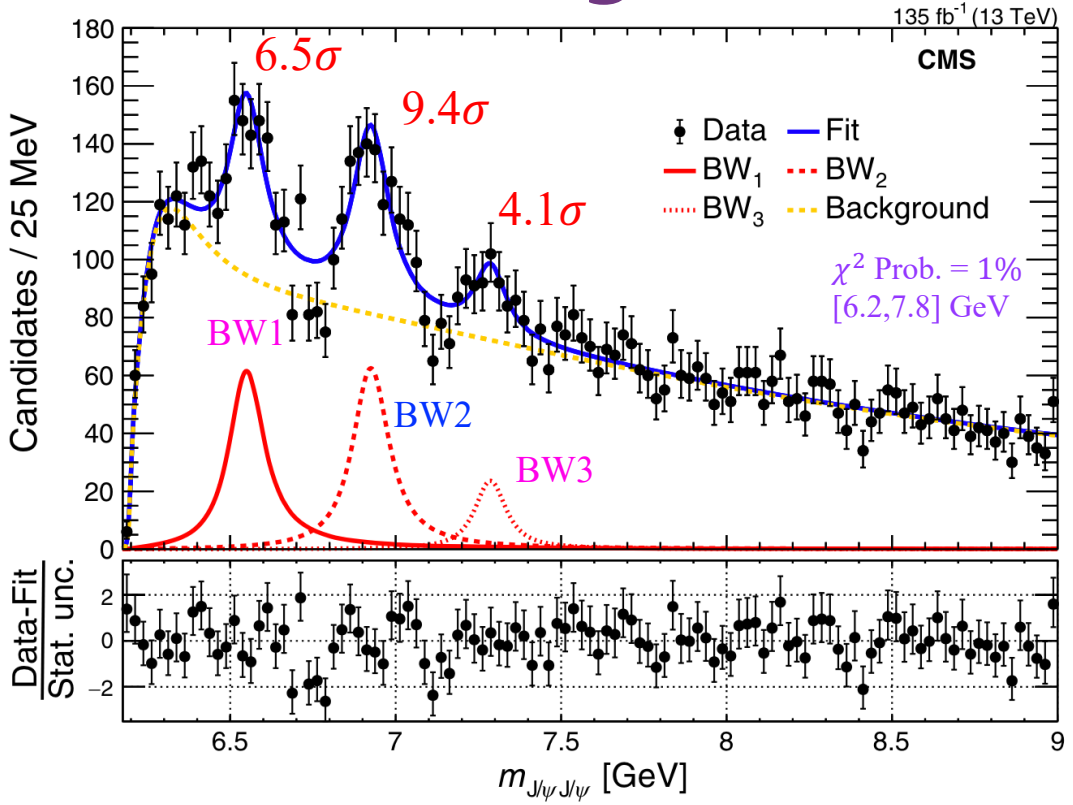




CMS merged 3 regions into one: [6.2, 7.8] GeV after LHCb's X(6900)

Final CMS model w/o interference: 3 BWs + Background

PRL 132 (2024), 111901



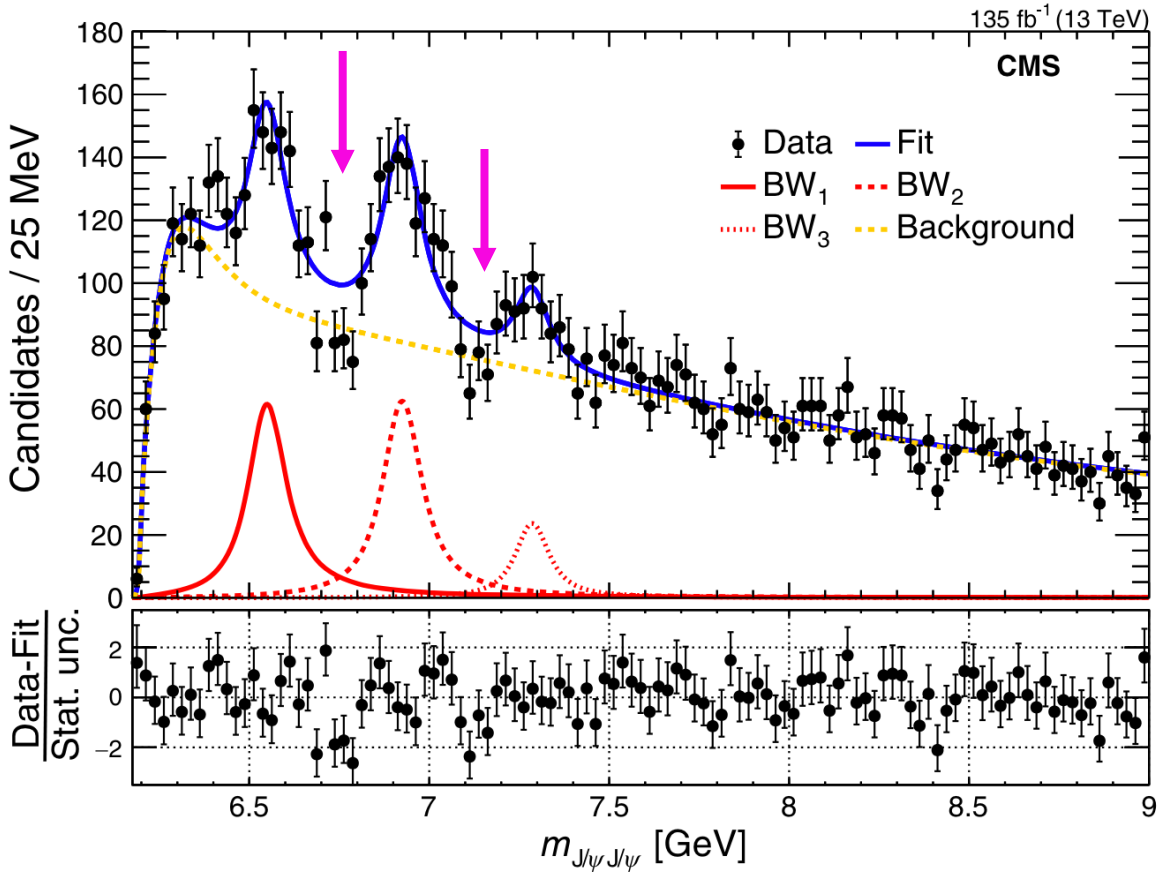
- BW2[X(6900)] (9.4σ) – confirmation
- Observation of BW1 (6.5σ)
- Evidence for BW3 (4.1σ)

	BW$_1$	BW$_2$	BW$_3$
m (MeV)	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
Γ (MeV)	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}

Statistical significance only based on: $2\ \ln(L_0/L_{max})$

The dips

PRL 132 (2024), 111901



➢ Possibility #1:

- Interference between structures?

➢ Possibility #2:

- Multiple fine structures?

- We explored possibility #1 in detail

Exploration of possible interference among BWs

- Pdf for three BW interference

$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \bigotimes R(M_0)$$

$$+N_{X\ and\ interf} \cdot \boxed{|r_1 \cdot e^{i\phi_1} \cdot BW_1 + BW_2 + r_3 \cdot e^{i\phi_3} \cdot BW_3|^2} \longleftarrow \textbf{Interf. term}$$

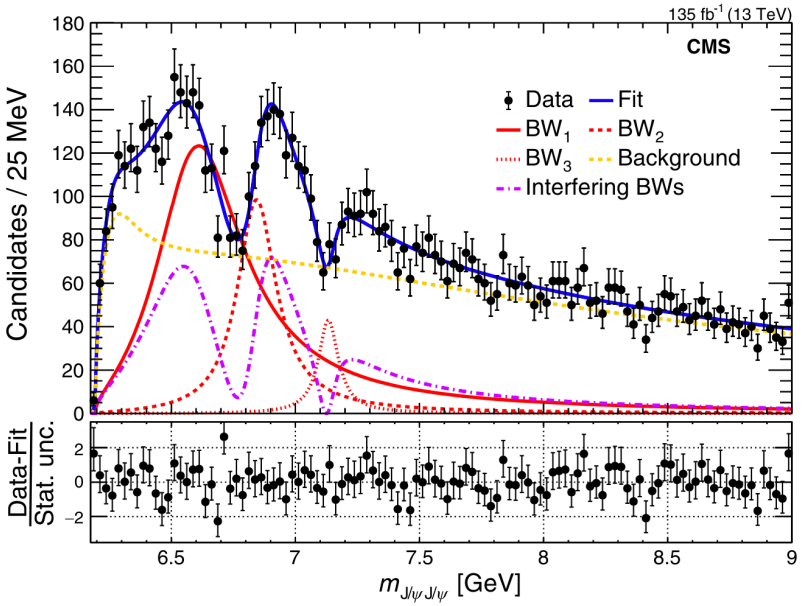
$$+N_{NRSPS} \cdot f_{NRSPS}(m) + N_{NRDPS} \cdot f_{NRDPS}(m)$$

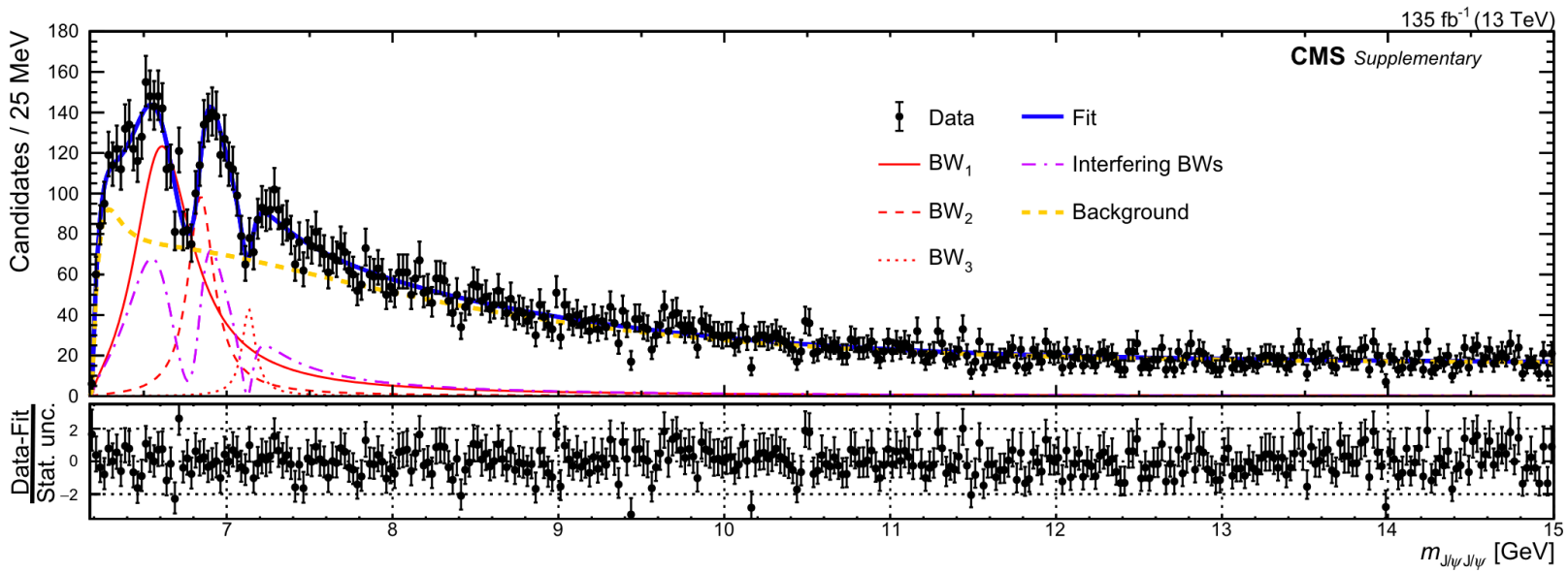
- Many ways of interference due to possible J^{PC} and quantum coherence
  - 2/3/4-object-interference between BW0, BW1, BW2, BW3

- Our choice: interference between BW1, BW2, BW3
  - $\chi^2\ prob$ < 30% for 2-body
  - No significant better description for 4-body
  - No significant improvement including interference with SPS background

CMS interference fit

PRL 132 (2024), 111901



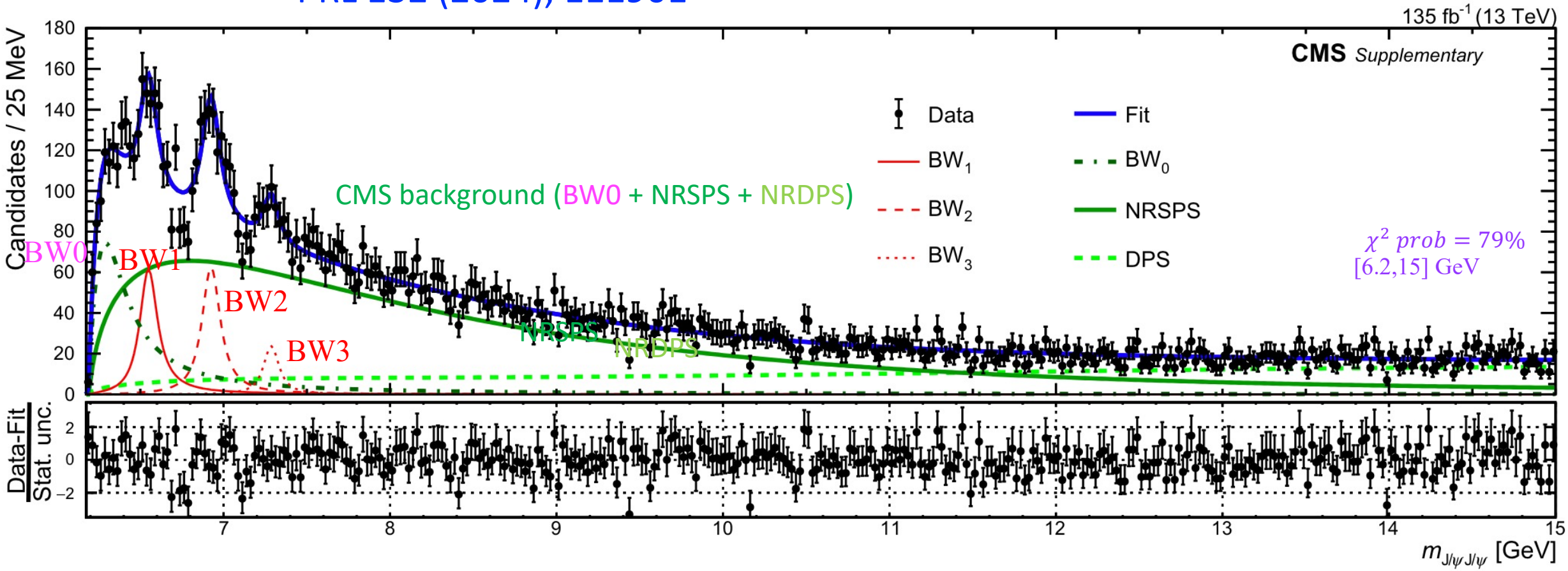


- Interference among BW1, BW2 and BW3 describes data well
- Measured mass and width in the interference fit

		BW_1	BW_2	BW_3
No interference	m (MeV)	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ (MeV)	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
	N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
Interference	m (MeV)	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ (MeV)	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

CMS background (BW0 + NRSPS + NRDPS)

PRL 132 (2024), 111901



4 significant structures: BW0, BW1, BW2, BW3

- treat BW0 as background now
- BW0+NRSPS+NRDPS as our background

Comparison with LHCb & ATLAS

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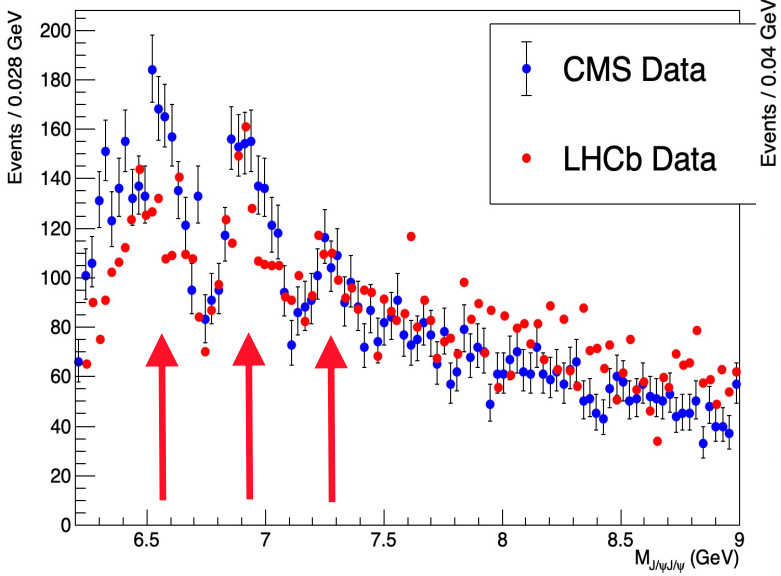
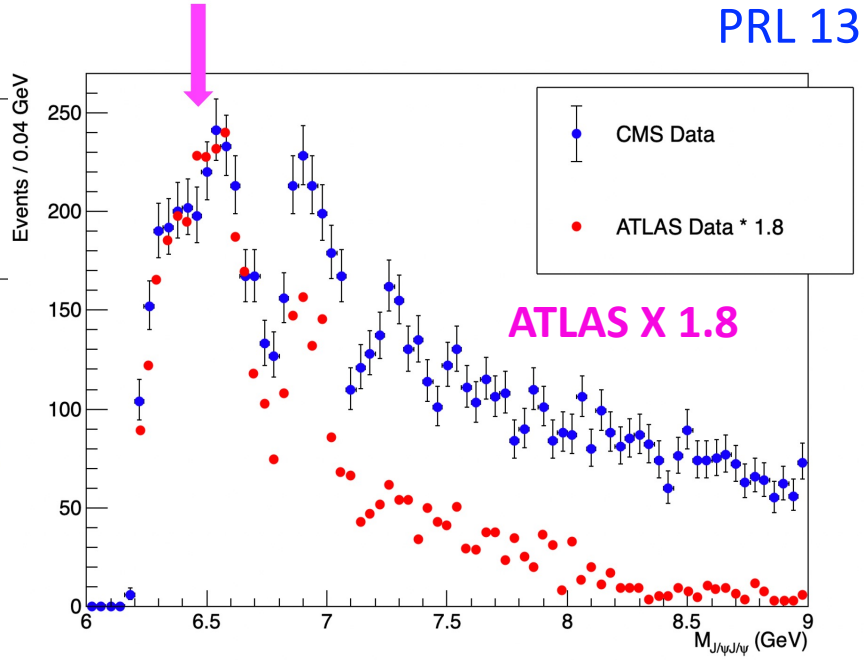
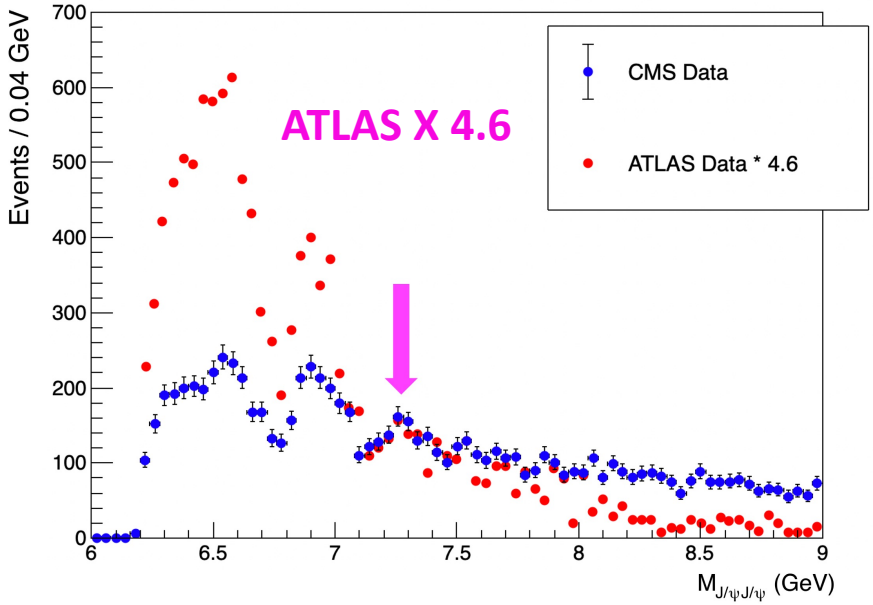


PRL 131 (2023) 151902





- Consistent shape for X(6900) for 3 experiments
- Consistent shape for X(7100) for 3 experiments after scaling
- Consistent shape for X(6600) for CMS and ATLAS after scaling

  Hard to say between CMS/ATLAS and LHCb

Comparison with some theoretical calculations

Nucl. Phys. B 966 (2021) 115393 *S-wave*

$T_{4Q}(nS)$ 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}

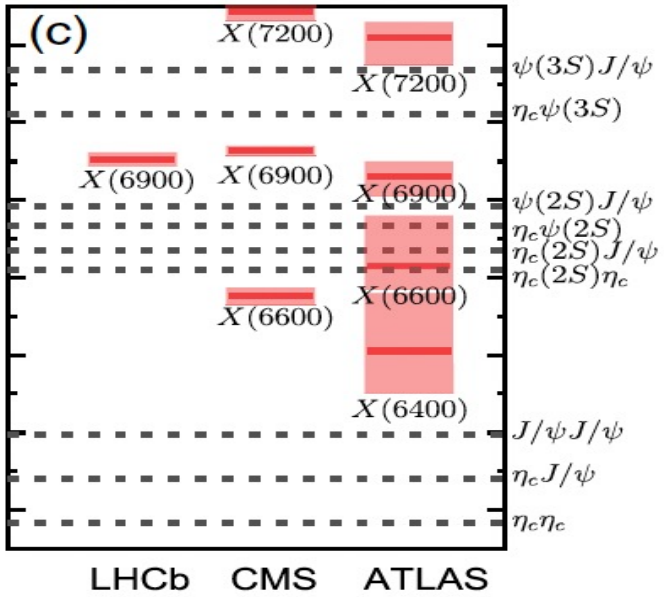
Ground states
Missing n=1

- Radial excited states?
- measure J^{PC} to clarify

M[BW1] = 6638^{+43+16}_{-38-31} MeV

M[BW2] = 6847^{+44+48}_{-28-20} MeV

M[BW3] = 7134^{+48+41}_{-25-15} MeV



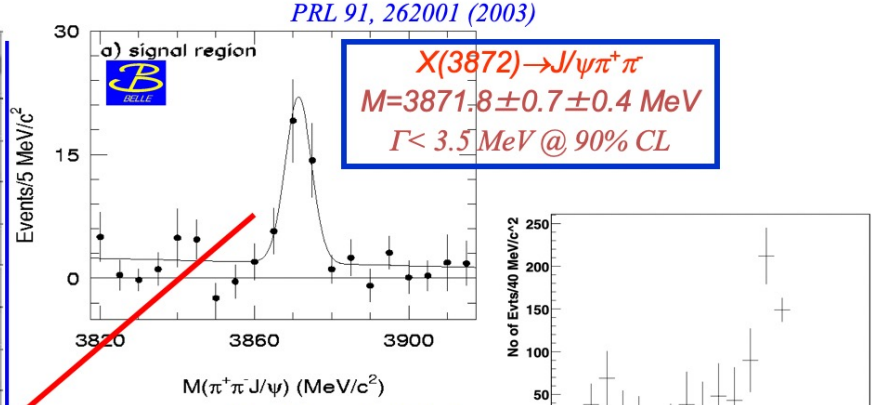
- PRD 109, 054034 (2024) new theoretical result
- More explanations?

How important is heavy quark

History: X(3872)—2003 (a slide from 2003)

$N^{2S+1}L_J$	J^{PC}	$u\bar{d}, u\bar{u}, d\bar{d}$ $I=1$	$u\bar{u}, d\bar{d}, s\bar{s}$ $I=0$	$c\bar{c}$ $I=0$
1^1S_0	0^{-+}	π	η, η'	$\eta_c(1S)$
1^3S_1	1^{--}	ρ	ω, ϕ	$J/\psi(1S)$
1^1P_1	1^{+-}	$b_1(1235)$	$h_1(1170), h_1(1380)$	$h_c(1P)$
1^3P_0	0^{++}	$a_0(1450)^*$	$f_0(1370)^*, f_0(1710)^*$	$\chi_{c0}(1P)$
1^3P_1	1^{++}	$a_1(1260)$	$f_1(1285), f_1(1420)$	$\chi_{c1}(1P)$
1^3P_2	2^{++}	$a_2(1320)$	$f_2(1270), f_2'(1525)$	$\chi_{c2}(1P)$
1^1D_2	2^{-+}	$\pi_2(1670)$	$\eta_2(1645), \eta_2(1870)$	
1^3D_1	1^{--}	$\rho(1700)$	$\omega(1650)$	$\psi(3770)$
1^3D_2	2^{--}			??
1^3D_3	3^{--}	$\rho_3(1690)$	$\omega_3(1670), \phi_3(1850)$	
1^3F_4	4^{++}	$a_4(2040)$	$f_4(2050), f_4(2220)$	
2^1S_0	0^{-+}	$\pi(1300)$	$\eta(1295), \eta(1440)$	$\eta_c(2S)$
2^3S_1	1^{--}	$\rho(1450)$	$\omega(1420), \phi(1680)$	$\psi(2S)$
2^3P_2	2^{++}	$a_2(1700)$	$f_2(1950), f_2(2010)$	
3^1S_0	0^{-+}	$\pi(1800)$	$\eta(1760)$	

PRL 91, 262001 (2003)



(Problematic) features
mass ~70 MeV > 1^3D_2 charmonium
$M(\pi^+\pi^-)$ peaks as a ρ, C=+, isospin=1 (charmonium--0)

Mass close to DD, molecule is speculated*

First particle challenging charmonium model, Revitalized exotic meson study

Mismatched mass directly points to exotic

2 heavy quarks inside

2 heavy + 2 light structures → 4 heavy structures

X(3872): 70 MeV > J/ψ, can be J/ψ excited state,

X(6600): 3500 MeV J/ψ, can be J/ψ excited state? Do not think so

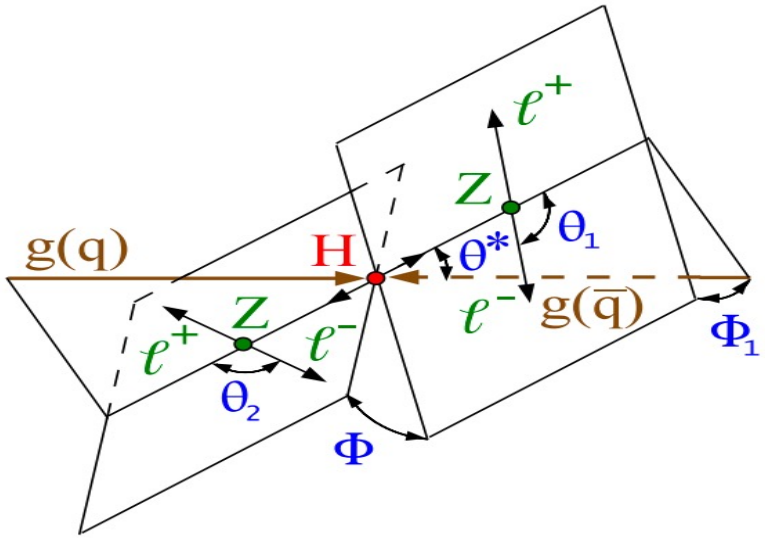
Summary

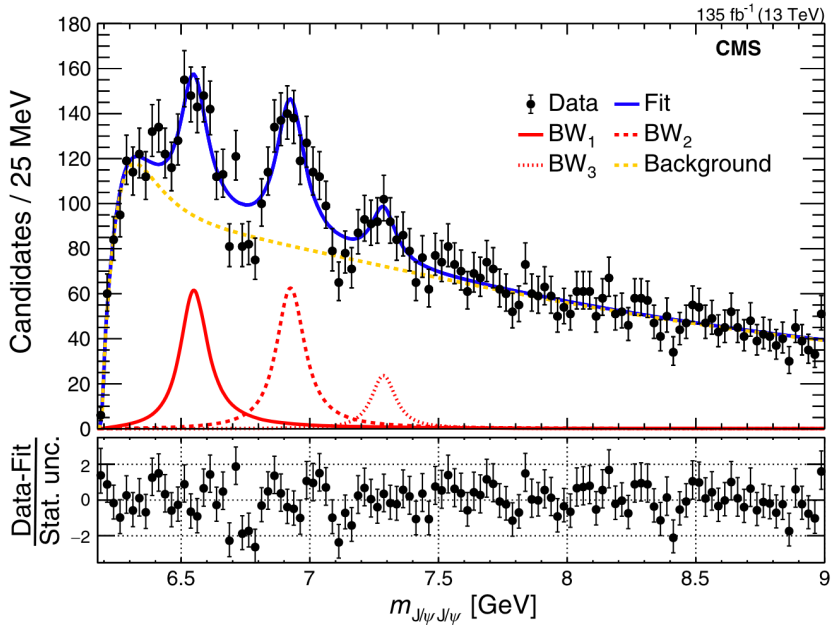
PRL 132 (2024), 111901

- CMS identified 3 significant $J/\psi J/\psi$ structures
  - Identified 2 new structures—X(6600) & X(7100), plus confirming X(6900)

- A possible family of structures of all-charm tetra-quarks!
  - Offer a system easier to understand, a new window for strong interaction

- J^{PC}, below 6.6 and beyond 7.1 GeV?





Is there an structure just at $J/\psi J/\psi$ threshold ? Why is or why not?

Backup