# Baryon spectroscopy at Belle

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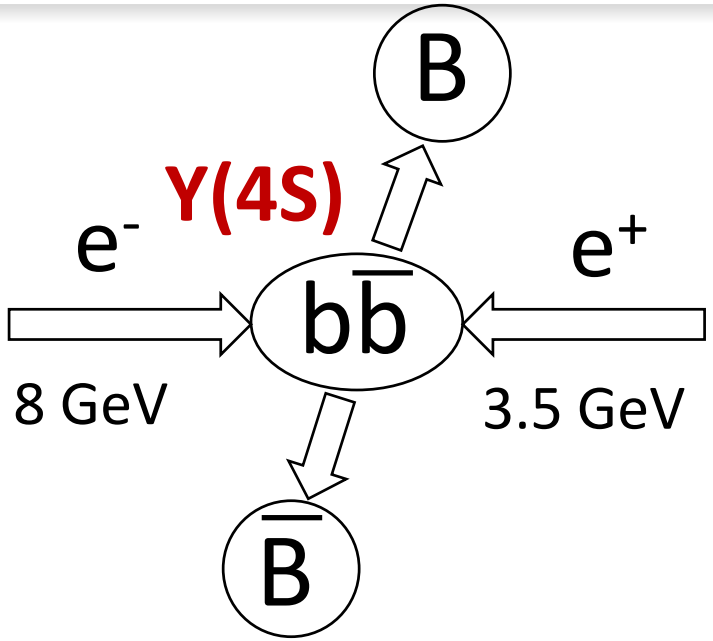
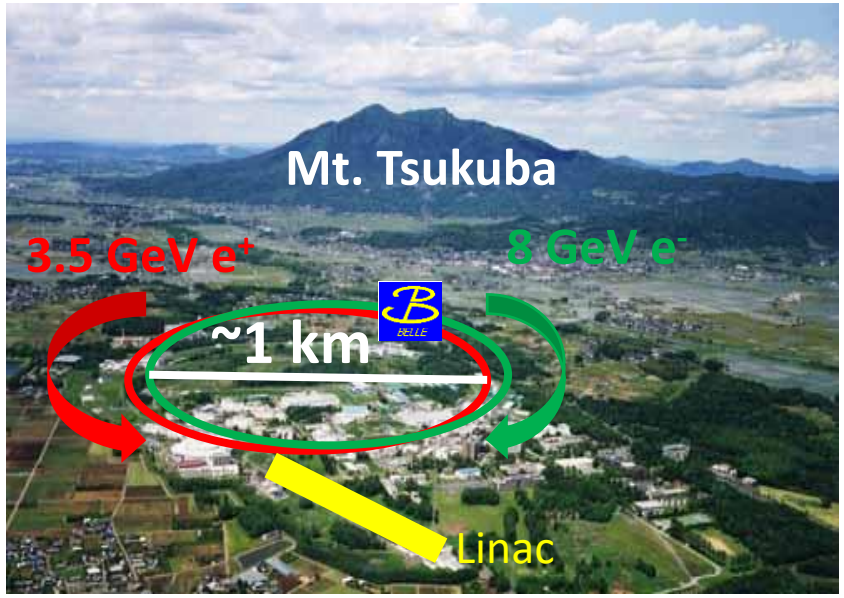
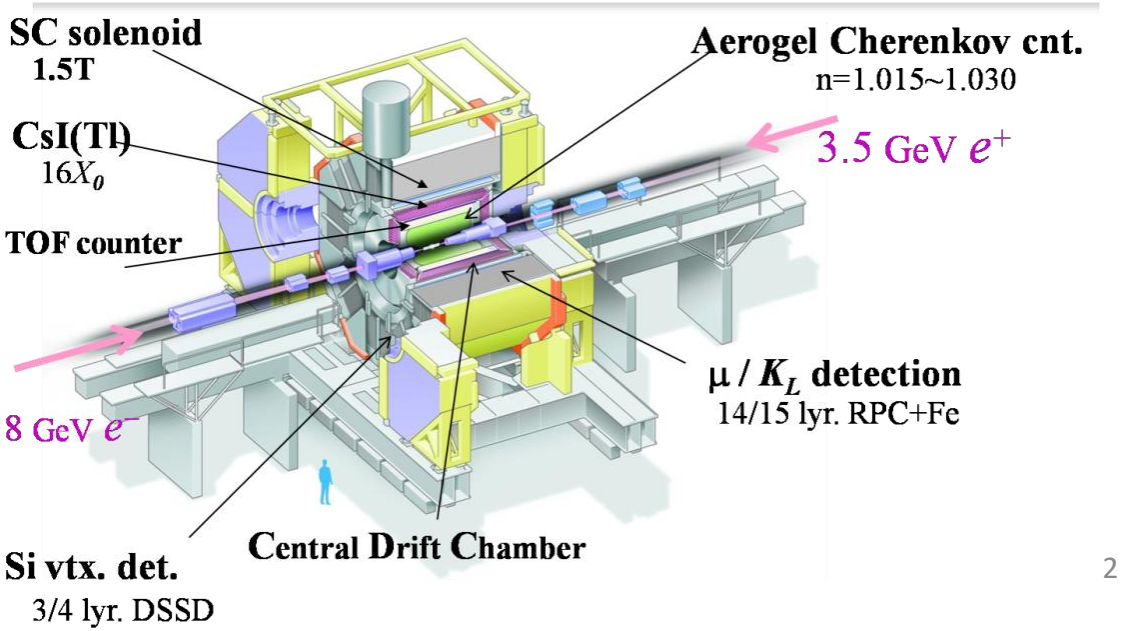
# KEKB/Belle experiment





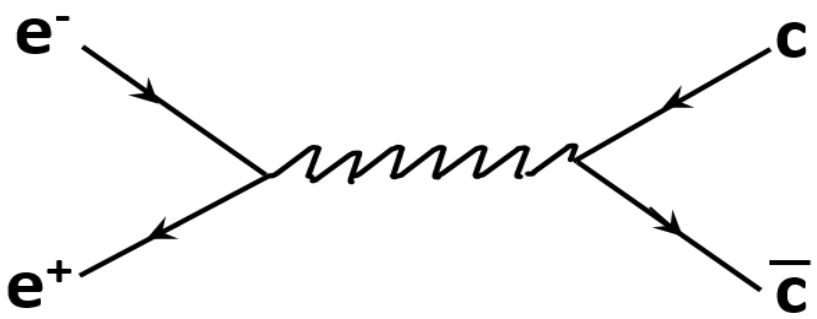

- Asymmetric energy $e^+e^-$ collider (mainly) at Y(4S) mass.
- Belle: General purpose 4π detector.
- Data taking was finished in 2010:
  $7.7\times10^8$ BB pairs, ~$10^9$ $e^+e^-\rightarrow c\bar{c}$, >30 $fb^{-1}$ for Y(1-3S)



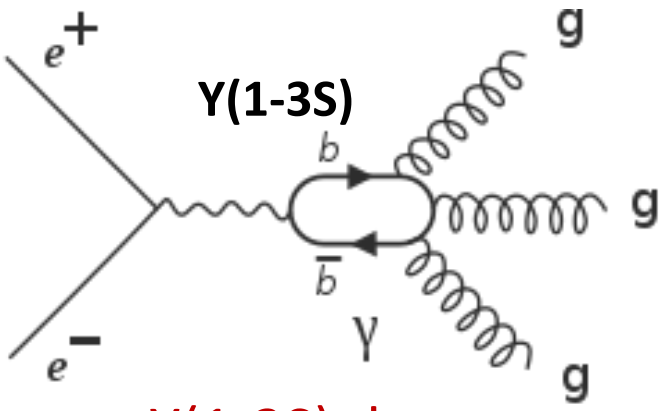
# Baryon spectroscopy at B-factories (outline)





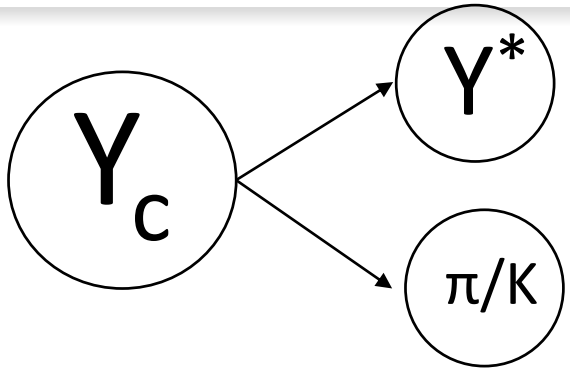

$e^+e^- \rightarrow c\bar{c}$

**"The traditional way"**
**>10 new charmed baryons discovered**



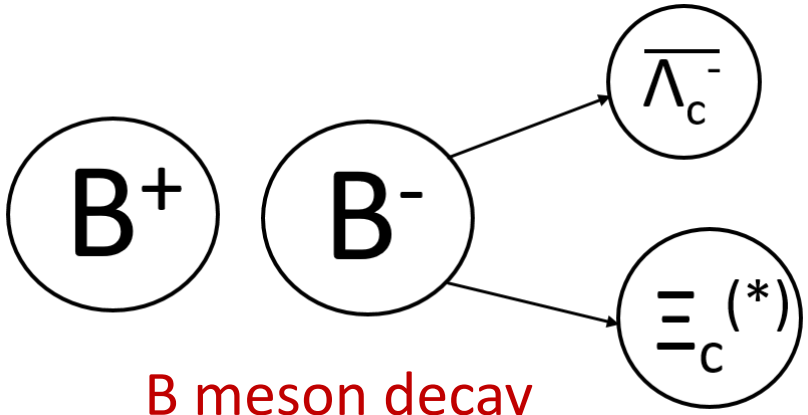

Y(1-3S) decays

2. Observation of $\Omega(2012) \rightarrow \Xi^-\pi^+$
3. Search for $\Omega(2012) \rightarrow \Xi(1530)\,\pi$




**Hyperon* from charmed baryon weak decay**

1. $\Xi_c^0 \rightarrow \Xi^-(1620/1690)\pi^+$




B meson decay

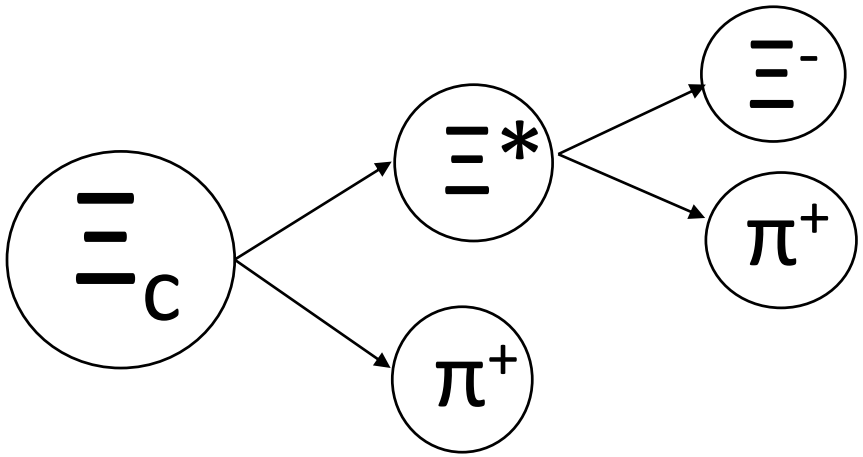
4. $\Xi_c^{+/0}$ branching fractions

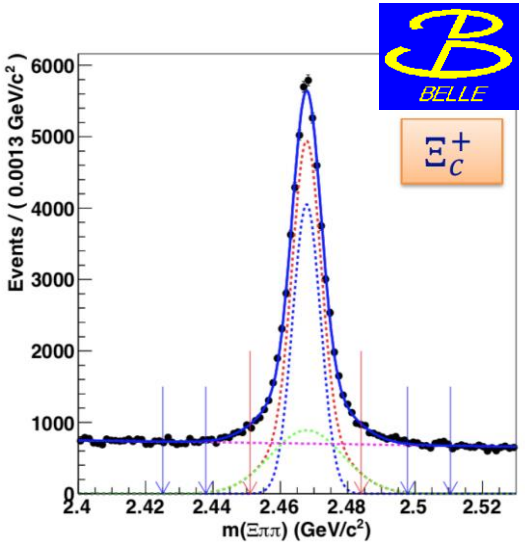
# $\Xi_c^+ \to \Xi(1620/1690)\pi^+$, $\Xi(1620/1690) \to \Xi^-\pi^+$



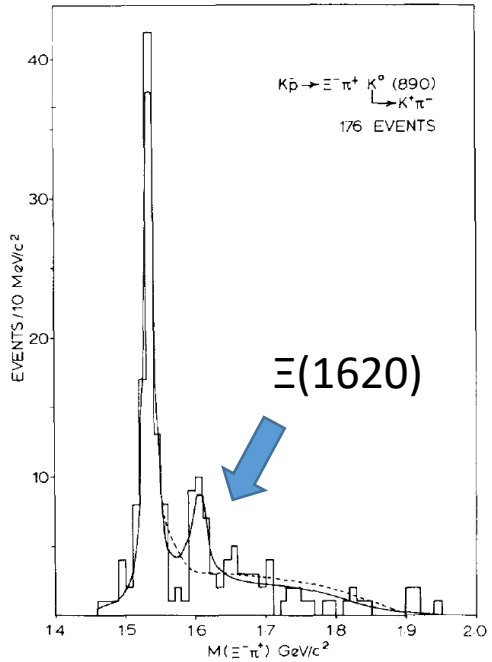
- Not much is known about the S=-2 baryon family(Ξ).
  - First orbital excitation with $J^P=1/2^-$ is not identified.
  - In the S=-1, $J^P=1/2^-$ = Λ(1405) is a candidate of meson-baryon molecule state.
  - Ξ(1620/1690) are candidates of Ξ analogue of Λ(1405).
    Evidence for Ξ(1620) is poor (1 star state) in PDG.

- Belle studied Ξ* in $\Xi_c^+ \to \Xi^*\pi$, $\Xi^* \to \Xi^-\pi^+$ ($\Xi^- \to \Lambda\pi^-$)
  ~50000 $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ with good S/N ratio.




**Old bubble chamber experiment**




Phys.Lett. 38B (1972) 177-180

# $M(\Xi^-\pi^+)$ distribution

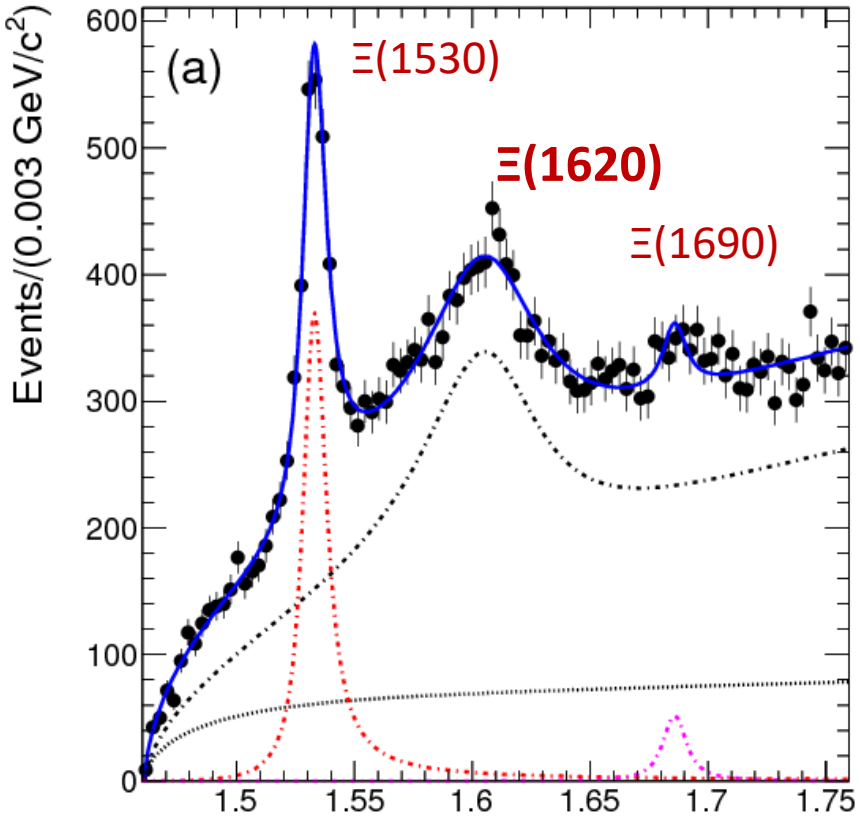


- Peaks correspond to Ξ(1530), Ξ(1620), and Ξ(1690) can be seen.
  - Ξ(1620) and Ξ(1690) are not visible in the $\Xi_c$ sideband.
- Fit is performed with floating Ξ(1530) and Ξ(1620) masses/widths. Ξ(1690) mass and width are fixed with PDG values.
- Interference with non-resonant S-wave component included.

| | Mass (MeV/$c^2$) | Width (MeV) | Significance |
|---|---|---|---|
| Ξ(1620) | $1610.4\pm6.0^{+6.1}_{-4.2}$ | $59.9\pm4.8^{+2.8}_{-7.1}$ | 25σ |
| Ξ(1690) | fixed | fixed | 4σ |

- Ξ(1620) is the first hyperon established by charm baryon decay!
- Full amplitude analysis to determine $J^P$ in the future.

Phys. Rev. Lett. 122, 072501



# Observation of Ω(2012) in Y(1-3S)→(Ξ K) X



- Even more less known about the Ω baryon family (=sss).
- Only two states established.
- Difficult to identify Ω(2250) as first P-wave excitation due to its large mass difference.

~600 MeV

| | | |
|---|---|---|
| $\Omega^-$ | $3/2^+$ | **** |
| $\Omega(2250)^-$ | | *** |
| $\Omega(2380)^-$ | | ** |
| $\Omega(2470)^-$ | | ** |

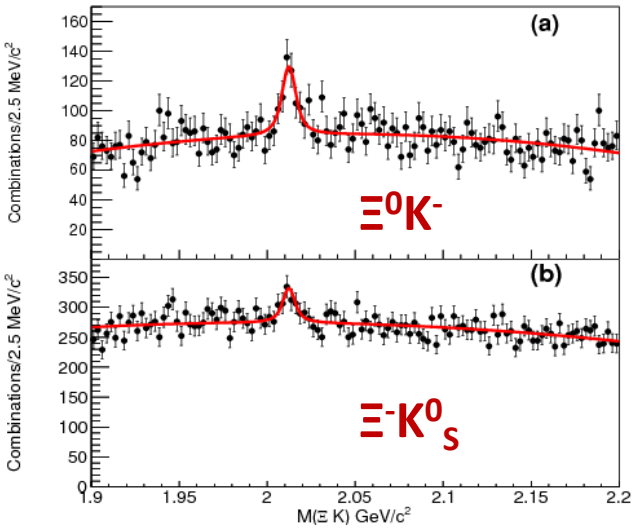
**Evidence of existence is only fair**

- Belle looked for Ω* in $\Xi^-K$ final state in Y(1-3S) data, whose decay is flavor blind.

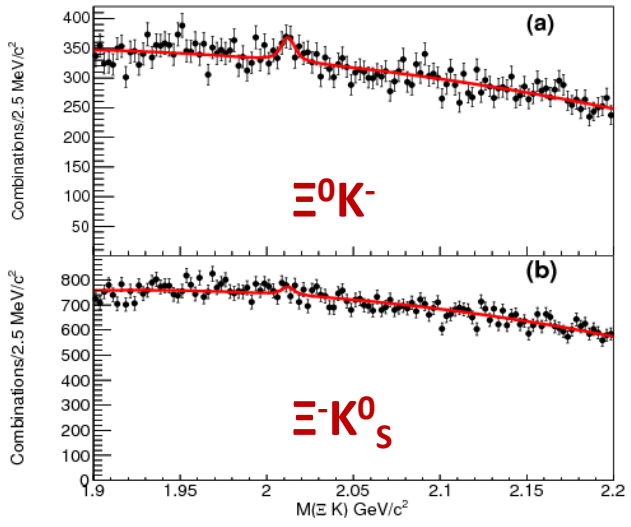
| | Y(1S) | Y(2S) | Y(3S) |
|---|---|---|---|
| Luminosity ($fb^{-1}$) | 5.7 | 24.9 | 2.9 |

M(ΞK)

Y(1-3S) data




Other (Y(4S), continuum..) data



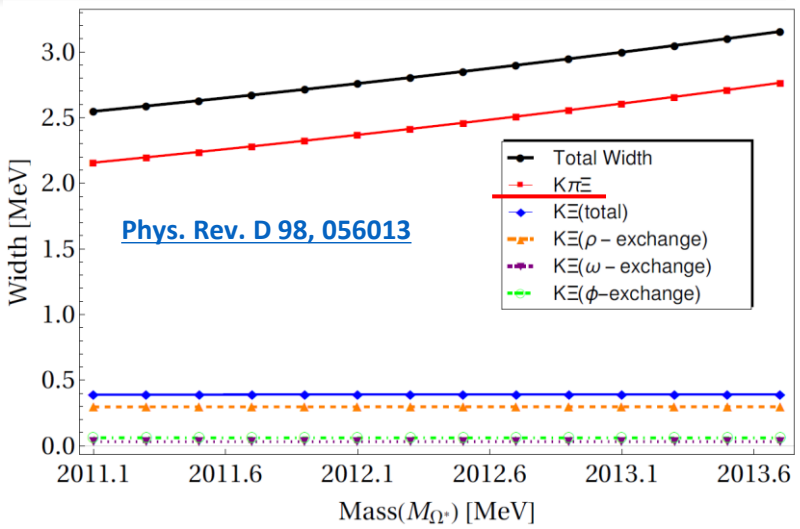

- First observation of Ω (2012) with 8.3σ!
  - Mass: $2012.4 \pm 0.7 \pm 0.6$ MeV/$c^2$
  - Width: $6.4^{+2.5}_{-2.0} \pm 1.6$ MeV.
- Consistent with P-wave (3/2-) Ω state from quark model/QCD sum rule, etc..

Phys. Rev. Lett. 121, 052003

# Search for Ω(2012) in Υ(1-3S)→(Ξ(1530) K) X



- Another possible interpretation of Ω(2012) is Ξ(1530)K molecule.
  It is just ~10 MeV above the threshold.
- Large branching fraction to Ξ(1530)K is predicted by several calculations.
- Search for Ω(2012)→Ξ(1530) π with Υ(1-3)S data.



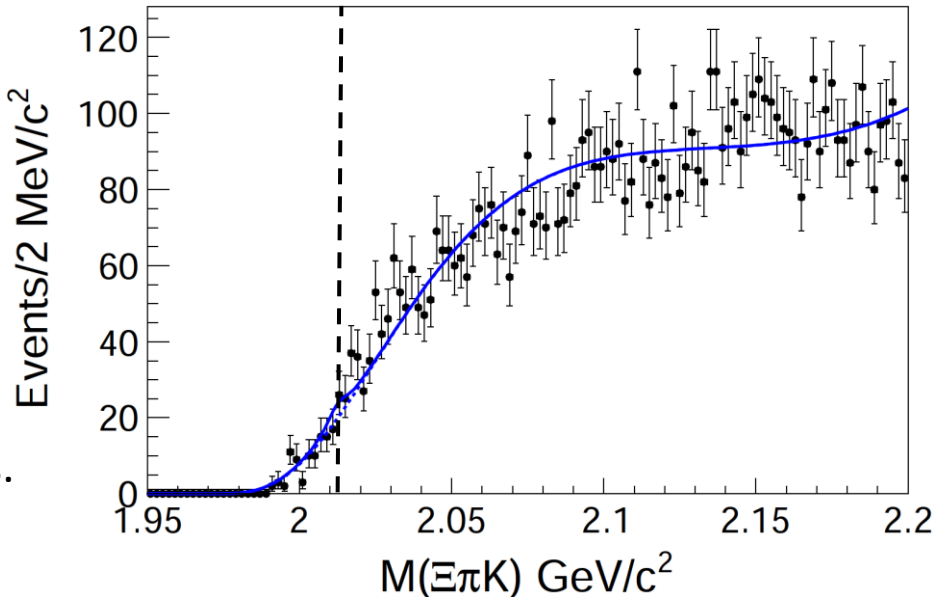

- There is no significant signal
- The upper limits on the ratio to Ξ-K decay are (stringent ones only):

$$\mathcal{R}^{\Xi^-\pi^+K^-}_{\Xi^-\bar{K}^0} = \frac{\mathcal{B}(\Omega(2012) \to \Xi(1530)^0(\to \Xi^-\pi^+)K^-)}{\mathcal{B}(\Omega(2012) \to \Xi^-\bar{K}^0)} < 9.3\%$$

$$\mathcal{R}^{\Xi^-\pi^+K^-}_{\Xi^0K^-} = \frac{\mathcal{B}(\Omega(2012) \to \Xi(1530)^0(\to \Xi^-\pi^+)K^-)}{\mathcal{B}(\Omega(2012) \to \Xi^0K^-)} < 7.8\%$$

- These values are contradicted/have tensions with many molecular scenarios.

arXiv:1906.00194

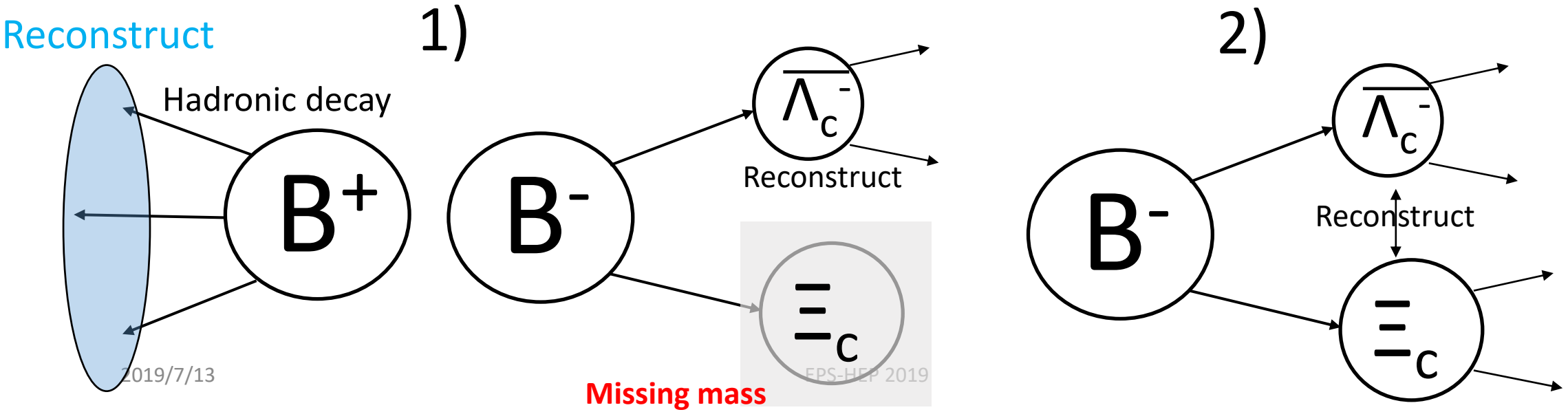


# Absolute branching fractions of $\Xi_c^{0/+}$



- $\Xi_c$ decay branching fractions were all measured ONLY relative to primary modes.
  - Absolute values awaited to determine production cross sections/partial decay widths.

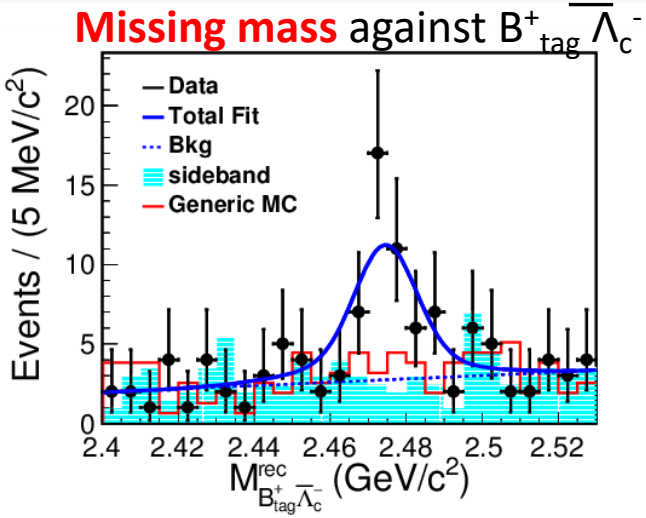
- Absolute values for
  $\Xi_c^0 \to \Xi^-\pi^+$, $\Lambda K^-\pi^+$, $pK^-K^-\pi^+$ and $\Xi_c^+ \to \Xi^-\pi^+\pi^-$, $pK^-\pi^+$, $pK^*$
  are measured in the following way
  1): Measure $Br(B^{-/0} \to \Lambda_c^- \Xi_c^{0/+})$ using missing mass.
  2): Measure $Br(B^- \to \Lambda_c^- \Xi_c^{0/+}) \times Br(\Xi_c^0 \to f)$ by exclusively reconstructing $\Xi_c$
  3): Divide 2) by 1).



# Results for $\Xi_c^0$



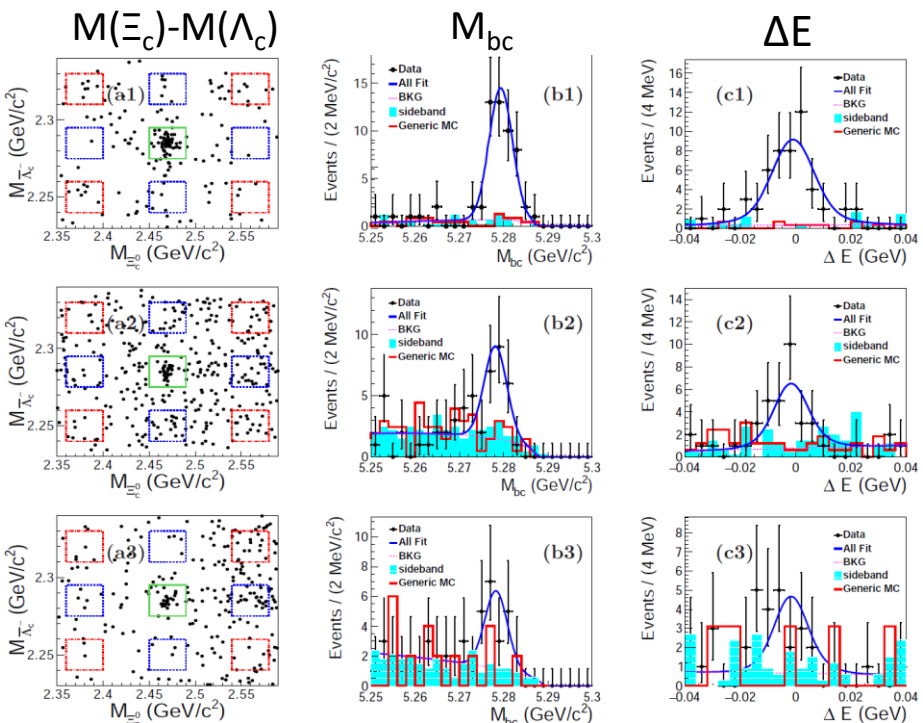
1)




Phys. Rev. Lett. 122, 082001

- $\Xi_c^0$ is observed by missing mass for the first time with 5.5σ (40.9±9.0 events)
- $Br(B^- \to \Lambda_c^- \Xi_c^0) = (9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$

2)




- 2 dimensional fit on $M_{bc}$-ΔE after selecting signal region in M($\Xi_c$)-M($\Lambda_c$) plane.

$\Xi^-\pi^+$

$\Lambda K^-\pi^+$

$pK^-K^-\pi^+$

3)

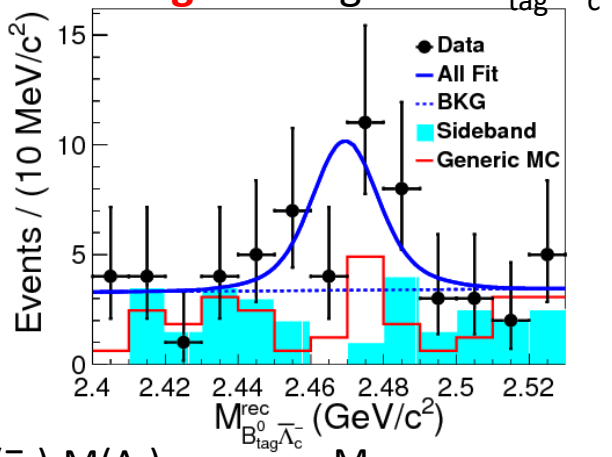
| Decay | $Br(B \to \Xi_c \Lambda_c) \times Br(\Xi_c \to f)$ ($10^{-5}$) | $Br(\Xi_c^0 \to f)$ (%) | Significance |
|---|---|---|---|
| $\Xi^-\pi^+$ | 1.71±0.28±0.15 | 1.8±0.5±0.14 | 9.5σ |
| $\Lambda K^-\pi^+$ | 1.11±0.26±0.10 | 1.17±0.37±0.09 | 6.8σ |
| $pK^-K^-\pi^+$ | 0.547±0.178±0.057 | 0.58±0.23±0.05 | 4.6σ |

# Results for $\Xi_c^+$ Belle Preliminary



1)

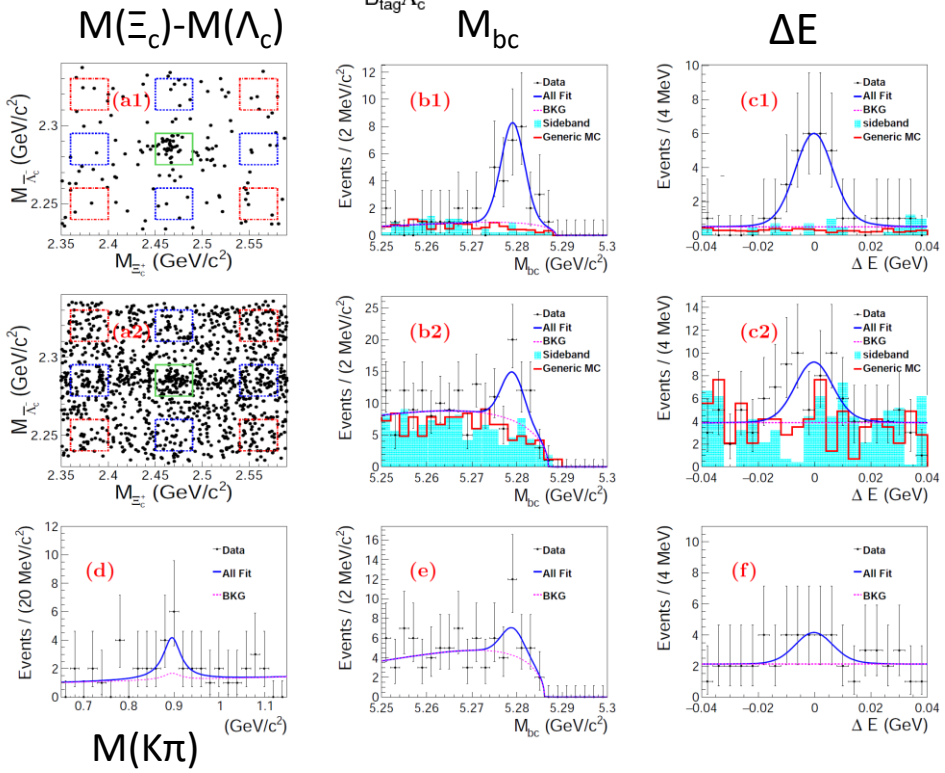
**Missing mass** against $B^0_{tag}\,\Lambda_c^-$




arXiv:1904.12093

- $\Xi_c^+$ is observed by missing mass for the first time with 3.2σ (18.8±6.8 events)
- $Br(B^0 \to \Lambda_c^- \Xi_c^+) = (1.16 \pm 0.42 \pm 0.15) \times 10^{-3}$

2)




$\Xi^-\pi^+\pi^-$

$pK^-\pi^+$

$pK^*$

- Signal yields are obtained by 2D fit on $M_{bc}$-ΔE after selecting signal region in $M(\Xi_c)$-$M(\Lambda_c)$ plane.

3)

| Decay | $Br(B \to \Xi_c \Lambda_c) \times Br(\Xi_c \to f)$ $(10^{-5})$ | $Br(\Xi_c^0 \to f)$ (%) | Significance |
|---|---|---|---|
| $\Xi^-\pi^+\pi^-$ | 3.32±0.74±0.33 | 2.86±1.21±0.38 | 6.9σ |
| $pK^-\pi^+$ | 5.27±1.51±0.69 | 0.45±0.21±0.07 | 4.5σ |
| $pK^*$ | 2.96±1.31±0.44 | 0.25±0.16±0.04 | 3.3σ |

# Summary



- After ~10 years from the end of data taking,
  Belle is actively working on the baryon spectroscopy.

- Variety of production mechanisms enabled various measurements.

- More studies with Belle data on going, and more data soon come from Belle II!

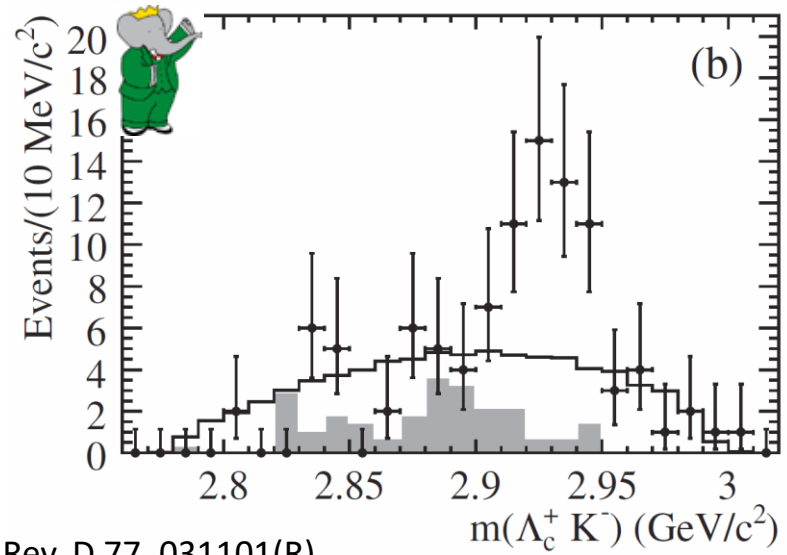
# Backup

# Observation of $\Xi_c(2930)^0$



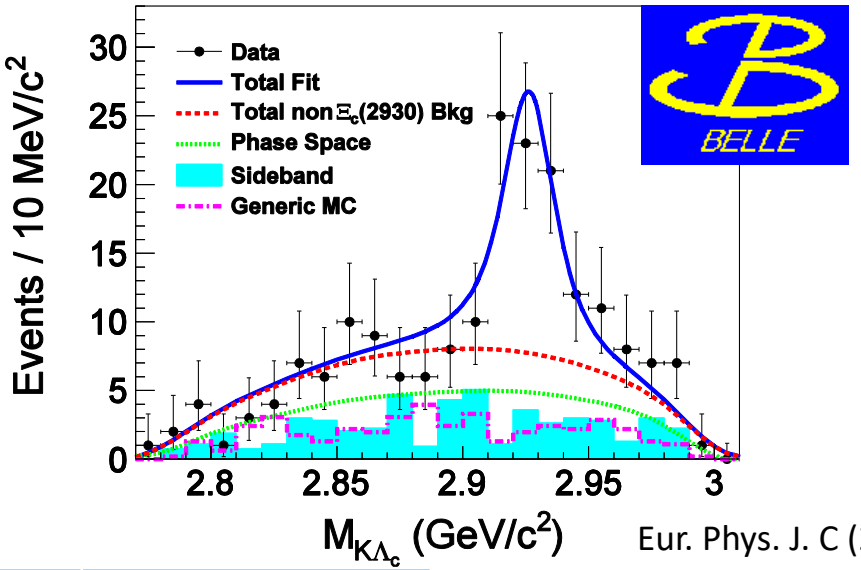
- Weak evidence of $\Xi_c(2930)$ was reported by BaBar in $B^- \to \Xi_c(2930)\bar{\Lambda}_c$ , $\Xi_c(2930) \to \Lambda_c^+ K^-$
- Assigned as one star in PDG (need confirmation) .
- Belle performed the same study with ~3 times statistics.

Previous study by BaBar (2008)




Phys. Rev. D 77, 031101(R)

New study by Belle (2018)




Eur. Phys. J. C (2018) 78: 252.

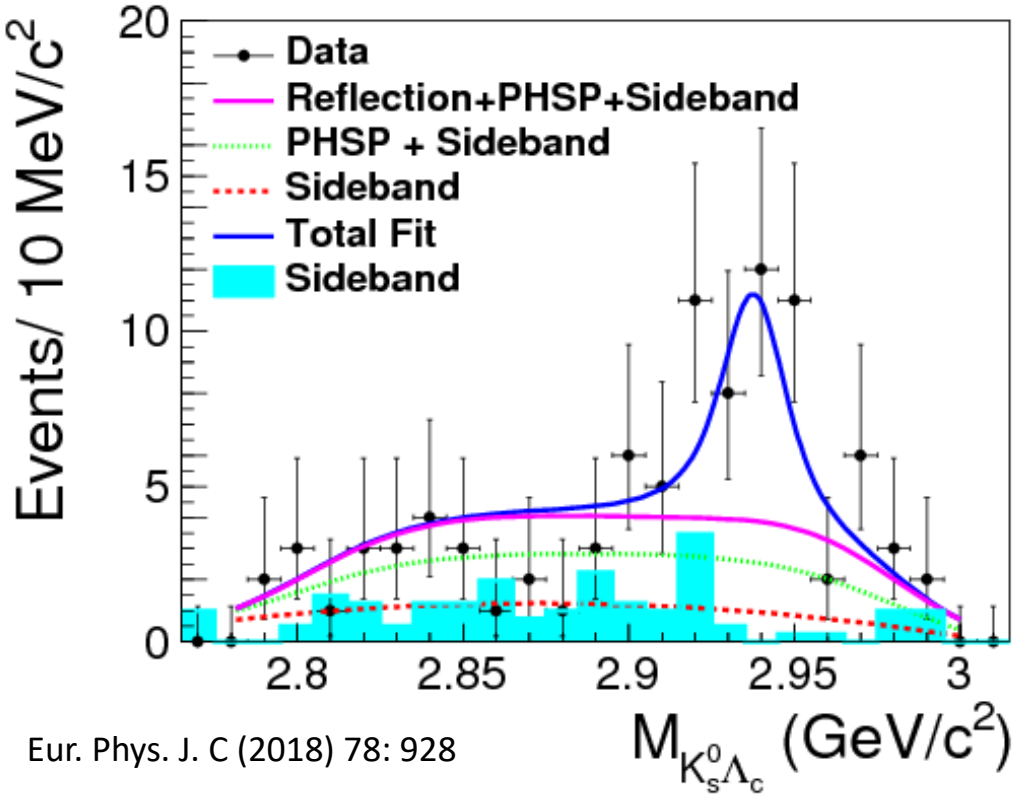
| | Mass (MeV/$c^2$) | Width (MeV) |
|---|---|---|
| BaBar | $2931 \pm 3 \pm 5$ | $36 \pm 7 \pm 11$ |
| Belle | $2928.9 \pm 3.0^{+0.8}_{-12.0}$ | $19.5 \pm 8.4^{+5.4}_{-7.9}$ |

- The statistical significance of the peak at Belle is 5.1σ.
- Mass and width are consistent each other

# Evidence for charged partner $\Xi_c(2930)^+$



Belle also found **4.1σ** evidence for charged partner $\Xi_c(2930)^+$ in $B^0 \to \Xi_c(2930)^+ \Lambda_c^-$, $\Xi_c(2930)^+ \to \Lambda_c^+ K_{S0}$



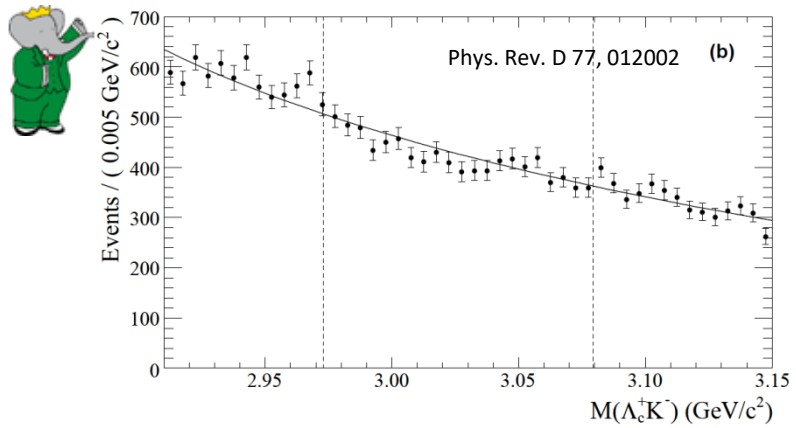

Eur. Phys. J. C (2018) 78: 928

| | Mass (MeV/$c^2$) | Width (MeV) |
|---|---|---|
| $\Xi_c(2930)^0$ | $2928.9 \pm 3.0^{+0.8}_{-12.0}$ | $19.5 \pm 8.4^{+5.4}_{-7.9}$ |
| $\Xi_c(2930)^+$ | $2942.3 \pm 4.4 \pm 1.5$ | $14.8 \pm 8.8 \pm 2.5$ |

# Some comments on $\Xi_c(2930)$

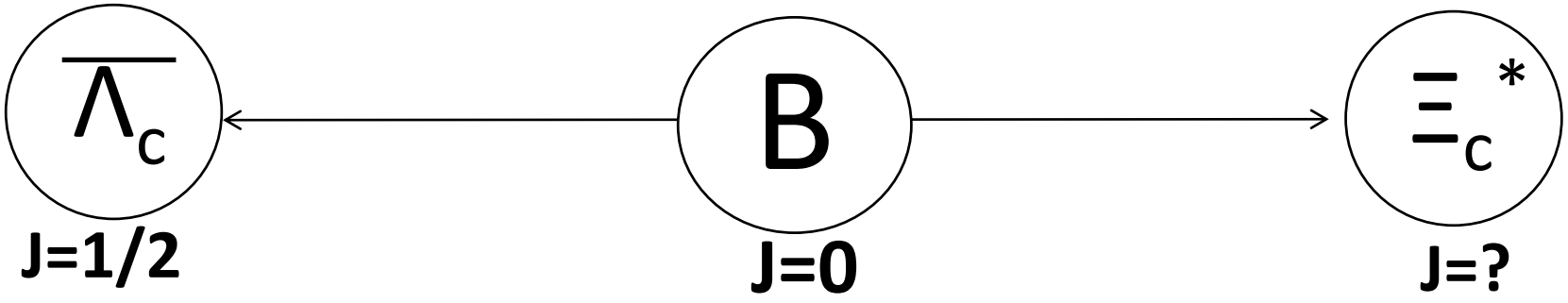


- $\Xi_c(2930)^0$ is the first charmed baryon **established in the B-decay**.




$M(\Lambda_c^+K^-)$ in $e^+e^-\to c\bar{c}$ by BaBar.

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



# Physics of charmed baryons

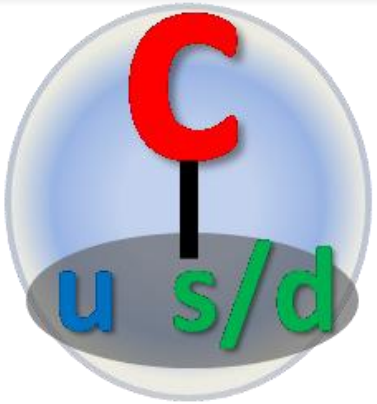


(1) Di-quark structure in the baryon

- Spin-spin interaction $\propto 1/m_1 m_2$
- Di-quark + charm quark
  - Di-quark as new degree of freedom.
  - Easier to understand baryons.

**Nucleon**

Pairs can not be distinguished.

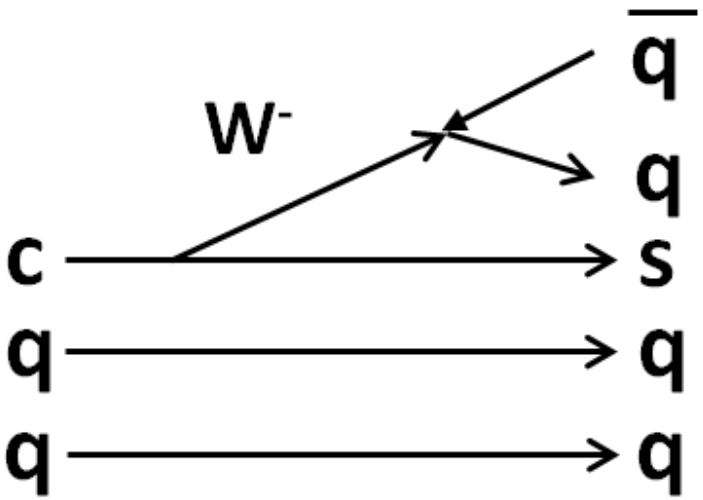



**Charmed baryon**

Light di-quark and charm quark.

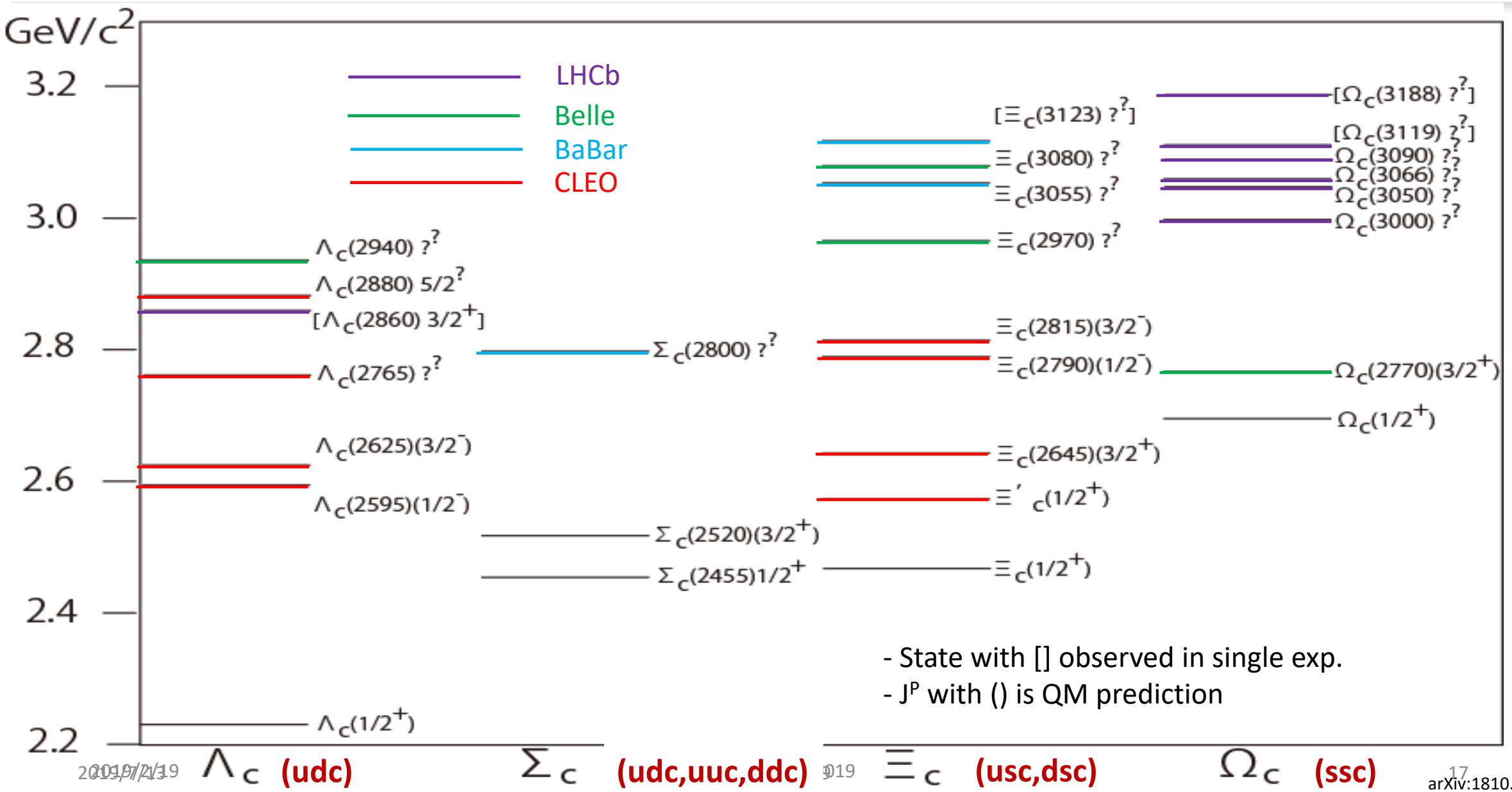
(2) Charm baryon as a hyperon laboratory

- Ground-state dominantly decay via c→s.
- Variety of hyperons are produced.



# Currently observed charmed baryons








arXiv:1810.03748