Heavy flavour spectroscopy and hadron properties from LHCb

Antimo Palano

INFN and University of Bari, Italy

On behalf of the LHCb Collaboration

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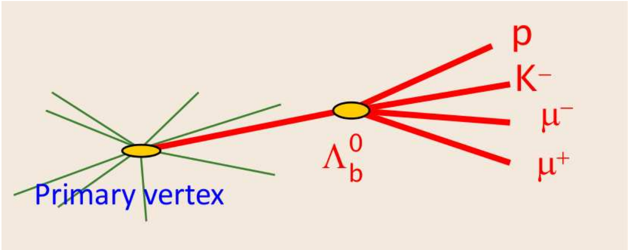
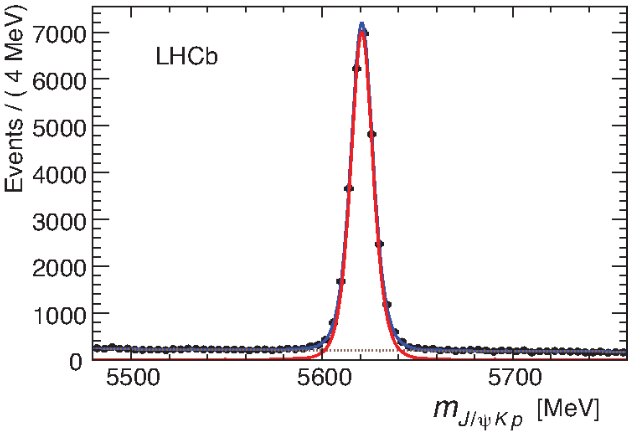
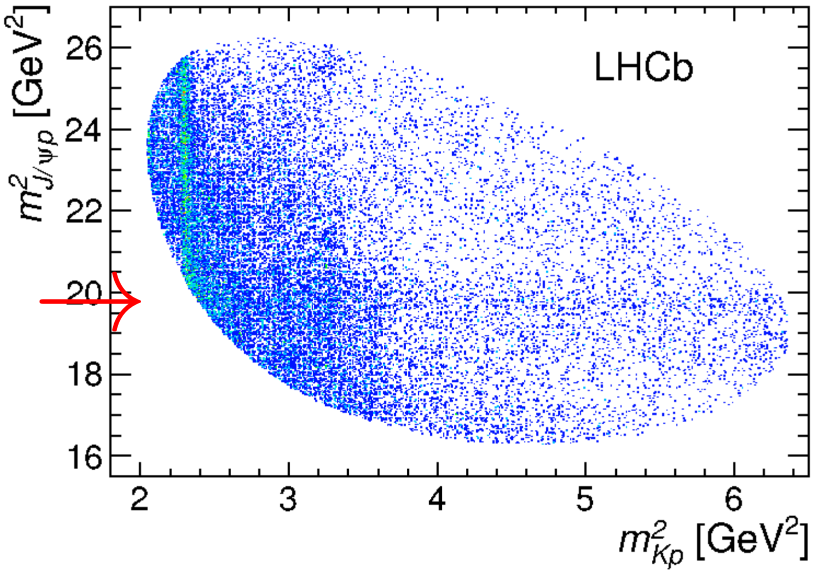
Observation of $J/\psi p$ pentaquarks candidates in $\Lambda_b^0 \to J/\psi p K^-$ decays



- ☐ Multivariate Analysis (MTVA) selection.
- ☐ $26,007 \pm 166$ Λ_b^0 events with 94.6% purity.
- ☐ The Dalitz plot shows rich Λ's resonant structures along the pK^- axis.
- ☐ Unexpected structure along the $J/\psi p$ axis.



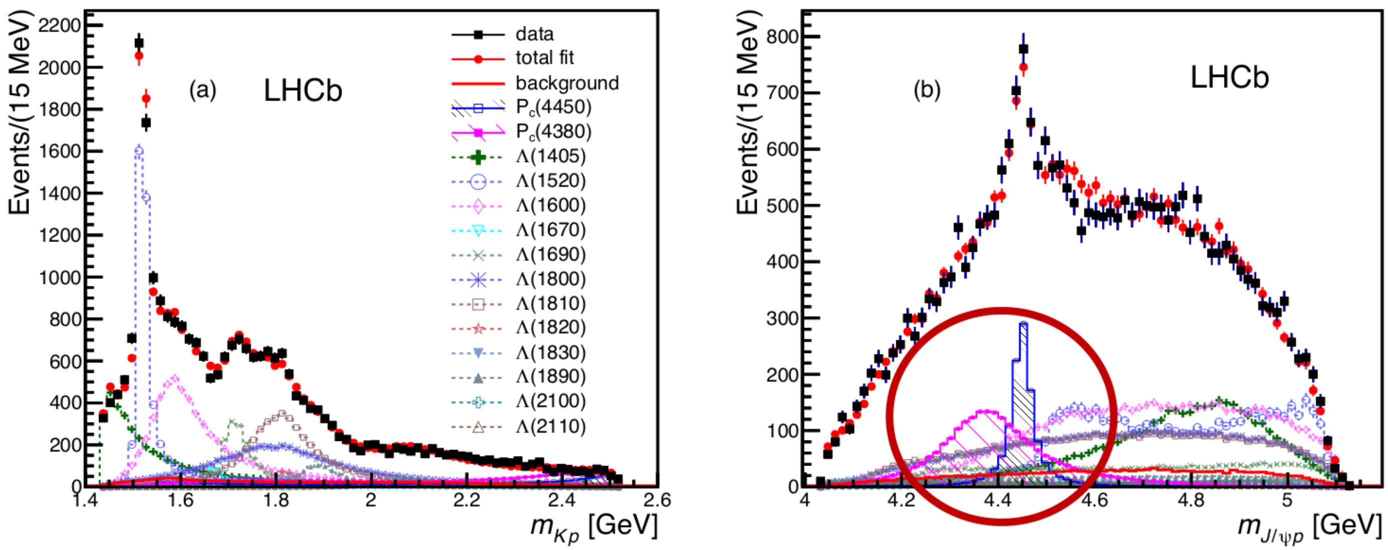


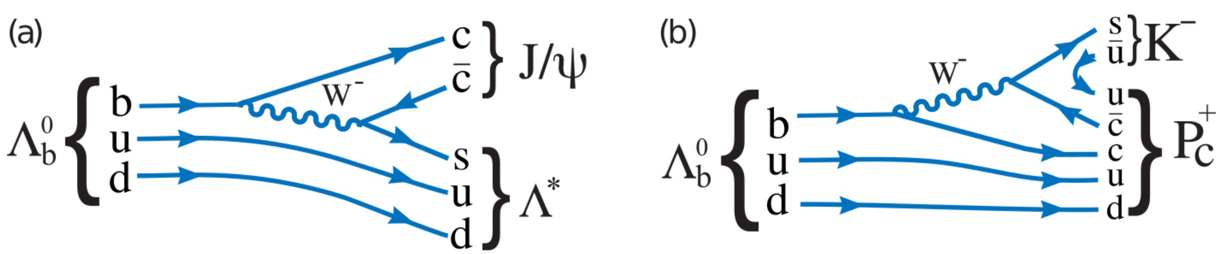
(PRL 115, 072001 (2015)).

Amplitude analysis and mass projections

□ Key point is a full amplitude analysis which also describes the complex resonant structure in the pK^- final state.

□ The analysis requires the presence of two new resonances (labelled P_c).





(PRL 115, 072001 (2015)).

Resonances parameters and angular analysis

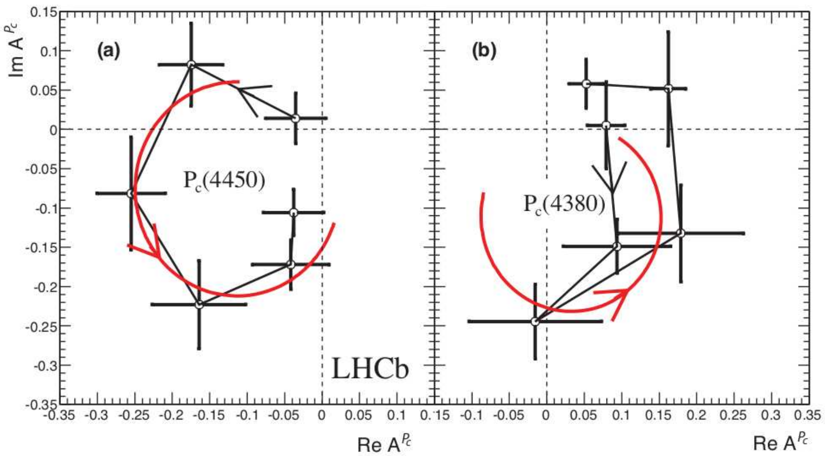
Resonance	Mass (MeV)	Width (MeV)	Significance	Fit fraction (%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	9σ	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	12σ	$4.1 \pm 0.5 \pm 1.1$

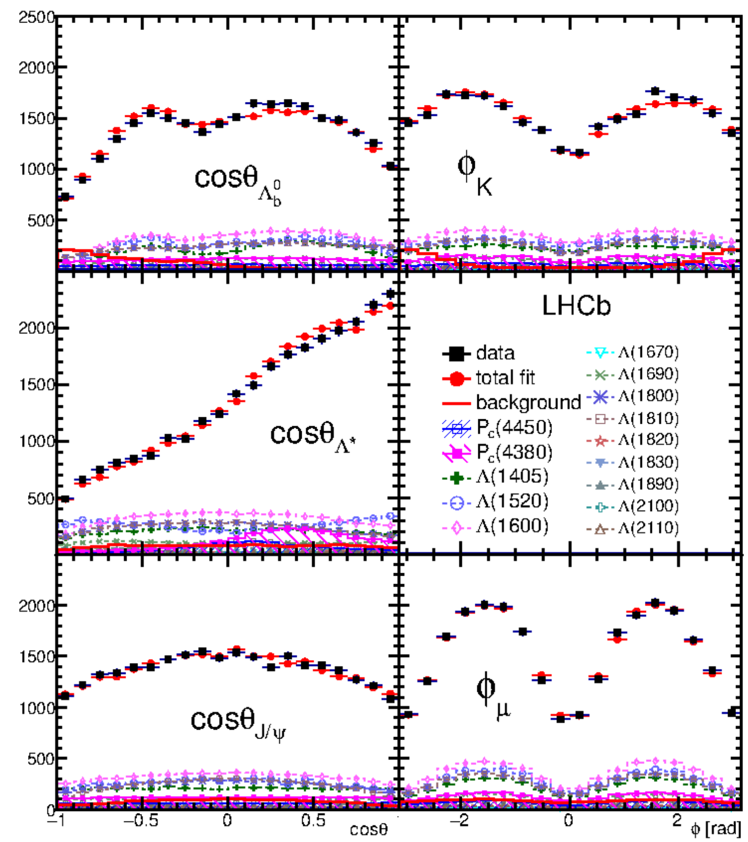
□ The best fit has $J^P = 3/2^-$ and $J^P = 5/2^+$.

□ Good description of the angular distributions.

□ Measure the real and imaginary parts of the P_c amplitudes (PRL 115, 072001 (2015)).

□ Argand Diagram consistent with expectations from a Breit-Wigner behaviour.



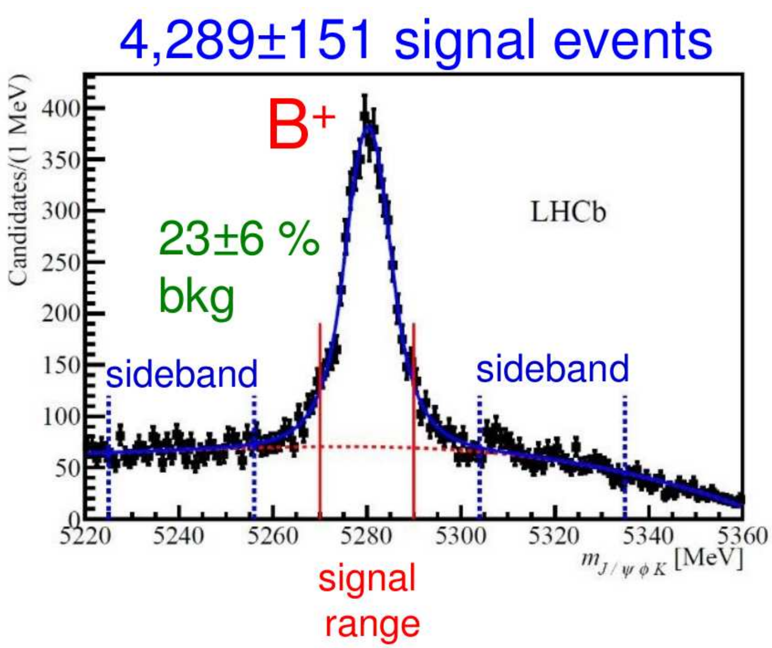


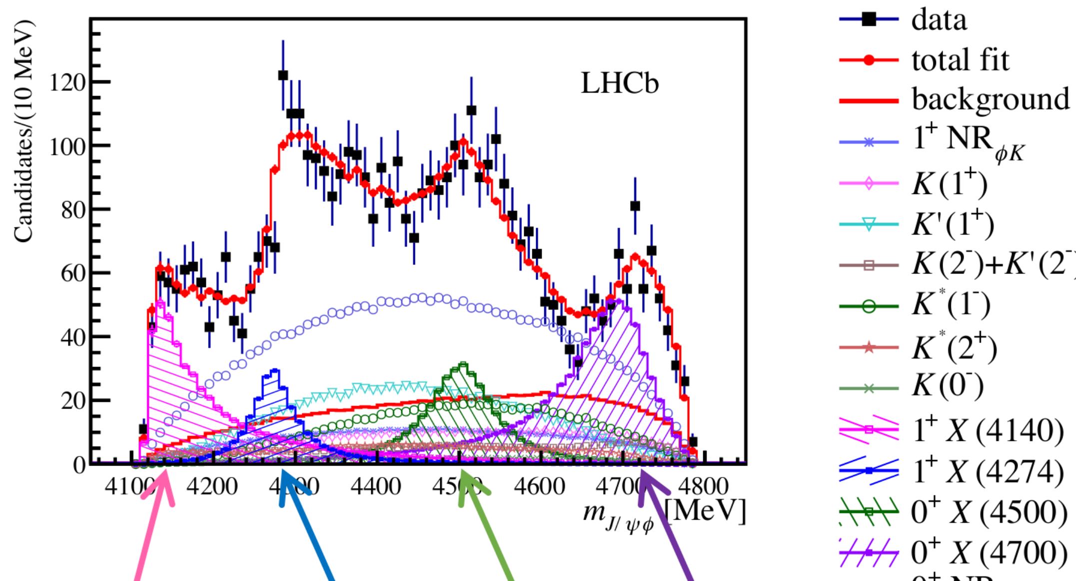
□ Model independent analysis gives consistent results (Phys. Rev. Lett. 117, 082002 (2016)).

□ The study of $\Lambda_b^0 \to J/\psi p \pi^-$ gives consistent results (Phys. Rev. Lett. 117, 082003 (2016)).

Results on $B^+ \to J/\psi\phi K^+$ from LHCb

- The X(4140) state is first claimed by the CDF collaboration in 2008. (PRL 102 242002).
- Narrow width: $\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$ MeV. Later more experimental results.
- Use Run1 data ($3fb^{-1}$) (PRL118, 022003 (2017), PRD95, 012002 (2017)).
- Six dimensional amplitude analysis.
- The best fit requires the presence of four X states and a non-resonant term.





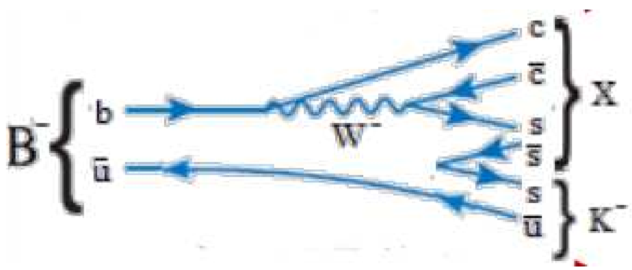
$X(4140)$, $X(4274)$, $X(4500)$, $X(4700)$

New results on $B^+ \to J/\psi\phi K^+$ from LHCb

- Resonances parameters (PRL118, 022003 (2017)).

	σ	J^{PC}	M (MeV)	Γ (MeV)
$X(4140)$	8.4	1^{++}	$4160 \pm 4^{+5}_{-3}$	$83 \pm 21^{+21}_{-14}$
$X(4274)$	5.8	1^{++}	$4273 \pm 8^{+17}_{-4}$	$56 \pm 11^{+8}_{-11}$
$X(4500)$	6.1	0^{++}	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
$X(4700)$	5.6	0^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

- The $X(4140)$ is not a narrow resonance.
- A possible diagram for producing a 4-quark state.



- Lot of discussions. Interpretation of these states still open.

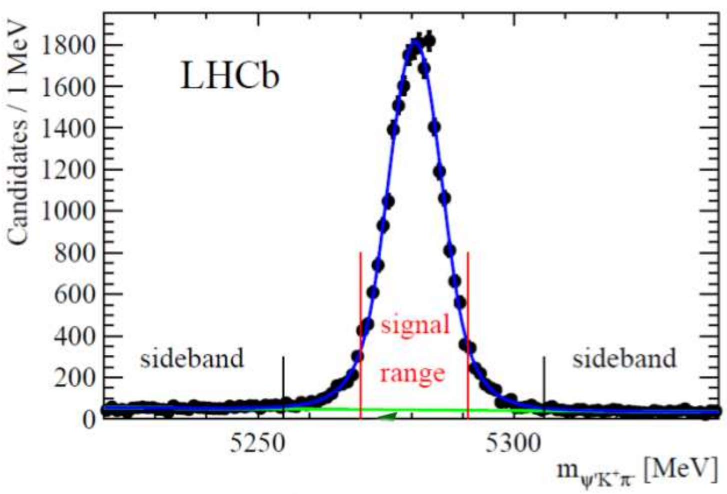
Study of $\bar{B}^0 \to \psi'\pi^- K^+$ in LHCb

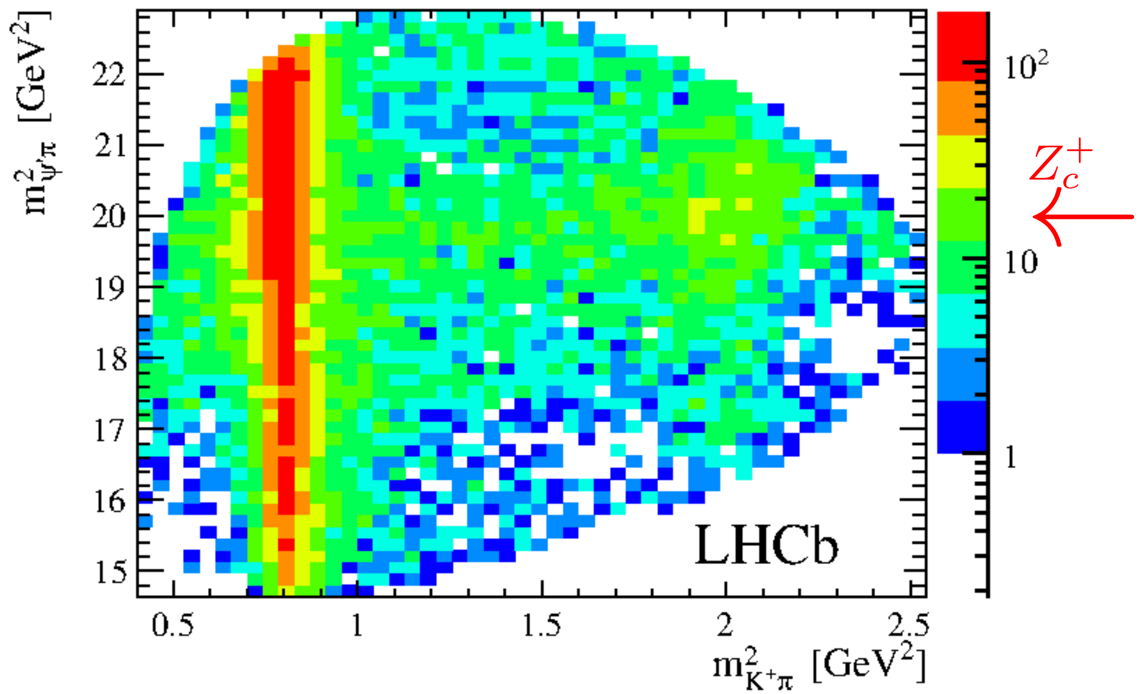
□ First analysis from Belle: observation of a new $Z_c(4430)^+ \to \psi'\pi^-$ in $B \to K\pi^+\psi'$ (PRL 100, 142001 (2008)).

□ Not confirmed by BaBar: data could be described without the presence of a $Z_c(4430)^+$ resonance (PRD 79, 112001 (2009)).

□ Recent analysis from LHCb (PRL 112, 222002 (2014)).

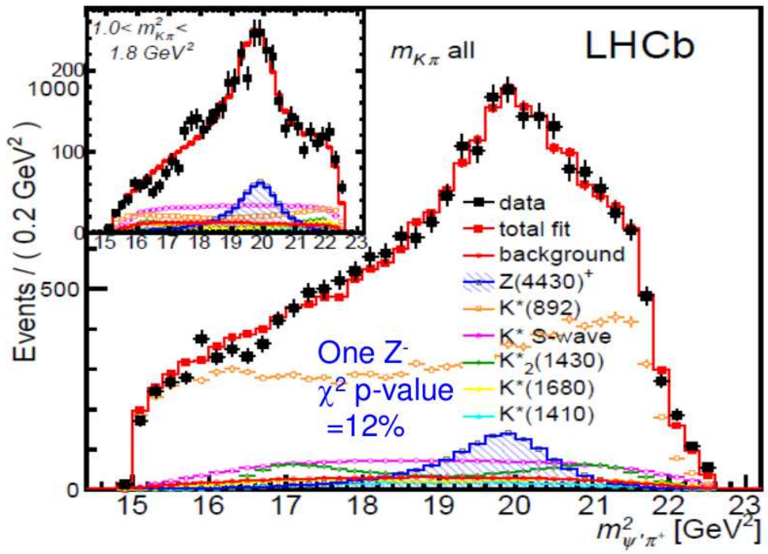
□ B^0 signal: 25,176 events (Belle: 2,010, BaBar: 2,021 events).

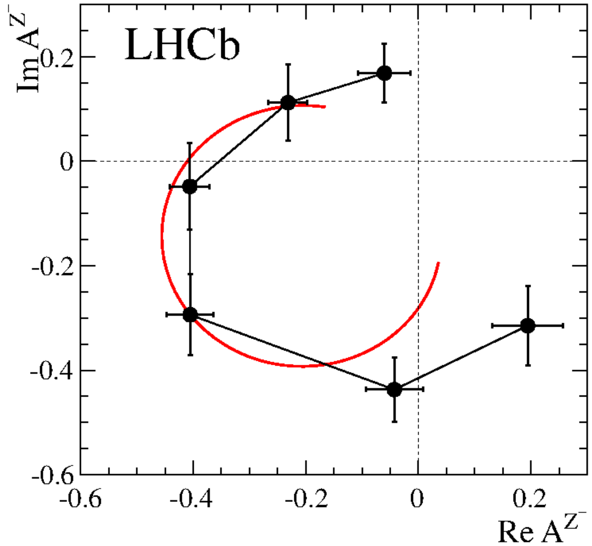




Study of $\bar{B}^0 \to \psi' \pi^- K^+$

- Amplitude analysis confirms the presence of the Z_c resonance (PRL 112, 222002 (2014)).

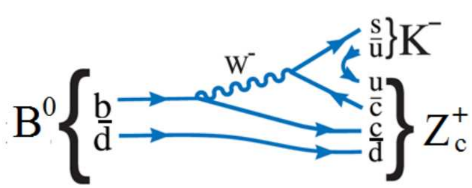


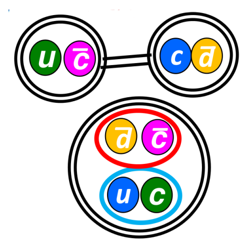


- Argand diagram shows typical resonance behaviour. Resonance parameters:

$$M(Z_c) = 4475 \pm 7^{+15}_{-25}\ MeV,\ \ \Gamma(Z_c) = 172 \pm 13^{+37}_{-34}\ MeV.$$

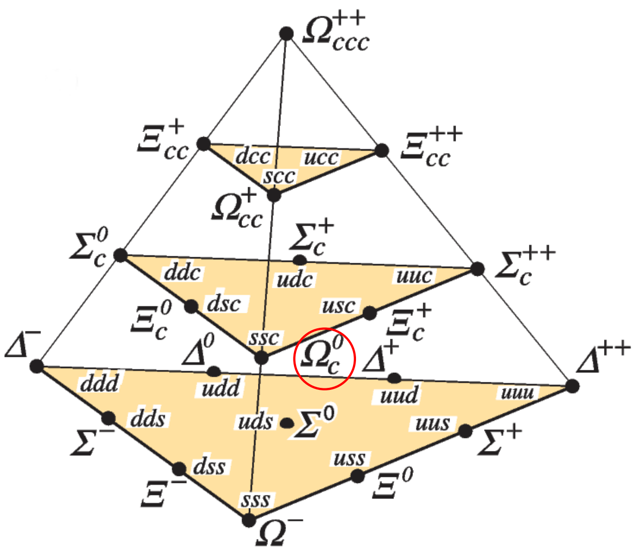
- In good agreement with Belle.
- Possible presence of an additional Z_c at a mass of 4239 MeV.
- Z_c is a charged charmonium state. Multiquark state?

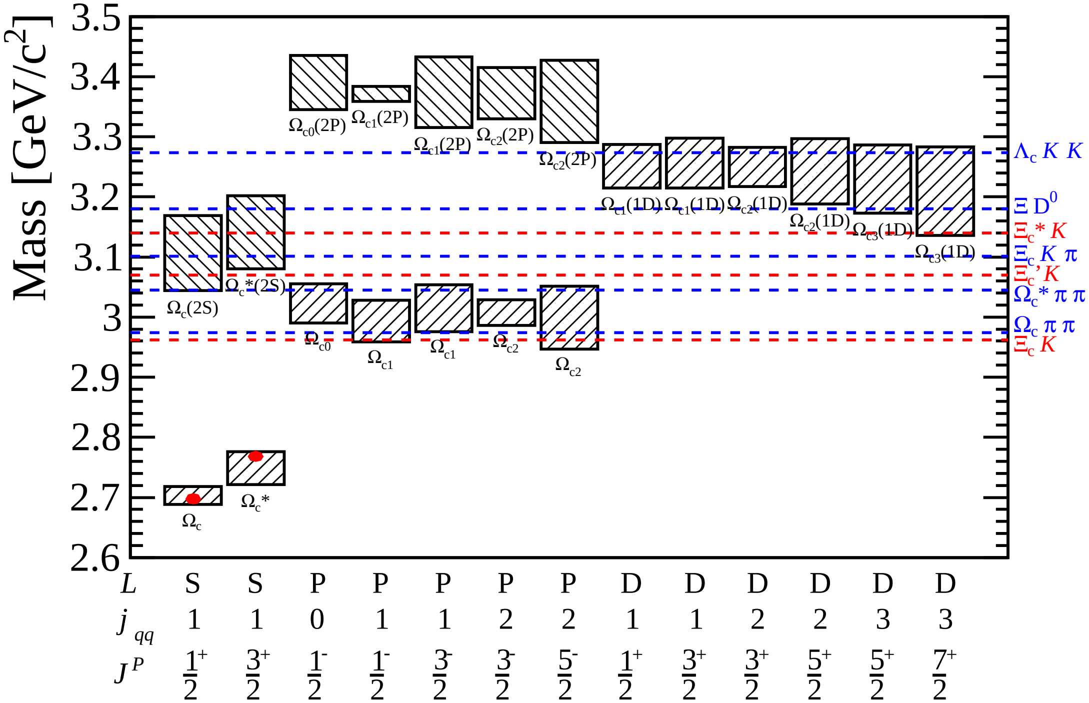




Baryon spectroscopy

- □ Heavy quark effective theory (HQET) predictions for Ω_c states.

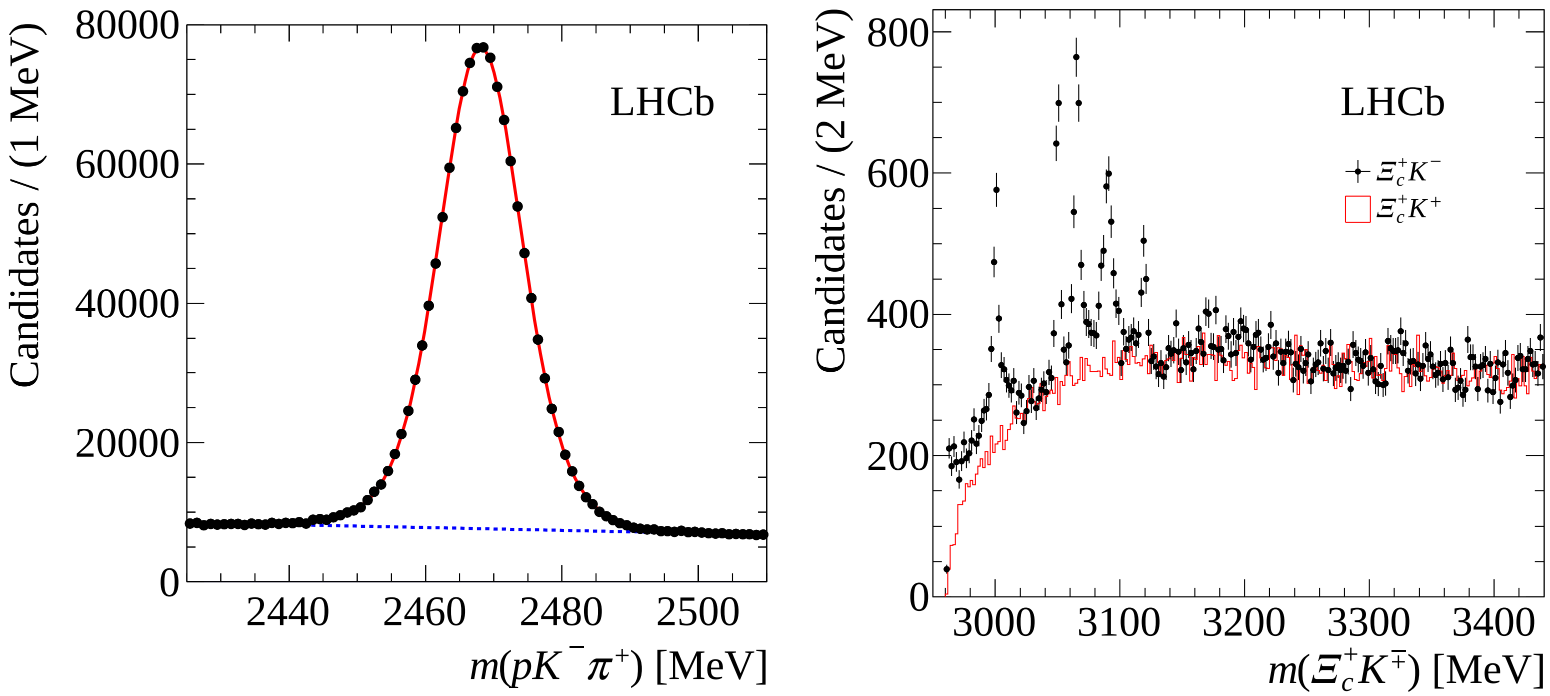




- □ Ω_c quark content: *ssc*.
- □ Only $1/2^+$ and $3/2^+$ ground states were known.

Observation of five new Ω_C states in LHCb

- Explore excited Ω_c states in their strong decay to $\Xi_c^+ K^-$ (PRL 118 (2017) 182001).
- Make use of data collected at 7,8 and 13 TeV (3.3 fb^{-1}).
- Ξ_c^+ reconstructed in the Cabibbo suppressed mode $\Xi_c^+ \to pK^-\pi^+$.
- $\approx 10^6$ Ξ_c^+ reconstructed with a 83% purity.
- Ξ_c^+ combined with a prompt K^-: five narrow Ω_C observed.
- No structure in the Ξ_c^+ sidebands or in the wrong sign $\Xi_c^+ K^+$ mass spectrum.

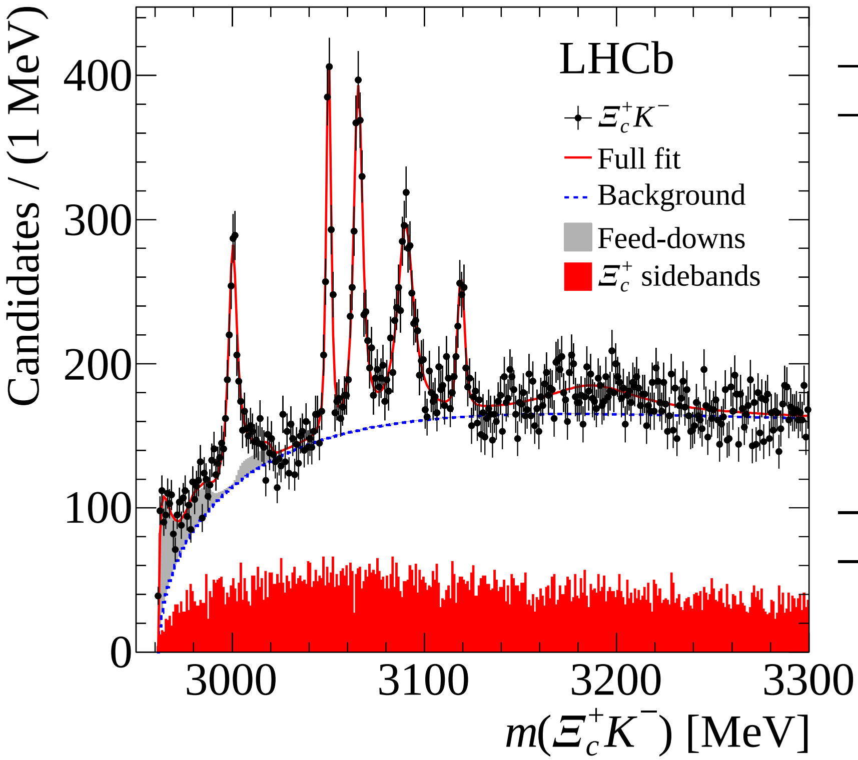


Observation of five new Ω_C states

□ Describe peaks with relativistic Breit-Wigner convoluted with Gaussian with σ from 0.7 to 1.7 MeV.

□ Account for feed-down from $\Omega_c \to K^- \Xi_c'(\to \Xi_c \gamma)$.

□ Model enhancement at ≈ 3200 MeV with one Breit-Wigner.



Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		< 1.2 MeV, 95% CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		< 2.6 MeV, 95% CL
$\Omega_c(3188)^0$	$3188.1 \pm 4.8 \pm 12.7$	$60 \pm 15 \pm 11$

□ $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ exceptionally narrow (PRL 118 (2017) 182001).

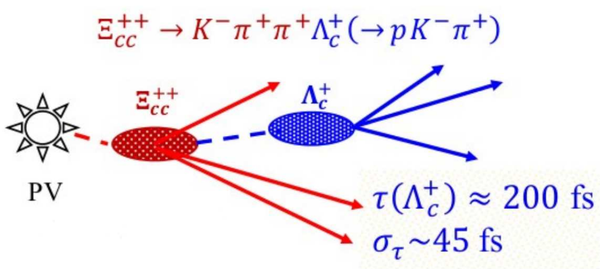
□ Many interpretations, including the possible presence of pentaquarks.

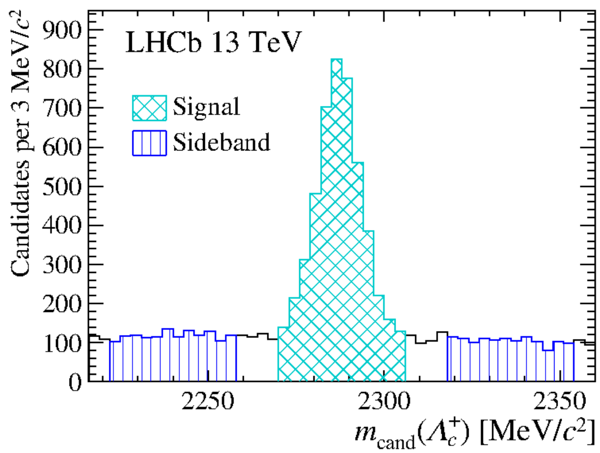
Observation of the double charmed baryon Ξ_{cc}^{++} in LHCb

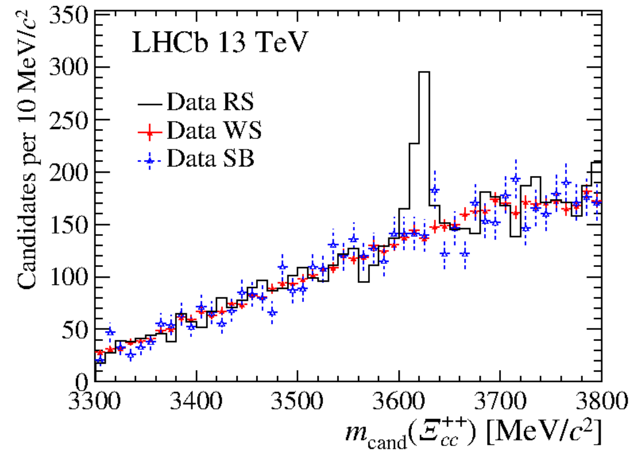
□ Search for the Ξ_{cc}^{++} (ucc) using the decay (Phys. Rev. Lett. 111 (2017) 180001).

$$\Xi_{cc}^{++} \to \Lambda_c K^- \pi^+ \pi^+, \quad \Lambda_c \to p K^- \pi^+ \; (BR = 10\%)$$

□ Analyze 1.7 fb^{-1} of Run2 using a dedicated high efficiency trigger.







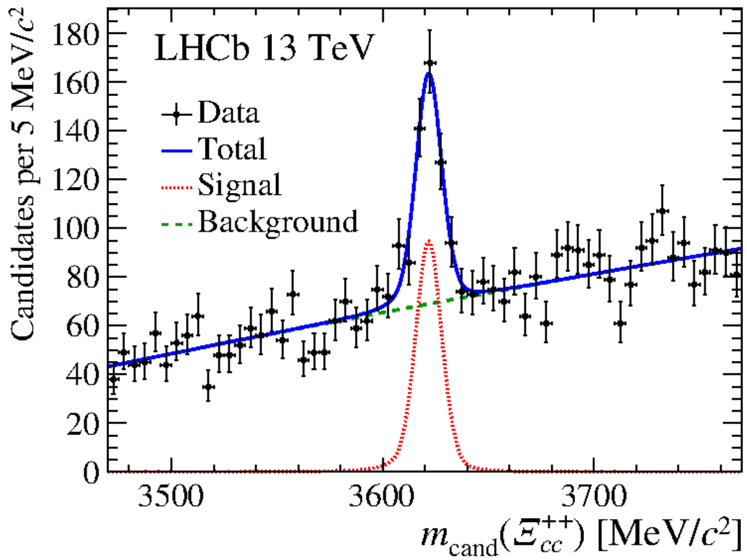
□ First observation.

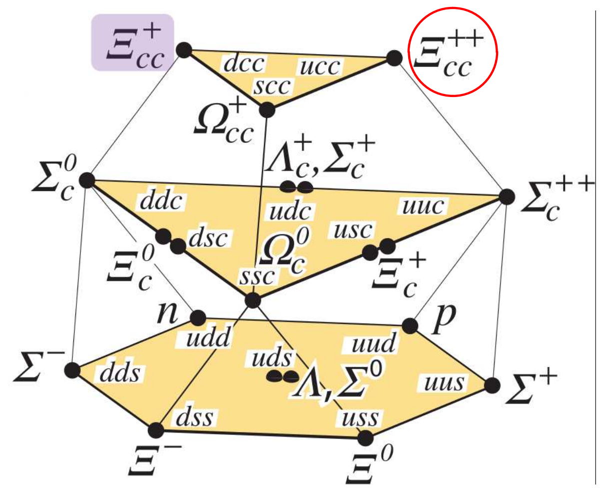
□ No signal observed in the Λ_c sidebands, no signal in the wrong sign $\Lambda_c K^- \pi^+ \pi^-$ combination.

□ Consistent signal also observed in the Run1 data.

Observation of the double charmed baryon Ξ_{cc}^{++}

- Significance $> 12\sigma$ (Phys. Rev. Lett. 111 (2017) 180001).
- Yield 313 ± 33 decays.





- Ξ_{cc}^{++} parameters.

$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c) MeV$$

- Mass difference with respect to the possible SELEX isospin partner (Ξ_{cc}^{+}):

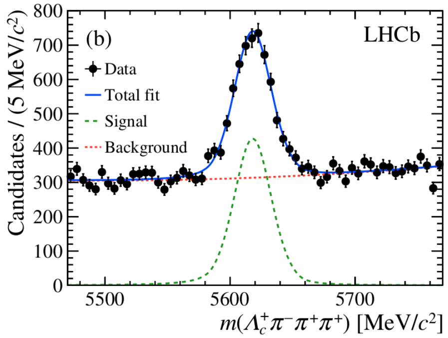
103 ± 2 MeV (PRL 89 (2002) 112001, PLB 628 (2005) 18)

- Inconsistent with expected isospin splitting for Ξ_{cc}^{+}.

Lifetime measurement of Ξ_{cc}^{++} (I)

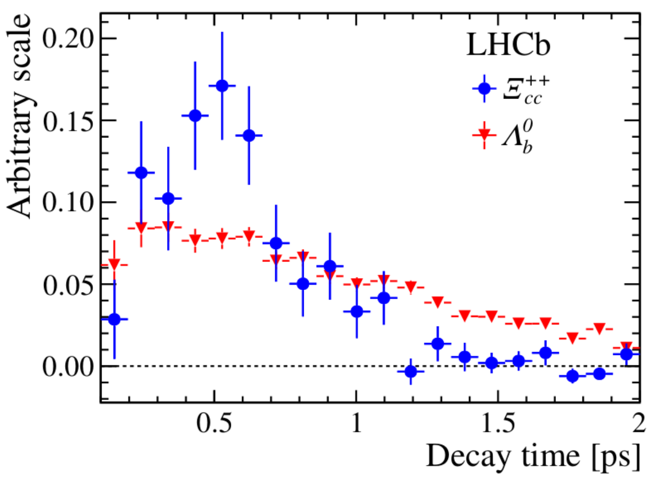
□ We perform a Ξ_{cc}^{++} lifetime measurement relative to that of the $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ having the same topology (arXiv:1806.02744).

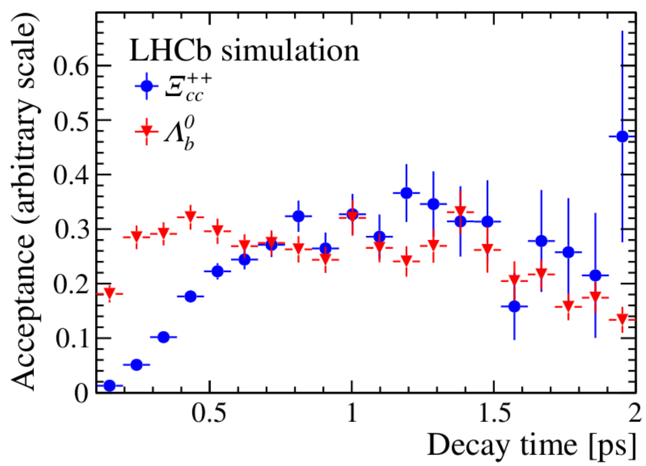
Λ_b^0 signal $\longrightarrow$



□ Unbinned maximum likelihood fit to the background subtracted (sFit) Ξ_{cc}^{++} decay time distribution.

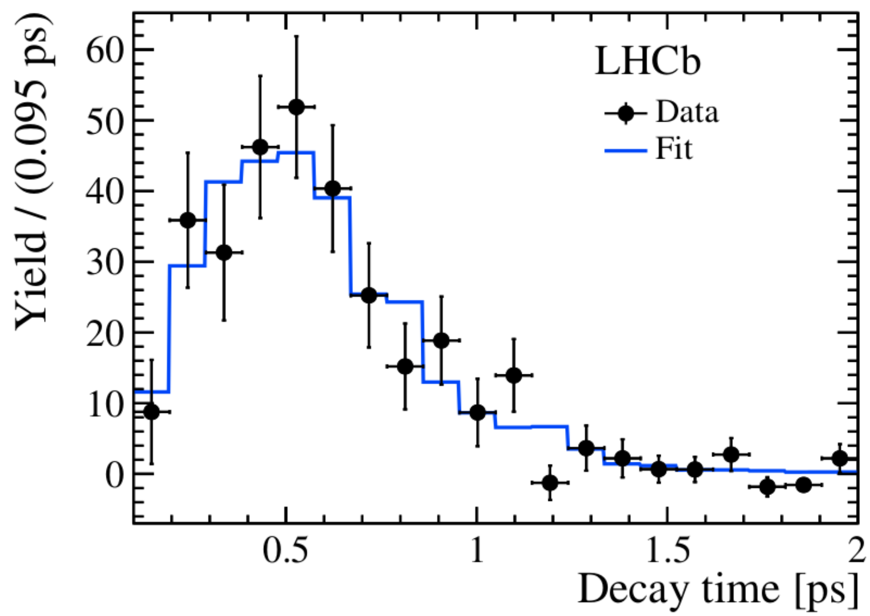
$$R(t) = \frac{f_{\Xi_{cc}^{++}}}{f_{\Lambda_b^0}} \times \frac{\epsilon_{\Lambda_b^0}(t)}{\epsilon_{\Xi_{cc}^{++}}(t)} = R(0) \times e^{-\left(\frac{1}{\tau_{\Xi_{cc}^{++}}} - \frac{1}{\tau_{\Lambda_b^0}}\right)t}$$





Lifetime measurement of Ξ_{cc}^{++} (II)

□ Fitted Ξ_{cc}^{++} lifetime distribution.



□ We measure

$$\tau_{\Xi_{cc}^{++}} = 0.256^{+0.024}_{-0.022} \pm 0.014 \; ps$$

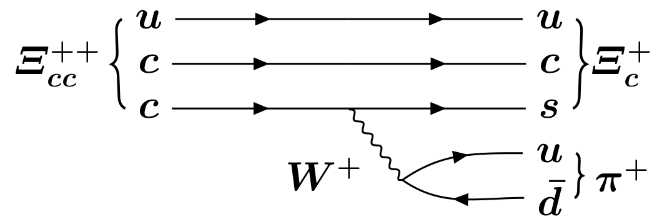
□ In the lower end but compatible with the expected theoretical predictions.

□ This confirms the weakly decay nature of the newly discovered Ξ_{cc}^{++} state.

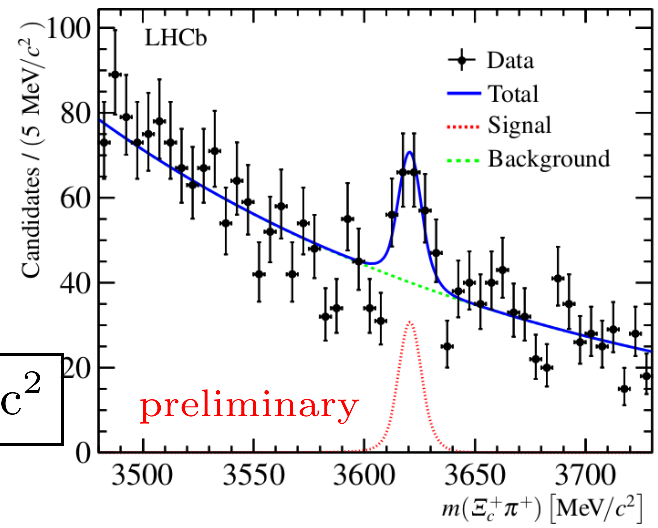
(arXiv:1806.02744).

Observation of a new $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decay mode

- Searching for new decay modes is critical to understand the dynamics of weak decays of doubly heavy baryons.



- Data sample: 1.7 fb^{-1} at 13 TeV [LHCb-PAPER-2018-026]
- Normalization channel: $\Xi_{cc}^{++} \to \Lambda_c K^- \pi^+ \pi^+$.
- Significant peak (5.9σ): 91 ± 20 events.



- Mass measurement:

$$m(\Xi_{cc}^{++}) = 3620 \pm 1.5(\mathrm{stat}) \pm 0.4(\mathrm{sys}) \pm 0.3(\Xi_c^+)\ \mathrm{MeV/c^2}$$

consistent with the previous measurement.

- The ratio of branching fractions is:

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c \to pK^-\pi^+)} = 0.035 \pm 0.009(\mathrm{stat}) \pm 0.003(\mathrm{syst})$$

Measurement of the Ω_c baryon lifetime

- Charm baryon lifetimes are known much less precisely than charm meson ones.
- The expected lifetime hierarchy should be:

$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$

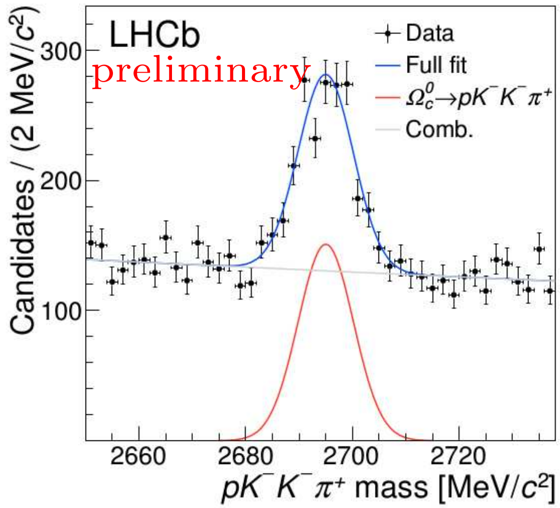
and current measurements are consistent with this.

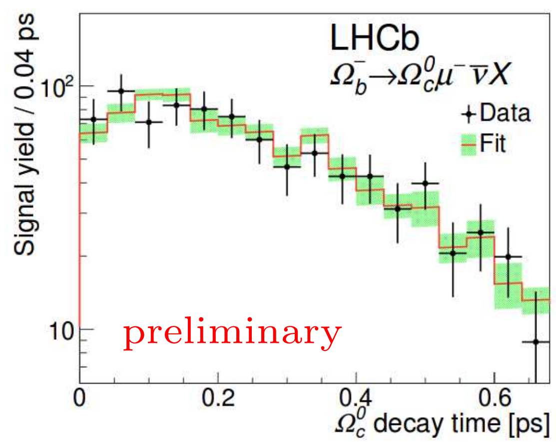
- We use semileptonic $\Omega_b^- \to \Omega_c^0 \mu^- \bar{\nu}_\mu X$ with $\Omega_c^0 \to p K^- K^- \pi^+$ [LHCb-PAPER-2018-028].
- To reduce uncertainties we measure the ratio with respect to the $D^+ \to K^- \pi^+ \pi^+$ lifetime.
- Dataset: 3 fb^{-1}. Measured lifetime:

$$\tau_{\Omega_c^0} = 268 \pm 21_{\,(\mathrm{stat})} \pm 10_{\,(\mathrm{syst})} \pm 2_{D^+} \; fs$$

- Four times larger than and inconsistent with the world average value of (69 ± 12) fs.
- With this measurement:

$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$





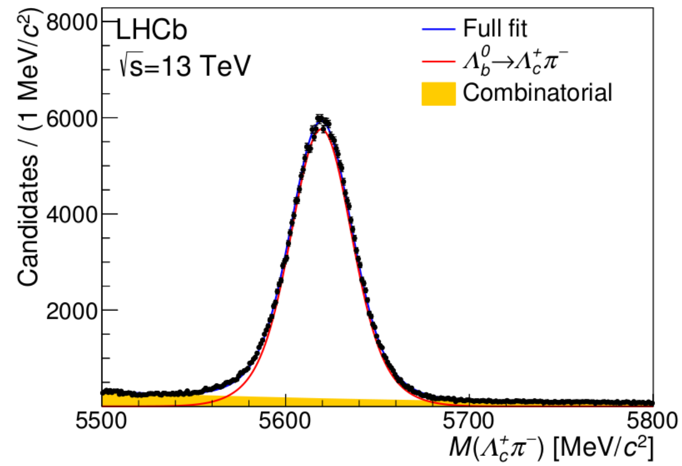
Observation of a new Ξ_b^- resonance (I).

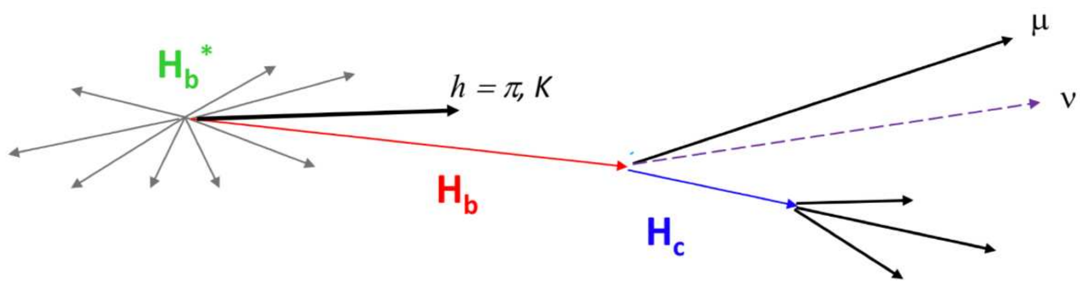
□ New $\Xi_b(6227)^-$ state observed decaying to both $\Xi_b^0\pi^-$ and $\Lambda_b^0 K^-$ (arXiv:1805.09418).

□ Dataset: 1.0 fb^{-1} (7 TeV) + 2.0 fb^{-1} (8 TeV) 1.5 fb^{-1} (13 TeV).

□ Three independent reconstructed decay chains:

$$\Xi_b(6227)^- \to \Lambda_b^0(\to \Lambda_c^+\pi^-)K^-$$
$$\Xi_b(6227)^- \to \Xi_b^0(\to \Xi_c^+\mu^- X)\pi^-$$
$$\Xi_b(6227)^- \to \Lambda_b^0(\to \Lambda_c^+\mu^- X)K^-$$





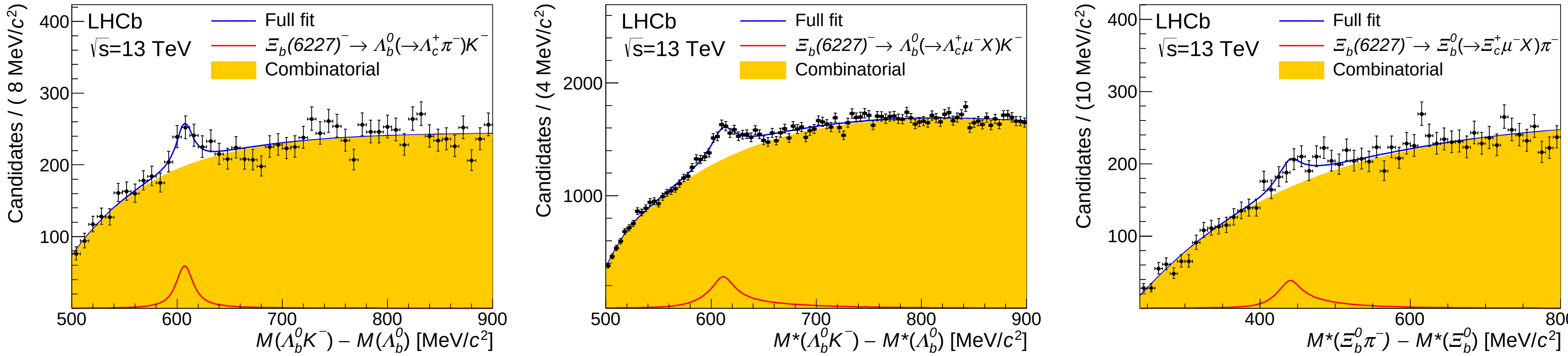
□ Semileptonic decays have branching fractions 10-20 times larger.

□ The missing p_ν momentum is reconstructed assuming a zero-mass particle that balances the momentum transverse to the direction of Λ_b^0/Ξ_b^0.

□ The total invariant mass is constrained to have the known Λ_b^0/Ξ_b^0 mass.

Observation of a new Ξ_b^- resonance (II).

- The new resonance is observed in three different mass spectra.



- Similar signals observed in the 7/8 TeV data.
- Resonance parameters

$$m_{\Xi_b(6227)^-} - m_{\Lambda_b^0} = 607.3 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst})\,\text{MeV}/c^2,$$

$$\Gamma_{\Xi_b(6227)^-} = 18.1 \pm 5.4\,(\text{stat}) \pm 1.8\,(\text{syst})\,\text{MeV}/c^2,$$

$$m_{\Xi_b(6227)^-} = 6226.9 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst}) \pm 0.2(\Lambda_b^0)\,\text{MeV}/c^2,$$

- The new state could be $\Xi_b(1P)$ or $\Xi_b(2S)$.

(arXiv:1805.09418)

Conclusions

□ LHCb is a flavor factory, exploring a large set of physics topics.

□ In particular, in the spectroscopy field, many new unexplored regions are being studied.

□ These studies are producing unexpected results, such as the discovery of "exotic" states, or the observation of many unexpected resonances and particles.

□ Basic ingredients of these results are high statistics and purity of the final states and highly sophisticated and newly developed full amplitude analyses.

□ This field is in rapid development and much more experimental and theoretical work is needed to understand the full pattern.

□ Many more analyses are underway, making use of the large amount of data which are being collected at LHC.