Latest results in charmed baryons spectroscopy

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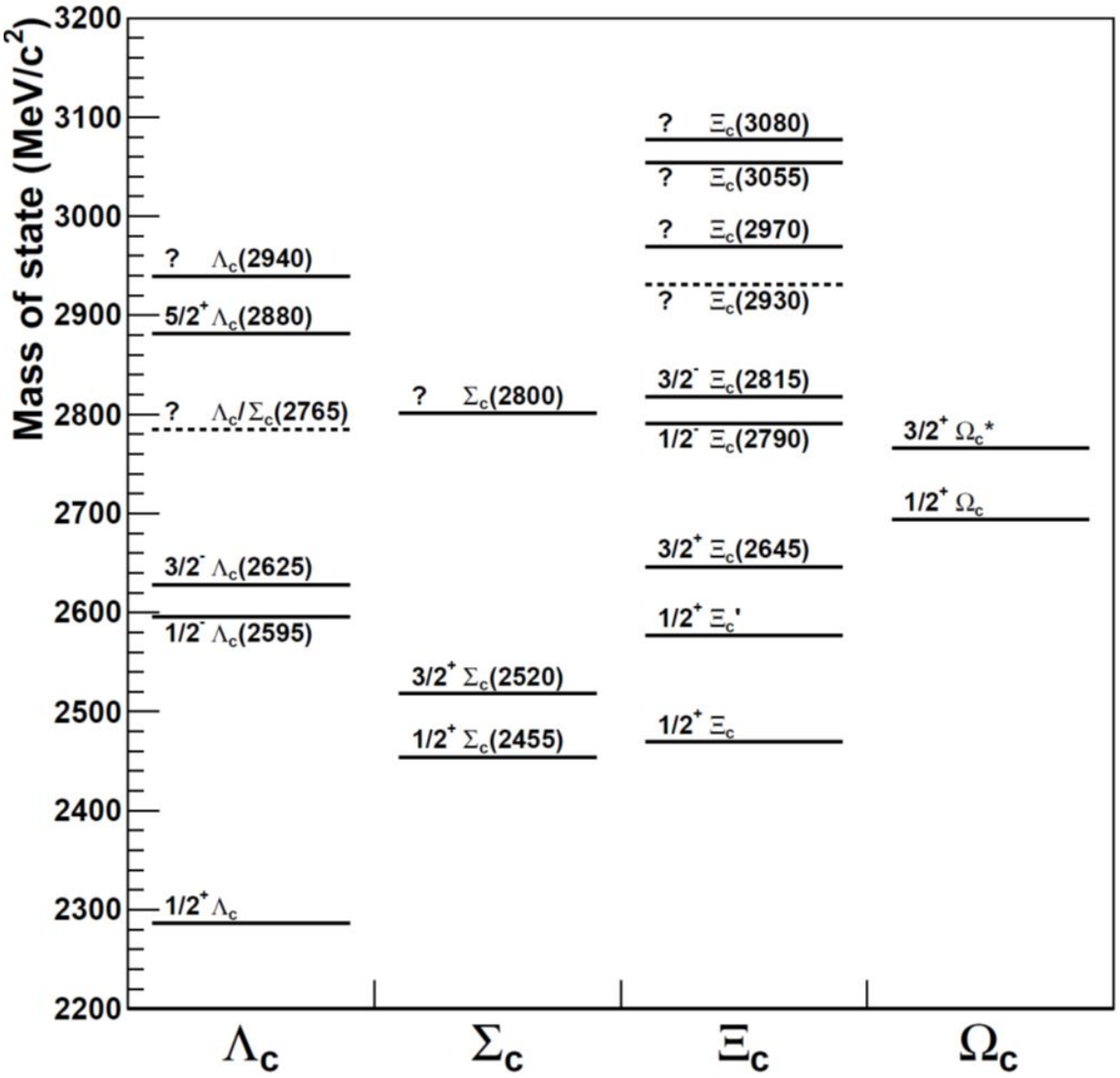
Known Charmed Baryon States



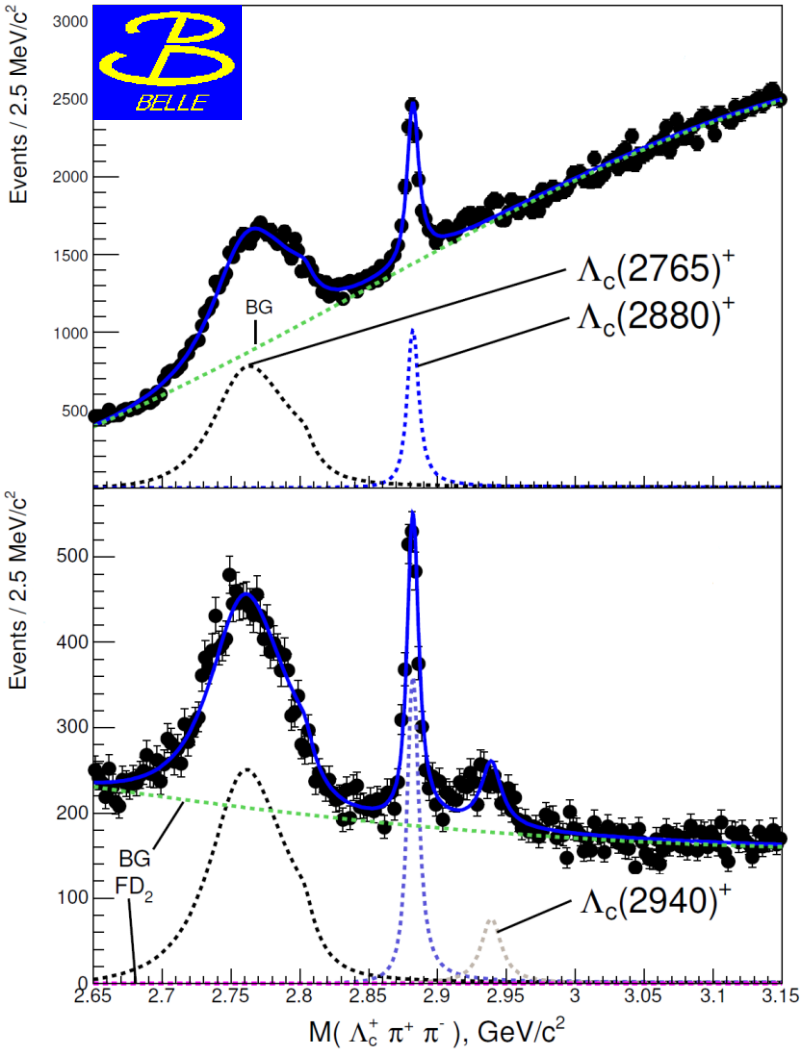
$\mathbb{B}_c = c$ + diquark

Quark content of diquark:

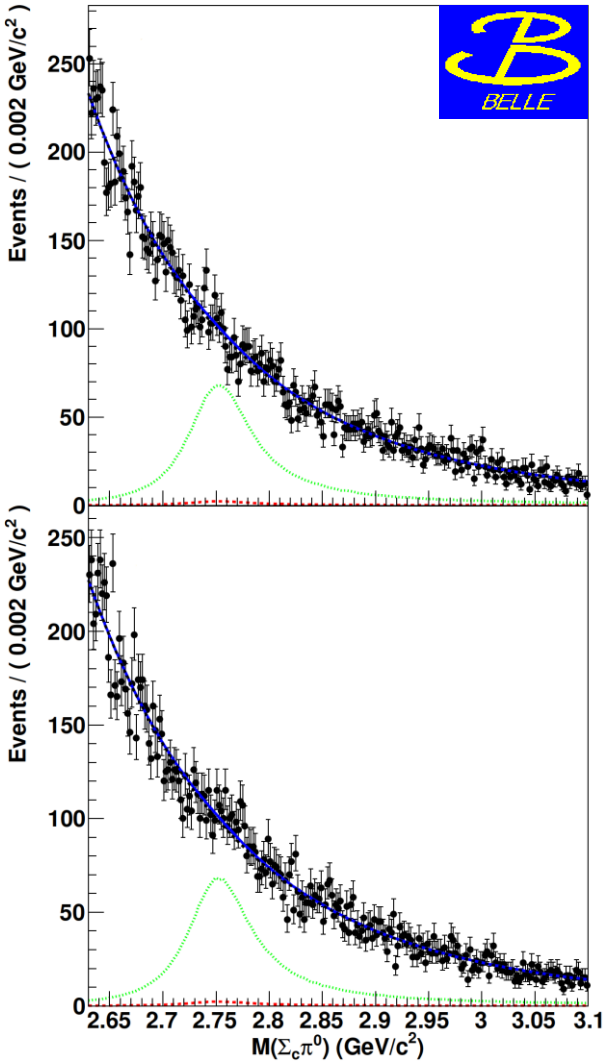
- qq with isospin 0 (flavor antisymmetric) — Λ_c **family**;
- qq with isospin 1 (flavor symmetric) — Σ_c **family**;
- qs with isospin $\frac{1}{2}$ — Ξ_c **family**;
- ss with isospin 0 (flavor symmetric) — Ω_c **family**.

$\Lambda_c(2765)^+$ / $\Sigma_c(2765)^+$

$\Lambda_c(2765)^+ \to \Sigma_c^{++/0}\pi^{-/+} \to \Lambda_c^+\pi^+\pi^-$



$\Sigma_c(2765)^{++/0} \to \Sigma_c^{++/0}\pi^0 \to \Lambda_c^+\pi^{+/-}\pi^0$

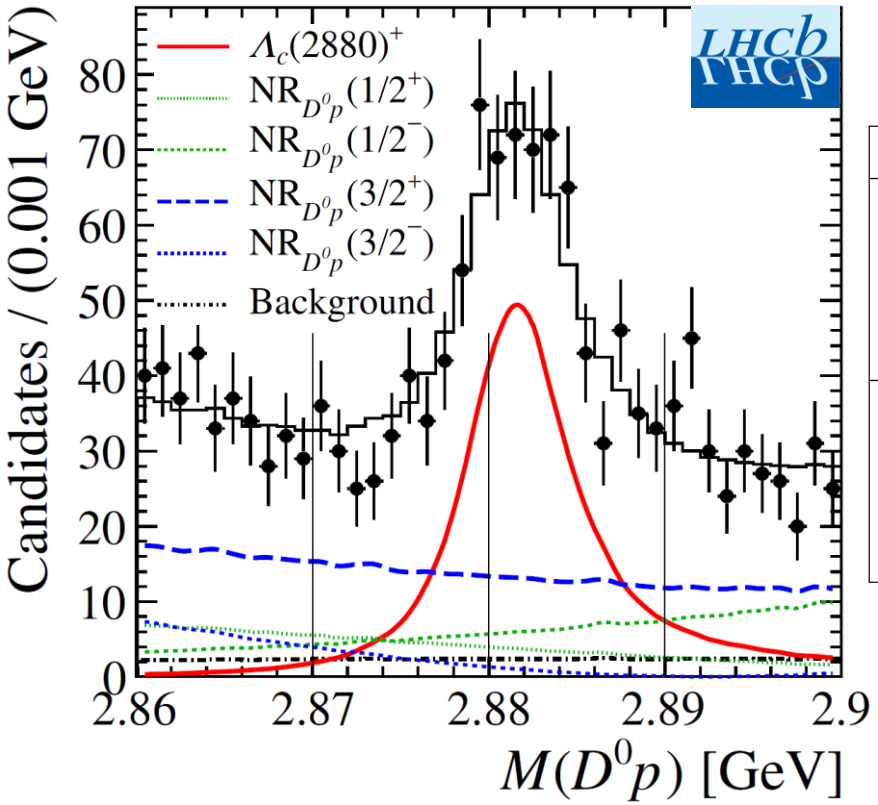


$\Rightarrow I = 0$

[A. Abdesselam *et al.* (Belle Collaboration), arXiv:1908.06235 [hep-ex] (2019)]

$\Lambda_c(2880)^+$

$\Lambda_b^0 \to D^0 p\pi^-$



Nonresonant model	$\Lambda_c(2880)^+$ J^P	$\Delta \ln \mathcal{L}$	χ^2/ndf	$P(\chi^2, \mathrm{ndf})$, %
Exponential	$1/2^+$	41.5	108.9/70	0.2
	$3/2^+$	35.5	99.4/70	1.2
	$5/2^+$	−0.2	65.6/70	62.7
	$7/2^+$	8.4	76.8/70	27.0
Linear	$1/2^+$	40.3	107.4/71	0.3
	$3/2^+$	35.7	98.8/71	1.6
	$5/2^+$	**0.0**	**69.2/71**	**53.8**
	$7/2^+$	8.6	76.2/71	31.5

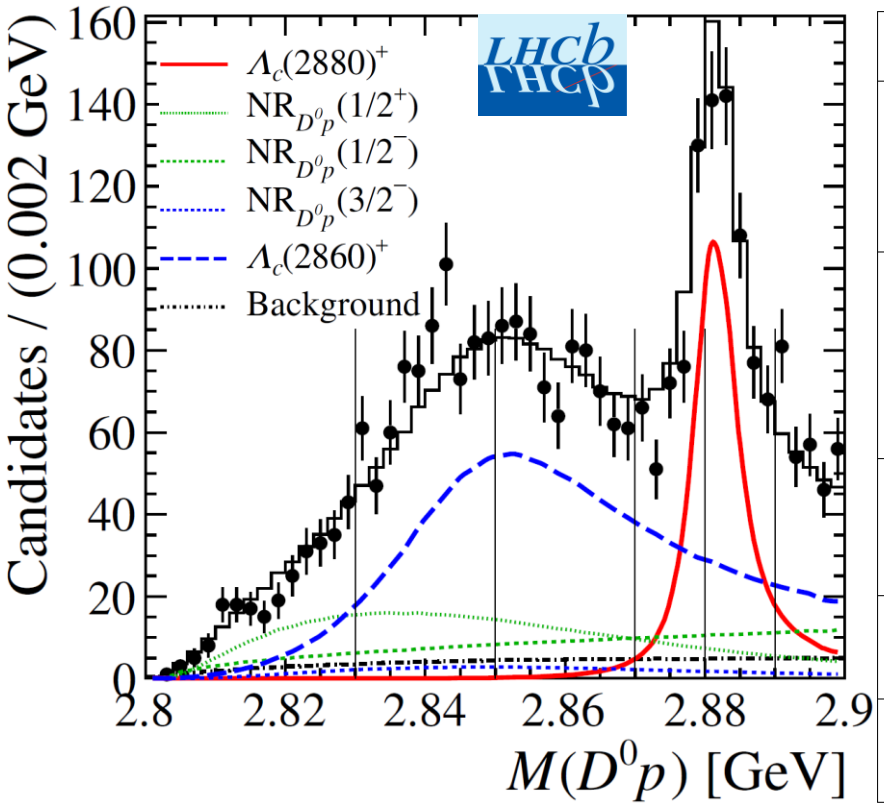
$$m(\Lambda_c(2880)^+) = [2881.75 \pm 0.29\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{syst.})\,^{+0.14}_{-0.20}\,(\mathrm{model})]\ \mathrm{MeV}/c^2$$

$$\Gamma(\Lambda_c(2880)^+) = \left[5.43\,^{+0.77}_{-0.71}\,(\mathrm{stat.}) \pm 0.29\,(\mathrm{syst.})\,^{+0.75}_{-0.00}\,(\mathrm{model})\right]\ \mathrm{MeV}$$

[R. Aaij *et al.* (LHCb Collaboration), J. High Energ. Phys. **2017**, 30 (2017)]

$\Lambda_c(2860)^+$

$\Lambda_b^0 \to D^0 p \pi^-$



Nonresonant model				Resonance				
$1/2^-$	$1/2^+$	$3/2^-$	$3/2^+$	Mass [MeV]	J^P	$\Delta \ln \mathcal{L}$	χ^2/ndf	$P(\chi^2, \mathrm{ndf})$ [%]
Exp	Exp	Exp	Exp	–	–	72.2	287.4/150	0.0
Exp	Exp	Exp	Exp	2765	$1/2^-$	53.6	247.2/146	0.0
Exp	Exp	Exp	Exp	2765	$1/2^+$	52.8	254.8/146	0.0
Exp	Exp	Exp	Exp	2765	$3/2^-$	45.8	240.5/146	0.0
Exp	Exp	Exp	Exp	2765	$3/2^+$	38.5	226.0/146	0.0
Exp	Exp	Exp	Exp	Float	$1/2^-$	8.2	162.7/145	14.9
Exp	Exp	Exp	Exp	Float	$1/2^+$	15.2	170.2/145	7.5
Exp	Exp	Exp	Exp	Float	$3/2^-$	9.3	162.1/145	15.7
Exp	Exp	Exp	Exp	Float	$3/2^+$	−3.3	139.5/145	61.3
Exp	Exp	–	–	Float	$3/2^+$	12.8	169.7/153	16.9
Exp	**Exp**	**Exp**	**–**	**Float**	**$3/2^+$**	**0.0**	**143.1/149**	**62.1**
CSpl	Exp	Exp	Exp	–	–	16.1	181.3/140	1.1
Exp	CSpl	Exp	Exp	–	–	2.0	154.8/140	18.5
Exp	Exp	CSpl	Exp	–	–	16.6	172.9/140	3.1
Exp	Exp	Exp	CSpl	–	–	−0.4	146.6/140	33.4
Exp	Exp	CSpl	–	–	–	63.1	234.8/143	0.0
Exp	Exp	–	CSpl	–	–	10.8	165.7/143	9.4
Exp	Exp	CSpl	CSpl	–	–	−4.7	146.1/130	15.8
Exp	Exp	RSpl	Exp	–	–	17.4	177.0/143	2.8
Exp	Exp	Exp	RSpl	–	–	15.4	174.5/143	3.8
Exp	Exp	RSpl	RSpl	–	–	−0.4	145.1/138	32.3

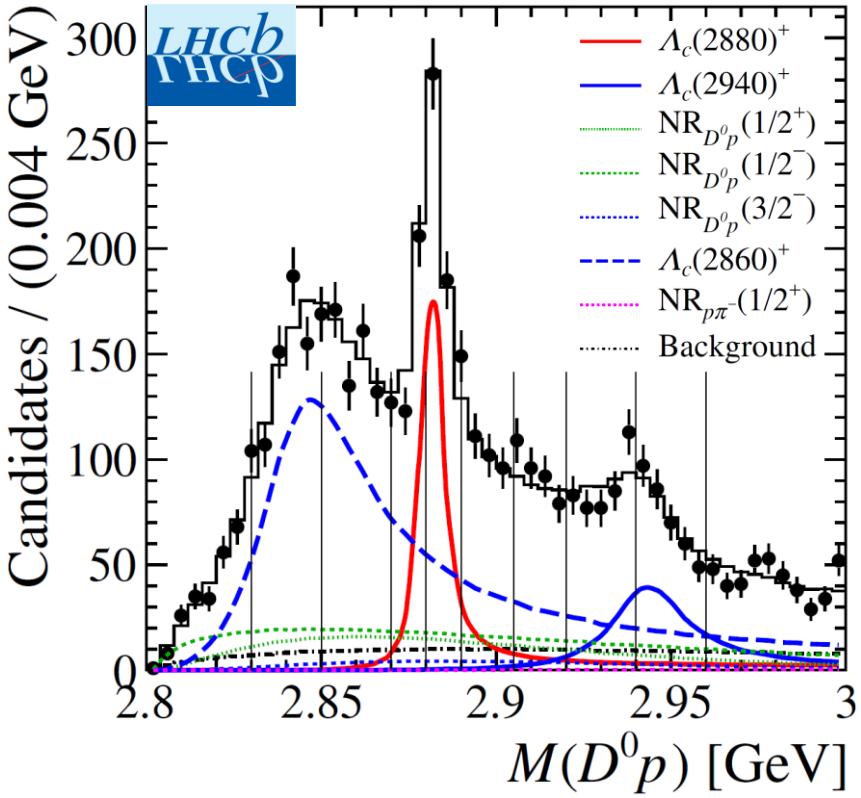
$$m(\Lambda_c(2860)^+) = \left[2856.1\ ^{+2.0}_{-1.7}\ (\mathrm{stat.}) \pm 0.5\ (\mathrm{syst.})\ ^{+1.1}_{-5.6}\ (\mathrm{model})\right]\ \mathrm{MeV}/c^2$$

$$\Gamma(\Lambda_c(2860)^+) = \left[67.6\ ^{+10.1}_{-8.1}\ (\mathrm{stat.}) \pm 1.4\ (\mathrm{syst.})\ ^{+5.9}_{-20.0}\ (\mathrm{model})\right]\ \mathrm{MeV}$$

[R. Aaij *et al.* (LHCb Collaboration), J. High Energ. Phys. **2017**, 30 (2017)]

$\Lambda_c(2940)^+$

$\Lambda_b^0 \to D^0 p\pi^-$



Nonresonant model	$\Lambda_c(2940)^+$ J^P	$\Delta \ln \mathcal{L}$	χ^2/ndf	$P(\chi^2, \mathrm{ndf})$ [%]
Exponential	No $\Lambda_c^+(2940)$	54.6	337.3/230	0.0
	$1/2^-$	25.5	293.1/228	0.2
	$1/2^+$	34.2	306.4/228	0.0
	$3/2^-$	**0.0**	**246.9/228**	**18.6**
	$3/2^+$	14.8	269.1/228	3.2
	$5/2^-$	14.5	269.9/228	3.0
	$5/2^+$	15.6	271.7/228	2.5
	$7/2^-$	23.0	276.4/228	1.6
	$7/2^+$	29.0	300.2/228	0.1
Polynomial	No $\Lambda_c^+(2940)$	25.5	296.0/228	0.2
	$1/2^-$	8.9	270.0/226	2.4
	$1/2^+$	7.2	266.1/226	3.5
	$3/2^-$	−4.2	238.0/226	27.9
	$3/2^+$	4.9	253.4/226	10.2
	$5/2^-$	−0.6	249.0/226	14.0
	$5/2^+$	4.9	250.5/226	12.6
	$7/2^-$	10.6	270.0/226	2.4
	$7/2^+$	11.7	273.0/226	1.8

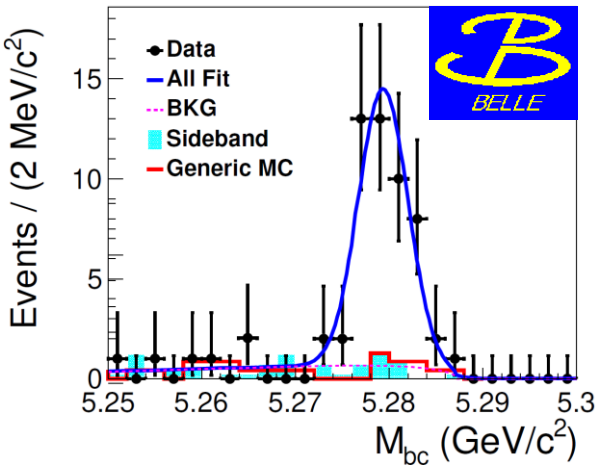
$$m(\Lambda_c(2940)^+) = \left[2944.8\ ^{+3.5}_{-2.5}\ (\mathrm{stat.}) \pm 0.4\ (\mathrm{syst.})\ ^{+0.1}_{-4.6}\ (\mathrm{model})\right]\ \mathrm{MeV}/c^2$$

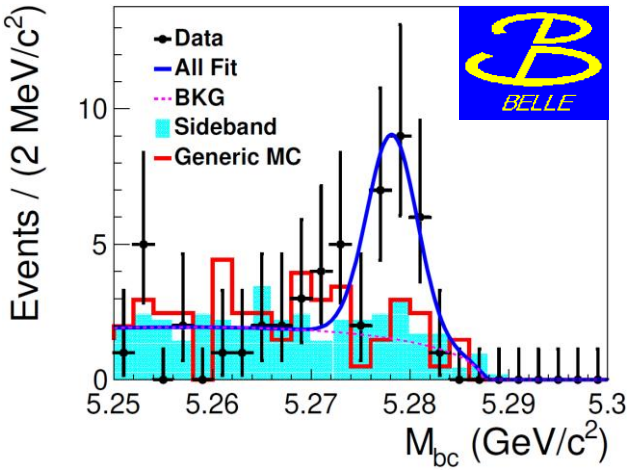
$$\Gamma(\Lambda_c(2940)^+) = \left[27.7\ ^{+8.2}_{-6.0}\ (\mathrm{stat.}) \pm 0.9\ (\mathrm{syst.})\ ^{+5.2}_{-10.4}\ (\mathrm{model})\right]\ \mathrm{MeV}$$

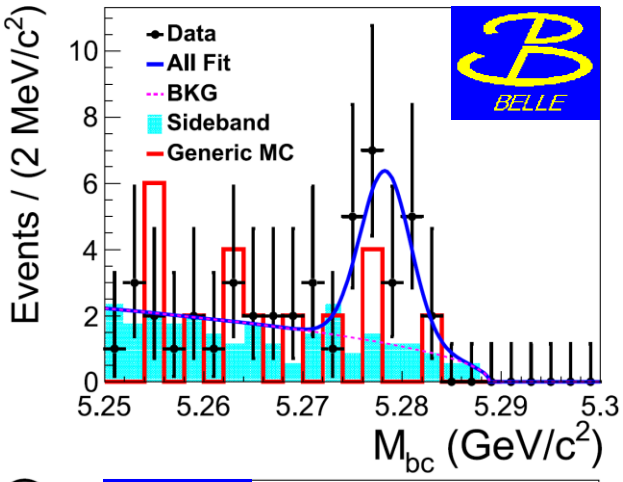
[R. Aaij *et al.* (LHCb Collaboration), J. High Energ. Phys. **2017**, 30 (2017)]

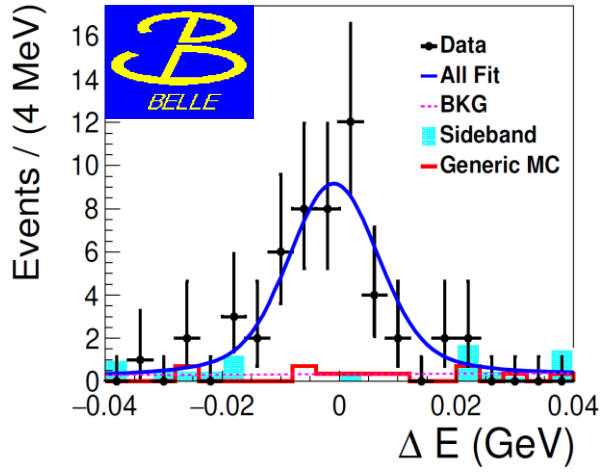
Ξ_c Branching Fraction

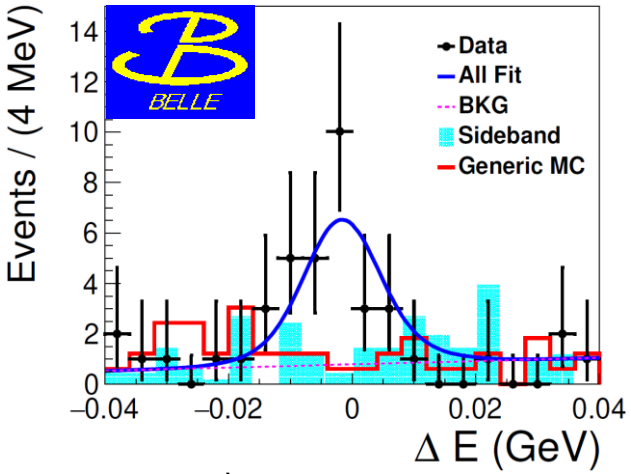
$B^- \to \Xi_c^0 \overline{\Lambda_c}^-$

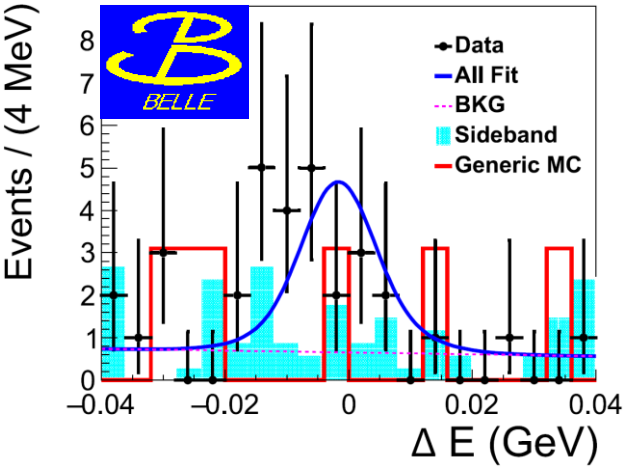












$\Xi^-\pi^+$: $(1.80 \pm 0.50 \pm 0.14)$ %

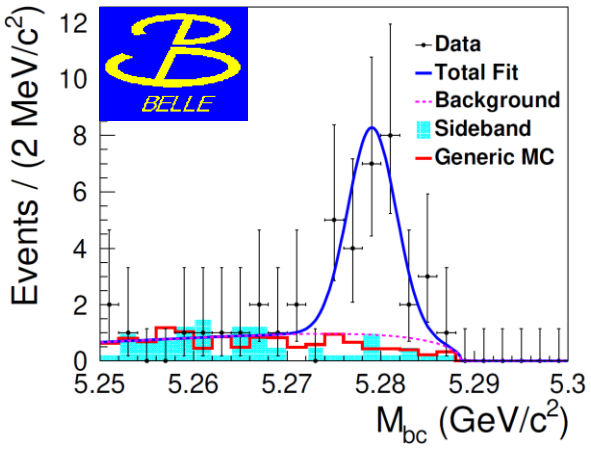
$\Lambda K^-\pi^+$: $(1.17 \pm 0.37 \pm 0.09)$%

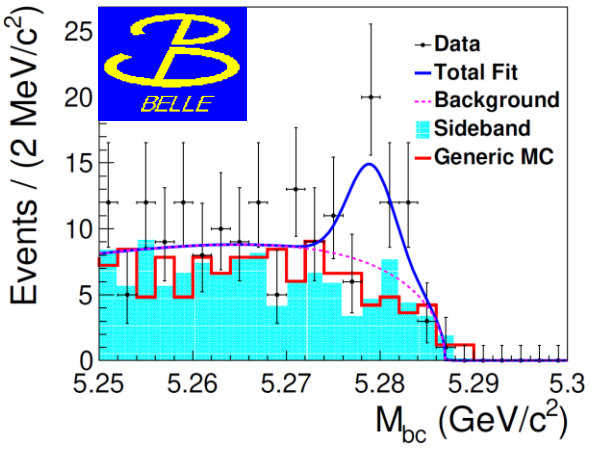
$pK^-K^-\pi^+$: $(0.58 \pm 0.23 \pm 0.05)$%

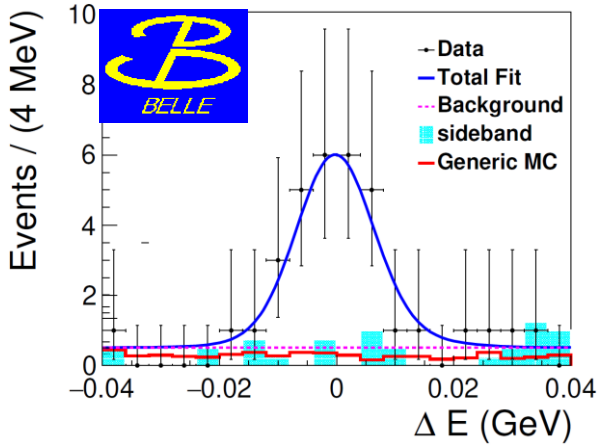
[Y.B. Li, C.P. Shen *et al.* (Belle Collaboration), Phys. Rev. Lett. **122**, 082001 (2019)]

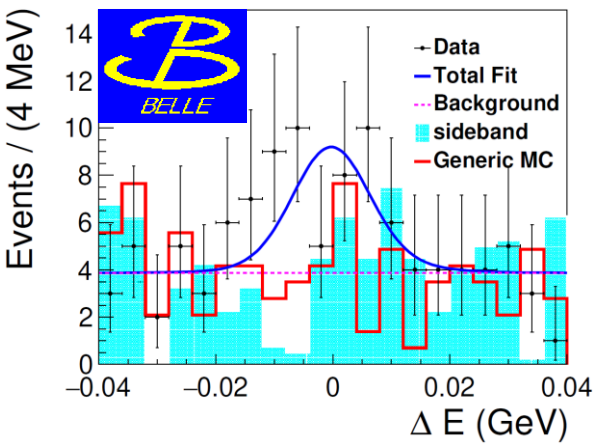
Ξ_c Branching Fraction

$B^0 \to \Xi_c^+ \overline{\Lambda_c}^-$









$\Xi^-\pi^+\pi^+$: $(2.86 \pm 1.21 \pm 0.38)\%$

$pK^-\pi^+$: $(0.45 \pm 0.21 \pm 0.09)\%$

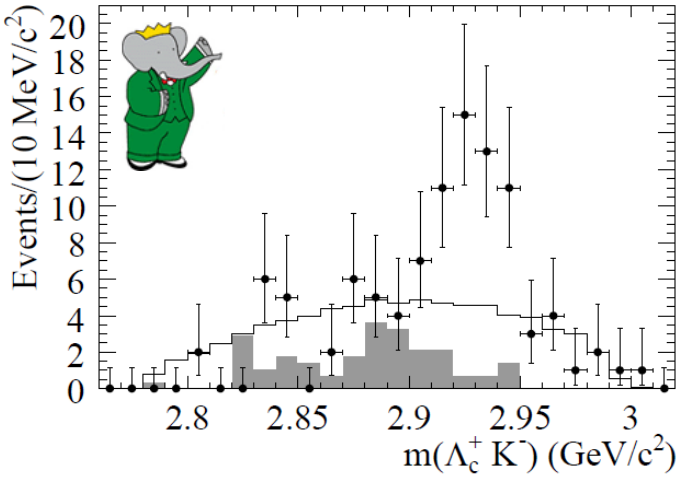
[Y.B. Li, C.P. Shen *et al.* (Belle Collaboration), Phys. Rev. D **100**, 031101(R) (2019)]

$\Xi_c(2930)^0$

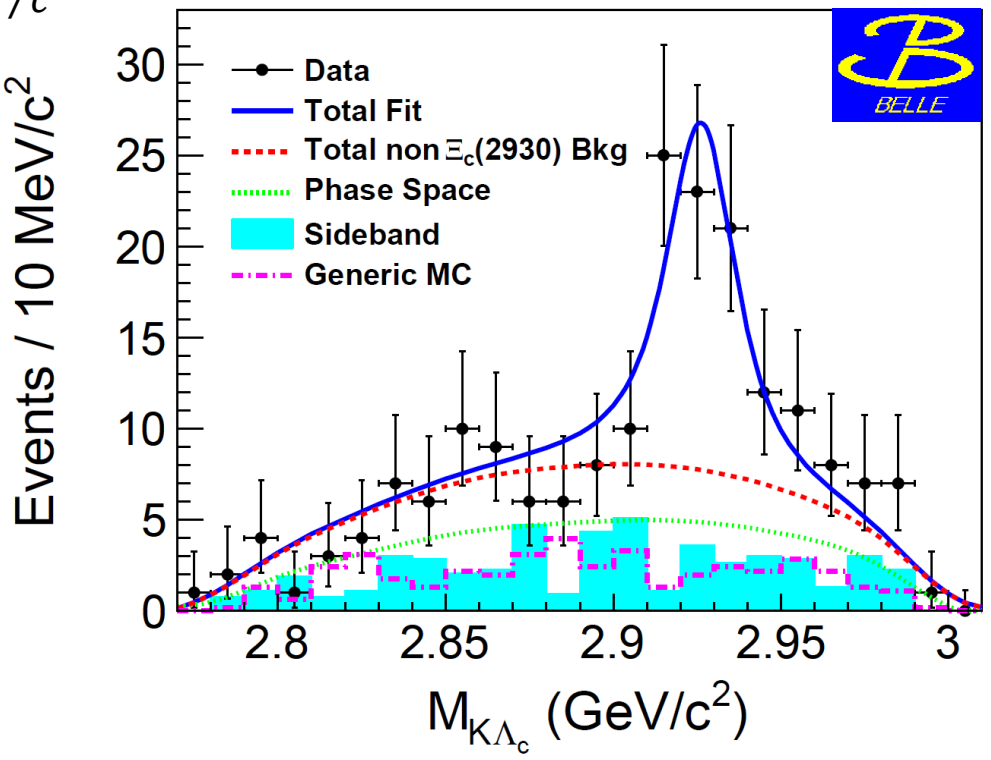
$$B^- \to \Lambda_c^+ \overline{\Lambda_c}^- K^-$$

$m_{\Xi_c(2930)^0} = (2931 \pm 3\,[stat.] \pm 5\,[syst.])\ MeV/c^2$

$\Gamma_{\Xi_c(2930)^0} = (36 \pm 7\,[stat.] \pm 11\,[syst.])\ MeV$



[B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. D **77**, 031101 (2008)]



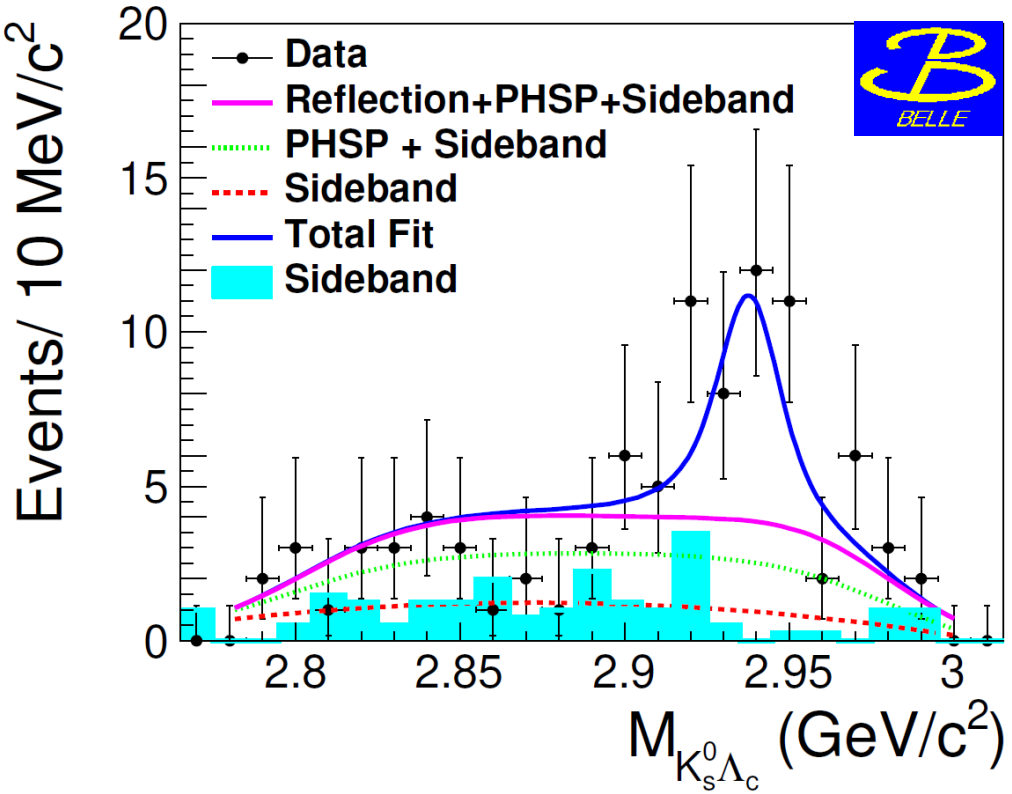
$m_{\Xi_c(2930)^0} = (2928.9 \pm 3.0\,[\text{stat.}]^{+0.9}_{-12.0}\,[\text{syst.}])\ \text{MeV}/c^2$

$\Gamma_{\Xi_c(2930)^0} = \left(19.5 \pm 8.4\,[\text{stat.}]^{+5.9}_{-7.9}\,[\text{syst.}]\right)\ \text{MeV}$

[Y.B. Li, C.P. Shen *et al.* (Belle Collaboration), Eur. Phys. J. C **78**, 252 (2018)]

$\Xi_c(2930)^+$

$B^0 \to \Lambda_c^+ \overline{\Lambda_c}^- K_S^0$



$m_{\Xi_c(2930)^+} = (2942.3 \pm 4.4\,[\text{stat.}] \pm 1.5\,[\text{syst.}])\ \text{MeV}/c^2$

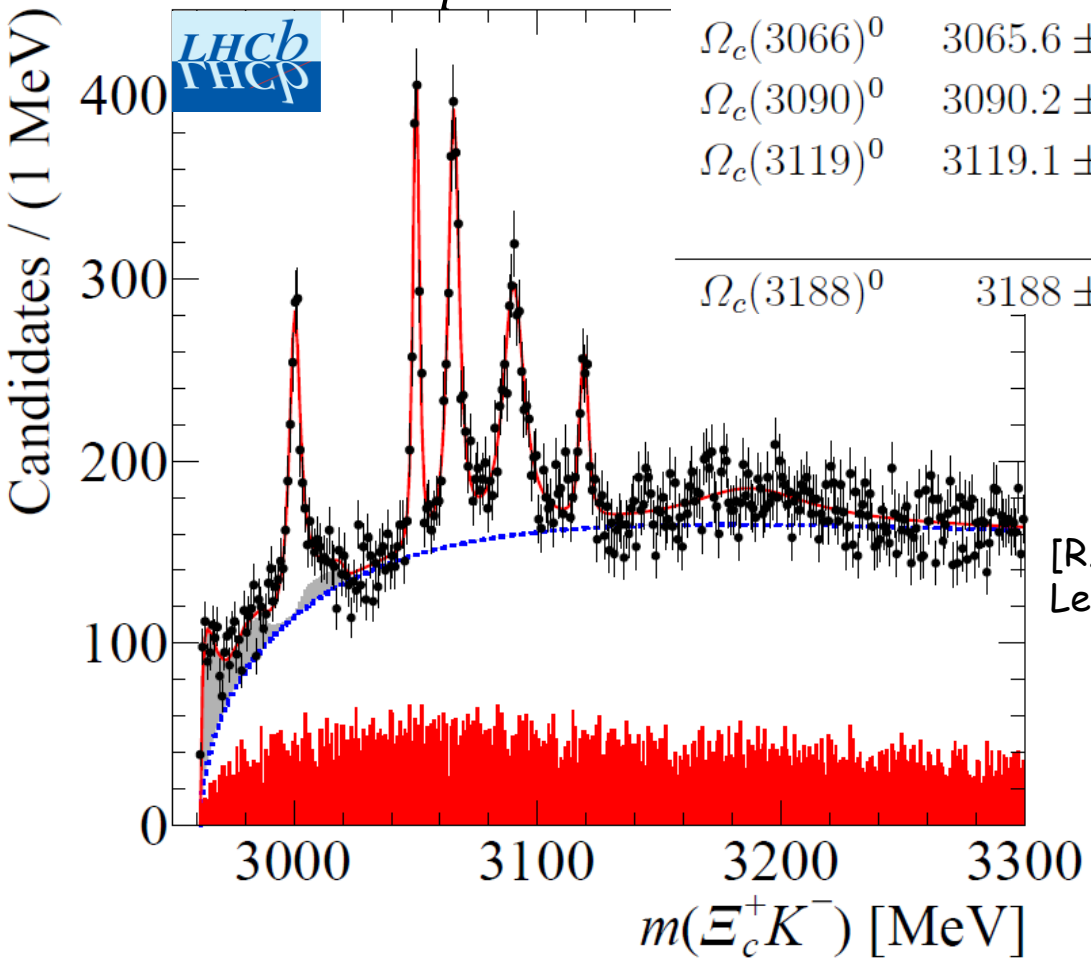
$\Gamma_{\Xi_c(2930)^+} = (14.8 \pm 8.8\,[\text{stat.}] \pm 2.5\,[\text{syst.}])\ \text{MeV}$

$\Delta m_{\Xi_c(2930)} = (-13.4 \pm 5.3\,[\text{stat.}]\ ^{+1.7}_{-12.1}\,[\text{syst.}])\ \text{MeV}/c^2$

[Y.B. Li, C.P. Shen *et al.* (Belle Collaboration), Eur. Phys. J. C **78**, 928 (2018)]

Ω_c Family

$$\Omega_c(X)^0 \to \Xi_c^+ K^-$$
$$\downarrow$$
$$pK^-\pi^+$$



Resonance	Mass (MeV)	Γ (MeV)	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	20.4
		$< 1.2\,\text{MeV}, 95\%$ CL	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	10.4
		$< 2.6\,\text{MeV}, 95\%$ CL	
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	

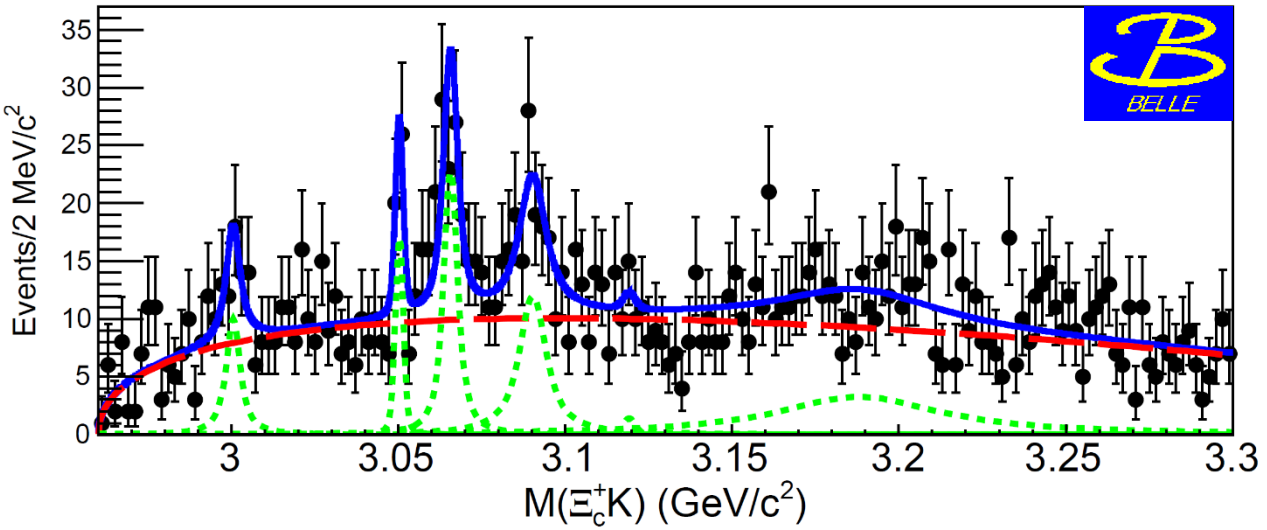
[R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **118**, 182001 (2017)]

Ω_c Family

$$\Omega_c(X)^0 \to \Xi_c^+ K^-$$

$$\downarrow$$

$$\Xi^-\pi^+\pi^+, \Lambda K^-\pi^+\pi^+, \Xi^0\pi^+, \Xi^0\pi^+\pi^-\pi^+, \Sigma^+K^-\pi^+, \Lambda K_S^0\pi^+, \Sigma^0 K_S^0\pi^+$$

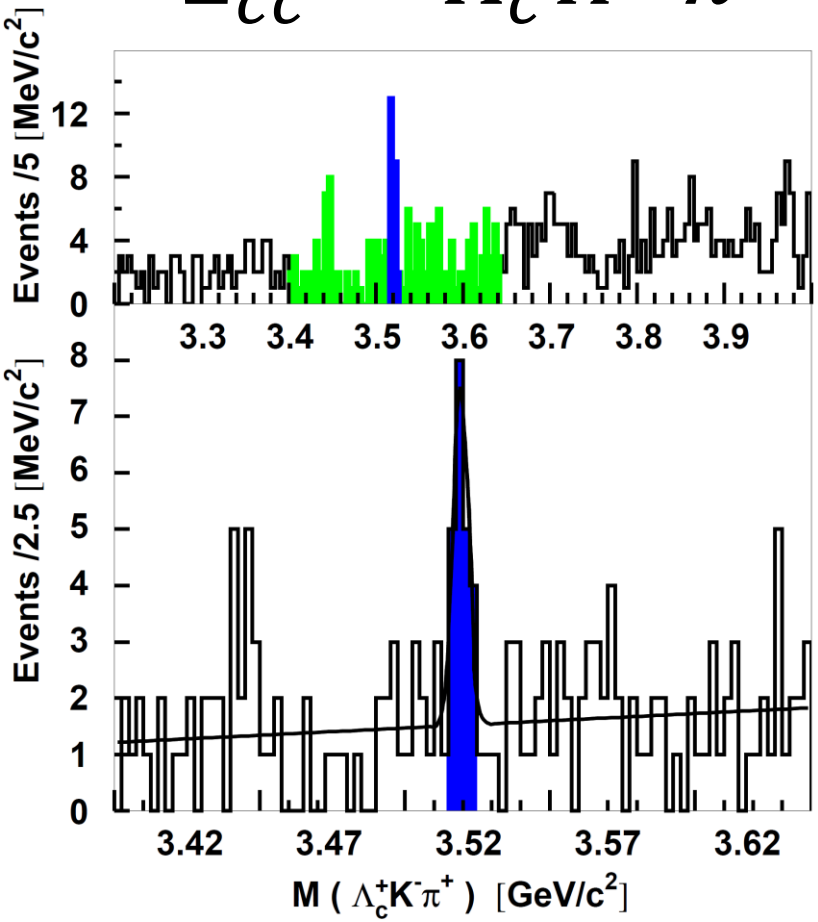


Ω_c Excited state	3000	3050	3066	3090	3119	3188
Yield	37.7 ± 11.0	28.2 ± 7.7	81.7 ± 13.9	86.6 ± 17.4	3.6 ± 6.9	135.2 ± 43.0
Significance	3.9σ	4.6σ	7.2σ	5.7σ	0.4σ	2.4σ
LHCb mass	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119 \pm 0.3 \pm 0.9$	$3188 \pm 5 \pm 13$
Belle mass (with fixed Γ)	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	$\cdots$	$3199 \pm 9 \pm 4$

[J. Yelton *et al.* (Belle Collaboration), Phys. Rev. D **97**, 051102 (2018)]

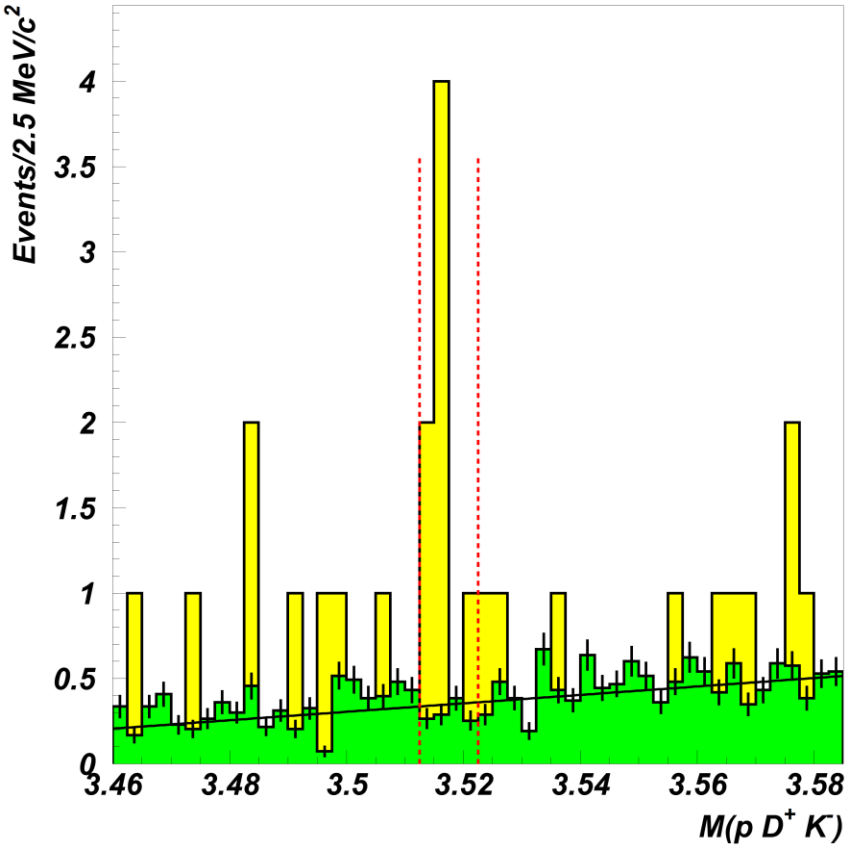
Ξ_{cc}

$$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$$



[M. Mattson *et al.* (SELEX Collaboration), Phys. Rev. Lett. **89**, 112001 (2002)]

$$\Xi_{cc}^{+} \to D^{+} p K^{-}$$

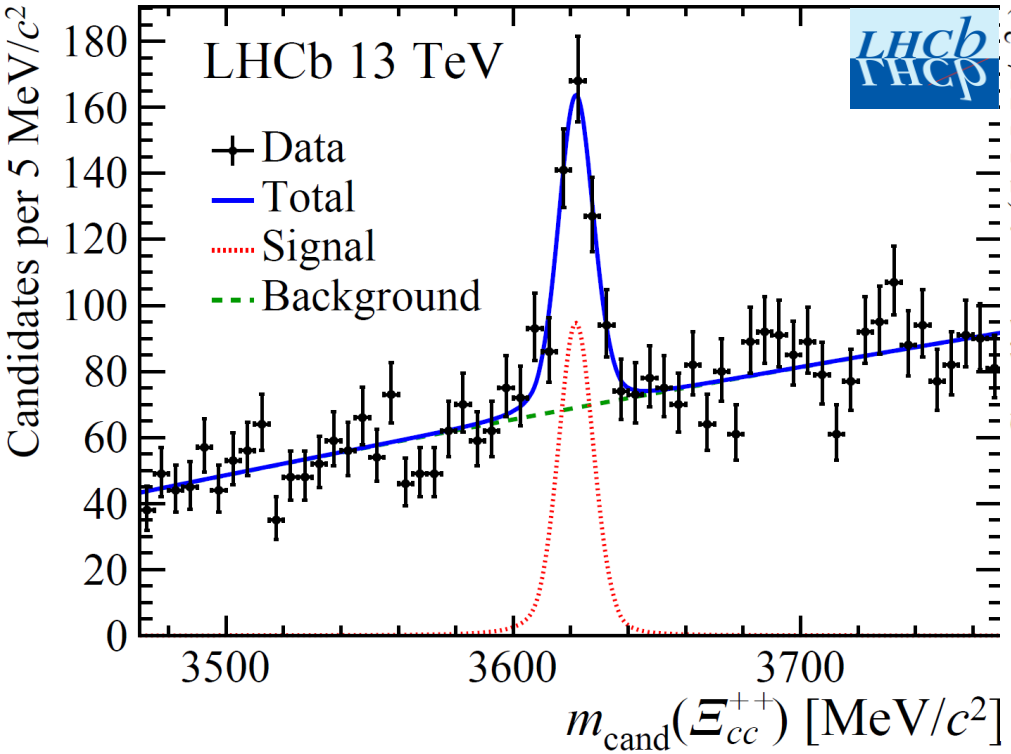


[A. Ocherashvili *et al.* (SELEX Collaboration), Phys. Lett. B **628**, 18 (2005)]

$$m_{\Xi_{cc}^{+}} = (3518.7 \pm 1.7)\ MeV/c^2$$

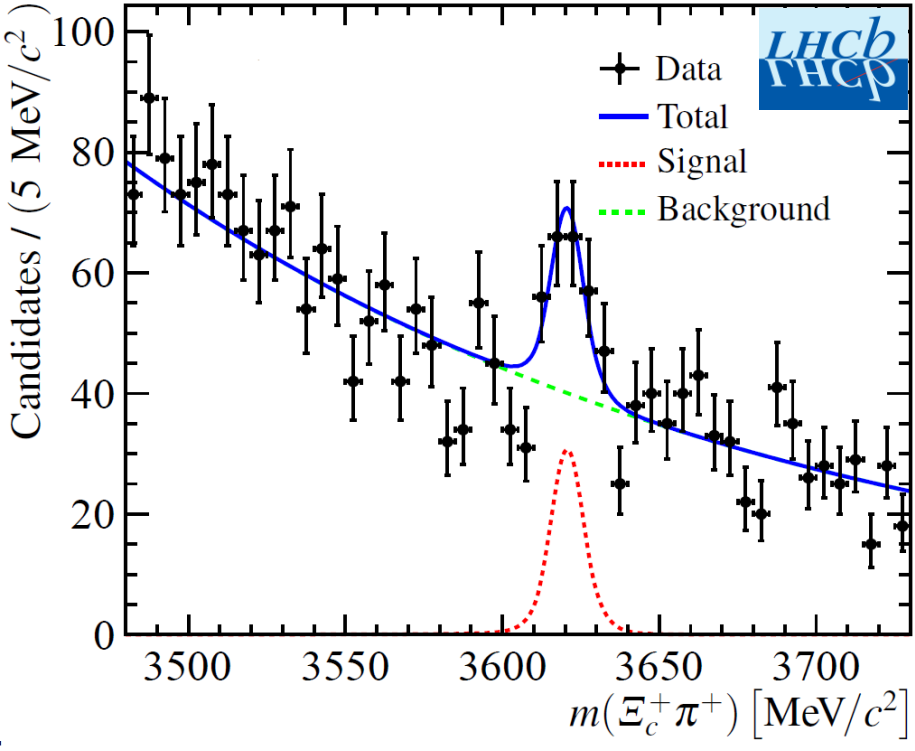
Ξ_{cc}

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$



[R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **119**, 112001 (2017)]

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

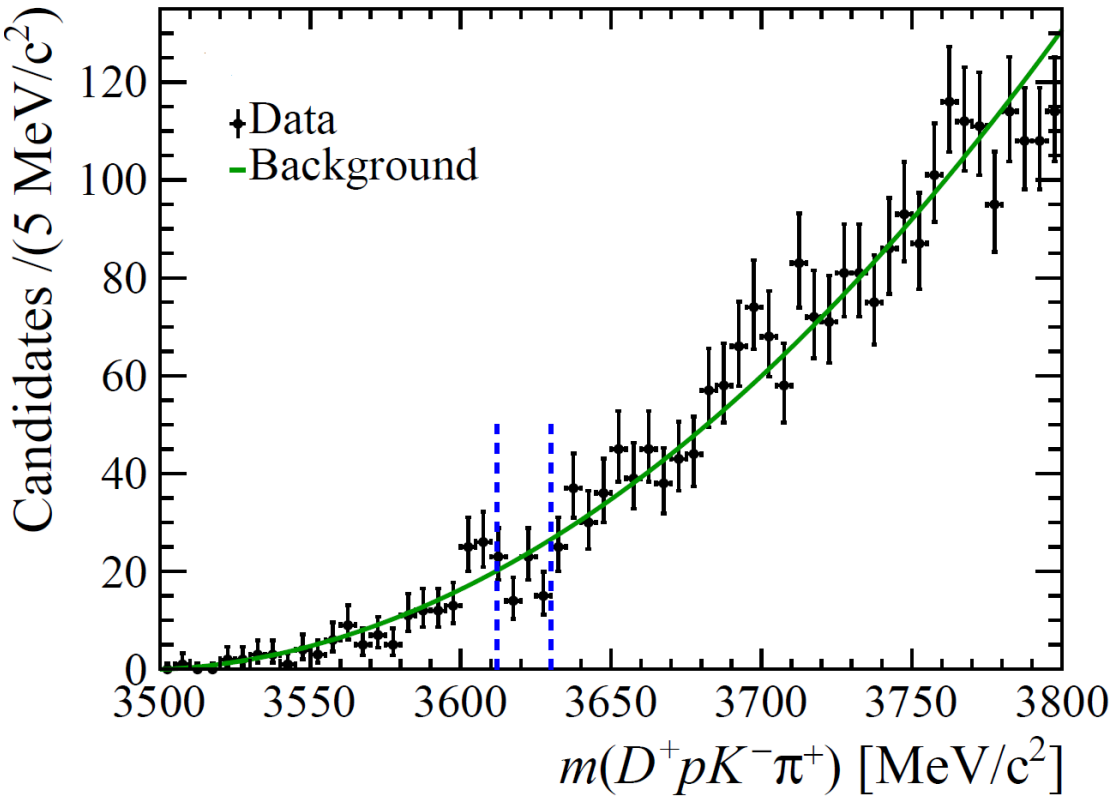


[R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **121**, 162002 (2018)]

$$m_{\Xi_{cc}^{++}} = (3621.24 \pm 0.65\,[\text{stat.}] \pm 0.31\,[\text{syst.}])\ \text{MeV}/c^2$$

$$m_{\Xi_{cc}^{++}} - m_{\Xi_{cc}^{+}} = (103 \pm 2)\ \text{MeV}/c^2$$

$\Xi_{cc}^{++} \to D^+ p K^- \pi^+$



$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} < 1.7 \times 10^{-2}$$

[R. Aaij *et al.* (LHCb Collaboration), arXiv:1905.02421 [hep-ex] (2019)]

Conclusions

- The $\Lambda_c(2765)^+$ / $\Sigma_c(2765)^+$ puzzle seems to be solved.
- First constraints on the spin and parity of the $\Lambda_c(2940)^+$ state are obtained.
- First measurements of the absolute branching fractions for the ground Ξ_c states is of both practical and theoretical interest.
- Recently observed excited Ω_c states present a unique opportunity to test and further improve theoretical models, that predict properties of heavy hadrons.
- The Ξ_{cc} state reported by LHCb is consistent with most theoretical expectations, but it is inconsistent with being an isospin partner to the Ξ_{cc} state reported previously by the SELEX Collaboration.