中国物理学会高能物理分会
HIGH ENERGY PHYSICS BRANCH OF CPS

華南師範大學

中国物理学会高能物理分会
第十二届全国会员代表大会暨学术年会

All-charm Tetraquarks at the CMS Experiment

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清華大學
Tsinghua University

2026年7月15日，华南师范大学

第十四届“晨光杯”青年优秀论文评选

CMS实验上全粲四夸克态家族自旋宇称的测量

Nature 648 (2025) 58: Determination of the spin and parity of all-charm tetraquarks

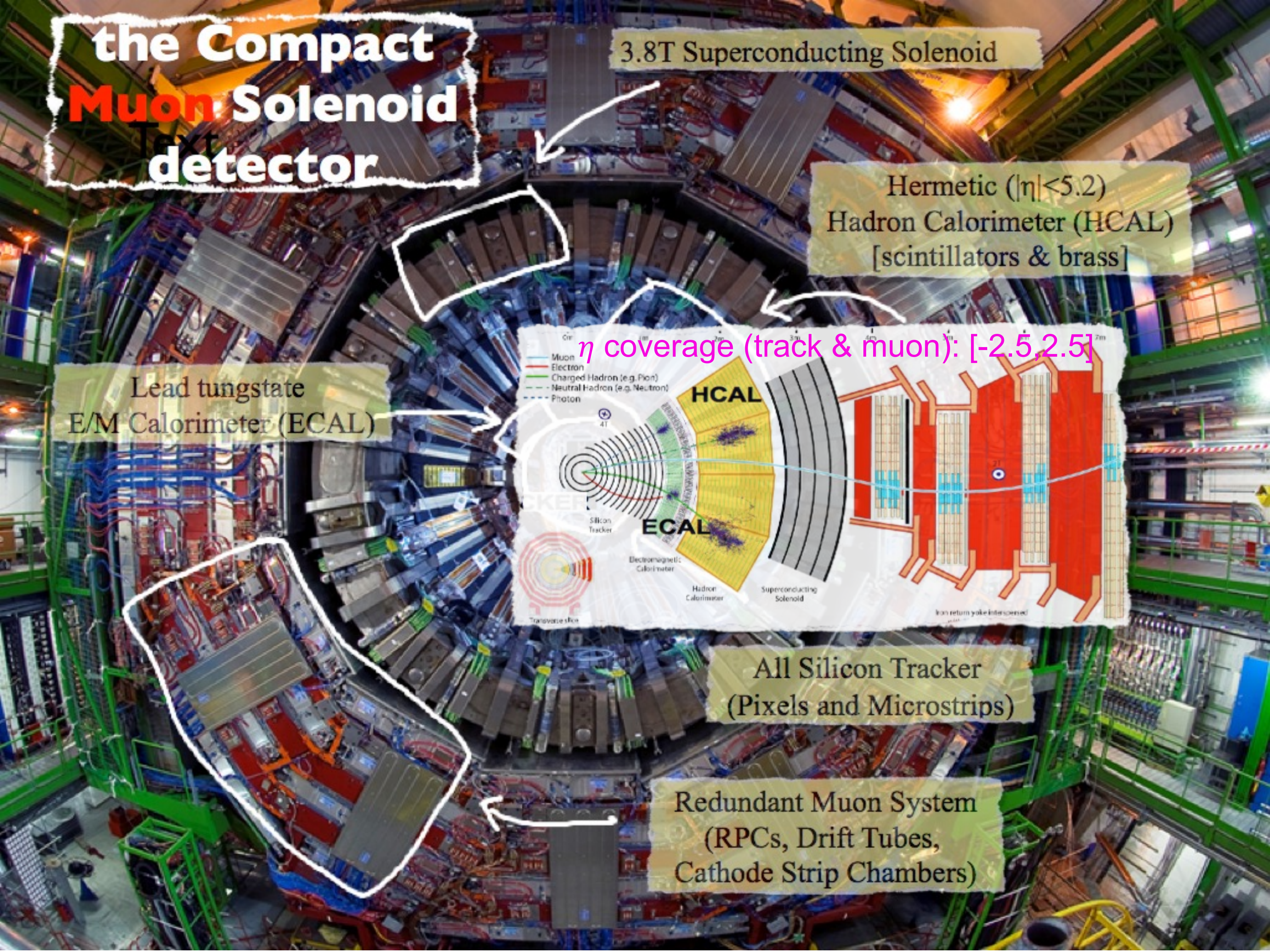
王晰宁
晨光杯

2026年7月15日

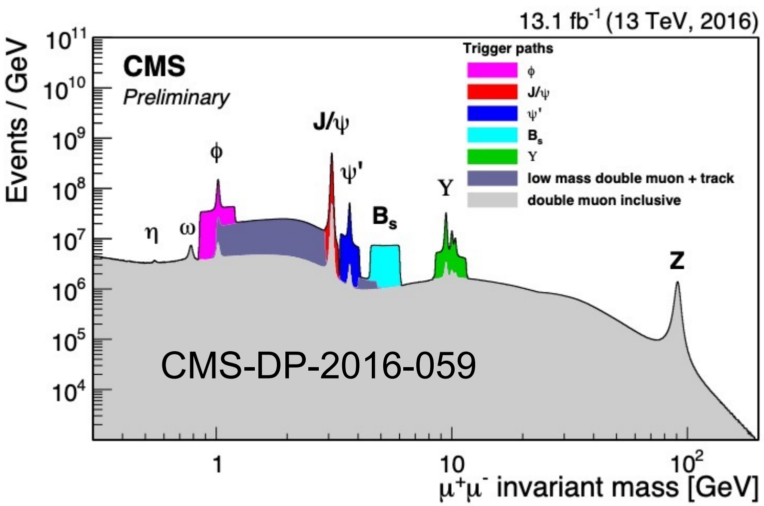
初评得分排名前15位的论文（进入终评）
（按姓氏拼音排序）

论文序号	论文题目	论文作者	单位
1	Dispersive determination of nucleon gravitational form factors	曹雄辉	中科院理论所 (2023年博士毕业)
2	Measurement of reactor neutrino oscillation with the first JUNO data	陈志源、Iwan Morton-Blake、孙明霞、王明远、张涵	高能所等（博士毕业、博士毕业、博士在读、博士在读、博士在读）
3	Baryon Electric Charge Correlation as a Magnetometer of QCD	顾锦彪	华中师范大学 (博士在读)
4	Establishing CP violation in b-baryon decays	韩佳杰	兰州大学 (博士后)
5	First Indication of Solar ^{8}B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT	刘可欣	清华大学 (在读博士)
6	Strong and Weak CP Tests in Sequential Decays of Polarized Σ^0 Hyperons	沈宏飞	高能所 (博士后)
7	1. Determination of the spin and parity of all-charm tetraquarks Review 2. Experimental road of the J/ψϕ mass spectrum, current status, and implications	王晰宁	清华大学 (博士在读)
8	Observation of the antimatter hypernucleus ^{4}H	吴俊霖	中国科学院大学 (博士后)
9	1. ω Meson from Lattice QCD 2. Emergence of the πδ1300Þ Resonance from Lattice QCD	燕浩波	北京大学 (博士在读)
10	Observation ofcharge-parity symmetry breaking in baryon decays	杨雪婷	北京大学 (博士在读)
11	Direct observation of the Migdal effect induced by neutron bombardment	易涤凡	中科院大学 (博士在读)
12	Precise measurement of matter-antimatter asymmetry withentangled hyperon antihyperon pairs	张景旭	兰州大学 (在读博士)
13	First Indication of Solar ^{8}B Neutrinos through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T	张敏祯	上海交通大学 (博士后)
14	Suppression of Spin Transfer to Λ Hyperon in Dcep-Inelastic Scattering	赵晓燕	山东大学 (2026年博士毕业)
15	1. Extracting the femtometer structure of strange baryons using the vacuum polarization effect 2. Observation of the Electromagnetic Radiative Decays of the Λ（1520） and Λ（1690） to $\gamma\Sigma^0$	郑文静	高能所 (博士后)

The **Large Hadron Collider** (**LHC**) at CERN is the world's largest particle collider. It lies in a tunnel 27 kilometres in circumference and as deep as 175 metres beneath the France–Switzerland border near Geneva.


the Compact Muon Solenoid detector
Text
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
η coverage (track & muon): [-2.5,2.5]
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
Lead tungstate
E/M Calorimeter (ECAL)
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

CMS trigger & dimuon spectrum

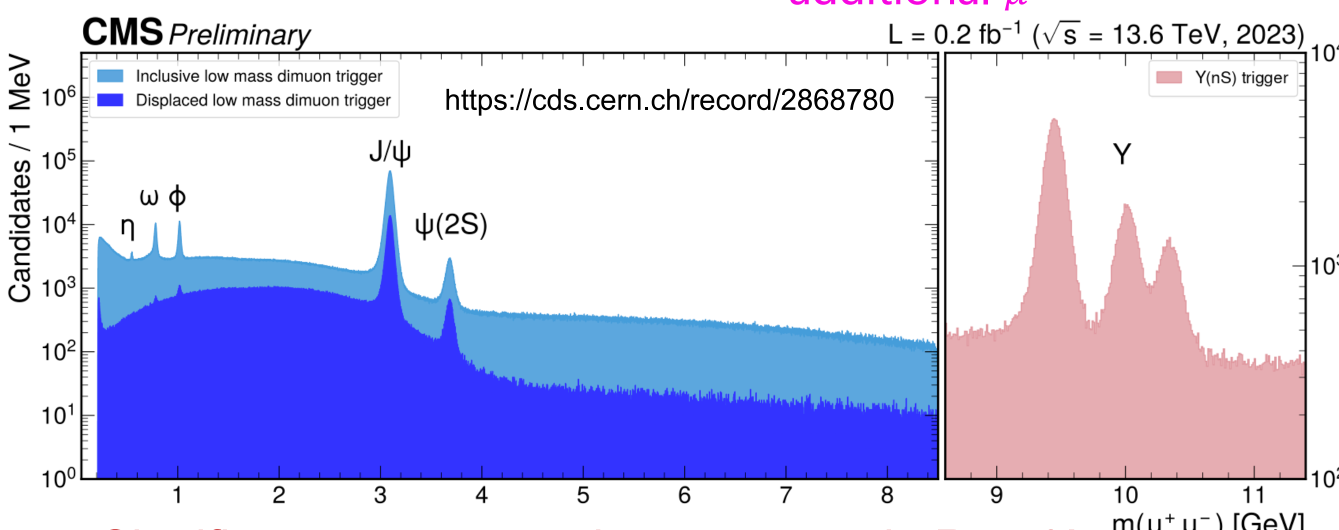


Excellent detector for studies with muons

- 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

Majority of analyses rely on dimuon triggers

- Special triggers for different analyses
  - μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ



Significant acceptance improvement in Run-3!

All-charm tetraquarks

- 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 precise calculation of 4c states (1981): Z. Phys. C 7 (1981) 317

K. T. Chao

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

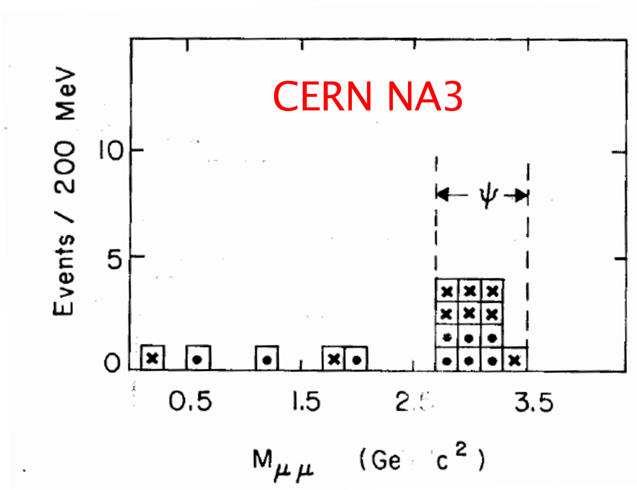
$(cc)_{\underline{3}^*} - (\bar{c}\bar{c})_{\underline{3}}$

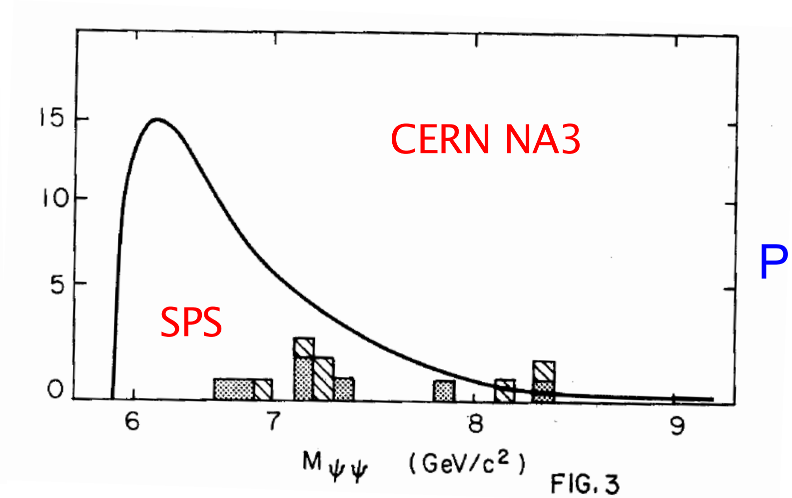
$(cc)_{\underline{6}} - (\bar{c}\bar{c})_{\underline{6}^*}$

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

- A different (all heavy) exotic system compared to exotics with light quarks

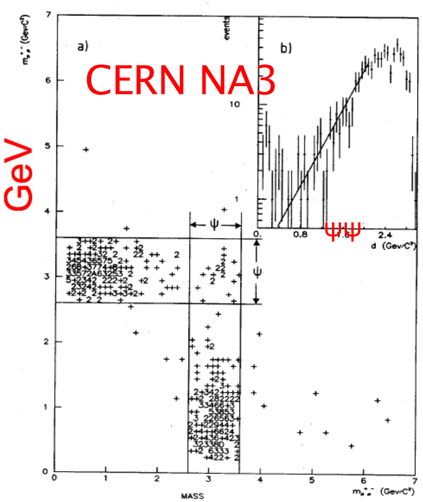
J/ψJ/ψ events - first evidence (1982)



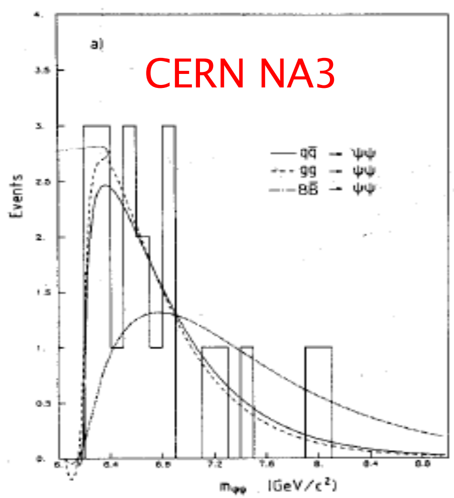


PLB114 (1982) 457

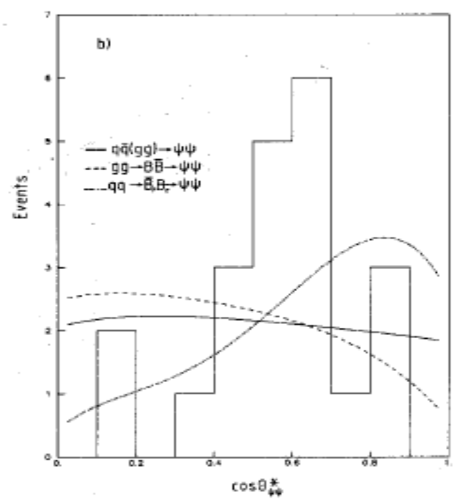
m(μ⁺μ⁻) GeV



m(μ⁺μ⁻) GeV



m(ψψ) GeV



cos(ψψ-helicity)

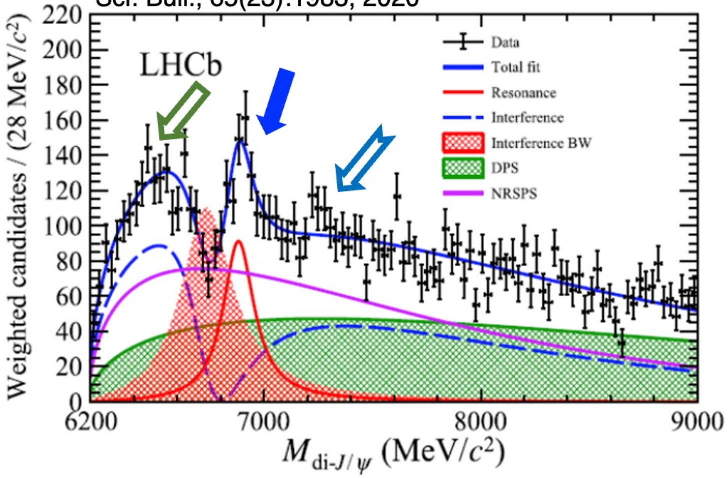
PLB158 (1985) 85

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

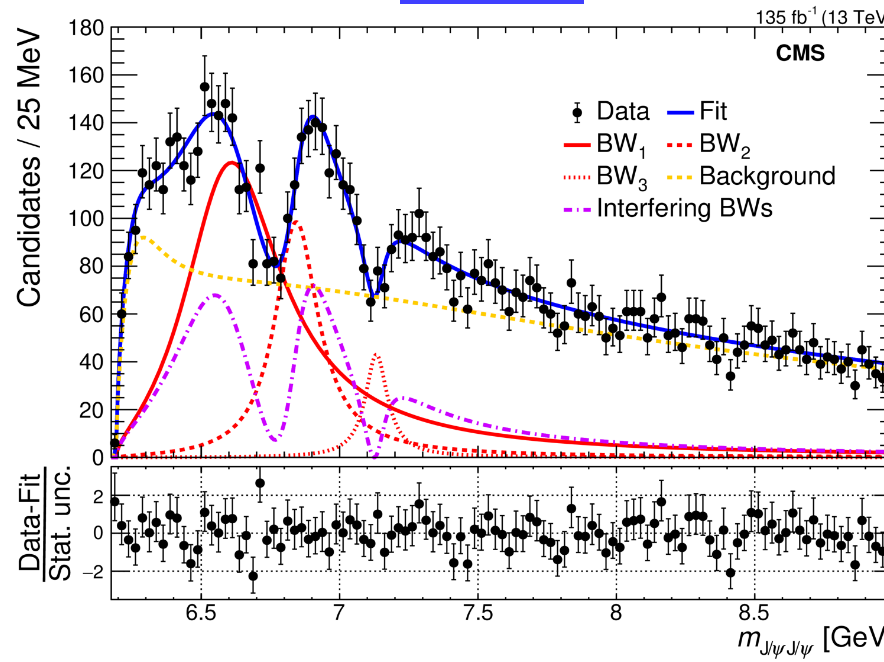
All-charm Tetraquarks at LHC

LHCb

Sci. Bull., 65(23):1983, 2020

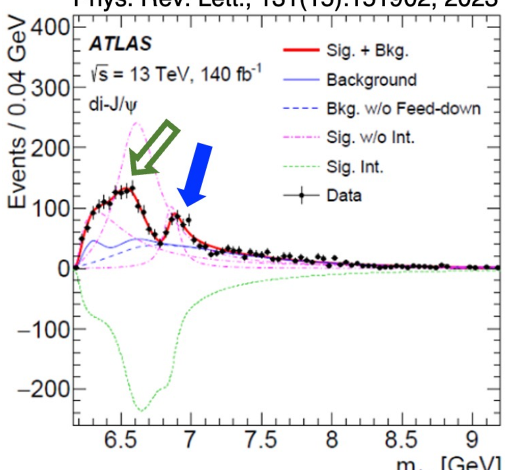


CMS



ATLAS

Phys. Rev. Lett., 131(15):151902, 2023

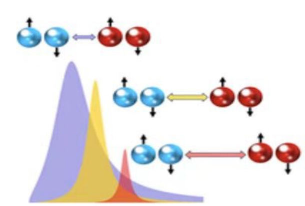


Editors' Suggestion

New Structures in the $J/\psi J/\psi$ Mass Spectrum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.* (CMS Collaboration)

Phys. Rev. Lett. **132**, 111901 (2024) – Published 15 March 2024

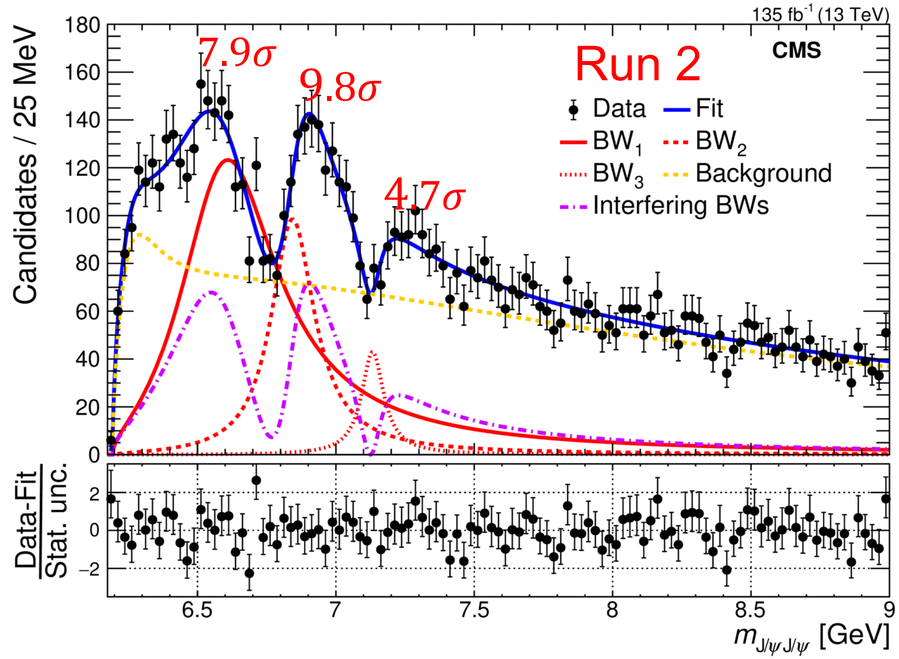


Three structures, $X(6900)$ and two new ones around 6.64 and 7.13 GeV, are seen in the $J/\psi J/\psi$ mass spectrum that are consistent with being part of a family of radial excitations.

Show Abstract +

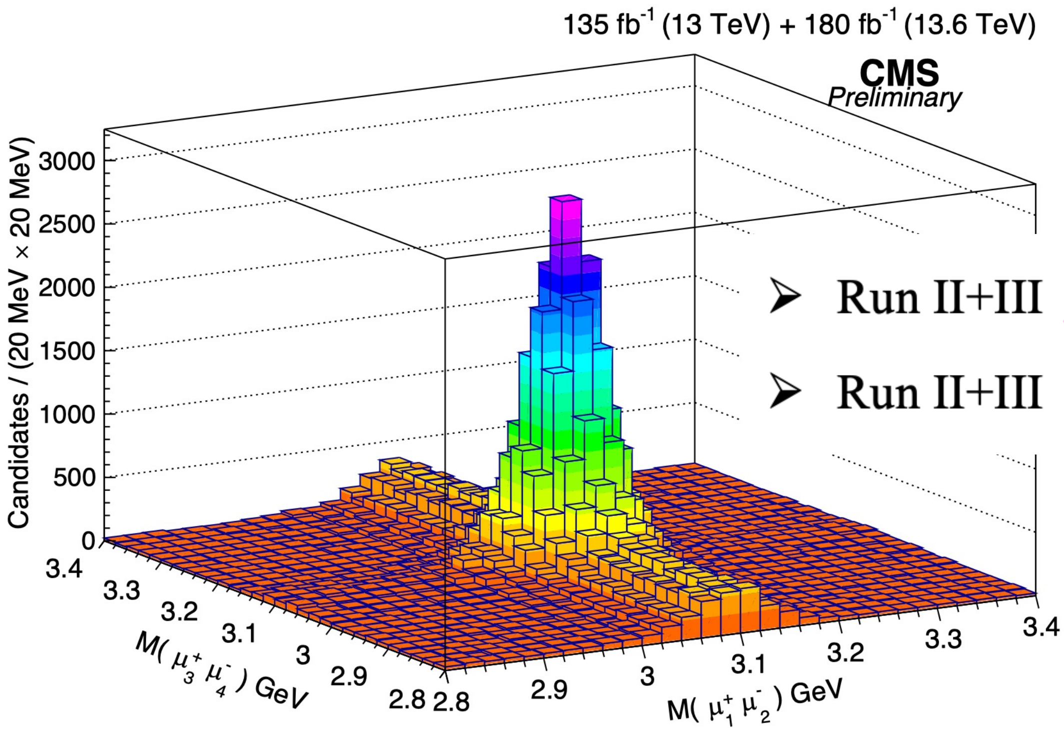
CMS J/ψJ/ψ Run 3

- **X(7100)**: 4.7σ & Interference < 4σ
- Significance of **ALL** states over 5σ ?
- Significance of **interference** over 5σ ?



- New data samples [315 fb^{-1}]
  - Run II: 135 fb^{-1} data taken in 2016, 2017 and 2018
  - Run III: 180 fb^{-1} data taken in 2022, 2023 and 2024

J/ψJ/ψ candidates Run 2+3

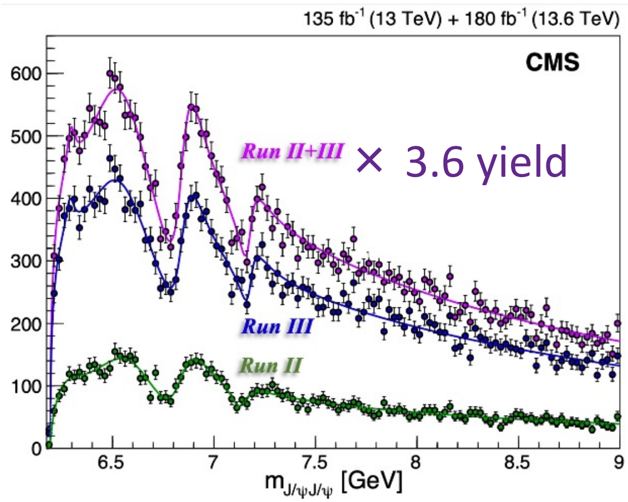


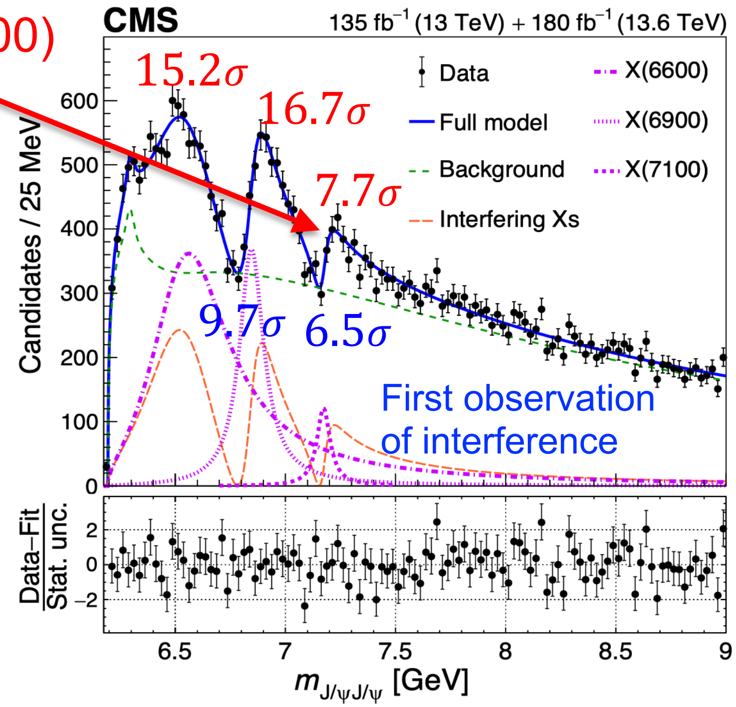
- Run II+III $J/\psi J/\psi$ yield is **3.6X** of Run II
- Run II+III **Luminosity** is **2.3X** of Run II !

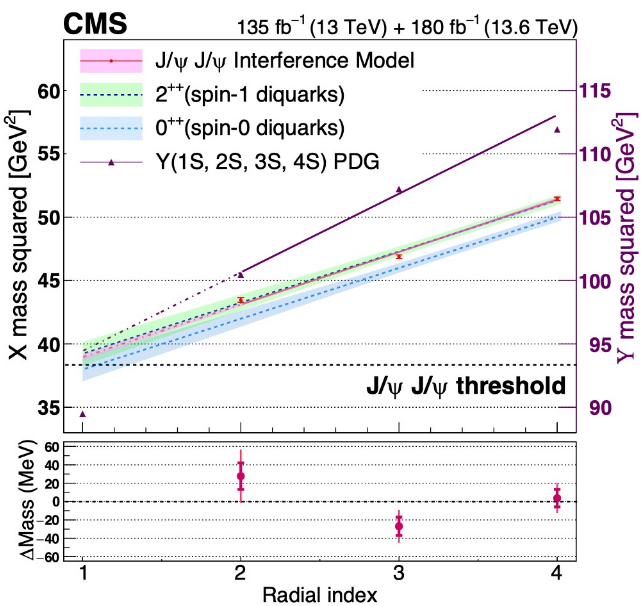
[6, 15] GeV	**N($J/\psi J/\psi$)**	N($J/\psi\mu\mu$)	N($\mu\mu J/\psi$)	N($\mu\mu\mu\mu$)
Run II	**12622 ± 165**	6451 ± 146	772 ± 52	1295 ± 60
Run III	**31802 ± 476**	33603 ± 491	4604 ± 166	33187 ± 267
Run II+III	**44936 ± 692**	39371 ± 698	5374 ± 181	34656 ± 278

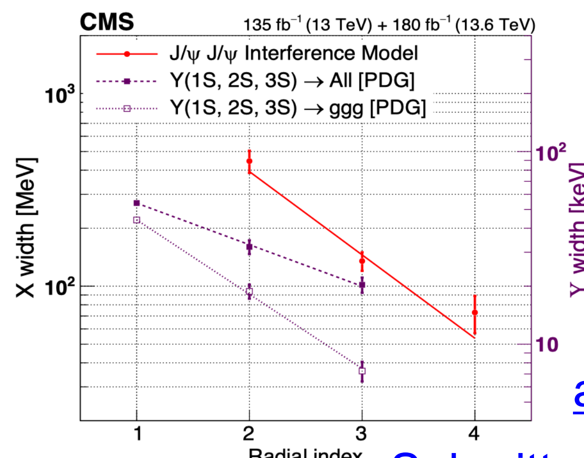
Observation of a family of all-charm tetraquarks

First observation of X(7100)







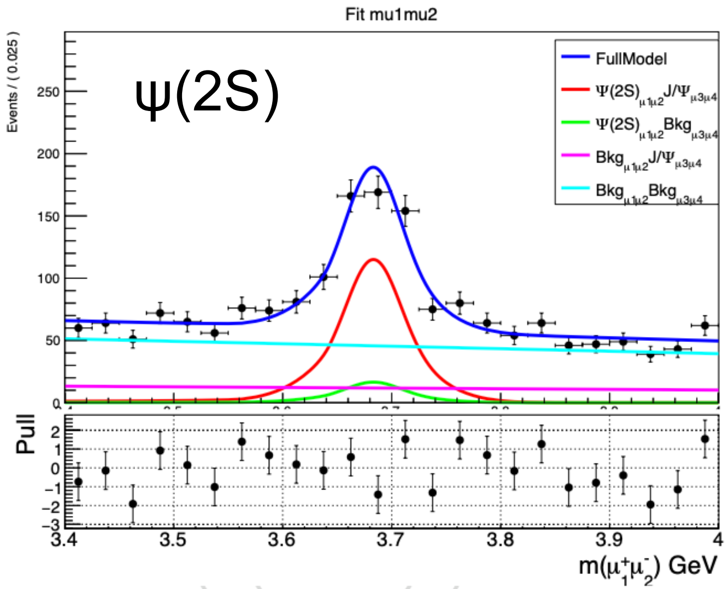


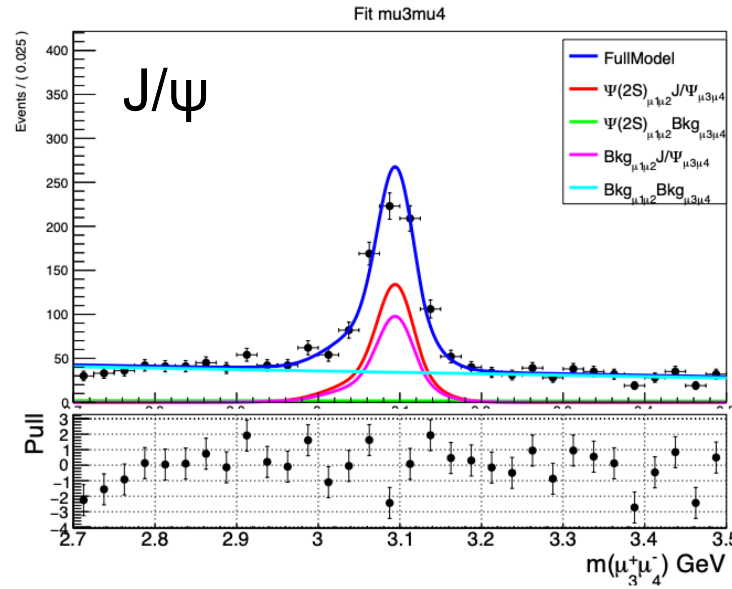
[arXiv:2602.02252]

[Submitted to Sci. Adv.]

ψ(2S)J/ψ candidates Run 2+3

CMS-PAS-BPH-22-004

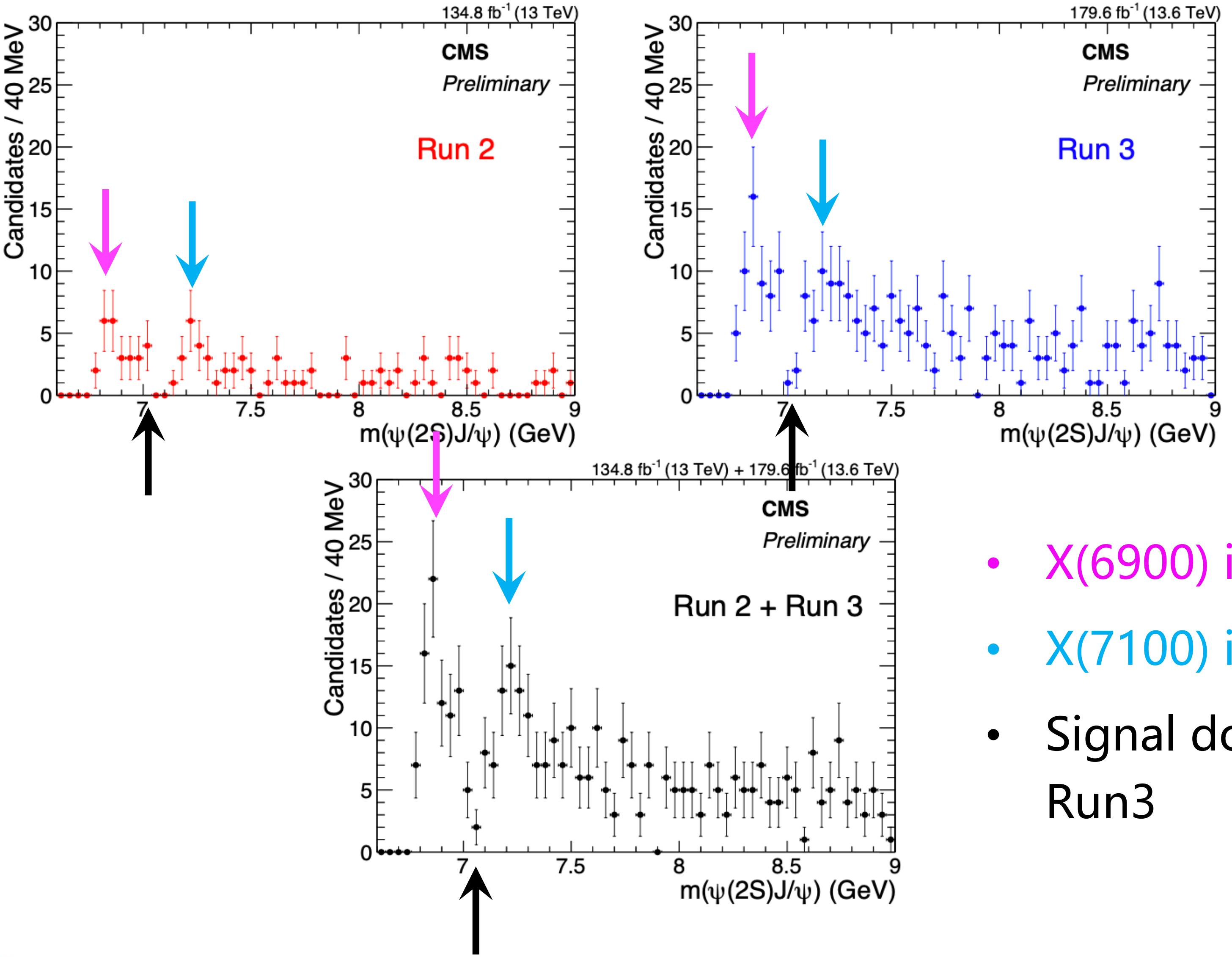




	Run2 + Run3 data		
$N(\psi(2S)\,J/\psi)$	386 ± 26	**S**	386 ± 26 (vs 109 ± 14 in Run2)
$N(\psi(2S)Bkg_2)$	56 ± 24	B	1427 ± 57 (vs 208 ± 22 in Run2)
$N(Bkg_1\,J/\psi)$	282 ± 28		
$N(Bkg_1\,Bkg_2)$	1089 ± 43		

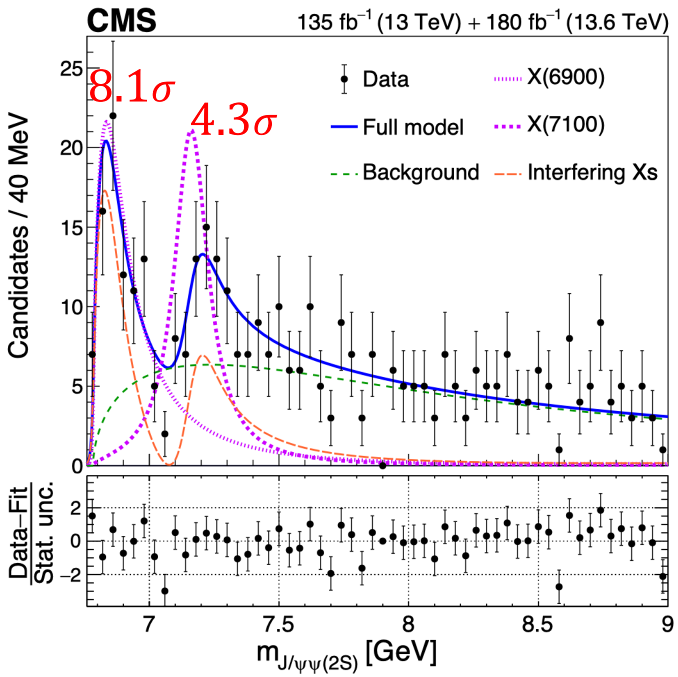
3.5 times yield

ψ(2S)J/ψ mass Run 2+3



- X(6900) is obvious
- X(7100) is visible
- Signal dominated by Run3

Observation of X(6900) → ψ(2S)J/ψ



First observation of
X(6900) → ψ(2S)J/ψ → 4μ

Evidence of X(7100) → ψ(2S)J/ψ: 4.3σ

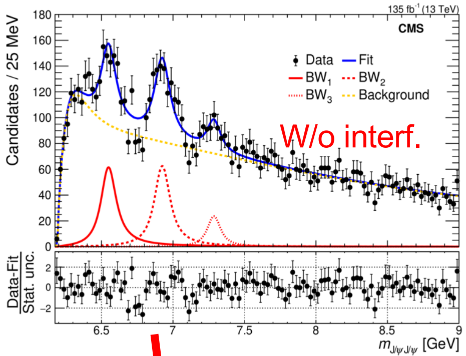
Interference: 2.5σ

[arXiv:2602.02252]

[Submitted to Science Adv.]

Fit	Sample	Interf.		$X(6600)$	$X(6900)$	$X(7100)$
f_{i23}	$J/\psi\psi(2S)$	BW_2, BW_3	m :	—	$6876^{+46+110}_{-29-110}$	7169^{+26+74}_{-52-70}
			Γ :	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
f_{JJ} [1]	$J/\psi J/\psi$	Interference	m (MeV)	$6593\ ^{+15}_{-14} \pm 25$	$6847\ ^{+10}_{-10} \pm 15$	$7173\ ^{+9}_{-10} \pm 13$
		(Run 2+Run 3)	Γ (MeV)	$446\ ^{+66}_{-54} \pm 87$	$135\ ^{+16}_{-14} \pm 14$	$73\ ^{+18}_{-15} \pm 10$
		Interference	m (MeV)	$6638\ ^{+43+16}_{-38-31}$	$6847\ ^{+44+48}_{-28-20}$	$7134\ ^{+48+41}_{-25-15}$
		(Run 2 [12])	Γ (MeV)	$440\ ^{+230+110}_{-200-240}$	$191\ ^{+66+25}_{-49-17}$	$97\ ^{+40+29}_{-29-26}$

Comparison with some theoretical calculations



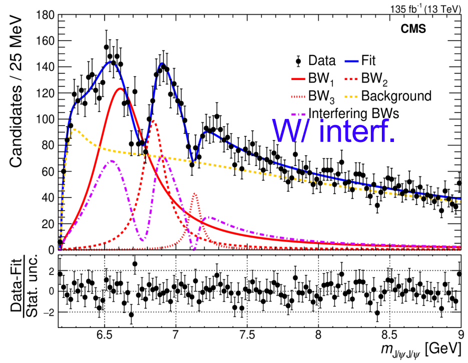


Table 1. Predictions of the masses (MeV) of S-wave fully heavy $T_{4Q}(nS)$ tetraquarks. Only 0^{++} and 2^{++} are considered for $T_{bc\bar{b}\bar{c}}$. The uncertainty is from the coupling constant $\alpha_s = 0.35 \pm 0.05$.

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}[illegible]	6890^{+27}[illegible]	7160^{+21}_{-22}
$T'_{cc\bar{c}\bar{c}}$	0^{++}	5984^{+64}_{-67}	6468[illegible]	[illegible]$^{+26}_{-26}$	[illegible]66^{+21}_{-22}
$T_{bc\bar{b}\bar{c}}$	0^{++}	12387^{+109}_{-120}	12911[illegible]	[illegible]$^{+35}_{-36}$	13429^{+29}_{-30}
	2^{++}	12401^{+117}_{-106}	12914^{+49}_{-49}	[illegible]$^{+35}_{-36}$	13430^{+29}_{-29}
$T'_{bc\bar{b}\bar{c}}$	0^{++}	12300^{+106}_{-117}	12816^{+48}_{-50}	[illegible]04^{+35}_{-35}	13333^{+29}_{-29}
$T_{bb\bar{b}\bar{b}}$	0^{++}	18475^{+151}_{-169}	19073^{+59}_{-63}	[illegible]53^{+42}_{-42}	19566^{+33}_{-35}
	2^{++}	18483^{+149}_{-168}	19075^{+59}_{-62}	[illegible]55^{+41}_{-43}	19567^{+33}_{-35}
$T'_{bb\bar{b}\bar{b}}$	0^{++}	18383^{+149}_{-167}	18976^{+59}_{-62}	[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

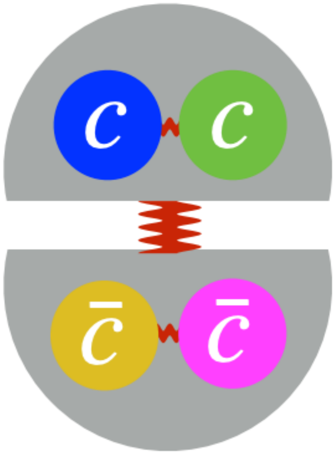
1^1P_1	1^{--}	363.9	320.3	-366.7	337.5	-14.4	0	0	-2.6	6553	-	-
1^3P_0	0^{-+}	356.7	320.2	-366.7	337.5	-7.2	-56.9	-43.1	-2.6	6460	6398.1	$\eta_c(1S)\chi_{c0}(1P)$
1^3P_1	1^{-+}	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554	6494.1	$\eta_c(1S)\chi_{c1}(1P)$
1^3P_2	2^{-+}	356.6	320.2	-366.7	337.5	-7.2	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	[illegible]	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	[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	6951	-	-
2^5P_1	1^{--}	398.7	689.5	-263.4	548.6	-5.6	-69.3	-24.2	-1.7	[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

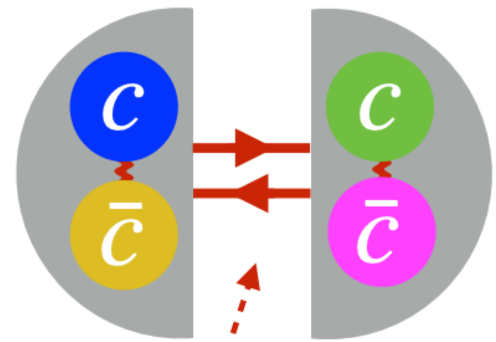
- Radial excited p-wave states (like J/ψ series)?
- Or Radial excited s-wave states?
- Theoretical situation difficulty & confusing
  - Important next step: measure J^{PC} to clarify



?

“True” tetraquark
connects
two colored objects
(cc) and $(\bar{c}\bar{c})$
through direct strong
interactions
like quarks in a proton
or neutron

“Molecule”
a bound state
of two mesons
connected by
residual nuclear
force, like proton
and neutron in a
nucleus



$$V(r) = g \cdot \frac{e^{-\frac{m_{\eta_c} c}{\hbar} r}}{r}$$

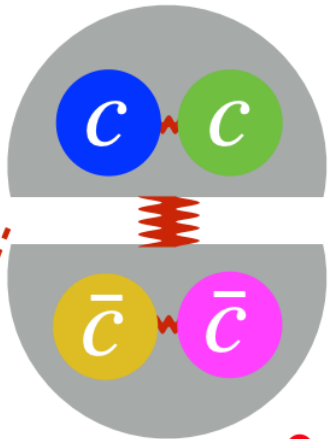
note $(c\bar{c})$ mass
$\times$ 22 heavier
than π

binding would be much weaker
than in a nucleus or light “tetraquarks”

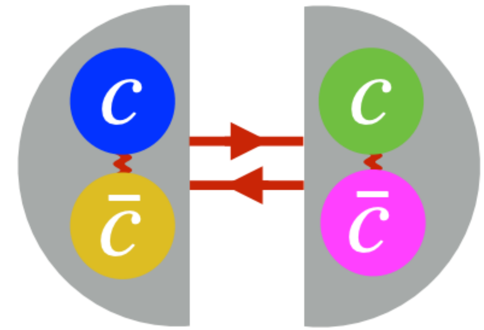
other empirical interactions?

Spin Parity Analysis

- Fundamental study of matter at quark level…
  — unique all-heavy tetraquark states



- Quantum numbers $J^{PC} = ?$
  directly related to structure:



- Tightly-bound tetraquark:

(cc) or $(\bar{c}\bar{c})$ identical ⇒ color anti-triplet (bg-gb,..) $L = 0$, axial vector $S_{1,2} = 1$

$(cc) + (\bar{c}\bar{c}) \Rightarrow L = 0\ (\mathrm{n}S):\ S = 0, 2 \Rightarrow J^P = 0^+, 2^+$ most likely for a tetraquark

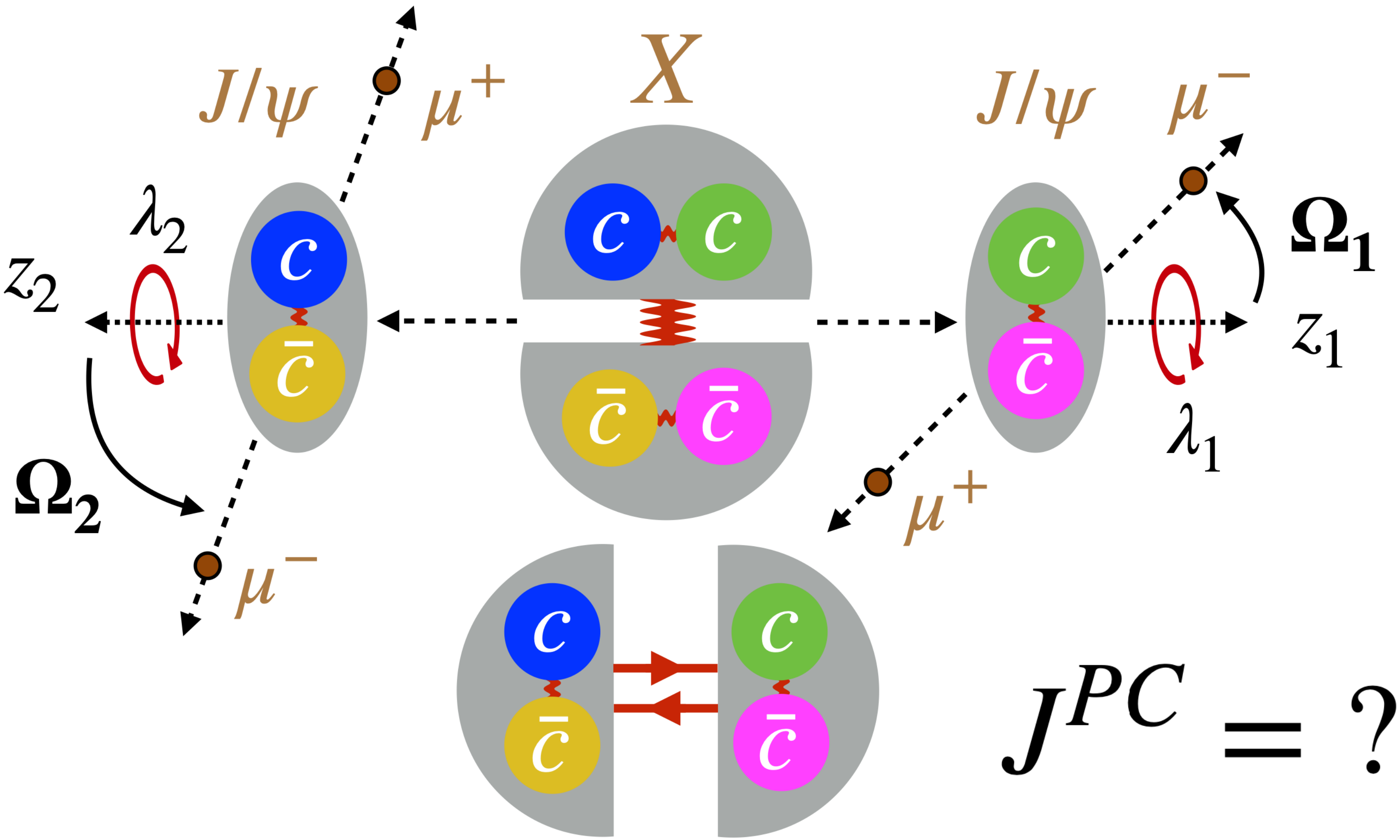
$L = 1\ (\mathrm{n}P):\ S = 1 \Rightarrow J^P = 0^-, 1^-, 2^-$ less likely

$n = 1,2,3,4,..$ $\quad L = 2\ (\mathrm{n}D):\ S = 0 \Rightarrow J^P = 2^+$

$S = 2 \Rightarrow J^P = 0^+, 1^+, 2^+, 3^+, 4^+ \quad \ldots$ unlikely

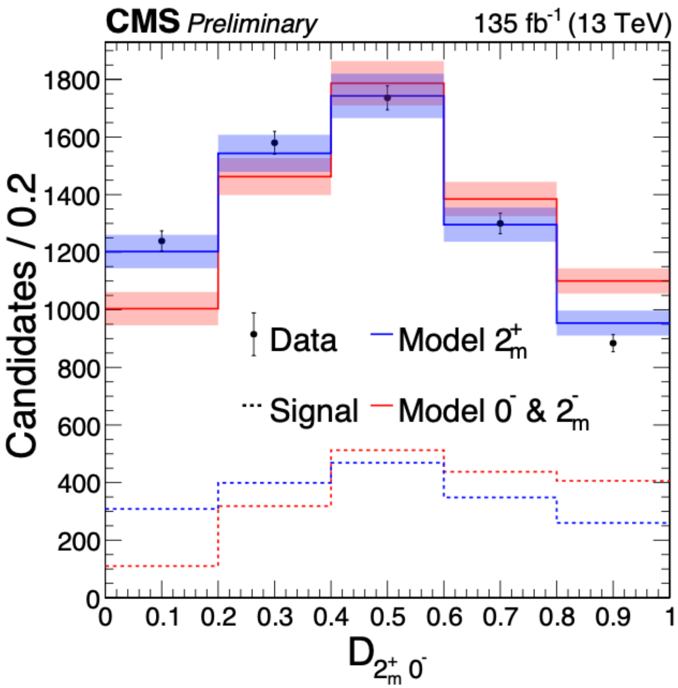
- Molecular: less restrictions (e.g. meson $S_{1,2} = 0,1$): recall $J^P = 1^+$

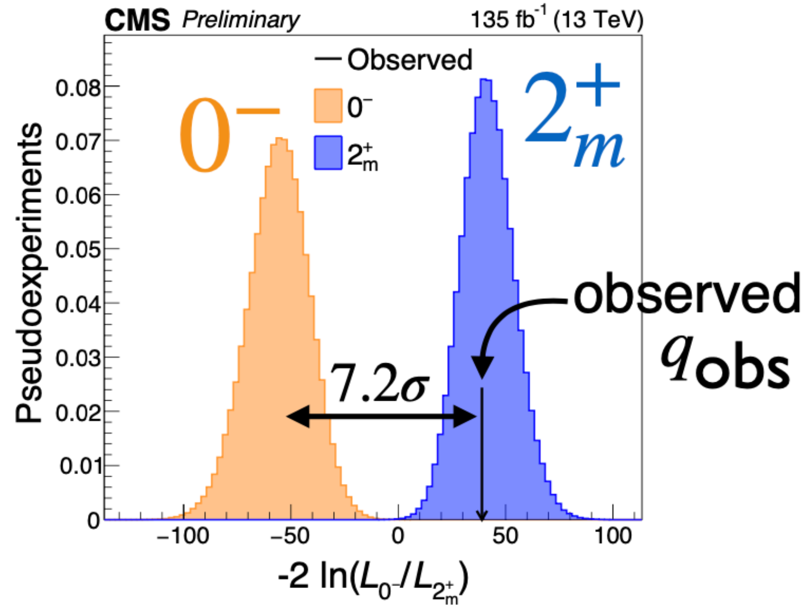
Decay angles



$J^{PC} = ?$

- 1D projection of data, optimal for $j = 0^-(2_m^-)$ vs $i = 2_m^+$





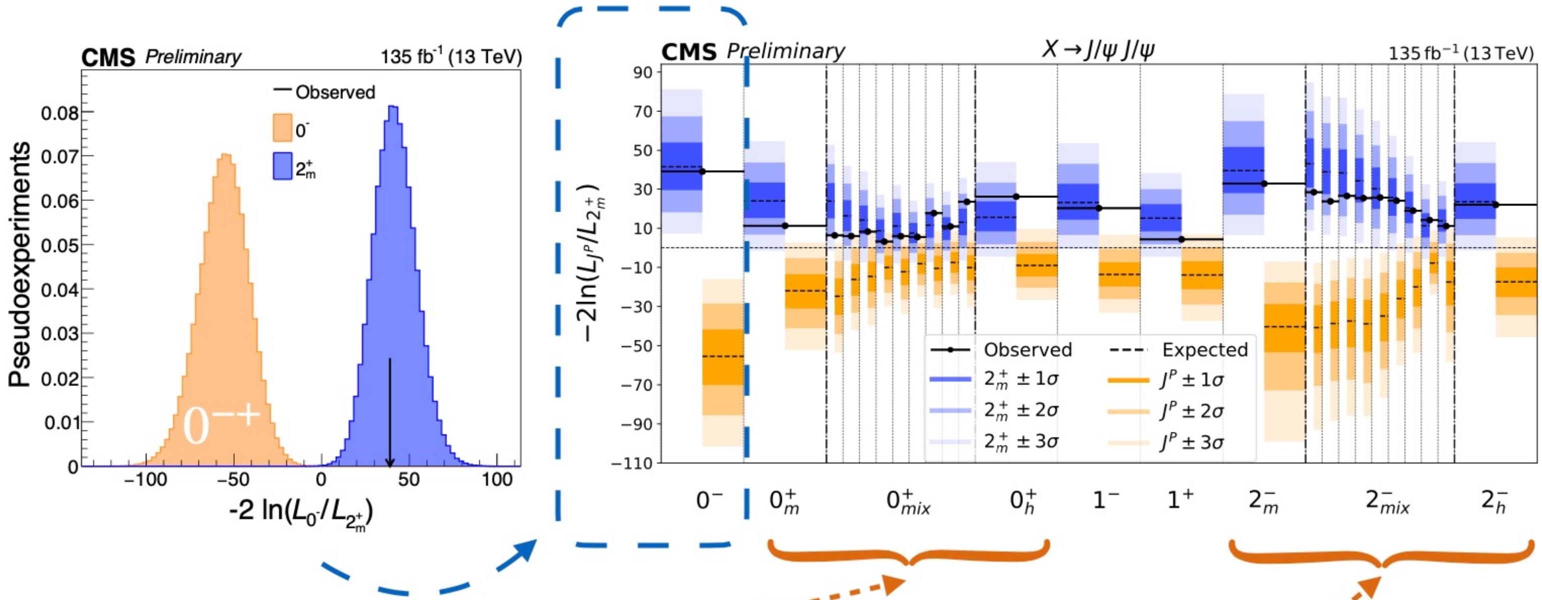
optimal observable

MELA $$\mathcal{D}_{ij}(\vec{\Omega}\,|\,m_{4\mu}) = \frac{\mathcal{P}_i(\vec{\Omega}\,|\,m_{4\mu})}{\mathcal{P}_i(\vec{\Omega}\,|\,m_{4\mu}) + \mathcal{P}_j(\vec{\Omega}\,|\,m_{4\mu})}$$

	Observed p-value	Observed Z-score	Expected p-value	Expected Z-score
0^-	2.7×10^{-13}	7.2	6.5×10^{-14}	7.4
2_m^+	4.2×10^{-1}	0.2	0.50	0.0

1D projections from 2D
$\Rightarrow$ limited information

Summary of Statistical Analysis



- Scan mixture of two 0^{++} amplitudes (11 steps)
  — constructive interference most conservative

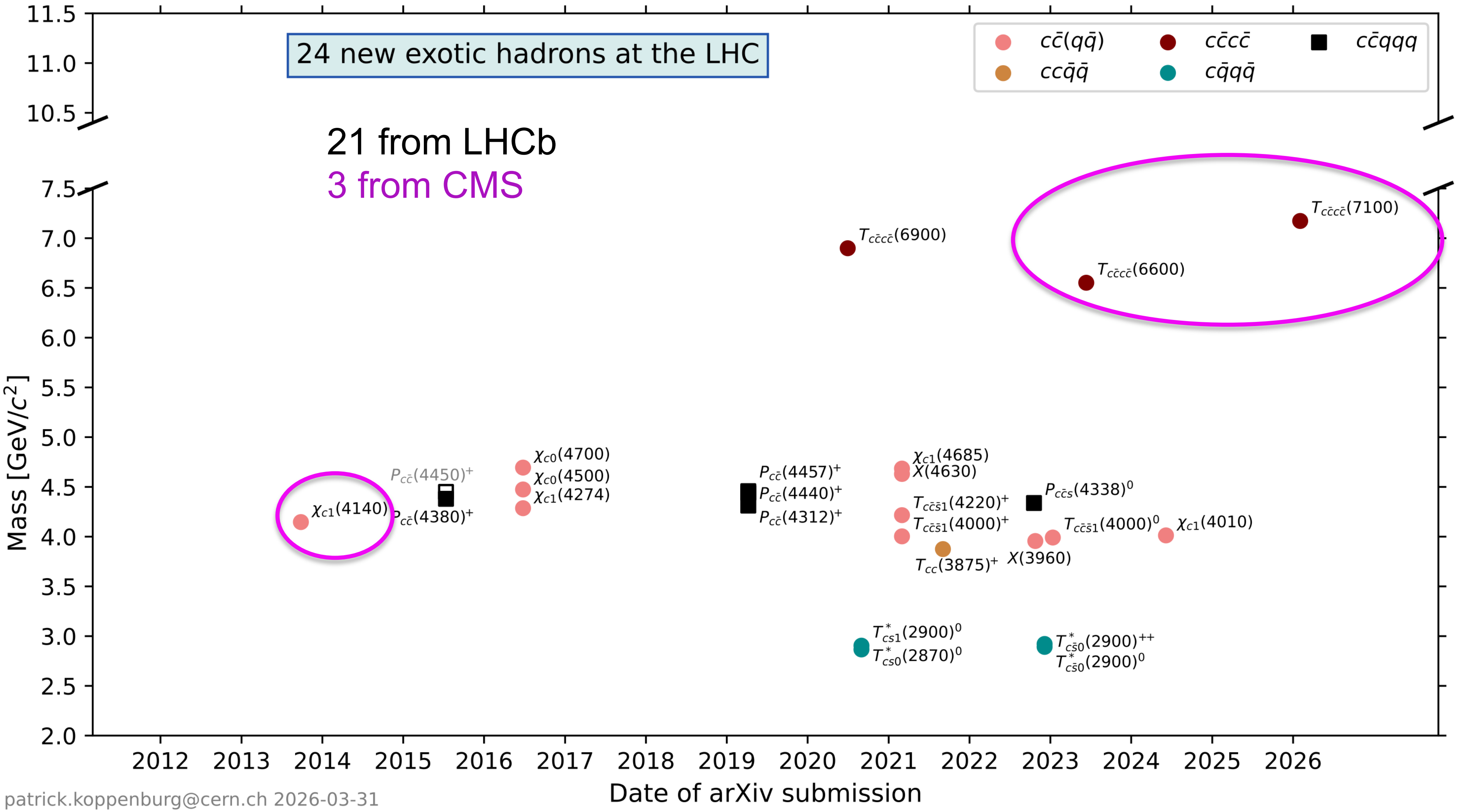
- Scan mixture of two 2^{-+} amplitudes (11 steps)
  — no interference (different spin projections)

- Data are consistent with a 2^{++} model, inconsistent with others

2^{++}: rare in nature

[Nature 648 (2025) 58]

Summary of new exotic hadrons at LHC



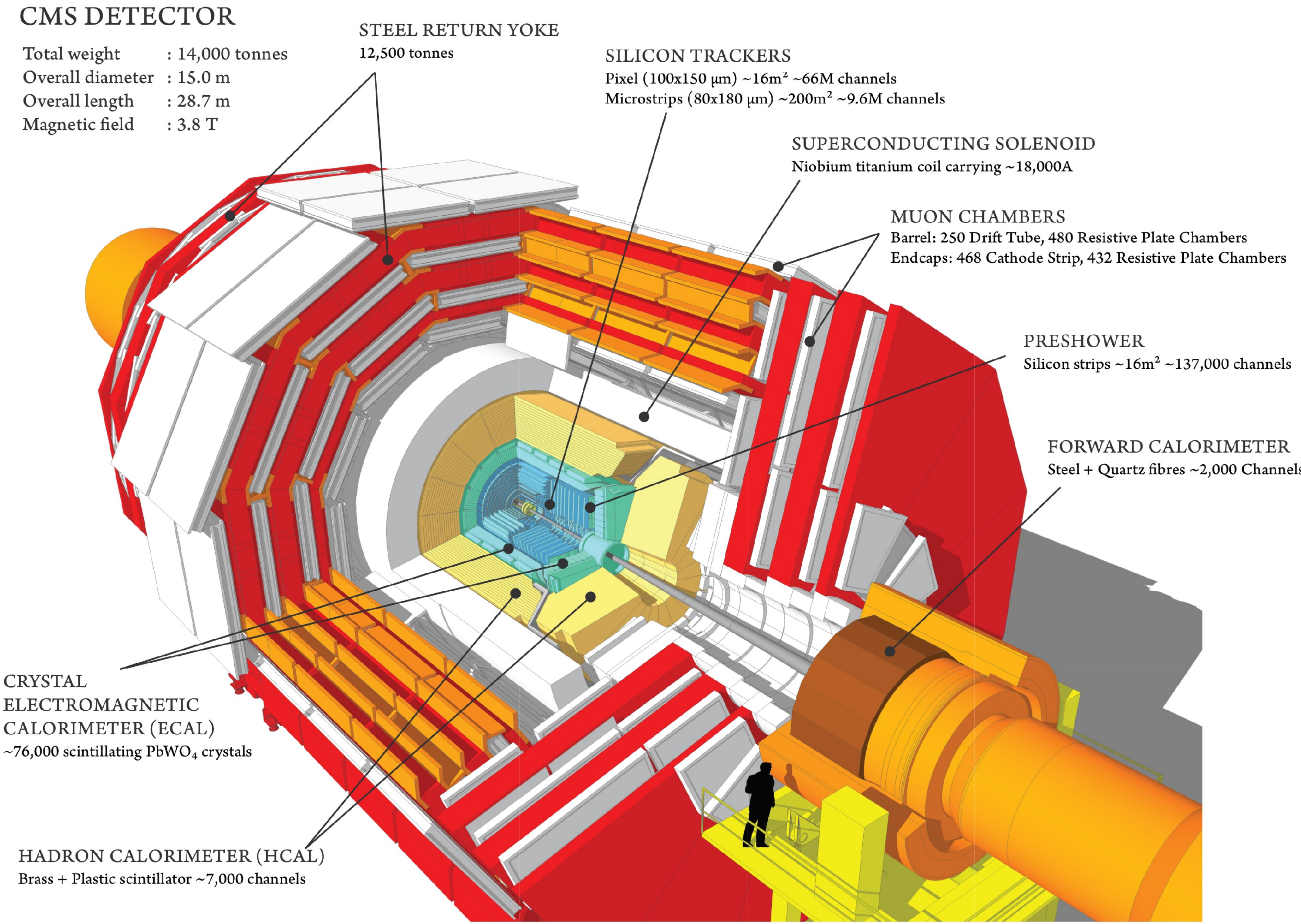
https://www.nikhef.nl/~pkoppenb/particles.html

Summary and outlook

- Recent CMS spectroscopy studies
  - Observation of X(6600), X(6900), X(7100)
  - First measurement of spin-parity reveals their $J^{PC} = 2^{++}$
  - CMS paints a full picture of the all-charm tetraquark family

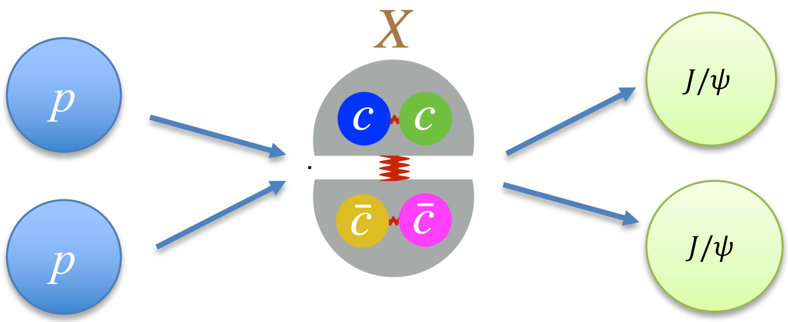
- Stay tuned for more results with larger Run 3&4 datasets
  - Cross-section measurement of X(6600), X(6900), X(7100)
  - Searching for more decay channels of 4c states
  - Searching for 2b2c, 4b, 6c, 4c2b, …

Thank you!


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) ~16m² ~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: 468 Cathode Strip, 432 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

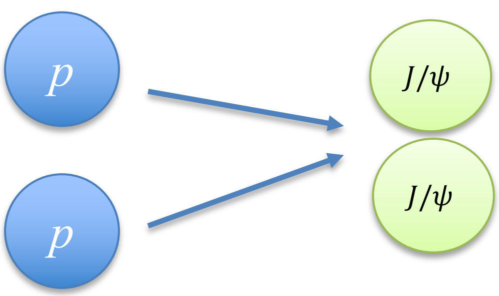
Signal and background

- Signal: $pp \rightarrow X \rightarrow J/\psi J/\psi$

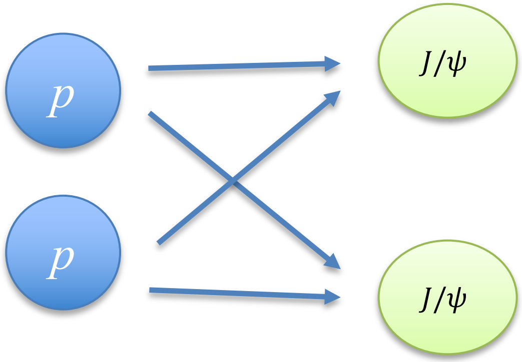


- Background: $pp \rightarrow J/\psi J/\psi$

Single Parton Scattering (SPS)

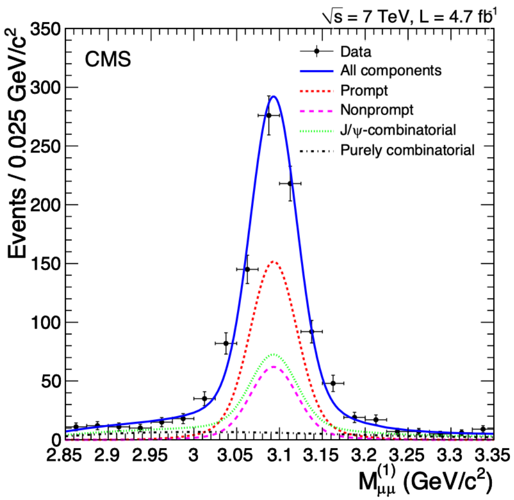


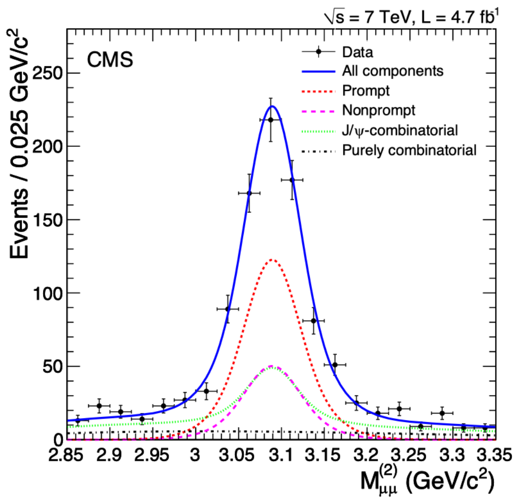
Double Parton Scattering (DPS)

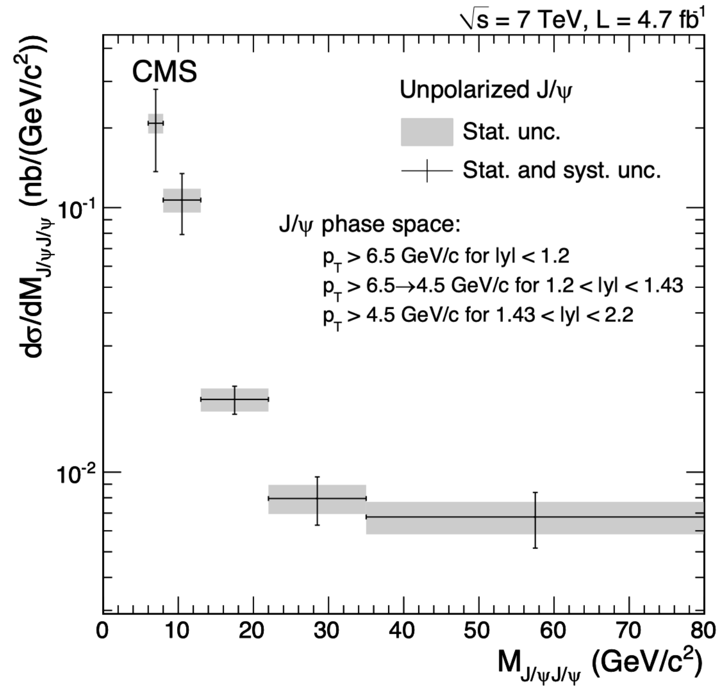


J/ψJ/ψ cross section at 7 TeV

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



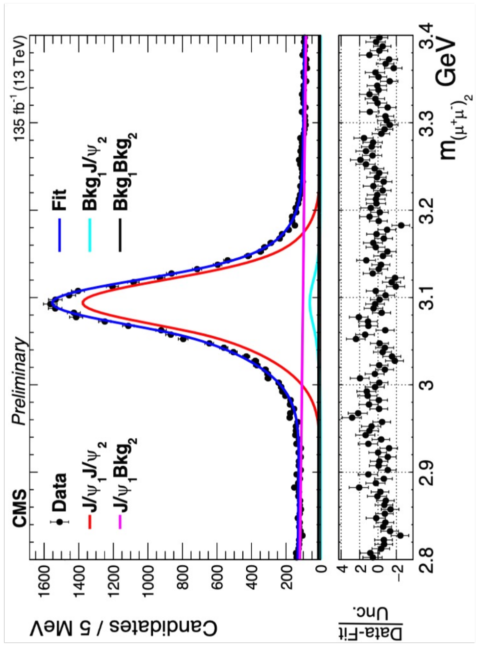


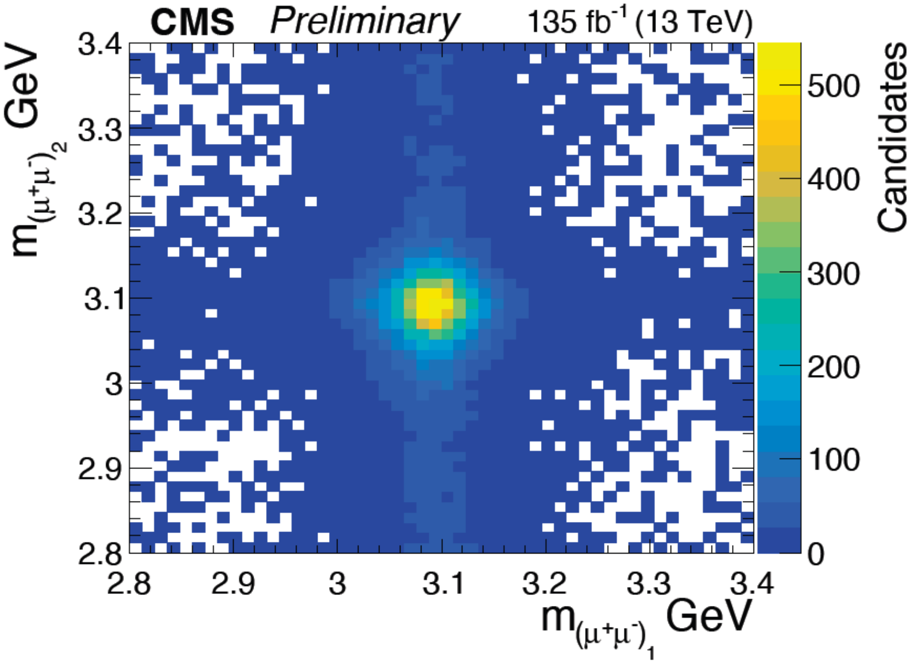


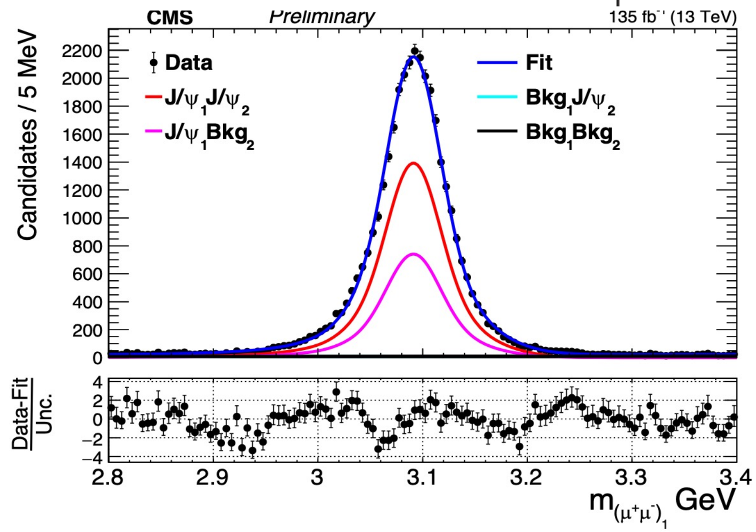
Total cross section, assuming unpolarized prompt J/ψJ/ψ pair production 1.49 ± 0.07 (stat.) ± 0.13 (syst.) nb

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

J/ψJ/ψ candidates at 13 TeV

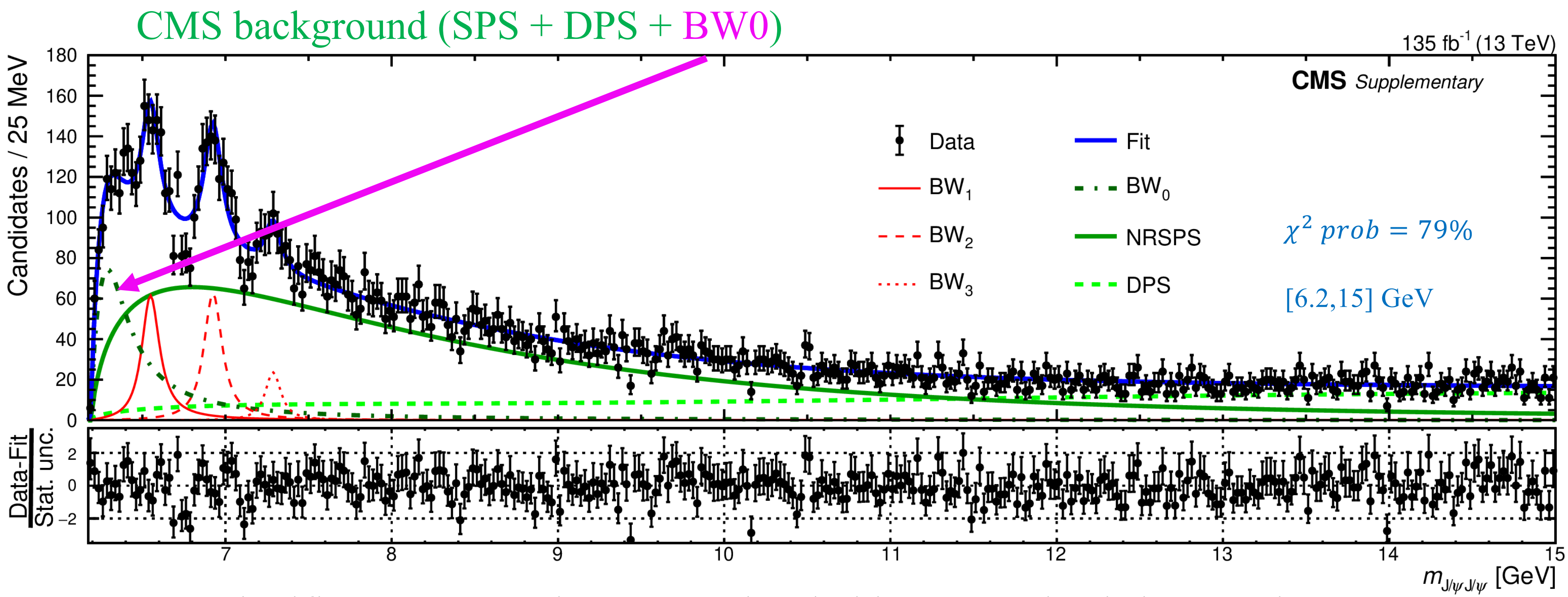






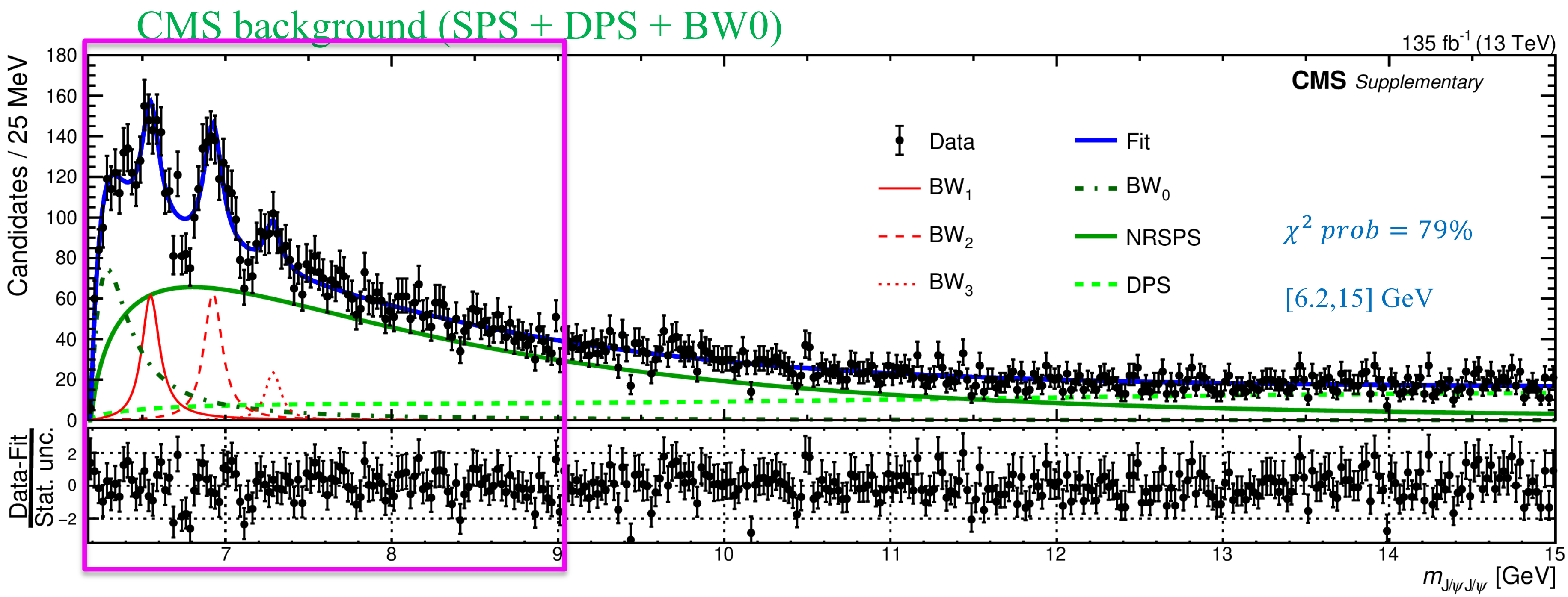
- CMS data: 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs
- J/ψ mass and vertex related cuts removed
- Clean J/ψ signals are seen

Background (SPS + DPS



- 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…

Background (SPS + DPS + BW0)



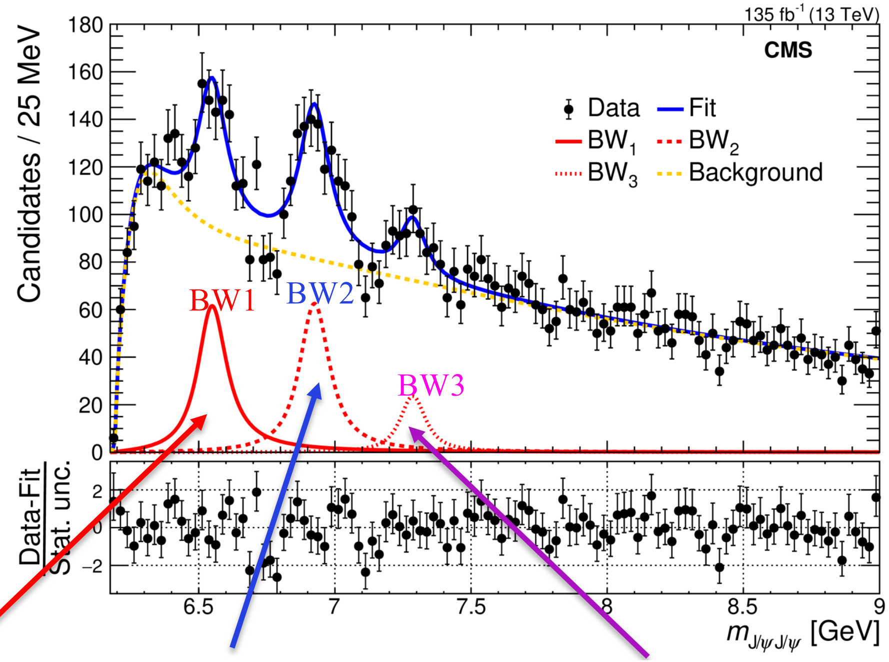
- Most significant structure is a BW at threshold, BW0--what is its meaning?
- Treat BW0 as part of background due to:
  - BW0 parameters very sensitive to SPS and DPS model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron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

First observation of X(6600)

χ^2 Prob. = 1%

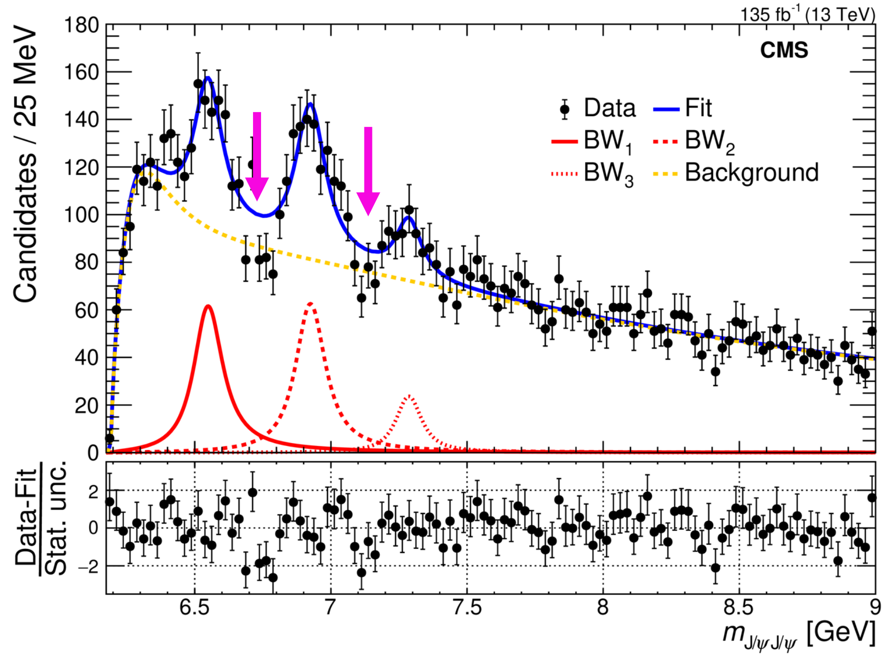
[6.2,7.8] GeV

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



	X(6600) (MeV)	X(6900) (MeV)	BW3 (MeV)
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
Γ	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
σ(stat.)	6.5	9.4	4.1
σ(stat. + syst.)	5.7	9.4	4.1
	First Observation	Confirmation of X(6900) from LHCb	Evidence

The dips



➢ Possibility #1:

- Multiple fine structures to reproduce the dips?
- No enough statistics to test

➢ Possibility #2:

- Interference among structures?

- More secrets to dig out
- We explored possibility #2 in detail

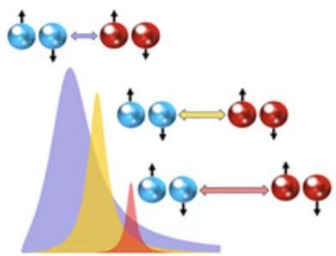
Interference fit

Editors' Suggestion

New Structures in the $J/\psi J/\psi$ Mass Spectrum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

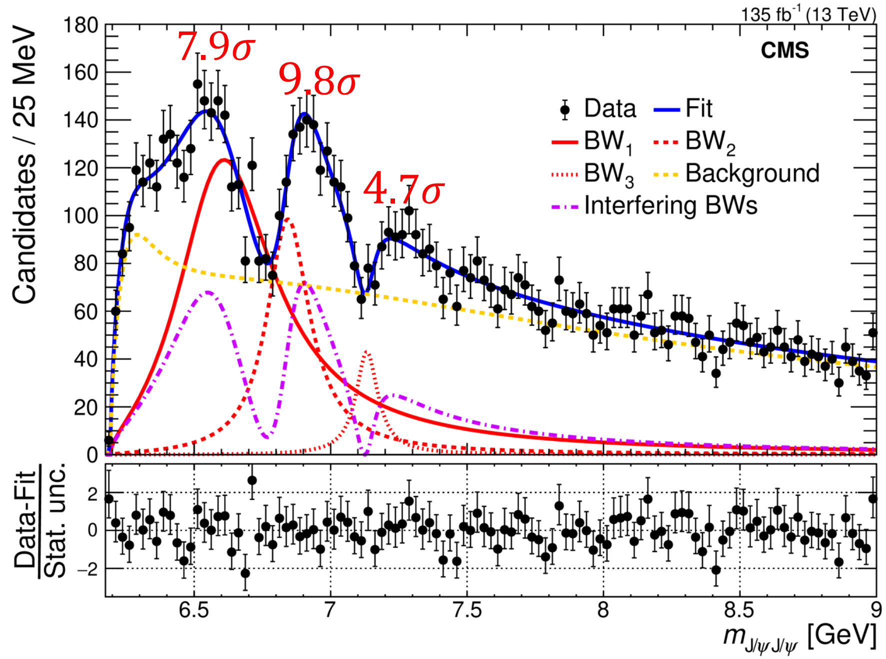
A. Hayrapetyan *et al.* (CMS Collaboration)

Phys. Rev. Lett. **132**, 111901 (2024) – Published 15 March 2024



Three structures, $X(6900)$ and two new ones around 6.64 and 7.13 GeV, are seen in the $J/\psi J/\psi$ mass spectrum that are consistent with being part of a family of radial excitations.

Show Abstract +

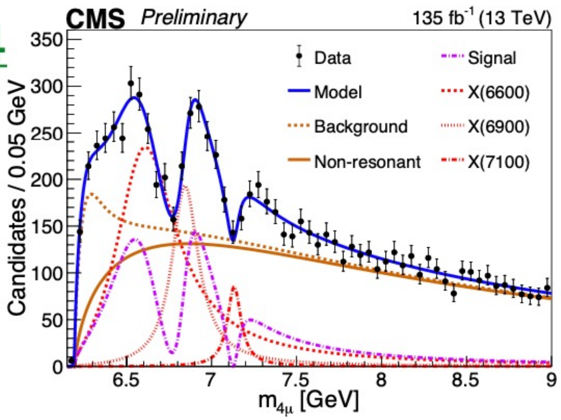


- Fit with interf. among BW1, BW2, and BW3 describes data well
- Measured mass and width in the interference fit

		X(6600)	X(6900)	X(7100)
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}

Concept of Analysis: All Input

(1) $m_{4\mu}$ spectrum $X \to 4\mu$ — arXiv:2306.07164



(2) p_T and p_Z of $X \to 4\mu$ — match to data

(3) polarization J_z or $J_{z'}$ of X — unpolarized

for $J = 0$ exact

for $J = 1,2,..$ depends on production mechanism

— vary J_z or $J_{z'}$ systematics or test

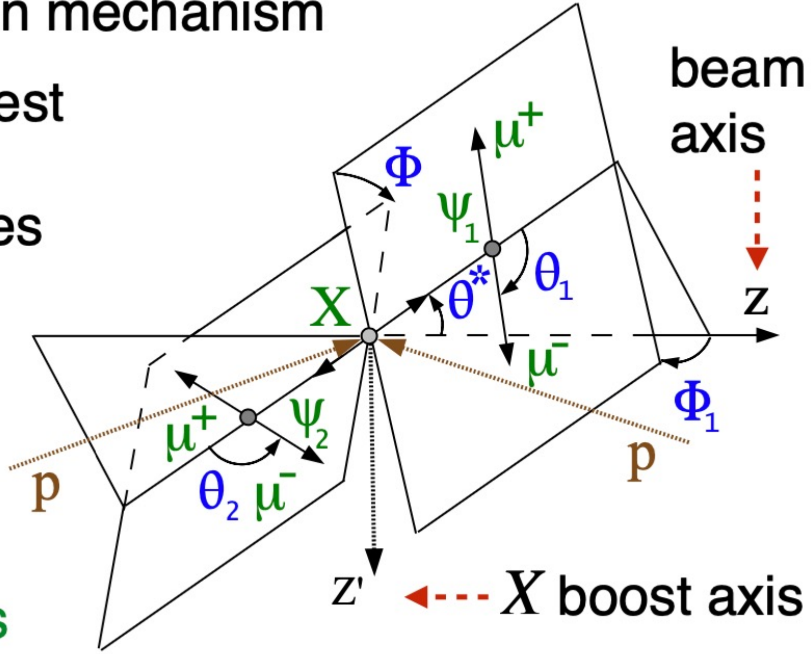
(4) Φ_1, θ^* or Φ_1', θ'^* production angles

flat for unpolarized — test in data

non-flat for polarized

do not use in the primary analysis

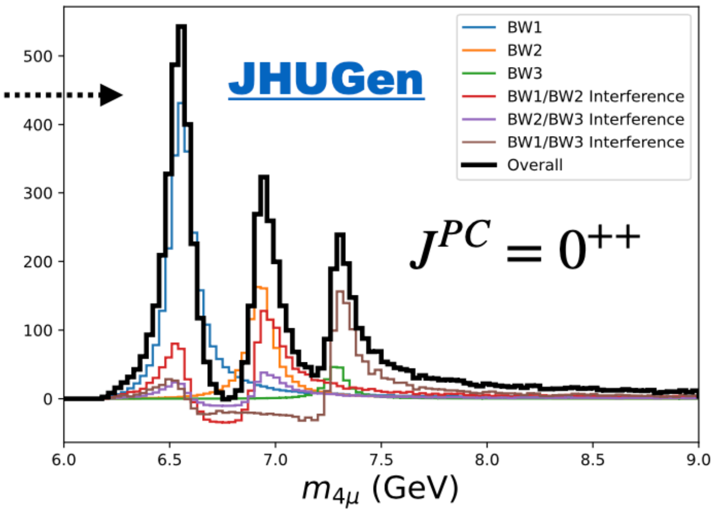
(5) Φ, θ_1, θ_2 decay angles — analysis



Simplification in Angular Analysis

- Full model possible, but very complex

$$\mathscr{P}(\Phi, \theta_1, \theta_2; m_{4\mu})$$



(1) Same properties of 3 resonances:

$$\mathscr{P}(m_{4\mu}, \vec{\boldsymbol{\Omega}}) = \underbrace{\mathscr{P}(m_{4\mu})}_{\text{empirical}} \cdot \underbrace{T(\vec{\boldsymbol{\Omega}}\,|\,m_{4\mu})}_{\text{angular}}$$

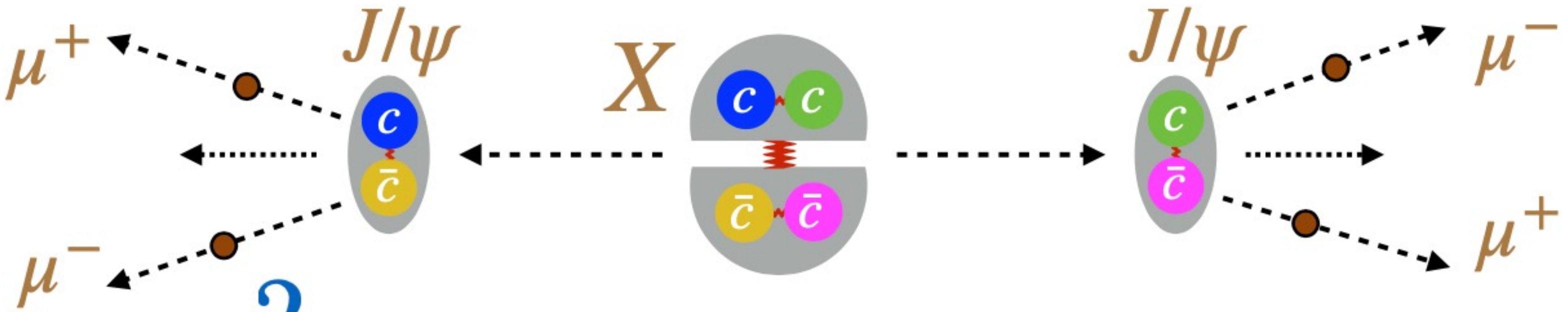
(2) Pairwise tests of J_X^P hypotheses i and j: arXiv:1208.4018

MELA $$\mathscr{D}_{ij}(\vec{\boldsymbol{\Omega}}\,|\,m_{4\mu}) = \frac{\mathscr{P}_i(\vec{\boldsymbol{\Omega}}\,|\,m_{4\mu})}{\mathscr{P}_i(\vec{\boldsymbol{\Omega}}\,|\,m_{4\mu}) + \mathscr{P}_j(\vec{\boldsymbol{\Omega}}\,|\,m_{4\mu})}$$

1 optimal observable $\Leftarrow$ Higgs boson discovery and spin-parity

- Final 2D model: $\boxed{\mathscr{P}_{ijk}(m_{4\mu}, \mathscr{D}_{ij}) = \mathscr{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathscr{D}_{ij}\,|\,m_{4\mu})}$

Summary of spin parity analysis



? $(c\bar{c})_{s=1} + (c\bar{c})_{s=1}$

most likely

? $(cc)_{s=1} + (\bar{c}\bar{c})_{s=1} \Rightarrow L = 0\ (\mathrm{n}S):\ S = 2 \Rightarrow \boxed{J^{PC} = 2^{++},\ n = (1,)2,3,4,\ldots}$

- J^{PC} analysis of exotic hadron decays at LHC (production-independent)
  - consistent picture: set of 3 exotic teraquark resonances with the same J^{PC}
  - $PC = ++$ very certain $\quad n = (1,)2,3,4$
  - $J \neq 1$ at $> 99\ \%$ CL
  - $J \neq 0$ at $> 95\ \%$ CL
  - $J > 2$ possible, but highly unlikely, require $L \geq 2$
  - $J = 2$ consistent, rare in nature, naively expected $J = 0$

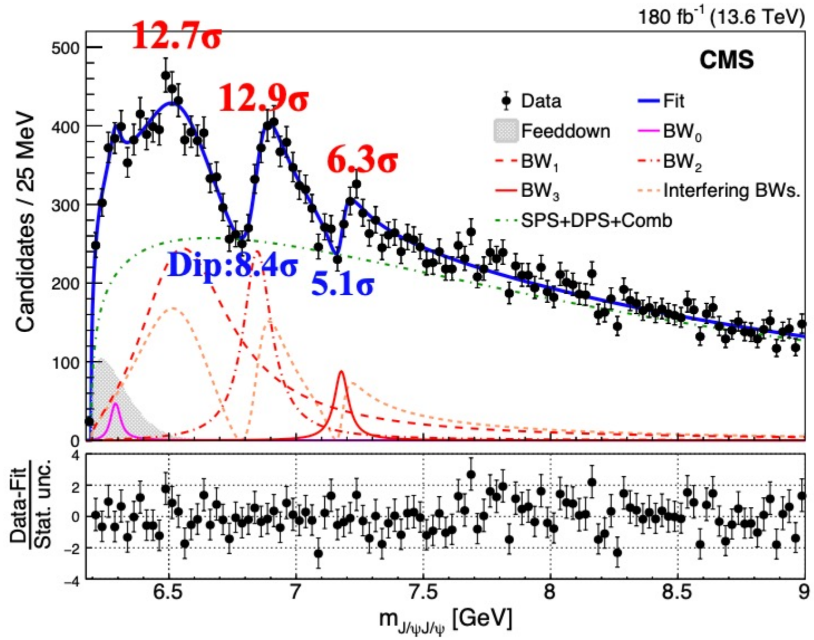
CMS J/ψJ/ψ fit – Run 3 only

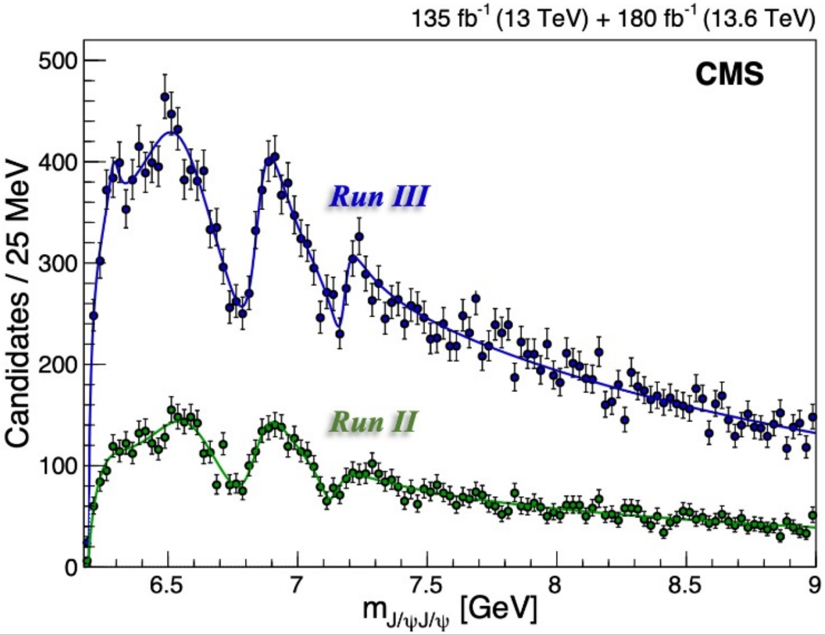
Chi2/nbins

[6, 15]: 363.20/353

[6, 9]: 117.33/113

[6.2, 7.8]: 56.66/64





	BW1	BW2	BW3	Interf BW1-BW2	Interf BW2-BW3	Interf BW1-BW2-BW3
Significance (σ)	12.7	12.9	6.3	8.4	5.1	8.4

First observation of interferene

	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	6588 ± 19	6849 ± 12	7179 ± 10
Γ	454 ± 74	136 ± 18	67 ± 18