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International Workshop on QCD Theory and Experiment

Recent results in hadron spectroscopy from CMS

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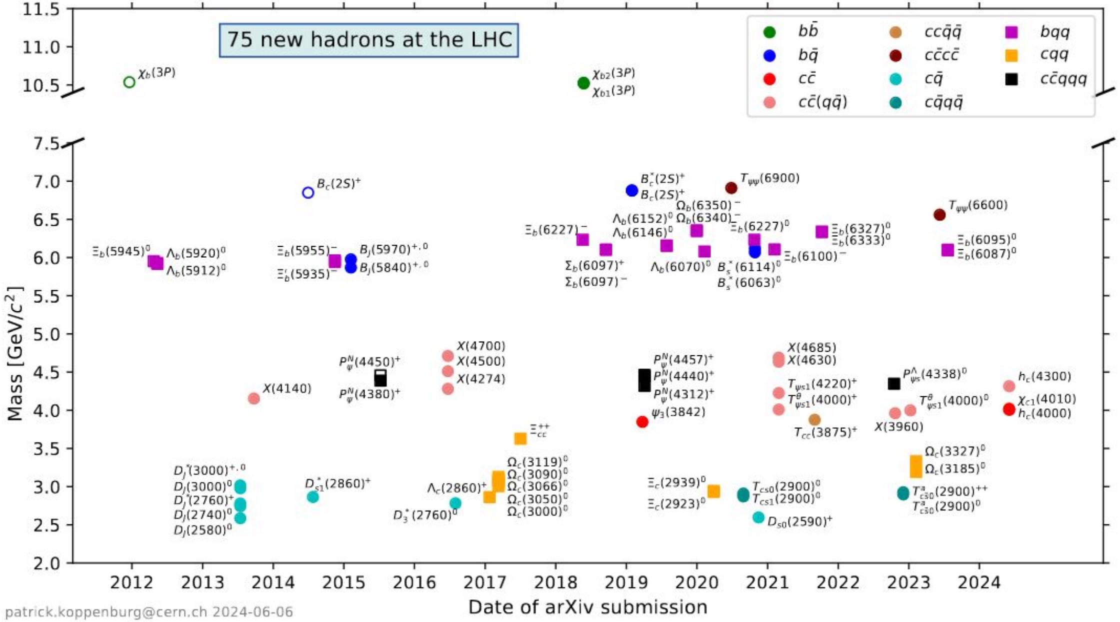
Heavy Flavour Physics at the LHC

LHC provides high luminosity for heavy flavour physics processes

Heavy flavor production cross section several order of magnitudes greater than at e-e colliders,

but the hadron collisions environment is characterized by **complex initial state and high background**

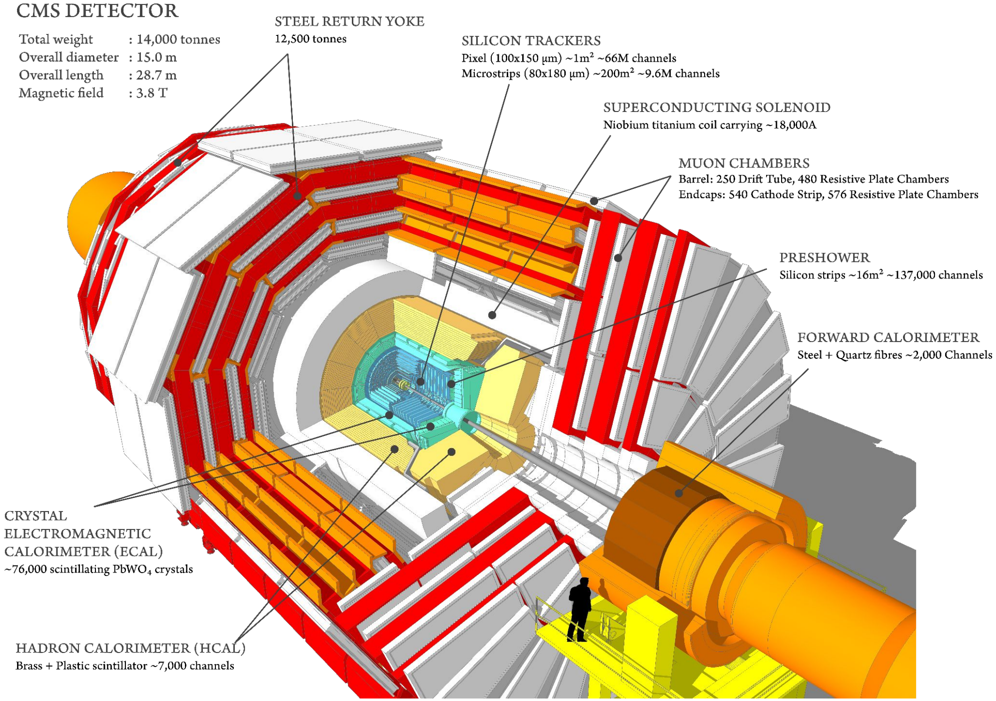


75 new hadrons discovered at LHC since its start!
23 new exotics hadrons

[LHCb-FIGURE-2021-001, 2024 updated]

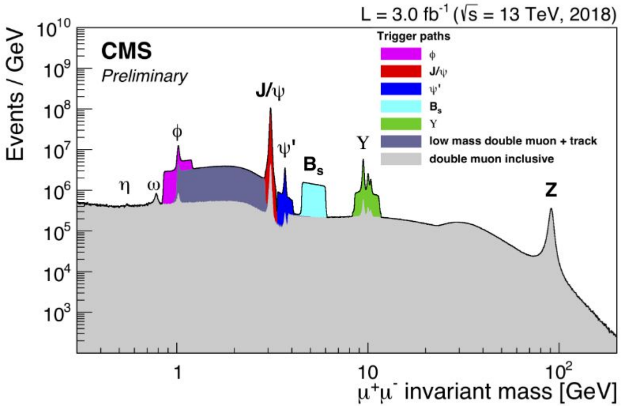
The CMS detector at the Large Hadron Collider

General purpose detector with **cylindrical symmetry** and (almost) **full coverage of the solid angle**



Strengths:

- muon reconstruction and identification
- large muons' acceptance
- high-performance tracking & vertexing



Selected recent results from CMS

- **New structures in the J/ψJ/ψ mass spectrum in pp collisions at $\sqrt{s}$ = 13 TeV** [PRL 132 (2024) 111901]
  - Observation of two structures near the di-J/ψ kinematical threshold, one of which compatible with the resonance X(6900) reported by LHCb [Sci. Bull. 65 (2020) 23] and confirmed by ATLAS [PRL 131 (2023) 151902], and evidence of a third (new) structure
- **Observation of $\Xi_b^- \to \psi(2S)\Xi^-$ and studies of Ξ_b^{*0}** [arXiv, submitted to PRD]
  - First observation of the $\Xi_b^- \to \psi(2S)\Xi^-$ decay and measurement of its branching fraction with respect to $\Xi_b^- \to J/\psi\Xi^-$, together with measurement of the properties of Ξ_b^{*0}
- **Observation of $\Lambda_b^0 \to J/\psi\Xi^-K^+$** [arXiv, submitted to EPJC]
  - Observation of a new Λ_b^0 decay and measurement of its branching fraction wrt $\Lambda_b^0 \to \psi(2S)\Lambda$

Di-charmonium spectrum at LHCb

Sci. Bull. 65 (2020) 23

$J/\psi J/\psi$ (→ 4μ) spectrum studied at LHCb using 9 fb^{-1} of pp collisions at $\sqrt{s}$ = 7, 8, 13 TeV

Background contribution for J/ψ-pair production:

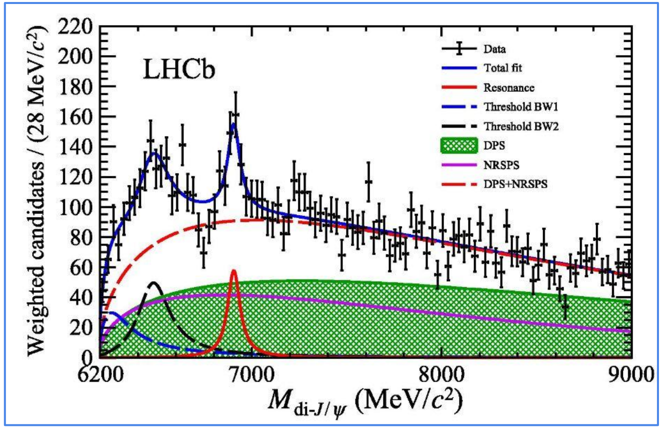
- NRSPS (Non-Resonant Single Parton Scattering)
- DPS (Double Parton Scattering)

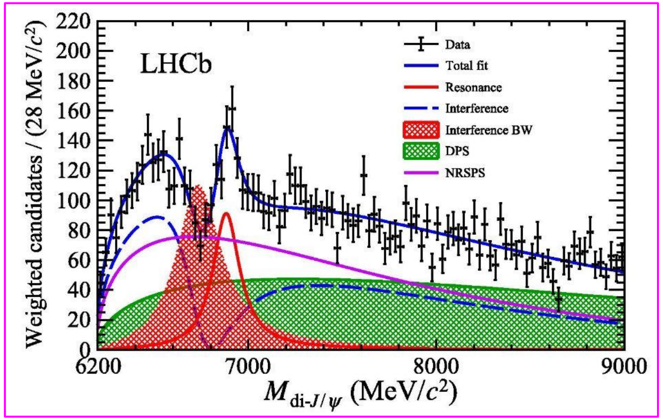
Two different signal models are considered:

I. **(top)** poor description of the "dip" at 6.7 GeV
   A. background DPS + NRSPS
   B. relativistic Breit-Wigner for X(6900)
   C. two auxiliary BWs near kinematic threshold

II. **(bottom)**
   A. background DPS + NRSPS
   B. relativistic Breit-Wigner for X(6900)
   C. a BW (X(6700)) to interfere with NRSPS

A broad structure near the di-J/ψ mass threshold and **a narrow resonance, X(6900), renamed $T_{\psi\psi}$(6900) reported**





Di-charmonium spectrum at ATLAS

PRL 131 (2023) 151902

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 140 fb^{-1} of pp collisions at √s = 13 TeV

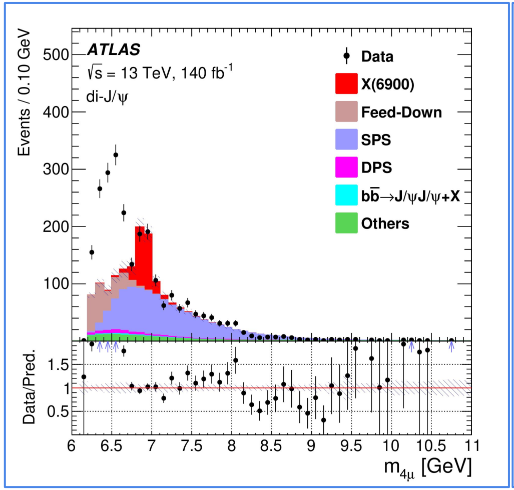
Prompt (SPS, DPS) and non-prompt ($b\bar{b} \to J/\psi J/\psi + X$) background contributions are considered

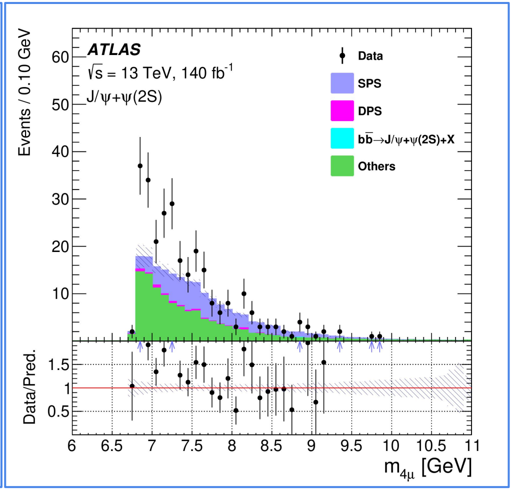
Feed-down included only for di-J/ψ channel

4μ mass data vs background predictions before fit for J/ψJ/ψ and J/ψ+ψ(2S)

Signal model: interfering BWs ⊗ Gaussian resolution (introduced gradually to improve the fit)

- di-J/ψ signal:
  - A) 3 interfering scalar BWs
  - B) 2 interfering scalar BWs, the first interferes also with SPS
- J/ψ+ψ(2S) signal:
  - α) 3 interfering BWs from A (fixed) + stand-alone 4th resonance
  - β) single resonance





Di-charmonium spectrum at ATLAS

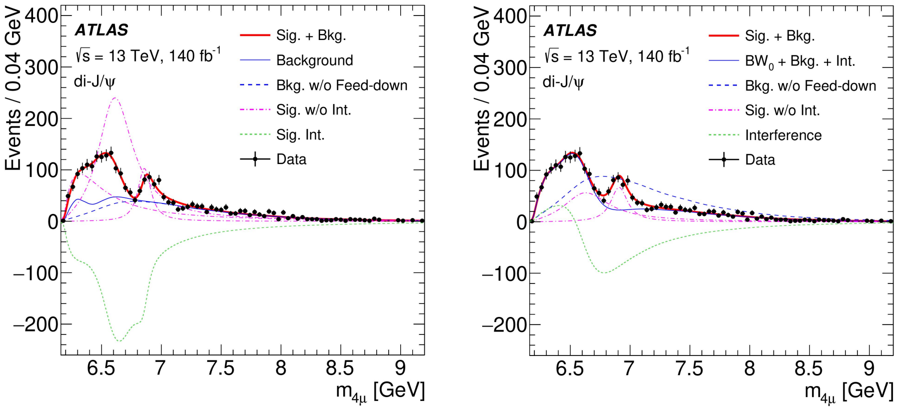
PRL 131 (2023) 151902

di-J/ψ: models A and B describe the spectrum better than models with fewer/no interference.

Significance for all resonances and for X(6900) alone greater than 5σ

The broad structure at low mass could result from other physical effects (e.g. feed-down from higher di-charmonium resonances)

fitted mass in SR, Model A (left) and Model B (right)

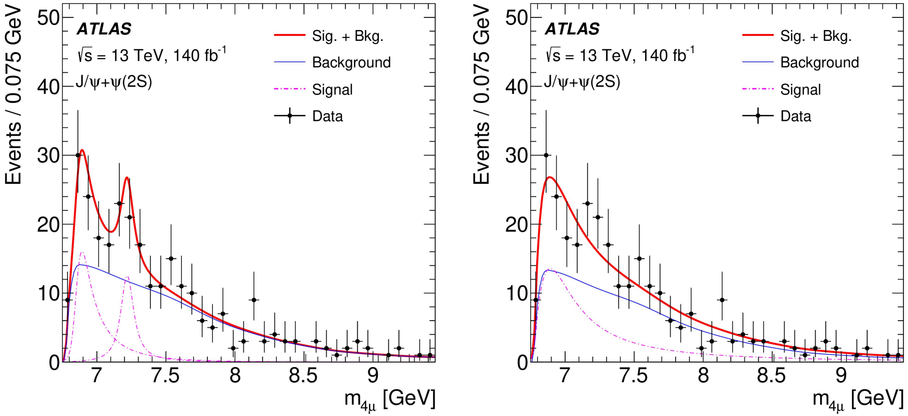


J/ψ+ψ(2S): significance for all resonances with model α (β) is 4.7σ (4.3σ)

Structure at 7.2 GeV alone in model α: 3.0σ

More statistics will help to better understand the structures in both channels

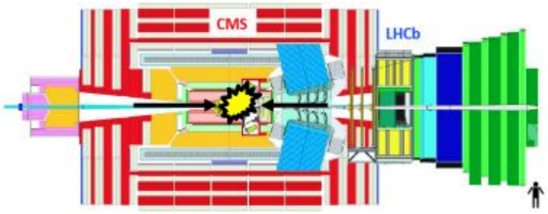
fitted mass in SR, Model α (left) and Model β (right)



Di-charmonium at CMS: background description

PRL 132 (2024) 111901

$J/\psi J/\psi$ ($\rightarrow 4\mu$) studied at CMS using 135 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV (2016-2018)

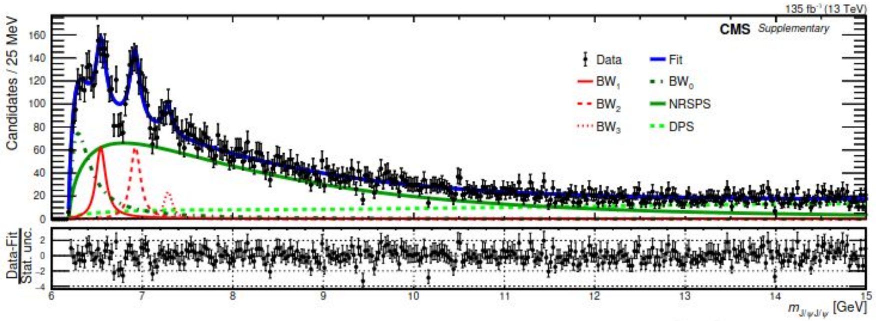


Different background modelling (different acceptance):

- **NRSPS** and **DPS**: parameterizations from MC
- **BW_0** near $J/\psi J/\psi$ threshold takes into account for
  - inadequacy of NRSPS near threshold
  - feed-down of partially reconstructed higher mass states
  - possible coupled-channel interactions, pomeron-exchange processes, etc.
  - near-threshold enhancement is commonly observed in mass spectra of vector states with same isospin (e.g. observed in $J/\psi\phi$ [LHCb PRL 127 (2021) 082001], $J/\psi\omega$ [BaBar PRD 82 (2010) 011101])
- **Signal model**: three BWs with Gaussian resolution from MC (ranging from 10 MeV @ 6.5 GeV to 18 MeV @ 7.3 GeV)

Fit on full spectrum up to 15 GeV to verify the adequacy of the background model: $P(\chi^2)$ = 98%

Fit fractions: 58% NRSPS, 25% DPS, 9% BW_0



Di-charmonium at CMS: non-interfering resonances

PRL 132 (2024) 111901

Fit features are added by checking sequentially their local statistical significance (> 3σ required)

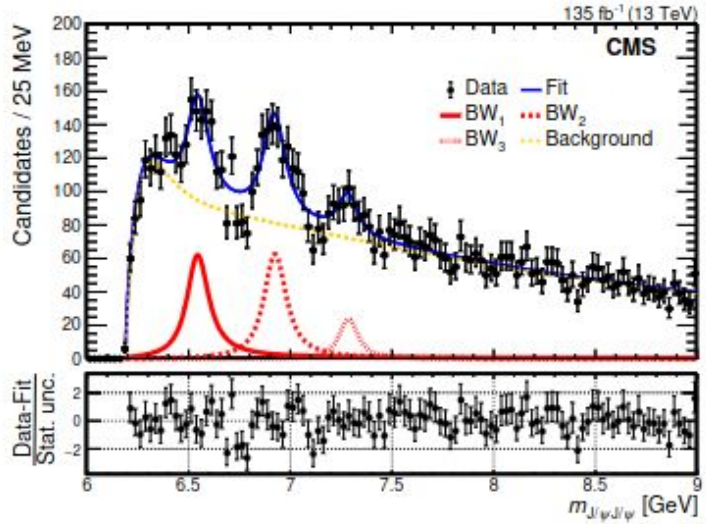
signal model: **3 non-interfering scalar Relativistic BW**

Two structures around 6.6 GeV (new) and 6.9 GeV (compatible with the LHCb observation) are observed. Evidence for a third structure around 7.3 GeV also reported.

Poor description of dips at 6750 MeV and 7150 MeV and overall poor fit $P(\chi^2)$ = 9% in the signal region

The description is improved by including interference between the three BW states (see next slide)

NRSPS interfering with BWs is considered less probable as it is a mixture of J^{PC} states



	Mass (MeV)	Width (MeV)	Local stat. signif.
BW_1	6552 ± 10 ± 12	$124\,^{+32}_{-26}$ ± 33	6.5σ
BW_2	6927 ± 9 ± 4	$122\,^{+24}_{-21}$ ± 18	9.4σ
BW_3	$7287\,^{+20}_{-18}$ ± 5	$95\,^{+59}_{-40}$ ± 19	4.1σ

first error is statistic, second is systematic

X(6900) confirmed at CMS. Values consistent with LHCb.

Di-charmonium at CMS: interfering resonances

PRL 132 (2024) 111901

Signal model with interference: improved fit $P(\chi^2) = 65\%$

"three-way" interference term (three $J^P = 0^+$ resonances)

$$|r_1 exp(i\phi_1)BW_1 + r_2 BW_2 + r_3 exp(i\phi_3)BW_3|^2$$

Local statistical significance improved for each signal (least significant: BW_3 4.7σ)

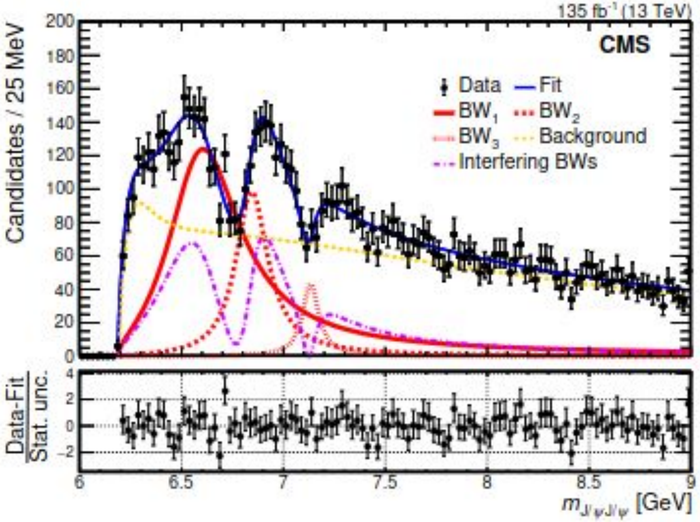
Global significance for BW_3 with MC pseudo-experiments: 3.4σ

Better fit w.r.t. any "two-way" interference option ($P(\chi^2) < 30\%$)

Improved descriptions of the dips

Two structures (X(6600) and X(7100)) **appear with X(6900)**

X(6900) is compatible with the LHCb observation within 2σ



	Mass (MeV)	Width (MeV)
BW_1	$6638^{+43}_{-38}{}^{+16}_{-31}$	$440^{+230}_{-200}{}^{+110}_{-240}$
BW_2	$6847^{+44}_{-28}{}^{+48}_{-20}$	$191^{+66}_{-49}{}^{+25}_{-17}$
BW_3	$7134^{+48}_{-25}{}^{+41}_{-15}$	$97^{+40}_{-29}{}^{+29}_{-26}$

first error is statistic, second is systematic error

Di-charmonium at CMS: fit with LHCb model

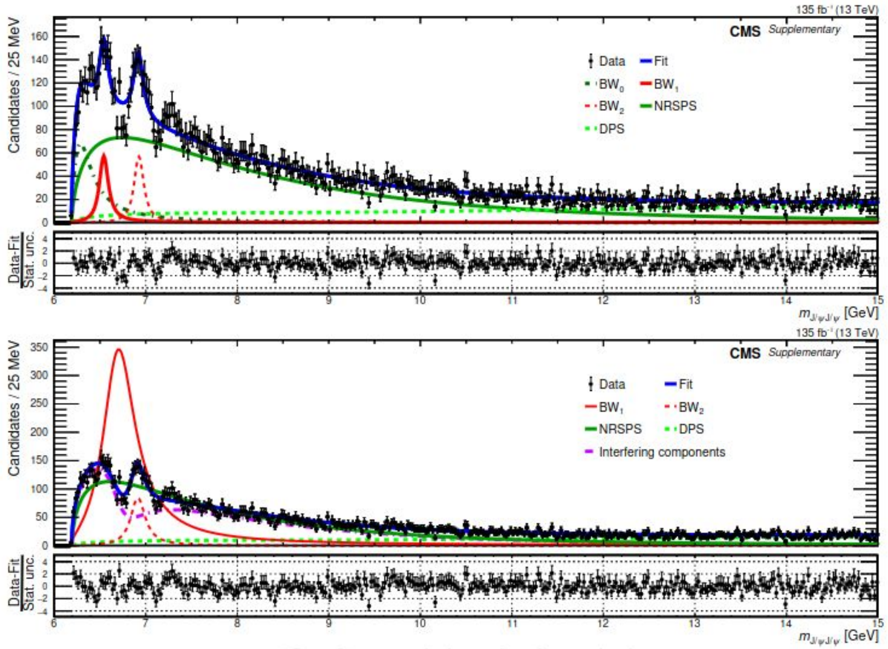
PRL 132 (2024) 111901

The LHCb signal models are also tested: similar results, but no improvement on the fit quality

LHCb signal models + CMS background

- **Model I (top):**
  [NRSPS + DPS + X(6900) +
  + 2BW below 6900]
  - X(6900) parameters in agreement
  - but dip at 6.7 not well described

- **Model II (bottom):**
  [NRSPS + DPS + X(6900) +
  + 1BW below 6900 interfering with NRSPS]
  - Larger X(6700) amplitude
  - X(7300) region not well described



Study of $\Xi_b^- \to \psi(2S)\Xi^-$ at CMS

arXiv:2402.17738

Ξ_b baryon family: isospin doublets composed of bsq triplets (Ξ_b (g.s.), Ξ_b', Ξ_b^*, according to j_{qs} and J^P)

First observation of $\Xi_b^- \to \psi(2S)\Xi^-$ (+ c.c.) at CMS using 140 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV (2016-2018).

Normalization channel: **$\Xi_b^- \to J/\psi\Xi^-$ decay** (well-known)

J/ψ / $\psi(2S) \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$

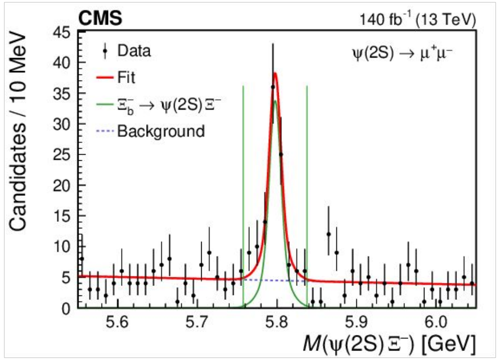
Signal yields extracted by means of UML fit:

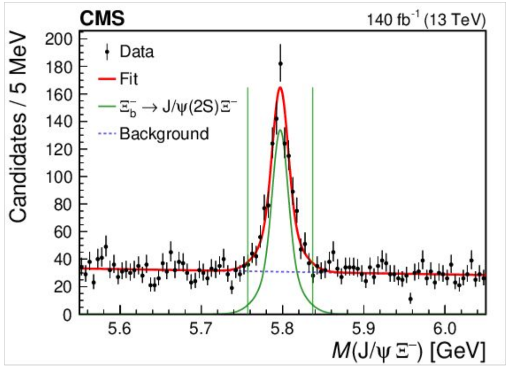
- signal: sum of two Gaussians with common mean
- background: 1st order polynomial

Yields corrected by total efficiency (acceptance, trigger, reconstruction) evaluated on MC

Branching fraction measurement obtained by

$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.84^{+0.21}_{-0.19}(stat) \pm 0.10(syst) \pm 0.02(\mathcal{B})$$





Study of $\Xi_b^- \to \psi(2S)\Xi^-$ at CMS

arXiv.2402.17738

Excited baryon Ξ_b^{*0} reconstructed in $\Xi_b^-\pi^+$ (p_T > 15 GeV, |y| < 2.4): structure not present in the same-sign $\Xi_b^-\pi^-$ control region [backup]

Improved precision on Ξ_b^{*0} mass and width wrt previous CMS measurement (5 fb^{-1}) and in agreement with LHCb results [JHEP 05 (2016) 161, PRL 131 (2023) 171901]

$$m(\Xi_b^{*0}) = 5952.4 \pm 0.1(stat+syst) \pm 0.6(m_{\Xi_b^-}) MeV$$

$$\Gamma(\Xi_b^{*0}) = 0.87^{+0.22}_{-0.20}(stat) \pm 0.16(syst) MeV$$

Ξ_b^{*0}/Ξ_b^- production rate in agreement with LHCb result:

$$R_{\Xi_b^{*0}} = \frac{\sigma(pp\to\Xi_b^{*0}X)\mathcal{B}(\Xi_b^{*0}\to\Xi_b^-\pi^+)}{\sigma(pp\to\Xi_b^- X)} = 0.23 \pm 0.04(stat) \pm 0.02(syst)$$

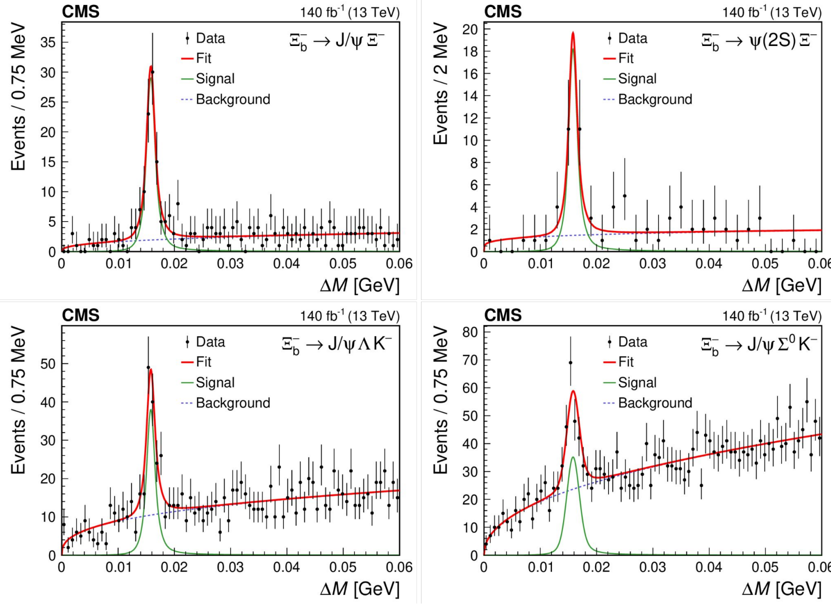
Ξ_b^{*-}/Ξ_b^- production rate from isospin considerations ≃ 1/9

→ Other excited states can be source of Ξ_b^-: prompt fraction in pp collisions expected to be less than 2/3

Ξ_b^- reconstructed (even partially) in many channels

- $\Xi_b^- \to \psi(2S)\Xi^-$
- $\Xi_b^- \to J/\psi\Xi^-$
- $\Xi_b^- \to J/\psi\Lambda^0K^-$
- $\Xi_b^- \to J/\psi\Sigma^0K^-$

- $\psi(2S) \to \mu^+\mu^-$ / $\mu^+\mu^-\pi^+\pi^-$
- $J/\psi^- \to \mu^+\mu^-$
- $\Xi^- \to \Lambda^0\pi^-$; $\Lambda^0 \to p\pi^-$
- $\Sigma^0 \to \Lambda^0\gamma_{lost}$



Observation of multibody decay with $J/\psi\Xi^-$ at CMS

arXiv:2401.16303

First observation of $\Lambda^0_b \to J/\psi\Xi^-K^+$ (+ c.c.) at CMS using 140 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV (2016-2018)

Signal yield extracted by means of an Unbinned Maximum Likelihood (UML) fit and later corrected by total efficiency (from MC):
$N(\Lambda^0_b \to J/\psi\Xi^-K^+) = 46 \pm 11$

- $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$
- $J/\psi^- \to \mu^+\mu^-$
- $\Xi^- \to \Lambda\pi^-$; $\Lambda \to p\pi^-$

UML fit:

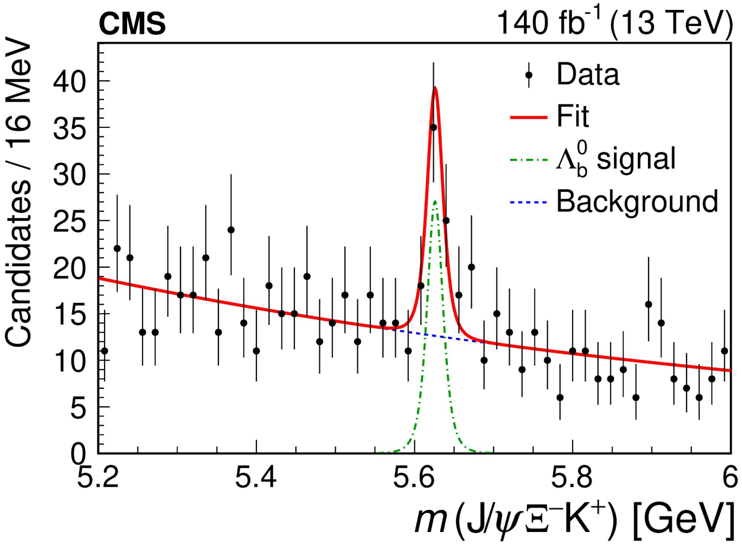
- **Signal**: t-Student (μ and σ free, n fixed from MC)
- **Background**: exponential

First observation of this Λ^0_b decay with 5.8σ

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

Normalization channel: $\Lambda^0_b \to \psi(2S)\Lambda$ (similar kinematics)

Large statistical uncertainties due to small signal yield



Searches for exotics in multibody decays

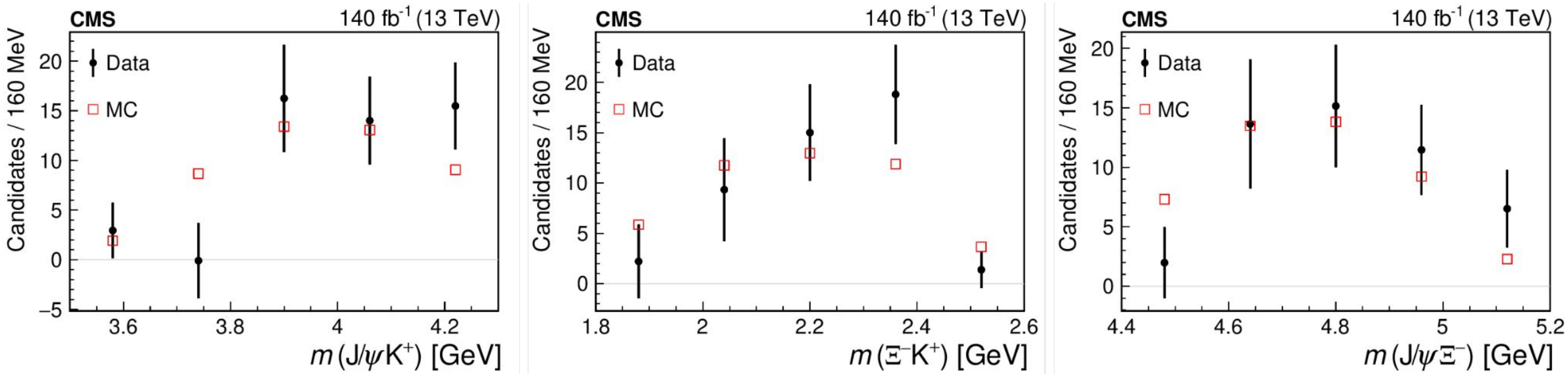
arXiv:2401.16303

Search for intermediate resonances limited by the low signal yield

Background-subtracted distributions (sPlot) to search for intermediate resonances are shown

Hidden-charm exotic states reported by LHCb in $J/\psi p$ and $J/\psi\Lambda$ systems (e.g pentaquarks in $\Lambda_b \rightarrow J/\psi p K^-$)

First discovered multibody decay with $J/\psi\Xi^-$: possible search for doubly-strange hidden-charm pentaquarks as intermediate resonance



Conclusions

- **LHC provides high luminosity (heavy flavor production cross section several order of magnitudes greater than at e^+e^- colliders) and the unique possibility to study heavy hadrons such as B_c and beauty baryons, which are not produced at Belle / Belle II.**

- **CMS - together with other LHC experiments - is able to investigate various aspects of the heavy flavour physics and explore different phase space regions**

- **As more pp collisions data are collected, new particles arise and are confirmed independently from different experiments. Many new multi-body decays are now accessible and represent a promising field to search for exotic hadrons once more statistics will be available.**

- **The Ξ_b^{*0} was the first particle ever observed at CMS (arXiv on 26 April 2012) and the second at LHCb. Larger data samples allow to establish the properties of the newly observed states, thus increasing the understanding of the heavy flavoured particles' spectra.**

THANKS FOR YOUR ATTENTION

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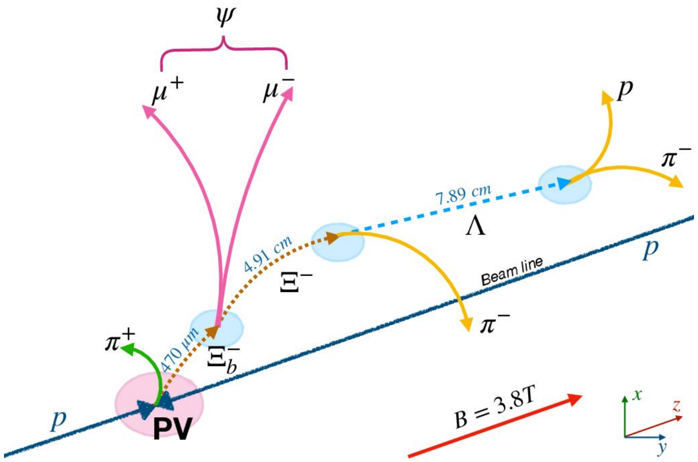
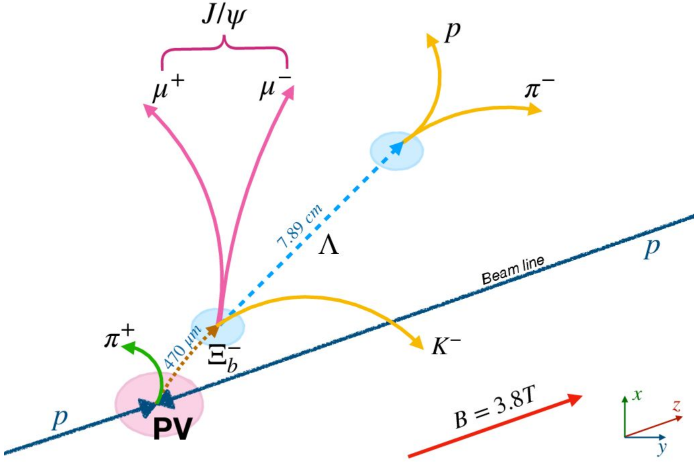
Measurement of Ξ_b^{*0} properties at CMS

- $\Xi_b^- \to \psi(2S)\Xi^-$
- $\Xi_b^- \to J/\psi\Xi^-$
- $\Xi_b^- \to J/\psi\Lambda^0 K^-$
- $\Xi_b^- \to J/\psi\Sigma^0 K^-$

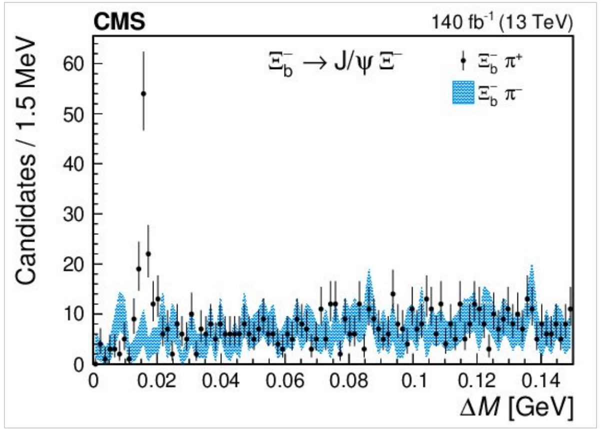
- $\psi(2S) \to \mu^+\mu^- / \mu^+\mu^-\pi^+\pi^-$
- $J/\psi^- \to \mu^+\mu^-$
- $\Xi^- \to \Lambda^0\pi^-;\ \Lambda^0 \to p\pi^-$
- $\Sigma^0 \to \Lambda^0\gamma_{lost}$

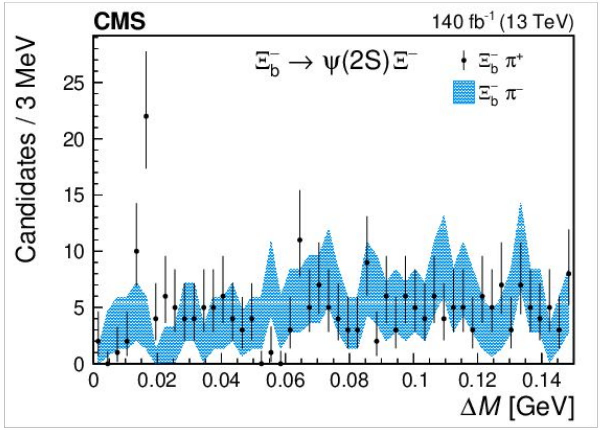


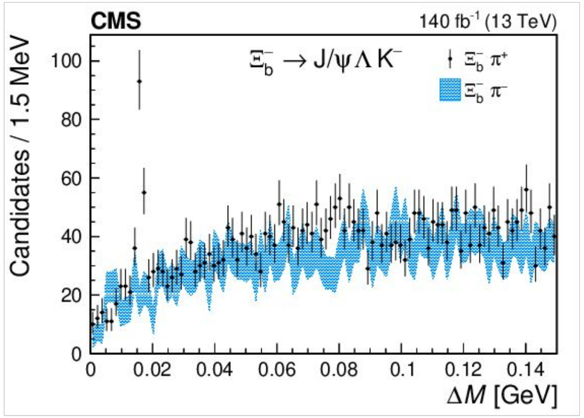


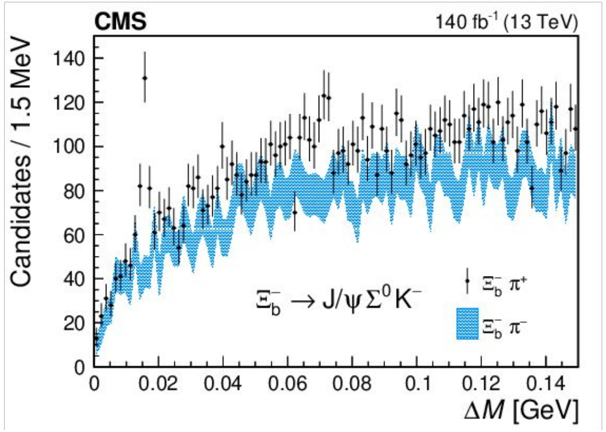
Measurement of Ξ_b^{*0} properties at CMS

arXiv.2402.17738









Considerations on Ξ_b^- isospin partners

Ξ_b^{*0}/Ξ_b^- production rate in agreement with LHCb result: $R_{\Xi_b^{*0}} = \frac{\sigma(pp\to\Xi_b^{*0}X)\mathcal{B}(\Xi_b^{*0}\to\Xi_b^-\pi^+)}{\sigma(pp\to\Xi_b^-X)} = 0.23 \pm 0.04(stat) \pm 0.02(syst)$

About ¼ of Ξ_b^- baryons is produced from Ξ_b^{*0} ... the other ¾?

Reasonable assumption: $\mathcal{B}(\Xi_b^* \to \Xi_b\pi) \simeq 100\%$ $\quad \mathcal{B}(\Xi_b^{*0} \to \Xi_b^-\pi^+) \simeq 2\mathcal{B}(\Xi_b^{*0} \to \Xi_b^0\pi^0) \simeq \frac{2}{3}$

Thus $\frac{\sigma(pp\to\Xi_b^{*0}X)}{\sigma(pp\to\Xi_b^-X)} \simeq 1/3$ and $R_{\Xi_b^{*-}} \simeq 1/9$ can be calculated assuming:

1. same cross sections' ratio
2. $B(\Xi_b^{*-} \to \Xi_b^-\pi^0) = B(\Xi_b^{*0} \to \Xi_b^0\pi^0) = ⅓$:

Overall ¼ of Ξ_b^- come from Ξ_b^{*0} + 1/9 from Ξ_b^{*-} → ¼ + 1/9 = ⅓ of Ξ_b^- from Ξ_b^*

Other higher-mass excited Ξ_b states are Ξ_b^- sources:

prompt production from pp collisions estimated to be less than 2/3