New resonances in $J/\psi J/\psi$ mass spectrum in pp collision at CMS experiment

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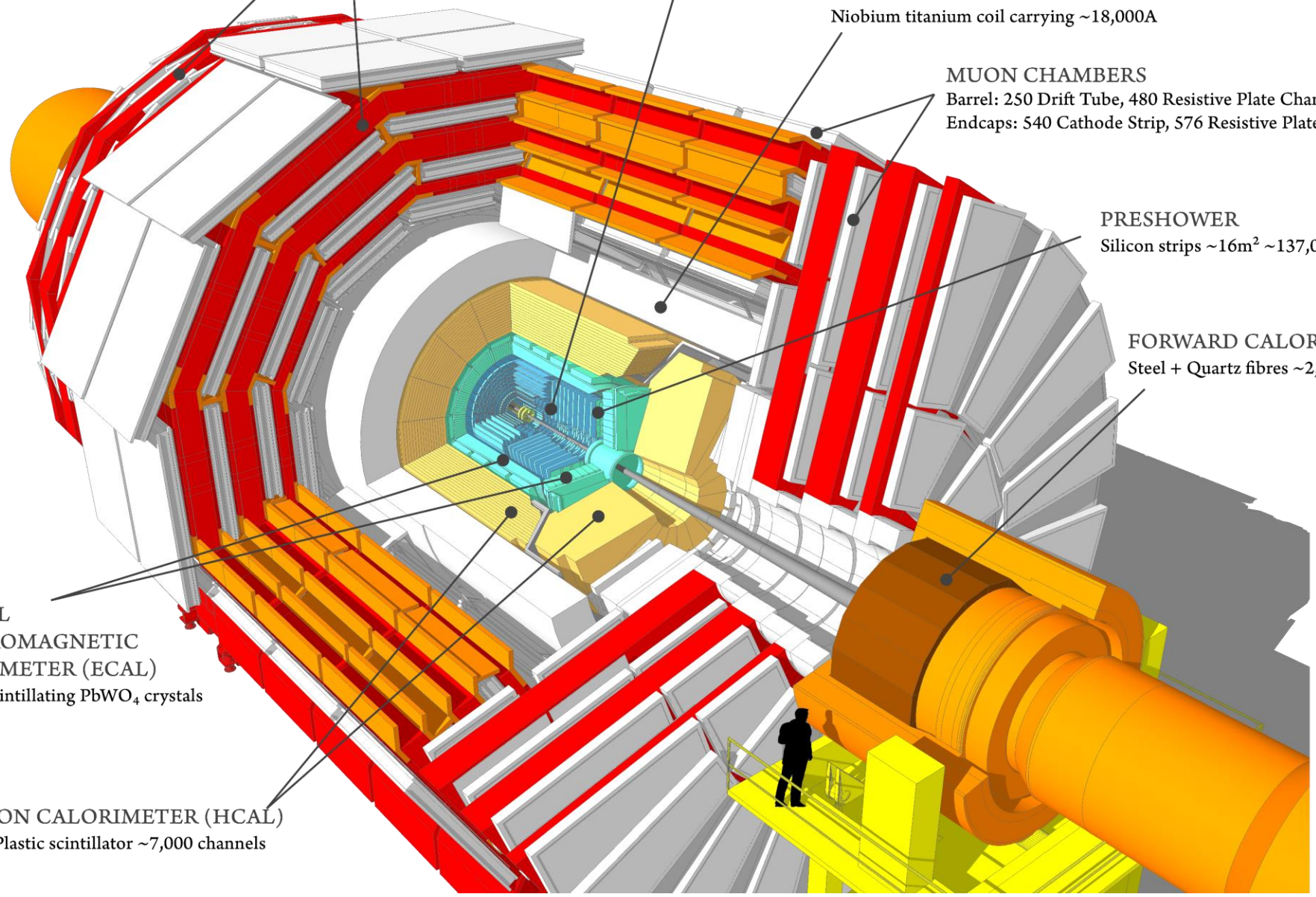
CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~1m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

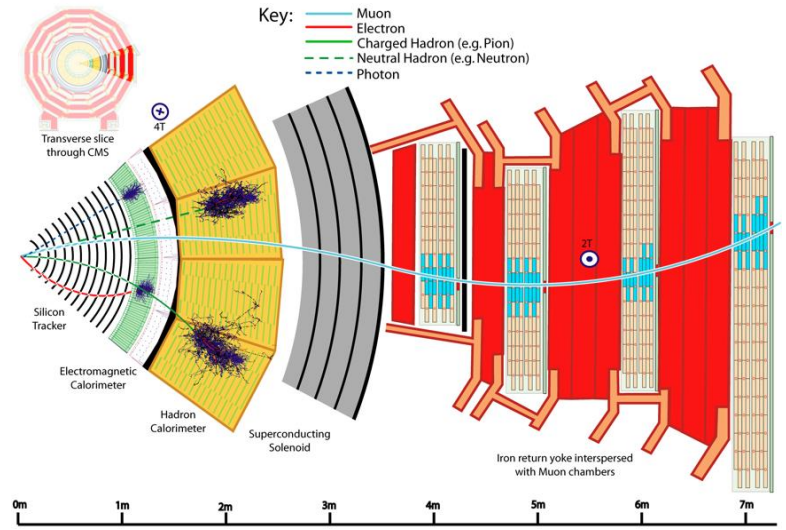
PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

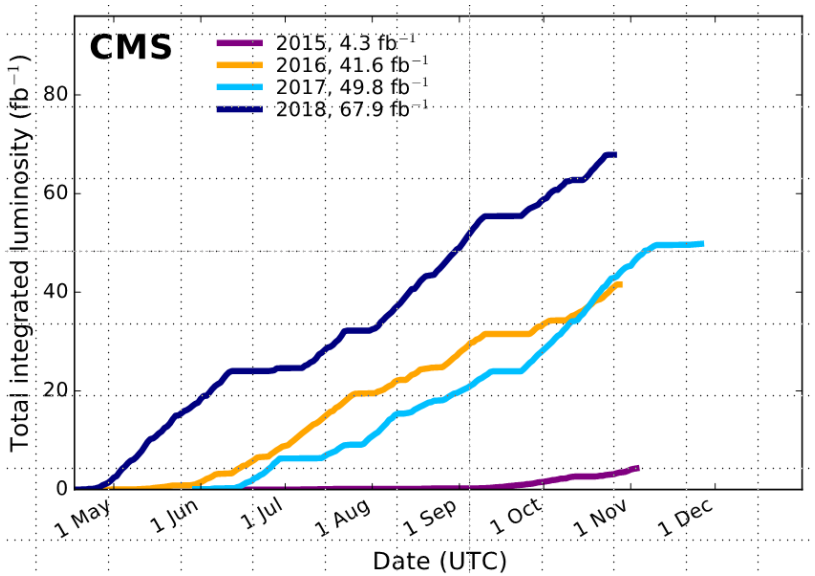
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

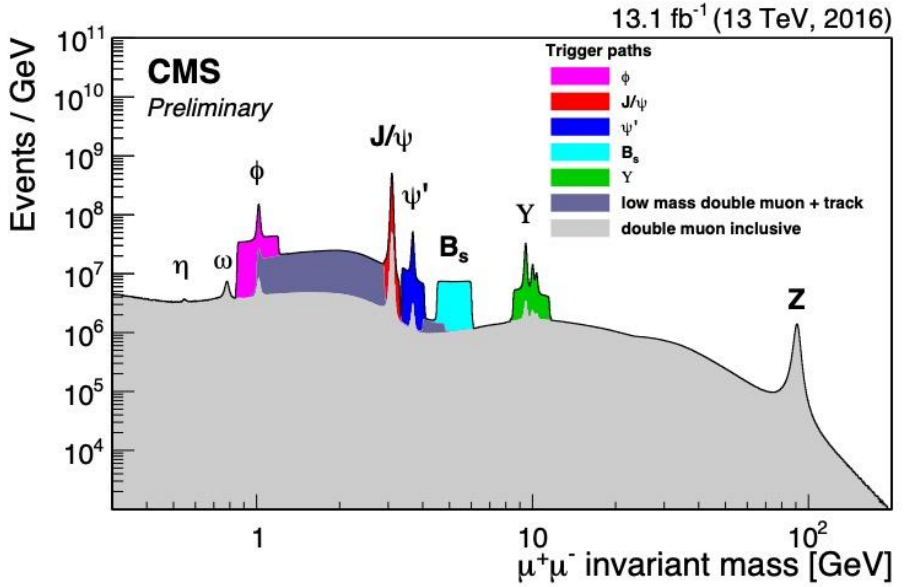
CMS detector & trigger



η coverage (track & muon): [-2.5, 2.5]



Int. lumi. of 2016 + 2017 + 2018: ~145 fb^{-1}



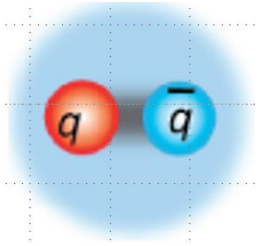
Excellent detector for (exotic) quarkonium

- Muon system
  High-purity muon ID, $\Delta m/m$~0.6% for J/ψ
- Silicon tracking detector
  B = 3.8 T, $\Delta p_T/p_T$~1% & excellent vertex resolution
- Special triggers for different analyses at increasing int. lumi
  Requirements on μ & $\mu^+\mu^-$ pT, mass and vertex of $\mu^+\mu^-$, and addition muon

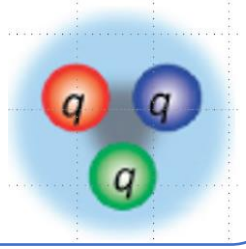
Exotic hadrons

Conventional hadrons in quark model

Meson

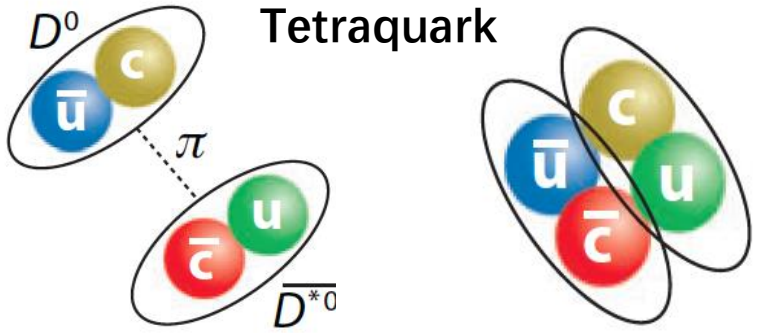


Baryon



Exotic hadrons in QCD

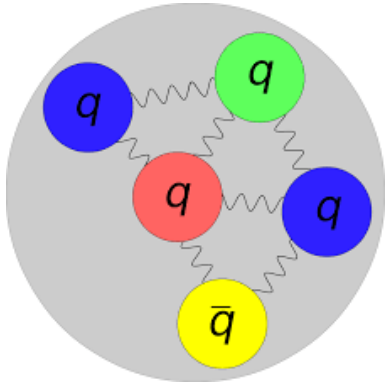
Tetraquark



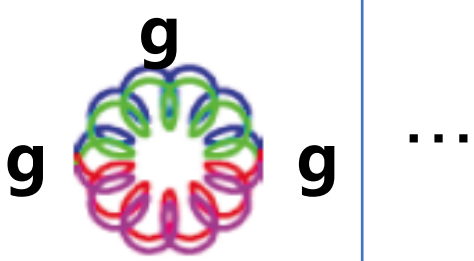
D^0–$\overline{D^{*0}}$ "molecule"

Diquark–diantiquark

Pentaquark



Glueball



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New Domain of Exotics: All-heavy Tetra-quarks

- First mention of 4c states: Y. Iwasaki, Prog. Theo. Phys. 54, 492 (1975)
- First calculation of 4c states: K.-T. Chao, Z. Phys. C 7, 317 (1981)

J^{PC} & mass

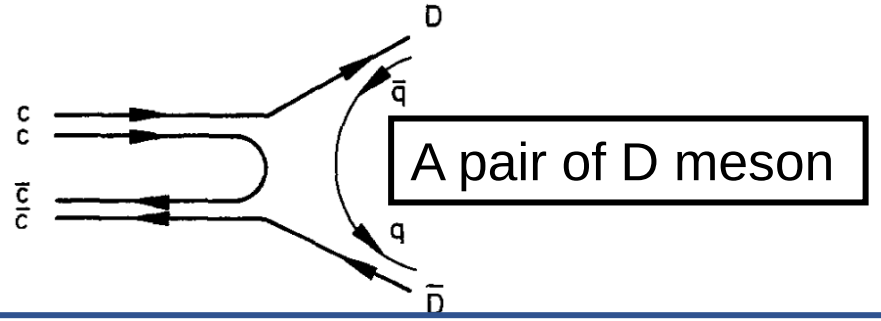
$(cc)_{\underline{3}} - (\overline{cc})_{\underline{3}}$

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

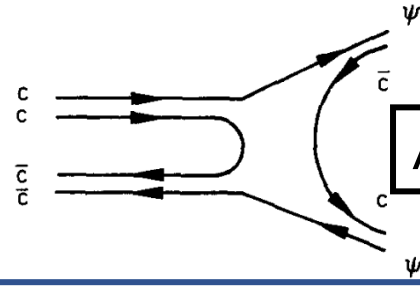
$(cc)_{\underline{6}} - (\overline{cc})_{\underline{6}}$

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

Two body decays



A pair of D meson

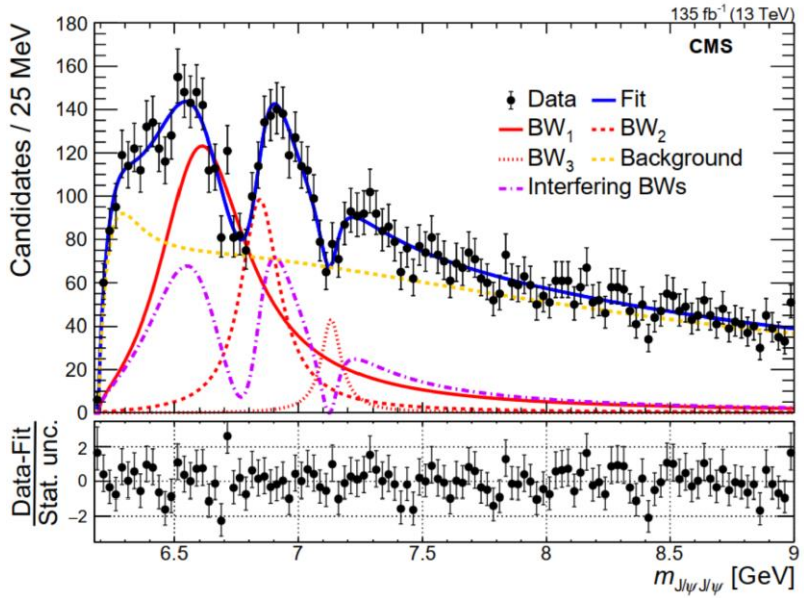


A pair of ψ meson

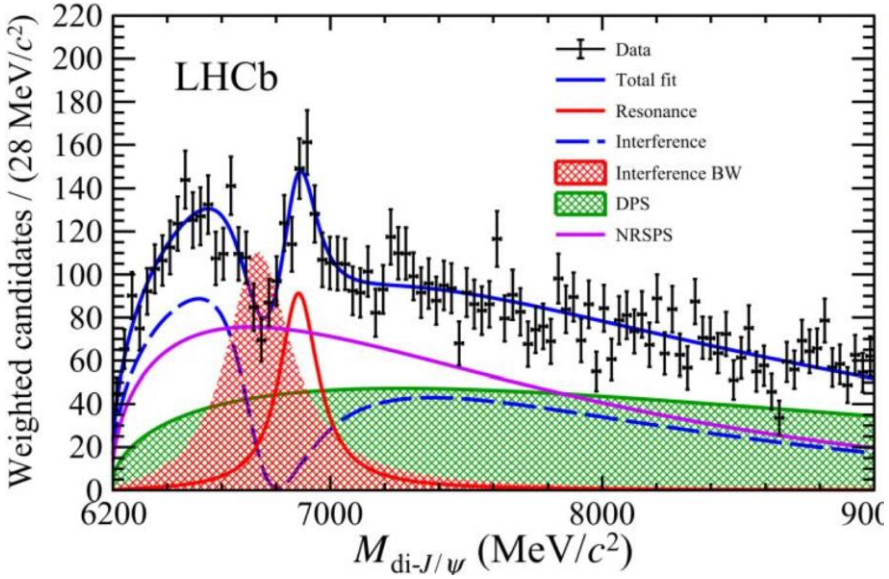
- Many other theoretical studies in recent years

Exotic hadrons with four-charm: in experiment

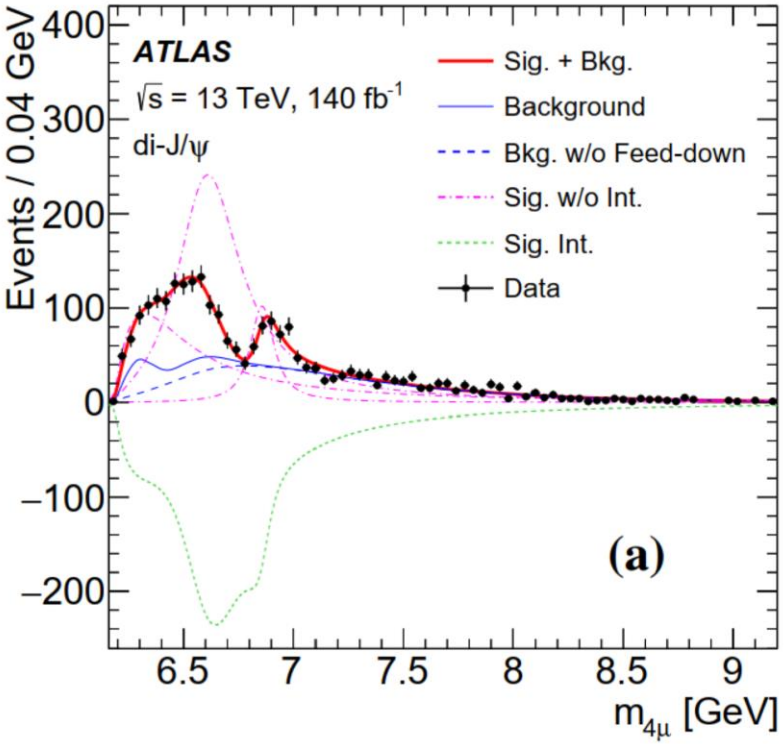
- Structures in $J/\psi J/\psi$ mass spectrum at CMS, LHCb and ATLAS
  - This talk focus on the CMS result



PRL132.111901(2024)



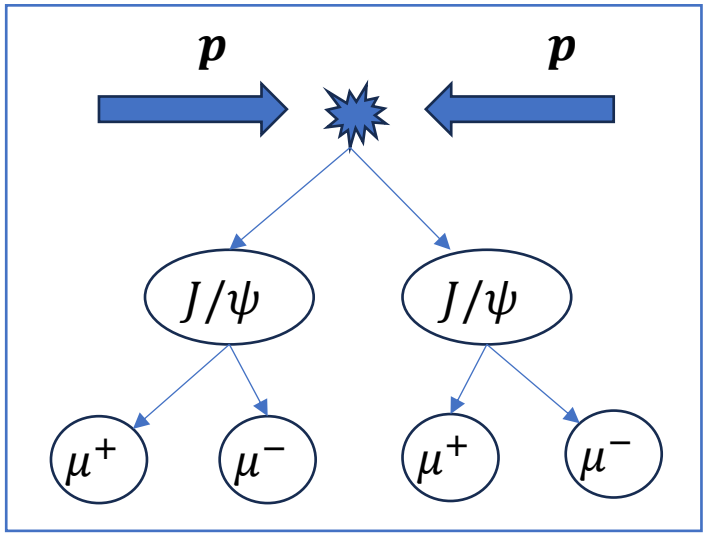
Sci.Bull.65(2020)23,1983-1993



PRL131.151902(2023)

$J/\psi J/\psi$ events at CMS

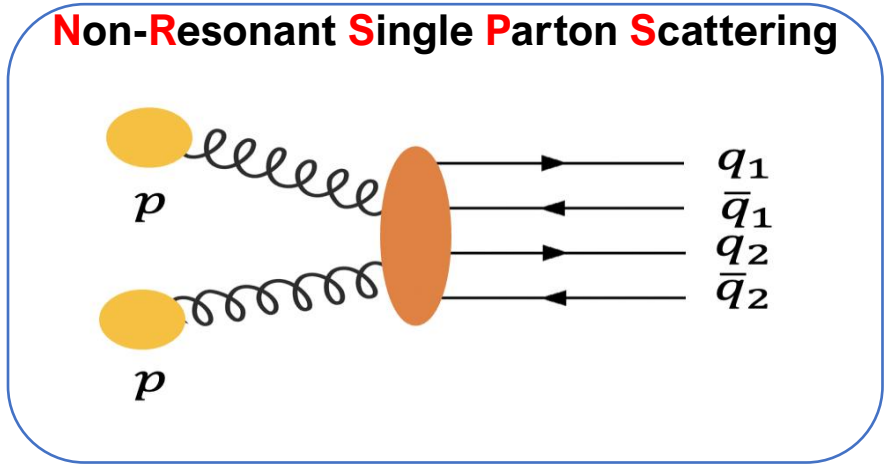
- Dataset:
  - 135 fb^{-1} pp collision at $\sqrt{s}$=13 TeV taken at CMS in 2016-2018
- Final state:
  - $J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$
- MC simulations for
  - Signal:
    - Generated using Pythia8, JHUGen
  - Background:
    - Generated using Pythia8, Cascade, HelacOnia

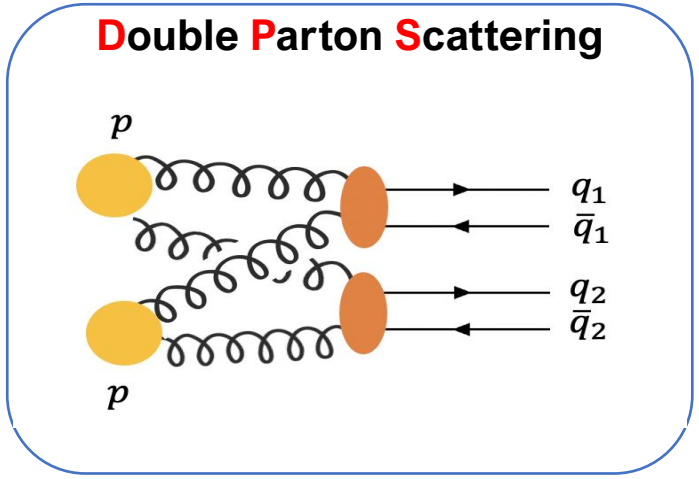


PRL312.111902(2024)

Background in $X \to J/\psi J/\psi$ process

- Two main background contributions
  - **NRSPS**: Non-Resonant Single Patron Scattering
  - **DPS**: Double Parton Scattering

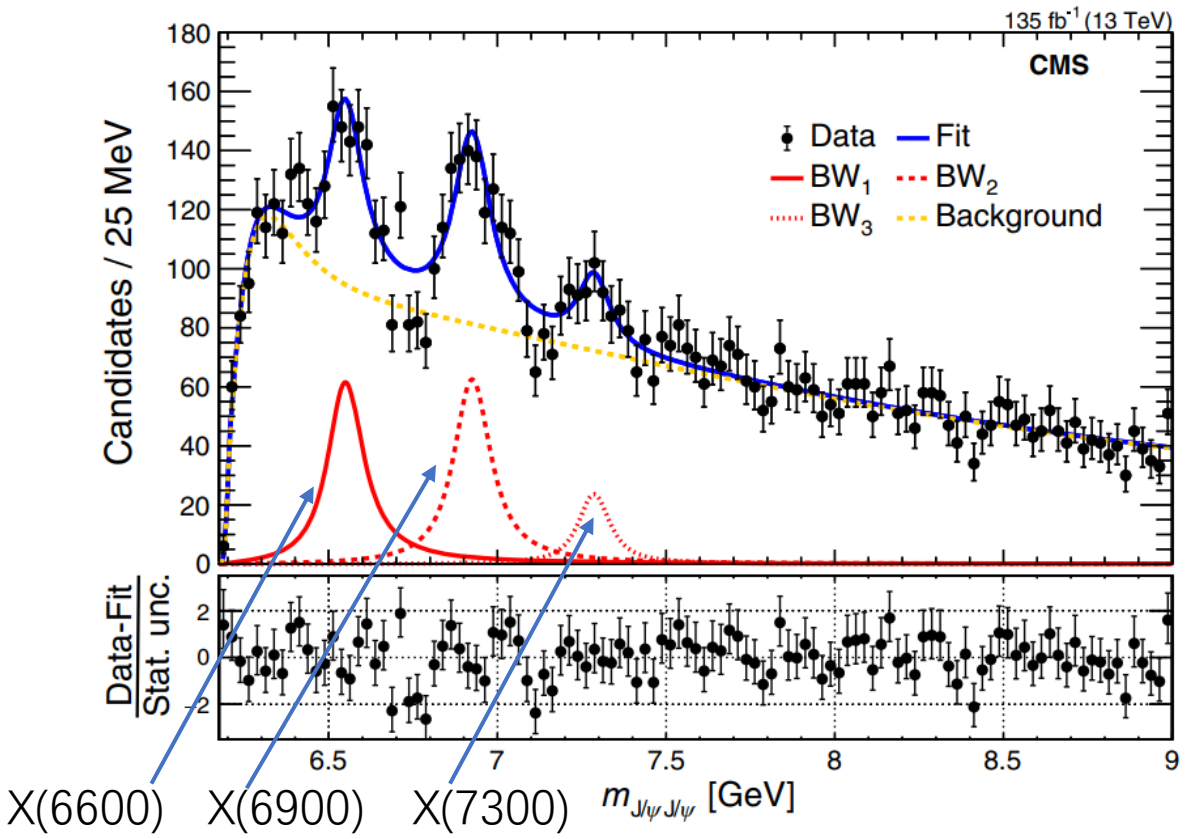


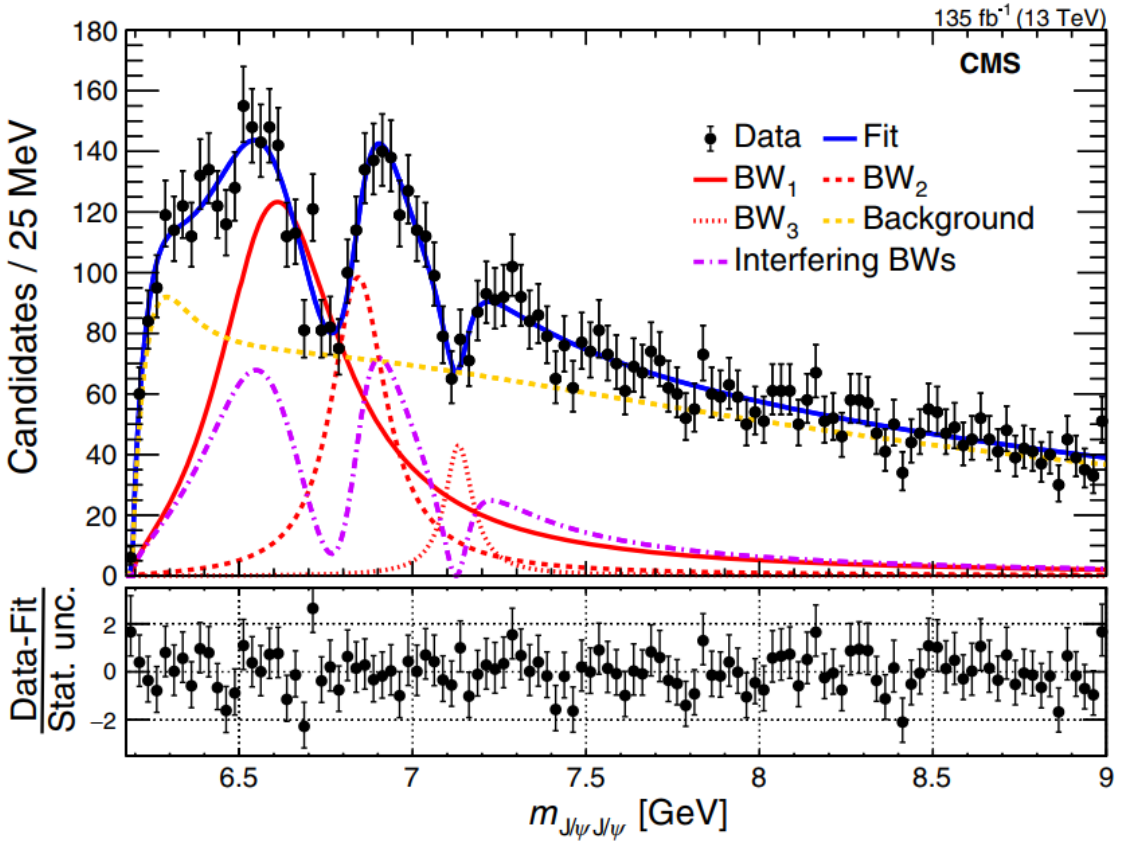


- Combinatorial background
  - Events contain one or zero J/ψ
  - Well described by NRSPS + DPS

PRL312.111902(2024)

New resonances in $J/\psi J/\psi$ mass at CMS

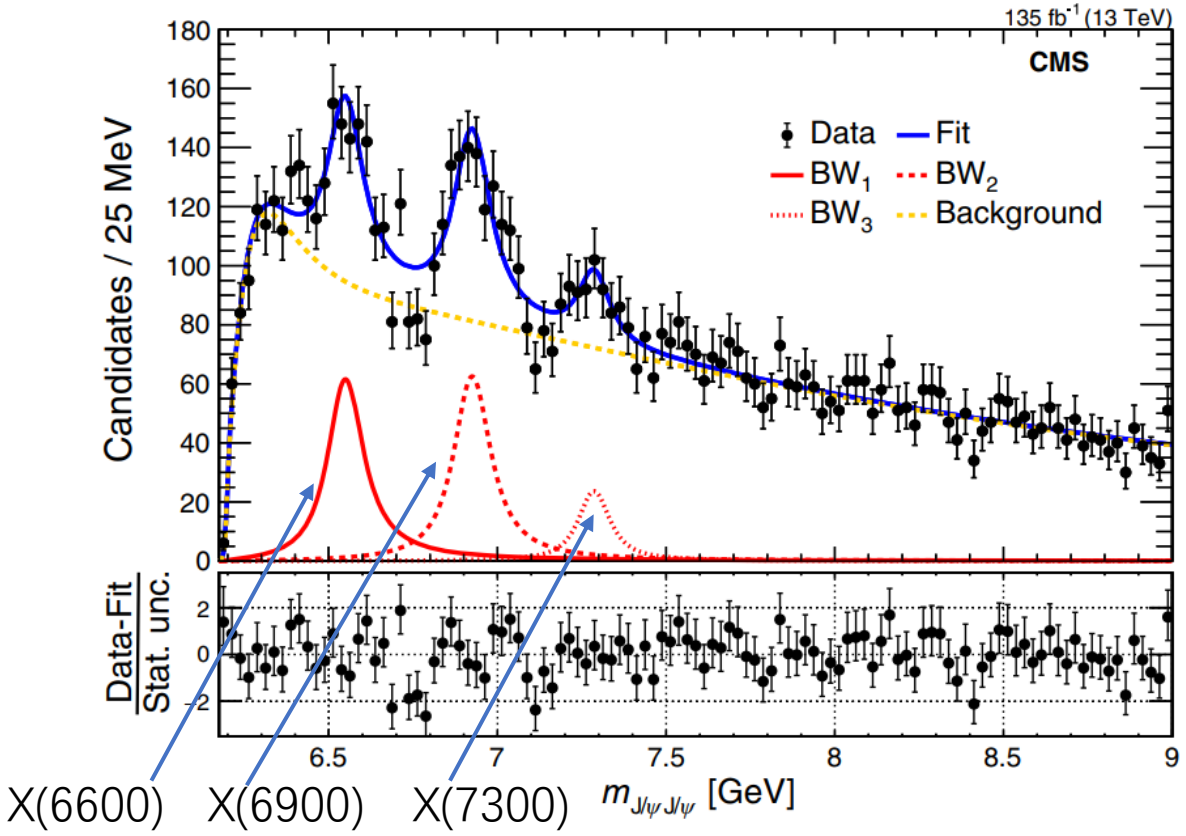




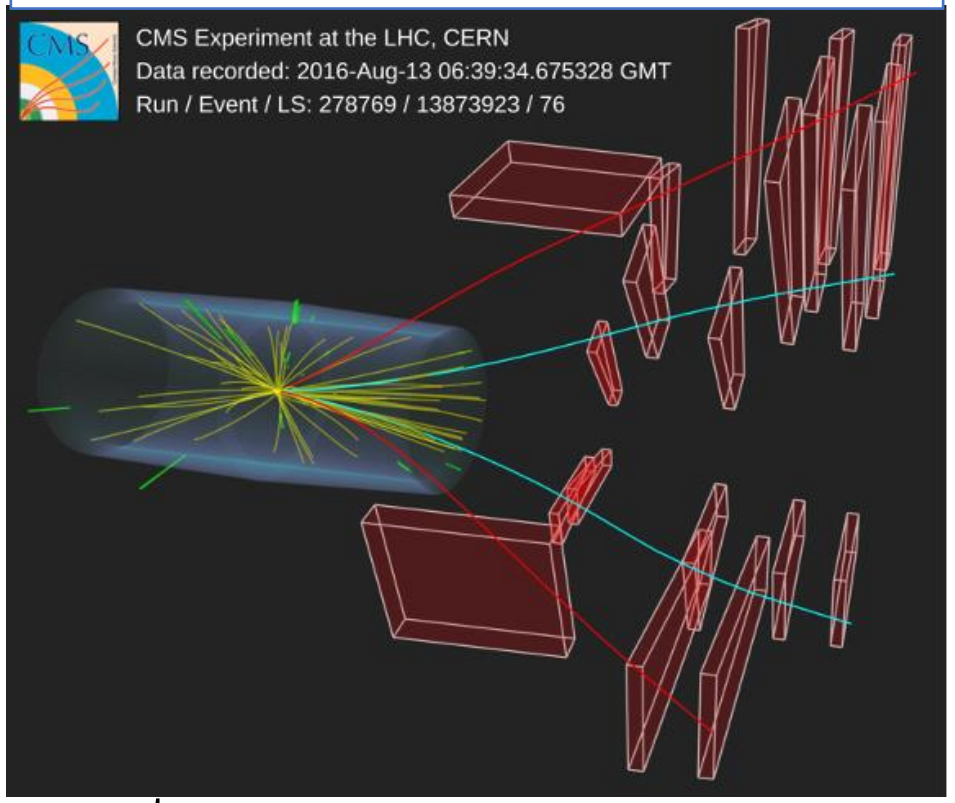
- Three resonances in $J/\psi J/\psi$ mass spectrum
  - X(6600) – 7.9σ (**NEW!**)
  - X(6900) – 9.8σ
  - X(7100) – 4.7σ (**NEW!**)

PRL312.111902(2024)

New resonances in $J/\psi J/\psi$ mass at CMS



Event display of a X(6600) candidate



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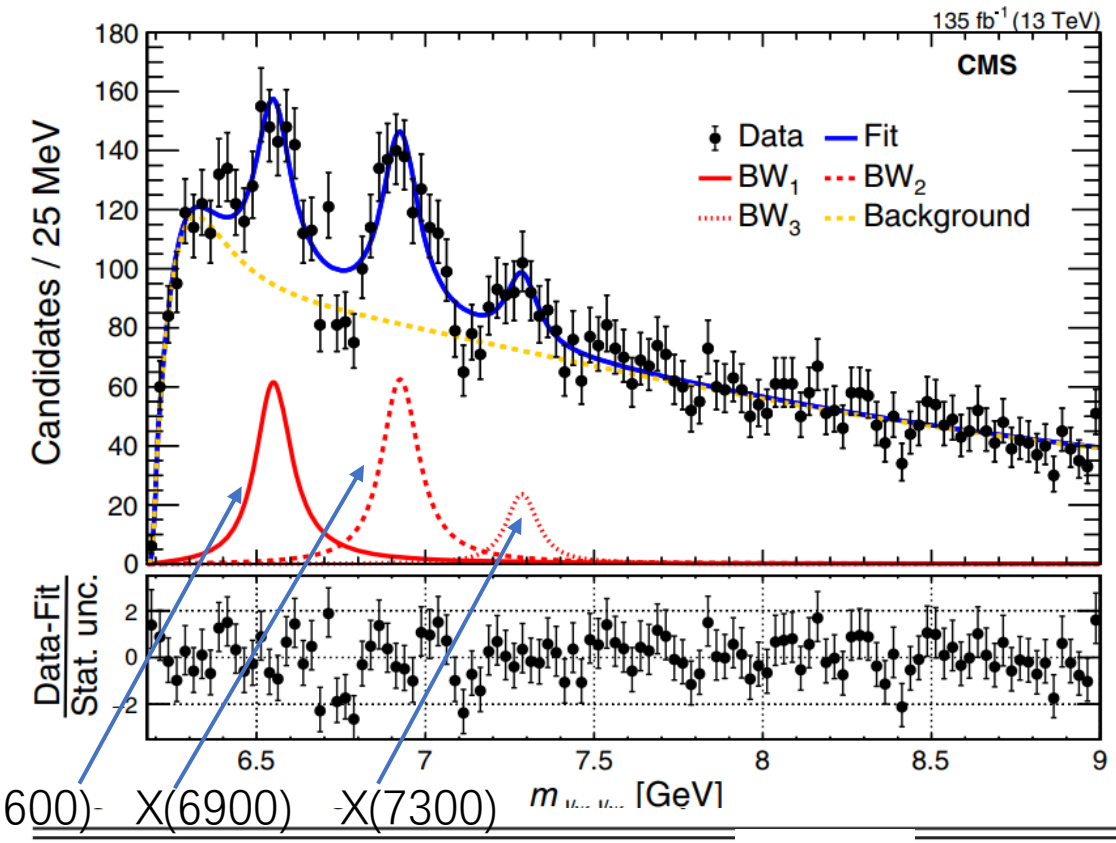
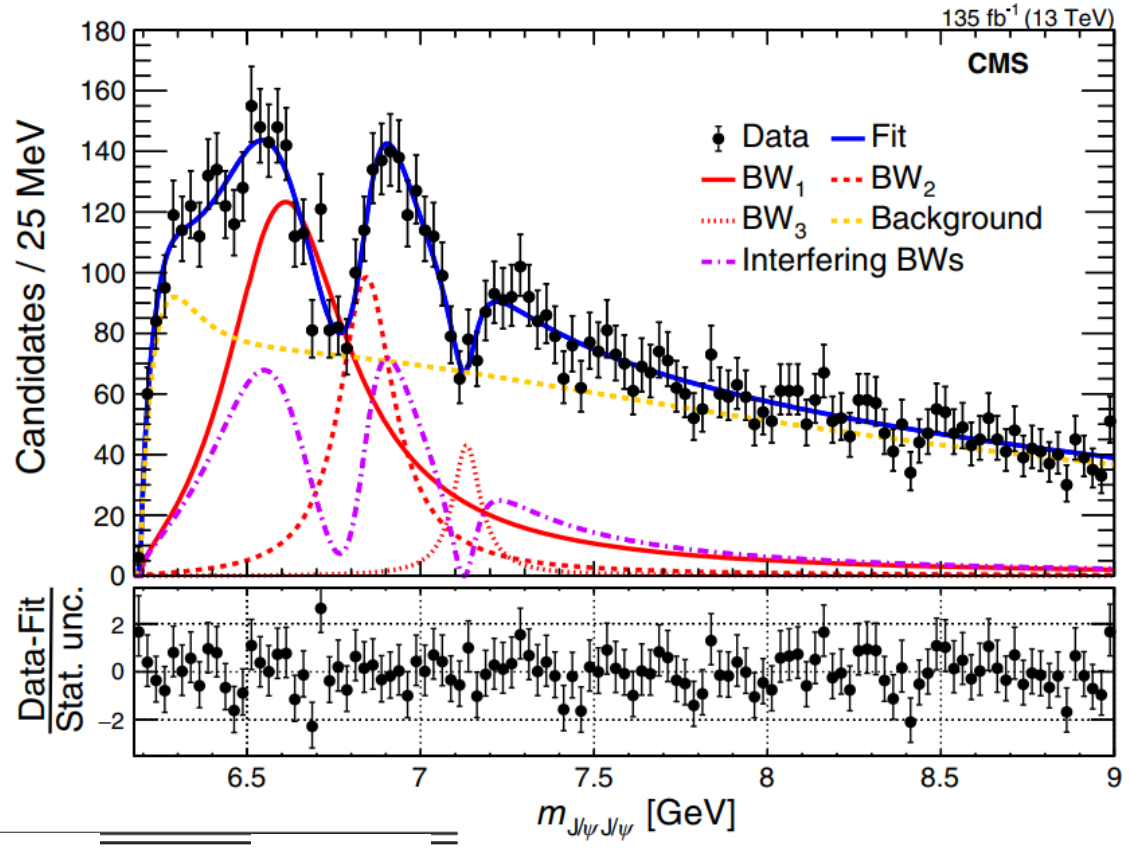
PRL312.111902(2024)

New resonances in $J/\psi J/\psi$ mass at CMS





X(6600) X(6900) X(7300)

		X(6600)	X(6900)	X(7300)
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}

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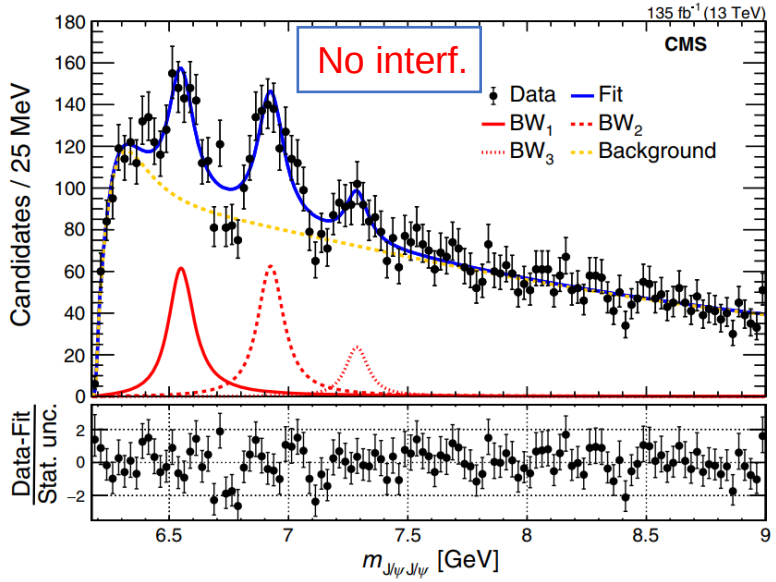
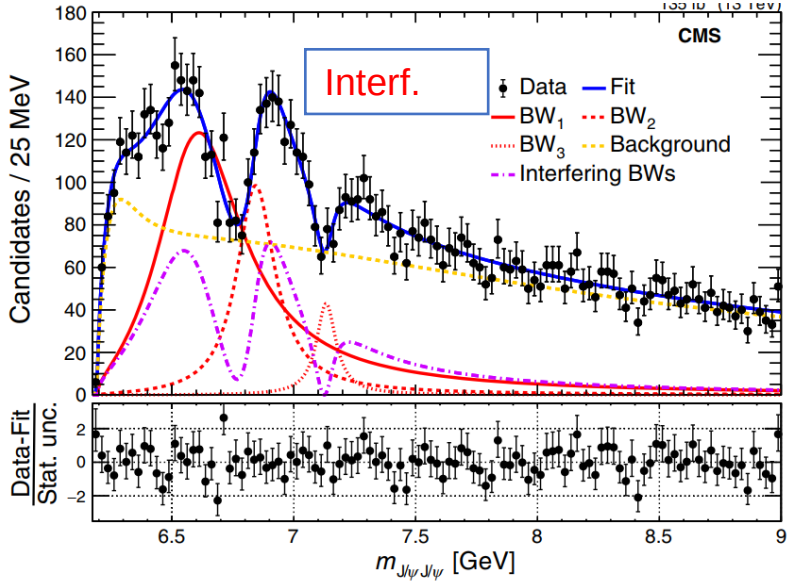
Comparison with some theoretical predictions





PRL312.111902(2024)

P-wave

$N^{2S+1}L_J$	J^{PC}	$\langle K.E.\rangle$	$E^{(0)}$	$\langle V_C^{(0)}\rangle$	$\langle V_L^{(0)}\rangle$	$\langle V_{SS}^{(1)}\rangle$	$\langle V_{LS}^{(1)}\rangle$	$\langle V_T^{(1)}\rangle$	$V^{(1)}(r)$	M_f
1^3P_1	1^{-+}	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554
2^3P_1	1^{-+}	410.0	689.6	-263.4	548.6	-5.6	-23.1	17.2	-1.6	6926
3^3P_1	1^{-+}	475.1	982.6	-215.5	727.7	-4.6	-20.9	15.5	-1.2	7220

M[BW1] = 6552 ± 10 ± 12 MeV

M[BW2] = 6927 ± 9 ± 5 MeV

M[BW3] = 7287 ± 19 ± 5 MeV

arXiv:2108.04017

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}

M[BW1] = 6638 ± 10 ± 12 MeV

M[BW2] = 6847 ± 9 ± 5 MeV

M[BW3] = 7134 ± 19 ± 5 MeV

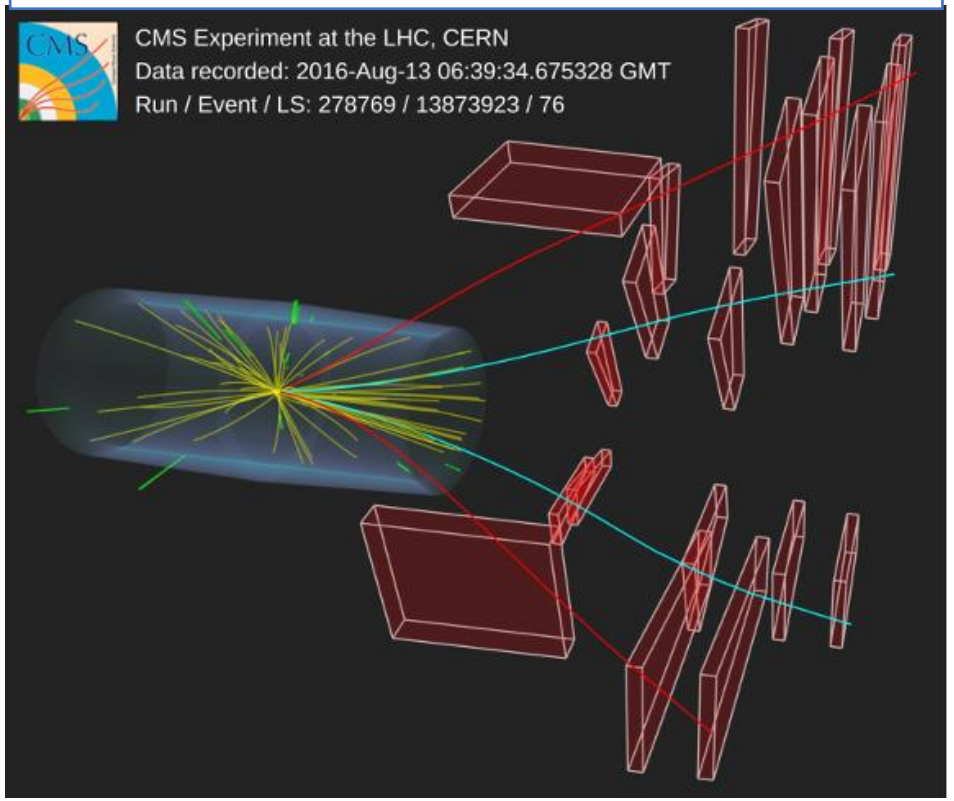
Nucl. Phys. B 966 (2021) 115393

- P-wave radial excitation (like ψ)?
- Or S-wave radial excitation?
- Theoretical situation difficulty & confusing
  - Important next step: measure J^{PC} to clarify

Summary & outlook

- New resonances in $J/\psi J/\psi$ mass spectrum at CMS
  - X(6600) – 7.9σ (**NEW!**)
  - X(6900) – 9.8σ
  - X(7100) – 4.7σ (**NEW!**)
- The coming Run III data will help in further study of their properties
  - Spin-parity, new decay mode …

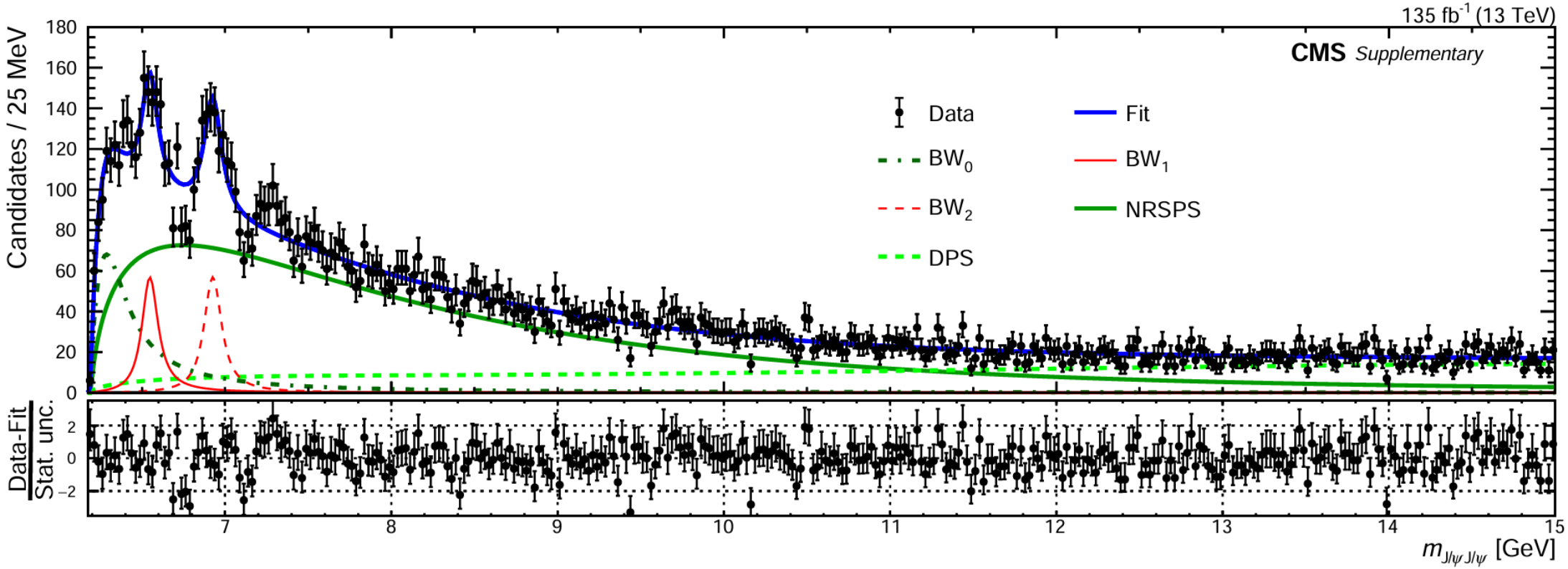
Event display of a X(6600) candidate



Thanks

Backup

Mimic of LHCb model I



Exp.	Fit	M_{BW_1}	Γ_{BW_1}	$M_{X(6900)}$	$\Gamma_{X(6900)}$
LHCb [1]	Model I	···	···	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [1]	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

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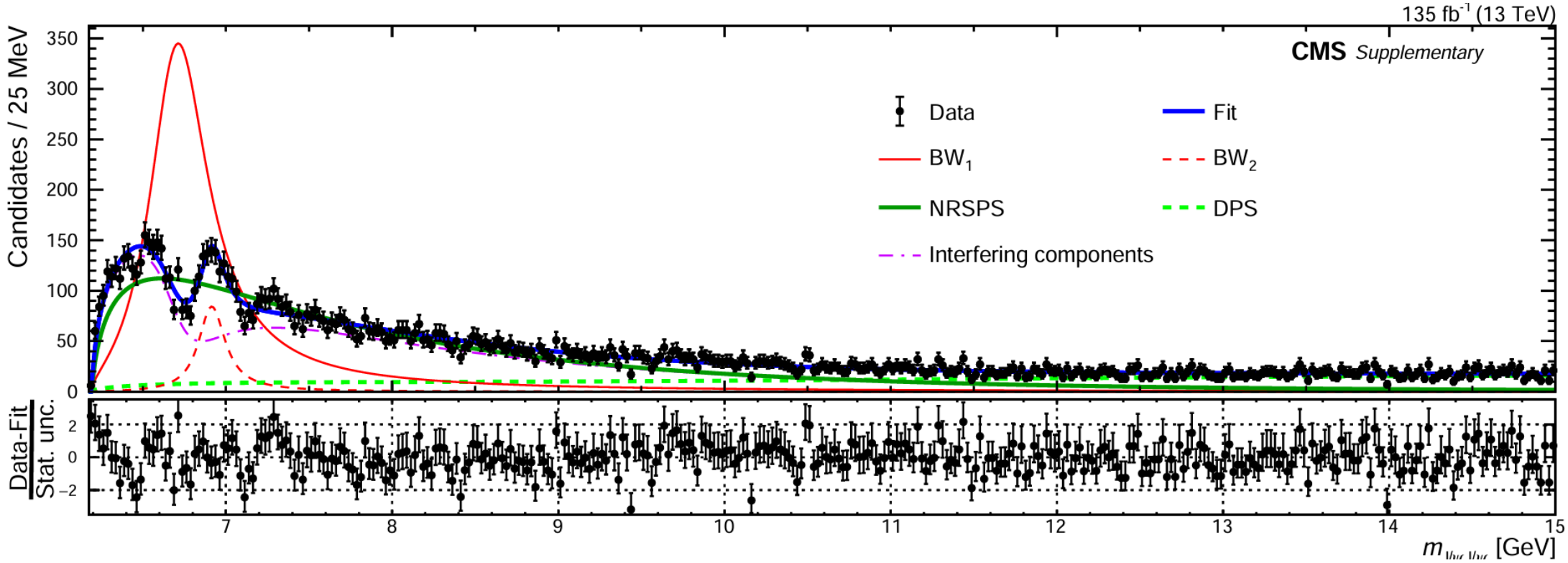
Mimic of LHCb model II



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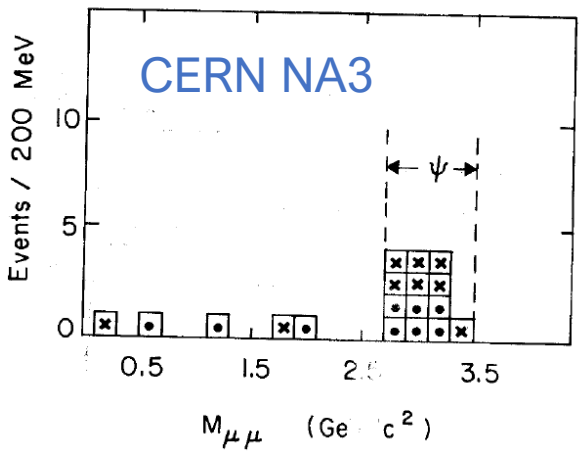
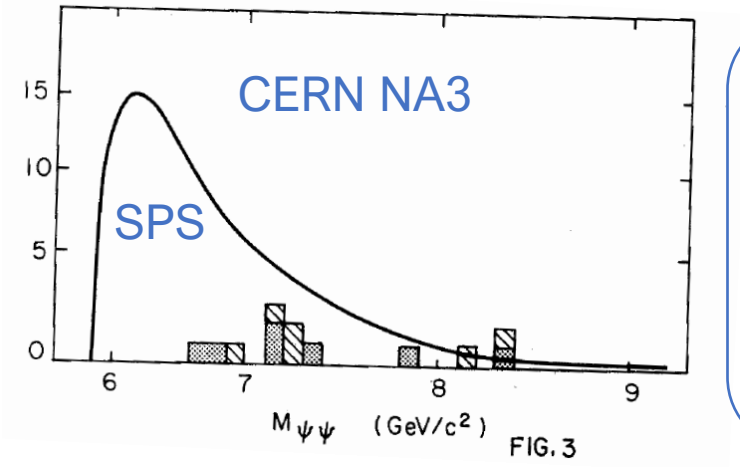
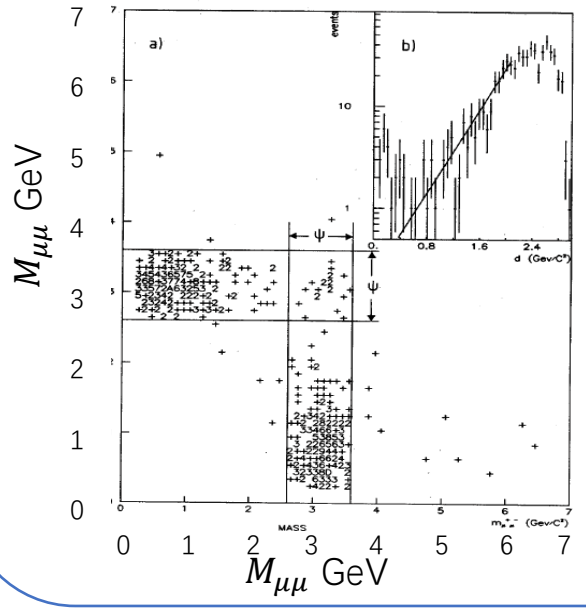
First evidence of $J/\psi J/\psi$ events in 1982



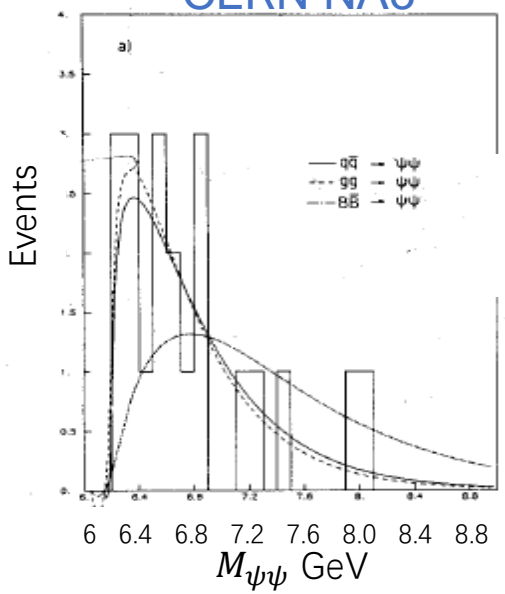


PLB114(1982)457
Was interpreted as 2^{++} 4-quark state

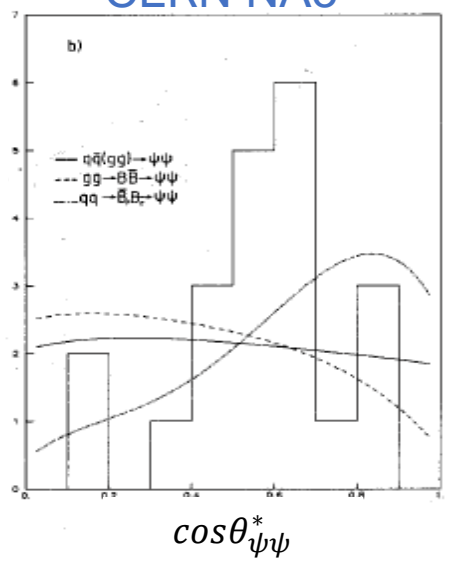
CERN NA3



CERN NA3



CERN NA3



PLB158 (1985) 85

Possible explanations of $J/\psi J/\psi$ 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