Status of Charmed Baryon Studies at Belle

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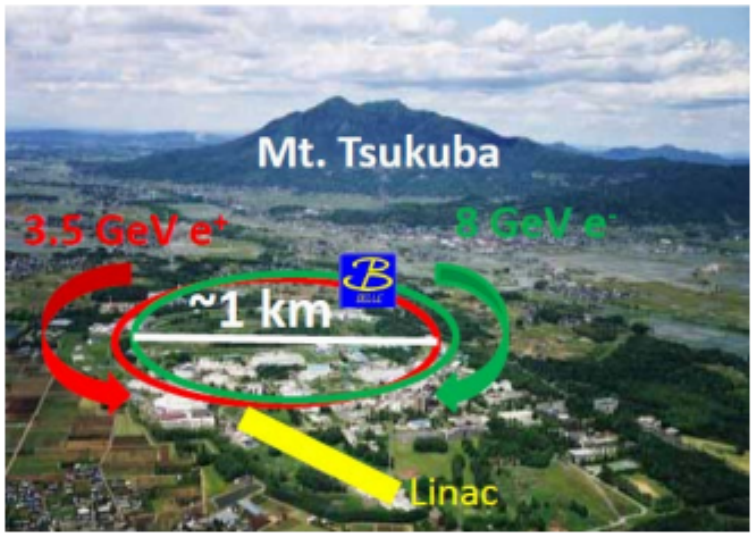
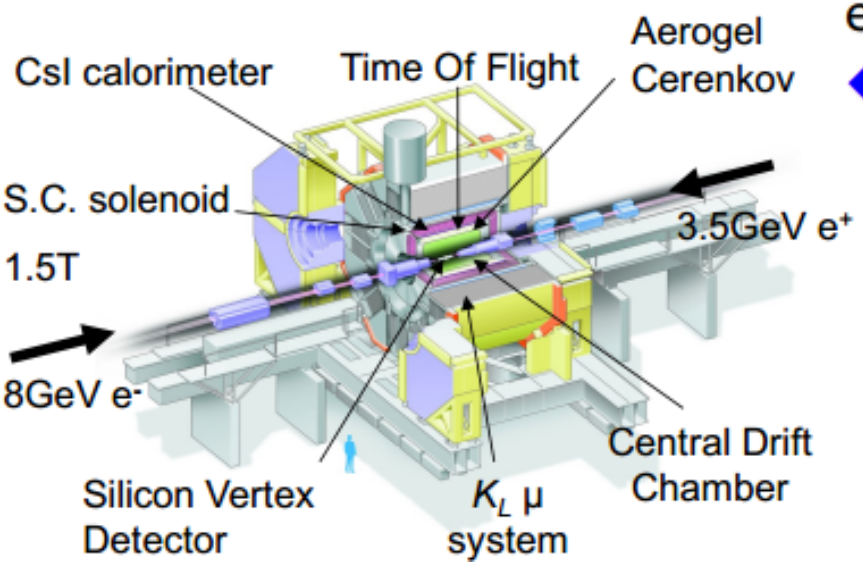
Joint Workshop on Charm Hadron Decays @ BESIII, Belle and LHCb, on September 23-24, 2017, at Nankai University

Outline

Introduction to the Belle experiment



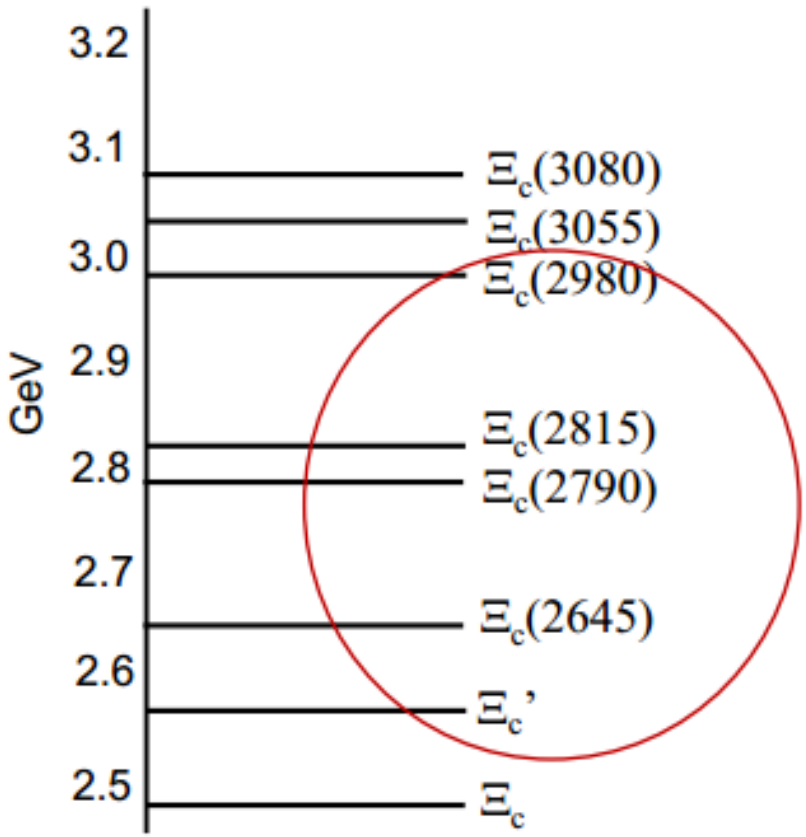


- Asymmetric energy e^+e^- collider
- General purpose detector
  - Detect charged particles and photons
  - Good momentum/vertex resolution
  - K/π separation up to 3.5 GeV/c
- Data at $\Upsilon(4S)$ and some other energies
- Integrated luminosity ~1 ab^{-1}

On resonance:	$\Upsilon(5S)$: 121 fb^{-1}
	$\Upsilon(4S)$: 711 fb^{-1}
	$\Upsilon(3S)$: 3 fb^{-1}
	$\Upsilon(2S)$: 25 fb^{-1}
	$\Upsilon(1S)$: 6 fb^{-1}
Off resonance/ scan:	~100 fb^{-1}

Study of excited Ξ_c States decaying into Ξ_c^0 and Ξ_c^+ Baryons

PRD 94, 052011 (2016)

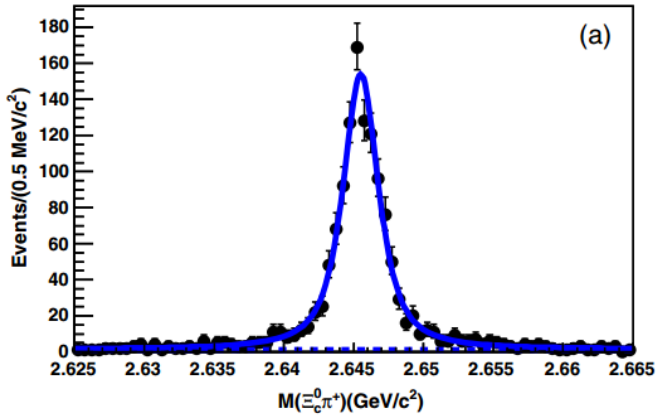


- $\Xi_c(2980) \to \Xi_c(2645)\pi$
- $\Xi_c(2815) \to \Xi_c(2645)\pi$
  - $\Xi_c(2645) \to \Xi_c\pi$
- $\Xi_c(2980) \to \Xi_c'\pi$
- $\Xi_c(2815) \to \Xi_c'\pi$
- $\Xi_c(2790) \to \Xi_c'\pi$
  - $\Xi_c' \to \Xi_c\gamma$

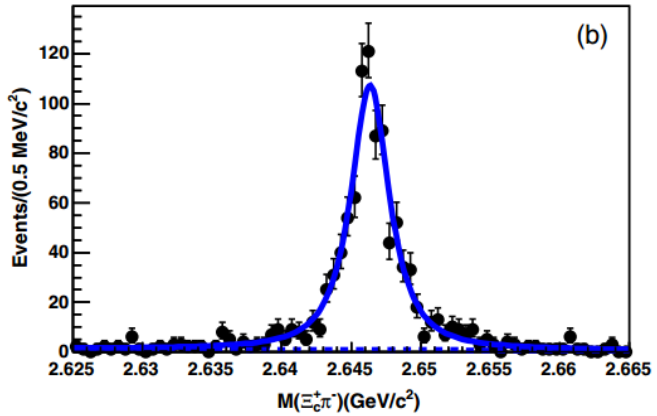
Introduction

- Like the ground Ξ_c, each of the excited Ξ_c has an isodoublet.
- Mass and width measurements of the first five isodoublets of excited Ξ_c states are performed using 980/fb of Belle data.
- Previous measurements (CLEO,BaBar, Belle) were with low statistics. For widths, only upper limits were given for many states.
- The ground Ξ_c^+ and Ξ_c^0 are reconstructed from 10 and 7 decay modes, respectively.

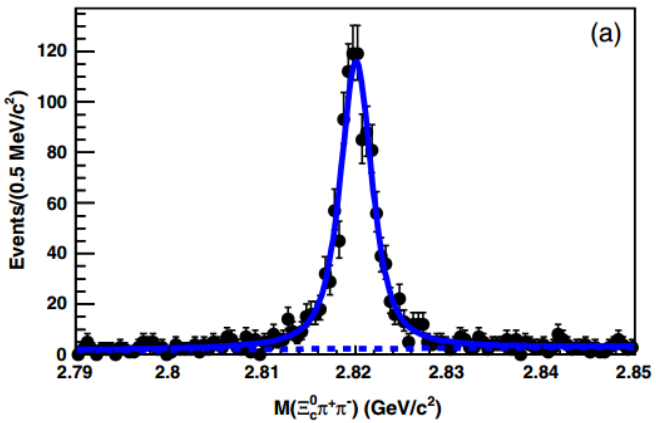
Mass and width of $\Xi_c(2645)/\Xi_c(2815)$ extracted from $M(\Xi_c\pi)/M(\Xi_c\pi\pi)$ spectra



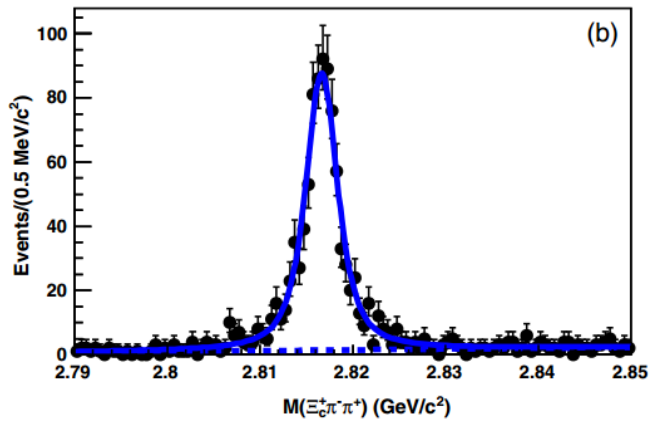
m=2645.58±0.06(stat.) MeV
Γ=2.06±0.13(stat.) MeV



m=2646.43±0.07(stat.) MeV
Γ=2.35±0.18(stat.) MeV

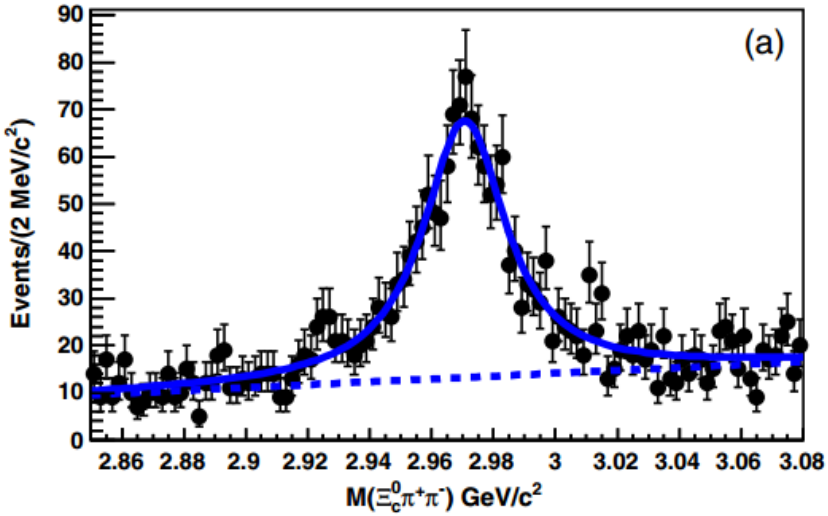


m=2820.20±0.08(stat.) MeV
Γ=2.54±0.18(stat.) MeV

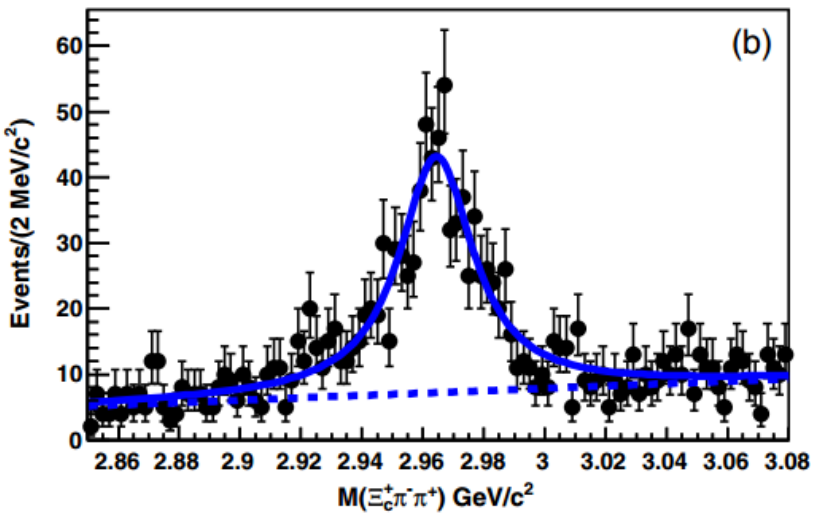


m=2816.73±0.08(stat.) MeV
Γ=2.43±0.20(stat.) MeV

Mass and width of $\Xi_c(2980)$ extracted from $M(\Xi_c\pi\pi)$ spectra



m=2970.8±0.7(stat.) MeV
Γ=30.3±2.3(stat.) MeV



m=2966.0±0.8(stat.) MeV
Γ=28.1±2.4(stat.) MeV

The results support the new name of the isodoublet, namely $\Xi_c(2970)$ instead of $\Xi_c(2980)$.

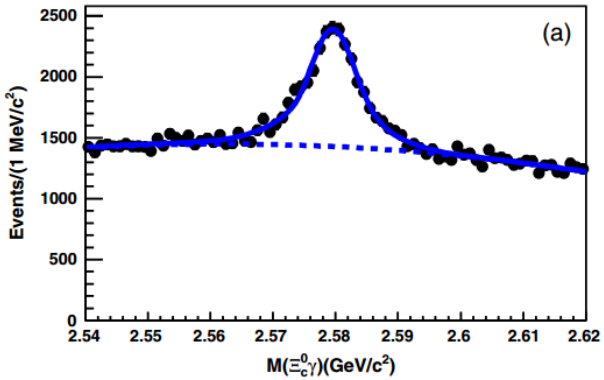
$\Xi_c(2970)$
was $\Xi_c(2980)$

$I(J^P) = \frac{1}{2}(?^?)$

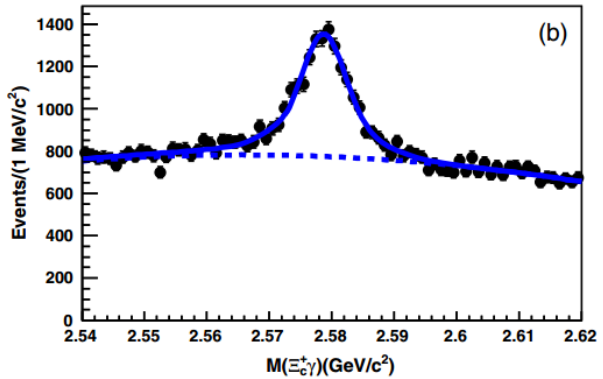
$\Xi_c(2970)^+$ $m = 2970.7 \pm 2.2$ MeV (S = 1.5)
$\Xi_c(2970)^0$ $m = 2968.0 \pm 2.6$ MeV (S = 1.2)

(PDG 2016)

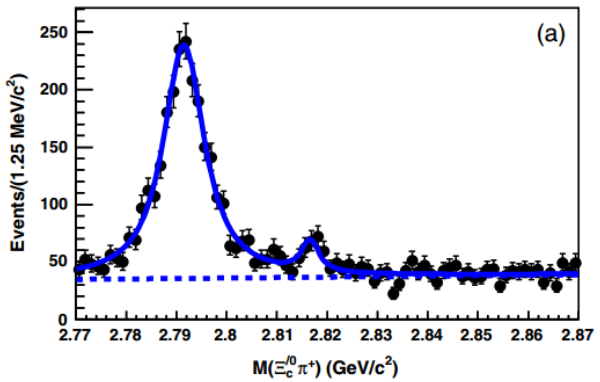
Mass and width of $\Xi_c'/\Xi_c(2790)$ extracted from $M(\Xi_c\gamma)/M(\Xi_c'\pi)$ spectra



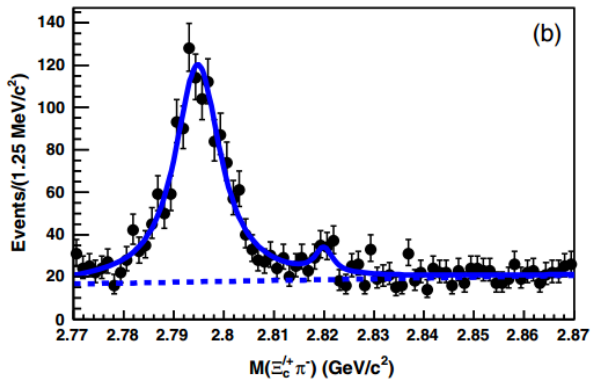
m=2579.2±0.1(stat.) MeV



m=2578.4±0.1(stat.) MeV



m=2791.6±0.2(stat.) MeV
Γ=8.9±0.6(stat.) MeV

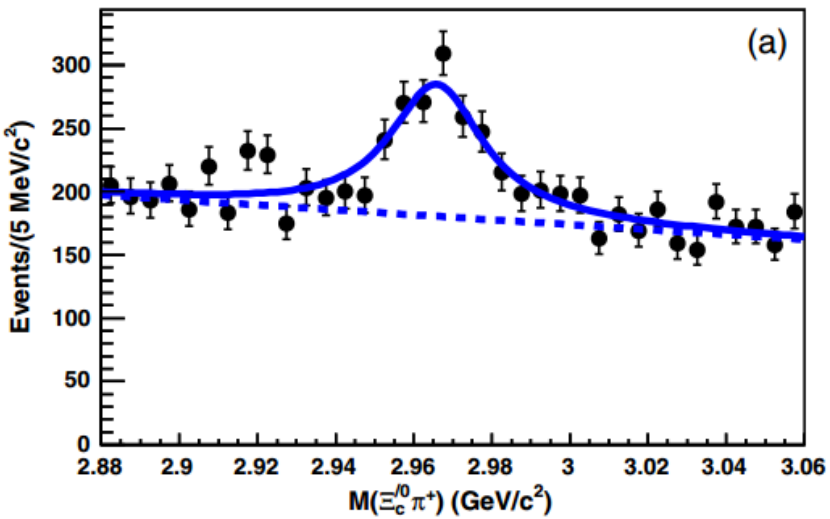


m=2794.9±0.3(stat.) MeV
Γ=10.0±0.7(stat.) MeV

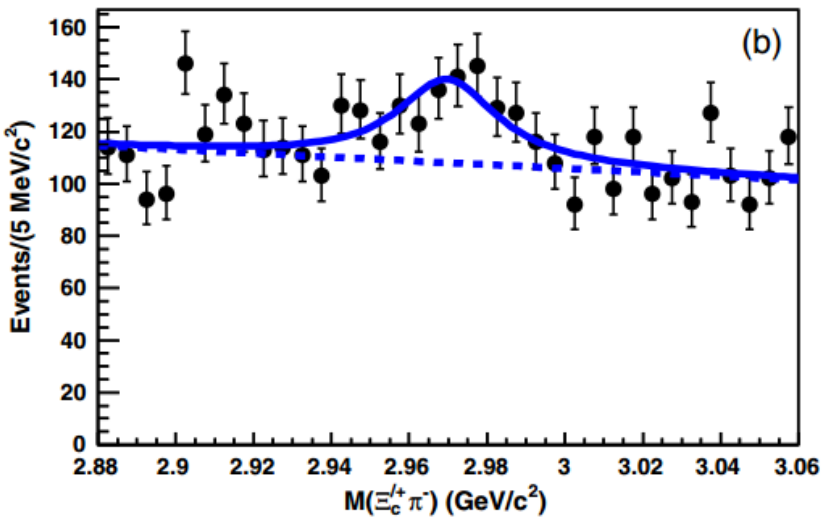
No width of Ξ_c' is given, because it decays electromagnetically and its intrinsic widths are experimentally negligible.

First observation of $\Xi_c(2980)$ in the $\Xi_c'\pi$ final state

signal yeild：845 ± 77



signal yeild：276 ± 59



- Signal shape: Breit-Wigner function convoluted with a double-Gaussian resolution function
- Background shape: Polynomial function

Results

Particle	Yield	Mass	Width
$\Xi_c(2645)^+$	1260 ± 40	$2645.58 \pm 0.06 \pm 0.07^{+0.28}_{-0.40}$	$2.06 \pm 0.13 \pm 0.13$
PDG		2645.9 ± 0.5	$2.6 \pm 0.2 \pm 0.4$
$\Xi_c(2645)^0$	975 ± 36	$2646.43 \pm 0.07 \pm 0.07^{+0.28}_{-0.40}$	$2.35 \pm 0.18 \pm 0.13$
PDG		2645.9 ± 0.5	< 5.5
$\Xi_c(2815)^+$	941 ± 35	$2816.73 \pm 0.08 \pm 0.06^{+0.28}_{-0.40}$	$2.43 \pm 0.20 \pm 0.17$
PDG		2816.6 ± 0.9	< 3.5
$\Xi_c(2815)^0$	1258 ± 40	$2820.20 \pm 0.08 \pm 0.07^{+0.28}_{-0.40}$	$2.54 \pm 0.18 \pm 0.17$
PDG		2819.6 ± 1.2	< 6.5
$\Xi_c(2980)^+$	916 ± 55	$2966.0 \pm 0.8 \pm 0.2^{+0.3}_{-0.4}$	$28.1 \pm 2.4^{+1.0}_{-5.0}$
PDG		2970.7 ± 2.2	17.9 ± 3.5
$\Xi_c(2980)^0$	1443 ± 75	$2970.8 \pm 0.7 \pm 0.2^{+0.3}_{-0.4}$	$30.3 \pm 2.3^{+1.0}_{-1.8}$
PDG		$2968.0 \pm 2.6 \pm 0.5$	20 ± 7
$\Xi_c'^+$	7055 ± 211	$2578.4 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	
PDG		2575.6 ± 3.0	
$\Xi_c'^0$	11560 ± 276	$2579.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	
PDG		2577.9 ± 2.9	
$\Xi_c(2790)^+$	2231 ± 103	$2791.6 \pm 0.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	$8.9 \pm 0.6 \pm 0.8$
PDG		2789.8 ± 3.2	< 15
$\Xi_c(2790)^0$	1241 ± 72	$2794.9 \pm 0.3 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	$10.0 \pm 0.7 \pm 0.8$
PDG		2791.9 ± 3.3	< 12

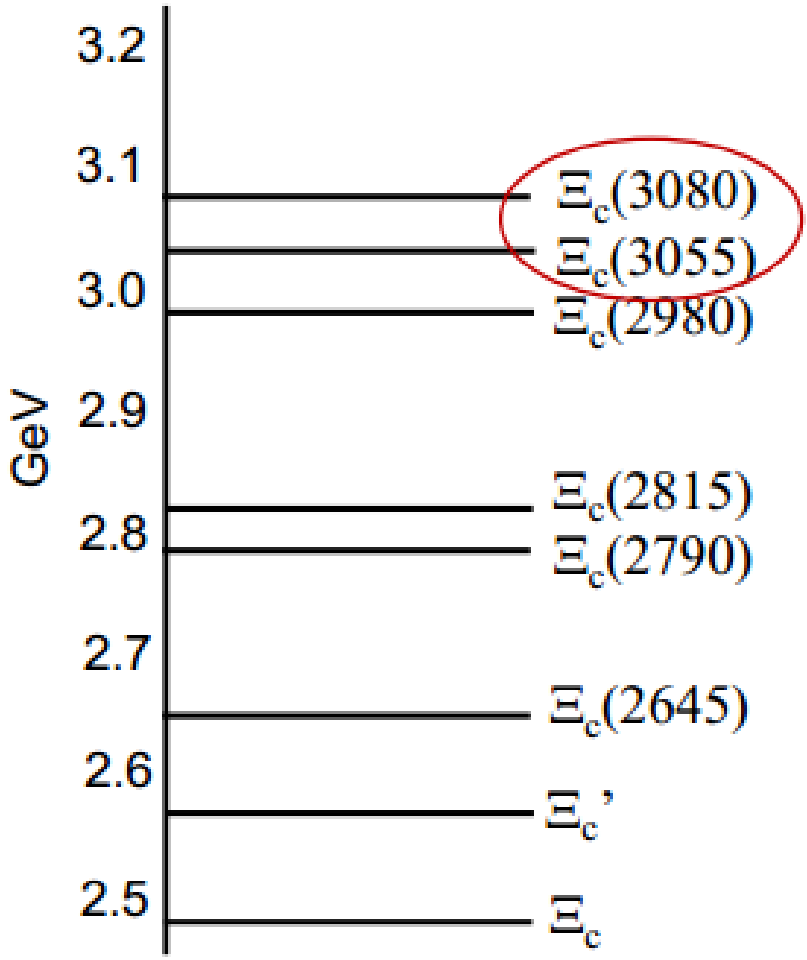
- Masses: $\sim$ 1 order improvement of precision
- widths: 5 first measurements
- Measurement of the isospin splitting consistent with nonrelativistic quark model (J. phys. G 29, 2685 (2003))

$\Downarrow$

Particle	$M(\Xi_c^+) - M(\Xi_c^0)$ (MeV/c^2)
$\Xi_c(2645)$	$-0.85 \pm 0.09 \pm 0.08 \pm 0.48$
$\Xi_c(2815)$	$-3.47 \pm 0.12 \pm 0.05 \pm 0.48$
$\Xi_c(2980)$	$-4.8 \pm 0.1 \pm 0.2 \pm 0.5$
Ξ_c'	$-0.8 \pm 0.1 \pm 0.1 \pm 0.5$
$\Xi_c(2790)$	$-3.3 \pm 0.4 \pm 0.1 \pm 0.5$

Study of excited Ξ_c States in the ΛD final state

PRD 94, 032002 (2016)



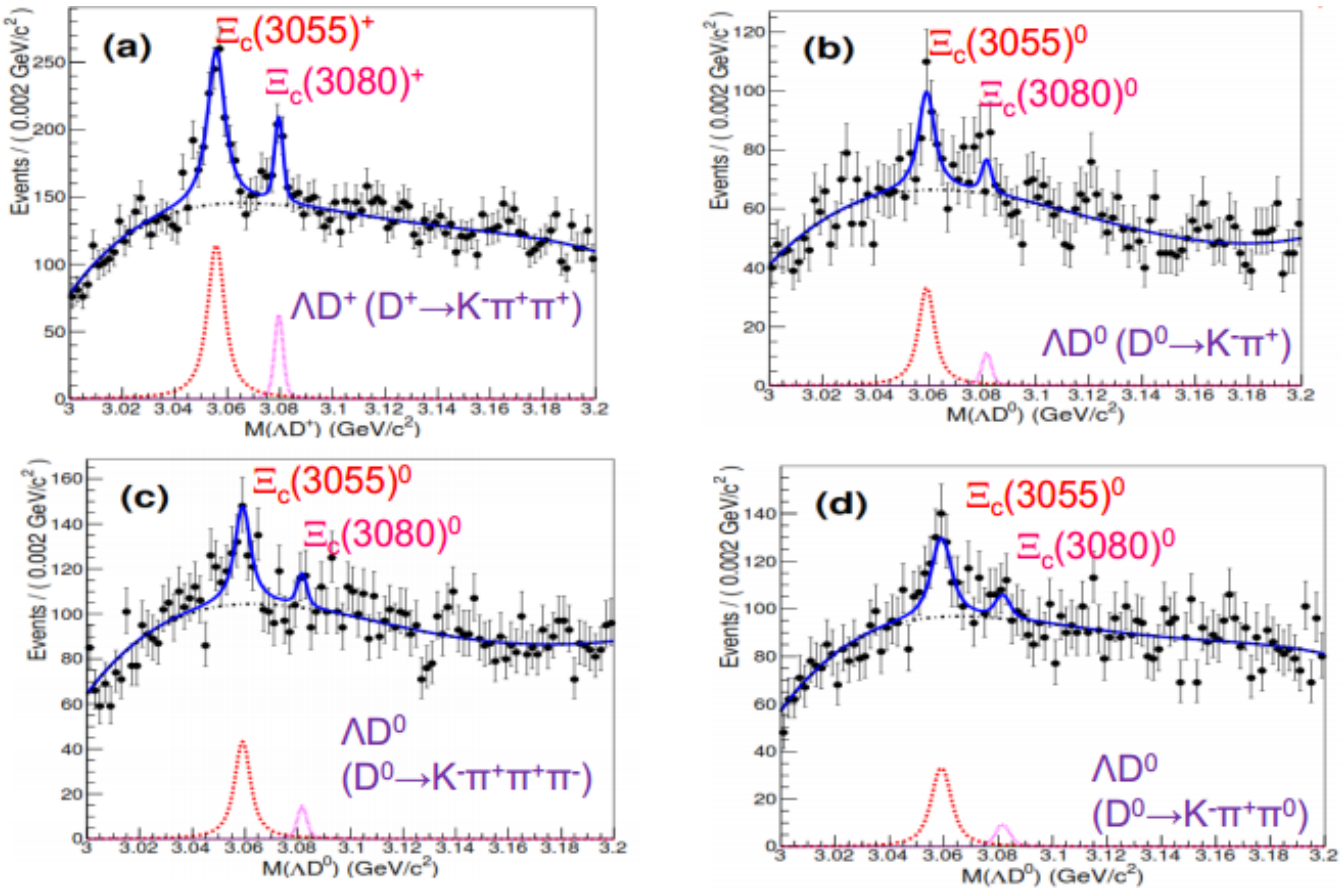
- $\Xi_c(3055) \to \Lambda D$
- $\Xi_c(3080) \to \Lambda D$

Introduction

- Relative branching fractions (BF) of $\Sigma_c K$ and ΛD decays reveal the internal structure of Ξ_c states.
  - Chiral quark model: $\Xi_c(3055)$, $\Xi_c(3080)$ as D-wave and S-wave excitation in N=2 (radial) states. Small coupling to ΛD. PRD86,034024(2012)

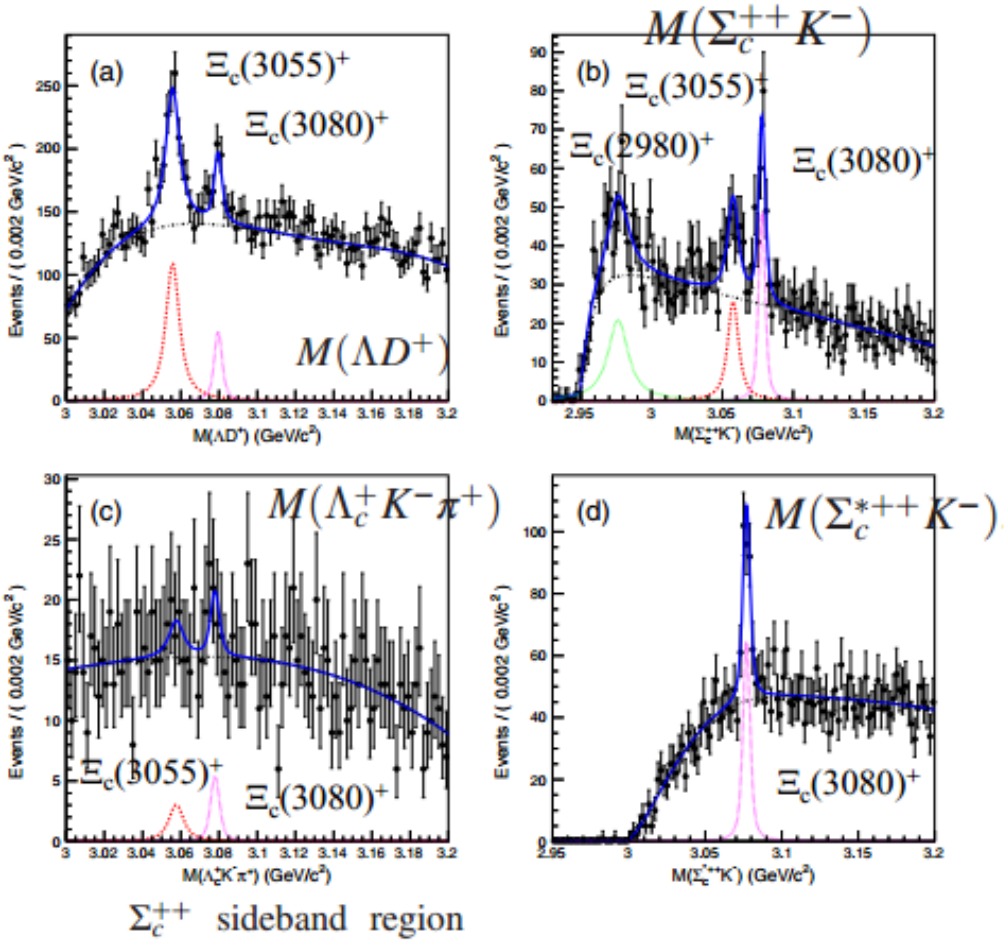
- Relative BFs (ΛD / $\Sigma_c K$) for $\Xi_c(3055)$, $\Xi_c(3080)$ are studied using 980/fb of Belle data.
- Relative BF ($\Sigma_c^* K$ / $\Sigma_c K$) for $\Xi_c(3080)$ is also studied.
- $D^{+/0}$ mesons are reconstructed in
  - $D^+ \to K^-\pi^+\pi^+$
  - $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^0$

Observation of $\Xi_c(3055)$ and $\Xi_c(3080)$ in the ΛD final state



Resonance	Mass (MeV/c^2)	Width (MeV)	Significance (σ)
$\Xi_c(3055)^0$	$3059.0 \pm 0.5 \pm 0.6$	$6.4 \pm 2.1 \pm 1.1$	8.6
$\Xi_c(3055)^+$	$3055.8 \pm 0.4 \pm 0.2$	$7.0 \pm 1.2 \pm 1.5$	11.7
$\Xi_c(3080)^+$	$3079.6 \pm 0.4 \pm 0.1$	< 6.3	4.8

Widths of $\Xi_c(3055)$ and $\Xi_c(3080)$ extracted from Simultaneous fit of ΛD, $\Sigma_c K$ and $\Sigma_c^* K$ modes



In the simultaneous fit, the masses are not constrained to be the same, because we find inconsistency for the mass of the $\Xi_c(3080)^+$ among the three decay modes.

Resonance	Width (MeV)
$\Xi_c(3055)^+$	$7.8 \pm 1.2 \pm 1.5$
$\Xi_c(3080)^+$	$3.0 \pm 0.7 \pm 0.4$

$BR(\Lambda D^+)/BR(\Xi_c^{++}K^-)$ and $BR(\Xi_c^{*++}K^-)/BR(\Xi_c^{++}K^-)$

State	$BR(\Lambda D^+)/BR(\Sigma_c^{++}K^-)$	$BR(\Sigma^*{}_c^{++}K^-)/BR(\Sigma_c^{++}K^-)$
$\Xi_c(3055)^+$	$5.09\pm1.01\pm0.76$	
$\Xi_c(3080)^+$	$1.29\pm0.30\pm0.15$	$1.07\pm0.27\pm0.01$

The chiral quark model has been used to identify $\Xi_c(3055)$ as *D*-wave excitation in N=2 shell, and predict **PRD86,034024 (2012)**

	$\Sigma_c\bar{K}$	$\Xi_c^*(2645)\pi$	$\Xi_c'\pi$	$\Sigma_c^*\bar{K}$	$D\Lambda$	total
$\|\Xi_c{}^2D_{\lambda\lambda}(3/2^+)\rangle$	2.3	0.5	1.0	0.1	0.1	4.0
$\|\Xi_c{}^2D_{\rho\rho}(3/2^+)\rangle$	5.6	0.8	3.3	0.3	-	10.0

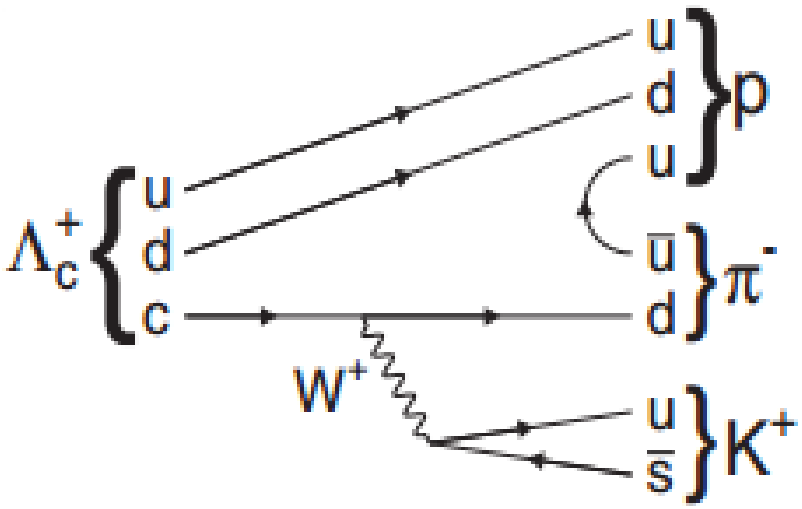
Further identifies *$\Xi_c(3080)$* as an *S*-wave excitation mode in N=2 shell and predicts that its decay into *ΛD* is forbidden.

- Belle results contradicts some theory results.
- Crucial input to understand the nature of excited Ξ_c baryons.

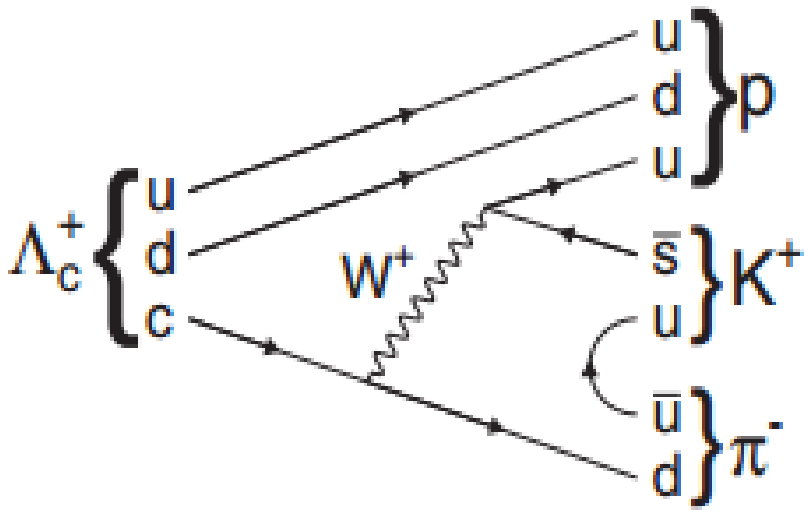
First observation of the doubly Cabibbo suppressed decay of a charmed baryon

$\Lambda_c^+ \to pK^+\pi^-$

PRL 117, 011801 (2016)



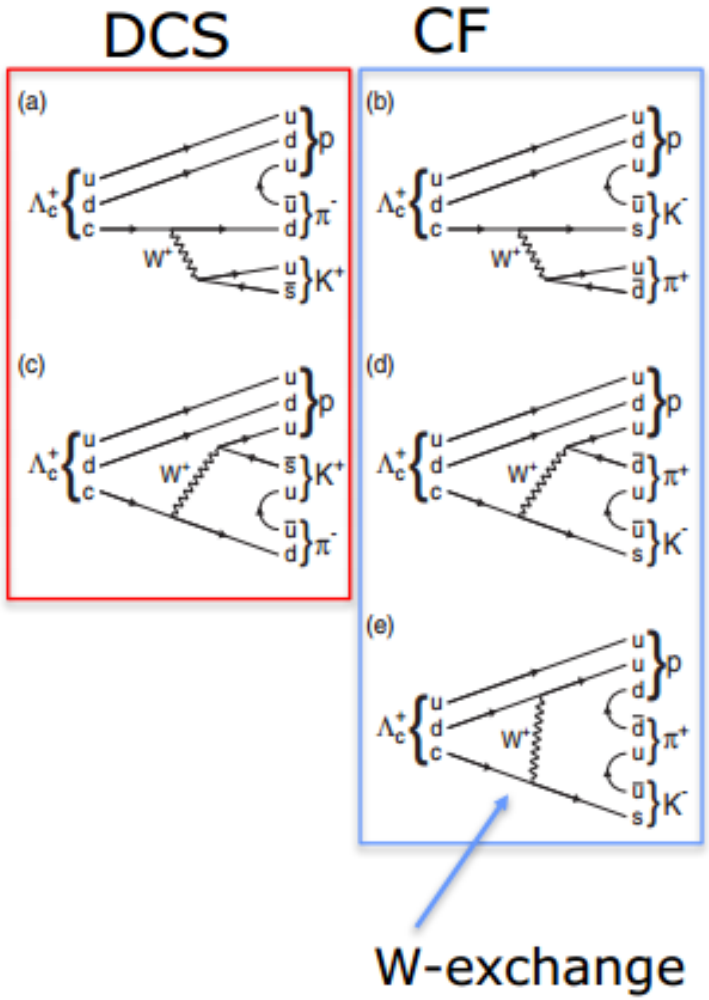
External W-emission



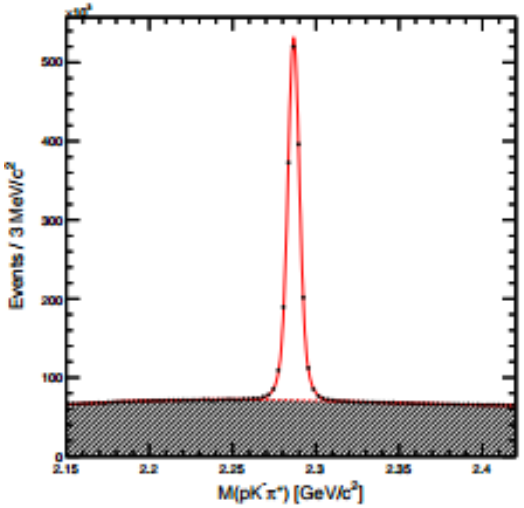
Internal W-emission

Introduction

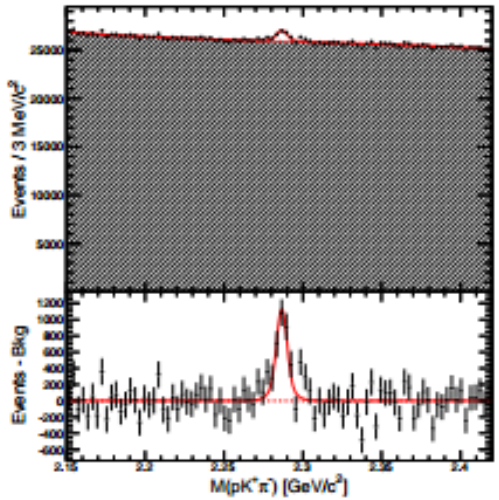
- Doubly Cabibbo-suppressed (DCS) decays seen in charm mesons, but not previously in baryons.
  Naïve expectation: $\frac{\mathcal{B}(DCS)}{\mathcal{B}(CF)} = tan^4\,\theta_c = 0.285\%$
  Since W-exchange diagram is absent in DCS decay, $\frac{\mathcal{B}(DCS)}{\mathcal{B}(CF)}$ may be smaller than the naïve expectation.
- This analysis uses 980/fb of data collected at and near $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \Upsilon(4S)$ and $\Upsilon(5S)$ resonances.



Study of $\Lambda_c^+ \to pK^+\pi^-$



1.45M events in Cabibbo favored (CF) decay



3587±380 events

After subtraction of $\Lambda_c^+ \to \Lambda K^+ \to p\pi^- K^+$, we observe 3379±380±78 DCS events with a significance > 9σ!

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$$
$$= (0.82 \pm 0.12)\, tan^4\, \theta_c$$

Absolute branching fraction

$$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-) = (1.61 \pm 0.23^{+0.07}_{-0.08}) \times 10^{-4}$$

(First observation)

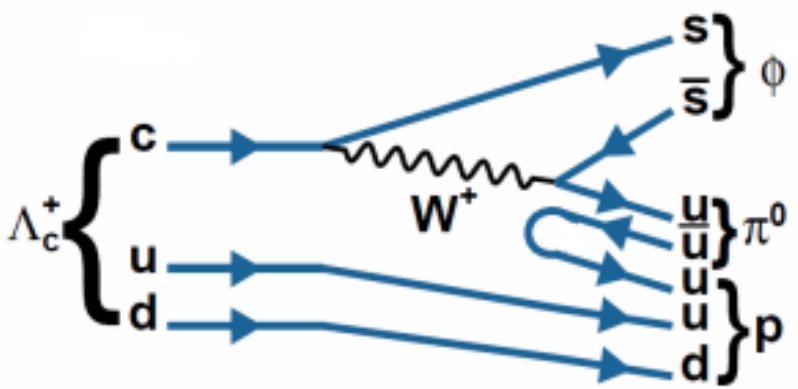
After subtracting the contribution $\Lambda^*(1520)$ and Δ isobar intermediates, which only contribute to CF decay, the revised ratio

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.10 \pm 0.17)\, tan^4\, \theta_c$$

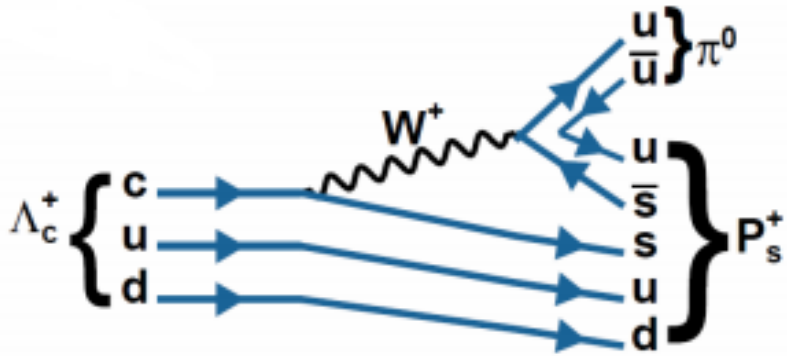
compatible with naïve expectation: no large W-exchange contribution in CF decay.

Study of $\Lambda_c^+ \to \phi p \pi^0$ with a search for the pentaquark state P_s^+ and measurement of $\Lambda_c^+ \to K^- \pi^+ p \pi^0$

PRD 96, 051102(R) (2017)



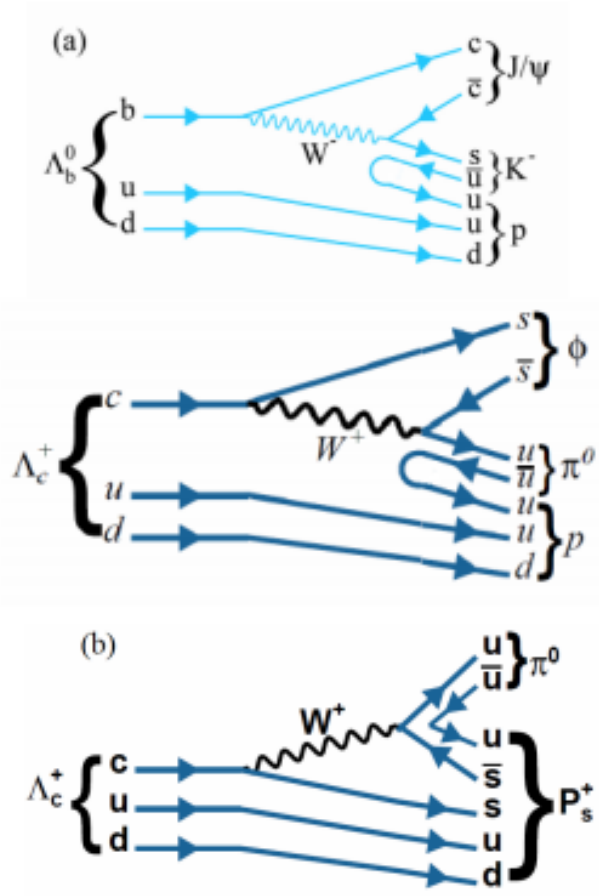
$\Lambda_c^+ \to \phi p \pi^0$



$\Lambda_c^+ \to P_s^+ \pi^0$

Introduction

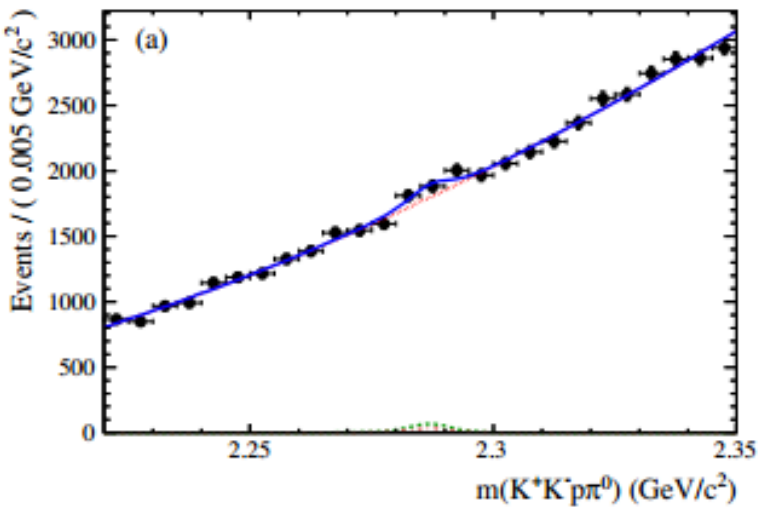
- LHCb's hidden-charm pentaquark (P_c^+) discovery in $J/\psi p$ of $\Lambda_b^0 \to J/\psi p K^-$
- Strange analog state (P_s^+) may appear in ϕp of $\Lambda_c^+ \to \phi p \pi^0$ assuming production mechanism is flavor independent
  - V. Kopeliovich, arxiv:1510.05958 [hep-ph], R. F. Lebed, PRD92, 114030
  - Cabibbo-suppressed decay
- LEPS & CLAS observed a bump at $\sqrt{s}$~2.2 GeV in ϕ photoproduction
  - PRL95, 182001, PRC89 055208, PRC90 019901
- This analysis used 916/fb of data collected at and near $\Upsilon(4S)$ and $\Upsilon(5S)$
- In addition, the precise measurement of branching fraction of Cabibbo favored decay $\Lambda_c^+ \to p\pi^+ K^- \pi^0$ is presented

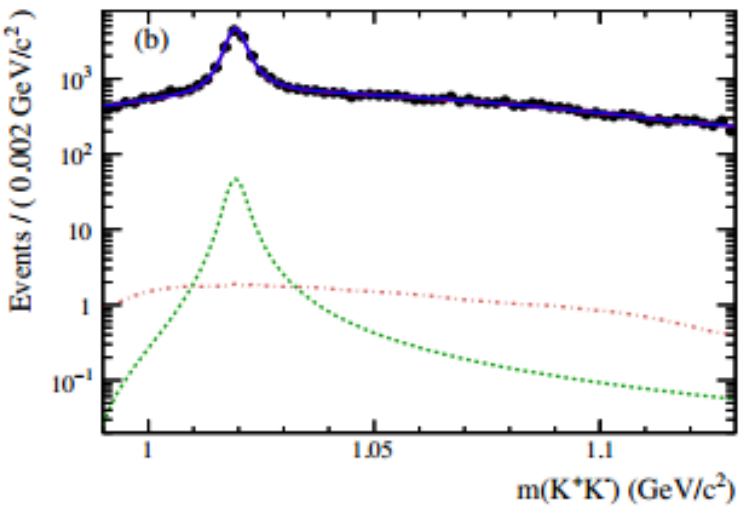


Study of $\Lambda_c^+ \to \phi p \pi^0$

- Exclude events of M($p\pi^0$) within 10 MeV of mass of Σ^+
- Two dimensional fit is performed to $pK^+K^-\pi^0$ and K^+K^- invariant masses in order to extract the Λ_c^+ signal yield
  - 148.4±61.8 for $\Lambda_c^+ \to p\phi\pi^0$ with 2.4σ statistical significance
  - 75.9±84.8 for $\Lambda_c^+ \to pK^+K^-\pi^0$ with 1.0σ statistical significance

$$\mathcal{B}(\Lambda_c^+ \to \phi p \pi^0) < 15.3 \times 10^{-5},$$
$$\mathcal{B}(\Lambda_c^+ \to K^+K^- p\pi^0)_{\rm NR} < 6.3 \times 10^{-5},$$



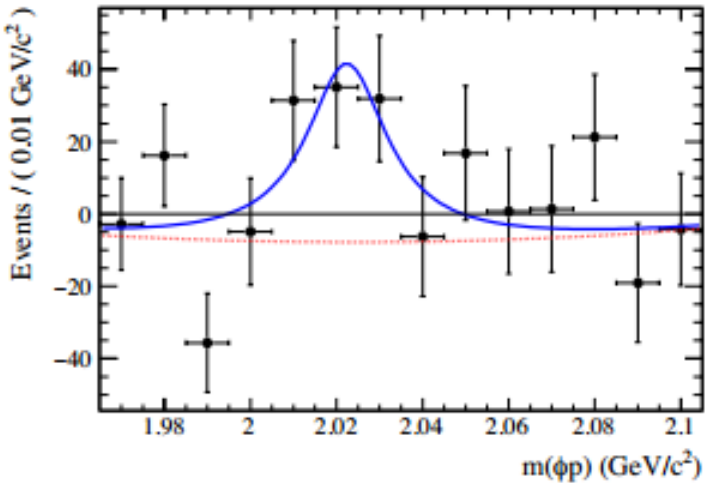


Search for P_s^+ and measurement of $\Lambda_c^+ \to K^-\pi^+p\pi^0$

$$M_{P_s^+} = (2.025 \pm 0.005)\,\mathrm{GeV}/c^2$$
$$\Gamma_{P_s^+} = (0.022 \pm 0.012)\,\mathrm{GeV}$$

- Select $\Lambda_c^+ \to pK^+K^-\pi^0$ candidates in which M(K^+K^-) is within 20 MeV of the mass of ϕ
  - 77.6±28.1 evens

$$\mathcal{B}(\Lambda_c^+ \to P_s^+\pi^0) \times \mathcal{B}(P_s^+ \to \phi p) < 8.3 \times 10^{-5}$$



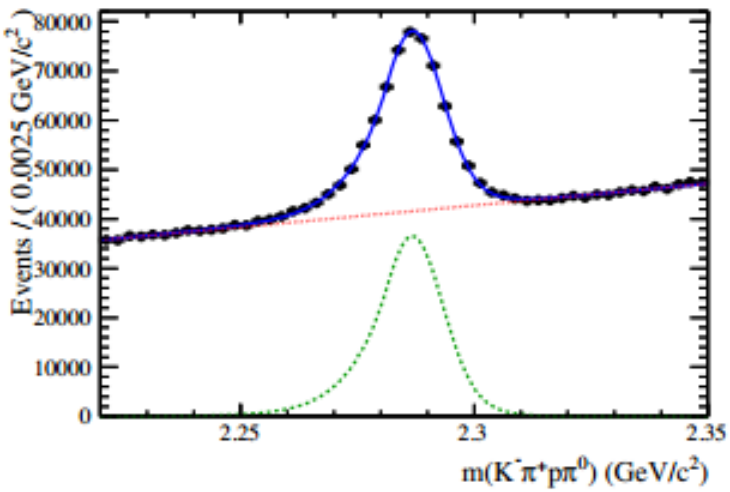
- Fit to M($pK^-\pi^+\pi^0$) spectrum
  - Two crystal ball functions with a common mean for signal, and a linear function for background

$$\mathcal{B}(\Lambda_c^+ \to K^-\pi^+p\pi^0) = (4.42 \pm 0.05 \pm 0.12 \pm 0.16)\%$$

  - World best measurement,

consistent with BESIII (PRL116, 052001)

$$\mathcal{B}(\Lambda_c^+ \to K^-\pi^+p\pi^0) = (4.53 \pm 0.23 \pm 0.30)\%$$



Measurement of branching fractions of hadronic decays of the Ω_c^0 state

Preliminary results to be submitted to PRD

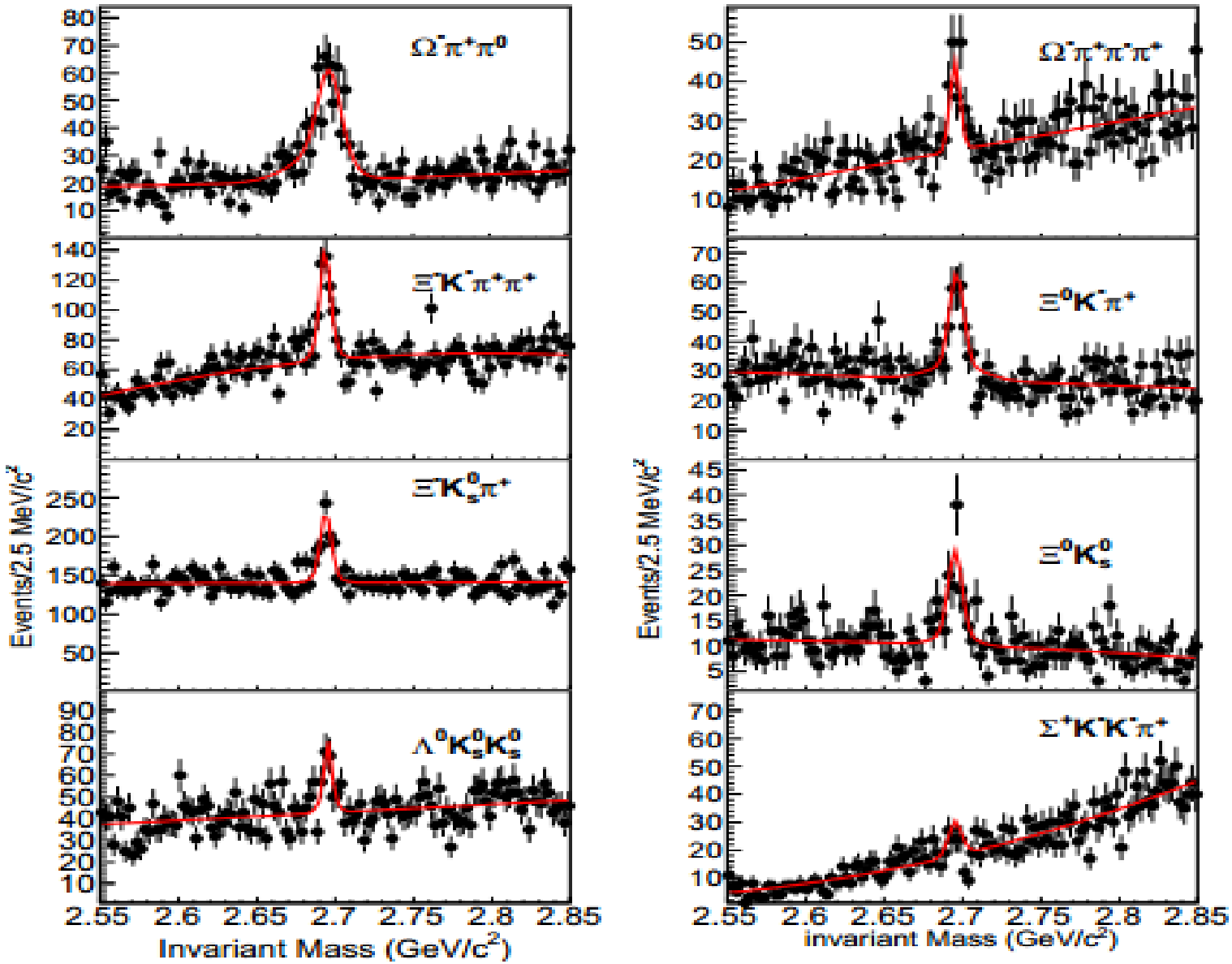
Signal modes:

- $\Omega_c^0 \to \Omega^- \pi^+ \pi^0$
- $\Omega_c^0 \to \Omega^- \pi^+ \pi^+ \pi^-$
- $\Omega_c^0 \to \Xi^- K^- \pi^+ \pi^+$
- $\Omega_c^0 \to \Xi^0 K^- \pi^+$
- $\Omega_c^0 \to \Xi^- \bar{K}^0 \pi^+$
- $\Omega_c^0 \to \Xi^0 \bar{K}^0$
- $\Omega_c^0 \to \Lambda \bar{K}^0 \bar{K}^0$
- $\Omega_c^0 \to \Sigma^+ K^- K^- \pi^+$

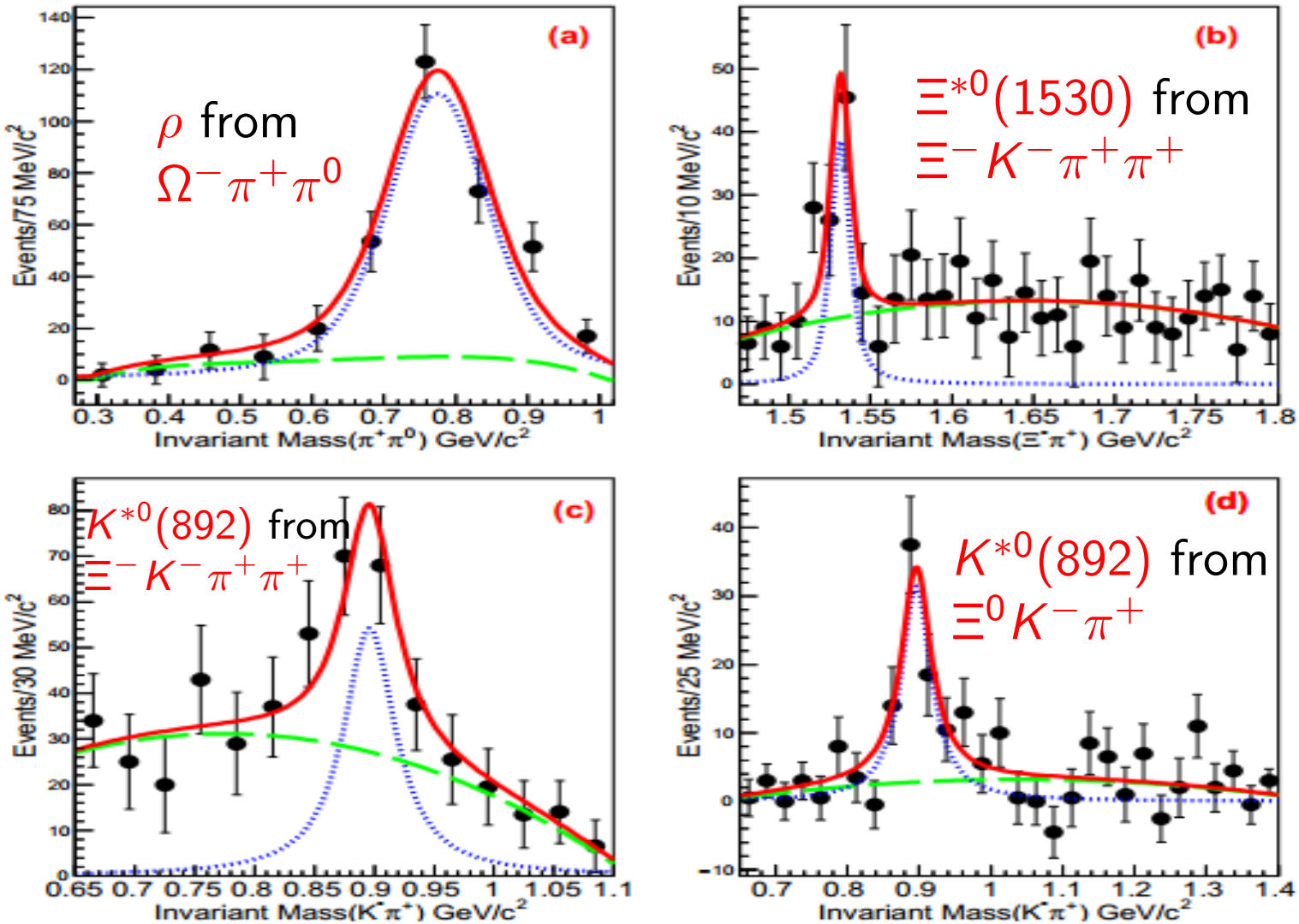
Normalizing mode:

- $\Omega_c^0 \to \Omega^- \pi^+$

Invariant mass distributions for signal modes (Preliminary)



Invariant mass distributions for resonant substructures in parts of signal modes (Preliminary)



Results (Preliminary)

Mode	Branching Ratio with respect to $\Omega^-\pi^+$	Substructure	Previous Measurement
$\Omega^-\pi^+$	1.0		
$\Omega^-\pi^+\pi^0$	$2.00 \pm 0.17 \pm 0.11$		$1.27 \pm 0.3 \pm 0.11$ [3]
$\Omega^-\rho^+$		$> 71\%$	
$\Omega^-\pi^+\pi^-\pi^+$	$0.32 \pm 0.05 \pm 0.02$		$0.28 \pm 0.09 \pm 0.01$ [3]
$\Xi^-K^-\pi^+\pi^+$	$0.68 \pm 0.07 \pm 0.04$		$0.46 \pm 0.13 \pm 0.03$ [3]
$\Xi^{*0}(1530) - K^-\pi^+$		$(55 \pm 16)\%$	
$\Xi^-\bar{K}^{*0}\pi^+$		$(33 \pm 9)\%$	
$\Xi^0K^-\pi^+$	$1.20 \pm 0.16 \pm 0.09$		$4.0 \pm 2.5 \pm 0.4$ [2]
$\Xi^0\bar{K}^*$		$(57 \pm 10\%)$	
$\Sigma^+K^-K^-\pi^+$	< 0.32		
$\Xi^-\bar{K}^0\pi^+$	$2.12 \pm 0.24 \pm 0.14$		
$\Xi^0\bar{K}^0$	$1.64 \pm 0.26 \pm 0.12$		
$\Lambda\bar{K}^0\bar{K}^0$	$1.72 \pm 0.32 \pm 0.14$		

- Most precise measurements of 4 branching fractions
- First measurements of 3 branching fractions
- Upper limit of 1 branching fraction
- Clear observations of 4 resonant substructures

Observation of excited Ω_c^0 charmed baryons in e^+e^- collisions

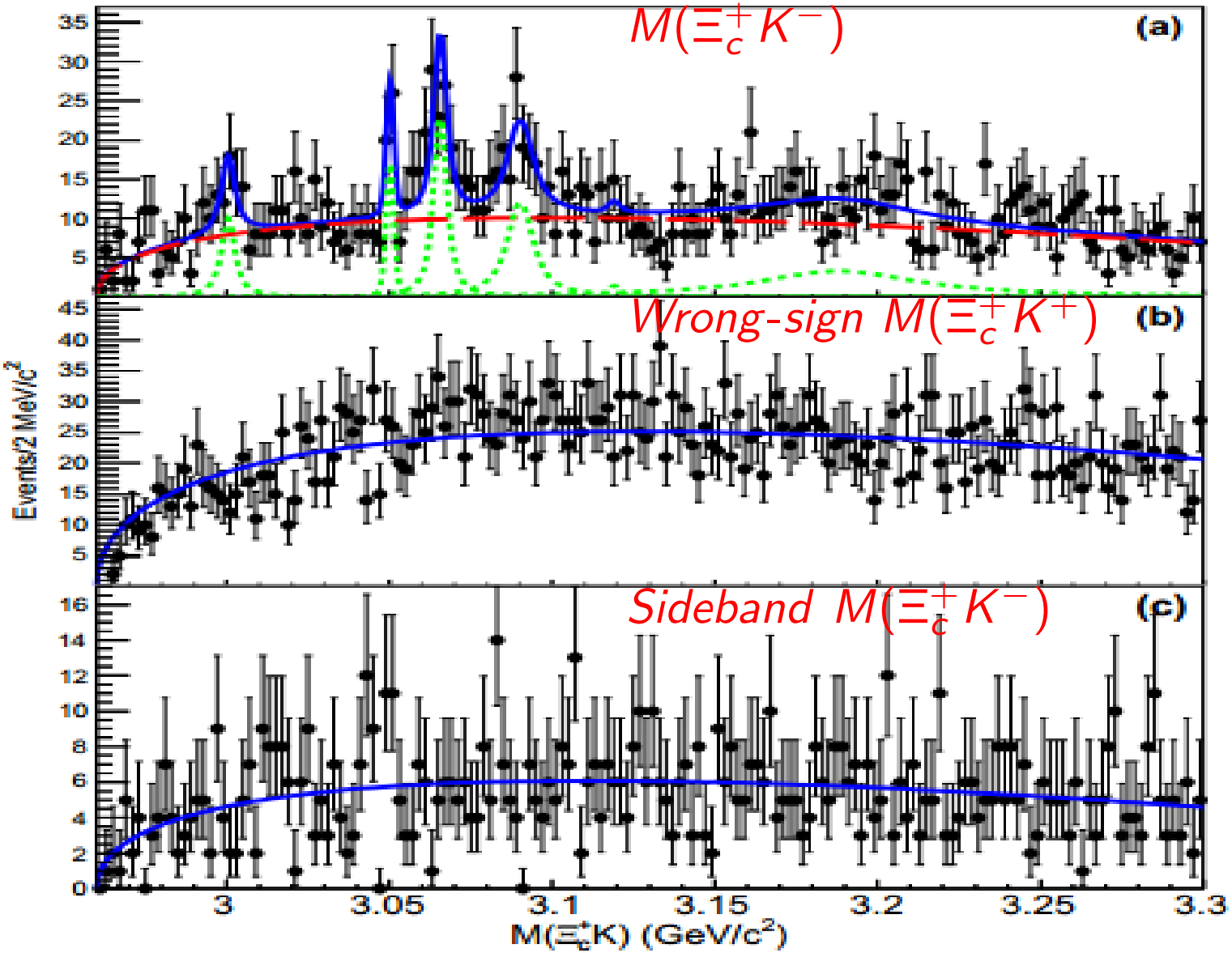
Preliminary results to be submitted to PRD (RC)

This year, five excited Ω_c^0 states were discovered by LHCb in $\Xi_c^+ K^-$:

- $\Omega_c^0(3000)$
- $\Omega_c^0(3050)$
- $\Omega_c^0(3066)$
- $\Omega_c^0(3090)$
- $\Omega_c^0(3119)$

We tried to confirm these states in e^+e^- collisions with Belle data.

$M(\Xi_c^+ K)$ (Preliminary)



Results (Preliminary)

- The masses and intrinsic widths of all six are fixed to the values given by LHCb
- Strong confirmation of $\Omega_c^0(3066)$ and $\Omega_c^0(3090)$
- confirmation of $\Omega_c^0(3000)$ and $\Omega_c^0(3050)$
- No confirmation of $\Omega_c^0(3119)$ (but no disagreement due to the small statistics)
- confirmation of wide excess at higher mass.

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, (σ)	4.0	4.7	7.4	5.8	0.6	3.2
LHCb Mass (MeV/c^2)	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119 \pm .0.3 \pm 0.9$	$3188 \pm 5 \pm 13$
Belle Mass (MeV/c^2) (fixed Γ)	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	-	$3199 \pm 9 \pm 4$

- Alternatively, the masses of the five signals are measured by fitting the same distribution without constraining the masses.
- In all cases, the results are consistent with the LHCb values.

Summary

- Mass and widths of 5 excited Ξ_c states decaying into $\Xi_c\pi$
  - Masses: ~1order improvement of precision
  - Widths: 5 first measurements ($\Xi_c(2645)^0$, $\Xi_c(2815)^+$, $\Xi_c(2815)^0$, $\Xi_c(2790)^+$, $\Xi_c(2790)^0$)
- Higher excited Ξ_c decaying into ΛD
  - Relative BFs (ΛD / $\Sigma_c K$) for $\Xi_c(3055)$, $\Xi_c(3080)$
  - Relative BF ($\Sigma_c^* K$ / $\Sigma_c K$) for $\Xi_c(3080)$
  - Mass and width of $\Xi_c(3055)^0$
- Studies of Λ_c^+ decay modes
  - Upper limit on $\Lambda_c^+ \to p\phi\pi^0$ and P_s
  - Precise measurement of B.F. of $\Lambda_c^+ \to pK^-\pi^+\pi^0$
  - First observation of DCS decay of $\Lambda_c^+ \to pK^+\pi^-$

- **Studies of the Ω_c^0 state and its excited states**
  - **Four of the Ω_c^0 decay branching fractions are measured most precise to date, and three are measured first time.**
  - **Four of the five Ω_c^0 excited states discovered by LHCb are confirmed.**

Thanks for your attention !

Backup

Study of $\Lambda_c^+ \to pK^+\pi^-$ — Dalitz Plot