Heavy flavor spectroscopy at CMS

Outline

-Observation of new structure in the $J/\psi J/\psi$ mass spectrum in proton-proton collisions at 13 TeV

-Observation of the $\Xi^-_b \to \psi(2S)\Xi^-$ decay

-Observation of the $\Lambda^0_b \to J/\psi \Xi^- K^+$ decay

-Observation of the η meson to four muons

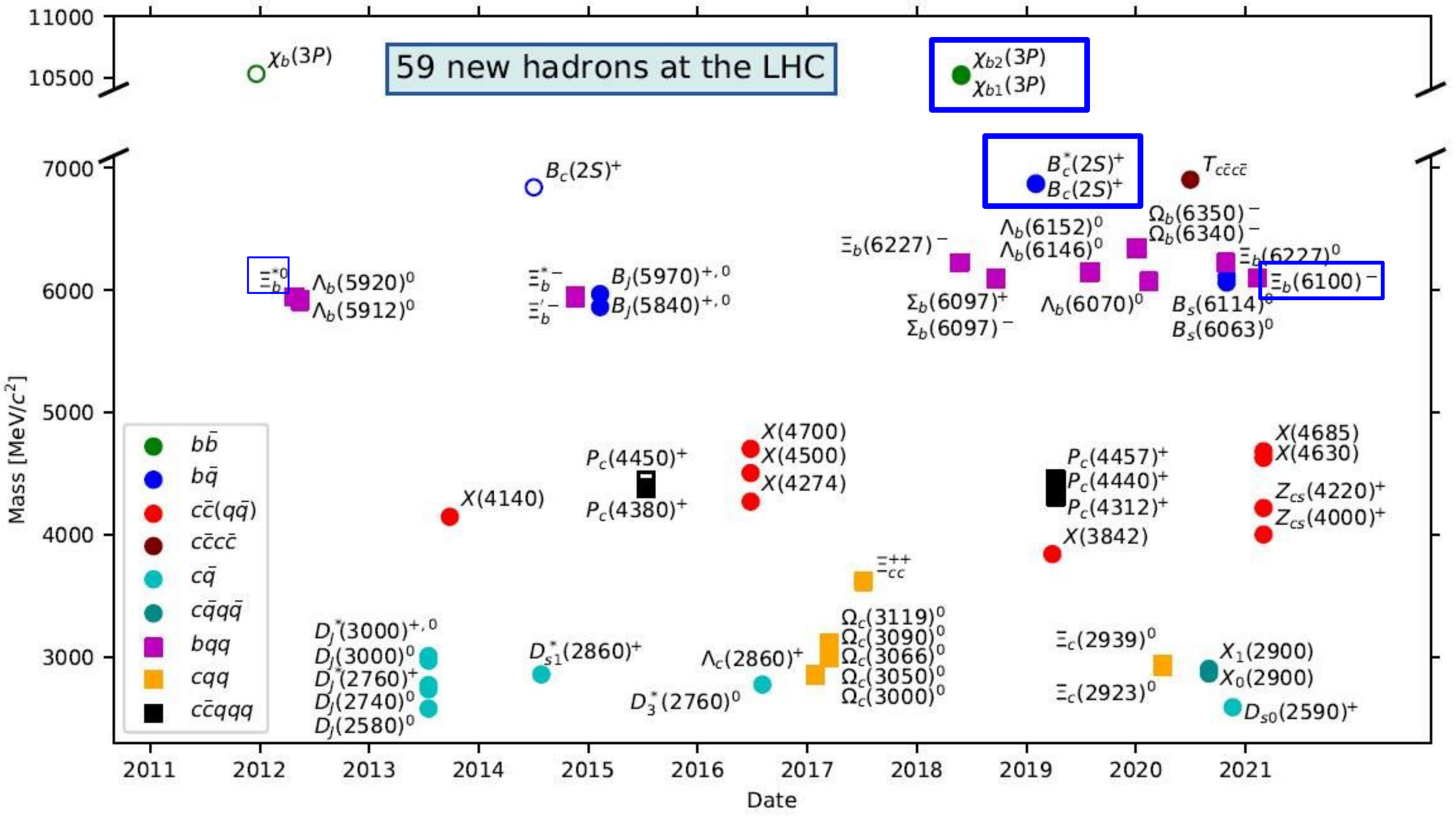
Jhovanny Andres Mejia Guisao

On behalf of the CMS collaboration

SILAFAE2024: XV Latin American Symposium on High Energy Physics, 4-8 Nov 2024, Mexico City (Mexico).

CERN Courier 59 new hadrons and counting

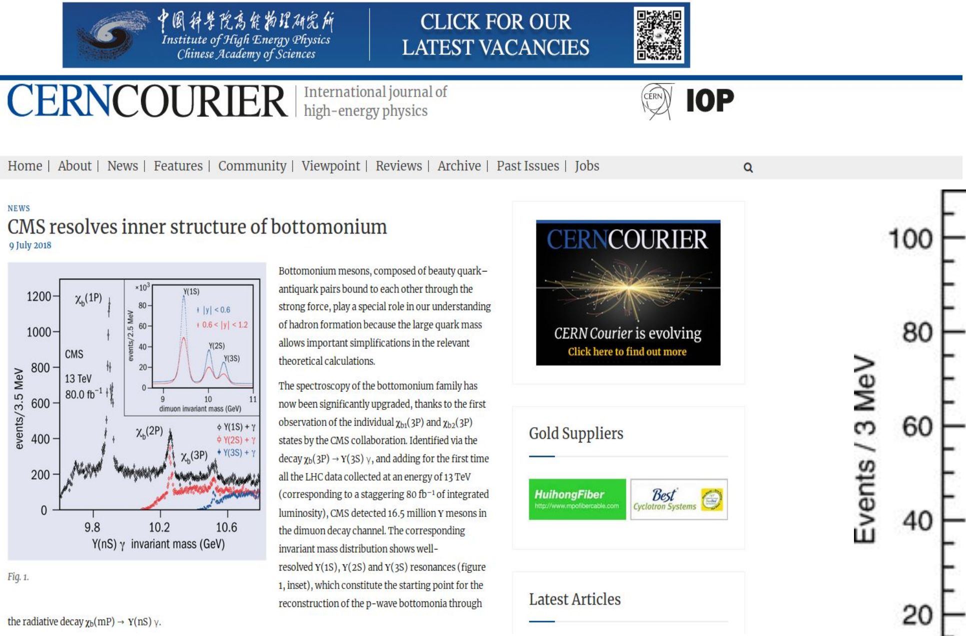
Over the past 10 years, the LHC has found more than 50 new particles called hadrons



Phys. Rev. Lett. 121, 092002
PRL 122 (2019) 132001
Phys. Rev. Lett. 126 (2021) 252003
Phys. Rev. Lett. 120 (2018) 202005

As a motivation let's briefly look at some previous results

We found new bb mesons!



CERNCOURIER International journal of high-energy physics

NEWS

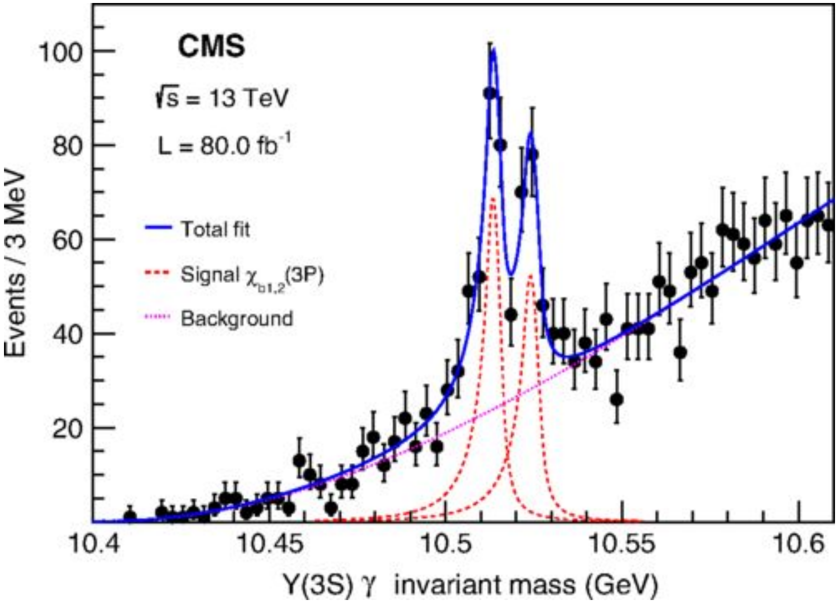
CMS resolves inner structure of bottomonium

9 July 2018

Fig. 1.

Bottomonium mesons, composed of beauty quark–antiquark pairs bound to each other through the strong force, play a special role in our understanding of hadron formation because the large quark mass allows important simplifications in the relevant theoretical calculations.

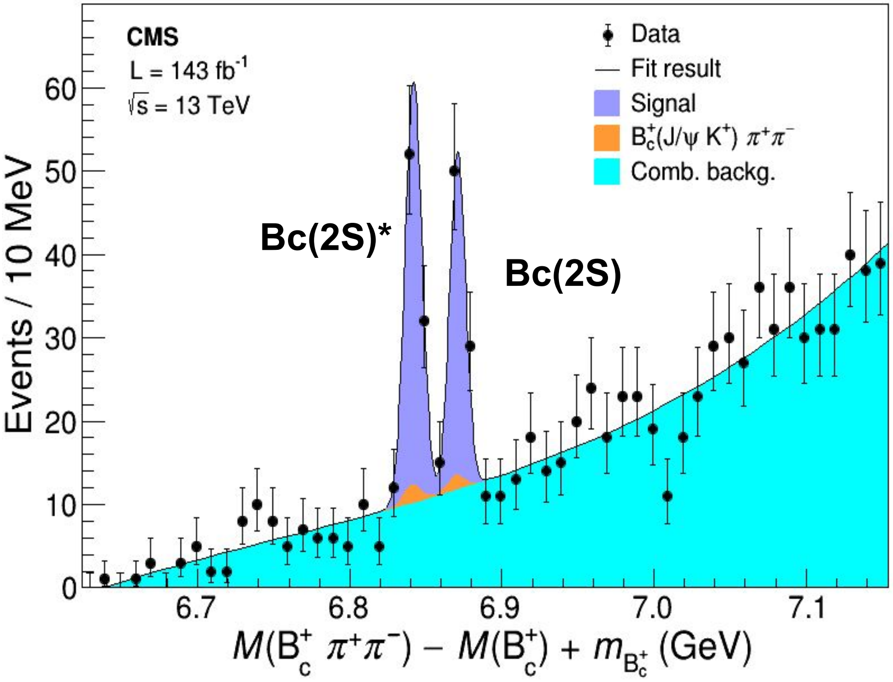
The spectroscopy of the bottomonium family has now been significantly upgraded, thanks to the first observation of the individual $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ states by the CMS collaboration. Identified via the decay $\chi_b(3P) \to \Upsilon(3S)\,\gamma$, and adding for the first time all the LHC data collected at an energy of 13 TeV (corresponding to a staggering 80 fb^{-1} of integrated luminosity), CMS detected 16.5 million Υ mesons in the dimuon decay channel. The corresponding invariant mass distribution shows well-resolved $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances (figure 1, inset), which constitute the starting point for the reconstruction of the p-wave bottomonia through the radiative decay $\chi_b(mP) \to \Upsilon(nS)\,\gamma$.

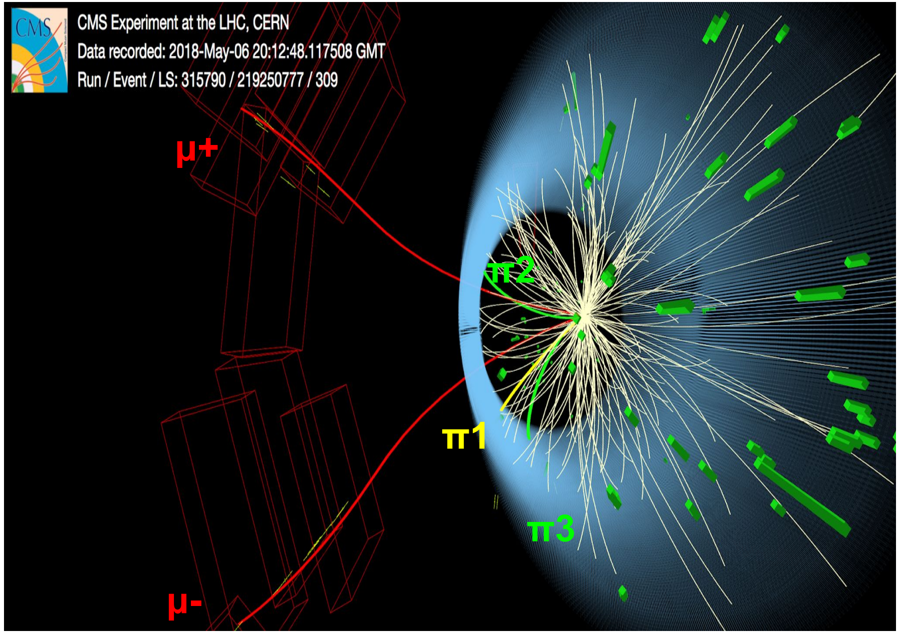


Observation of the χb1(3P) and χb2(3P) measurement of their masses using the χbJ(3P) → Y(3S)γ

[Phys. Rev. Lett. 121, 092002]

We found new Bc mesons!






PHYSICAL REVIEW LETTERS
moving physics forward

Dear Sir or Madam,

We are pleased to inform you that the Letter

Observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV

A.M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **122**, 132001 (2019)

Published 2 April 2019

has been highlighted by the editors as an Editors' Suggestion. Publication of a Letter is already a considerable achievement, as *Physical Review Letters* accepts fewer than 1/4 of submissions, and is ranked first among physics and mathematics journals by the Google Scholar five-year h-index. A highlighted Letter has additional significance, because only about one Letter in six is highlighted as a Suggestion due to its particular importance, innovation, and broad appeal. Suggestions are downloaded twice as often as the average Letter, and are covered in the press substantially more often. If Suggestions were a separate publication, they would have an Impact Factor of 17. More information about our journal and its history can be found on our webpage prl.aps.org

Yours sincerely,

Hugues Chaté
Editor
Physical Review Letters

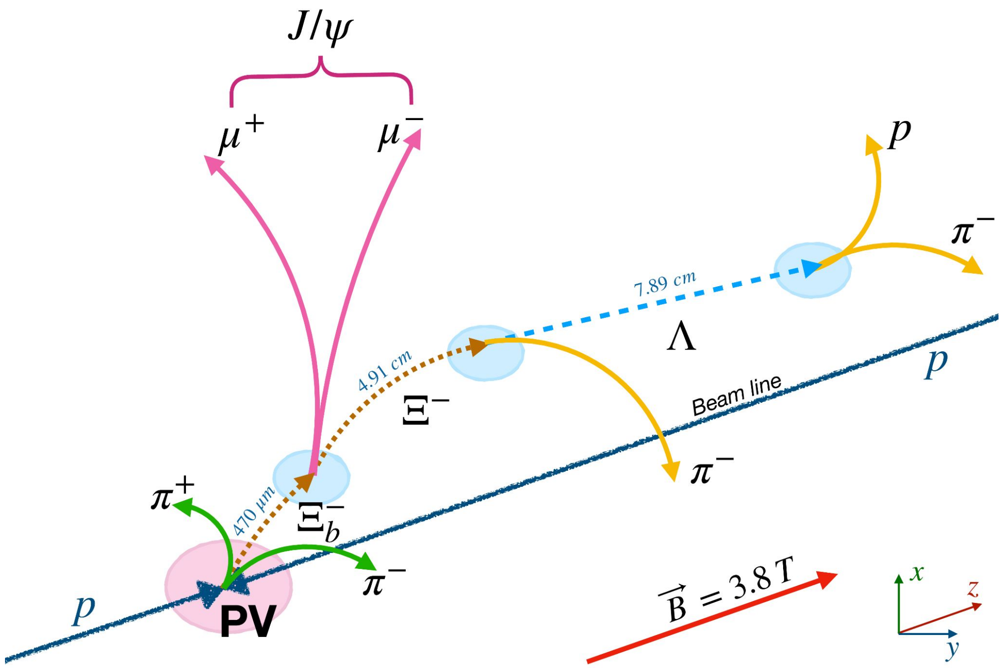
Michael Thoennessen
Editor in Chief
Physical Review

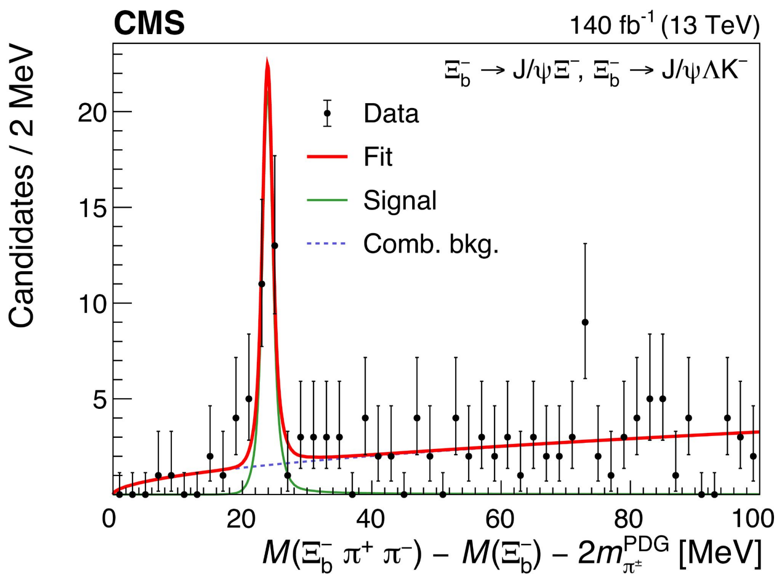
Physical Review Letters, 1 Research Road, Ridge, NY 11961-2701

Observation of Two Excited B_c States and Measurement of the $B_c(2S)$ Mass in pp Collisions at $\sqrt{s}$ = 13 TeV

PRL 122 (2019) 132001

Observation of a new excited beauty strange baryon decaying to $\Xi_b \pi^+ \pi^-$

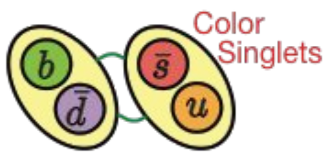




[Phys. Rev. Lett. 126 (2021) 252003]

Search for resonance-like structures in the $B_s^0\pi$ invariant mass spectrum

- D0 observed an unexpected narrow structure, named X(5568), in the $B_s^0\pi$ system.
- State w/ **4 different flavors of quarks**



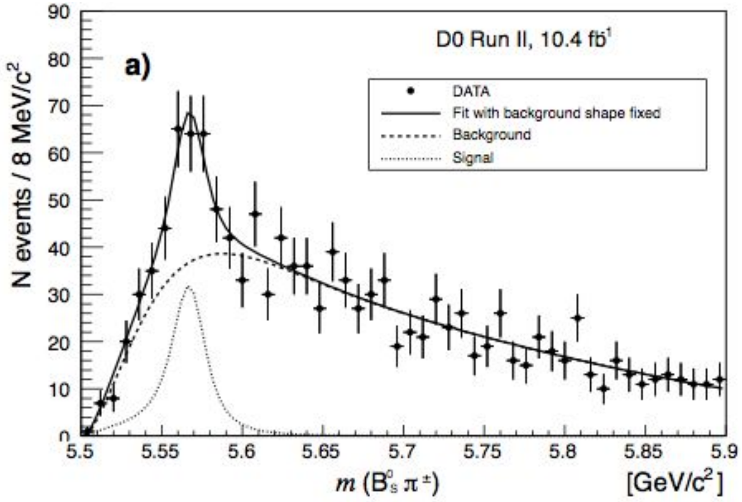
Loosely Bound Hadronic Molecule?

Tetraquark?

Given the large difference between Mx and the B^0 $K^{\pm}$ mass threshold, a molecular hypothesis is unlikely

If confirmed, Tetraquark interpretation would be favored. However, Theory predicts more states.

arXiv:1602.07588



Phys. Rev. Lett. 117, 022003 (2016)

$$M_X = 5567.8 \pm 2.9\,^{+0.9}_{-1.9}\ \mathrm{MeV}$$

$$\Gamma_X = 21.9 \pm 6.4\,^{+5.0}_{-2.5}\ \mathrm{MeV}$$

Strong decay!

$$N_X = 133 \pm 31 \pm 15\ \mathrm{cand.}$$

- If $X(5568)^- \to B_s^0\pi^-$ then $J^P = 0^+$
- If $X(5617)^- \to B_s^{0*}\pi^-$, $\hookrightarrow B_s^0\gamma$ miss! then $J^P = 1^+$

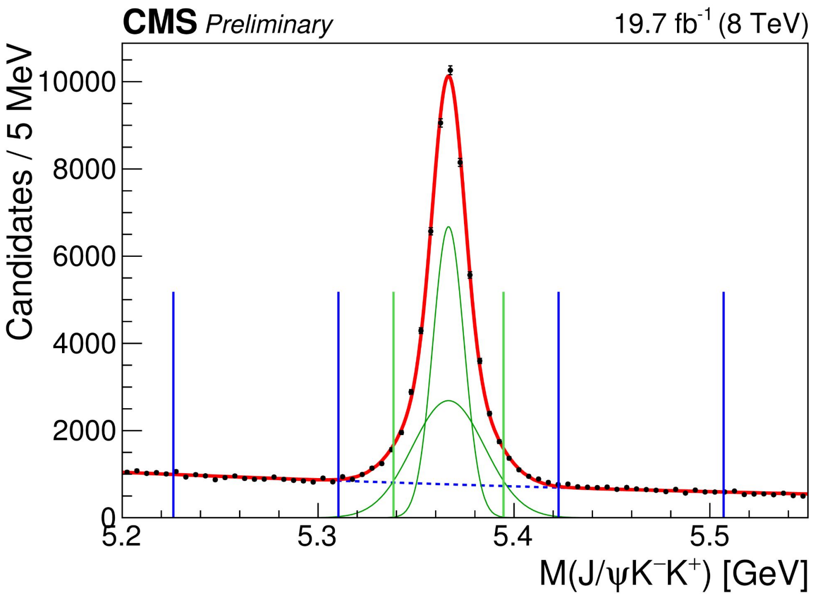
Not confirmed by LHCb

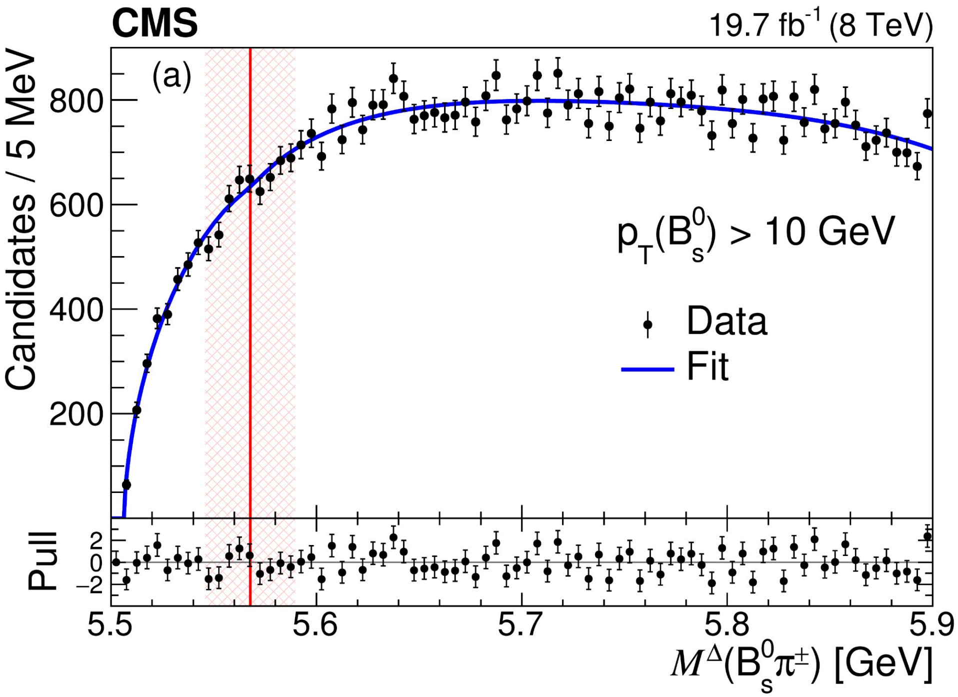
Not confirmed by CMS

Not confirmed by ATLAS

Not confirmed by CDF

Search for $X^+(5568) \to B_s^0\pi^+$: CMS



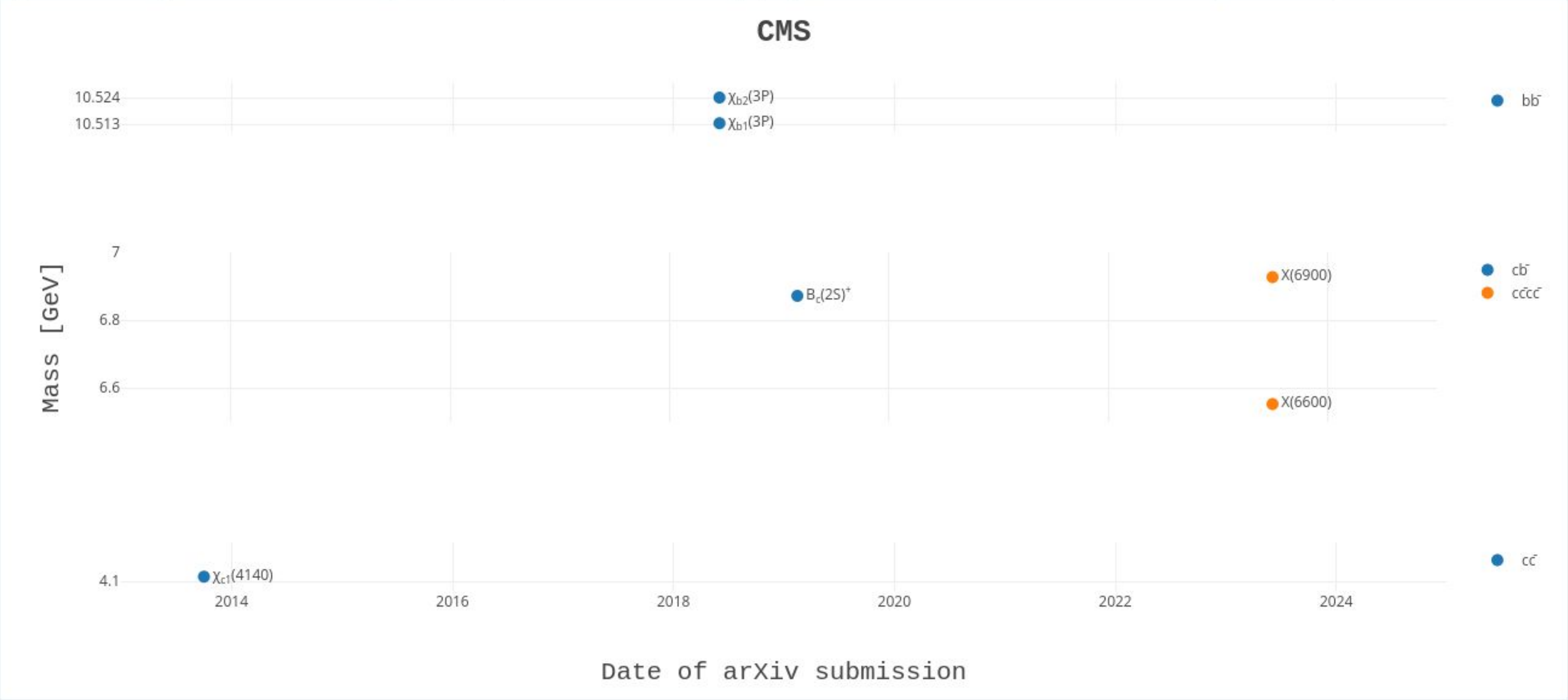


Despite of a much higher $B_s^0 \to J/\Psi KK$ sample, No significant signal observed for $X^+(5568)$

Phys. Rev. Lett. 120 (2018) 202005

Quarkonium Working Group

The figure shows states as observed by CMS as a function of year of observation.
On putting the mouse on the state a box will appear with information on PDG mass, JPC, and arXiv number of the discovery paper. On clicking on the state additional information will appear below the figure: PDG mass with errors, width, JPC, direct links to the discovery paper(s) and some comments about how this state change with subsequent observations.



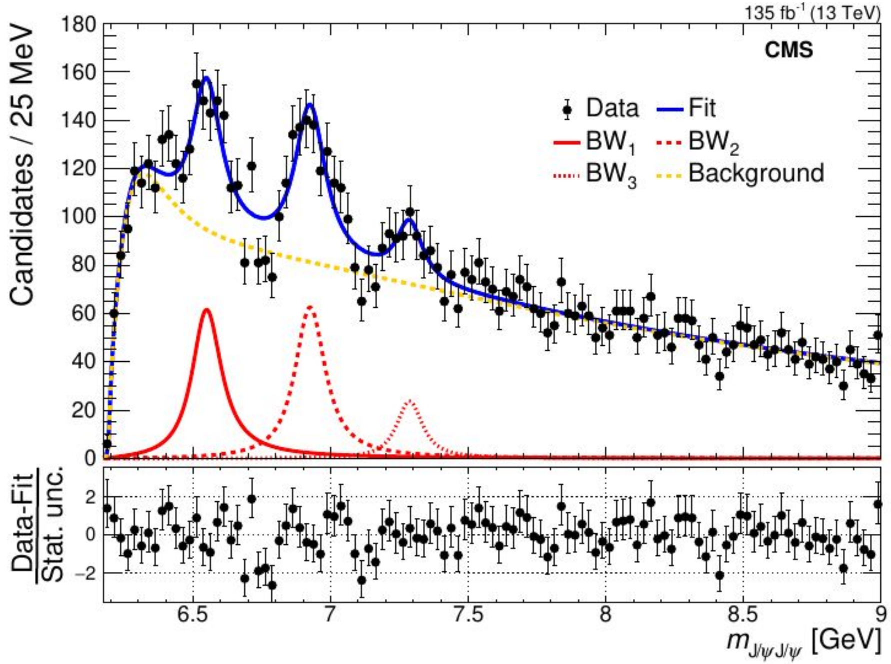
link

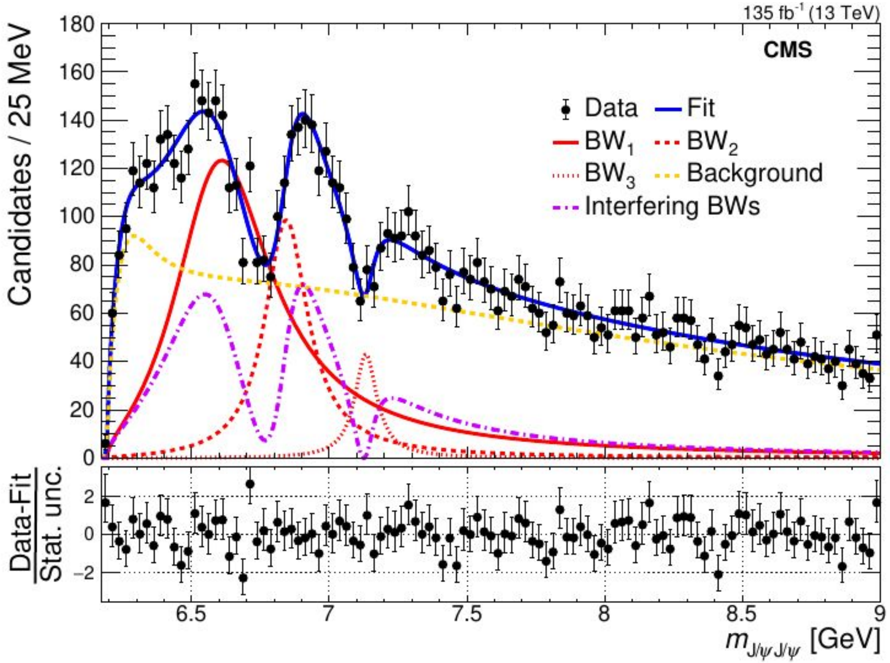
arXiv:2306.07164,
CMS-BPH-21-003 ; CERN-EP-2023-109
Phys. Rev. Lett. 132 (2024) 111901

Observation of new structure in the J/ψJ/ψ mass spectrum in proton-proton collisions at 13 TeV

While many tetraquark candidates containing heavy quarks are now known, questions still abound, including which of these are truly exotic hadrons, and if they are bound states, what is their internal structure (e.g., molecules, bound states of diquarks, etc).

The J/ψJ/ψ invariant mass spectrum in the range up to 9 GeV





(Left) Fit without interference.
(Right) Fit that includes interference,.
Only the sum of the three background components (NRSPS+DPS+BW0) is shown.
The lower portion of the plots shows the pulls.

Summary fit results and dominant contributions to the systematic uncertainties

The ``Total uncertainty" is the quadratic sum of all individual components, including the unlisted non-dominant contributions.

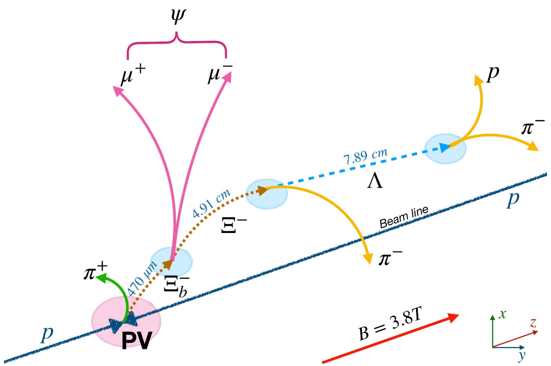
Fit	Dominant sources	M_{BW_1}	M_{BW_2}	M_{BW_3}	Γ_{BW_1}	Γ_{BW_2}	Γ_{BW_3}
No-interference	Signal shape	3	3	3	10	5	5
	NRSPS shape	3	1	1	18	15	17
	Feed-down	11	1	1	25	8	6
	Total uncertainty	12	4	5	33	18	19
Interference	Signal shape	7	12	7	56	8	7
	DPS shape	1	3	2	18	6	2
	NRSPS shape	9	14	13	85	9	20
	Mass resolution	8	4	1	24	7	13
	Combinatorial bkg.	7	2	<1	5	3	2
	Feed-down	${}^{+0}_{-27}$	${}^{+44}_{-0}$	${}^{+38}_{-0}$	${}^{+0}_{-210}$	${}^{+19}_{-0}$	${}^{+12}_{-0}$
	Total uncertainty	${}^{+16}_{-31}$	${}^{+48}_{-20}$	${}^{+41}_{-15}$	${}^{+110}_{-240}$	${}^{+25}_{-17}$	${}^{+29}_{-26}$

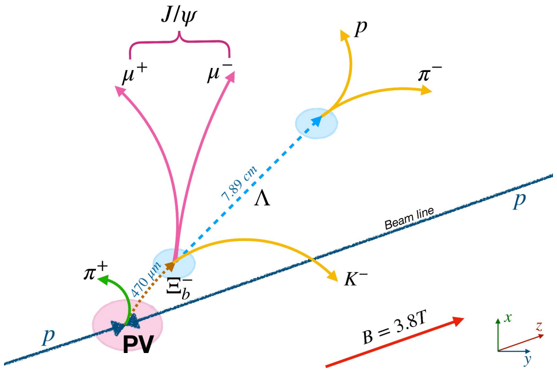
		BW_1	BW_2	BW_3
No-interference	m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
	N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}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

Two new structures, tentatively named **X(6600) and X(7300)**, are found, and the **X(6900)** structure observed by LHCb is confirmed. The local significances of these peaks are, for increasing mass, **6.5, 9.4, and 4.1 standard deviations**. Adding interference terms between the three signals results in better agreement to the data in the regions between the resonances and results in shifts of the resonance parameters.

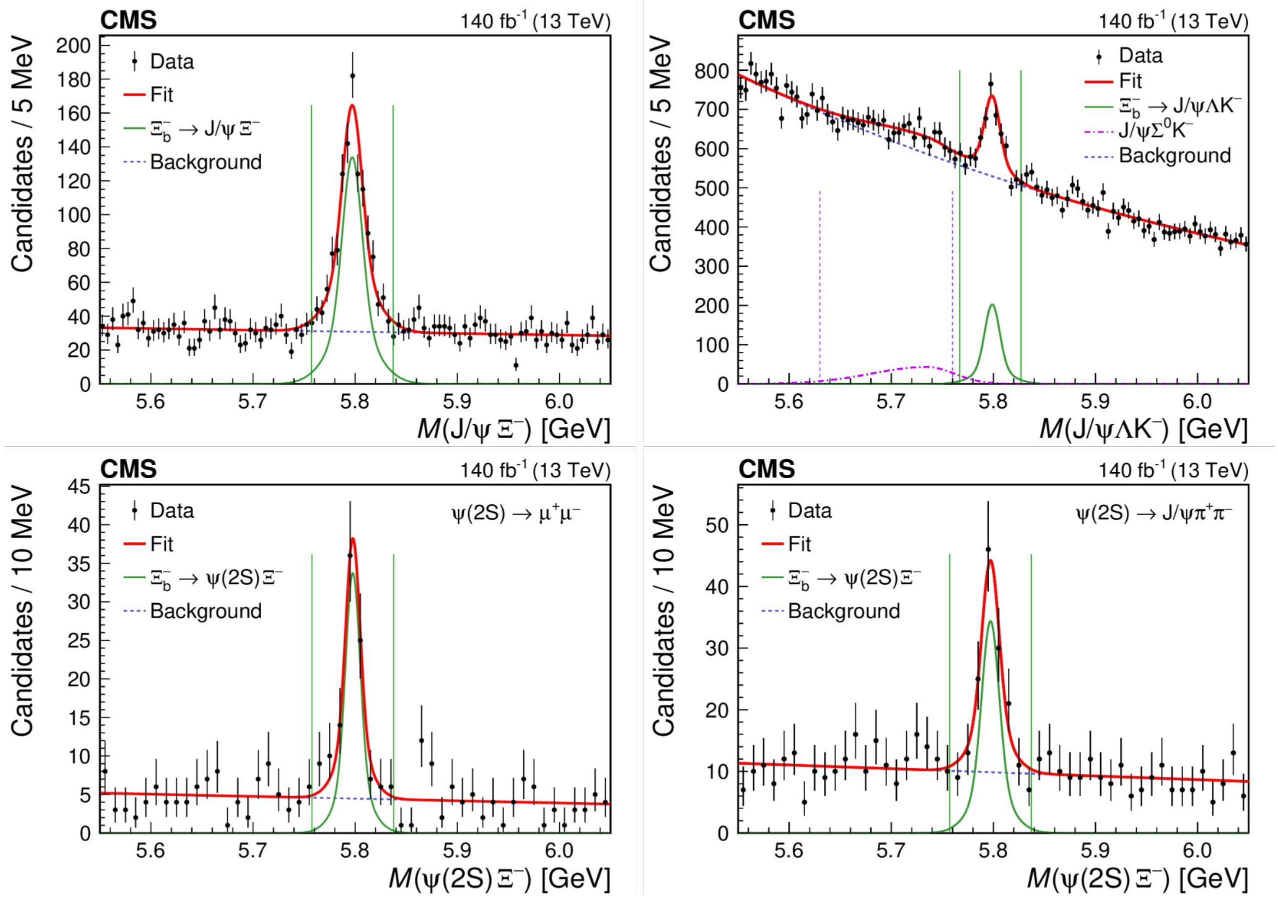
arXiv:2402.17738,
CMS-BPH-23-002 ;
Phys. Rev. D 110 (2024) 012002

Observation of the $\Xi^-_b \to \psi(2S)\Xi^-$ decay and studies of the Ξ^{*0}_b baryon in proton-proton collisions at 13 TeV





Ξ^-_b invariant mass distributions



The ground states were discovered more than a decade ago at the Fermilab Tevatron through decay to **$J/\psi\Xi^-$**

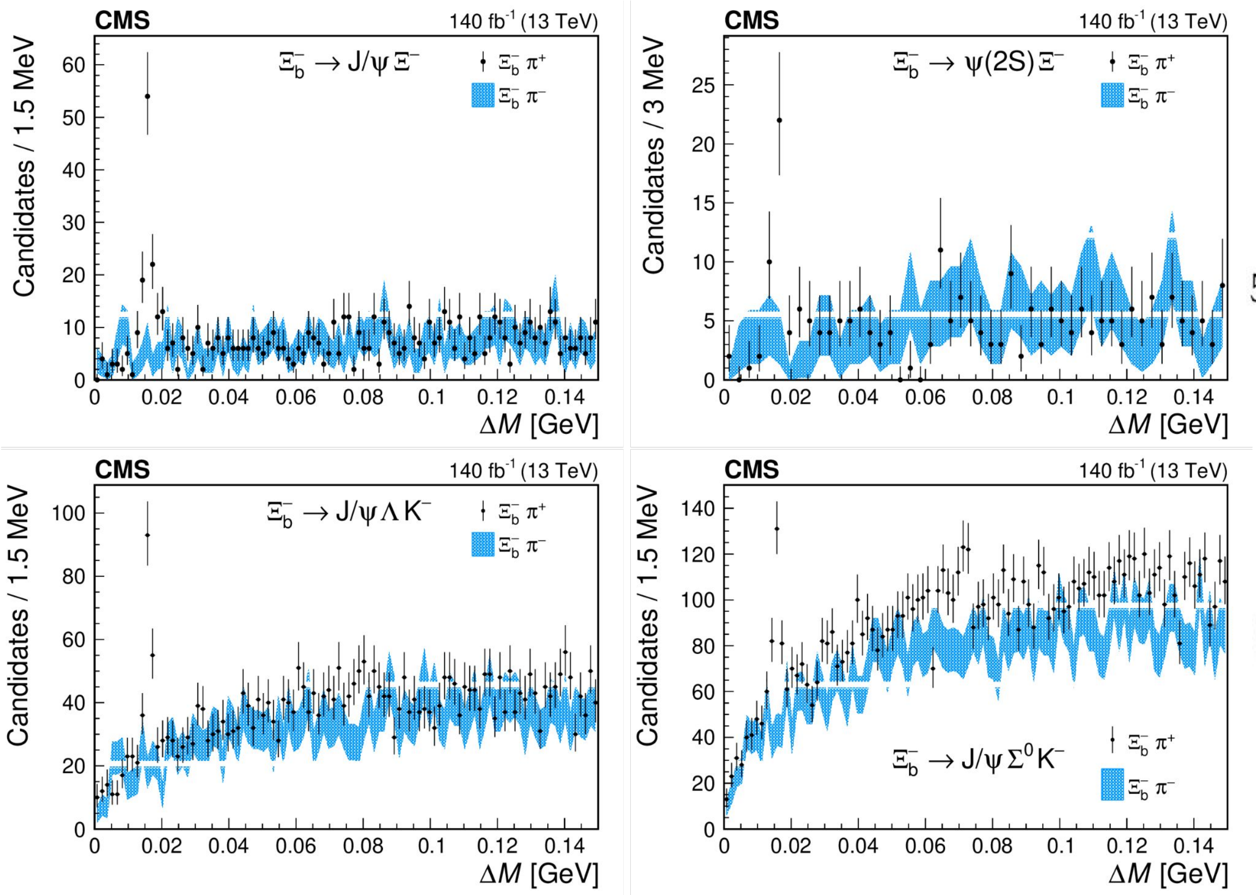
Observation of the

$\Xi^-_b \to \psi(2S)\Xi^-$

$$\frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)}$$

$$0.84^{+0.21}_{-0.19}\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.02\,(\mathcal{B})$$

$\Xi_b(5945)^0 \to \Xi^-_b \pi^+$ invariant mass distributions



$$M(\Xi_b(5945)^0) =$$

$$5952.4 \pm 0.1\,(\text{stat+syst}) \pm 0.6(m_{\Xi_b^-})$$

$$\Gamma(\Xi_b(5945)^0) =$$

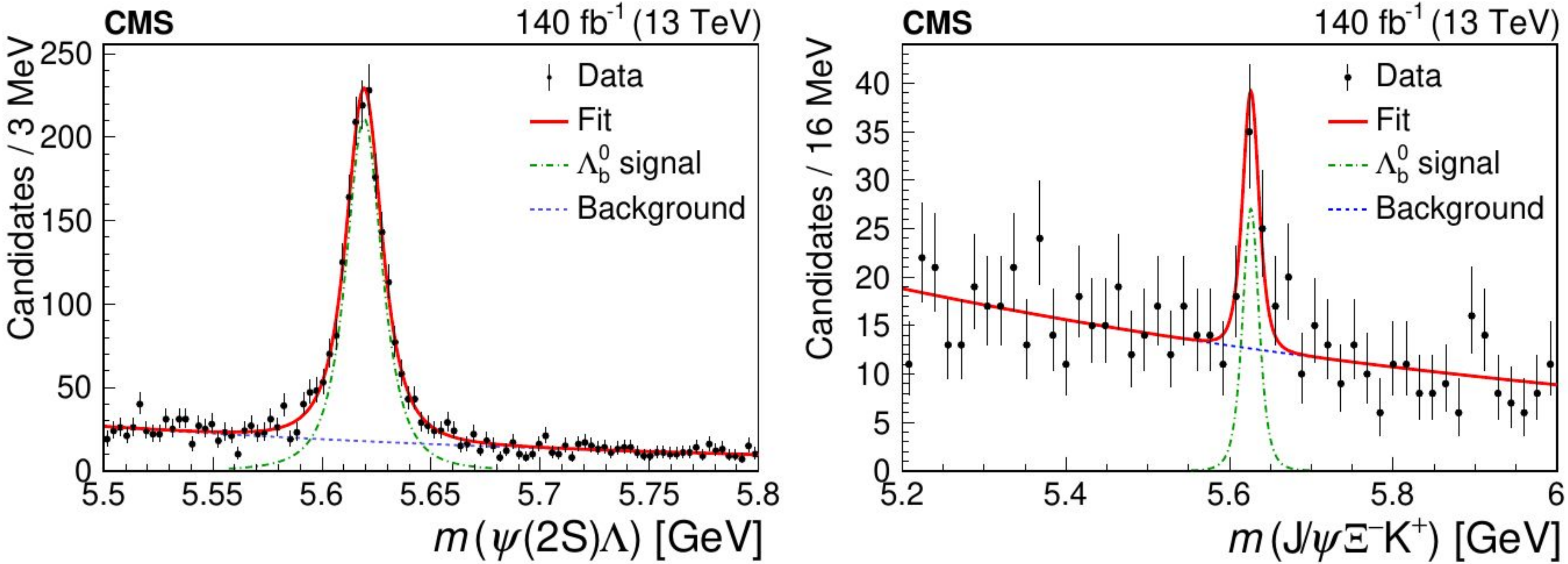
$$0.87^{+0.22}_{-0.20}\,(\text{stat}) \pm 0.16\,(\text{syst})$$

arXiv:2401.16303v1,
CMS-BPH-22-002 ; CERN-EP-2024-006
Eur. Phys. J. C 84 (2024) 1062

Observation of the $\Lambda^0_b \to J/\psi \Xi^- K^+$ decay

Up to now, the hidden-charm pentaquark candidates have been reported only in $J/\psi p$ and $J/\psi \Lambda$ systems. Investigation of other channels with heavier baryons in the decay products, such as Ξ^- and Ω^-, could unveil the existence of doubly or triply strange pentaquarks.

Measured $\psi(2S)\Lambda$ and $J/\psi\Xi^-K^+$ invariant mass distributions

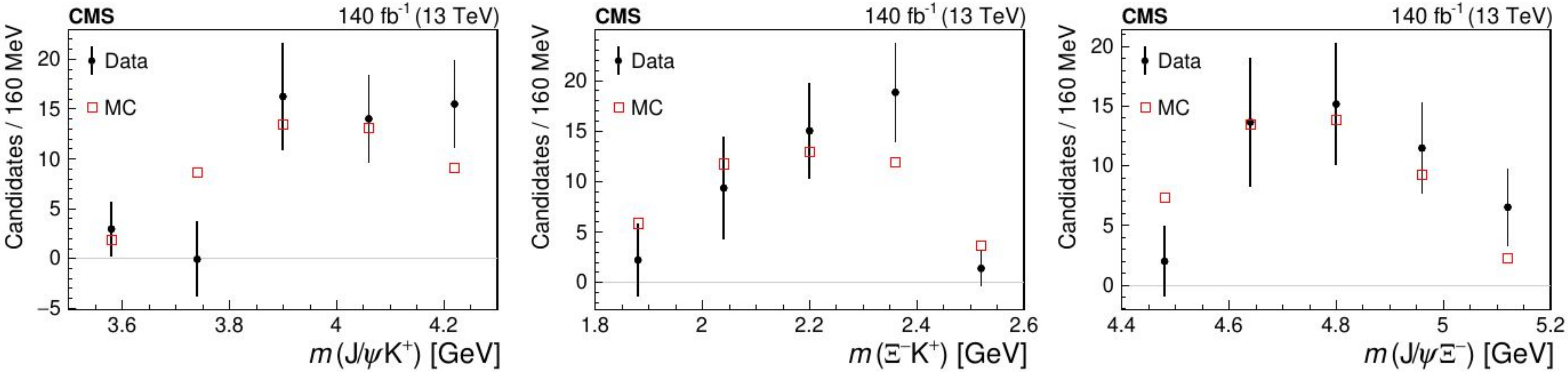


$$N(\Lambda_b^0 \to \psi(2S)\Lambda) = 1744 \pm 63$$

$$N(\Lambda_b^0 \to J/\psi\Xi^-K^+) = 46 \pm 11$$

Signal significance is found to be 5.8 standard deviations

Intermediate invariant mass distributions of the $\Lambda^0_b \to J/\psi \Xi^- K^+$



The filled circles and empty squares show the measured background-subtracted distributions and the results from the simulation with a phase-space model, respectively.

Branching fraction ratio measurement

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{N(\Lambda_b^0 \to \psi(2S)\Lambda)} \frac{\epsilon_{\psi(2S)\Lambda}}{\epsilon_{J/\psi \Xi^- K^+}} \frac{\mathcal{B}(\psi(2S) \to J/\psi \pi^+ \pi^-)}{\mathcal{B}(\Xi^- \to \Lambda \pi^-)}$$

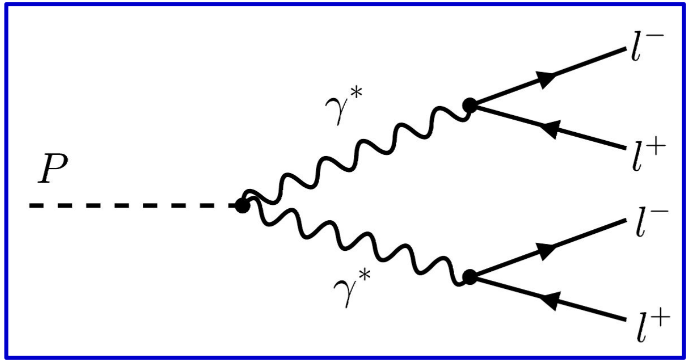
$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = [3.38 \pm 1.02\,(\text{stat}) \pm 0.61\,(\text{syst}) \pm 0.03\,(\mathcal{B})]\%$$

In summary

- The $\Lambda^0_b \to J/\psi \Xi^- K^+$ decay is observed with a significance exceeding 5 standard deviations.
- The distributions of intermediate invariant masses are also presented.
- This is the first discovered multibody decay containing the $J/\psi \Xi^-$ system.

arXiv:2305.04904,
CMS-BPH-22-003 ; CERN-EP-2023-071
Phys. Rev. Lett. 131, 091903

Observation of the rare decay of the η meson to four muons



Observing these rare decays is important because :

- They can serve as precision tests of the standard model.
- **They offer sensitivity to different new physics scenarios.**
- **The interaction between pseudoscalars and photons contributes to the hadronic light-by-light component of the anomalous magnetic moment of the muon.**

“Data scouting”

Standard dimuon triggers:

➔ The HLT processes events at an output rate of about **1 kHz with approximately 1 MB.**

➔ pT Tthresholds
  - $pT(\mu_1)>15$ GeV, $pT(\mu_2)>7$GeV [2018]
  - $pT(\mu_1)>12$GeV, $pT(\mu_2)>5$GeV [2017]

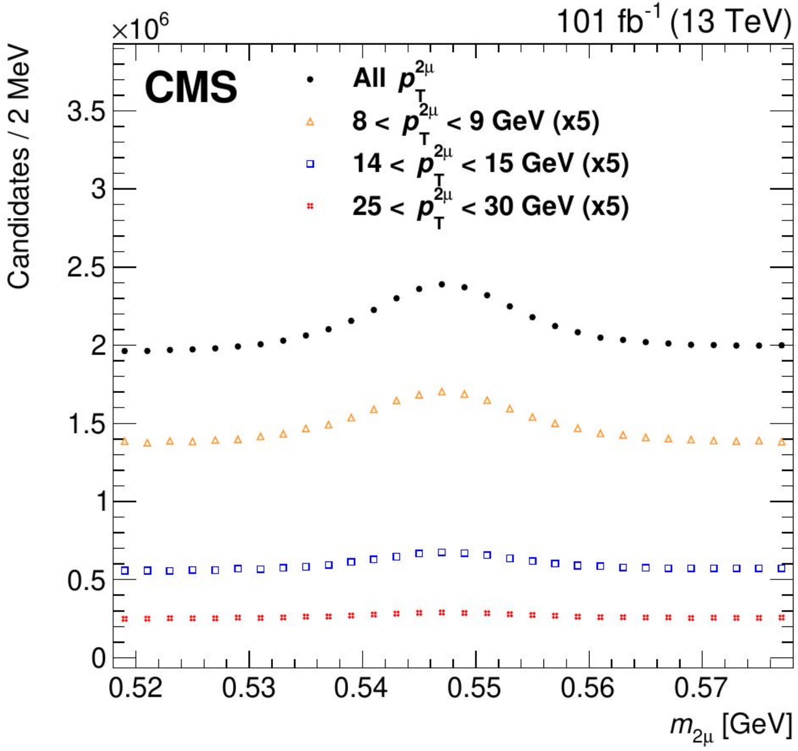
➔ **For dimuon resonance masses below about 40 GeV, the performance of the standard muon triggers deteriorates**

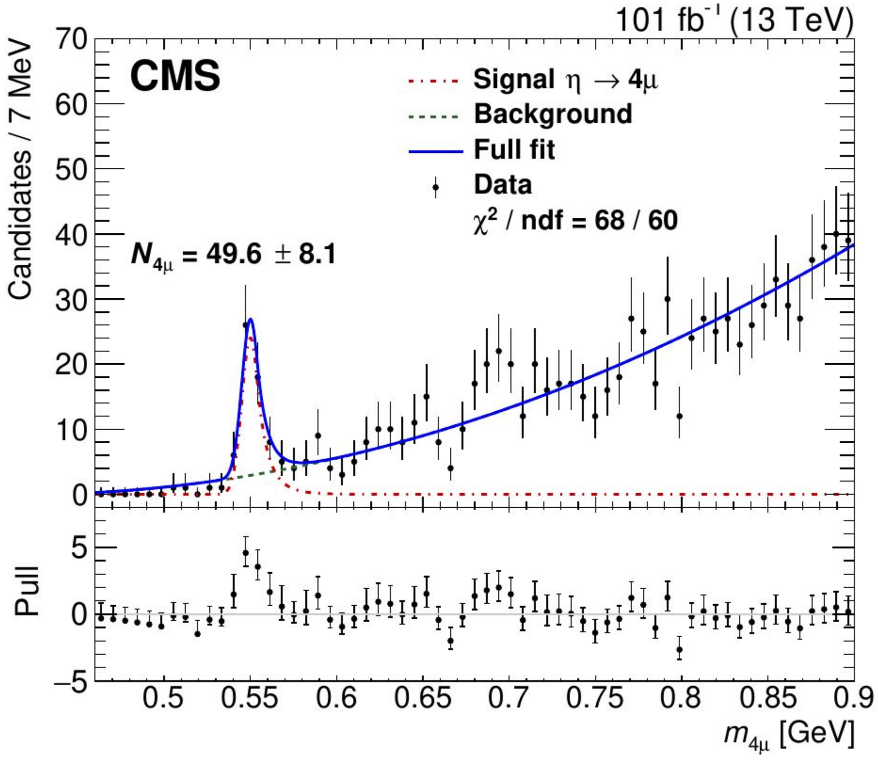
Dedicated set of high-rate dimuon triggers:

- Considerably lower muon pT threshold (see table)
- **But, store only a limited amount of information per event**
  - **only muons reconstructed at the HLT**
  - **limited event-level information**
- Event size of around 4 kB in 2017 and 8 kB in 2018

L1 path	p_T [GeV]	$\|\eta\|$	ΔR	$m_{2\mu}$ [GeV]	Charge	Fraction
#1	>4.0 (4.5)	—	<1.2	—	OS	90%
#2	—	< 1.5	< 1.4	—	OS	48%
#3	>15, >7	—	—	—	—	46%
#4	>4.5	< 2.0	—	7–18	OS	9%

Invariant mass spectrum





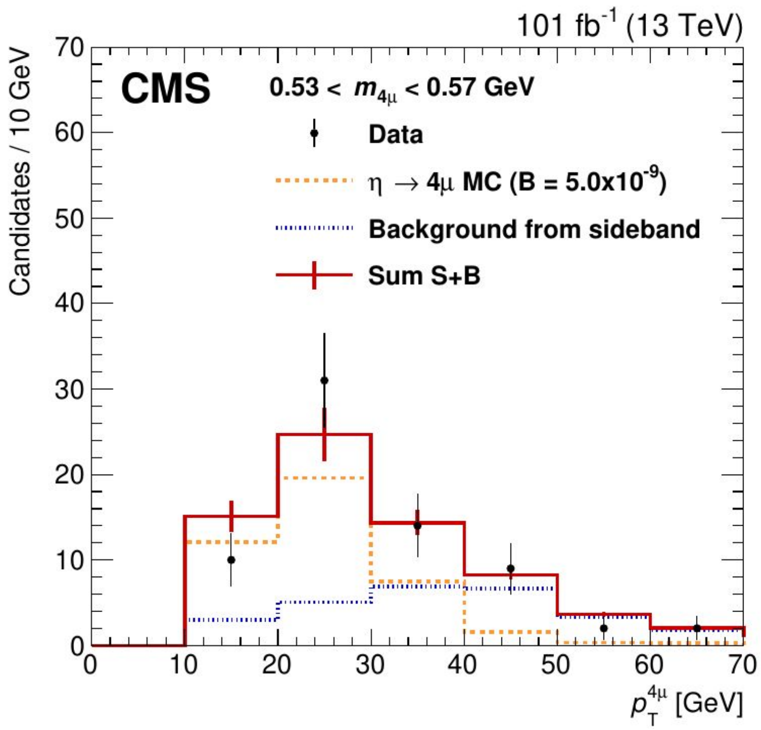
4.5 million η → 2μ decays

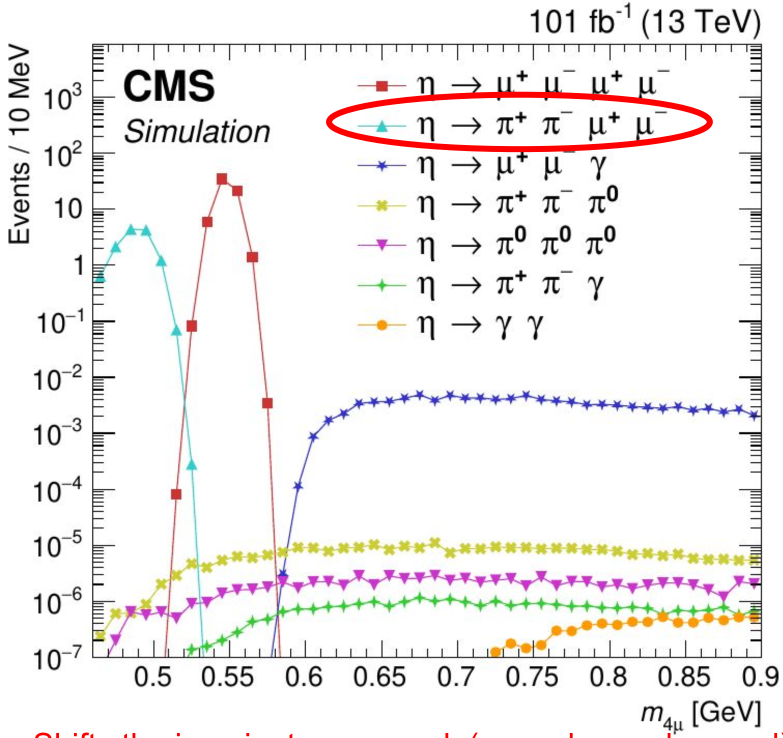
number of events in the selected pT ranges multiplied by five for better visibility.

Signal = 49.6 ± 8.1, background 16.6 ± 0.6

Significance in excess of 5 standard deviations

Checks: pT spectrum and background contributions



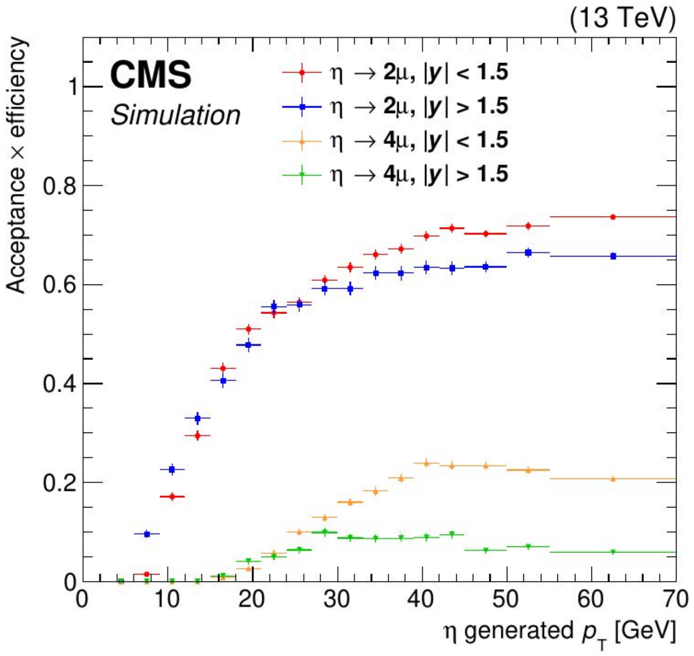


Shifts the invariant mass peak (never been observed).

The signal pT$^{4\mu}$ distribution reweighted based pT differential production rate measured with the two-muon channel.

Other decay modes of the η meson provide a negligible contribution.

The branching fraction



The total efficiencies for the four-muon (red and blue points) and two-muon (orange and green points), evaluated through MC simulation

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$

32 bins in pT in the range 7–70 GeV and two bins in |y|

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = [0.86 \pm 0.14(\text{stat}) \pm 0.12(\text{syst})] \times 10^{-3}$$

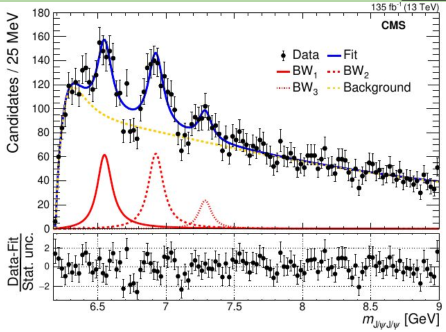
$$\mathcal{B}(\eta \to 4\mu) = [5.0 \pm 0.8(\text{stat}) \pm 0.7(\text{syst}) \pm 0.7(\mathcal{B}_{2\mu})] \times 10^{-9}$$

In summary,

- **The first observation of the η meson's raredouble-Dalitz decay to four muons is reported.**
- This result is in agreement with theoretical predictions.
- With high-rate triggers in future will enable a detailed study of doubly virtual pseudoscalar transition form factors (TFF's)

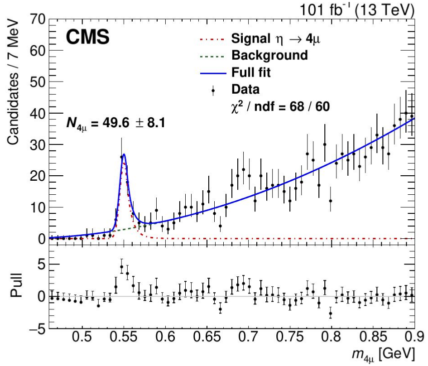
Observation of new structure in the J/ψJ/ψ mass spectrum

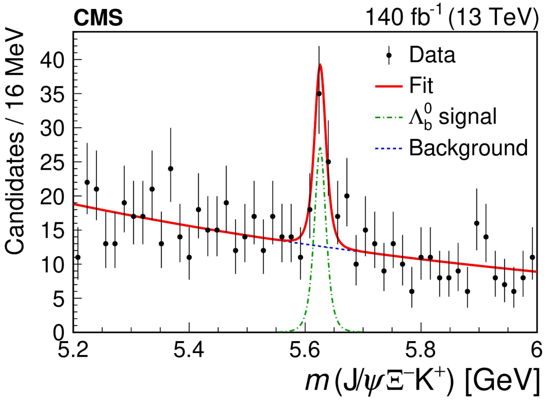
Two new structures, tentatively named **X(6600) and X(7300)**, are found, and the **X(6900)** structure observed by LHCb is confirmed

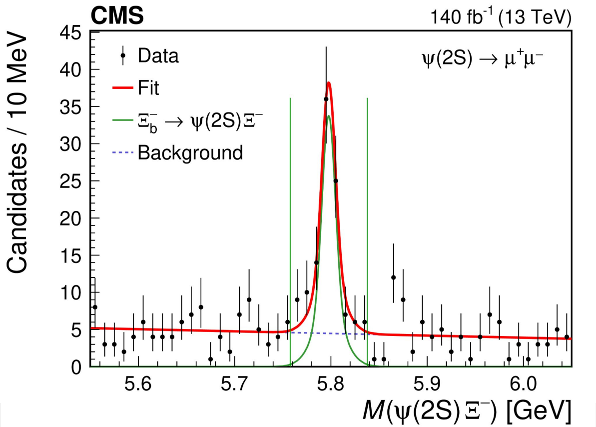


Observation of the rare decay of the η meson to four muons

With high-rate triggers in future will enable a detailed study of doubly virtual pseudoscalar transition form factors (TFF's)





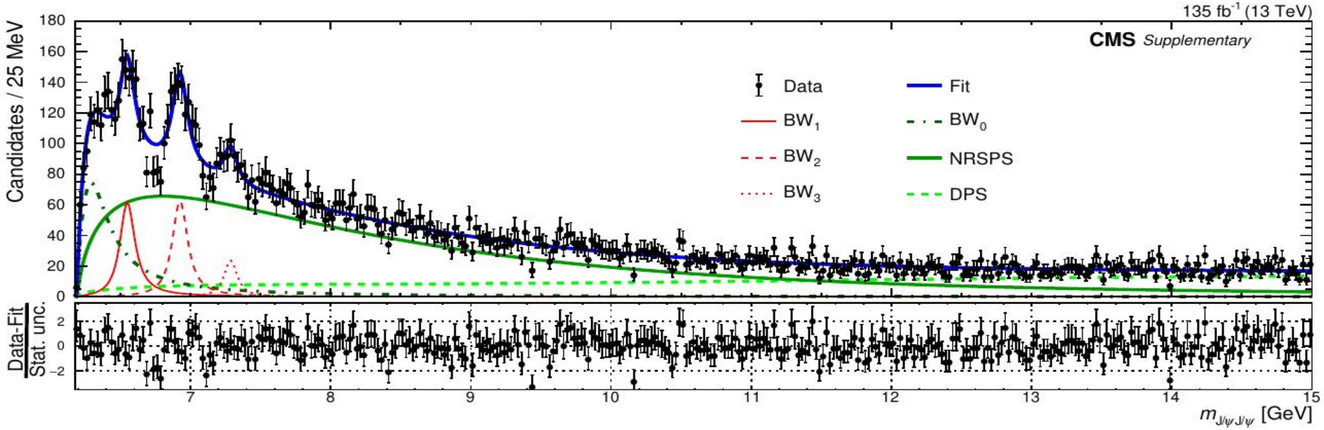


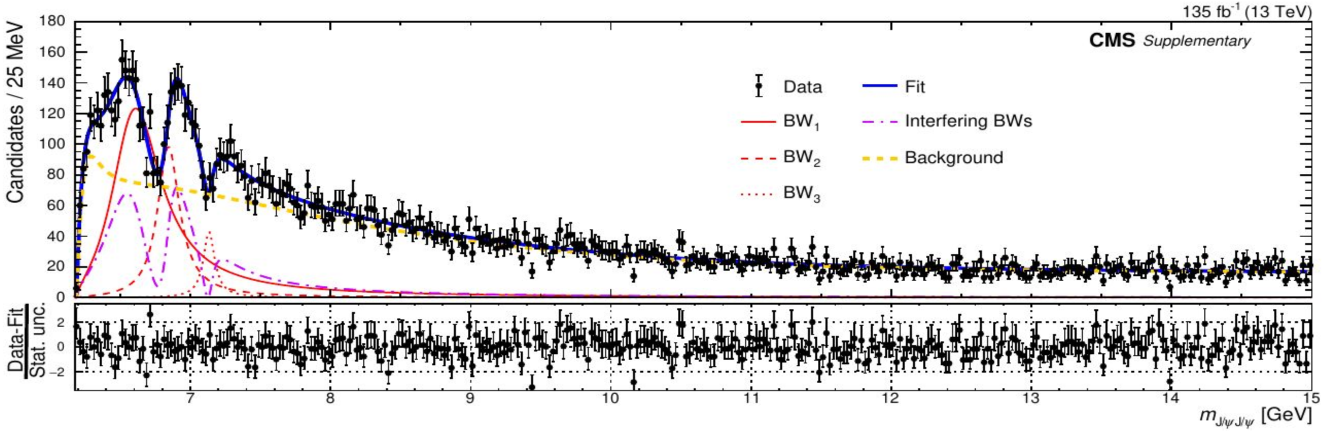
The new results are important for understanding the strong interaction processes in hadronic decays.

THANKS for listening!

Backup slides

The J/ψJ/ψ invariant mass spectrum in the range up to 15 GeV



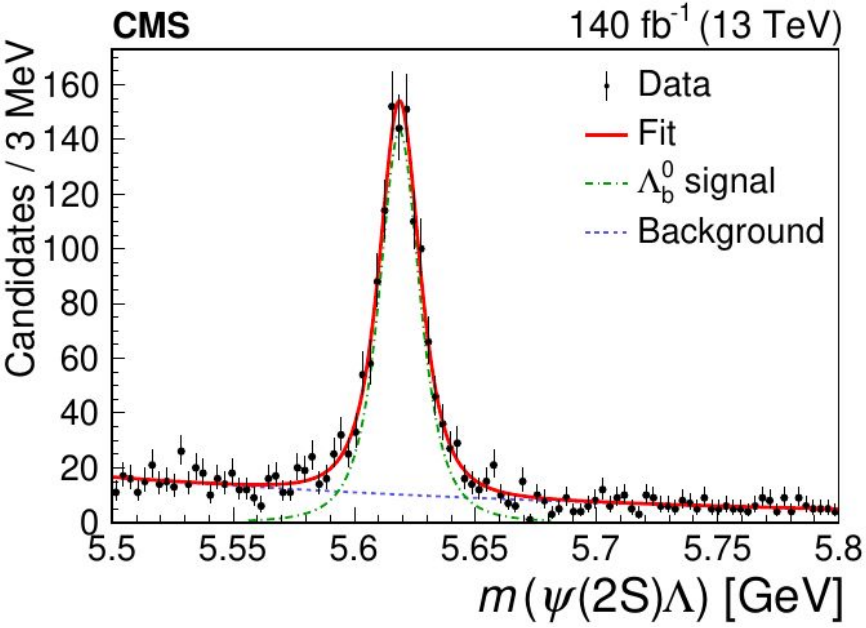


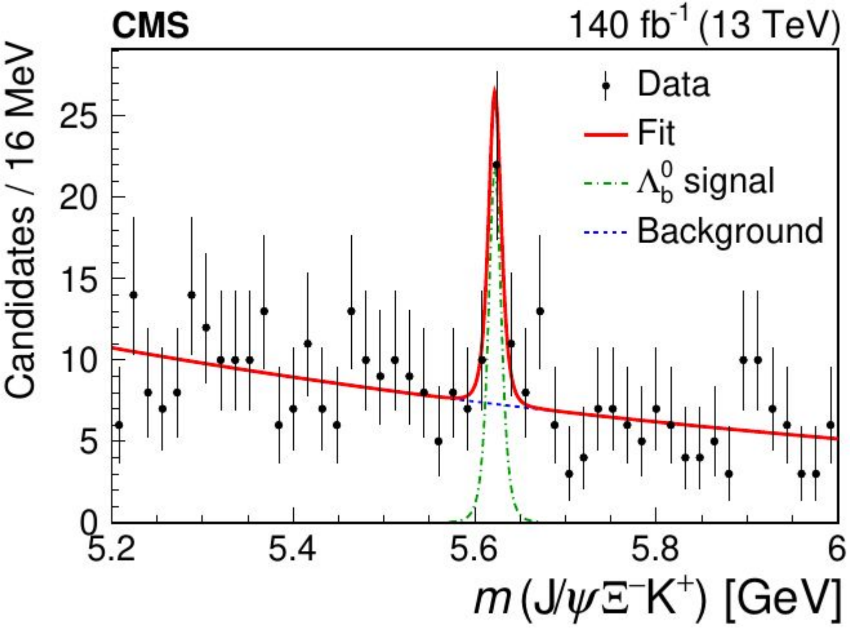
The J/ψJ/ψ invariant mass spectrum with the no-interference fit (upper) and the interference fit (lower) in the full fit range. The ``Interference BWs'' curve is the total contribution of all the interference amplitudes and their cross terms. The lower portion of the plots shows the pulls, i.e.,, the number of standard deviations (statistical uncertainties only) that the binned data differ from the fit.

Optimized selection criteria for the signal decay mode $\Lambda^0_b \rightarrow J/\psi \Xi^- K^+$

Variable	Selection
$\lvert m(\mathrm{p}\pi^-) - m_{\mathrm{PDG}}(\Lambda) \rvert$	$<8\,\mathrm{MeV}$
$\lvert m(\Lambda\pi^-) - m_{\mathrm{PDG}}(\Xi^-) \rvert$	$<6\,\mathrm{MeV}$
$p_{\mathrm{T}}(\Lambda^0_{\mathrm{b}})$	$>11.5\,\mathrm{GeV}$
$p_{\mathrm{T}}(\mathrm{J}/\psi)$	$>6.5\,\mathrm{GeV}$
$p_{\mathrm{T}}(\Xi^-)$	$>2.6\,\mathrm{GeV}$
$p_{\mathrm{T}}(\Lambda)$	$>2.2\,\mathrm{GeV}$
$p_{\mathrm{T}}(\mathrm{K}^+)$	$>1.2\,\mathrm{GeV}$
$\mu^+\mu^-\Xi^-\mathrm{K}^+$ vertex fit probability	$>5\%$
$\Lambda\pi^-$ vertex fit probability	$>5\%$
$\mathrm{p}\pi^-$ vertex fit probability	$>1\%$
Ξ^- vertex displacement from Λ^0_{b} vertex	>3 s.d.
Λ vertex displacement from Ξ^- vertex	>0 s.d.
Λ^0_{b} vertex displacement from PV	>3 s.d.
Angle between Ξ^- momentum and displacement	<0.0447 rad
Angle between Λ momentum and displacement	<0.14 rad
Angle between Λ^0_{b} momentum and displacement	<0.0447 rad
PV impact parameter for pion from Ξ^- decay	>0.4 s.d.
PV impact parameter for kaon	>0.4 s.d.

Measured ψ(2S)Λ and J/ψΞ⁻K⁺ invariant mass distributions





Corresponding fits used for the measurement of R.

The relative systematic uncertainties in the measurement of R.

Source	Uncertainty (%)
Tracking efficiency	2.3
$p_{\mathrm{T}}(\Lambda_{\mathrm{b}}^{0})$ spectrum	4.7
Signal model	3.9
Background model	6.7
Non-$\psi(2S)$ contribution	2.5
Limited size of MC samples	5.6
Selection efficiency	14.3
Total	18.2