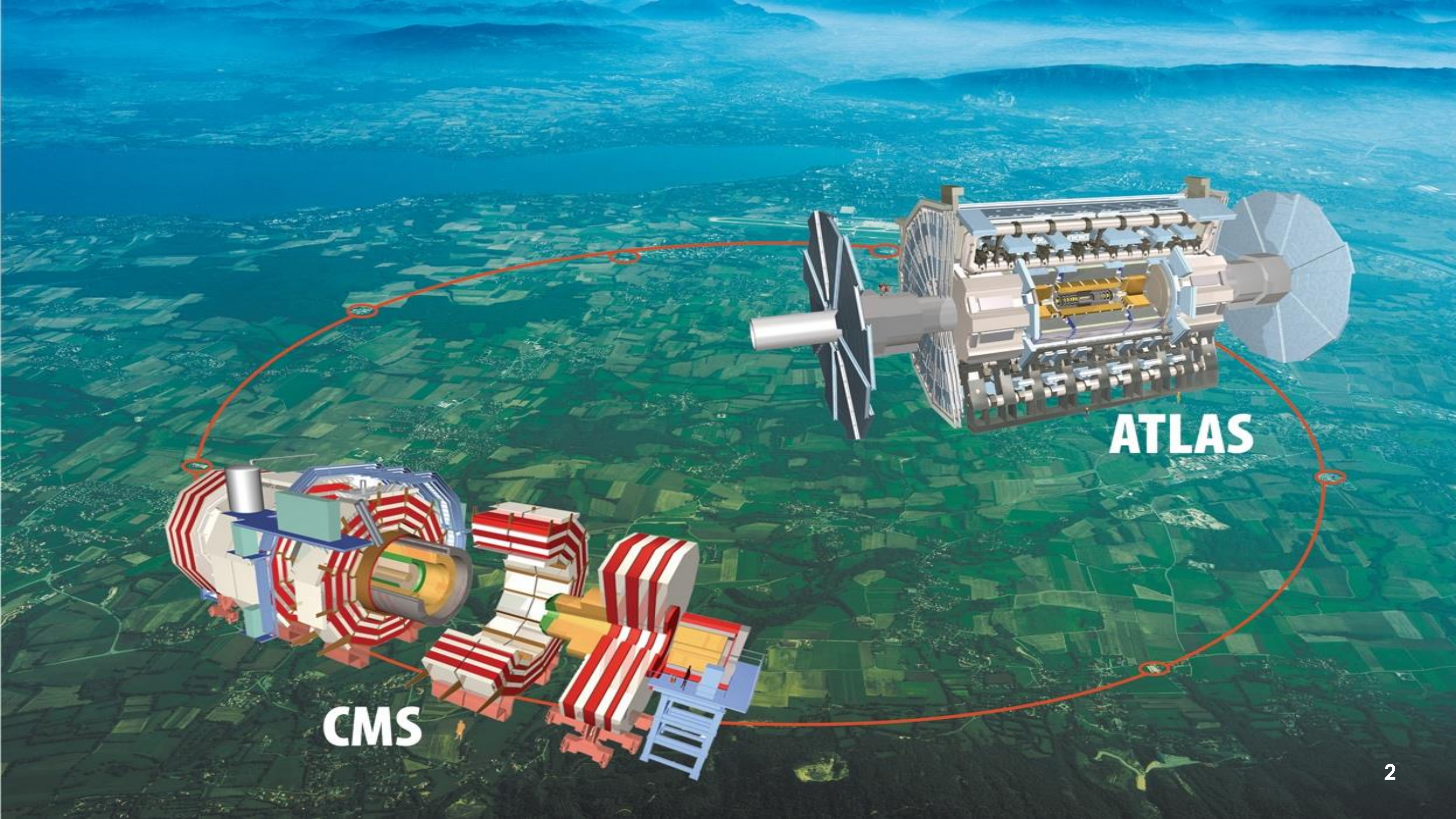
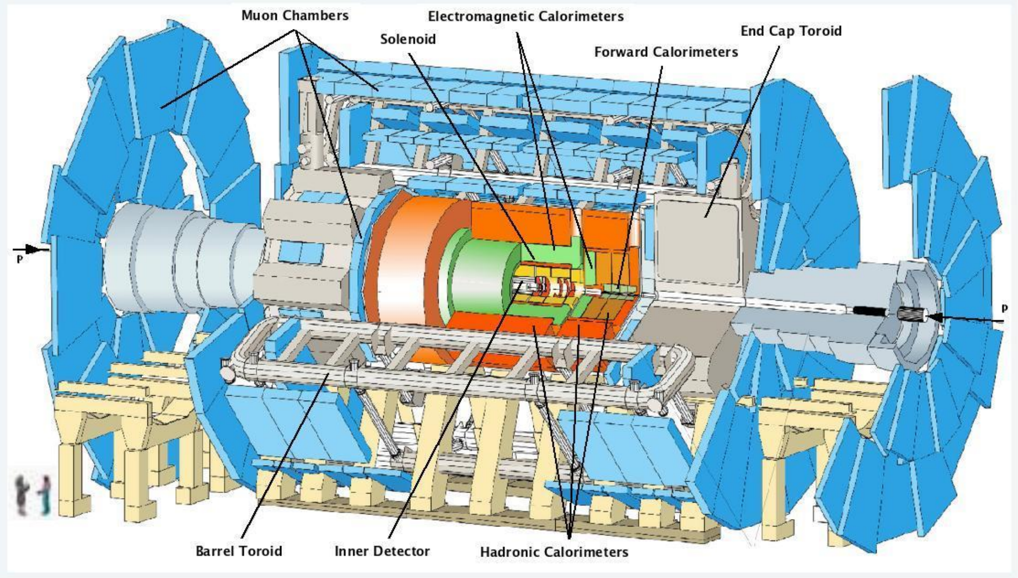
Status and perspectives on Spectroscopy in ATLAS and CMS

Valentina Mariani
on behalf of the ATLAS and CMS collaboration


ATLAS
CMS

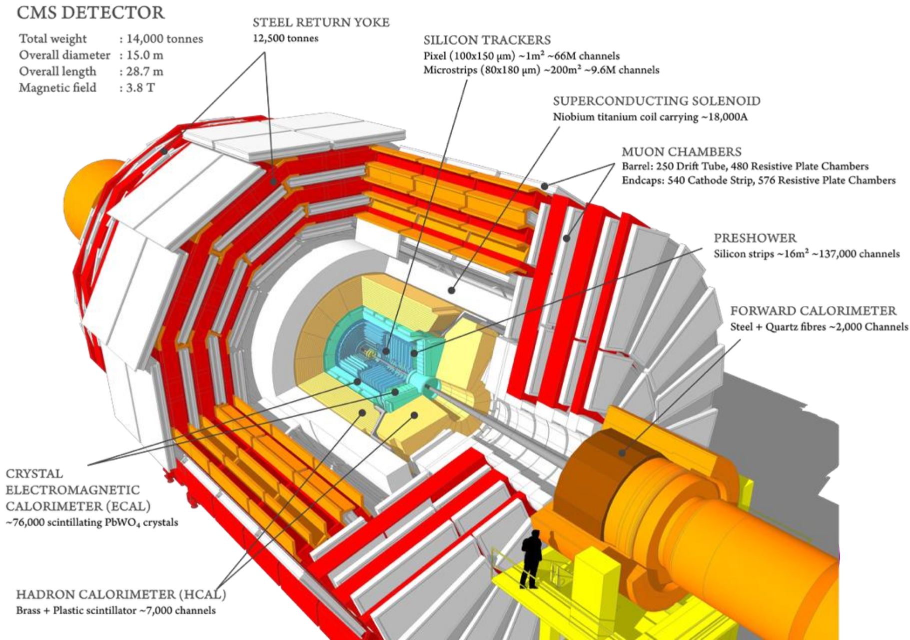
The esperiments



Both ATLAS and CMS are **general purpose experiments**

⇒ designed to do physics in a very wide spectrum:

- Standard Model, Higgs sector, BSM searches …and flavor physics!



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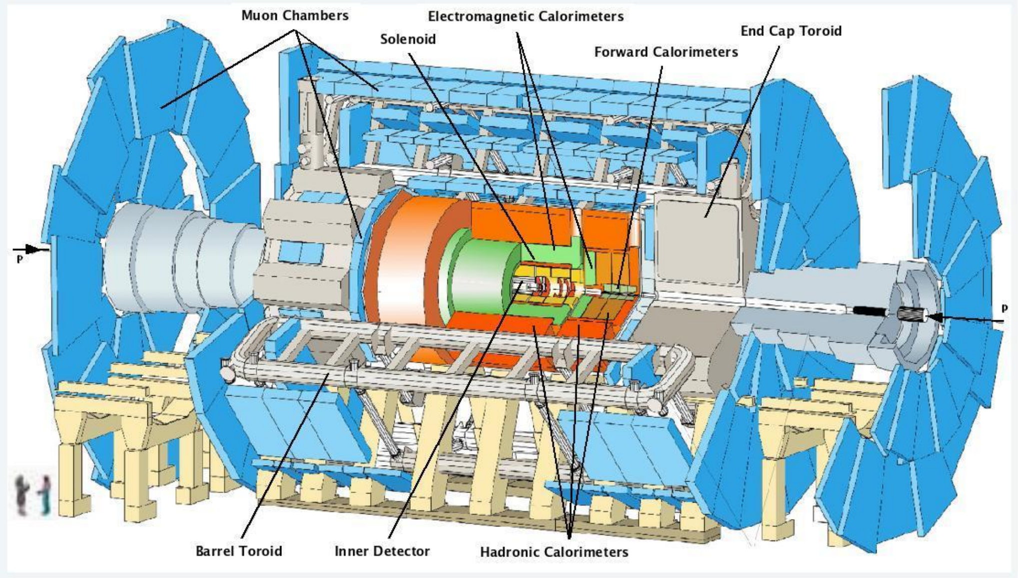

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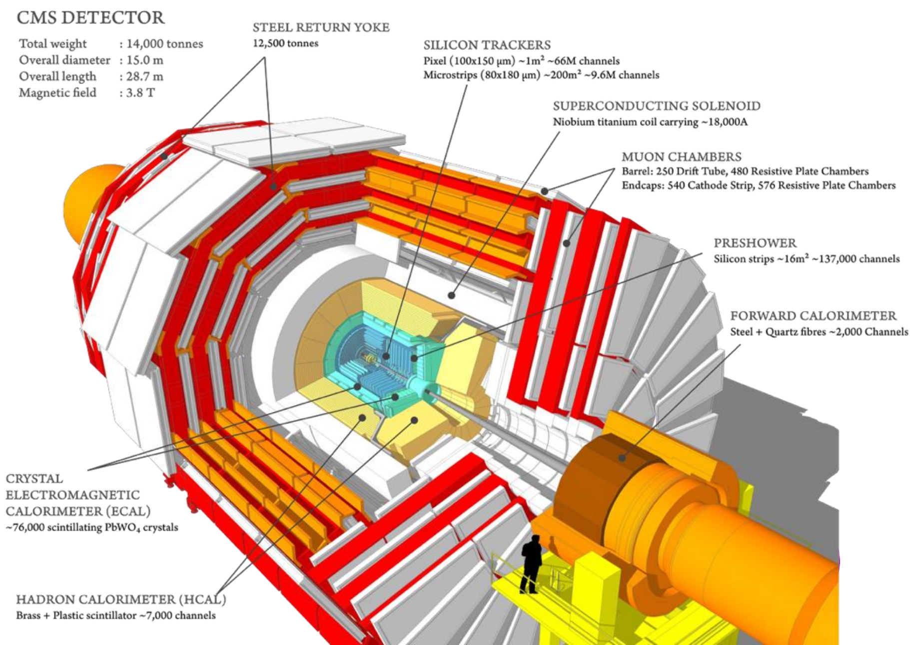
Like the bumblebee, they don't know they are not designed for flavour physics and they do (good!) flavor physics anyway!



Why spectroscopy?

- Deepens our understanding of **non-perturbative QCD**
- Provides crucial theoretical and experimental **inputs for precision tests** of the Standard Model
- Enables **discovery of exotic states** and new forms of hadronic matter
- Strengthens the **connection between theoretical prediction and experimental observations** in flavor physics

Flashing flavoured results

Observation of structures in the $J/\psi + \psi(2S)$ mass spectrum with the ATLAS detector

The ATLAS Collaboration

First exclusive reconstruction of the B^{*+}, B^{*0}, and B_s^{*0} mesons and precise measurement of their masses

The CMS Collaboration*

Observation of X(6900) and evidence for X(7100) in the $J/\psi\psi(2S) \to \mu^+\mu^-\mu^+\mu^-$ mass spectrum in 314 fb^{-1} of pp collisions at CMS

The CMS Collaboration

That's a limited, personal and biased selection!

Observation of a family of all-charm tetraquark candidates at the LHC

The CMS Collaboration

Determination of the spin and parity of all-charm tetraquarks

The CMS Collaboration*

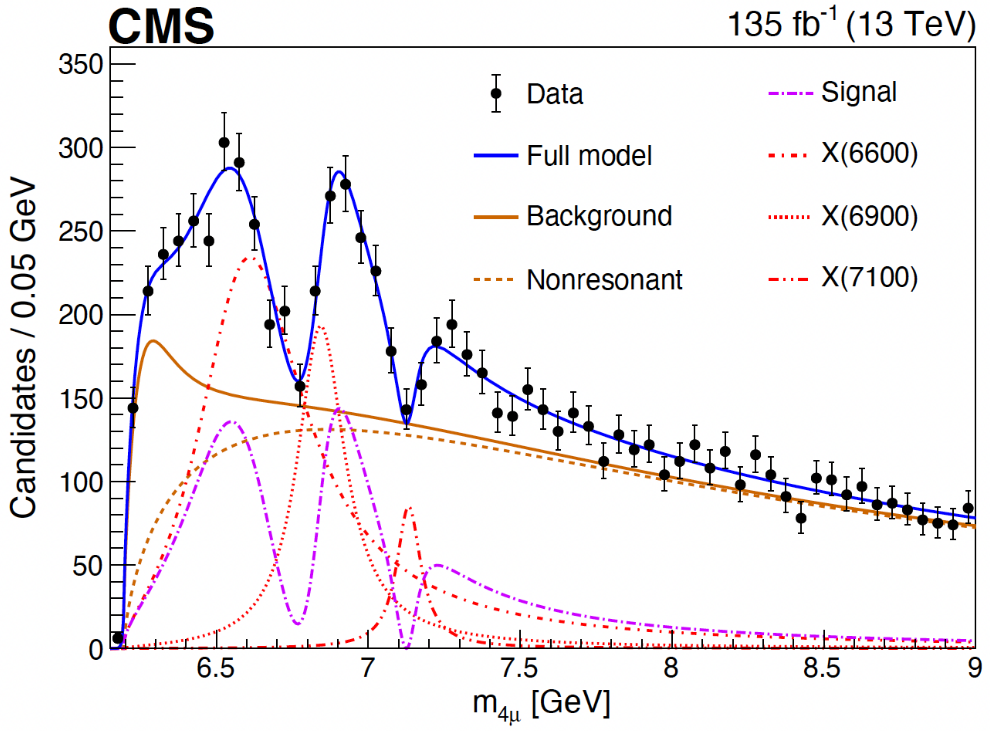
All-charm tetraquark family

Spin and parity of all-charm tetraquarks

arXiv:2506.07944v1
Submitted to Nature

Exotic structure like tetra and pentaquarks have been largely observed by the LHC collaborations.

CMS observed three similar states like $c\bar{c}c\bar{c}$ in $J/\psi J/\psi$ final state (with 4μ): X(6600), X(6900), X(7100) [ref]



Ambigous nature of these states:

- tightly-bound tetraquark
- loosely-bound molecule of two $c\bar{c}$ mesons

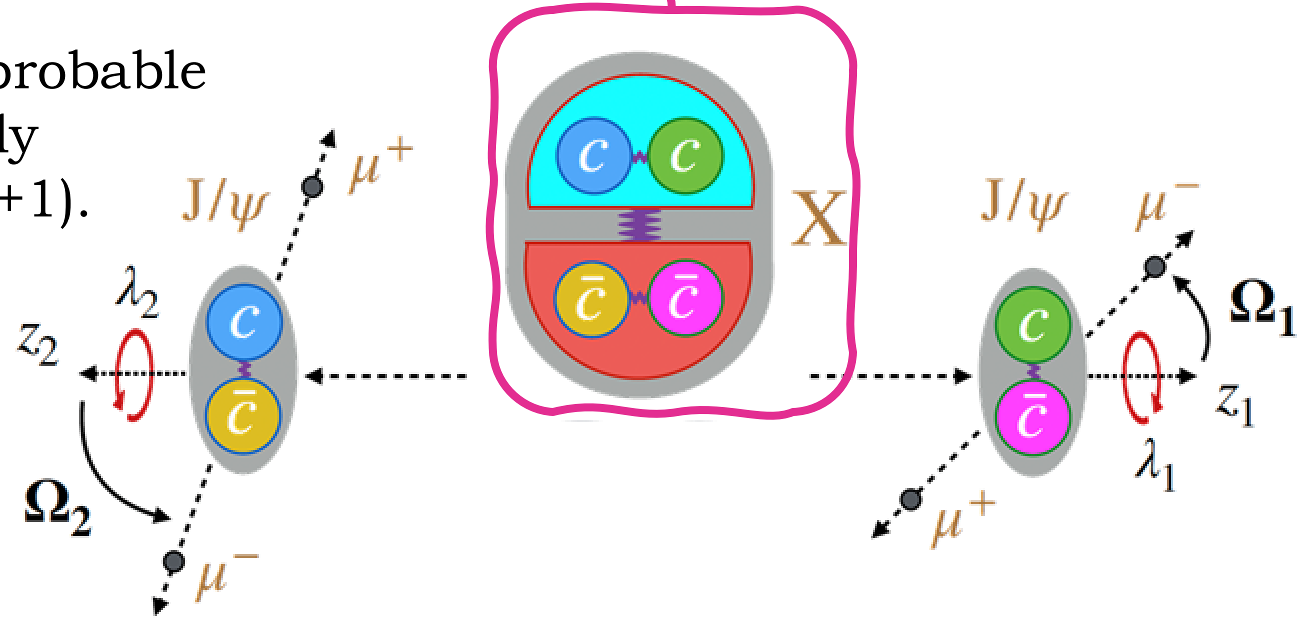
Spin and parity of all-charm tetraquarks

arXiv:2506.07944v1
Submitted to Nature

If it's a **tetraquark** parity is given by $P = (-1)^L$.
The lowest and most probable energy state is spatially symmetric ($L = 0$, $P = +1$).

- If symmetric configuration
  => $J = 0$ or 2.

- If antisymmetric
  => $J = 0, 1,$ or 2.



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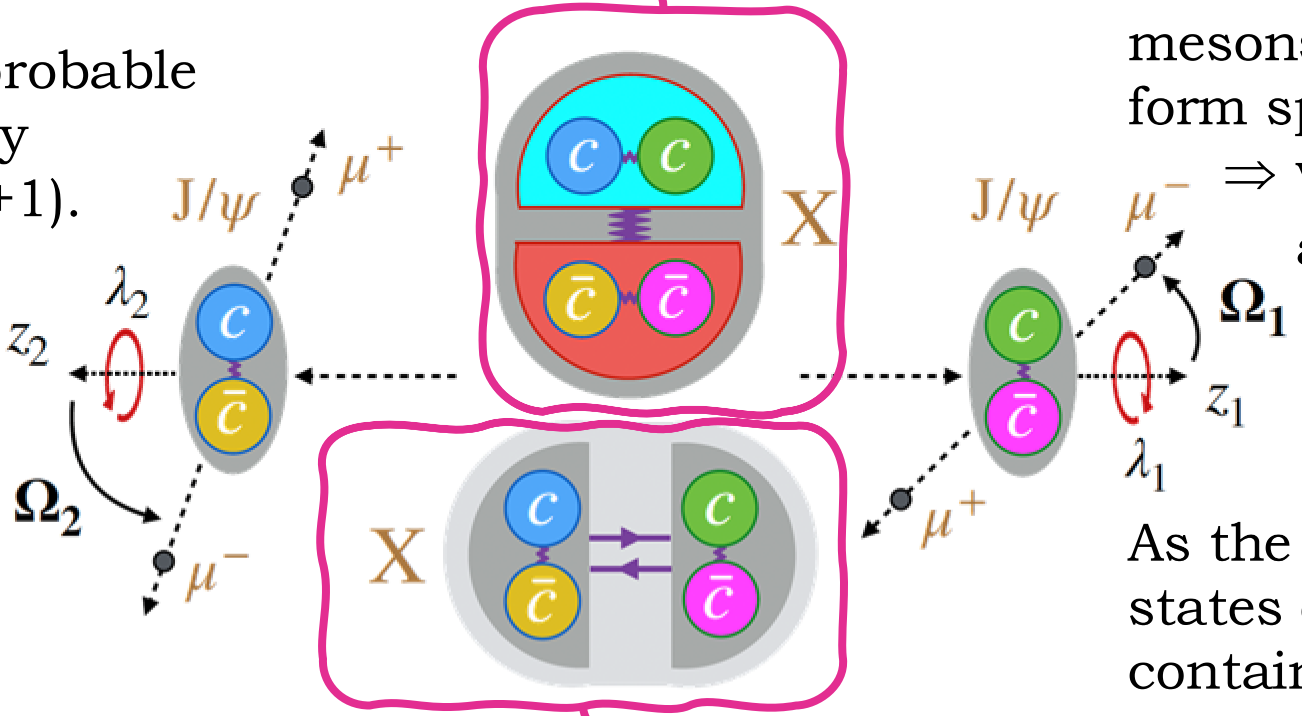

If it's a **molecule** the two mesons are not restricted to form spin -1 states
⇒ values of J = 0 or 1 are more likely.

As the deutron, the two $c\bar{c}$ states exchange a meson containing charm quarks

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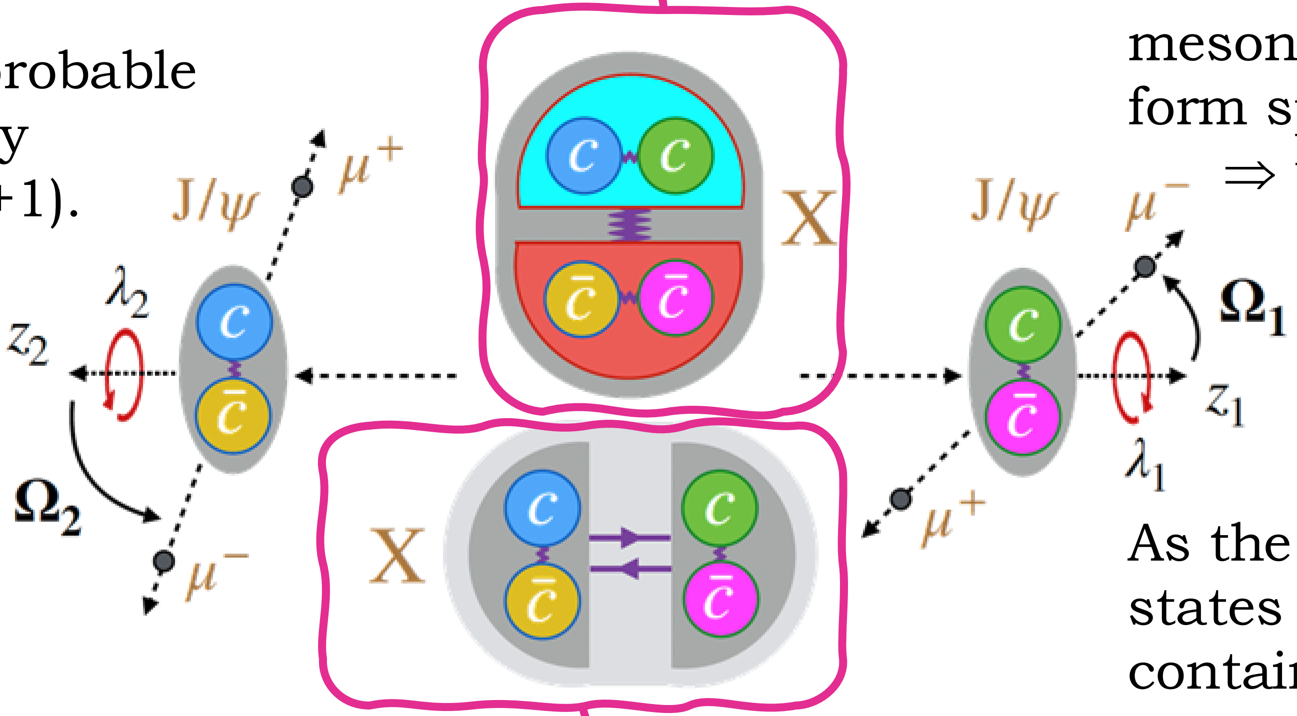

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The angular distributions in the decay of X can be expressed as a function of three angular observables θ_1, θ_2, and $\Phi = (\Phi 1 + \Phi 2)$

Spin and parity of all-charm tetraquarks

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⇒ Compare the angular distributions in the decay of observed X particles with the predicted distributions for various J^{PC} models and select the one that best matches data.

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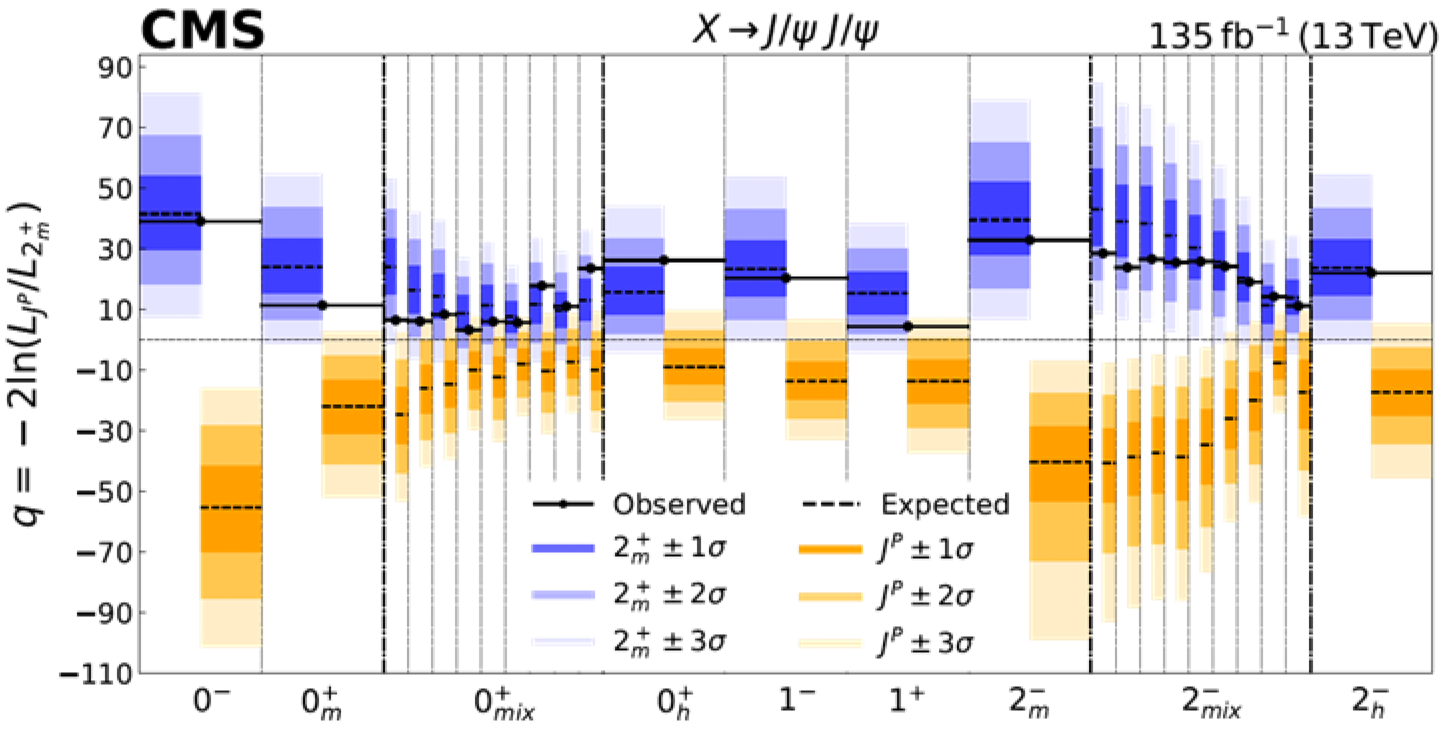
⇒ Compare the angular distributions in the decay of observed X particles with the predicted distributions for various J^{PC} models and select the one that best matches data.

$J^{PC}=2^{++}$ scenario is favoured!



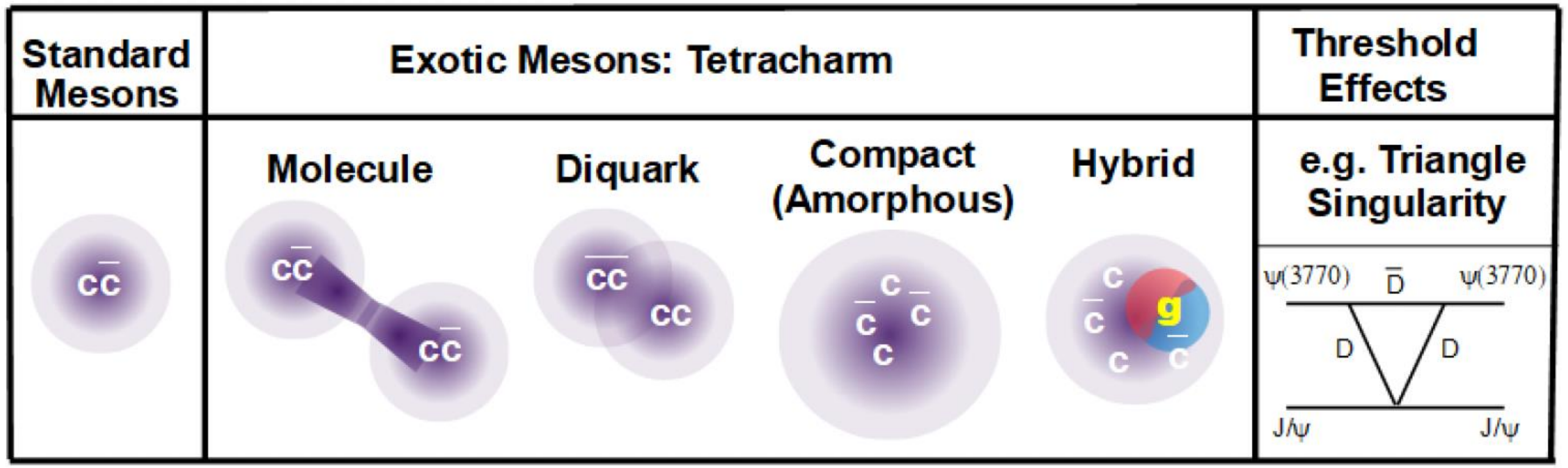
- Less likely for molecule since $q\bar{q}$ pairs are not required to be spin-1 mesons
- A **tightly-bound $c\bar{c}c\bar{c}$ tetraquark** with a diquark-antidiquark structure requires both diquarks to be in spin-1 => naturally favours J = 2

Family of all-charm tetraquarks

BPH-24-003

Critical issues on the characterization on the three tetracharm states remain.

- The X(7100) structure needs to be firmly established (below 5σ)
- All experiments preferred fit models utilizing quantum interference, but the models were incongruent and the **interference was not statistically conclusive**.
- All experiments reported an unexplained excess of J/ψ pairs just above the threshold.



Family of all-charm tetraquarks

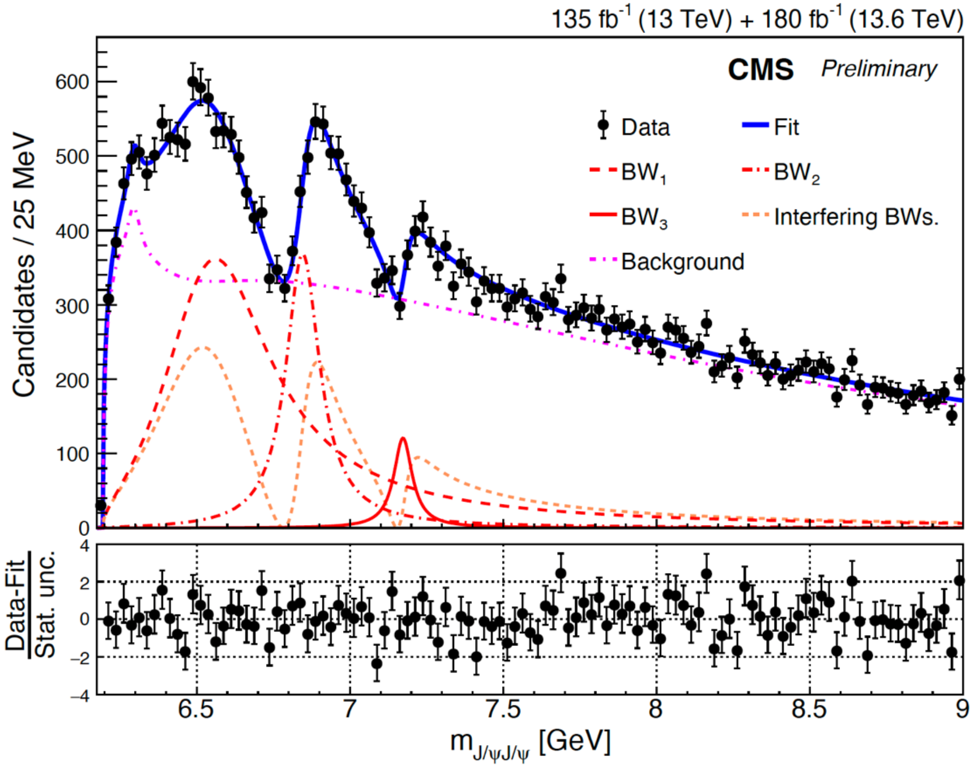
BPH-24-003

The tetraquark family investigation has been **enriched with Run3 data**:

- 135 fb^{-1} from Run2 @13TeV + 180 fb^{-1} from Run3 (2022-24) @13.6TeV

  $\Rightarrow$The Run3 yield exceeds that of Run2 by over 250%, despite $\frac{L_{Run3}}{L_{Run2}} \sim \frac{4}{3}$ by virtue of an enhanced trigger efficiency

		BW_1	BW_2	BW_3
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)	$440\,^{+230+110}_{-200-240}$	$191\,^{+66+25}_{-49-17}$	$97\,^{+40+29}_{-29-26}$



Family of all-charm tetraquarks

BPH-24-003

The local significances of the structures in the Run 2+3 interference fit are:

- 15.2σ for X(6600)
- 16.7 σ for X(6900)
- 7.7 σ for X(7100)

⇒ The **X(7100) structure now exceeds 5σ** in a single experiment for the first time, firmly establishing a collection of three structures

Similarly, interference among the 3 structures is now statistically compelling.

Interference implies that the structures have common J^{PC} quantum numbers

⇒suggesting a **family of states**

J/Psi + Psi(2S) resonance search

J/ψ + $\psi(2S)$ resonance search

arXiv:2509.13101v1
Submitted to PRL

Searching similar structure in the **J/ψ + $\psi(2S)$ production** to gain more insight into these exotic states in two different final states:

- $J/\psi \to 2\mu$ and $\psi(2S) \to 2\mu$ (4μ)
- $J/\psi \to 2\mu$ and $\psi(2S) \to J/\psi\pi^-\pi^+ \to 2\mu\pi^-\pi^+$ ($4\mu 2\pi$)
  - BR ~ twice than the 4μ final state

Run2 analysis with data @13TeV - 140 fb^{-1}

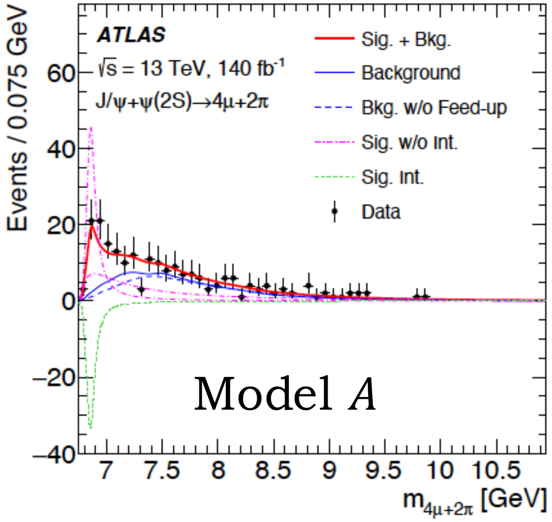
$J/\psi + \psi(2S)$ resonance search

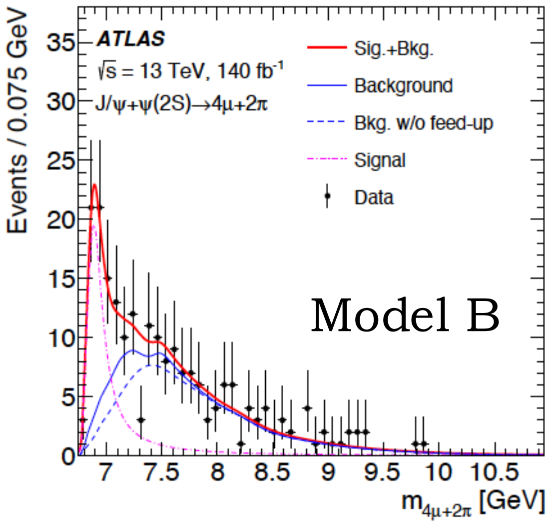
arXiv:2509.13101v1
Submitted to PRL

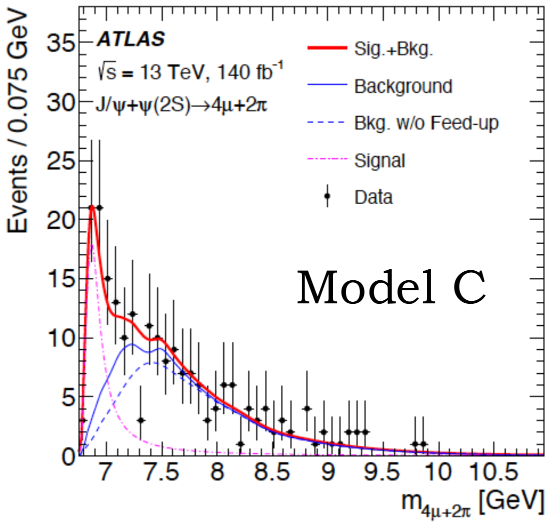
Three different fit models are carried out.

- Model A (two interfering resonances)
- Model B (one interfering with SPS and the other standalone)
- Model C assumes a standalone resonance in the J/ψ+ψ(2S) channels.

assume that $X(6900)$ decays into both the di-J/ψ and J/ψ+ψ(2S)







Complete set of plots in backup

$J/\psi + \psi(2S)$ resonance search

arXiv:2509.13101v1
Submitted to PRL

- Fitted masses and widths and the ratio of partial widths R

	model A	model B	model C
m / GeV	$6.860 \pm 0.023 \pm 0.010$	$6.902 \pm 0.008 \pm 0.010$	$6.884 \pm 0.017^{+0.058}_{-0.005}$
Γ / GeV	$0.082 \pm 0.032 \pm 0.015$	$0.183 \pm 0.025 \pm 0.007$	$0.178 \pm 0.054^{+0.176}_{-0.024}$
R	$1.08 \pm 0.20^{+0.40}_{-0.09}$	$0.93 \pm 0.17 \pm 0.11$	—

- The three fitting models seems to be consistent with each other

J/ψ + $\psi(2S)$ resonance search

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- Fitted masses and widths and the ratio of partial widths R
- The three fitting models seems to be consistent with each other
- The signal significance is 8.9σ for the resonance near 6.9 GeV in the J/ψ+$\psi(2S)$ channels.
- The existence of $X(7200)$ in the J/ψ+$\psi(2S)$ channels is tested in each model. The ratio of signal yields for $X(7200)$ to $X(6900)$ is found to be 0.12 ± 0.11, with an upper limit of 0.41 at 95% CL.

$\Rightarrow$ These results **confirm the presence of structures in the J/ψ+$\psi(2S)$** channels, favoring a single-resonance hypothesis near **6.9 GeV**, while the existence of a **potential resonance near 7.2 GeV is not supported** by the current data.

$J/\psi + \psi(2S)$ resonance search

BPH-22-004

Search in the $J/\psi \rightarrow 2\mu$ and $\psi(2S) \rightarrow 2\mu$ (4μ) final state with Run2+Run3 data (314 fb^{-1}) carried out by CMS as well.

The strategy follows what already done for J/ψ J/ψ

J/ψ + $\psi(2S)$ resonance search

BPH-22-004

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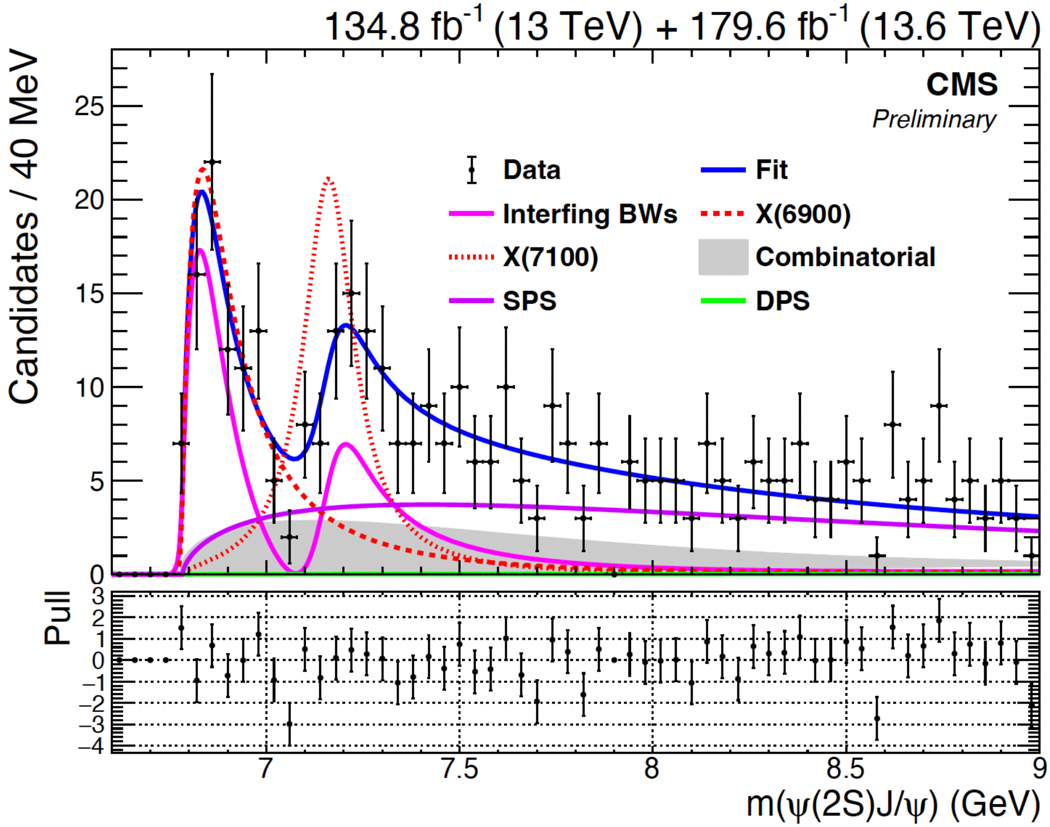
$\Rightarrow$X(6900) and X(7100) clearly visible with 7.9σ and 4.0σ respectively



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]	$J/\psi J/\psi$	BW_1, BW_2, BW_3	m :	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
			Γ :	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

Reconstruction of the B^{*+}, B^{*0}, and B_s^{*0} mesons

First exclusive reconstruction of the B^{*+}, B^{*0}, and B_s^{*0} mesons

arXiv:2508.05820v1
Submitted to PRL

The ground states of beauty mesons B^+, B^0, and B_s^0 are well known while the corresponding **excited states B^{*+}, B^{*0}, and B_s^{*0} are much less explored**.

$\Rightarrow$ The main challenge stems from the low-energy (40–50MeV) photons emitted in $B^* \rightarrow B\gamma$ decays

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⇒ The main challenge stems from the low-energy (40–50MeV) photons emitted in $B^* \to B\gamma$ decays

The analysis uses Run2 data @13TeV, with 140 fb^{-1}.

- Low-energy γ are reconstructed through the conversions into e^+e^- pairs
- Ground-state B mesons are reconstructed using the decays: $B^+ \to \psi K^+$, $B^0 \to \psi K^{*0}$, and $B_s^0 \to \psi\phi$
  - ψ stands for the J/ψ and $\psi(2S)$ mesons in $\mu^+\mu^-$ decay
  - K^{*0} and ϕ refer to the $K^*(892)^0$ and $\phi(1020)$ mesons, reconstructed through their decays to $K^+\pi^-$ and K^+K^-

First exclusive reconstruction of the B^{*+}, B^{*0}, and B_s^{*0} mesons

arXiv:2508.05820v1
Submitted to PRL

Photon conversion candidates are formed from two OS tracks with:

- small angular separation and small distance of closest approach
- conversion vertex at least 1.5 cm away from the beam axis
- and a χ^2 probability above 0.05% for a kinematic fit that constrains the two tracks to originate from a common vertex with 0 invariant mass

⇒ Only photon candidates with p_T > 300MeV and $|\eta| < 1.5$ are kept

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The measured momenta of the $e^{\pm}$ tracks tend to be lower than the true momenta due to loosing energy while traversing the tracker

$\Rightarrow$photon energy scale (PES) correction is performed using $\pi^0 \to \gamma\gamma$ reconstructed from two converted γ in several ranges of p_T and $|\eta|$.

$\Rightarrow$PES is 1.002–1.04 in the kinematic range relevant for this analysis

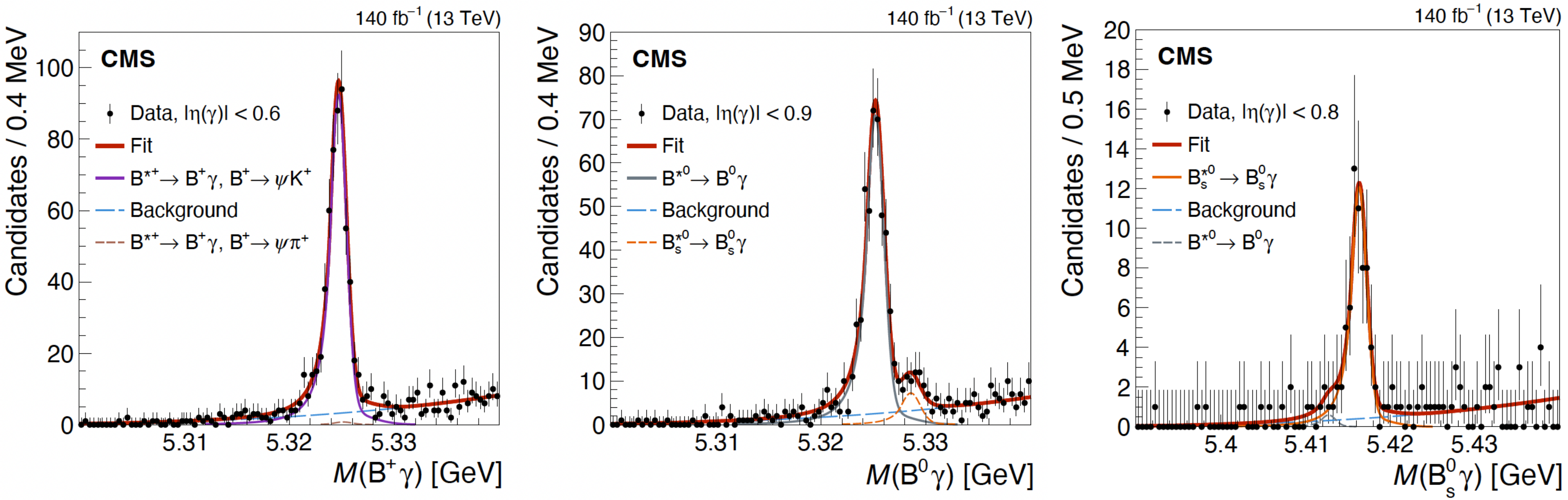
First exclusive reconstruction of the B^{*+}, B^{*0}, and B_s^{*0} mesons

arXiv:2508.05820v1
Submitted to PRL

The Bγ invariant mass is evaluated using $M(B\gamma) = m(B\gamma) - m(B) + M_B^{PDG}$

$M(B\gamma)$ resolution depends strongly on $|\eta(\gamma)|$

⇒from 0.7MeV at $|\eta(\gamma)|$ close to zero to about 2MeV at $|\eta(\gamma)|$ around 1.5



First exclusive reconstruction of the B^{*+}, B^{*0}, and B_s^{*0} mesons

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The fit returns

$$\begin{aligned}
\Delta m(\mathrm{B}^{*+}) &\equiv m(\mathrm{B}^{*+}) - m(\mathrm{B}^{+}) & 45.277 \pm 0.039 \pm 0.027\,\mathrm{MeV}\\
\Delta m(\mathrm{B}^{*0}) &\equiv m(\mathrm{B}^{*0}) - m(\mathrm{B}^{0}) & 45.471 \pm 0.056 \pm 0.028\,\mathrm{MeV}\\
\Delta m(\mathrm{B}_s^{*0}) &\equiv m(\mathrm{B}_s^{*0}) - m(\mathrm{B}_s^{0}) & 49.407 \pm 0.132 \pm 0.041\,\mathrm{MeV}
\end{aligned}$$

$\Rightarrow$Values are **consistent with the world average value and one order of magnitude more precise!**

Conclusion

Spectroscopy is an active field for both ATLAS and CMS collaborations

- A large attention is devoted to the **tetraquark candidates**, that may brings us closer to uncovering tetraquarks true nature beyond the traditional quark model

- Transitions that involve **low energy photons** are tricky and challenging to measure, but experimental performances demonstrated to be good enough to reach results

Run 3 data will be crucial (for both statistics and new trigger strategy!) to continue the investigation toward – hopefully – new states!


Thank you
for your
attention

backup

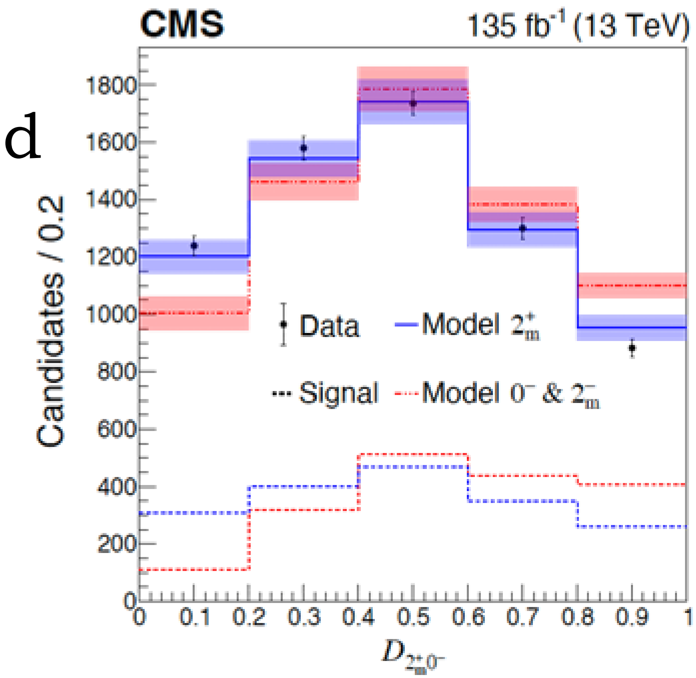
Spin and parity of all-charm tetraquarks

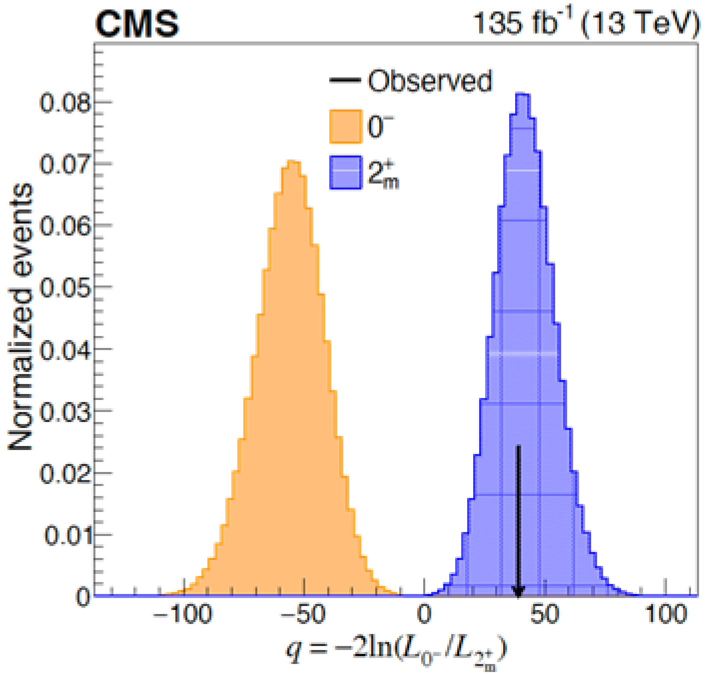
arXiv:2506.07944v1
Submitted to Nature

The aim: identify the model that best matches the experimental data.

⇒ compare the angular distributions in the decay of observed X particles in the experiment with the predicted distributions for various J^{PC} models and select the model that is consistent with the data.

⇒ Single observable D_{ij} defined: constructed from the likelihood ratio between two models labelled i and j.





Spin and parity of all-charm tetraquarks

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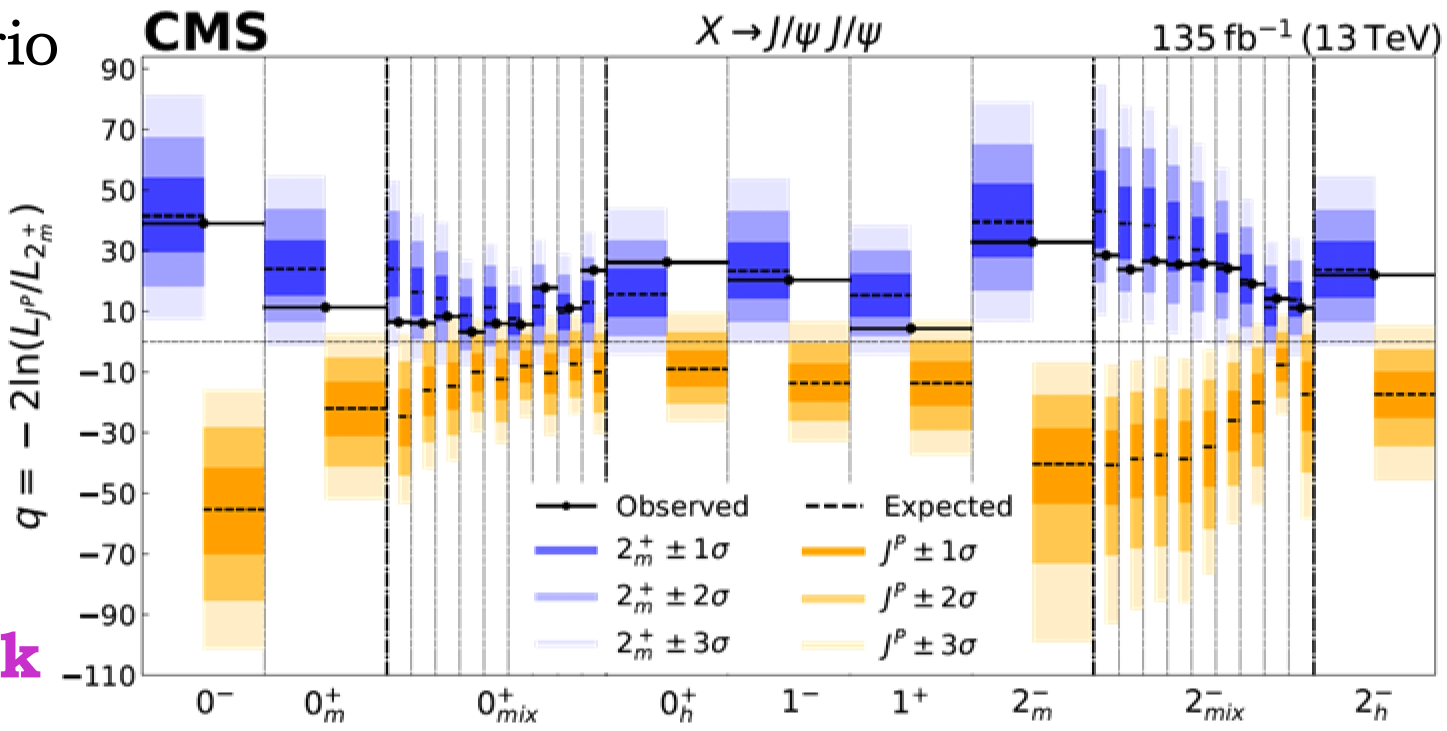
The results favour $J^{PC}=2^{++}$ scenario



- In a molecular scenario, the $q\bar{q}$ pairs are not required to be spin-1 mesons, making a J = 2 configuration less likely
- A **tightly-bound $c\bar{c}c\bar{c}$ tetraquark** with a diquark-antidiquark structure requires both diquarks to be in spin-1 states, which naturally favours a J = 2 configuration

$J/\psi + \psi(2S)$ resonance search

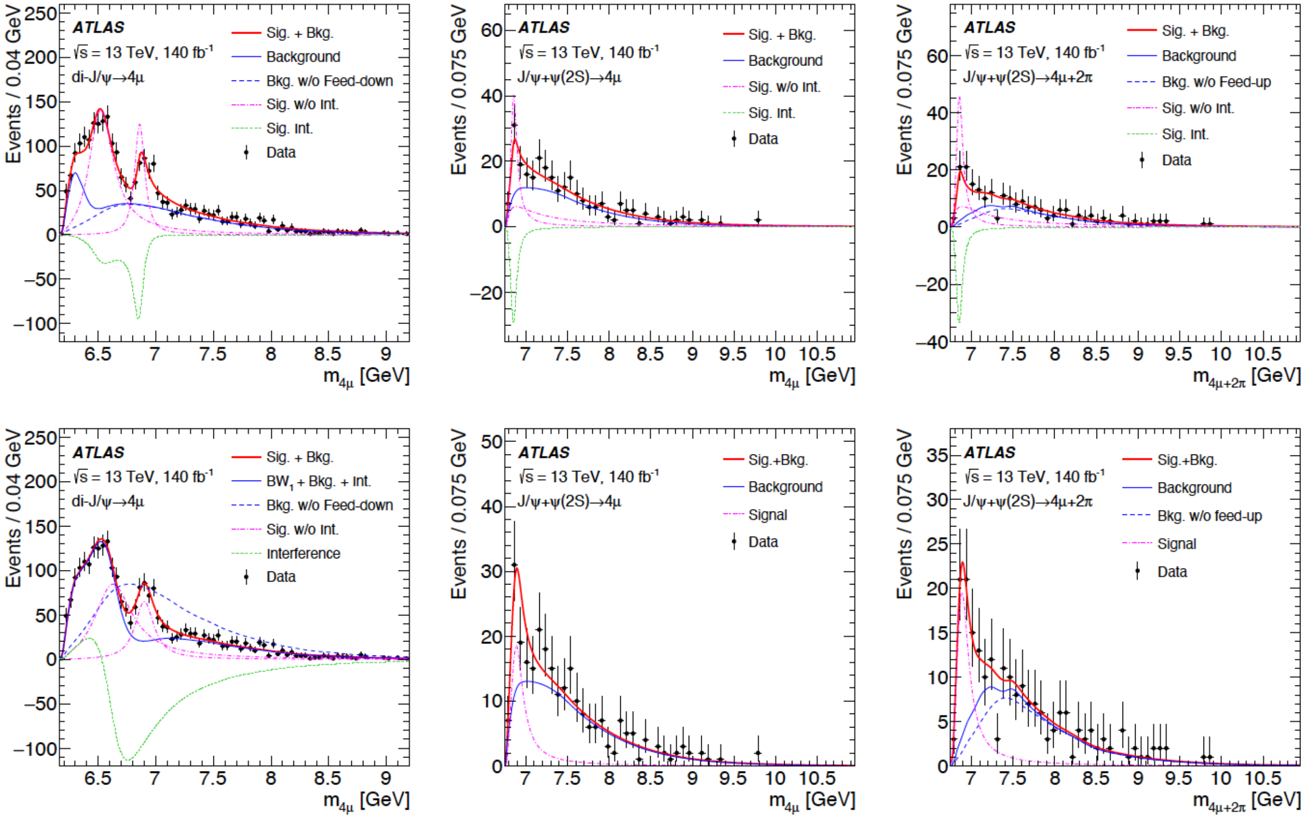
arXiv:2509.13101v1
Submitted to PRL

Different backgrounds are considered:

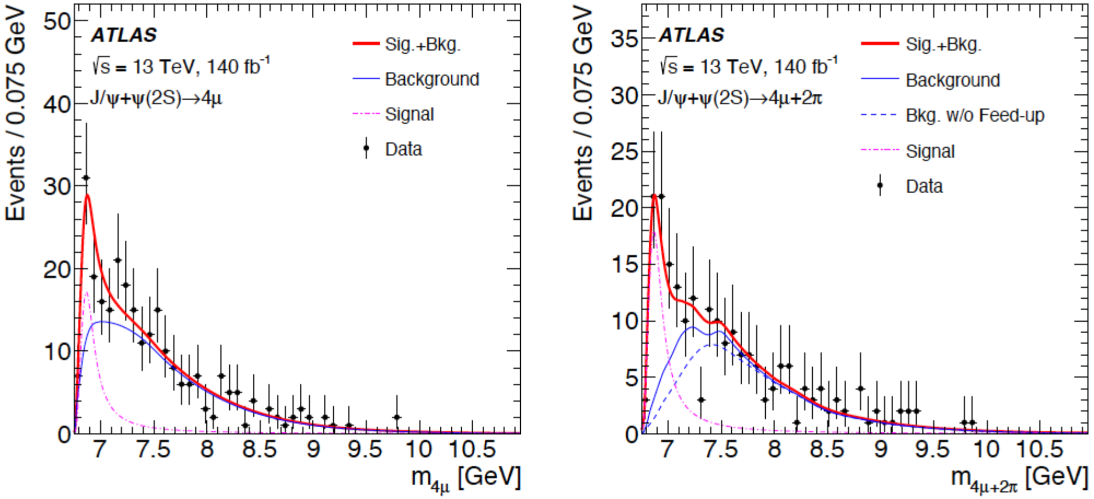
- "others", with at most one real charmonium modeled from data requiring at least one charmonium candidate to contain a track that fails μ identification
- non-prompt, estimated in MC and corrected and normalised in CR with reverse L_{xy}^{charm} request
- DPS and SPS, estimated in MC and corrected in several kinematic variables in dedicated CR
- Several feed-down backgrounds are limited with a BDT -> reduced by ~65% while keeping 92% of the signal

4μ channel		$4\mu + 2\pi$ channel	
SR	CR	SR	CR
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *Loose* muons, $p_{T1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, $m_{\psi(2S)} \in [3.56, 3.80]$ GeV			
—		Two *loose* OS ID tracks with $p_T > 0.5$ GeV for pions, BDT requirement	
$\chi^2_{4\mu}/N < 3$, $\lvert L^{4\mu}_{xy}\rvert < 0.2$ mm, $\lvert L^{\mathrm{charm}}_{xy}\rvert < 0.3$ mm, $m_{4\mu} < 11$ GeV		$\chi^2_{4\mu+2\pi}/N < 3$, $\lvert L^{4\mu+2\pi}_{xy}\rvert < 0.2$ mm, $\lvert L^{\mathrm{charm}}_{xy}\rvert < 0.3$ mm, $m_{4\mu+2\pi} < 11$ GeV	
$\Delta R(J/\psi, \psi(2S)) < 0.25$	$\Delta R(J/\psi, \psi(2S)) \geq 0.25$	$\Delta R(J/\psi, \psi(2S)) < 0.25$	$\Delta R(J/\psi, \psi(2S)) \geq 0.25$

J/ψ + $\psi(2S)$ resonance search



Fits to the di-J/ψ and J/ψ + $\psi(2S)$ mass spectra in the SRs for model A (top) and B (bottom).
For each model, the di-J/ψ spectrum (left) and the J/ψ + $\psi(2S)$ spectra in the 4μ (middle) and 4μ + 2π (right) channels are shown. The purple dash-dotted lines represent the components of individual resonances, and the green short dashed ones represent the interferences. No interference is present in the J/ψ + $\psi(2S)$ channels with model B since $X(6900)$ is standalone.



Fits to the J/ψ+$\psi(2S)$ mass spectra with model C in the SRs of the 4μ (left) and 4μ + 2π (right) channels.
The purple dash-dotted lines represent the signal resonances.