Study of the $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay at LHCb

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On behalf of the LHCb-China Group

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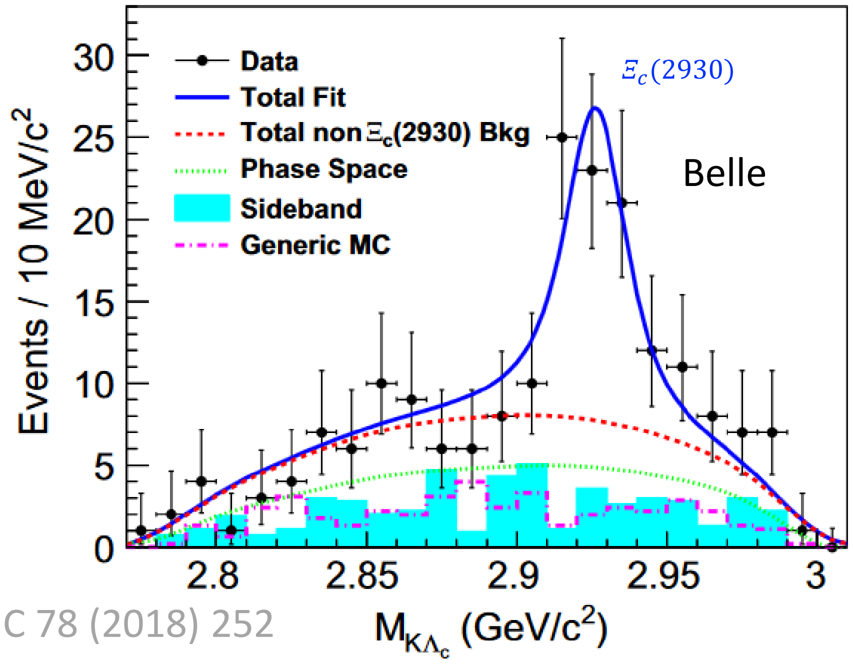
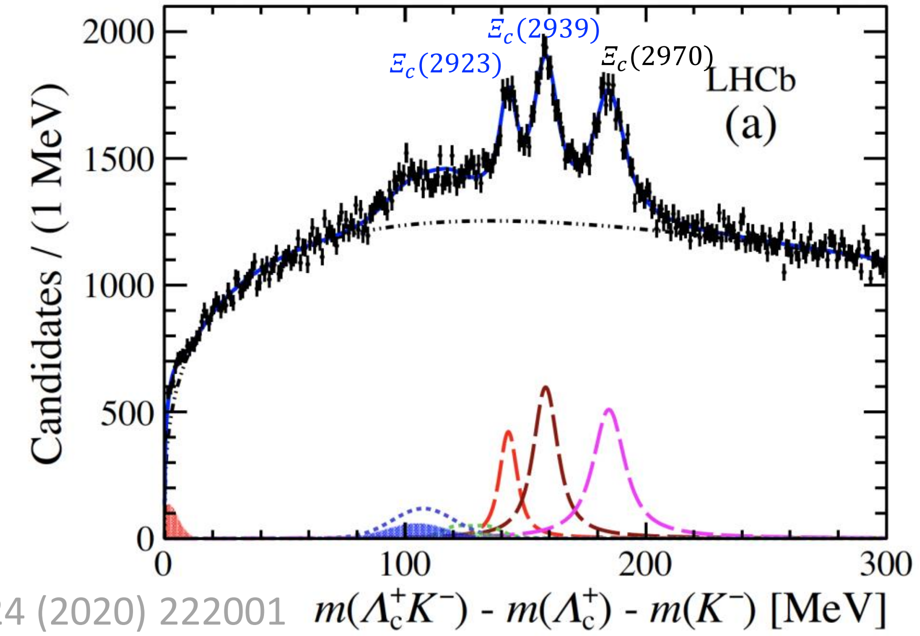
Motivation of $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ study

- Search for excited Ξ_c states in $\Lambda_c^+ K^-$ system
  - *BaBar found evidence of $\Xi_c(2930)^0$ in $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$, confirmed by Belle*
  - *LHCb observed three excited Ξ_c in prompt $\Lambda_c^+ K^-$ system, and a lower bump near 2880 MeV can not be concluded as a structure due to the possible feed-down from $\Xi_c(3055)^0$ and $\Xi_c(3080)^0$*
  - *Study of $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ with higher statistics and better mass resolution will allow separation neighbouring resonances and confirmation of less-prominent states*



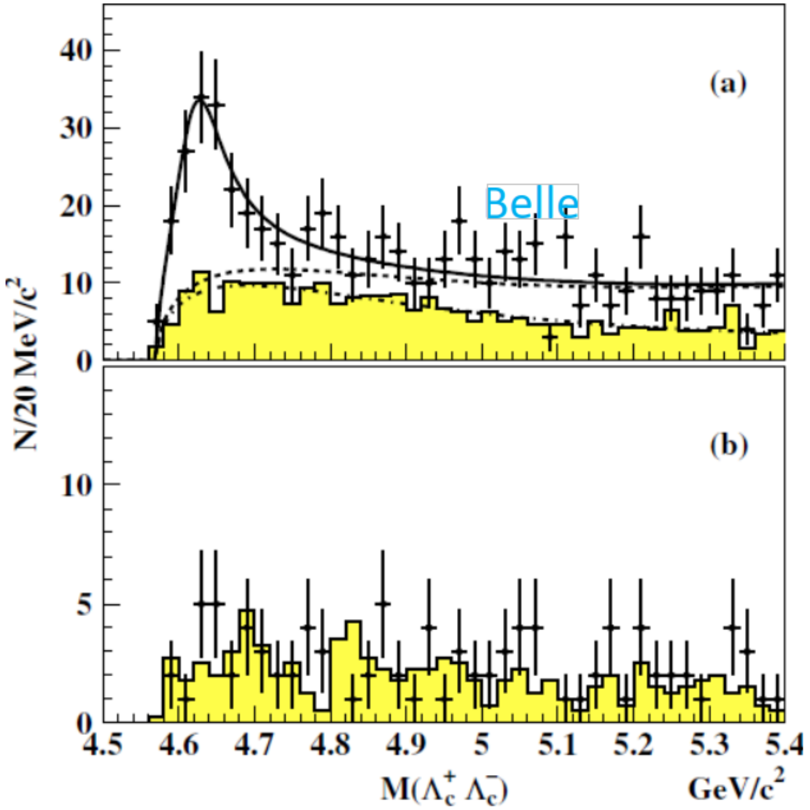
EPJC 78 (2018) 252



PRL 124 (2020) 222001

Motivation of $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ study

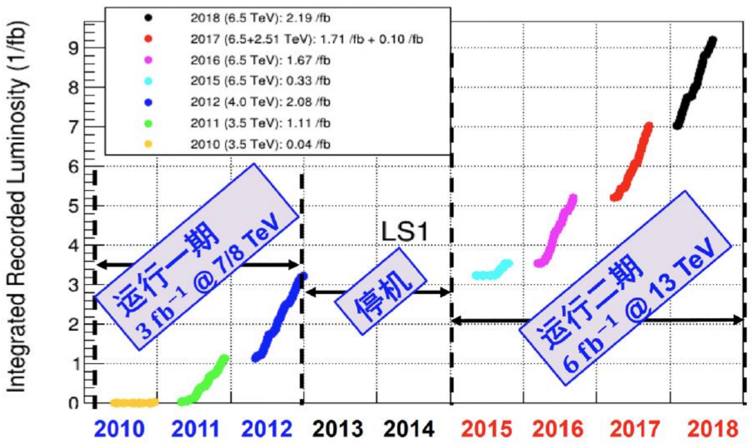
- Search for structures in $\Lambda_c^+ \bar{\Lambda}_c^-$ system
  - *Unconventional state $X(1835)$ is found at $p\bar{p}$ threshold, indicating the possibility of such a state near $\Lambda_c^+ \bar{\Lambda}_c^-$ threshold*
  - *Belle observe such an candidate around 4630 MeV in the $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$ process*
- Search for exotic state in $\Lambda_c^+ K^+$ system
  - *No conventional state expected*

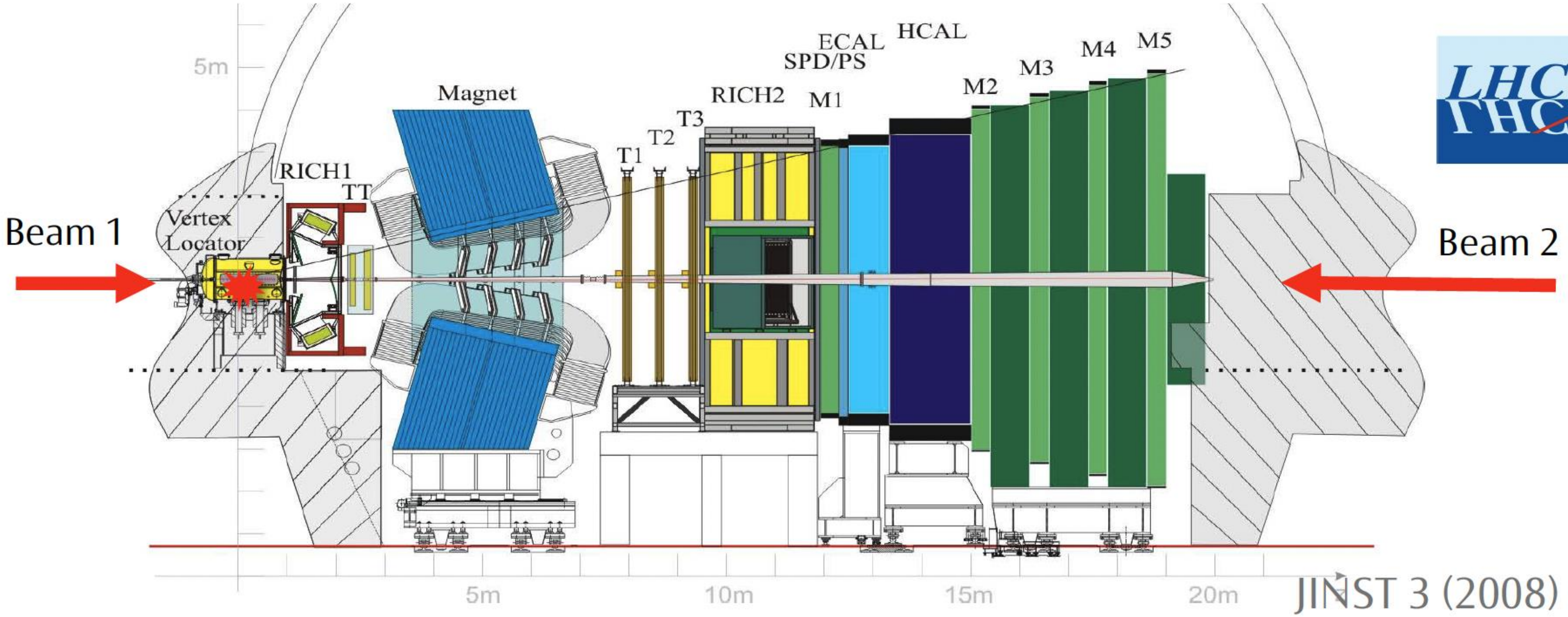


PRL 101, 172001

LHCb experiment

- Single-armed forward detector at the LHC
- Dedicated to heavy flavour study
- Excellent momentum resolution and particle identification





JINST 3 (2008) S08005

Int. J. Mod. Phys. A 30 (2015) 1530022

Study of $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ at LHCb

- $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ is studied for first time in pp collisions
  - *Using data collected at LHCb from 2016-2018,* $\mathcal{L} = 5\ fb^{-1}$
  - $\Lambda_c^+ \to pK^-\pi^+$
- Search for resonance structures
  - *Excited* Ξ_c *states in* $\Lambda_c^+ K^-$ *system*
  - *Exotic states in* $\Lambda_c^+ \bar{\Lambda}_c^-$ *or* $\bar{\Lambda}_c^- K^-$
- Measure relative fraction:
  - $R_{\mathcal{B}} = \frac{\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-)}{\mathcal{B}(B^- \to D^- D^+ K^-)}$
  - $D^+ \to K^-\pi^+\pi^+$

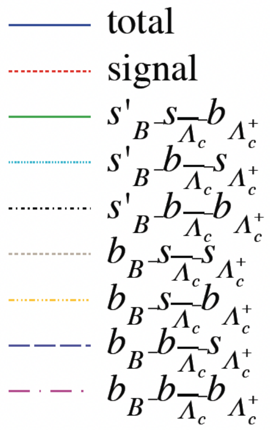
New

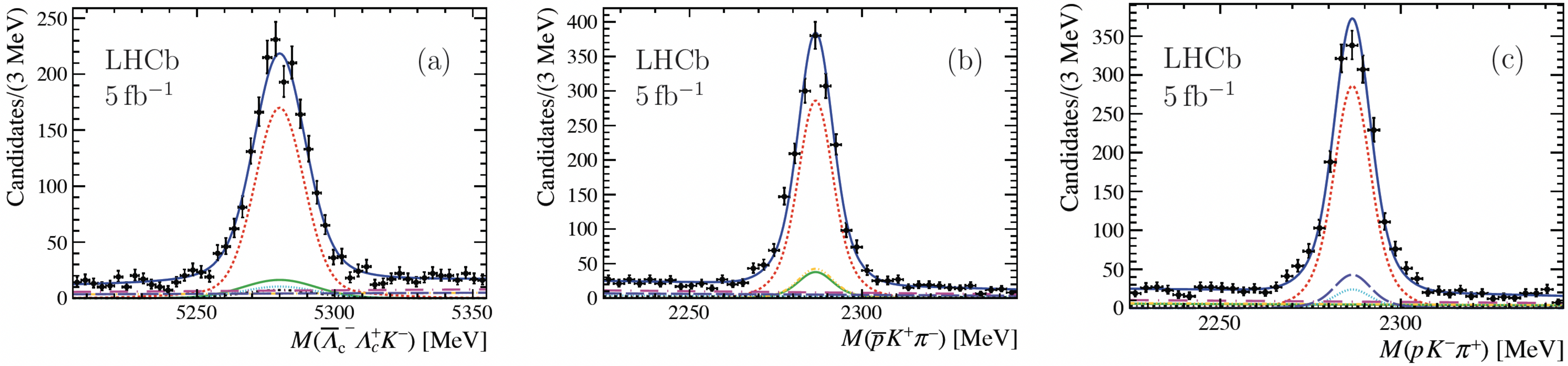
LHCb-PAPER-2022-028
Under preparation

*Charge conjugation is implied throughout the talk

Signal extraction

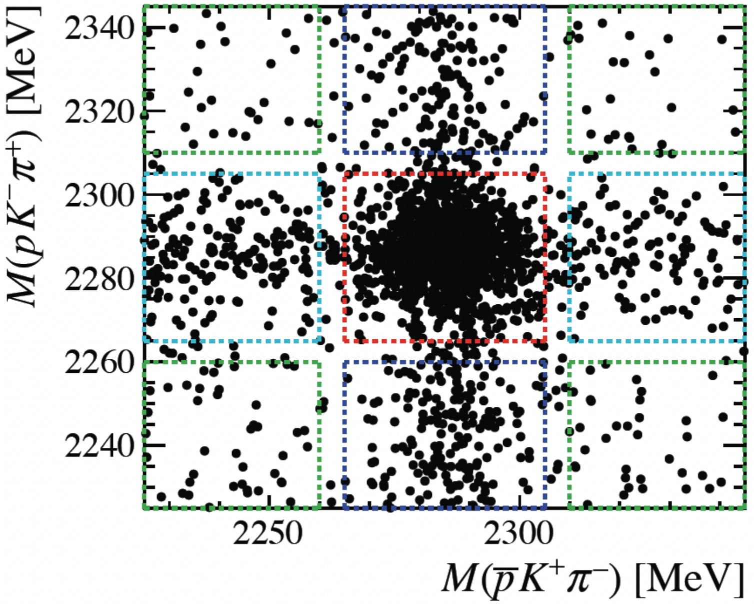
- The B^- Signal is selected using a loose preselection, followed by a BDT, optimized using MC simulation
- Signal is extracted by a 3D fit the the B^-, $\bar{\Lambda}_c^-$ and Λ_c^+ invariant masses
  - *Signal yield: 1365 +/- 42*





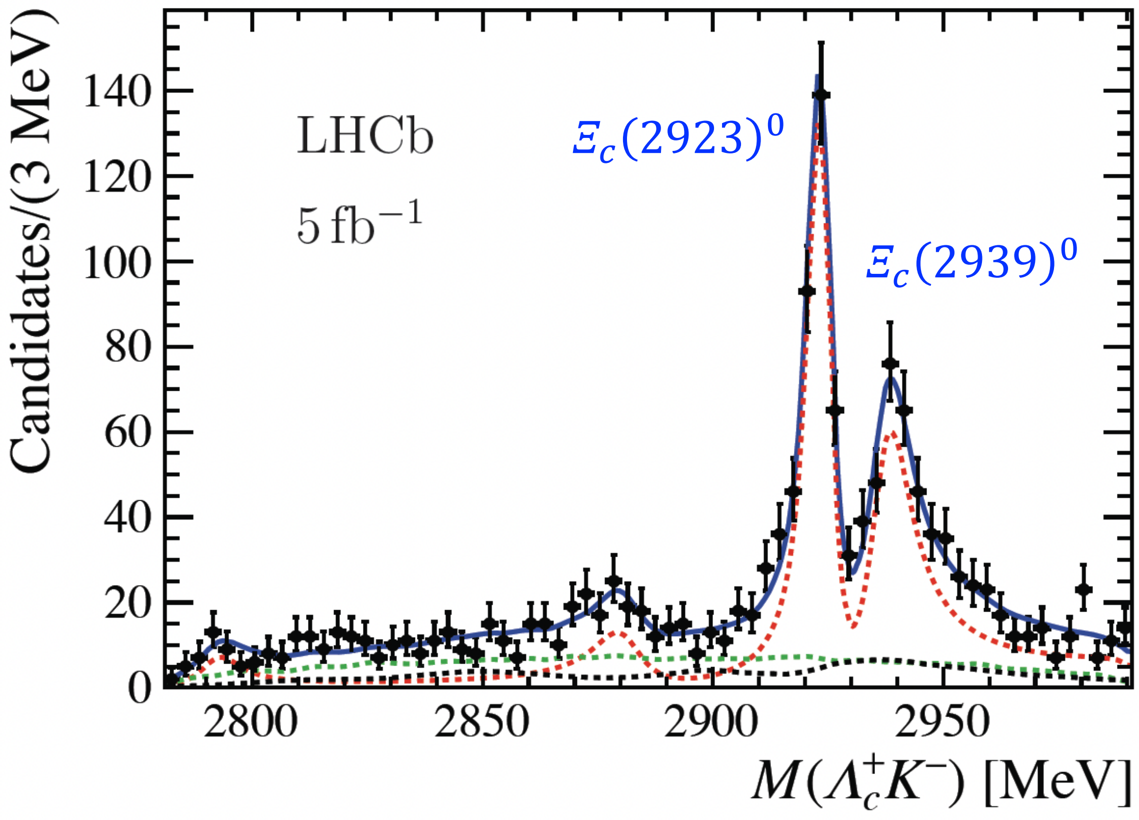
Preparation for resonance study

- Tighter mass windows: $2265 < M(\Lambda_c^{\pm}) < 2305$ MeV, $5240 < M(B^+) < 5320$ MeV
- Refit of decay performed, fixing Λ_c^+ and B^- masses
  - Track momenta from refit used to calculate $M(\Lambda_c^+ K^-), M(\bar{\Lambda}_c^- K^-)$ and $M(\Lambda_c^+ \bar{\Lambda}_c^-)$
- Background subtraction from $M(\bar{\Lambda}_c^-)$ - $M(\Lambda_c^+)$ sideband
  - In 3D fit it is found that $b_{B^-} s_{\bar{\Lambda}_c^-} s_{\Lambda_c^+}$ component is negligible



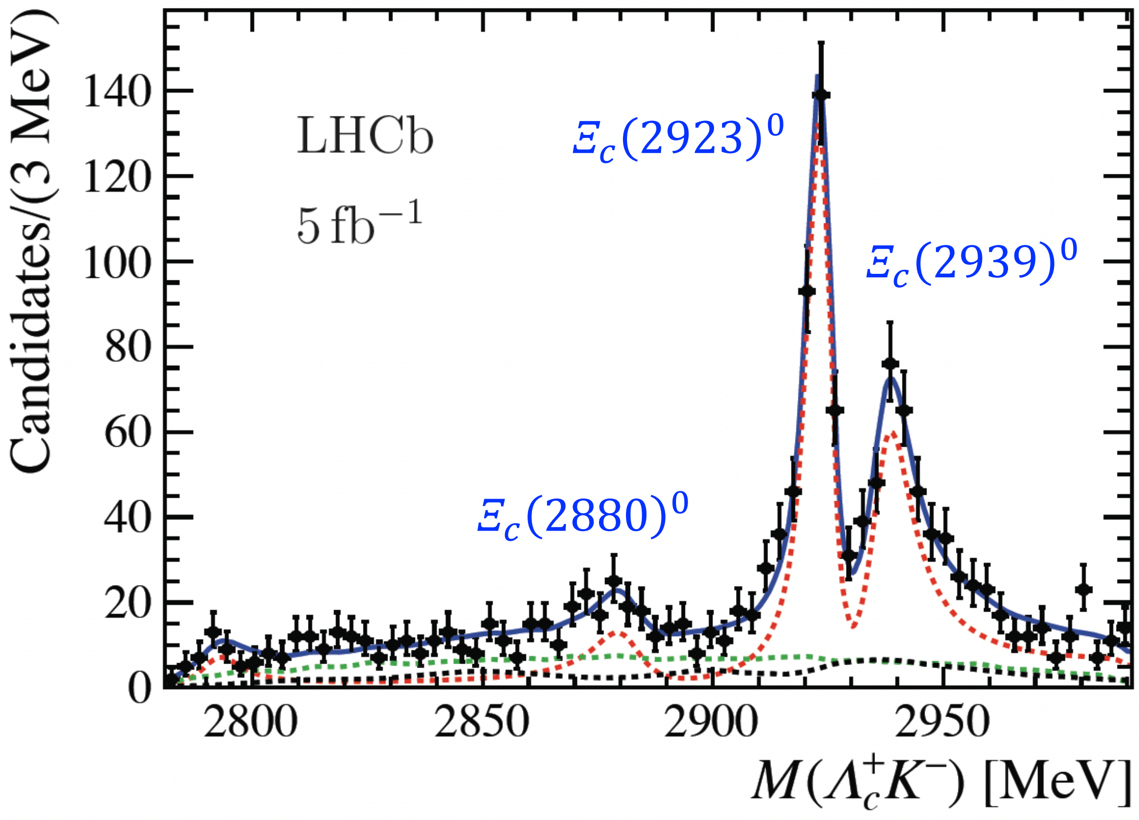
Backgound in signal region
= average of $\bar{\Lambda}_c^-$ sideband
+ average of Λ_c^+ sideband
- double-counted combinatorial background

The excited Ξ_c states in $\Lambda_c^+ K^-$



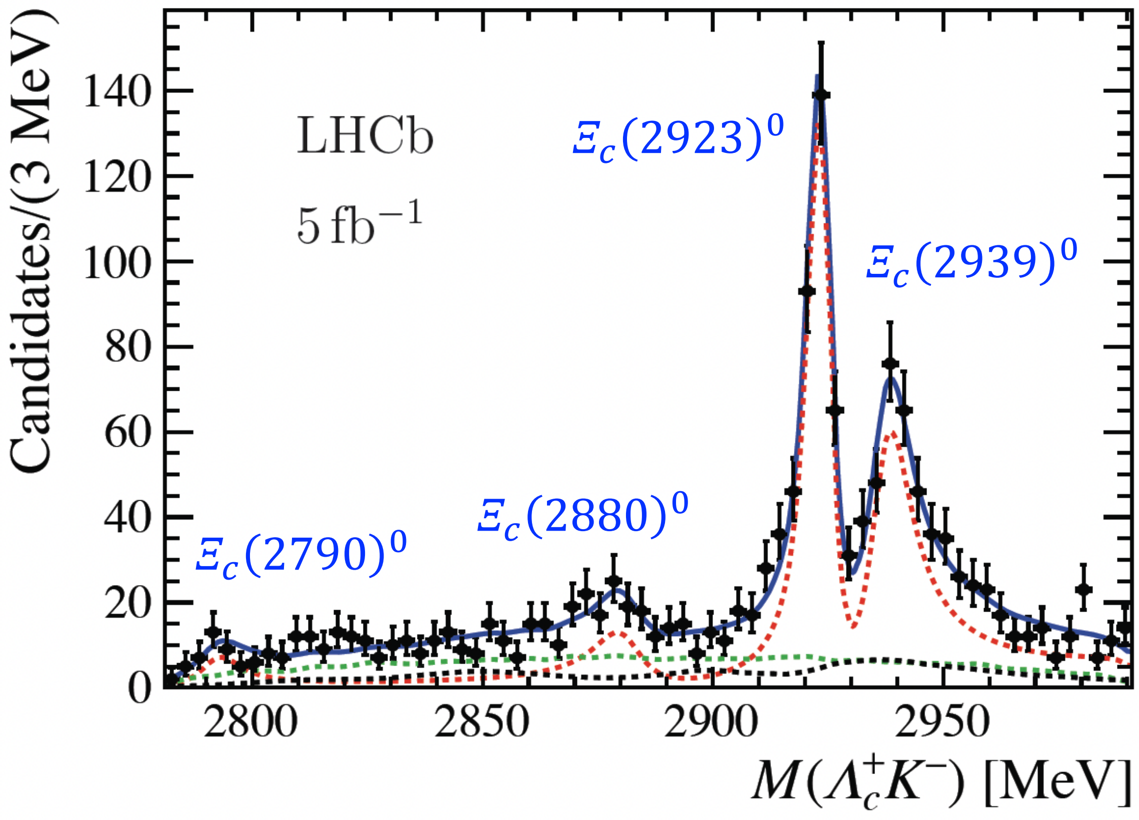
- $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ well separated!
  - *The interference cannot be neglected*

The excited Ξ_c states in $\Lambda_c^+ K^-$



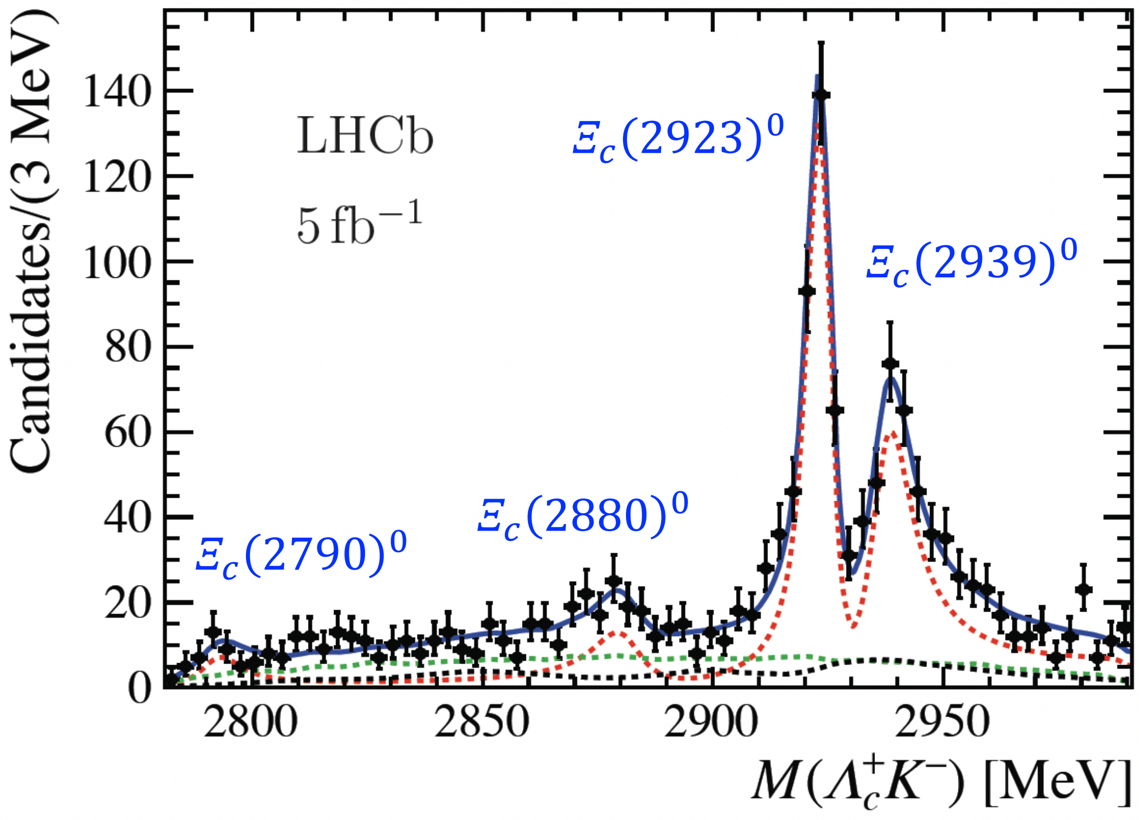
- $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ well separated!
  - *The interference cannot be neglected*
- Structure of $\Xi_c(2880)^0$ is a resonance
  - *Cannot attribute to* $\Xi_c(3055), \Xi_c(3080)^0$ *since* $B^- \to \bar{\Lambda}_c^- \, \Xi_c(3055)^0$ *with missing particle will not peak at B mass*
  - *Other b-decay like* $\Lambda_b^0 \to D^- \Xi_c(3055)^0$ *cannot pass event selection either*

The excited Ξ_c states in $\Lambda_c^+ K^-$



- $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ well separated!
  - *The interference cannot be neglected*
- Structure of $\Xi_c(2880)^0$ is a resonance
  - *Cannot attribute to feed-down from* $\Xi_c(3055), \Xi_c(3080)^0$
- $\Xi_c(2790)^0$ and $\Xi_c(2815)^0$ expected
  - *Mass, width, J^P all fixed to PDG*
  - $\Xi_c(2815)^0$ *significance is too low to be included in the fit*

The excited Ξ_c states in $\Lambda_c^+ K^-$



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  - *The interference cannot be neglected*
- Structure of $\Xi_c(2880)^0$ is a resonance
  - *Cannot attribute to feed-down from* $\Xi_c(3055), \Xi_c(3080)^0$
- $\Xi_c(2790)^0$ *mass, width, J^P=(1/2)- fixed to PDG*
- Current statistics doesn't allow determination of quantum numbers for the Ξ_c states
  - *Assuming J^P =(1/2)-, (3/2)-, (3/2)- for* $\Xi_c(2880)^0$, $\Xi_c(2923)^0$, $\Xi_c(2939)^0$

K.L. Wang, L.Y. Xiao, and X.H. Zhong, PRD102 (2020) 034029

Fitting the $\Lambda_c^+ K^-$ invariant mass

Unbinned maximum likelihood fit is performed

Ξ_c yield — Detector resolution — Yield of PHSP decay — Bkg number

$$f(s) = \frac{N_{\Xi_c}}{N_{\mathrm{evt}}} f_{\Xi_c}(s) \otimes g(\sigma_{\mathrm{res}}) + \frac{N_{\mathrm{phsp}}}{N_{\mathrm{evt}}} f_{\mathrm{phsp}}(s) + \frac{N_{\mathrm{bkg}}}{N_{\mathrm{evt}}} f_{\mathrm{bkg}}(s),$$

Ξ_c line shape — PHSP shape — Bkg shape

Amplitudes of states with the same J^P are added coherently

J^P: (1/2)- (1/2)- (3/2)- (3/2)-

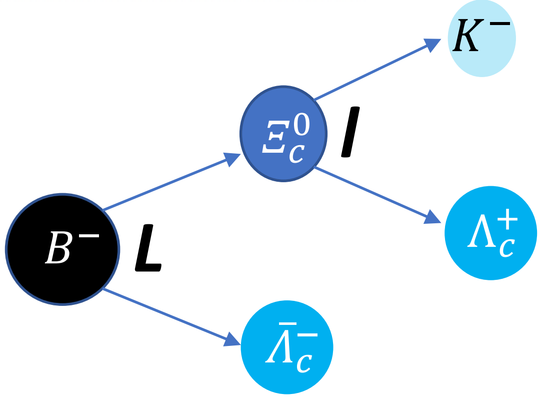
$$f_{\Xi_c} = p\,q\left(\left|\mathcal{M}_{\Xi_c(2790)^0} + \mathcal{M}_{\Xi_c(2880)^0}\right|^2 + \left|\mathcal{M}_{\Xi_c(2923)^0} + \mathcal{M}_{\Xi_c(2939)^0}\right|^2\right)$$

$$\mathcal{M}_\alpha(s) = \hat{A}_\alpha(s) F_{l,\alpha}(q) F_{L,\alpha}(p)$$

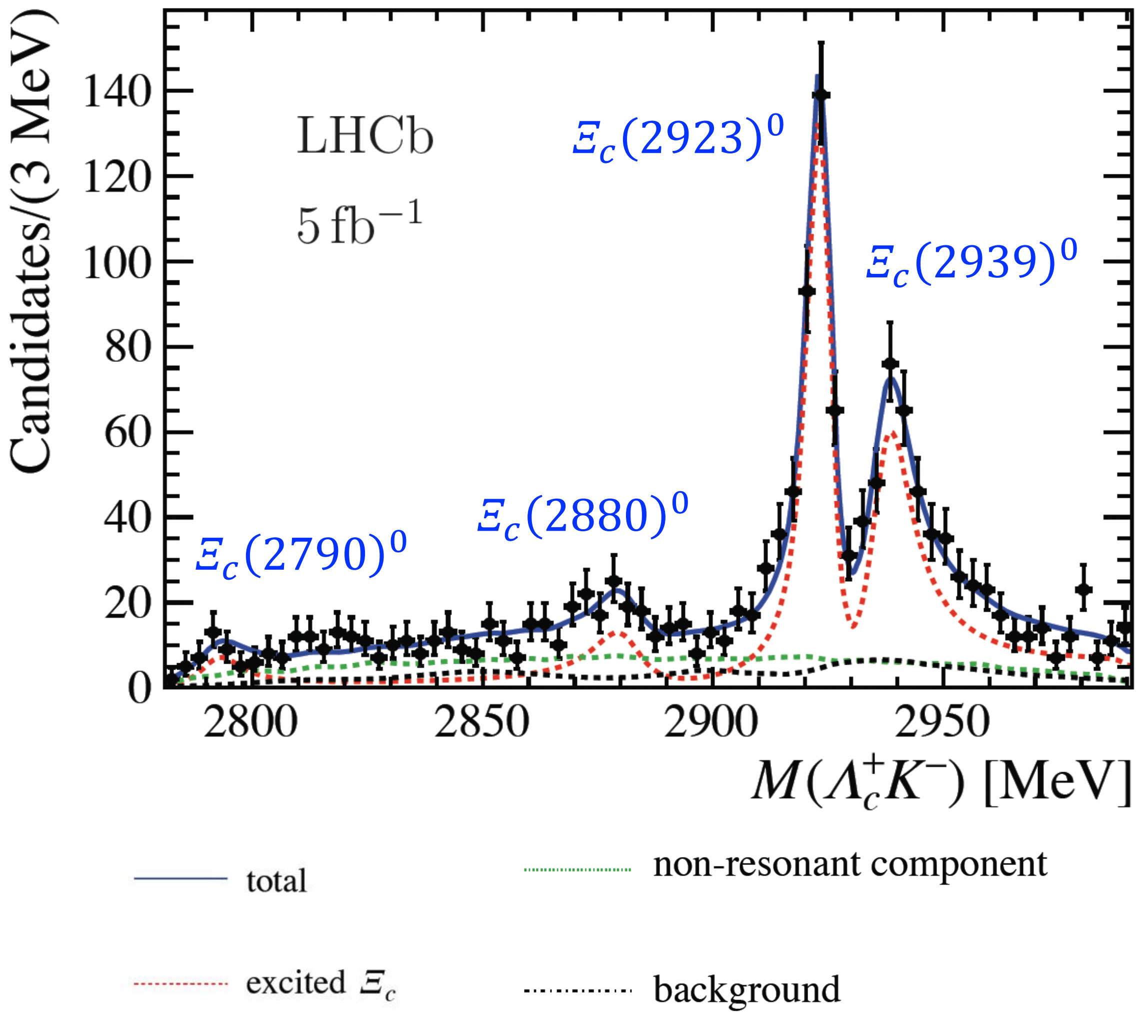
q, p: breakup momenta

RBW *Blatt-Weisskopf barrier*

$$\hat{A}_\alpha(s) = \frac{c_\alpha}{m_\alpha^2 - s - i\, m_\alpha \Gamma_\alpha \frac{q}{q_\alpha} \cdot \frac{m_\alpha}{\sqrt{s}} \cdot \frac{F_{l,\alpha}(q)^2}{F_{l,\alpha}(q_\alpha)^2}},$$



Fitting the $\Lambda_c^+ K^-$ invariant mass



State	Mass (MeV)	Width (MeV)
$\Xi_c(2880)^0$	2881.8 ± 3.1	12.4 ± 5.2
$\Xi_c(2923)^0$	2924.5 ± 0.4	4.8 ± 0.9
$\Xi_c(2939)^0$	2938.5 ± 0.9	11.0 ± 1.9

- Potential bias on mass & width corrected using pseudo-experiments
- Yield of excited Ξ_c is 873 +/- 80
- Significance of $\Xi_c(2880)^0$ and $\Xi_c(2790)^0 \to \Lambda_c^+ K^-$ is 3.9 σ without systematic uncertainty

Systematic uncertainties on $\varXi_c$ masses and widths

- Model assumptions
- Line shape formalism
- Insufficient statistical uncertainty
- Momentum scale
- Mass comstraint
- Energy loss
- Bacgkround effect

Alternative assumptions tested:

- $\varXi_c(2923)^0$ *and* $\varXi_c(2939)^0$ *J^P: (1/2)-, (1/2)+, (3/2)+*
- $\varXi_c(2880)^0$ *J^P: (1/2)+, (3/2)+, (3/2)-*
- *Effective radius: 2.0 - 4.0 GeV^{-1}*
- *Varying* $\varXi_c(2790)^0$ *mass/width within uncertainty*
- *Adding* $\varXi_c(2815)^0$ or $\varXi_c(2970)^0$
- Interference with non-resonant decay
- …

Alternative line shape of K-matrix used:

$$\hat{A}(s) = \frac{P(s)}{1 - i\,\rho(s) F_l^2(q)\, K}\,, \qquad K(s) = \sum_i \frac{g_i^2}{m_i^2 - s}\,,$$

Systematic uncertainties on Ξ_c masses and widths

Values in MeV	$\Xi_c(2923)^0$		$\Xi_c(2939)^0$		$\Xi_c(2880)^0$	
Source	Mass	Width	Mass	Width	Mass	Width
Model assumption	0.8	1.4	1.9	7.0	8.4	4.1
Line shape formalism	0.7	0.1	1.3	0.8	1.1	0.0
Insufficient stat. uncertainty	0.2	0.4	0.4	2.1	–	–
Momentum scaling	0.0	–	0.1	–	0.0	–
Mass constraint	0.1	0.1	0.1	0.5	0.1	0.4
Background	0.1	0.3	0.2	0.8	0.7	4.0
Total	1.1	1.5	2.3	7.5	8.5	5.8

- Significance of $\Xi_c(2880)^0$ is 3.8 σ considering systematic uncertainty
- Significance of $\Xi_c(2790)^0 \to \Lambda_c^+ K^-$ is 3.7 σ considering systematic uncertainty

Results of Ξ_c masses and widths

Resonance	Mass [MeV]	Width [MeV]
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.3 \pm 5.8$

- The masses and widths of $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ consistent with prompt $\Lambda_c^+ K^-$ study

Resonance	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

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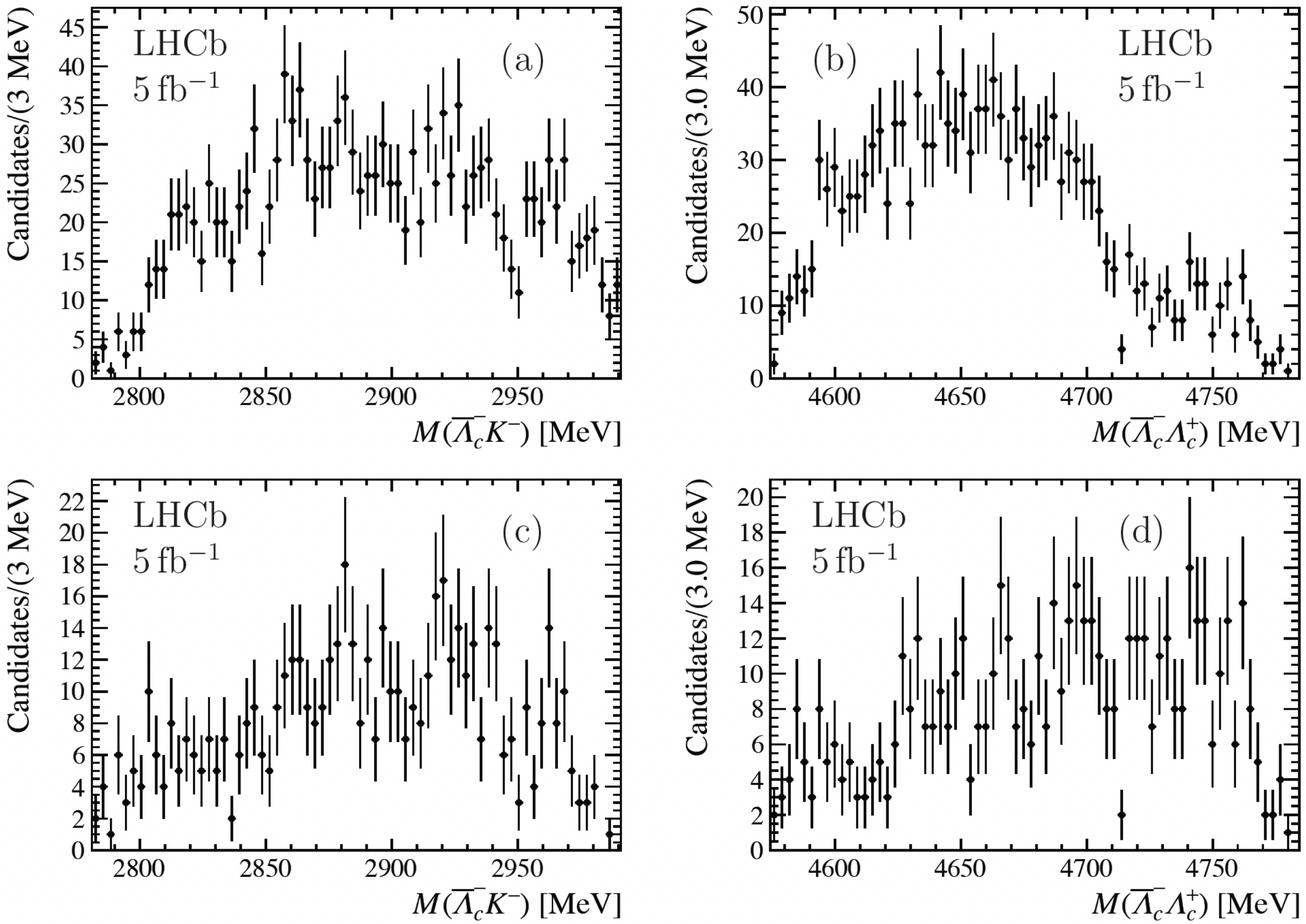
$M(\overline{\Lambda}_c^- K^-)$ and $M(\Lambda_c^+ \overline{\Lambda}_c^-)$

No significant structures observed

- With the full sample :

- Or after vetoing the candidates in 2900 < $M(\Lambda_c^+ K^-)$ < 2970 MeV:



Branching fraction measurement

$$R_{\mathcal{B}} = \frac{N(B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-)}{N(B^- \to D^+ D^- K^-)} \times \frac{\varepsilon_{\rm tot}(B^- \to D^+ D^- K^-)}{\varepsilon_{\rm tot}(B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-)} \times \frac{\mathcal{B}^2(D^+ \to K^-\pi^+\pi^+)}{\mathcal{B}^2(\Lambda_c^+ \to pK^-\pi^+)}.$$

Yields obtained from 3D fits

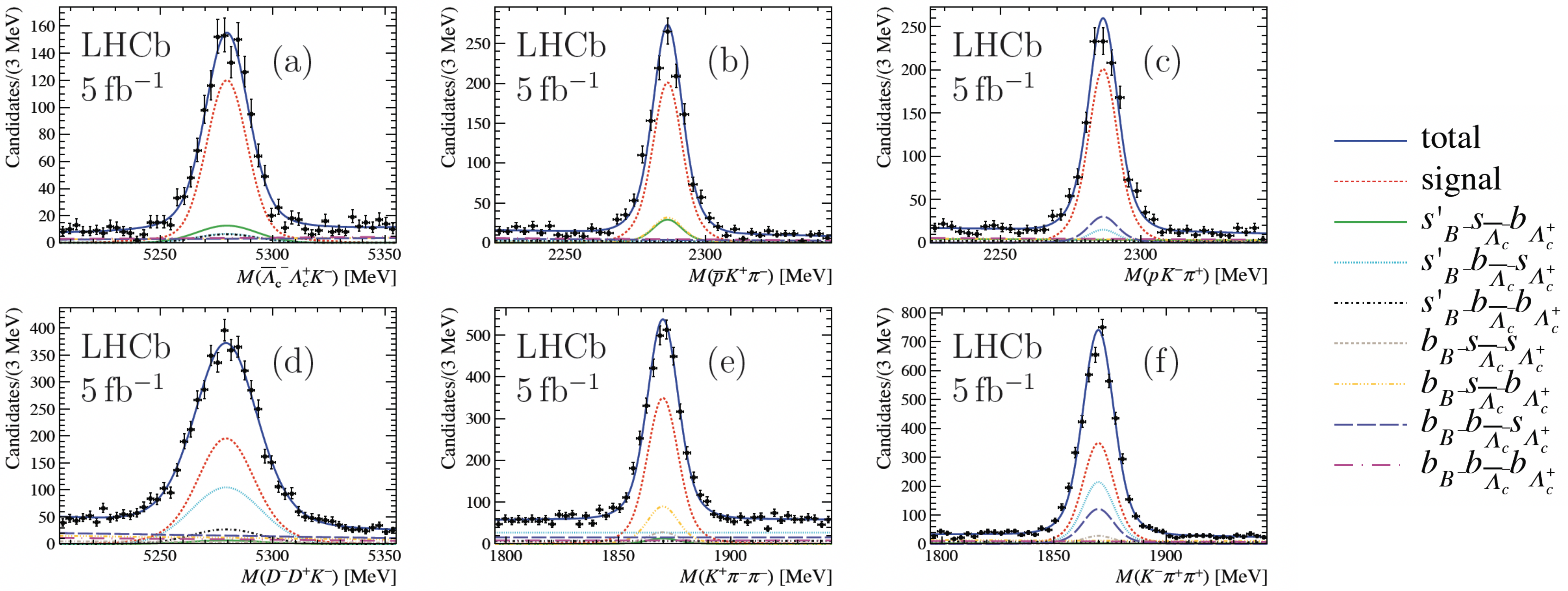
Efficiency calculated using simulation, or data where applicable

From PDG

Branching fraction measurement

All events are required to be triggered on the B^- candidates.

$N(B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-) = 977 \pm 36, N(B^- \to D^- D^+ K^-) = 2212 \pm 62$



$\varepsilon(B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-) = (3.41 \pm 0.02) \times 10^{-4}, \varepsilon\,(B^- \to D^- D^+ K^-) = (8.15 \pm 0.11) \times 10^{-4}$

Branching fraction measurement: results

$\boldsymbol{R_{\mathcal{B}} = 2.36 \pm 0.11(\text{stat}) \pm 0.22(\text{syst}) \pm 0.25(\text{ext})}$

- Dominated by external uncertainty of charm hadron decays
- Improved with respect to PDG value $R_{\mathcal{B}} = 2.23 \pm 0.78$

Source	$B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$	$B^- \to D^+ D^- K^-$	$R_{\mathcal{B}}$
BDT working point	1.5	0.2	
Fit range	1.2	0.6	
Detector resolution	0.0	0.3	
Signal model	0.0	1.6	
Simulation weighting	2.6	3.8	
Decay phase space	0.1	0.2	
PID resampling	0.6	0.9	
Detector parametrisation			0.8
Trigger	5.6	4.9	
Simulation sample size	0.9	1.2	
Total			9.4

Summary

- The $B^- \to \bar{\Lambda}_c^- \Lambda_c^+ K^-$ is studied at LHCb with *pp* collision data of 5 fb^{-1}
  - $\Xi_c(2930)^0$ found at *B*-factories is two finer structures $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$
  - Evidence of $\Xi_c(2880)^0$ is found with significance of 3.8 σ
  - A new decay $\Xi_c(2790) \to \Lambda_c K$ is found with significance of 3.7 σ
  - No significance structure found in $M(\bar{\Lambda}_c^- K^-)$ and $M(\bar{\Lambda}_c^- \Lambda_c^+)$.
- The relative branching fraction is measured
  - Largely improved comparing to PDG value

$$R_{\mathcal{B}} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25,$$

$$\begin{aligned}
m(\Xi_c(2923)^0) &= 2924.5 \pm 0.4 \pm 1.1\,\mathrm{MeV} \\
\Gamma(\Xi_c(2923)^0) &= 4.8 \pm 0.9 \pm 1.5\,\mathrm{MeV} \\
m(\Xi_c(2939)^0) &= 2938.5 \pm 0.9 \pm 2.3\,\mathrm{MeV} \\
\Gamma(\Xi_c(2939)^0) &= 11.0 \pm 1.9 \pm 7.5\,\mathrm{MeV} \\
m(\Xi_c(2880)^0) &= 2881.8 \pm 3.1 \pm 8.5\,\mathrm{MeV} \\
\Gamma(\Xi_c(2880)^0) &= 12.4 \pm 5.3 \pm 5.8\,\mathrm{MeV}
\end{aligned}$$

Thank you!