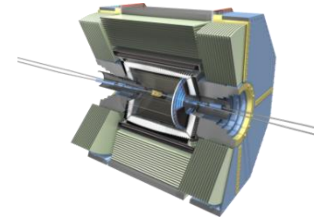
In memory of Simon Eidelman



Results of Belle and the perspectives for Belle II

Vishal Bhardwaj

(on the behalf of Belle(II) collaboration)

IISER Mohali

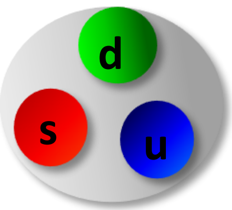
Hadron 2021, Mexico 26-31 July 2021

IN PURSUIT OF KNOWLEDGE

BELLE

Belle II

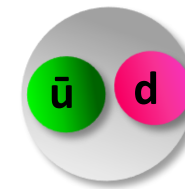
Real particles are color singlet



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

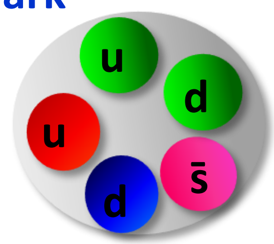


π=ūd

Other possible combinations of quarks and gluons :

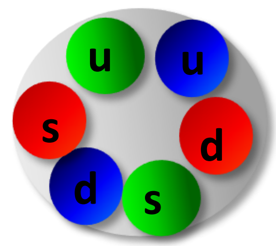
Pentaquark

S= +1 Baryon



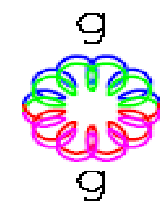
H di-Baryon

Tightly bound 6 quark state



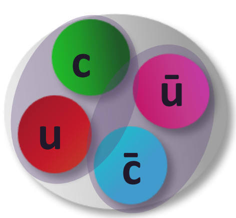
Glueball

Color-singlet multi-gluon bound state



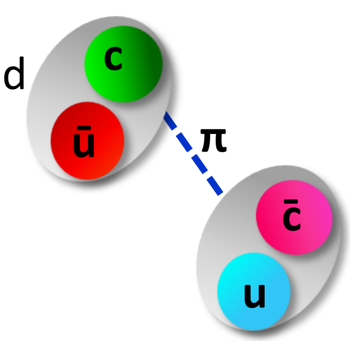
Tetraquark

Tightly bound diquark & anti-diquark

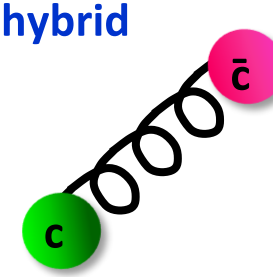


Molecule

loosely bound meson-antimeson “molecule”



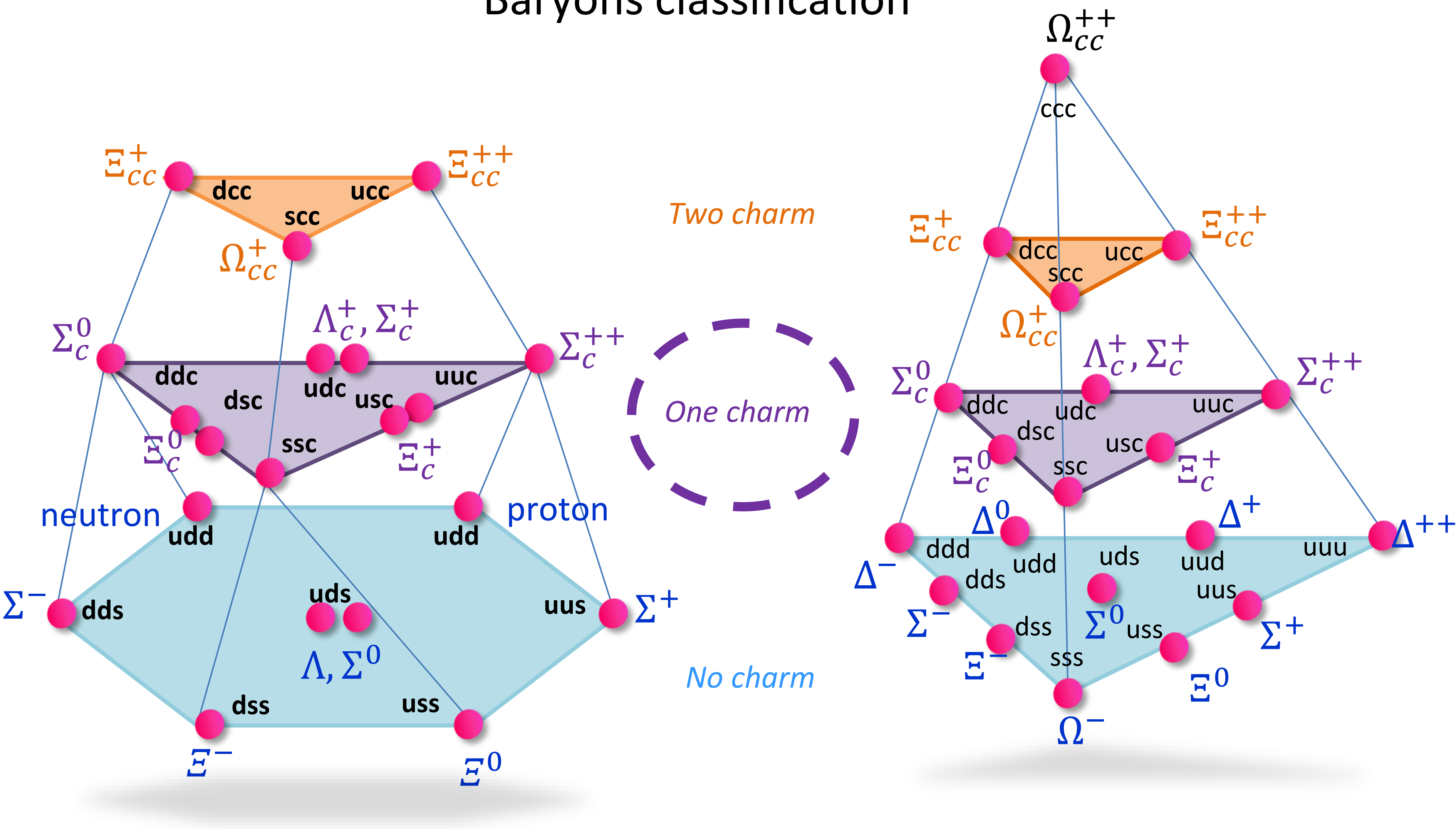
qq̄ -gluon hybrid mesons



This talk is limited till charm,
for beauty : please see T. Pedlar and B. Fulsom talk

artistic illustration

Baryons classification



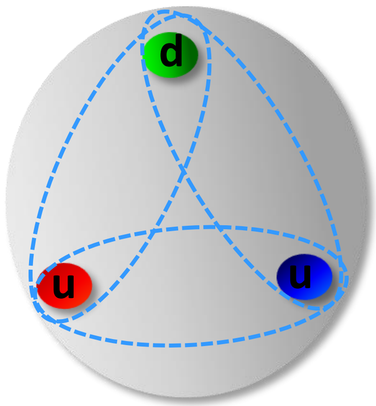
1/2⁺ Baryons

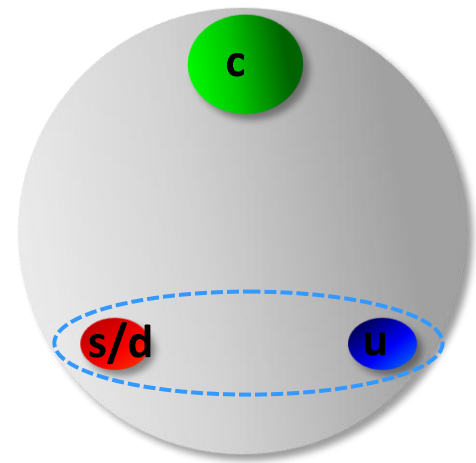
3/2⁺ Baryons

Charmed Baryons

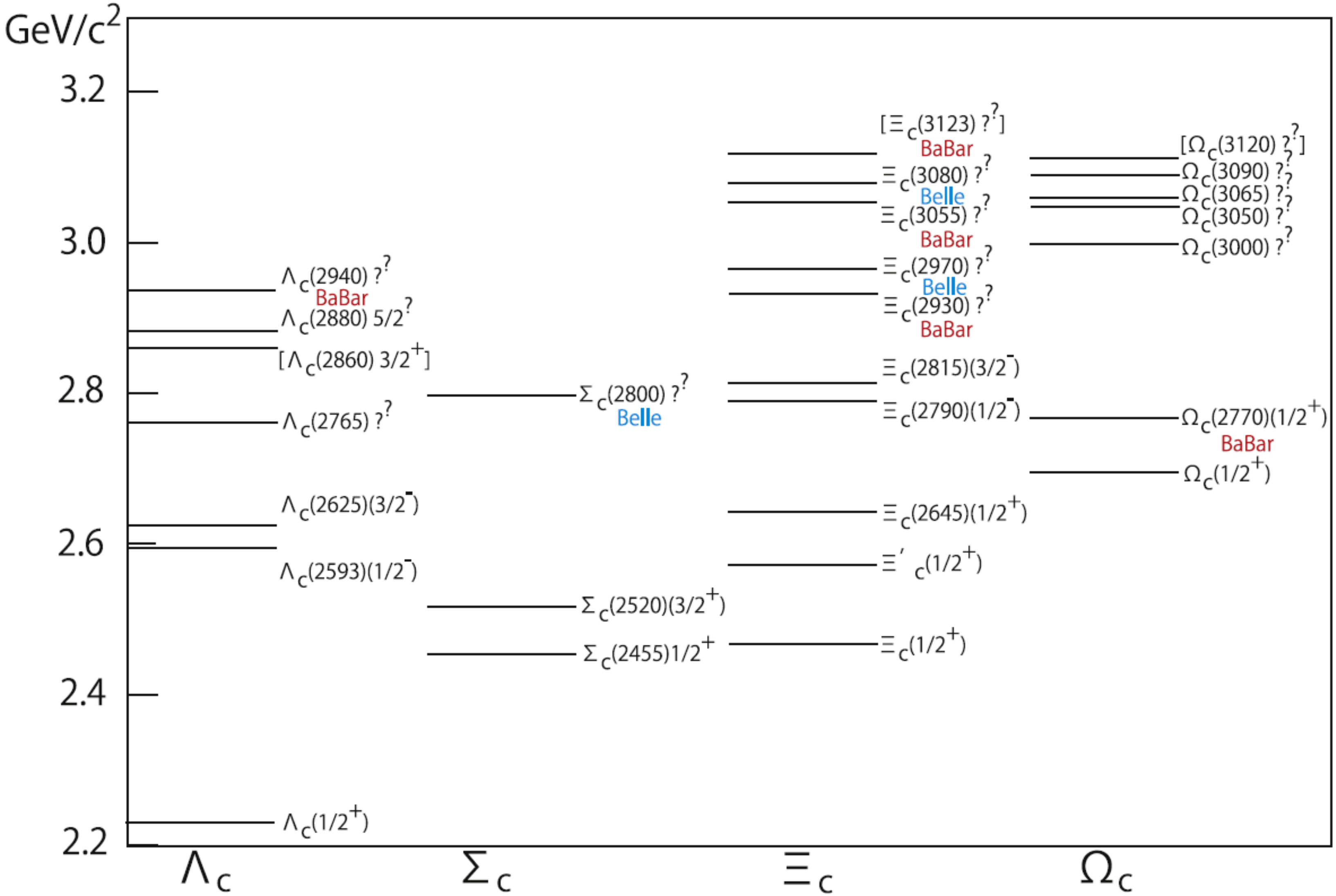
What makes singly charmed baryons physics so special ?

Charm quark is heavy > > up, down and strange quark





- Charmed baryons can be interpreted as a bound state of a light di-quark and charm quark.
- Heavy Quark symmetry can be also applied to the charmed baryons.
- Their study helps in improving our understanding of the quark confinement mechanism.
- Spectroscopy of the charmed baryon provides an information to understand the role of heavy quark in baryons.

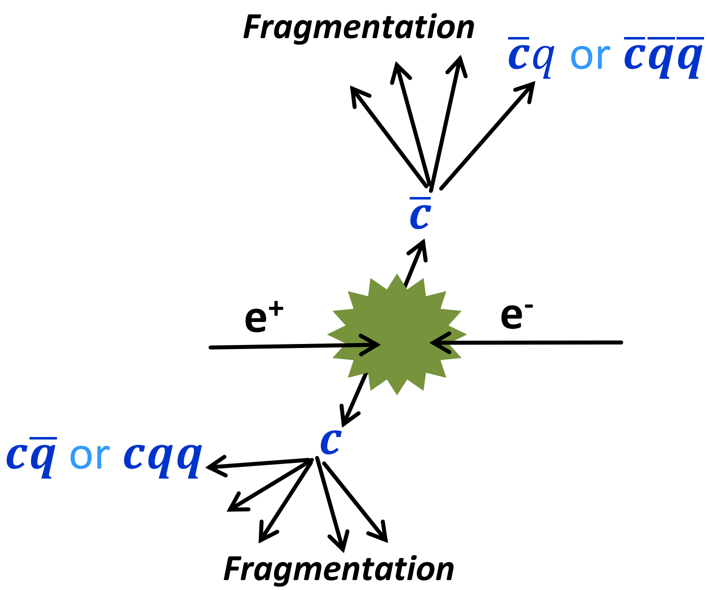


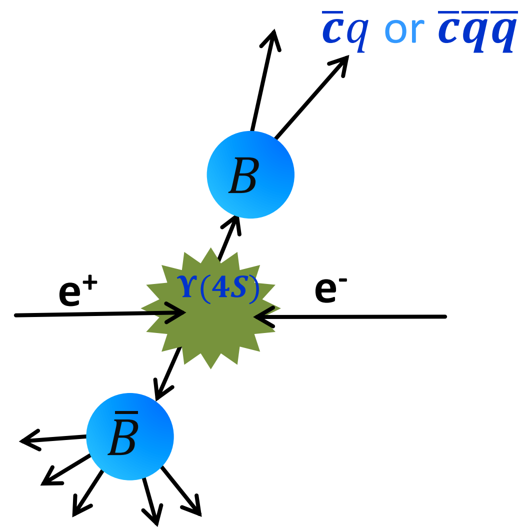
Kato, Iijima, Progress in Particle and Nuclear Physics 105, 61 (2019)

All ground states and many excited states observed

Many of the excited states are discovered in e^+e^- colliders.

Charmed hadron production @ Belle

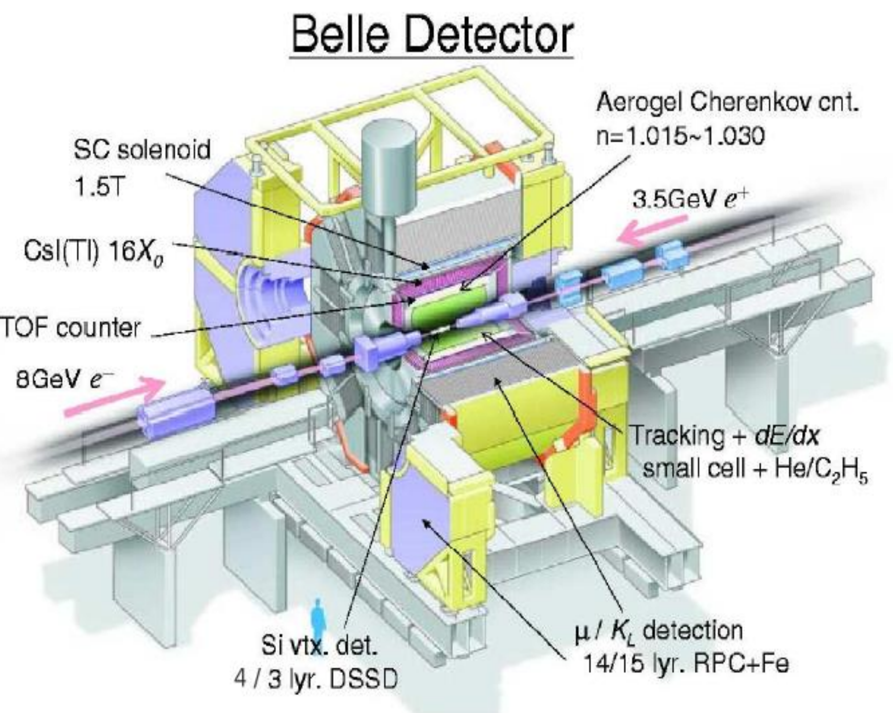


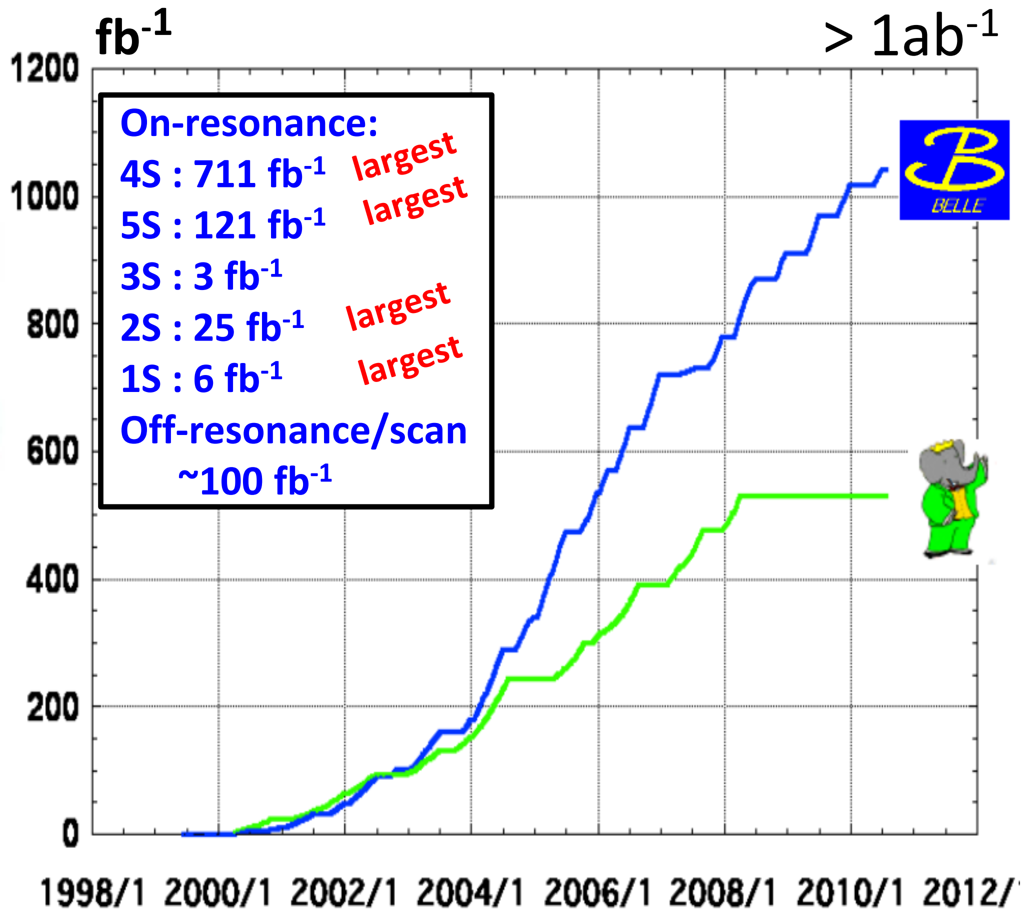


- Reconstruction is the only final state (cut on the momentum of charmed baryon to reduce background)
- Poor signal purity but large production rate.
- Spin is not trivial to be identified. Use final state angular distribution.
- Access to higher spin: production of them is not suppressed.

- Mainly by $b \to c$ (the whole B is reconstructed)
- Good signal purity but small production rate.
- The helicity of the produced charmed hadrons is constrained. Easy to study the spin
- Production of a higher spin state is suppressed in B decays.

Belle detector





Belle (1 ab^{-1})

- 1.3 x 10^9 (D)
- 1.5 x 10^8 (Λ_c^+)

General purpose detector, built to test Standard Model mechanism for CP violation in B decays to charmonium ($B^0 \rightarrow J/\Psi, \Psi', \chi_{c1} K^0$).

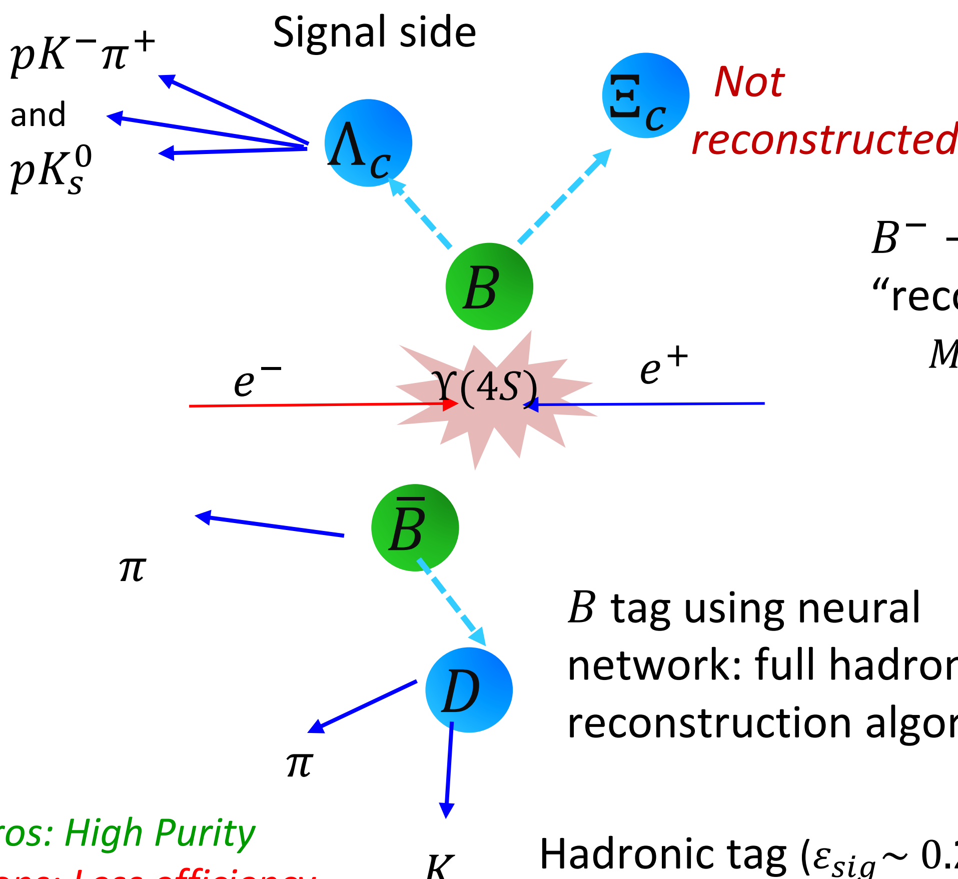
Belle,PRL 108, 171802 (2012)

Measurements of $\mathcal{B}(B \to \Lambda_c \Xi_c)$

$B^- \to \overline{\Lambda}_c^- \Xi_c^0$ proceed via $b \to c\bar{c}s$ transition and has relatively large branching fraction, $\mathcal{O}(10^{-3})$.

Measurements of their production rate provide a good test for the theoretical calculation of $b \to c\bar{c}s$.

Further, it provides an opportunity to search for missing excited Ξ_c^0 states.



Pros: High Purity

Cons: Less efficiency

B tag using neural network: full hadron reconstruction algorithm

Hadronic tag ($\varepsilon_{sig} \sim 0.2\%$)

$B^- \to \overline{\Lambda}_c^- \Xi_c^0$ decays are identifies using "recoil mass".

$$M^{rec}_{B_{tag}\Lambda_c} \equiv M^{miss}_{B_{tag}\Lambda_c} + M_{B_{tag}} - m_B + M_{\Lambda_c} - m_{\Lambda_c}$$

$M^{miss}_{B_{tag}\Lambda_c}$ = *Recoil invariant mass*

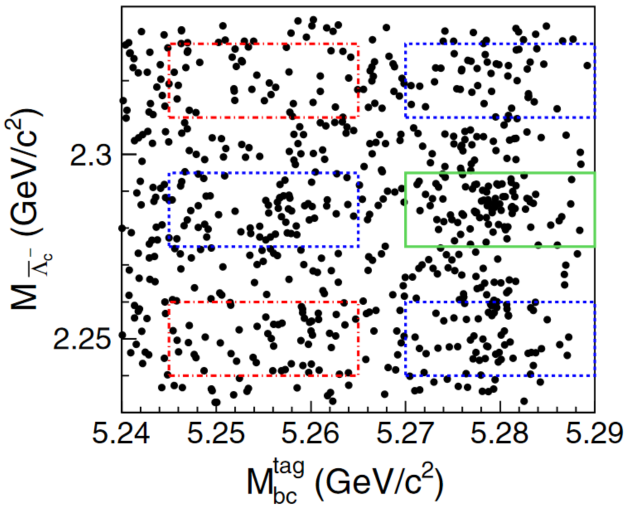
M: reconstructed mass

m: nominal mass

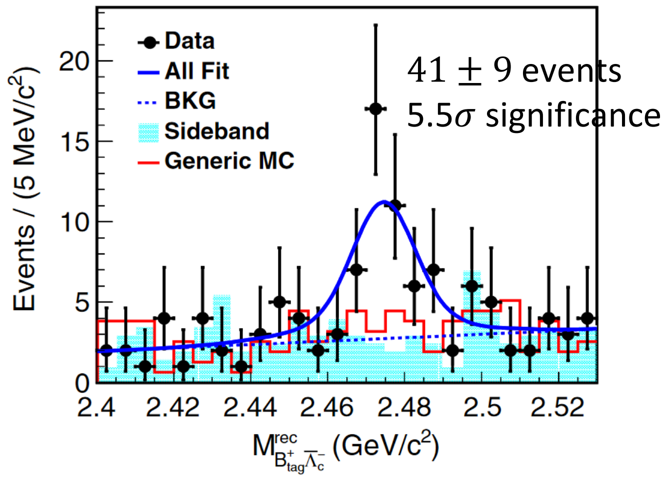
711fb⁻¹ data is used

Belle, PRL 122, 082001 (2019)

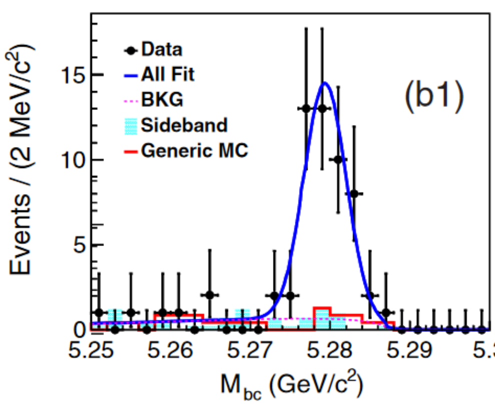
Absolute $\mathcal{B}(B^- \to \overline{\Lambda}_c^- \Xi_c^0)$ measurement

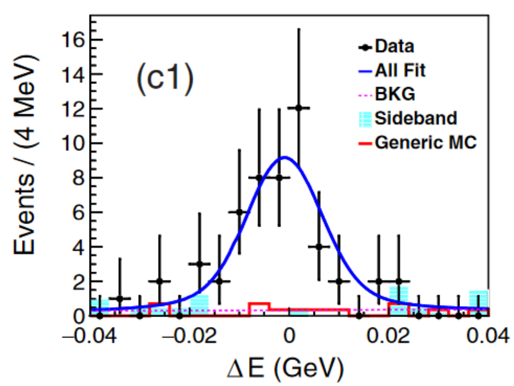


Signal region, M_{bc}^{tag} sideband and M_{Λ_c} sideband



$$\mathcal{B}(B^- \to \overline{\Lambda}_c^- \Xi_c^0) = (9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$$





Instead of recoil and tag, exclusive reconstruction of the signal B is done.

$$B \to \Lambda_c \Xi_c^0$$

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

$\Lambda_c \to pK_s^0$

$\Xi_c^0 \to \Xi^-\pi^+$

$\Xi_c^0 \to \Lambda K^-\pi^+$

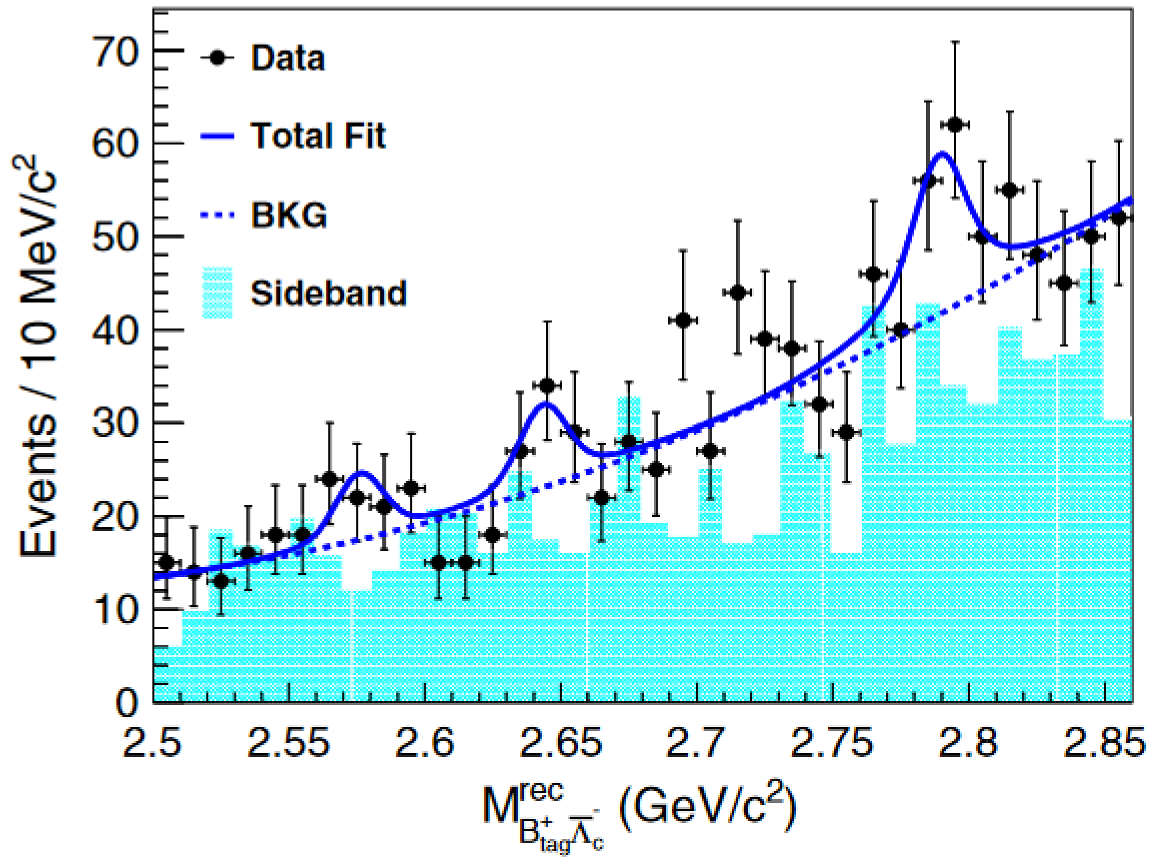
$\Xi_c^0 \to pK^-K^-\pi^+$

We get the absolute branching fraction of Ξ_c^0 decays

$$B(\Xi_c^0 \to \Xi^-\pi^+) = 1.80 \pm 0.50 \pm 0.14\%$$
$$B(\Xi_c^0 \to \Lambda K^-\pi^+) = 1.17 \pm 0.37 \pm 0.09\%$$
$$B(\Xi_c^0 \to pK^-K^-\pi^+) = 0.58 \pm 0.23 \pm 0.05\%$$

Search for the excited Ξ_c^0 states

Belle, PRD 100 112010 (2019)



	N_{sig}	$\mathcal{B}(B^- \to \bar{\Lambda}_c^- \Xi_c^{*0})$ [Upper limit]	Significance (σ)
$\Xi_c'^0$	17.9 ± 10.4	$(3.4 \pm 2.0) \times 10^{-4}$ [6.5×10^{-4}]	1.7
$\Xi_c(2645)^0$	24.1 ± 13.0	$(4.4 \pm 2.4) \times 10^{-4}$ [7.9×10^{-4}]	1.9
$\Xi_c(2790)^0$	59.9 ± 22.5	$(1.1 \pm 0.4) \times 10^{-3}$	3.1

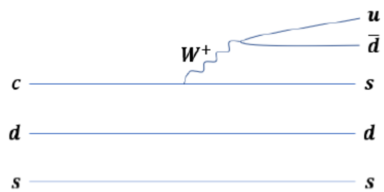
First-time measurement of the branching fractions.

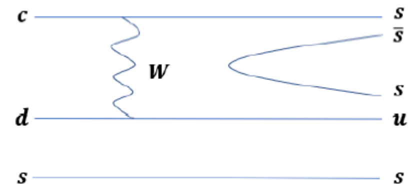
This opens up a new portal: one can search for new excited states !

Please see Yang Li's talk

Belle, arXiv:2012.05607

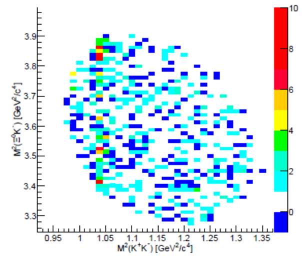
Branching fraction measurement of $\Xi_c^0 \to \Xi^0 K^+ K^-$

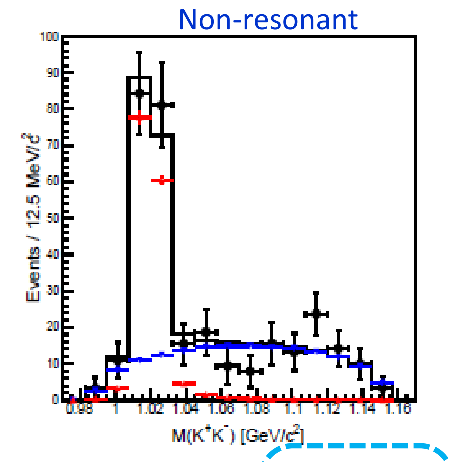




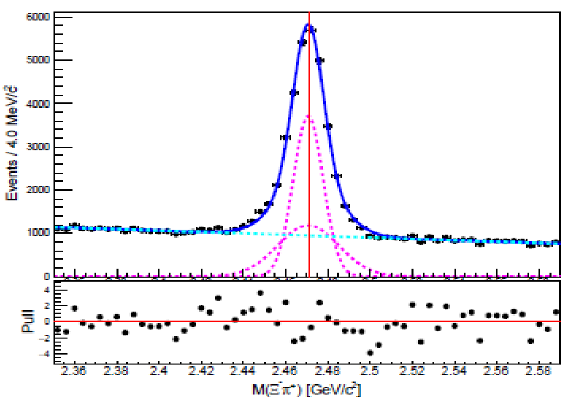
Ξ_c^0 occur via $c \to s$ transition :

- Cabibbo allowed W-exchange ($\Xi_c^0 \to \Xi^- \pi^+$)
- Also occur via W-exchange between c and d quarks ($cd \to W^+ \to su(g \to s\bar{s})$ such a $\Xi_c^0 \to \Xi^0 K^+ K^-$).

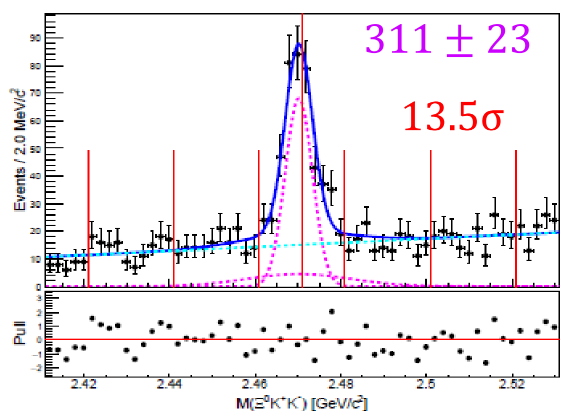


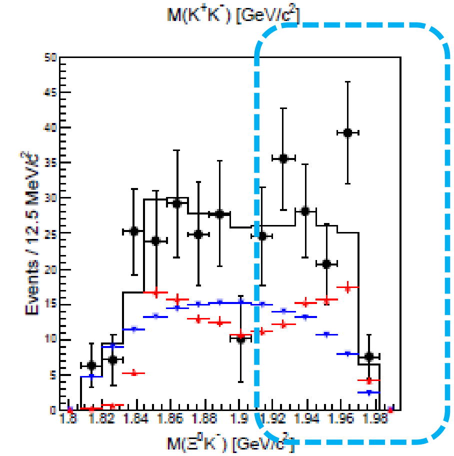


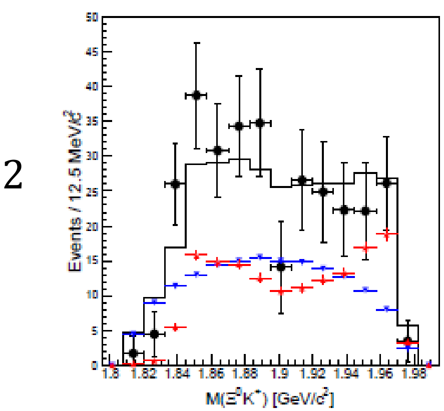
$\Xi_c^0 \to \Xi^- \pi^+$



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







$\Lambda \to p\pi^-$ $\quad \Xi^- \to \Lambda\pi^-$ $\quad \Xi^0 \to \Lambda\pi^0$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0 K^+ K^-)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = 0.039 \pm 0.004 \pm 0.002$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0 \phi(\to K^+ K^-))}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = 0.036 \pm 0.004 \pm 0.002$$

preliminary

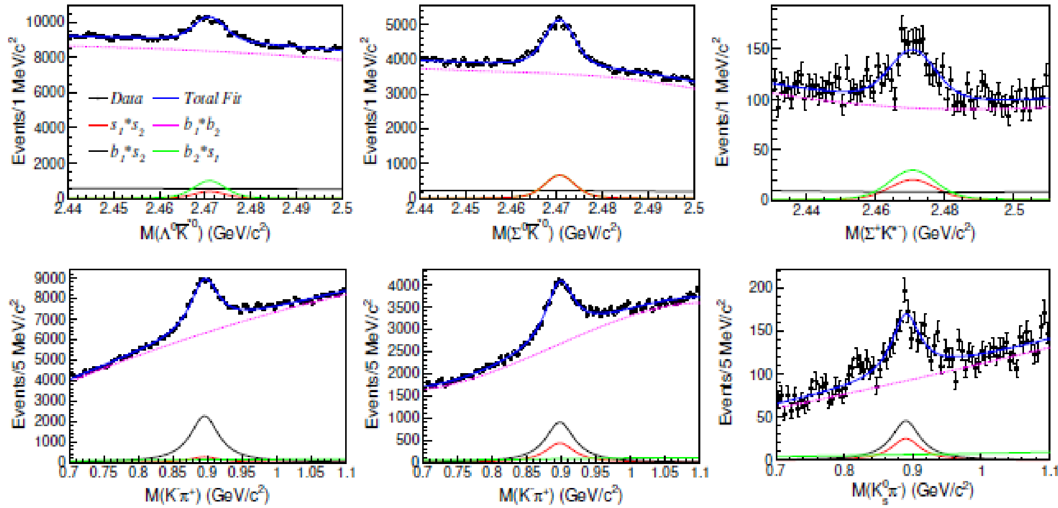
- $M(\Xi^0 K^-)$ shows some events at 1.95 GeV, will be interesting to visit the study with more data at Belle II.

Branching fraction and asymmetry measurement of Ξ_c

Please see Yang Li's talk

- Non-leptonic weak decays are caused by the *W*-boson exchanges with QCD corrections.
- Not easy to make quantitative predictions of decay rates and asymmetries with QCD corrections.
- Theoretical calculations for the hadronic decays of the Ξ_c have been performed based on $SU(3)_F$ flavor symmetry and dynamical models.

$\Xi_c^0 \to \Lambda \bar{K}^{*0}$ $\Xi_c^0 \to \Sigma^0 \bar{K}^{*0}$ $\Xi_c^0 \to \Sigma^+ K^{*-}$



$\Lambda \to p\pi^-$, $\Sigma^0 \to \gamma\Lambda$ and $\Sigma^+ \to p\pi^0$ $K^{*0} \to K^+\pi^-$ and $K^{*+} \to K_S^0\pi^+$

$\mathcal{B}(\Xi_c^0 \to \Lambda \bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	$0.18 \pm 0.02(\text{stat.}) \pm 0.01(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to \Lambda \bar{K}^{*0})$	$(3.3 \pm 0.3(\text{stat.}) \pm 0.2(\text{syst.}) \pm 1.0(\text{ref.})) \times 10^{-3}$
$\mathcal{B}(\Xi_c^0 \to \Sigma^0 \bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	$0.69 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to \Sigma^0 \bar{K}^{*0})$	$(12.4 \pm 0.5(\text{stat.}) \pm 0.5(\text{syst.}) \pm 3.6(\text{ref.})) \times 10^{-3}$
$\mathcal{B}(\Xi_c^0 \to \Sigma^+ K^{*-})/\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$	$0.34 \pm 0.06(\text{stat.}) \pm 0.02(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to \Sigma^+ K^{*-})$	$(6.1 \pm 1.0(\text{stat.}) \pm 0.4(\text{syst.}) \pm 1.8(\text{ref.})) \times 10^{-3}$

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

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

$\alpha(\Xi_c^0 \to \Lambda \bar{K}^{*0})\alpha(\Lambda \to p\pi^-)$	$0.115 \pm 0.164(\text{stat.}) \pm 0.031(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^0 \bar{K}^{*0})\alpha(\Sigma^0 \to \gamma\Lambda)$	$0.008 \pm 0.072(\text{stat.}) \pm 0.008(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^+ K^{*-})\alpha(\Sigma^+ \to p\pi^0)$	$0.514 \pm 0.295(\text{stat.}) \pm 0.012(\text{syst.})$
$\alpha(\Xi_c^0 \to \Lambda \bar{K}^{*0})$	$0.15 \pm 0.22(\text{stat.}) \pm 0.04(\text{syst.})$
$\alpha(\Xi_c^0 \to \Sigma^+ K^{*-})$	$-0.52 \pm 0.30(\text{stat.}) \pm 0.02(\text{syst.})$

Belle, JHEP 06 ,160 (2021)

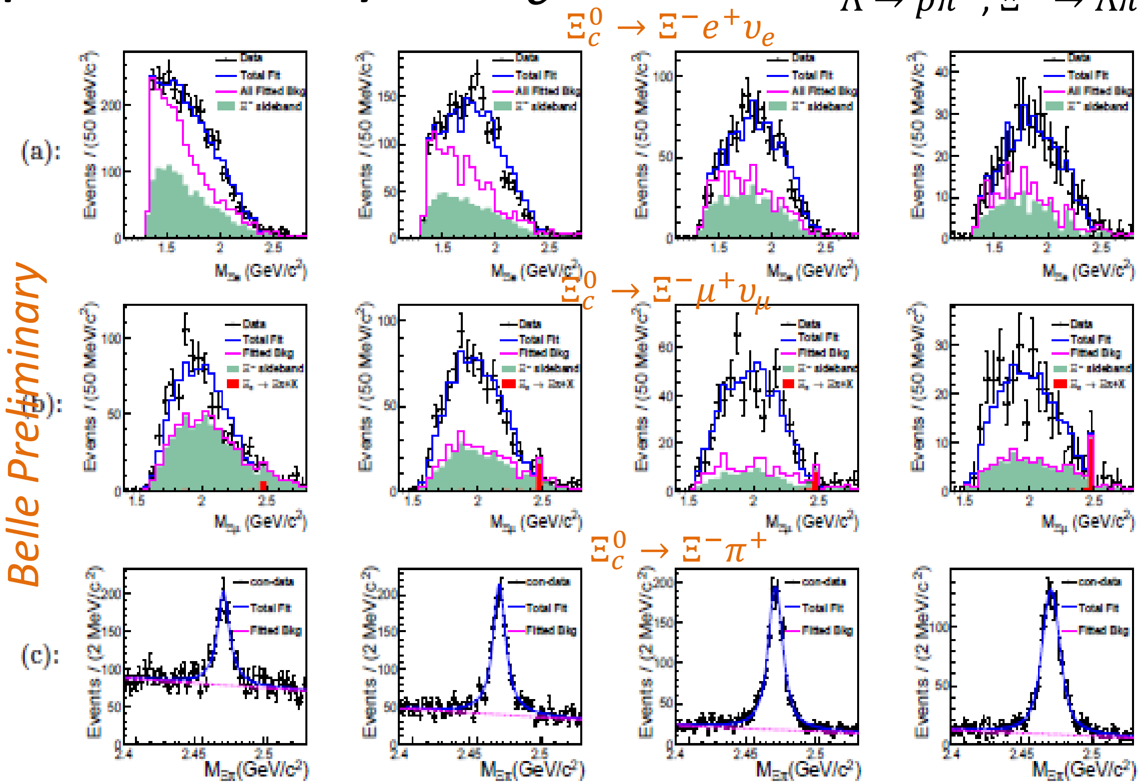
Semileptonic decay of Ξ_c^0

Belle, arXiv:2103.0649

$89.5\ \mathrm{fb}^{-1}$ @ $\sqrt{s} = 10.52$ GeV

Please see Yang Li's talk

$\Lambda \to p\pi^-$, $\Xi^- \to \Lambda\pi^-$



$p^*_{\Xi^- X}/p^*_{\max}$ region: [0.45, 0.55) [0.55, 0.65) [0.65, 0.75) ≥ 0.75

- Plays an important role in strong and weak interactions.
- Theoretical calculation of form factors and hadronic structure can be performed in relatively simple versions of QCD.
- One can also use these decays to test lepton flavor universality (LFU) tests.
- Similar to the hint of LFU in $b \to s\ell\ell$ and $b \to c\ell\nu$ processes.

$$\mathcal{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell) \equiv \frac{\varepsilon_{\rm pop}^{\Xi^-\pi^+} \Sigma_i \frac{N_i^{\Xi^-\ell^+}}{\varepsilon_i^{\Xi^-\ell^+}}}{\varepsilon_{\rm pop}^{\Xi^-\ell^+} \Sigma_i \frac{N_i^{\Xi^-\pi^+}}{\varepsilon_i^{\Xi^-\pi^+}}} \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+),$$

$p^*_f/p^*_{\max}$	[0.45, 0.55)	[0.55, 0.65)	[0.65, 0.75)	≥ 0.75	$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)}$
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	$(8.71 \pm 0.74) \times 10^2/15.79\%$	$(9.15 \pm 0.77) \times 10^2/18.87\%$	$(5.13 \pm 0.56) \times 10^2/21.60\%$	$(2.13 \pm 0.30) \times 10^2/22.54\%$	0.954 ± 0.055
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	$(3.10 \pm 0.72) \times 10^2/6.43\%$	$(5.24 \pm 0.64) \times 10^2/10.47\%$	$(4.34 \pm 0.44) \times 10^2/14.37\%$	$(2.05 \pm 0.40) \times 10^2/17.81\%$	0.952 ± 0.094
$\Xi_c^0 \to \Xi^- \pi^+$	$(9.41 \pm 0.07) \times 10^2/23.36\%$	$(1.29 \pm 0.07) \times 10^3/24.71\%$	$(1.51 \pm 0.06) \times 10^3/25.91\%$	$(1.22 \pm 0.06) \times 10^3/27.13\%$	...

Belle Preliminary

$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu)} = 1.00 \pm 0.11 \pm 0.09$$

$$\mathcal{A}_{CP} = \frac{\alpha_{\Xi^-\pi^+} + \alpha_{\Xi^+\pi^-}}{\alpha_{\Xi^-\pi^+} - \alpha_{\Xi^+\pi^-}} = 0.015 \pm 0.052 \pm 0.017$$

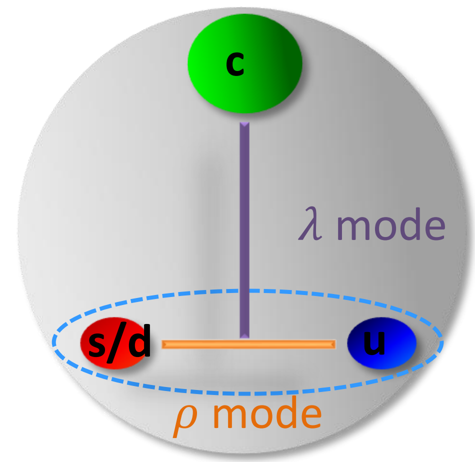
Semi-leptonic decay branching fractions are greatly improved.

Present the first measurement of the CP asymmetry in Ξ_c^0 decays, consistent with no CP violation

Electromagnetic decays of $\Xi_c(2790)$ and $\Xi_c(2815)$

EM decays provide useful information regarding L=1 orbital excitations of the ground states.

- ❖ λ mode : where the unit of angular momentum is between the charm quark and a spin-0 light diquark system.
- ❖ ρ mode: is between the two light quarks.

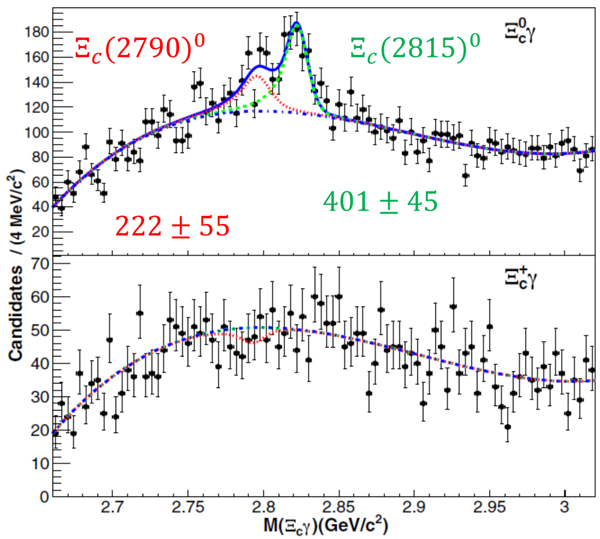


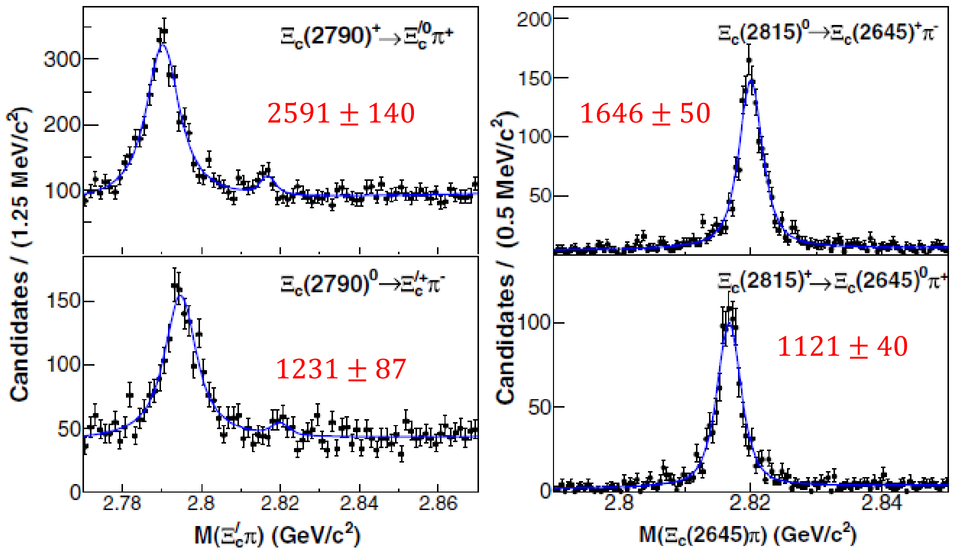
Observation of EM decay of Ξ_c^* baryons:
$\Xi_c(2790)^0 \rightarrow \Xi_c^0\gamma$ and $\Xi_c(2815)^0 \rightarrow \Xi_c^0\gamma$ provides crucial Information for the charmed baryon models.

Please see Jin Li's talk

Mode	WYZZ [14]			IKLR [15]	GJR [16]	
	λ excitation	ρ excitation	ρ excitation	λ excitation	dynamically generated states	Actual total width [3]
$\Xi_c(2790)^+ \rightarrow \Xi_c^+\gamma$	4.65	1.39	0.79	...	246	$8900 \pm 600 \pm 800$
$\Xi_c(2790)^0 \rightarrow \Xi_c^0\gamma$	263	5.57	3.00	...	117	$10000 \pm 700 \pm 800$
$\Xi_c(2815)^+ \rightarrow \Xi_c^+\gamma$	2.8	1.88	2.81	190 ± 5	...	$2430 \pm 200 \pm 170$
$\Xi_c(2815)^0 \rightarrow \Xi_c^0\gamma$	292	7.50	11.2	497 ± 14	...	$2540 \pm 180 \pm 170$

Belle, PRD 102, 071103(R) (2020)





Modes	Ratio
$\frac{\mathcal{B}(\Xi_c(2815)^0 \to \Xi_c^0\gamma)}{\mathcal{B}(\Xi_c(2815)^0 \to \Xi_c^0(2645)^+\pi^- \to \Xi_c^0\pi^+\pi^-)}$	$0.41 \pm 0.05 \pm 0.03$
$\frac{\mathcal{B}(\Xi_c(2790)^0 \to \Xi_c^0\gamma)}{\mathcal{B}(\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to \Xi_c^+\gamma\pi^-)}$	$0.13 \pm 0.03 \pm 0.01$
$\frac{\mathcal{B}(\Xi_c(2815)^+ \to \Xi_c^+\gamma)}{\mathcal{B}(\Xi_c(2815)^+ \to \Xi_c^0(2645)^0\pi^+ \to \Xi_c^+\pi^+\pi^-)}$	< 0.09
$\frac{\mathcal{B}(\Xi_c(2815)^0 \to \Xi_c^0\gamma)}{\mathcal{B}(\Xi_c(2790)^+ \to \Xi_c'^0\pi^+ \to \Xi_c^0\gamma\pi^+)}$	< 0.06

Please see Jin Li's talk

$\Gamma[\Xi_c(2790)^0 \to \Xi_c^0\gamma] \sim 300$ keV/c^2, $\Gamma[\Xi_c(2815)^0 \to \Xi_c^0\gamma] \sim 800$ keV/c^2, $\Gamma[\Xi_c(2790)^+ \to \Xi_c^+\gamma] < 350$ keV/c^2, $\Gamma[\Xi_c(2815)^+ \to \Xi_c^+\gamma] < 80$ keV/c^2

- Consistent with charmed baryon model with orbital excitation between charmed quark and spin-0 light diquark system (λ mode)

Measurement of Spin and Parity of $\Xi_c(2970)^+$

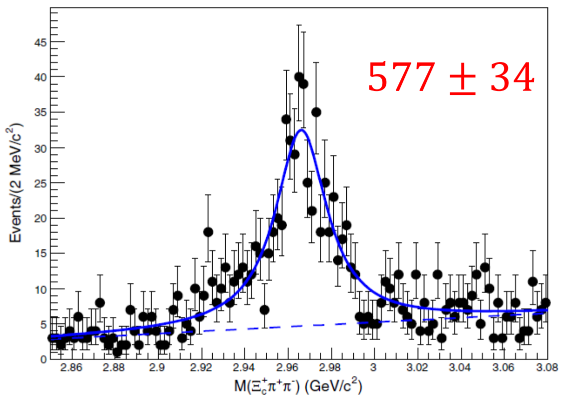
Belle, PRD 103, L111101 (2021)

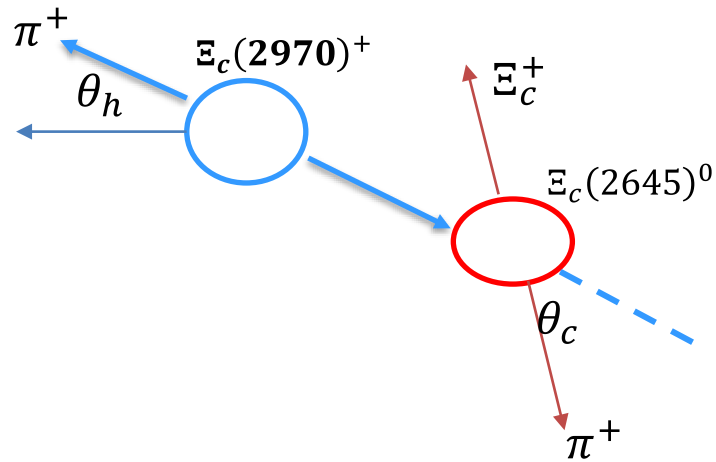
First successful attempt to measure spin.

There are many possibilities for the spin-parity assignment of $\Xi_c(2970)^+$

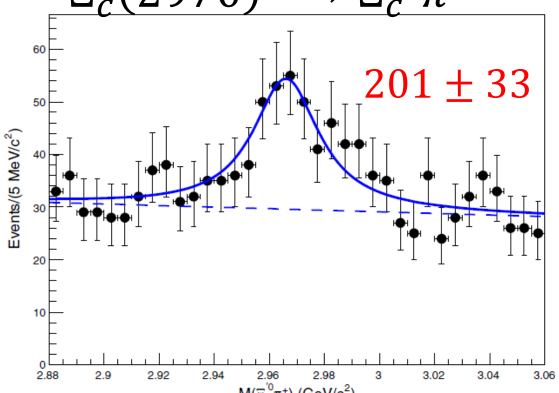
The unclear theoretical situation on J^P motivates an experimental determination.

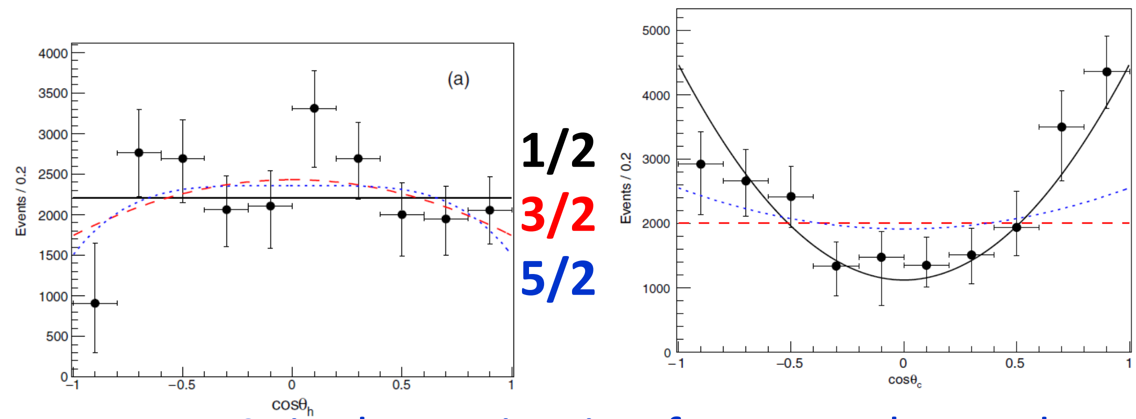
$\Xi_c(2970)^+ \rightarrow \Xi_c^0(2645)\pi^+ \rightarrow \Xi_c^+\pi^-\pi^+$





$\Xi_c(2970)^+ \rightarrow \Xi_c'^0\pi^+$





Spin determination from angular study strongly favours J=1/2

Parity determination from branching fraction ratio.

$$\frac{\mathcal{B}(\Xi_c(2970)^+ \rightarrow \Xi_c^0(2645)\pi^+)}{\mathcal{B}(\Xi_c(2970)^+ \rightarrow \Xi_c'^0\pi^+)} = 1.67 \pm 0.29^{+0.15}_{-0.09}$$

Please see Jin Li's talk

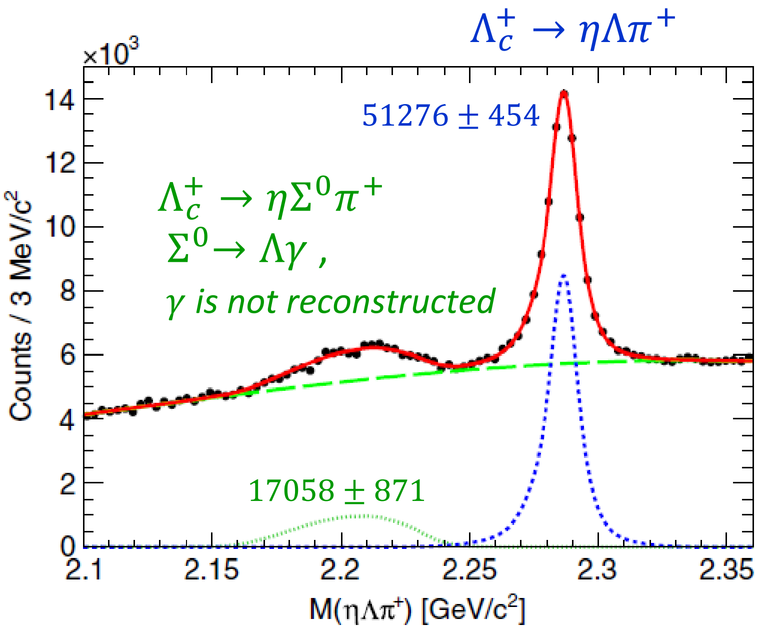
Favours $J^P = 1/2^+$ state

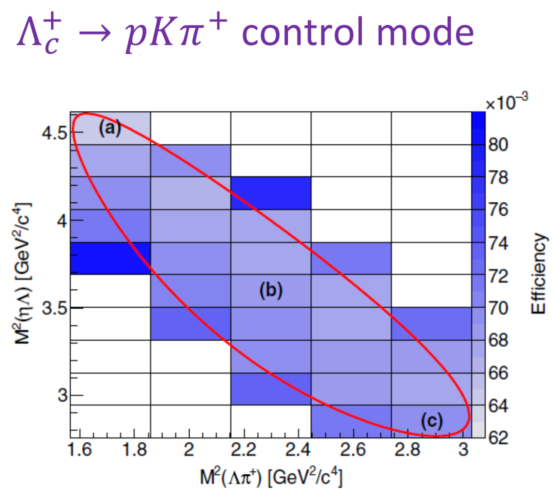
Please see Yang Li's talk

Belle, PRD 103, 052005 (2021)

Branching fractions of $\Lambda_c^+ \to \eta\Lambda\pi^+$, $\Lambda_c^+ \to \eta\Sigma^0\pi^+$

$\Lambda_c^+ \to \eta\Lambda\pi^+$ decay mode is ideal decay mode to study $\Lambda(1670)$.

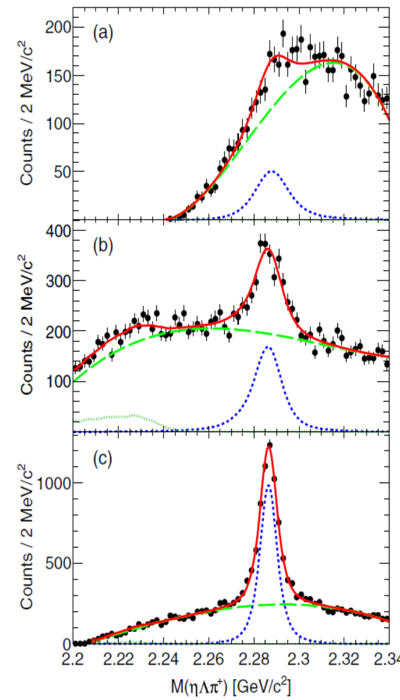


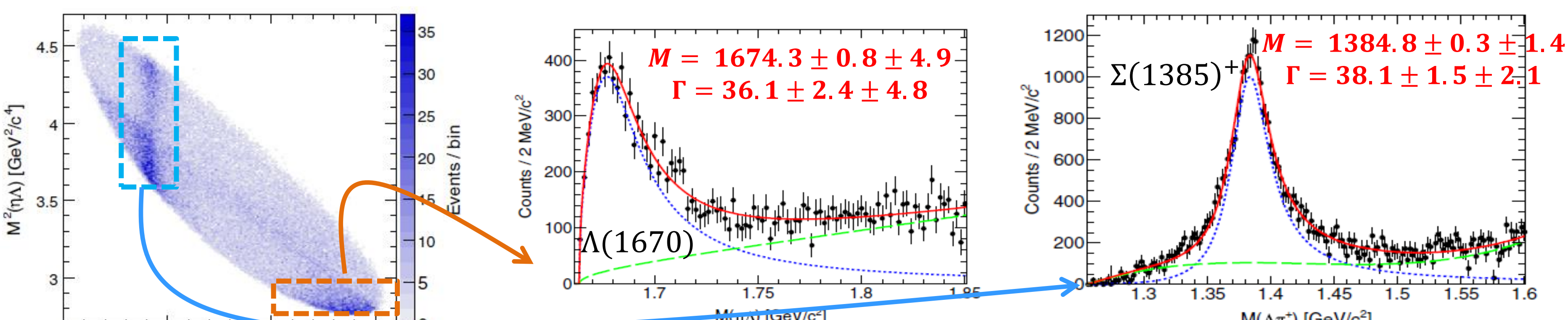


$$\frac{\mathcal{B}(\Lambda_c^+ \to \eta\Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.293 \pm 0.003 \pm 0.014,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \eta\Sigma^0\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.120 \pm 0.006 \pm 0.010.$$

Yield extraction in each bin





First measurement of $\Lambda(1670)$ mass and width determined directly from a peaking structure in the mass distribution.

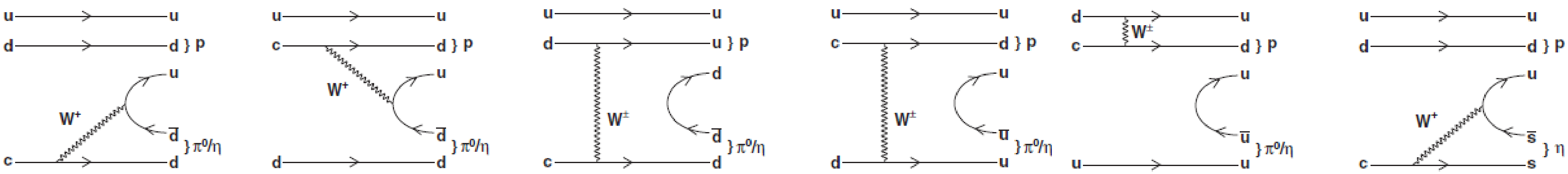
SCS decays of $\Lambda_c^+ \to p\eta, p\pi^0$

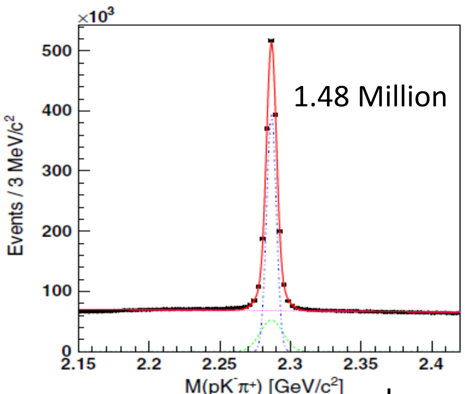
Please see Yang Li's talk

Weak decays of charmed baryons are useful for testing theory.

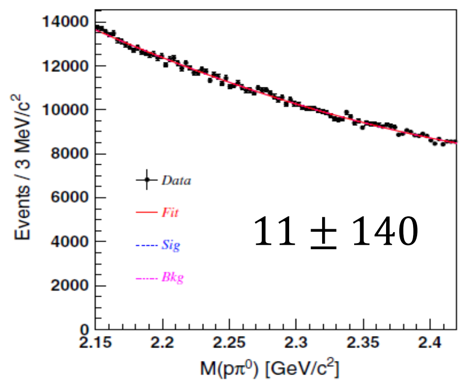
Belle, PRD 103, 072004 (2021)

Singly Cabibbo Suppressed (SCS) decays proceed via *W*-emission and *W*-exchange.

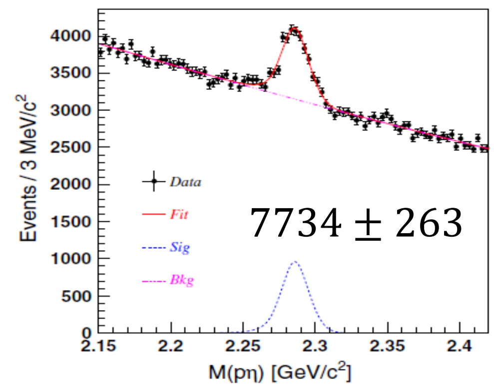




$\Lambda_c \to pK^-\pi^+$



$\Lambda_c \to p\pi^0$



$\Lambda_c \to p\eta$

- $\Lambda_c^+ \to p\eta$ decay mode with significant events observed.
- Measured ratio of $\frac{\mathcal{B}(\Lambda_c^+ \to p\eta)}{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^+)} = (2.258 \pm 0.077 \pm 0.122) \times 10^{-2}$.
- One can estimate $\mathcal{B}^*(\Lambda_c^+ \to p\eta) = (1.42 \pm 0.05 \pm 0.11) \times 10^{-3}$, consistent with previous measurement but much more precise.
- Also provide $\mathcal{B}^*(\Lambda_c^+ \to p\pi^0) < 8.0 \times 10^{-5}$ (90% CL) which is three times more stringent than the earlier precise measurement.
- Measured $\mathcal{B}(\Lambda_c^+ \to p\eta)$ is an order of magnitude larger than $\mathcal{B}(\Lambda_c^+ \to p\pi^0)$, which is consistent with theoretical prediction of an internal W-emission mechanism involving an s quark in $\Lambda_c^+ \to p\eta$

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

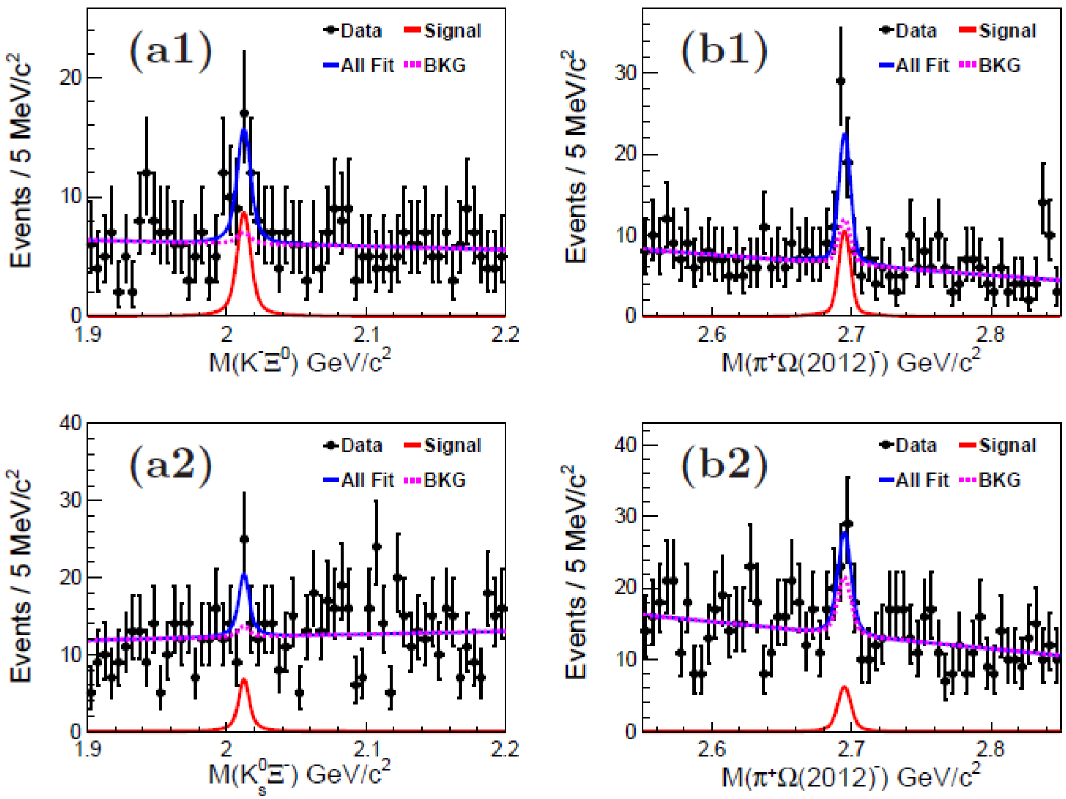
Please see Yang Li's talk

Predict $\Omega(2012)^-$ structure in $\Omega_c^0 \to \pi^+(K^-\Xi^0)$ and $\to \pi^+(\bar{K}\Xi^-)$ decays. PRD 102, 076009 (2020)

$\Omega(2012)^- \to \bar{K}\Xi^-$ is observed but no evidence of $\Omega(2012)^- \to \bar{K}\Xi(1530)^-$ decays.

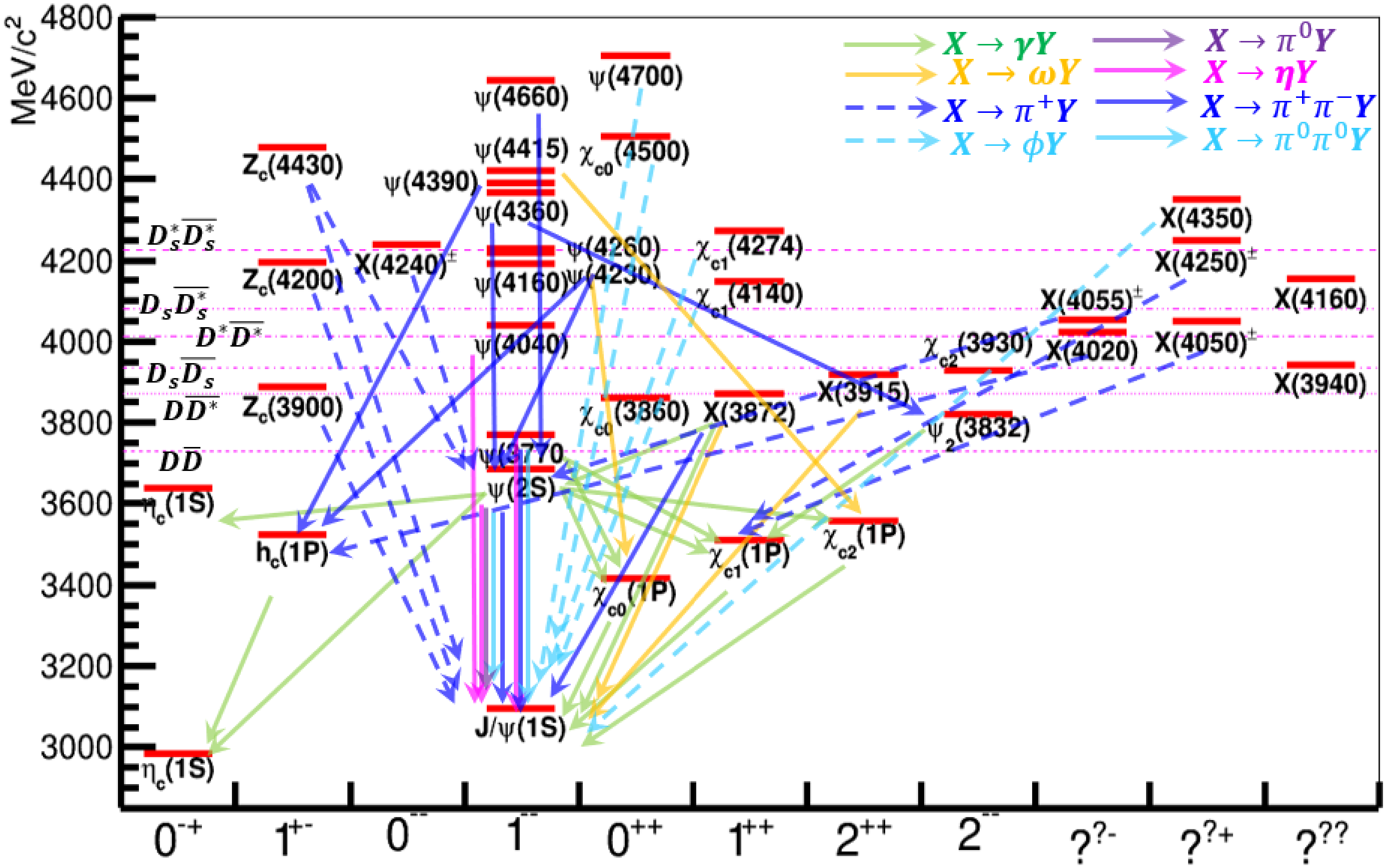
2D fit to $M(\bar{K}\Xi^-)$ and $M(\pi^+\Omega(2012)^-)$ distributions.

Belle, PRD 103, 112002 (2021)



→ 44.7±12.4 $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$ events with 4.2σ significance

$q\bar{q}$ (-like) states till now



- 1.7 decade has passed after the discovery of first $c\bar{c}$-like [*X(3872)*] by the Belle collaboration
- Plenty of states have been found.
- Several states are seen in one process (not easy to understand).
- States have a non-zero charge, suggesting them to be tetraquark/molecule-like states.
- Instead of conventional spectroscopy, it is now *exotic spectroscopy*.
- However, the limited statistics always come as the evil limiting factor.

Search for $\eta_{c2}(1D)$

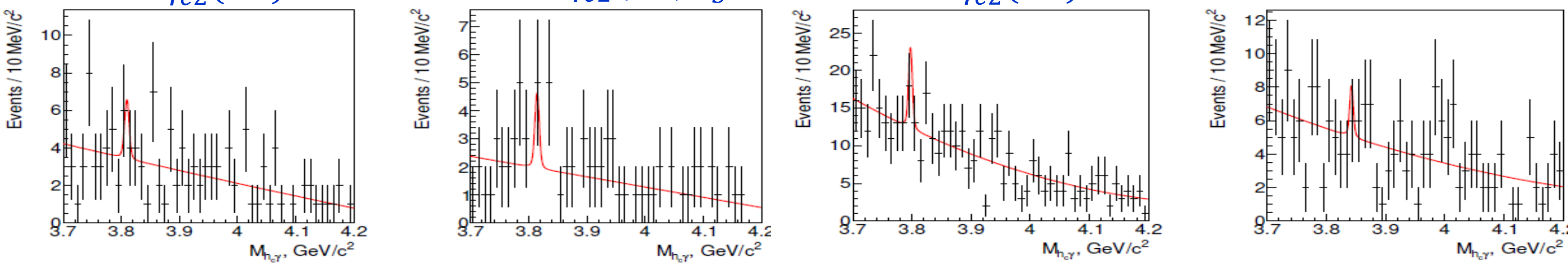
- Mass of $\psi_2(1D)[\,1^3D_1\,]$ and $\eta_{c2}(1D)$ $[1^1D_2]$ are very close.
- $\eta_{c2}(1D)$ is expected to decay predominantly via E1 transitions to $h_c\gamma$.
- $\mathcal{B}(B^+ \to \eta_{c2}(1D)K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma)$ is expected to be 1.0×10^{-5}.

Belle, JHEP 2020, 34 (2020)

$\eta_{c2}(1D) \to h_c\gamma$ and $h_c \to \eta_c\gamma$

$\eta_c \to K^+K_S^0\pi^-, K^+K^-\pi^0, K_S^0K_S^0\pi^0, K^+K^-\eta, K^+K^-K^+K^-, \eta'(\to \eta\pi^+\pi^-), \bar{p}p,\ \bar{p}p\,\pi^0, p\bar{p}\,\pi^+\pi^-, and\ \bar{\Lambda}\Lambda$

$B^+ \to \eta_{c2}(1D)K^+$ $B^0 \to \eta_{c2}(1D)K_S^0$ $B^0 \to \eta_{c2}(1D)\pi^-K^+$ $B^+ \to \eta_{c2}(1D)\pi^+K_S^0$



Channel	Mass, MeV/c^2	Yield	Local significance
$B^+ \to \eta_{c2}(1D)K^+$	3809.6 ± 4.3	3.3 ± 3.0	1.3σ
$B^0 \to \eta_{c2}(1D)K_S^0$	3814.4 ± 2.7	2.7 ± 2.3	1.5σ
$B^+ \to \eta_{c2}(1D)K^+$ and $B^0 \to \eta_{c2}(1D)K_S^0$	3821.8 ± 4.4	1.6 ± 3.2	0.7σ
$B^0 \to \eta_{c2}(1D)\pi^-K^+$	3797.0 ± 1.6	9.4 ± 5.1	2.1σ
$B^+ \to \eta_{c2}(1D)\pi^+K_S^0$	3842.3 ± 3.4	2.6 ± 3.1	1.0σ

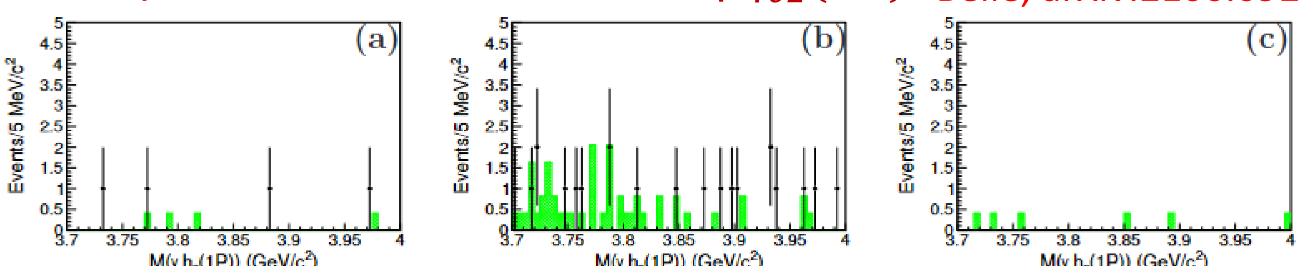
$$\mathcal{B}(B^+ \to \eta_{c2}(1D)K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 3.7 \times 10^{-5},$$
$$\mathcal{B}(B^0 \to \eta_{c2}(1D)K_S^0) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 3.5 \times 10^{-5},$$
$$\mathcal{B}(B^0 \to \eta_{c2}(1D)\pi^-K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 1.0 \times 10^{-4},$$
$$\mathcal{B}(B^+ \to \eta_{c2}(1D)\pi^+K_S^0) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 1.1 \times 10^{-4}.$$

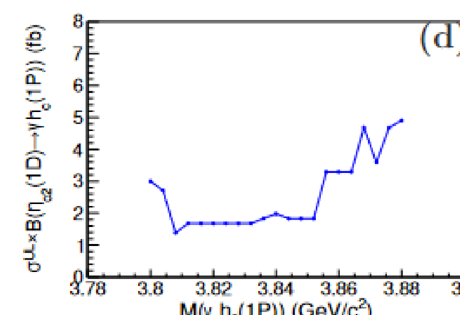
Recently, we also search for $e^+e^- \to \gamma\eta_{c2}(1D)$

Belle, arXiv:2106.09224

preliminary

$$\sigma^{\rm UL}(e^+e^- \to \gamma\eta_{c2}(1D))\mathcal{B}(\eta_{c2}(1D) \to \gamma h_c(1P)) = \frac{N^{\rm UL} \times |1-\Pi|^2}{\mathcal{L} \times (1+\delta)_{\rm ISR} \times \Sigma_i \mathcal{B}_i\varepsilon_i},$$





Taking $\mathcal{B}(\eta_{c2}(1D) \to \gamma h_c(1P)) > 50\%$, the value of $\sigma\big(e^+e^- \to \gamma\eta_{c2}(1D)\big) <$ 9.8 fb (@ 90 %CL).

PRD 102, 034018 (2021)

Consistent with theoretical prediction of 1.5 fb.

$e^+e^- \rightarrow \gamma_{ISR} D_s^+ D_{s2}^*(2573)^-(\rightarrow \overline{D^0} K^-)$

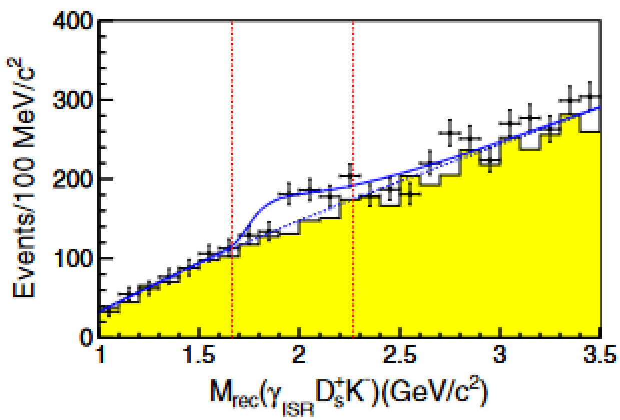
Belle PRD **101, 091101** (2020)

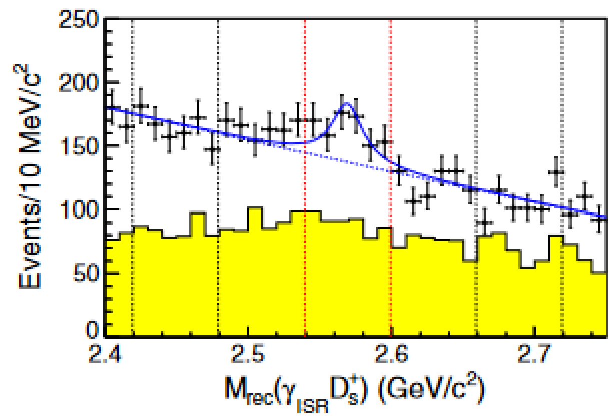
We require full reconstruction of γ_{ISR}, D_s^+, and K

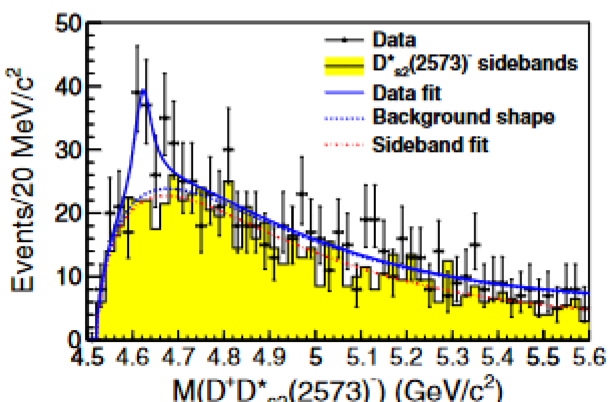
$$D_s^+ \rightarrow \phi\pi^+, K^{*0}K^+, K_S^0K^+, K^+K^-\pi^+\pi^0, K_S^0\pi^0K^+, K^{*+}K_S^0, \eta\pi^+, and\ \eta'\pi^+$$

For the signal, mass recoiling against $D_S^+ K^- \gamma_{ISR}$ system should peak around the D^0 nominal mass

$$M_{rec}(\gamma_{ISR} D_S^+ K^-) = \sqrt{\left(E_{cm}^* - E_{\gamma\mathrm{ISR}D_S^+K^-}^*\right)^2 - \left(p_{\gamma\mathrm{ISR}D_S^+K^-}^*\right)^2}$$







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

Measured mass is consistent with the structure observed in $e^+e^- \rightarrow \gamma_{ISR} D_S^+ D_{s1}(2536)^-(\rightarrow \overline{D^{*0}} K^-)$

Search for $R^{++} \to D^+ D_s^{*+}$

Belle, PRD 102, 112001 (2020)

By exchanging a kaon, a $D^+ D_{s0}^{*+}(2317)$ molecular state can be formed (regardless of whether $D_{s0}^{*+}(2317)$ is a $c\bar{s}$ state or a DK molecule).

M.S. Sanchez et al, PRD 98, 054001 (2018)

One expect to have the molecule state at 4140 MeV/c^2 as (denote as R^{++})

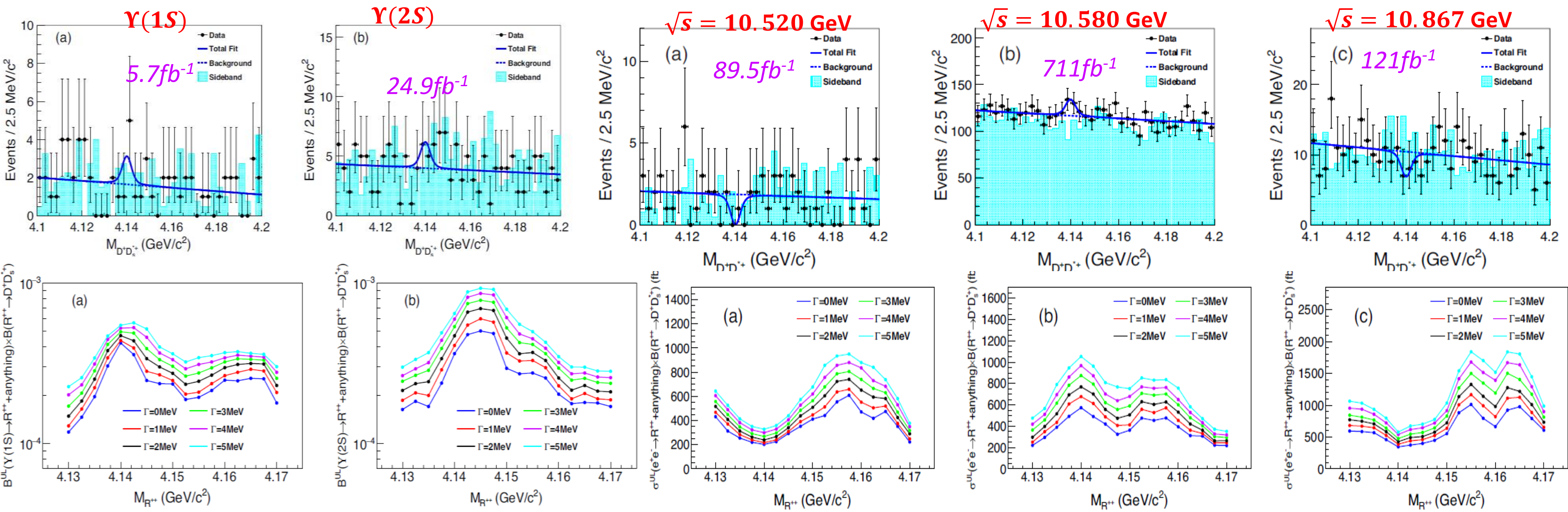
A.M. Torres et al, PRD 99, 076017 (2019)

A doubly-charged and doubly-charmed molecule R^{++} expected to decay to $D^+ D_s^{*+}$ with modest rates.

Mass of R^{++} is predicted to be in the range of 4.13-4.17 GeV/c2 with width of (2.3-2.5) MeV.

$e^+e^- \to D^+ D_s^{*+} + X$ $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K_S^0(\to \pi^+\pi^-)$ $D_s^+ \to \phi\pi^+$ and $D_s^+ \to K^*(892)^0 K^+$

R^{++} mass of 4.14 GeV/c^2 with a width of 2 MeV.



No significant signal for $R^{++} \to D^+ D_s^{*+}$ is observed

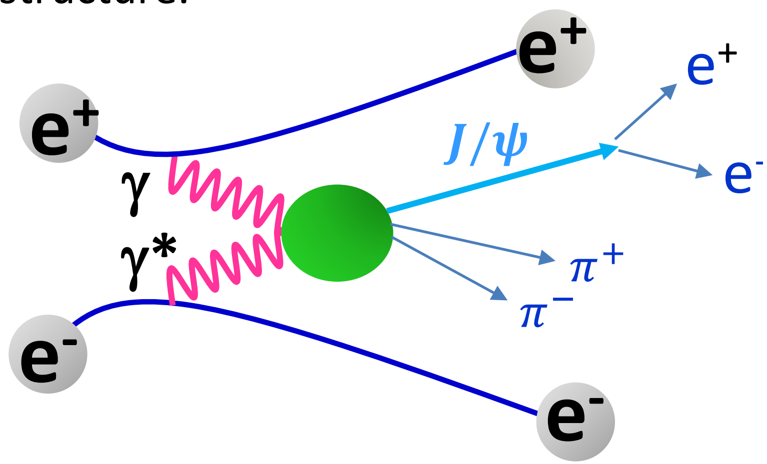
Evidence for $X(3872) \to \pi^+\pi^- J/\psi$ produced in single-tag two photon interactions

Belle, PRL 126, 122001 (2021)

X(3872) with $J^{PC} = 1^{++}$ is not allowed in $\gamma\gamma \to X(3872)$, but if one or both photons are virtual then, $X(3872)$ can be produced. $\gamma\gamma^* \to X(3872)$

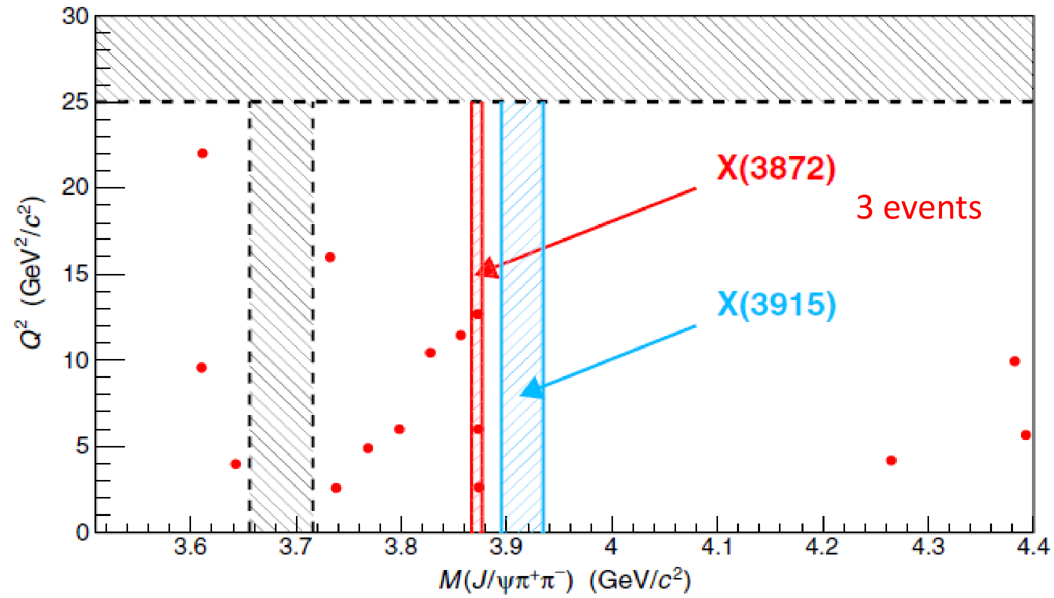
Nucl. Phys. B 523, 423 (1998).

Measurement of $X(3872)$ in two-photon reactions will help to understand its internal structure.



If X(3872) has a molecular component in its structure, it must have a steeper Q² dependence than regular charmonium state.

-Q² is the invariant mass-squares of the virtual photon.

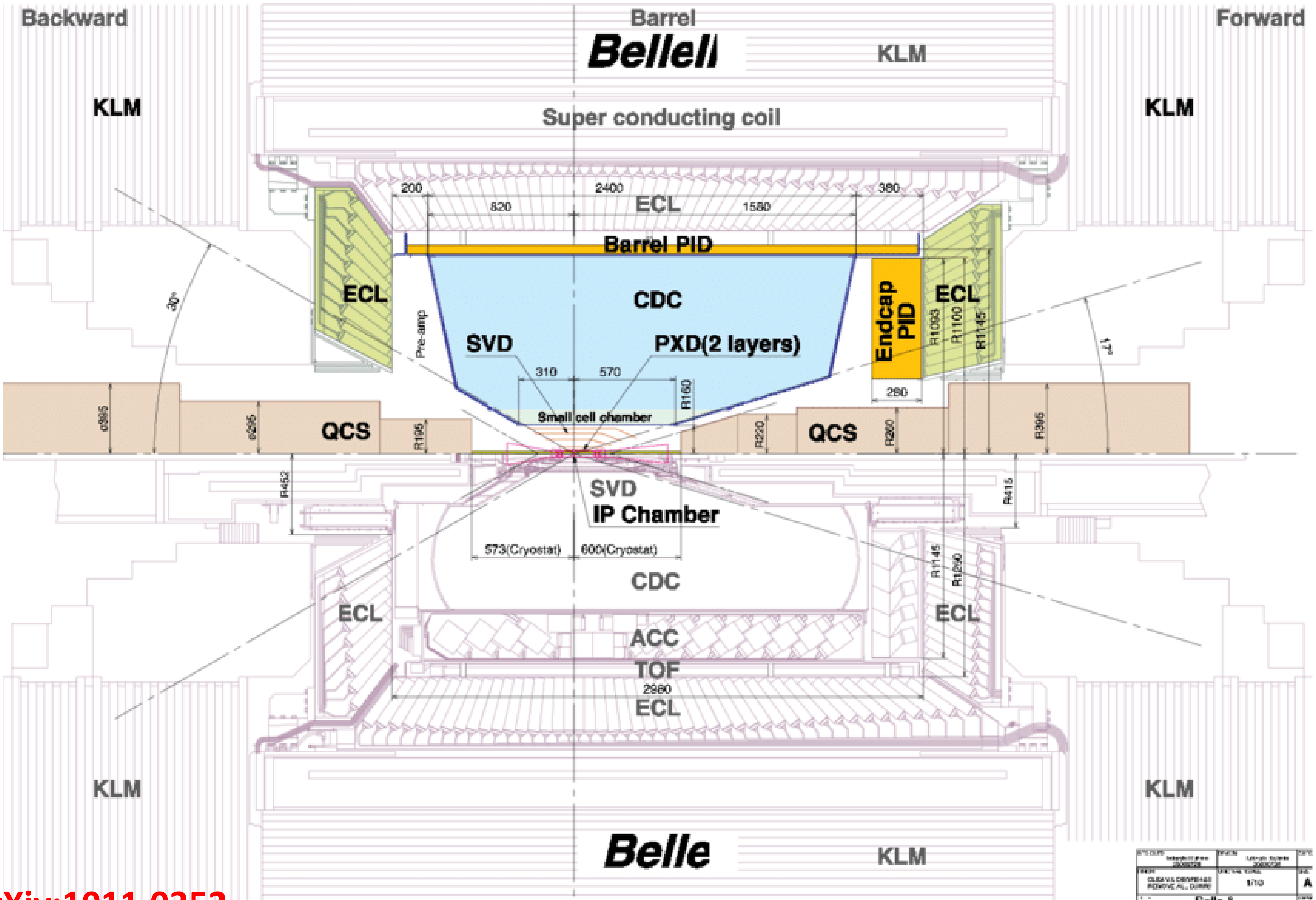


- $M(X(3872) = (3.8723 \pm 0.0012)$ GeV/c²
- With 0.11 ± 0.10 backgrounds events,
- Number of signal events is $2.9^{+2.2}_{-2.0} \pm 0.1$ with significance of 3.2σ. $\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X(3872) \to J\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8} \pm 0.7$ eV
- Obtain $0.995 < N_{sig} < 7.315$ (@90% CL) gives $20 < \tilde{\Gamma}_{\gamma\gamma} <$ 500eV. Values consistent with $c\bar{c}$ model.

Schuler *et al*, Nucl. Phys. B 523, 423 (1998).
T. Branz *et al*, PRD 83, 114015 (2011).

For more details, see Y. Teramoto's talk

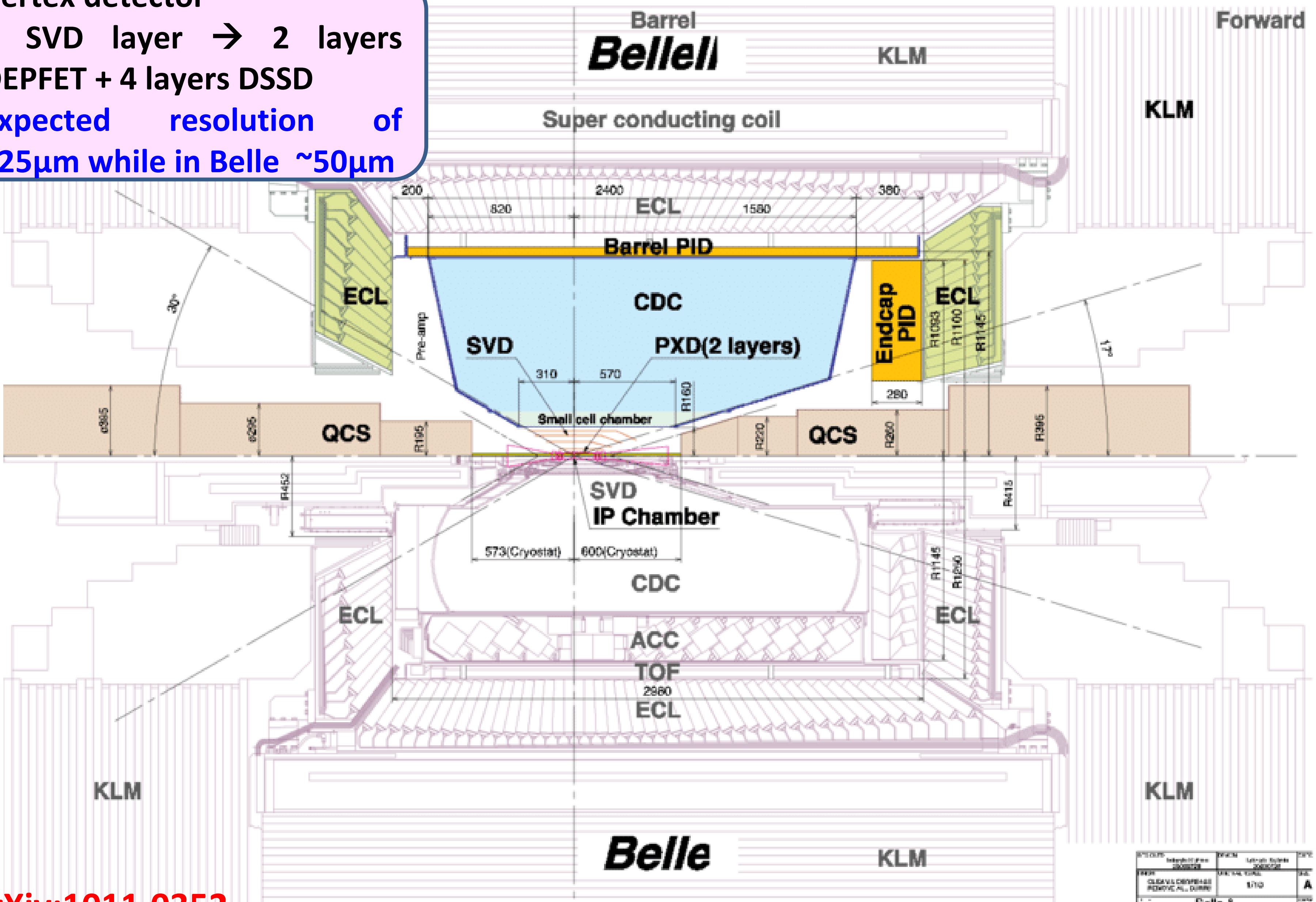
Belle to Belle II



arXiv:1011.0352

Belle to Belle II

Vertex detector
4 SVD layer → 2 layers DEPFET + 4 layers DSSD
Expected resolution of ~25µm while in Belle ~50µm



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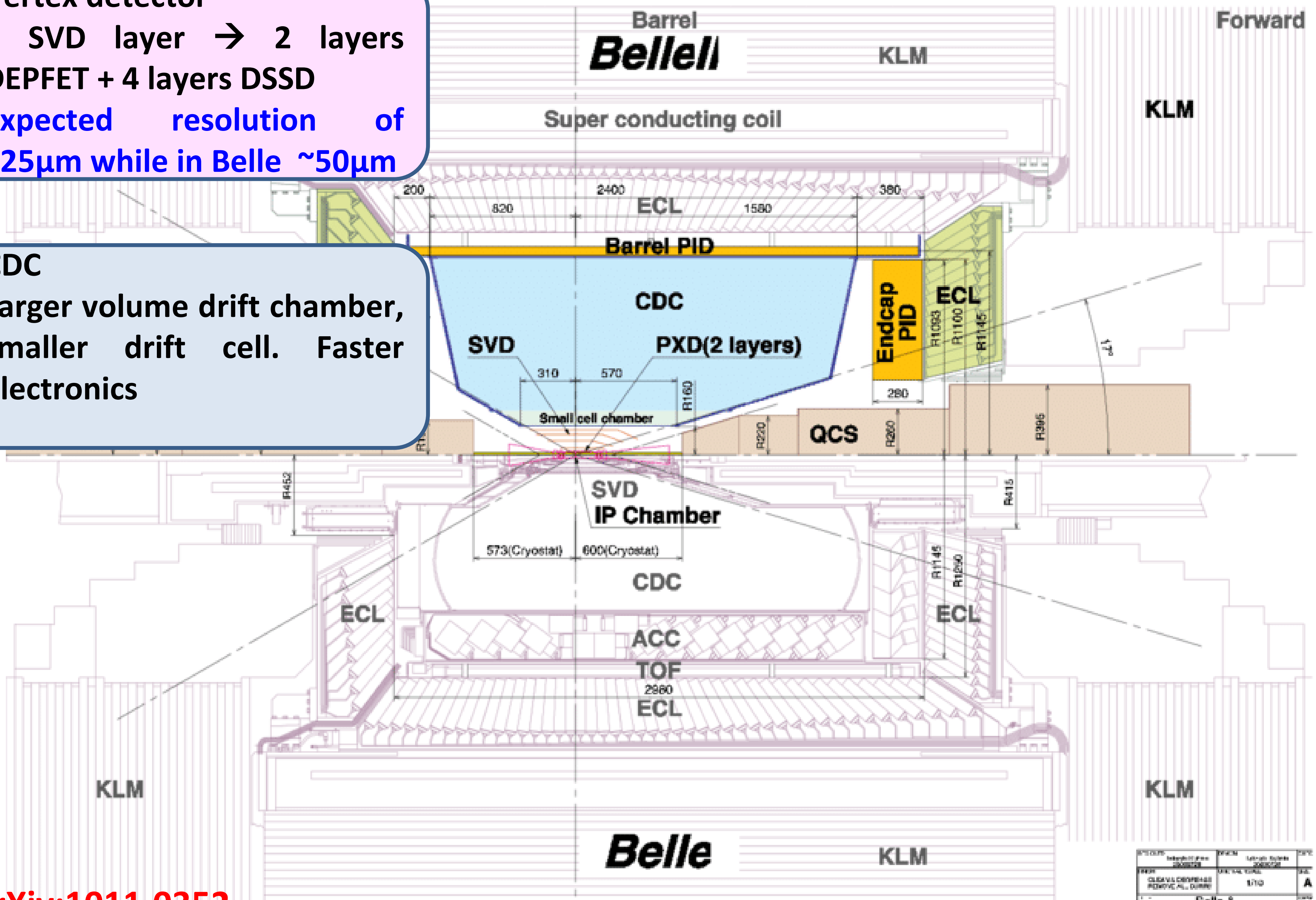
Larger volume drift chamber, smaller drift cell. Faster electronics



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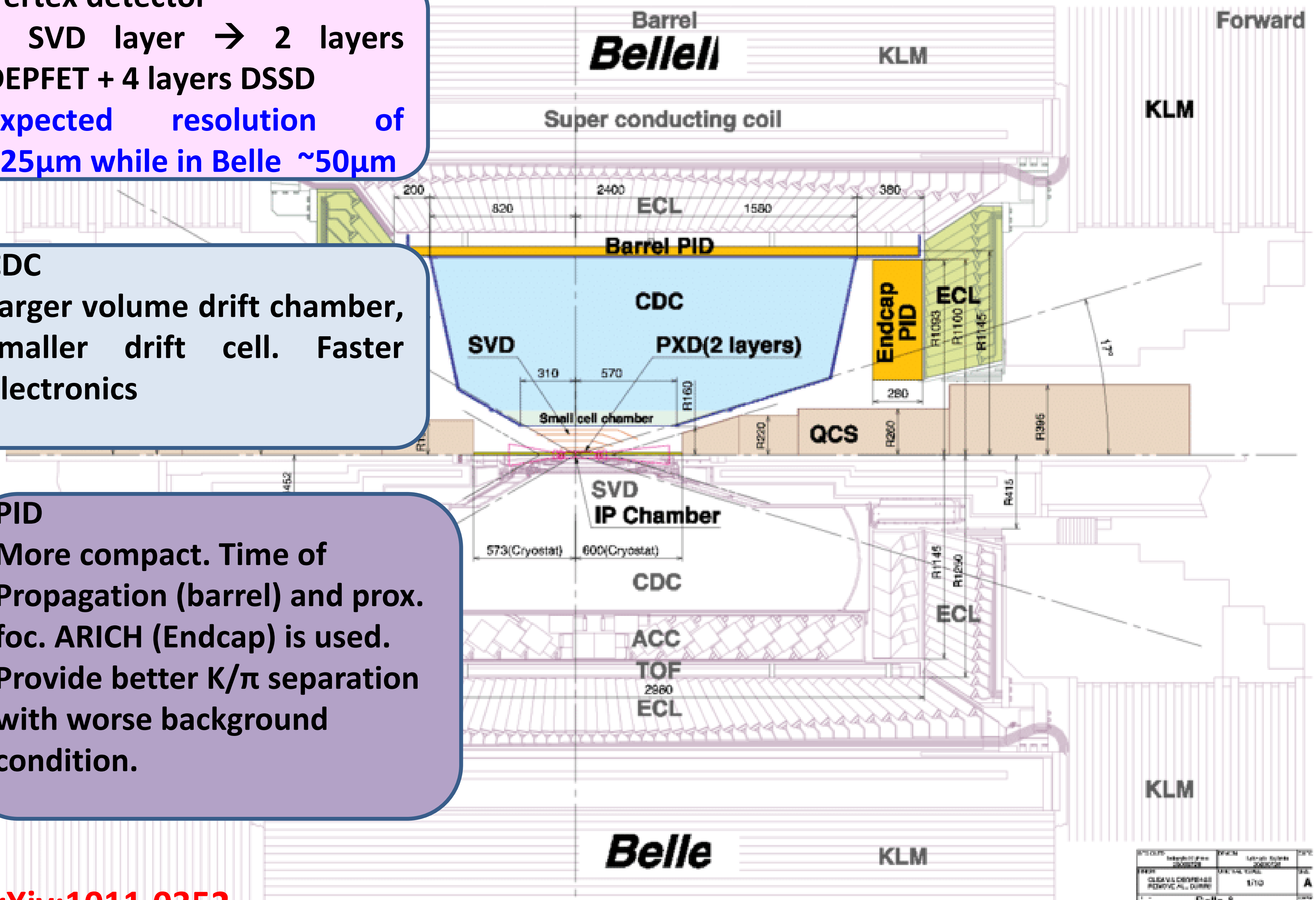
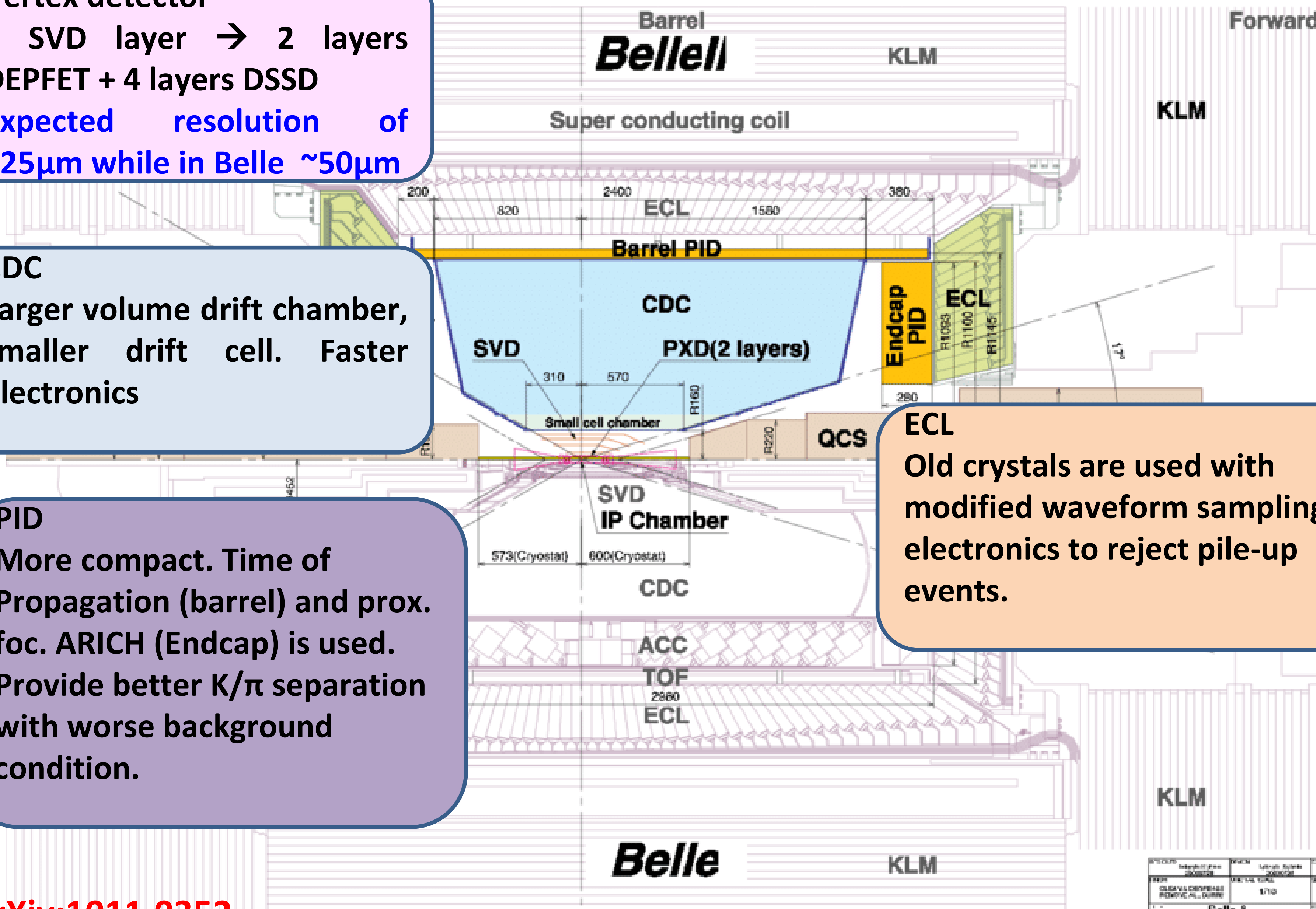
PID
More compact. Time of Propagation (barrel) and prox. foc. ARICH (Endcap) is used. Provide better K/π separation with worse background condition.



arXiv:1011.0352

Belle to Belle II



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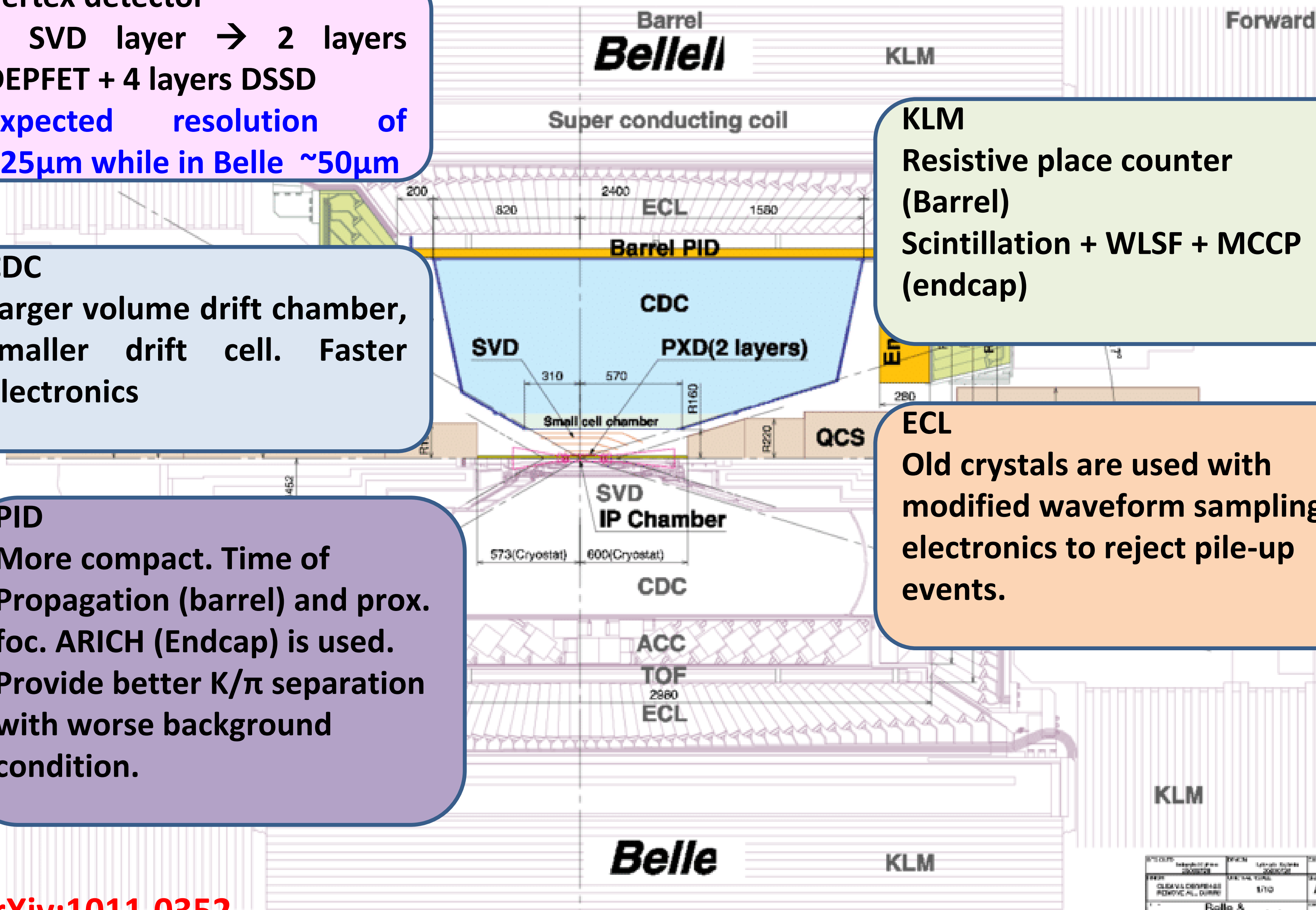
ECL
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

arXiv:1011.0352

Belle to Belle II



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KLM
Resistive place counter (Barrel)
Scintillation + WLSF + MCCP (endcap)

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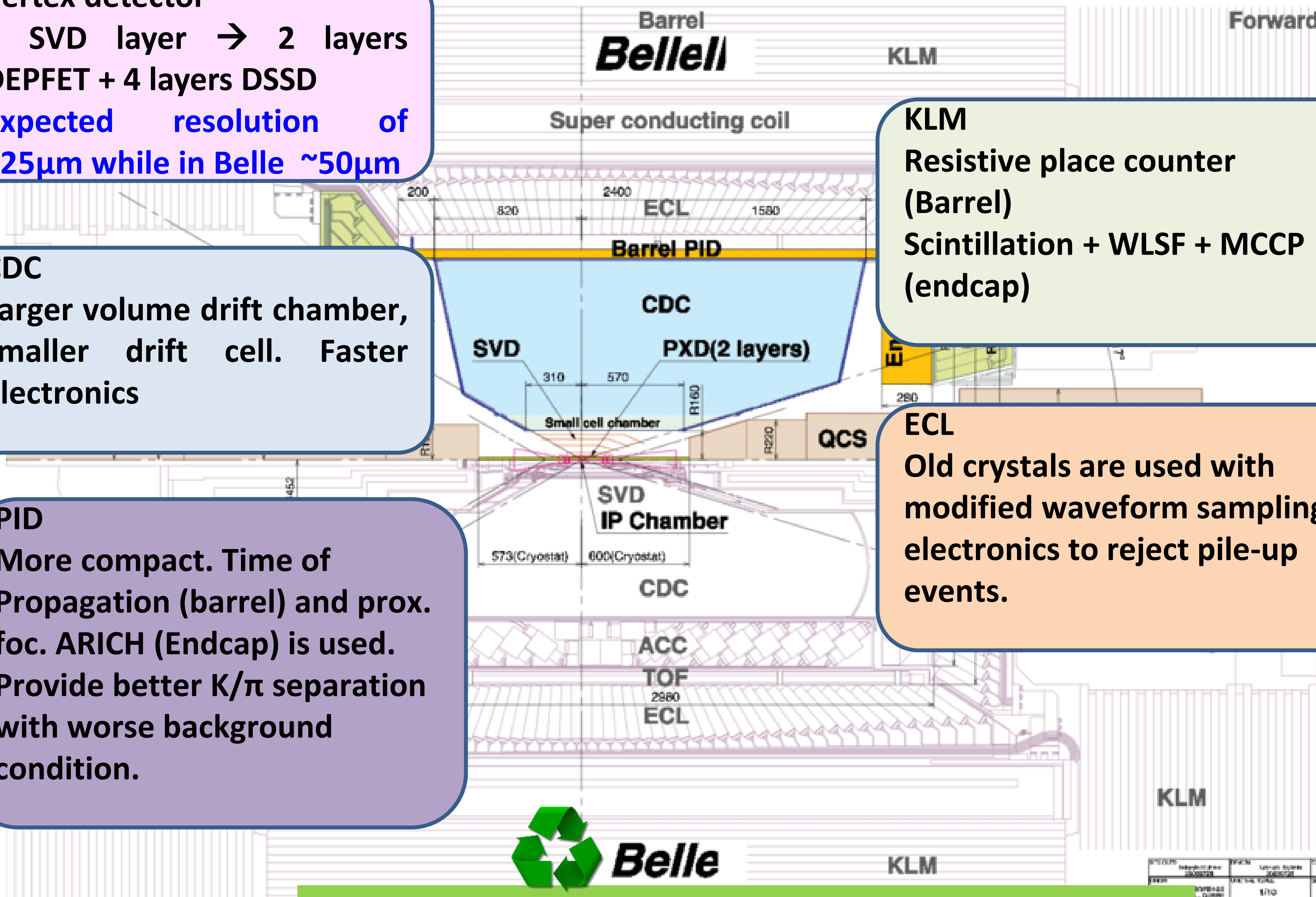
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

arXiv:1011.0352

Belle to Belle II



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Scintillation + WLSF + MCCP (endcap)

ECL
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

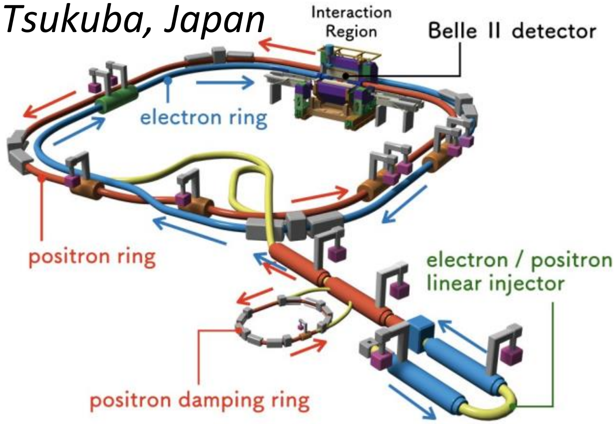
arXiv:1011.0352

ECL crystals and part of KLM sub-detector are re-used.

SuperKEKB: asymmetric *e-*(7GeV) - *e+*(4 GeV) Collider

See talk by E. Prencipe, B. Fulsom & B. Scavino

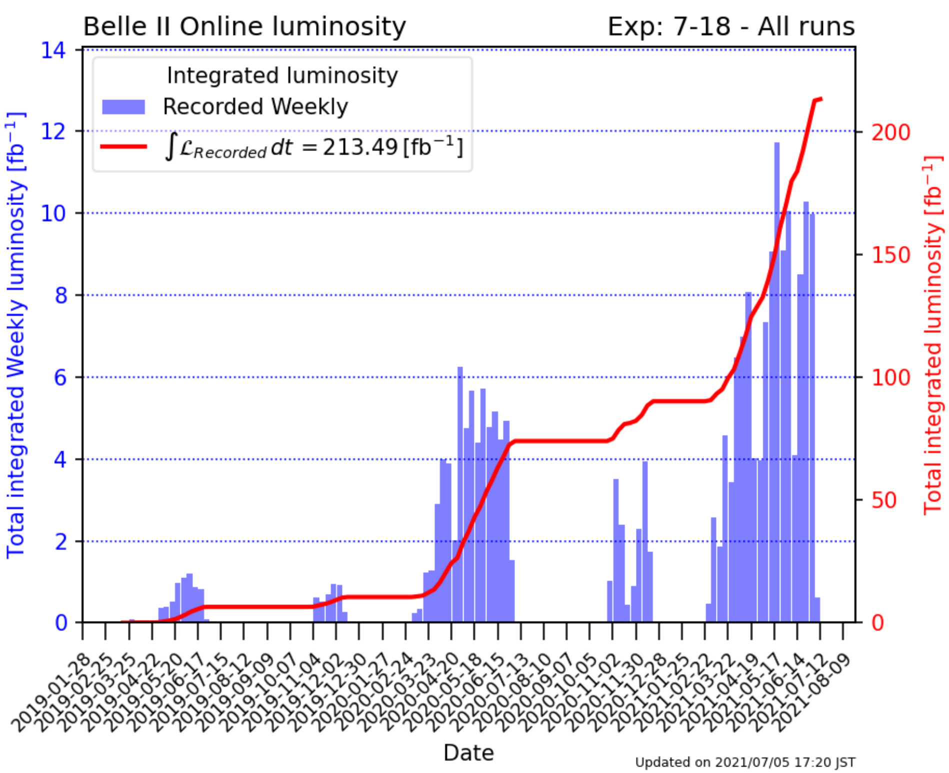
Tsukuba, Japan

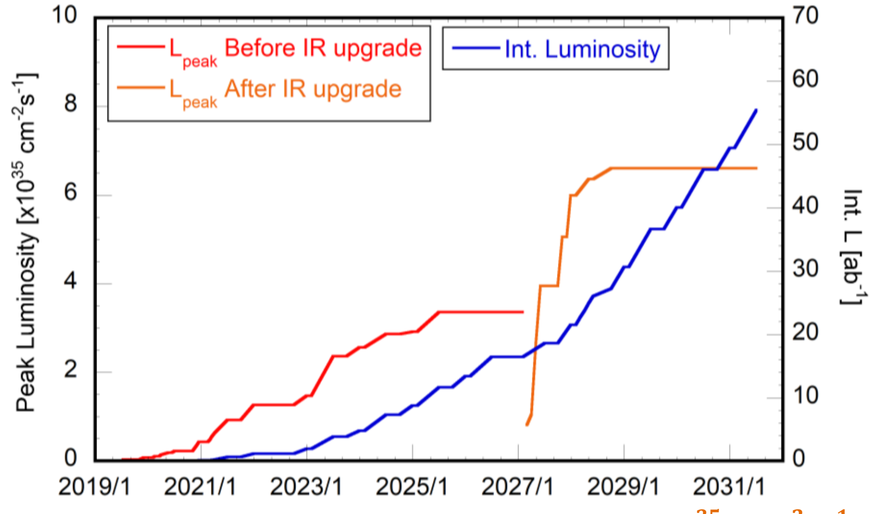


Goal > ~ 30 x KEKB instantaneous luminosity $\mathcal{L}$ =$6 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Luminosity record : $3.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

SuperKEKB breaks the *world record* for integrated luminosity in a single month and integrates 40.3 fb^{-1} in May 2021.





$\int \mathcal{L} = 0.5 - 1$ ab^{-1} 2022

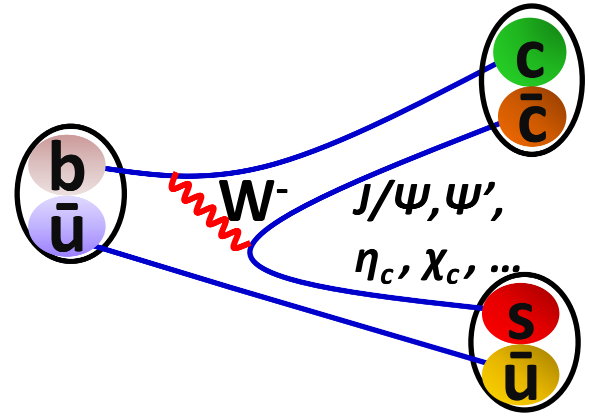
$\int \mathcal{L} = 10$ ab^{-1} 2026

$\mathcal{L}_{peak} = 6 \times 10^{35}$ cm^{-2}s^{-1} 2029

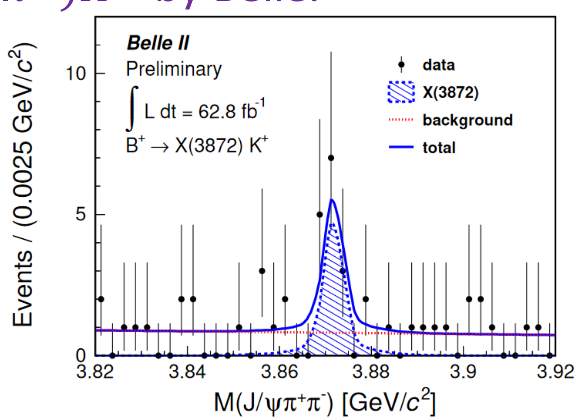
$\int \mathcal{L} = 50$ ab^{-1} 2031

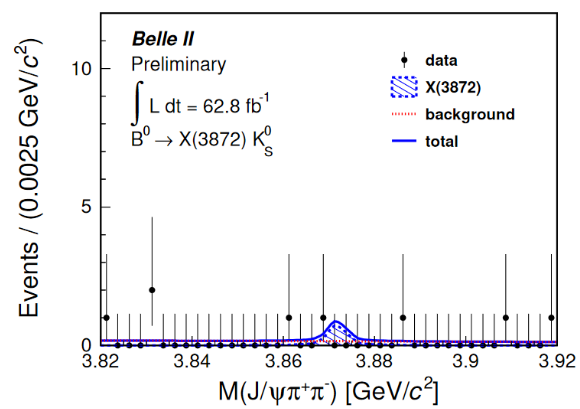
B to $\bar{c}c$ decays at Belle II

See talk by E. Prencipe



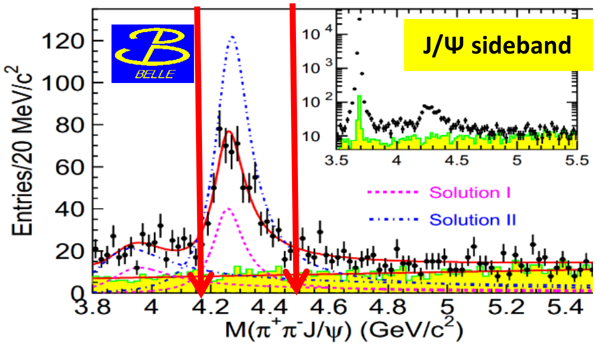
- At Belle II, possible to study $J/\psi\ \pi^+\pi^-$ and DD^* , the coupling will provide information about the X(3872) nature.
- Production of $X(3872)[\ B \to X(3872)K\ \pi]$ also provides useful information about the nature of X(3872)
- At Belle II, *one can do full reconstruction and*, using the missing mass technique calculates the $\mathcal{B}(B^+ \to X(3872)\ K^+)$.
  - Able to measure by 7σ (*naïve estimation*).
- One can also measure $\mathcal{B}(B^+ \to X(3915)\ K^+)$.
- Searching for the molecular/tetraquark partners are important tasks that can be done at the Belle II.
- Amplitude analysis at three-body *B* decays ($B \to (\bar{c}c)K\ \pi$) provides the opportunity to search or understand these states. (Reminder: first charged state was seen in $B \to (\psi(2S)\pi^+)K^-$ by Belle.

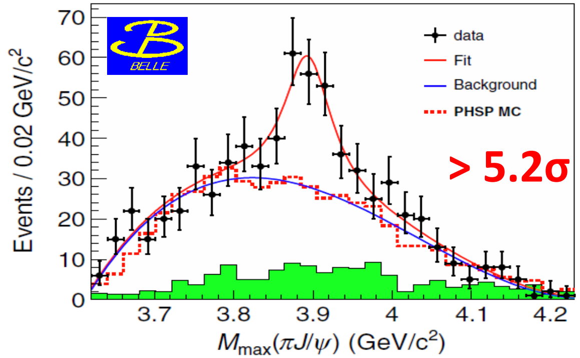


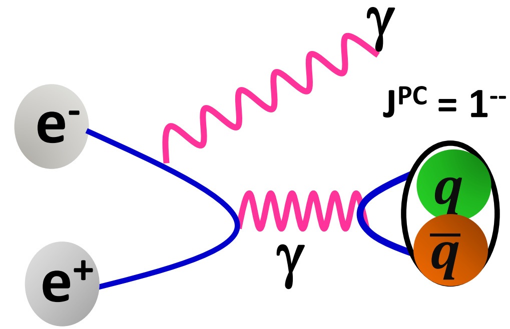


Rediscovery of X(3872) with 14.4 ± 4.6 signal events (4.6σ) at Belle II.

Initial state radiation







See talk by S. Jia

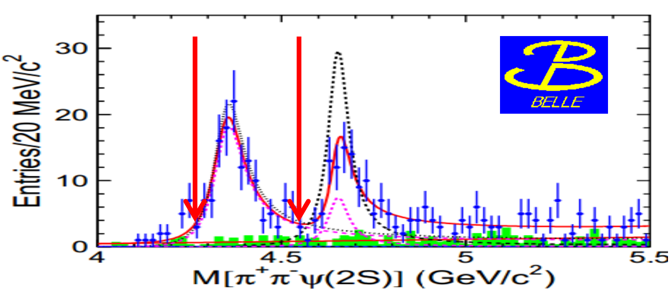
$$\frac{BR[Y(4260) \rightarrow Z(3895)^{\pm}\pi^{\mp}]}{BR[Y(4260) \rightarrow J/\psi\pi^{+}\pi^{-}]} = (29.0 \pm 8.9)\%$$

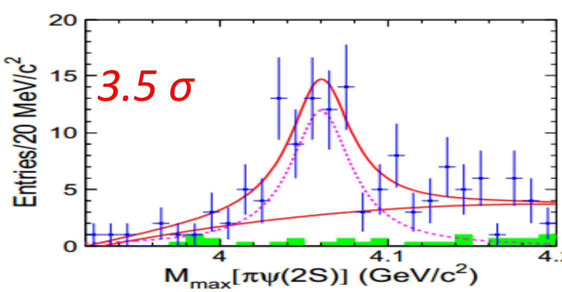
Measured properties

- Mass = (3894.5±6.6± 4.5) MeV
- Width = (63±24±26) MeV

- Belle II will compliment BESIII here.
- Expects improvement in mass resolution due to longer CDC
- One possible study $e^+e^- \rightarrow Y(\rightarrow J/\psi\pi^0\pi^0)\gamma_{ISR}$ for neutral partner

$e^+e^- \rightarrow \psi'\pi^+\pi^-$ study **Belle, PRD 91, 112007 (2015)**





Mass = (4054±3± 1) MeV
Width = (45±11±6) MeV

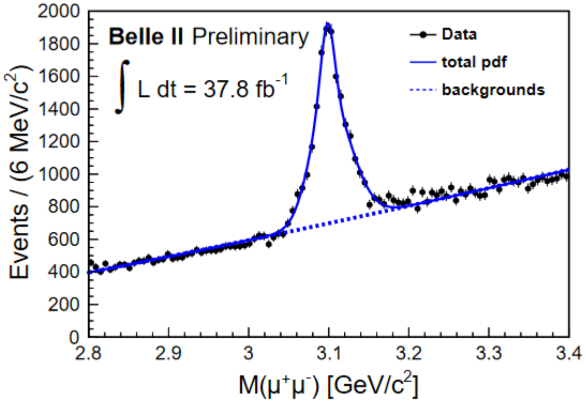
Any relation to $Z(4050)^+ \rightarrow \chi_{c1}\pi^+$?
Search $Z(4430)^+ \rightarrow \psi'\pi^+$ as in $B^0 \rightarrow \psi'\pi^+K^-$?

- One can also search for Z_{cs}^{+} in $e^+e^- \rightarrow J/\psi KK$.
- Further, interesting to study $e^+e^- \rightarrow D^0D^-\pi^+$ and $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$.

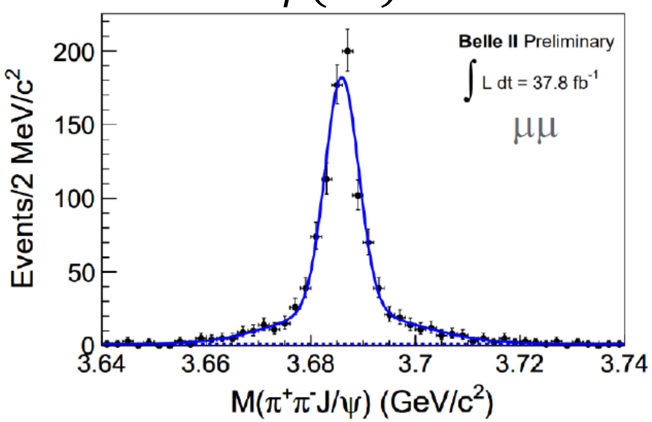
ISR preliminary results

See talk by S. Jia

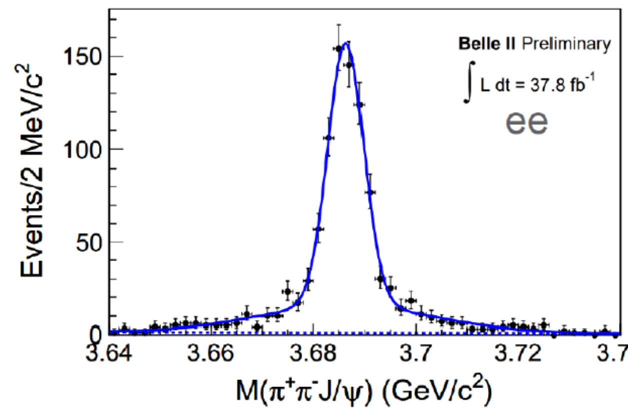
J/ψ



$\psi(2S)$



$\psi(2S)$



- Clear observation of ISR J/ψ and $\psi(2S)$ signal
- Soon, we can expect $Y(4260)$ rediscovery (~60 events per 100 fb^{-1})

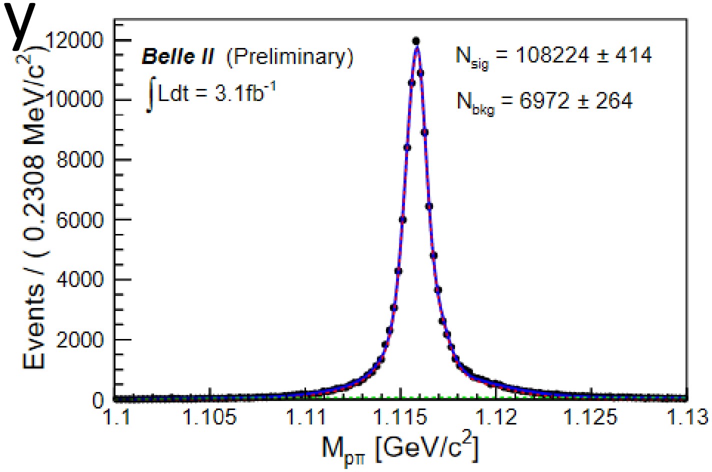
Baryon spectroscopy

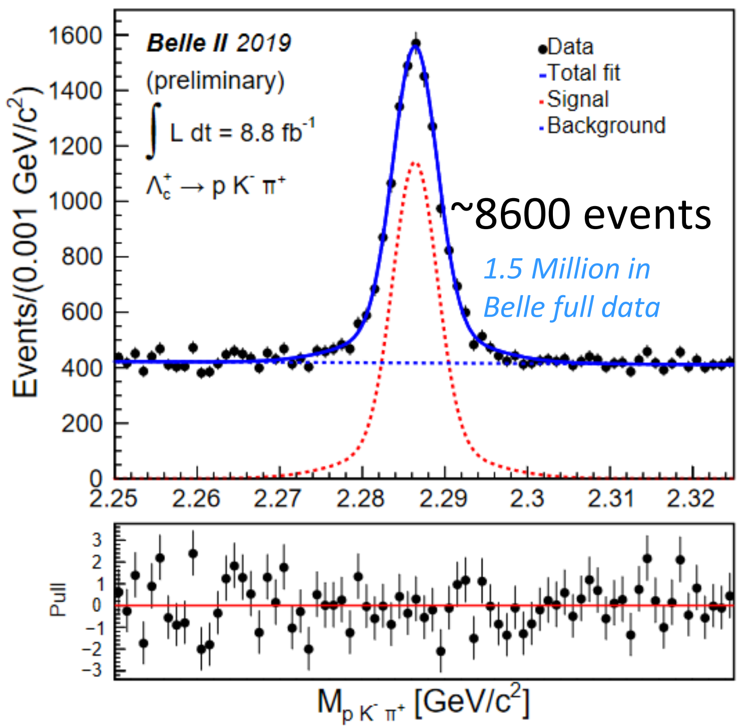
- Ground states along with many excited states have been observed.
- Still, J^P of only a few has been determined.
- One can utilize the Belle II data to increase our understanding of the charmed baryons.
- Learn more about the $\lambda - \rho$ modes.

- Search for new states and new decays.
- Absolute branching fractions will be done in the Belle.

- One can expect to search for New Physics using the semi-leptonic decays of the charmed baryons.

- Lifetime measurements of the charmed baryons.





Summary

- Belle has a vibrant Hadron spectroscopy program.
- Still exciting results are coming from the Belle final data.

- Belle II has started and already taken over the luminosity record.
- One can search for new hadrons and study their properties.

- Direct as well production from *B* decays provide a unique opportunity to get insight inside the hadrons.

For more details, please see

- Recent results on charmed baryon weak decays from Belle: Yang Li
- Study of charmonium-like states in two-photon collisions at Belle: Yoshiki Teramoto
- Recent results on charmed baryon spectroscopy from Belle: Jin Li
- Study of $\chi_{bJ}(nP) \to \omega\Upsilon(1S)$ in Belle: Zachary Stottler
- Exploration of bottomonium states at Belle : Todd Pedlar
- Studies of the X(3872) at Belle II: Elisabetta Precipe
- Bottomonium-like exotics and new physics in bottomonium decay at Belle II: Bianca Scavino
- Bottomonium results and prospects at Belle II: Bryan Fulsom
- ISR studies at Belle II: Sen Jia

Thank you