



# Charmed Hadron Spectroscopy at Belle

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on behalf of Belle Collaboration

9th International Workshop on Charm Physics
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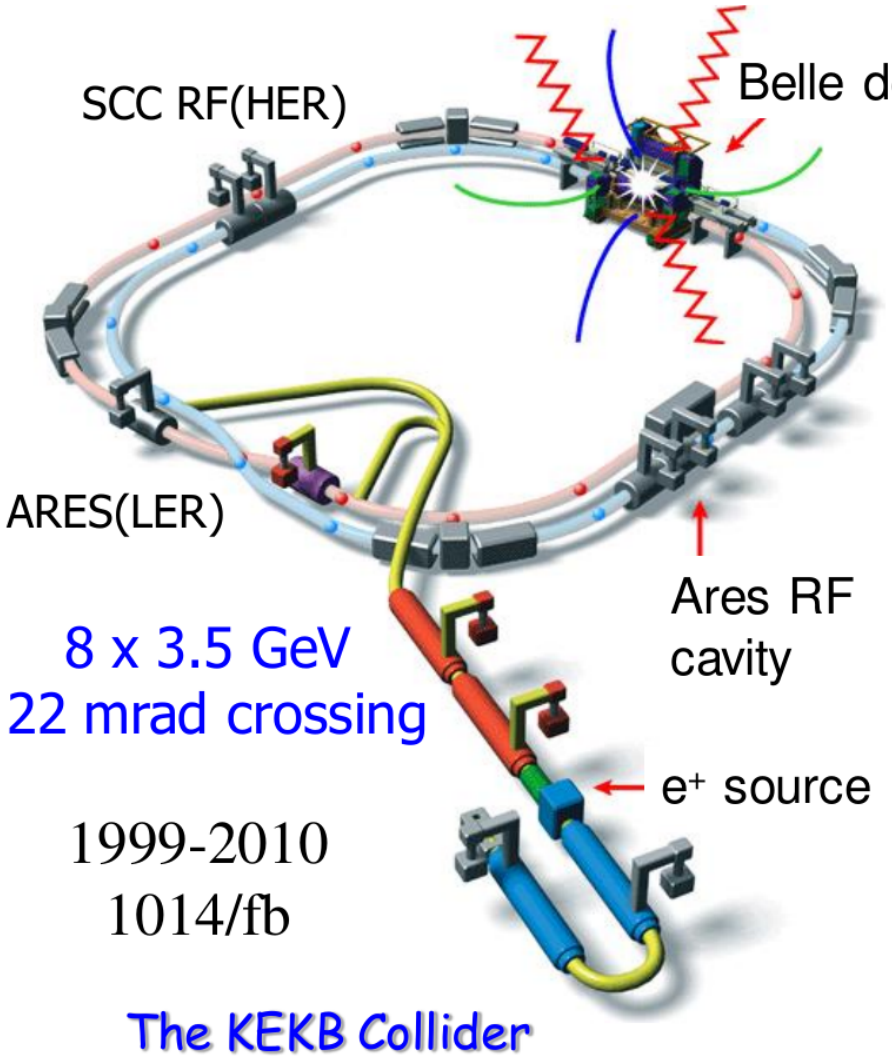
# The Belle Experiment

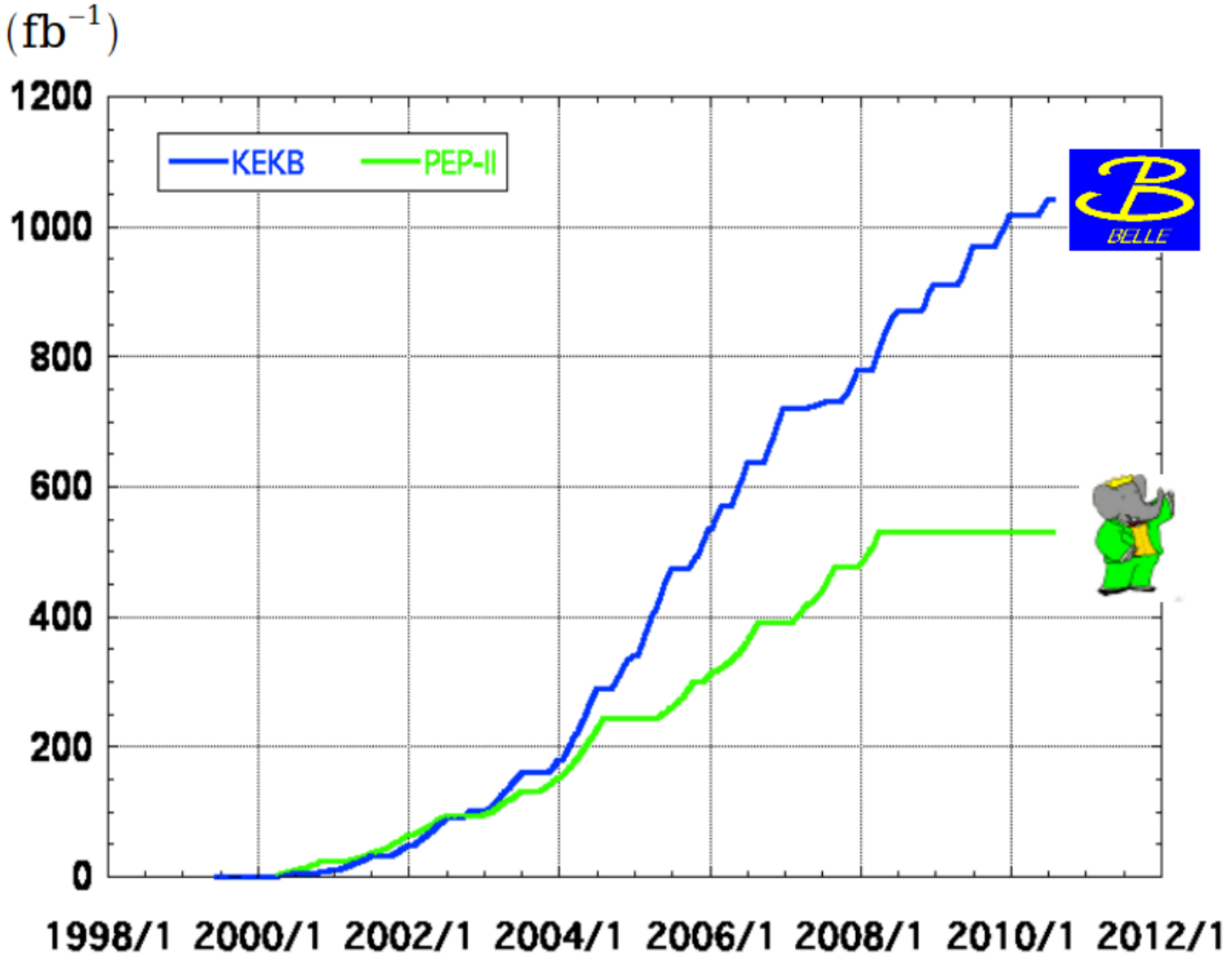



World record:

$L = 2.1 \times 10^{34}/cm^2/sec$


The new generation SuperKEKB has been launched, and Belle II recorded the first collisions on April 26, 2018, JST!

# Integrated Luminosities of B-factories




**$> 1\ ab^{-1}$**

**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 reson./scan:**

$\sim 100\ fb^{-1}$

**$\sim 550\ fb^{-1}$**

**On resonance:**

$\Upsilon(4S)$: 433 $fb^{-1}$

$\Upsilon(3S)$: 30 $fb^{-1}$

$\Upsilon(2S)$: 14 $fb^{-1}$

**Off resonance:**

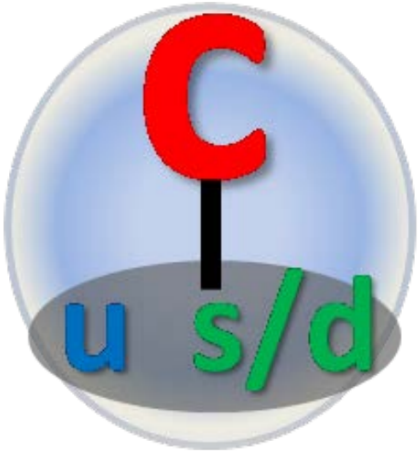
$\sim 54\ fb^{-1}$

- Charm quark is the first heavy quark, much heavier than $u$, $d$, $s$ quarks
- Spin-Spin interaction is $\propto 1/m_1 \cdot m_2$
- Di-quark structure in light quarks
  - Di-quark as new degree of freedom.
  - Easier to understand baryon system

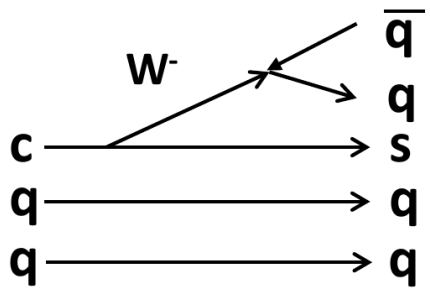
**Nucleon**


Every pair can not be distinguished.

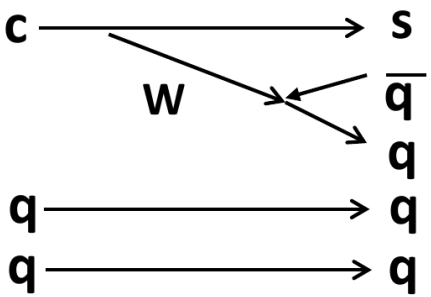
**Charmed baryon**



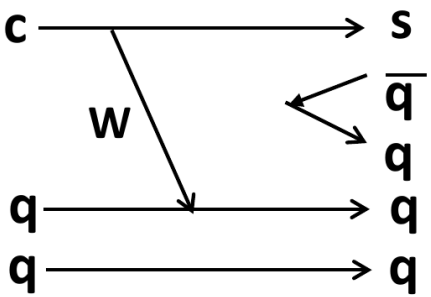

Light di-quark and charm quark.




Spectator




Internal W

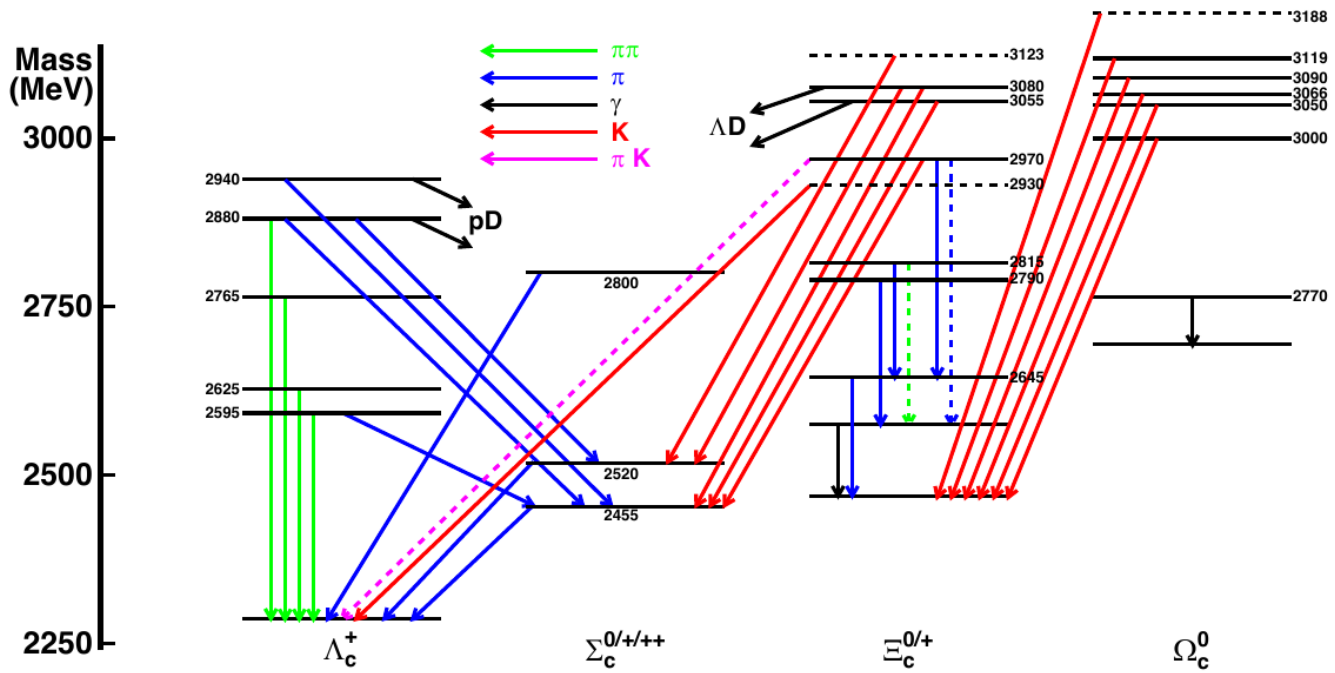



W-exchange

- The weak decay of charmed baryon has not been understood well.
- Three diagrams contribute in the tree level, but their strengths are not known.
- Ground state charm baryon is a good laboratory for studying strange baryons as decay proceed via $c \to s$ transition.
- Belle has collected $\sim 1\ \mathrm{ab}^{-1}$ $\mathrm{e}^+\mathrm{e}^-$ data samples (mainly at $\Upsilon(4S)$).
  - $10^9$ $e^+e^- \to c\bar{c}$ samples
  - $7.7 \times 10^8$ $B\bar{B}$ samples
- Huge data sample enable to study various charmed baryons.

# Outline

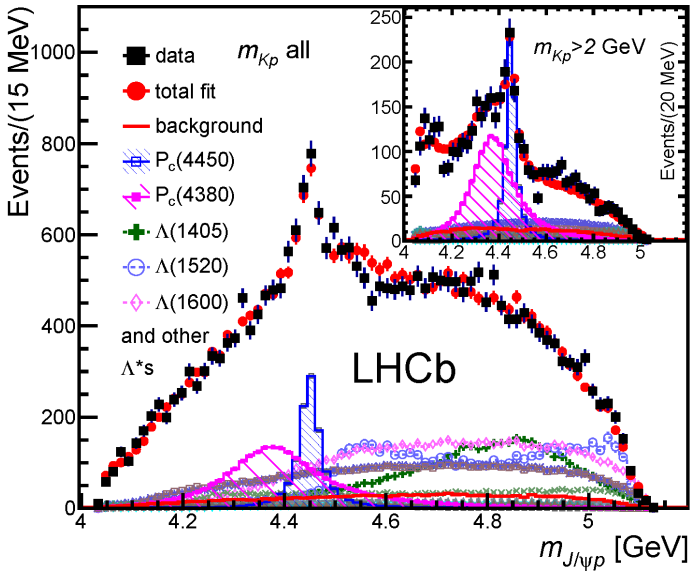
1. Search for a $s-$version pentaquark via $\Lambda_c^+ \to \pi^0 p\phi$ decay
2. $\Omega_c$ decays: 5 most precise measurements and 3 first measurements
3. Observation of $\Xi_c(2930)$ in $B^- \to K^-\Lambda_c^+\Lambda_c^-$
4. Evidence of $\Xi_c(2930)^{\pm}$ in $B^0 \to K^0\Lambda_c^+\Lambda_c^-$
5. Confirmation of excited $\Omega_c'$



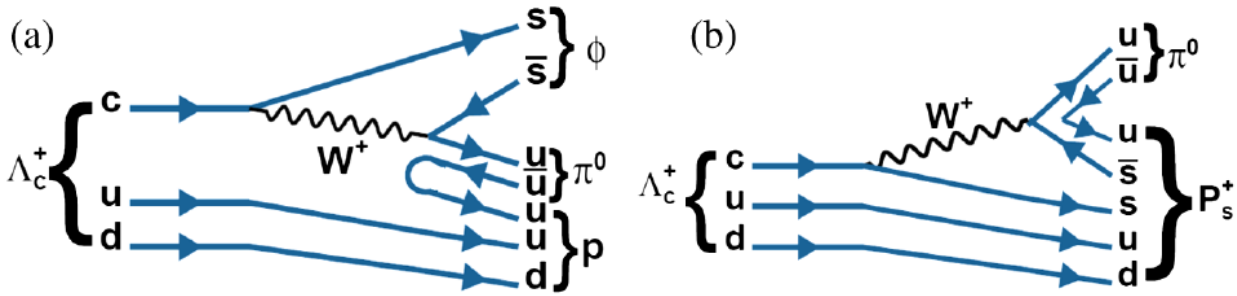
# Search for a strange pentaquark via $\Lambda_c^+ \to \pi^0 p\phi$ decay

- LHCb observed hidden charm pentaquark state in $\Lambda_b^0 \to K^- P_c^+ \to K^-(J/\psi p)$.

**R. Aaij et al., PRL115, 072002(2015)**

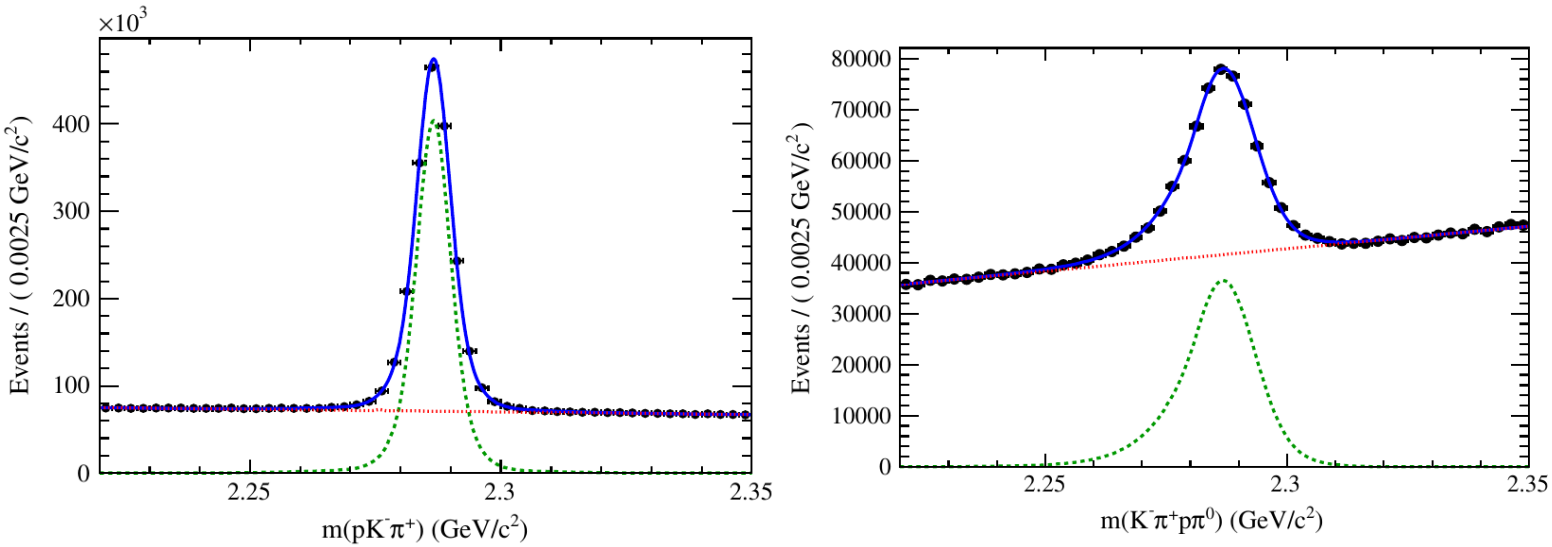



- Analogue search for hidden-strange pentaquark by switching $b \to c(\Lambda_b^0 \to \Lambda_c^+)$, $c \to s(J/\psi \to \phi)$: $\Lambda_c^+ \to \pi^0 P_s^+ \to \pi^0(\phi p)$.
- $\Lambda_c^+ \to \pi^0 \phi p$ decay has not been measured so far.



# Reference channels

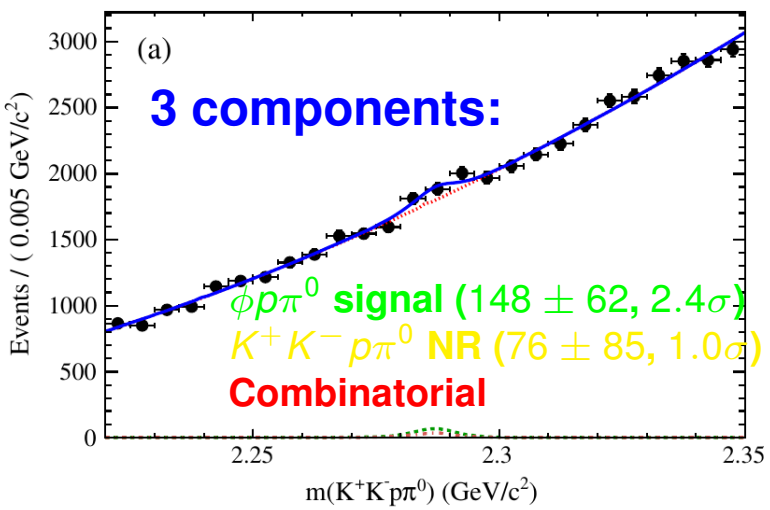
- $\Lambda_c^+ \to \phi p \pi^0$ is Cabibbo-suppressed decay.
- $\Lambda_c^+ \to p K^- \pi^+$ is used for reference, and the Cabibbo-favored decay $\Lambda_c^+ \to K^- \pi^+ p \pi^0$ is measured.

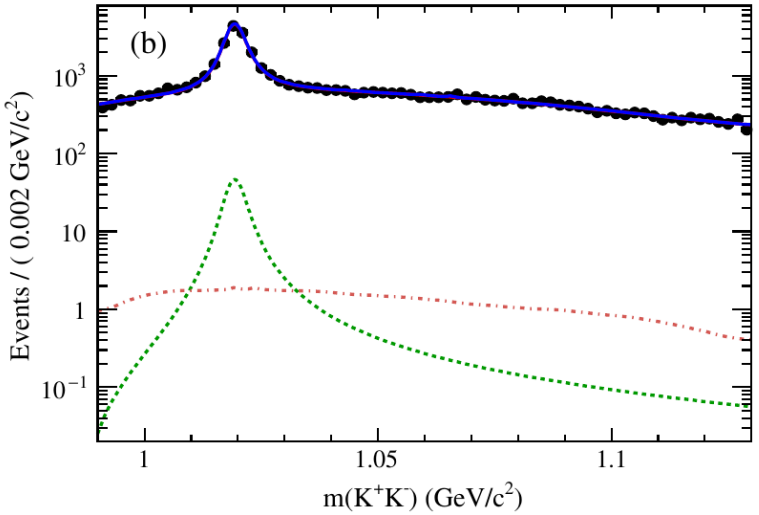



- $\frac{\mathcal{B}(\Lambda_c^+ \to K^- \pi^+ p \pi^0)}{\mathcal{B}(\Lambda_c^+ \to K^- \pi^+ p)} = (0.685 \pm 0.007 \pm 0.018)$
- Most precise measurement:
  $\mathcal{B}(\Lambda_c^+ \to K^- \pi^+ p \pi^0) = (4.42 \pm 0.05 \pm 0.12 \pm 0.16)\%$
- Previous measurement from BESIII: $(4.53 \pm 0.23 \pm 0.30)\%$

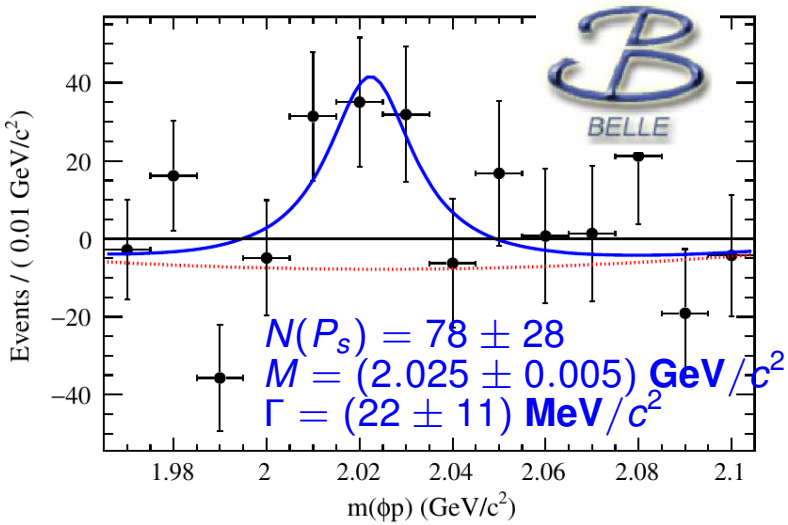
B. Pal *et al.*, Phys.Rev.D96, 051102(R)(2017)

# Search for a strange pentaquark via $\Lambda_c^+ \to \pi^0 p\phi$ decay (results)




- Perform 2D fit to $M_{K^+K^-p\pi^0}$ vs $M_{K^+K^-}$ plane.




$$e^{-\sum_j Y_j} \prod_i^N \left( \sum_j Y_j \mathcal{P}_j[m^i(K^+K^-p\pi^0), m^i(K^+K^-)] \right)$$

- No significant $\Lambda_c^+$ signal is observed. New upper limits:
  - $\mathcal{B}(\Lambda_c^+ \to \phi p\pi^0) < 15.3 \times 10^{-5}$
  - $\mathcal{B}(\Lambda_c^+ \to \phi p\pi^0)_{NR} < 6.3 \times 10^{-5}$
- Also perform 2D fit in each $M_{K^+K^-}$ bin. No significant $P_s^+$ signal.
  - $\mathcal{B}(\Lambda_c^+ \to \pi^0 P_s^+) \times \mathcal{B}(P_s^+ \to \phi p) < 8.3 \times 10^{-5}$.

B. Pal *et al.*, Phys.Rev.D96, 051102(R)(2017)

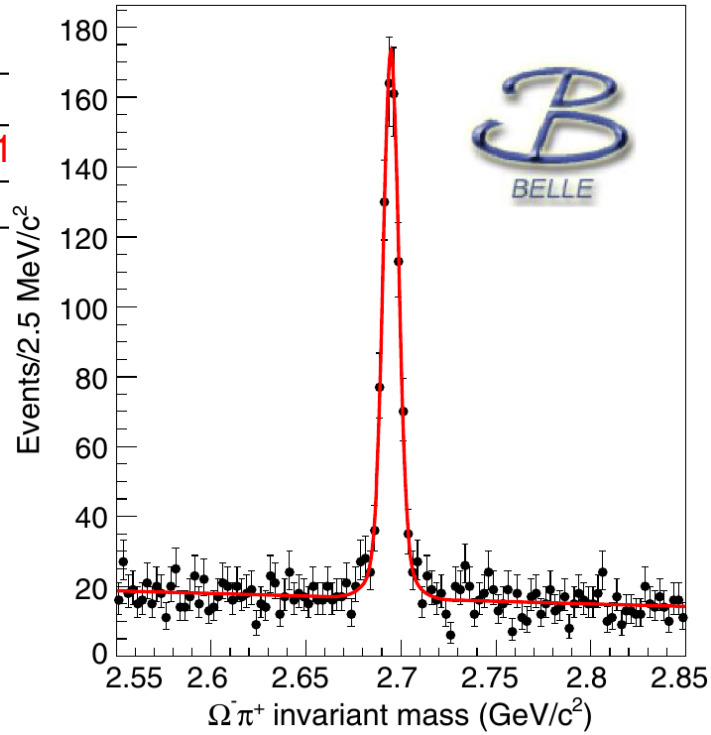
# Hadronic decays of $\Omega_c$

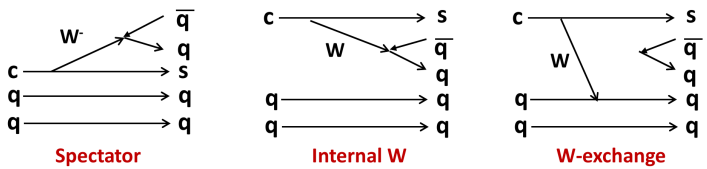
- Among 4 ground state charmed baryons, $\Omega_c(css)$ is not studied well as cross section is small.

| State | $\Lambda_c^+$ | $\Xi_c^0$ | $\Xi_c^+$ | $\Omega_c$ |
|---|---|---|---|---|
| $\tau(ps)$ | $200 \pm 6$ | $112^{+13}_{-10}$ | $442 \pm 26$ | $69 \pm 1$ |
| $\Delta\tau/\tau$ (%) | 3 | 1 | 6 | 17 |

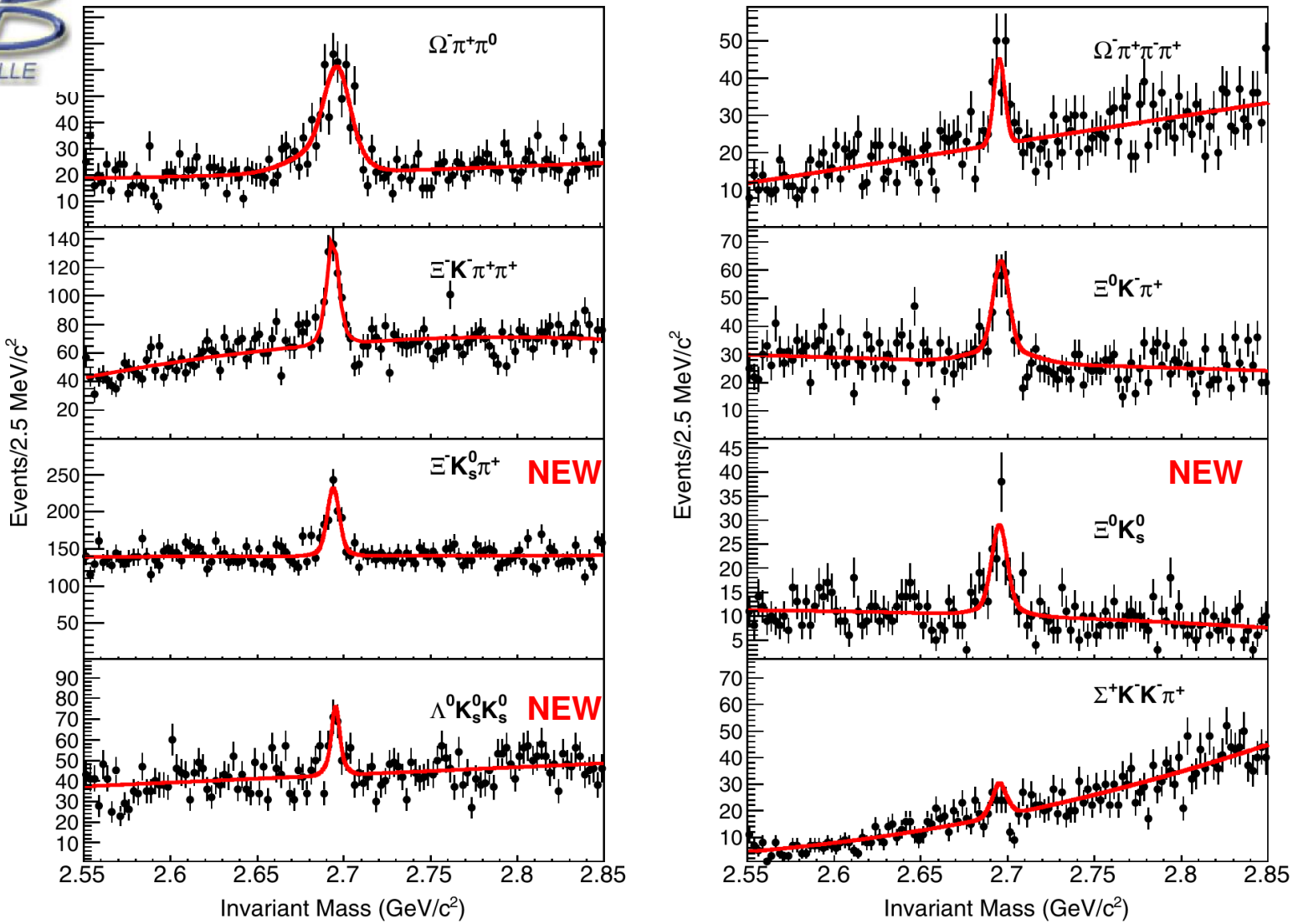
- Only $\Omega_c$ has the same flavor light quarks ($ss$). Constructive interference is thought to be the origin of its short life time.
- Precise measurements will shed light on the dynamics of baryon weak decays.
- Belle performed measurements of 8 decay modes relative to the bench mark mode: $\Omega^-\pi^+$.
  - Most precisements: $\Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^-\pi^+$, $\Xi^-K^-\pi^+\pi^+$, and $\Xi^0K^-\pi^+$.
  - First measurements: $\Xi^-\bar{K}^0\pi^+$, $\Xi^0\bar{K}^0$ and $\Lambda\bar{K}^0\bar{K}^0$.

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



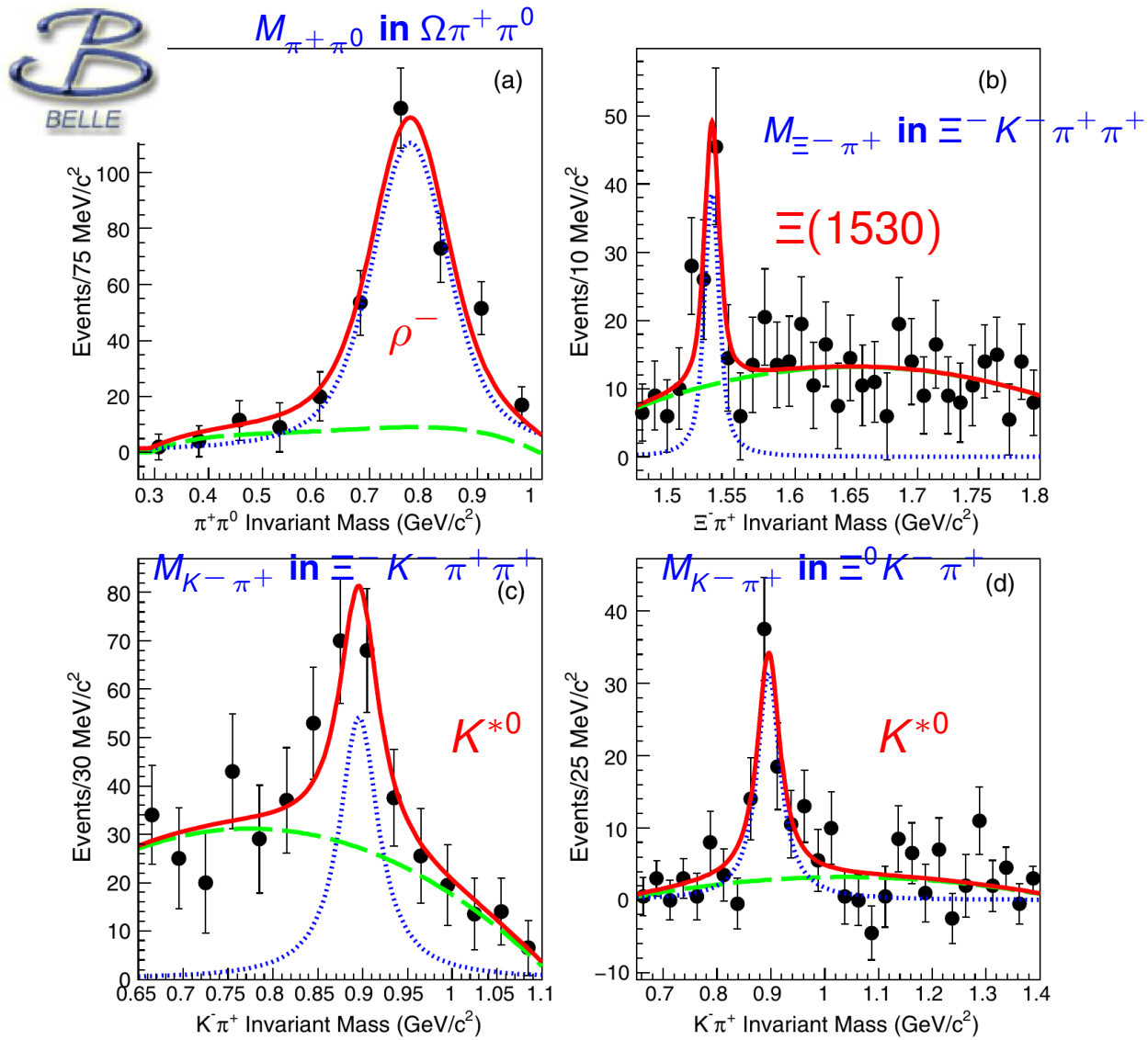
# Mass distributions for eight decay modes




J. Yelton *et al.*, Phys. Rev. D 97, 032001(2018)

# Search for intermidiate states

Intermediate resonances are studied for the first time in 3 decays.




J. Yelton *et al.*, Phys. Rev. D 97, 032001(2018)

# Results of the branching fractionss

| Mode | Branching ratio with respect to $\Omega^-\pi^+$ | Substructure | Previous measurement |
|---|---|---|---|
| $\Omega^-\pi^+$ | 1 | | |
| $\Omega^-\pi^+\pi^0$ | $2.00 \pm 0.17 \pm 0.11$ | | $1.27 \pm 0.3 \pm 0.11$ [4] |
| $\Omega^-\rho^+$ | | >71% | |
| $\Omega^-\pi^+\pi^-\pi^+$ | $0.32 \pm 0.05 \pm 0.02$ | | $0.28 \pm 0.09 \pm 0.01$ [4] |
| $\Xi^-K^-\pi^+\pi^+$ | $0.68 \pm 0.07 \pm 0.03$ | | $0.46 \pm 0.13 \pm 0.03$ [4] |
| $\Xi^0(1530)K^-\pi^+$ | | $(33 \pm 9)\%$ | |
| $\Xi^-\bar{K}^{*0}\pi^+$ | | $(55 \pm 16)\%$ | |
| $\Xi^0K^-\pi^+$ | $1.20 \pm 0.16 \pm 0.08$ | | $4.0 \pm 2.5 \pm 0.4$ [2] |
| $\Xi^0\bar{K}^{*0}$ | | $(57 \pm 10)\%$ | |
| $\Xi^-\bar{K}^0\pi^+$ | $2.12 \pm 0.24 \pm 0.14$ **NEW** | | |
| $\Xi^0\bar{K}^0$ | $1.64 \pm 0.26 \pm 0.12$ **NEW** | | |
| $\Lambda\bar{K}^0\bar{K}^0$ | $1.72 \pm 0.32 \pm 0.14$ **NEW** | | |
| $\Sigma^+K^-K^-\pi^+$ | <0.32 (90% CL) | | |

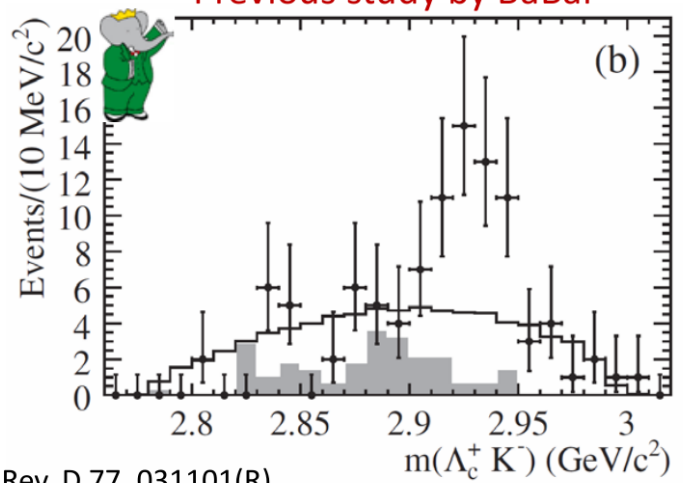
- Precision improved by  factor 2 for already measured modes.
- First measurements of intermediate resonances.
  - Dominant contributions.
- Three first observations.

J. Yelton *et al.*, Phys. Rev. D 97, 032001(2018)

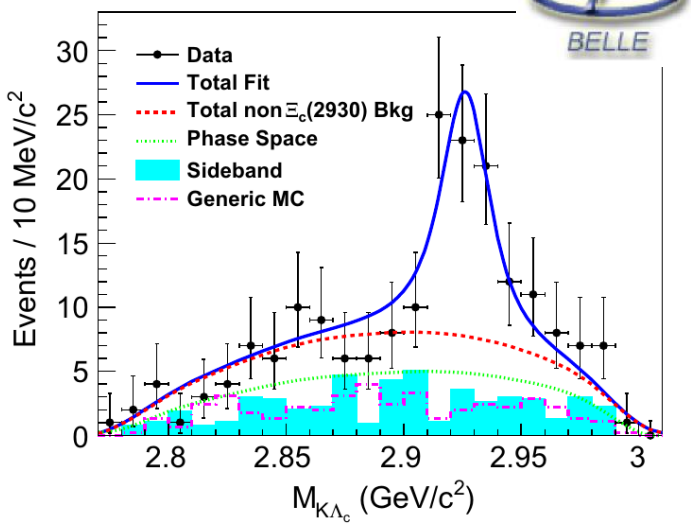
# Observation of $\Xi_c(2930)$

- Weak evidence of $\Xi_c(2930)$ was reported by BaBar in $B^- \to \Xi_c(2930)\bar{\Lambda}_c$, $\Xi_c(2930) \to \Lambda_c^+ K^-$.
- Assigned as one star in PDG (need confirmation).
- Belle performed the study with $\sim$ 3 times larger statistics.

Previous study by BaBar




Phys. Rev. D 77, 031101(R)



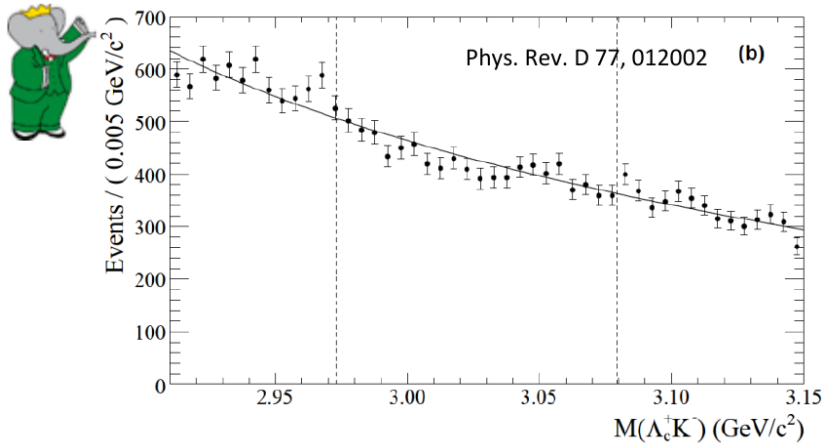

Y.B. Li *et al.*, EPJC78,252(2018)

| | Mass (MeV/$c^2$) | Width (MeV) |
|---|---|---|
| BaBar | $2931 \pm 3 \pm 5$ | $36 \pm 7 \pm 11$ |
| Belle | $2928.9 \pm 3.0^{+0.8}_{-12.0}$ | $19.5 \pm 8.4^{+5.4}_{-7.9}$ |

- The statistical significance of the peak at Belle is $5.1\sigma$.
- Mass and width are consistent with each other.

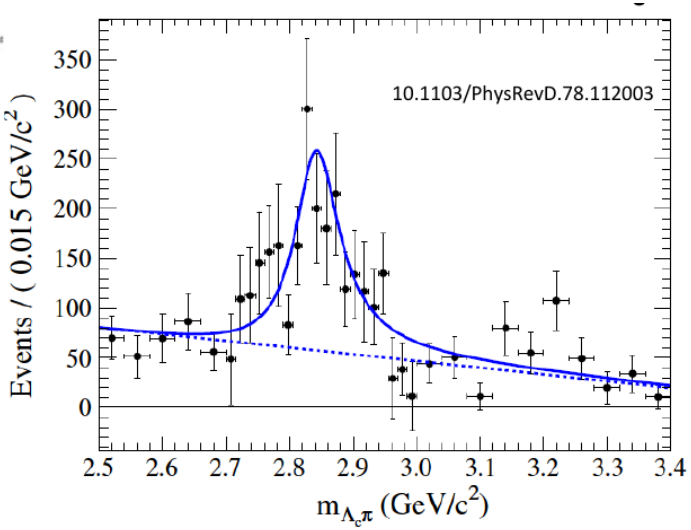
# Comments on $\Xi_c(2930)$

- $\Xi_c(2930)^0 = csd$ is the first charmed-strange baryon established in B decay.




M($\Lambda_c^+K^-$) in $e^+e^-\to c\bar{c}$ by BaBar.
No signal.

- Candidates of corresponding $\Lambda_c$, $\Sigma_c$ states?

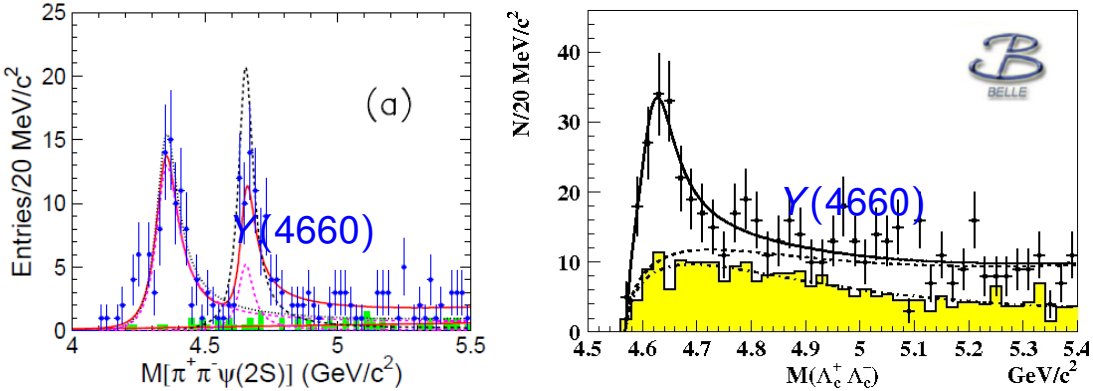



- $B \to (\Lambda_c^+)\bar{p}$ by BaBar
  - $M = (2846 \pm 8 \pm 10)$ MeV$/c^2$
  - $\Gamma = 86^{+33}_{-22}$ MeV
- Possibly $\Sigma_c(2800)$, may be a different state.
- $M_{\Xi_c'} - M_{\Sigma_c}$ is about 120 MeV$/c^2$
- Good candidate as partner of $\Xi_c(2930)$.
- Need confirmation by Belle/Belle II.

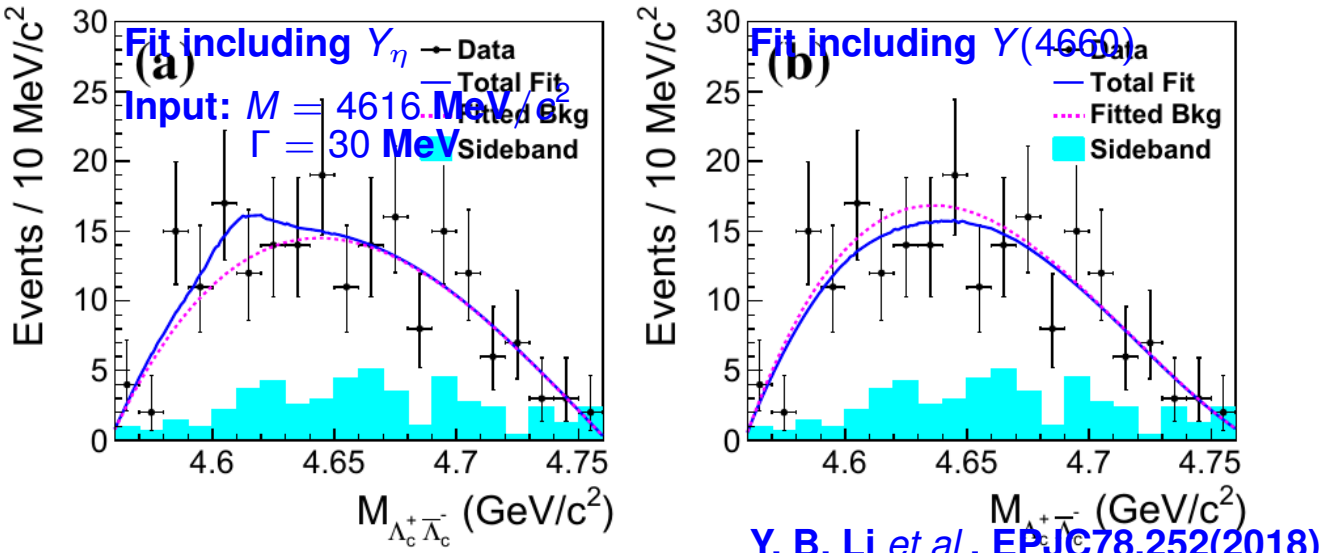
- As it is two-body B decay, spin can be determined un-ambiguously from helicity constraint if we have enough statistics. $\to$ Belle II

# Search for $Y$ in $\Lambda_c^+\bar{\Lambda}_c^-$

- $Y(4630)$ observed in $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ when searching for $Y(4660)$




- $Y(4660)$ and its spin partner, $Y_\eta$, are searched for in the $\Lambda_c^+\bar{\Lambda}_c^-$ invariant mass spectrum.

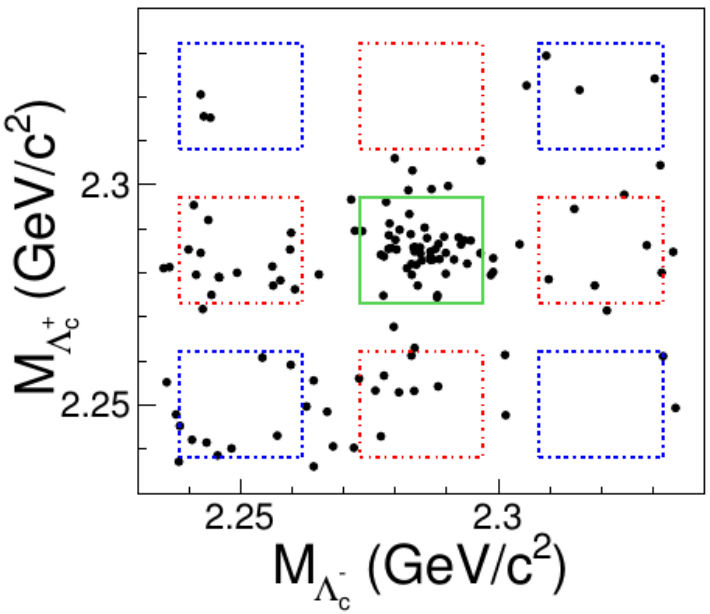


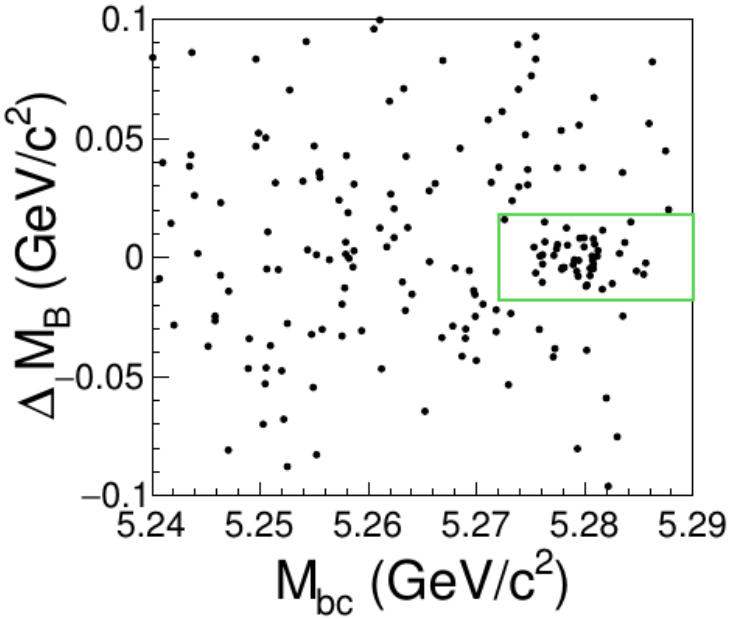

**Y. B. Li *et al.*, EPJC78,252(2018)**

- No significant signals seen in the $\Lambda_c^+\bar{\Lambda}_c^-$ mass spectrum.
  - $\mathcal{B}(B^- \to K^- Y(4660))\mathcal{B}(Y(4660) \to \Lambda_c^+\bar{\Lambda}_c^-) < 1.2 \times 10^{-4}$ at 90% C.L.
  - $\mathcal{B}(B^- \to K^- Y_\eta)\mathcal{B}(Y_\eta \to \Lambda_c^+\bar{\Lambda}_c^-) < 2.0 \times 10^{-4}$ at 90% C.L.

# Update on $B^0 \to K^0 \Lambda_c^+ \bar{\Lambda}_c^-$

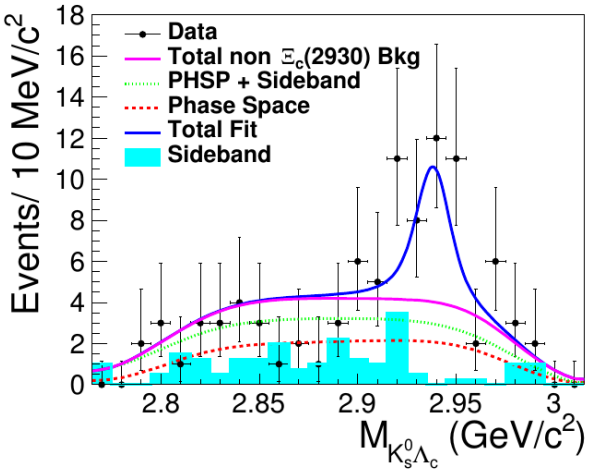
- $I(\Xi_c(2930)) = \frac{1}{2} \to$ need to search for $\Xi_c(2930)^{\pm}$ in $B^0 \to K_s^0 \Lambda_c^+ \bar{\Lambda}_c^-$
- BaBar and Belle have studied $B^0 \to K^0 \Lambda_c^+ \bar{\Lambda}_c^-$ with $230 \times 10^6$ and $386 \times 10^6$ $B\bar{B}$ pairs, and found signals of $1.4\sigma$ and $6.6\sigma$ significanes, respectively.
- Using $772 \times 10^6$ $B\bar{B}$ pairs and the reconstructions: $K_s^0 \to \pi^+\pi^-$ and $\Lambda_c^+ \to pK^-\pi^+/pK_s^0/\Lambda\pi^+(\to p\pi^-\pi^+)$.
- Quite clear $\Lambda_c^+ \bar{\Lambda}_c^-$ signals and $B^0$ signals.
  - $N^{\rm sig} = 34.9 \pm 6.6$ with a statistical signal significance above $8.3\sigma$
  - $\mathcal{B}(B^0 \to K^0 \Lambda_c^+ \bar{\Lambda}_c^-) = (3.84 \pm 0.73 \pm 0.48) \times 10^{-4}$




Being submitted to EPJC

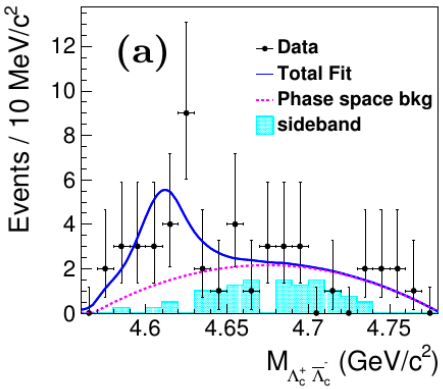
# $\Xi_c(2930)^{\pm}$ signals and search for $Y(4660)$

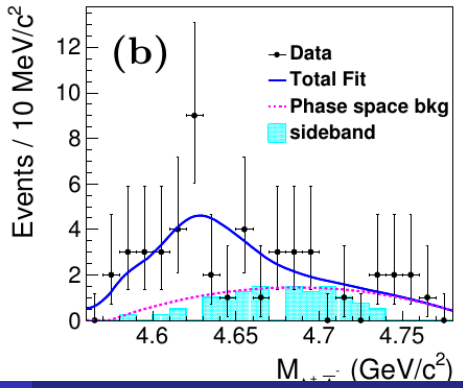



- $N_{\Xi_c^{\pm}} = 21.2 \pm 4.6$, stat. significance $4.1\sigma$
- $M_{\Xi_c^{\pm}(2930)} = 2942.3 \pm 4.4 \pm 1.6$ MeV$/c^2$
- $\Gamma_{\Xi_c^{\pm}(2930)} = 14.8 \pm 8.8 \pm 7.1$ MeV

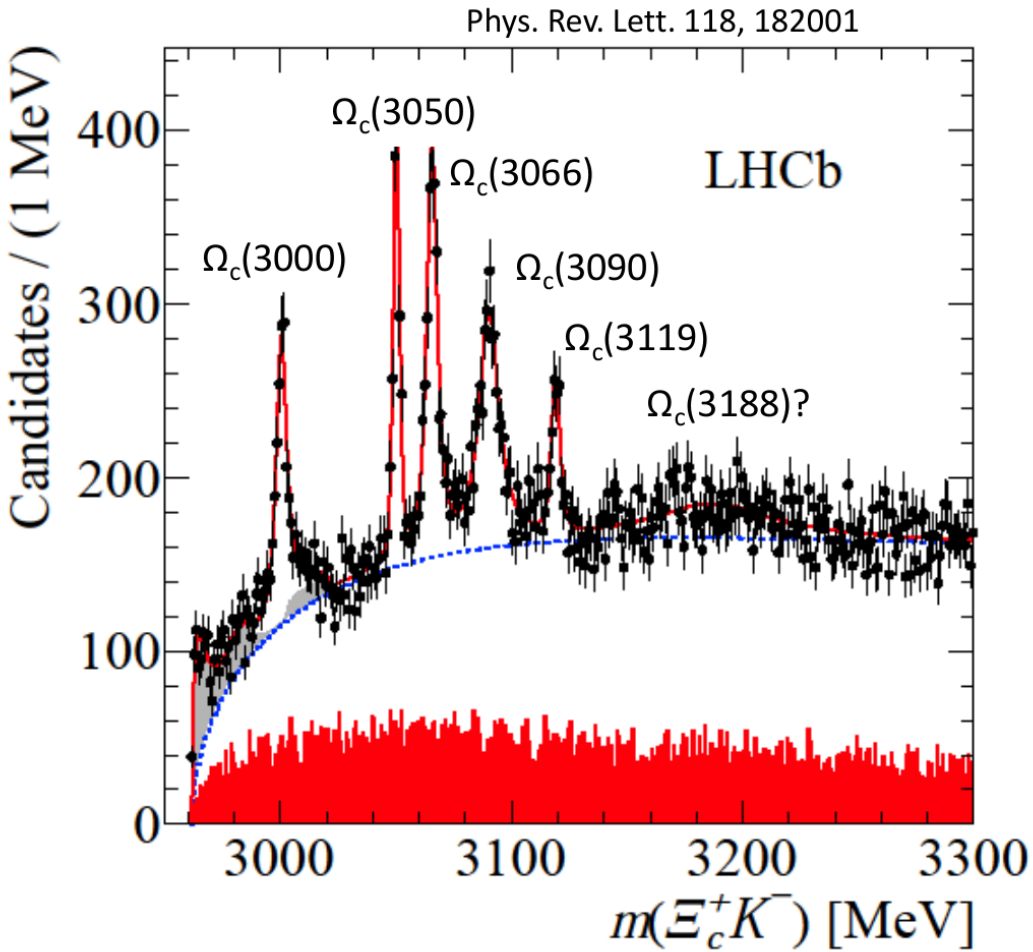
- No obvious $Y(4660)$ or $Y_\eta$ signal in $M_{\Lambda_c^+\bar{\Lambda}_c^-}$ distribution.
- Inputs: $Y(4660)$ parameters from Belle II, $M_{Y_\eta} = 4616$ MeV$/c^2$ and $\Gamma_{Y_\eta} = 30$ MeV
- Upper Limits at 90% C.L.
  - $\mathcal{B}(B^0 \to K^0 Y(4660))\mathcal{B}(Y(4660) \to \Lambda_c^+\bar{\Lambda}_c^-) < 3.2 \times 10^{-4}$
  - $\mathcal{B}(B^0 \to K^0 Y_\eta)\mathcal{B}(Y_\eta \to \Lambda_c^+\bar{\Lambda}_c^-) < 4.9 \times 10^{-4}$

Being submitted to EPJC



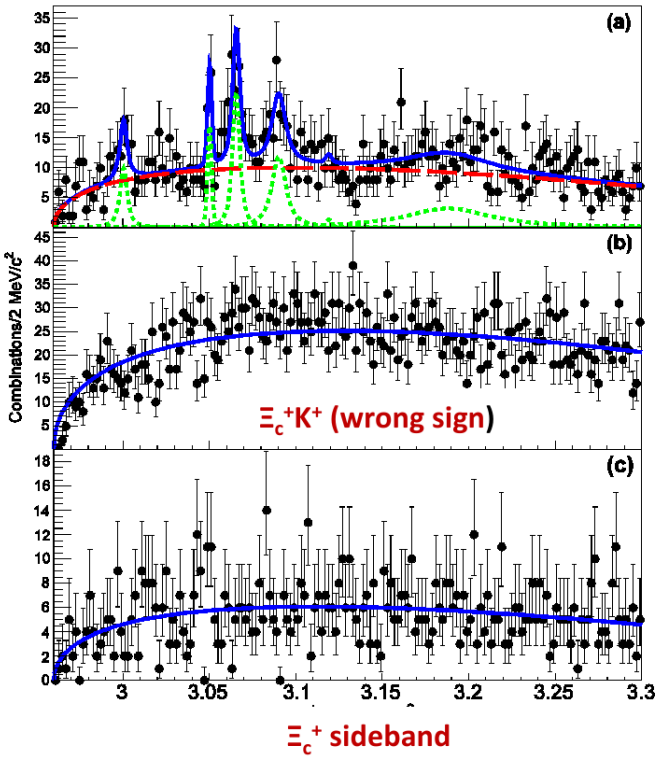



# Excited $\Omega_c$ states




- LHCb reported 5 (+1) excited $\Omega_c$ states in the $\Xi_c^+ K^-$ final states.
- Belle studied the same final state to confirm their existence.
- Though statistical sensitivity of Belle is much lower than LHCb, study with different production may shed light on the nature of these states.

# Confirmation by Belle




J. Yelton *et al.*, PRD97, 051102(R)(2018)

- The $\Xi_c^+$ is reconstructed in 7 decay modes: $\Xi^-\pi^+\pi^+$, $\Lambda K^-\pi^+\pi^+$, $\Xi^0\pi^+$, $\Xi^0\pi^+\pi^-\pi^+$, $\Sigma^+K^-\pi^+$, $\Lambda K_s\pi^+$, and $\Sigma^0 K_s\pi^+$
- Widths are fixed to the value obtained by LHCb in the fit.
- 4 of the 5 states are confirmed ($> 3\sigma$), except the $\Xi_c(3119)$.
- The mass is consistent with LHCb.

| | LHCb | Belle |
|---|---|---|
| $\Omega_c(3000)$ | $3000.4\pm0.2\pm0.4^{+0.3}_{-0.5}$ | $3000.7\pm1.0\pm0.2$ (3.9σ) |
| $\Omega_c(3050)$ | $3050.2\pm0.1\pm0.1^{+0.3}_{-0.5}$ | $3050.2\pm0.4\pm0.2$ (4.6σ) |
| $\Omega_c(3066)$ | $3065.6\pm0.1\pm0.3^{+0.3}_{-0.5}$ | $3064.9\pm0.6\pm0.2$ (7.2σ) |
| $\Omega_c(3090)$ | $3090.2\pm0.3\pm0.5^{+0.3}_{-0.5}$ | $3089.3\pm1.2\pm0.2$ (5.7σ) |
| $\Omega_c(3119)$ | $3119.1\pm0.3\pm0.9^{+0.3}_{-0.5}$ | $3119.0\pm0.3\pm0.9$ (0.4σ) |

# Summary

- Belle is still actively working on the charmed baryons.
  - First measurement of $\Lambda_c^+ \to p\phi\pi^0$ from Belle, but no obvious $P_s$ pentaquark state is observed.
  - Branching fractions of hadronic decay of $\Omega_c$ have been measured, 5 modes have the most precised measurements plus 3 modes of first observations.
  - Observation of $\Xi_c(2930^0)$ in $B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$
  - Evidence ($4.1\sigma$) of $\Xi_c(2930)^\pm$ in $B^0 \to K^0 \Lambda_c^+ \bar{\Lambda}_c^-$
  - Confirmation of excited $\Omega_c$ states discovered by LHCb, 4 of the 5 states are confirmed with $> 3\sigma$ significance.
- Belle II will enable us to discover more states, determination of quantum numbers!

Thank you!

# Back-up