

LHCb results on multiquarks

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On behalf of the LHCb Collaboration

Outline:

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

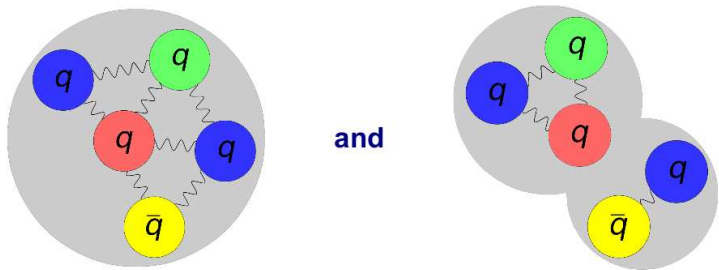
LHC Days in Split, 17-22 September 2018

Split, Croatia

Multiquark states

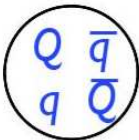
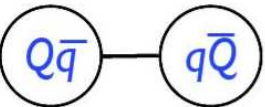
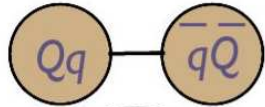
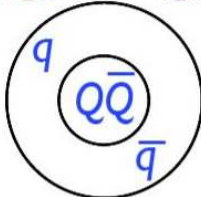
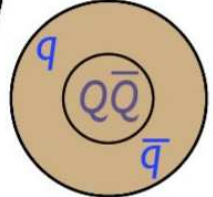
- In the original Gell-Mann paper (“A schematic model for baryons and mesons”, Phys. Lett. 8, (1964)).
- “Baryons can now be constructed from quarks by using combinations (qqq) , $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc.
- Today $qqqq\bar{q}$ baryons are called pentaquarks, $qq\bar{q}\bar{q}$ mesons are called tetraquarks.

Pentaquarks



and

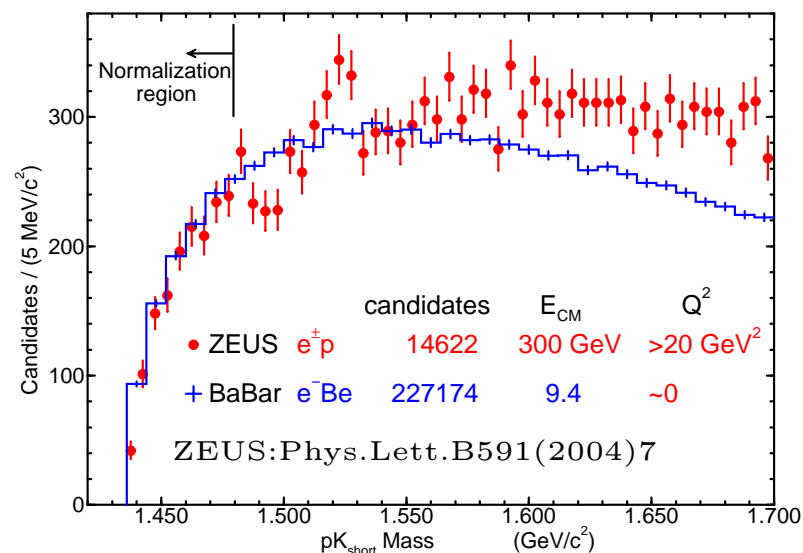
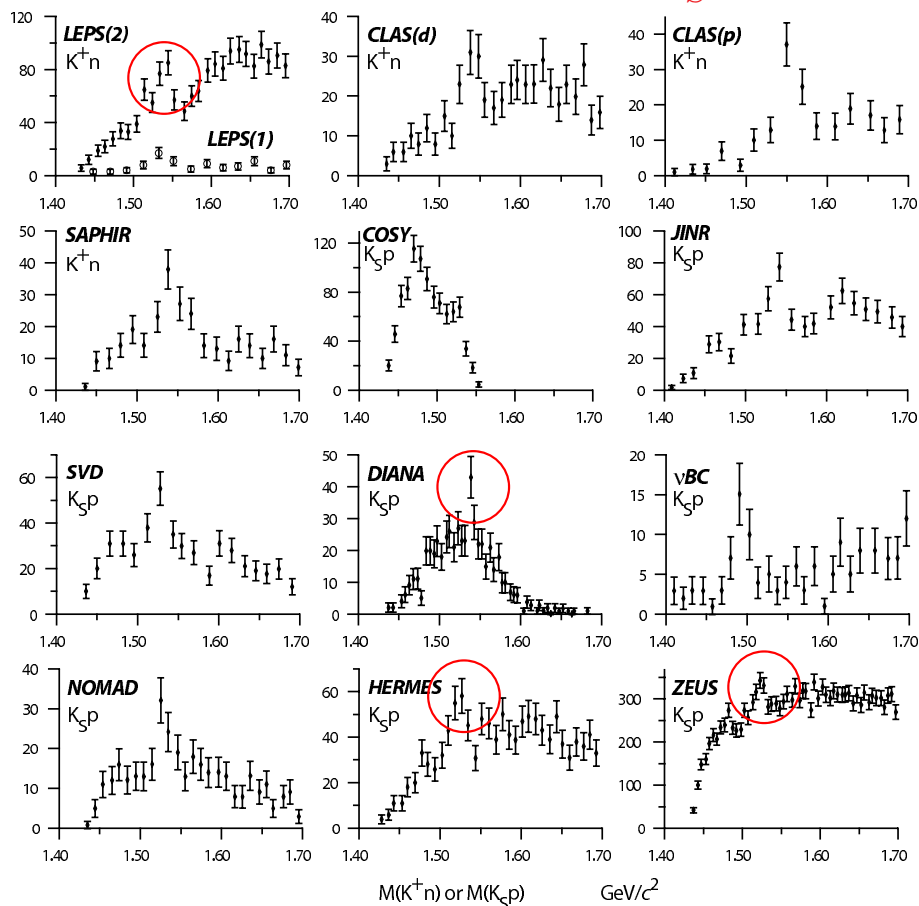
Quarkonium Tetraquarks

- compact tetraquark 
- meson molecule 
- diquark-onium 
- hadro-quarkonium 
- quarkonium adjoint meson 

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 .

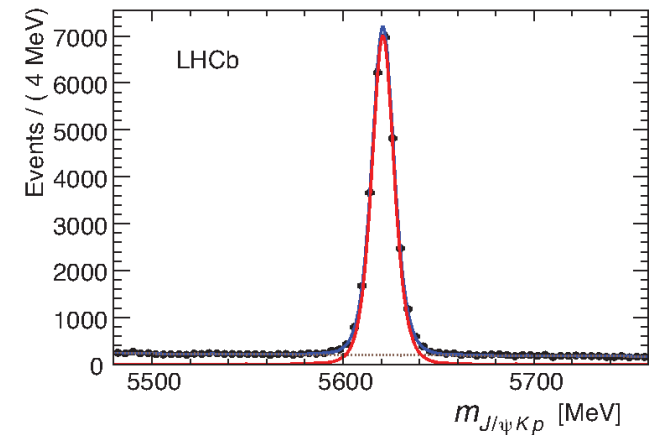
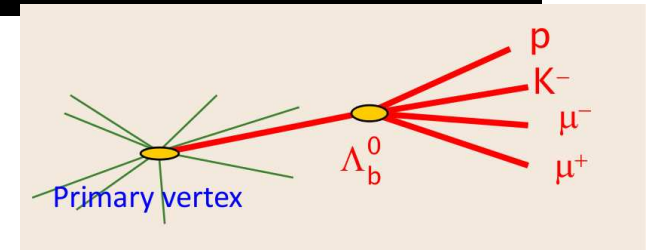
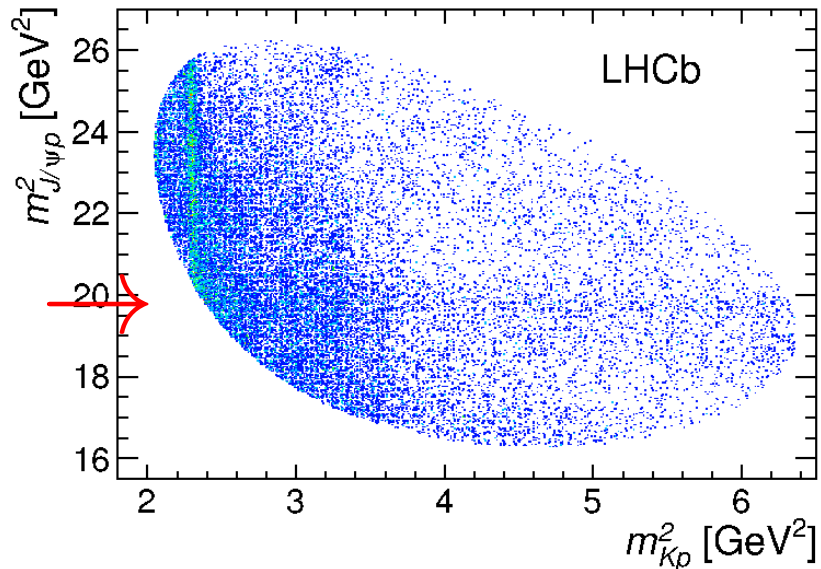


□ Significances in these data were largely overestimated and high statistics searches gave negative results (See for example BaBar: Phys.Rev.Lett. 95 (2005) 042002, FOCUS: Phys.Lett. B639 (2006) 604) .

□ Around 2007 pentaquarks were dead.

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

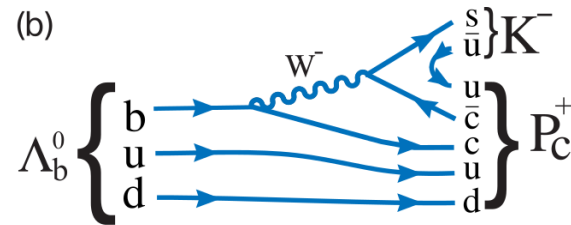
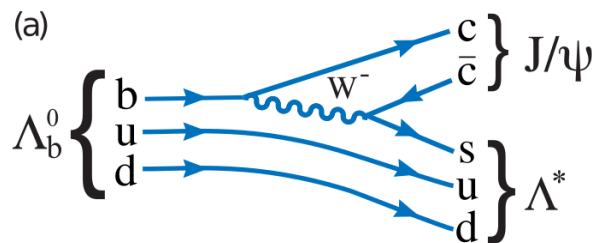
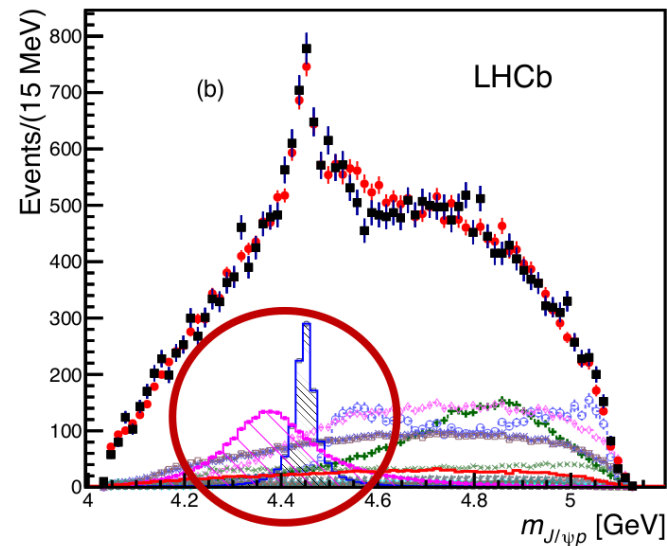
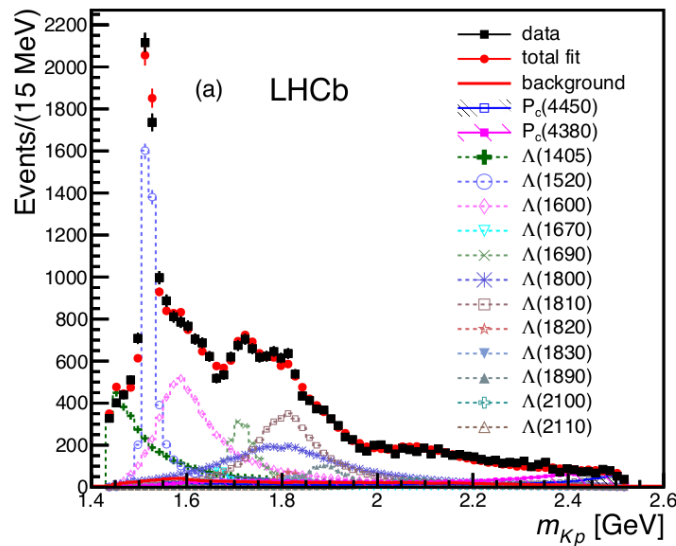
- Multivariate Analysis (TMVA) selection.
- $26,007 \pm 166 \Lambda_b^0$ events with 94.6% purity.
- The Dalitz plot shows rich Λ 's resonant structures along the pK^- axis.
- Unexpected structure along the $J/\psi p$ axis.



(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).

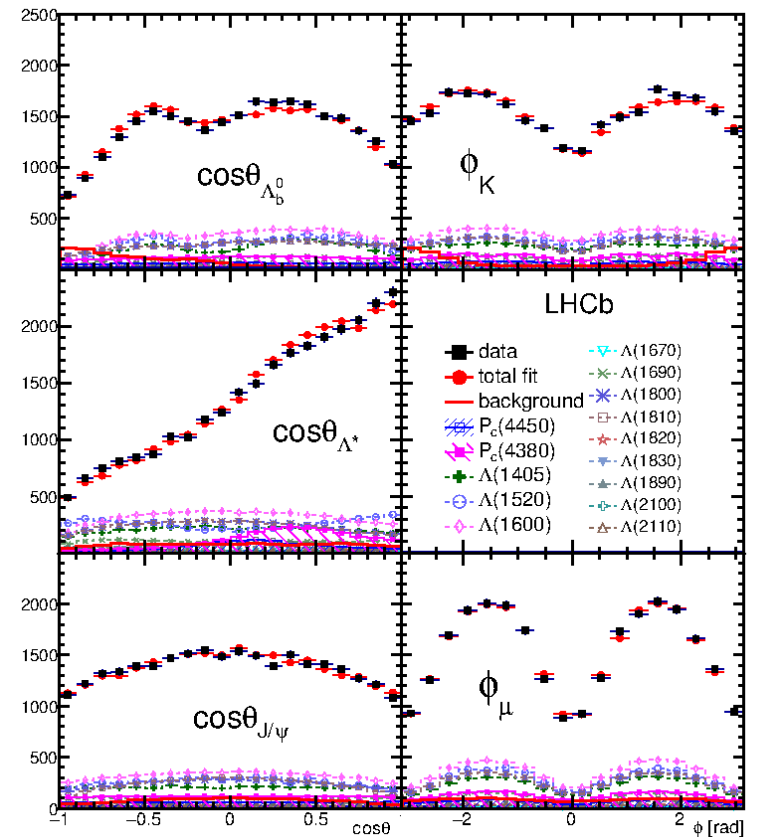
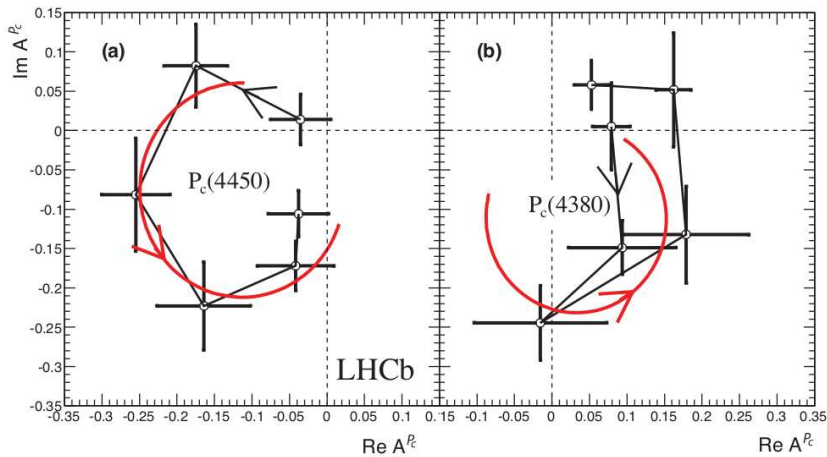


(PRL 115, 072001 (2015)).

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	$4.1 \pm 0.5 \pm 1.1$

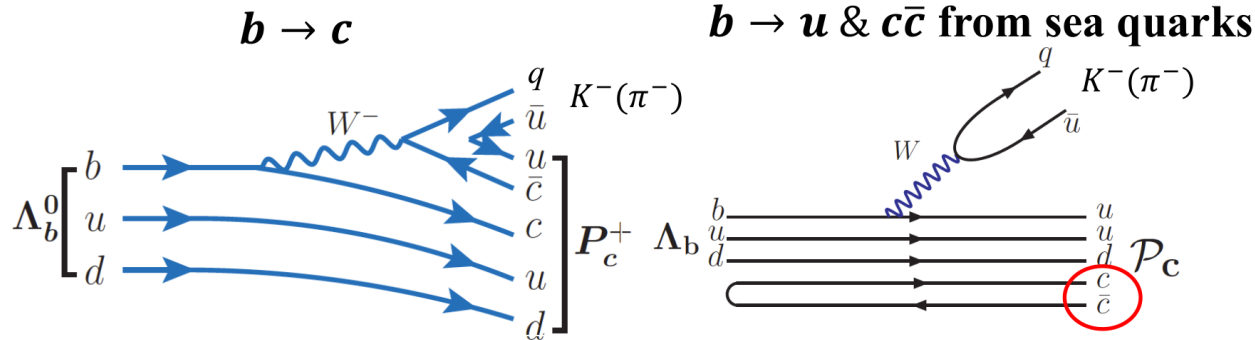
- The best fit has $J^P = 3/2^-$ and $J^P = 5/2^+$.
- Good description of the angular distributions.
- Measure the real and imaginary parts of the P_c amplitudes (PRL 115, 072001 (2015)).
- Argand Diagram consistent with expectations from a Breit-Wigner behaviour.



- 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.



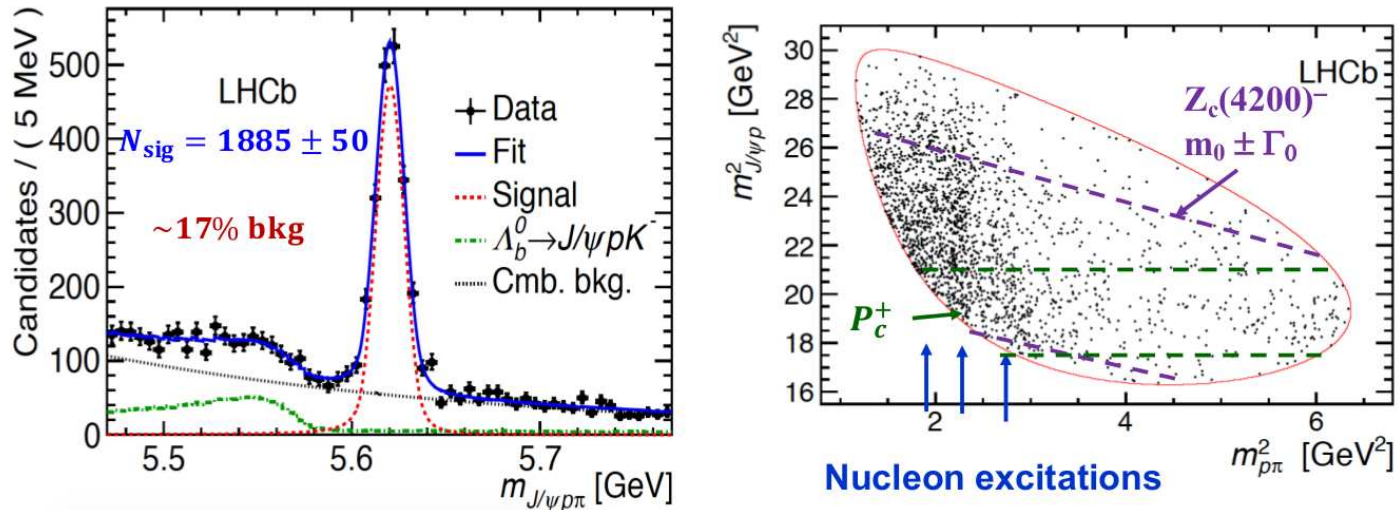
- The two cases can be tested using the $R_{\pi/K}$ ratio which is expected to be very different.

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

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

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

- Branching fraction for the Cabibbo suppressed $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ is $\approx 8\%$ of the Cabibbo favoured $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay mode.
- More complex because of the possible contribution of $Z_c(4200)^- \rightarrow J/\psi \pi^-$ (observed by Belle in $B^0 \rightarrow J/\psi K^+ \pi^-$ (PRD 90 (2014) 112009)).

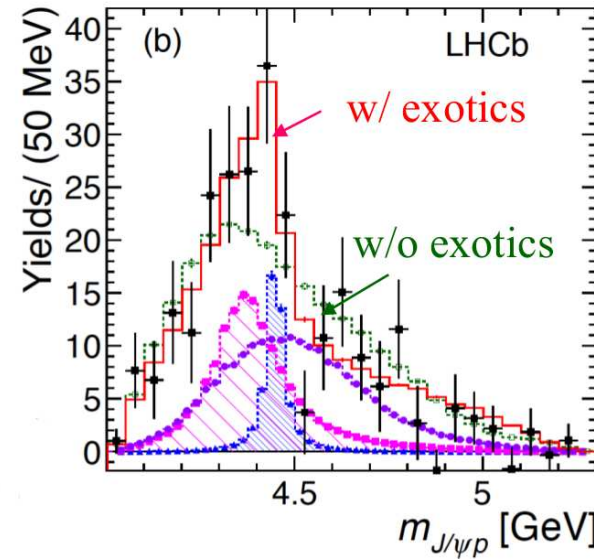
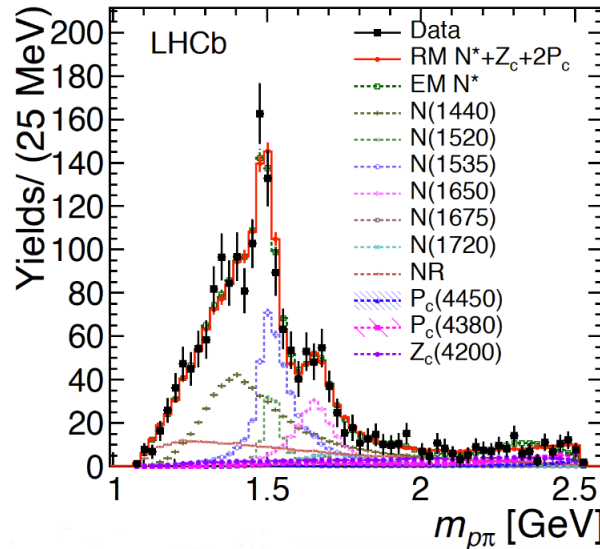


- Full amplitude analysis. Accurate description of the rich resonant structure in the $p \pi^-$ final state.

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

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

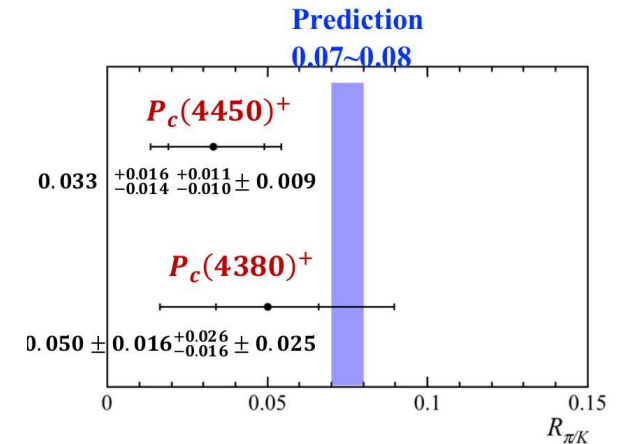
- $Z_c(4200)^-$, N^* and exotic states parameters fixed.
- Each P_c : 4 free parameters +6 fixed to that from $\Lambda_b^0 \rightarrow J/\psi p K^-$.



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

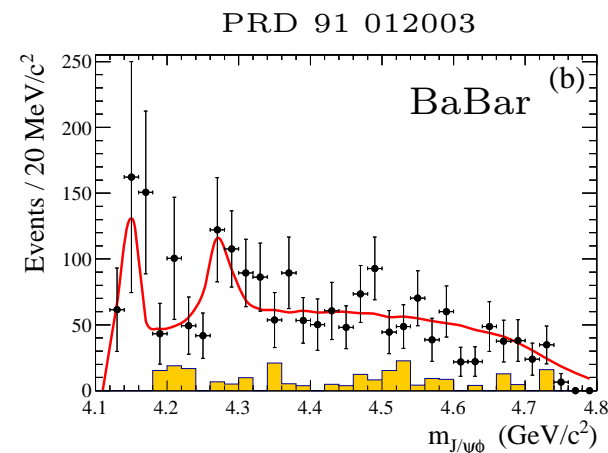
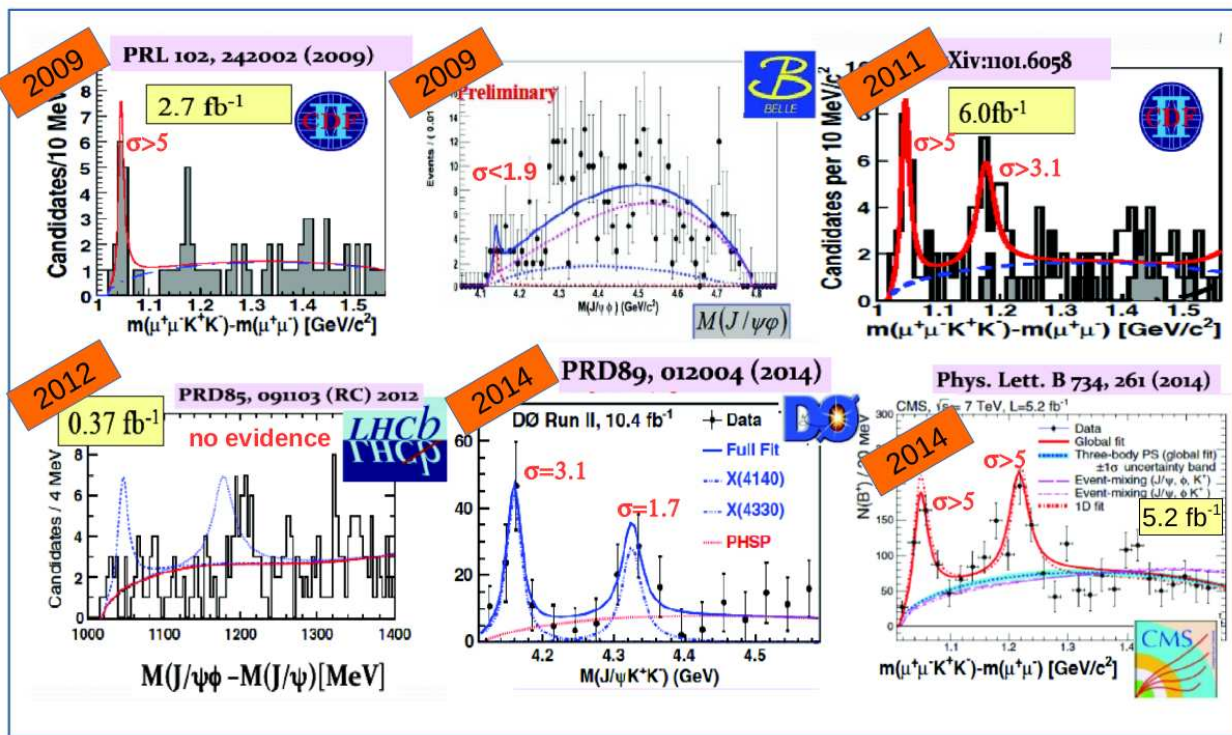
- The $b \rightarrow c$ diagram strongly favoured.

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



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

- The X(4140) state is first claimed by the CDF collaboration in 2008. (PRL 102 242002).
- Narrow width: $\Gamma = 11.7_{-5.0}^{+8.3} \pm 3.7$ MeV. Results from several experiments.

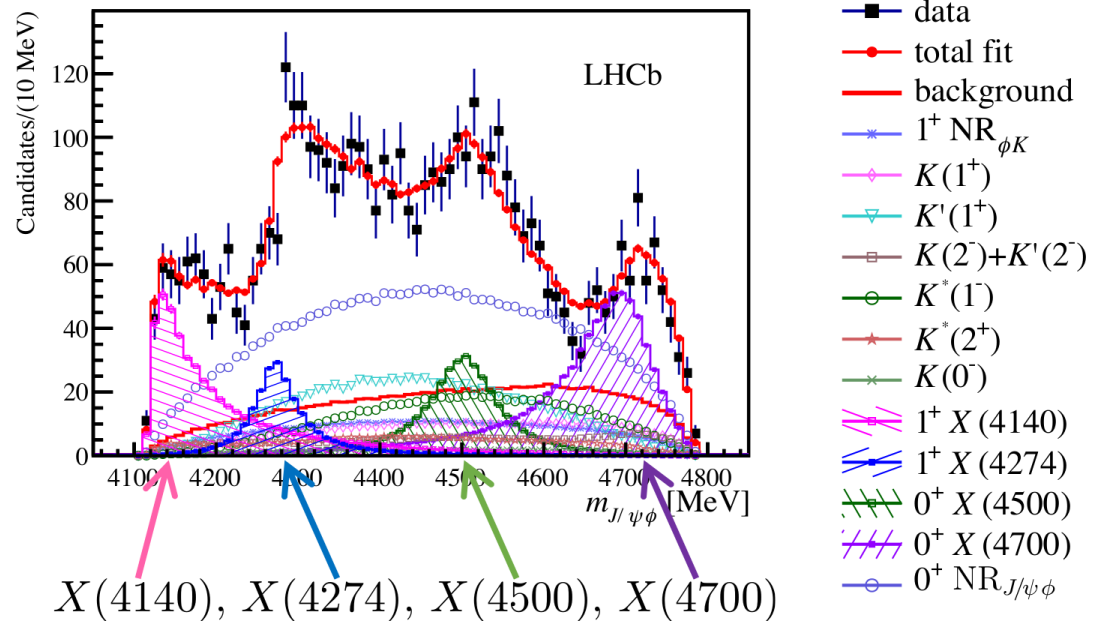
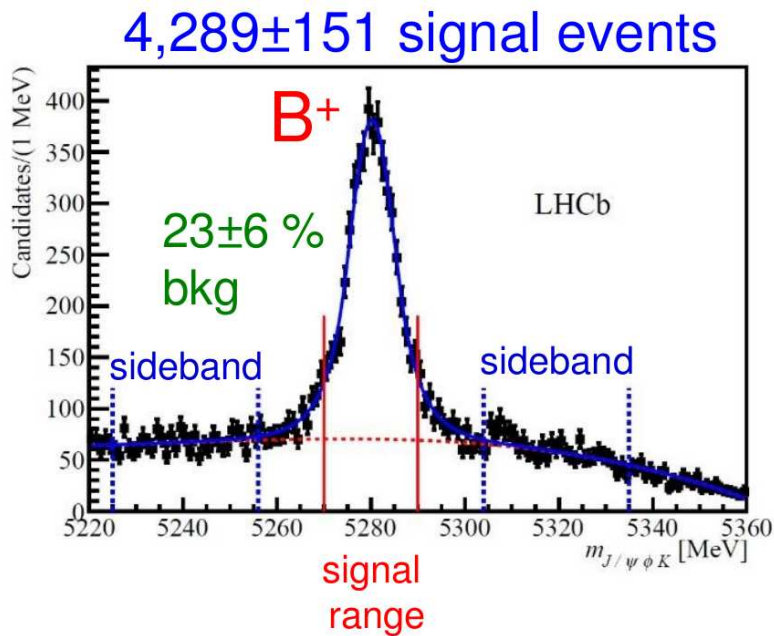


- Summary of the experimental evidences.

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 $B^+ \rightarrow J/\psi\phi K^+$ 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.



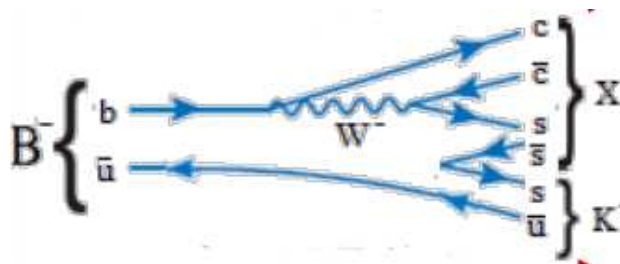
New results on $B^+ \rightarrow J/\psi\phi K^+$ from LHCb

□ 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.

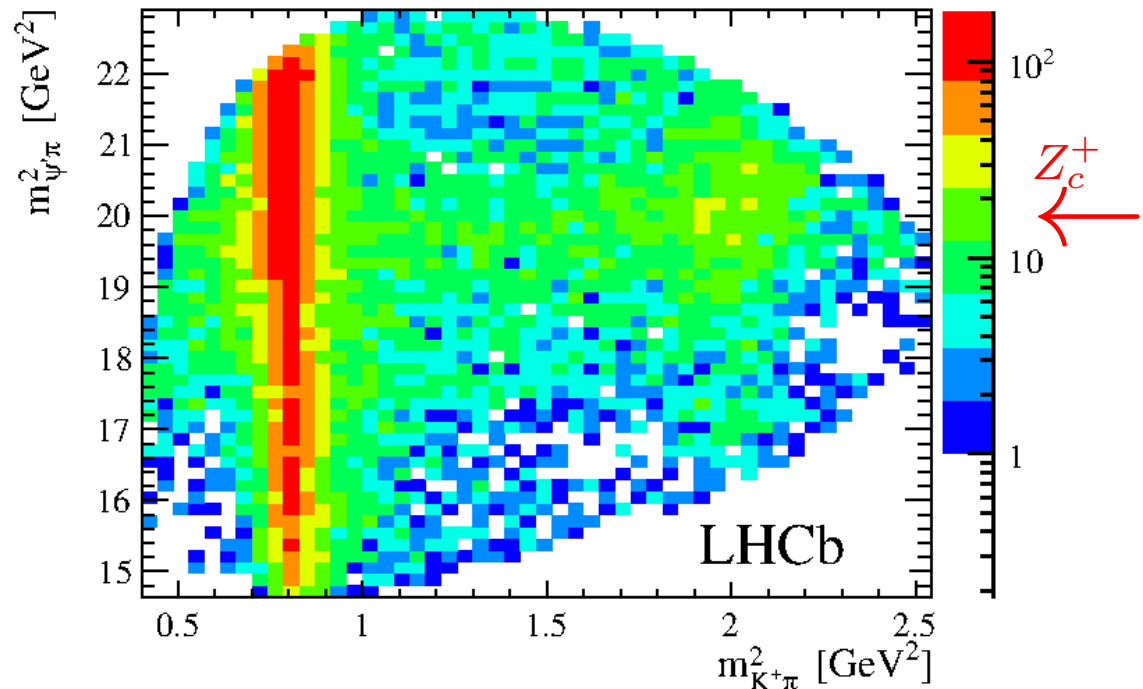
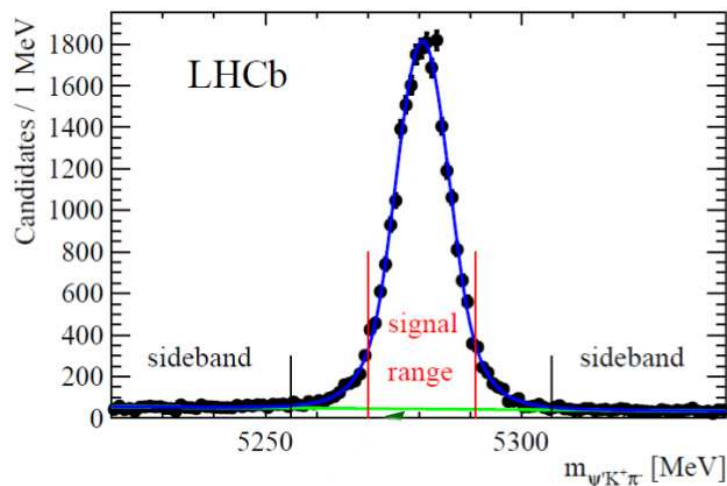
□ Interpretation of these states still open. A diagram for producing a 4-quark state.



□ X(4140) proposed as a $1^{++} D_s^+ D_s^{*-}$ cusp (E. Swanson: Int.J.Mod.Phys.E25, 1642010 (2016)).

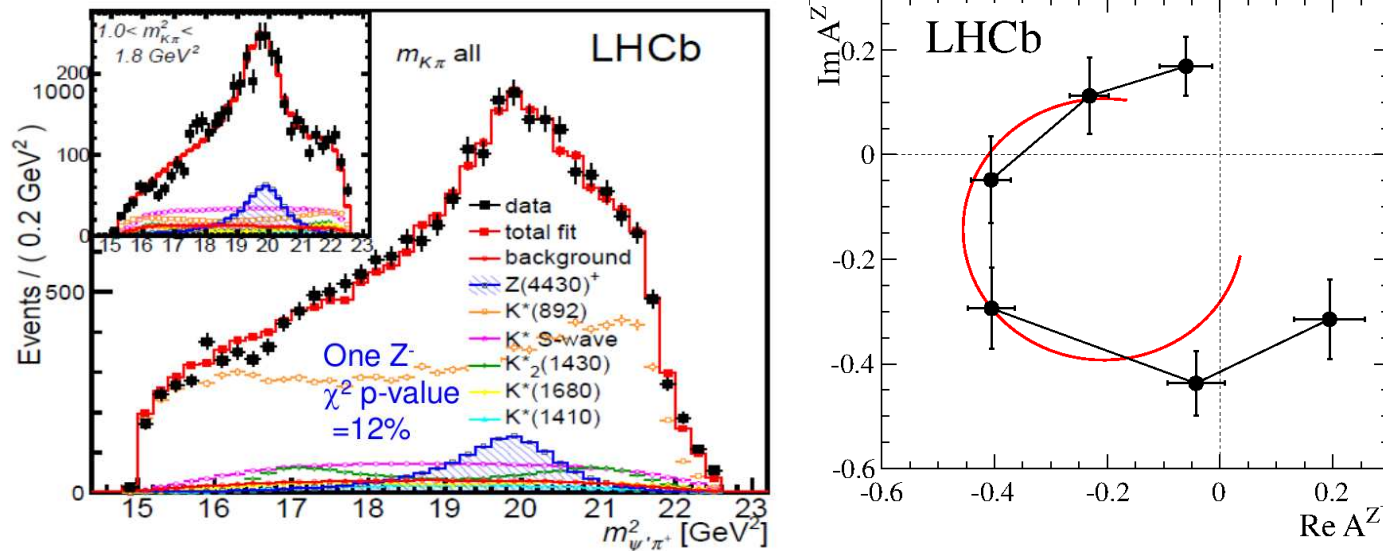
Study of $\bar{B}^0 \rightarrow \psi' \pi^- K^+$ in LHCb

- First analysis from Belle: observation of a new $Z_c(4430)^+ \rightarrow \psi' \pi^-$ in $B \rightarrow K \pi^+ \psi'$ (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 $\bar{B}^0 \rightarrow \psi' \pi^- K^+$

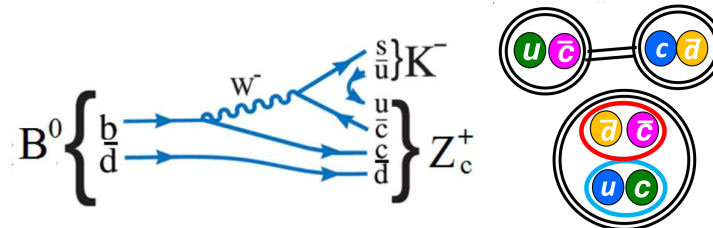
- Amplitude analysis confirms the presence of the Z_c resonance (PRL 112, 222002 (2014)).



- Argand diagram shows typical resonance behaviour. Resonance parameters:

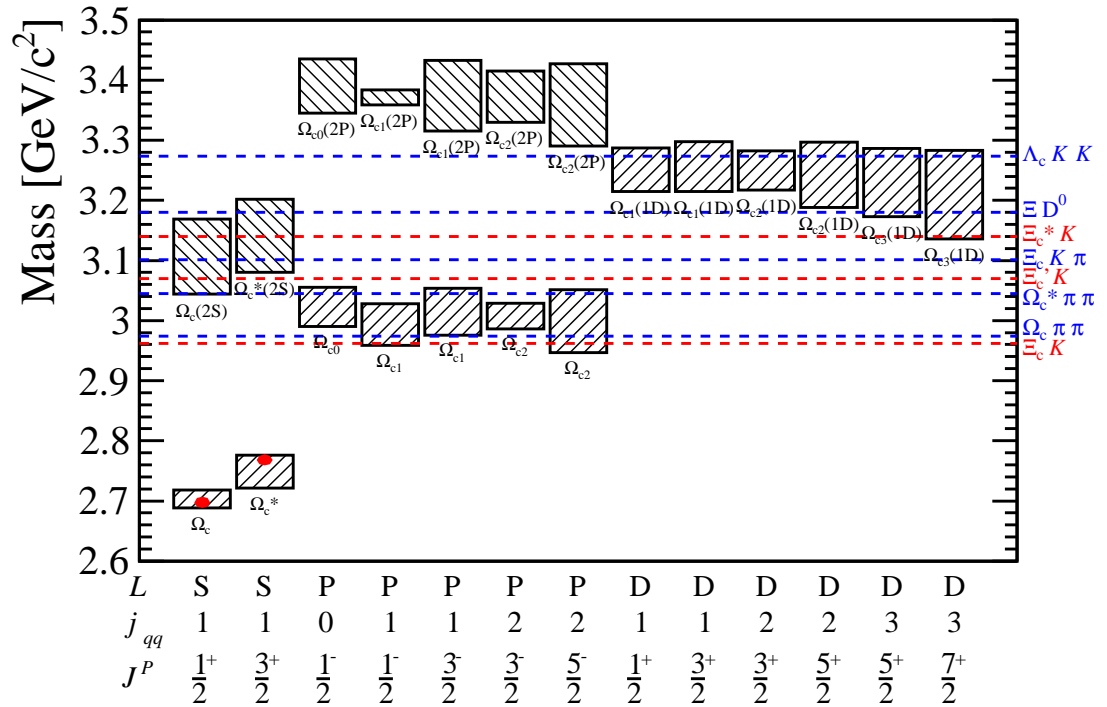
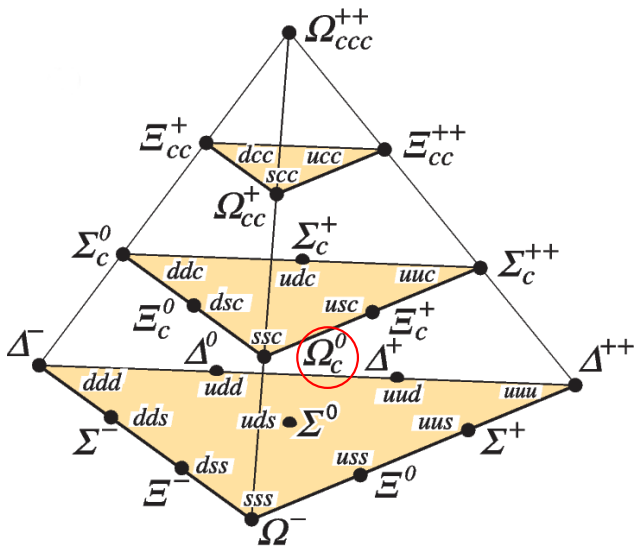
$$M(Z_c) = 4475 \pm 7_{-25}^{+15} \text{ MeV}, \quad \Gamma(Z_c) = 172 \pm 13_{-34}^{+37} \text{ MeV}.$$

- 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.

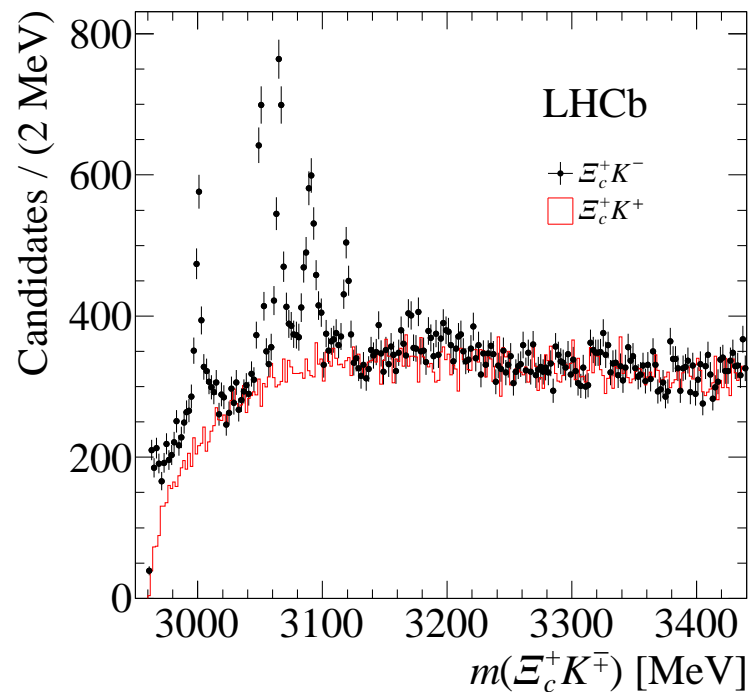
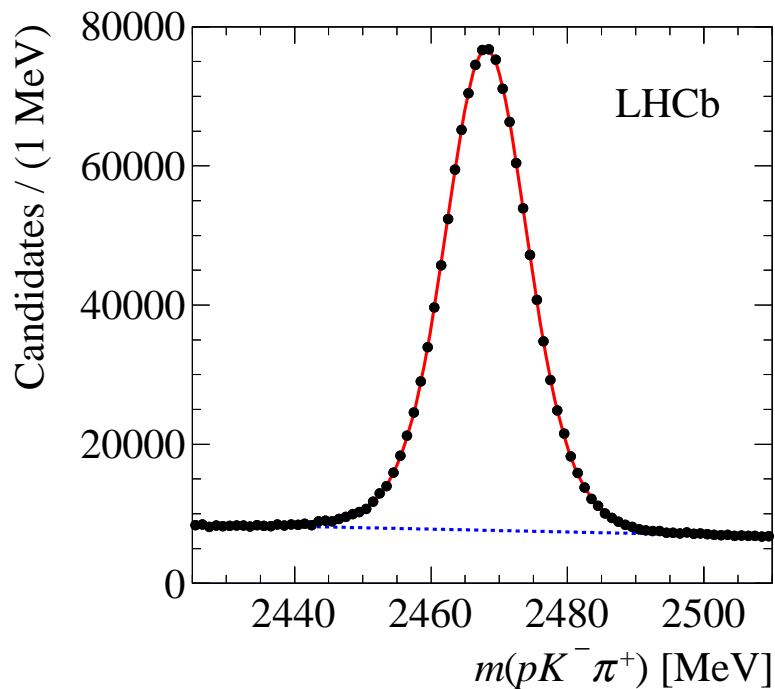


□ Ω_c quark content: ssc .

□ Only $1/2^+$ and $3/2^+$ ground states were known.

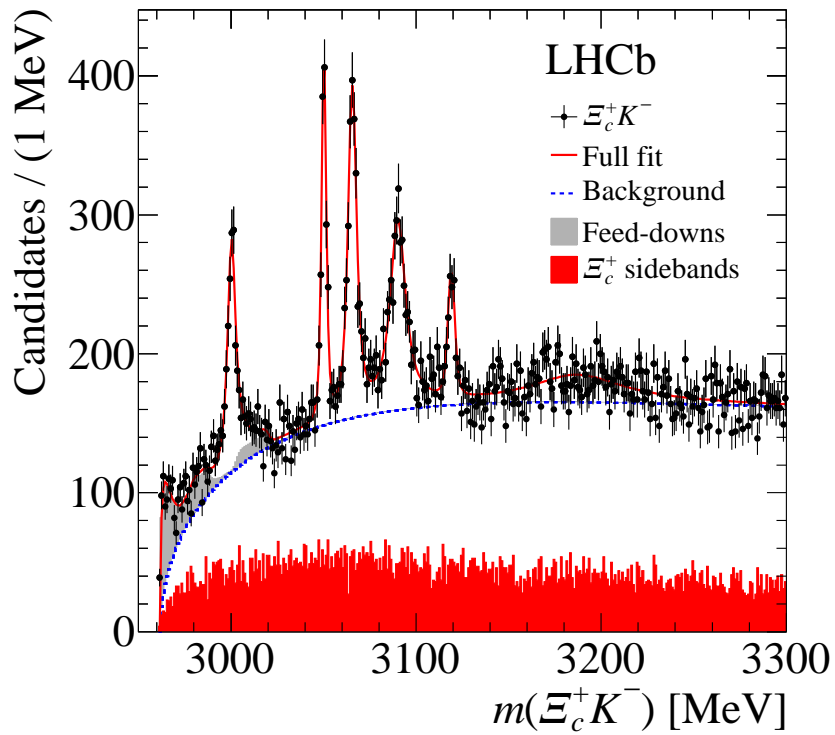
Observation of five new Ω_C states in LHCb

- 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 $\Xi_c^+ \rightarrow pK^- \pi^+$.
- $\approx 10^6$ 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 $\Omega_c \rightarrow K^- \Xi'_c (\rightarrow \Xi_c \gamma)$.
- Model enhancement at ≈ 3200 MeV with one Breit-Wigner.
- Resonances parameters.

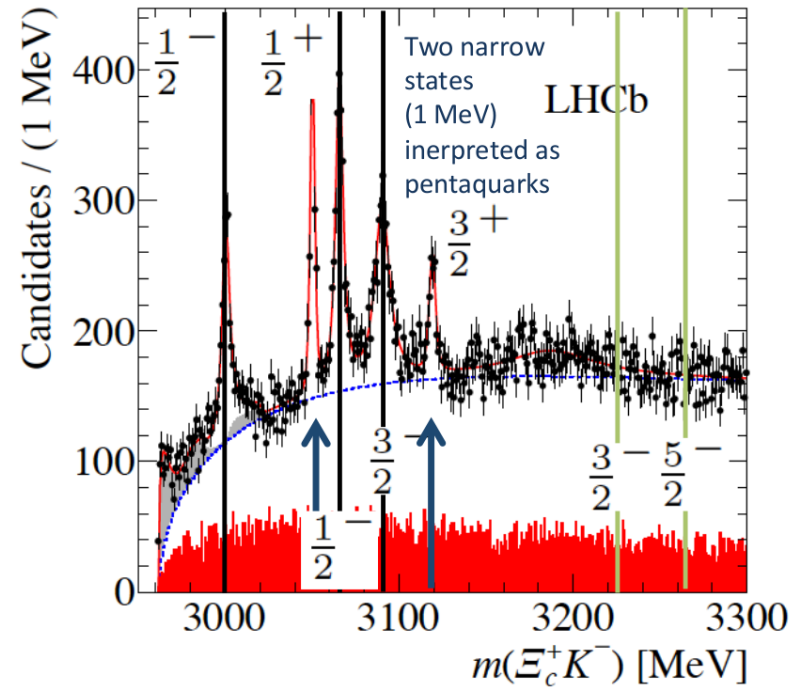
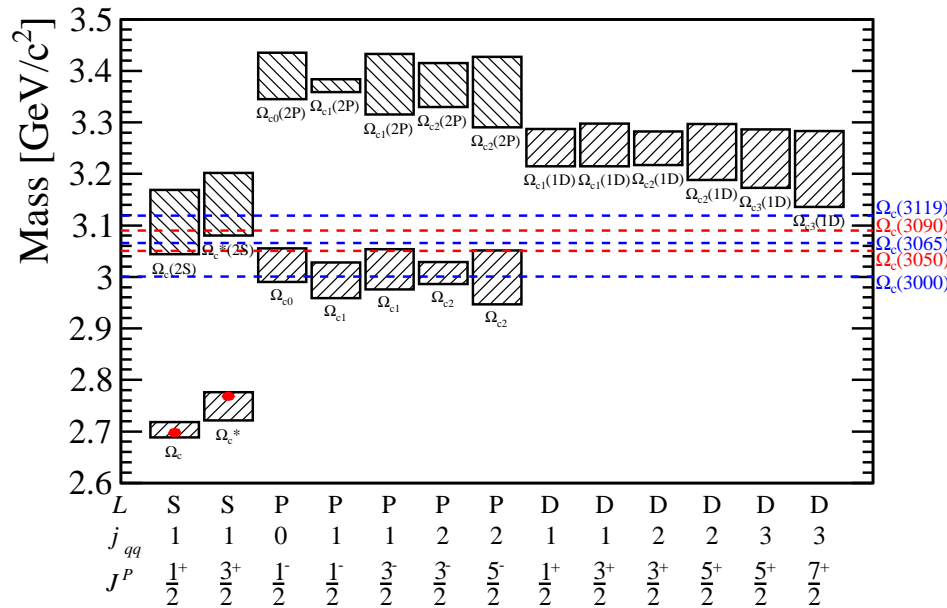


Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	< 1.2 MeV, 95% CL
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm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

- $\Omega_c(3050)^0$ 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. See for example (M. Praszalowicz: arXiv:1808.10761).

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.