Spectroscopy on conventional and non-conventional hadrons at Belle

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On behalf of Belle Collaboration

XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects
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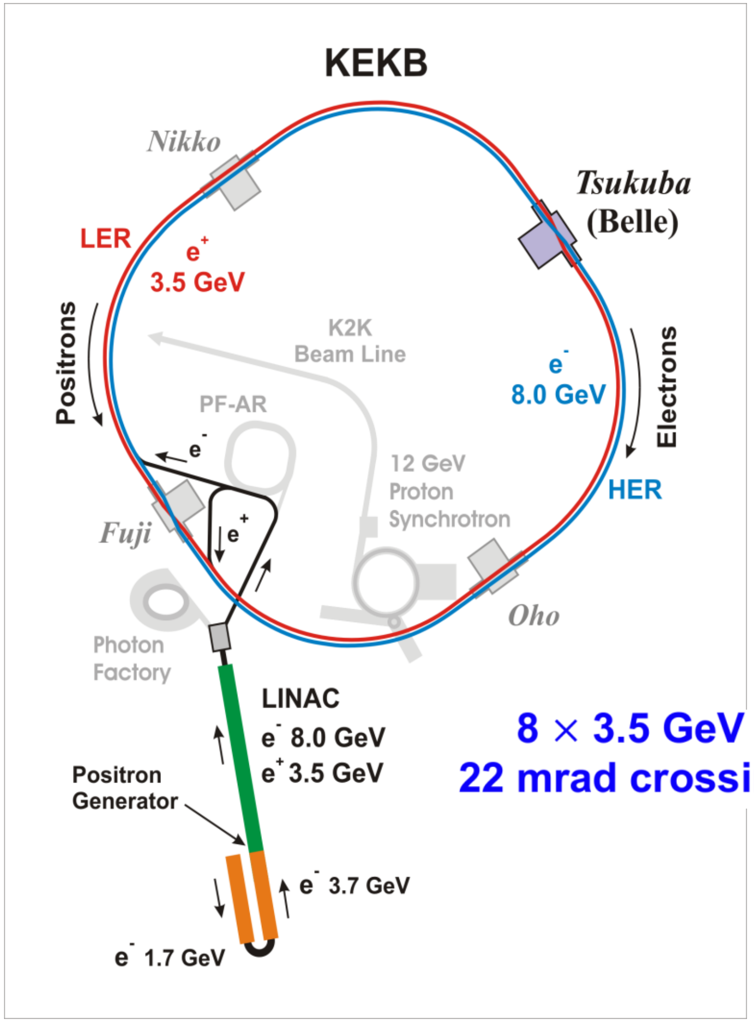
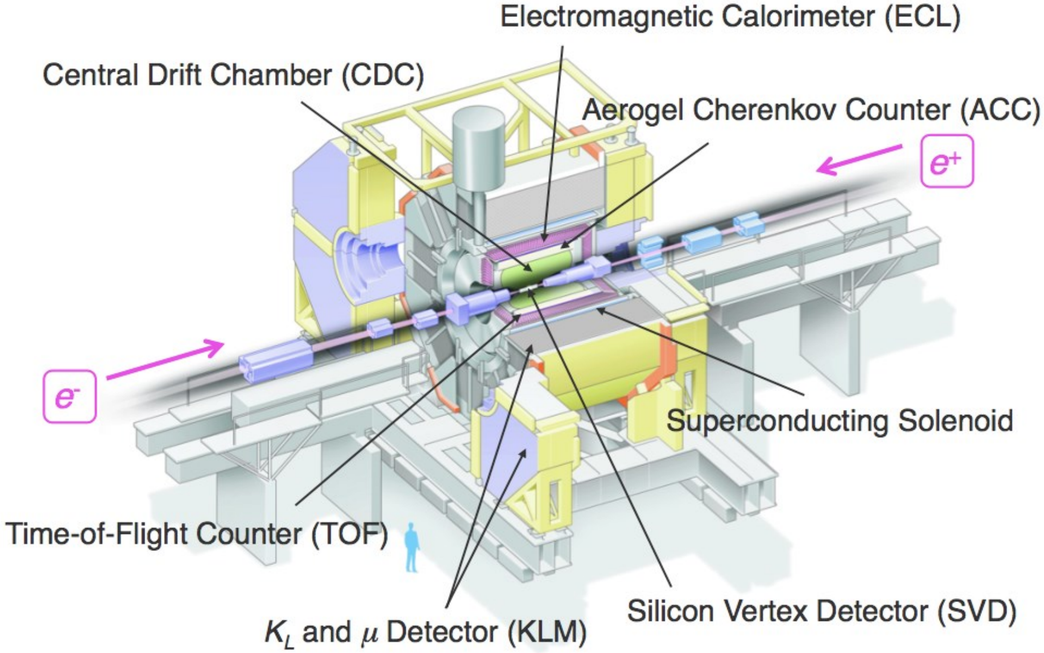
Belle Experiment and data samples





8 × 3.5 GeV
22 mrad crossing

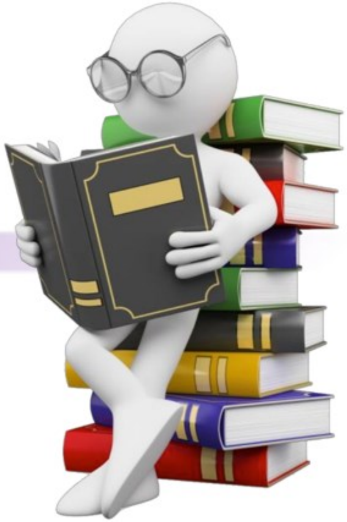
Data taking: 1999 – 2010

On/off/Scan $\Upsilon(nS)$ peaks

Total luminosity: 980 fb^{-1}

772M $B\bar{B}$ events @$\Upsilon(4S)$

Selected topics



Conventional hadrons at Belle:

- Branching fraction measurement of $\Lambda_c^+ \to p\eta/\pi^0$
- Radiative decays of excited Ξ_c baryons

Non-Conventional hadrons at Belle:

- $X(3872) \to J/\psi\,\pi^+\pi^-$ in two-photon productions

Branching fraction measurement of $\Lambda_c^+ \to p\eta/\pi^0$

arxiv:2102.12226 Accepted by PRD

Motivation:

- 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)
  - $B(\Lambda_c^+ \to p\eta) = (\mathbf{1.24} \pm \mathbf{0.28} \pm \mathbf{0.10}) \times \mathbf{10^{-3}}$
    (with a statistical significance of **4.2σ**)
  - $B(\Lambda_c^+ \to p\pi^0) < \mathbf{2.7} \times \mathbf{10^{-4}}$ at 90% C.L.

- The theoretical prediction with current-algebra approach gives (PRD 97, 074028 (2018))
  - $B(\Lambda_c^+ \to p\eta) = 1.28 \times 10^{-3}$
  - $B(\Lambda_c^+ \to p\pi^0) = 7.5 \times 10^{-5}$.

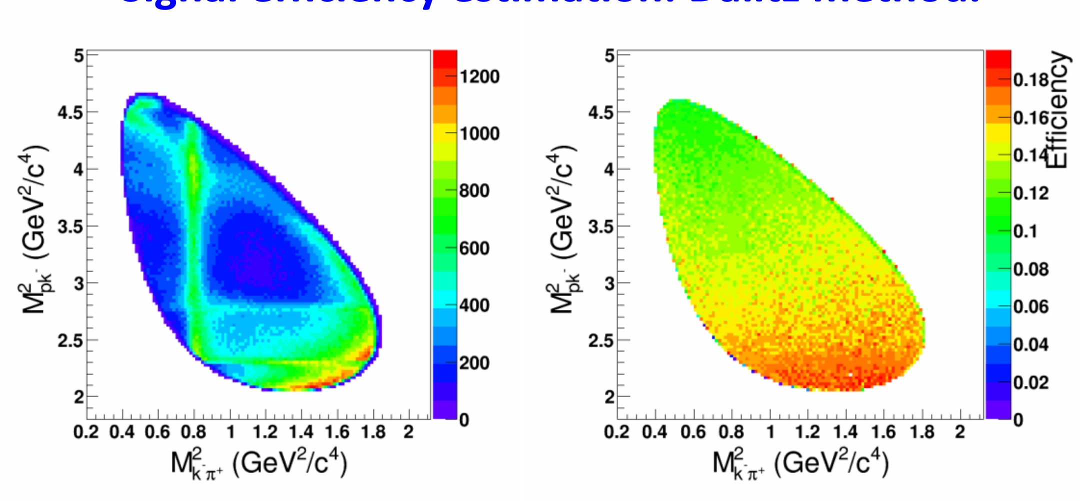
- To improve the measurement precision, we measure the branching fractions of the signal decays at Belle.

Measurement of Normalization mode

- **Normalization mode:** $\boldsymbol{\Lambda_c^+ \to pK^-\pi^+}$ (Cabiboo-favored)
- **Method:**

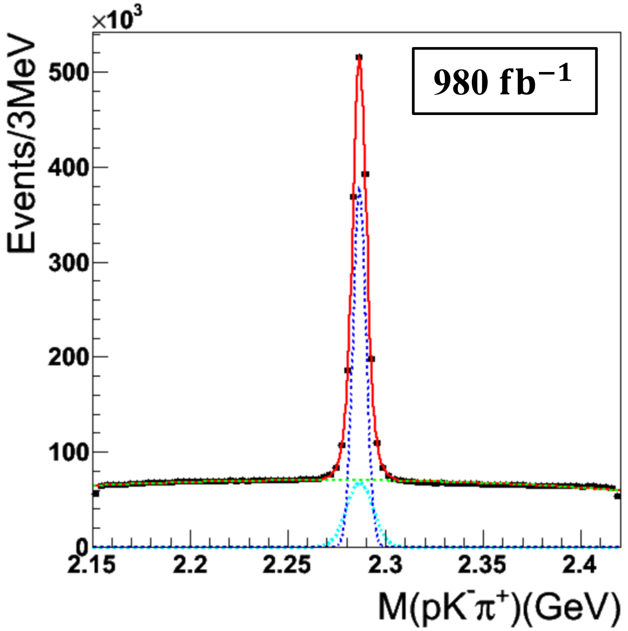
$$\frac{B(SCS)}{B(CF)} = \frac{N^{obs}(SCS)}{\epsilon^{MC}(SCS)} \times \frac{\epsilon^{MC}(CF)}{N^{obs}(CF)}$$

Signal efficiency estimation: Dalitz method.



Left: Dalitz plot from data; Right: Dalitz plot of efficiency from signal MC.

$$\varepsilon = \sum s_i \Big/ \sum_j (s_j/\varepsilon_j) = \left(\mathbf{14.06 \pm 0.01}\right)\%.$$



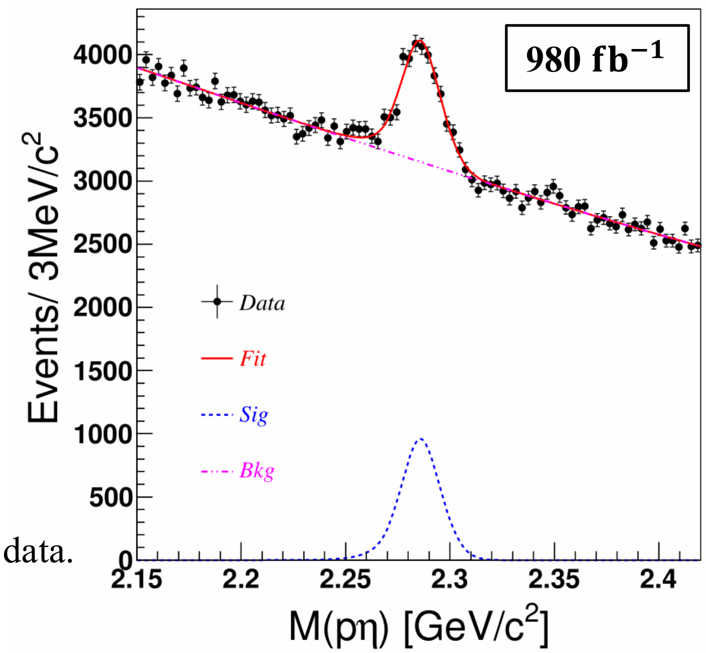
Fit to M($pK^-\pi^+$) from data.

Double Gaussian + second-order polynomial

Yield: **1476200 ± 1560**
χ^2/ndf=1.06

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

- Reconstruct the signal mode: $\Lambda_c^+ \to p\eta(\to \gamma\gamma)$
- The signal detection **efficiency** : $(8.279 \pm 0.030)\%$.



Fit to M($p\eta$) from data.

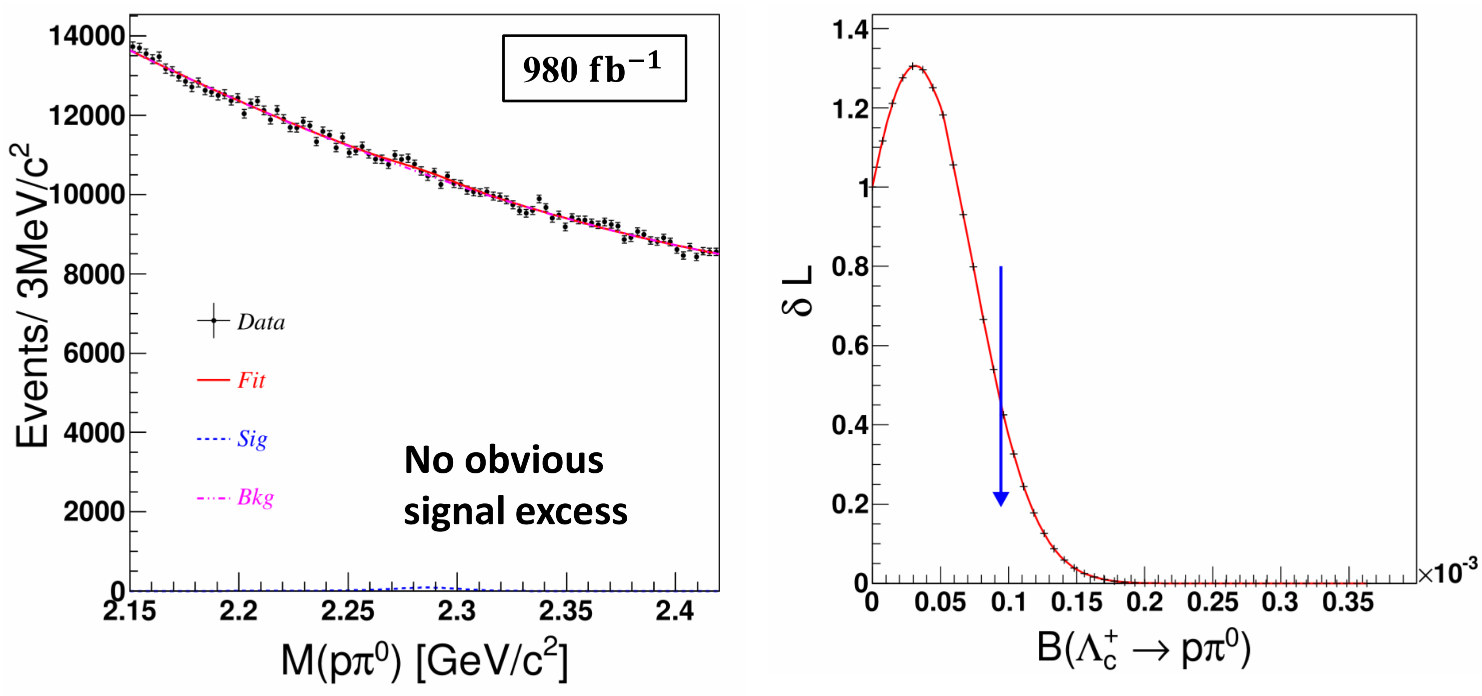
Gaussian + CB for signal.
Second-order polynomial for background.

Yield: 7734 ± 263
χ^2/ndf=1.23

- A significant Λ_c^+ signal is observed from data.
- **Measured $B(\Lambda_c^+ \to p\eta) = (1.42 \pm 0.05 \pm 0.11) \times 10^{-3}$**
- Consistent with BESIII result $(1.24 \pm 0.30) \times 10^{-3}$ with much **improved precision.**
- Consistent with theoretical prediction 1.28×10^{-3}

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

- The signal detection **efficiency** : $(8.891 \pm 0.030)\%$.



Left: fit to M($p\pi^0$) from data. Right: The likelihood distribution changing with the branching fraction with the systematic uncertainty involved.

- **Measured** $B(\Lambda_c^+ \to p\pi^0) < 8.0 \times 10^{-5}$ at 90% C.L.
- reducing the value to more than half of the BESIII result 2.7×10^{-4}.
- Consistent with theoretical prediction 7.5×10^{-5}

Radiative decays of excited Ξ_c baryons

Motivation:

PRD 102, 071103 (2020)

- A recent study reported measurement of the masses and widths of the $\Xi_c(2790)^{+/0}$ and $\Xi_c(2815)^{+/0}$ states. PRD 94, 052011 (2016)

- They can also decay via the π^0 decays that are harder to see, and the $\Xi_c(2815)$ has been seen in $\Xi_c'\pi$. PRD 94, 052011 (2016)

- But what about the radiative decays?

$$\Xi_c(2790)^{+/0} \to \Xi_c^{+/0}\gamma$$
$$\Xi_c(2815)^{+/0} \to \Xi_c^{+/0}\gamma$$

- The theoretical predictions show: (PRD 96, 116016 (2017))
  - Neutral states (Γ ~200 keV) – **would be seen**
  - Charged states (Γ < 10 keV) – **would not be seen**

Basic technique

[1.] Reconstruct the ground states $\Xi_c^{0/+}$

- Ξ_c^0: with ten decay modes.
- Ξ_c^+: with seven decay modes.

[2.] Reconstruct the excited Ξ_c from $\boldsymbol{\Xi_c^{+/0}\gamma}$

$$E_\gamma > 0.55 \text{ GeV}$$

[3.] Fit the M($\Xi_c^{+/0}\gamma$) in the region of the $\Xi_c(2790)$ and $\Xi_c(2815)$.

[4.] Divide by the yield in the known decay modes:

$$\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to (\Xi_c^+\gamma)\pi^- \;;$$
$$\Xi_c(2815)^0 \to \Xi_c(2645)^+\pi^- \to (\Xi_c^0\pi^+)\pi^-$$

PRD 94, 052011 (2016)

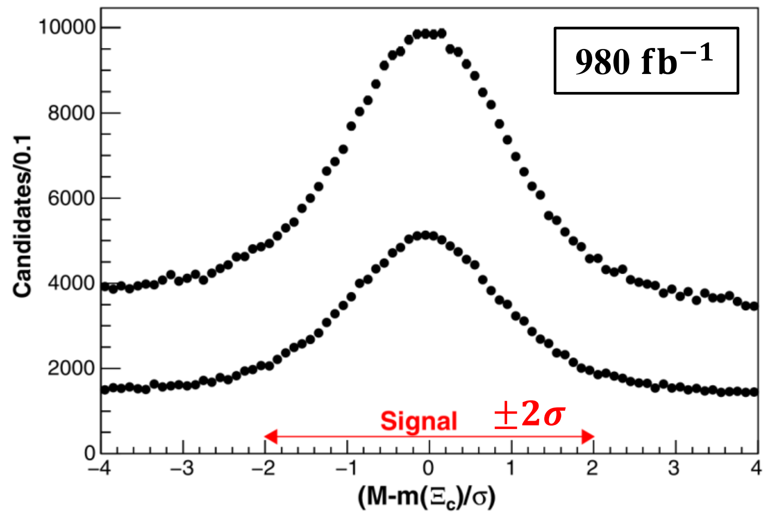


FIG. 1. Pull mass distribution for the Ξ_c^0 (upper data points), and Ξ_c^+ (lower data points) candidates.

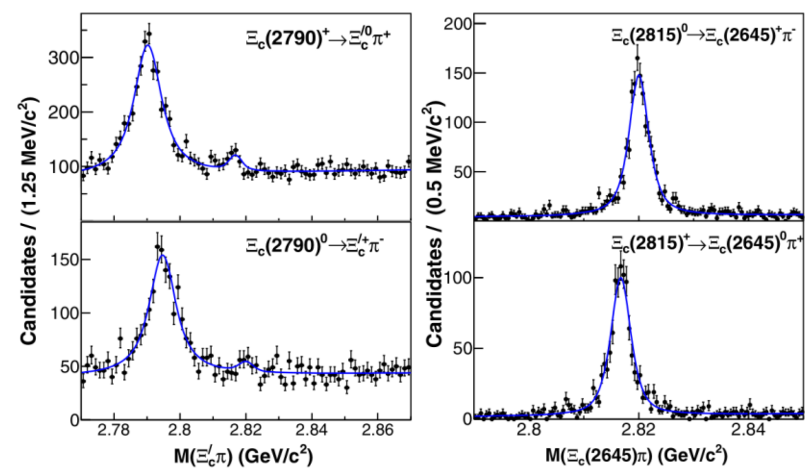
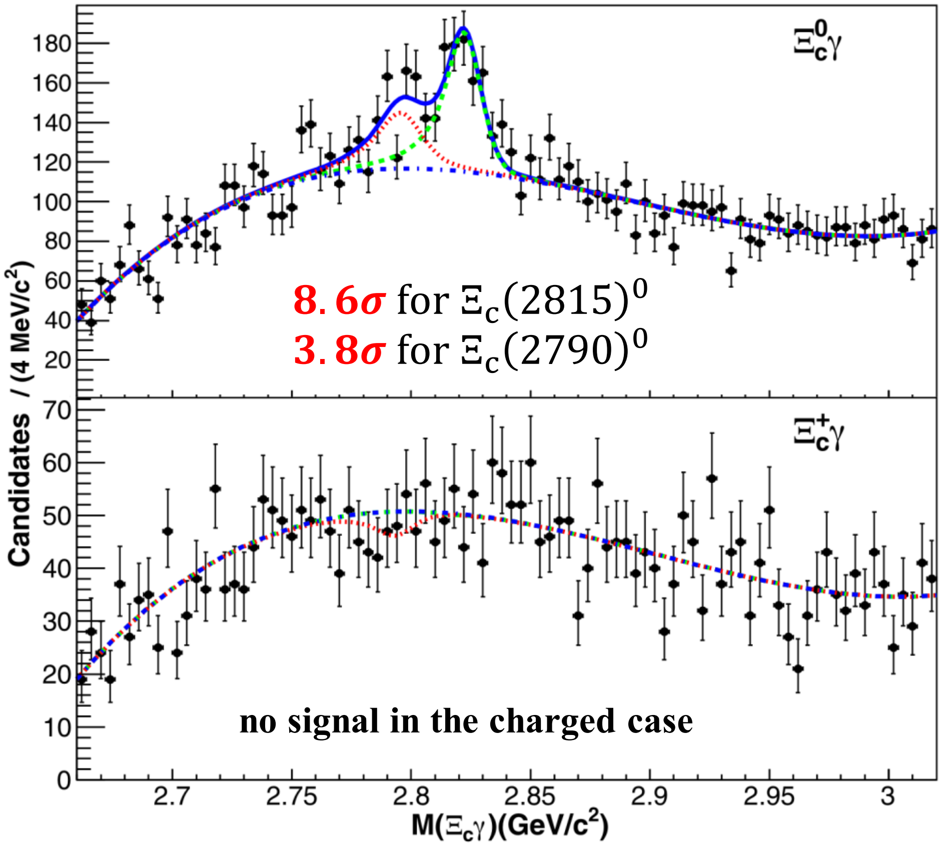


FIG. 3. The signals used as normalization modes in the analysis.

Result:

980 fb^{-1}



$$\frac{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c(2645)^+\pi^- \to \Xi_c^0\pi^+\pi^-]} = 0.41 \pm 0.05 \pm 0.03$$

$$\frac{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to \Xi_c^+\gamma\pi^-]} = 0.13 \pm 0.03 \pm 0.02$$

$$\frac{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c(2645)^0\pi^+ \to \Xi_c^+\pi^-\pi^+]} < 0.09 \text{ at 90\% C.L.}$$

$$\frac{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c'^0\pi^+ \to \Xi_c^0\gamma\pi^+]} < 0.06 \text{ at 90\% C.L.}$$

- First observation of the radiative decays of excited Ξ_c .
- Give the BR.
- Confirm the theoretical prediction.

$X(3872) \to J/\psi\,\pi^+\pi^-$ in single-Tag two-photon productions

- X(3872) with $J^{PC} = 1^{++}$ could be produced if one or both photons are highly virtual [Nucl. Phys. B 523, 423 (1998)].
- The measurement of X(3872) in two-photon reactions help to understand its internal structure.

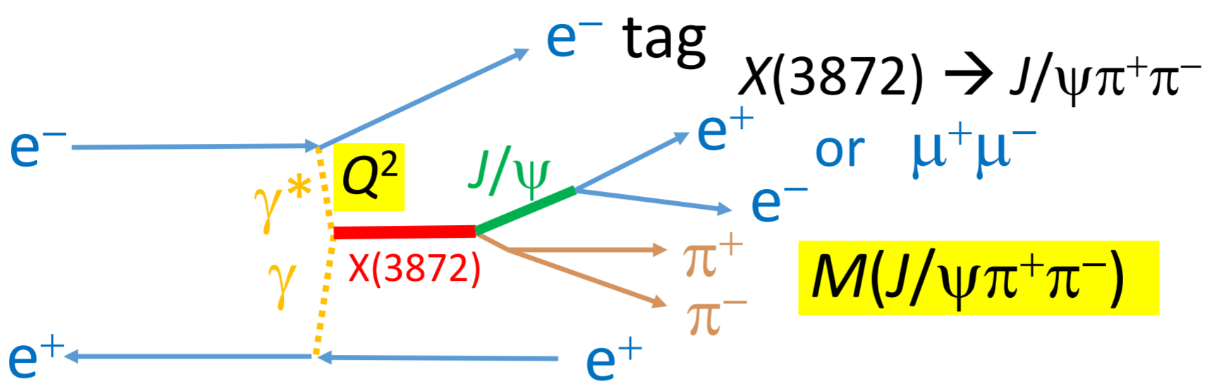
PRL 126, 122001 (2021)

X(3872): $J^{PC} = 1^{++}$

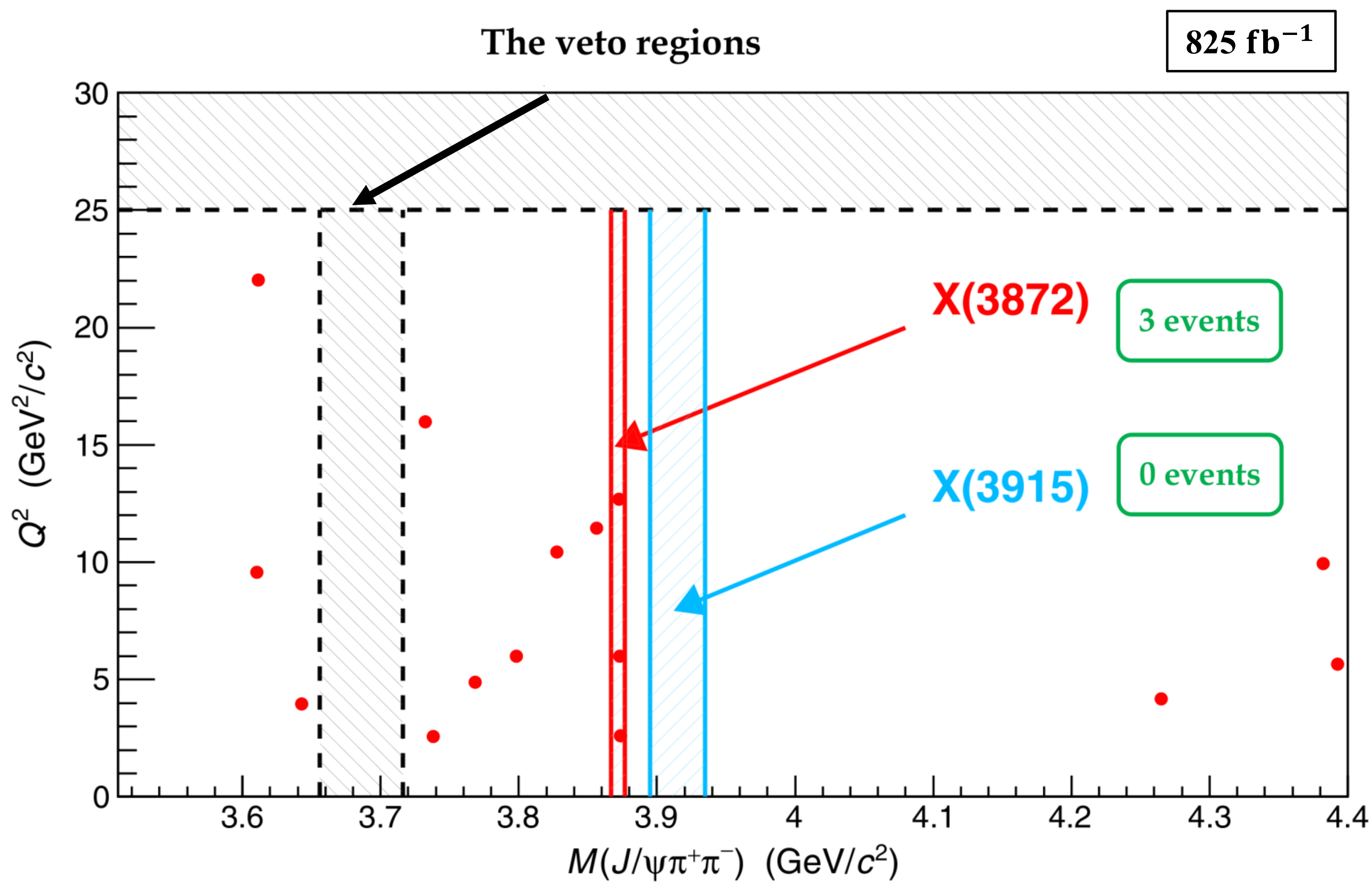
$\gamma\gamma \to X(3872)$ ➡ Not allowed

But, $\gamma^*\gamma \to X(3872)$ ➡ Allowed

Single-tag



$-Q^2$ is the invariant mass-squared of the virtual photon.



- M(X(3872)) = (3.8723±0.0012) GeV/c^2
- With 0.11±0.10 background events, **the number of signal events is $N_{sig} = 2.9^{+2.2}_{-2.0}(\text{stat.}) \pm 0.1(\text{syst.})$ with a significance of 3.2σ** (Feldman-Cousins method applied [Phys. Rev. D 57, 3873 (1998)]).
- **$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) = 5.5^{+4.1}_{-3.8}(\text{stat.}) \pm 0.7(\text{syst.})$ eV** using the Q^2 dependence expected from a $c\bar{c}$ meson model.

Summary

- Although Belle has stopped data taking for ~10 years, we are still producing exciting results.
- We report the BR measurement of $\Lambda_c^+ \to p\eta/\pi^0$.
- We report the first observation of radiative decays of excited Ξ_c and give the BR.
- We report the first evidence for $X(3872) \to J/\psi\,\pi^+\pi^-$ produced in single-tag two-photon interactions.
- Belle II will provide greater sensitivity and precise measurements in hadron physics with 50 ab^{-1}.

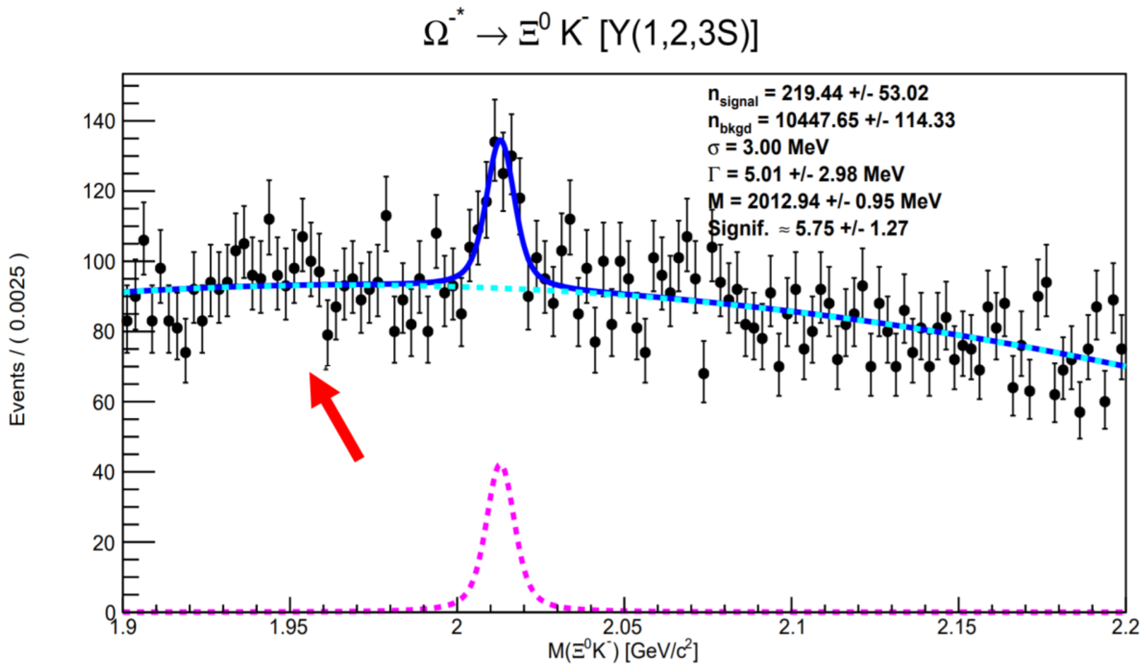
Thanks for your attentions!

Backup

Study of $\Xi_c^0 \to \Xi^0 K^+ K^-$

arxiv:2012.05607 Submitted to PRD

Background Motivation in Excited Ω Searches



Recently, an excited $\mathbf{\Omega(2012)}$ baryon was observed in narrow resonance data by the Belle Collaboration near 2.012 GeV/c^2. PRL 121, 052003 (2018)

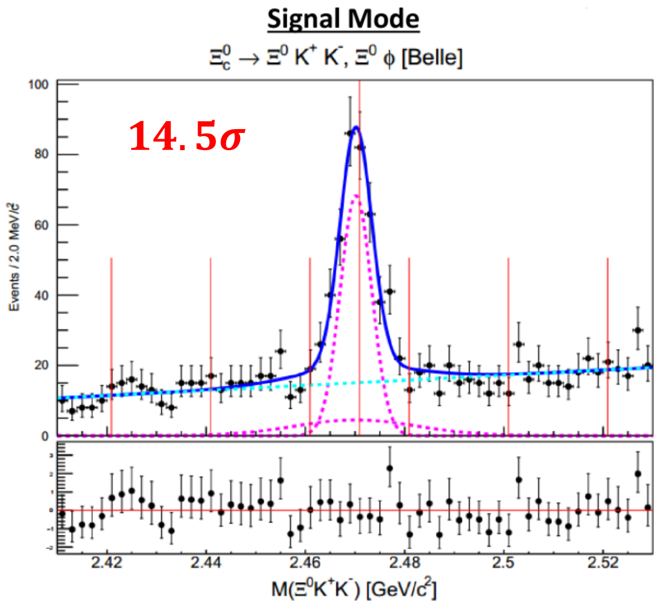
From quark model prediction, it can be expected that $\mathbf{\Omega(2012)}$ could have a partner near **1.95** GeV/c^2 and low-statistics indications of an excess in $\mathbf{M(\Xi^0 K^-)}$ has been noticed. PRD 100, 032006 (2019)

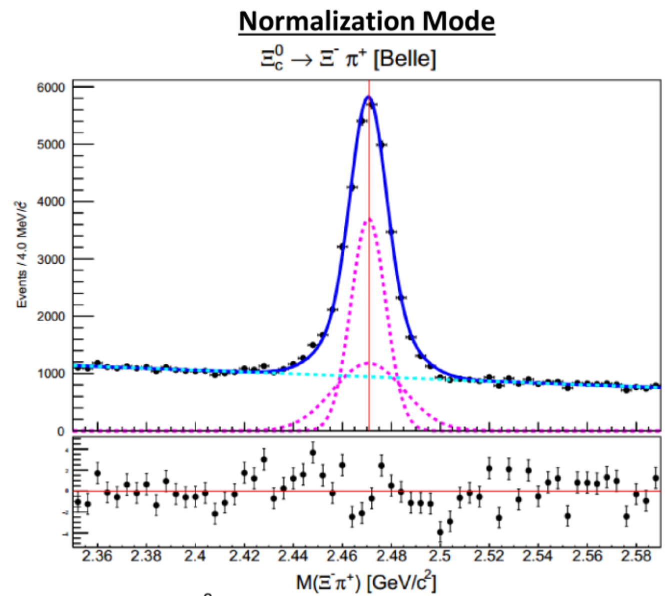
It is then necessary to study all decays which could confuse future excited $\mathbf{\Omega}$ searches in the $\mathbf{M(\Xi^0 K^-)}$

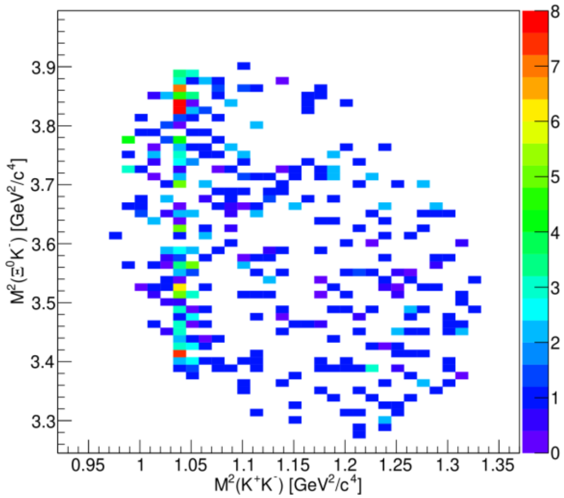
Decay channels of Ξ_c^0

Full Belle data sample

- The $\Xi^0 \to \Lambda\pi^0$ is reconstructed.
- Normalization mode $\Xi_c^0 \to \Xi^-\pi^+$



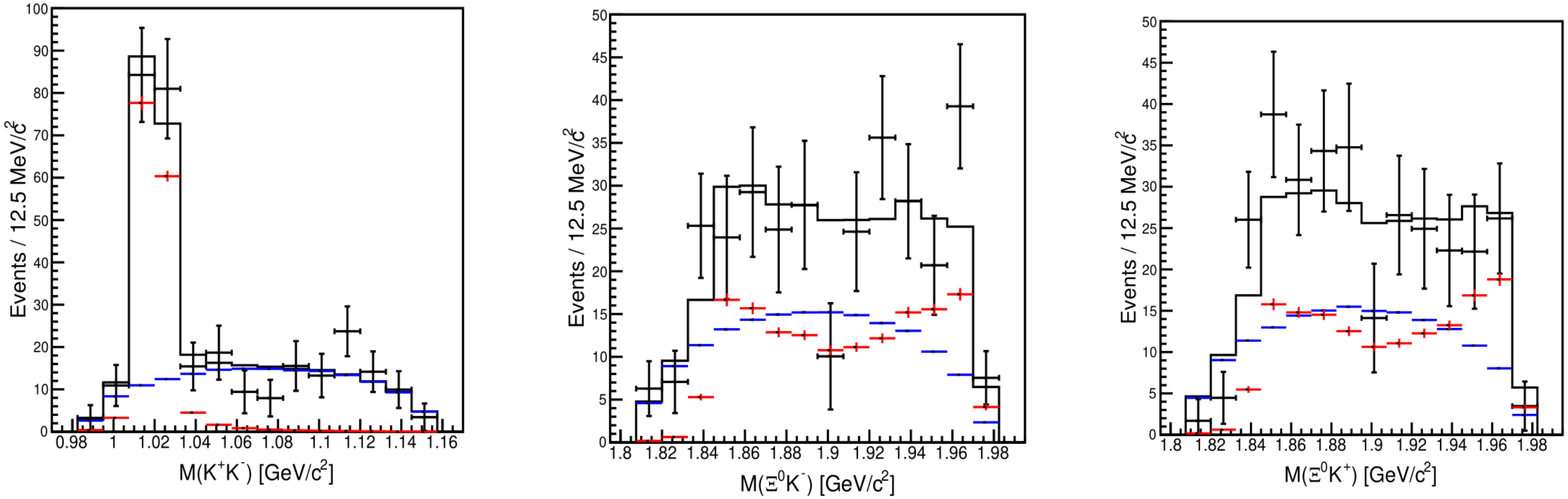




Dalitz plot distribution of $\Xi_c^0 \to \Xi^0 K^+ K^-$ decays in the sideband-subtracted Ξ_c^0 signal region.

Amplitude analysis

- The amplitude analysis is performed to measure the branching fractions of the
  - Resonant decay $\Xi_c^0 \to \Xi^0\phi(\to K^+K^-)$
  - non-resonant decay $\Xi_c^0 \to \Xi^0K^+K^-$



- Fit the Dalitz plot distribution as a coherent sum of resonant and non-resonant amplitudes outlined
- freely vary the helicity amplitude ratios of the resonant decay

$$\frac{B\left(\Xi_c^0 \to \Xi^0\phi(\to K^+K^-)\right)}{B\left(\Xi_c^0 \to \Xi^0K^+K^-\right)} = (48.1 \pm 4.6)\% \qquad \frac{B\left(\Xi_c^0 \to \Xi^0\phi K^+K^-(\text{non})\right)}{B\left(\Xi_c^0 \to \Xi^0K^+K^-\right)} = (51.9 \pm 3.3)\%$$

$$\frac{B\left(\Xi_c^0 \to \Xi^0\phi(\to K^+K^-)\right)}{B\left(\Xi_c^0 \to \Xi^-\pi^+\right)} = 0.036 \pm 0.004 \pm 0.002 \qquad \frac{B\left(\Xi_c^0 \to \Xi^0\phi K^+K^-(\text{non})\right)}{B\left(\Xi_c^0 \to \Xi^-\pi^+\right)} = 0.039 \pm 0.004 \pm 0.002$$

only minor cusping peaks occur in the background of $\Omega^{*-} \to \Xi^0K^-$ due to these Ξ_c^0 decays.

First determination of the spin and parity of $\Xi_c(2970)^+$

arxiv:2007.14700 Submitted to PRL

Ξ_c(2970) States

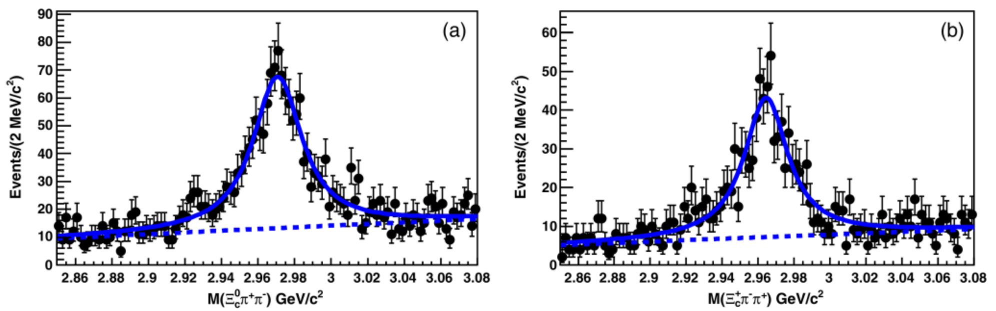


FIG. 6. The (a) $\Xi_c^0\pi\pi$ and (b) $\Xi_c^+\pi\pi$ invariant mass distributions with a cut on $\Xi_c(2645)$ invariant mass of the intermediate state and a scaled momentum cut of $x_p > 0.7$. Both show clear $\Xi_c(2980)$ signals. The fits are described in the text. The dashed lines represent the combinatorial background contributions.

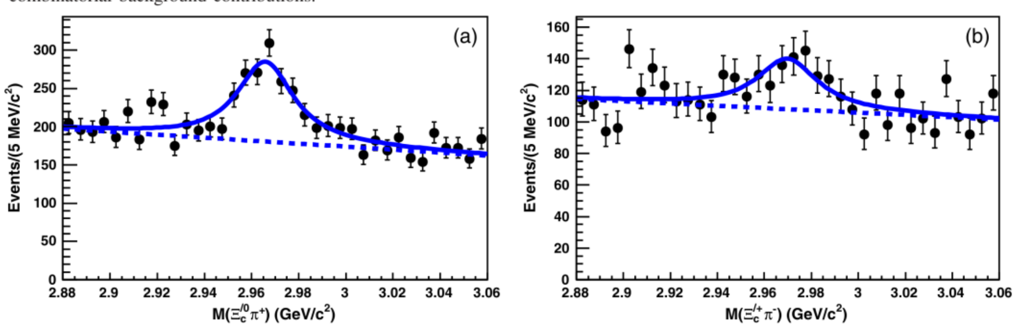


FIG. 9. The (a) $\Xi_c'^0\pi^+$ and (b) $\Xi_c'^+\pi^-$ invariant mass distributions. The fits are described in the text. The dashed lines represent the combinatorial background contributions.

- **Mass and width were measured precisely via:**

  $\Xi_c(2970) \to \Xi_c(2645)\pi \to \Xi_c\pi\pi$

- **The $\Xi_c(2970)$ is also observed from the decay:**

  $\Xi_c(2970) \to \Xi_c'\pi \to \Xi_c\gamma\pi$

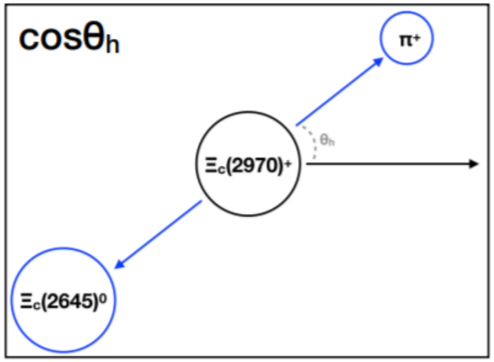
PRD 94, 052011 (2016)

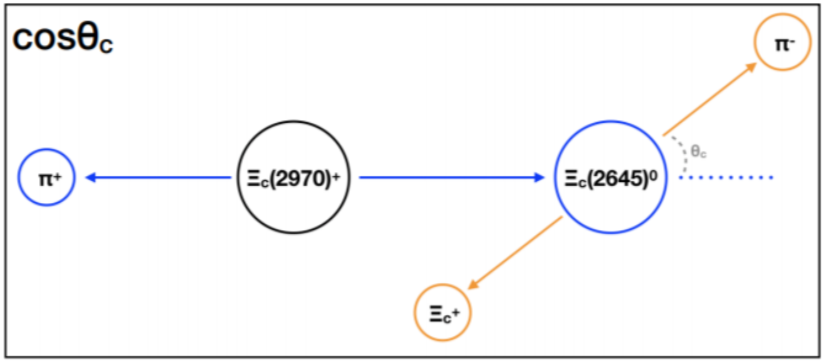
- **Spin and parity of the Ξ_c(2970) is not determined yet.**
- **There is not even a presumed spin-parity.**

Principle of Determination

- **Spin**
- For the decay $\Xi_c(2970)^+ \to \Xi_c(2645)^0\pi_1^+ \to \Xi_c^+\pi_1^-\pi_2^+$,
- Two decay angular distribution are studied.
    - $\cos\theta_h$: Helicity angle of $\Xi_c(2970)^+$
    - $\cos\theta_c$: Helicity angle of $\Xi_c(2645)^0$

θ_h : angle bet.
direction of $\Xi_c(2970)^+$ in beam CM frame and
direction of π^+ in $\Xi_c(2970)$'s rest frame.
θ_c : angle bet.
direction of $\Xi_c(2645)^0$ in $\Xi_c(2970)$'s rest frame
and direction of π^- in $\Xi_c(2645)$'s rest frame.





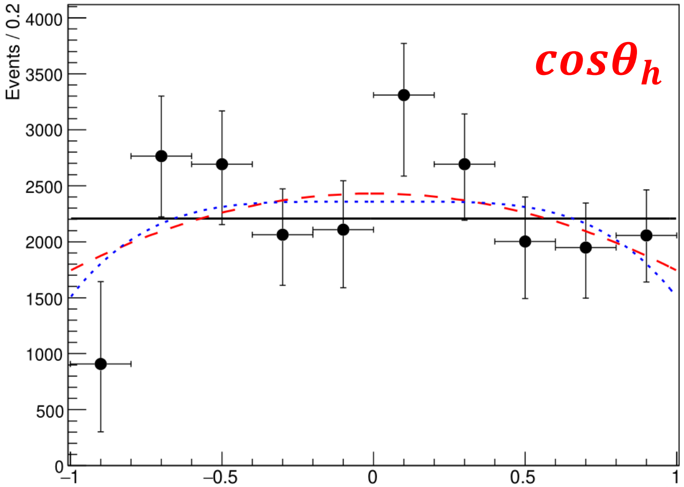
- **Parity**
    - Ratio of branching fractions is studied.
        - Compared with the prediction from Heavy Quark Spin Symmetry (HQSS)

$$R = \frac{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c(2645)^0\pi^+)}{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c'^0\pi^+)}$$

Determination of the Spin

Full Belle data sample

- Divide the data into 10 equal bins for $cos\theta_h$ and $cos\theta_c$.
- Fit $M(\Xi_c\pi\pi)$ in each bin.
- Fit the angular distributions with the expected decay angular distributions $W_{1/2}, W_{3/2}, W_{5/2}$



$$W_{\frac{1}{2}} = constant$$

$$W_{\frac{3}{2}} = \rho_{33}\left\{1+T\left(\frac{3}{2}\cos^2\theta_h - \frac{1}{2}\right)\right\} + \rho_{11}\left\{1+T\left(-\frac{3}{2}\cos^2\theta_h + \frac{1}{2}\right)\right\}$$

$$W_{\frac{5}{2}} = \frac{3}{32}[\rho_{55}5\{(-\cos^4\theta_h - 2\cos^2\theta_h + 3) + T(-5\cos^4\theta_h + 6\cos^2\theta_h - 1)\} + \rho_{33}\{(15\cos^4\theta_h - 10\cos^2\theta_h + 11) + T(75\cos^4\theta_h - 66\cos^2\theta_h + 7))\} + \rho_{11}2\{(-5\cos^4\theta_h + 10\cos^2\theta_h + 3) + T(-25\cos^4\theta_h + 18\cos^2\theta_h - 1)\}]$$

Spin hypothesis	1/2	3/2	5/2
χ^2/n.d.f.	9.3/9	7.7/7	7.5/6
Probability	41%	36%	28%
T	–	-0.5 ± 1.1	0.7 ± 1.6
ρ_{11}	0.5	0.13 ± 0.26	0.08 ± 0.27
ρ_{33}	–	0.37 ± 0.26	0.12 ± 0.09
ρ_{55}	–	–	0.30 ± 0.28

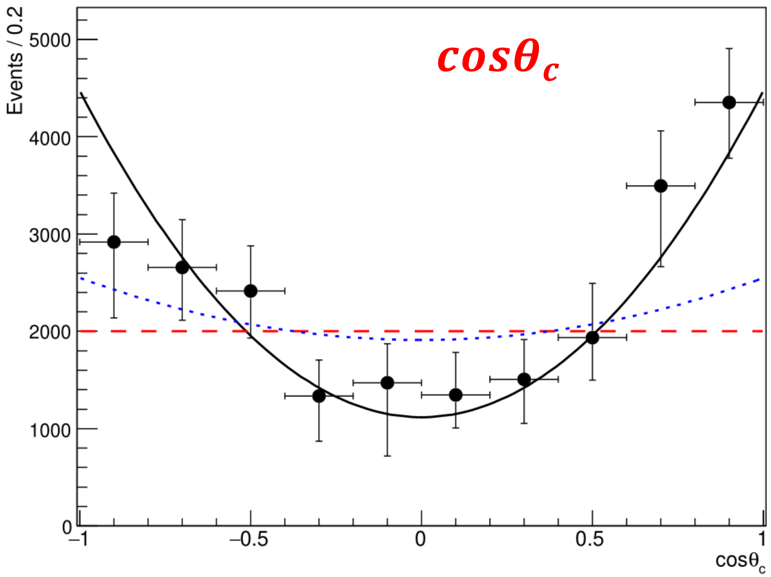
- Best fit is the spin 1/2 hypothesis
- Exclusion level of the spin 3/2 (5/2) hypothesis is as small as 0.8σ (0.5σ).
- Therefore, the result is inconclusive.

Determination of the Spin

Full Belle data sample

- To draw a more decisive conclusion, we fit angular distributions of $cos\theta_c$ with the expected angular distribution

$$W(\theta_c) = 3/2[\rho^*_{33}\sin^2\theta_c + \rho^*_{11}(1/3 + \cos^2\theta_c)]\ ,\ \rho^*_{33} + \rho^*_{11} = 1/2$$



J^P	$1/2^{\pm}$	$3/2^{-}$	$5/2^{+}$
χ^2/n.d.f.	6.4/9	32.2/9	22.3/9
Exclusion level (s.d.)	-	5.5	4.8

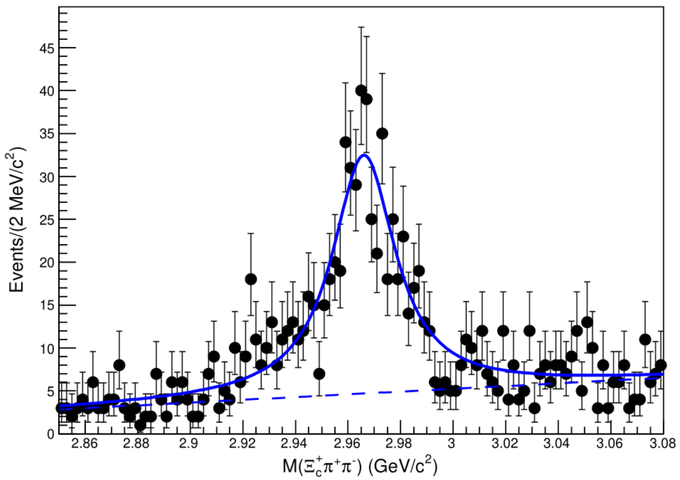
- This result is most consistent with the spin ½ hypothesis.
- The $1/2^{\pm}$ scenario is preferred over $3/2^{-}$ ($5/2^{+}$) by 5.5σ (4.8σ).
- Excludes the Ξ_c^* spin of 1/2 in which the distribution should be flat.

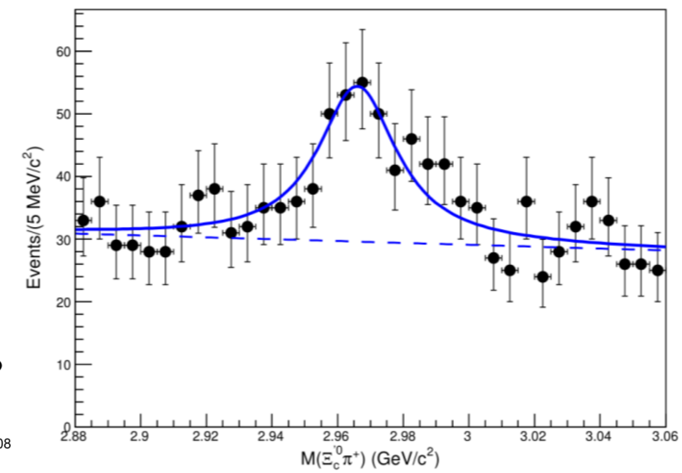
Determination of the Parity

- The branching ratio R is sensitive to the parity.

$$R = \frac{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c(2645)^0 \pi^+)}{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c'^0 \pi^+)}$$

- Fit the M($\Xi_c^+\pi^-\pi^+$) and M($\Xi_c'^0\pi^+$) for two mode.





- Branching ratio $R = 1.67 \pm 0.29^{+0.15}_{-0.09} \pm 0.17(\text{IS})$, where IS is Isospin symmetry.

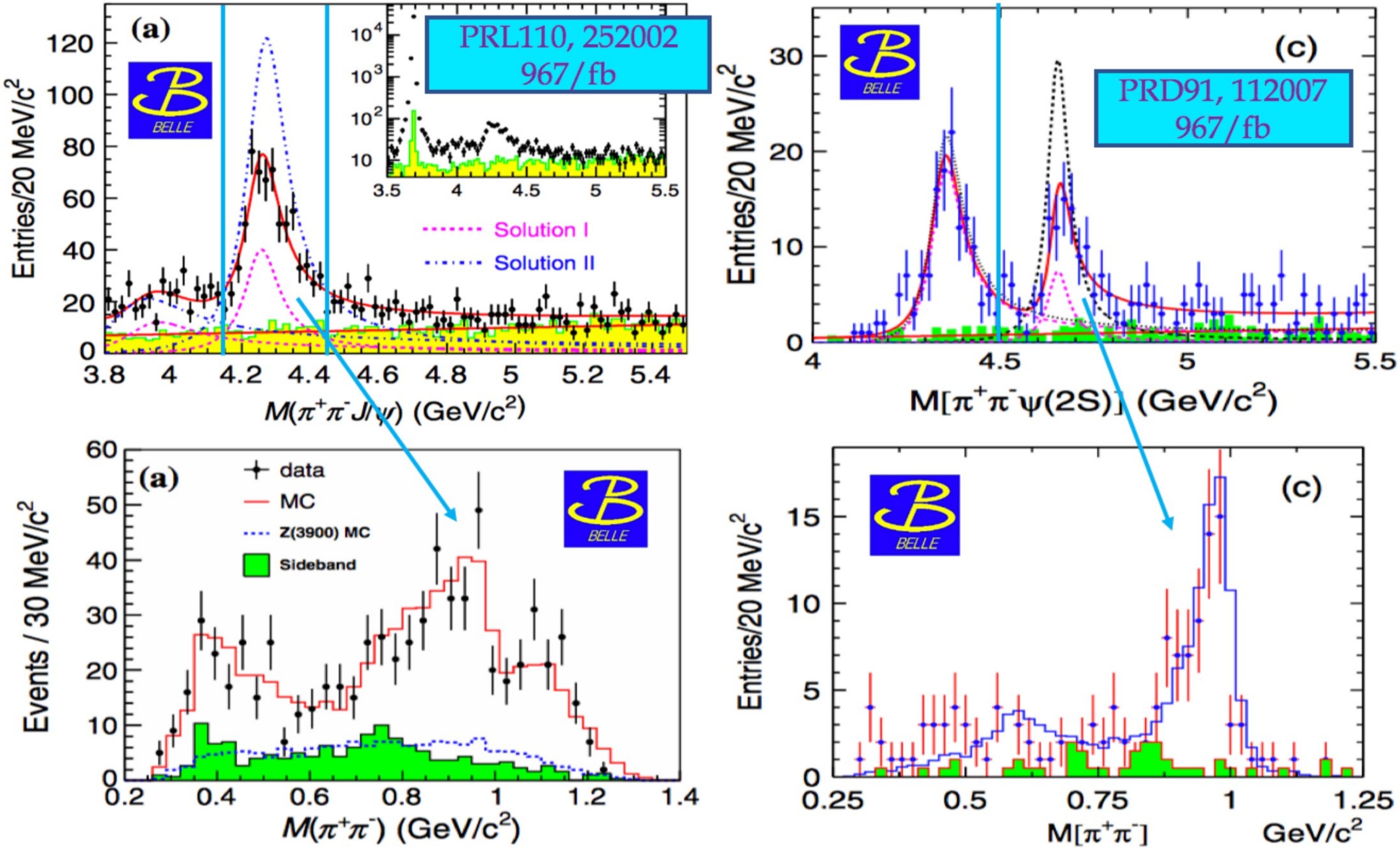
Heavy-quark spin symmetry (HQSS) prediction

Parity	+	+	−	−
Brown-muck spin s_ℓ	0	1	0	1
R	1.06	0.26	0	$\ll 1$

our result favors a positive-parity assignment with $sl = 0$

Search for resonant states with $c\bar{c}s\bar{s}$ quark content

Motivation: Y(4260) and Y(4660) have a $c\bar{c}s\bar{s}$ component



- $Y(4260) \to f_0(980)(\to \pi^+\pi^-)J/\psi$, $Y(4660) \to f_0(980)(\to \pi^+\pi^-)\psi(2S)$
  $f_0(980)$ has a $s\bar{s}$ component, and J/ψ has a $c\bar{c}$ component.
- **It is natural to search for such Y states with a quark component of $(c\bar{s})(\bar{c}s)$, e.g., $D_s\bar{D}_{s1}(2536)$ and $D_s\bar{D}^*_{s2}(2536)$.**

Analysis method

$$e^+e^- \to \gamma_{ISR} D_s^+ D_{s1}(2536)^- (\to \bar{D}^{*0}K^- / D^{*-}K_S^0)$$

We require full reconstruction of the γ_{ISR}, D_s^+ , and K^-/K_S^0.

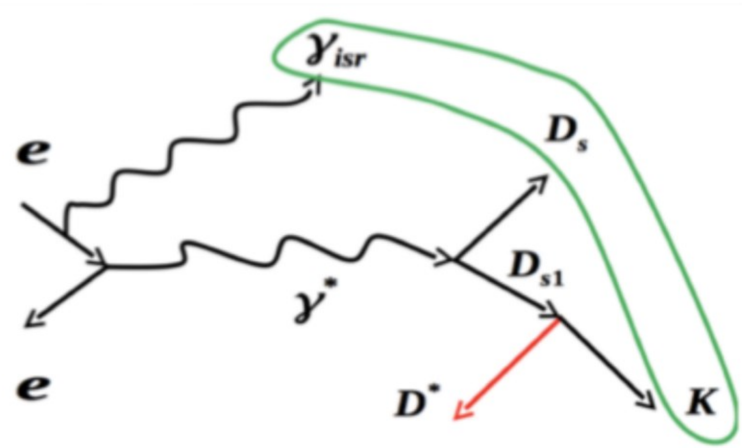
- $D_s^+ \to \phi\pi^+$, $\bar{K}^{*0}K^+$, $K_S^0K^+$, $K^+K^-\pi^+\pi^0$, $K_S^0\pi^0K^+$, $K^{*+}K_S^0$, $\eta\pi^+$, and $\eta'\pi^+$
- For the signals, the spectrum of the mass recoiling against the $D_s^+K^-\gamma_{ISR}$ system should be accumulated at the $\bar{D}^{*0}/D^{*-}$ nominal mass.

$$M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0) = \sqrt{(E^*_{c.m.} - E^*_{\gamma_{ISR}D_s^+K^-/K_S^0})^2 - \left(p^*_{\gamma_{ISR}D_s^+K^-/K_S^0}\right)^2}$$

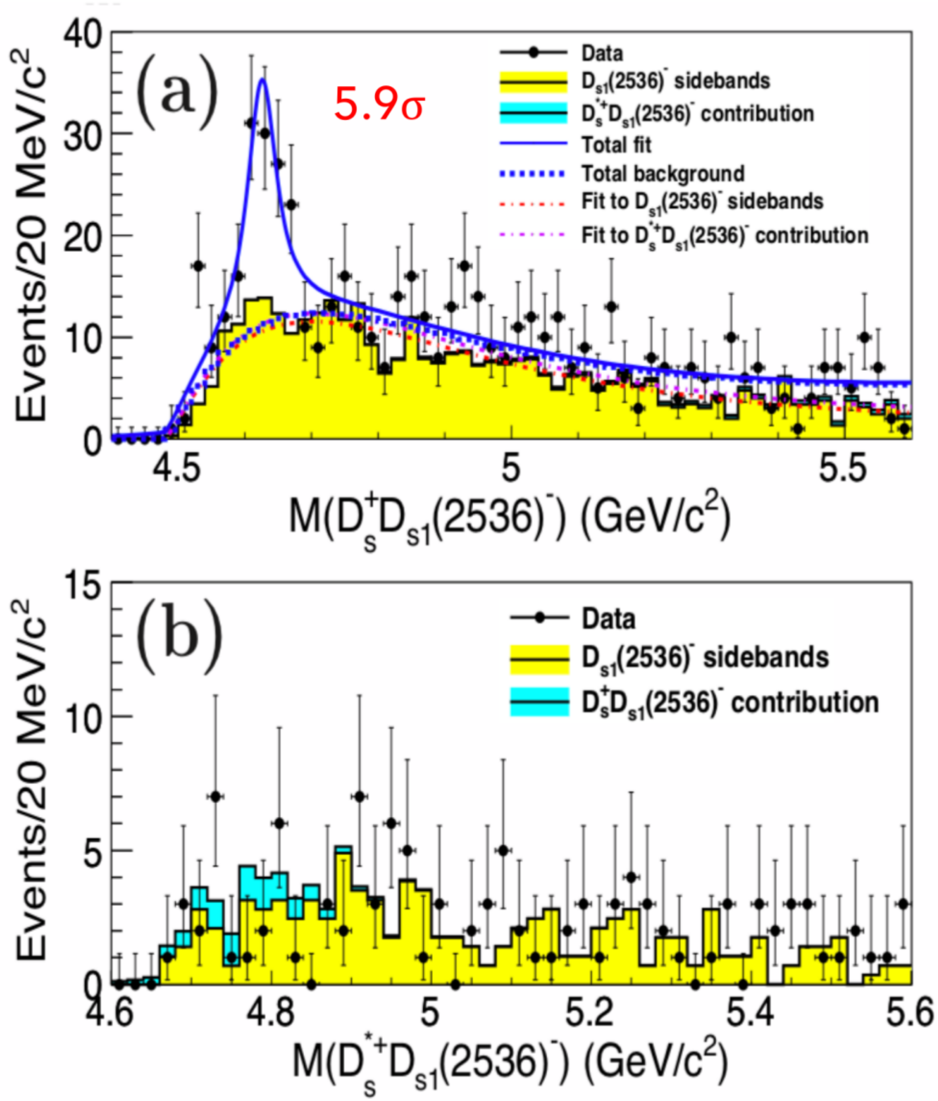
- To improve the $M_{rec}(\gamma_{ISR})$ resolution, $M_{rec}(\gamma_{ISR}D_s^+K^-/K_S^0)$ is constrained to be the nominal mass of the $\bar{D}^{*0}/D^{*-}$.

Data samples:

$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})
10.52	89.5±1.3
10.58	711±10
10.867	121.4±1.7
Total	921.9±12.9



$M(D_s^+ D_{s1}(2536)^-)$



PRD 100, 111103(R) (2019)

An unbinned simultaneous likelihood fit:

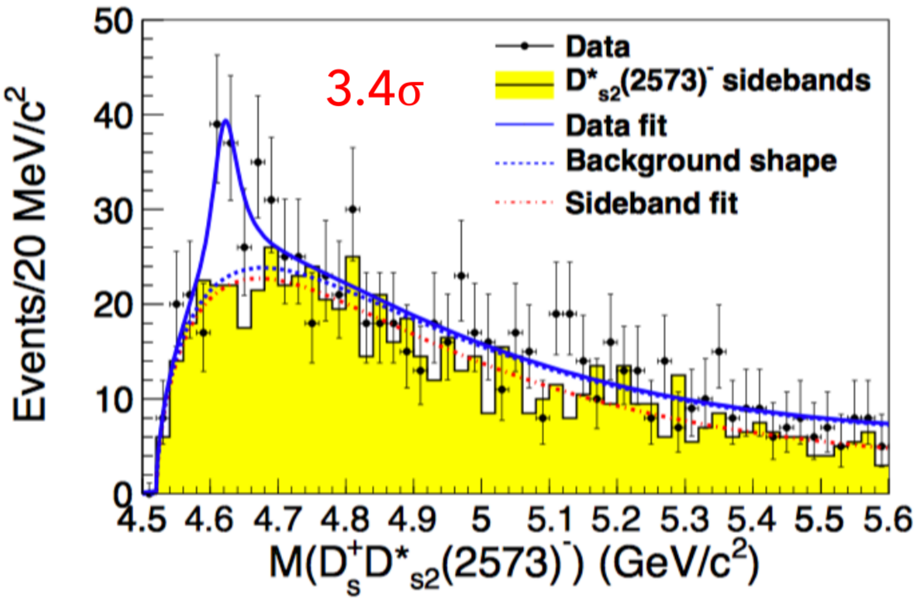
- Signal: a BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s1}(2536)^-$ mass sidebands: a threshold function
- $e^+e^- \to D_s^{*+} D_{s1}(2536)^-$ background contribution: a threshold function
- A non-resonant contribution: a two-body phase space form

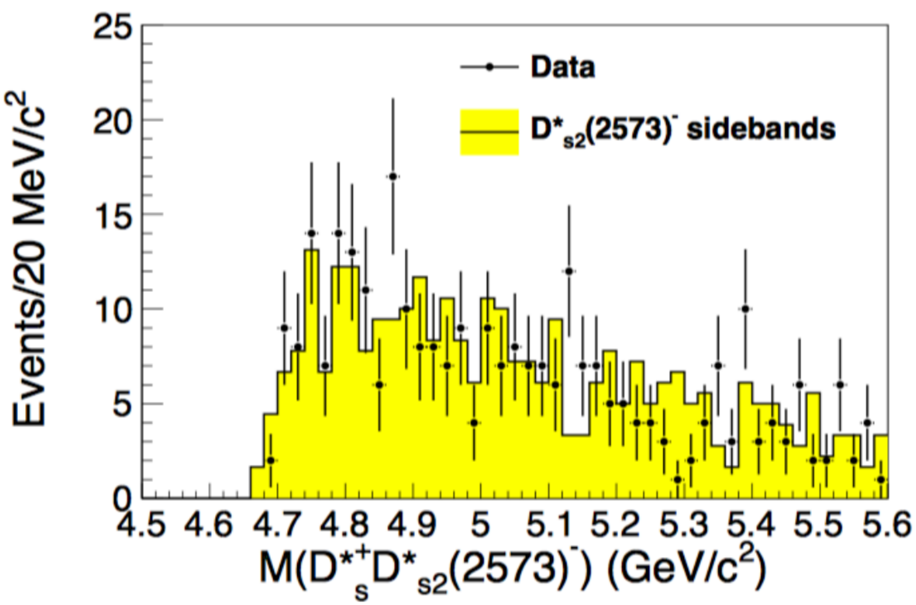
$M=(4625.9^{+6.2}_{-6.0}(\text{stat.}) \pm 0.4(\text{syst.})\ \text{MeV}/c^2$
$\Gamma = (49.8^{+13.9}_{-11.5}(\text{stat.}) \pm 4.0(\text{syst.})\ \text{MeV}$
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s1}(2536)^-) \times \mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0} K^-) = (14.3^{+2.8}_{-2.6}(\text{stat.}) \pm 1.5(\text{syst.})\ \text{eV}$

One possible background is from $e^+e^- \to D_s^{*+}(\to D_s^+ \gamma) D_{s1}(2536)^-$.
No obvious structure is observed in the $e^+e^- \to D_s^{*+}(\to D_s^+ \gamma) D_{s1}(2536)^-$.

$M(D_s^+ D_{s2}^*(2573)^-)$

PRD 101, 091101(R) (2020)



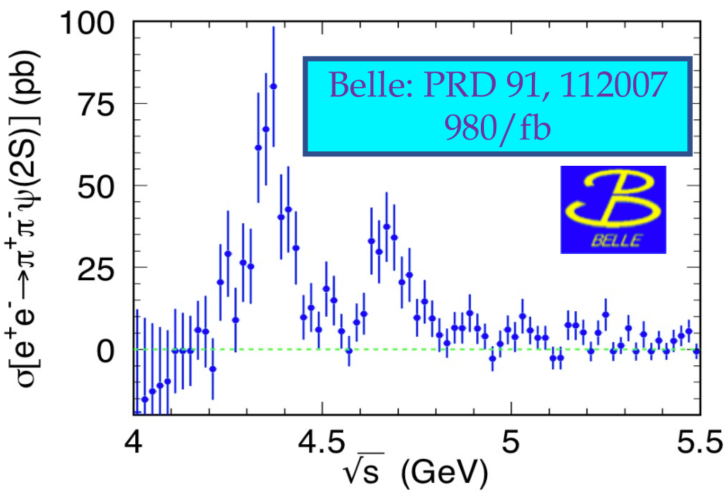


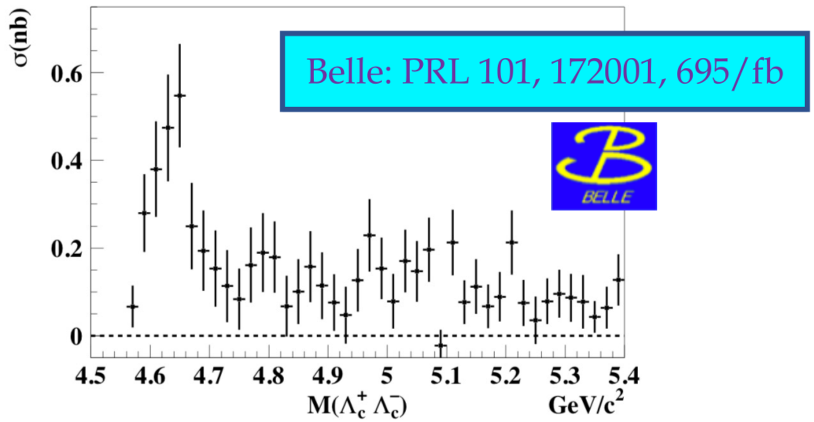
An unbinned simultaneous likelihood fit:

- Signal: a BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s2}^*(2573)^-$ mass sidebands: a threshold function
- A non-resonant contribution: a two-body phase space form

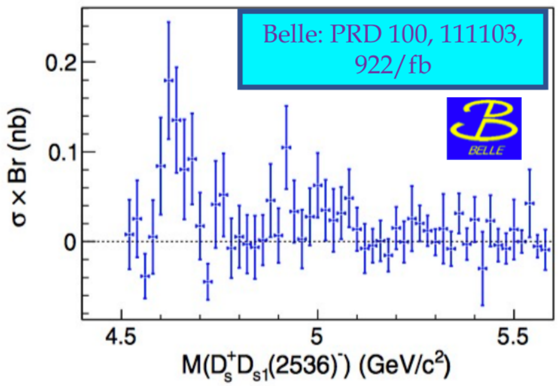
$M=(4619.8^{+8.9}_{-8.0}(\text{stat.}) \pm 2.3(\text{syst.})\ \text{MeV}/c^2$
$\Gamma = (47.0^{+31.3}_{-14.8}(\text{stat.}) \pm 4.6(\text{syst.})\ \text{MeV}$
$\Gamma_{ee} \times \mathcal{B}(Y \to D_s^+ D_{s2}^*(2573)^-) \times \mathcal{B}(D_{s2}^*(2573)^- \to \bar{D}^0 K^-) = (14.7^{+5.9}_{-4.5}(\text{stat.}) \pm 3.6(\text{syst.})\ \text{eV}$

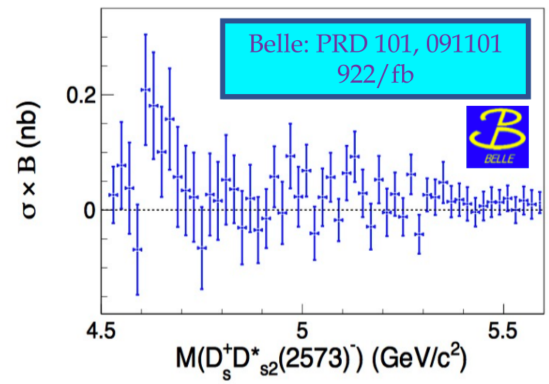
Y(4630) = Y(4660)?

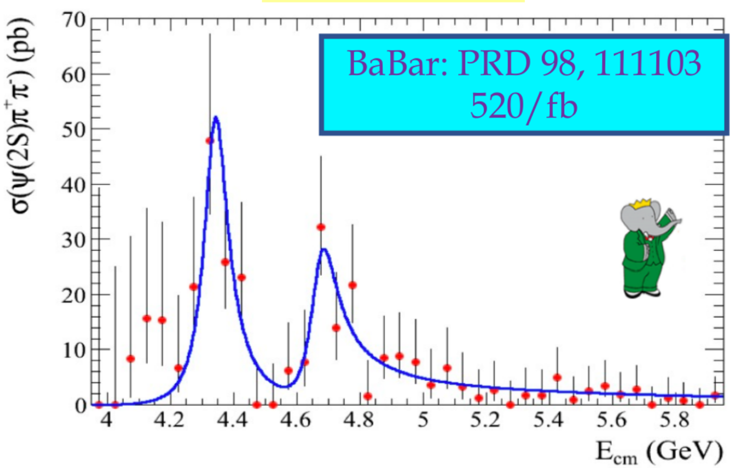




$e^+e^- \to \pi\pi\psi'$







Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda_c^+\bar{\Lambda}_c^-$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, $\pi^+\pi^-\psi(2S)$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$
BaBar, $\pi^+\pi^-\psi(2S)$	$4669 \pm 21 \pm 3$	$104 \pm 48 \pm 10$
Belle, $D_s^+ D_{s1}(2536)^-$	$4626^{+7}_{-7} \pm 1$	$49.8^{+14}_{-12} \pm 4$
Belle, $D_s^+ D_{s2}^*(2573)^-$	$4620^{+9}_{-8} \pm 3$	$47.0^{+32}_{-15} \pm 5$