Recent results on charmed baryon weak decays from Belle

Yang Li (Fudan University)
On behalf of Belle Collaboration

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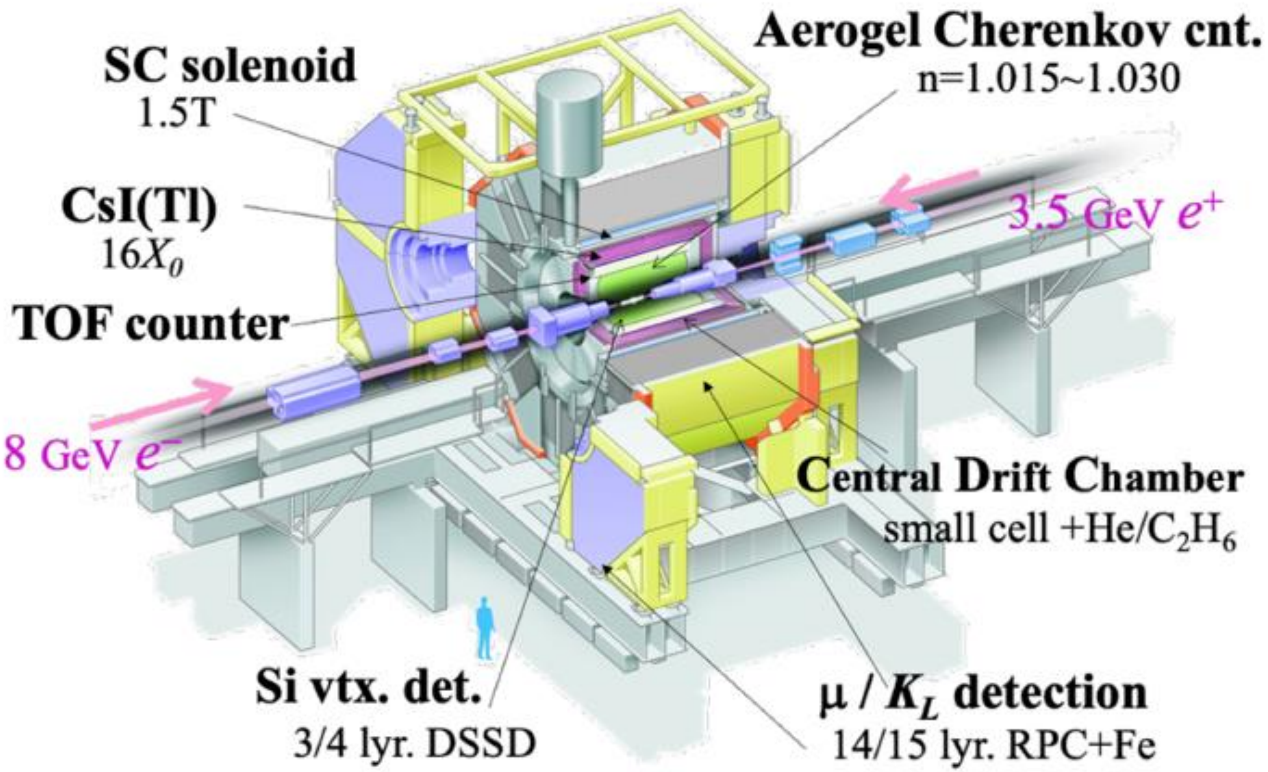
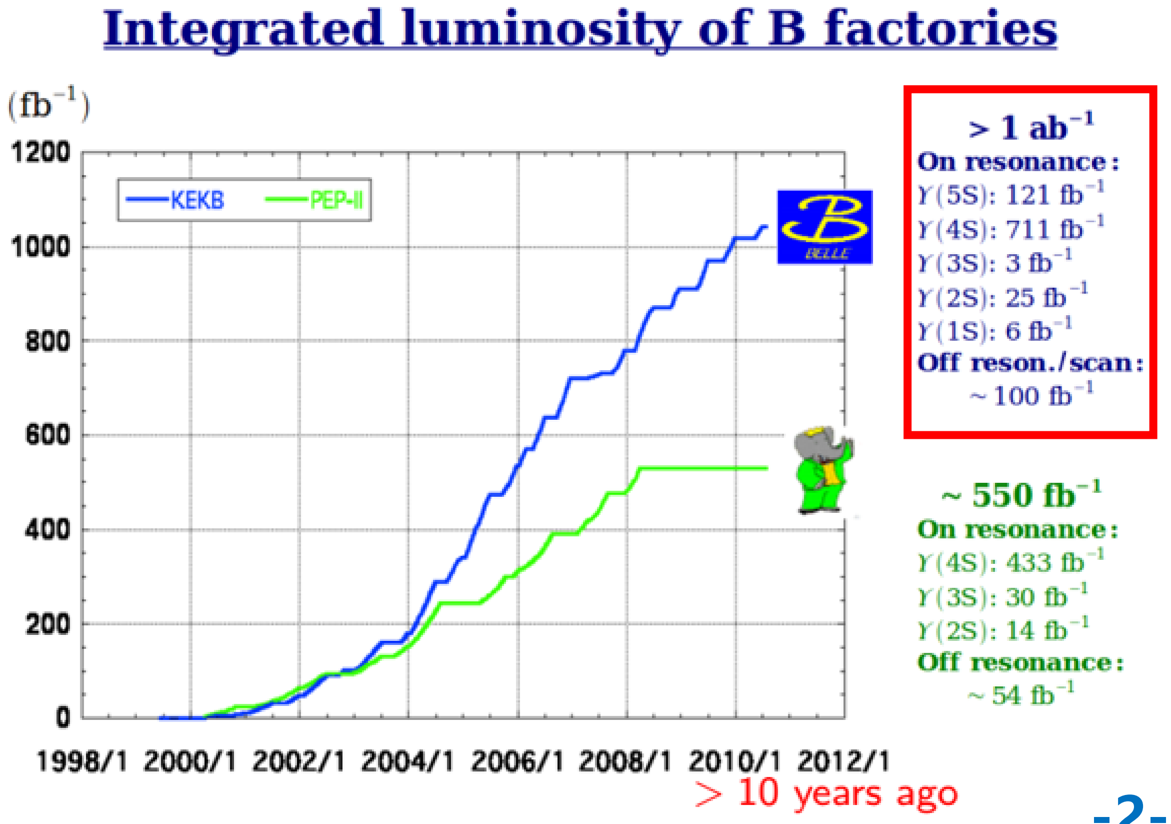
in memoriam Simon Eidelman
July 26~31, 2021

Belle experiment and data samples

- KEKB is an asymmetric-energy e^+e^- collider operating near $\Upsilon(4S)$ mass peak (~10.58GeV/c^2, > $B\bar{B}$ threshold);
- Belle detector has good performances on momentum/vertex resolution; particle identification, etc;
- Accumulated data set of ~1 ab^{-1}: not only including a large $B\bar{B}$ sample as a B-factory, but also providing us a large charm sample to study charm physics.





Outline

- ✓ Measurements of branching fractions of $\Lambda_c^+ \to p(\eta, \pi^0), \pi^+\eta(\Lambda, \Sigma^0)$, $\pi^+\Lambda(1670)$, and $\eta\Sigma(1385)^+$; [PRD103, 072004 (2021), PRD103, 052005 (2021)]
- ✓ Measurements of the resonant and non-resonant branching ratios in $\Xi_c^0 \to \Xi^0 K^+ K^-$; [PRD 103 112002 (2021)]
- ✓ Measurements of branching fractions and asymmetry parameters of $\Xi_c^0 \to \Lambda\overline{K}^{*0}/\Sigma^0\overline{K}^{*0}/\Sigma^+K^{*-}$; [JHEP 06(2021) 160]
- ✓ Evidence for $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\overline{K}\Xi)^-$; [arXiv:2106.00892, accepted by PRD]
- ✓ Summary

Measurements of branching fractions of $\Lambda_c^+ \to p(\eta, \pi^0)$

Motivation:

- In theory, the singly Cabibbo-suppressed (SCS) decays $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$ proceed predominantly through internal W-emission and W-exchange;

- The theoretical calculations predict $\mathrm{Br}(\Lambda_c^+ \to p\eta)$ is at least an order of magnitude greater than that of $\mathrm{Br}(\Lambda_c^+ \to p\pi^0)$: [PRD 97, 074028 (2018)]

$$\mathrm{Br}(\Lambda_c^+ \to p\eta) = 1.28 \times 10^{-3},\ \mathrm{Br}(\Lambda_c^+ \to p\pi^0) = 7.5 \times 10^{-5};$$

- In experiment, the branching fractions of SCS decays of $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$ are firstly measured by BESIII Collaboration. [PRD 95, 111102 (2017)]

$$\mathrm{Br}(\Lambda_c^+ \to p\eta) = (1.24 \pm 0.30) \times 10^{-3}(4.2\sigma), \mathrm{Br}(\Lambda_c^+ \to p\pi^0) < 2.7 \times 10^{-4} \text{ at 90\% C.L..}$$

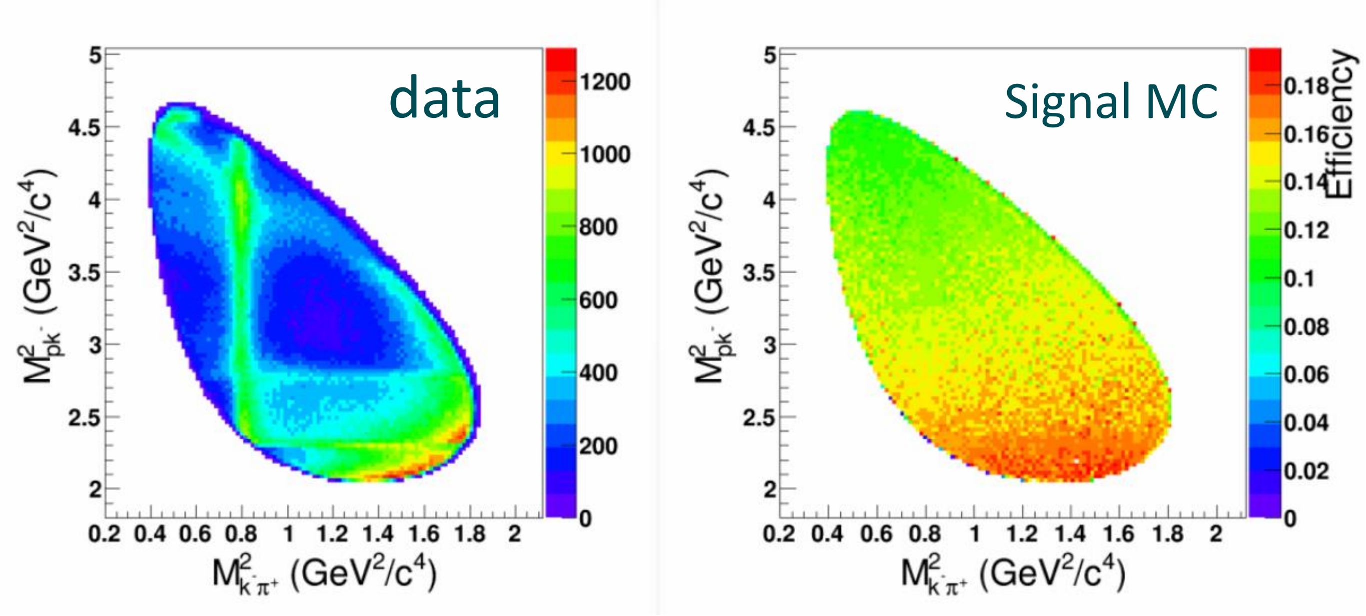
- To improve the measurement precision, we measure the branching fractions of $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$ using all Belle data sets.

Measurement of normalization mode

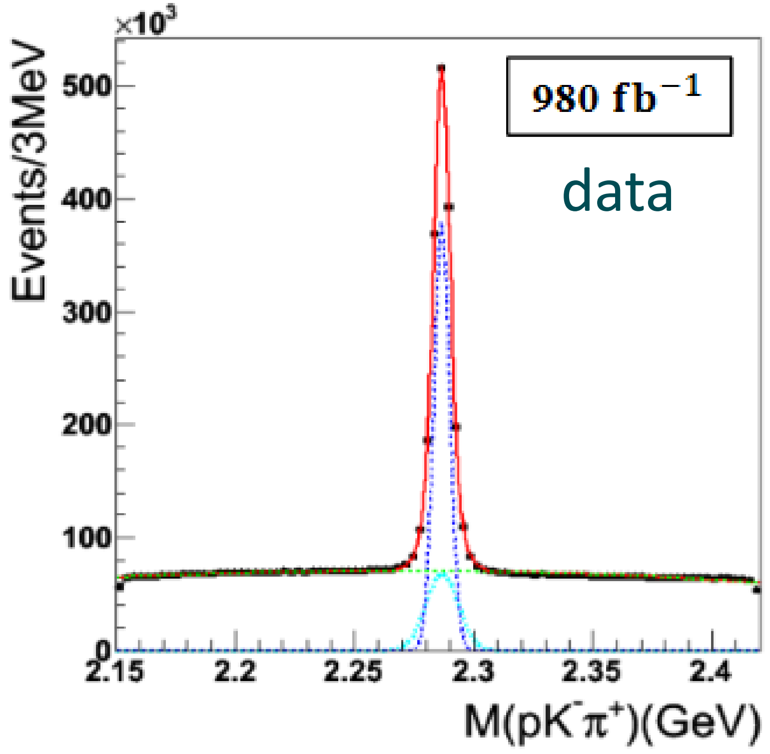
- A method of branching ratio with respect to Cabibbo favored (CF) decay $\Lambda_c^+ \to pK^-\pi^+$ (normalization mode) is applied to measure the branching fractions of two SCS decays.

$$\frac{Br(SCS)}{Br(CF)} = \frac{N^{obs}(SCS)}{\epsilon\,(SCS) \times Br(\eta/\pi^0 \to \gamma\gamma)} \times \frac{\epsilon(CF)}{N^{obs}(CF)}$$

Signal efficiency estimation: Dalitz method.



efficiency: $\epsilon = \frac{\Sigma s_i}{\Sigma(s_j/\epsilon_j)} = (14.06 \pm 0.01)\%$



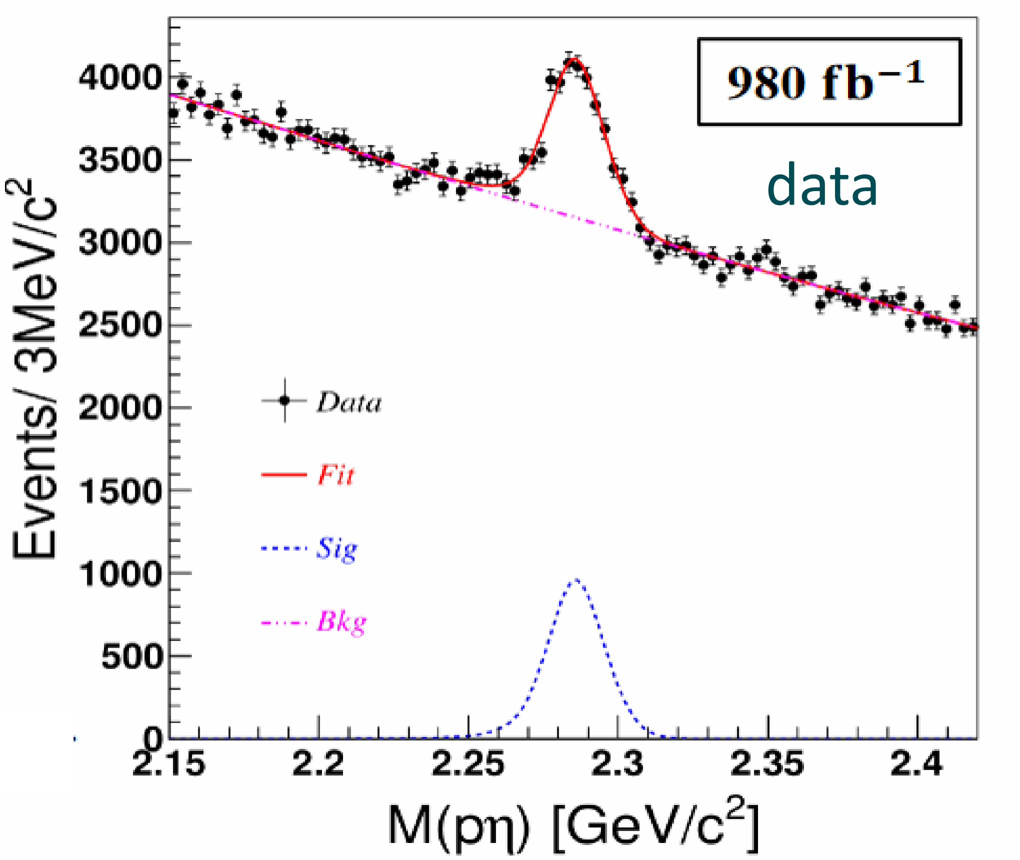
Double Gaussian + second-order polynomial

Signal yield: 1476200 ± 1560
$\chi^2/\mathrm{ndf} = 1.06$

Measurement of $\Lambda_c^+ \to p\eta(\to \gamma\gamma)$ decay

[PRD103, 072004 (2021)]

- The efficiency estimated from signal MC sample is $(8.279 \pm 0.030)\%$.



Gaussian + CB for signal,
Second-order polynomial for background.

Signal yield: 7734 ± 263
$\chi^2/\mathrm{ndf} = 1.23$

✓ A significant Λ_c^+ signal is observed in data;

✓ Measured $Br(\Lambda_c^+ \to p\eta) = (1.42 \pm 0.05(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})) \times 10^{-3}$;

✓ Consistent with BESIII result $(1.24 \pm 0.30) \times 10^{-3}$ with much improved precision;

✓ Consistent with theoretical prediction 1.28×10^{-3}.

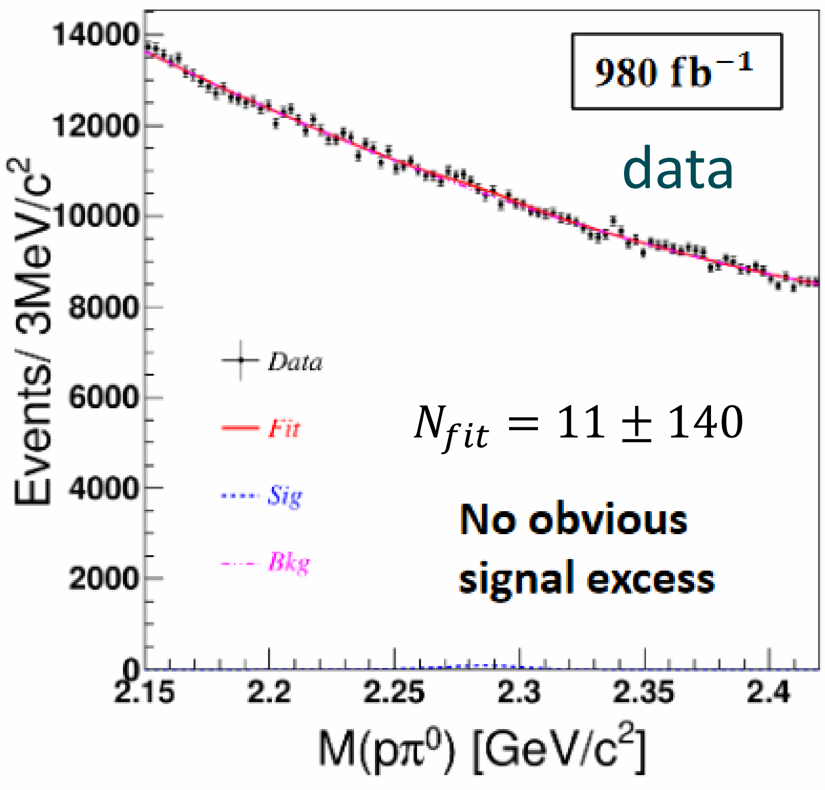
[PRD 95, 111102 (2017); PRD 97, 074028 (2018)]

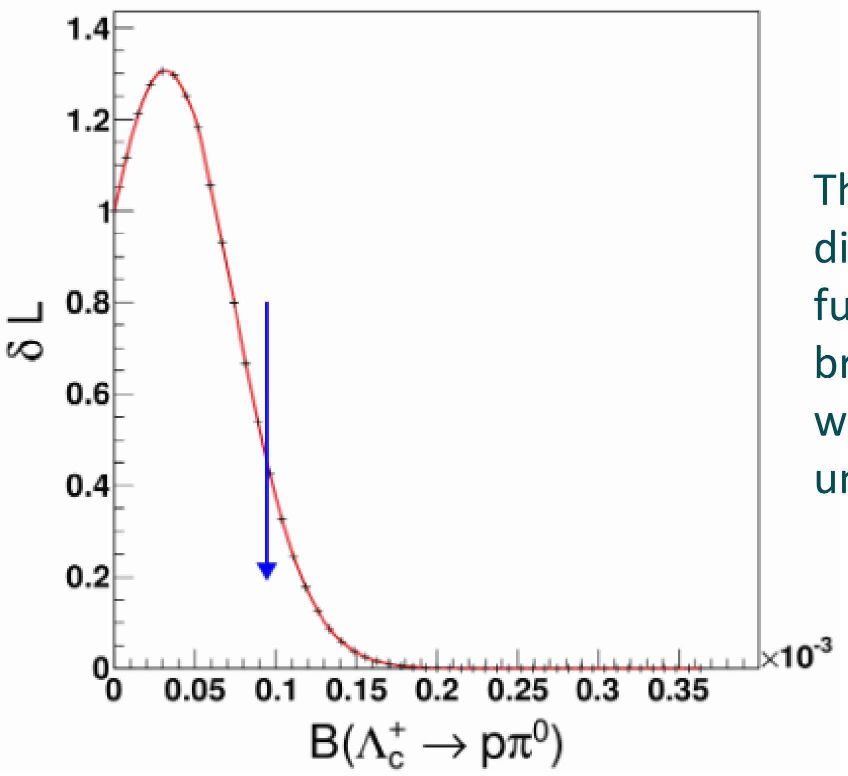
Measurement of $\Lambda_c^+ \to p\pi^0 (\to \gamma\gamma)$ decay

[PRD103, 072004 (2021)]

- The efficiency estimated from signal MC sample is $(8.891 \pm 0.030)\%$.

fit to $M(p\pi^0)$ from data





The likelihood distribution as a function of the branching fraction, with the systematic uncertainty involved.

✓ Measured $Br(\Lambda_c^+ \to p\pi^0) < 8.0 \times 10^{-5}$;

✓ reducing the value to more than three times of the BESIII result 2.7×10^{-4};

✓ Consistent with theoretical prediction 7.5×10^{-5}. [PRD 95, 111102 (2017); PRD 97, 074028 (2018)]

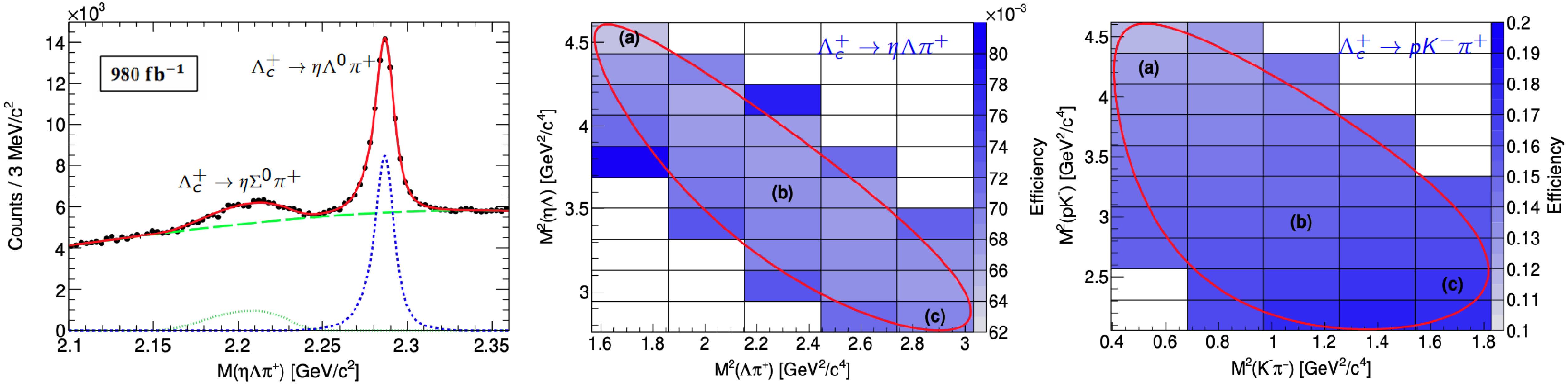
Measurements of $\Lambda_c^+ \to \eta\Lambda\pi^+/\eta\Sigma^0\pi^+$

[PRD103, 052005 (2021)]

- A method to measure the branching fractions of above two decays is:

$$\frac{Br(\text{Decay mode})}{Br(\Lambda_c^+ \to pK^-\pi^+)} = \frac{y(\text{Decay mode})}{Br_{PDG} \times y(\Lambda_c^+ \to pK^-\pi^+)}$$

(y refers to the efficiency-corrected yield, Br_{PDG} denotes subdecay branching fractions of the η, Λ, and Σ^0)

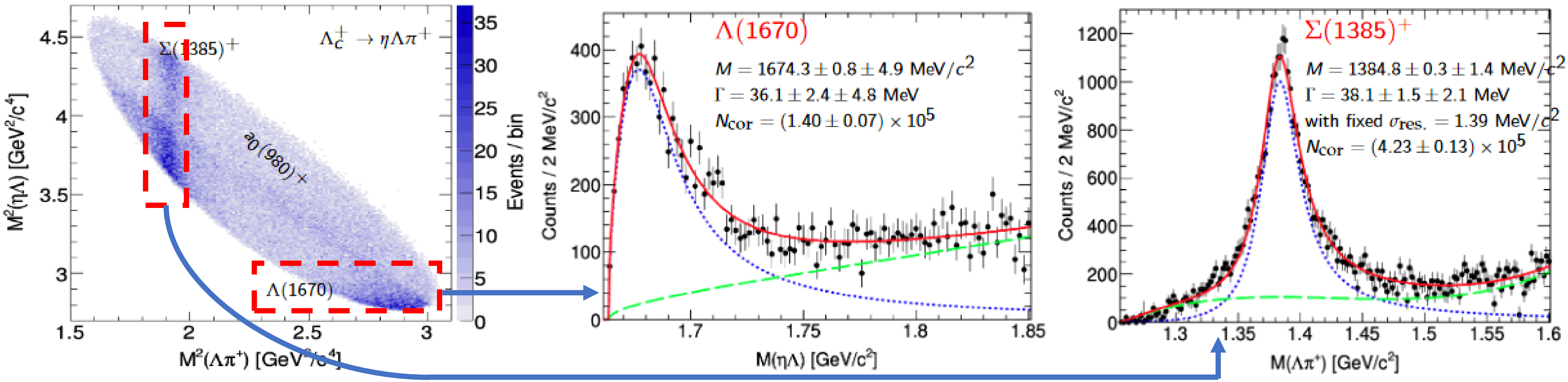


Decay mode	$y(\times 10^5)$	Branching fraction	Reference mode	$y(\times 10^5)$
$\Lambda_c^+ \to \eta\Lambda\pi^+$	$(7.41 \pm 0.07(stat.))$	$(1.84 \pm 0.02(\text{stat.}) \pm 0.09(\text{sys.}))\%$	$\Lambda_c^+ \to pK^-\pi^+$	$(100.47 \pm 0.10(\text{stat.}))$
$\Lambda_c^+ \to \eta\Sigma^0\pi^+$	$(3.05 \pm 0.16(stat.))$	$(7.56 \pm 0.39(\text{stat.}) \pm 0.37(\text{sys.})) \times 10^{-3}$		

Measurements of $\Lambda_c^+ \to \Lambda(1670)\pi^+/\eta\Sigma(1385^+)$

[PRD103, 052005 (2021)]

- $\Lambda_c^+ \to \Lambda(1670)\pi^+$ and $\Lambda_c^+ \to \eta\Sigma(1385)^+$ are visible in Dalitz plot.
- Fit to the $M(\eta\Lambda\pi^+)$ distributions in every 2 MeV/c^2 bin of the $M(\eta\Lambda)$ and $M(\Lambda\pi^+)$ distributions to extract the signal yields.
- Clear $\Lambda(1670)$ and $\Sigma(1385)^+$ signals show up.



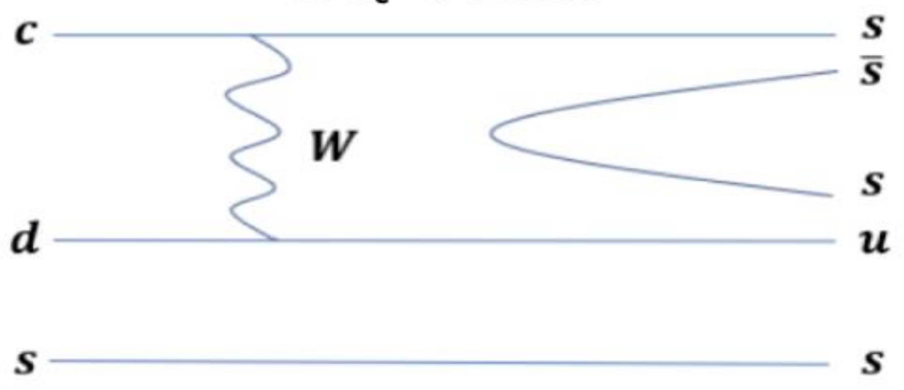
Decay mode	Yield	$y(\times 10^5)$	Branching fraction
$\Lambda_c^+ \to \Lambda(1675)\pi^+$	$9760 \pm 519(\text{stat.})$	$(1.40 \pm 0.07(\text{stat.}))$	$(3.48 \pm 0.19(\text{stat.}) \pm 0.46(\text{sys.})) \times 10^{-3}$ *
$\Lambda_c^+ \to \eta\Sigma(1385)^+$	$29372 \pm 875(\text{stat.})$	$(4.23 \pm 0.13(\text{stat.}))$	$(1.21 \pm 0.04(\text{stat.}) \pm 0.16(\text{sys.}))\%$

*$Br(\Lambda_c^+ \to \Lambda(1670)\pi^+) \times Br(\Lambda(1670 \to \eta\Lambda))$

Measurements of the (non-)resonant Brs in $\Xi_c^0 \to \Xi^0 K^+ K^-$

- Spin-Polarized $\Xi_c^0 \to \Xi^0\phi(\to K^+K^-)$ substructure:

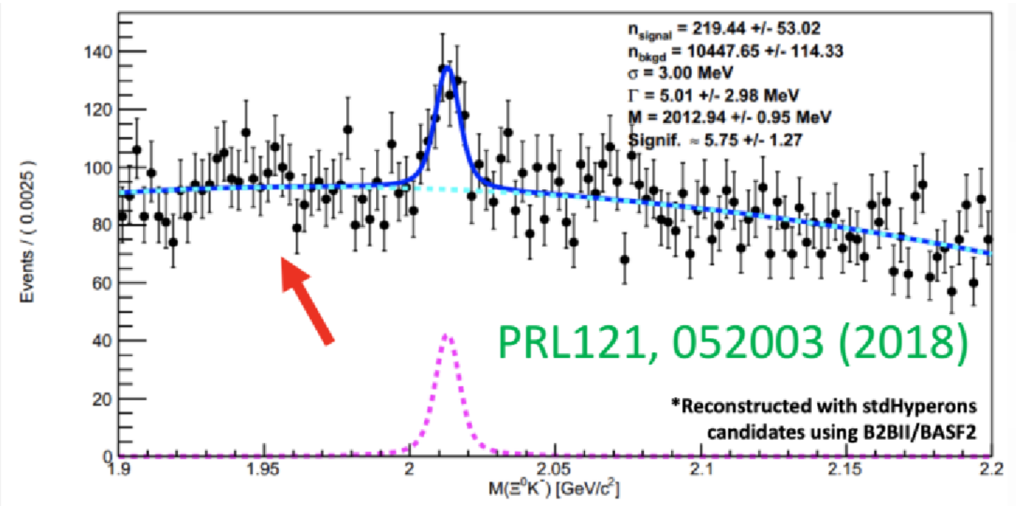
Cabbibo-allowed, W-Exchange $s\bar{s}$-popping decay of $\Xi_c^0 \to \Xi^0 K^+ K^-$



[PRD 103 112002 (2021)]

- A resonant $\phi(\to K^+K^-)$ in the decay channel $\Xi_c^0 \to \Xi^0\phi(\to K^+K^-)$ is known to be polarized due to the spin helicities of the parent baryon decay $(\frac{1}{2} \to \frac{1}{2} + 1)$.

- Background motivation in excited Ω search:



- From quark model predictions, it can be expected that Ω(2012) could have a partner near 1.95 GeV/c^2 [PRD 101, 016002 (2020)], and low-statistics indications of an excess in $M(\Xi^0 K^-)$ has been noticed.

Dalitz Plot

[PRD 103 112002 (2021)]

- Across the entire $\mathrm{M}(\Xi^0 \mathrm{K}^+ \mathrm{K}^-)$ phase-space only a signal resonance ($\phi \to K^+ K^-$) at $\mathrm{M}^2(\mathrm{K}^+ \mathrm{K}^-) = 1.04\ \mathrm{GeV}^2/c^4$ is observed;
- This non-uniform substructure is specifically observed near $M^2(\Xi^0 K^-) \approx 3.85\ \mathrm{GeV}^2$ and $3.425\ \mathrm{GeV}^2$ a long the ϕ band.
- The non-uniform contributions to the resonant substructure in the $\Xi_c^0 \to \Xi^0 \phi$ decay are modelled using an amplitude analysis over the decay phase space. [AmpTools (v.10.2)]

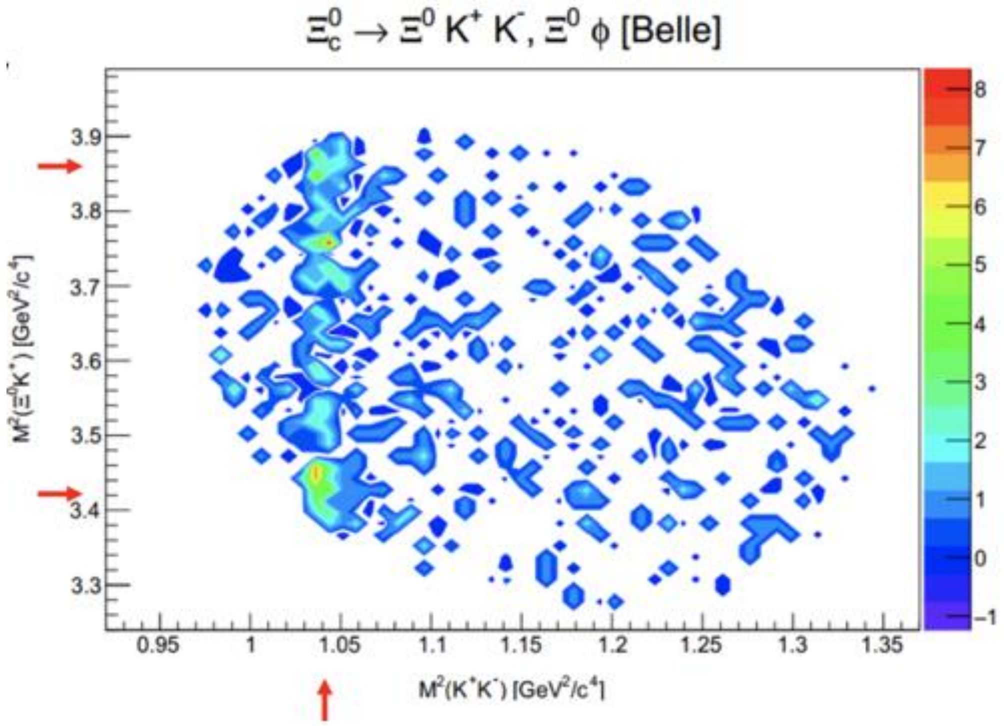


Figure: Dalitz plot distribution of the $\Xi_c^0 \to \Xi^0 K^+ K^-$ decays in the sideband-subtracted Ξ_c^0 signal region.

Amplitude Model to Analyze the Dalitz Plot:

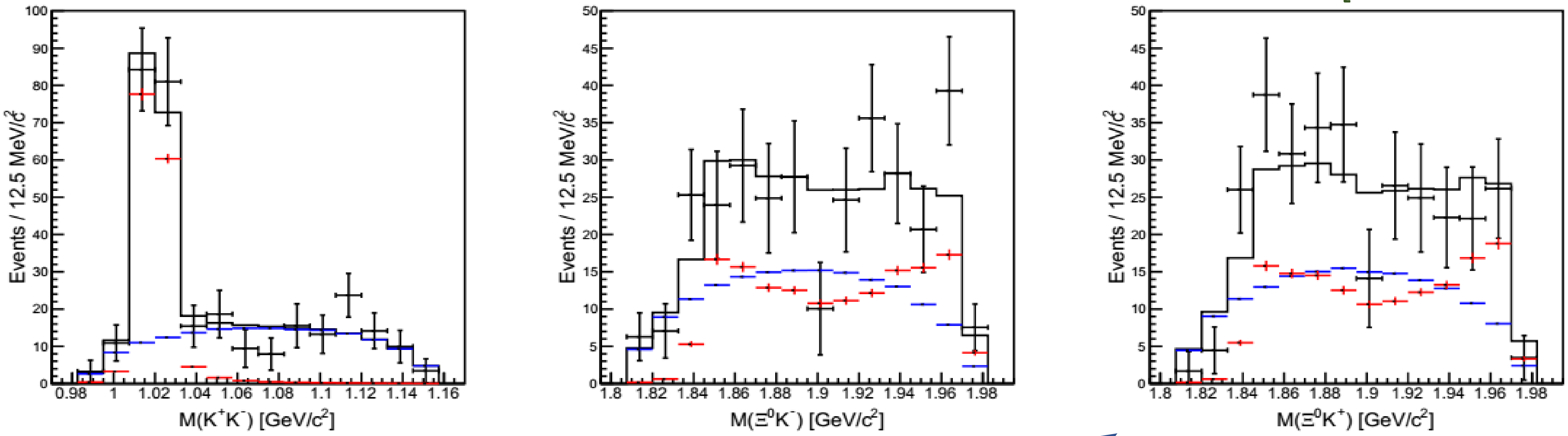
$$< \Xi_c^0 | H | \Xi^0 K^+ K^- > = < \Xi_c^0 | H | \Xi^0 K^+ K^- > + < \Xi_c^0 | H | \Xi^0 \phi >$$

Direct process, phase space decays are modelled with a constant, phase space amplitude (A_{phsp})

Polarized resonances are modelled with a Breit-Wigner and Spin-Polarization amplitude

Amplitude fit over the Belle data sample

[PRD 103 112002 (2021)]



$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0 \phi(\to K^+K^-))}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)}$	0.036±0.004(stat.)±0.002(syst.)
$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0 K^+K^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)}$	0.039±0.004(stat.)±0.002(syst.)

Resonant Amplitude

Non-Resonant Amplitude

Amplitude Sum (Resonant and Non-Resonant)

- The measurements of these Ξ_c^0 decay modes, which can only proceed via W-exchange together with $s\bar{s}$ production, add to our knowledge of the weak decay of charmed baryons.
- It is suggest that only minor cusping peaks occur in the combinatorial background of $\Omega^{*-} \to \Xi^0 K^-$ due to these Ξ_c^0 decays.

Measurements of branching fractions and asymmetry parameters of $\Xi_c^0 \to \Lambda\overline{K}^{*0}/\Sigma^0\overline{K}^{*0}/\Sigma^+K^{*-}$

- There are some difficulties for the theoretical study in the non-leptonic decays of charmed baryons due to the failure of the factorization approach.
- Branching fraction measurements help to distinguish different theoretical models.
- The asymmetry parameters of Ξ_c^0 are still not well measured, which is important to test parity violation in charmed-baryon sectors.

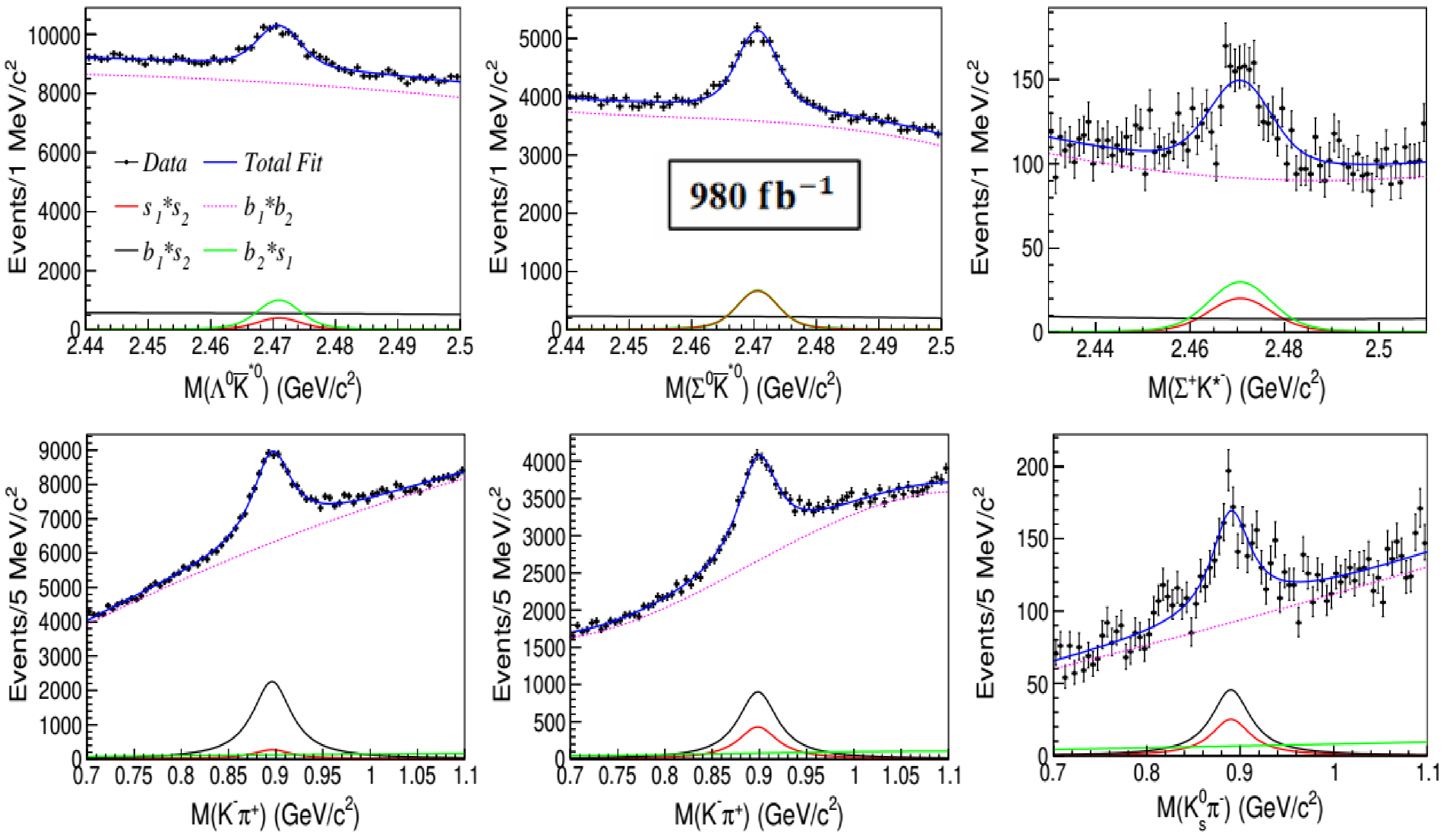
Tables: Decay branching fractions (%) and asymmetry parameters of the Cabibbo favored $B_c \to B_n + V$ decay in QCD and $SU(3)_F$ approaches.

Branching fractions	KK[ZPC 55, 659(1992)]	Zen[PRD 50,5787(1994)]	HYZ[PLB 792, 35(2019)]	GLT[PRD 101,053003(2020)]
$\Xi_c^0 \to \Lambda\overline{K}^{*0}$	1.55	1.15	0.46±0.21	1.37±0.26
$\Xi_c^0 \to \Sigma^0\overline{K}^{*0}$	0.85	0.77	0.27±0.22	0.42±0.23
$\Xi_c^0 \to \Sigma^+K^{*-}$	0.54	0.37	0.93±0.29	0.24±0.17

Asymmetry parameters	KK[ZPC 55, 659(1992)]	Zen[PRD 50,5787(1994)]	GLT[PRD 101,053003(2020)]
$\Xi_c^0 \to \Lambda\overline{K}^{*0}$	0.58	0.49	-0.67 ± 0.24
$\Xi_c^0 \to \Sigma^0\overline{K}^{*0}$	-0.87	0.25	-0.42 ± 0.62
$\Xi_c^0 \to \Sigma^+K^{*-}$	-0.60	0.51	$-0.76^{+0.64}_{-0.24}$

Measurements of Branching fractions

[JHEP 06(2021) 160]



- ✓ The signal yields are extracted via $M(\Xi_c^0)$ vs $M(\bar{K}^*)$ 2D fit.
- ✓ Then we have relative BF after efficiency correction:

$$\frac{Br(\Xi_c^0 \to \Lambda\bar{K}^{*0})}{Br(\Xi_c^0 \to \Xi^-\pi^+)} = 0.18 \pm 0.02 \pm 0.01$$

$$\frac{Br(\Xi_c^0 \to \Sigma^0\bar{K}^{*0})}{Br(\Xi_c^0 \to \Xi^-\pi^+)} = 0.69 \pm 0.03 \pm 0.03$$

$$\frac{Br(\Xi_c^0 \to \Sigma^+K^-)}{Br(\Xi_c^0 \to \Xi^-\pi^+)} = 0.34 \pm 0.06 \pm 0.02$$

- ✓ By using $Br(\Xi_c^0 \to \Xi^-\pi^+)$, we have absolute BFs below for the first time:

$$Br(\Xi_c^+ \to \Lambda\bar{K}^{*0}) = (3.3 \pm 0.3 \pm 0.2 \pm 1.0(\text{ref.})) \times 10^{-3}$$

$$Br(\Xi_c^+ \to \Sigma^0\bar{K}^{*0}) = (12.4 \pm 0.5 \pm 0.5 \pm 3.6(\text{ref.})) \times 10^{-3}$$

$$Br(\Xi_c^+ \to \Sigma^+K^-) = (6.1 \pm 1.0 \pm 0.4 \pm 1.8(\text{ref.})) \times 10^{-3}$$

- ✓ $\mathcal{B}(\Xi_c^0 \to \Sigma^0\bar{K}^{*0}) > \mathcal{B}(\Xi_c^0 \to \Lambda\bar{K}^{*0})$, which contradicts all the predictions based on $SU(3)_F$ flavor symmetry and dynamical models.

Asymmetry parameters extractions

- For $\Xi_c^0 \to \Lambda \bar{K}^{*0}$, $\Xi_c^0 \to \Sigma^0 \bar{K}^{*0}$ and $\Xi_c^0 \to \Sigma^+ K^{*-}$, the differential decay rates [PRD 101, 053002 (2020)] are given by:

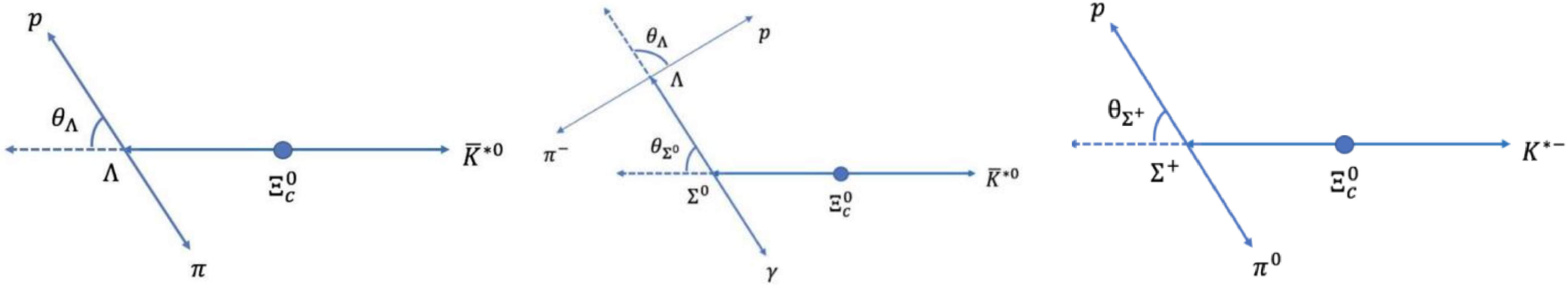
[JHEP 06(2021) 160]

$$\frac{dN}{dcos\theta_\Lambda} \propto 1 + \alpha(\Xi_c^0 \to \Lambda \bar{K}^{*0})\alpha(\Lambda \to p\pi^-)cos\theta_\Lambda,$$

$$\frac{dN}{dcos\theta_{\Sigma^0}} \propto 1 + \alpha(\Xi_c^0 \to \Sigma^0 \bar{K}^{*0})\alpha(\Sigma^0 \to \Lambda\gamma)cos\theta_{\Sigma^0},$$

$$\frac{dN}{dcos\theta_{\Sigma^+}} \propto 1 + \alpha(\Xi_c^0 \to \Sigma^+ K^{*-})\alpha(\Sigma^+ \to p\pi^0)cos\theta_{\Sigma^+},$$

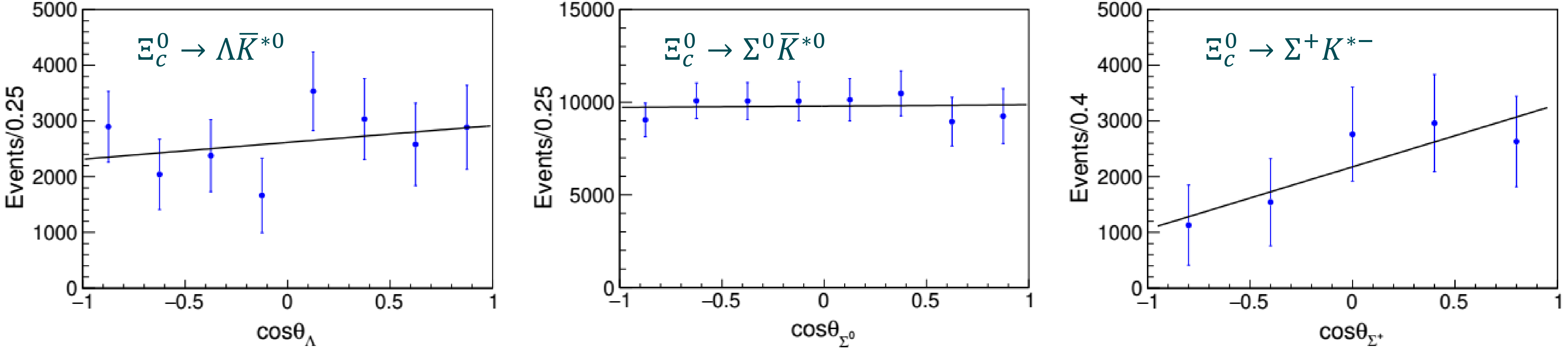
Definitions of θ_Λ, θ_{Σ^0}, and θ_{Σ^+}:



- The asymmetry parameter $\alpha(\Sigma^0 \to \Lambda\gamma)$ is expected to be zero due to the case of parity conservation for an electromagnetic decay of $\Sigma^0 \to \Lambda\gamma$. Thus, the distribution of $\cos\theta_{\Sigma^0}$ is expected to be flat.

Asymmetry parameters

[JHEP 06(2021) 160]



$\alpha(\Xi_c^0 \to \Lambda\bar{K}^{*0})\alpha(\Lambda \to p\pi^-)$	$0.115 \pm 0.164(\text{stat.}) \pm 0.038(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^0\bar{K}^{*0})\alpha(\Sigma^0 \to \gamma\Lambda)$	$0.008 \pm 0.072(\text{stat.}) \pm 0.008(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^+K^{*-})\alpha(\Sigma^+ \to p\pi^0)$	$0.514 \pm 0.295(\text{stat.}) \pm 0.012(\text{syst.})$
$\alpha(\Xi_c^0 \to \Lambda\bar{K}^{*0})$	$0.15 \pm 0.22(\text{stat.}) \pm 0.05(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^+K^{*-})$	$-0.52 \pm 0.30(\text{stat.}) \pm 0.02(\text{syst.})$

Note that $\alpha(\Lambda \to p\pi^-) = 0.747 \pm 0.010$ and $\alpha(\Sigma^+ \to p\pi^0) = -0.980 \pm 0.017$ from PDG.

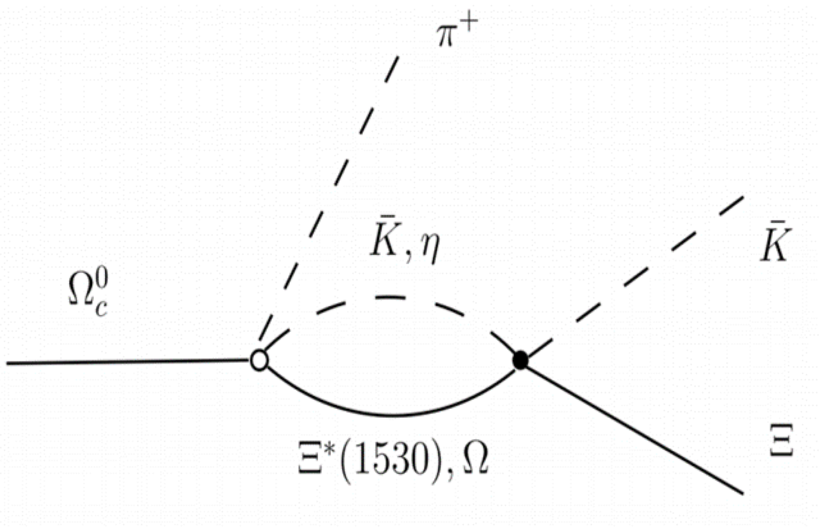
Evidence for $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$

Motivation:

- A theoretical study of the $\Omega(2012)^-$ in the nonleptonic weak decays of $\Omega_c^0 \to \pi^+\bar{K}\,\Xi(1530)(\eta\Omega) \to \pi^+(\bar{K}\pi\Xi)^-$ and $\pi(\bar{K}\Xi)^-$was reported; the authors predicted the clearly $\Omega(2012)^-$peak in the $(\bar{K}\Xi)^-$ invariant mass spectrum of the $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$.

  [PRD 102, 076009 (2020)]

- Searching for new production model is very important to understand the nature of $\Omega(2012)^-$;



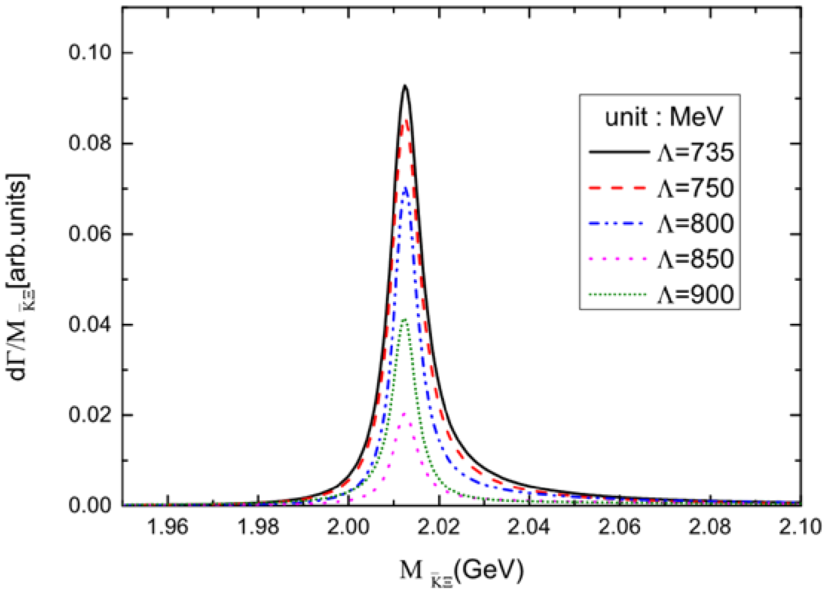
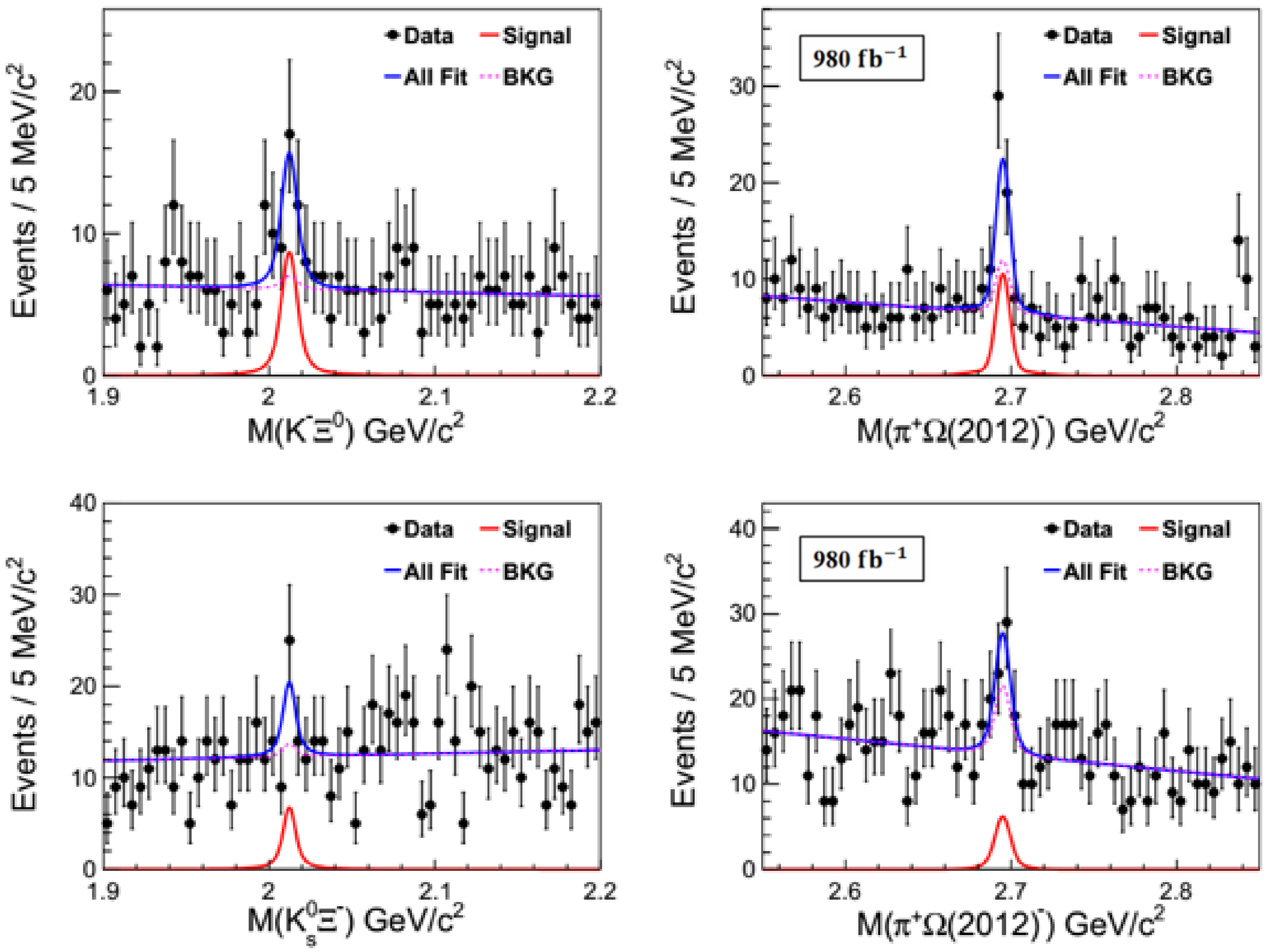


Figure: Diagram for the meson-baryon final-state interaction for the $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$ decay (left); $\bar{K}\Xi$ invariant mass distributions of the $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$ decay (right).

$M(K^-\Xi^0/K_S^0\Xi^-)$ and $M(\pi^+\Omega(2012)^-)$ distributions

- To extract the $\Omega(2012)^-$ signal events from Ω_c^0 decay, a 2D maximum-likelihood fit is performed to $M(K^-\Xi^0)/M(K_S^0\Xi^-)$ and $M(\pi^-\Omega(2012))$.

[arXiv: 2106.00892 (2021)]



$N_{fit}(K^-\Xi^0) = 28.3 \pm 8.9$

Statistical significance: 4.0σ

$$\frac{Br(\Omega_c^0 \to \pi^+\Omega(2012)^-)Br(\Omega(2012)^- \to K^-\Xi^0)}{Br(\Omega_c^0 \to \pi^+K^-\Xi^0)}$$

$= (9.64 \pm 3.04(\text{stat.}) \pm 1.89(\text{syst.}))\%$

$N_{fit}(K_S^0\Xi^-) = 17.9 \pm 8.9$

Statistical significance: 2.3σ

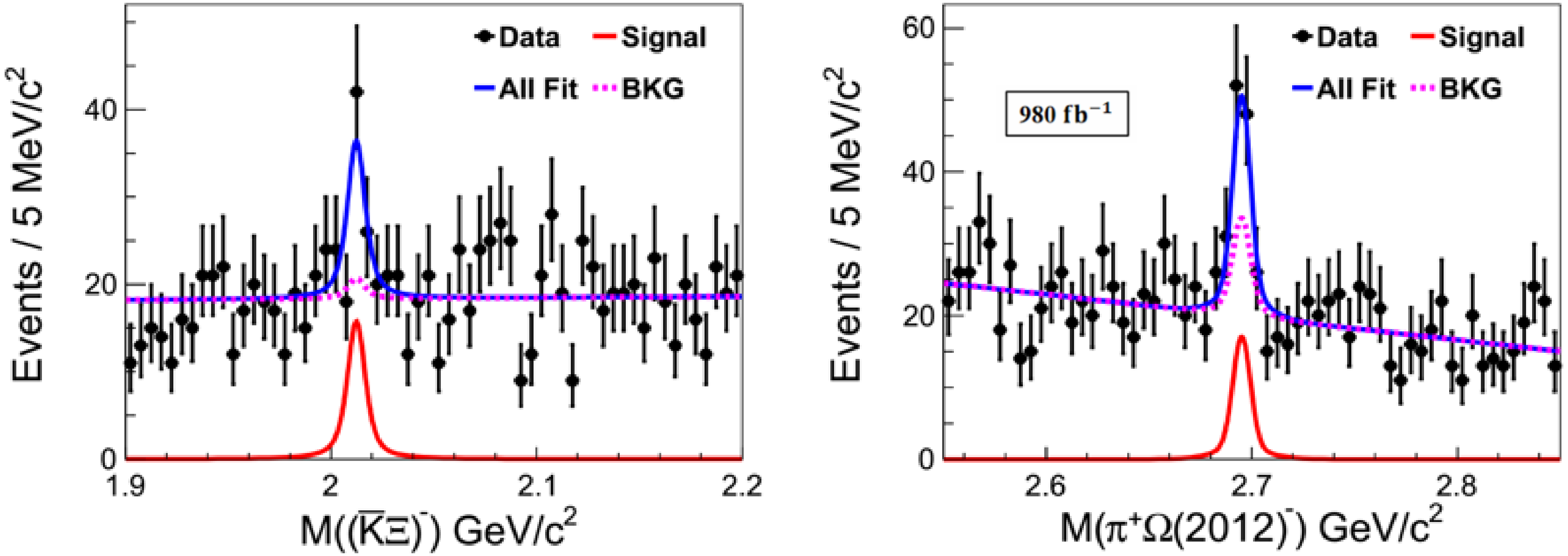
$$\frac{Br(\Omega_c^0 \to \pi^+\Omega(2012)^-)Br(\Omega(2012)^- \to \bar{K}^0\Xi^-)}{Br(\Omega_c^0 \to \pi^+\bar{K}^0\Xi^-)}$$

$= (4.62 \pm 2.30(\text{stat.}) \pm 0.75(\text{syst.}))\%$

Combined $M((\bar{K}\Xi)^-)$ and $M(\pi^+\Omega(2012)^-)$distributions

- Assuming $Br(\Omega(2012)^- \to K^-\Xi^0)$=$Br(\Omega(2012)^- \to \bar{K}^0\Xi^-)$ based on isospin symmetry, the expected signal yields of $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+K^-\Xi^0$ and $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+K_S^0\Xi^-$ is 57.1%:42.9%;
- A 2D un-binned maximum-likelihood simultaneous fit is performed to $M((\bar{K}\Xi)^-)$ and $M(\pi^+\Omega(2012)^-)$ distributions.

[arXiv: 2106.00892 (2021)]



$N_{fit} = 46.6 \pm 12.3$

Signal significance: 4.2σ
(including systematic uncertainties)

$$\frac{Br(\Omega_c^0 \to \pi^+\Omega(2012)^-) \times Br(\Omega(2012)^- \to (\bar{K}\Xi)^-)}{Br(\Omega_c^0 \to \pi^+\Omega^-)}$$

$$= 0.220 \pm 0.059(\text{stat.}) \pm 0.035(\text{syst.})$$

Summary

- Although Belle has stopped data taking for ~11 years ago, we are still producing exciting results;
- We report measurements of the branching fractions of SCS decays $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$ with much improved precision;
- We analyze the $\eta\Lambda\pi^+$ final state to study Λ_c^+ decay, the branching fractions $\Lambda_c^+ \to \eta\Lambda\pi^+$ and $\Lambda_c^+ \to \eta\Sigma(1385)^+$ are measured with much improved precision; the $\Lambda_c^+ \to \eta\Sigma^0\pi^+$ and $\Lambda_c^+ \to \Lambda(1670)\pi^+$ are observed for the first time;
- The CF W−exchange, $s\bar{s}$−popping decay of $\Xi_c^0 \to \Xi^0 K^+ K^-$ which can resonate through $\phi \to K^+K^-$ has been observed;
- The branching fractions and asymmetry parameters of CF decays $\Xi_c^0 \to \Lambda\bar{K}^{*0}/\Sigma^0\bar{K}^{*0}/\Sigma^+K^{*-}$ are measured for the first time;
- We present evidence for the $\Omega(2012)^-$ in the resonant substructure of $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$ decays.

Thanks for your attentions!