Spectroscopy results from the LHC

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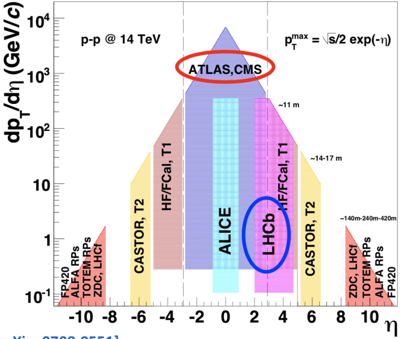
Heavy flavour spectroscopy at LHC

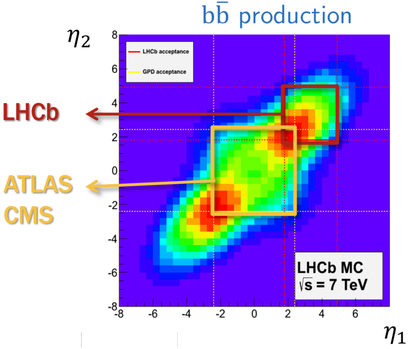
- Opportunities to test QCD and its effective models
  - Various theoretical models probing QCD make predictions on the heavy hadron production and properties
  - New states/decays provide inputs to theory
  - Understanding the structure and properties of hadrons from QCD remains a challenge due to non-perturbative long distance effects involved
  - Many observed states which are not fitting the standard picture still lack of interpretation (e.g. exotic states)
- But also to be able to fully understand processes which are the Standard Model background in the search for new physics

LHCb, ATLAS and CMS experiments

- LHCb, ATLAS and CMS are complementary in heavy flavour spectroscopy studies
  - ATLAS and CMS cover high p_{T} and low rapidity range
  - LHCb covers low p_{T} and higher rapidity region
    - In addition LHCb has an excellent vertexing and particle identification capabilities: dedicated to heavy flavour physics



[arXiv: 0708.0551]

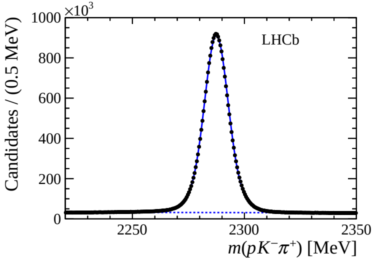


Charmed baryons

Excited Ξ_c^0 states at LHCb [arXiv:2003.13649]

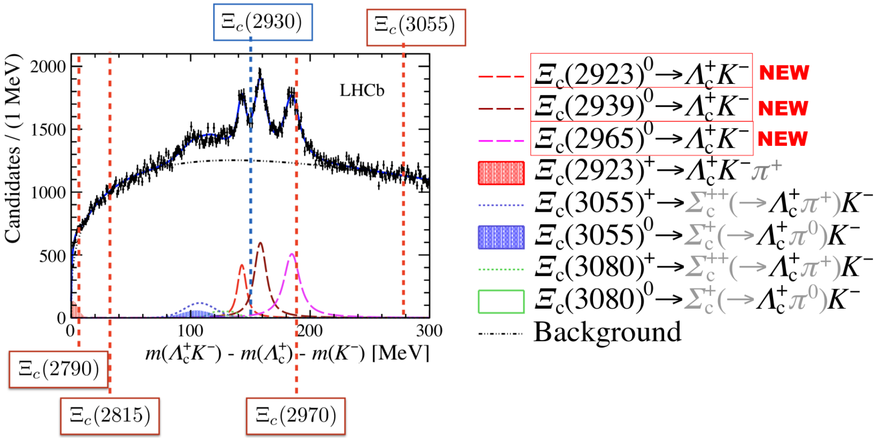
- Investigate a different charm spectrum to understand the nature of the excited Ω_c states decaying to $\Xi_c^+ K^-$ [LHCb PRL118 (2017) 182001, Belle PRD97(2018) 051102]
- Search for analogous excited Ξ_c^0 resonances in the $\Lambda_c^+ K^-$ spectrum with $\Lambda_c^+ \to pK^-\pi^+$
- Data sample: $5.6\,\mathrm{fb}^{-1}$ in 2016-2018 at $\sqrt{s} = 13\,\mathrm{TeV}$
- Mass spectrum already studied by Belle [EPJC78(2018)252] and BaBar [PRD77 (2018) 031101, PRD77 (2008) 012002]: peaking structure interpreted as the $\Xi_c(2930)^0$

- ~125M Λ_c signal, purity: 93%
- Ξ_c^0 reconstructed combining Λ_c selected candidates with a K^- candidate from primary vertex (PV)
- Combinatorial background due to the large number of K^- candidates: optimizing selection on particle identification response/p_T
- Optimisation of the selection figure of merit for a new discovery [Punzi FoM, eConf C030908 (2003) MODT002]



shown only 20% of the full selected candidates

$\Lambda_c^+ K^-$ spectrum [arXiv:2003.13649]



- Three new peaks are observed for the first time
- Relativistic BW convolved with mass-resolution function for signals
- Several feed-down decays considered
- Background modelled by empirical function

Charmed Ξ_c^0 baryons [arXiv:2003.13649]

- Three new peaks are observed

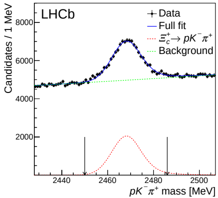
Resonance	Peak of ΔM [MeV]	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$142.91 \pm 0.25 \pm 0.20$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$158.45 \pm 0.21 \pm 0.17$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$184.75 \pm 0.26 \pm 0.14$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

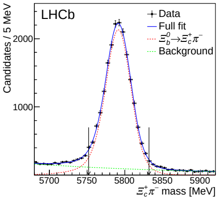
- Two structures observed in the vicinity of the previously observed $\Xi_c(2930)^0$: $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$
    - broad $\Xi_c(2930)^0$ could be the overlap of these two narrower states?
- $\Xi_c(2965)^0$ is close in mass to the $\Xi_c(2970)^0$
    - Mass and width are lower for $\Xi_c(2965)^0$ wrt $\Xi_c(2970)^0$
    - $\Xi_c(2970)^0$ observed in different decay modes (not in $\Lambda_c^+ K^-$) by Belle [EPJC78(2018)252] and BaBar [PRD77 (2018) 031101, PRD77 (2008) 012002]
    - Different baryons?
- More studies required...
- Equal spacing rule [Phys.Rev.125 (1962) 1067, Prog.Theor.Phys,27 (1962) 949] seems to work for the new states: relation to the excited Ω_c^0 baryons observed in the $\Xi_c^+ K^-$ spectrum

Beauty baryons

Excited Ω_b^- resonances at LHCb [PRL124 (2020) 082002]

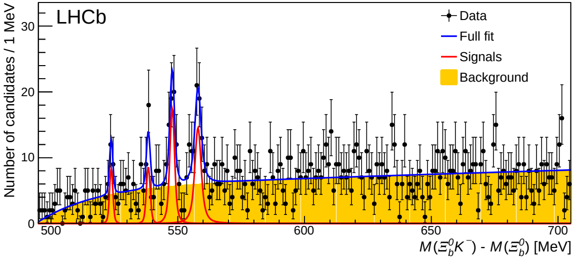
- Several theoretical models aiming to describe observed Ω_c peaks: predictions also on Ω_b states
- Search for analogous excited Ω_b states in the $\Xi_b^0 K^-$ spectrum using full Run 1 + 2 data sample ($9\,\mathrm{fb}^{-1}$)
- Ξ_b candidate is reconstructed pairing a Ξ_c (reconstructed in $\to pK^-\pi^+$ final state) with a π^- candidate: selection based on topology of the decays and particle identification requirements
- Ξ_b candidate is combined then with a K^- candidate from PV: large combinatorial background suppressed using particle identification requirement on the bachelor kaon

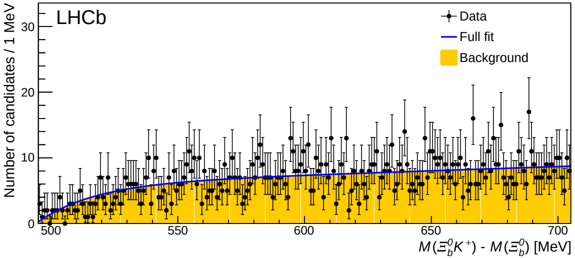




$\Xi_b^0 K^-$ spectrum [PRL124 (2020) 082002]

- Simultaneous fit to right-sign (RS) and wrong-sign (WS) spectra
- Four peaks modeled with a relativistic BW convolved with a Gaussian resolution function in the RS spectrum





Excited Ω_b^- resonances: results [PRL124 (2020) 082002]

	δM_{peak} [MeV]	Mass [MeV]	Width [MeV]
$\Omega_b(6316)^-$	$523.74 \pm 0.31 \pm 0.07$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	$<2.8(4.2)$ 2.1 σ
$\Omega_b(6330)^-$	$538.40 \pm 0.28 \pm 0.07$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	$<3.1(4.7)$ 2.6 σ
$\Omega_b(6340)^-$	$547.81 \pm 0.26 \pm 0.05$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	$<1.5(1.8)$ 6.7 σ
$\Omega_b(6350)^-$	$557.98 \pm 0.35 \pm 0.05$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	$<2.8(3.2)$ 6.2 σ
			$1.4^{+1.0}_{-0.8} \pm 0.1$

Global significances taking into account look-elsewhere effect

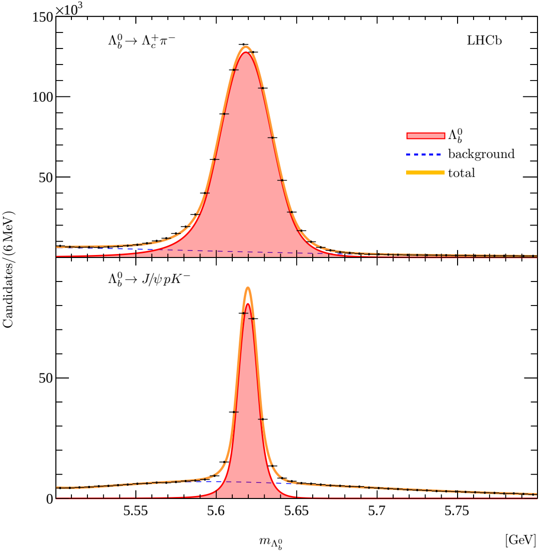
- Possible interpretations
  - Excited Ω_b^- states ($L = 1$ angular momentum excitations or $n = 2$ radial excitations)
  - Decay of higher-mass excited Ω_b^- state: $\Omega_b^{**-} \to \Xi_b^{\prime 0}(\to \Xi_b^0 \pi^0) K^-$ where π^0 is undetected and assuming $m_{\Xi_b^{\prime 0}} > m_{\Xi_b^0} + m_{\pi^0}$
- Spectra observed in $\Xi_b^0 K^-$ and $\Xi_c^0 K^-$ are similar as expected from heavy quark symmetry

Excited Λ_b baryons

- A number of excited Λ_b baryon states are predicted with masses in the range 5.9-$6.4\,\mathrm{GeV}$
- $\Lambda_b^0\pi^+\pi^-$ mass spectrum extensively studied
- Low mass region (near threshold) studied by LHCb with $1\,\mathrm{fb}^{-1}$: two narrow $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states [PRL109 (2012) 172003], heavier state confirmed by CDF [PRD88 (2013) 071101]
- Recently high mass $\Lambda_b^0\pi^+\pi^-$ spectrum (6.10-6.25 GeV) with Run1+Run2 data sample $(9\,\mathrm{fb}^{-1})$ studied by LHCb [PRL123 (2019) 152001]
- Intermediate mass region studied by CMS [PLB803(2020)135345]] with 2016-2018 data corresponding to $140\,\mathrm{fb}^{-1}$ and LHCb [2002.05112] with Run1+Run2 data sample $(9\,\mathrm{fb}^{-1})$

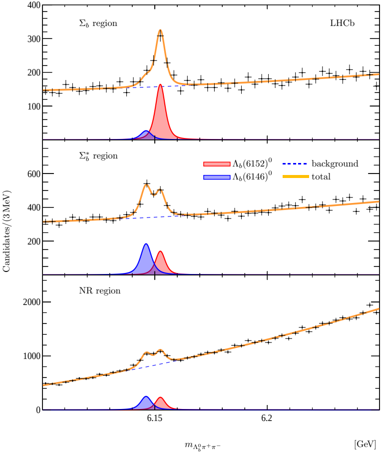
Excited Λ_b^0 baryons

- Most recent two analysis performed at LHCb [PRL123 (2019) 152001, arXiv:2002.05112] use similar strategy
  - Λ_b^0 candidates are reconstructed in $\Lambda_c^+\pi^-$ and $J/\psi pK^-$ final states
  - Yield for $\Lambda_b^0 \to J/\psi pK^-$ is smaller: used as cross-check
- CMS [PLB803 (2020) 135345]:
  - Λ_b^0 candidates reconstructed in $J/\psi\Lambda$ and $\psi(2S)\Lambda$ final states
- Add then two prompt pions



LHCb high-mass region: 6.1-6.25 GeV [PRL123 (2019) 152001]

- Observed clear excess: $\sim 6.15\,\mathrm{GeV}$
- Treated at the beginning as a single broad state
- Above $\Sigma_b^{*\mp}\pi^{\pm}$ threshold: investigate spectrum in three nonoverlapping $\Lambda_b^0\pi^{\pm}$ regions
  - $\Sigma_b^{\pm}$
  - $\Sigma_b^{*\pm}$
  - Non resonant
- Simultaneous fit in the three regions
- Two signal hypothesis favored at 7σ significance
- Consistent with a $\Lambda_b(1D)^0$ doublet with $J^P = \frac{3}{2}^+/\frac{5}{2}^+$
- Interpretation as excited Σ_b cannot be excluded



$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\ \mathrm{MeV}$$

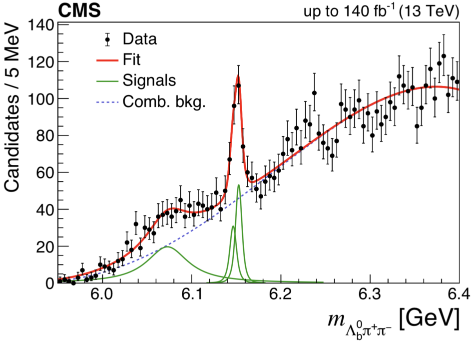
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\ \mathrm{MeV}$$

$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3\ \mathrm{MeV}$$

$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3\ \mathrm{MeV}$$

$\Lambda_b^0\pi^+\pi^-$ at CMS [PLB803(2020)135345]

- Narrow peak at $\sim 6500\,\mathrm{GeV}$ consistent with the overlap of the $\Lambda_b(6146)^0$ and $\Lambda_b(6150)^0$ signal
- Broad enhancement in the region below $6100\,\mathrm{MeV}$
- Fit using three signal functions (BW convolved with a double-Gaussian resolution function) and a smooth background



$$M_{\Lambda_b(6146)^0} = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2\,\mathrm{MeV}$$

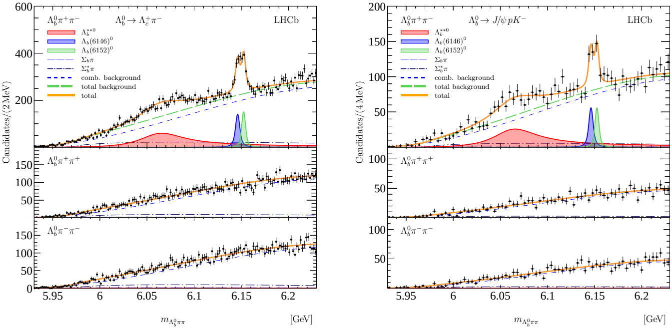
$$M_{\Lambda_b(6152)^0} = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2\,\mathrm{MeV}$$

In good agreement with the LHCb measurements

- Broad excess: $M = 6073 \pm 5\,\mathrm{MeV}$ and $\Gamma = 55 \pm 11\,\mathrm{MeV}$
  - It seems to be related to the intermediate $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ baryon states
  - It could be a superposition of several narrow states

$\Lambda_b^0\pi^+\pi^-$ at LHCb

- Simultaneous binned maximum-likelihood fit (200 keV bin width) to the six distributions

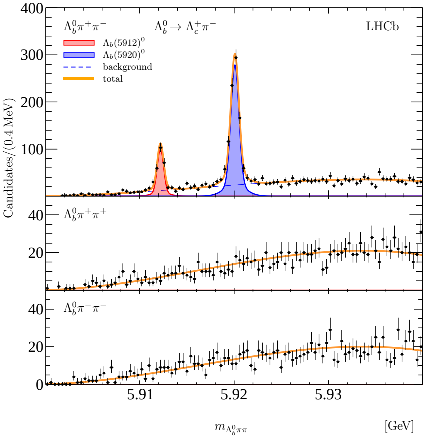


$$m_{\Lambda_b^{**0}} = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2\,\text{MeV}$$
$$\Lambda_{\Lambda_b^{**0}} = 72 \pm 11 \pm 2\,\text{MeV}$$

- Consistent with the CMS broad excess
- Agreement with expectations for the $\Lambda_b(2S)^0$ state
- It could be a superposition of more than one narrow states
- Interpretation of these states as excited Σ_b resonances disfavoured

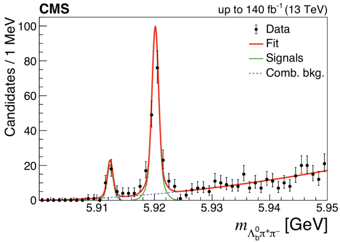
$\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$

LHCb [arXiv:2002.05112]



$$M_{\Lambda_b(5912)^0} = 5912.21 \pm 0.03 \pm 0.01 \pm 0.21\,\text{MeV}$$
$$M_{\Lambda_b(5920)^0} = 5920.11 \pm 0.02 \pm 0.01 \pm 0.21$$
$$\Gamma(\Lambda_b(5912)^0) < 0.28\,\text{MeV}$$
$$\Gamma(\Lambda_b(5920)^0) < 0.20\,\text{MeV}$$

CMS [PLB803(2020)135345]

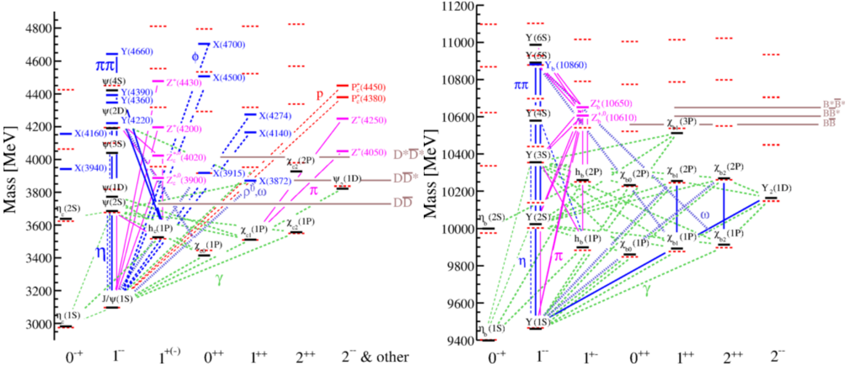


$$M_{\Lambda_b(5912)^0} = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17\,\text{MeV}$$
$$M_{\Lambda_b(5920)^0} = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17$$

Exotic states

Exotic spectroscopy

- The observation of states with properties inconsistent with pure $c\bar{c}$ and $b\bar{b}$ states raised the interest of the so-called exotic (non-standard) quarkonium states from both the theoretical and experimental point of view starting from the discovery of the $X(3872)$ state
- Then, a plethora of unexpected neutral (X, Y) and charged (Z^+, P_c^+) states have been discovered
- The nature and the internal structure of these states are still unclear (molecular/tightly bound): many efforts needed to uncover their nature



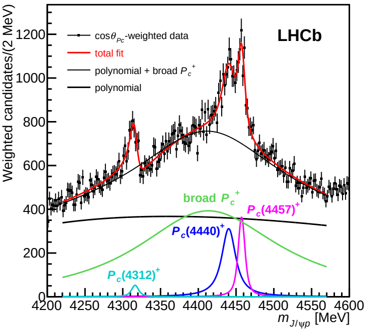
[Rev.Mod.Phys 90 (2018) 015003]

Pentaquarks

Pentaquarks at LHCb [PRL122(2019)222001]

- Investigate $J/\psi p$ invariant mass using $\Lambda_b \to J/\psi p K^-$ decays
- Update of Run1 analysis [PRL 115 (2015) 072001, PRL 117 (2016) 082002]
- Using Run1+Run2 data $(3+6\,\mathrm{fb}^{-1})$: order of magnitude increase in signal yield
- More $J/\psi p$ structures (not significant in the Run1 analysis): $P_c^+(uudc\bar{c})$ states
  - Narrow peak at $4312\,\mathrm{MeV}$ with a width comparable to the mass resolution $(\sim 2 \div 3\,\mathrm{MeV})$
  - The structure at $4450\,\mathrm{MeV}$: resolved into two narrow peaks at $4440\,\mathrm{MeV}$ and $4457\,\mathrm{MeV}$

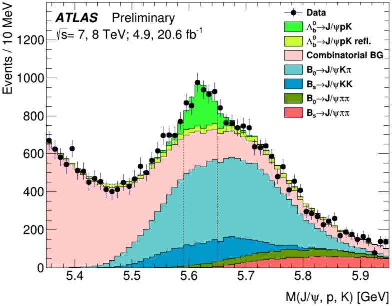
1D fit to $m_{J/\psi p}$



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Pentaquarks at ATLAS [ATLAS-CONF-2019-048]

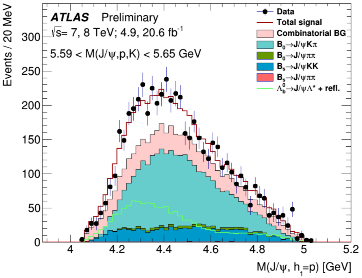
- Motivated by the LHCb observation of $P_c^+(uudc\bar{c})$ states
- Run 1 data corresponding to 4.9 and $20.6\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$
- No particle identification: background dominated by $H_b \to J/\psi h_1 h_2$ where $h_{1,2} =$ p, K, π are coming from light neutral mesons (Λ^*, K^*, ϕ, f_2)
- Remove events with $M(\pi K/K\pi) < 1.55\,\mathrm{GeV}$
- Same-sign two-hadron background is subtracted



N($\Lambda_b^0 \to J/\psi p K^-$) $= 1010 \pm 140$
in the signal region

Pentaquarks at ATLAS: results

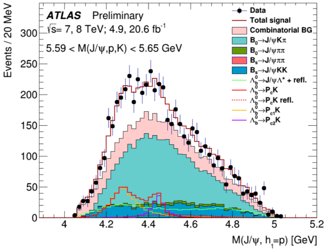
- Data prefer two or more P_c^+s model
- Model with no pentaquarks not excluded: p-value $= 0.91\%$



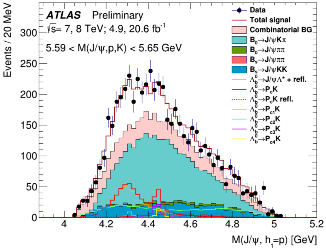
- Two pentaquarks fit: masses and widths compatible with LHCb

$m(P_{c1})$	4282^{+33}_{-26}(stat)$^{+28}_{-7}$(syst) MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV

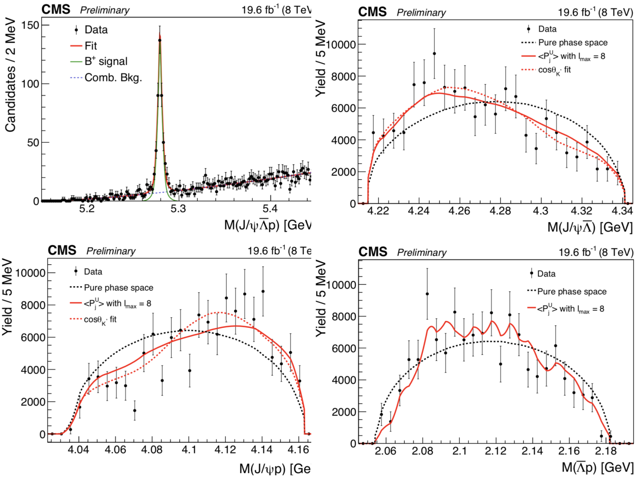
2-P_c p-value $= 55.7\%$



4-P_c p-value $= 68.6\%$



Searches of new exotic resonances at CMS: $B^+ \to J/\psi \bar{\Lambda} p$ [JHEP 12 (2019) 100]

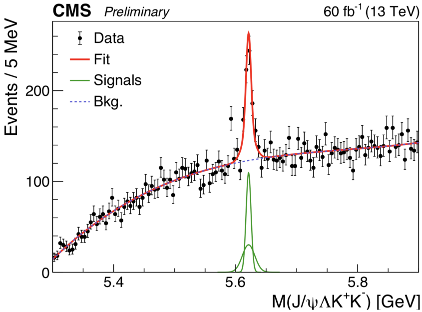


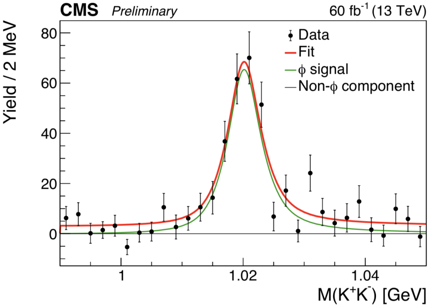
- Using 2012 $\sqrt{s} = 8\,\text{TeV}$ $(19.6\,\text{fb}^{-1})$ data sample
- Possibility to study both near-threshold $J/\psi p$ and $J/\psi\bar{\Lambda}$ systems
- Spectra consistent with $K^* \to \bar{\Lambda} p$ contributions

$$\mathcal{B}(B^+ \to J/\psi \bar{\Lambda} p)/\mathcal{B}(B^+ \to J/\psi K^{*+}) = (1.054 \pm 0.057 \pm 0.028 \pm 0.011) \times 10^{-2}$$

Searches of new exotic resonances at CMS: $\Lambda_b^0 \to J/\psi\Lambda\phi$ observation

[PLB802(2020)135203]



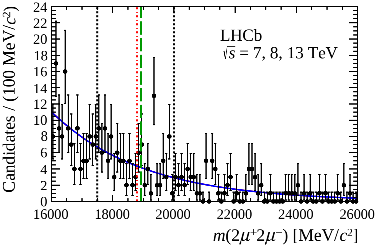


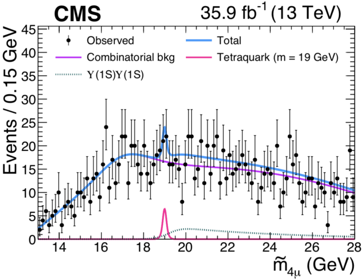
- using a data sample corresponding to $60\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13\,\mathrm{TeV}$
- Observation of $\Lambda_b^0 \to J/\psi\Lambda\phi$ with 286 ± 29 events
- $\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda\phi)/\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda\phi) = (8.26 \pm 0.90 \pm 0.68 \pm 0.11) \times 10^{-2}$
- Opportunity to further explore $J/\psi\phi$ and $J/\psi\Lambda$ systems

Tetraquarks

Search for $X_{bb\bar{b}\bar{b}}$ at CMS [arXiv:2002.06393]

- Using data corresponding to $35.9\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$
- Search for heavy bottom tetraquark in the $\Upsilon(1S)\mu^+\mu^-$ final state in $[17.5, 19.5]\,\text{GeV}$
- LHCb: no hint of signal [JHEP10(2018)086]
- Probe of a kinematical region not accessible at LHCb
- In addition generic search for narrow resonances in an extended mass window $[16.5, 27]\,\text{GeV}$
- No significant excess is observed
- Largest excess: $m = 25.1\,\text{GeV}$ with a local significance of 2.4σ

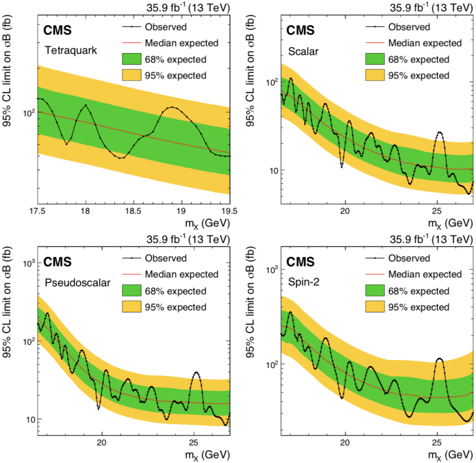




Example with $m = 19\,\text{GeV}$ with $\sim 1\sigma$

Search for $X_{bb\bar{b}\bar{b}}$ at CMS [arXiv:2002.06393]

- ULs set on $\sigma(X_{bb\bar{b}\bar{b}} \times \mathcal{B}(X_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu^+\mu^-)$ using different signal models



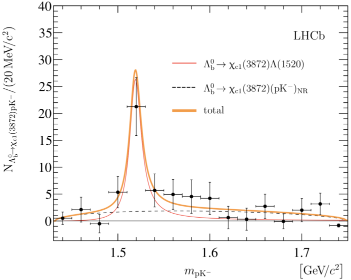
- ULs between 5 and $380\,\mathrm{pb}$ depending on the mass and signal model

$X(3872)$

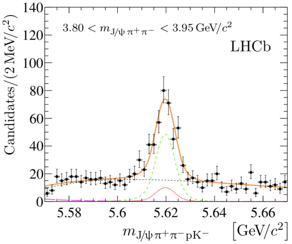
- Observed for the first time in 2003 by the Belle collaboration [JHEP09(2019)028]
- First observation of an unexpected charmonium candidate: resurrection of the interest in the non-conventional states spectroscopy
- Nature of $X(3872)$ still unclear: suggested several exotic interpretations (tetraquark, molecule, mixture ...)
- More measurements of b hadron decays involving $X(3872)$ production would provide important inputs for understanding its internal structure and creation dynamics
- In addition lineshape studies can shed a light on the nature of this state

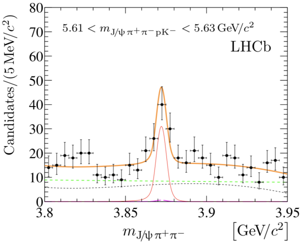
$\Lambda_b^0 \to X(3872)pK^-$ at LHCb [JHEP09(2019)028]

- Using data corresponding to 1.0, 2.0 and $1.9\,\mathrm{fb}^{-1}$ at 7, 8 and 13 TeV
- First observation $\Lambda_b^0 \to X(3872)pK^-$ with $X(3872) \to J/\psi\pi^+\pi^-$
- Signal yield determined from a 2D fit to $(M_{J/\psi\pi^+\pi^- pK^-}, m_{J/\psi\pi^+\pi^-})$



$(58 \pm 15)\%$ proceed via $\Lambda_b^0 \to X(3872)\Lambda(1520)$



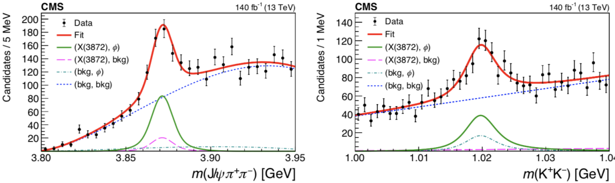


$N = 55 \pm 11$ with 7σ

$$\frac{\mathcal{B}(\Lambda_b^0 \to X(3872)pK^-)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)pK^-)} \times \frac{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (5.4 \pm 1.1 \pm 0.2) \times 10^{-2}$$

$B_s^0 \to X(3872)\phi$ at CMS [arXiv:2005.04764]

- Using data corresponding to $140\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13\,\mathrm{TeV}$
- Observation of $B_s^0 \to X(3872)\phi$ with $X(3872) \to J/\psi\pi^+\pi^-$ and $\phi \to K^+K^-$
- Signal yield determined from a 2D fit to $(M_{J/\psi\pi^+\pi^-}, m_{K^+K^-})$
- $N(B_s^0 \to X(3872)\phi) = 299 \pm 39$ with $> 6\sigma$



$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi)} \times \frac{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (2.21 \pm 0.29 \pm 0.17)\%$$

- Significant difference in branching fraction ratio compared to $\psi(2S)$ modes

$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 0.482 \pm 0.063 \pm 0.037 \pm 0.070$$

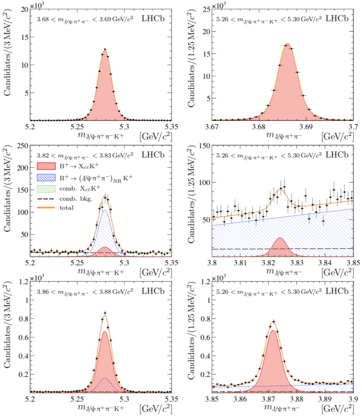
$$\frac{\mathcal{B}(B_s^0 \to \psi(2S)\phi)}{\mathcal{B}(B^+ \to \psi(2S)K^+)} = 0.87 \pm 0.10$$

- $X(3872)$ formation in B meson decays is different from $\psi(2S)$ formation: $X(3872)$ is not a pure charmonium state

$X(3872)$ and $\psi_2(3823)$ at LHCb [arXiv:2005.13422]

- Using data corresponding to $9\,\text{fb}^{-1}$ at $\sqrt{s} = 7$, 8 and $13\,\text{TeV}$
- First observation of $B^+ \to (\psi_2(3823) \to J/\psi\pi^+\pi^-)K^+$ with 5σ $(N = 137 \pm 26)$
  $\frac{\mathcal{B}(B^+\to\psi_2(3823)K^+)\times\mathcal{B}(\psi_2(3823)\to J/\psi(2S)\pi^+\pi^-)}{\mathcal{B}(B^+\to\psi(2S)K^+)\times\mathcal{B}(\psi(2S)\to J/\psi(2S)\pi^+\pi^-)} = (1.31 \pm 0.25 \pm 0.04) \times 10^{-3}$
- Using a BW parametrisation masses and widths are measured
  $m_{\psi_2(3823)} = 3824.08 \pm 0.53 \pm 0.14 \pm 0.01\,\text{MeV}$
  $m_{\chi_{c1}(3872)} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01\,\text{MeV}$
  $\Gamma_{\psi_2(3823)} < 5.2(6.6)\,\text{MeV}$ at $90(95)\%$
  $\Gamma_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21\,\text{MeV}$

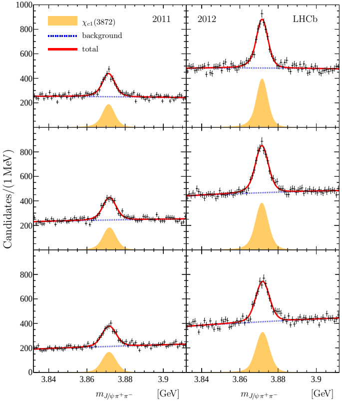
2D fit to $(M_{J/\psi\pi^+\pi^-K^-}, m_{J/\psi\pi^+\pi^-})$



$X(3872)$ lineshape at LHCb [arXiv:2005.13419]

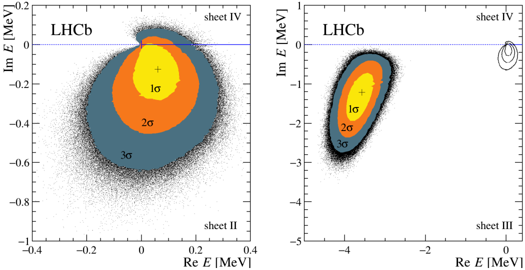
- Run1 data ($3\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7,\ 8\,\mathrm{TeV}$)
- $X(3872) \to J/\psi\pi^+\pi^-$ from b-hadron decays
- Mass resolution is studied using simulation samples and the large sample of $\psi(2S) \to J/\psi\pi^+\pi^-$ decays
- Analysis is performed in $p_{\pi^+\pi^-}$ bins to consider resolution dependence

- Breit-Wigner fit
  $m_{X(3872)} - m_{\psi(2S)} = 185.598 \pm 0.067 \pm 0.068\,\mathrm{MeV}$
  $m_{X(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010\,\mathrm{MeV}$
  $\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10\,\mathrm{MeV}$
  $\delta E = m_{D^0} + m_{\bar{D}^{*0}} - m_{X(3872)} = 0.01 \pm 0.14\,\mathrm{MeV}$
- Flatté lineshape accounts for the opening up of $\bar{D}^0 D^{*0}$ threshold
- Flattè fit:
  Mode $= 3871.69^{+0.00+0.05}_{-0.04-0.13}\,\mathrm{MeV}$ (in agreement with the mean of the BW lineshape)
  FWHM $= 0.22^{+0.06+0.25}_{-0.08-0.17}$
- FWHM $\ll \Gamma_{BW}$: importance of a physically well-motivated lineshape parameterization



$X(3872)$ lineshape at LHCb [arXiv:2005.13419]

- To investigate the nature: analytic structure of the amplitude examined in the vicinity of the $D^0\bar{D}^0$ threshold
- Two poles are found: one pole appears on the physical sheet; the other on the unphysical sheet $\Rightarrow$ quasi-bound $D^0\bar{D}^0$ state (with $E_b < 100\,\mathrm{keV}$)
- First pole allowed on the unphysical sheet at the 2σ level: quasi-virtual state assignment cannot be excluded.



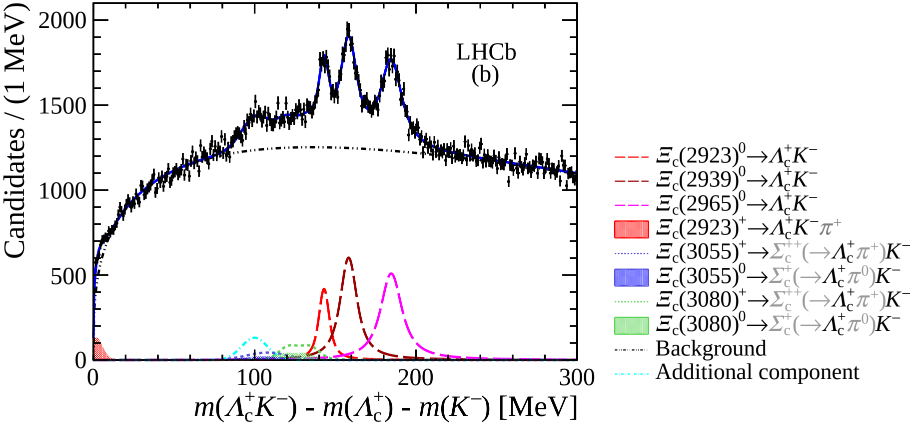
- Asymmetry of the locations of the two poles: information on the composition of the $X(3872)$ state: molecular or compact state
- Relative fraction of compact component is 15% and can reach a maximum of 33%

Conclusions

- After the discovery of the five excited Ω_c states, observation of the analogous Ω_b^{**-} and Ξ_c^0 resonances!
- Observed now five excited Λ_b^0
- Possibility for discovering new exotic states is opening up
  - New channels with potential for discovery of exotic states are under study
  - Search for fully heavy tetraquark states started
- Knowledge of the $X(3872)$ is constantly improving
  - Non-pure charmonium state is suggested from the study of b-decays
  - Improvement in the mass and width measurements
  - Study of the Flatté lineshape
- Continuing to exploit LHC experiment potential adding Run2 data
- Long Shutdown 2 started, the detectors are going to be upgraded: collect a larger data sample with high efficiency starting in 2021!

Spare slides

$\Lambda_c^+ K^-$ spectrum



Nominal fit model does not accurately describe the data in the mass region close to the kinematic threshold: additional component due to the partial reconstruction of the state that peaks around $\Delta M \simeq 140\,\mathrm{MeV}$ when it decays directly to the $\Lambda_c K^- \pi^+$ final state without any intermediate resonance.