Baryons and pentaquarks

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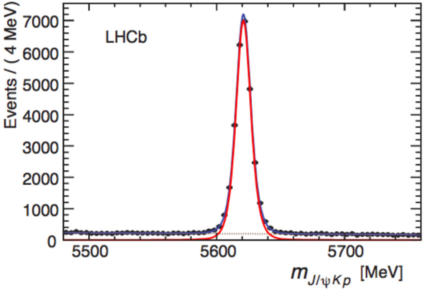
Outline

- Pentaquarks searches
  - Exotic baryonic resonances in $\Lambda_b^0 \to J/\psi p K^-$ [LHCb, PRL 115 (2015) 072001 - LHCb, PRL 117, 082002 (2016)]
  - and in $\Lambda_b^0 \to J/\psi p \pi^-$ [LHCb, PRL 117, 082002 (2016)]
  - Observation of $\Xi_b^- \to J/\psi \Lambda K^-$ [LHCb, arXiv: 1701.05274]
  - Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ decays [LHCb, arXiv: 1704.07900
- Standard baryon spectroscopy
  - Heavy-dilight baryons
    - Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$ [LHCb, PRL 118 (2017) 182001]
    - Excited Λ_c^+ states in $\Lambda_b^0 \to D^0 p \pi^-$ [LHCb, arXiv:1701.07873]
    - Improved measurement of Ξ_c masses and first observation of $\Xi_c(3055)^0$ state [Belle, PRD 94, 032002 - Belle, PRD 94, 052011 (2016)]
  - Beauty baryons
    - Ξ_b^* states [CMS, PRL 108 (2012) 252002, LHCb, PRL 114 (2015) 062004 - LHCb, JHEP 05 (2016) 161]

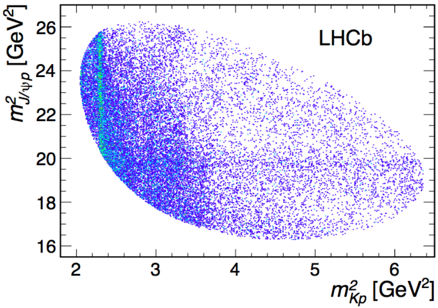
Exotic baryonic resonances in $\Lambda_b^0 \to J/\psi p K^-$ [LHCb, PRL 115 (2015) 072001, PRL 117, 082002 (2016)] and in $\Lambda_b^0 \to J/\psi p \pi^-$ [LHCb, PRL 117, 082002 (2016)]

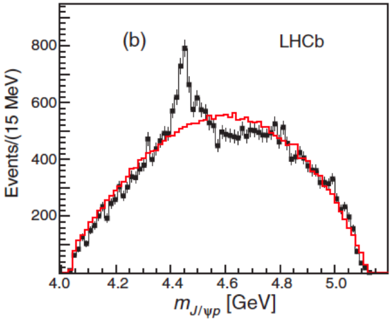
$\Lambda_b \to J/\psi K^- p$ [LHCb, PRL 115 (2015) 072001]

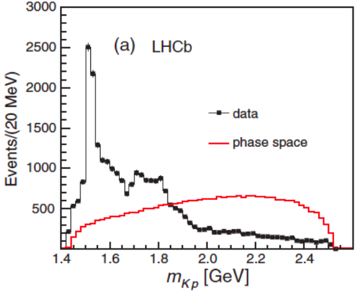
- Sample with > 26000 Λ_b^0 signal candidates in $3\,\mathrm{fb}^{-1}$
- Background from sidebands: only 5.4% of combinatorial bkg in the signal region



- The decay was used to measure Λ_b^0 lifetime [LHCb, PRL111 (2013) 102003]
- But looking closer at the $J/\psi pK$ Dalitz plot with $3\,\mathrm{fb}^{-1}$ of data





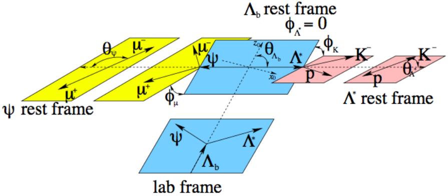


- Large activity due to Λ^* excited states

- Unexpected narrow peak in the $m_{J/\psi p}$ at $19.5\,\mathrm{GeV}^2$
- Cross-checks to exclude possible artifacts:
  - Efficiencies vary smoothly
  - Veto of the $B_s \to J/\psi KK$ and $B^0 \to J/\psi K\pi$ after swapping the mass hypothesis of the Λ_b daughters
  - Removed clone and ghost tracks
  - Not a partially reconstructed Ξ_b decay
- None of them explained the narrow peak

- Could the interference between Λ^* resonances generate a peak in the $J/\psi p$ mass spectrum?
- Analyze all dimensions of the $\Lambda_b^0 \to J/\psi p K^-$, $J/\psi \to \mu^+\mu^-$ decay kinematics:
  - to maximise sensitivity to the decay dynamics
  - to avoid biases due to averaging over some dimensions in presence of the non-uniform detector efficiency
- 6D amplitude fit based on the helicity formalism using the isobar model: the matrix element $\mathcal{M}$ is parametrized as a function of the invariant mass m^2_{pK} and 5 angles (helicity and decay planes angles)
- Two different background subtraction methods have been investigated

Λ^* decay chain



Amplitude analysis with Λ^*

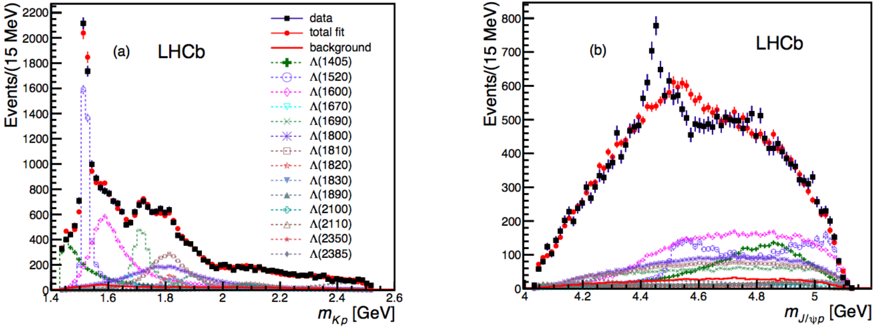
- Dynamical amplitudes given by relativistic Breit-Wigners plus the Flatte parametrization for the $\Lambda(1405)$
- Two models: Reduced (No high-J^P high-mass states, less LS-coupling) and Extended with all known Λ^* states

State	J^P	M_0 (MeV)	Γ_0 (MeV)	Red.	Ext.
Λ(1405)	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
Λ(1520)	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
Λ(1600)	$1/2^+$	1600	150	3	4
Λ(1670)	$1/2^-$	1670	35	3	4
Λ(1690)	$3/2^-$	1690	60	5	6
Λ(1800)	$1/2^-$	1800	300	4	4
Λ(1810)	$1/2^+$	1810	150	3	4
Λ(1820)	$5/2^+$	1820	80	1	6
Λ(1830)	$5/2^-$	1830	95	1	6
Λ(1890)	$3/2^+$	1890	100	3	6
Λ(2100)	$7/2^-$	2100	200	1	6
Λ(2110)	$5/2^+$	2110	200	1	6
Λ(2350)	$9/2^+$	2350	150		6
Λ(2585)	?	≈2585	200		6
				64	146

Last columns show number of parameters are left free. Masses and Width are fixed.

Fit results without pentaquark states

- m_{Kp} projection looks fine, but the fit projection can't reproduce the peaking structure in $J/\psi p$

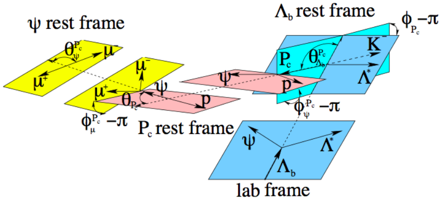


- Extended model used in this fit: adding more Λ resonances does not help
- Letting the width and masses floating does not help
- Additions of non-resonant term and suppressed Σ^* states does not help

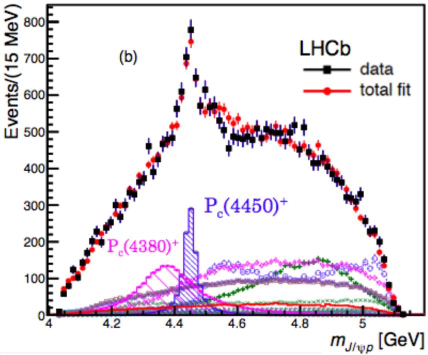
P_c^+: Fit results with pentaquark states

[LHCb, PRL 115 (2015) 072001]

Adding a $\Lambda_b^0 \to P_c K^-$ decay chain allowed to interfere with $\Lambda_b^0 \to J/\psi \Lambda^*$ chain



Reduced Λ^* model keeping only well motivated 12 states + 2 P_c^+

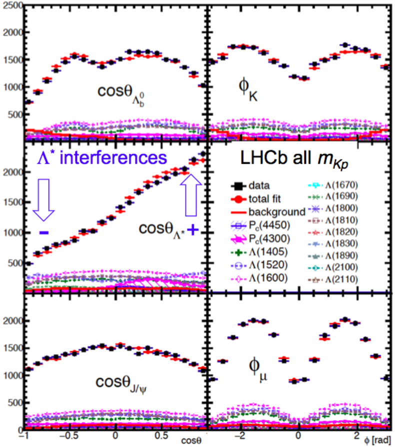


- Reduced Λ^* model + 2 pentaquarks
  - Good fit even with the reduced Λ^* model
  - Best fit has $J^P = (3/2^-, 5/2^+)$ also $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ preferred
  - Adding further states (also in $J/\psi K$) did not improve the fit significance

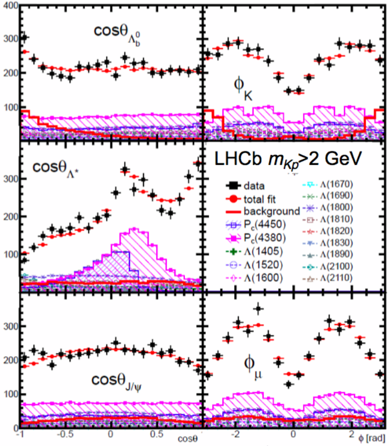
Angular distributions

[LHCb, PRL 115 (2015) 072001]

All data



P_c enriched region



- Good description of the data in all 6 dimensions!

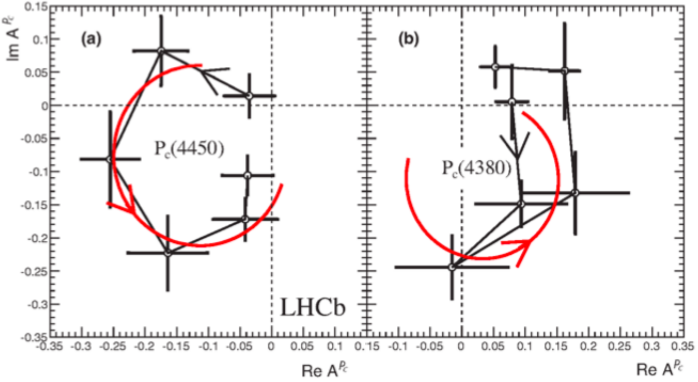
Significances and results [LHCb, PRL 115 (2015) 072001]

- Simulations of pseudo-experiments are used to quote the significances
  - $P_c(4450)^+$: 12σ
  - $P_c(4380)^+$: 9σ
- Main systematic uncertainty: difference between extended and reduced fit models
- Systematic uncertainty included when computing significances
- Spin-parity assignment not conclusive

State	Mass [MeV]	Width [MeV]	fav. J^P	Fit fraction
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$	$(8.4 \pm 0.7 \pm 4.2)\%$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+$	$(4.1 \pm 0.5 \pm 1.1)\%$

Argand diagrams [LHCb, PRL 115 (2015) 072001]

- Alternative fit: replace BW amplitude with 6 independent complex numbers in 6 bins of $m_{J/\psi p}$ in region $m_0 \pm \Gamma_0$ where m_0 is the mass of P_c^+

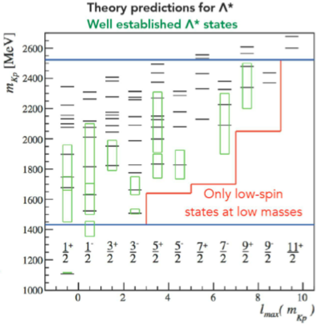


- $P_c(4450)$ shows resonance behaviour: a rapid counter-clockwise change of phase across the pole mass
- The errors for $P_c(4380)$ are too large to be conclusive

Model independent analysis of $\Lambda_b^0 \to J/\psi p K^-$

[LHCb, PRL 117 082002]

- Amplitude analyses are powerful tool but are model dependent
- The Λ^* spectroscopy is complex and not completely understood
- High density of states with large widths
- Not trivial to model NR components: the NR $K^- p$ component could have non trivial mass-dependence
- Isobar model has well known limitation: unitarity violation when adding broad overlapping states. K-matrix formalism?

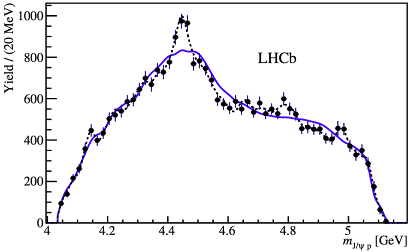


- Strategy: assess level of consistency of data with only $\Lambda_b^0 \to J/\psi \Lambda^*$ hypothesis (H_0)
- Inspect the data with a model independent approach wrt $K^- p$ contributions
- Allow a maximum spin of Λ^* components in each interval of Kp invariant mass
- Decompose angular distribution in each m_{Kp} bin into the sum of Legendre polynomials calculated from the Λ^* helicity angle $\frac{dN}{d\cos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$

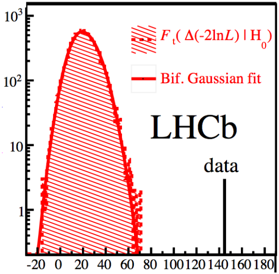
Model independent analysis of $\Lambda_b^0 \to J/\psi p K^-$

[LHCb, PRL 117 082002]

- A normalized weight is calculated and used to reweight generated uniformly in $(m_{Kp}, \cos\theta_{\Lambda^*})$ simulated events by the m_{Kp} and moments to obtain a prediction for $m_{J/\psi p}$ distribution
- null hypothesis gives poor description of $m_{J/\psi p}$



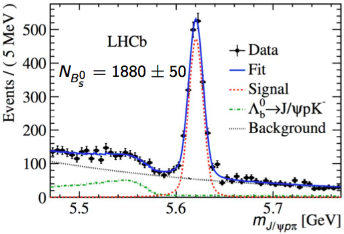
- Hypothesis test through likelihood ratio
- Compare null hypothesis with data

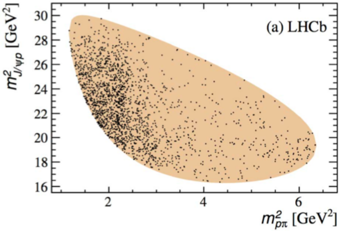


- The hypothesis that data can be described by reflections of Kp structures is excluded at 9σ!
- This result supports the amplitude model-dependent observation of the $J/\psi p$ resonances

Search for exotics in $\Lambda_b^0 \to J/\psi p \pi^-$ [LHCb, PRL 117, 082003 (2016)]

- Observing the same P_c^+ states in a different decay mode could indicate they are really resonances and not some kinematic effects [arXiv:1512.01959]
- No striking features in the Dalitz plot [$N(1535)$, $Z_c(4200)^+$?, P_c?]

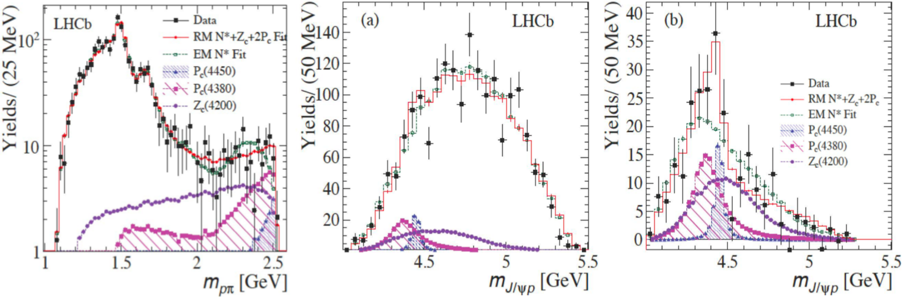




- Limited sample size (Cabibbo suppressed decay with statistics about factor 10 lower and background $\sim 20\%$, $3\times$ larger)
- Six-dimensional fit to interfering amplitudes: more complicated dynamics
  - $\Lambda_b^0 \to J/\psi N^*$ dominant contributions
  - $\Lambda_b^0 \to P_c^+ \pi^-$
  - $\Lambda_b^0 \to Z_c p$ [PRD 90 (2014) 112009]

- $N^* \to p\pi^-$ contributions:
  - Baseline: isobar $p\pi^-$ with 7-14 states
  - Tried BW and Flatté for N(1535) (opening of nη threshold)
  - Cross-check: K-matrix for $1/2^-$ $p\pi^-$ contributions [arXiv:0911.5277]
- P_c^+ and Z_c^- parameters fixed (limited statistics)

$m_{p\pi} > 1.8\,\mathrm{GeV}$



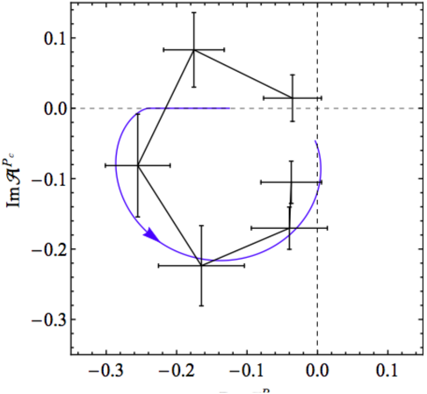
- The combined significance of these three exotic states together is more than 3σ: evidence for exotic hadrons. Individual exotic hadron contributions are not significant.
- Fit fractions consistent with what expected for the Cabibbo suppressed decay

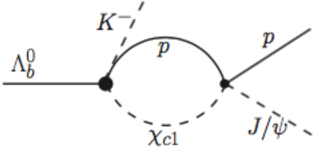
Observation of $\Lambda_b \to \chi_{c(1,2)} p K^-$ decays and measurement of the Λ_b^0 mass

[LHCb, arXiv: 1704.07900]

Test of the exotic nature of $P_c(4450)$

- $P_c(4450)^+$ is close to $\chi_{c1}p$ threshold: could be explained by kinematic rescattering effects [PLB 751 (2015) 59, PRD 91 (2015) 071502 (R)]
- Information from $\chi_{c1}p$ can help to understand observed pentaquarks: would not explain narrow enhancement in $\chi_{c1}p$



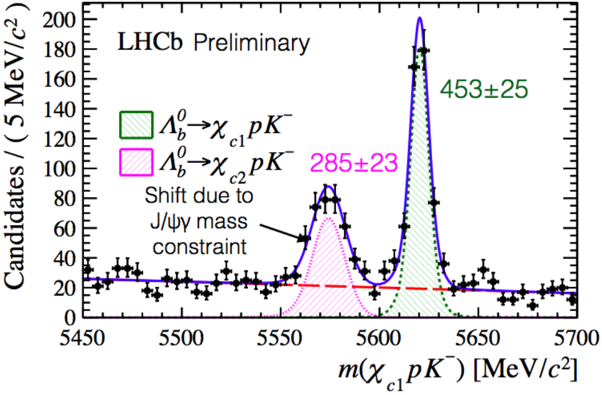


Observation of $\Lambda_b \to \chi_{c(1,2)} p K^-$

[LHCb, arXiv: 1704.07900]

- Reconstructed with $\chi_{c(1,2)} \to J/\psi\gamma$ with $J/\psi\gamma$ mass constrain to the χ_{c1} mass

- Dataset: $3\,\mathrm{fb}^{-1}$
- Selection consisting of a multivariate classifier based on a gradient-boosted decision tree



- Observed two modes: $\Lambda_b^0 \to \chi_{c1} p K$ (29σ) and $\Lambda_b^0 \to \chi_{c2} p K$ (17σ)

Observation of $\Lambda_b \to \chi_{c(1,2)} p K^-$ - Results

[LHCb, arXiv: 1704.07900]

- Measured branching ratios wrt $\Lambda_b^0 \to J/\psi p K$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = 1.02 \pm 0.10 \pm 0.02 \pm 0.05$$

where the first uncertainty is statistical, the second systematic and the third due to the uncertainty on the branching fractions of the $\chi_{c1(2)} \to J/\psi\gamma$ decays

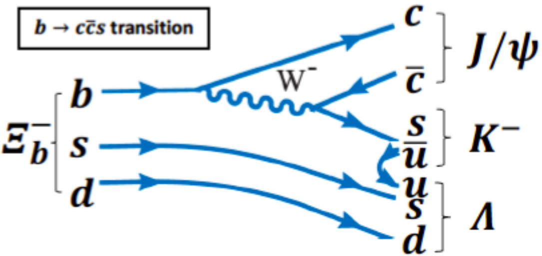
- Using both decay modes, measurement of the mass of Λ_b^0:

$$m(\Lambda_b^0) = 5619.44 \pm 0.28 \pm 0.25\,\mathrm{MeV}/c^2$$

Observation of $\Xi_b \to J/\psi \Lambda K$ [LHCb, arXiv:1701.05274]

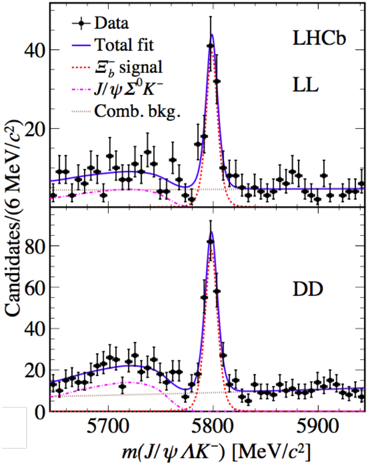
Observation of $\Xi_b \to J/\psi\Lambda K$ [LHCb, arXiv:1701.05274]

- With observation of two hidden charm pentaquark states, quest for other such states
- Suggested to search for strangeness hidden charm pentaquark state ($udsc\bar{c}$) in the $J/\psi\Lambda$ system: predicted state with a mass of $4650\,\mathrm{MeV}$ and a width of order of $10\,\mathrm{MeV}$ [PRC 93 (2016) 065203]
- $\Xi_b \to J/\psi\Lambda K$ channel has a similar topology to $\Lambda_b^0 \to J/\psi pK$ mode by replacing the u by the s quark



Observation of $\Xi_b \to J/\psi \Lambda K$ [LHCb, arXiv:1701.05274]

- Λ can decay inside (LL) or outside the vertex detector (DD)
- ~ 300 candidates in Run1 $(3\,\mathrm{fb}^{-1})$
- J/ψ and Λ mass constrained
- First observation!
- Branching ratio measured relative to $\Lambda_b^0 \to J/\psi \Lambda$:



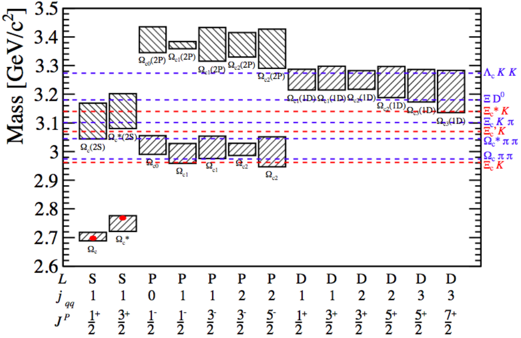
$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \lambda)} = (4.19 \pm 0.29(\mathrm{stat}) \pm 0.14(\mathrm{syst})) \times 10^{-2}$$

Baryon spectroscopy

Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$ [LHCb, PRL 118 (2017) 182001]

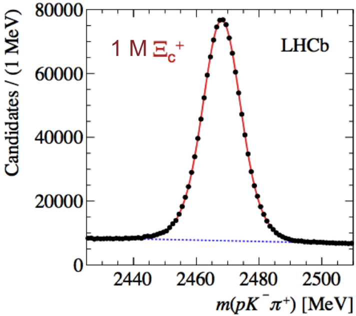
Excited Ω_c^0 states

- Spectroscopy of charmed baryons is intricate
- Spectrum predictions using HQET: precise measurements of the excited heavy meson properties to test of the validity of HQET
- Only two ground states Ω_c^0 $(J^P = 1/2^+)$ and Ω_c^{*0} $(J^P = 3/2^+)$ are known
- Decays to $\Omega_c^0\pi^0$ and $\Omega_c^{*0}\pi^0$ final states are suppressed by isospin-violation
- $\Xi_c K$ is the lowest hadronic threshold



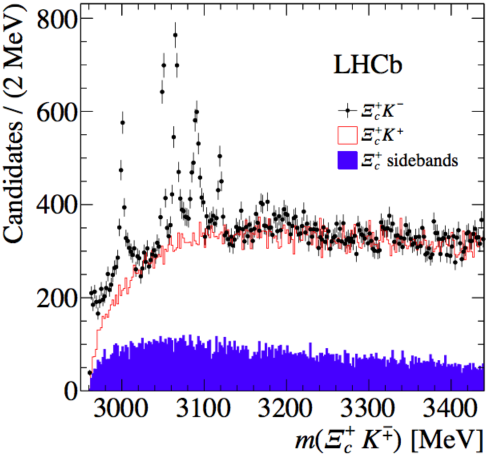
Ξ_c^+ sample

- $\Xi_c^+ \to pK^-\pi^+$: Cabibbo suppressed $c \to d$ decay
- No hyperons in the final state (tend to decay outside the vertex detector)
- Data sample: $1.0\,\text{fb}^{-1}$ (7 TeV) + $2.0\,\text{fb}^{-1}$ (8 TeV) + $0.3\,\text{fb}^{-1}$ (13 TeV)
- Dedicated trigger in the 13 TeV data (and the larger collision energy): boost of the number of reconstructed Ξ_c^+ candidates in the $13\,\text{TeV}$ sample $(\times 3)$
- Data-driven multivariate selection based on likelihood ratios (vertex χ^2, proton and kaon PID, Ξ_c^+ FD, Ξ_c^+ p_T): 83% signal purity



$\Xi_c^+ K^-$ invariant mass

- Ξ_c^+ candidates combined with opposite charge kaons
- 5 narrow peaks in the $\Xi_c^+ K^-$ mass spectrum
- in addition an ehnancement around a mass of 3180 MeV
- No peaks in the wrong sign sample $\Xi_c^+ K^+$
- No peaks in the Ξ_c^+ sidebands K^- sample

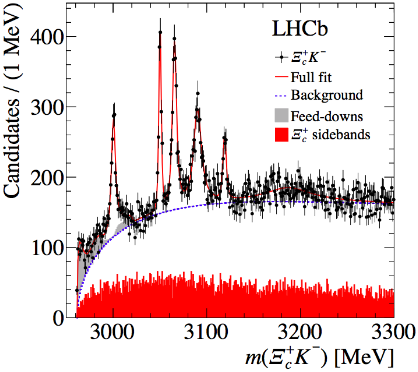


Fit model

- 6 RBW convolved with Gaussian PDF (resolution 0.7-$1.7\,\mathrm{MeV}$)
- 3 feed-downs due to $\Omega_c^0 \to \Xi_c'^+ K^-$ with $\Xi_c'^+ \to \Xi_c^+ \gamma$
  - States with masses $M > m(\Xi_c') + m(K)$ could decay also to $\Xi_c' K^-$ and appear into $\Xi_c K^-$ as partially reconstructed decays (i.e. feed-downs)
- Wrong-sign sample to study combinatorial background parameterisation

$$B(m) = \begin{cases} P(m) e^{a_1 m + a_2 m^2} & \text{for } m < m_0, \\ P(m) e^{b_0 + b_1 m + b_2 m^2} & \text{for } m > m_0, \end{cases}$$

where $P(m)$ is a two-body phase-space factor, m_0, a and b are free parameters



Results

- Observation of 5 new excited Ω_c states with significances greater than 5σ
- The broad state ($\Omega_c(3188)$) could be a superposition of several states
- The largest systematic uncertainty is due to possible interference and due to the Ξ_c^+ mass knowledge

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\text{MeV}, 95\%$ CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\text{MeV}, 95\%$ CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\text{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\text{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\text{fd}}$			$190 \pm 70 \pm 20$	

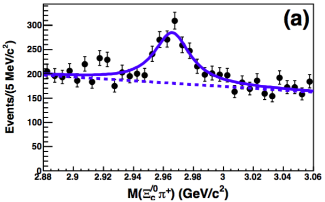
Ξ_c Charmed Baryon Decays at Belle using the entire $980\,\mathrm{fb}^{-1}$ of data [Belle, PRD 94, 032002 - Belle, PRD 94, 052011 (2016)]:

- using particles produced in the charm continuum
- easier to detect and with a better signal/noise ratio
- $\Xi_c^{*(*)} \rightarrow \Xi_c X$ decays
- $\Xi_c^{*(*)} \rightarrow \Lambda D$ decays

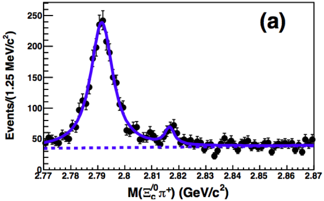
Ξ_c Charmed Baryon Decays at Belle [Belle, PRD 94, 032002]

- Study of 5 different Ξ_c states:
  $\Xi_c^{'}$ $(J^P = 1/2^+)$,
  $\Xi_c^{'}(2646)$ $(J^P = 3/2^+)$,
  $\Xi_c(2790)$ $(J^P = 1/2^-)$,
  $\Xi_c(2815)$ $(J^P = ?)$
  using several decay modes
- Measurements of masses and widths
- All measured values significantly more precise than PDG: to investigate hadron mass models including isospin splittings
- Good agreement with theoretical expectations, modest disagreement for the $\Xi_c(2980)$ state wrt previous measurements

$\Xi_c(2980) \to \Xi_c^{'}\pi^+$

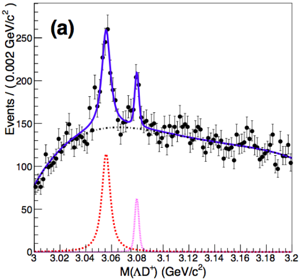


$\Xi_c(2790) \to \Xi_c^{'}\pi^+$
$\Xi_c(2815) \to \Xi_c^{'}\pi^+$



Ξ_c Charmed Baryon Decays at Belle

$\Xi_c^+(3055)$, $\Xi_c^+(3080)$



$\Lambda D^+(\rightarrow K\pi\pi)$

- Study of Ξ_c^* decaying to ΛD^+ and ΛD^0 states
- First observation of the $\Xi_c(3055)^0$ with 8.6σ
  $M(\Xi_c(3055)^0) = 3059.0 \pm 0.5 \pm 0.6$
  $\Gamma(\Xi_c(3055)^0) = 6.4 \pm 2.1 \pm 1.1$
- Combined analysis coomparing ΛD^+ with $\Sigma_c^{++}K^-$ and $\Sigma_c^{*++}K^-$

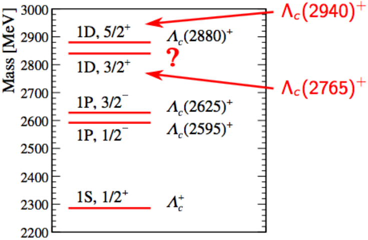
$$\mathcal{B}(\Xi_c(3055)^+ \rightarrow \Lambda D^+)/\mathcal{B}(\Xi_c(3055)^+ \rightarrow \Sigma_c^{++}K^-) = 5.09 \pm 1.01 \pm 0.76$$
$$\mathcal{B}(\Xi_c(3080)^+ \rightarrow \Lambda D^+)/\mathcal{B}(\Xi_c(3080)^+ \rightarrow \Sigma_c^{++}K^-) = 1.29 \pm 0.30 \pm 0.15$$
$$\mathcal{B}(\Xi_c(3080)^+ \rightarrow \Sigma_c^{++}(2520)K^-)/\mathcal{B}(\Xi_c(3080)^+ \rightarrow \Sigma_c^{++}K^-) = 1.07 \pm 1.01 \pm 0.76$$

- Contradictions with expectations from theory

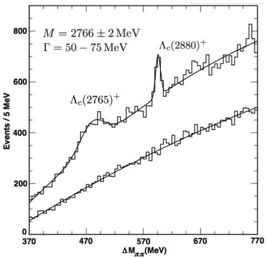
$\Lambda_c^+(2940)$ and other states in D^0p [LHCb, arXiv:1701.07873]

Excited Λ_c^+ states

[EPJC A51 (2015) 82]

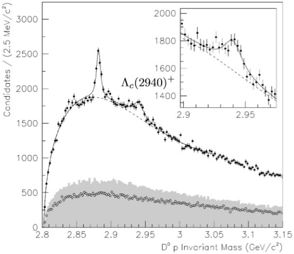


CLEO, PRL86 4479 (2001)



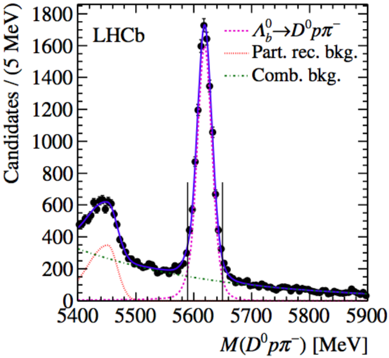
- $J^P = 3/2^+$ state (2nd member of the D-wave doublet) is missing in data
- Two experimentally observed states without clear assignment: $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$
- $\Lambda_c(2940)^+$: mass close to the D^*N threshold: possible molecular interpretation

BABAR, PRL 98 012001 (2007)



Amplitude analysis of $\Lambda_b^0 \to D^0 p\pi^-$ decay at LHCb [LHCb, arXiv:1701.07873]

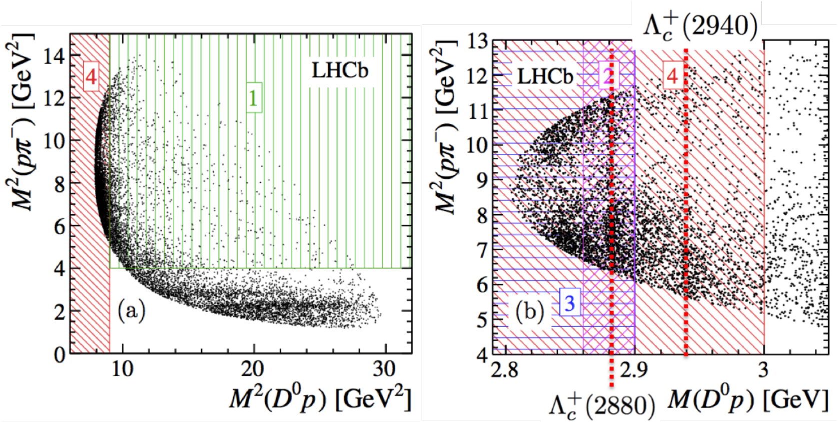
- Search for excited Λ_c^+ states in exclusive b decays: $\Lambda_b^0 \to D^0 p\pi^-$, $D^0 \to K^-\pi^+$
- Advantages: well-defined initial state, low background, access to quantum numbers



Signal yield: 11212 ± 126 events
Background: $\sim 16\%$

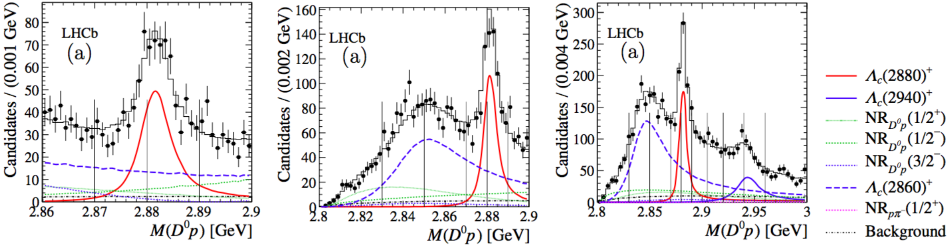
Amplitude analysis of $\Lambda_b^0 \to D^0 p \pi^-$ decay

- Λ_b^0 polarisation small: 2 DoF, 2D Dalitz plot phase space
- PWA in the low-$M(D^0p)$ region (admixture of $p\pi^-$ amplitude is small)

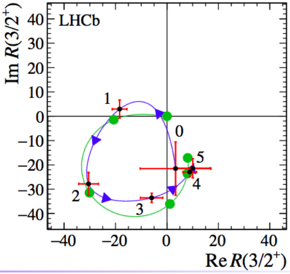


Amplitude analysis of $\Lambda_b^0 \to D^0 p \pi^-$ decay

- Fit in subregions, gradually extended since many unexplored contributions: large number of unknown parameters and large range of systematic variations



- Fit model: $\Lambda_c(2880)^+$, ($J^P = 5/2^+$), $\Lambda_c^+(2940)$, $\Lambda_c(2860)^+$ (J^P varied) and non resonant (exponential or 2nd-order polynominal, $J^P = 1/2^\pm, 3/2^\pm$).
- Rotation of phase for $J^P = 3/2^+$ component ($\Lambda_c(2860)^+$) wrt. non-resonant amplitude



Amplitude analysis of $\Lambda_b^0 \to D^0 p \pi^-$ decay

- Near-threshold enhancement in the $D^0 p$ amplitude: $\Lambda_c(2860)^+$, $J^P = 3/2^+$

$$M(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7} \pm 0.5(syst)^{+1.1}_{-5.6}(model)\,\mathrm{MeV}$$

$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1} \pm 1.4(syst)^{+5.9}_{-20.0}(model)\,\mathrm{MeV}$$

- Phase rotation obtained in a model independent way consistent with resonant behaviour
- Fits well into Λ_c^+ spectrum as $1D$ state (nonrelativistic heavy quark-light diquark model [arXiv:1609.07967]/QCD sum rules in the HQET framework [PRD94 (2016) 114016])
- First constraints on the spin and parity of the $\Lambda_c(2940)$: preferred $J^P = 3/2^-$

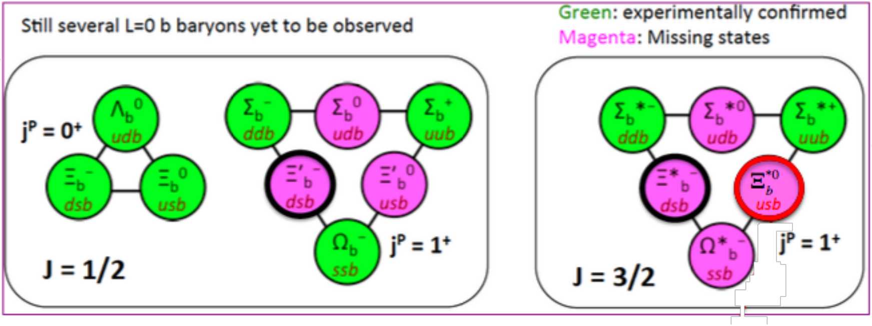
$$M(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5} \pm 0.4(syst)^{+0.1}_{-4.6}(model)\,\mathrm{MeV}$$

$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0} \pm 0.9(syst)^{+5.2}_{-10.4}(model)\,\mathrm{MeV}$$

- $J^P = 3/2$ (1/2 and 7/2 cannot be excluded) consistent with molecular interpretation [PRD89 (2014) 096006, PLB 718 (213) 1381, 1405.0919] or radial $2P$ excitation [EPJ A51 (2015) 82].

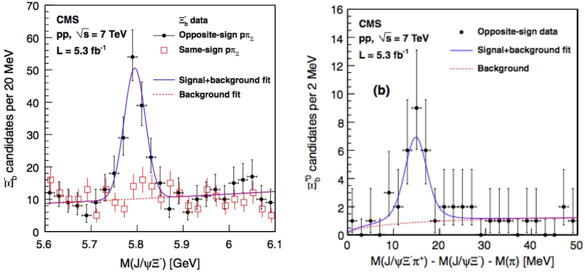
Beauty baryons spectroscopy:

- The system of baryons containing a b quark remains largely unexplored
- Large production cross-section of baryons at LHC



$\Xi_b^{*0} \to \Xi_b^- \pi^+$ observation at CMS [CMS, PRL108 (2012) 252002]

- Observation of a new b baryon in the $\Xi_b^- \pi^+$ with $\Xi_b^- \to J/\psi(\to \mu\mu)\Xi^-(\to \Lambda\pi)$

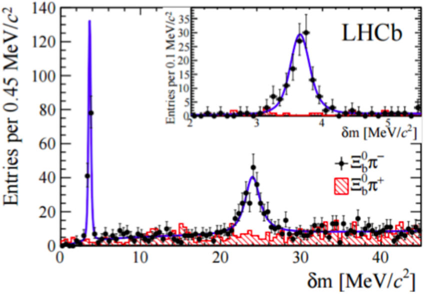


Ξ_b^{*0}: 21 candidates observed, 3 expected (BKG)

- Identified as the $J^P = 3/2^+$ neutral state
- No observation of the $J^P = 1/2^+ (j^P = 1+)$ partner $\Xi_b^{\prime 0}$ in agreement with theoretical models
  - $m(\Xi_b^{\prime}(J^P = 1/2^+) \sim m(\Xi_b) + m(\pi)$
  - $m(\Xi_b^{*}(J^P = 3/2^+) > m(\Xi_b) + m(\pi)$

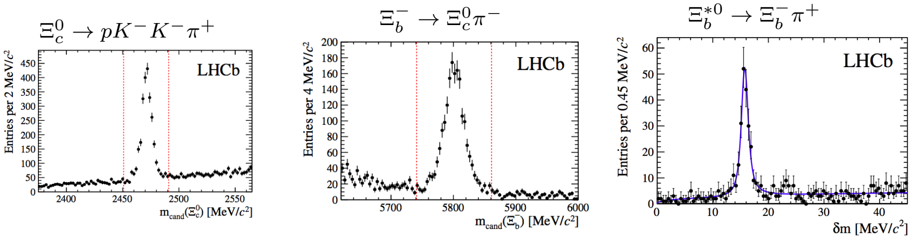
Two new Ξ_b^- baryon resonance [LHCb, PRL 114 (2015) 062004]

- Study of the $\Xi_b^0\pi^-$ combinations in $\Xi_b^0 \to \Xi_c^+\pi^-$ and $\Xi_c^+ \to \Lambda_c^+ pK^-$ using $3\,\mathrm{fb}^{-1}$ of data
- Taking wrong-sign combination as background proxy
- Observation of two narrow peaks, interpreted as $\Xi_b^{'}$ $[1/2^+]$ and Ξ_b^* $[3/2^+]$: mass and angular distributions consistent with expected values
- Very unlikely scenario: narrow peak at $3\,\mathrm{MeV}$ as feed-down of $\Xi_b^{**-} \to \Xi_b^{'0}(\Xi_b^0\pi^0)\pi^-$ (Ξ_b^{**-}=L=1, $J^P = (1/2)^-$)



$$
\begin{aligned}
m(\Xi_b^{\prime -}) - m(\Xi_b^0) - m(\pi^-) &= 3.653 \pm 0.018 \pm 0.006\,\mathrm{MeV}/c^2 \\
m(\Xi_b^{*-}) - m(\Xi_b^0) - m(\pi^-) &= 23.96 \pm 0.12 \pm 0.06\,\mathrm{MeV}/c^2 \\
\Gamma(\Xi_b^{*-}) &= 1.65 \pm 0.31 \pm 0.10\,\mathrm{MeV}
\end{aligned}
$$

Measurement of Ξ_b^{*0} properties [LHCb, JHEP 05 (2016) 161]



- Precise mass measurement

$$m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+) = 15.727 \pm 0.068 \pm 0.023\,\mathrm{MeV}/c^2$$
$$\Gamma(\Xi_b^{*0}) = 0.90 \pm 0.16 \pm 0.08\,\mathrm{MeV}$$

- Compatible with CMS result
- Width compatible with theory expectations [PRD85 (2012) 114508, PRD75 (2007) 094017]

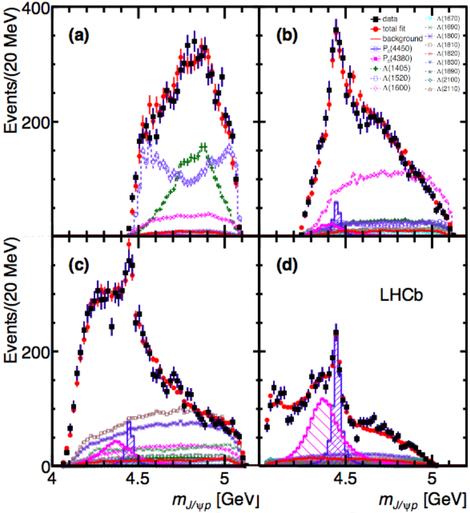
Conclusions

- Followed on pentaquarks observation
  - Check in model independent way
  - Decay $\Lambda_b \to J/\psi p \pi$ consistent with $\Lambda_b \to J/\psi p K$
  - Observed other decays we can use for further searches of pentaquarks
  - Further studies are required: e.g. Cusps can also mimic the circle in the Argand diagram
- Also "conventional" spectroscopy: many excited states are still missing
- 5 narrow peaks observed in $\Xi_c^+ K^-$: excited Ω_c states
  - These states are likely 1P and 2S
  - Determination of their quantum numbers from Ω_b decays might be possible
  - None of the theoretical models predicted the mass splitting exactly
  - Search for other decay modes are ongoing
- Observed new excited Λ_c^+ state
- Missing double heavy baryons (bcq, ccq) [LHCb, JHEP 12 (2013) 090]
- Good experimental prospects with increasing LHC(b) data size and its upgrade program and with Belle II

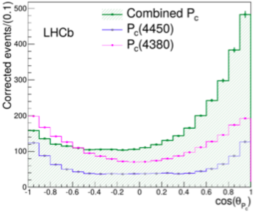
Spare slides

P_c interference [LHCb, PRL 115 (2015) 072001]

$m_{Kp} < 1.55$ GeV $1.55 < m_{Kp} < 1.70$ GeV



$1.70 < m_{Kp} < 2.00$ GeV 2.00 GeV $< m_{Kp}$



- The peaking structure in $m_{J/\psi p}$ is asymmetric as a function of m_{Kp} (or $\cos\theta_{P_c}$)
- This can be explained by interference of two states with opposing parity
- The need for a second broad P_c^+ state becomes visually apparent in the region where the $\Lambda^* \to pK^-$ background is the smallest

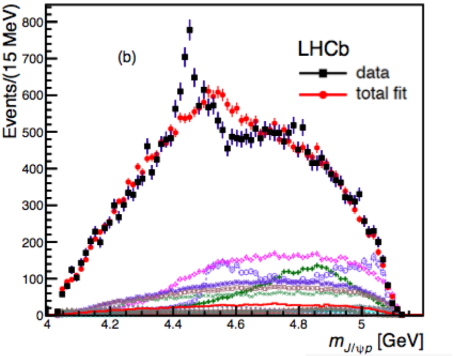
Ξ_b^-

- Ξ_b isodoublets: Ξ_b^0 (bsu) and Ξ_b^- (bds)
- Three such Ξ_b isodoublets that are neither orbitally nor radially excited are expected to exist
- Categorized by
  - j: the spin of the su or the sd diquark
  - J^P: spin-parity of the baryon
- $J = (1/2)^+$ and $j^P = 0$ (Ξ_b decays weak, lightest ones)
- $J = (1/2)^+$ and $j^P = 1$ ($\Xi_b^{'}$)
- $J = (3/2)^+$ and $j^P = 1$ (Ξ_b^*)
- The other should decay strongly ($\Xi_b^{(',*)} \rightarrow \Xi_b \pi$) if their masses are above the kinematich threshold (otherwise electromagnetically)
- $m(\Xi_b^*) - m(\Xi_b)$: above kinematic threshold
- $m(\Xi_b^{'}) - m(\Xi_b)$: close to kinematic threshold

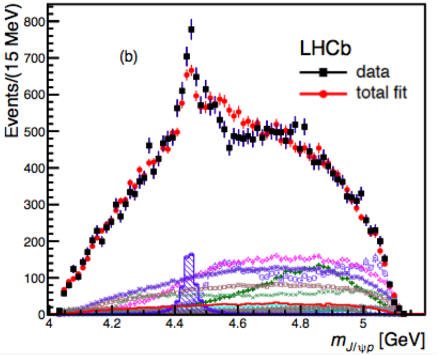
P_c^+: Fit results with pentaquark states

[LHCb, PRL 115 (2015) 072001]

Extended Λ^* model



Extended Λ^* model + 1 P_c^+



- Extended Λ^* model + 1 pentaquark
  - Explored all J^P up to $7/2^{\pm}$
  - Best fit has $J^P = 5/2^+$ but still not a good fit
  - Improvement wrt to fit without P_c: $\sqrt{\Delta 2\mathcal{L}} = 14.7\sigma$

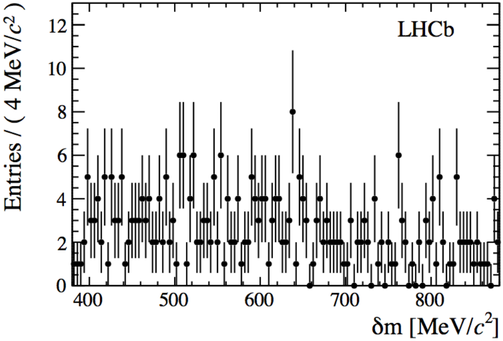
Ξ_c Charmed Baryon Decays at Belle

- Chiral quark model: $\Xi_c(3055)^+$ as D-wave excitation in the $N = 2$ shell
- $\mathcal{B}(\Xi_c(3055)^+ \to \Sigma_c^{++} K^-) : \mathcal{B}(\Xi_c(3055)^+ \to \Lambda D^+) = 2.3 : 0.1$ or $5.6 : 0.0$ depending on the possible excitation modes
- $\Xi_c(3080)^+$ as an S-wave excitation mode in $N = 2$ shell and predicts that its decay into ΛD is forbidden. [PRD 86, 034024 (2012)]

Double Heavy Baryons

- No signal found in $0.6\,\mathrm{fb}^{-1}$

$$\frac{\sigma(\Xi_{cc}^{+})\mathcal{B}(\Xi_{cc}^{+}\to\Lambda_c^{+}K^{-}\pi^{+})}{\sigma(\Lambda_c^{+})} < 1.5\times10^{-2} \text{ at } 95\% \text{ CL}$$



$m(\Lambda_c K\pi)-m(\Lambda_c)-m(K)-m(\pi)$

Additional cross-checks

- Many additional cross-check have been performed
  - Same P_c^+ structure found using very different selections by different LHCb teams
  - Two independently coded fitters using different background subtractions (cFit-sFit)
  - Split data show consistency: $2011/2012$, magnet up/down, ...
  - Extended model fits tried without P_c states, but with two additional high mass Λ^* resonances allowing masses and widths to vary, or 4 non-resonant terms of J up to $3/2$

Systematic uncertainties

Source	M_0 (MeV) low	M_0 (MeV) high	Γ_0 (MeV) low	Γ_0 (MeV) high	Fit fractions (%) low	Fit fractions (%) high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	0.01
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L^{P_c}_{\Lambda_b^0}$ $\Lambda_b^0 \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi p$	4	0.4	31	7	0.63	0.37		
$L^{\Lambda_n^*}_{\Lambda_b^0}$ $\Lambda_b^0 \to J/\psi \Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

Isobar Model helicity amplitudes for $\Lambda_b \to J/\psi\Lambda^*$

- Angular structure of J/ψ decay (no free parameters)
- Helicity coupling for Λ^* decay (complex fit parameters)
- Λ^* resonant amplitudes (masses/widths)

Wigner D-functions for $A \to BC$:

$$D^{J_A}_{\lambda_A,\Delta\lambda_{BC}}(\phi,\theta,0) = \langle J\,\Delta\lambda|\mathcal{R}(\phi,\theta,0)|J\lambda\rangle = e^{i\lambda_A\phi} d^{J_A}_{\lambda_A,\Delta\lambda_{BC}}(\theta)$$

$$D^{\ell}_{m0}(\alpha,\beta,0) = \sqrt{\frac{4\pi}{2\ell+1}}\,Y^{m*}_{\ell}(\alpha,\beta)$$

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu} = \sum_n R_n(m_{Kp})\,\mathcal{H}^{\Lambda^*_n\to Kp}_{\lambda_p}\,\sum_{\lambda_\psi} e^{i\lambda_\psi\phi_\mu}\, d^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi)\;\times$$

$$\sum_{\lambda_{\Lambda^*}} \mathcal{H}^{\Lambda_b\to\Lambda^*_n\psi}_{\lambda_{\Lambda^*},\lambda_\psi}\, e^{i\lambda_{\Lambda^*}\phi_K}\, d^{\frac{1}{2}}_{\lambda_{\Lambda_b},\lambda_{\Lambda^*}-\lambda_\psi}(\theta_{\Lambda_b})\, d^{J_{\Lambda^*_n}}_{\lambda_{\Lambda^*},\lambda_p}(\theta_{\Lambda^*})$$

- Helicity coupling for Λ_b decay (complex fit parameters)
- Angular structure of Λ_b decay (no free parameters)
- Angular structure of Λ^* decay (no free parameters)

Resonance parametrisation

Dynamical Terms $R_n(m_{Kp})$ given by

- Relativistiv, single-channel Breit-Wigner amplitudes $BW(M_{Kp}|M_0^{\Lambda_n^*}, \Gamma_0^{\Lambda_n^*})$
- special case $\Lambda(1405)$ is subthreshold: Flatté ($\mathrm{K}\ \mathrm{p}$ and $\Sigma\ \pi$ channels)
- Blatt-Weiskopf barrier factors $B'_\ell(p, p_0, d)$

$$R_n(M_{Kp}) = B'_{\ell_{\Lambda_b}^{\Lambda_n^*}}(p, p_0, d) \left(\frac{p}{M_{\Lambda_b}}\right)^{\ell_{\Lambda_b}^{\Lambda_n^*}} \times BW(M_{Kp}|M_0^{\Lambda_n^*}, \Gamma_0^{\Lambda_n^*}) \times B'_{\ell_{\Lambda_n^*}}(q, q_0, d) \left(\frac{q}{M_0^{\Lambda_n^*}}\right)^{\ell_{\Lambda_n^*}} .$$

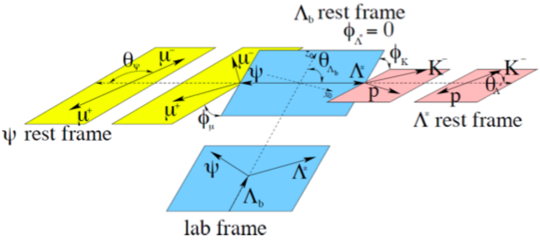
$$BW(M|M_0, \Gamma_0) = \frac{1}{M_0^2 - M^2 - iM_0\Gamma(M)} ,$$

where

$$\Gamma(M) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2\,\ell_{\Lambda^*}+1} \frac{M_0}{M} B'_{\ell_{\Lambda^*}}(q, q_0, d)^2 .$$

$p(q)$ are momenta of the daughter particles in the rest-frame of the decaying particle.

$p_0(q_0)$ calculated on the nominal resonance mass



4-6 independent **complex** helicity couplings per Λ_n^* resonance

6 independent data variables: 1 mass, 5 angles

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^*$$

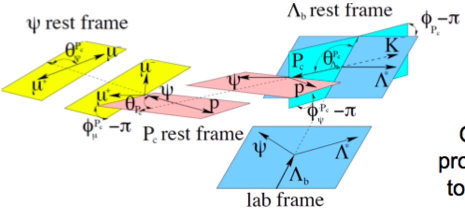
$$\mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp})\, D^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

$$R_X(m) = B'_{L^X_{\Lambda_b^0}}(p,p_0,d)\left(\frac{p}{M_{\Lambda_b^0}}\right)^{L^X_{\Lambda_b^0}} \mathrm{BW}(m|M_{0X},\Gamma_{0X})\, B'_{L_X}(q,q_0,d)\left(\frac{q}{M_{0X}}\right)^{L_X}$$

Blatt-Weisskopf functions

$$\mathrm{BW}(m|M_{0X},\Gamma_{0X}) = \frac{1}{M_{0X}{}^2 - m^2 - iM_{0X}\Gamma(m)}$$

Breit-Wigner



1 mass ($m_{J/\psi p}$), 6 angles
all derivable from the Λ^* decay variables

One more angle than in Λ^* decay: P_c^+ production angles must be defined relative to the Λ_b reference frame established for $\Lambda_b \to J/\psi\Lambda^*$ decay

3-4 independent **complex** helicity couplings per P_{cj}^+ resonance depending on its J^P

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0}\, D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^*$$
$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}}\, D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^*\, R_{P_{cj}}(m_{\psi p})\ \, D^{1}_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

$$R_X(m) = B'_{L^X_{\Lambda_b^0}}(p,p_0,d)\left(\frac{p}{M_{\Lambda_b^0}}\right)^{L^X_{\Lambda_b^0}} \mathrm{BW}(m|M_{0X},\Gamma_{0X})\, B'_{L_X}(q,q_0,d)\left(\frac{q}{M_{0X}}\right)^{L_X}$$

Blatt-Weisskopf functions

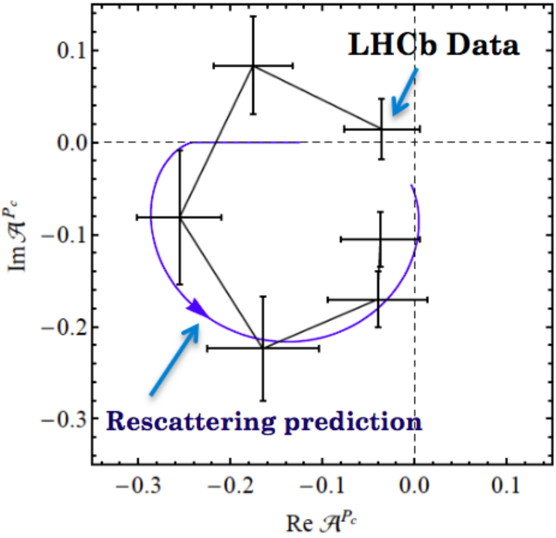
$$\mathrm{BW}(m|M_{0X},\Gamma_{0X}) = \frac{1}{M_{0X}{}^2 - m^2 - iM_{0X}\Gamma(m)}$$

Breit-Wigner

Pentaquark states as threshold effects or cusps:

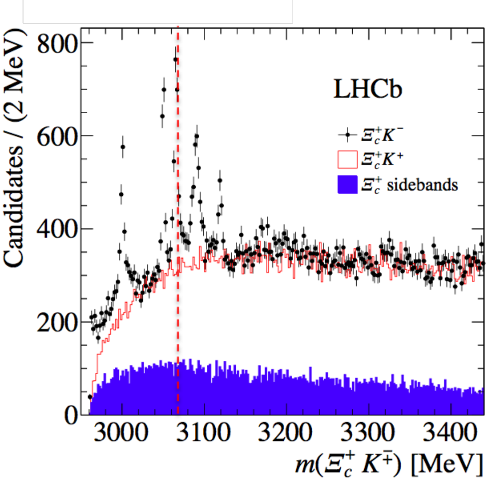
- closest threshold $= 4457.1 \pm 0.3\,\mathrm{MeV} = \Lambda_c(2595)^+\bar{D}^0$: higher than the peak mass
- $\Lambda_c(2595)^+\bar{D}^0$: structure with $J^P = 1/2^+$
- no threshold close to the lower state

Test of the exotic nature of $P_c(4450)$



Ξ_c'

- States with masses $M > m(\Xi_c') + m(K)$ could decay also to $\Xi_c' K^-$ and appear into $\Xi_c K^-$ as partially reconstructed decays (i.e. feed-downs)



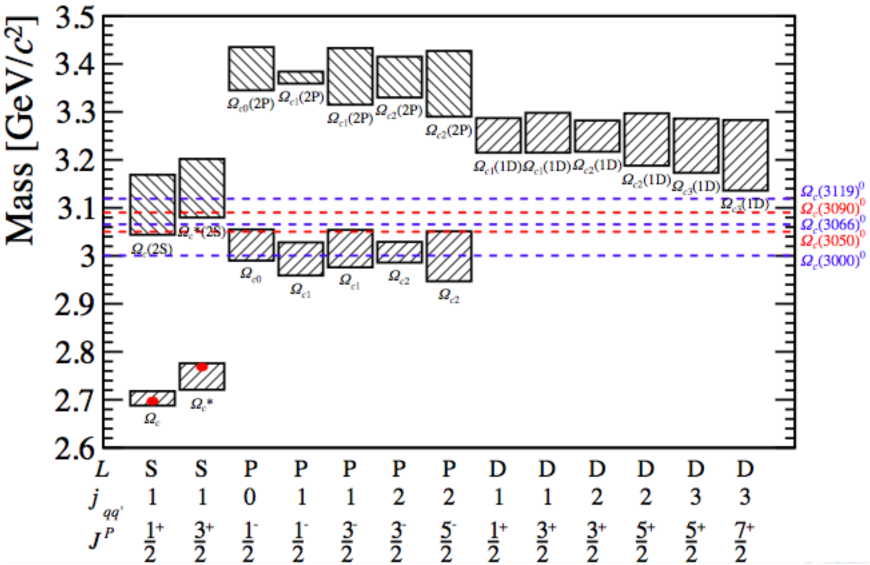
Combinatorial bkg parameterization for Ω_c states

- Wrong-sign $\Xi_c^+ K^+$ used to study the combinatorial background parameterization

$$B(m) = \begin{cases} P(m)e^{a_1 m + a_2 m^2} & \text{for } m < m_0, \\ P(m)e^{b_0 + b_1 m + b_2 m^2} & \text{for } m > m_0, \end{cases}$$

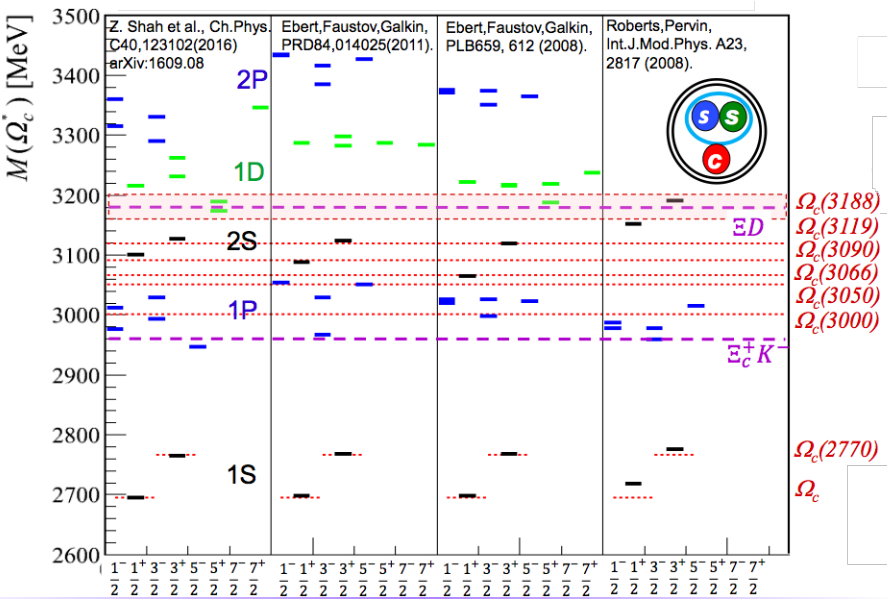
- $P(m)$ is a two-body phase-space factor, m_0, a and b are free parameters

Ω_c^0



Mass [GeV/c²]
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
Ω_c0(2P)
Ω_c1(2P)
Ω_c1(2P)
Ω_c2(2P)
Ω_c2(2P)
Ω_c1(1D)
Ω_c1(1D)
Ω_c2(1D)
Ω_c2(1D)
Ω_c3(1D)
Ω_c3(1D)
Ω_c(2S)
Ω_c*(2S)
Ω_c0
Ω_c1
Ω_c1
Ω_c2
Ω_c2
Ω_c
Ω_c*
Ω_c(3119)⁰
Ω_c(3090)⁰
Ω_c(3066)⁰
Ω_c(3050)⁰
Ω_c(3000)⁰
L S S P P P P P D D D D D D
j_qq' 1 1 0 1 1 2 2 1 1 2 2 3 3
J^P 1+/2 3+/2 1-/2 1-/2 3-/2 3-/2 5-/2 1+/2 3+/2 3+/2 5+/2 5+/2 7+/2

Ω_c^0



$M(\Omega_c^*)$ [MeV]
3500
3400
3300
3200
3100
3000
2900
2800
2700
2600
Z. Shah et al., Ch.Phys. C40,123102(2016) arXiv:1609.08
Ebert,Faustov,Galkin, PRD84,014025(2011).
Ebert,Faustov,Galkin, PLB659, 612 (2008).
Roberts,Pervin, Int.J.Mod.Phys. A23, 2817 (2008).
2P
1D
2S
1P
1S
s
s
c
ΞD
$\Xi_c^+ K^-$
$\Omega_c(3188)$
$\Omega_c(3119)$
$\Omega_c(3090)$
$\Omega_c(3066)$
$\Omega_c(3050)$
$\Omega_c(3000)$
$\Omega_c(2770)$
Ω_c
$\frac{1}{2}^-$ $\frac{1}{2}^+$ $\frac{3}{2}^-$ $\frac{3}{2}^+$ $\frac{5}{2}^-$ $\frac{5}{2}^+$ $\frac{7}{2}^-$ $\frac{7}{2}^+$