7-10 May 2024 - Consiglio Nazionale delle Ricerche, Rome, Italy
Standard Model at the LHC 2024

Heavy Flavour production and spectroscopy at the LHC

Speaker:
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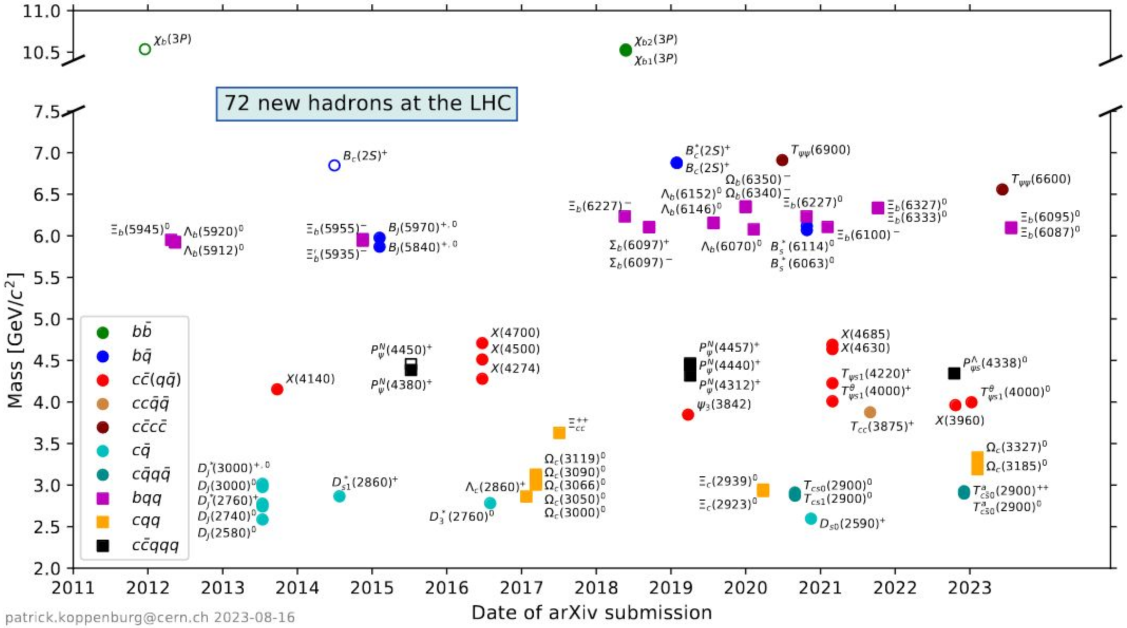
CMS Collaboration

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**



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

LHCb-FIGURE-2021-001, 2024 updated

Selected recent results from ATLAS, CMS, and LHCb

- **Structures in the di-charmonium mass spectrum**
  - **LHCb:** Sci. Bull. 65 (2020) 23
  - **CMS:** PRL 132 (2024) 111901
  - **ATLAS:** PRL 131 (2023) 151902

- **Charmonium production:**
  - **ATLAS:** Measurement of the production cross section of J/ψ and $\psi(2S)$ [EPJC 84 (2024) 169]
  - not discussed **LHCb**: Measurement of associated J/ψ-$\psi(2S)$ production cross section [arXiv, submitted to JHEP]
  - not discussed **LHCb**: J/ψ-pair production and gluon transverse-momentum dependent PDFs [JHEP 03 (2024) 088]

- **Conventional spectroscopy:**
  - **CMS:** Observation of $\Xi_b^- \to \psi(2S)\Xi^-$ and studies of Ξ_b^{*0} [arXiv, submitted to PRD]
  - **LHCb:** Observation of new baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ systems [PRL 131 (2023) 171901]

- **Exotic spectroscopy:**
  - **LHCb:** First observation of the $\Lambda_b^0 \to D^+D^-\Lambda$ decay [arXiv, submitted to JHEP]
  - **LHCb:** Search for prompt production of pentaquarks [arXiv, submitted to PRD]
  - not discussed **LHCb**: First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++}D^{(*)-}K^-$ [arXiv, submitted to PRD Lett]
  - **CMS:** Observation of $\Lambda_b^0 \to J/\psi\Xi^-K^+$ [arXiv, submitted to EPJC]

X(6900) at LHCb in 2020

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:

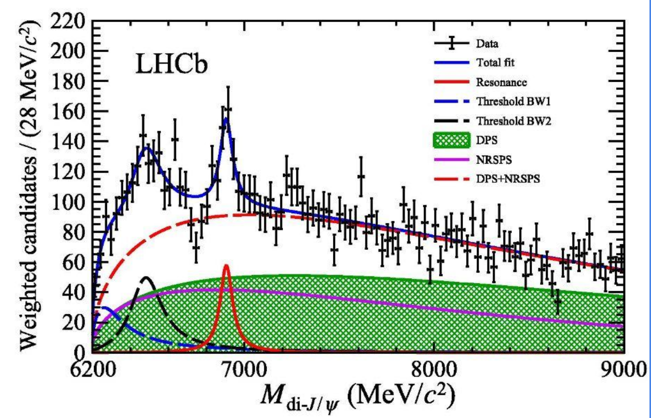
- NRSPS (Non-Resonant Single Parton Scattering)
- DPS (Double Parton Scattering)

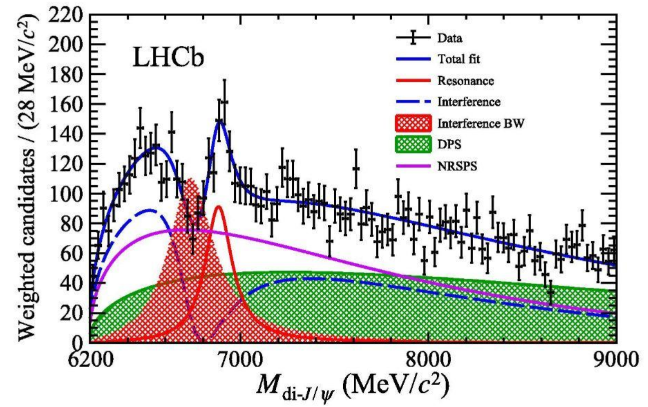
Two different signal models are considered:

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**

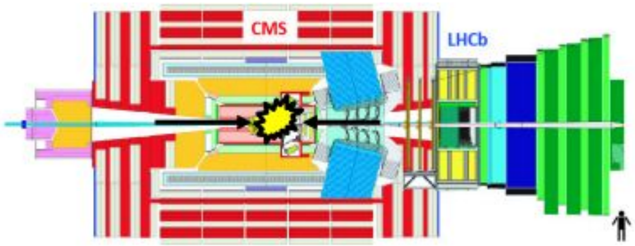




X(6900) at CMS: background description

J/ψJ/ψ (→ 4μ) studied at CMS using 135 fb^{-1} of pp collisions at √s = 13 TeV (2016-2018)

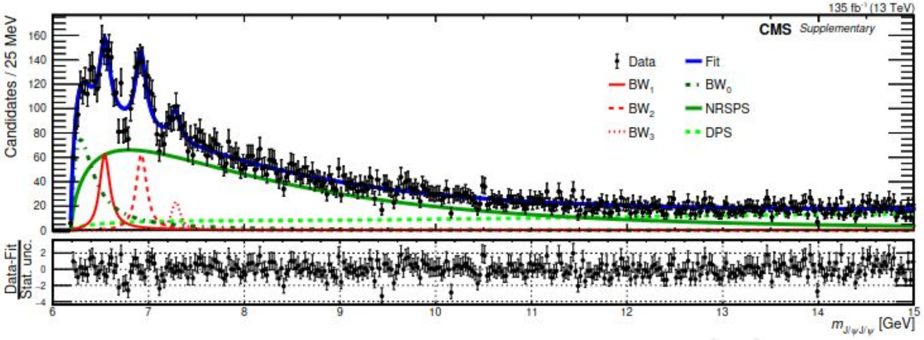
Different background modelling (different acceptance):



- **NRSPS** and **DPS**: parameterizations from MC
- **BW_0** near J/ψJ/ψ 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.
- **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



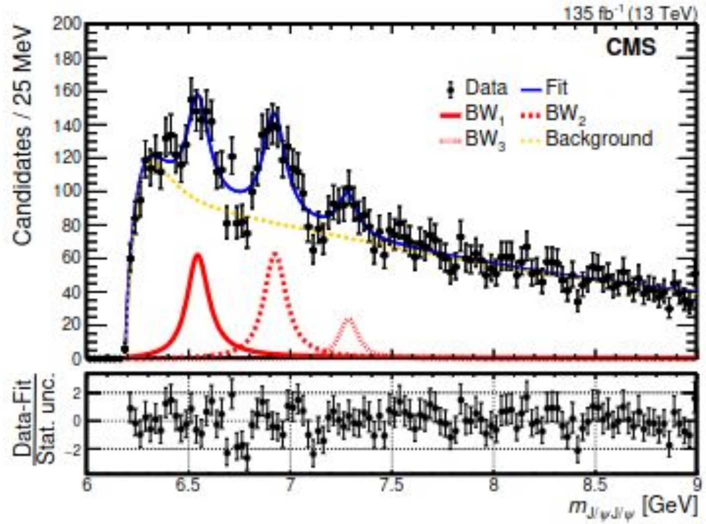
X(6900) at CMS: non-interfering resonances

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**

Result: **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)

	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

The two LHCb models - with NRSPS interfering with BWs - are also investigated (see backup): no improvement on fit.

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

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

X(6900) 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)

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

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

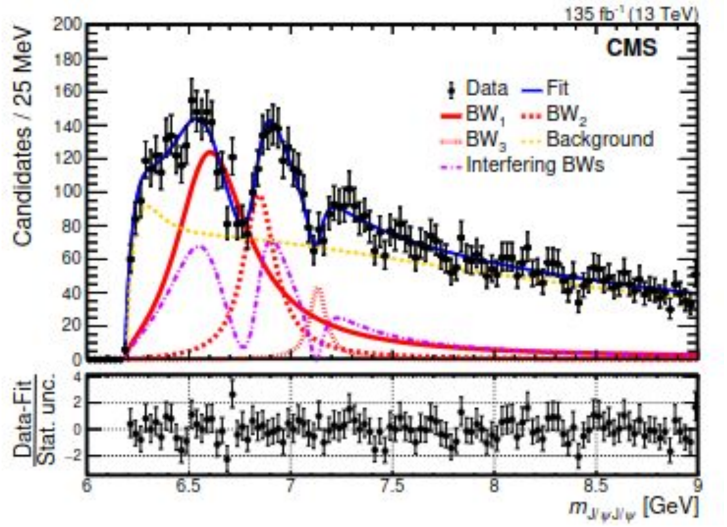
Global significance for BW_3 with MC pseudo-experiments: 3.4σ

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

X(6900) 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

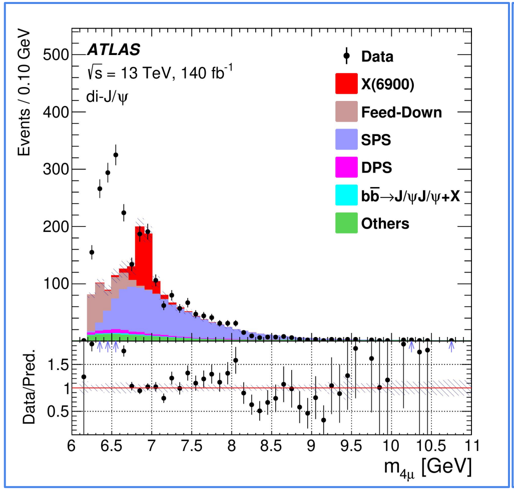
Prompt (SPS, DPS) and non-prompt ($b\bar{b} \rightarrow J/\psi J/\psi + X$) background contributions are considered

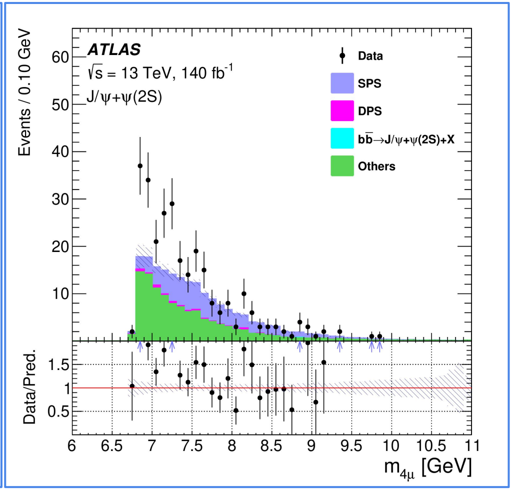
Feed-down included only for di-J/ψ channel

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)

- J/ψJ/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





X(6900) at ATLAS

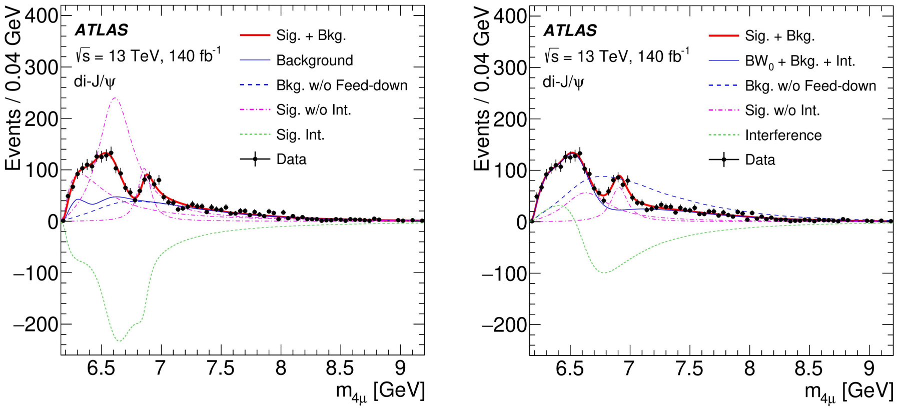
PRL 131 (2023) 151902

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)

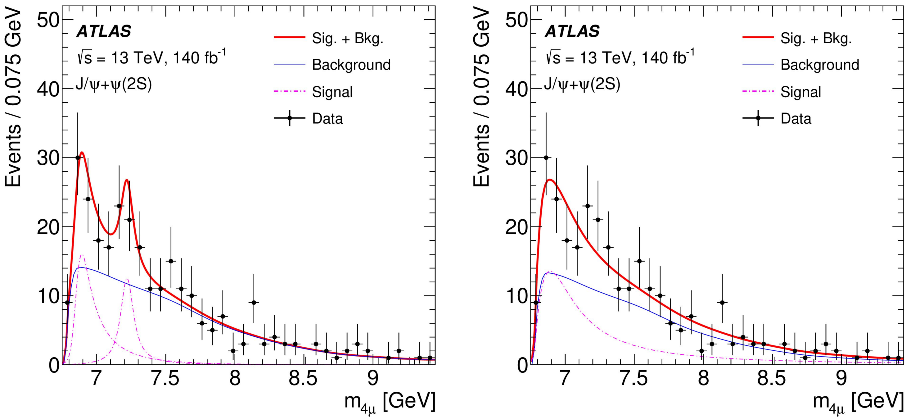


J/ψ+ψ(2S): significance for all resonances with model α (β) is 4.7σ (4.3σ)

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 production at ATLAS

EPJC 84 (2024) 169

Measurement of **differential production cross-sections of prompt and non-prompt J/ψ and ψ(2S)** at ATLAS using 140 fb^{-1} of pp collisions at √s = 13 TeV

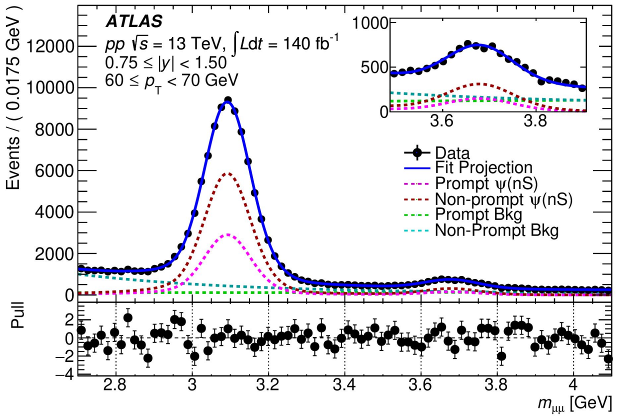
Extended probed phase-space wrt previous ATLAS measurements (√s = 7, 8 TeV, EPJC 76 (2016) 283) using different trigger strategies. 102 (p_T, y) analysis bins defined in the range:

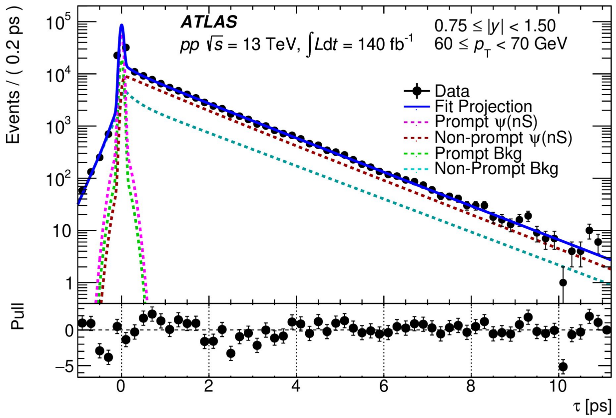
- J/ψ: 8 < p_T < 360 GeV, |y| < 2
- ψ(2S): 8 < p_T < 140 GeV, |y| < 2

In each analysis bin, 2D UML fit to extract signal yield:

- di-muon invariant $m_{μμ}$
- pseudo-proper decay time τ

Signal yield is corrected bin-by-bin by overall efficiency (acceptance, trigger and reconstruction efficiency from MC)



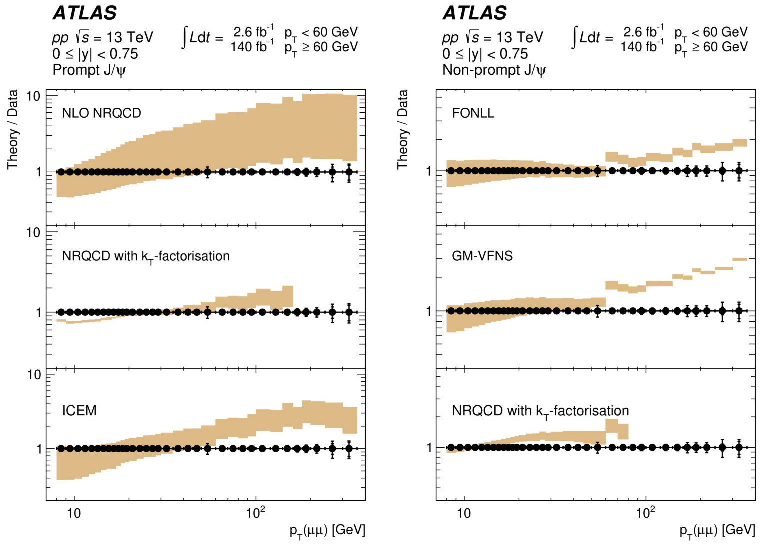


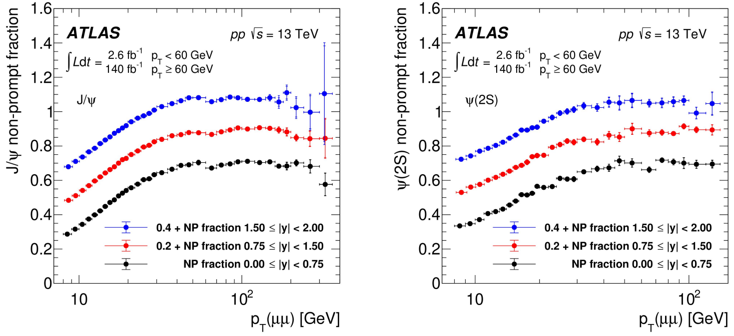
(Non-)prompt J/ψ / ψ(2S) production

EPJC 84 (2024) 169

- **Comparison with predictions from different theoretical models** done separately for prompt (left) and non-prompt (right) J/ψ [plots for ψ(2S) in backup]
- Predictions largely overlap considering theoretical uncertainties
- For prompt production predictions systematically have a harder spectrum, description at $p_T > 100$ GeV needs improvement
- **Extended p_T reach can provide input to refine the theoretical models**

P and NP: similar p_T-dependence for $p_T(\mu\mu) > 100$ GeV for both J/ψ and ψ(2S)





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

arXiv:2402.17738

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

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

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

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)

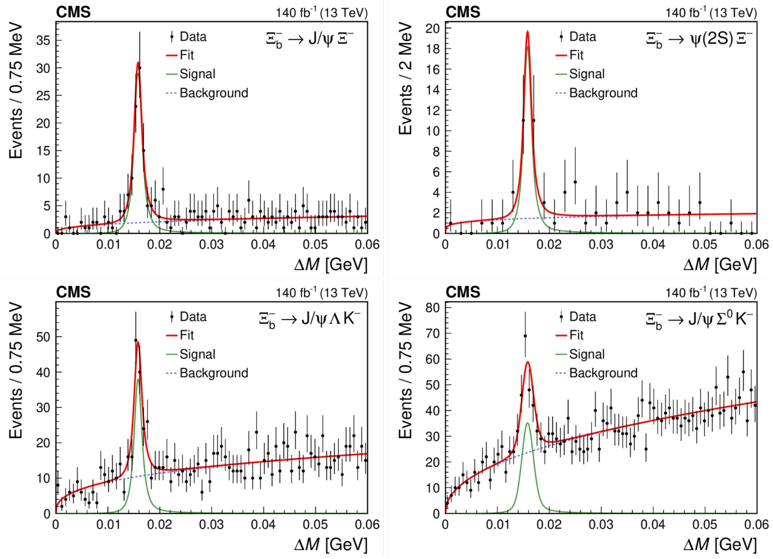
$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.84^{+0.21}_{-0.19}(stat) \pm 0.10(syst) \pm 0.02(\mathcal{B})$$

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

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]

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

$$R_{\Xi_b^{*0}} = 0.23 \pm 0.04(stat) \pm 0.02(syst)$$



Ξ_b excited states at LHCb

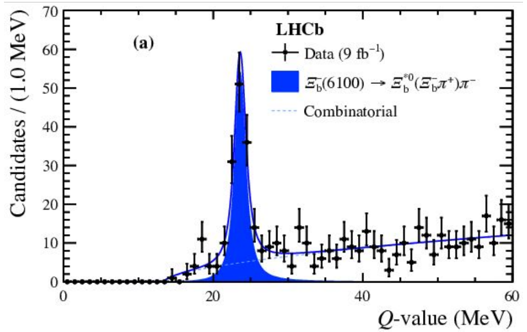
PRL 131 (2023) 171901

Study of $\Xi_b^0\pi^+\pi^-$ and $\Xi_b^-\pi^+\pi^-$ at LHCb using 9 fb^{-1} of pp collisions (7, 8, 13 TeV), together with $\Xi_b^0 \rightarrow \Xi_c^+\pi^-\pi^+\pi^-$ decay observed for the first time

- $\Xi_b^- \rightarrow \Xi_c^0\pi^-$ or $\Xi_c^0\pi^-\pi^+\pi^-$
- $\Xi_b^0 \rightarrow \Xi_c^+\pi^-$ or $\Xi_c^+\pi^-\pi^+\pi^-$
- $\Xi_c^0 \rightarrow pK^-K^-\pi^+$
- $\Xi_c^+ \rightarrow pK^-\pi^+$

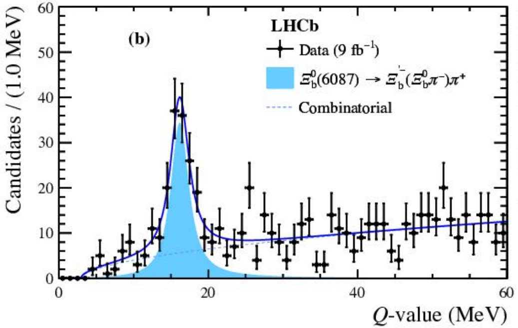
$\Xi_b^{(-,0)}$ combined with one charged pion or two opposite-sign pions
Additional requirement on $\Xi_b^{(-,0)}\pi^+\pi^-$: intermediate Ξ_b^{*0}, $\Xi_b^{\prime -}$ or Ξ_b^{*-}

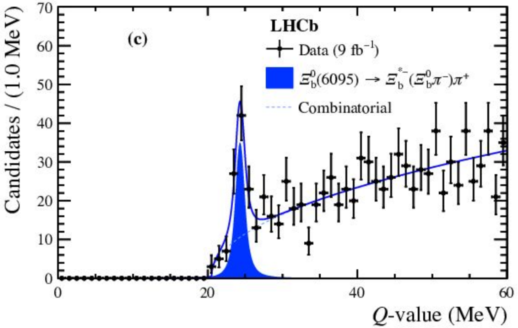
$\Xi_b^-(6100)$ observed at CMS now confirmed (12σ)
$\Gamma = (0.94 \pm 0.30\ (\text{stat.}) \pm 0.08\ (\text{syst.}))$ MeV
CMS set CL@95%: $\Gamma < 1.9$ MeV [PRL 126 (2021) 252003]



First observation of two baryonic structures in $\Xi_b^0\pi^+\pi^-$ (10σ and 8σ)

Final states with up to 9 tracks: excellent momentum resolution and PID improve mass and width resolution of known baryons





Further statistics is needed to understand spin-parity and better study the spectrum

Search for pentaquarks at LHCb

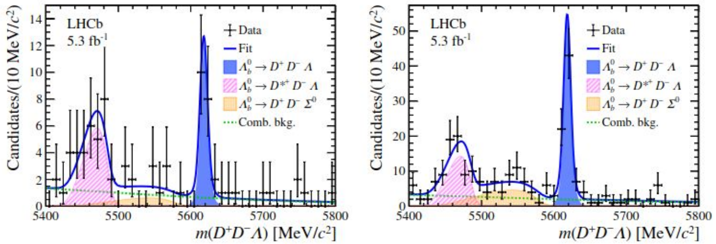
arXiv:2403.03586

First observation of $\Lambda^0_b \to D^+D^-\Lambda$ and $\Lambda^0_b \to D^{*+}D^-\Lambda$ (as partially reconstructed) at LHCb using 5.3 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV (2016-2018)

- $D^+ \to K^-\pi^+\pi^+$
- $D^{*+} \to D^+\pi^0$
- $K_s^0 \to \pi^+\pi^-$
- $\Lambda \to p\pi^-$

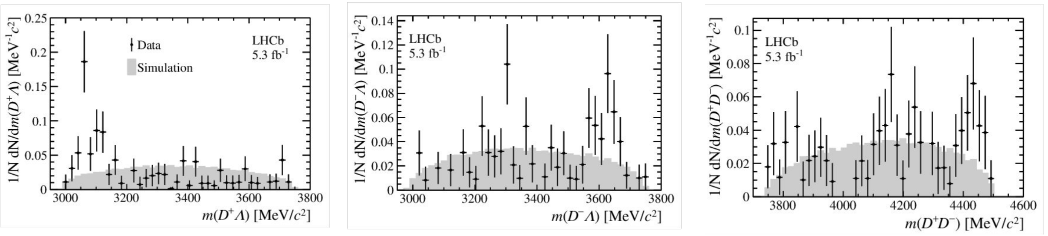
Reference channel: $B^0 \to D^+D^-K_s^0$ (known BF)

$$\mathcal{B}(\Lambda^0_b \to D^+D^-\Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4},$$

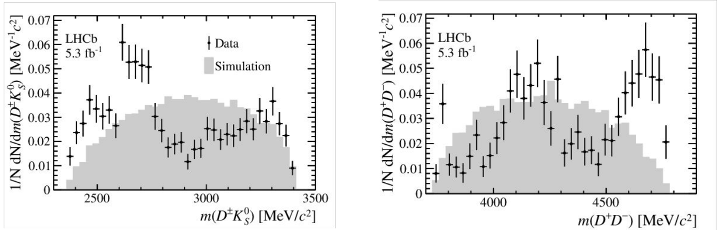


$D^\pm\Lambda$ and D^+D^- invariant mass distributions are probes for potential intermediate resonances:

- $\Xi_c^{**+} \to D^+\Lambda$
- D^+D^- bound state (e.g. X(3700)) can be produced near mass threshold
- open-charmed pentaquark $P_{\bar{c}s}$ can be present in the $D^-\Lambda$ final state



Search on both signal (top) and control (bottom) channels: **deviations from phase-space suggest presence of intermediate states**



Prompt production of pentaquarks at LHCb

arXiv.2404.07131

No significant signals found in the **search for hidden-charm** ($\Sigma_c\underline{D}^{(*)}$, $\Sigma_c{}^*\underline{D}^{(*)}$, $\Lambda_c{}^+\underline{D}^{(*)}$, $\Lambda_c{}^+\pi\underline{D}^{(*)}$,+ c.c.) and **doubly-charmed pentaquarks** ($\Sigma_c D^{(*)}$, $\Sigma_c{}^* D^{(*)}$, $\Lambda_c{}^+ D^{(*)}$, $\Lambda_c{}^+\pi D^{(*)}$,+ c.c.) using 5.7 fb^{-1} of pp data at $\sqrt{s}$ = 13 TeV

Signal yields for known pentaquarks $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$ are also **consistent with zero**

Upper limit is set on 20 channels (out of 30) with enough statistics (>30 candidates)

- $\Lambda_c{}^+ \rightarrow pK^-\pi^+$ (norm.)
- $D^0 \rightarrow K^-\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$

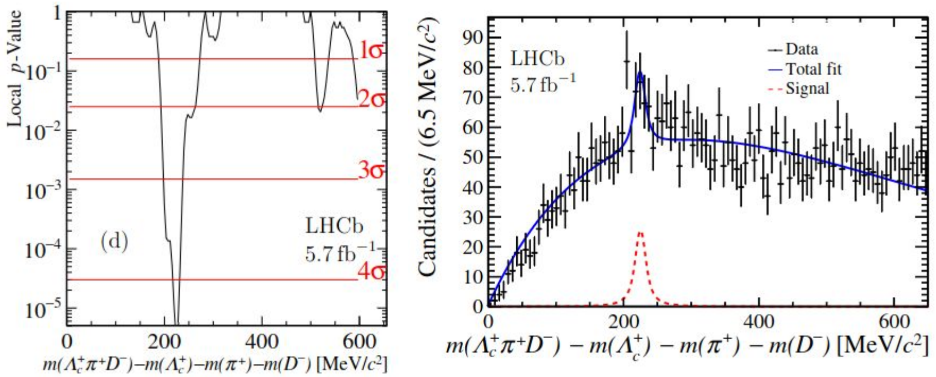
Pentaquarks predicted to be narrow → Voigtian (σ_{resol} ~ 4 MeV, Γ = 5, 10, 15 MeV)
sig+bkg hypothesis tested against bkg-only independently in each channel

Pentaquark signal mass scan in steps of 4 MeV

Excesses observed in few channels for signals with Γ = 15 MeV (largest excess in $\Lambda_c{}^+\pi^+D^-$ of 4.5σ) are **compatible with statistical fluctuations**

Evaluation with 1000 MC pseudo-experiments to verify the background fluctuation

$\Lambda_c{}^+\pi^+D^-$ (signal scan and fit example, Γ = 15 MeV)



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

arXiv:2401.16303

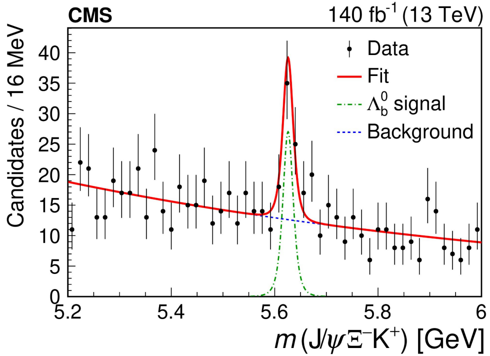
First observation of $\Lambda^0_b \rightarrow J/\psi\Xi^-K^+$ (+ c.c.) at CMS using 140 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV (2016-2018)

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

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

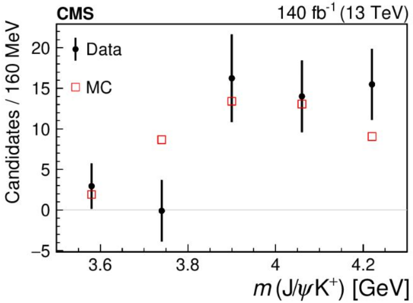
$$R = \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = [3.38 \pm \underset{\text{(stat)}}{1.02} \pm \underset{\text{(syst)}}{0.61} \pm \underset{\text{(BF)}}{0.03}]\%$$

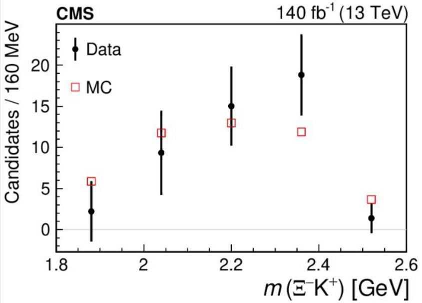
Search for intermediate resonances limited by the low signal yield: N($\Lambda^0_b \rightarrow J/\psi\Xi^-K^+$) = 46 ± 11

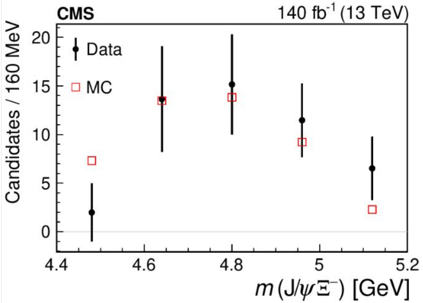


Bkg-subtracted distributions (sPlot) to search for intermediate resonances are shown

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 possibility to study heavy hadrons such as B_c and beauty baryons, which are not produced at Belle / Belle II.**

- **The LHC experiments are able to investigate various aspects of the heavy flavour physics and explore different phase space regions, thus complementing each other and providing valuable input for theoretical predictions**

- **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.**

THANKS FOR YOUR ATTENTION

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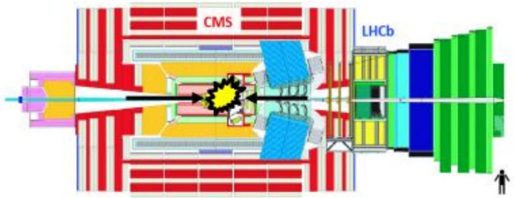
X(6900) at LHCb in 2020

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

Phase-space investigated by LHCb:

- $2 < \eta < 5$
- $p_T(\mu) > 0.65$ GeV
- $p(\mu) > 6$ GeV

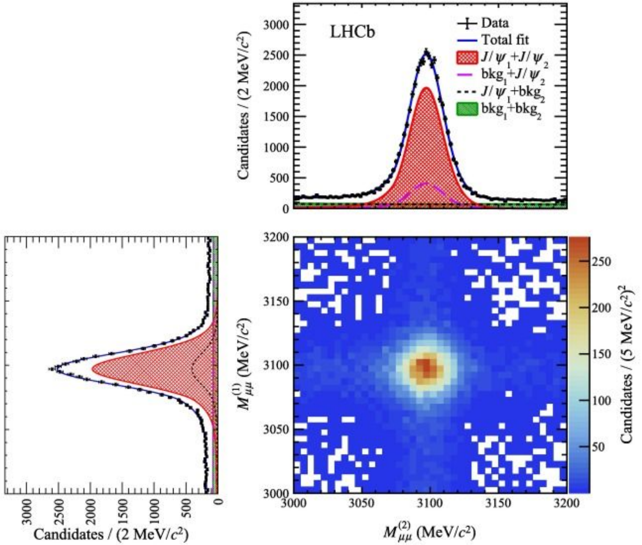


Background contribution for J/ψ pair production:

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

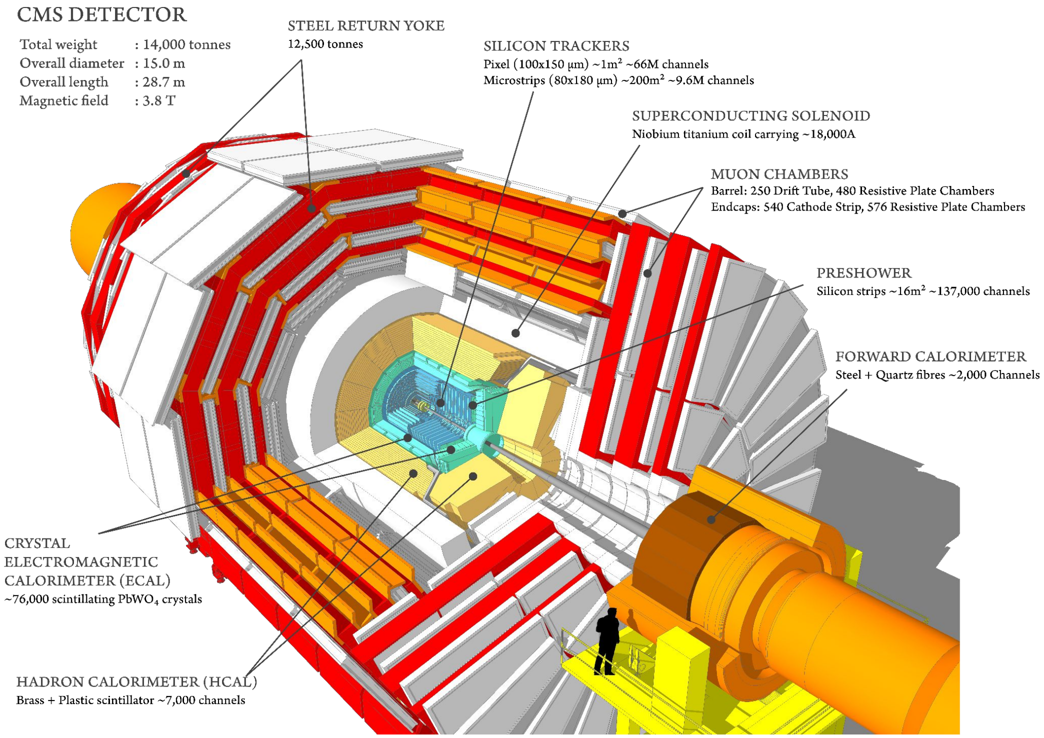
Two structures are reported:

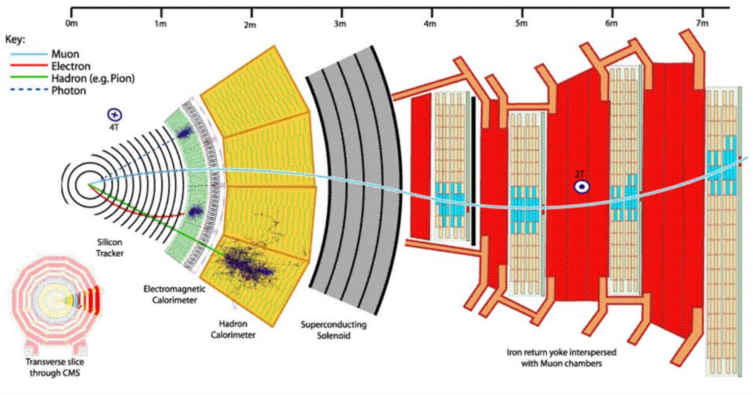
- A broad structure near the di-J/ψ mass threshold
- **A narrow resonance, X(6900), renamed $T_{\psi\psi}$(6900)**



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

X(6900) at CMS: event selection

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

Event selection and reconstruction:

- **3-μ trigger**: $\mu^+\mu^-$ from J/ψ + third muon (on muons from J/ψ: $p_T(\mu^+\mu^-) > 3.5$ GeV in 2017-2018)
- **blinded signal region m(J/ψJ/ψ) in [6.2, 7.8] GeV** (from preliminary investigation on 2011-2012 data)
- four muons: $p_T(\mu) > 2.0$ GeV, $|\eta(\mu)| < 2.4$, "soft muon" identification JINST 7 (2012) P10002
- $m(\mu^+\mu^-)$ in [2.95, 3.25] GeV; $p_T(\mu^+\mu^-) > 3.5$ GeV $P_{vtx}(\mu^+\mu^-) > 0.5\%$
- common vertex fit: $P_{vtx}(4\mu) > 0.5\%$
- Arbitration of multiple candidates:
  - Select best combination of same 4μ (from MC: 0.2%)
  - Keep all candidates arising from more than four muons (from MC: 0.2%)

$$\chi^2_m = \left(\frac{m_1(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

X(6900) at CMS: fit with LHCb model

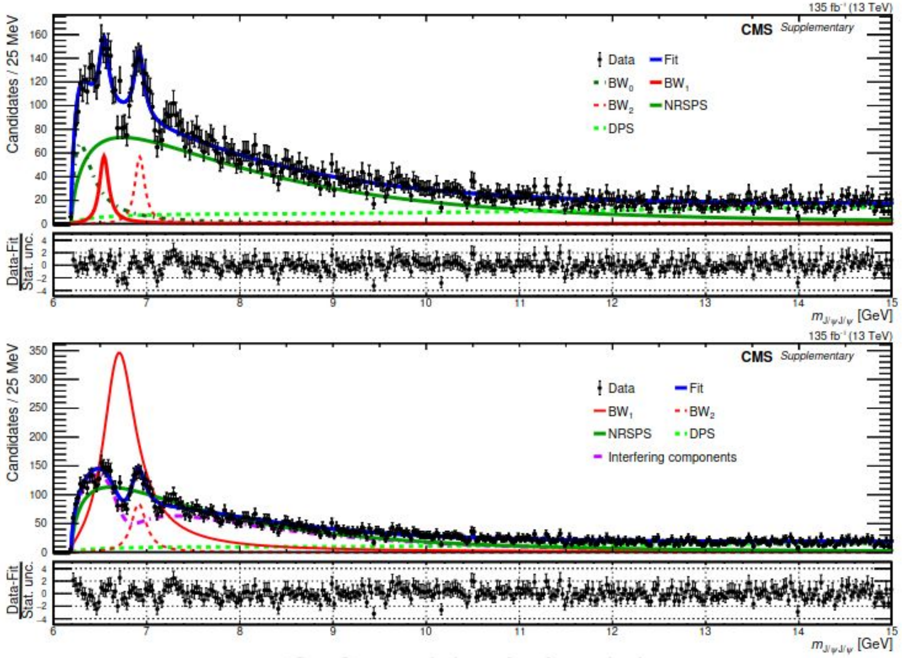
The LHCb signal models are also tested:

similar results, but worse fit quality

LHCb signal models + CMS background

- **Model 1 [NRSPS+DPS+X(6900)+2BW below 6900]**
  - X(6900) parameters in agreement
  - but dip at 6.7 not well described

- **Model 2: [NRSPS+DPS+X(6900)+1BW below 6900 interfering with NRSPS]**
  - Larger X(6700) amplitude
  - X(7300) region not well described



X(6900) at ATLAS: event selection and results

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 140 fb^{-1} of pp 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-Jpsi channel

Event selection, reconstruction and definition of signal and control regions

Signal region	Control region	Nonprompt region
Dimuon or trimuon triggers, oppositely charged muons from each charmonium, *loose* muons, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, or $m_{\psi(2S)} \in [3.56, 3.80]$ GeV, Loose vertex requirements $\chi^2_{4\mu}/N < 40$ ($N = 5$) and $\chi^2_{\text{di-}\mu}/N < 100$ ($N = 2$),		
Vertex $\chi^2_{4\mu}/N < 3$, $L^{4\mu}_{xy} < 0.2$ mm, $\lvert L^{\text{di-}\mu}_{xy}\rvert < 0.3$ mm, $m_{4\mu} < 11$ GeV,		Vertex $\chi^2_{4\mu}/N > 6$,
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	or $\lvert L^{\text{di-}\mu}_{xy}\rvert > 0.4$ mm

Fit results

Di-J/ψ	Model A	Model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	...
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	...

$J/\psi + \psi(2S)$	Model α	Model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

(Non-)prompt J/ψ / ψ(2S) production

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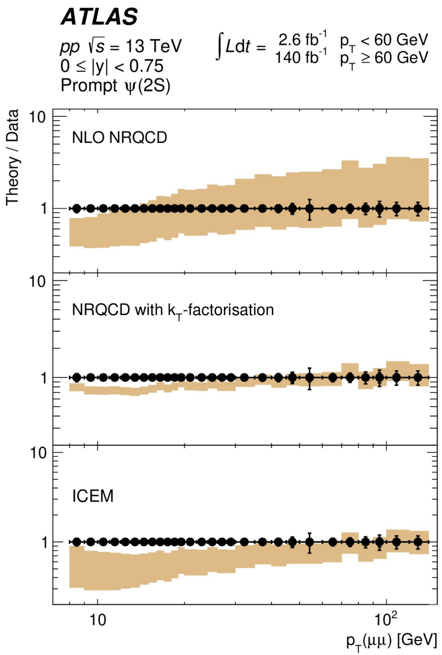
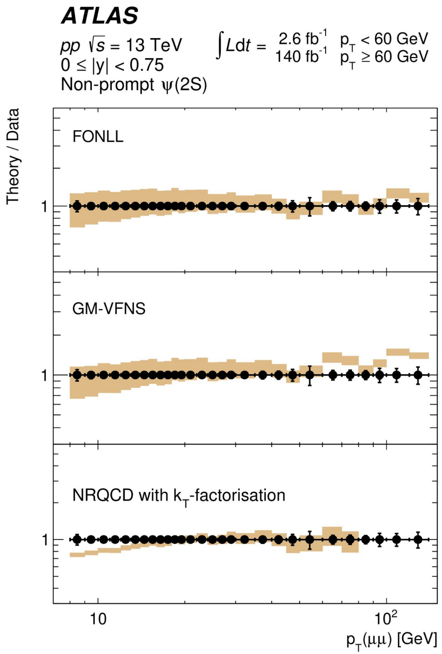
Comparison with predictions from different theoretical models done separately for prompt (left) and non-prompt (right) contributions

Predictions largely overlap considering theoretical uncertainties. Extended p_T reach can provide input to refine the theoretical models





(Non-)prompt J/ψ / ψ(2S) production

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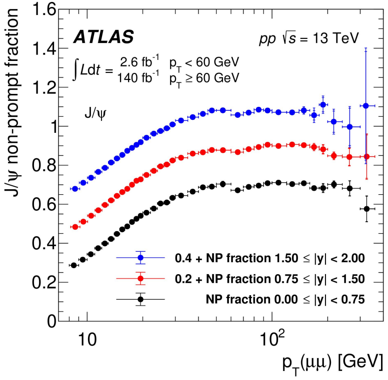
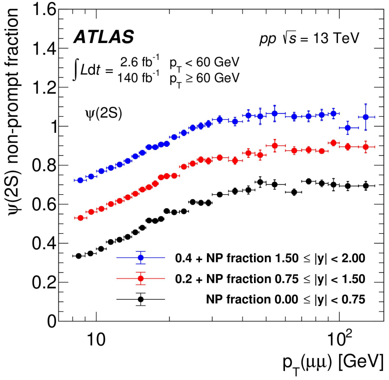
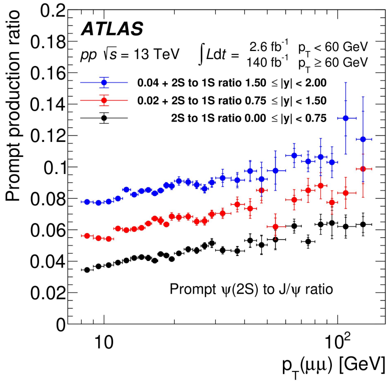
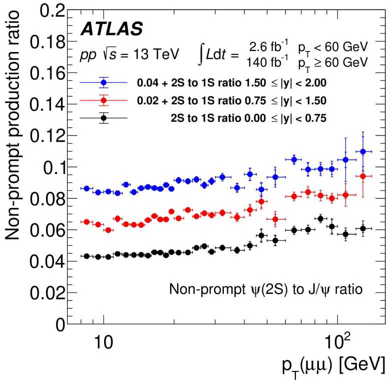
P and NP: similar p_T-dependence for $p_T(\mu\mu) > 100$ GeV





ψ(2S)-to-J/ψ production ratios

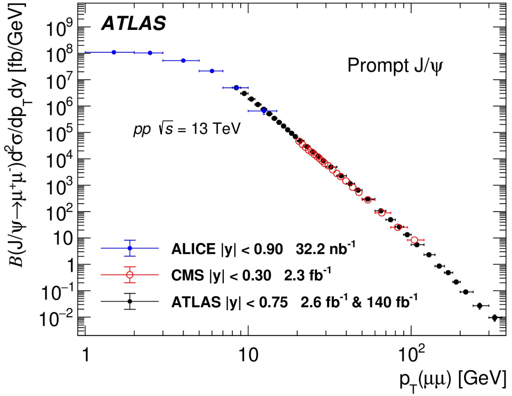




ATLAS extended the phase-space probed by the other LHC experiments

Differential production cross-section for prompt-J/ψ in similar rapidity range:

- CMS:
- ALICE:



New excited beauty strange baryon into $\Xi_b^-\pi^+\pi^-$ (CMS)

Search on 140 fb^{-1} of pp collisions data at $\sqrt{s}$ = 13 TeV during 2016-2018 at LHC

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

Search for Ξ_b^- excited states in $\Xi_b^-\pi^+\pi^-$, with Ξ_b^- reconstructed in:

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

- $J/\psi^- \to \mu^+\mu^-$
- $\Xi^- \to \Lambda^0\pi^-$
- $\Lambda^0 \to p\pi^-$
- $\Sigma^0 \to \Lambda^0\gamma_{soft}$

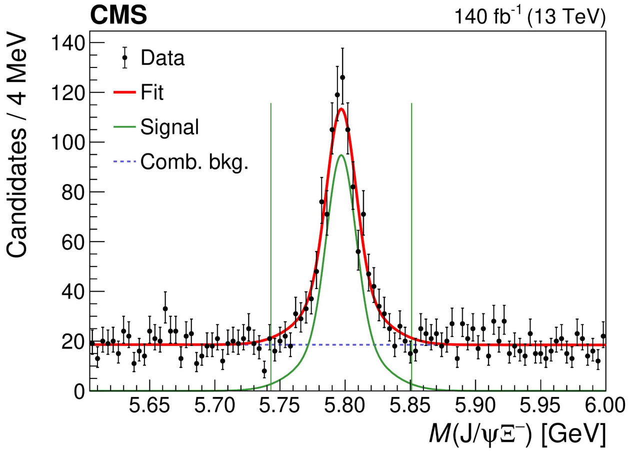
soft photon **not** reconstructed

Event selection for Ξ_b^- reconstruction:

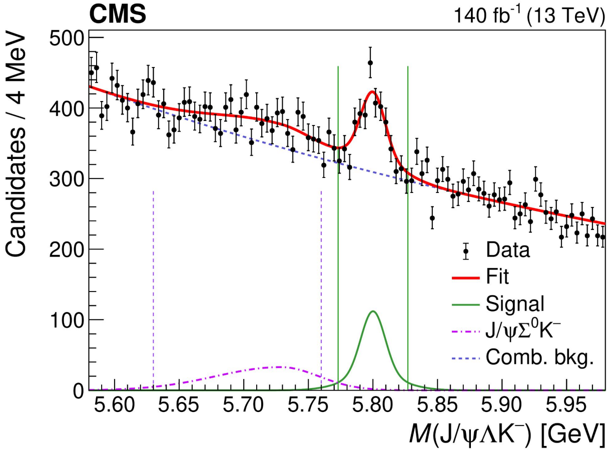
- combination of **triggers targeting $J/\psi \to \mu^+\mu^-$**
- $p_T(\mu) > 3$ GeV; $|\eta(\mu)| < 2.4$; $P_{vtx}(\mu\mu) > 1\%$; $|m(\mu\mu) - M_{J/\psi}^{PDG}| < 100$ MeV
- $|m(p\pi^-) - M_\Lambda^{PDG}| < 10$ MeV; $p_T(\Lambda) > 1$ GeV; $P_{vtx}(p\pi^-) > 1\%$
- **Further selection separately optimized for each decay channel**, including selection on Ξ_b^- flight distance and its alignment with Ξ_b^- momentum

Ξ_b^- signal extraction: UML fit to data (CMS)

- **Fully reconstructed signals:**
  Double-Gaussian (resolution from MC)
- **Partially reconstructed signal:**
  Asymmetric Gaussian (shape from MC)
- **Combinatorial background:**
  - $J/\psi\Xi^-$: 1st order polynomial
  - $J/\psi\Lambda K^-$: exponential function



$N(\Xi_b^- \to J/\psi\Xi^-) = 859 \pm 36$ events
$N(\Xi_b^- \to J/\psi\Lambda^0 K^-) = 815 \pm 74$ events
$N(\Xi_b^- \to J/\psi\Sigma^0 K^-) = 820 \pm 158$ events



Excited Ξ_b^- candidates' reconstruction:

- Mass windows for Ξ_b^- candidates (see plots)
- Two OS tracks from same PV as Ξ_b^-
  (negligible $\tau(\Xi_b^-) \simeq 1.6$ ps)
- Control region: SS tracks from same PV as Ξ_b^-
- Mass variable $\Delta M = m(\Xi_b^- \pi^+ \pi^-) - m(\Xi_b^-) - 2m_\pi^{PDG}$
  (insensitive to potential mass shift due to lost γ_{soft})

Excited Ξ_b^- signal extraction (CMS)

Dominant contribution of intermediate Ξ_b^{*0}: $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$, $\Xi_b^{*0} \to \Xi_b^-\pi^+$ is suggested by analogy with Ξ_c family and theoretical studies

Additional cut: $m(\Xi_b^{*0})-m(\Xi_b^-)+m_\pi^{PDG} < 20.73$ MeV (peak expected at 15.73 MeV)

Fully reconstructed channels are combined
(same resolution, $\Xi_b^- \to J/\psi\Sigma^0K^-$ 30% larger res.)

UML simultaneous fit:

- **Signal**: Relativistic BW⊗Double-Gaussian
- **Background**: $(\Delta M)^\alpha$ threshold function

$M(\Xi_b^{**-})$ = 6100.3 ± 0.2(stat) ± 0.1(syst) ± 0.6(Ξ_b^-) MeV
$\Gamma(\Xi_b^{**-})$ < 1.9 MeV @ CL=95%
(narrow resonance, 13 MeV below $\Lambda_b^0K^-$ threshold)
Local statistical significance: 6.2-6.7σ

The decay sequence suggest: $j_{qs} = 1$, $J^P = 3/2^-$
beauty partner of the charmed Ξ_c(2815) baryon