

Recent results in searches for tetraquark states in CMS

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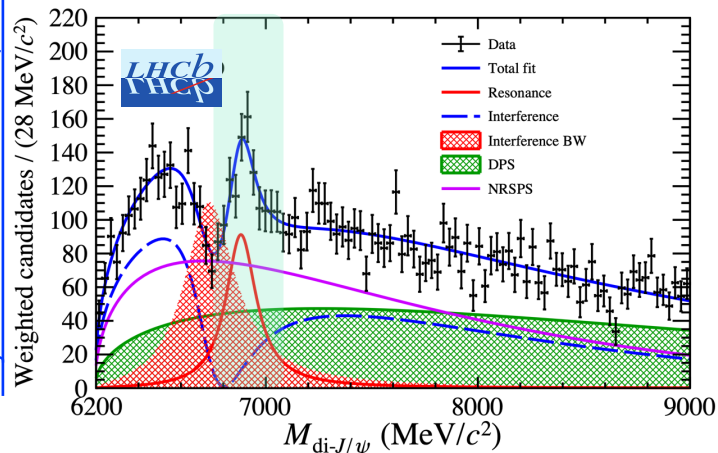
On behalf of CMS Collaboration

QCD@LHC 2026

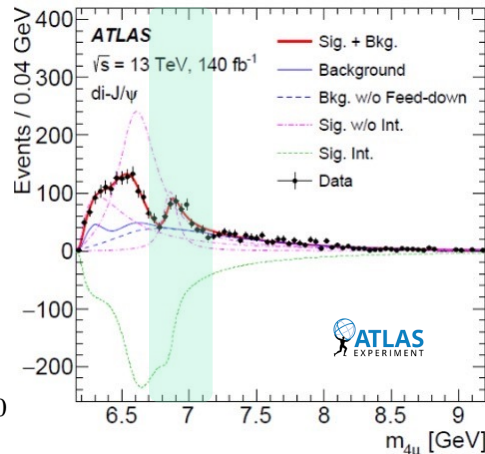
Peaking Structures in $J/\psi J/\psi$

Phys. Rev. Lett. 132 (2024) 111901
Nature 648 (2025) 58
CMS-BPH-24-003

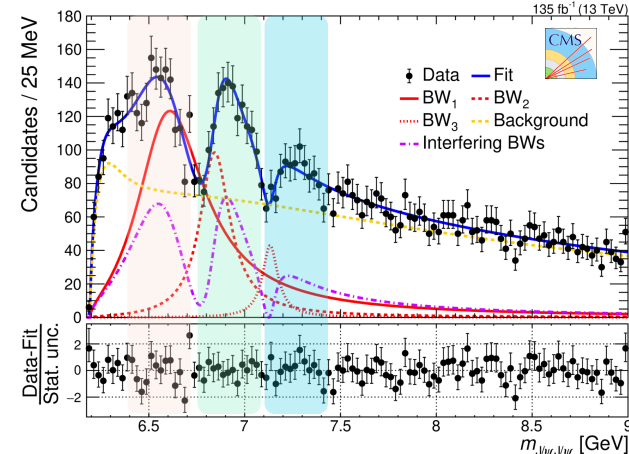
- Run II offered various hints of structures in the $J/\psi J/\psi$ mass spectrum. CMS, ATLAS and LHCb all observe structures in the spectrum.
- LHCb, ATLAS and CMS all observed $X(6900)$ (+ some structure[s]).
- CMS observed $X(6600)$ and $X(7100)$.



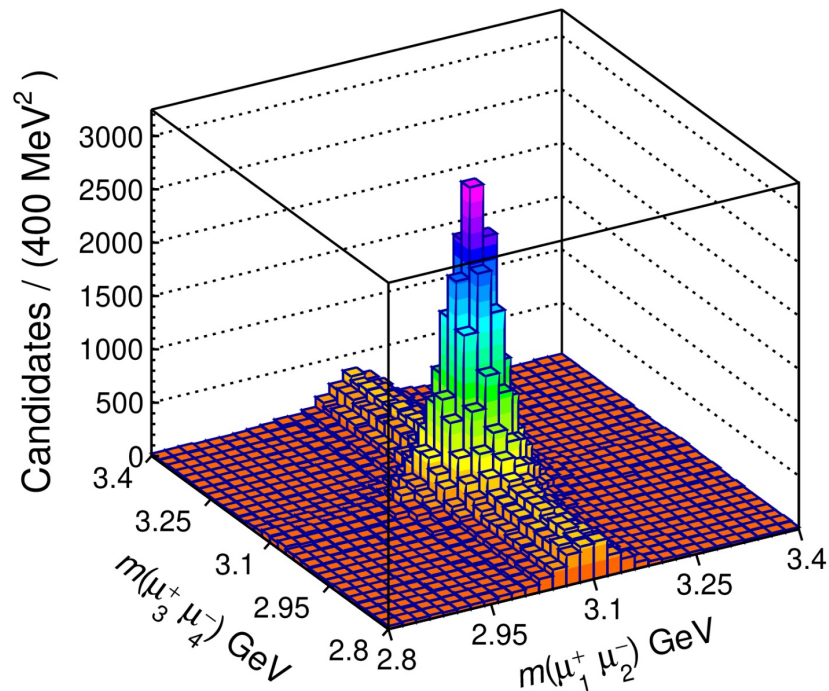
[SB, 65\(23\):1983, 2020](#)



[PRL, 131\(15\):151902, 2023](#)

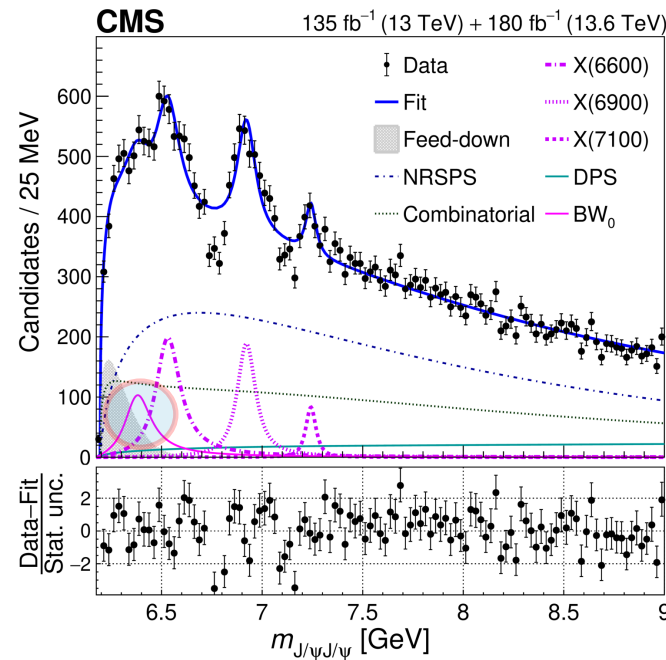
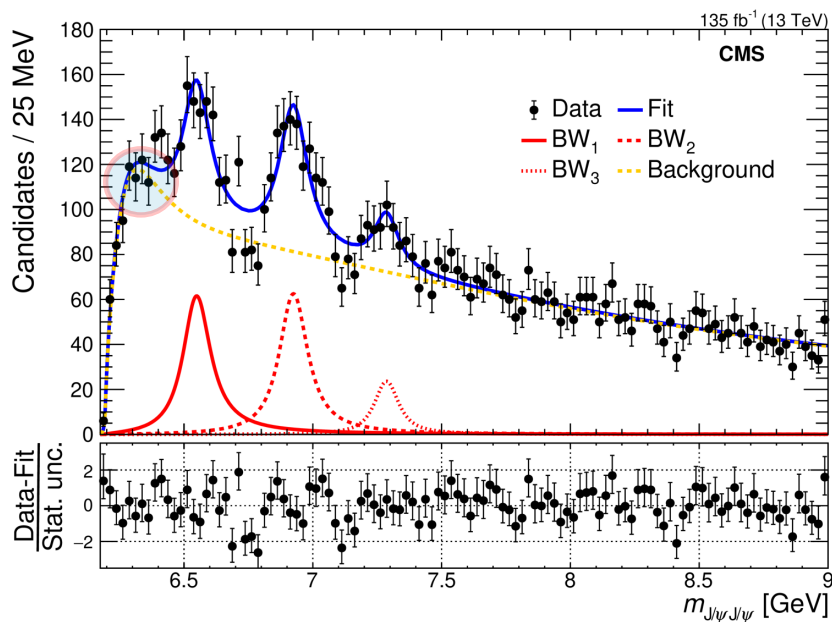


[PRL, 132 \(2024\) 111901](#)



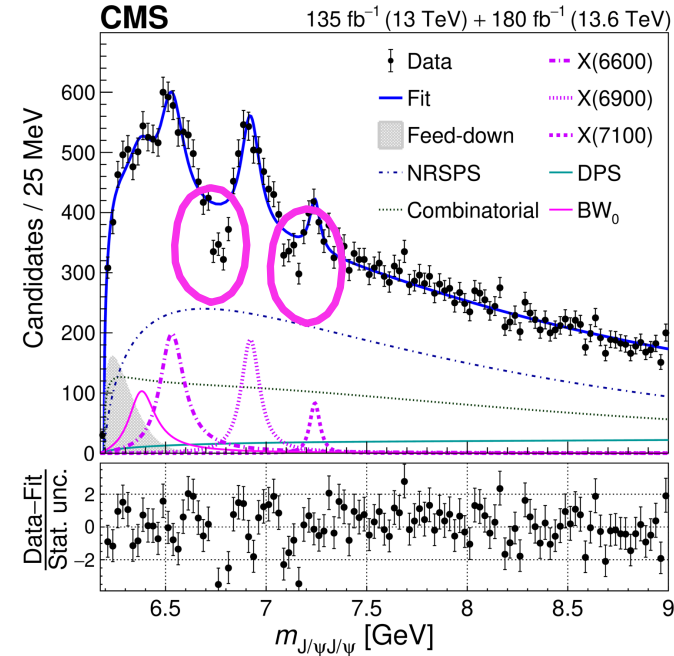
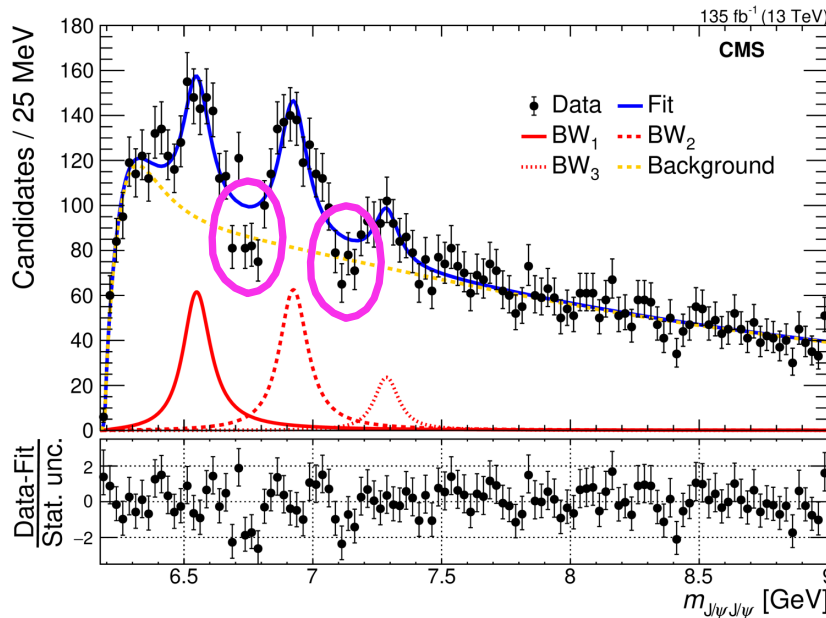
- [CMS-BPH-24-003](#)
- 135 [Run2] + 180 [Run3] fb^{-1}
- J/ψ reconstructed via its $\mu^+\mu^-$ decays
- J/ψ J/ψ candidates
 - 12622 ± 165 [Run2]
 - 44936 ± 692 [Run3]
- Trigger
 - 3 muons, $p_T > 5, 3, 3$ GeV [Run2]
 - 2muons, $p_T > 4, 3$ GeV [Run3]

- 2 genuine J/ψ s combined randomly: non-resonant single parton scattering (NRSPS) or double parton scattering (NRDPS)
- Shapes from simulation that includes: direct production + feed-down processes (J/ψ as decay product). Additional feed-down processes from double-charmonium resonances: generated separately.
- Inadequacy of NRSPS near threshold (a resonance? a near-threshold enhancement? feed-down effects?)
 - + additional ad hoc background [modelled empirically by a B.-W. (BW_0) with free m & Γ]



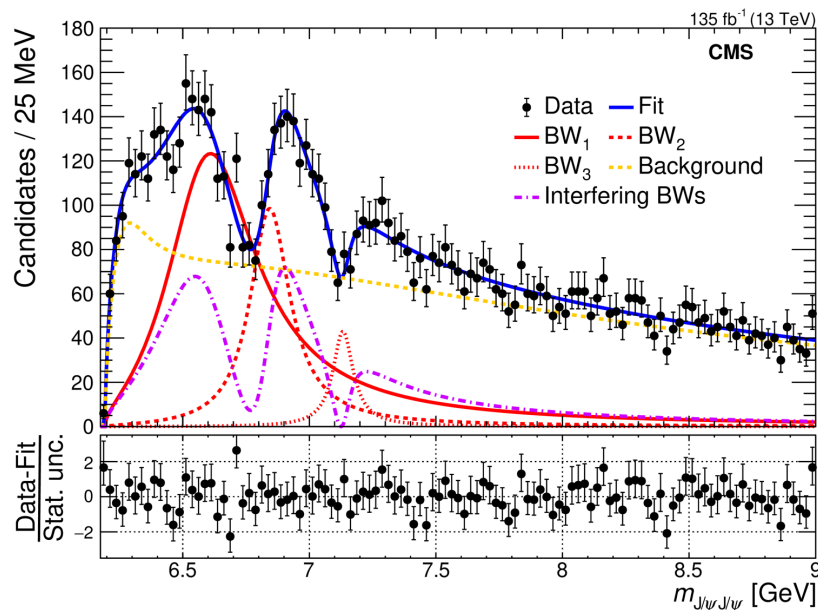
- No interference model: 3BW's with no interference between signal components and between signal(s) & background. Dips poorly described.

$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m) + N_{NRDPS} \cdot f_{NRDPS}(m) + N_{Comb} \cdot f_{Comb}(m) + N_{Feeddown} \cdot f_{Feeddown}(m)$$

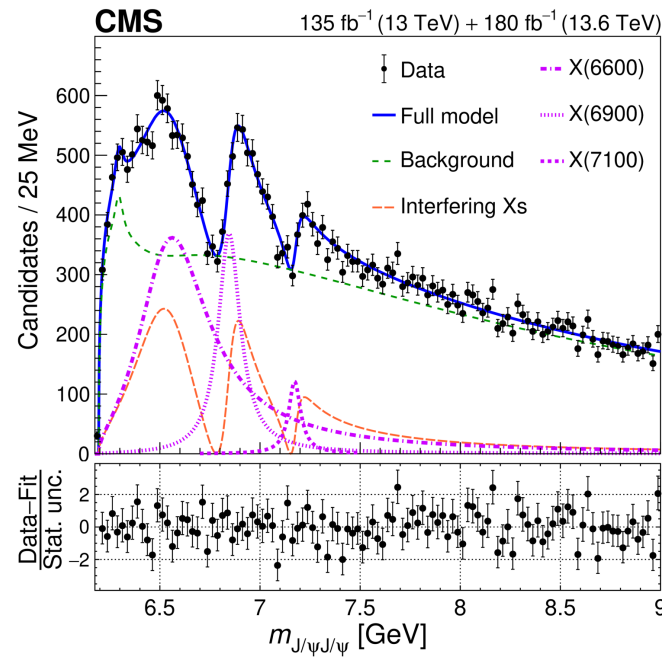


- **No-interference model:** 3BW's with no interference between signal components and between signal(s) & background. *Dips poorly described.*
- **3-way interference model:** three $J^P = 0^+$ resonances. Better description, improved fit, improved statistical significance.

$$\begin{aligned}
 Pdf(m) = & N_{X_0} \cdot |BW_0|^2 \otimes R(M_0) \\
 & + N_{X \text{ and interf}} \cdot |r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2 \\
 & + N_{NRSPS} \cdot f_{NRSPS}(m) + N_{DPS} \cdot f_{DPS}(m) \\
 & + N_{Feeddown} \cdot f_{Feeddown}(m) + N_{Comb} \cdot f_{Comb}(m),
 \end{aligned}$$



Run 2



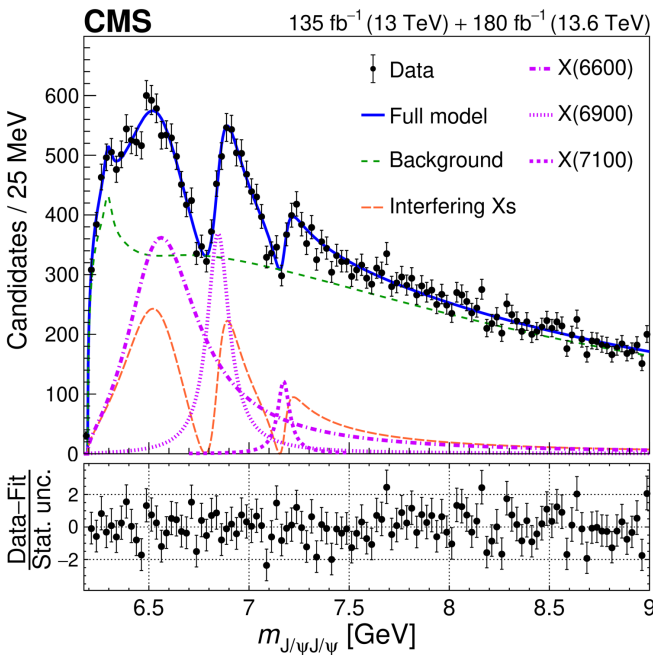
Run 2+3

- No-interference model: 3BW's with no interference between signal components and between signal(s) & background. Dips poorly described.
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$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \otimes R(M_0) + N_{X \text{ and interf}} \cdot |r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2 + N_{NRSPS} \cdot f_{NRSPS}(m) + N_{DPS} \cdot f_{DPS}(m) + N_{Feeddown} \cdot f_{Feeddown}(m) + N_{Comb} \cdot f_{Comb}(m),$$

		X(6600)	X(6900)	X(7100)
		BW ₁	BW ₂	BW ₃
Interference	m (MeV)	6593 ⁺¹⁵ ₋₁₄ ± 25	6847 ⁺¹⁰ ₋₁₀ ± 15	7173 ⁺⁹ ₋₁₀ ± 13
(Run 2+Run 3)	Γ (MeV)	446 ⁺⁶⁶ ₋₅₄ ± 87	135 ⁺¹⁶ ₋₁₄ ± 14	73 ⁺¹⁸ ₋₁₅ ± 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

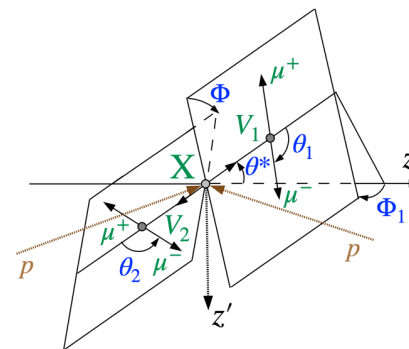
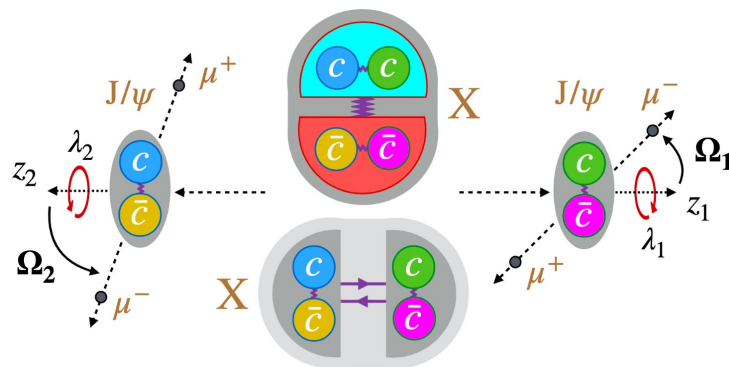
- > 5σ for each of X(6600), X(6900), and X(7100)
- > 5σ for interference (two dips)
- > 5σ for each single dip (@6750 and @7150)



Run 2+3

- These states are all $cc\bar{c}\bar{c}$. How to distinguish between **tetraquarks, molecules, ...** ?
- J^{PC} study can help to better understand its nature. How? We can *infer* it from the experimental angular distributions.
- J^{PC} affects $A(X \rightarrow VV)$ that affects the angular distributions $\vec{\Omega} = (\theta_1, \theta_2, \Phi)$.

$$\mathcal{P}(\Phi, \theta_1, \theta_2; m_{4\mu}) \propto |A(X \rightarrow VV)|^2$$



- After symmetries conditions, 8 models of J^{PC} to test: $0^-_m, 0^+_h, 0^+_h, 1^-, 1^+, 2^-_m, 2^-_h, 2^+_m$

A full amplitude analysis is possible but would be very complex

(simultaneously describing the three resonances, their interference, their line shapes, and their angular dependence.)

- Factorize the mass and angular dependence

$$\wp(m_{4\mu}, \vec{\Omega}) = \wp(m_{4\mu}) \cdot T(\vec{\Omega} | m_{4\mu})$$

An empirical model of the four-muon invariant-mass spectrum, describing the resonances and background.

The angular distribution predicted by a given spin-parity hypothesis, conditional on 4μ mass.

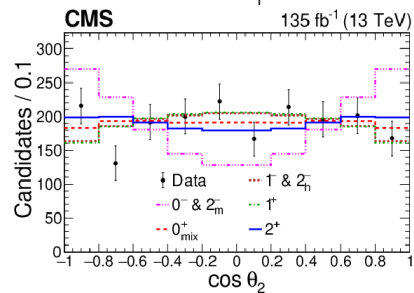
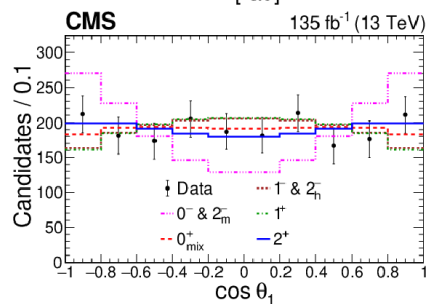
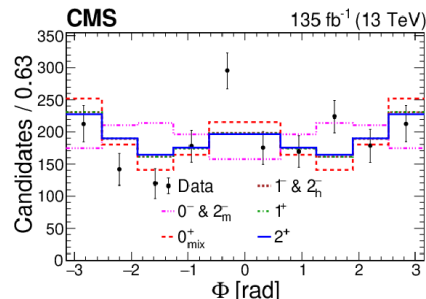
- Pairwise tests on J_X^{PC} hypotheses $[i;j] \rightarrow$ MELA = Matrix Element Likelihood Approach

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

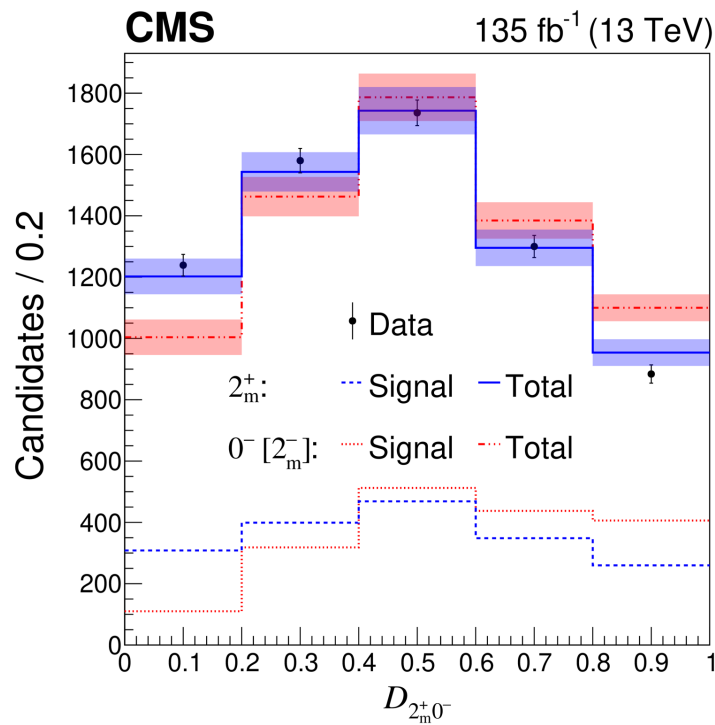
Final two-dimensional analysis for i vs j – for each *process* k (=signal, SPS, DPS,...)

$$\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij} | m_{4\mu})$$

- Decay angles (bkg subtracted)



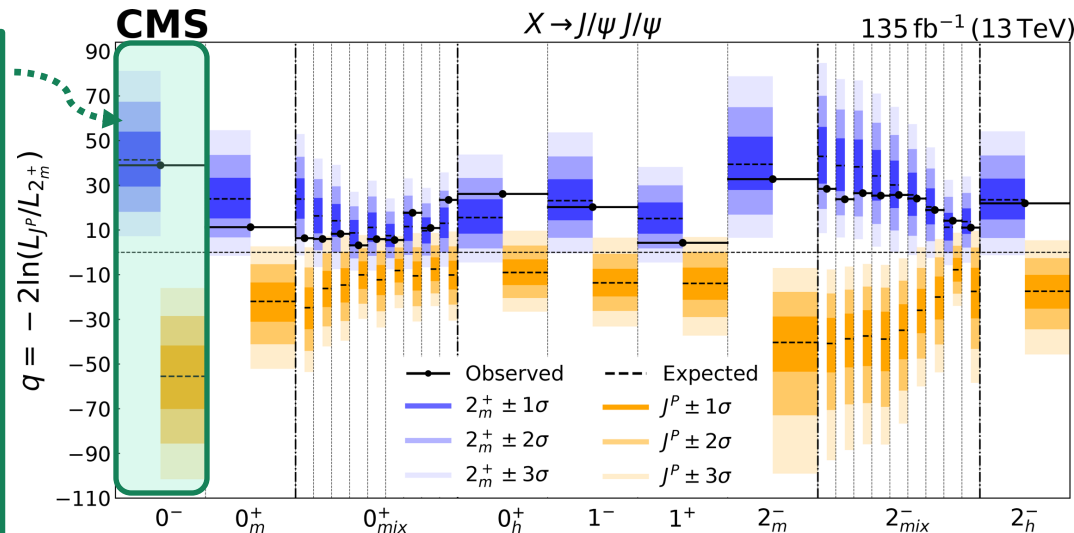
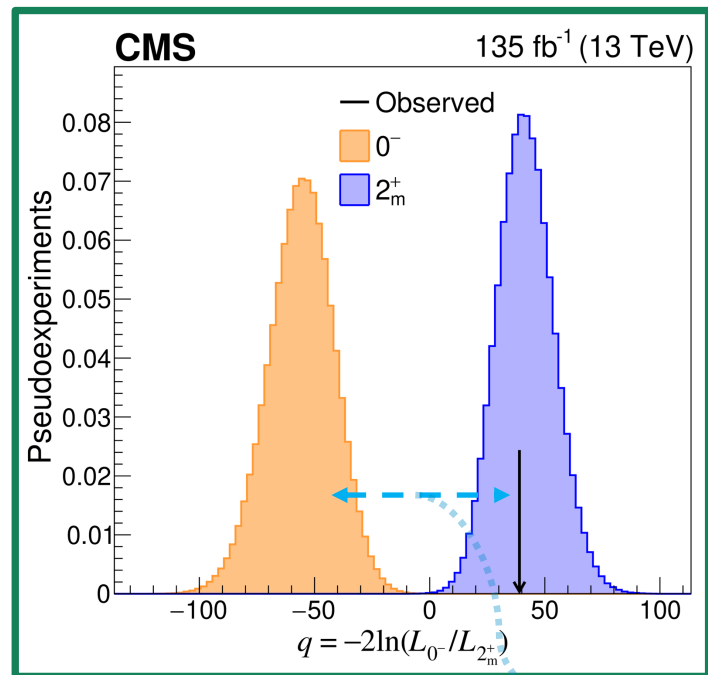
- Pairwise discriminator (an example)



$$j = 0^-(2^-_{\text{m}}) \text{ vs } i = 2^+_{\text{m}}$$

Hypothesis Testing: 0^- vs. 2^+

- Likelihood test comparison: data favours 2^+ vs 0^- .

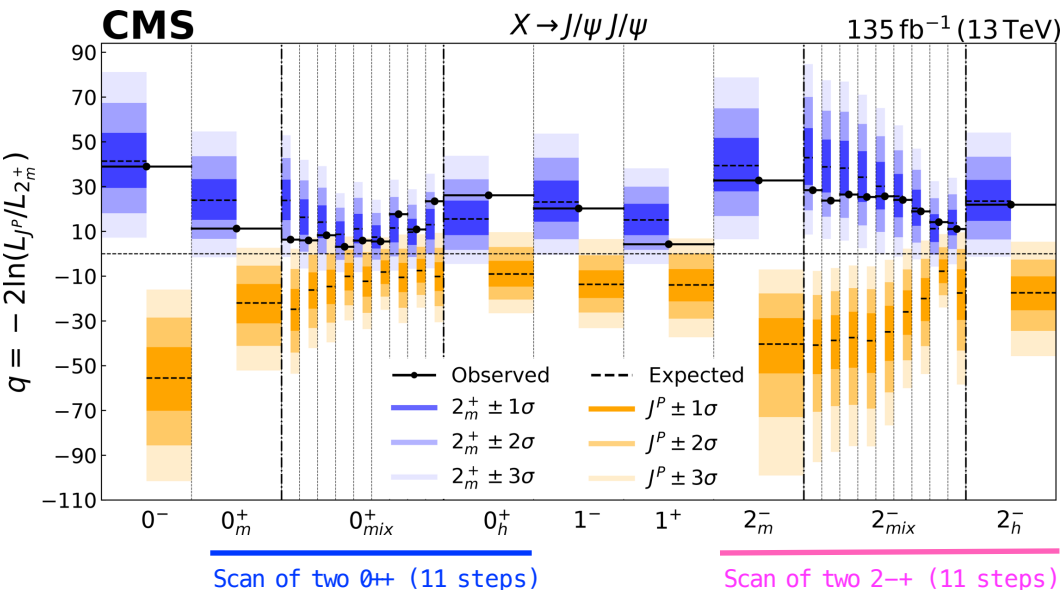


		Observed		Expected	
		p-value	Z-score	p-value	Z-score
0^- vs 2_m^+	0^-	2.7×10^{-13}	7.2	6.5×10^{-14}	7.4
	2_m^+	4.2×10^{-1}	0.2	0.50	0.0

Full Scan Hypothesis Testing

■ Data consistent with **2⁺⁺** vs all the other hypotheses:

- $PC = ++; P \neq -1; L \neq 1$
- $J \neq 1$ at $> 99\%$ CL; $J \neq 0$ at 95% CL
- $J > 2$ possible, but highly unlikely; requires $L \geq 2$
- $J = 2$ consistent, rare in nature, naively expected $J = 0$



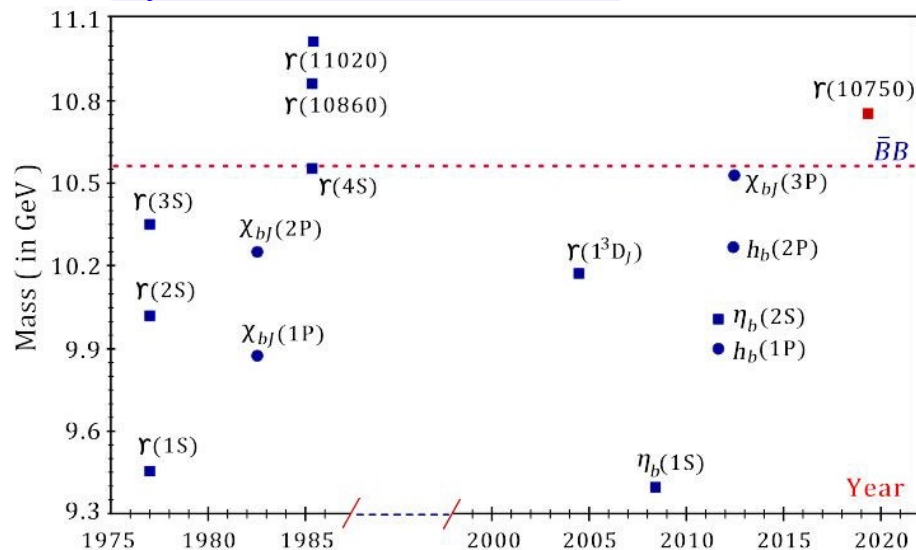
J_X^P	p-value	Z-score reject J_X^P
0^-	2.7×10^{-13}	7.2
0_m^+	4.3×10^{-5}	3.9
0_{mix}^+	1.4×10^{-2}	2.2
0_h^+	3.1×10^{-9}	5.8
1^-	8.0×10^{-8}	5.2
1^+	4.7×10^{-3}	2.6
2_m^-	4.1×10^{-12}	6.8
2_{mix}^-	6.5×10^{-4}	3.2
2_h^-	2.2×10^{-8}	5.5

$J^P = 2_m^+$ consistent with data

Peaking Structure in $Y(1S)\phi$

- The bottomonium sector is poorly known compared to the charmonium sector. It is characterized by a **rich spectrum** that is an **important tool for verifying perturbative and non-perturbative QCD calculations** and thus testing our understanding of bottomonium states in the context of the quark model.

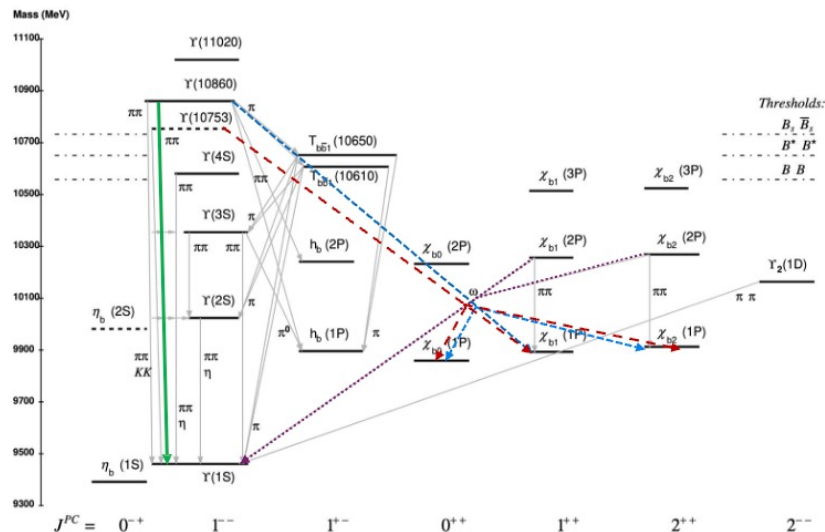
[Phys. Rev. D 101 \(2020\) 014020](#)



- Recently there was no further experimental progress except the observation of the resonance $Y(10753)$ [JHEP 07 (2024) 116].
- Completing the bottomonium spectrum is an important validation of Lattice QCD calculations.

The initial idea to explore the $Y(1S)\phi$ final state was inspired by ... the analogy with the $J/\psi\phi$ final state: for Heavy Quark Symmetry considerations, there could be possible partners (promptly produced in this case) of the states observed by LHCb, as $J/\psi\phi$ structures, in the $B^+ \rightarrow J/\psi\phi K^+$ decay : [X(4140), X(4274), X(4500), X(4700)]

- The hadronic transitions are typically involving the emission of a di-pion and rarely of η or ω mesons



- Recent observations involve ω :

- $\chi_{b(1,2)}(2P) \rightarrow Y(1S)\omega$ [*]
- $Y(10860) \rightarrow \chi_{bJ}(1P) \omega$ [**]
- $Y(10753) \rightarrow \chi_{bJ}(1P) \omega$ [***]

- Di-kaon transitions are expected to be suppressed (mainly for phase-space considerations); only one has been observed so far, by Belle: $Y(10860) \rightarrow Y(1S)KK$ in PRL 100 (2008) 112001.

PRL 92 (2004) 222002

[*] PRL 135 (2025) 121902

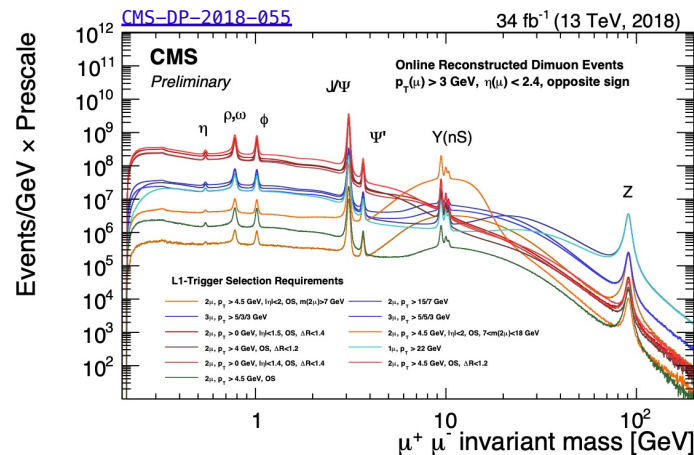
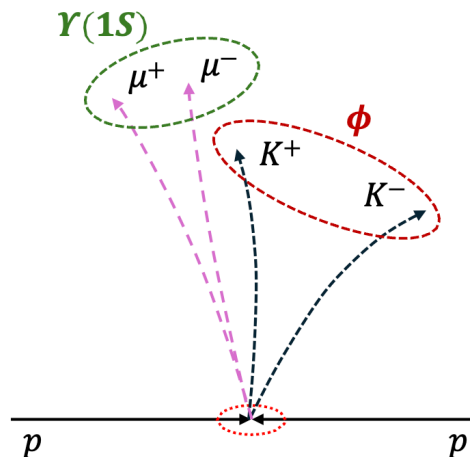
PRD 113 (2026) 052010

[**] PRL 113 (2014) 142001

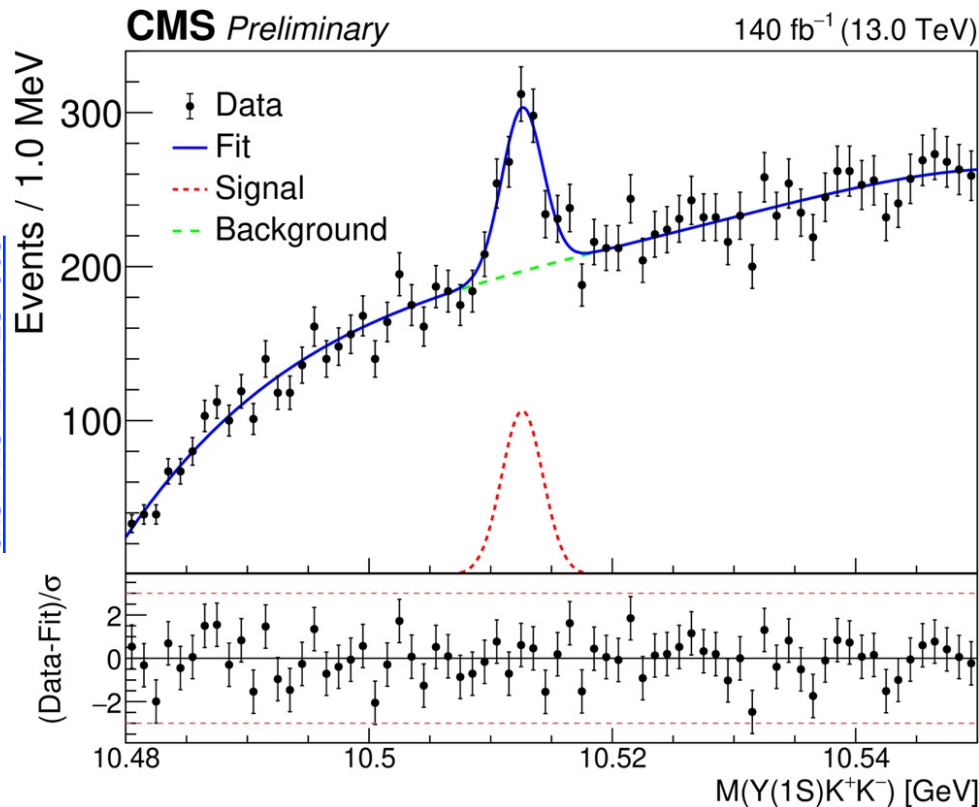
[***] PRL 130 (2023) 091902

Study of the $\Upsilon(1S) \phi$ final state

- Exploiting the Run-2 (2016-18) dataset with the dedicated $\Upsilon(nS)$ [$n = 1,2,3$] dimuon trigger.
- Final state $\Upsilon(1S)\phi \rightarrow \mu\mu KK$
- Very simple candidate selection. **No optimisation.**
- Reinforcing and aligning (along years) trigger cuts for $\mu\mu$
 - $|\eta| < 1.4$; $p_T > 12$ GeV.



- High quality tracks from the best PV assigned Kaon mass.
- Candidates:
 - Υ : $9.3 < m(\mu\mu) < 9.6$ GeV.
 - ϕ : $|m(KK) - m_{PDG}(\phi)| < 6.15$ MeV.
 - $\Upsilon \phi$: common vertex fit with Υ mass constrained to PDG.
- Keep both $K^\pm K^\mp$ (RS) and $K^\pm K^\pm$ (WS) for background checks.
- No multiple candidates: better $\mu\mu KK$ vertex cut (only 2.2%).



- Extended Unbinned ML fit to the $Y(1S)K^+K^-$ mass:

- Background: 4th order Chebyshev
- Signal: Gaussian

- Measured:

- Yield: 450 ± 59
- $\sigma = (1.69 \pm 0.22)\text{MeV}$
 - compatible with the mass resolution $\sigma_{\text{res}} \approx 1.87\text{MeV}$
- $m = 10512.60$
 - ± 0.21 (stat)
 - ± 0.20 (syst)
 - ± 0.11 (M_Y) [$Y(1S)$ constrained mass]

- The measured mass is compatible (within 2σ) with the $\chi_{b1}(3P)$ mass measured by CMS (via radiative decays to $Y(3S)\gamma$ in PRL 121 (2018) 092002).
- Assuming we are observing for the first time the hadronic transition $\chi_{b1}(3P) \rightarrow Y(1S)\phi$ we evaluate (local) statistical significance $> 10\sigma$.

Extensive checks have been carried out to verify the robustness and reliability of the observed peak

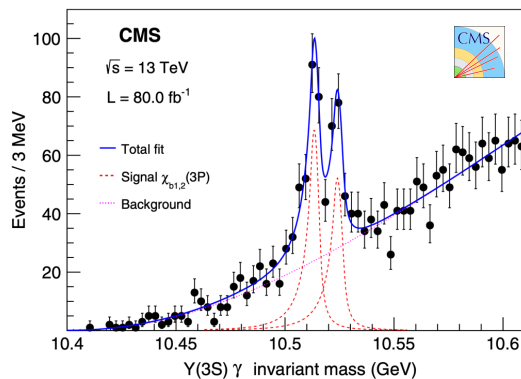
- The (RS) background spectrum is consistent with the WS one, also when considering only the candidates from the sidebands of the ϕ -signal window
- The analysis was (consistently) repeated by splitting the data sample into subsamples of different data-taking years.
- The results are consistent when increasing the p_T thresholds and the four-track vertex probability ($\mu\mu k k$).
- No PID @ CMS: reflection of other misreconstructed known states. Investigated contributions from
 - $\Upsilon(2S, 3S) \rightarrow \Upsilon(1S)\pi\pi$ treated as source of systematic uncertainty
 - $\chi_{b(1,2)}(2P) \rightarrow \Upsilon(1S)\omega (\rightarrow \pi^+\pi^-\pi^0)$ negligible
 - $\rightarrow \Upsilon(1S)K^*(892)^0$ with $K^*(892)^0 \rightarrow K^\mp\pi^\pm$ negligible
- If we observed the $\chi_{b1}(3P)$ transition to $\Upsilon(1S)\phi$, a *natural* question arises:

Where is the spin-2 partner [$\chi_{b2}(3P)$]?

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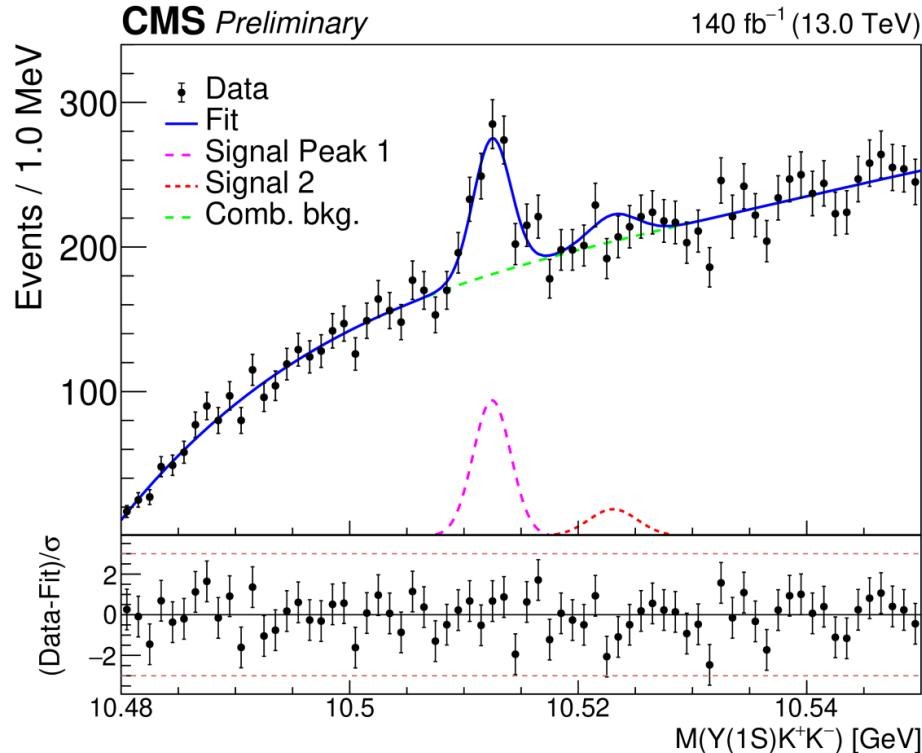
- If we observed the $\chi_{b1}(3P)$ transition to $\Upsilon(1S)\phi$ then we could expect also the $\chi_{b2} \rightarrow \Upsilon\phi$ observed in the $\Upsilon(3S)\gamma$ spectrum at 10524 MeV

PRL 121 (2018) 092002



- Yield for a second peak @ χ_{b2} mass is 49 ± 48
- significance $\sim 1\sigma$.

- No evidence of the possible spin partner $\chi_{b2}(3P)$ with Run-II data.



Could it be suppressed? Could it be something else?

- No selection rules prevent the $\chi_{b2}(3P) \rightarrow \Upsilon\phi$ transition.
- $\chi_{b(1,2)}(3P)$ are produced mostly promptly. In PLB 743 (2015) 383 CMS measured at **8 TeV** $\frac{\sigma(pp \rightarrow \chi_{b2}(1P))}{\sigma(pp \rightarrow \chi_{b1}(1P))} \approx 0.85 \pm 0.11$ so compatible with 1.

1. We may expect $\chi_{b(1,2)}(3P)$ to be produced promptly with the same rate in pp collisions (N.B. different $\sqrt{s}$ and $1P$).

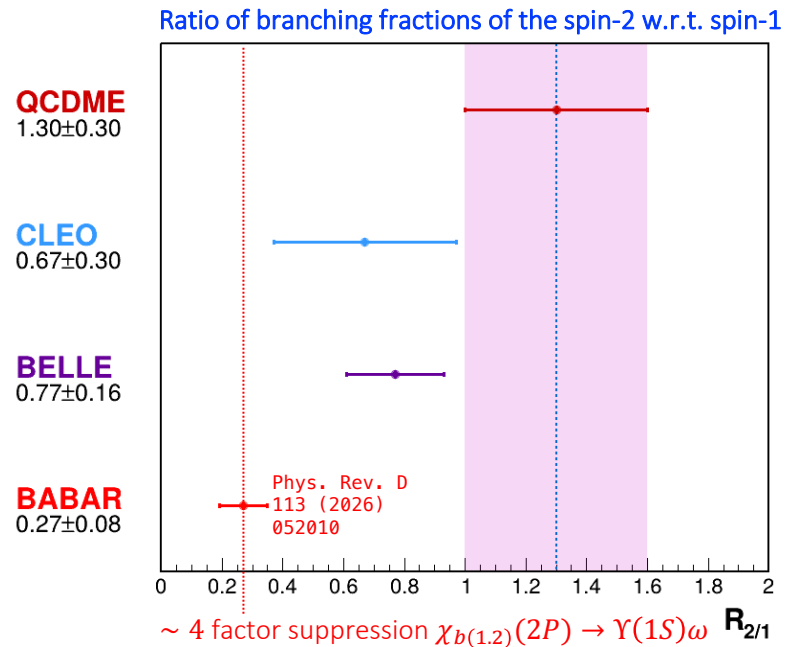
- A yield difference would point towards different decay dynamics:

- For a similar decay chain in Phys. Rev. D 113 (2026) 052010

$$R_{2/1} \equiv \frac{\mathcal{B}(\chi_{b2}(2P) \rightarrow \Upsilon(1S)\omega)}{\mathcal{B}(\chi_{b1}(2P) \rightarrow \Upsilon(1S)\omega)} = 0.27 \pm 0.08$$

2. Similar suppression may characterise the $\chi_{b(1,2)}(3P)$ decays
3. Additional suppression of the spin-2 state may come from detector acceptance & reconstruction efficiency considerations.

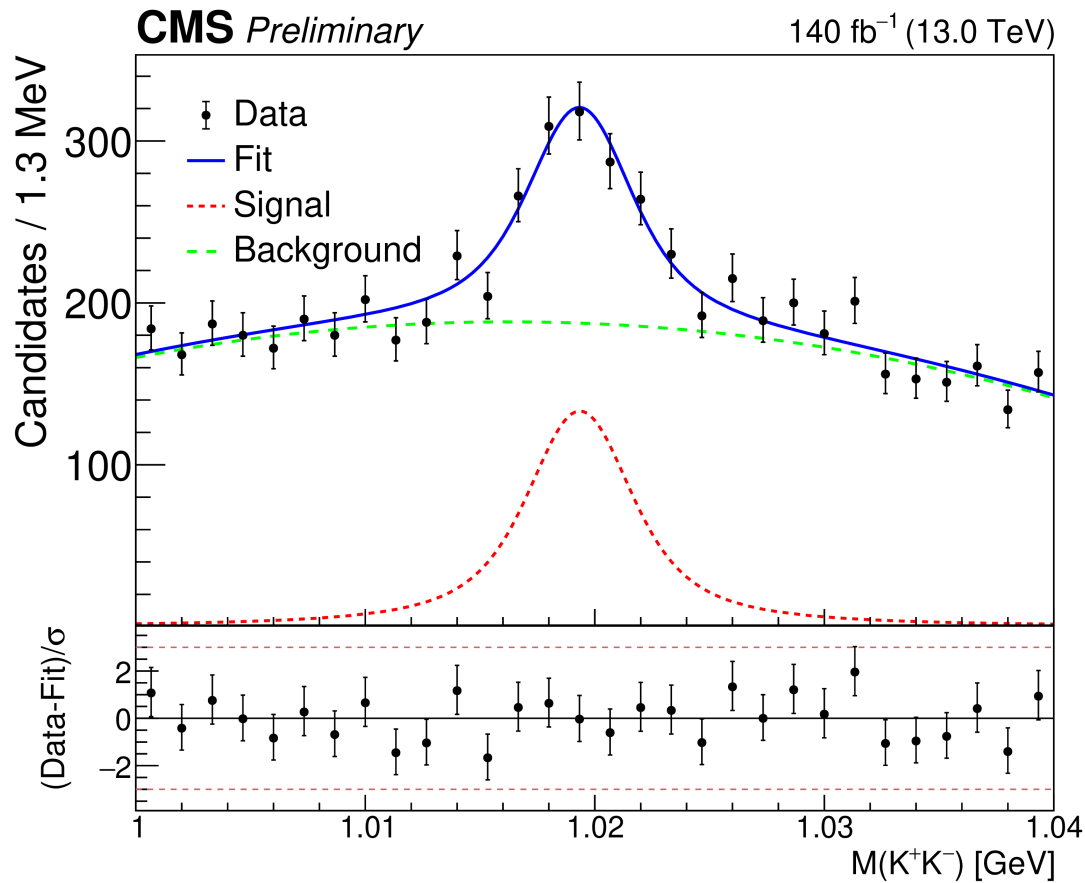
- An exotic interpretation ($b\bar{b}s\bar{s}$ tetraquark, hybrid, ...) cannot be excluded given the non-observation on of the $\chi_{b2}(3P)$.

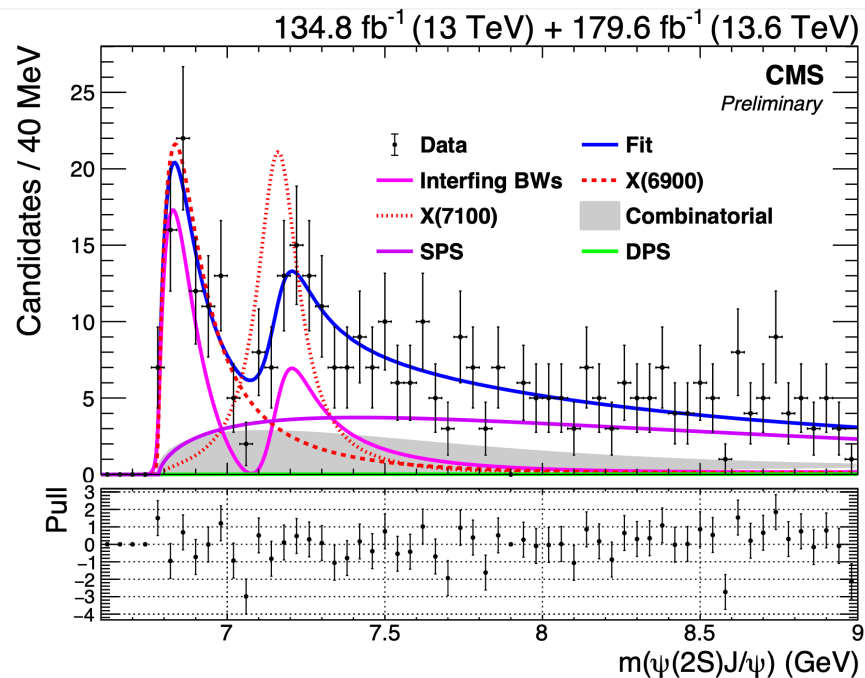


A further analysis based on full Run2+Run3 is needed to shed light on this puzzle.

Questions?

Back-up





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}
			$\Gamma :$	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
$f_{JJ} [1]$	$J/\psi J/\psi$	BW_1, BW_2, BW_3	$m :$	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
			$\Gamma :$	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}