Recent results on Hadron spectroscopy in LHCb

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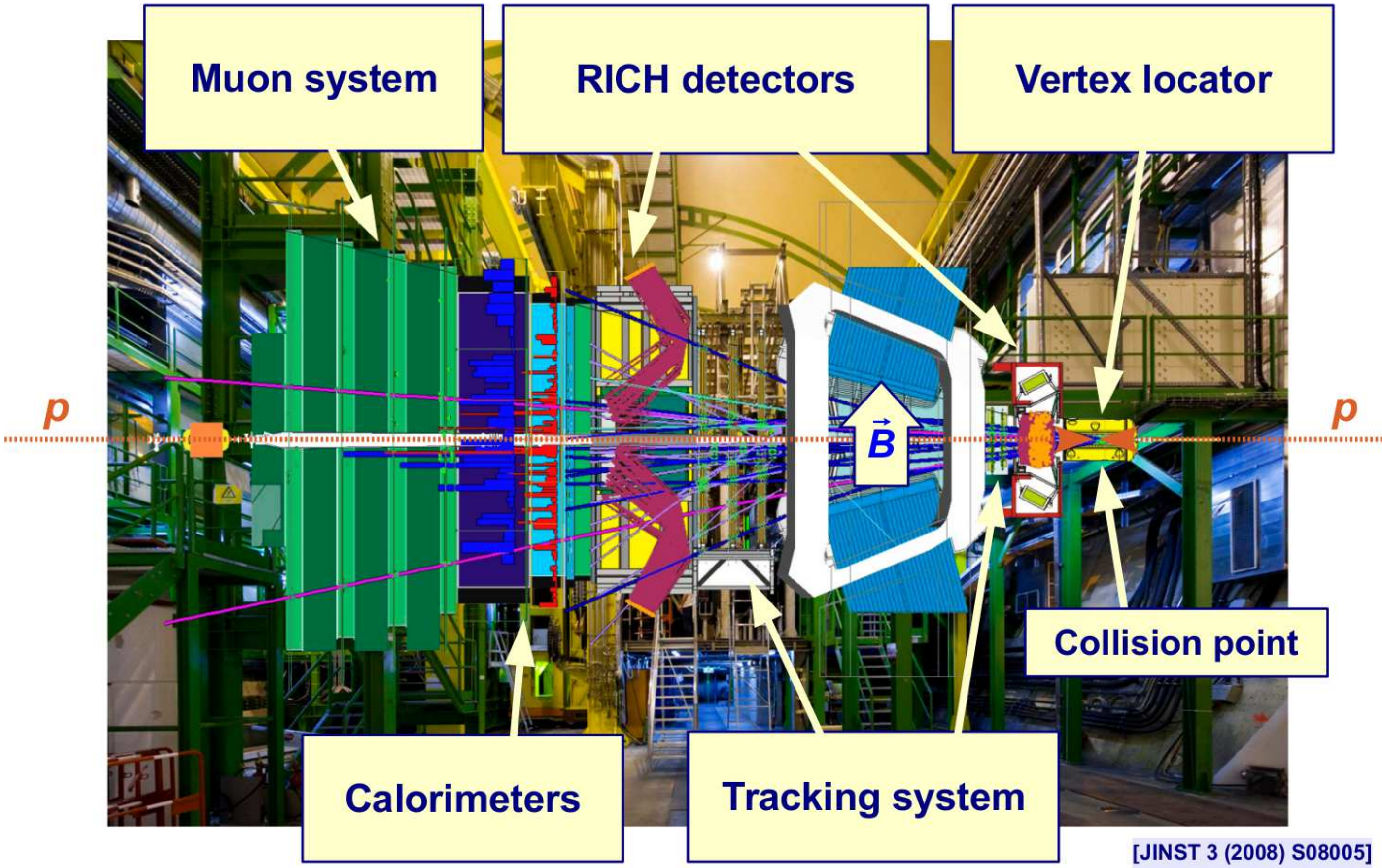
On behalf of the LHCb Collaboration

Outline:

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

Genova, November 24, 2017

The LHCb experiment

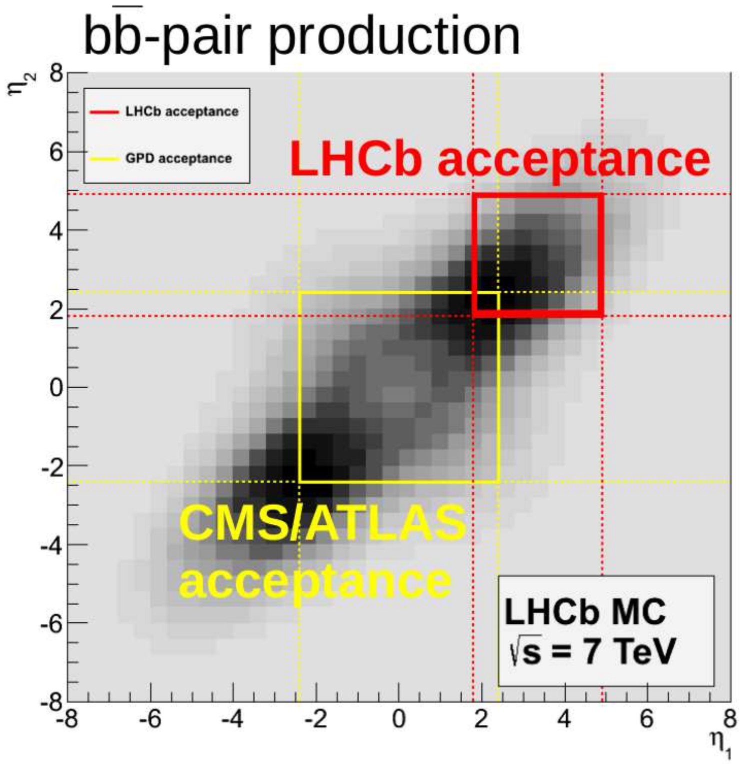


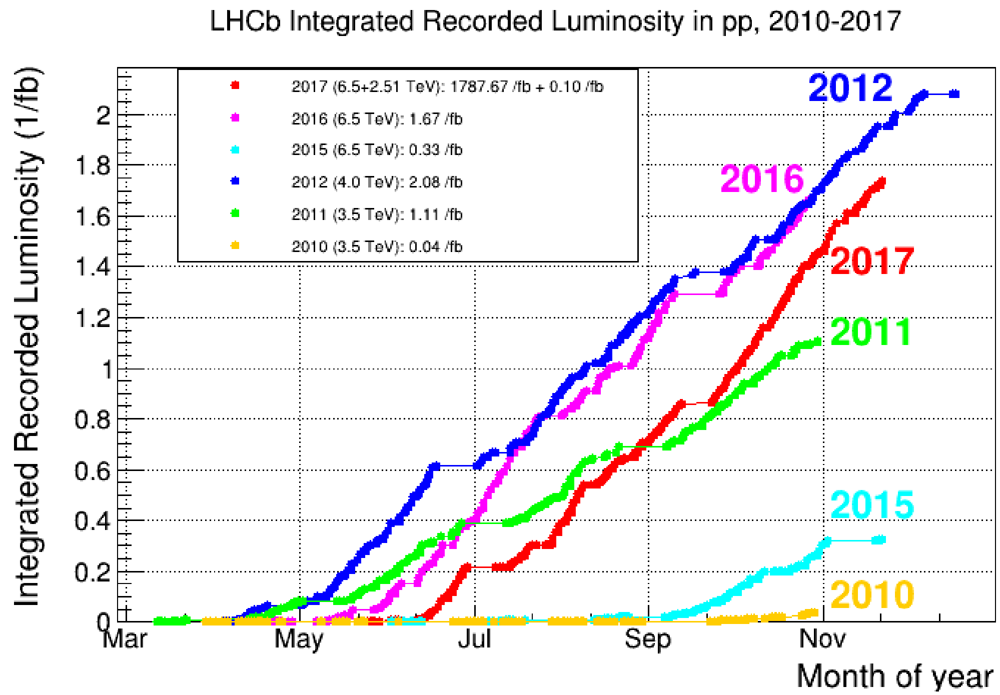
[JINST 3 (2008) S08005]

- □ 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.

Charm meson spectroscopy

☐ Two methods for studying or discovering new states in LHCb.

- Inclusive studies of $D^0\pi^+$, $D^+\pi^-$ and $D^{*+}\pi^-$;

  $$pp \to D_J X$$

  Inclusive studies of D^0K^+, $D^+K^0_S$, and $D^{*+}K^0_S$

  $$pp \to D_{sJ} X$$

  - All resonances can be produced.
  - Signal to background ratio can be poor.
  - Spin-parity analysis of three-body decays can only distinguish between Natural and Unnatural Parity assignments.
  - No spin analysis possible for two-body decays.

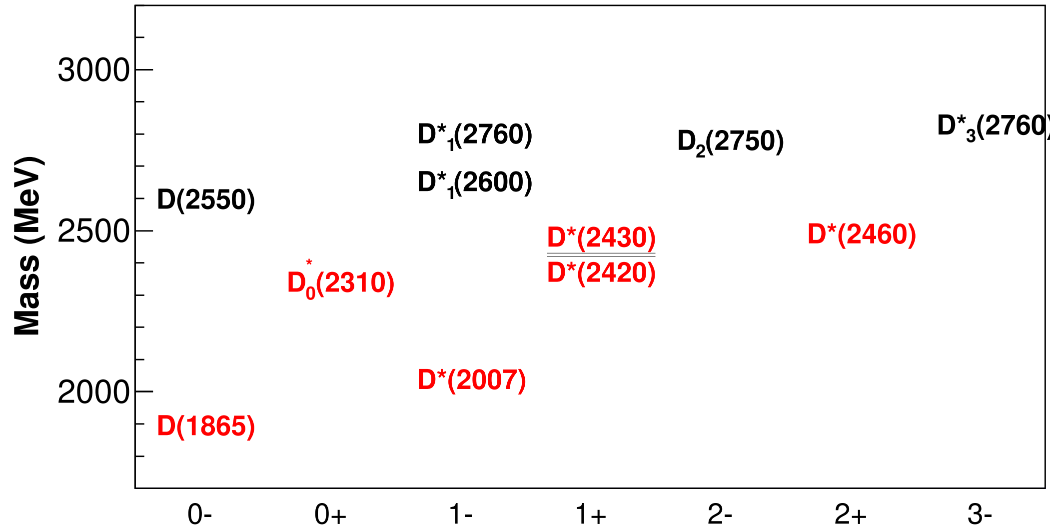
- Exclusive approach: Dalitz plot analysis of B and B_s decays.
  - Full spin-parity analysis possible.
  - High mass resonances can have low rates or may not be produced.
  - The analysis can be complicated by the presence of multiple interfering contributions.

Recent experimental status of the D_J spectroscopy.

□ The quark model predicts many states with different quantum numbers in limited mass regions (Godfrey,Isgur, Phys.Rev.D32,189 (1985)), (Godfrey,Moats, Phys.Rev.D93,034035 (2016)).

□ In black are the new states.

□ Tentative assignments.



□ States having $J^P = 0^+, 1^-, 2^+, 3^-, ..$ are defined as having "Natural Parity".

□ States having $J^P = 0^-, 1^+, 2^-, ...$ are defined as having "Unnatural Parity".

□ A resonance decaying to $D\pi$ has "Natural Parity". Labelled with D^*.

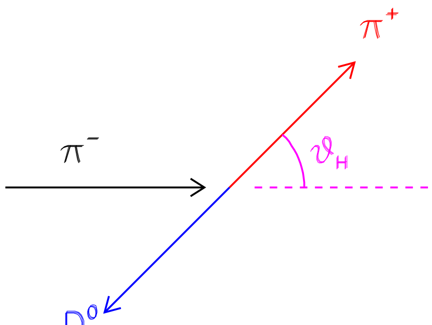
□ The $D^*\pi$ system can access to both "Natural Parity" and "Unnatural Parity", except for $J^P = 0^+$ which is forbidden.

□ The $D\pi$ and $D^*\pi$ systems have been studied by BaBar (Phys.Rev.D(RC) 82 111101 (2010)) and LHCb: (JHEP09 (2013), 145.)

Study of the $D^{*+}\pi^-$ system: The helicity angle distribution

□ The $D^{*+}\pi^-$ final state gives information on the spin-parity assignment of a given resonance.

□ In the rest frame of the $D^{*+}\pi^-$, we define the helicity angle θ_H as the angle between the π^- and the π^+ from the D^{*+} decay.



□ Expected θ_H distributions for different J^P assignments.

J^P	Helicity Distribution
0^+	decay not allowed
1^-	$\propto \sin^2\theta_H$
2^+	$\propto \sin^2\theta_H$
3^-	$\propto \sin^2\theta_H$
0^-	$\propto \cos^2\theta_H$
1^+	$\propto 1 + h\cos^2\theta_H$
2^-	$\propto 1 + h\cos^2\theta_H$

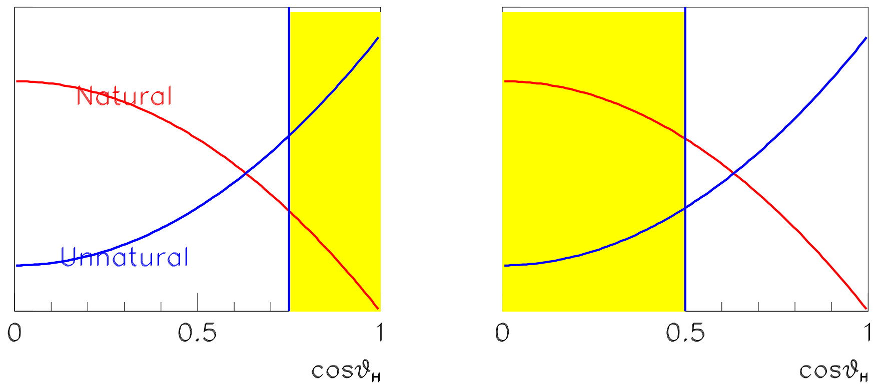
□ We divide the data into two samples:

$|\cos\theta_H| > 0.75$, **Enhanced Unnatural Parity Sample.**

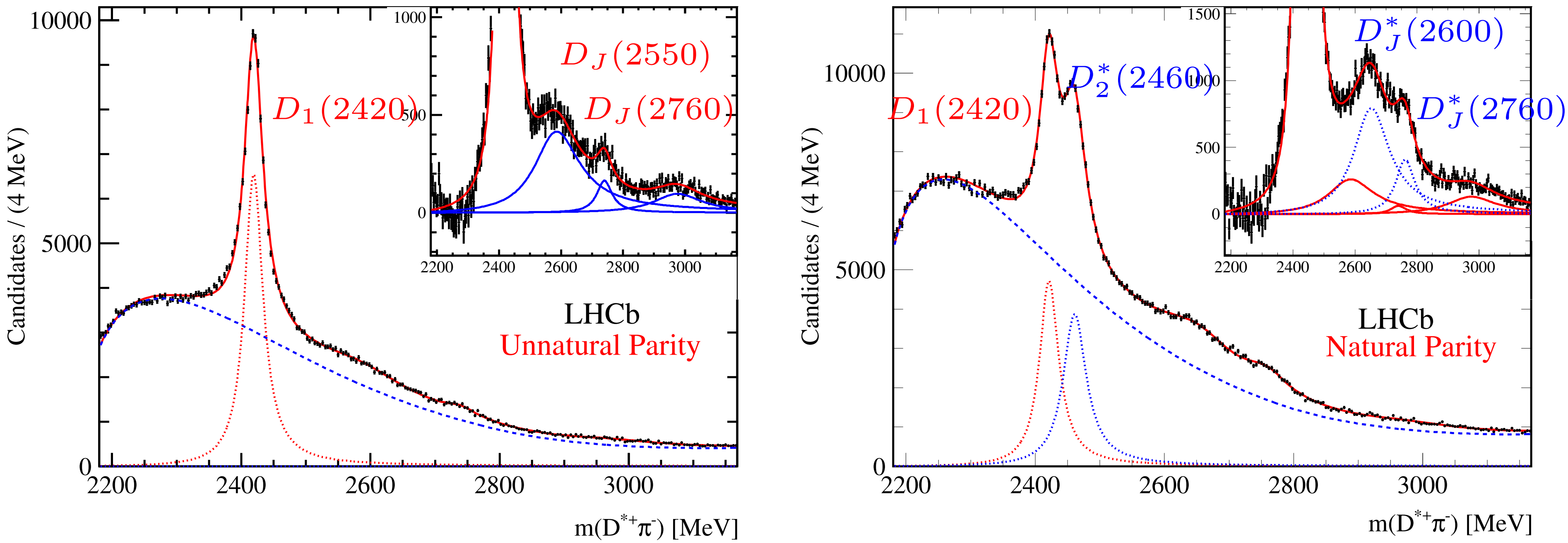
Natural Parity suppressed by a factor 11.6

$|\cos\theta_H| < 0.5$, **Natural Parity Sample.**

Natural Parity suppressed by a factor 1.5



Fits to the two $D^{*+}\pi^-$ data samples



- ☐ LHCb study of the $D\pi$ and $D^*\pi$ systems ($1\ \text{fb}^{-1}$) (JHEP09 (2013), 145).
- ☐ Enhanced Unnatural Parity: **Observe three further structures:**

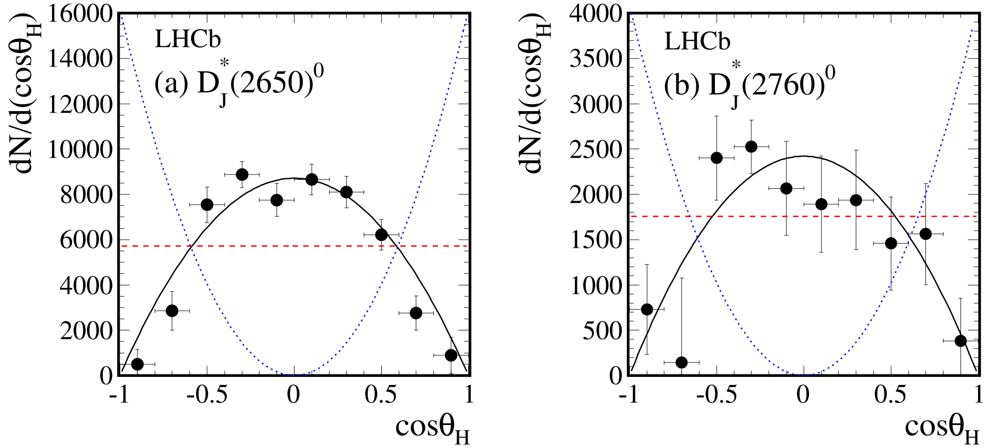
$$D_J(2550)^0, D_J(2760)^0, D_J(3000)^0$$

- ☐ Fix the parameters of these new states and fit the Natural Parity sample.
- ☐ **Observe two further structures:**

$$D_J^*(2600)^0, D_J^*(2760)^0$$

Angular distributions

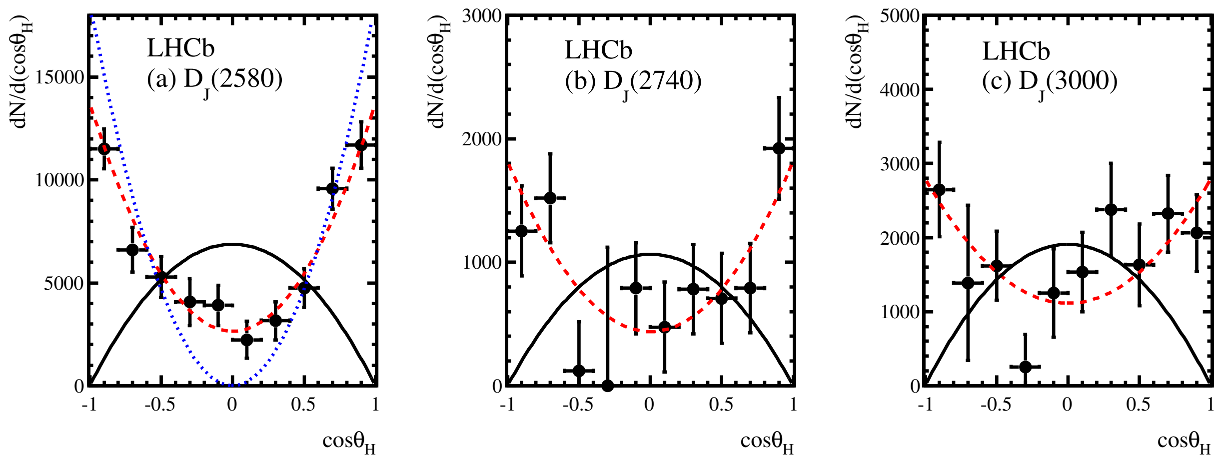
□ Angular distributions for $D_J^*(2600)$ and $D^*(2760)$.



□ Consistent with having Natural Parity: fitted with $sin^2\theta_H$.

□ Angular distributions for $D_J(2550)^0$, $D_J(2760)^0$, and $D_J(3000)^0$.

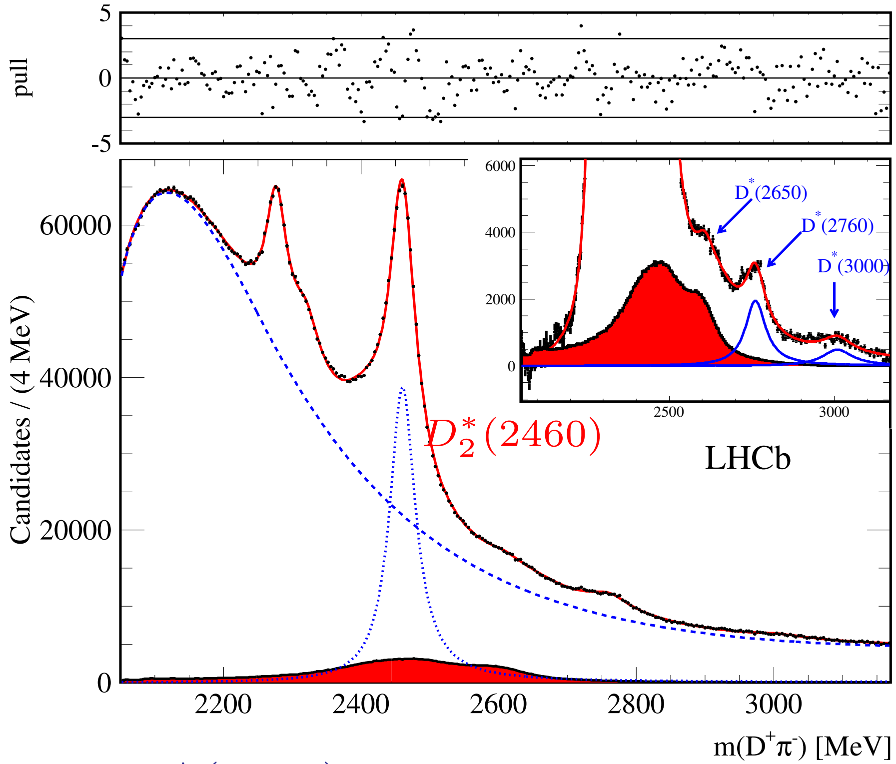
(black: natural parity), *(dashed red: unnatural parity)*, *(dotted blue: $J^P = 0^-$)*

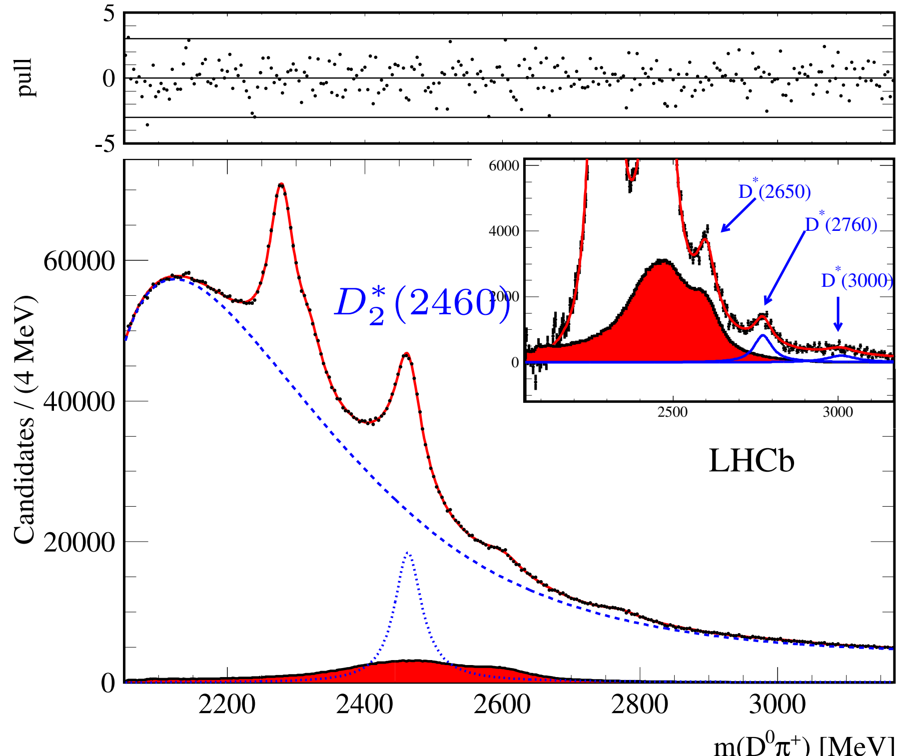


□ Consistent with having Unnatural Parity:

Fit to the $D^+\pi^-$ and $D^0\pi^+$ mass spectra

☐ Cross-feeds (in red) produce a distortion of the $D_2^*(2460)$ and $D_J^*(2650)$ lineshapes.





☐ For $D_J^*(2650)$ we rely on the results obtained from the $D^{*+}\pi^-$ mass analysis.

☐ We observe the $D_J^*(2760)$.

☐ The fits requires the presence of a broad structure around 3.0 GeV which we label $D_J^*(3000)$.

Dalitz plot analyses of three-body B and B_s^0 decays

- We have performed the following full Dalitz plot analyses.
- Study of the D_J^* mesons in the decays:

$$B^- \to D^+ K^- \pi^-$$

$$B^0 \to \bar{D}^0 \pi^+ \pi^-$$

$$B^0 \to \bar{D}^0 K^+ \pi^-$$

$$B^- \to D^+ \pi^- \pi^-$$

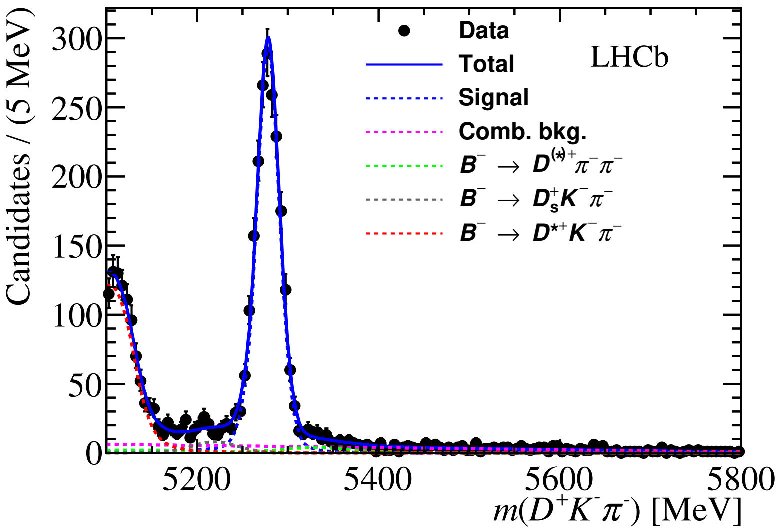
- Study of the D_{sJ}^* mesons in the decay:

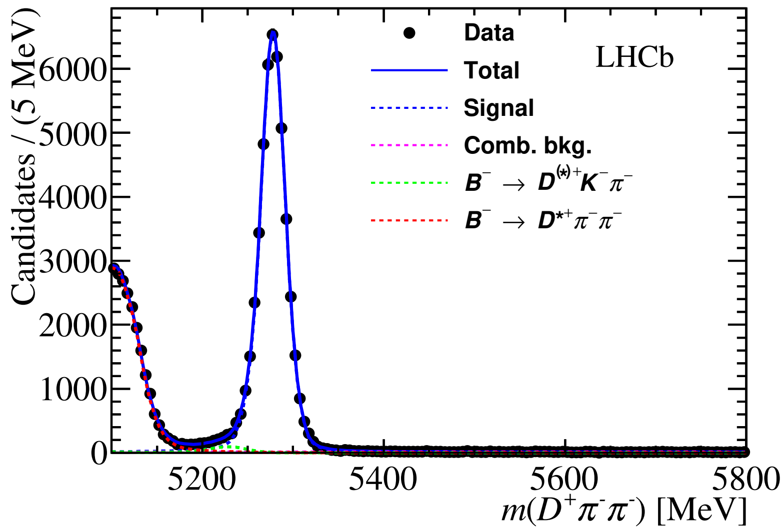
$$B_s^0 \to \bar{D}^0 K^- \pi^+$$

First observation and Dalitz plot analysis of $B^- \to D^+K^-\pi^-$

(Phys.Rev.D91, 092002 (2015))

- The $D^+K^-\pi^-$ mass spectrum contains $\approx 2K$ events in the B^- signal region.
- Integrated luminosity: 3 fb^{-1}.

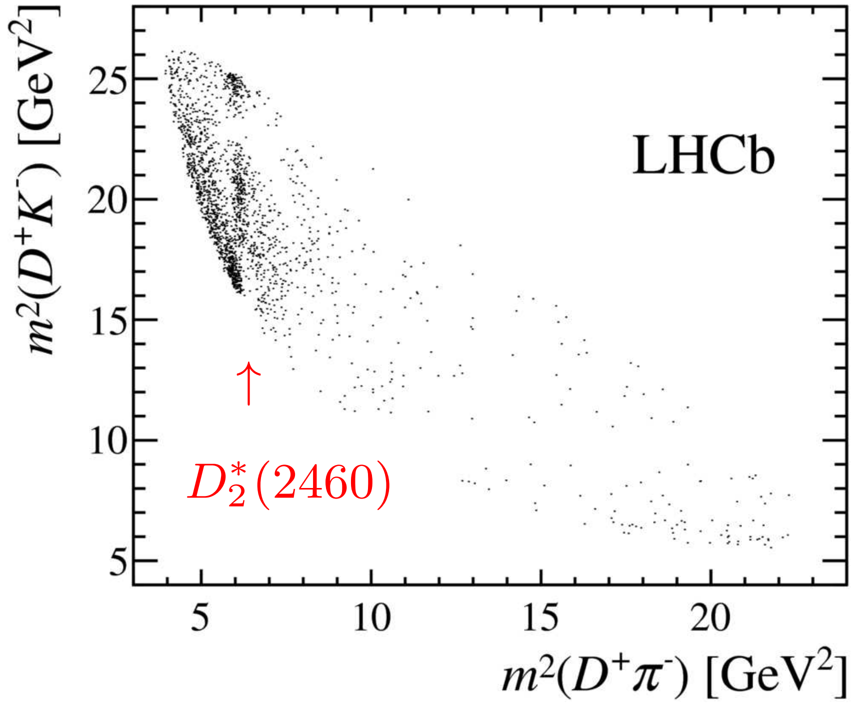




- Use of neural network's trained by control samples, especially $B^- \to D^+\pi^-\pi^-$ ($\approx 49K$ events).

Dalitz plot analysis of $B^- \to D^+ K^- \pi^-$

- □ The Dalitz plot.
- □ Need to introduce virtual $D_v^*(2007)^0$ B_v^{*0} and Nonresonant contributions.
- □ Clear spin-2 $D_2^*(2460)$ signal.
- □ A $D_J^*(2760)^0$ spin-1 resonance.

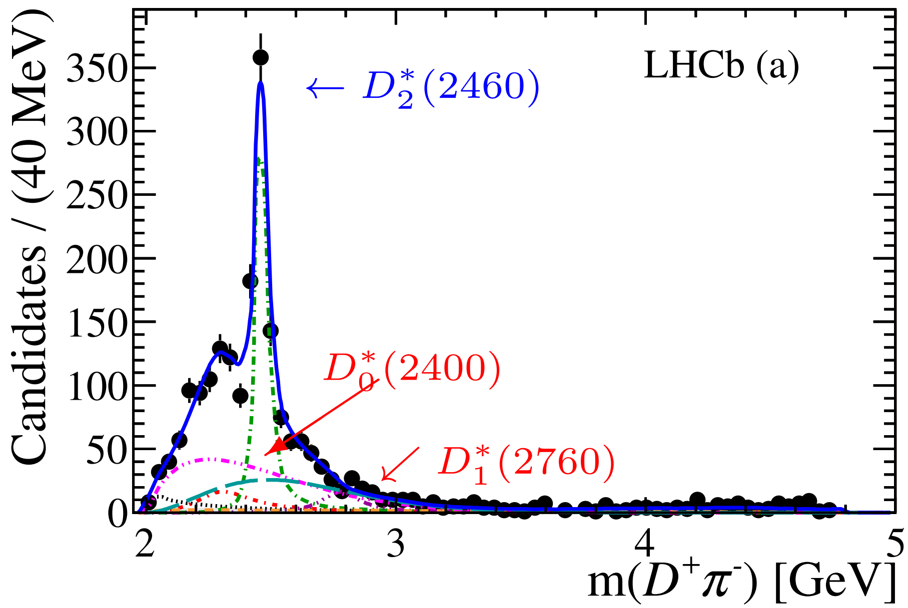


Resonance	Spin	Parameters
$D_0^*(2400)^0$	0	PDG
$D_2^*(2460)^0$	2	$m = 2464.0 \pm 1.4$ MeV, $\Gamma = 43.8 \pm 2.9$ MeV
$D_J^*(2760)^0$	1	$m = 2781 \pm 18$ MeV, $\Gamma = 177 \pm 32$ MeV
Nonresonant	0	$R_0(m) = e^{-\alpha m^2}$
Nonresonant	1	$R_1(m) = e^{-\beta m^2}$

Dalitz plot analysis of $B^- \to D^+ K^- \pi^-$

□ $D^+\pi^-$ fit projection.

Resonance	Fit fraction (%)
$D_0^*(2400)^0$	$8.3 \pm 2.6 \pm 0.6 \pm 1.9$
$D_2^*(2460)^0$	$31.8 \pm 1.5 \pm 0.9 \pm 1.4$
$D_1^*(2760)^0$	$4.9 \pm 1.2 \pm 0.3 \pm 0.9$
S-wave nonresonant	$38.0 \pm 7.4 \pm 1.5 \pm 10.8$
P-wave nonresonant	$23.8 \pm 5.6 \pm 2.1 \pm 3.7$
$D_v^*(2007)^0$	$7.6 \pm 2.3 \pm 1.3 \pm 1.5$
B_v^*	$3.6 \pm 1.9 \pm 0.9 \pm 1.6$



Errors are statistical, systematic and model.

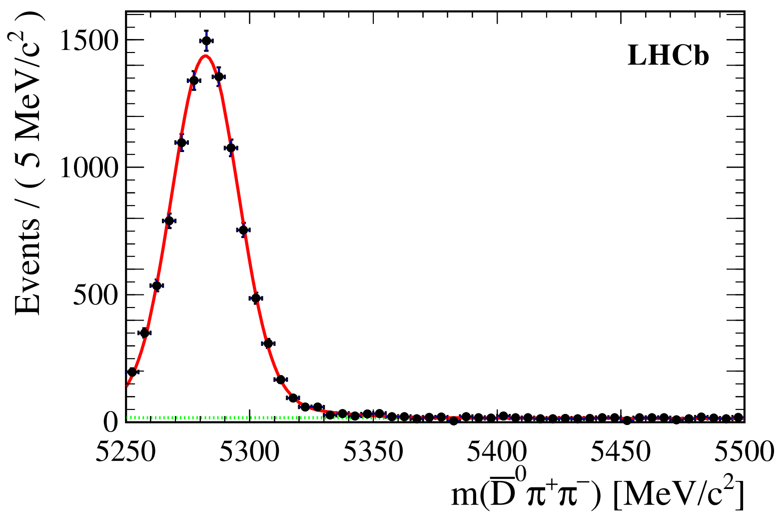
□ The Dalitz analysis of $B^0 \to \bar{D}^0\pi^+\pi^-$ gives evidence for a $D_3^*(2760)$ spin-3 resonance.

□ This state is not observed in this B^- decay channel.

Dalitz plot analysis of $B^0 \to \bar{D}^0\pi^+\pi^-$

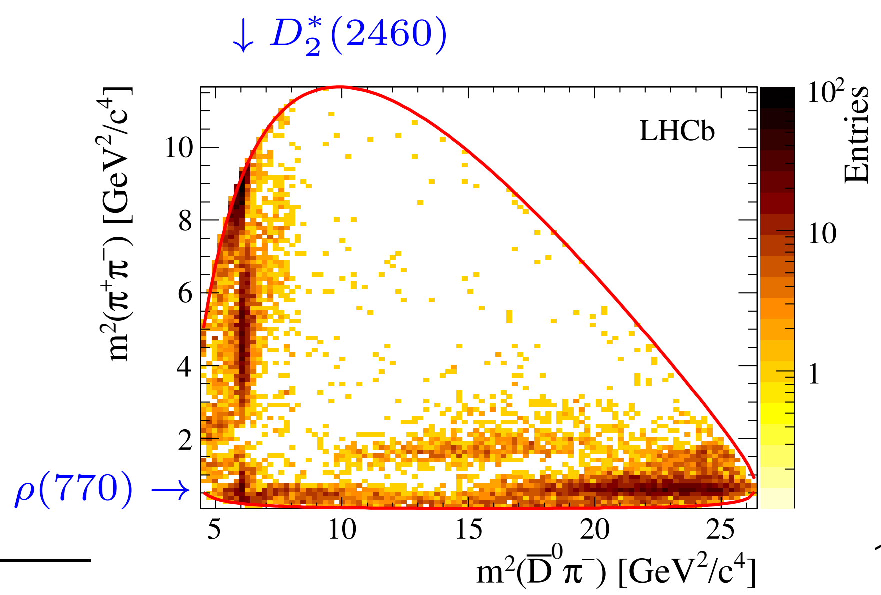
(Phys.Rev.D92, 032002 (2015))

- ☐ $B^0 \to \bar{D}^0\pi^+\pi^-$ mass spectrum.
- ☐ Green line is background.
- ☐ Integrated luminosity: 3 fb^{-1}.



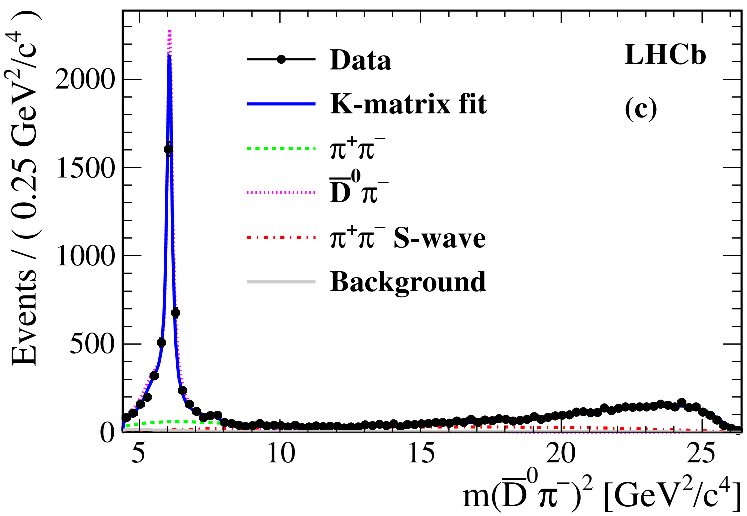
- ☐ 9565 events with 97.8% purity.
- ☐ Dalitz plot.

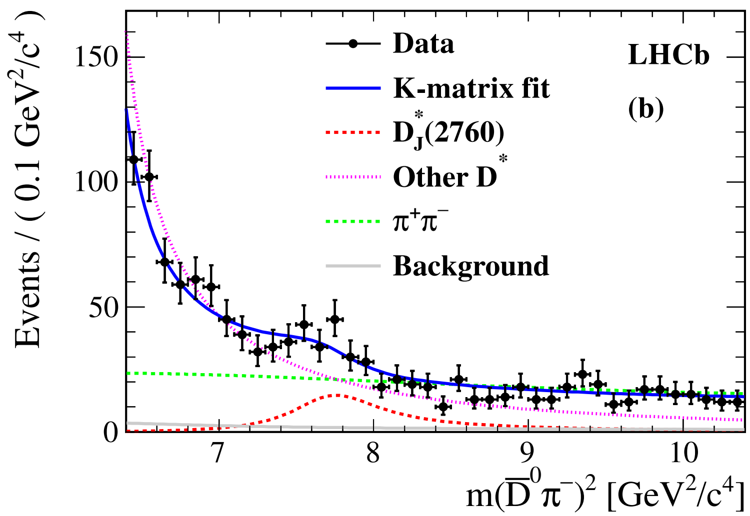
- ☐ Presence of resonant structure along the $\pi^+\pi^-$ and $\bar{D}^0\pi^-$ axis.
- ☐ Clear spin-2 $D_2^*(2460)$ signal.
- ☐ Clear spin-1 $\rho(770)$ signal.



Dalitz plot analysis of $B^0 \to \bar{D}^0\pi^+\pi^-$

□ $\bar{D}^0\pi^-$ fit projections.





□ Amplitudes fractions.

Resonance	Isobar ($\mathcal{F}_i$ %)	K-matrix ($\mathcal{F}_i$ %)
$\bar{D}^0\pi^-$ P-wave	$9.21 \pm 0.56 \pm 0.24 \pm 1.73$	$9.22 \pm 0.58 \pm 0.67 \pm 0.75$
$D_0^*(2400)^-$	$9.00 \pm 0.60 \pm 0.20 \pm 0.35$	$9.27 \pm 0.60 \pm 0.86 \pm 0.52$
$D_2^*(2460)^-$	$28.83 \pm 0.69 \pm 0.74 \pm 0.50$	$28.13 \pm 0.72 \pm 1.06 \pm 0.54$
$D_3^*(2760)^-$	$1.22 \pm 0.19 \pm 0.07 \pm 0.09$	$1.58 \pm 0.22 \pm 0.18 \pm 0.07$

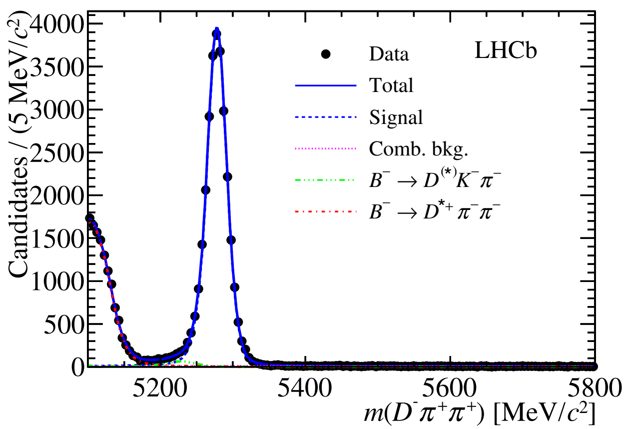
□ Observation of a $J^P = 3^-$ resonance.

$$m(D_3^*(2760)) = 2798.0 \pm 7 \pm 1 \pm 7 \text{ MeV}, \qquad \Gamma(D_3^*(2760)) = 105 \pm 18 \pm 6 \pm 23 \text{ MeV}$$

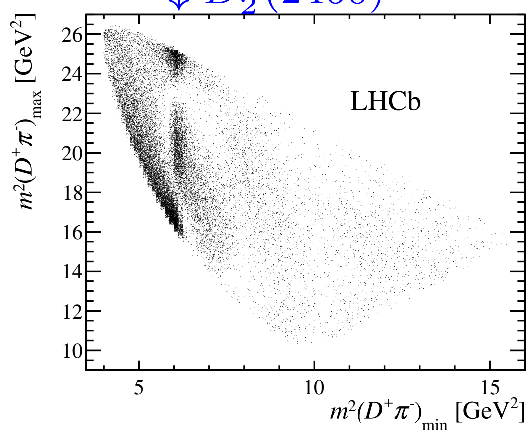
Dalitz plot analysis of $B^- \to D^+\pi^-\pi^-$

(Phys.Rev.D94, 072001 (2016))

□ $B^- \to D^+\pi^-\pi^-$ mass spectrum. 28000 events. Integrated luminosity: 3 fb^{-1}.



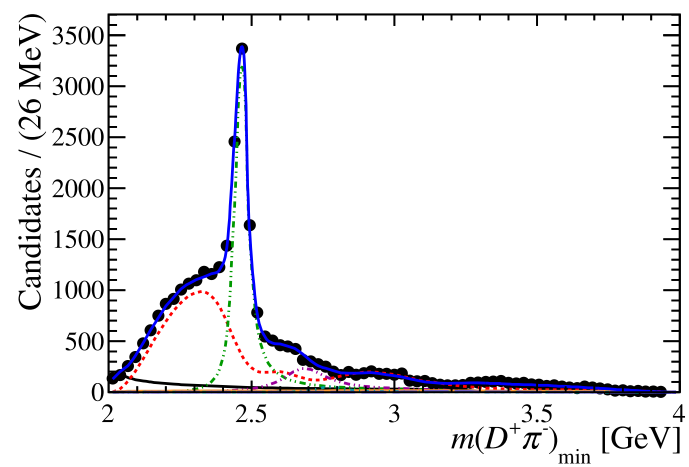
$\downarrow D_2^*(2460)$



□ S-wave described by a Model Independent Partial Wave Analysis.
□ Masses and widths determined in the fit to data.

□ $D^+\pi^-$ mass projection from the Dalitz analysis.

Contribution	Mass (MeV)	Width (MeV)
$D_2^*(2460)^0$	2463.7 ± 0.4	47.0 ± 0.8
$D_1^*(2680)^0$	2681.1 ± 5.6	186.7 ± 8.5
$D_3^*(2760)^0$	2775.5 ± 4.5	95.3 ± 9.6
$D_2^*(3000)^0$	3214 ± 29	186 ± 38

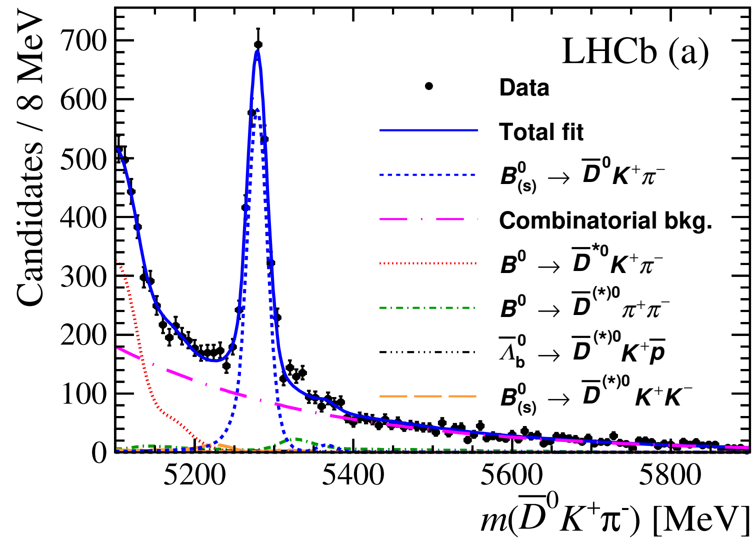


Dalitz plot analysis of $B^0 \to \bar{D}^0 K^+ \pi^-$

(Phys.Rev.D92, 012012 (2015))

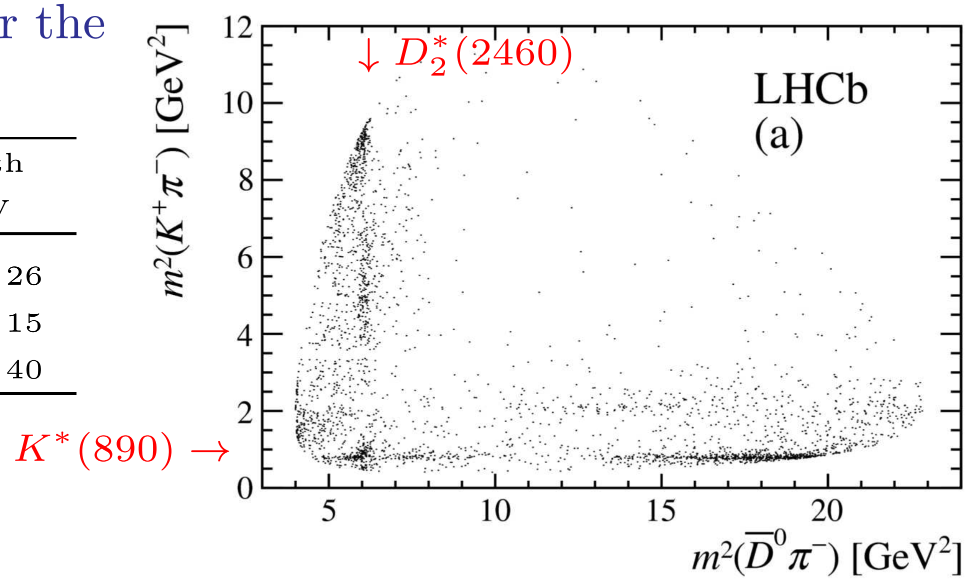
□ 2344 events in the B^0 signal region.

□ Integrated luminosity: 3 fb^{-1}.



□ B^0 Dalitz plot.

□ B^0 mass constraint is applied in the Dalitz plot analysis.



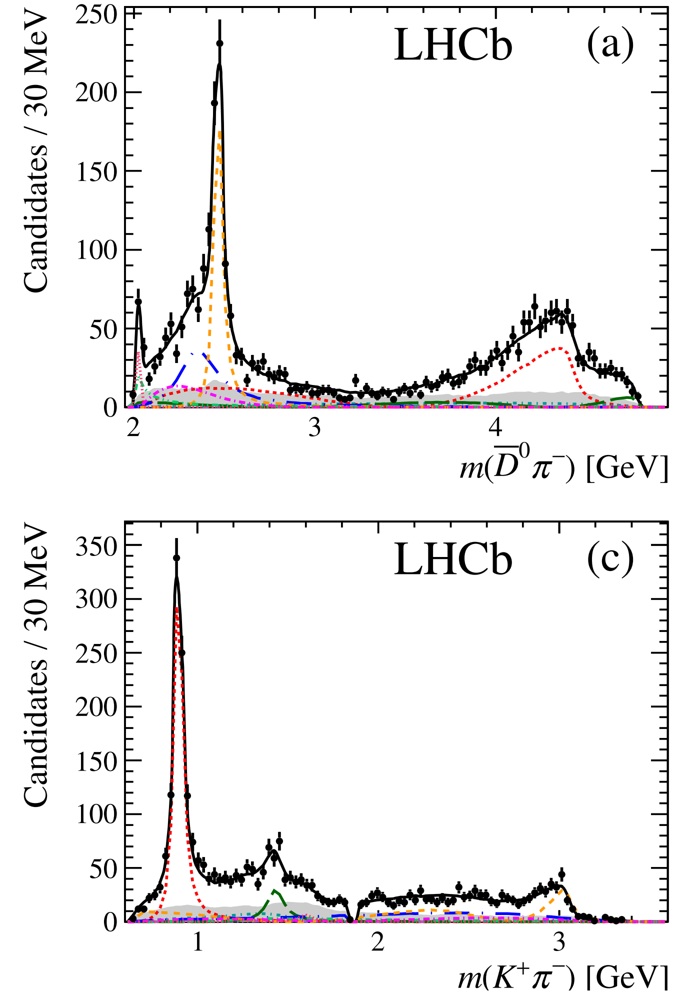
□ New parameters have been obtained for the broad $D_0^*(2400)$ resonance.

Final state	Method	Mass MeV	Width MeV
$B^0 \to \bar{D}^0 K^+ \pi^-$	Free	2360 ± 15	255 ± 26
$B^0 \to \bar{D}^0 \pi^+ \pi^-$	Free	2354 ± 7	230 ± 15
$B^- \to D^+ K^- \pi^-$	(PDG)	2318 ± 29	267 ± 40

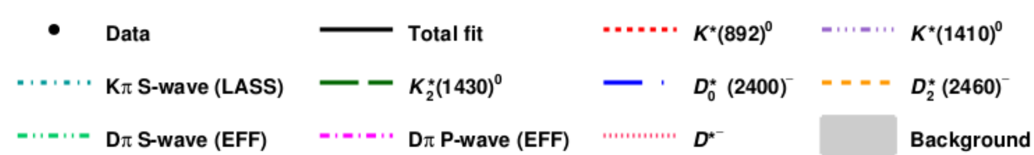
Dalitz plot analysis of $B^0 \to \bar{D}^0 K^+ \pi^-$

□ Dalitz plot analysis and fit projections.

Resonance	Fit fraction (%)
$K^*(892)^0$	37.4 ± 1.5
$K^*(1410)^0$	0.7 ± 0.3
$K^*_0(1430)^0$	5.1 ± 2.0
$K\pi$ S-wave LASS nonresonant	4.8 ± 3.8
LASS total	6.7 ± 2.7
$K^*_2(1430)^0$	7.4 ± 1.7
$D^*_0(2400)^-$	19.3 ± 2.8
$D^*_2(2460)^-$	23.1 ± 1.2
$D\pi$ S-wave (nonresonant)	6.6 ± 1.4
$D\pi$ P-wave (Form Factor)	8.9 ± 1.6
Total fit fraction	113.4

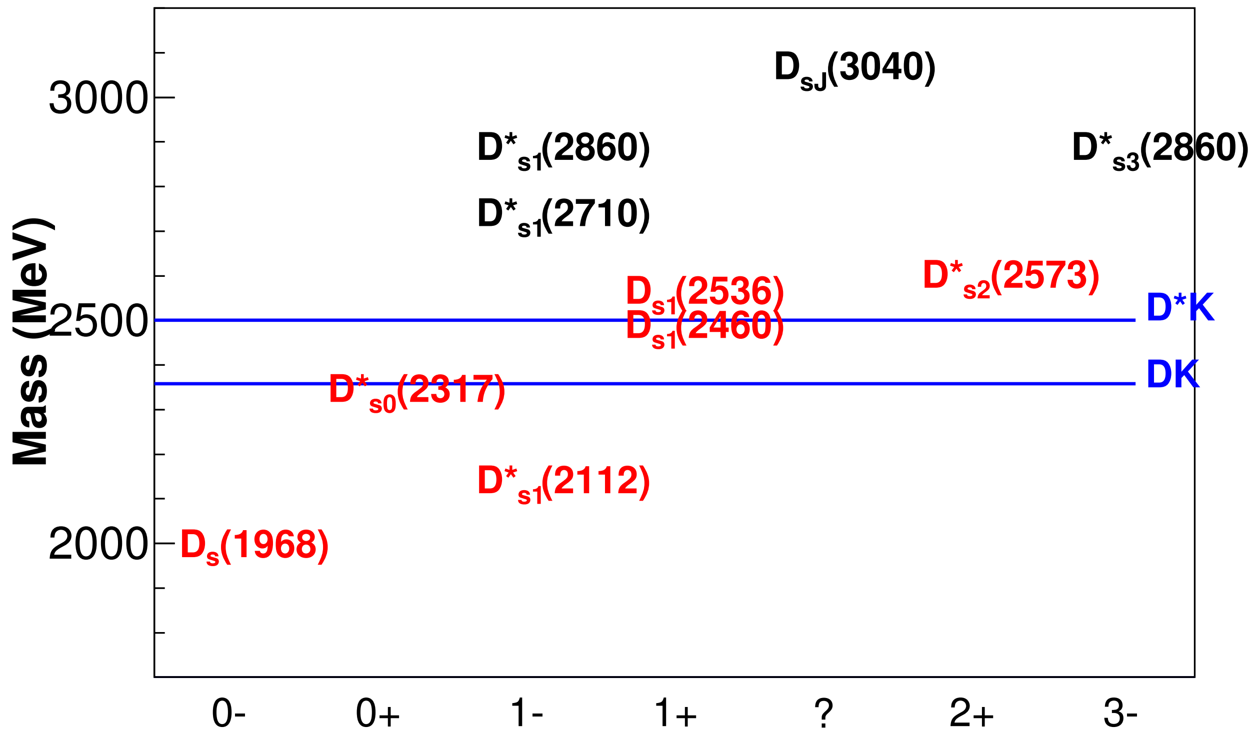


□ No evidence is found for additional spin-1 or spin-3 D^*_J resonances.



Experimental status of the D_s mesons

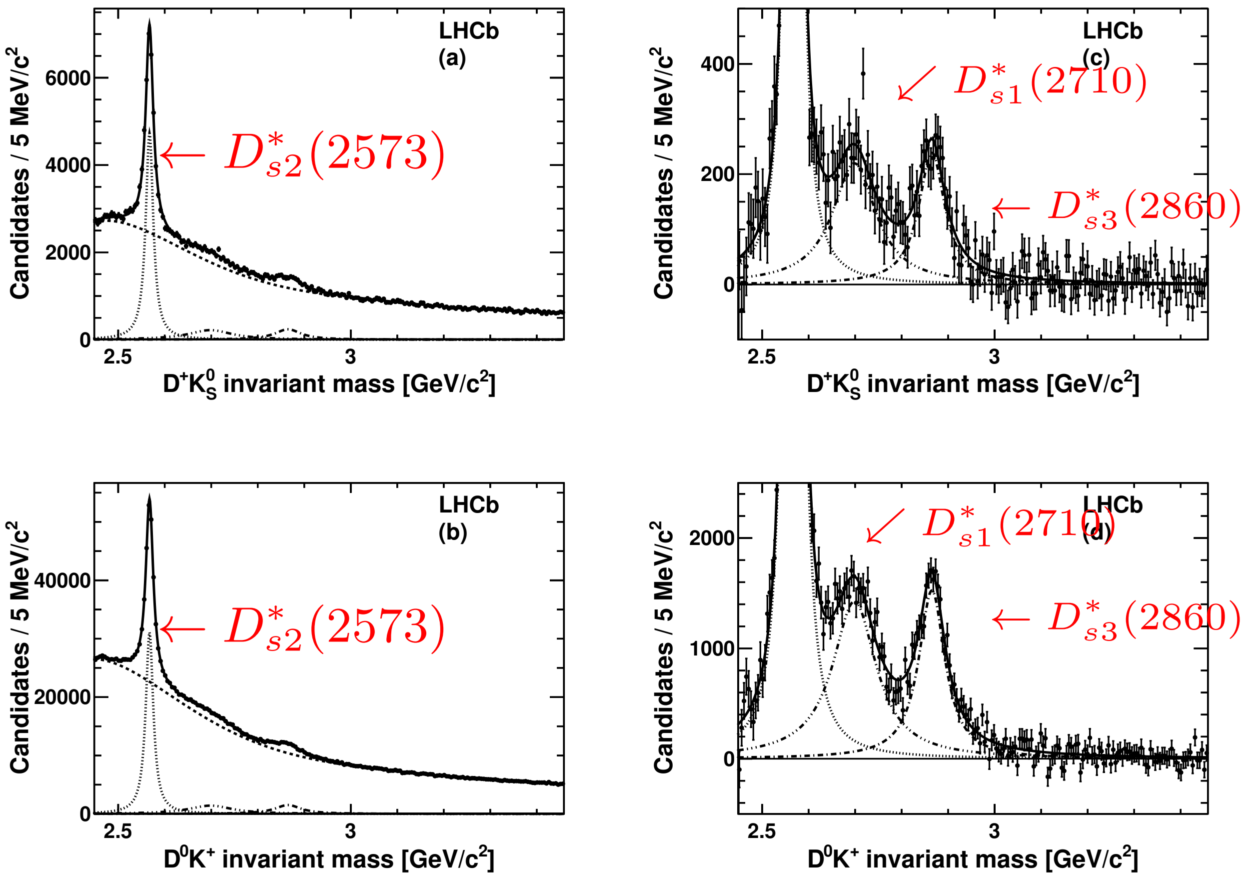
- Recent calculation of the $c\bar{s}$ spectrum (S. Godfrey, K. Moats, Phys.Rev.D93,034035 (2016)).
- Experimental spectrum.



- $D^*_{s1}(2710)^+$, $D^*_{s3}(2860)^+$ and $D^*_{sJ}(3040)^+$ discovered by BaBar (Phys.Rev.Lett.97, (2006) 222001), (Phys.Rev.D 80 (2009) 092003).
- Several new states (in black) being studied in the DK and D^*K mass spectra.

Inclusive: Observation of $D_{s1}^{*}(2710)^{+}$ and $D_{s3}^{*}(2860)^{+}$

□ Inclusive approach: study of $D^{+}K_{S}^{0}$ and $D^{0}K^{+}$ final states ($1\ \mathrm{fb}^{-1}$) (JHEP 1210 (2012) 151).



□ Observation of $D_{s2}^{*}(2573)$, $D_{s1}^{*}(2710)$, and $D_{s3}^{*}(2860)$.

Dalitz plot analysis of $B_s^0 \to \bar{D}^0 K^- \pi^+$

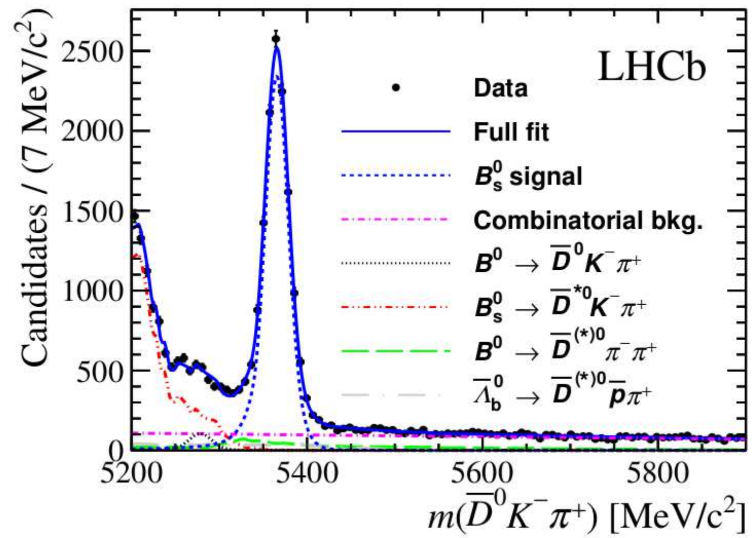
□ $\bar{D}^0 K^- \pi^+$ mass spectrum

(Phys. Rev. D 90, 072003 (2014)),

(Phys.Rev.Lett. 113, 162001 (2014).

□ 11302 ± 159 signal events.

□ 3 fb^{-1} integrated luminosity.



□ The largest components are:

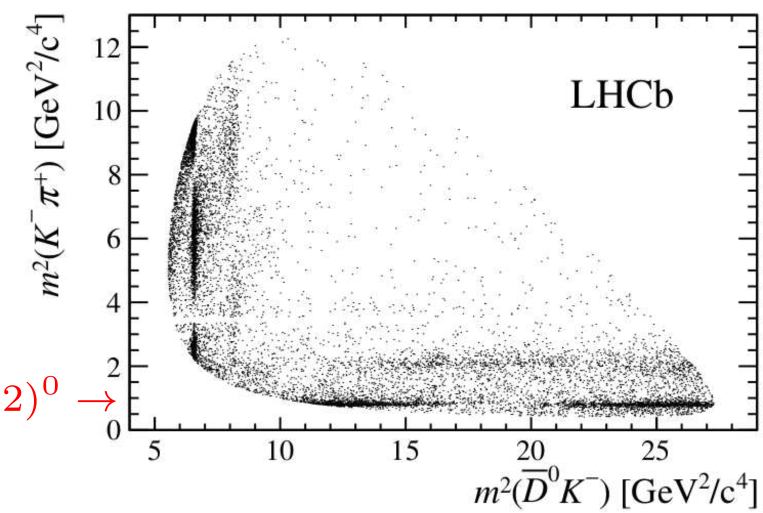
$\bar{K}^*(892)^0$ ($\approx 29\,\%$),

$D_{s2}^*(2573)^-$ ($\approx 26\,\%$),

$K\pi$ S-wave (LASS) ($\approx 21\,\%$)

$\bar{D}^0 K^-$ nonresonant ($\approx 12\,\%$).

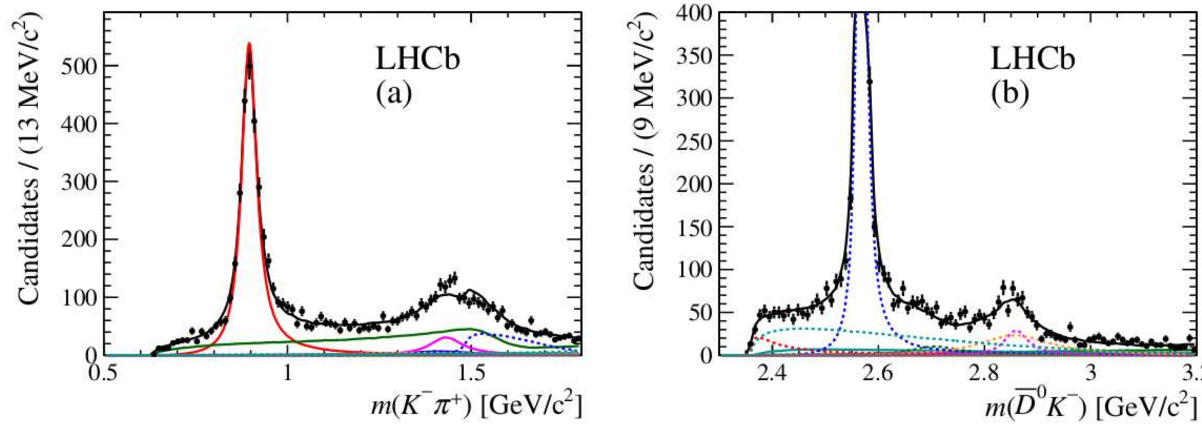
↓ $D_{s2}^*(2573)$



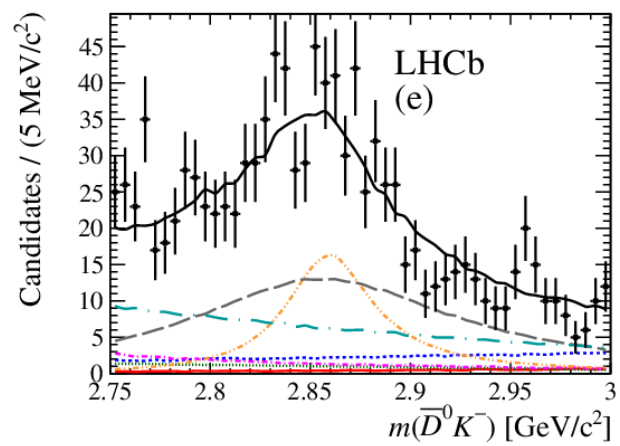
$\bar{K}^*(892)^0$ →

Dalitz plot analysis of $B_s \to \bar{D}^0 K^- \pi^+$

□ Fit projections.



□ Signal present in the 2860 MeV $\bar{D}^0 K^-$ mass region described by a superposition of
a spin-1 $(5.0 \pm 1.2 \pm 0.7 \pm 3.3)\,\%$
and a spin-3 $(2.2 \pm 0.1 \pm 0.3 \pm 0.4)\,\%$ resonance.



□ Resonances parameters:

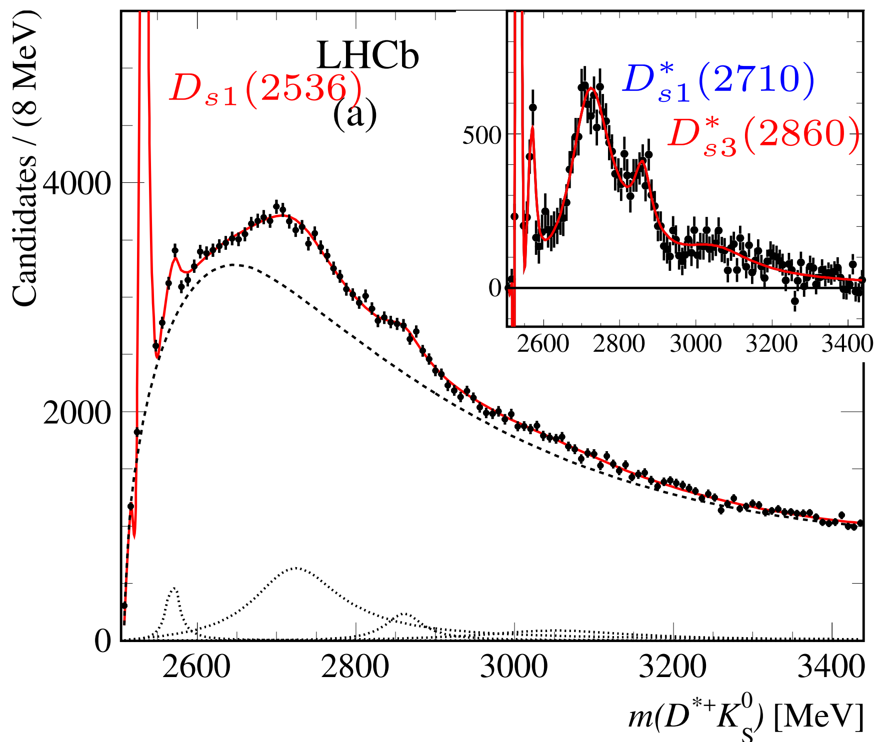
$m(D^*_{s1}(2860)^-) = 2859 \pm 12 \pm 6 \pm 23$ MeV, $\Gamma(D^*_{s1}(2860)^-) = 159 \pm 23 \pm 27 \pm 72$ MeV

$m(D^*_{s3}(2860)^-) = 2860.5 \pm 2.6 \pm 2.5 \pm 6.0$ MeV, $\Gamma(D^*_{s3}(2860)^-) = 53 \pm 7 \pm 4 \pm 6$ MeV

Inclusive $D^{*+}K^0_S$ mass spectrum

□ $D^{*+}K^0_S$ with enhanced Natural Parity contributions $|cos\theta_H| < 0.5$. $D^0 \to K^-\pi^+$.

(JHEP 02 (2016) 133)



□ Resonances $D^*_{s1}(2710)^+$ and $D^*_{s3}(2860)^+$ are also observed and their parameters are measured to be:

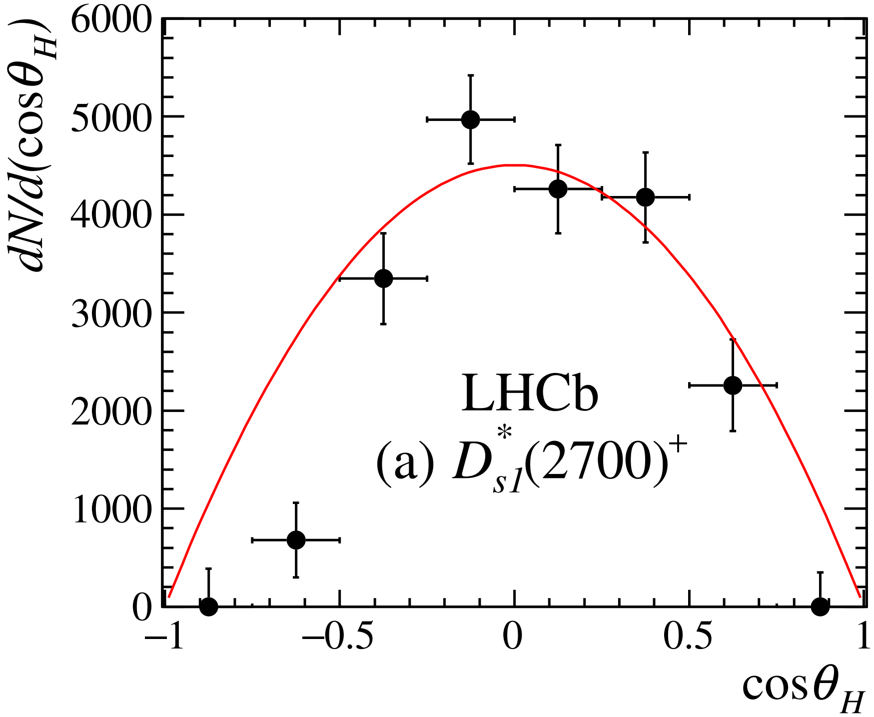
$$m(D^*_{s1}(2710)^+) = 2732.3 \pm 4.3 \pm 5.8,\ \Gamma(D^*_{s1}(2710)^+) = 136 \pm 19 \pm 24 \ \ \text{MeV}$$

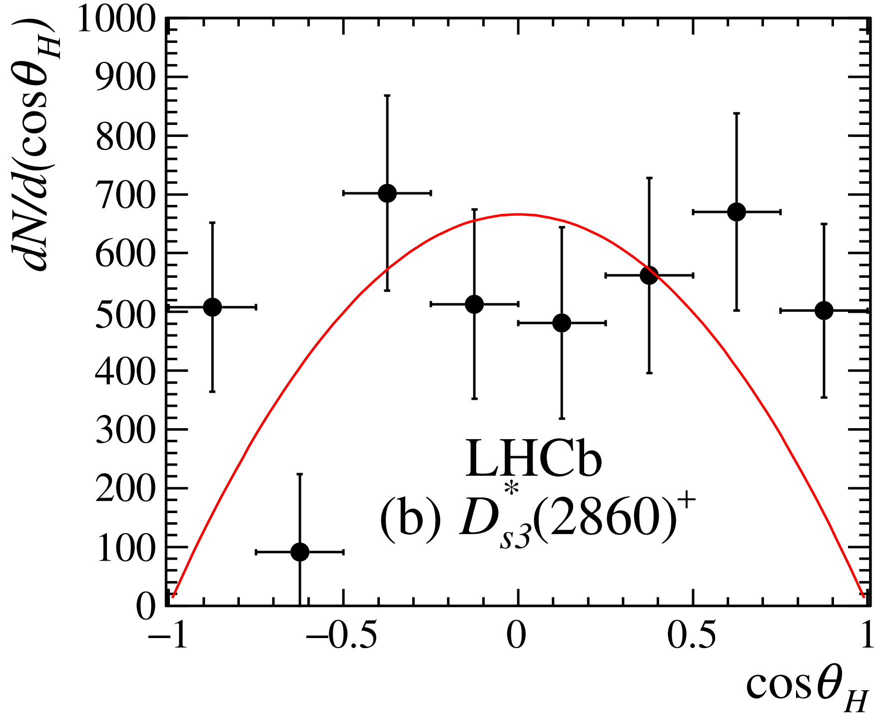
$$m(D^*_{s3}(2860)^+) = 2867.1 \pm 4.3 \pm 1.9,\ \Gamma(D^*_{s3}(2860)^+) = 50 \pm 11 \pm 13 \ \ \text{MeV}$$

□ Significances are 7.6σ and 7.1σ respectively.

□ Same χ^2/ndf and a statistical significance of the $D^*_{s1}(2860)^+$ of 3.3σ: *the data are not sensitive to the presence of the* $D^*_{s1}(2860)^+$ *resonance.*

$D^*_{s1}(2710)^+$ and $D^*_{s3}(2860)^+$ angular distributions



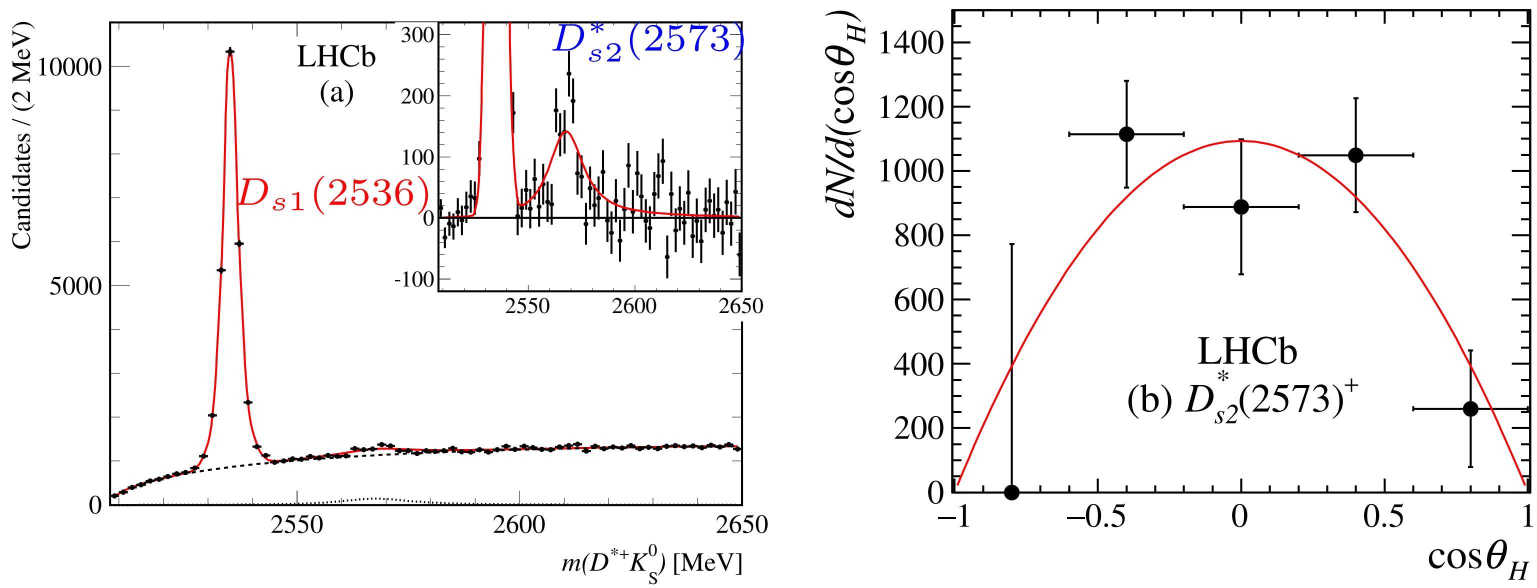


□ Both consistent with Natural Parity assignment.

□ The poor qualtity of the $D^*_{s3}(2860)^+$ angular distribution suggests the possible presence of Unnatural Parity contributions.

First observation of the decay $D_{s2}^*(2573)^+ \to D^{*+} K_S^0$

□ Fits to the $D^* K$ mass spectrum in the threshold region.



□ $D_{s2}^*(2573)^+$ mass consistent with the DK measurements. Significance: 6.9σ.

□ Angular distribution as expected for a $J^P = 2^+$ Natural Parity assignment.

□ Relative branching fraction of the decay $D_{s2}^*(2573)^+ \to D^{*+} K_S^0$:

$$\frac{\mathcal{B}(D_{s2}^*(2573)^+ \to D^{*+} K_S^0)}{\mathcal{B}(D_{s2}^*(2573)^+ \to D^+ K_S^0)} = 0.044 \pm 0.005\,(\text{stat}) \pm 0.011\,(\text{syst}). \quad (1)$$

□ In agreement with expectations from the QM calculations which predict a value of 0.058 for this ratio.

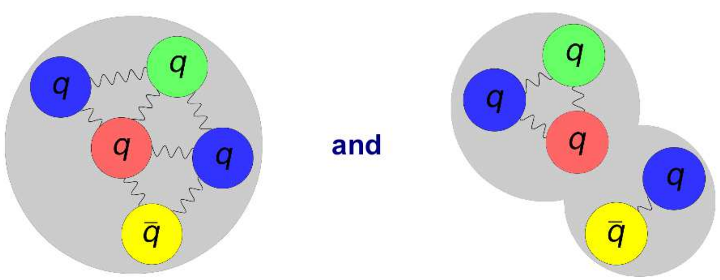
Multiquark states

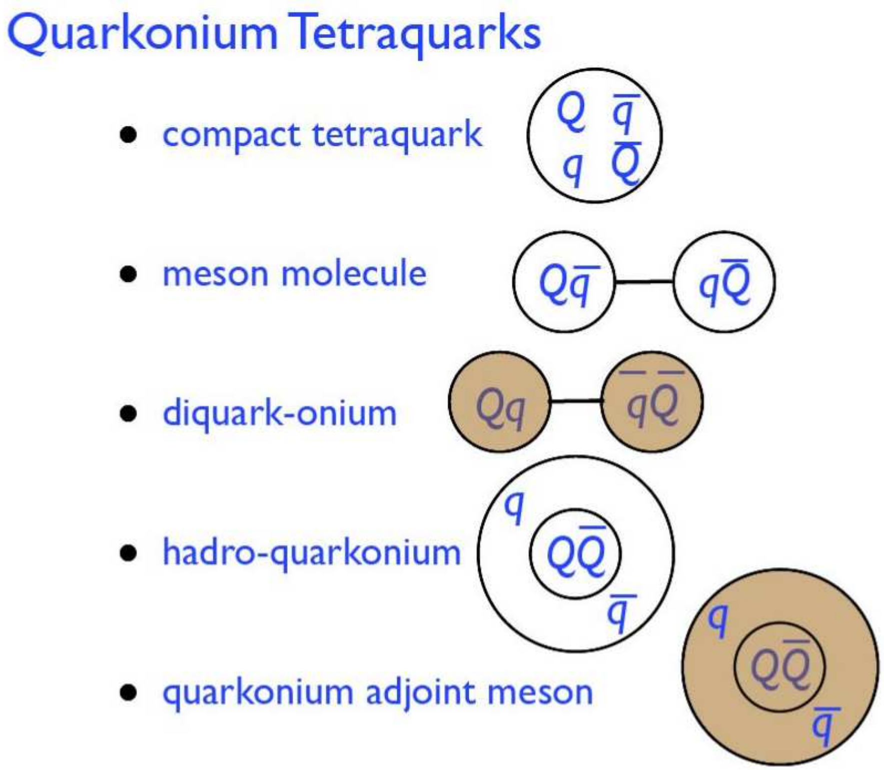
□ In the original Gell-Mann paper ("A schematic model for baryons and mesons", Phys. Lett. 8, (1964)).

□ "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

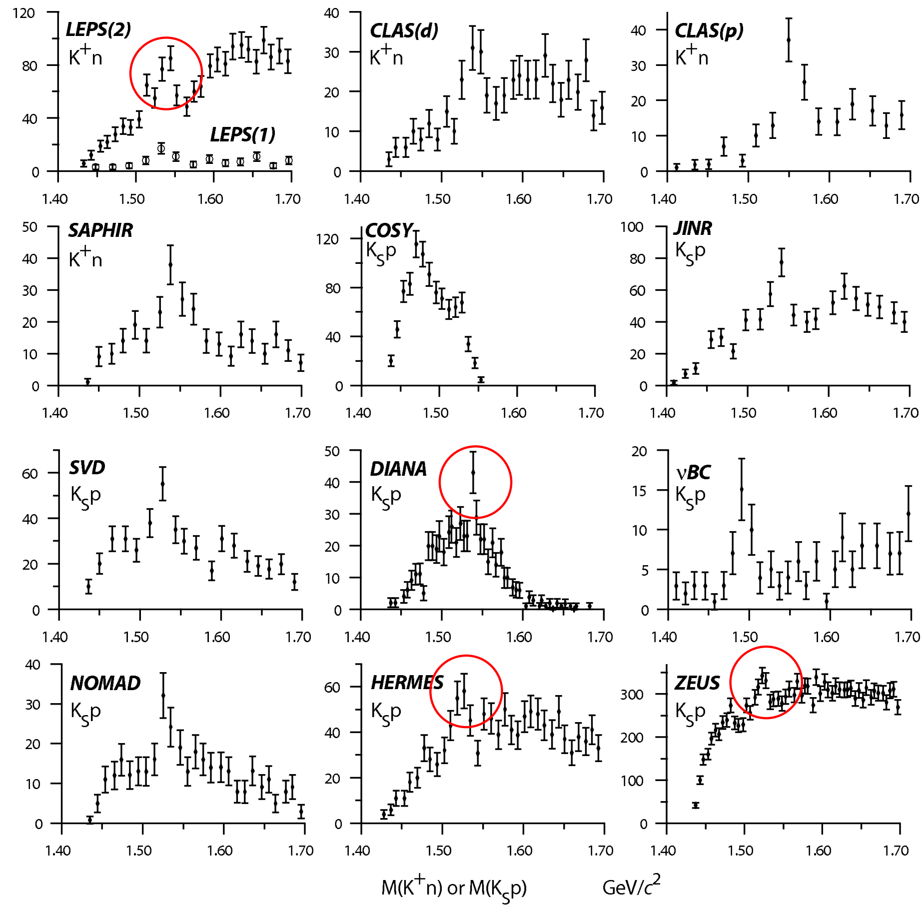


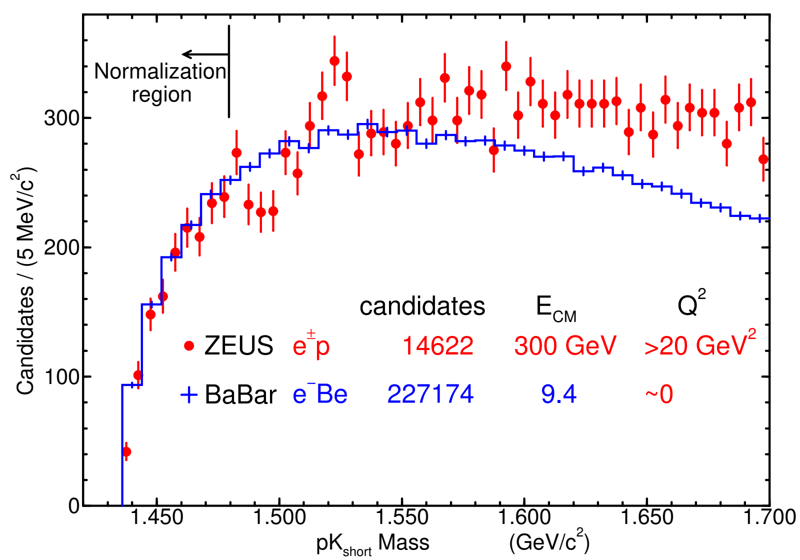


The rise and fall of pentaquarks

□ 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^0_S.

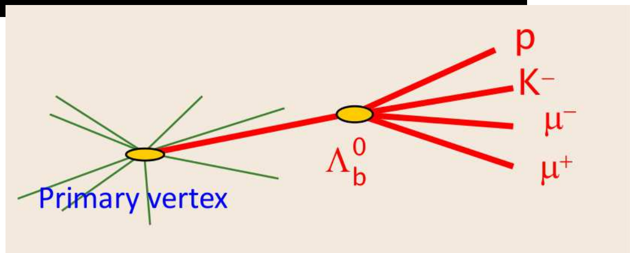




□ Significances in these data were largely overestimated and high statistics searches gave negative results (See for example BaBar: Phys.Rev.Lett. 95 (2005) 042002, FOCUS: Phys.Lett. B639 (2006) 604) .

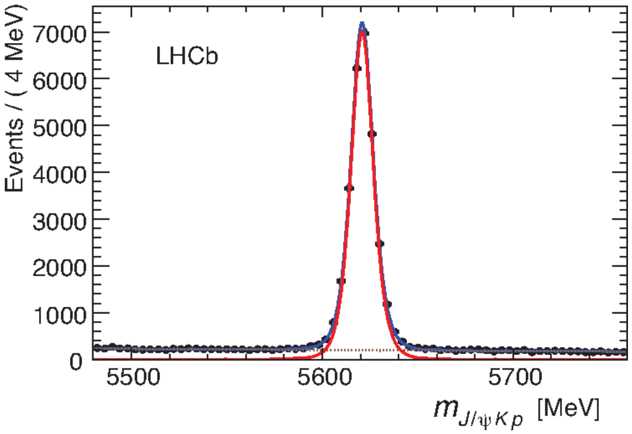
□ Around 2007 pentaquarks were dead.

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



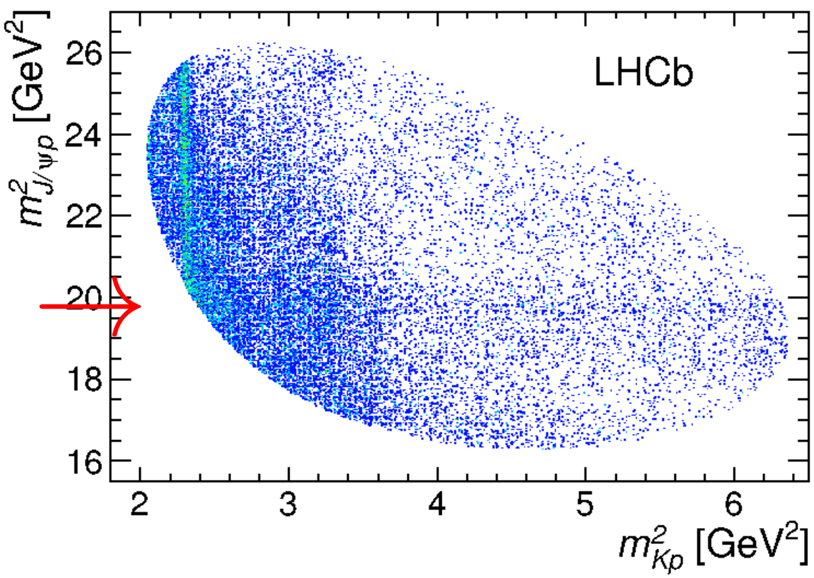
□ Multivariate Analysis (MTVA) selection.

□ $26,007 \pm 166$ 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.

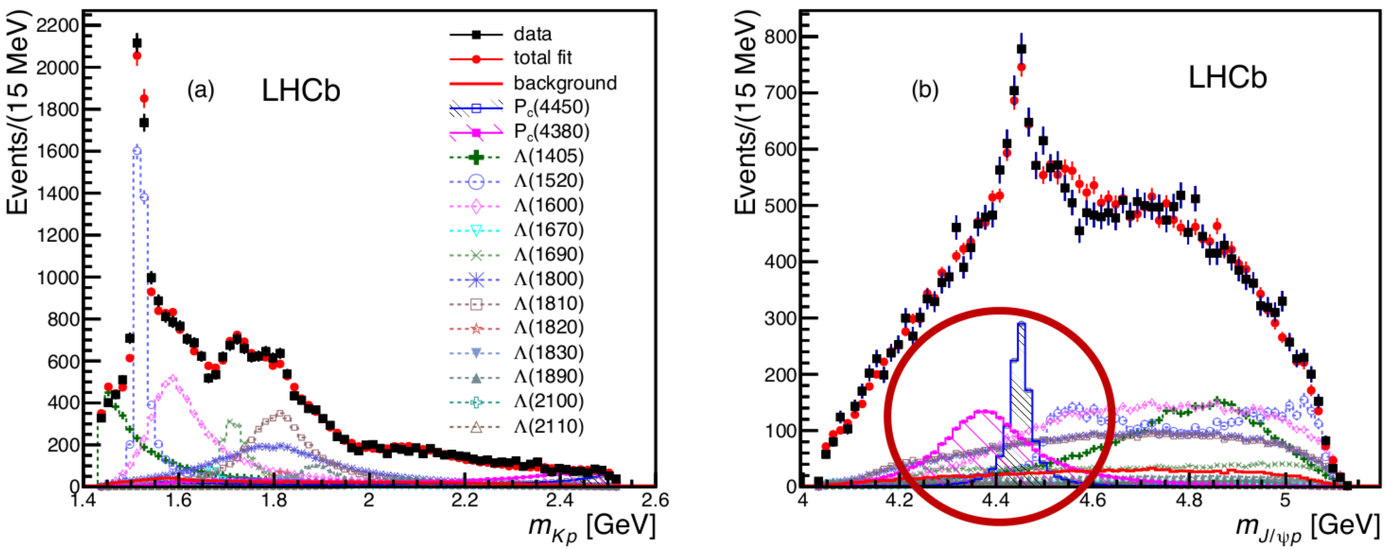


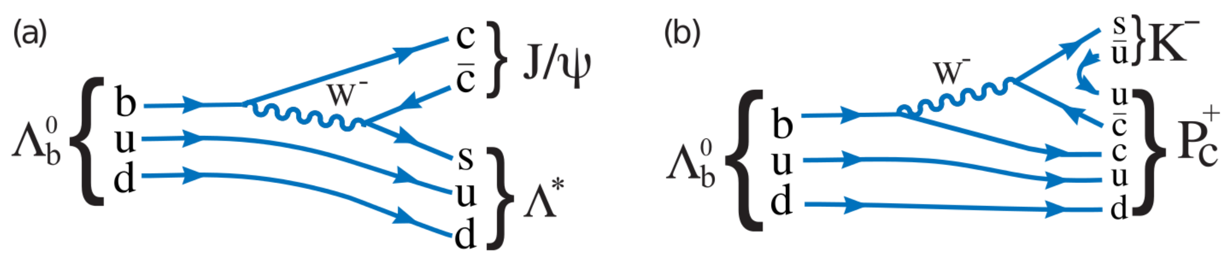
(PRL 115, 072001 (2015)).

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).



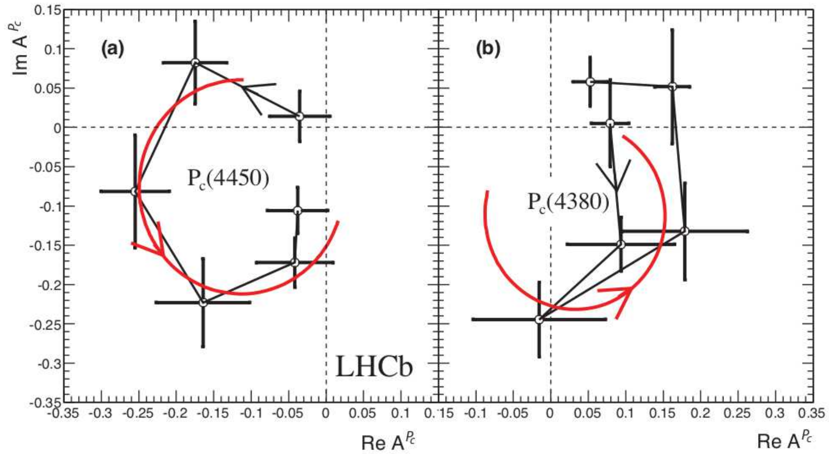


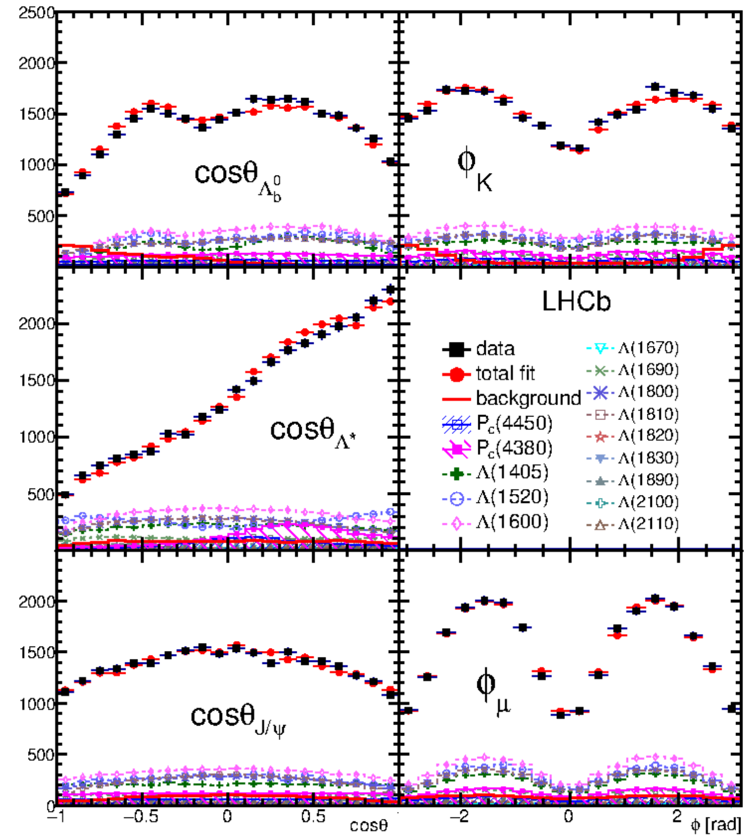
(PRL 115, 072001 (2015)).

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.



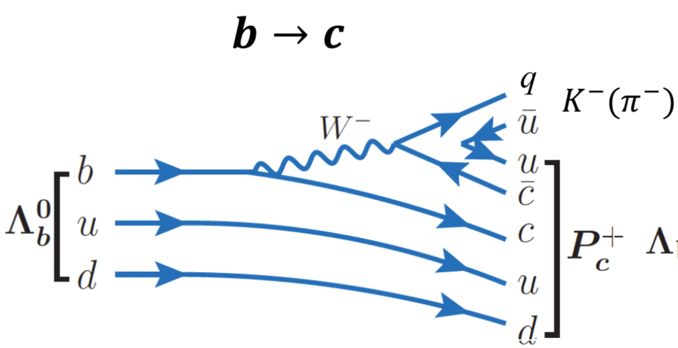


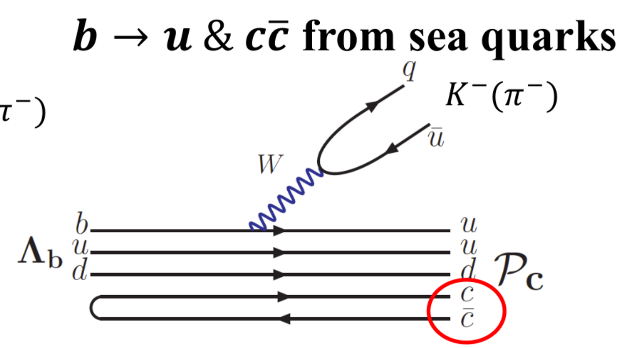
- □ Model independent analysis gives consistent results (Phys. Rev. Lett. 117, 082002 (2016)).

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.

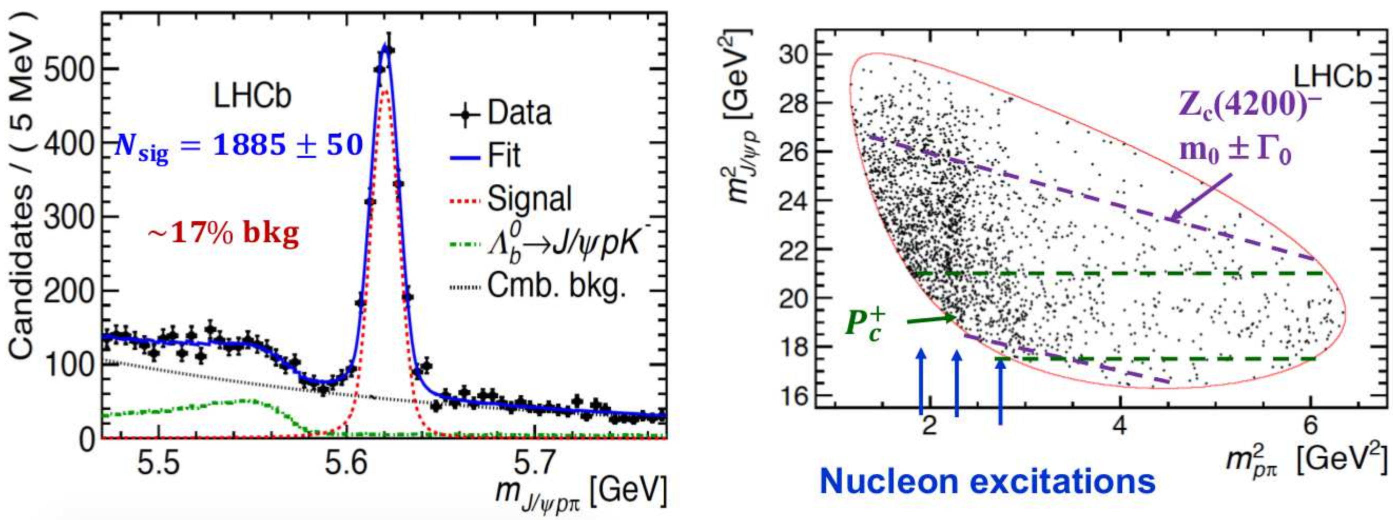
$$R_{\pi/K} = \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08, \quad R_{\pi/K} = 0.58 \pm 0.05$$

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)).



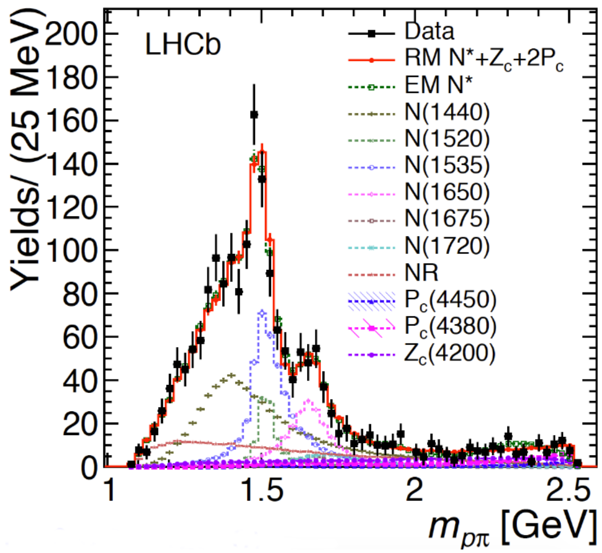
□ Full amplitude analysis. Accurate description of the rich resonant structure in the $p\pi^-$ final state.

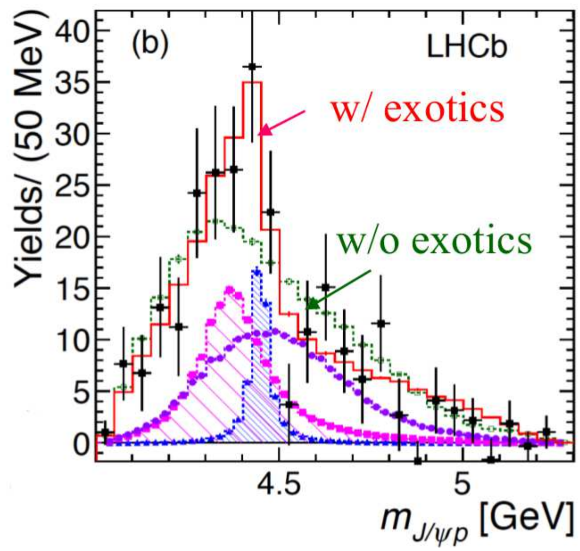
$$\Lambda_b \to J/\psi N^*(\to p\pi^-),\ \Lambda_b \to \pi^- P_c^+(\to J/\psi p),\ \Lambda_b \to p Z_c(4200)^-(\to J/\psi \pi^-)$$

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

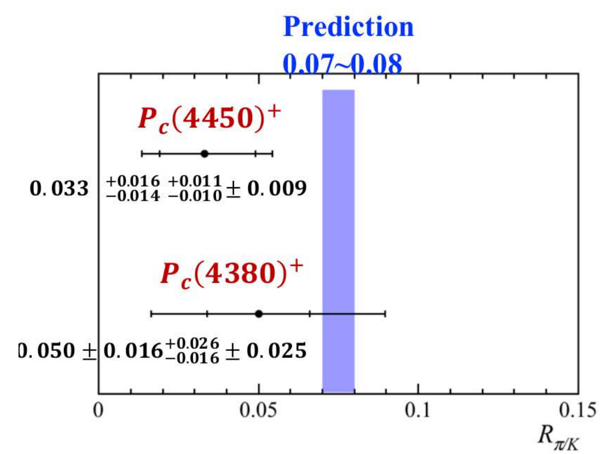
Study of $\Lambda_b^0 \to J/\psi p \pi^-$ decays

- $Z_c(4200)^-$, 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.

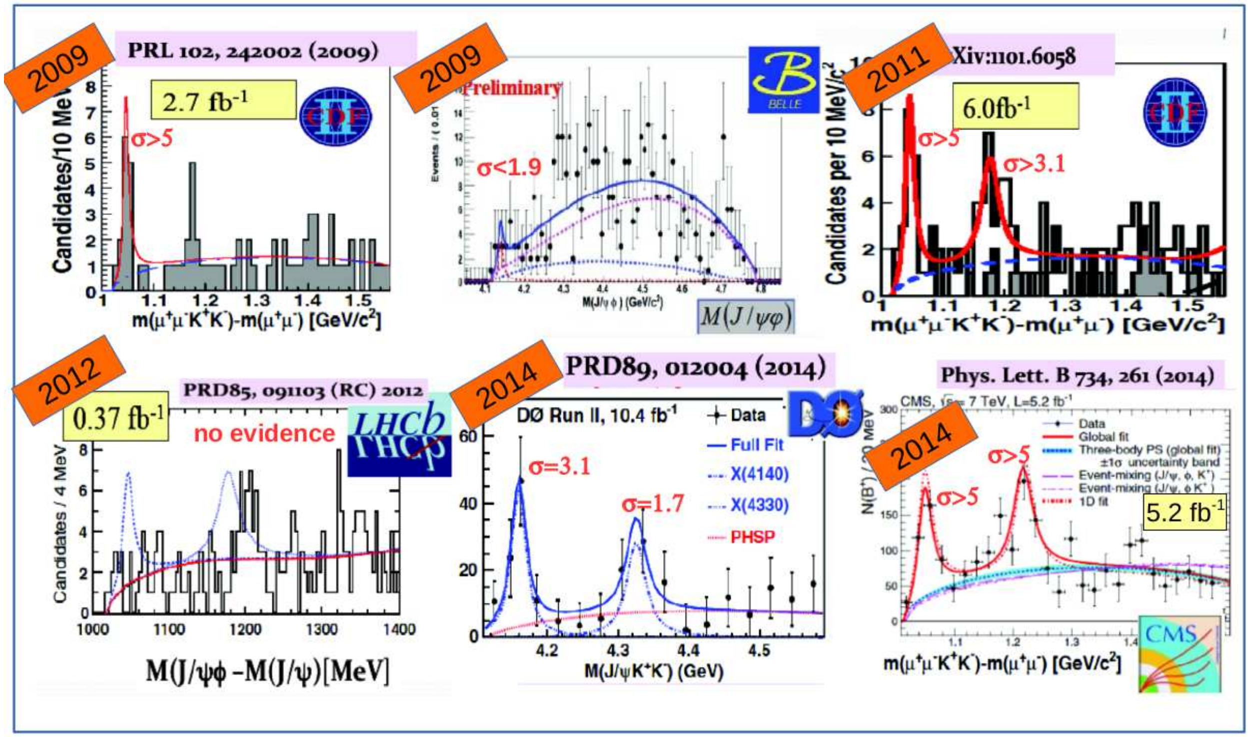


- The $b \to c$ diagram strongly favoured.

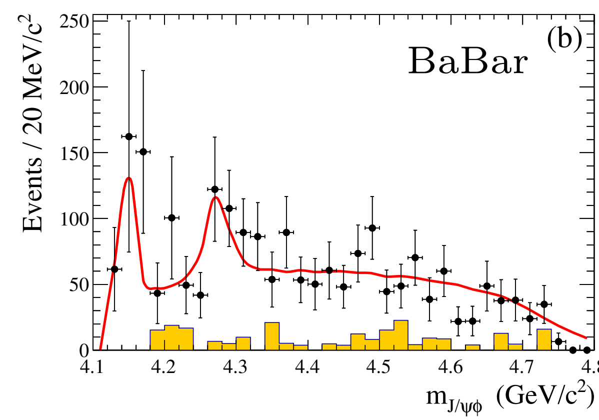
Phys. Rev. Lett. 117, 082003 (2016)

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

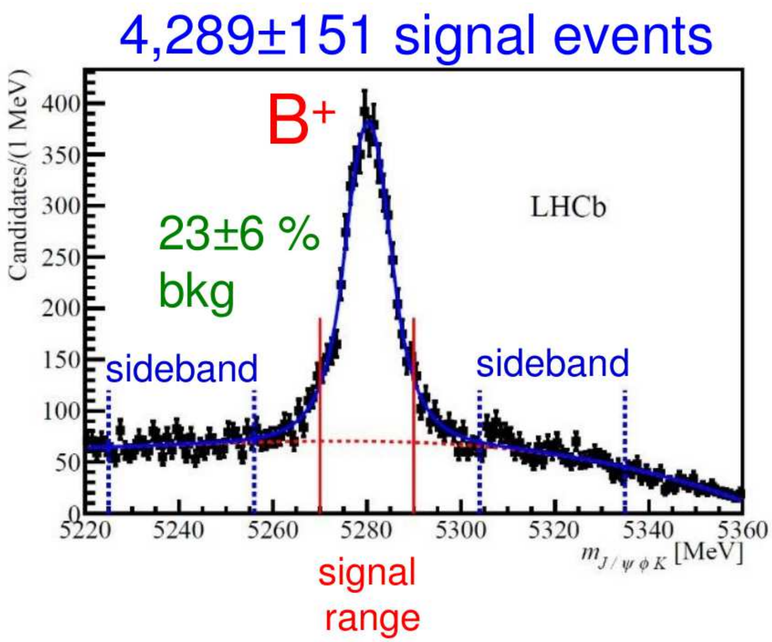


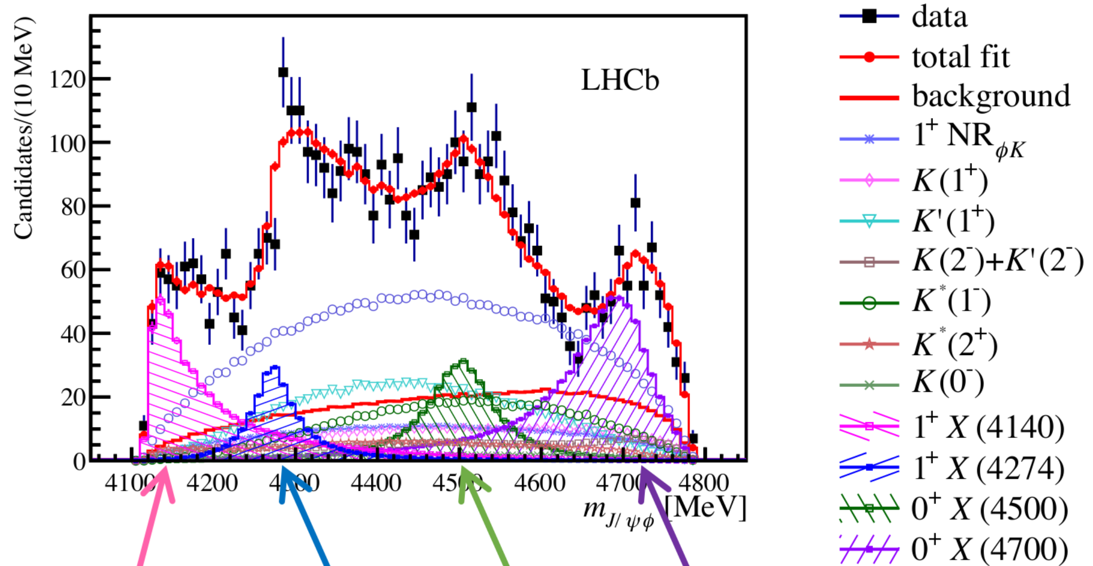
- Summary of the experimental evidences.

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.





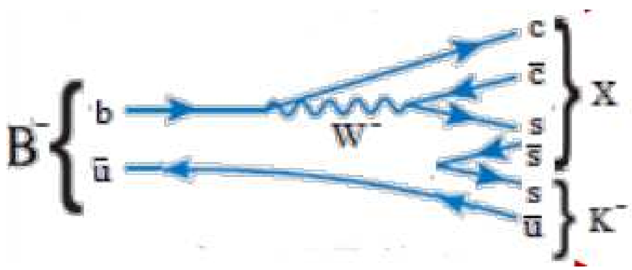
$X(4140)$, $X(4274)$, $X(4500)$, $X(4700)$

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^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

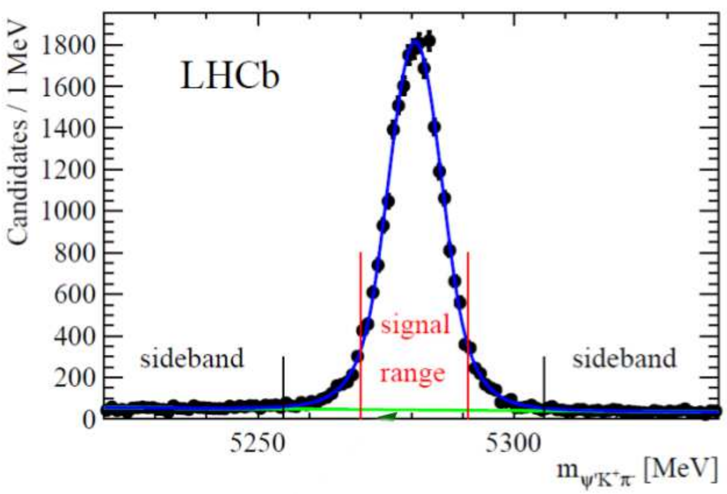
- The $X(4140)$ **is not** a narrow resonance.
- A possible diagram for producing a 4-quark state.

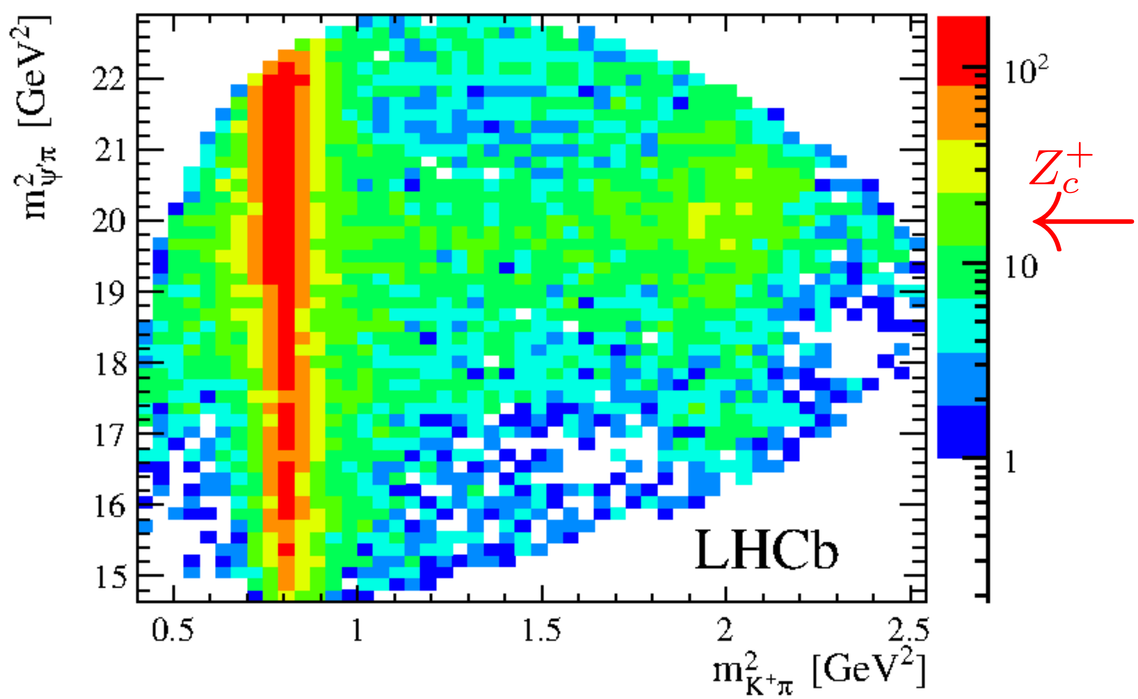


- Lot of discussions. Interpretation of these states still open.

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

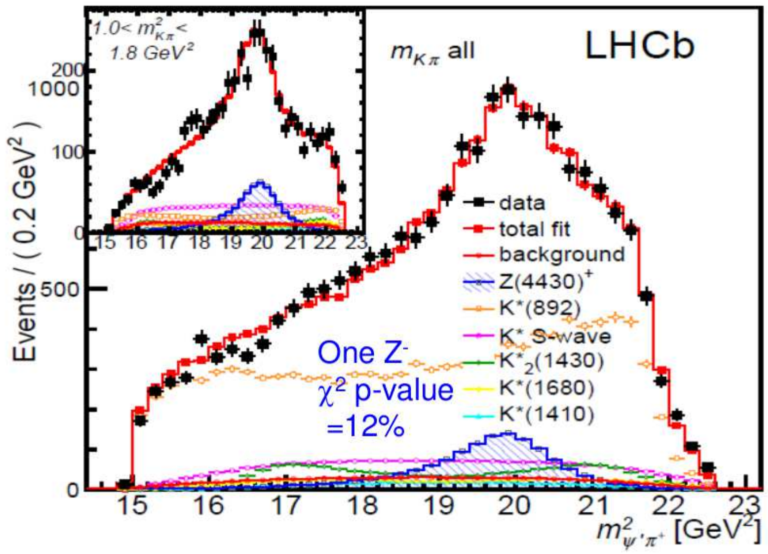
- First analysis from Belle: observation of a new $Z_c(4430)^+ \to \psi'\pi^-$ in $B \to K\pi^+\psi'$ (PRL 100, 142001 (2008)).
- Not confirmed by BaBar: data could be described without the presence of a $Z_c(4430)^+$ resonance (PRD 79, 112001 (2009)).
- Recent analysis from LHCb (PRL 112, 222002 (2014)).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

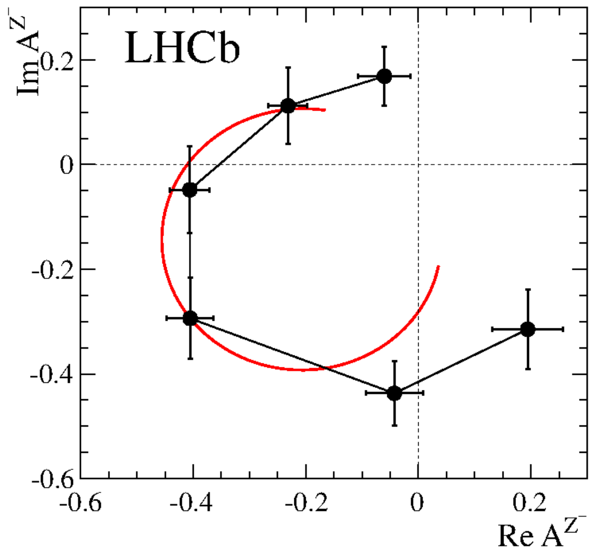




Study of $\bar{B}^0 \to \psi' \pi^- K^+$

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

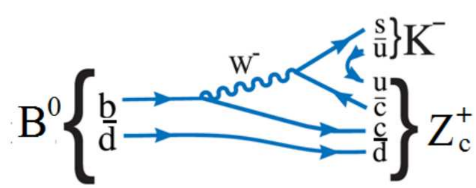


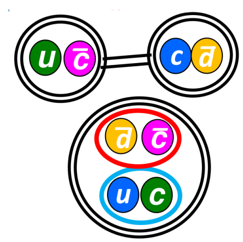


- Argand diagram shows typical resonance behaviour. Resonance parameters:

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

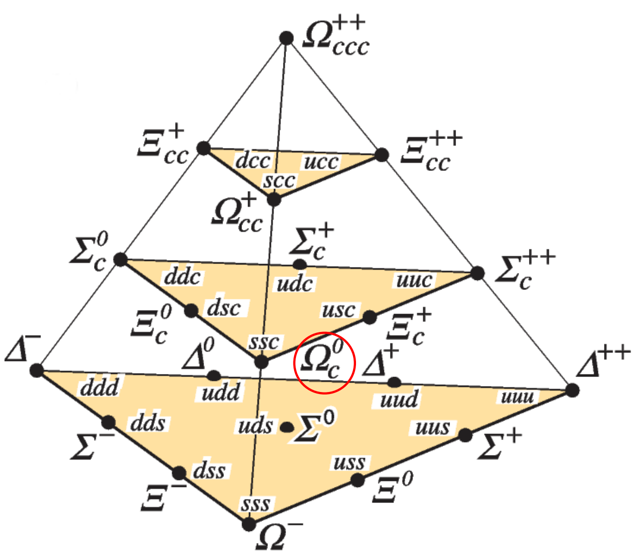
- In good agreement with Belle.
- Possible presence of an additional Z_c at a mass of 4239 MeV.
- Z_c is a charged charmonium state. Multiquark state?

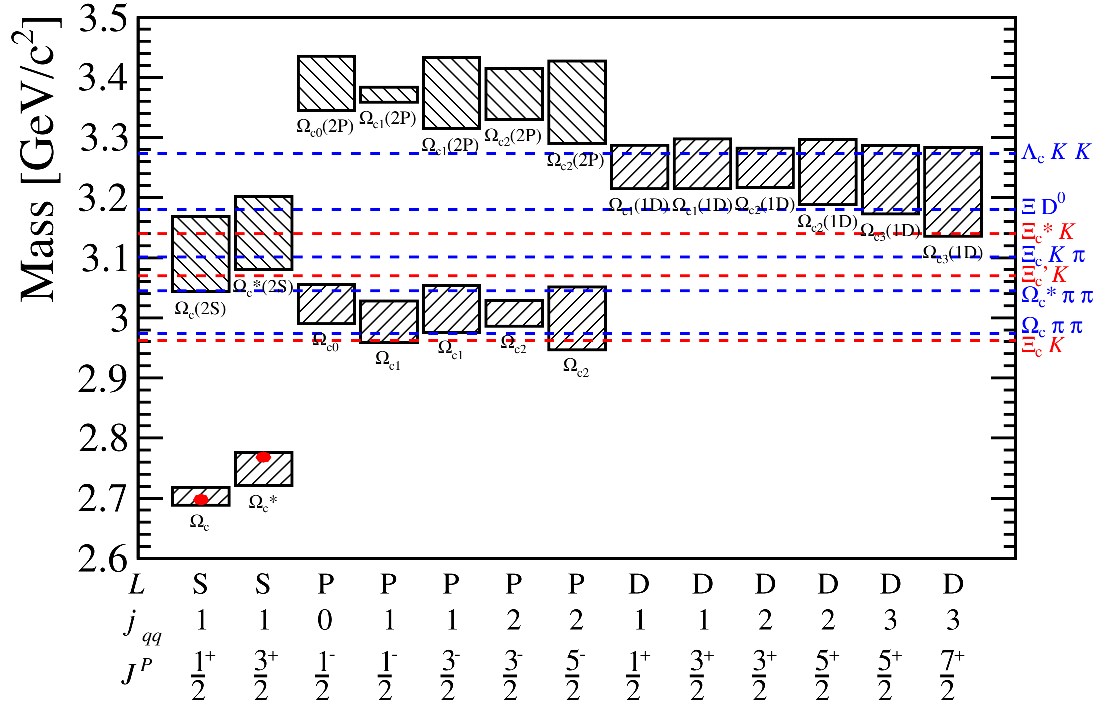




Baryon spectroscopy: New Ω_c states

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



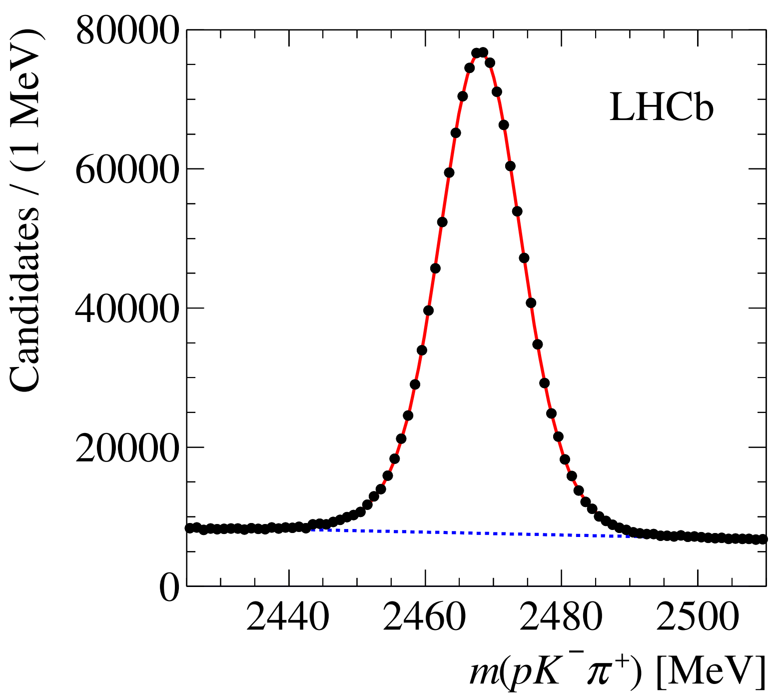


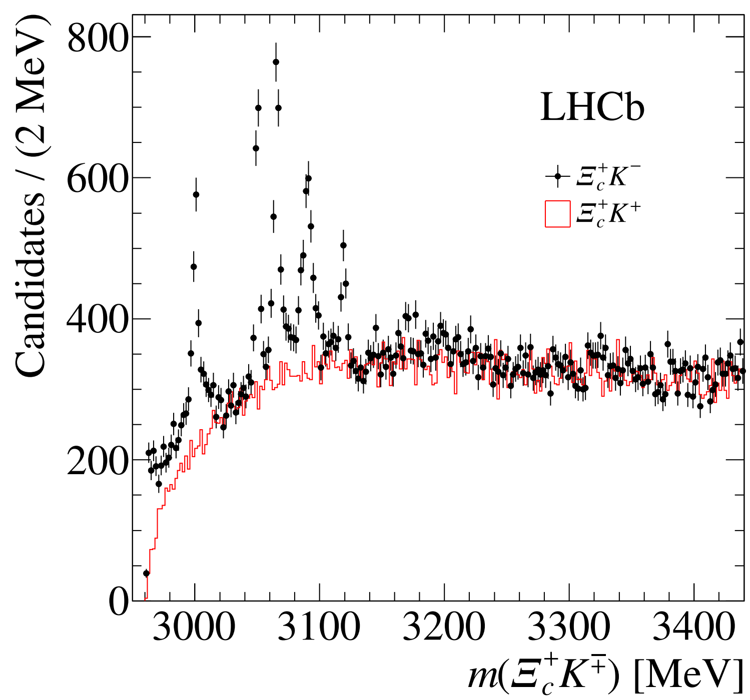
□ Ω_c quark content: *ssc*.

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

Observation of five new Ω_c states in LHCb

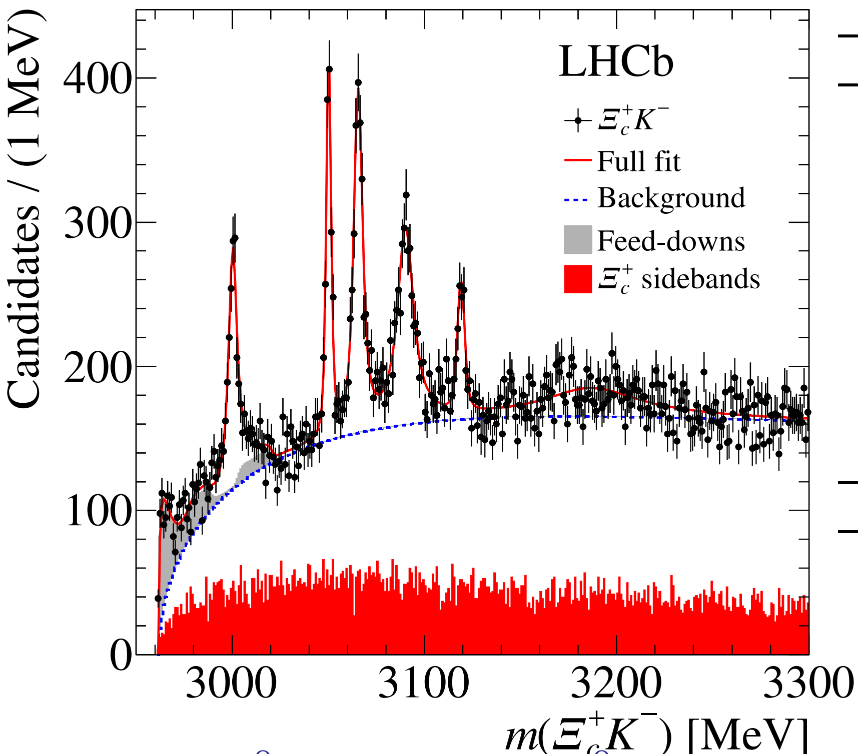
- □ Explore excited Ω_c states in their strong decay to $\Xi_c^+ K^-$ (PRL 118 (2017) 182001).
- □ Make use of data collected at 7,8 and 13 TeV (3.3 fb^{-1}).
- □ Ξ_c^+ reconstructed in the Cabibbo suppressed mode $\Xi_c^+ \to pK^-\pi^+$.
- □ $\approx 10^6$ Ξ_c^+ reconstructed with a 83% purity.
- □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

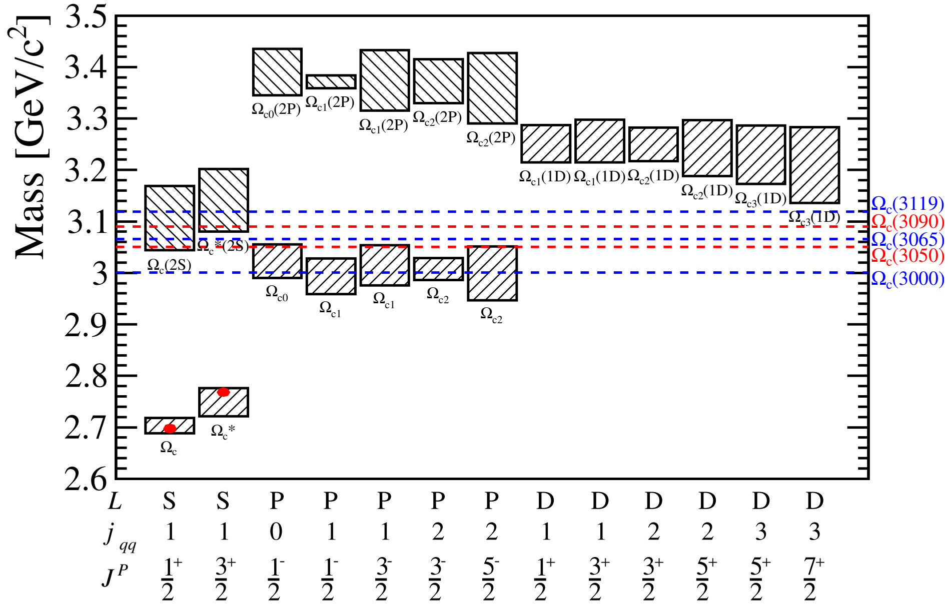


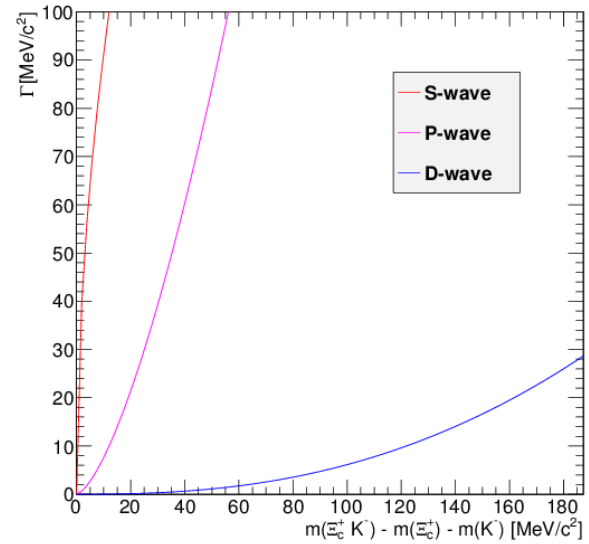
Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		< 1.2 MeV, 95% CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$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





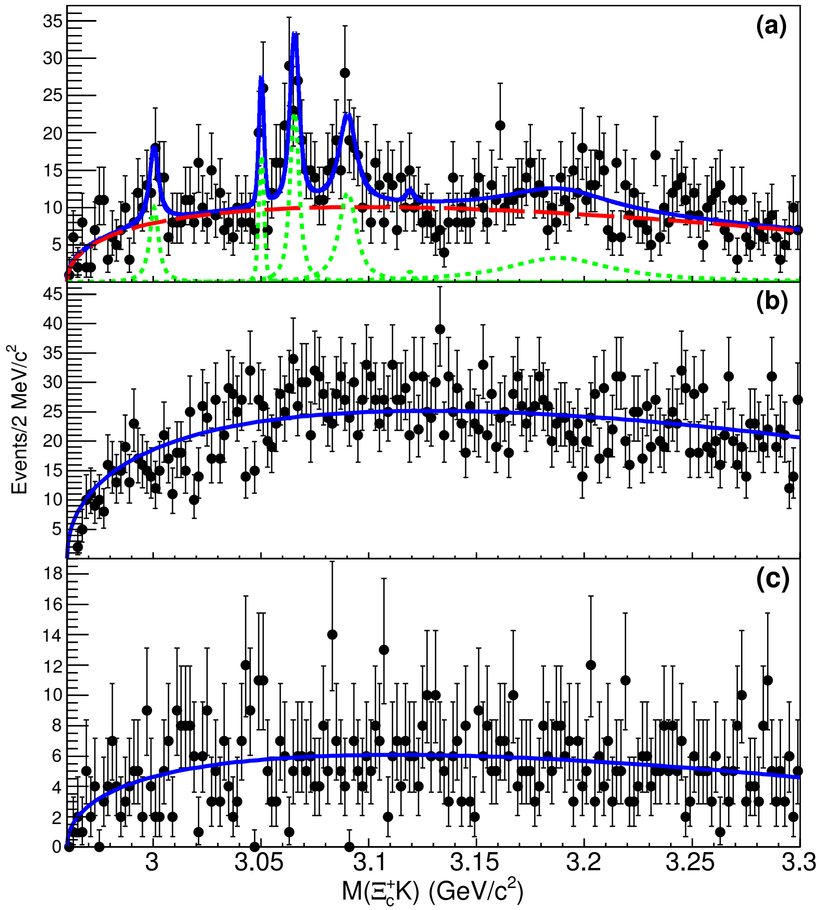
- D and P-wave states may be narrow (G. Chiladze, A. Falk arXiv: 9707507).
- Need to measure the quantum numbers of these states.
- Many phenomenological interpretations, including the possible presence of pentaquarks.

Confirmation of the new Ω_c states

□ Very recent Belle analysis (arXiv:1711.07927,21 Nov 2017).

□ Use of seven Ξ_c^+ decay modes: ($\Xi^-\pi^+\pi^+$, $\Lambda K^-\pi^+\pi^+$, $\Xi^0\pi^+$, $\Xi^0\pi^+\pi^-\pi^+$, $\Sigma^+K^-\pi^+$, $\Lambda K_S^0\pi^+$, and $\Sigma^0 K_s^0\pi^+$).

□ $\Xi_c^+ K^-$ mass spectrum from Ξ_c^+ signal region, wrong sign and sidebands.

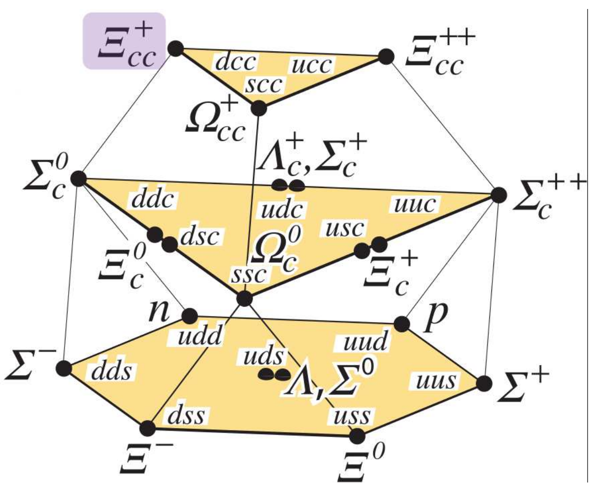


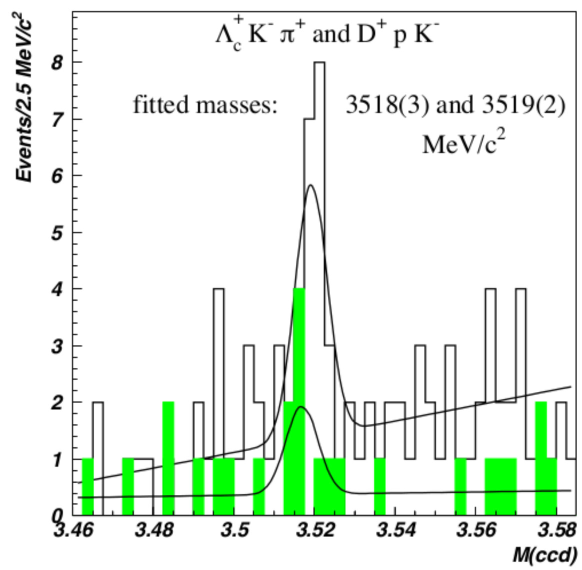
□ Mass spectrum fitted using the Ω_c parameters measured by LHCb.

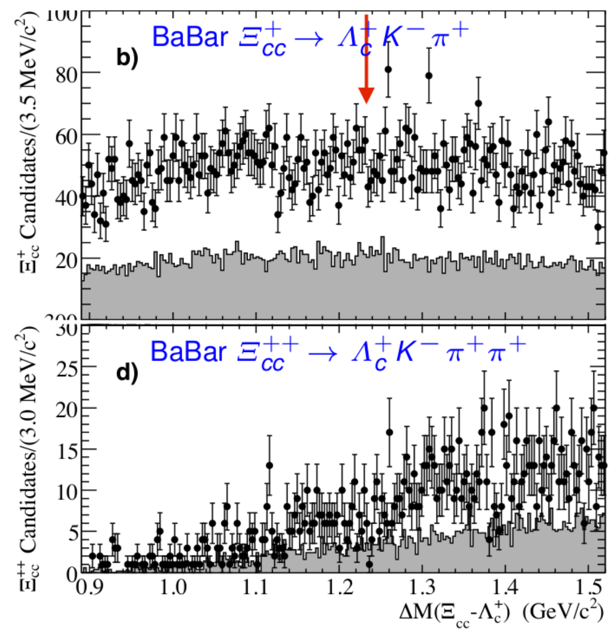
The search for double charmed baryons Ξ_{cc} states

□ 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).

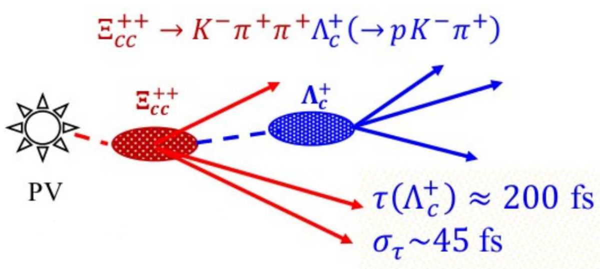
□ Different production mechanisms?

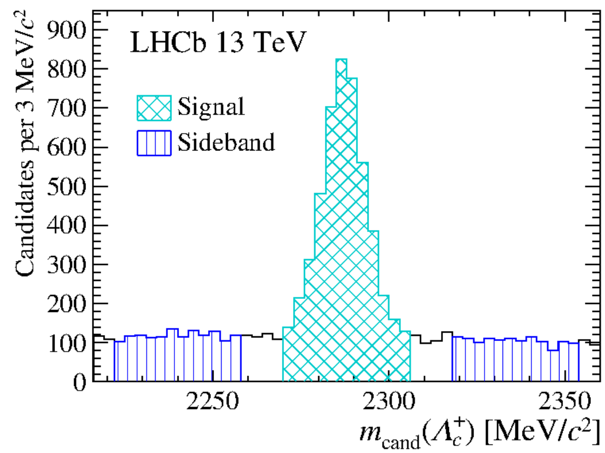
Observation of the double charmed baryon Ξ_{cc}^{++} in LHCb

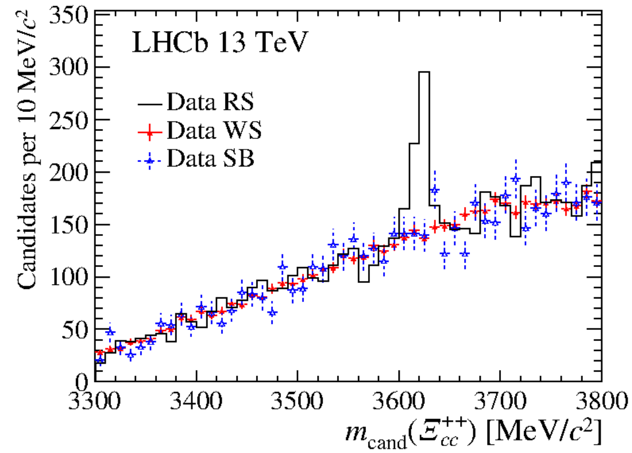
□ Search for the Ξ_{cc}^{++} (ucc) using the decay (Phys. Rev. Lett. 111 (2017) 180001).

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

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







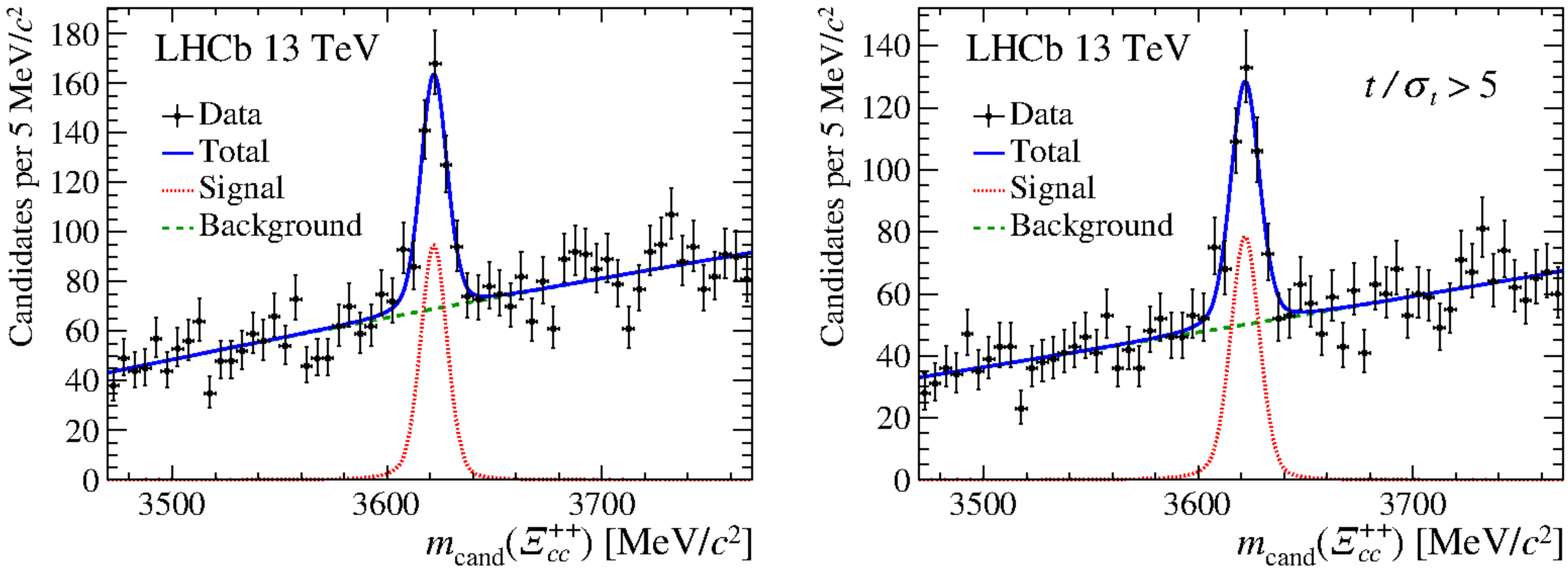
□ First observation.

□ 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.



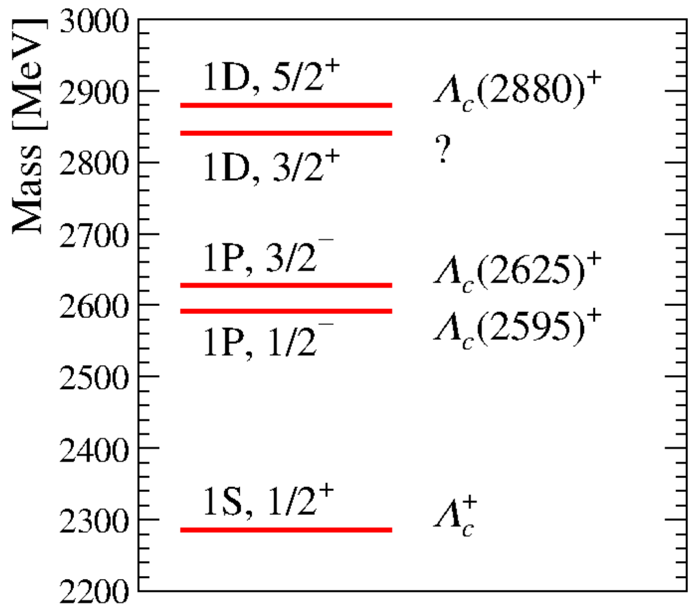
- ☐ The signal persists after a lifetime cut.
- ☐ Ξ_{cc}^{++} parameters.

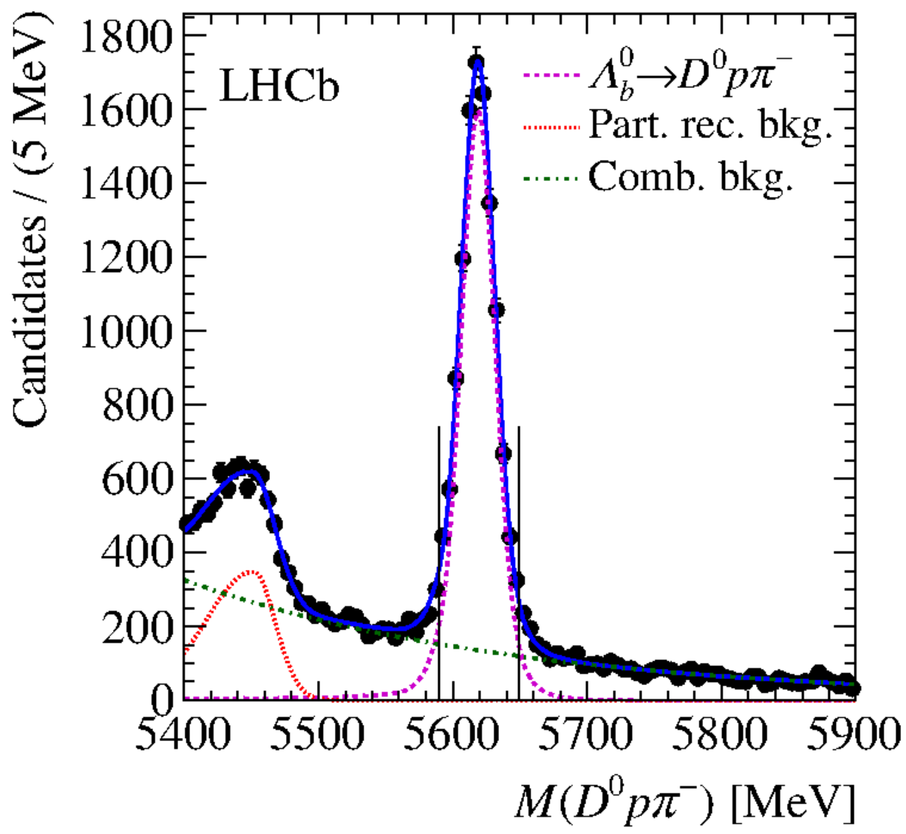
$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c) MeV$$

- ☐ 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).

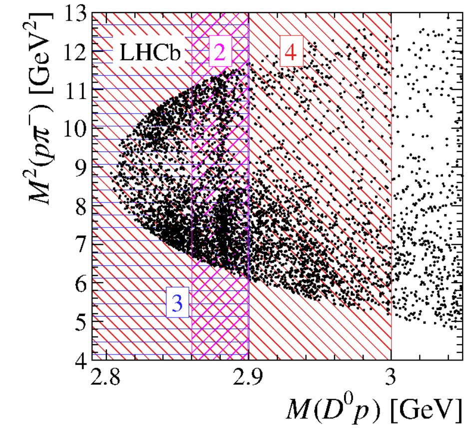




Amplitude analysis of $\Lambda_b \to D^0 p \pi^-$

□ 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), $J^P = 3/2^+$:

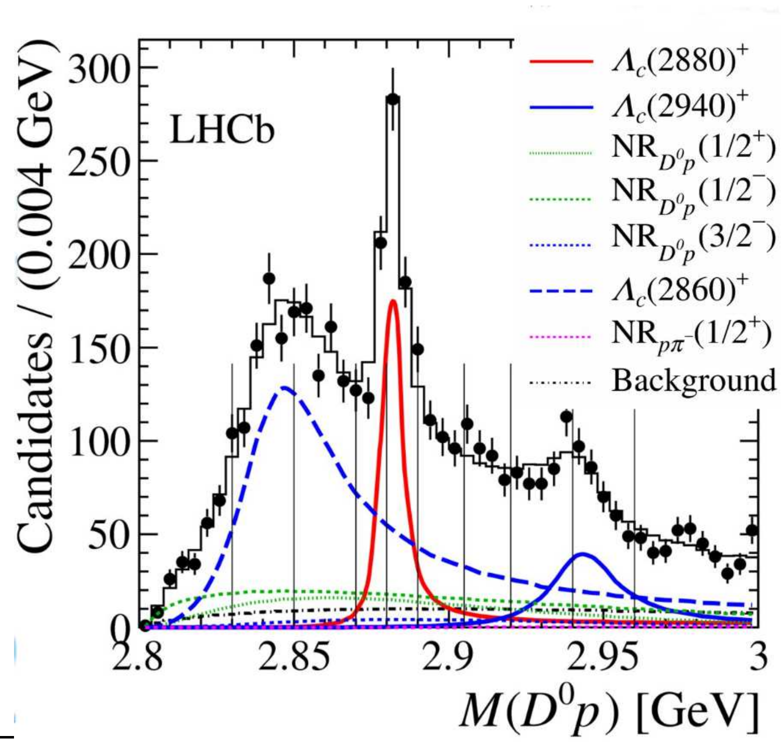
$$m = 2856.1^{+2.0}_{-1.7}(stat) \pm 0.5(syst)^{+1.1}_{-5.6}(model)\ \text{MeV}$$
$$\Gamma = 67.6^{+10.1}_{8.1}(stat) \pm 1.4(syst)^{+5.9}_{-20.0}(model)\ \text{MeV}$$

□ $\Lambda_c(2880)^+$ 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.