Hadron spectroscopy in LHCb

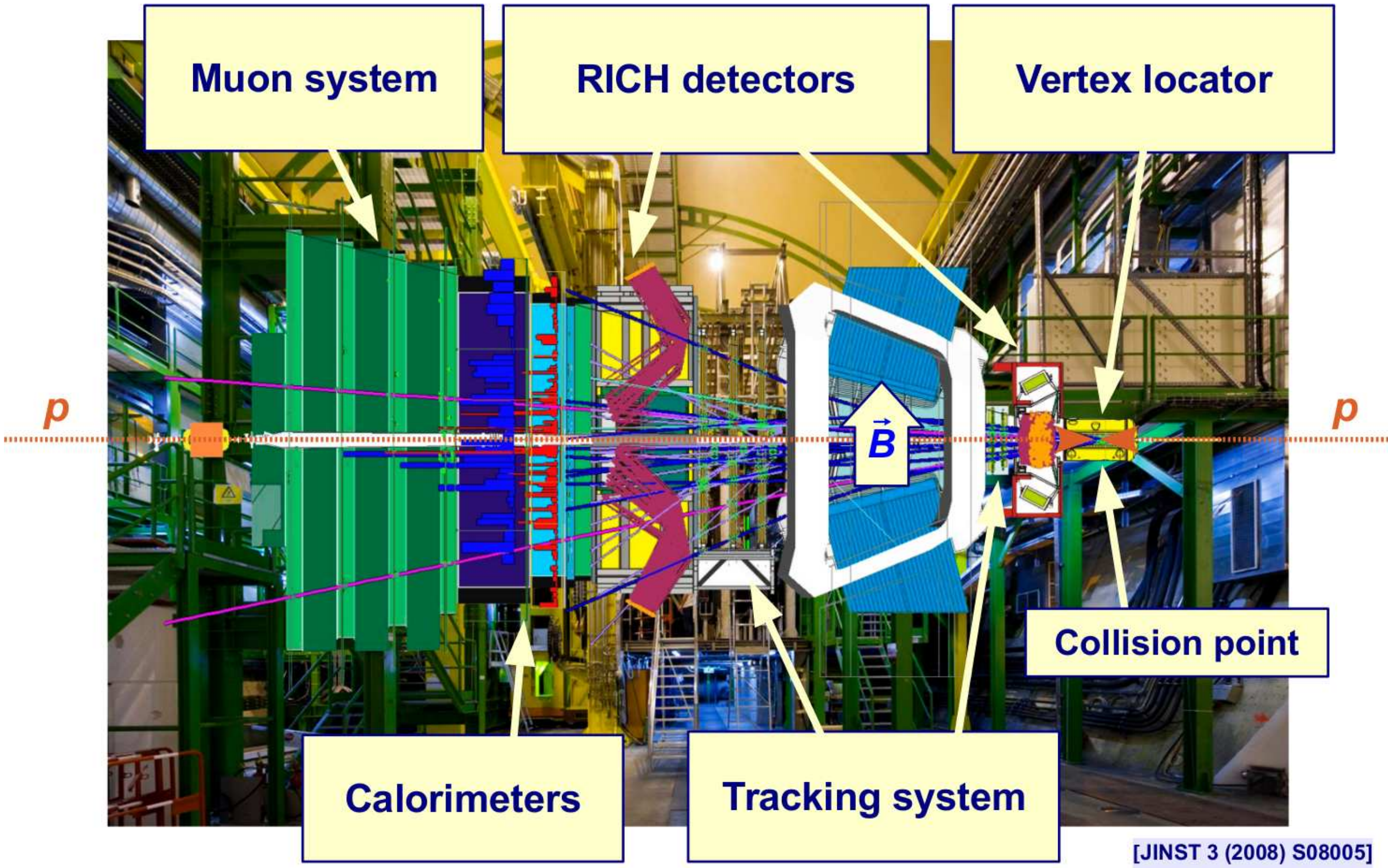
Antimo Palano
INFN and University of Bari, Italy
On behalf of the LHCb Collaboration

Outline:

- The LHCb experiment.
- The observation of pentaquark candidates
- Observation of possible tetraquark states
- Observation of new Baryonic states

EXA 2017 - International Conference on Exotic Atoms and Related Topics,
Wien, September 11-15, 2017

The LHCb experiment



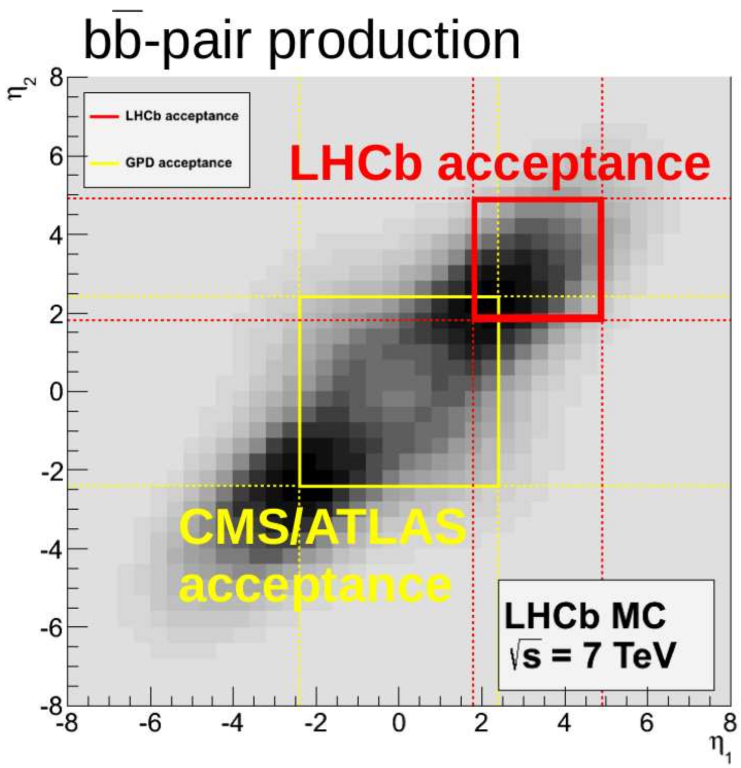
[JINST 3 (2008) S08005]

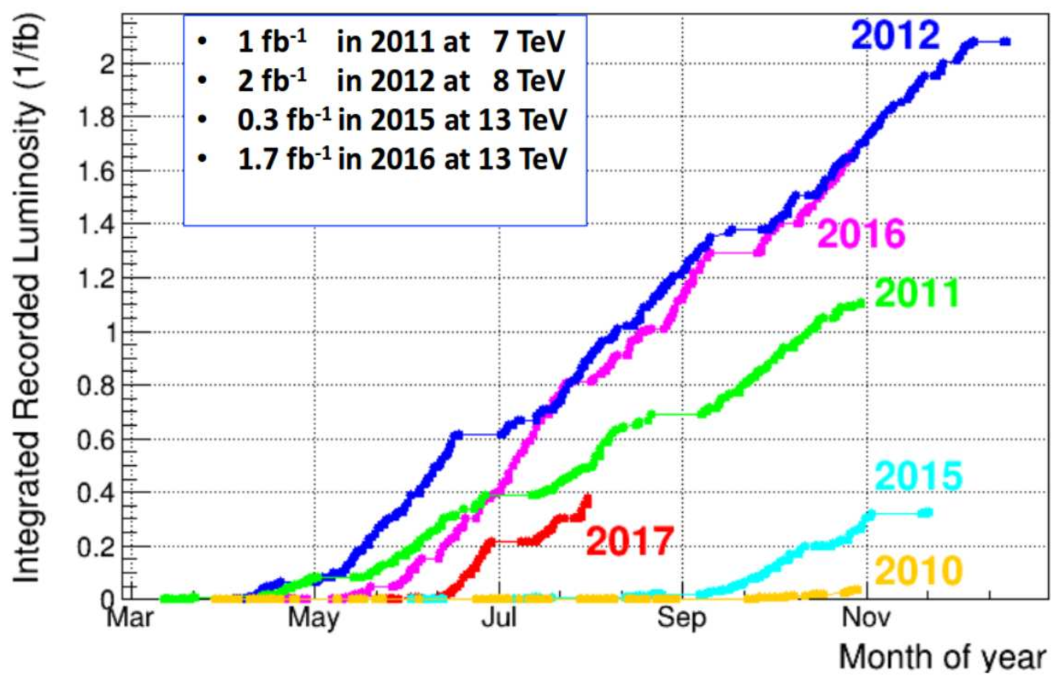
- ☐ High cross-section of heavy-quark production.
- ☐ Excellent decay time resolution.
- ☐ Excellent particle identification.
- ☐ Excellent momentum resolution.
- ☐ Flexible trigger.

The LHCb experiment

□ Efficiency for $b\bar{b}$ production in LHCb is 27% of b or $\bar{b}$ and 25% of $b\bar{b}$ pair.

□ Collected Luminosity.





□ Most of the analyses presented here made use of Run1(7+8 TeV) ($3fb^{-1}$) dataset only.

□ A few analyses make use also of the Run2 (13 TeV) ($1.7fb^{-1}$) data.

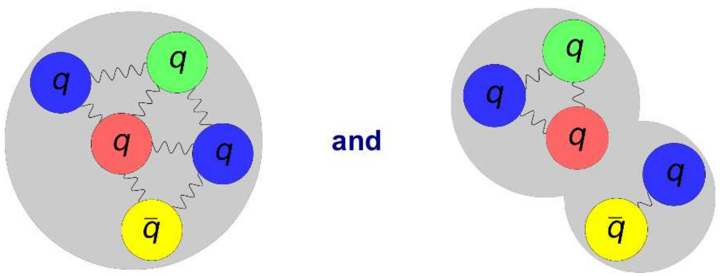
Multiquark states

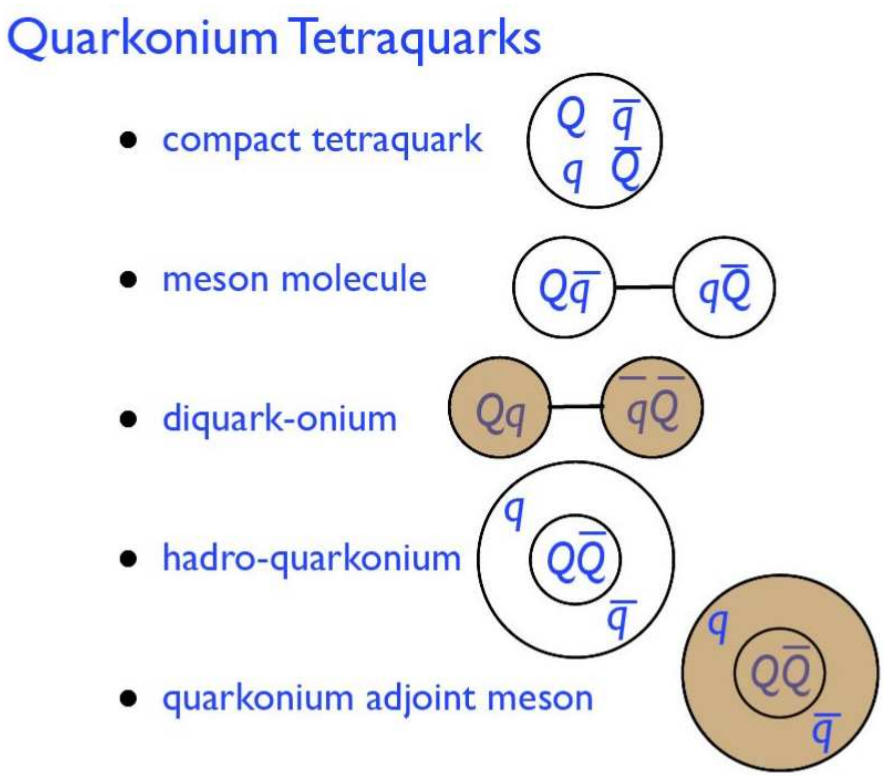
□ In the original Gell-Mann paper ("A schematic model for baryons and mesons", Phys. Lett. 8, (1964)).

□ "Baryons can now be constructed from quarks by using combinations $(qqq), (qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q}), (qq\bar{q}\bar{q})$, etc.

□ Today $qqqq\bar{q}$ baryons are called pentaquarks, $qq\bar{q}\bar{q}$ mesons are called tetraquarks.

Pentaquarks

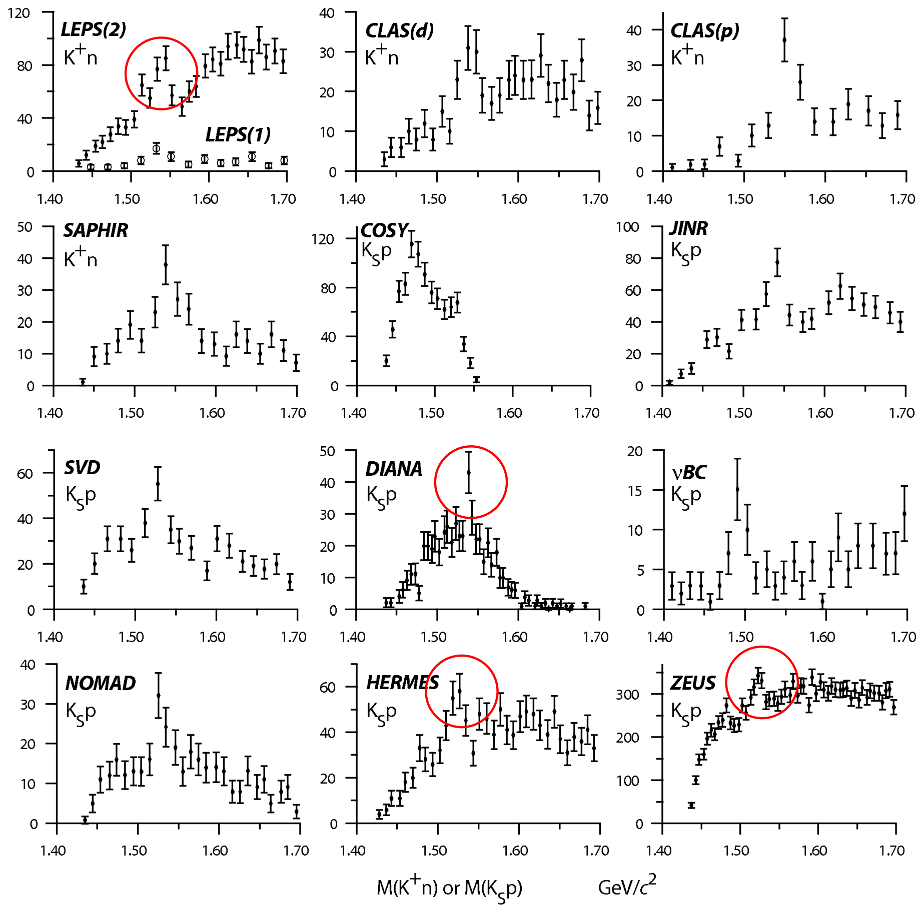


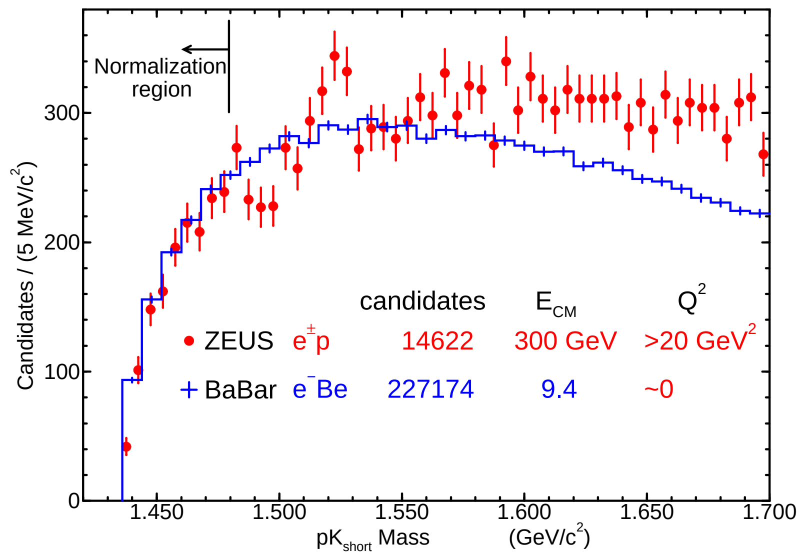


The rise and fall of pentaquarks

□ Low statistics evidences for "pentaquarks" were provided by several experiments around 2005-2006 (see A. Dzierba, C. Mayer and A. Szczepaniak, hep-ex/04120).

□ Evidences for Θ^+ in the nK^+ and pK_S^0.

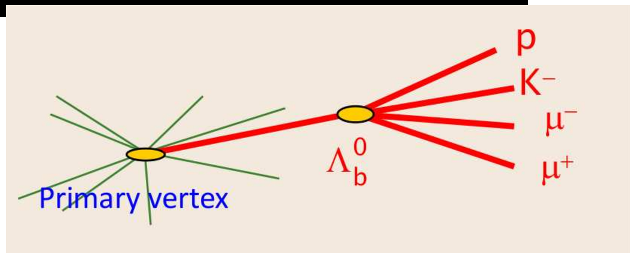




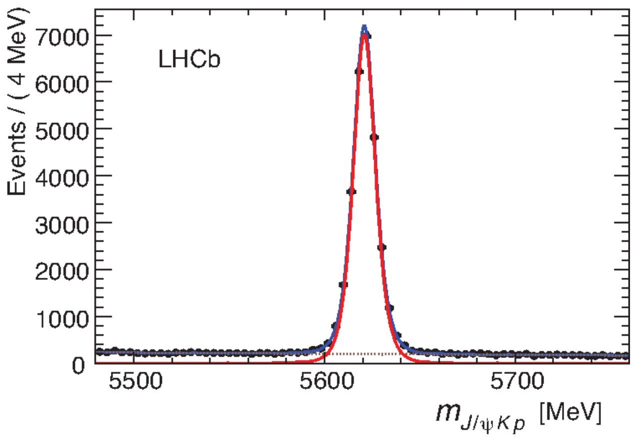
□ Significances in these data were largely overestimated and high statistics searches gave negative results (See for example BaBar: Phys.Rev.Lett. 95 (2005) 042002, FOCUS: Phys.Lett. B639 (2006) 604) .

□ Around 2007 pentaquarks were dead.

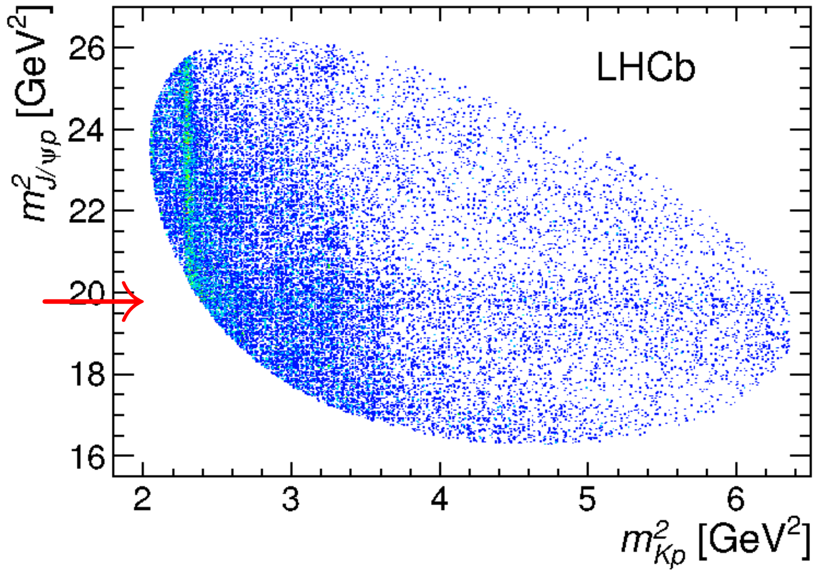
Observation of $J/\psi p$ resonances in $\Lambda_b^0 \to J/\psi p K^-$ decays in LHCb



- 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.

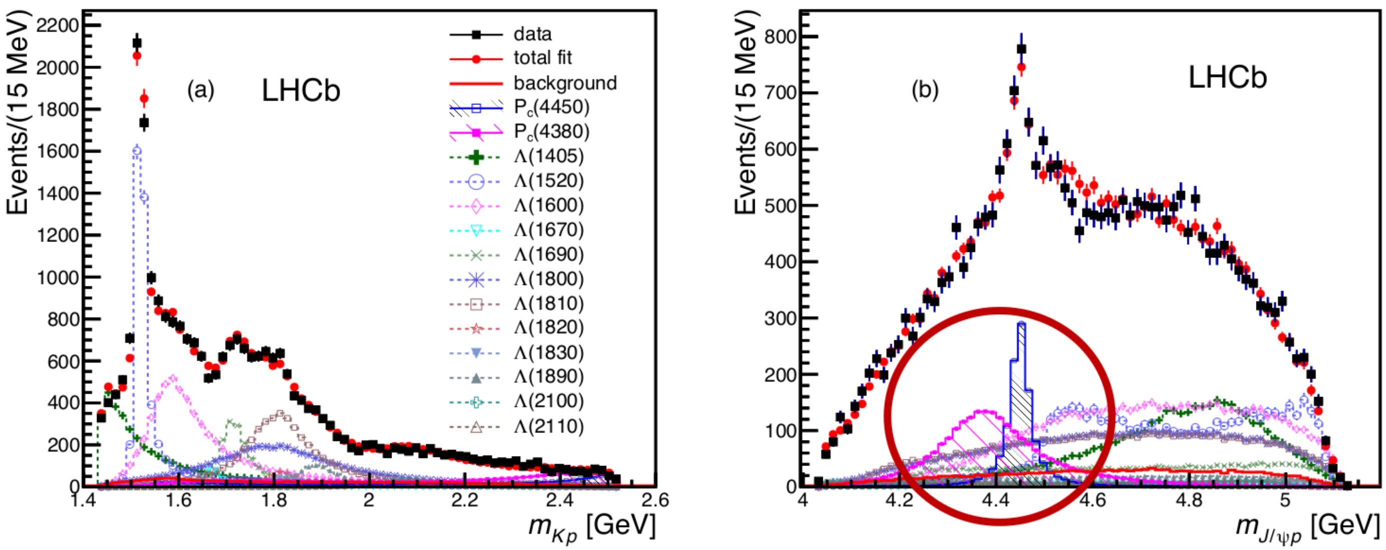


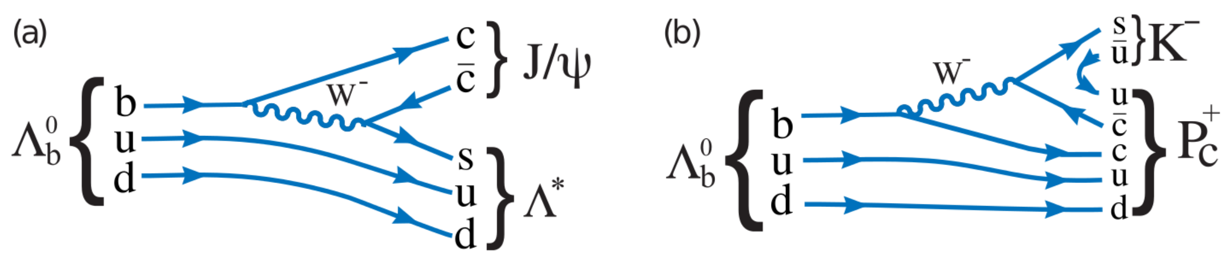
(PRL 115, 072001 (2015)).

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).



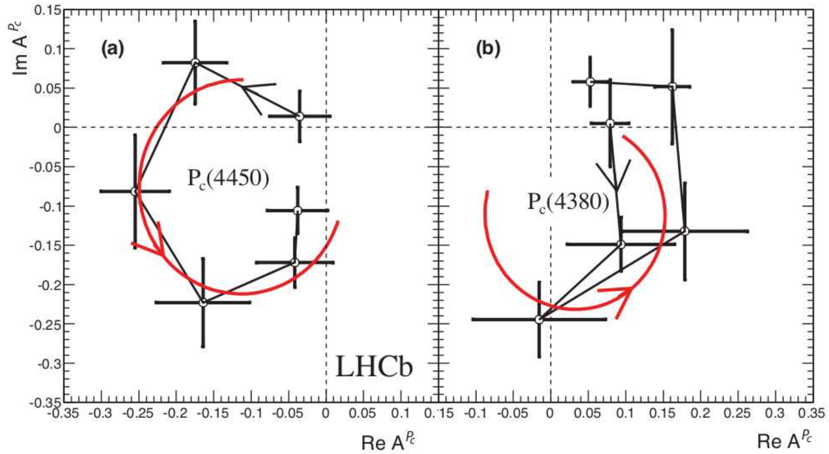


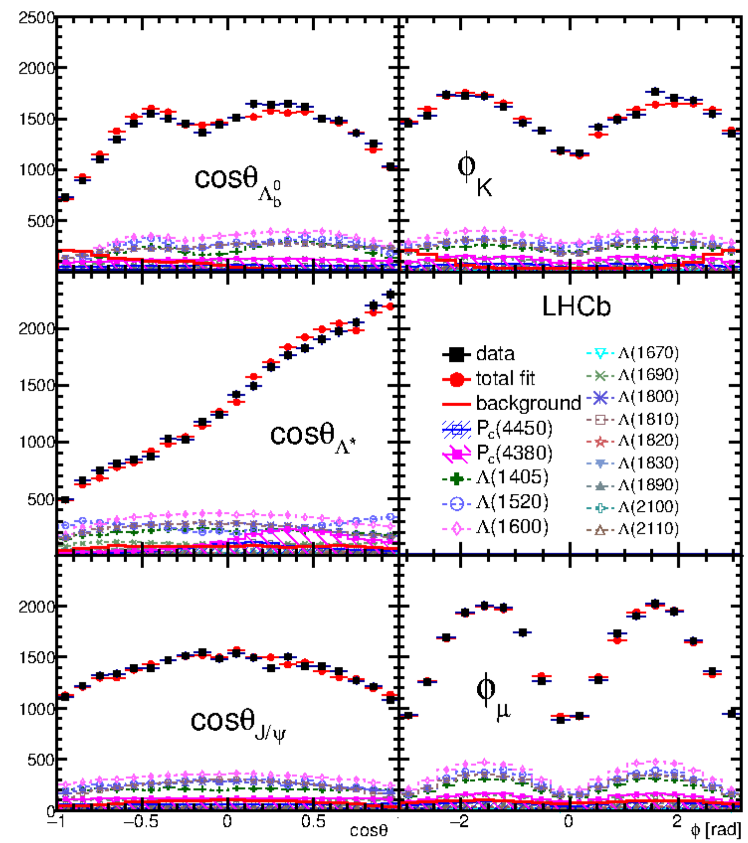
(PRL 115, 072001 (2015)).

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.



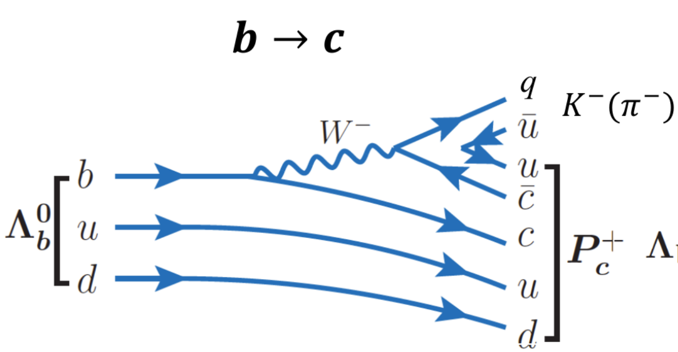


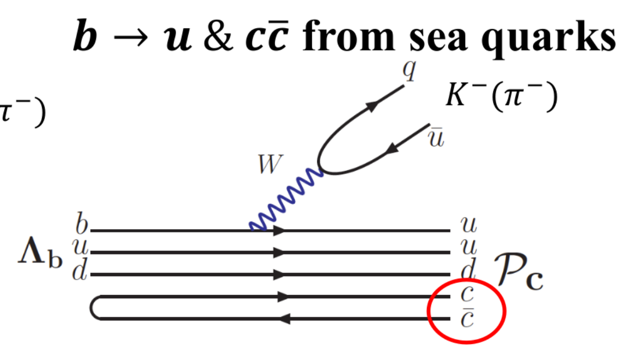
- □ Model independent analysis gives consistent results (Phys. Rev. Lett. 117, 082002 (2016)).

Search for other P_c^+ decay modes

□ Finding the same P_c^+ in other channels is helpful to understand P_c^+ production mechanism and internal structure.

□ Two P_c^+ production mechanisms predicted.





□ The two cases can be tested using the $R_{\pi/K}$ ratio which is expected to be very different.

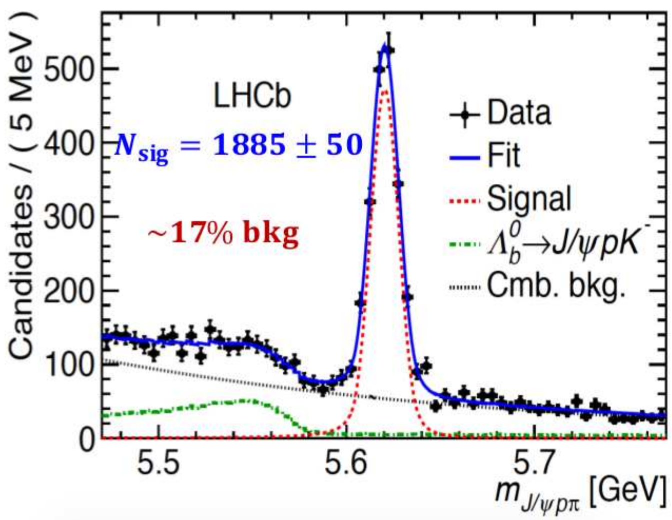
$$R_{\pi/K} = \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08, \quad R_{\pi/K} = 0.58 \pm 0.05$$

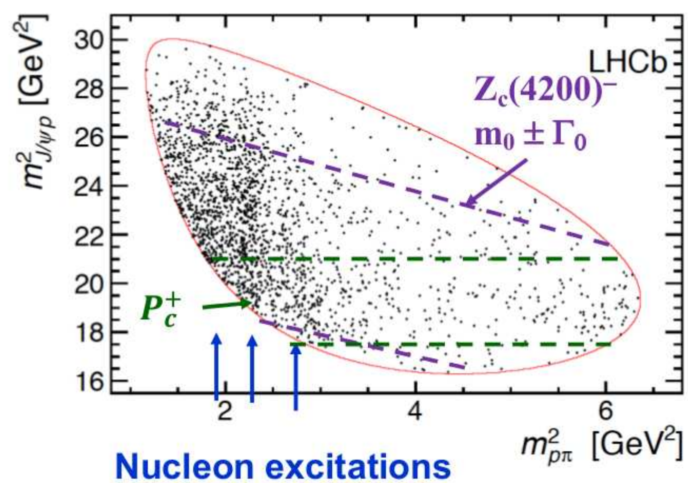
Cheng, Phys. Rev. D 92, 096009 (2015),Hsiao, Phys. Lett. B 751, 572 (2015)

Study of $\Lambda_b^0 \to J/\psi p \pi^-$ decays in LHCb

□ Branching fraction for the Cabibbo suppressed $\Lambda_b^0 \to J/\psi p \pi^-$ is $\approx 8\%$ of the Cabibbo favoured $\Lambda_b^0 \to J/\psi p K^-$ decay mode.

□ More complex because of the possible contribution of $Z_c(4200)^- \to J/\psi \pi^-$ (observed by Belle in $B^0 \to J/\psi K^+ \pi^-$(PRD 90 (2014) 112009)).





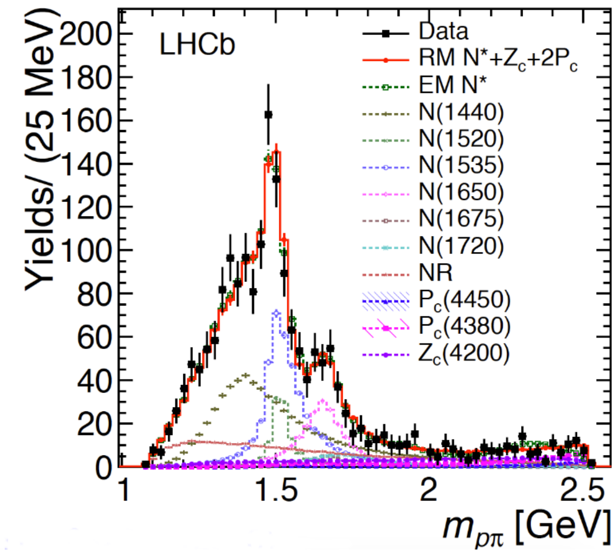
□ Full amplitude analysis. Accurate description of the rich resonant structure in the $p\pi^-$ final state.

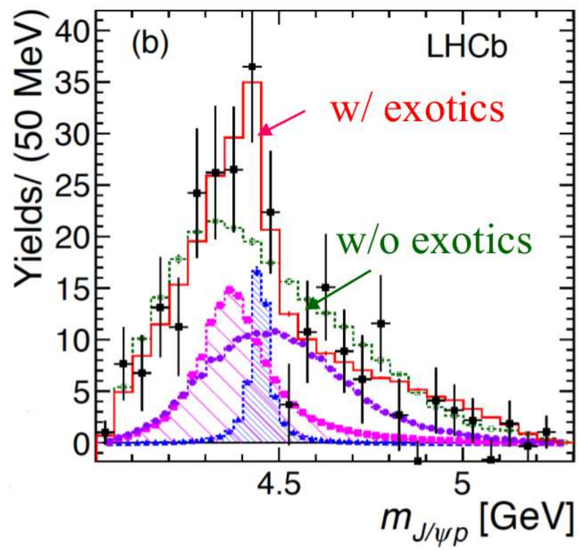
$$\Lambda_b \to J/\psi N^*(\to p\pi^-),\ \Lambda_b \to \pi^- P_c^+(\to J/\psi p),\ \Lambda_b \to p Z_c(4200)^-(\to J/\psi \pi^-)$$

Phys. Rev. Lett. 117, 082003 (2016)

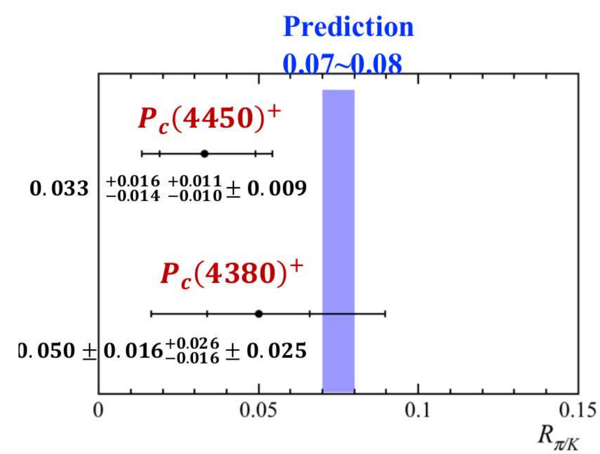
Study of $\Lambda_b^0 \to J/\psi p \pi^-$ decays

- □ $Z_c(4200)^-$, N^* and exotic states parameters fixed.
- □ Each Pc: 4 free parameters +6 fixed to that from $\Lambda_b^0 \to J/\psi p K^-$.





- □ Significance of the two P_c^+ is 3.1σ.

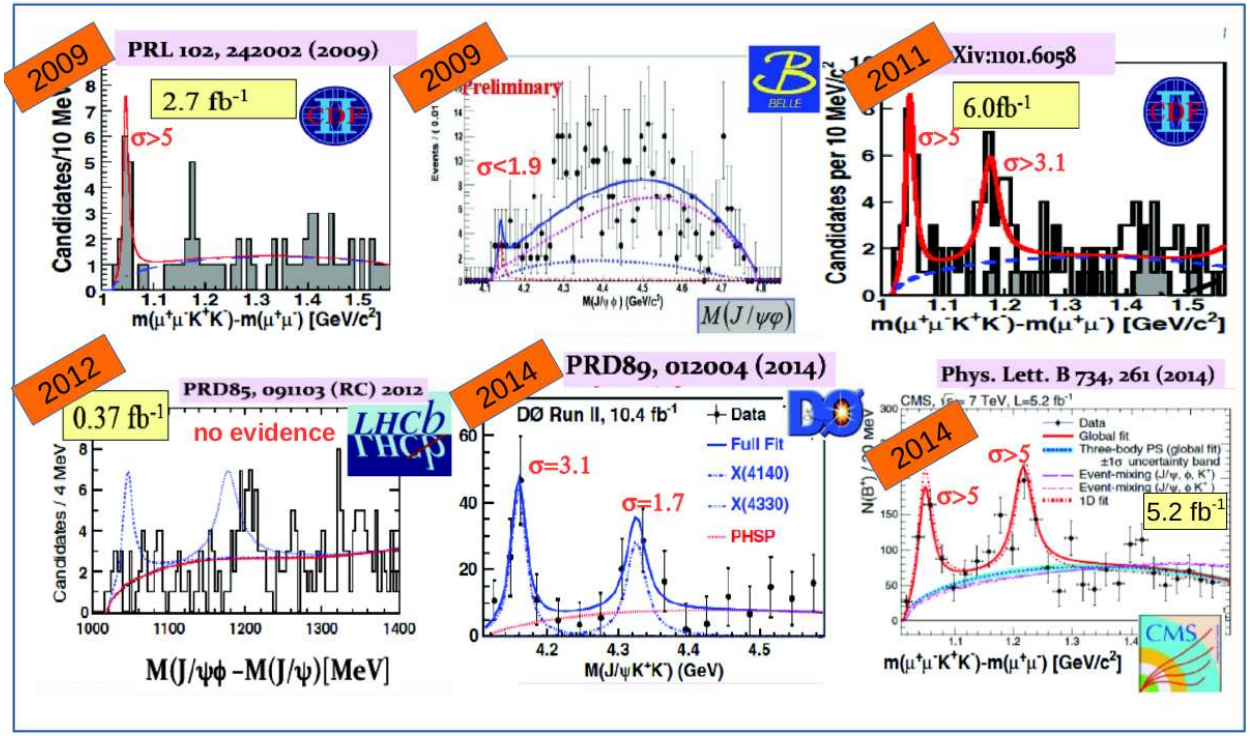


- □ The $b \to c$ diagram strongly favoured.

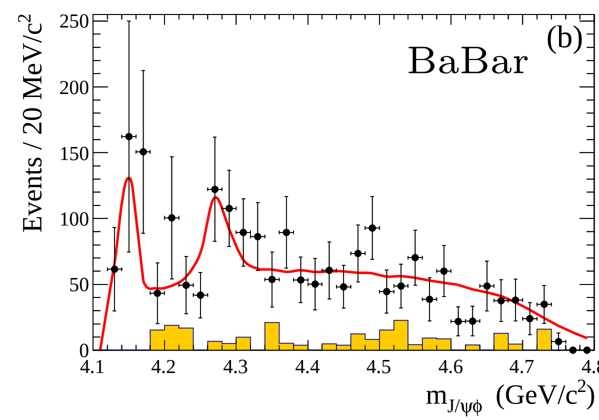
Phys. Rev. Lett. 117, 082003 (2016)

Resonances decaying to $J/\psi\phi$ in $B^+ \to J/\psi\phi K^+$

- 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. Many experiments results.



PRD 91 012003

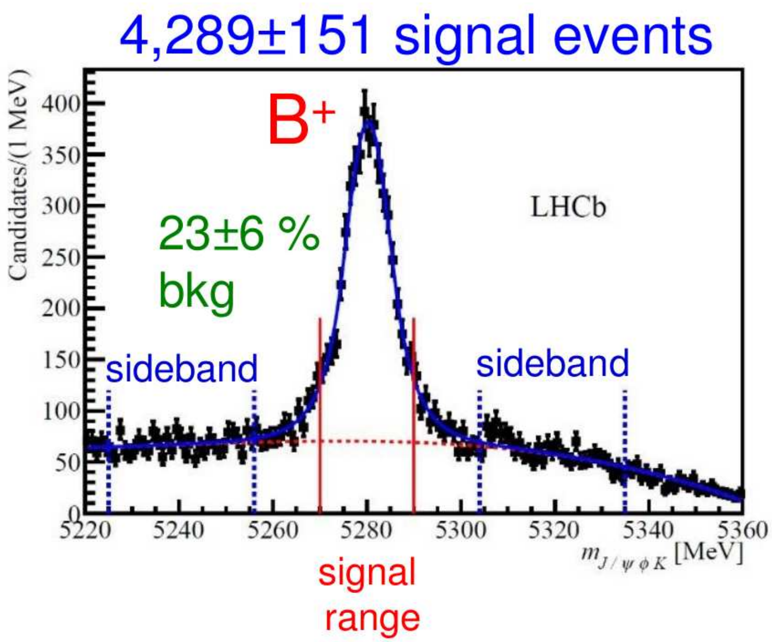


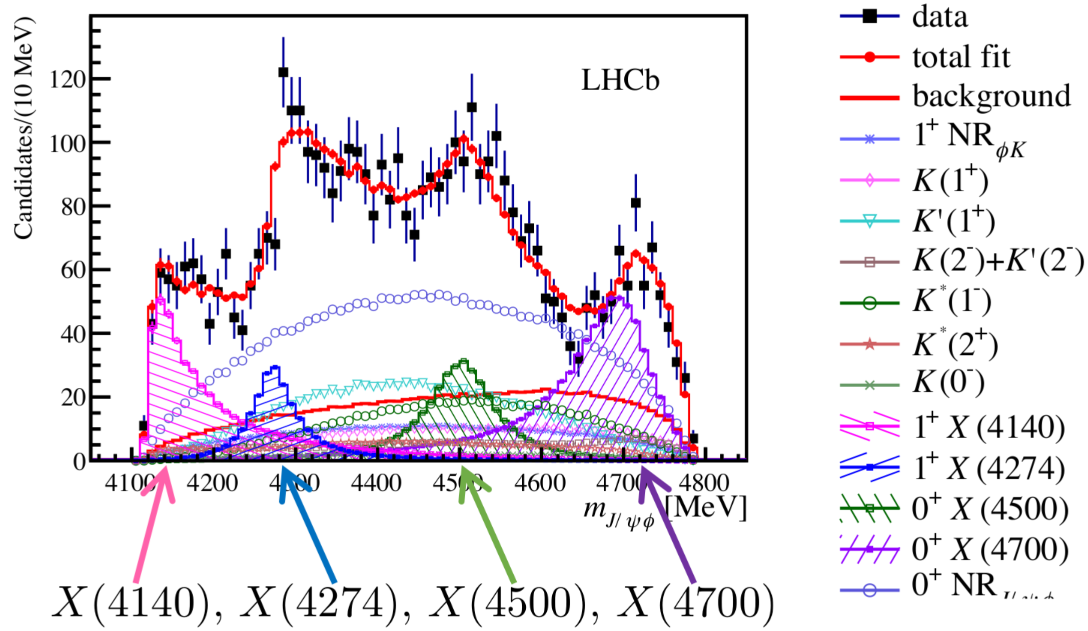
- Summary of the experimental evidences.

Experiment	CDF	Belle	CDF	LHCb	CMS	D0	BaBar
year	2008	2009	2011	2011	2013	2013	2014
Significance ($N\sigma$)	3.8	1.9	5.0	1.4	5.0	3.1	1.6

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

- Update of the analysis using 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.





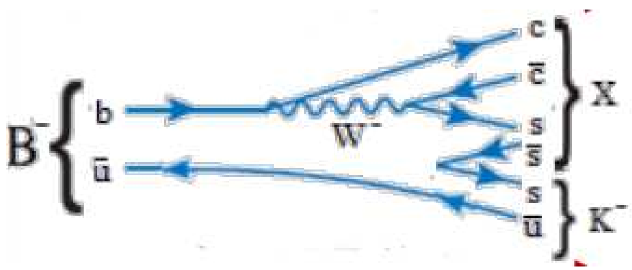
New results on $B^+ \to J/\psi\phi K^+$ from LHCb

☐ 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.

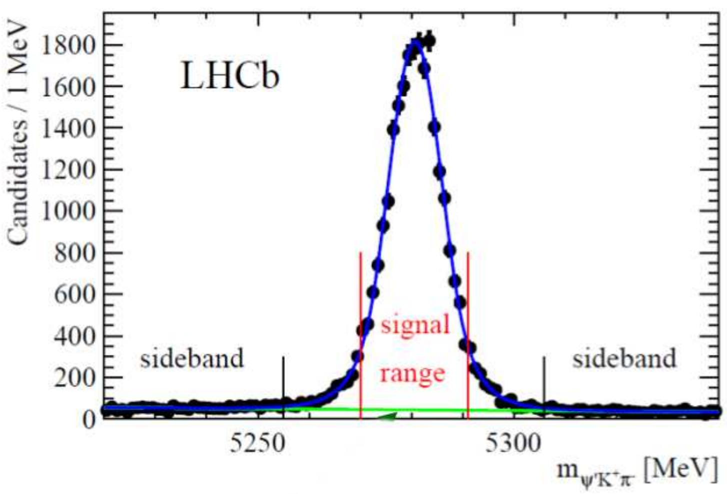
☐ A possible diagram for producing a 4-quark state.

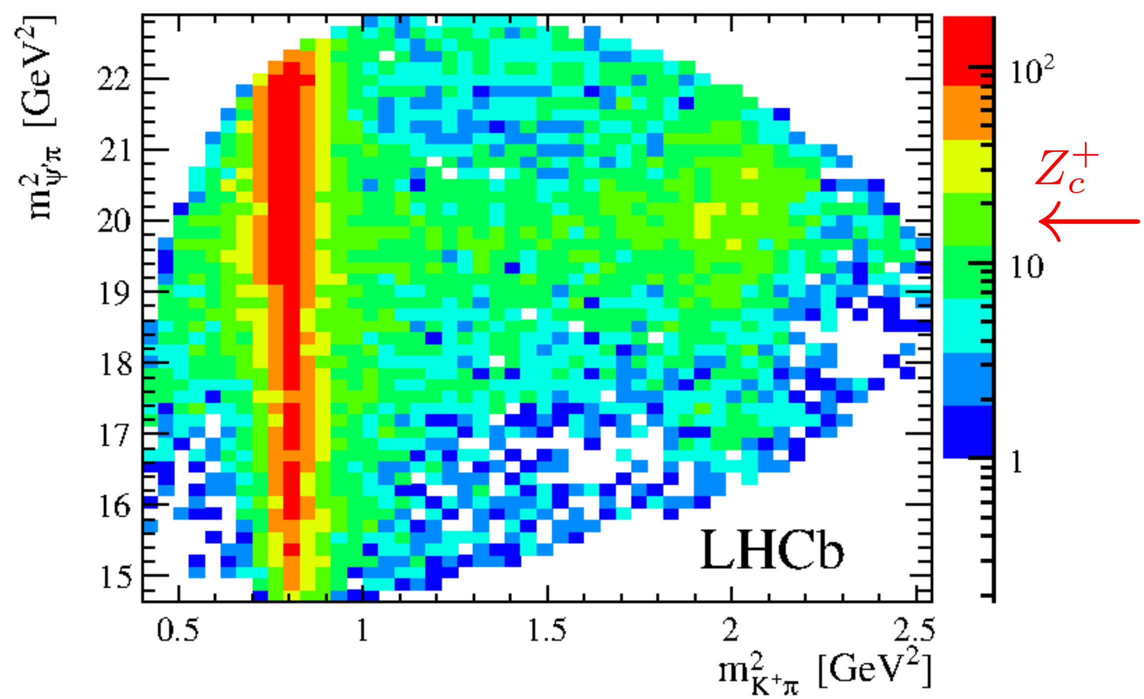


☐ Lot of discussions. Interpretation of these states still open.

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

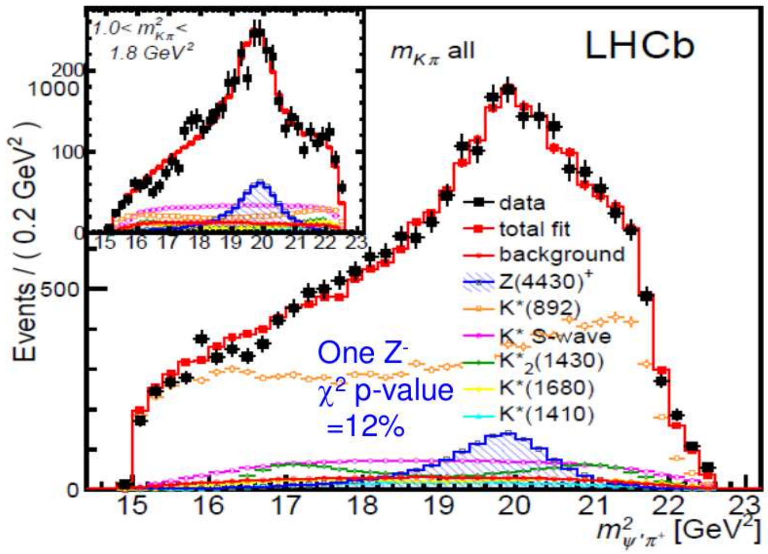
- □ First analysis from Belle: observation of a new $Z_c(4430)^+ \to \psi'\pi^-$ in $B \to K\pi^+\psi'$ (PRL 100, 142001 (2008)).
- □ Not confirmed by BaBar: data could be described without the presence of a $Z_c(4430)^+$ resonance (PRD 79, 112001 (2009)).
- □ Recent analysis from LHCb (PRL 112, 222002 (2014)).
- □ B^0 signal: 25,176 events (Belle: 2,010, BaBar: 2,021 events).

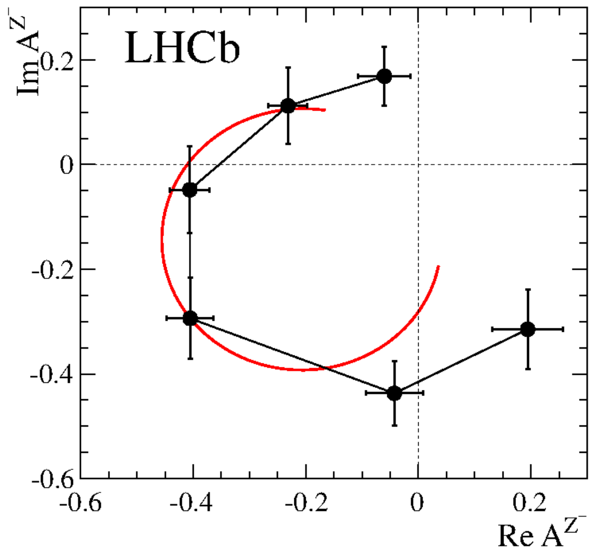




Study of $\bar{B}^0 \to \psi' \pi^- K^+$

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

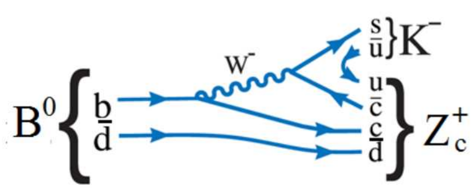


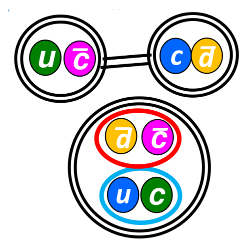


- Argand diagram shows typical resonance behaviour. Resonance parameters:

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

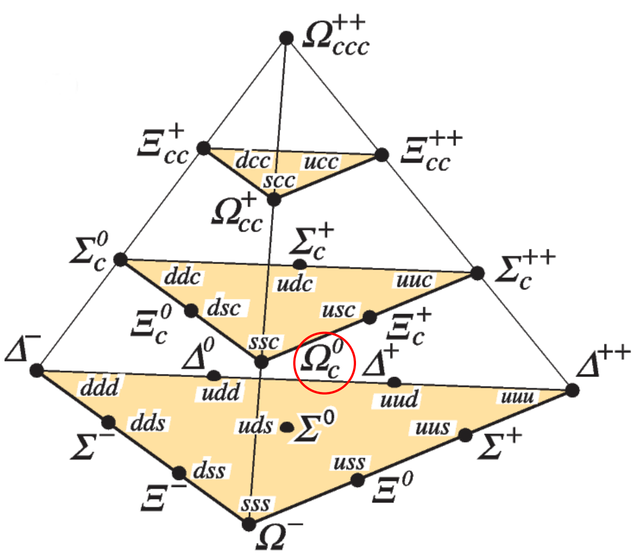
- In good agreement with Belle.
- Possible presence of an additional Z_c at a mass of 4239 MeV.
- Z_c is a charged charmonium state. Multiquark state?

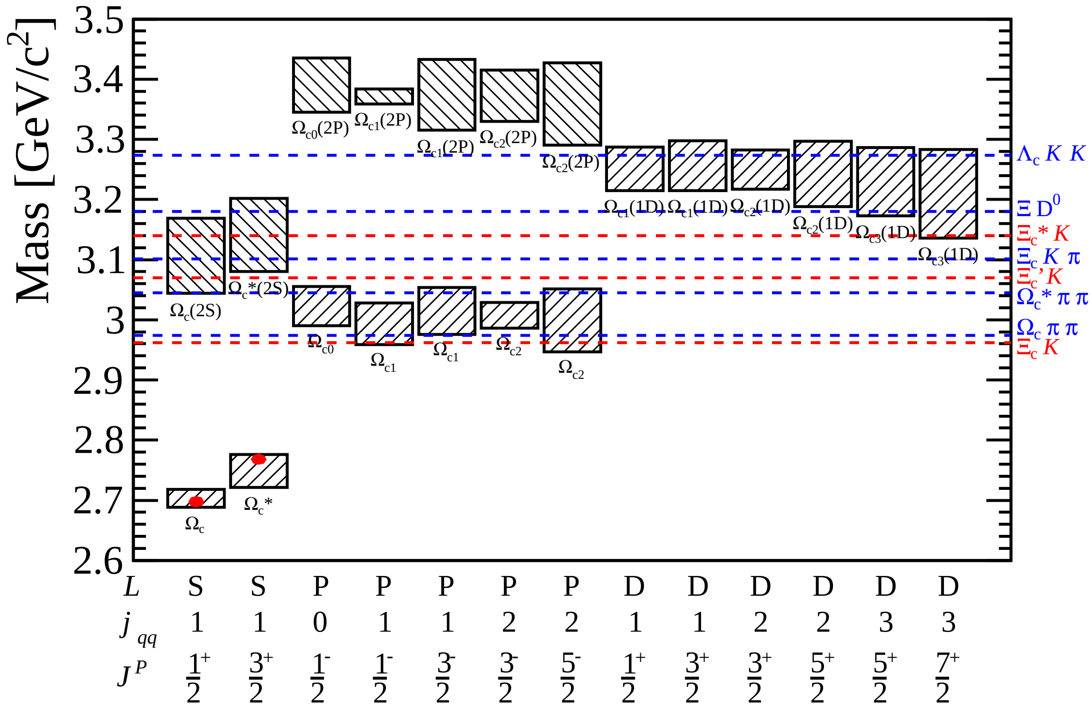




Baryon spectroscopy

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

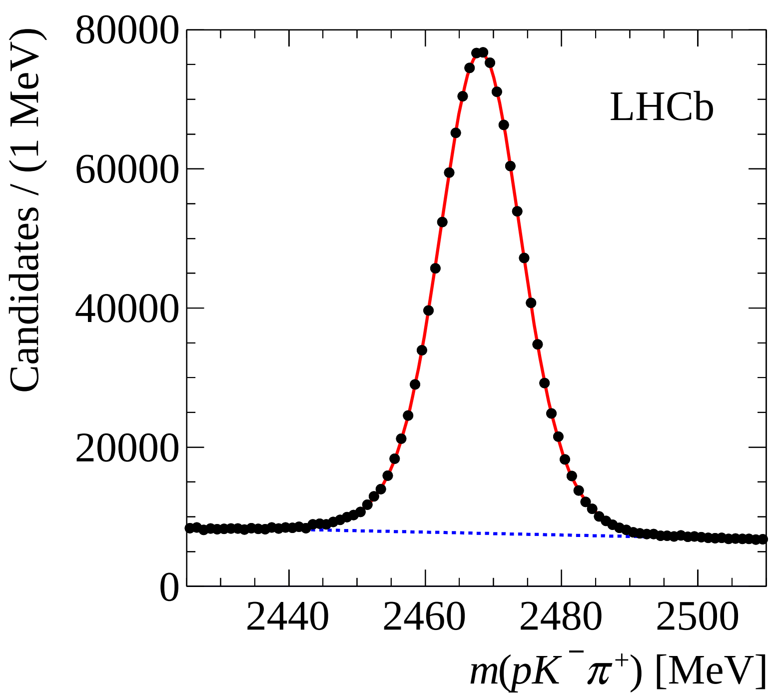


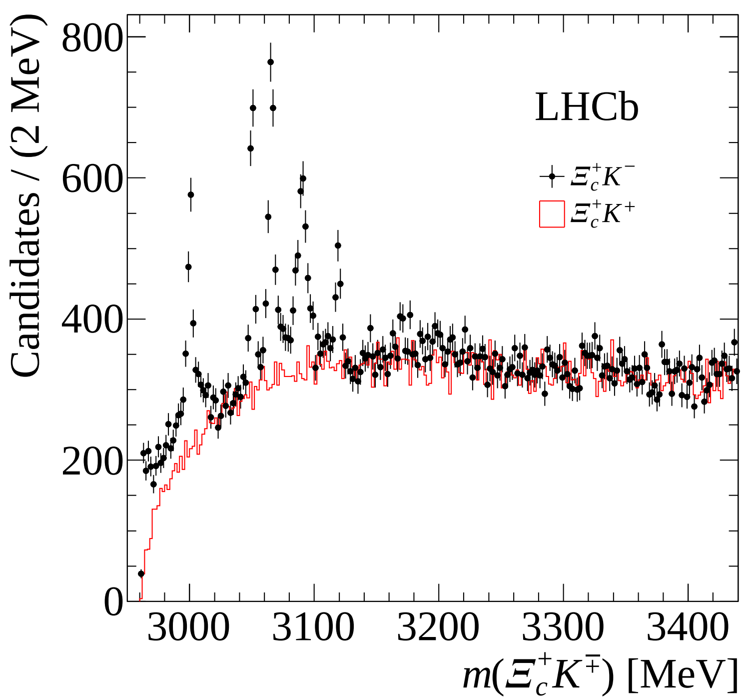


- Ω_c quark content: *ssc*.
- Only $1/2^+$ and $3/2^+$ ground states were known.

Observation of five new Ω_C states in LHCb

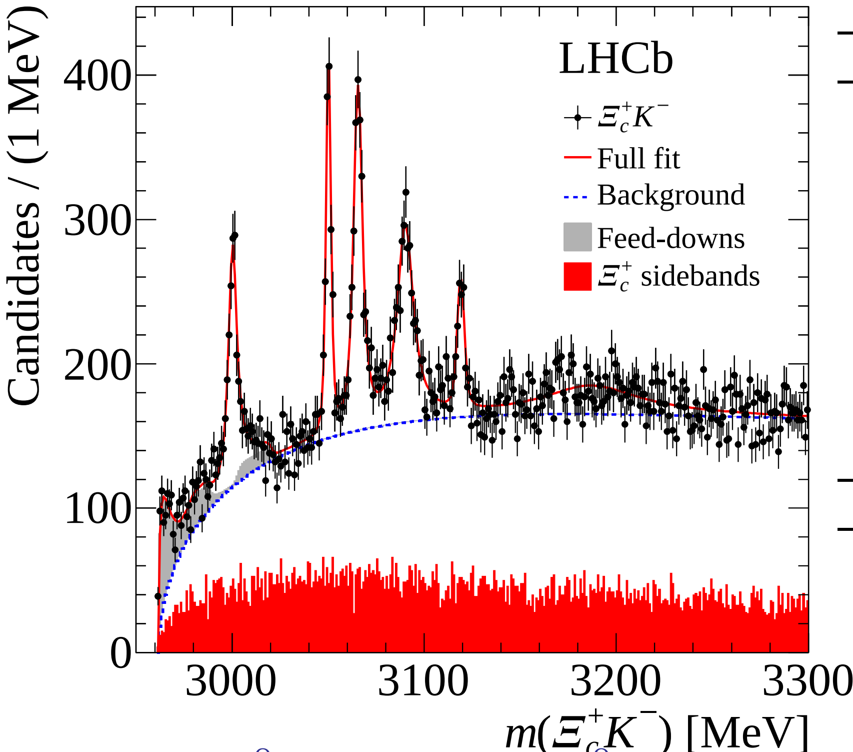
- Explore excited Ω_c states in their strong decay to $\Xi_c^+ K^-$ (PRL 118 (2017) 182001).
- Make use of data collected at 7,8 and 13 TeV (3.3 fb^{-1}).
- Ξ_c^+ reconstructed in the Cabibbo suppressed mode $\Xi_c^+ \to pK^-\pi^+$.
- $\approx 10^6$ Ξ_c^+ reconstructed with a 83% purity.
- Ξ_c^+ combined 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 $\approx$ 3200 MeV with one Breit-Wigner.
- Resonances parameters.

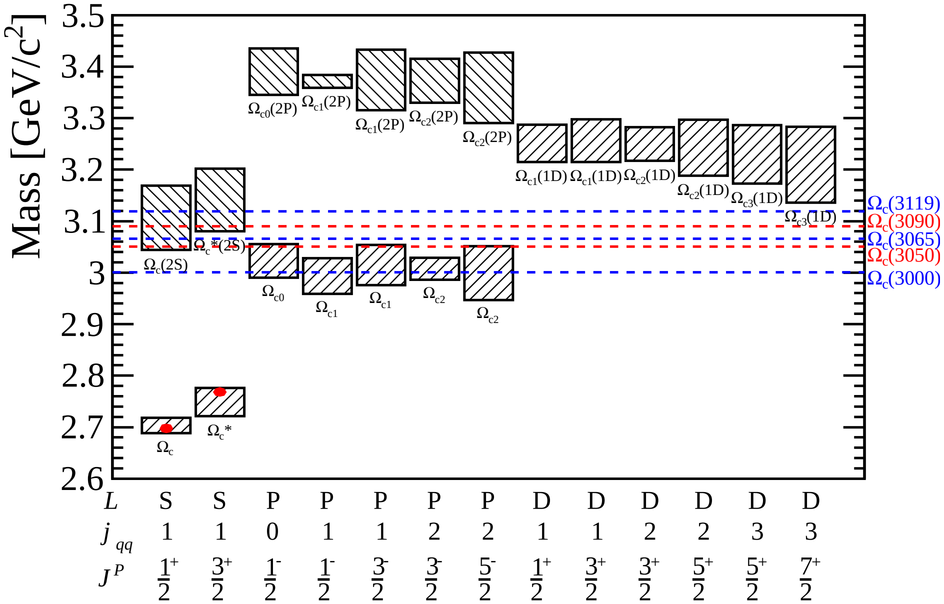


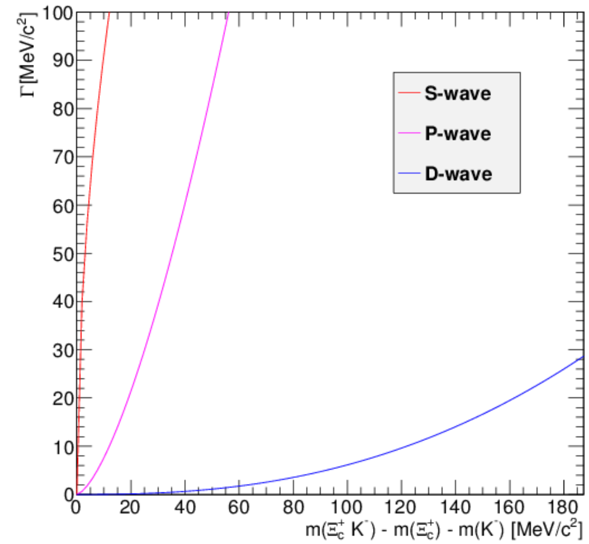
Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		$<$ 1.2 MeV, 95% CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$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

Observation of five new Ω_C states

□ Comparison with theoretical expectations.





□ D and P-wave states may be narrow (G. Chiladze, A. Falk arXiv: 9707507).

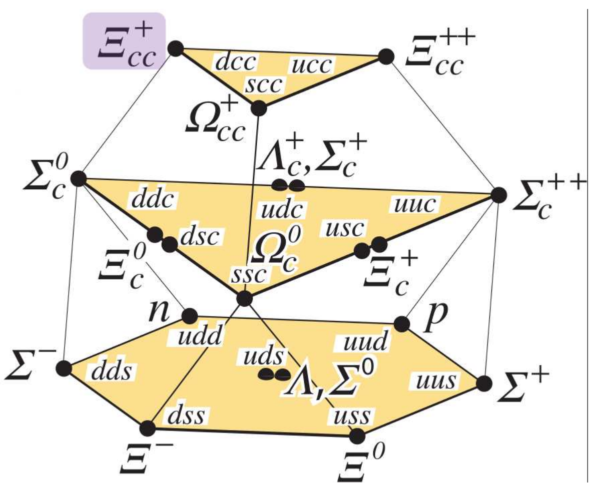
□ Need to measure the quantum numbers of these states.

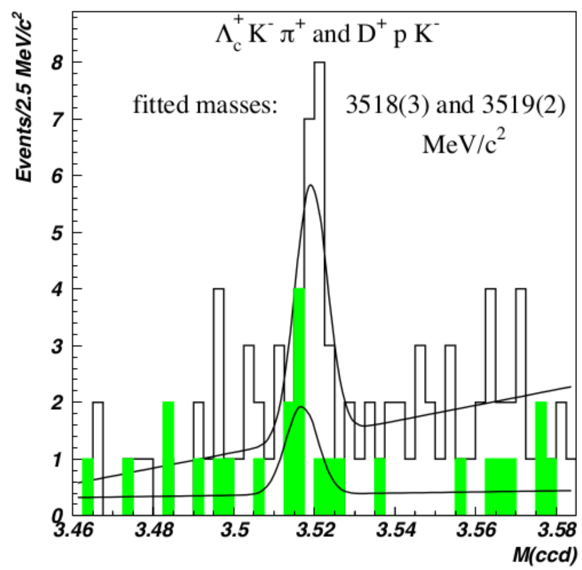
□ Many phenomenological interpretations, including the possible presence of pentaquarks.

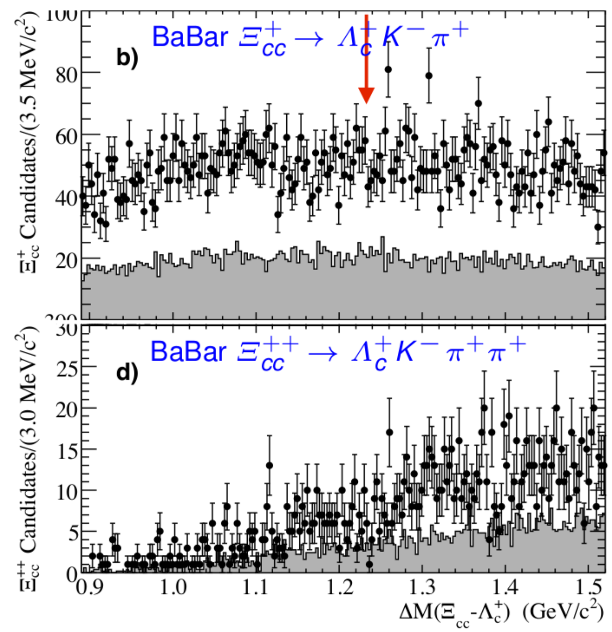
The search for double charmed baryons Ξ_{cc} states

□ The first claim for observing the Ξ_{cc}^{+} (dcc) state comes from SELEX experiment

(PRL 89 (2002) 112001, PLB 628 (2005) 18)







□ Not observed by BaBar (Phys.Rev. D74 (2006) 011103), nor by Belle (Phys.Rev.Lett. 97 (2006) 162001).

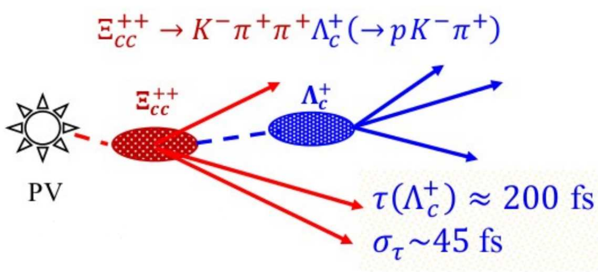
□ Different production mechanisms?

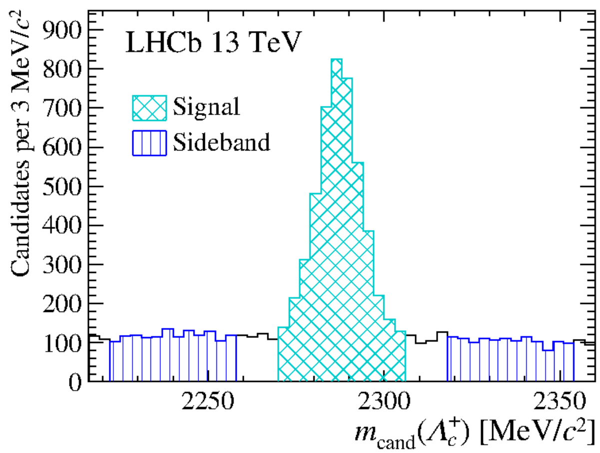
Observation of the double charmed baryon Ξ_{cc}^{++} in LHCb

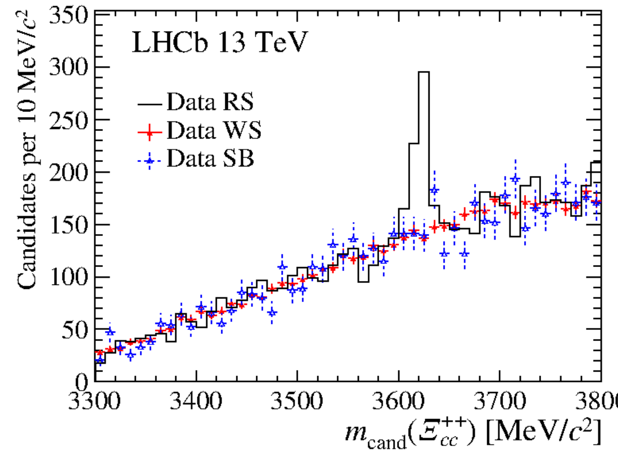
□ Search for the Ξ_{cc}^{++} (ucc) using the decay (Phys. Rev. Lett. 111 (2017) 180001).

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

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







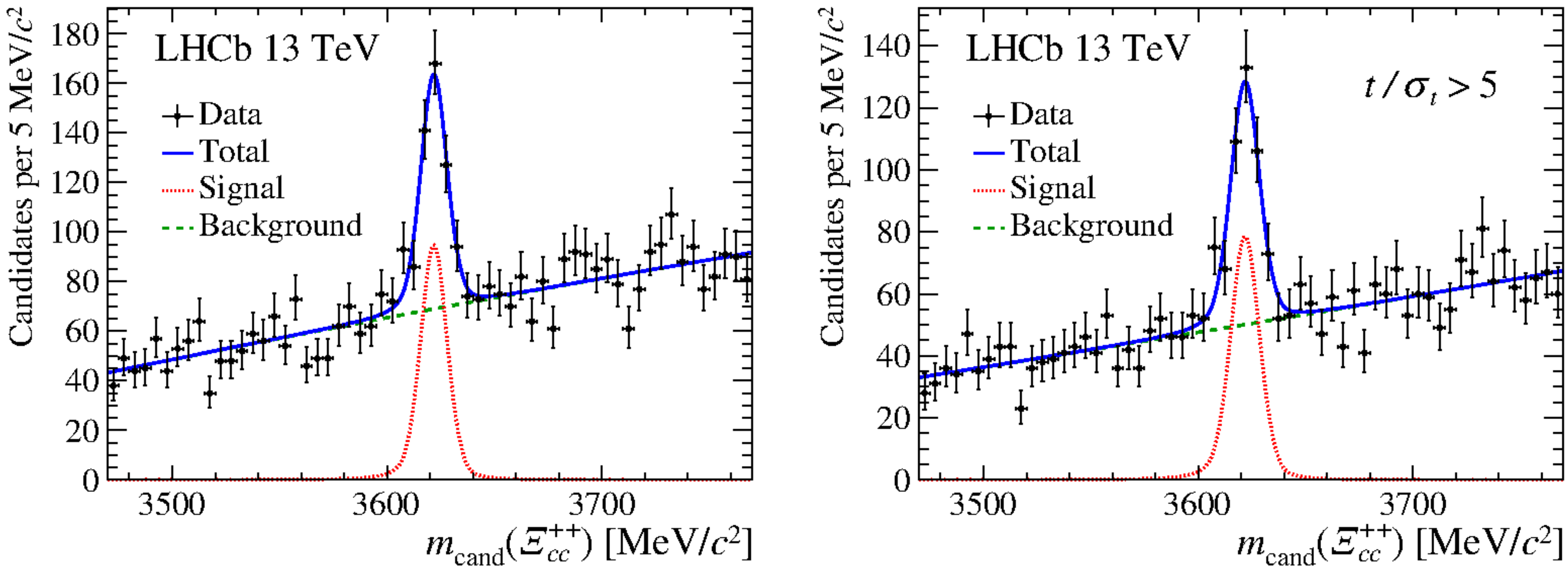
□ First observation.

□ 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.



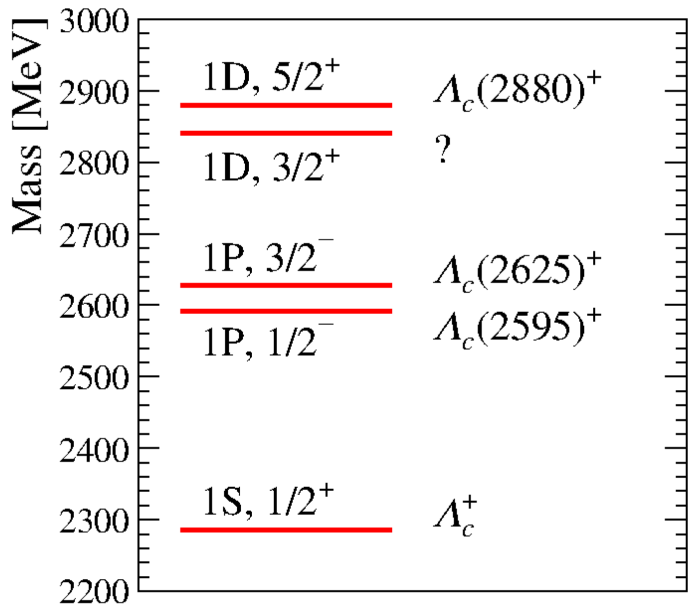
- The signal persists after a lifetime cut.
- Ξ_{cc}^{++} parameters.

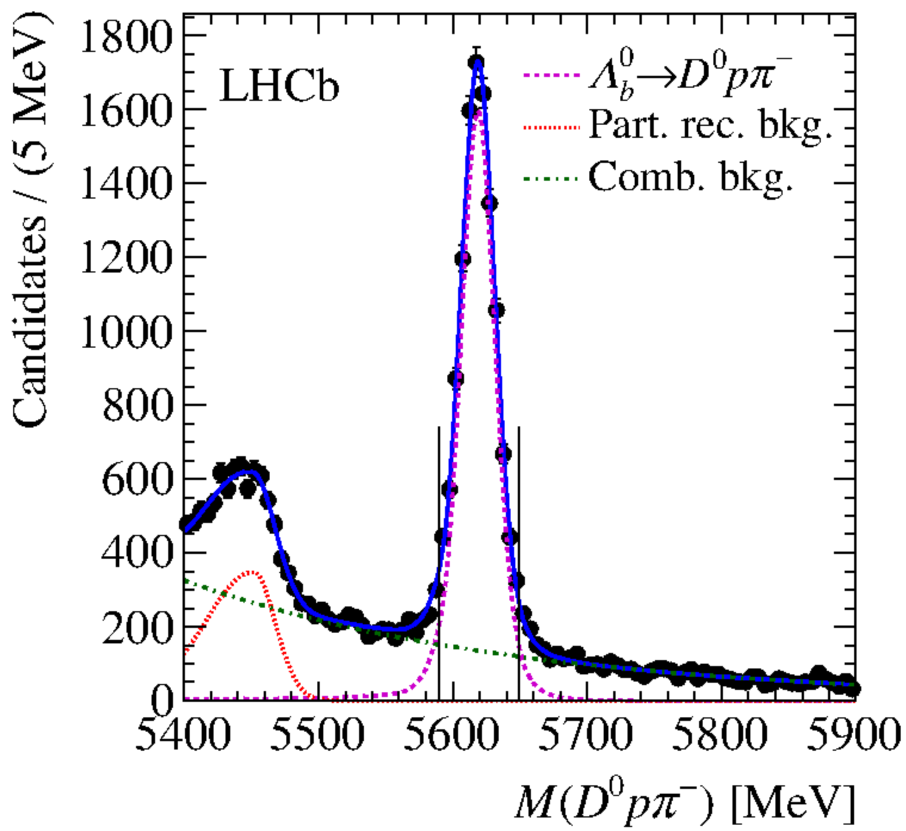
$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c) MeV$$

- Mass difference with respect to the possible SELEX isospin partner: 103 ± 2 MeV.
- Inconsistent with expected isospin splitting for Ξ_{cc}^{+}.

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

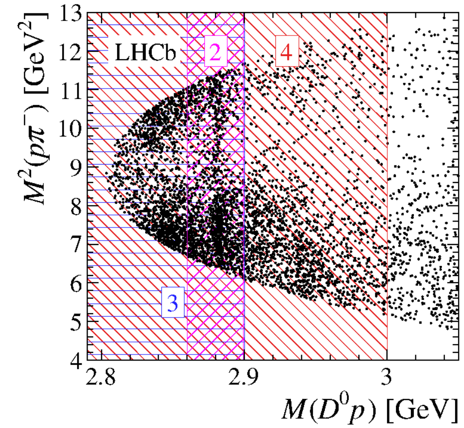
- □ The Λ_c spectrum needs to be completed.
- □ Explore the Λ_c spectroscopy using the $D^0 p$ final state (JHEP 05 (2017) 30).
- □ The inclusive $D^0 p$ was studied by BaBar (PRL 98 (2007) 01).
- □ High statistics clean Λ_b signal in LHCb (11,200 events, 86% purity).





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

- Follow helicity formalism to describe 5D amplitude of $D^0 p$ and $p\pi^-$ masses (JHEP 05 (2017) 30).
- Dalitz plot and $D^0 p$ mass projection.



- $\Lambda_c(2860)^+$ parameters (first observation), $J^P = 3/2^+$:

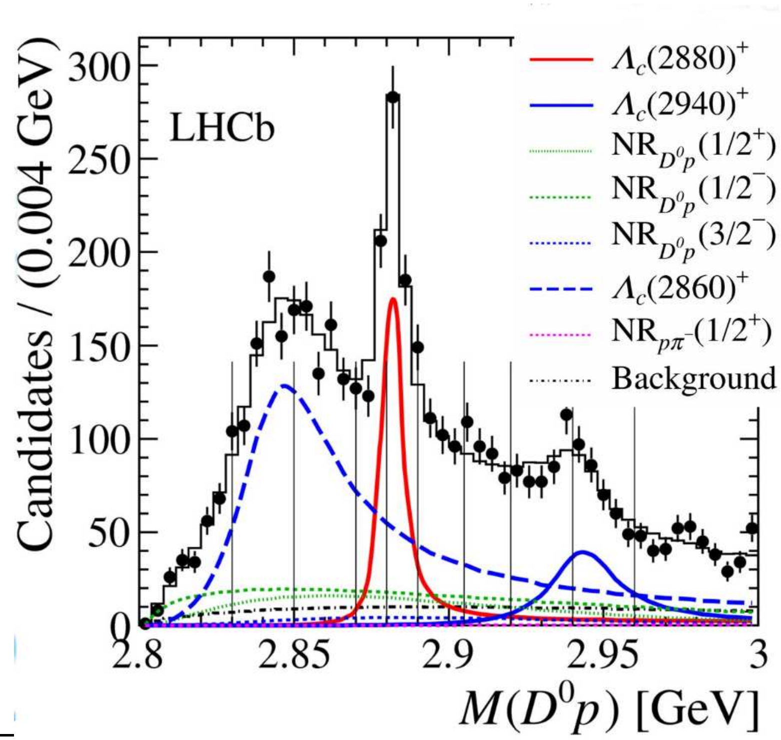
$$m = 2856.1^{+2.0}_{-1.7}(stat) \pm 0.5(syst)^{+1.1}_{-5.6}(model)\ \text{MeV}$$
$$\Gamma = 67.6^{+10.1}_{8.1}(stat) \pm 1.4(syst)^{+5.9}_{-20.0}(model)\ \text{MeV}$$

- $\Lambda_c(2880)^+$ parameters, $J^P = 5/2^+$ preferred:

$$m = 2881.75 \pm 29(stat) \pm 0.07(syst)^{+0.14}_{-0.20}(model)\ \text{MeV}$$
$$\Gamma = 5.43^{+0.77}_{0.71}(stat) \pm 0.29(syst)^{+0.75}_{-0.00}(model)\ \text{MeV}$$

- $\Lambda_c(2940)^+$ parameters, $J^P = 3/2^-$ preferred:

$$m = 2944.8^{+3.5}_{-2.5}(stat) \pm 0.4(syst)^{+0.1}_{-4.6}(model)\ \text{MeV}$$
$$\Gamma = 27.7^{+8.2}_{-6.0}(stat) \pm 0.9(syst)^{+5.2}_{-10.4}(model)\ \text{MeV}$$



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 experimantal 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.