Spin-related measurements on charmed baryons at Belle

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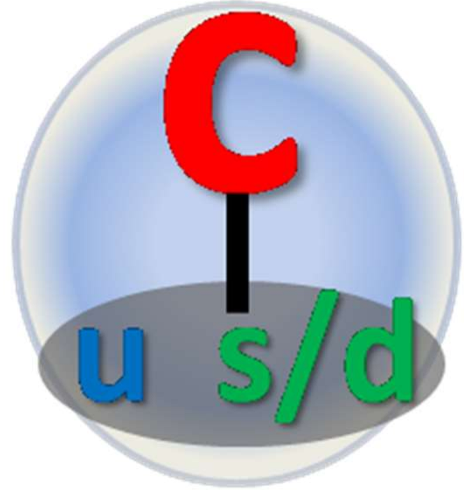
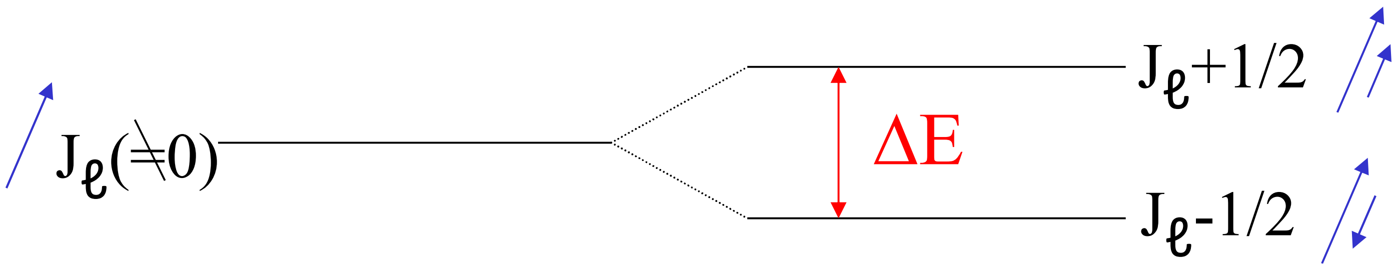
Spin in charmed baryons

- 2 distinct features
  1. Heavy quark symmetry
     Heavy quark spin is (approximately) conserved

→Spin doublets; J=j±1/2
(j: brown-muck spin)

Charmed baryon



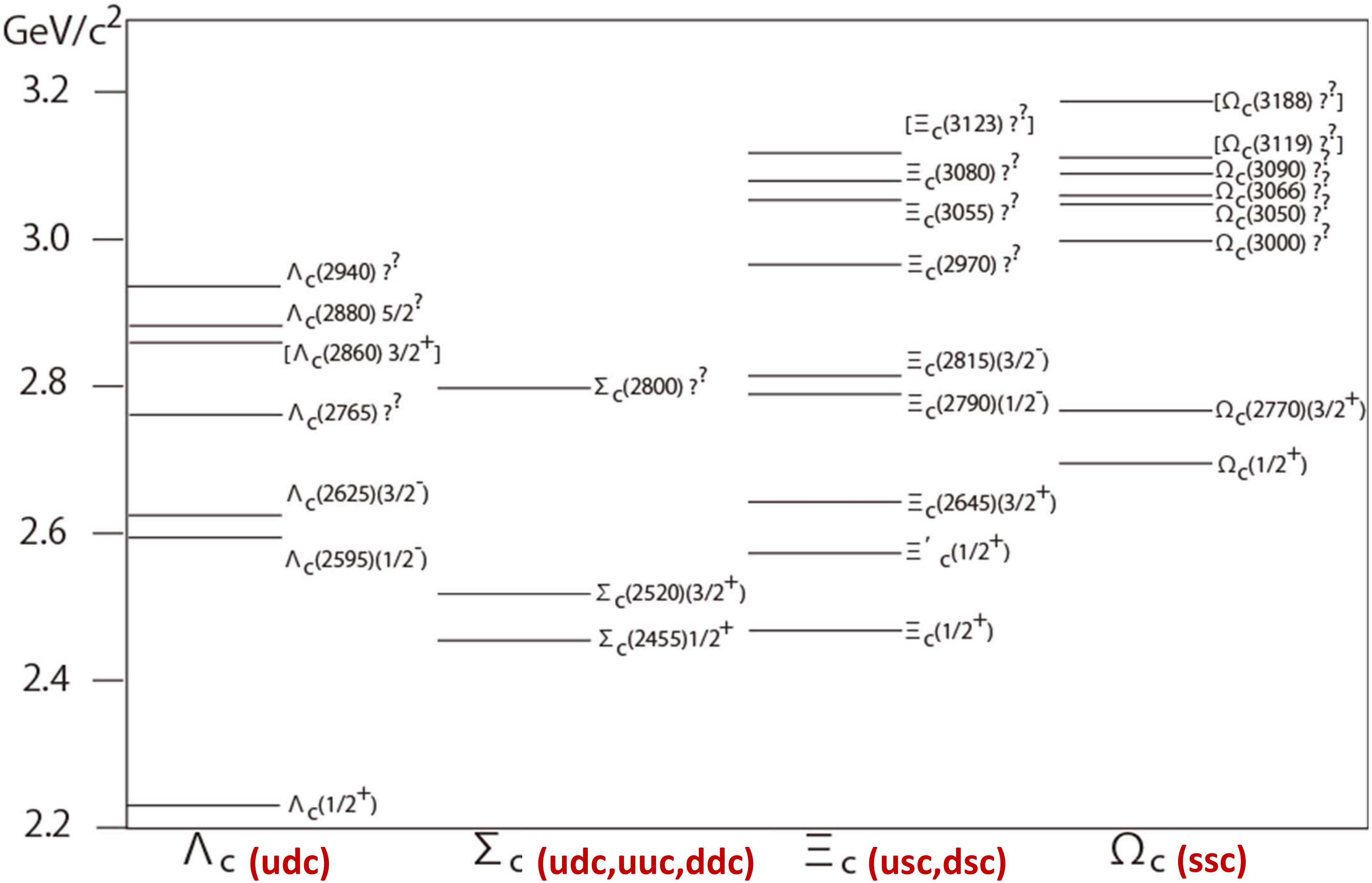


2. Weak decay
   Violates parity → decay asymmetry (or polarization)
   hint on decay mechanism and baryon structure

Known charmed baryons

- ~40 states are known
- $I(J^P)$ are experimentally determined for very few states – none for charmed-strange baryons
- Quark model predictions are quite good up to excitation energy ∼400 MeV – assignment of $I(J^P)$
  - Clear doublet structure seen

Known charmed baryons

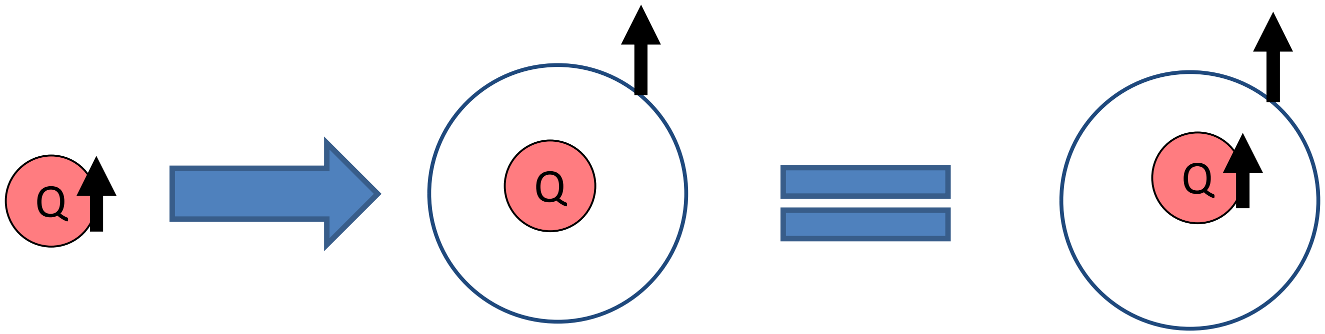


Known charmed baryons

- ~40 states are known
- I(JP) are experimentally determined for very few states – none for charmed-strange baryons
- Quark model predictions are quite good up to excitation energy ～400 MeV – assignment of I(JP)
  - Clear doublet structure seen
- There are many predicted states above that
  - What are exotic and what are not??
  - Which ones make HQS doublets?
  - Identification needs (at least) experimental determination of $I(J^P)$

Weak decay & baryon spin structure

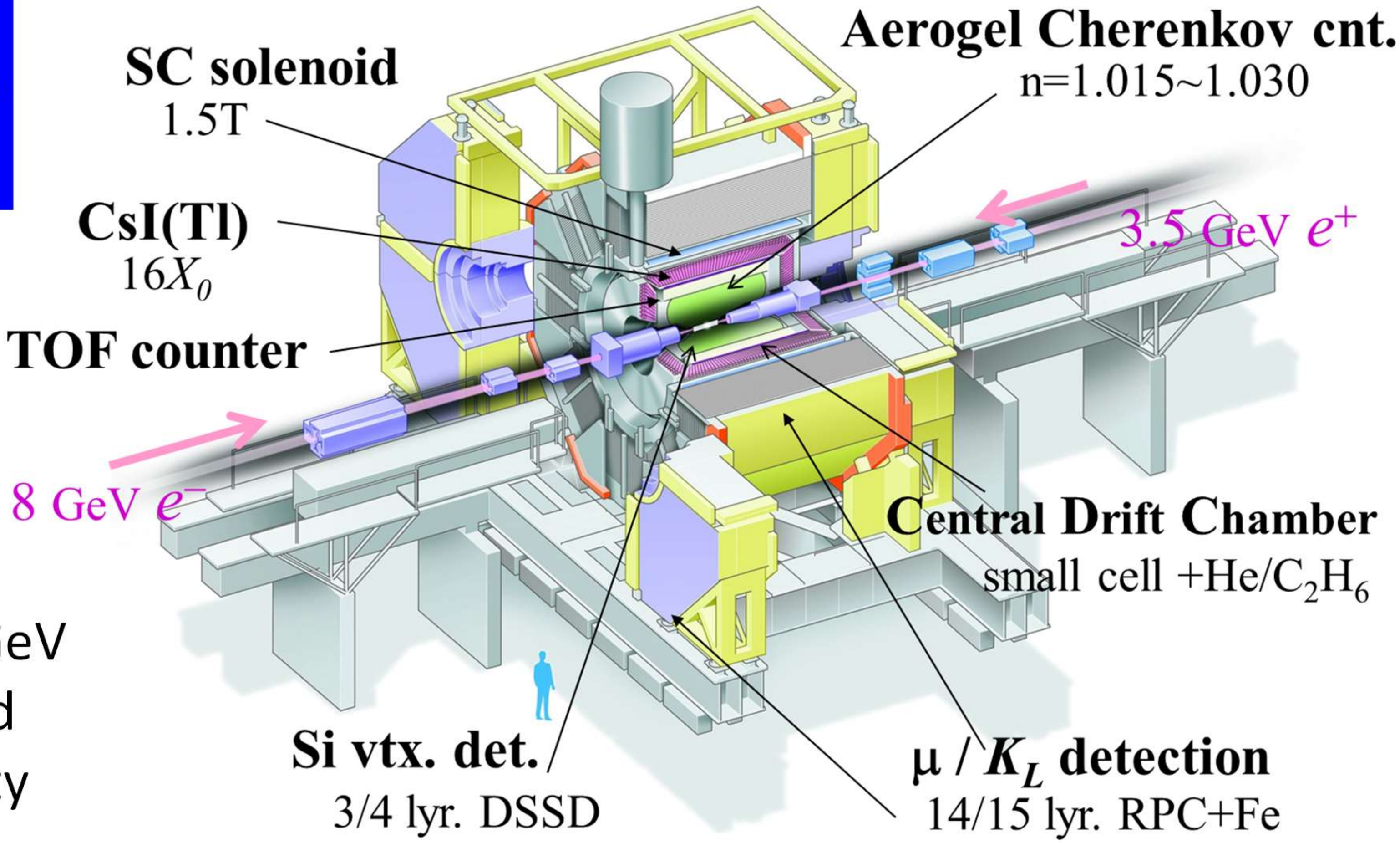
- Large quark polarization in weak decays
  - 100% polarization for massless quarks neglecting spontaneous chiral symmetry breaking effect (PCAC)
- Quark spin contribution to baryon: Δq
  → Fraction of quark spin in baryon spin
- Analog in fragmentation: polarization transfer
  - Polarized quark → polarized baryon
- Naïvely those two are equal [Augustin and Renard (1979)]



Examples

- Existing data from PDG:
  - $\Lambda_c \rightarrow \Lambda + e(\mu) + \nu$: $P = \alpha = -0.86 \pm 0.04$
  - $\Lambda_c \rightarrow \Lambda + \pi^+$: $P = -0.91 \pm 0.15$
  - $\Lambda_c \rightarrow \Sigma^+ + \pi^0$: $P = -0.45 \pm 0.32$
- Λ polarization can be understood well from the naïve quark model – s quark carries all the spin
- Σ case is more complicated, and anyway the uncertainty is still large.

Belle experiment



- √s~10.6 GeV
- Integrated Luminosity ~ 1 ab^{-1}

- Almost 4π, good momentum resolution (Δp/p～0.1%), EM calorimeter, PID & Si Vertex detector
- Finished ~10 years ago, still producing ~20 papers/year

Topics of the day

0. Introduction
1. Spin-parity measurement of $\Xi_c(2970)$
   [PRD**103**, L111101 (2021)]
2. Decay asymmetry of $\Xi_c^0 \to \Xi^- \pi^+$
   [PRL**127**, 121803 (2021)]
3. Decay asymmetries of $\Xi_c^0 \to \Lambda \overline{K}^{*0}, \Sigma^0 \overline{K}^{*0}, \Sigma^+ K^{*-}$
   [JHEP**06**, 160 (2021)]
4. Future prospects
5. Summary

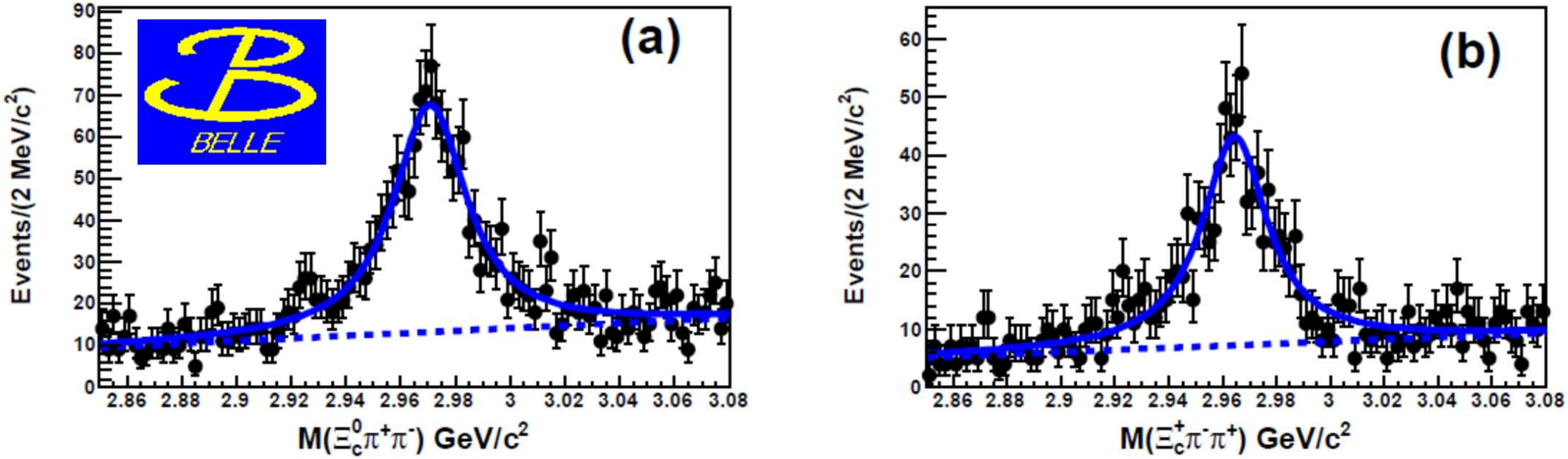
1. Spin-parity measurement of $\Xi_c(2970)$

[PRD**103**, L111101 (2021)]

$\Xi_c(2970)$

- Relatively low excitation energy
  - Good statistics & S/N ratio

Belle, PRD**94**, 052011 (2016)



- Important decay mode: $\Xi_c(2970) \rightarrow \Xi_c^*(2645)\pi$
  - $\Xi_c^*(2645)$ has spin 3/2

Predictions by theory

Model	J^P	Mass (MeV/c^2)	Description
Rel. Q.M. [12]	$\frac{1}{2}^+$	$2923(s_\ell = 0)$	Q-dq
		$2984(s_\ell = 1)$	
	$\frac{1}{2}^-$	$2934(s_\ell = 1)$	
Flux tube model [13]	$\frac{1}{2}^+$	$2959(s_\ell = 0)$	Q-dq
Nonrel. Q.M. [19]	$\frac{1}{2}^+$	2924	
	$\frac{3}{2}^+$	3012	
	$\frac{5}{2}^+$	3004	
	$\frac{5}{2}^-$	2989	
Feddeev Model [20]	$\frac{3}{2}^-$	2951	
Hypercoulomb Potential [21]	$\frac{1}{2}^+$	2956	
	$\frac{3}{2}^+$	2993	
Hypercoulomb Potential [22]	$\frac{1}{2}^+$	$2969(s_\ell = 1)$	Q-dq
Covariant Q.M. [23]	$\frac{1}{2}^+$	2948	
	$\frac{1}{2}^-$	2964	
	$\frac{3}{2}^-$	2971	
$SU(6)_{lsf} \times HQSS$ [24]	$\frac{3}{2}^-$	2942	
QCD Sum Rule [25]	$\frac{1}{2}^-$	2960	
	$\frac{3}{2}^-$	2980	

Wide variety

controversial

Predicted states within ~50 MeV

How to determine J^P?

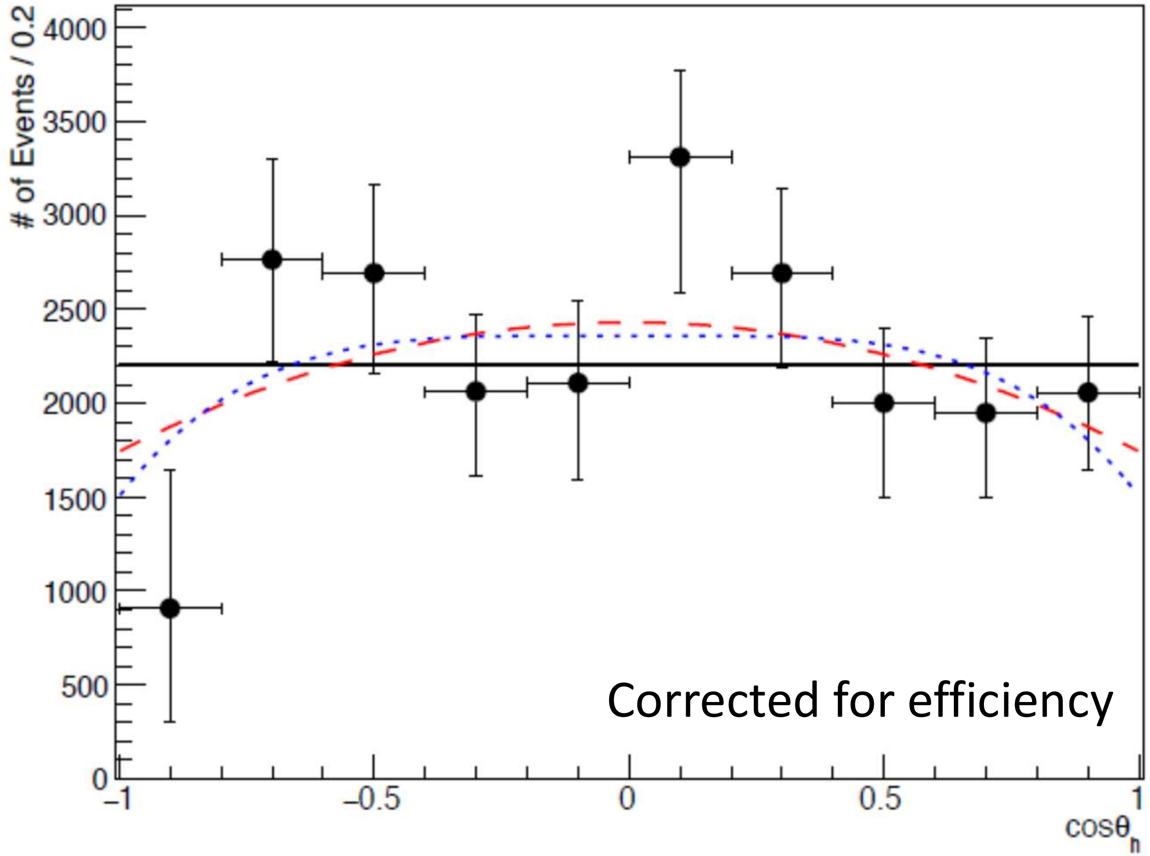
- Spin (J): angular distribution of the decay
  $\Xi_c(2970) \rightarrow \Xi_c^*(2645)\pi$
  & angular correlation of two pions in
  $\Xi_c(2970) \rightarrow \Xi_c^*(2645)\pi_1 \rightarrow \Xi_c\pi_1\pi_2$

- Parity (P): Branching ratio

$$\mathrm{R} = \frac{\Gamma(\Xi_c(2970) \rightarrow \Xi_c^*\pi)}{\Gamma(\Xi_c(2970) \rightarrow \Xi_c'\pi)}$$

  utilizing heavy quark symmetry

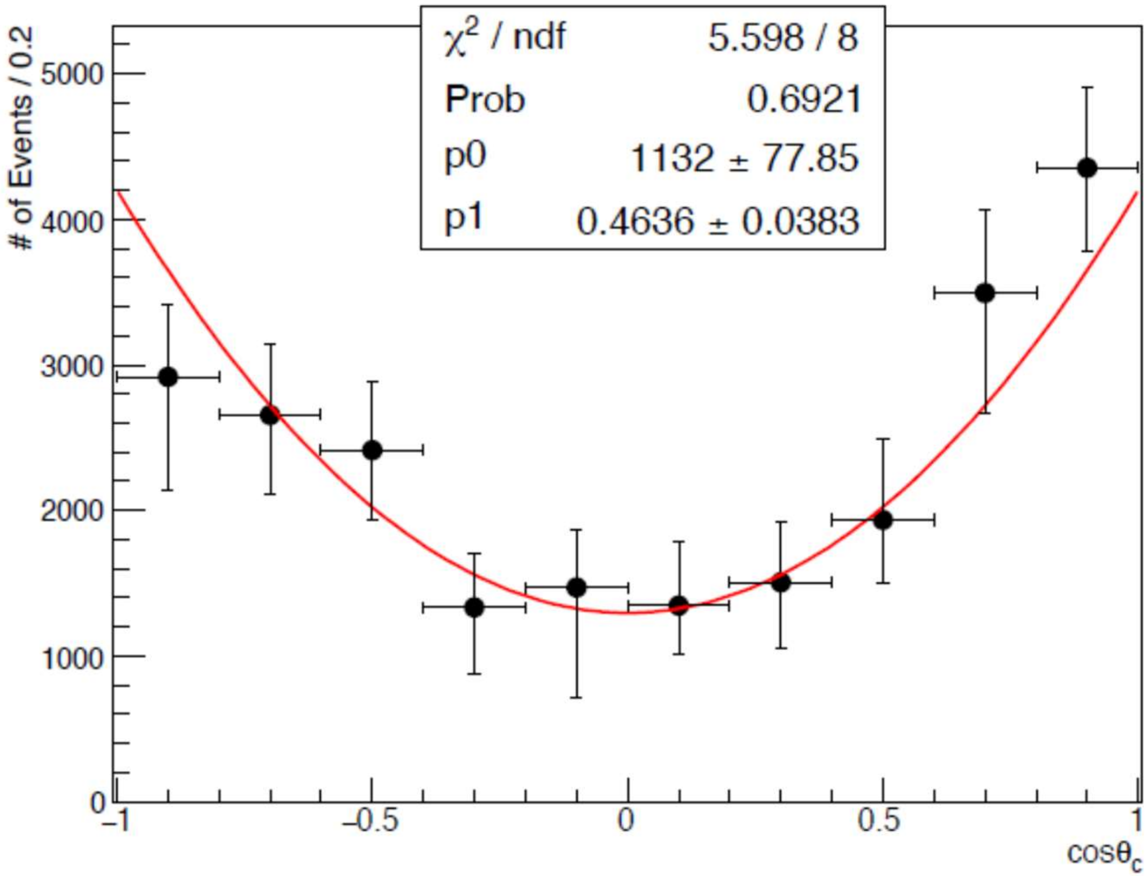
Angular distribution of $\Xi_c(2970) \rightarrow \Xi_c^*(2645)\pi$



1/2 black
3/2 red
5/2 blue

- Unfortunately, flat – any J can reproduce it

Angular correlation of $\Xi_c(2970) \rightarrow \Xi_c^*(2645)\pi_1 \rightarrow \Xi_c\pi_1\pi_2$



- Consistent with $1+3\cos^2\theta$ → J = 1/2

  [see also: Arifi, Hosaka, Nagahiro, and Tanida, PRD101, 111502(R)(2020)]

Decay to Ξ_c^* and Ξ_c'

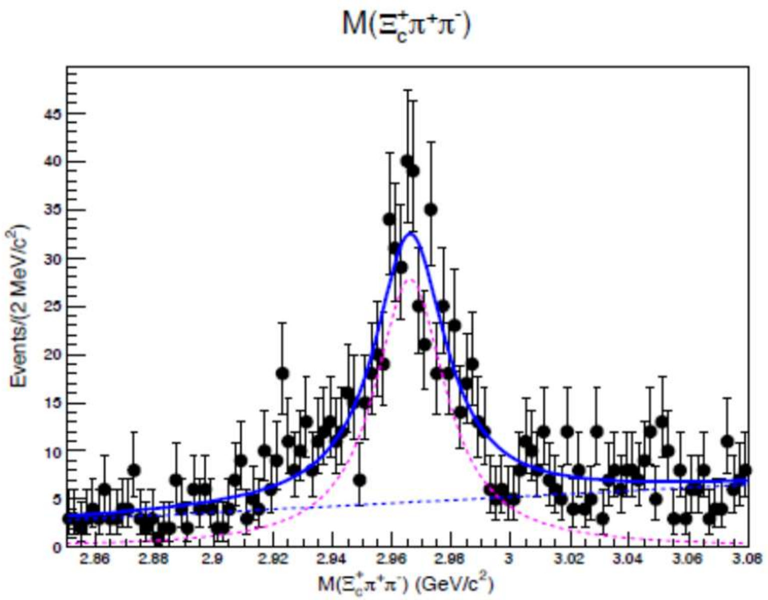
- HQS doublet with brown-muck spin j=1
→ J=1/2 (Ξ_c') and 3/2 (Ξ_c^*)
(quark model: *us* diquark has L=0, S=1 structure)

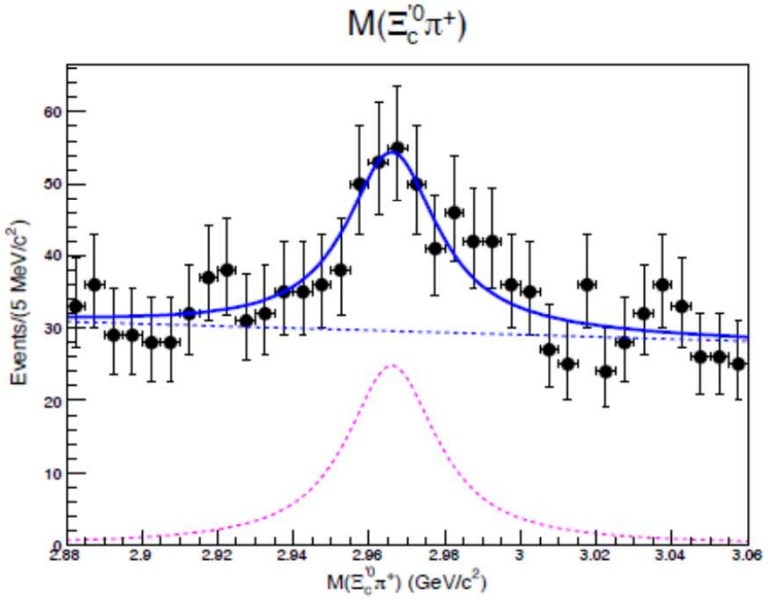
- Then, $R = \frac{\Gamma(\Xi_c(2970)\to\Xi_c^*\pi)}{\Gamma(\Xi_c(2970)\to\Xi_c'\pi)}$ is calculable for positive parity.

Parity	+	+
Diquark spin s_ℓ	0	1
R	1.06	0.26

- Negative parity: R<<1 expected because the decay
$\Xi_c(2970) \to \Xi_c'\pi$ is in S-wave, while
$\Xi_c(2970) \to \Xi_c^*\pi$ is in D-wave.

Parity





- We got

$$\boxed{R = 1.67 \pm 0.29(\text{stat.})^{+0.15}_{-0.09}(\text{syst.}) \pm 0.25(\text{IS})}$$

  – Consistent with P=+ and brown-muck spin s_ℓ=0 only.
- Therefore, the parity is +
  – with s_ℓ=0.

Parity	+	+
Diquark spin s_ℓ	0	1
R	1.06	0.26

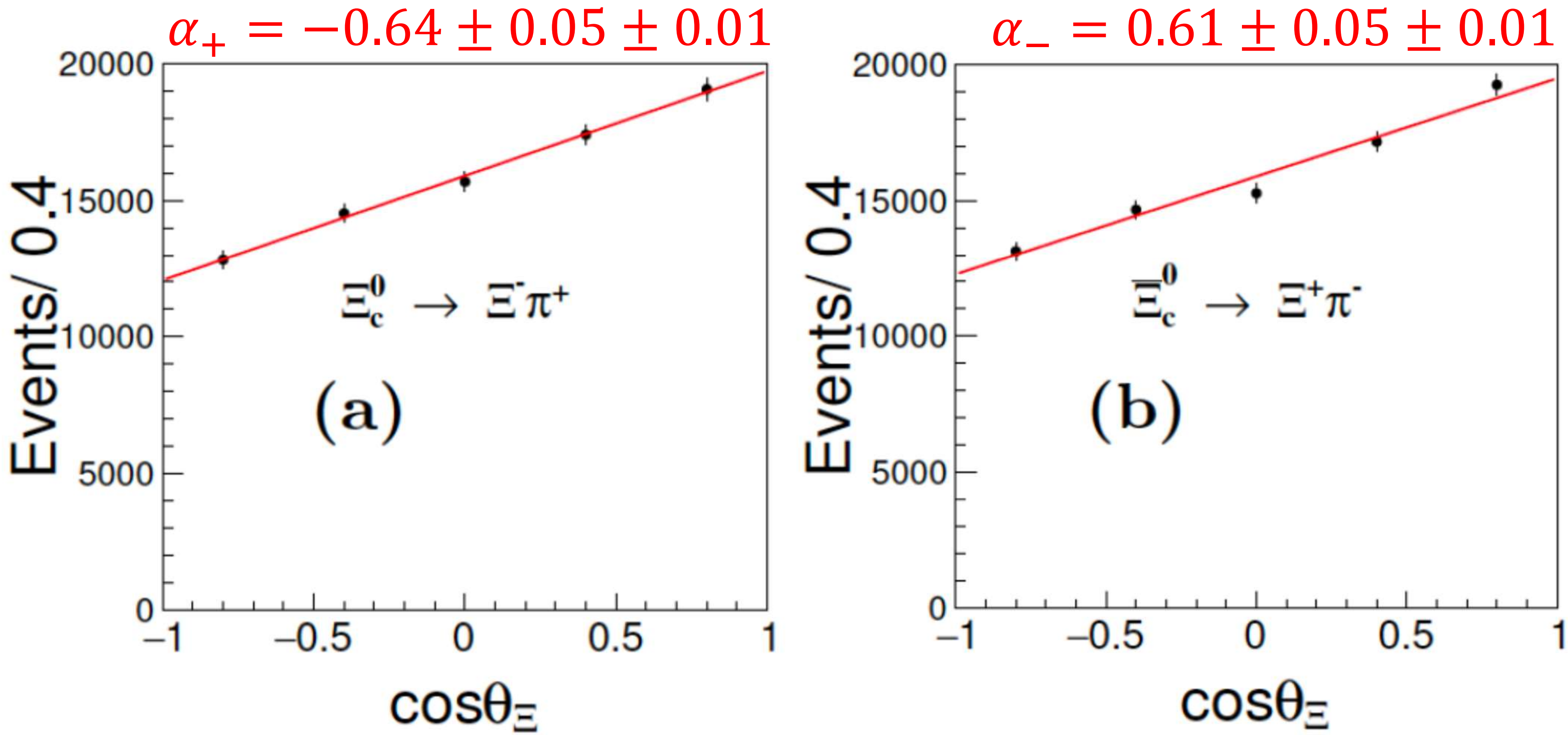
Discussion

- We got $J^P=1/2^+$. What can we say from this?
- This is the same as infamous Roper resonance, N(1440), the first excited state of nucleon.
  - Excitation energy (~500 MeV) is also the same.
- Difficult to explain Roper in quark model
  - Single quark excitation: 1st excited state should be a negative parity state (ex. N(1530)).
  - Surprisingly, difficult even in Lattice QCD.
  - The present measurement may give a hint.

2. Decay asymmetry of $\Xi_c^0 \rightarrow \Xi^- \pi^+$

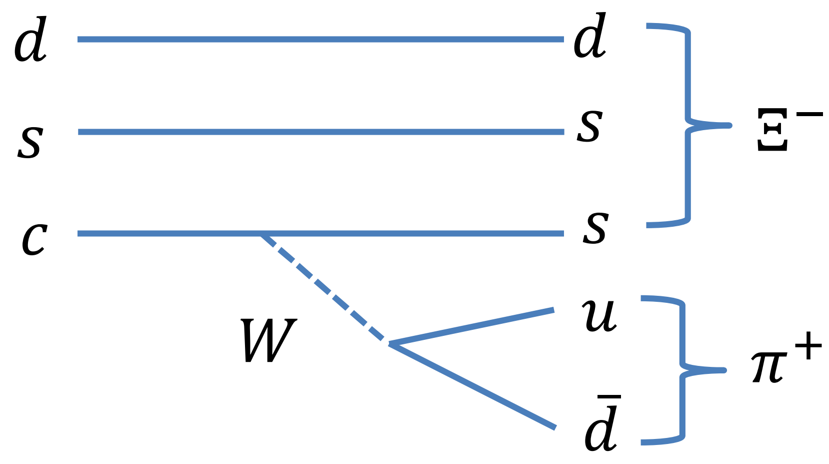
[PRL **127**, 121803 (2021)]

Decay asymmetry



- No significant CP violation

Naïve interpretation

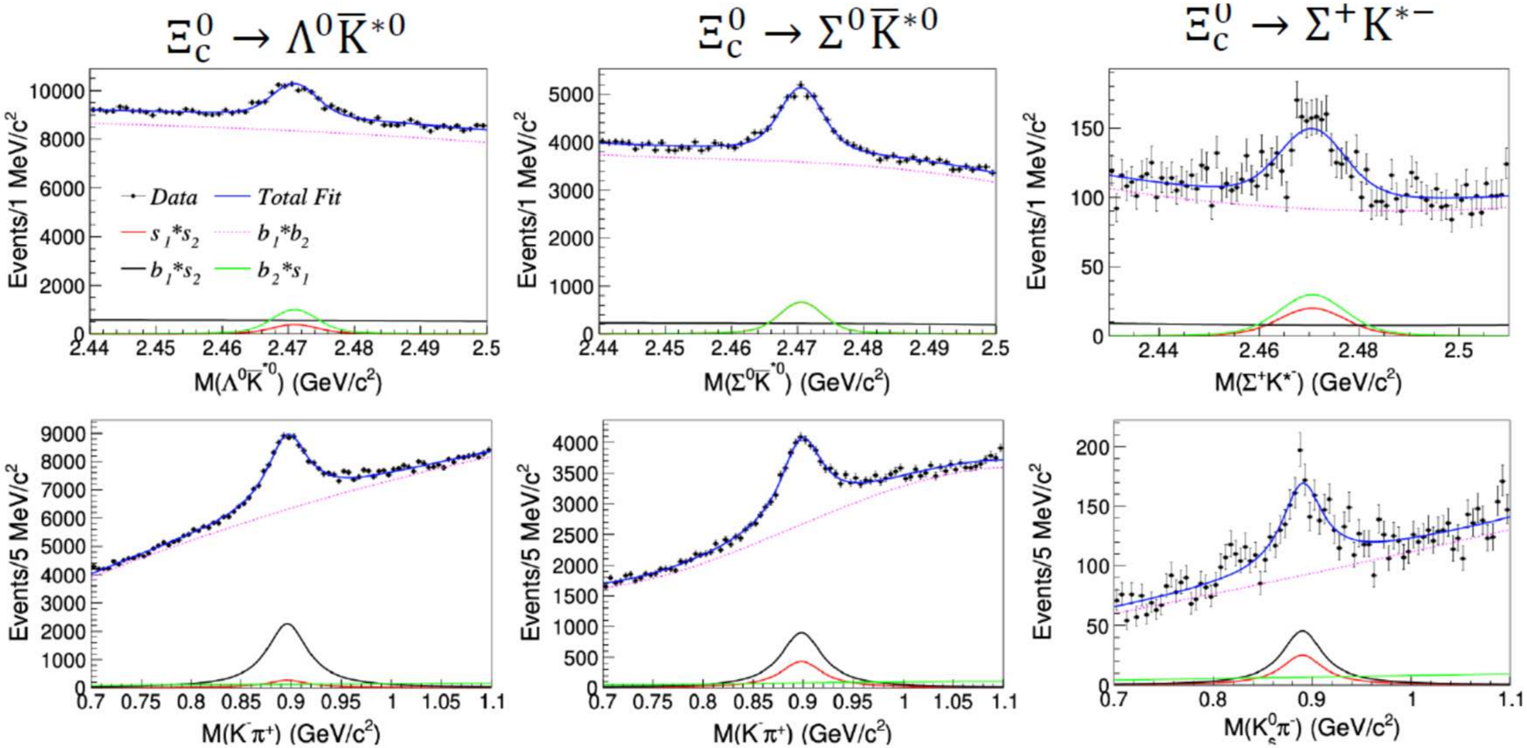


- In naïve QM, spin of Ξ^- is mostly carried by the s quarks, with the opposite d quark spin.
  – A large negative asymmetry is (qualitatively) consistent with this picture
- More sophisticated calculations awaited.

3. Decay asymmetries of $\Xi_c^0 \to \Lambda \overline{K}^{*0}, \Sigma^0 \overline{K}^{*0}, \Sigma^+ K^{*-}$

[JHEP**06**, 160 (2021)]

Decay branches

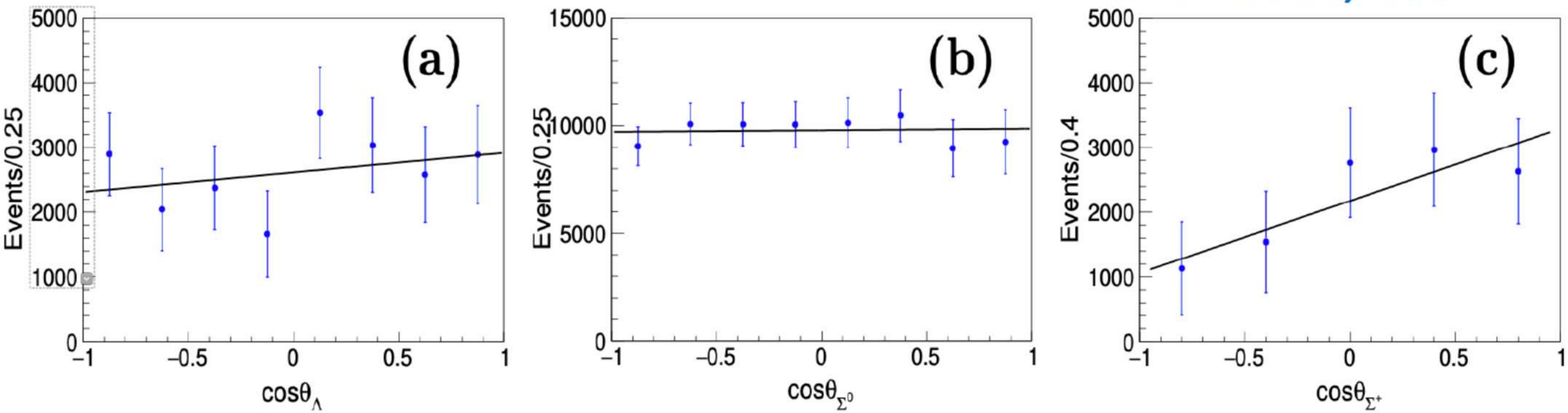


$\mathcal{B}(\Xi_c^0 \to \Lambda \bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$0.18 \pm 0.02(\text{stat.}) \pm 0.01(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to \Sigma^0 \bar{K}^{*0})/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$	$0.69 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})$
$\mathcal{B}(\Xi_c^0 \to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

JHEP 2021, 160

Asymmetries

JHEP 2021, 160



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

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

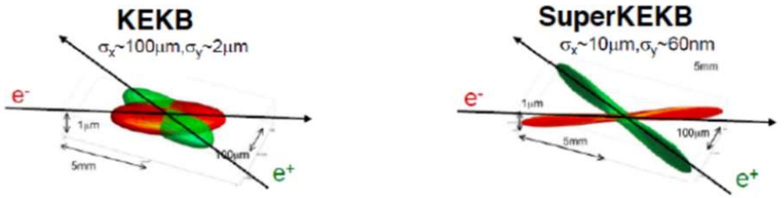
4. Future prospects
— Belle II —

SuperKEKB and Belle II

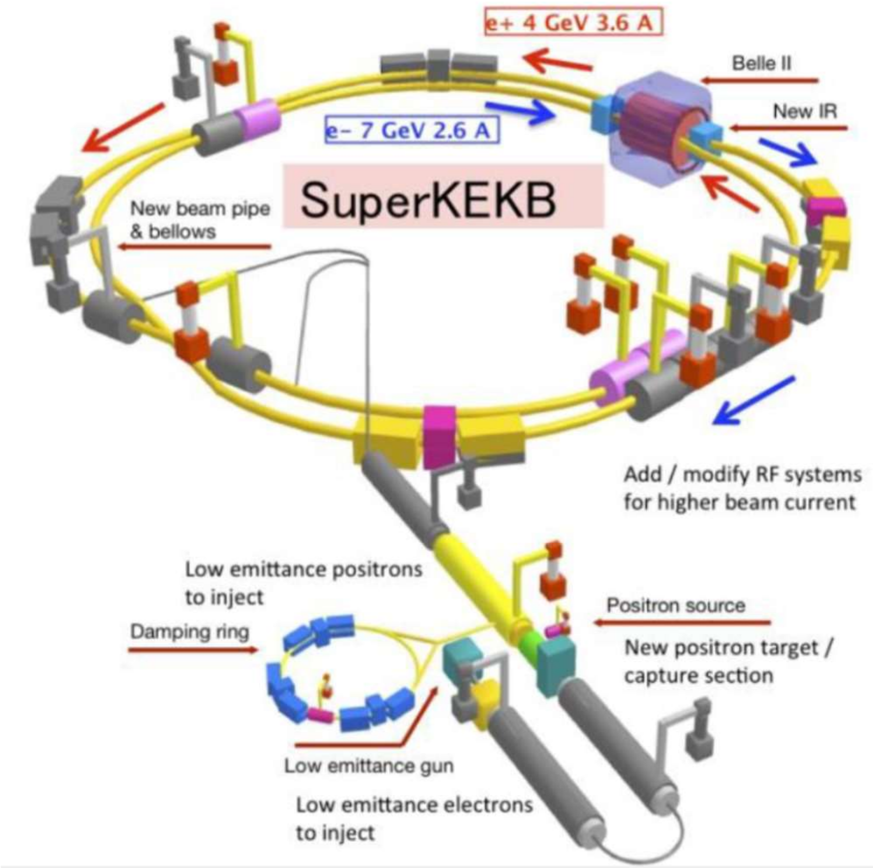
Upgrade for SuperKEKB and Belle II to achieve 30x peak $\mathcal{L}$

- Reduction in the beam size by 1/20 at the IP.
- Doubling the beam currents.

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

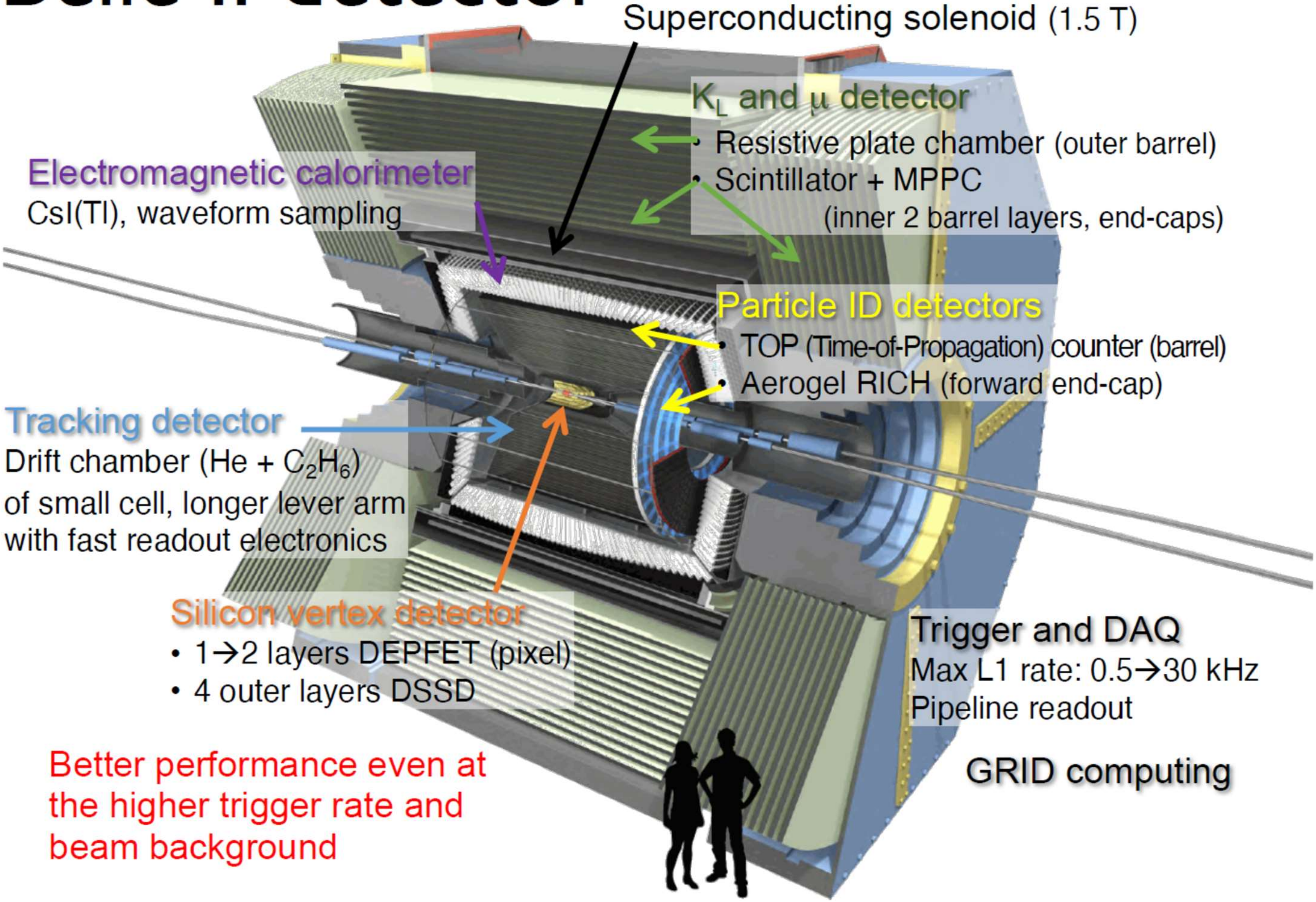


- *First turns achieved Feb. 2016*
- *Beam-background studies ongoing*



Goal: x50 more statistics than Belle

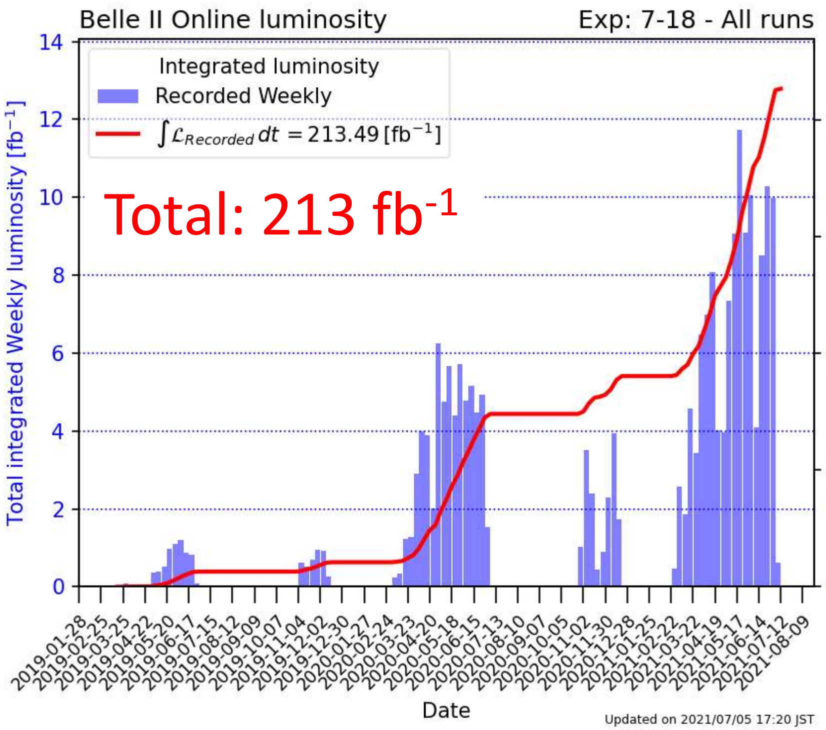
Belle II detector



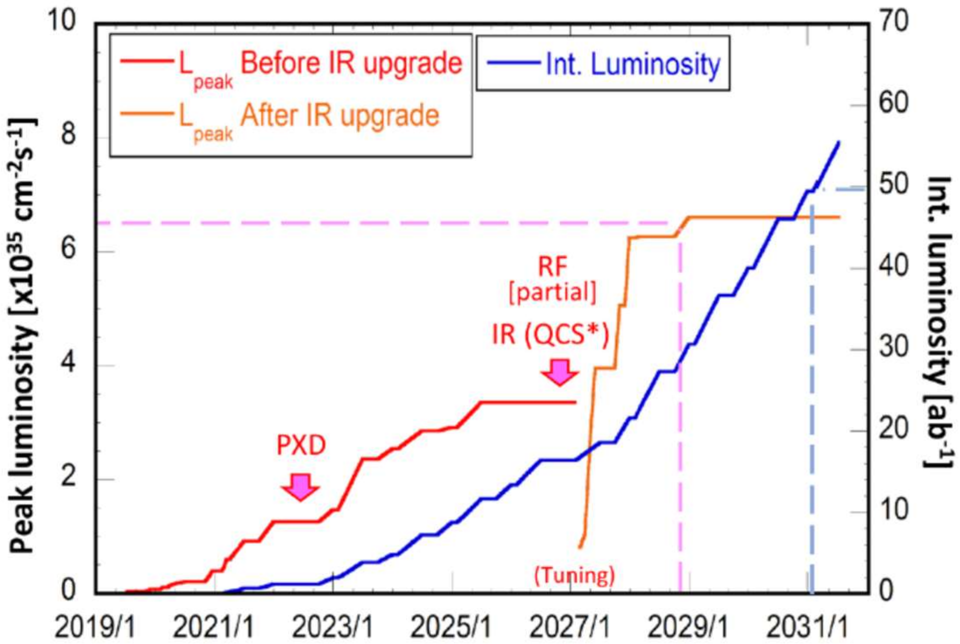
Better performance even at the higher trigger rate and beam background

Belle II integrated luminosity

Achieved



Prospect



- Instantaneous luminosity already exceeded Belle
- Integrated luminosity will exceed Belle within a few years
- Goal: 50 ab^{-1} around 2031.

Summary

- Spin-related measurements at Belle
  - Spin-parity determination
  - Decay asymmetry → baryon spin structure
- J^P of $\Xi_c(2970)$
  - Angular correlation → J=1/2, decay branch → P=+
  - The same as the notrious Roper resonance
- Decay asymmetries in Ξ_c decays
  - $\Xi_c^0 \to \Xi^- \pi^+$ can be understood with a native picture
  - Statistically limited for $\Xi_c^0 \to \Lambda \bar{K}^{*0}, \Sigma^0 \bar{K}^{*0}, \Sigma^+ K^{*-}$
- More measurements

  → Even more with Belle II, promising