Excited hadrons at Belle (II) experiment

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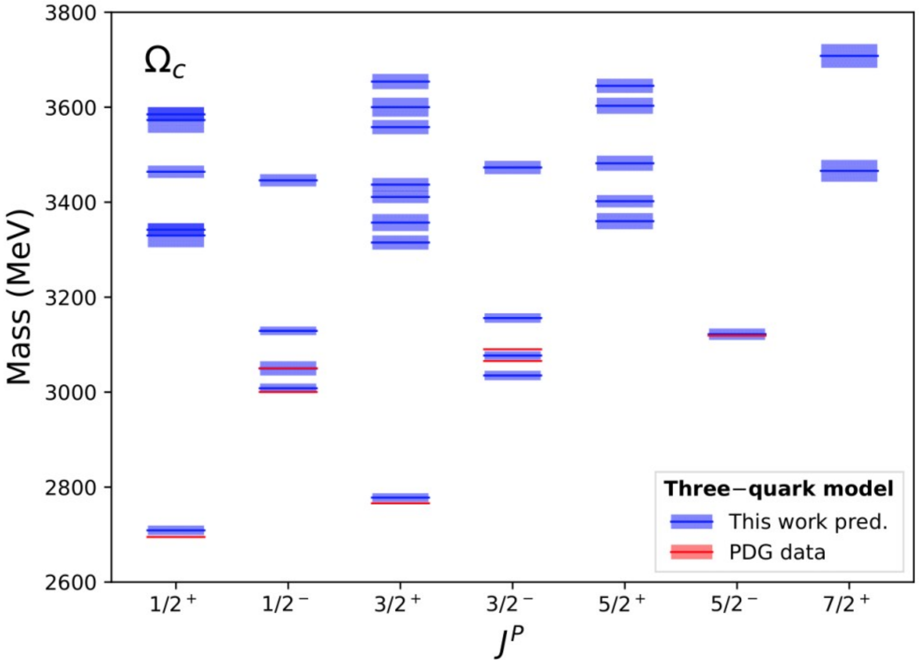
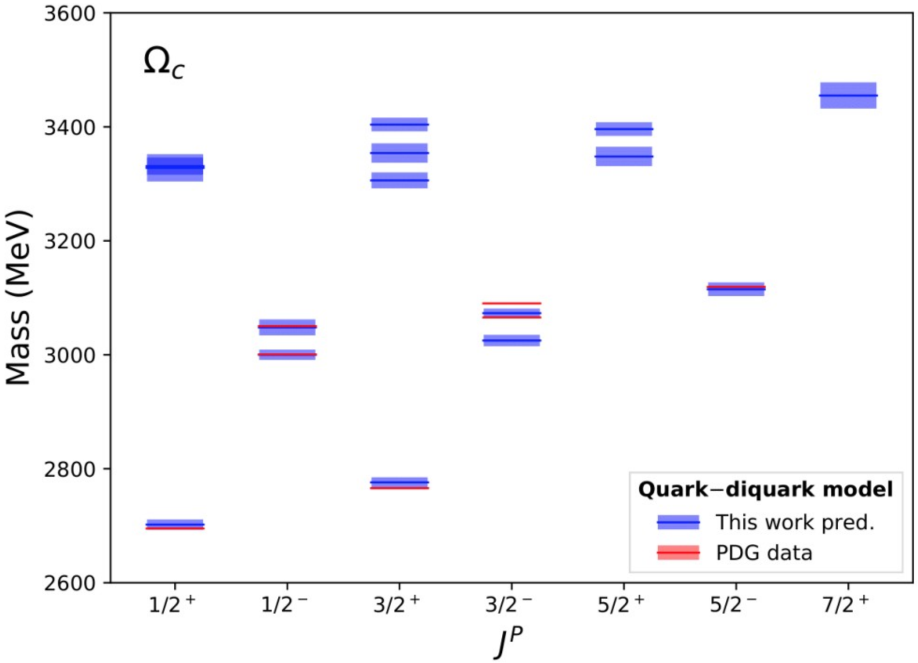
Advertisement:
Theoretical work at Kyungpook National University

H. Garcia-Tecocoatzi, A. Giachino, J. Li, A. Ramirez-Morales, E. Santopinto,
“Strong decay widths and mass spectra of charmed baryons”, *arXiv:2205.07049* (2022)

Calculate masses and widths of charmed baryons up to the D-wave states in a constituent quark model.

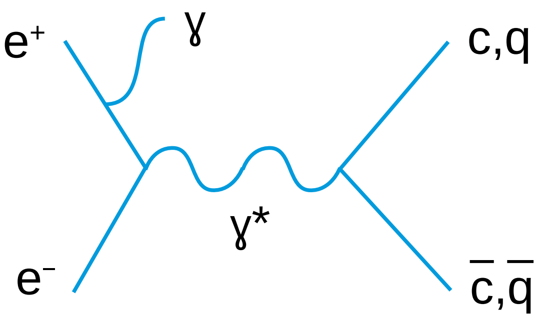


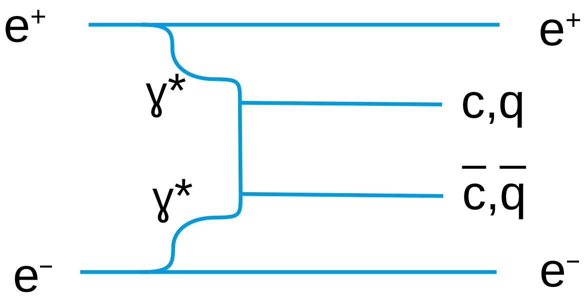


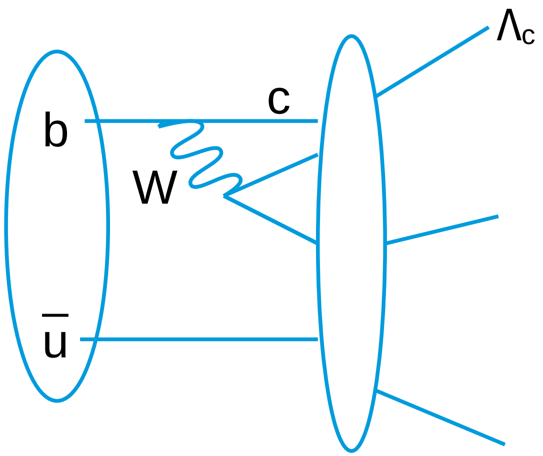
Outline

- Hadron production at Belle.
- Observation and subsequent theoretical and experimental development for the new multiple strange $\Omega(2012)^-$.
- Various theoretical inputs for experimental charmed baryon study.
- Future studies.

Production of baryons at lepton collider







Direct production

Resonance or fragmentation.
Possible initial state radiation.
Hyprons can produced.

2-phonon process for
resonance production

Indirect production from
cascade decays

Some of recent (< 1.3 y) hadron results from Belle (total 26)

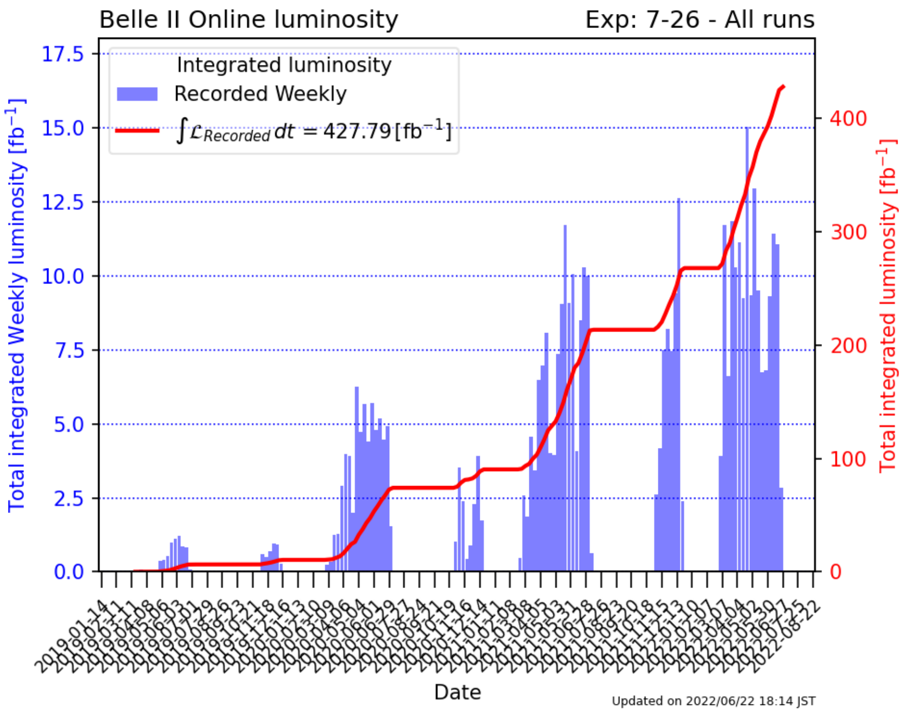
$e^+e^-\to\eta\phi$ via ISR (to be submitted to PRD)
$\Lambda_c\to\Sigma^+\gamma$, $\Xi_c^0\to\Xi^0\gamma$ (to be submitted to PRD)
Peak structure in $\Lambda_c\to pK^-\pi^+$ (to be submitted to PRL)
$\gamma\gamma\to\chi_{c2}(1P)\to J/\psi\gamma$ (to be submitted to JHEP)
$\Omega(2012)\to\Xi(1530)\bar{K}$ (arXiv:2207.03090)
2-hadron correlation in e^+e^- collisions (arXiv:2206.09440)
New baryon $\Lambda_c(2910)$ in B decay (arXiv:2206.08822)
$\Xi_c^0\to\Lambda_c\pi^-$ (arXiv:2206.08527)
Search for $X(3872)\to\pi^+\pi^-\pi^0$ (arXiv:2206.08592)
Exotics in $\gamma\gamma\to\gamma\psi(2S)$ (PRD 105 (2022) 112011)
$\Lambda_c\to p\eta'$ (JHEP 03 (2022) 090)
Search for $X_{cc\bar{s}\bar{s}}$ in $D_s^{(*)+}D_s^{(*)+}$ (PRD105 (2022) 032002)
$\Xi_c^0\to\Lambda K_S^0,\Sigma^0K_S^0,\Sigma^+K^-$ (PRD105 (2022) L011102)
$e^+e^-\to\Upsilon(1,2S)\eta$, $\Upsilon(1S)\eta'$ (PRD104 (2021) 112006)
$\Lambda_c\to p\omega$ (PRD104 (2021) 072008)
$\Omega(2012)$ in Ω_c decay (PRD104 (2021) 052005)
Mass and width of $\Sigma_c^{(*)+}$ (PRD104 (2021) 052003)
$\Xi_c^0\to\Xi^-l^+\nu_l$, $\Xi^-\pi^+$ (PRL127 (2021) 121803)

Search for $\eta_{c2}(1D)$ in $e^+e^-\to\gamma\eta_{c2}(1D)$ (PRD104 (2021) 012012)
$\Xi_c^0\to\Lambda\bar{K}^{*0},\Sigma^0\bar{K}^{*0},\Sigma^+\bar{K}^{*-}$ (JHEP 06 (2021) 160)
Energy dependence of $e^+e^-\to B^{(*)}\bar{B}^{(*)}$ (JHEP 06 (2021) 137)
Spin-parity measurement of $\Xi_c(2970)$ (PRD103 (2021) L111101)
$\Xi_c^0\to\Xi^0K^+K^-$ (PRD103 (2021) 112002)
$\Lambda_c\to p\eta$ and $p\pi^0$ (PRD103 (2021) 072004)
$\Lambda_c\to\Lambda\eta\pi^+$ decay and $\Lambda(1670)$ (PRD103 (2021) 052005)
Evidence of $\gamma\gamma^*\to X(3872)$ (PRL126 (2021) 122001)
… more past and coming …

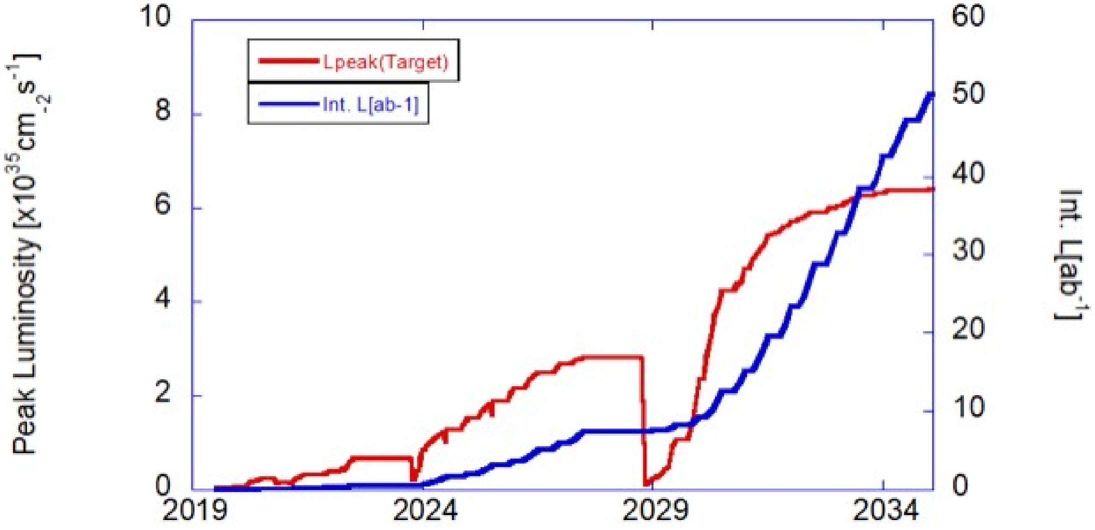
I am covering a tiny fraction of them (>20 hadron results per year!) , colored in blue, mainly on strange baryon $\Omega(2012)$.

Future Belle II (50 × Belle Lum, better recon.)

Past



Future



Latest peak record: 4.65 ×10^{34} cm^{-2}s^{-1} on June 22, 2022

$\Omega(2012)$: example to show the importance of direct interplay between theorist and experimentalist.

Predictions of excited Ω before observation (Theory 1)

Quark Model:

K.-T. Chao, N. Isgur, and G. Karl, Phys. Rev. D 23, 155 (1981).- Non-relativistic,SU(6), predicts $M(3/2^-)$=2020 MeV, Gamma=3.9 MeV, decay is ΞK only.

R. N. Faustov and V. O. Galkin, Strange baryon spectroscopy in the relativistic quark model,Phys. Rev. D 92, 054005 (2015). - Relativistic (2038 MeV)

Skyrme model:

Yongseok Oh, Ξ and Ω baryons in the Skyrme model, Phys. Rev. D 75, 074002 (2007).

$M(\Omega(J^P{:}3/2^-))$=1978 MeV

Chiral Unitarity Approach:

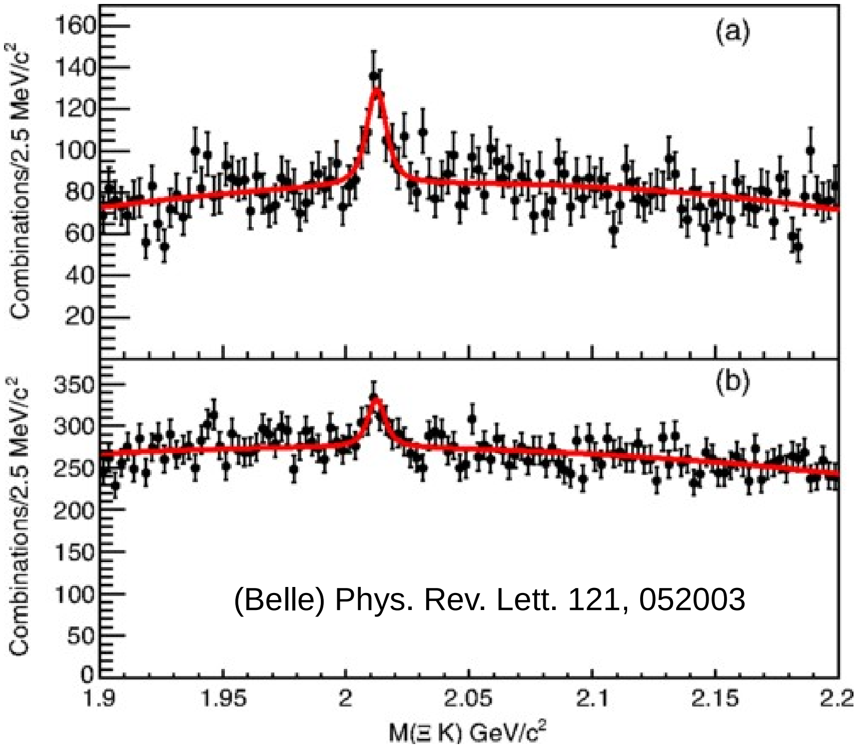
Sourav Sarkar et al., Baryonic resonances from baryon decuplet-meson octet interaction, Nuclear Physics A 750 (2005), 294-323 – mass and width (2141 − i38) MeV

Xu Si-Qi, et al., The $\Xi^*\bar{K}$ and Ωη Interaction Within a Chiral Unitary Approach, Commun. Theor. Phys. 65, (2016) 53 – different subtraction a(μ) in renormalization can affect mass

Observation of an excited Ω^- baryon (Theory 1 ⇨ Exp 1)

$\Xi^0 K^-$

$\Xi^- K^0_S$



Mass:

$$2012.4 \pm 0.7(\text{stat}) \pm 0.6(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma = 6.4^{+2.5}_{-2.0}(\text{stat}) \pm 1.6(\text{syst})\ \text{MeV}.$$

$$\mathcal{R} = \frac{\mathcal{B}(\Omega^{*-} \to \Xi^0 K^-)}{\mathcal{B}(\Omega^{*-} \to \Xi^- \bar{K}^0)} = 1.2 \pm 0.3$$

Narrow width can be explained with d-wave only decay ⇨ $J^P = 3/2^-$ preferred.

After the observation (Exp 1 ⇨ Theory 2(explanation))

Quark model:
Ming-Sheng Liu, Kai-Lei Wang, Qi-Fang Lü, and Xian-Hui Zhong, Ω baryon spectrum and their decays in a constituent quark model, Phys. Rev. D 101, 016002 (2020). - no 3 body width, $1/2^-$ not completely ruled out.

Hadronic molecule:
R.Pavao and E.Oset, Coupled channels dynamics in the generation of the Ω(2012) resonance, Eur. Phys. J. C78, 857 (2018);arXiv:1808.01950. - $\Gamma(\bar{K}\pi\Xi)\sim$ 3MeV, similar to $\Gamma(\bar{K}\Xi)$.
Y.H.Lin and B.S.Zou,Hadronic molecular assignment for the newly observed Ω* state,Phys. Rev. D98, 056013 (2018);arXiv:1807.00997. - $\Gamma(\bar{K}\pi\Xi) = 6\times\Gamma(\bar{K}\Xi)$. (2.4 and 0.4 MeV)

Response of Theory 2. ⇨ Exp 2

S. Jia et al. (Belle Collaboration), Search for Ω(2012)→KΞ(1530)→KπΞ at Belle, Phys. Rev. D 100, 032006 (2019)

$$\mathcal{R}^{\Xi\pi K}_{\Xi K} = \frac{\mathcal{B}(\Omega(2012) \to \Xi(1530)(\to \Xi\pi)K)}{\mathcal{B}(\Omega(2012) \to \Xi K)} < 11.9\%$$

at 90% C.L.

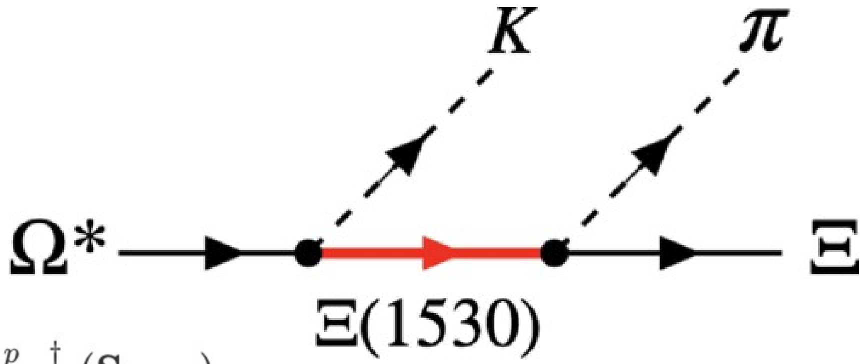
Using theoretical relations between BF ratios:

$$\mathscr{R}^{\Xi^-\pi^+K^-}_{\Xi^-\bar{K}^0} : \mathscr{R}^{\Xi^-\pi^0\bar{K}^0}_{\Xi^-\bar{K}^0} : \mathscr{R}^{\Xi^0\pi^-\bar{K}^0}_{\Xi^0 K^-} : \mathscr{R}^{\Xi^0\pi^0 K^-}_{\Xi^0 K^-} = 1 : \frac{1}{2} : \frac{1}{1.2} : \frac{1}{2.4}.$$

It seems that Ω*(2012) Is not a molecular ?

Experiment 2 ⇨ Theory 3.1 (quark model)

A. J. Arifi, D. Suenaga, A. Hosaka, and Y. Oh, Strong decays of multi-strangeness baryon resonances in the quark model, Phys.Rev.D 105, 094006 (2022). - Relativistic correction, 3-body decay computed, Γ(Ω→Ξ¯Kπ)/Γ(Ω→Ξ¯K)=4.5%.



See also:
Xuejie Liu, Hongxia Huang, Jialun Ping, and Dianyong Chen,Investigating Ω(2012) as a molecular state., Phys. Rev. C 103 025202 (2021).
- Not suitable for a molecule state, Ξ* and $\bar{K}$ are repulsive.

$$-i\mathcal{T}_{\Xi^*}\mathcal{T}_{\to\Xi\pi} = g_2^p \chi_\Xi^\dagger \left(\mathbf{S}\cdot\mathbf{q}_2\right)\chi_{\Xi^*}$$

$$-iT^{(s)}_{\Omega^*\to\Xi^*\bar{K}} = g_1^s \chi^\dagger_{\Xi^*}\chi_\Omega,$$

$$-iT^{(d)}_{\Omega^*\to\Xi^*\bar{K}} = g_1^d \chi^\dagger_{\Xi^*}(V_{ij}q_{1i}q_{1j})\chi_\Omega,$$

$$-i\mathcal{T} = -i\frac{\mathcal{T}_{\Xi(1530)\to\Xi\pi}\mathcal{T}_{\Omega\to\Xi(1530)\bar{K}}}{m_{\Xi\pi} - M_{\Xi(1530)} + \frac{i}{2}\Gamma_{\Xi(1530)}}$$

$$\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M_i^3}\int \overline{|\mathcal{T}|^2}\, dm^2_{\Xi\pi}\, dm^2_{\pi\bar{K}}$$

Experiment 2 ⇨ Theory 3.2 (Hadronic molecule)

Yong-Hui Lin, Fei Wang, and Bing-Song Zou, Reanalysis of the newly observed Ω* state in a hadronic molecule model, Phys. Rev. D 102, 074025 (2020). - 1/2+ or 3/2+ or $\bar{K}\Xi(1530)$ molecule.

Thomas Gutsche and Valery E Lyubovitskij, Strong decays of the hadronic molecule $\Omega_*(2012)$, J. Phys. G: Nucl. Part. Phys. 48 025001 (2021).- explain the BF ratio if big mixing between ΞK and Ωη component.

Natsumi Ikeno, Genaro Toledo, and Eulogio Oset, Molecular picture for the Ω(2012) revisited, Phys. Rev. D 101, 094016 (2020). - molecular picture of $\bar{K}\Xi^*$, ηΩ, $\bar{K}\Xi$ interactions.

Jun-Xu Lu, Chun-Hua Zeng, En Wang, Ju-Jun Xie & Li-Sheng Geng, Revisiting the Ω(2012) as a hadronic molecule and its strong decays, Eur. Phys. J. C 80, 361 (2020). - from the coupled channels interactions of the $\bar{K}\Xi^*(1530)$ and $\eta\Omega$ in s-wave and $\bar{K}\Xi$ in d-wave.

Three couplings

Unitarized scattering amplitude

Loop function, diagonal

$$T = V + VGT = [1 - VG]^{-1}V$$

Lippmann-Schwinger

Tree level transition from chiral Lagrangians

$$V = \begin{array}{cc} \begin{array}{ccc} \bar{K}\Xi^* & \eta\Omega & \bar{K}\Xi \end{array} & \\ \begin{pmatrix} 0 & 3F & \alpha q_{\rm on}^2 \\ 3F & 0 & \beta q_{\rm on}^2 \\ \alpha q_{\rm on}^2 & \beta q_{\rm on}^2 & 0 \end{pmatrix} & \begin{array}{c} \bar{K}\Xi^* \\ \eta\Omega \\ \bar{K}\Xi \end{array} \end{array}$$

$$F = -\frac{1}{4f^2}(k^0 + k'^0); \qquad q_{\rm on} = \frac{\lambda^{1/2}(s, m_{\bar{K}}^2, m_{\Xi}^2)}{2\sqrt{s}},$$

Energies of $\overline{\text{K}}$ and η

Close to the pole:

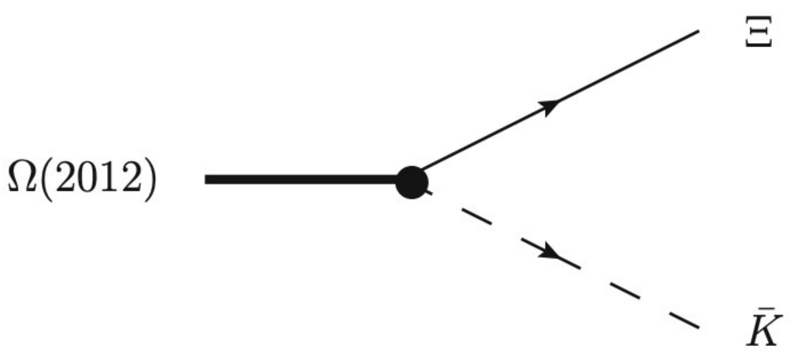
$$z_R = M_R - i\Gamma_R/2,$$

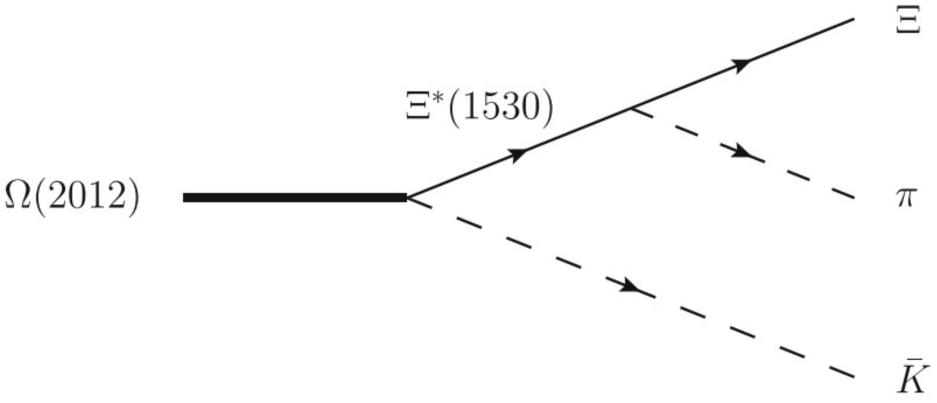
$$T_{ij} = \frac{g_i g_j}{z - z_R}$$

$$g_i^2 = \lim_{z \to z_R}(z - z_R)T_{ii}$$

$$g_j = g_i \left.\frac{T_{ij}}{T_{ii}}\right|_{z=z_R}$$

Decay calculation





$$\Gamma_{\Omega(2012)\to\bar{K}\Xi} = \frac{|g_{\Omega^*\bar{K}\Xi}|^2}{2\pi}\frac{M_\Xi}{M}q_{\bar{K}}$$

$$\frac{d\Gamma_{\Omega(2012)\to\bar{K}\pi\Xi}}{dM_{\pi\Xi}} = \frac{M_{\pi\Xi}}{\pi^2 M}\frac{|g_{\Omega^*\bar{K}\Xi^*}|^2 p_{\bar{K}}\tilde{\Gamma}_{\Xi^*}}{4(M_{\pi\Xi}-M_{\Xi^*})^2+\tilde{\Gamma}^2_{\Xi^*}}$$

Experimental mass and width ⇨ determination of g_{ij}, α, β

Fitted parameters from Exp 1

$R = R^{\bar{K}\Xi\pi}_{\bar{K}\Xi}$

$q_{\max}$ (MeV)	α (10^{-8} MeV^{-3})	β (10^{-8} MeV^{-3})	(M_R, Γ_R) (MeV)	R (%)
735	-6.6 ± 0.8	16.5 ± 0.8	$(2012.3 \pm 0.4, 8.3 \pm 0.6)$	11.88
750	-9.9 ± 0.5	18.5 ± 0.5	$(2012.2 \pm 0.4, 7.8 \pm 0.8)$	10.50
800	-17.5 ± 0.6	20.6 ± 0.5	$(2012.4 \pm 0.5, 6.4 \pm 1.3)$	11.90
850	-20.2 ± 1.0	19.6 ± 0.8	$(2012.4 \pm 0.5, 6.4 \pm 1.1)$	9.00
900	-20.8 ± 1.7	17.5 ± 1.1	$(2012.4 \pm 0.5, 6.4 \pm 1.3)$	7.22

Useful for further study of production and decays.

$g_{\Omega^*\bar{K}\Xi^*}$	$g_{\Omega^*\eta\Omega}$	$g_{\Omega^*\bar{K}\Xi}$
(1.826, −0.064)	(3.350, 0.159)	(−0.419, −0.040)
(1.796, −0.128)	(3.448, 0.298)	(−0.399, −0.109)
(1.574, 0.188)	(3.590, −0.313)	(−0.307, 0.201)
(1.386, 0.090)	(3.777, −0.151)	(−0.353, 0.109)
(1.251, 0.063)	(3.853, −0.111)	(−0.363, 0.082)

Theory 3.2 ⇨ Theory 3.3 ($\Omega(2012)$ from Ω_c)

Chun-Hua Zeng, Jun-Xu Lu, En Wang, Ju-Jun Xie, and Li-Sheng Geng, Theoretical study of the $\Omega(2012)$ state in the $\Omega^0_c \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$ and $\pi^+(\bar{K}\Xi\pi)^-$ decays, Phys. Rev. D 102, 076009 (2020). arXiv:2006.15547 - Suggest an experimental study of $\Omega(2012)$ in charmed baryon decays.

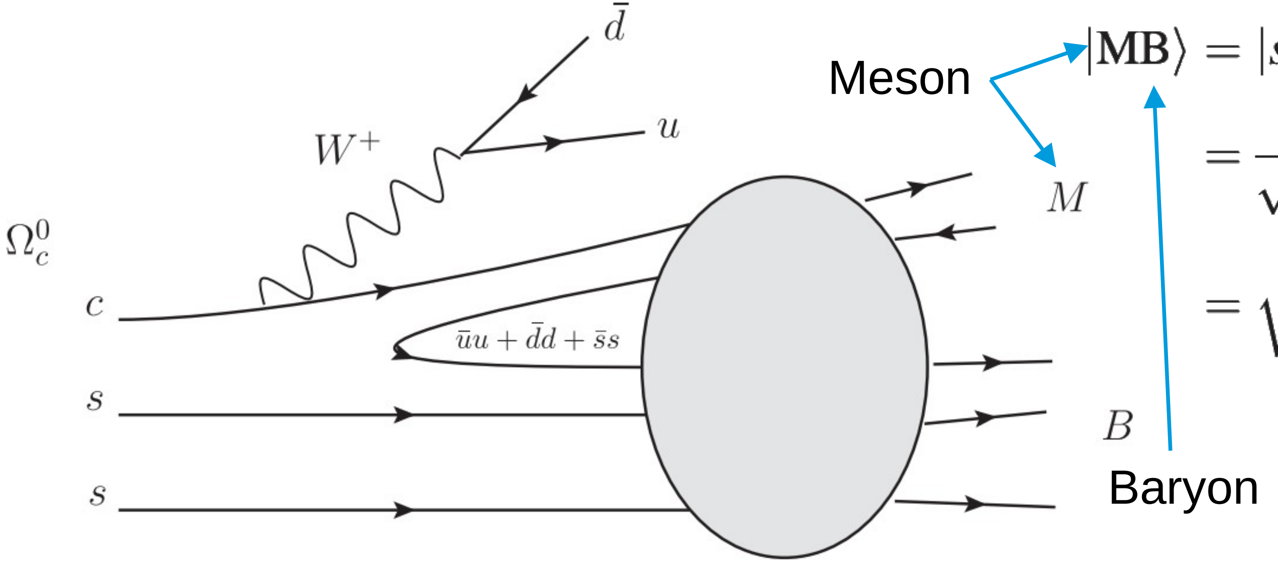
Decay of $\Omega^0_c \to \pi^+(\bar{K}\Xi\pi)^-$ is from $\Omega^0_c \to \pi^+(\bar{K}\Xi(1530)^*)^-$ at tree level from molecular model, which will not contribute to the production of the $\Omega(2012)^-$ from its three body $(\bar{K}\Xi\pi)^-$ channel.

$$R^{\bar{K}\Xi\pi}_{\bar{K}\Xi} = \frac{\Gamma[\Omega^0_c \to \pi^+\Omega(2012)^- \to \pi^+\bar{K}\Xi\pi]}{\Gamma[\Omega^0_c \to \pi^+\Omega(2012)^- \to \pi^+\bar{K}\Xi]}$$

TABLE II. Predicted ratio $R^{\bar{K}\Xi\pi}_{\bar{K}\Xi}$ for different cutoffs.

$\Lambda = q_{\max}$ (MeV)	735	750	800	850	900
$R^{\bar{K}\Xi\pi}_{\bar{K}\Xi}$ (%)	13.9	13.8	13.5	10.0	7.3

Charmed baryon decay to Ω(2012)



$$|\mathrm{MB}\rangle = |s(\bar{u}u + \bar{d}d + \bar{s}s)ss\rangle$$
$$= \frac{1}{\sqrt{3}}(|K^-\Xi^{*0}\rangle + |\bar{K}^0\Xi^{*-}\rangle) - \frac{1}{\sqrt{3}}|\eta\Omega\rangle,$$
$$= \sqrt{\frac{2}{3}}|\bar{K}\Xi^*\rangle_{I=0} - \frac{1}{\sqrt{3}}|\eta\Omega\rangle,$$

$$|\Xi^{*0}\rangle = \frac{1}{\sqrt{3}}|uss + sus + ssu\rangle,$$

$$|\Xi^{*-}\rangle = \frac{1}{\sqrt{3}}|dss + sds + ssd\rangle,$$

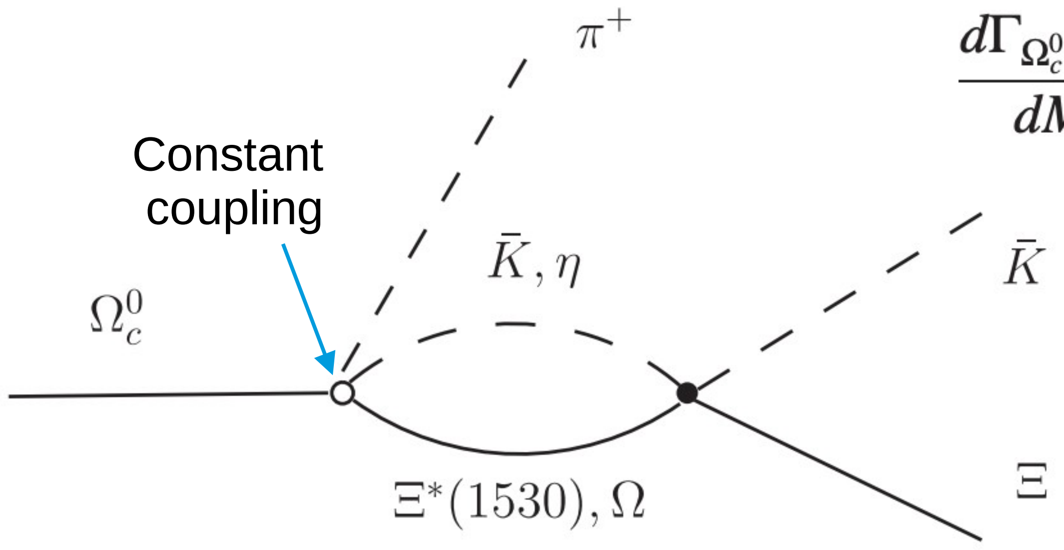
$$|\Omega\rangle = |sss\rangle,$$

$$|\eta\rangle = \frac{1}{\sqrt{3}}|\bar{u}u + \bar{d}d - \bar{s}s\rangle.$$

KΞ production

L=1

$$\frac{d\Gamma_{\Omega_c^0\to\pi^+\bar{K}\Xi}}{dM_{\bar{K}\Xi}} = \frac{1}{16\pi^3}\frac{M_\Xi}{M_{\Omega_c^0}} p_\pi^3 p_{\bar{K}} \sum |\mathcal{M}_{\Omega_c^0\to\pi^+\bar{K}\Xi}|^2$$



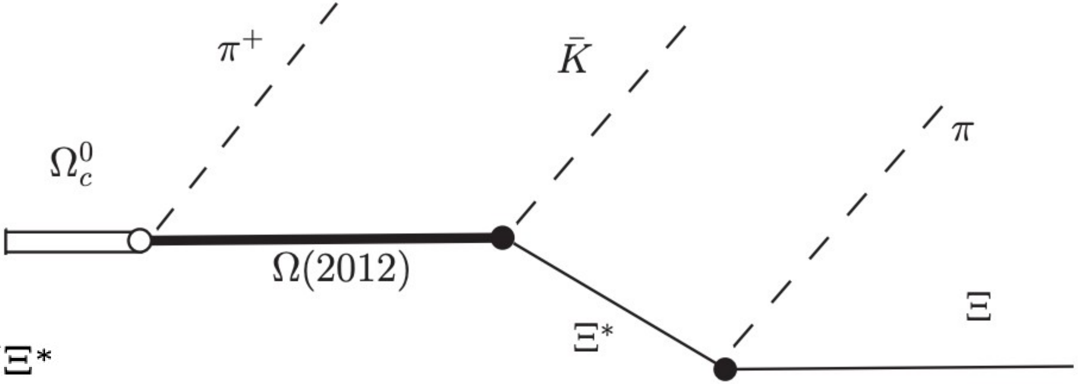
Coupling constants *g*'s from coupled channel study Eur. Phys. J. C 80, 361 (2020).

$$\mathcal{M}_{\Omega_c^0\to\pi\bar{K}\Xi} = V_p\left(\sqrt{\frac{2}{3}}G_{\bar{K}\Xi^*}(M_{\rm inv})\underbrace{t_{\bar{K}\Xi^*\to\bar{K}\Xi}(M_{\rm inv})}_{\frac{g_{\Omega^*\bar{K}\Xi^*}g_{\Omega^*\bar{K}\Xi}}{M_{\rm inv}-M_{\Omega^*}+i\Gamma_{\Omega^*}/2}}\right.$$

$$\left. - \sqrt{\frac{1}{3}}G_{\eta\Omega}(M_{\rm inv})\underbrace{t_{\eta\Omega\to\bar{K}\Xi}(M_{\rm inv})}_{\frac{g_{\Omega^*\eta\Omega}g_{\Omega^*\bar{K}\Xi}}{M_{\rm inv}-M_{\Omega^*}+i\Gamma_{\Omega^*}/2}}\right),$$

Three body production of (KΞπ)⁻

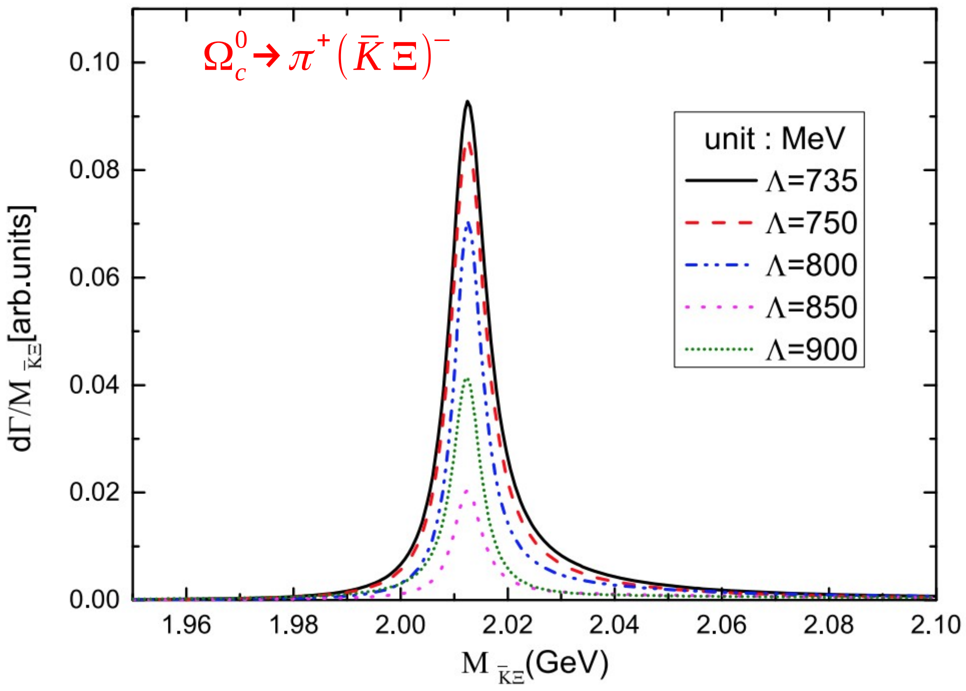
Two consecutive propagators.



$$\mathcal{M}_{\Omega_c^0\to\pi^+\bar{K}\Xi\pi} = \frac{g_{\Xi^*\Xi\pi}\bar{p}_\pi \mathcal{M}_{\Omega_c^0\to\pi^+\bar{K}\Xi^*}}{M_{\Xi\pi} - M_{\Xi^*} + i\Gamma_{\Xi^*}/2}$$

$$\mathcal{M}_{\Omega_c^0\to\pi\bar{K}\Xi^*} = V_p\left(\sqrt{\frac{2}{3}}[1 + G_{\bar{K}\Xi^*}(M_{\text{inv}})\underbrace{t_{\bar{K}\Xi^*\to\bar{K}\Xi^*}(M_{\text{inv}})}_{\frac{g_{\Omega^*\bar{K}\Xi^*}g_{\Omega^*\bar{K}\Xi^*}}{M_{\text{inv}} - M_{\Omega^*} + i\Gamma_{\Omega^*}/2}}] - \sqrt{\frac{1}{3}}G_{\eta\Omega}(M_{\text{inv}})\underbrace{t_{\eta\Omega\to\bar{K}\Xi^*}(M_{\text{inv}})}_{\frac{g_{\Omega^*\eta\Omega}g_{\Omega^*\bar{K}\Xi^*}}{M_{\text{inv}} - M_{\Omega^*} + i\Gamma_{\Omega^*}/2}}\right).$$

Invariant mass of 2 and 3 body Ω(2012) decay in Ω_c production



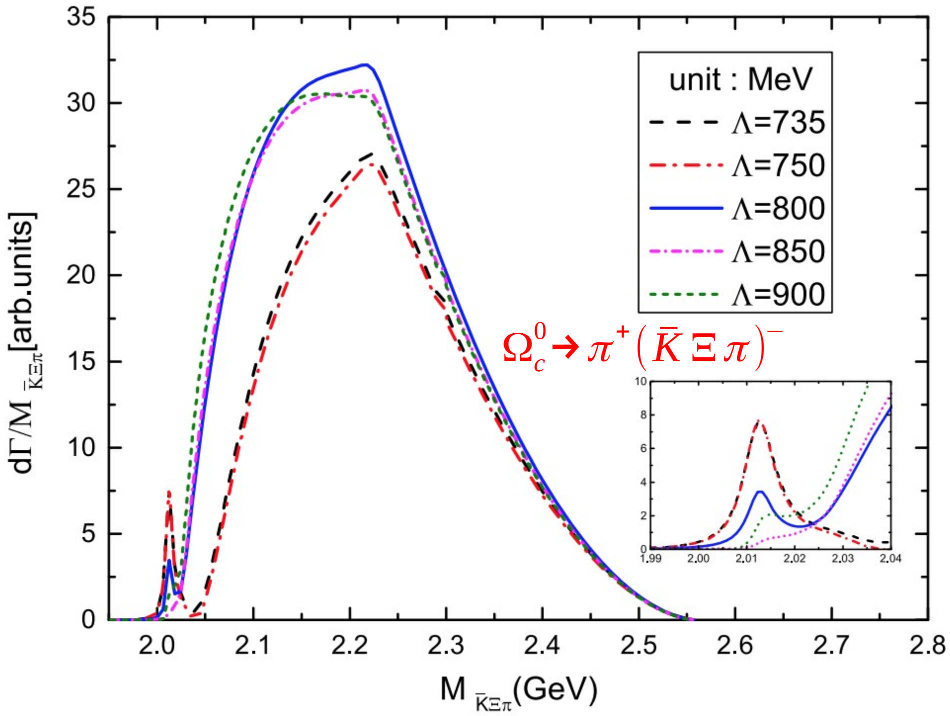
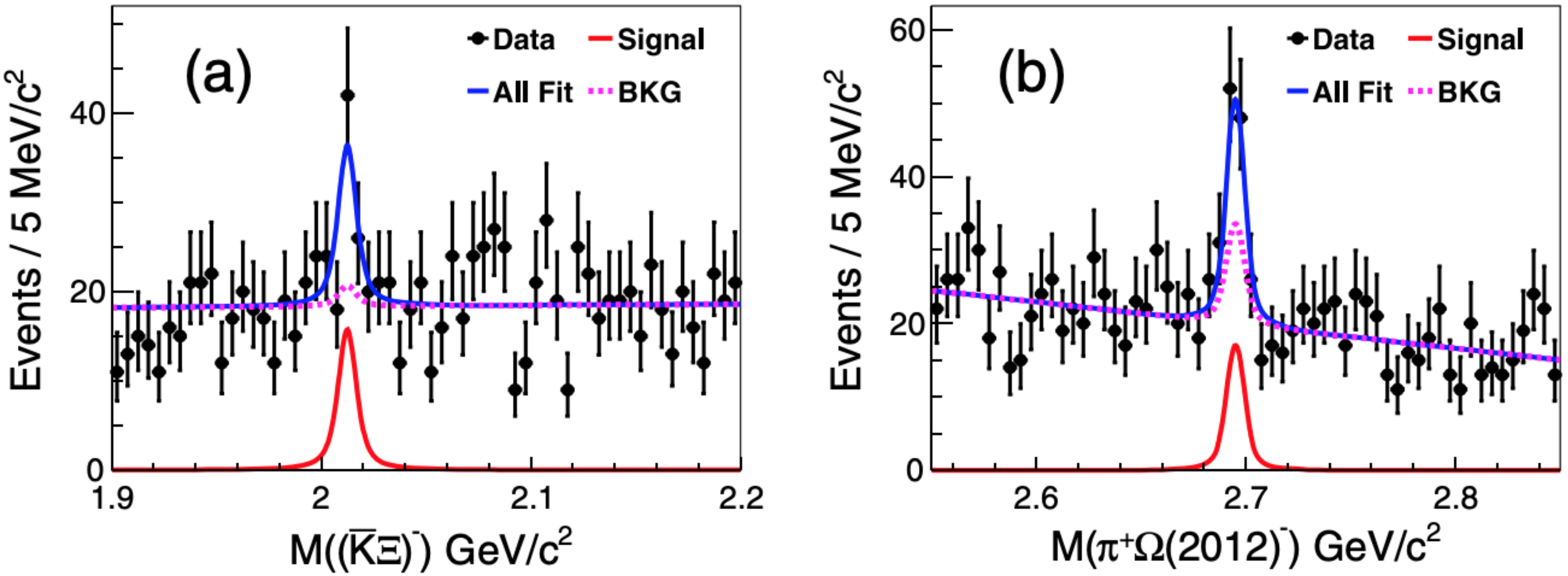


TABLE II: Predicted ratio $R_{\bar{K}\Xi}^{\bar{K}\Xi\pi}$ for different cutoffs.

$\Lambda = q_{\rm max}$(MeV)	735	750	800	850	900
$R_{\bar{K}\Xi}^{\bar{K}\Xi\pi}$(%)	13.9	13.8	13.5	10.0	7.3

Small peak over dominant tree level BG

Theory 3.3 ⇨ Exp 3: Evidence for $\Omega^0_c \to \pi^+[\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-]$ from Belle



Nsig = 46.6 ± 12.3

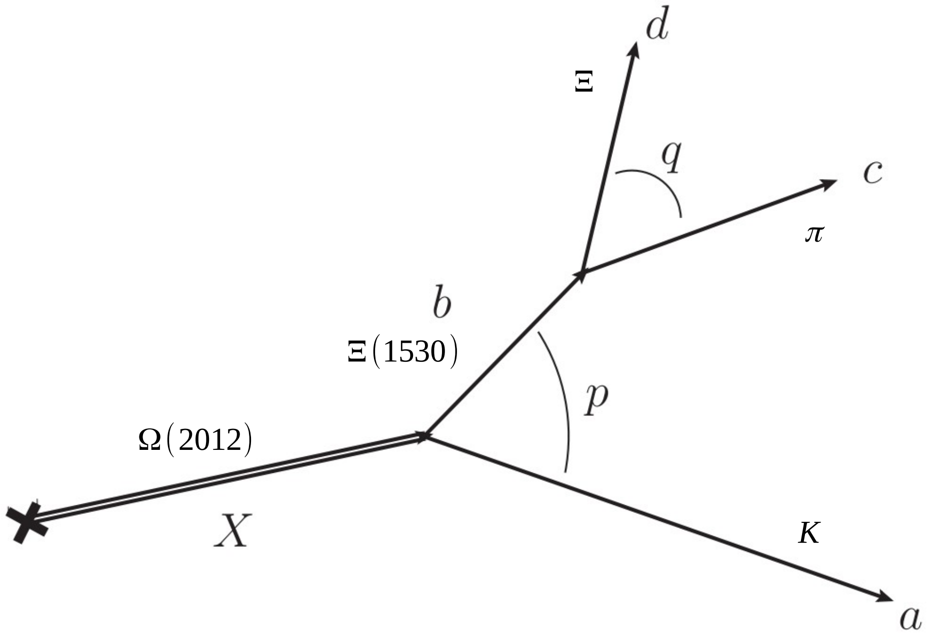
Significance: 4.2σ

$$\frac{\mathcal{B}\left(\Omega_c^0 \to \pi^+[\Omega(2012)^- \to (\bar{K}\Xi)^-]\right)}{\mathcal{B}\left(\Omega_C^0 \to \pi^+(\bar{K}\Xi)^-\right)} = (6.50 \pm 1.22(\mathrm{stat.}) \pm 0.94(\mathrm{syst.}))\%$$

Phys. Rev. D 104, 052005 (2021)

Theory 4 (lineshape) ⇨ Experiment 4 at Belle for Ω(2012)

Experiment should use the accurate lineshape instead of Breit-Wigner like:



- All decay is near-threshold.
- Intermediate b and X has finite width.

The lineshapes of X[Ω(2012)] and b[Ξ(1530)] are completely distorted from the naive BW !

How to calculate them?

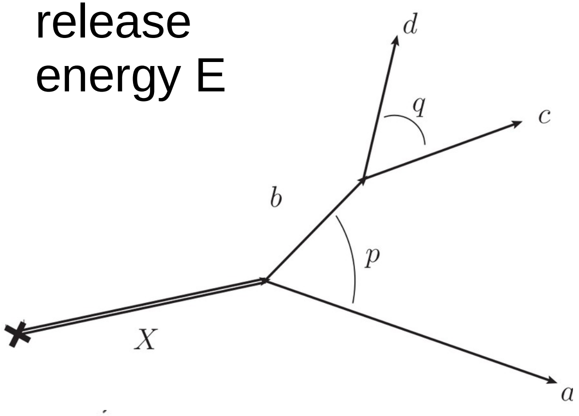
Fortunately, **theory 4** came to rescue us.

C. HANHART, YU. S. KALASHNIKOVA, AND A. V. NEFEDIEV, Lineshapes for composite particles with unstable constituents, PHYSICAL REVIEW D 81, 094028 (2010)

Much more advanced Flatte distribution.

Theory 4 (lineshape)

For small release energy E



$$g_l = g_{cd}(2\mu_q)^{l+1/2}$$ in cd system

μ: reduced mass

$$k_{\rm eff}(E) = \frac{g_l}{2\pi\mu_p}\int_0^{\sqrt{2\mu_p E}} \times \frac{p^2dp(E-\frac{p^2}{2\mu_p})^{(2l+1)/2}}{(E_R - E + \frac{p^2}{2\mu_p})^2 + \frac{g_l^2}{4}(E-\frac{p^2}{2\mu_p})^{2l+1}}$$

$$\frac{d\,\mathrm{Br}(a[cd])}{dE} = \mathcal{B}\frac{1}{2\pi}\frac{g_{ab}k_{\rm eff}(E)}{|E - E_X + \frac{1}{2}g_{ab}[\kappa_{\rm eff}(E) + ik_{\rm eff}(E)] + \frac{i}{2}\Gamma_0|^2}$$

Self-energy term

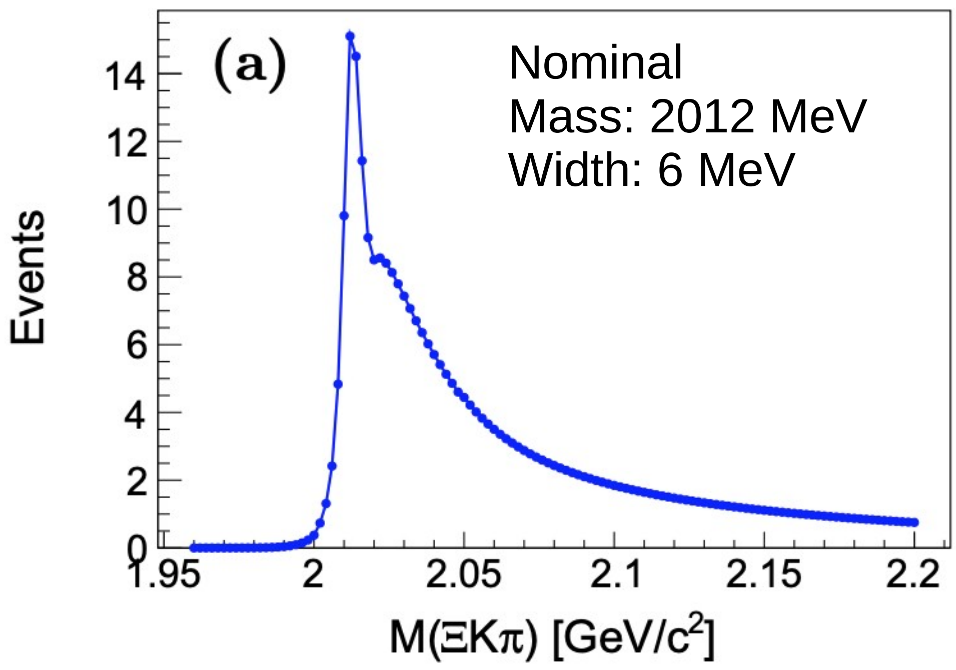
Can add energy term from other channel

$$\kappa_{\rm eff}(E) = \kappa_1(E) + \kappa_2(E) - \kappa_1(E_X) - \kappa_2(E_X)$$

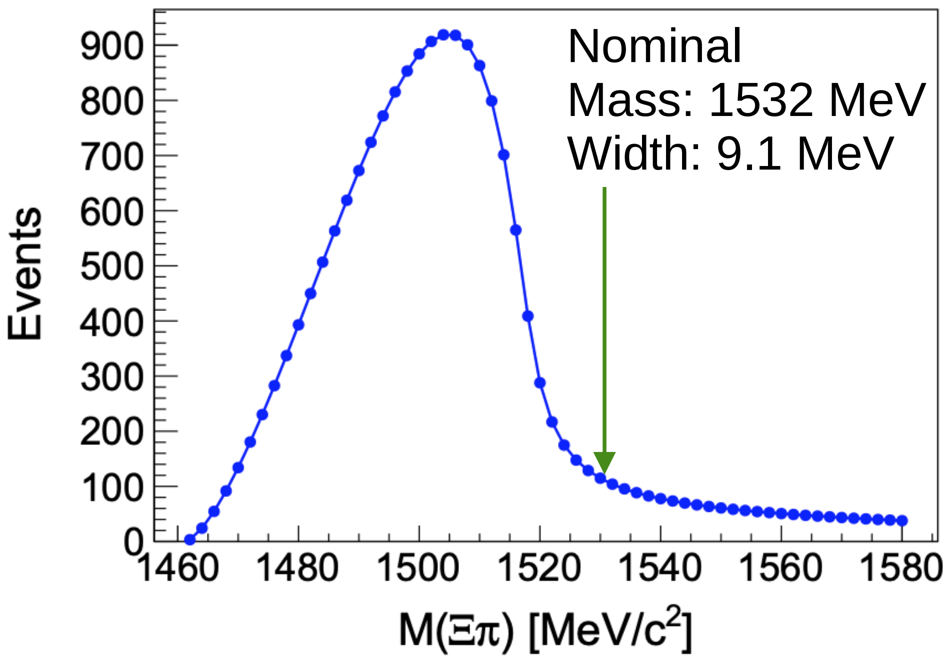
$$\kappa_1(E) = \frac{1}{\pi\mu_p}\int_0^\infty p^2dp \times \frac{E_R - E + \frac{p^2}{2\mu_p}}{(E_R - E + \frac{p^2}{2\mu_p})^2 + \frac{g_l^2}{4}(E - \frac{p^2}{2\mu})^{2l+1}}$$

$$\kappa_2(E) = -\frac{g_l}{2\pi\mu_p}\int_{\sqrt{2\mu_p E}}^\infty p^2dp \times \frac{(\frac{p^2}{2\mu_p} - E)^{(2l+1)/2}}{(E_R - E + \frac{p^2}{2\mu_p})^2 + \frac{g_l^2}{4}(E - \frac{p^2}{2\mu})^{2l+1}}$$

“Correct” lineshapes for $\Xi\pi K$ and $\Xi\pi$ in $\Omega(2012) \to [\Xi(1530) \to \Xi\pi]K$

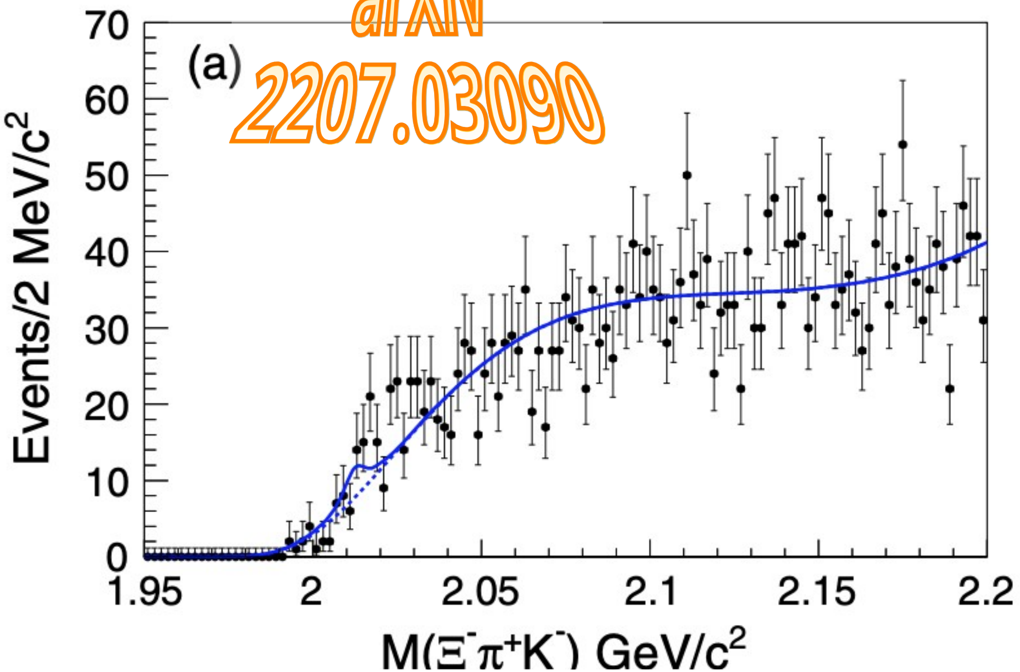


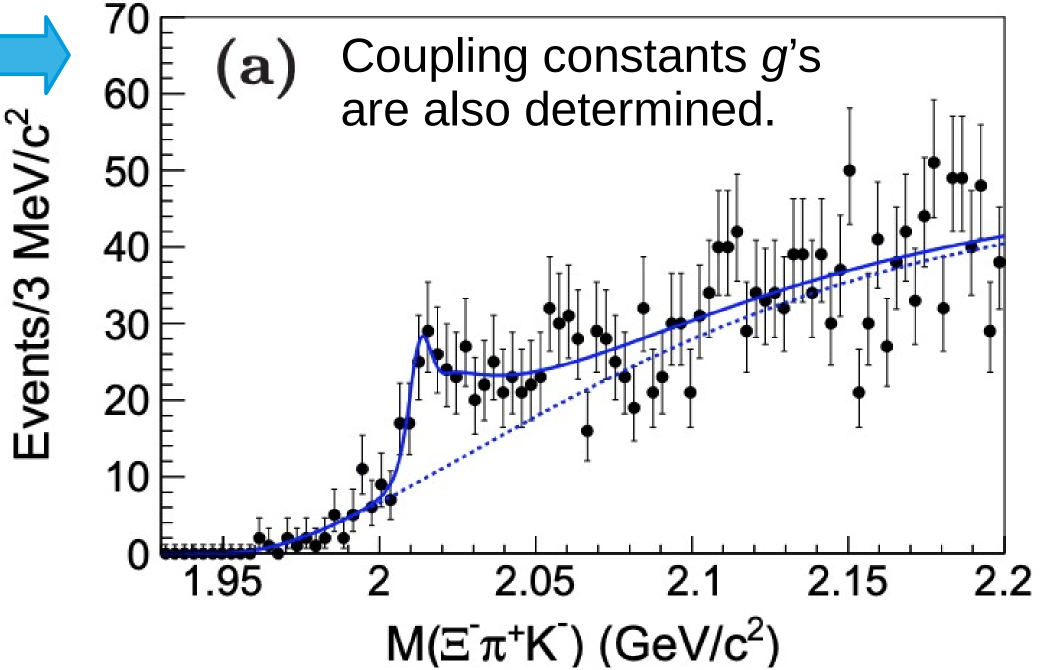
Weird shape with extremely long tail



Peak completely off position.

Experiment 4: Need to Revise selection and fit in Exp. 2 !





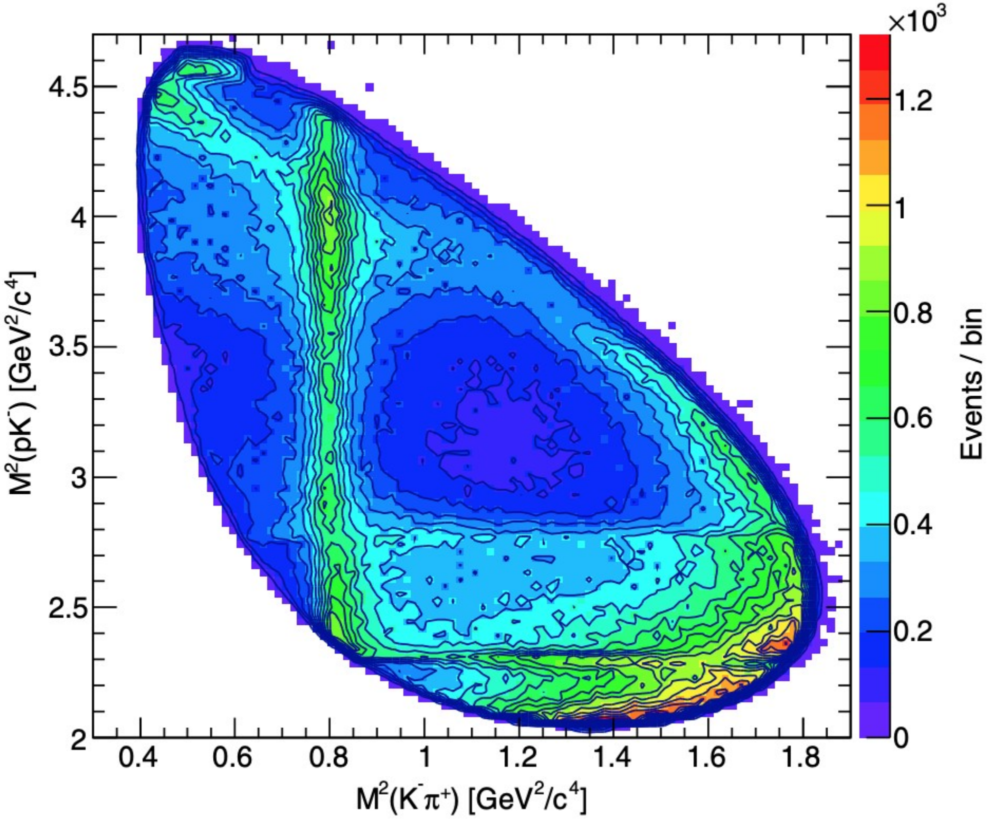
$$\mathcal{R}^{\Xi\pi K}_{\Xi K} = \frac{\mathcal{B}(\Omega(2012) \to \Xi(1530)(\to \Xi\pi)K)}{\mathcal{B}(\Omega(2012) \to \Xi K)} < 11.9\%$$

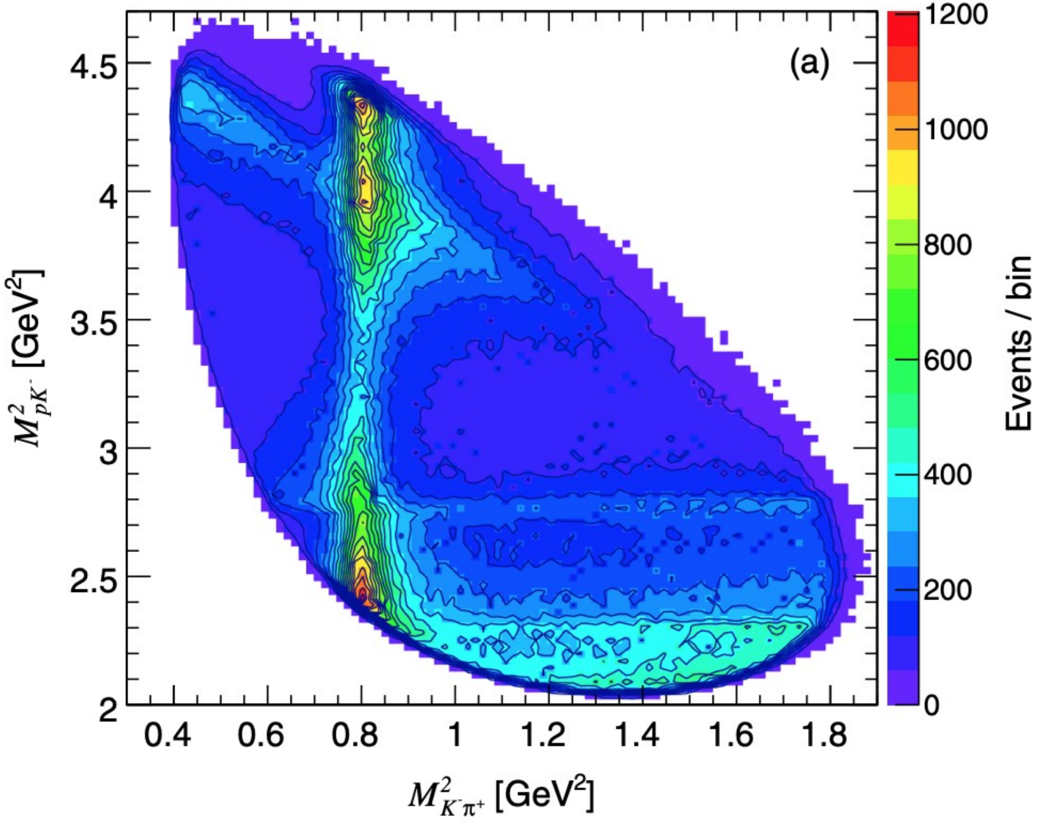
at 90% C.L.

$$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} = 0.97 \pm 0.24 \pm 0.07$$

I expect a new round of theory explanation.

Λ(1670) in Λ_c decay

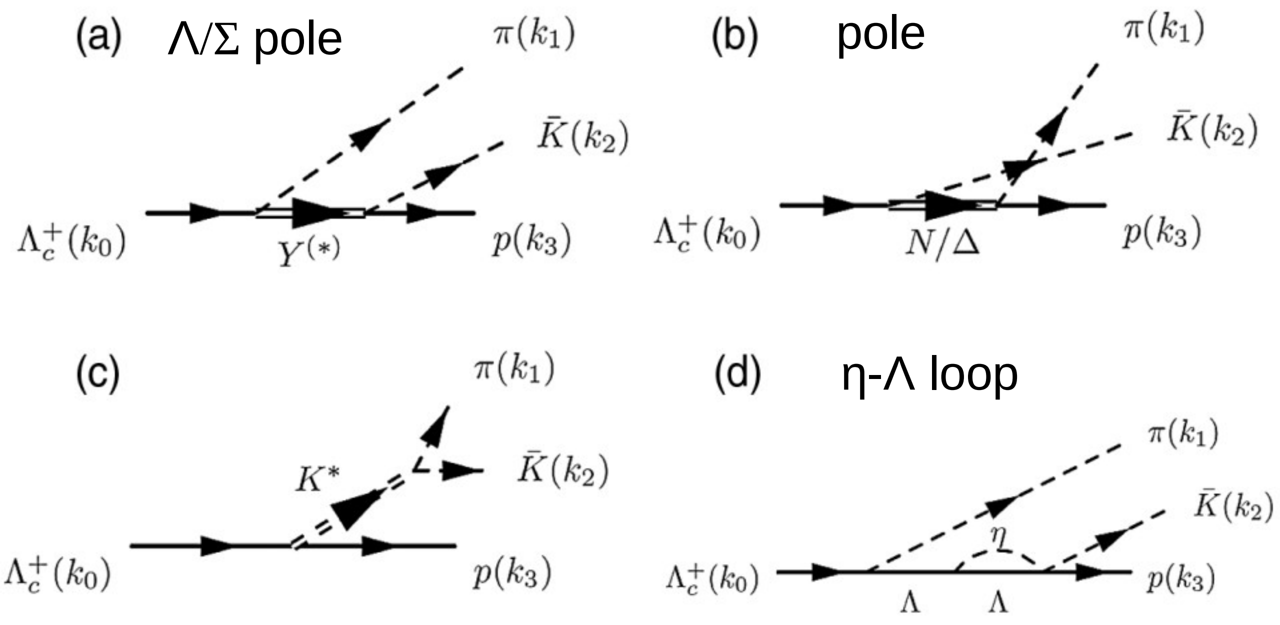




Exp: (Belle) Phys. Rev. Lett. 117, 011801

Theory: Jung Keun Ahn, et al., PHYS. REV. D 100, 034027 (2019)

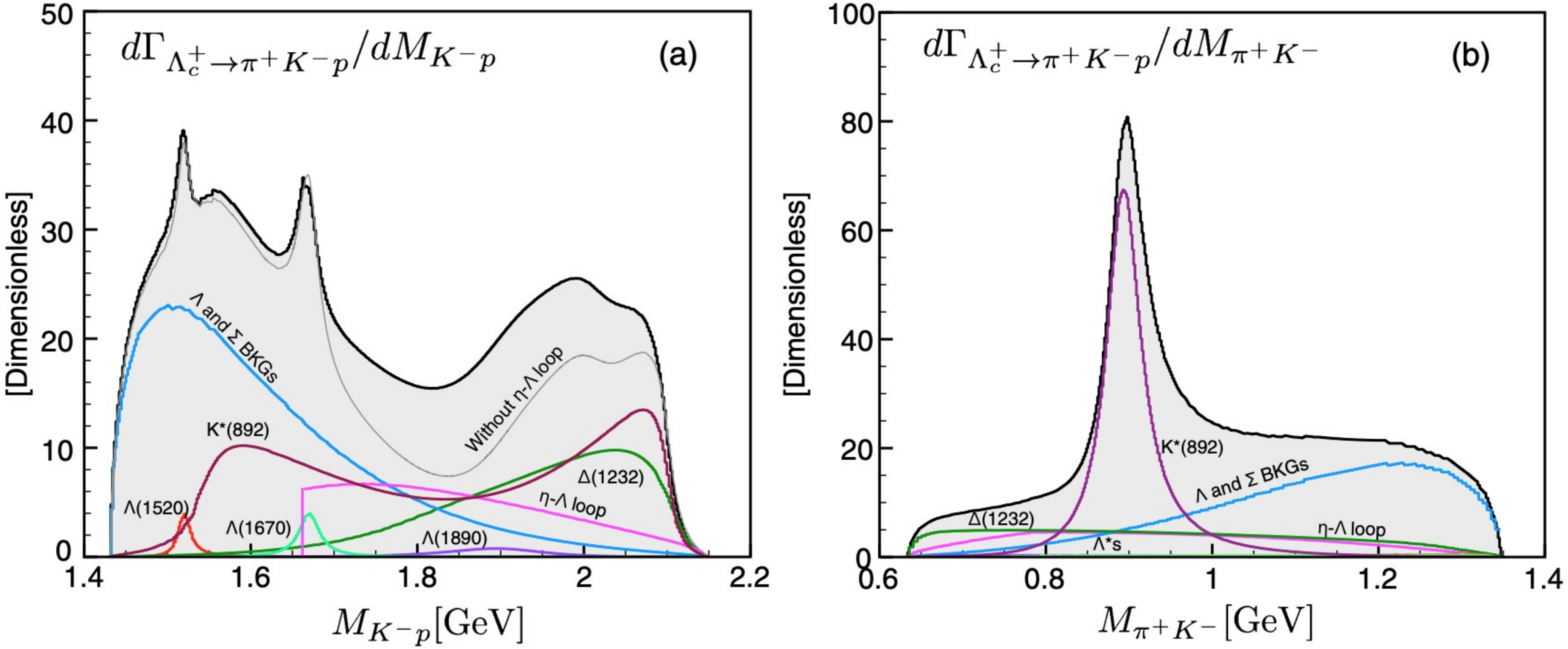
Theoretical interpretation of $\Lambda_c \to pK^-\pi^+$



Effective Lagrangians and corresponding propagators in amplitudes.

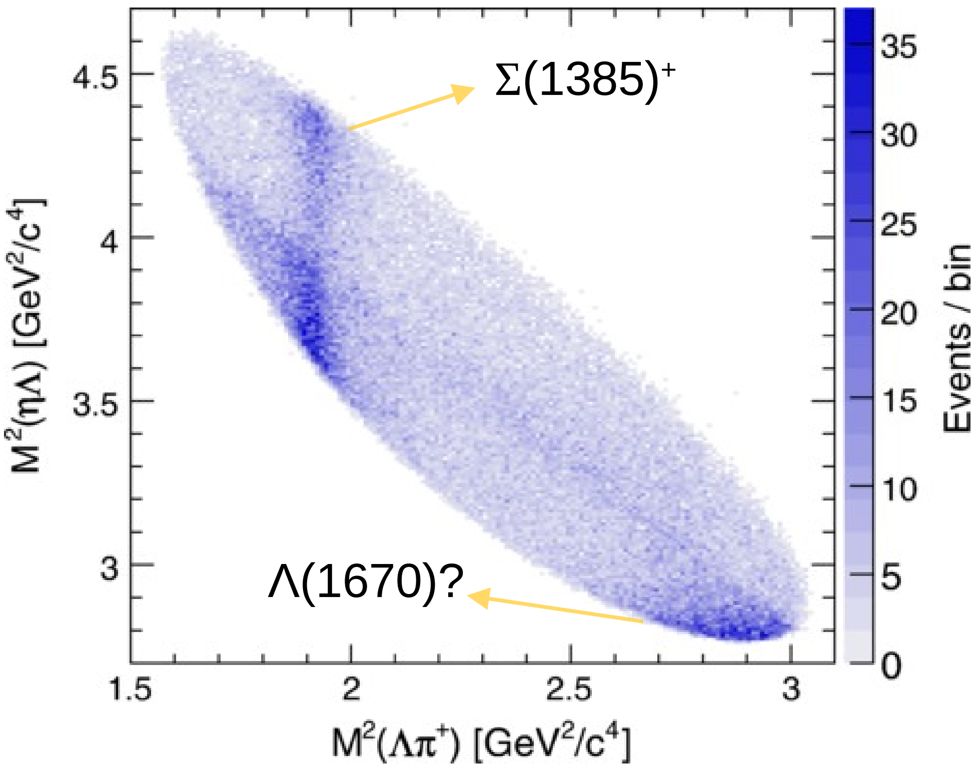
Assume same parity conserving and parity violating couplings for the hyperon resonances.

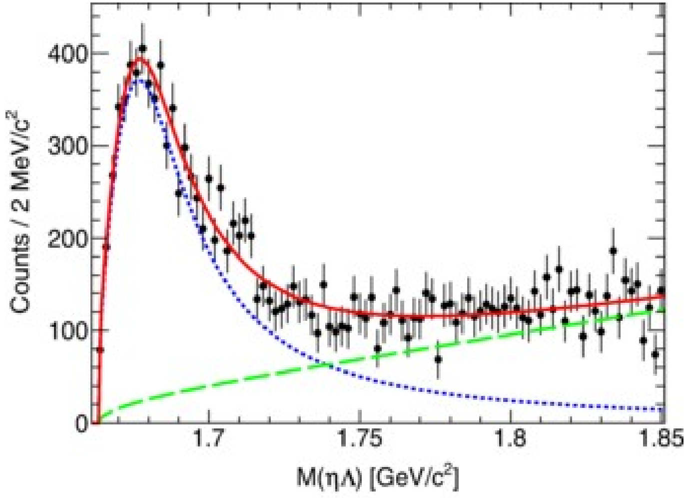
Theory projections

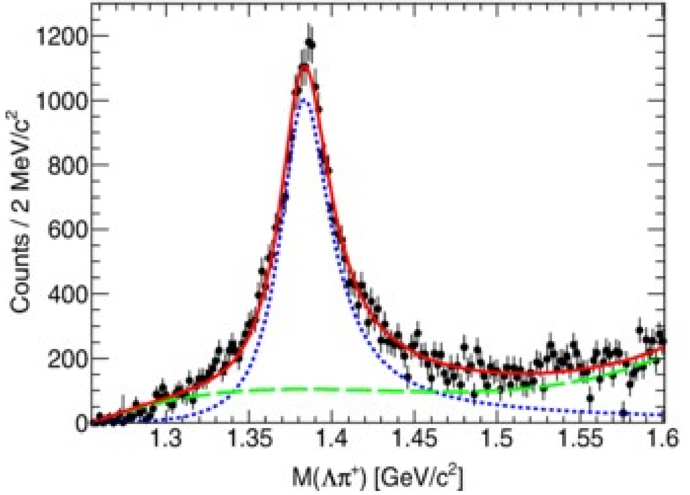


Solid black curve includes interference terms.

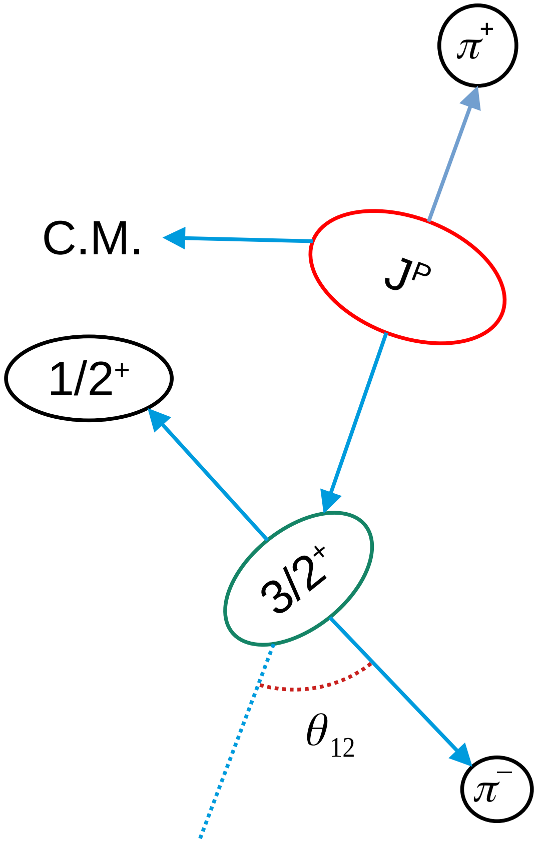
Experiment to theory for Λ(1670) and Σ(1385)$^+$ in $\Lambda_c \to \eta\Lambda\pi^+$?







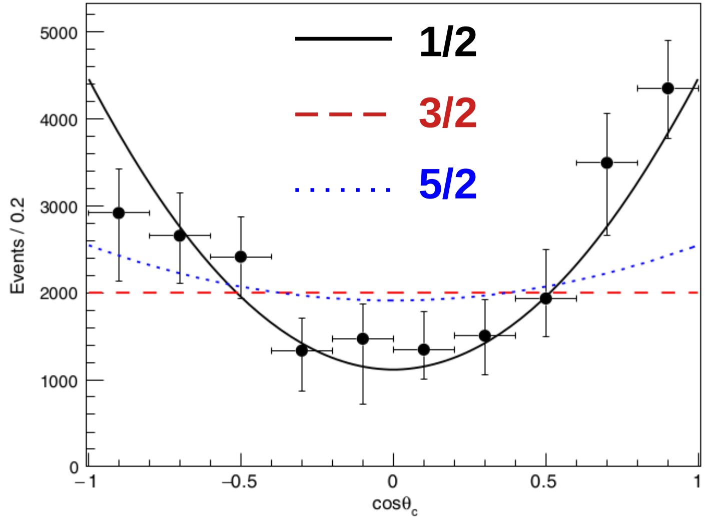
Angular Distribution of $J^P \rightarrow [3/2^+ \rightarrow 1/2^+\pi]\ \pi$



$J(j)^P$	L	$W(\theta_{12})$
$1/2(0)^-$	$\cancel{d}$	$\cdots$
$1/2(1)^-$	d	$1+3\cos^2\theta_{12}$
$1/2(0)^+$	p	$1+3\cos^2\theta_{12}$
$1/2(1)^+$	p	$1+3\cos^2\theta_{12}$
$3/2(1)^-$	$s,\ d$	1
$3/2(2)^-$	$\cancel{s},\ d$	1
$3/2(1)^+$	$p,\ \cancel{f}$	$1+6\sin^2\theta_{12}$
$3/2(2)^+$	$p,\ f$	$1+6\sin^2\theta_{12}$
$5/2(2)^-$	$d,\ \cancel{g}$	$1+(15/4)\sin^2\theta_{12}$
$5/2(2)^+$	$p,\ f$	$1+(1/3)\cos^2\theta_{12}$
$5/2(3)^+$	$\cancel{p},\ f$	$1+(3/8)\sin^2\theta_{12}$
$7/2(3)^+$	$f,\ \cancel{h}$	$1+3\sin^2\theta_{12}$

Theory: PHYS. REV. D 101, 094023 (2020)

J determination of $\Xi_c(2970)^+$ in its $\Xi_c(2645)^0[\Xi_c^+\pi^-]\pi^+$ channel



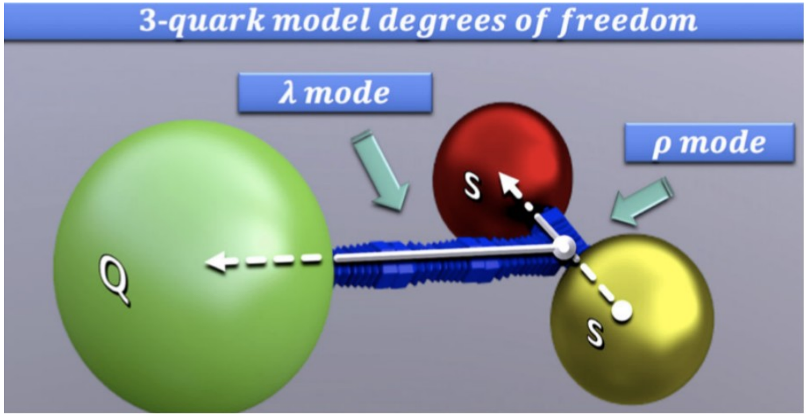
Favors **J=1/2**

- consistent with **$1+3\cos^2\theta_c$**

Exp: (Belle) Phys. Rev. D 103, 111101

Radiative transition of charmed baryon

- EM transitions of charmed baryons are observed only for strong decay forbidden states: $\Xi'_c \rightarrow \Xi_c\gamma$ and $\Omega_c(2770) \rightarrow \Omega_c\gamma$.
- Theoretical predictions of observable partial width (~300 keV) for decays from $\Xi_c(2790)$ and $\Xi_c(2815)$ to $\Xi_c\gamma$ (3-10 % level of BR).
- Input of EM decay measurements is crucial for interpretation of λ-ρ modes and theoretical modeling.



K-L. Wang, Y-X. Yao, X-H. Zhong, and Q. Zhao, Phys. Rev. D 96, 116016 (2017)

Phys. Rev. D 94, 052011 (2016)

Mode	WYZZ [14] λ excitation	WYZZ [14] ρ excitation	ρ excitation	Actual total width [3]
$\Xi_c(2790)^+ \rightarrow \Xi_c^+\gamma$	4.65	1.39	0.79	$8900 \pm 600 \pm 800$
$\Xi_c(2790)^0 \rightarrow \Xi_c^0\gamma$	263	5.57	3.00	$10000 \pm 700 \pm 800$
$\Xi_c(2815)^+ \rightarrow \Xi_c^+\gamma$	2.8	1.88	2.81	$2430 \pm 200 \pm 170$
$\Xi_c(2815)^0 \rightarrow \Xi_c^0\gamma$	292	7.50	11.2	$2540 \pm 180 \pm 170$

$\Xi_c(2790)$ & $\Xi_c(2815)$ radiative decay results

Typically interpreted as an HQS doublet with orbital L=1 (λ-mode), with expected J^P = $1/2^-$ and $3/2^-$.

PRD 102, 071103(R) (2020)

Clear signal for neutral channel, but not charged.

$$\frac{\mathcal{B}\left(\Xi_c(2815)^0 \to \Xi_c^0 \gamma\right)}{\mathcal{B}\left(\Xi_c(2815)^0 \to \Xi_c(2645)^+ \pi^- \to \Xi_c^0 \pi^+ \pi^-\right)} = 0.45 \pm 0.05 \pm 0.03$$

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

$$\Gamma\left(\Xi_c(2815)^0 \to \Xi_c^0 \gamma\right) = 320 \pm 45^{+45}_{-80}\ \text{keV}$$

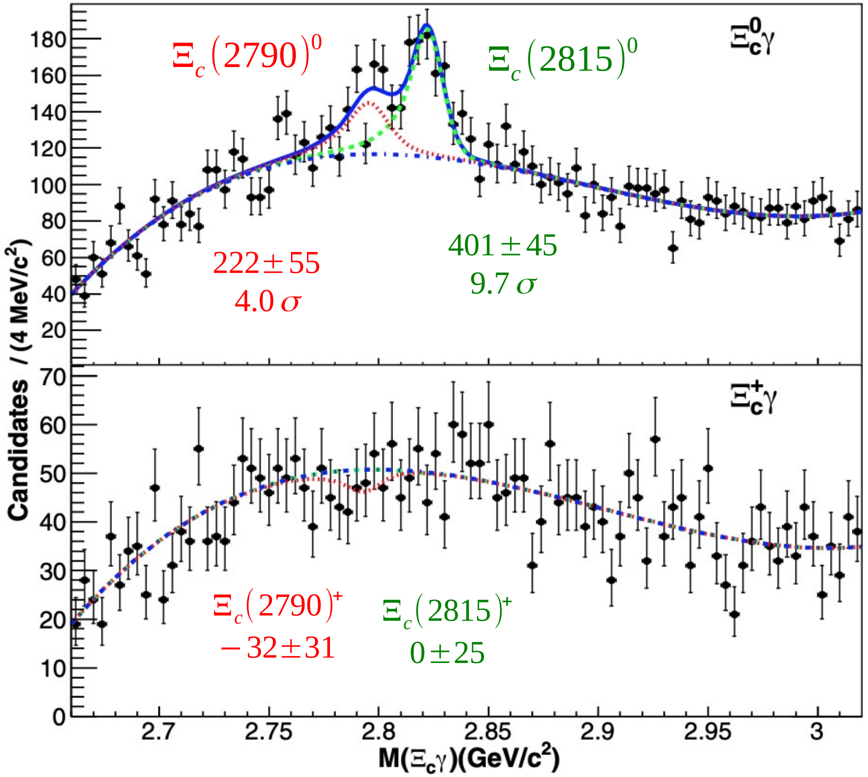
$$\Gamma\left(\Xi_c(2790)^0 \to \Xi_c^0 \gamma\right) \sim 800\ \text{keV (uncertainty} \sim 40\%\text{)}$$

$$\Gamma\left(\Xi_c(2815)^+ \to \Xi_c^+ \gamma\right) < 80\ \text{keV}$$

$$\Gamma\left(\Xi_c(2790)^+ \to \Xi_c^+ \gamma\right) < 350\ \text{keV}$$

Consistent with orbital excitation interpretation.

Phys.Rev. D 96, 116016 (2017)



Summary and Upcoming interplay

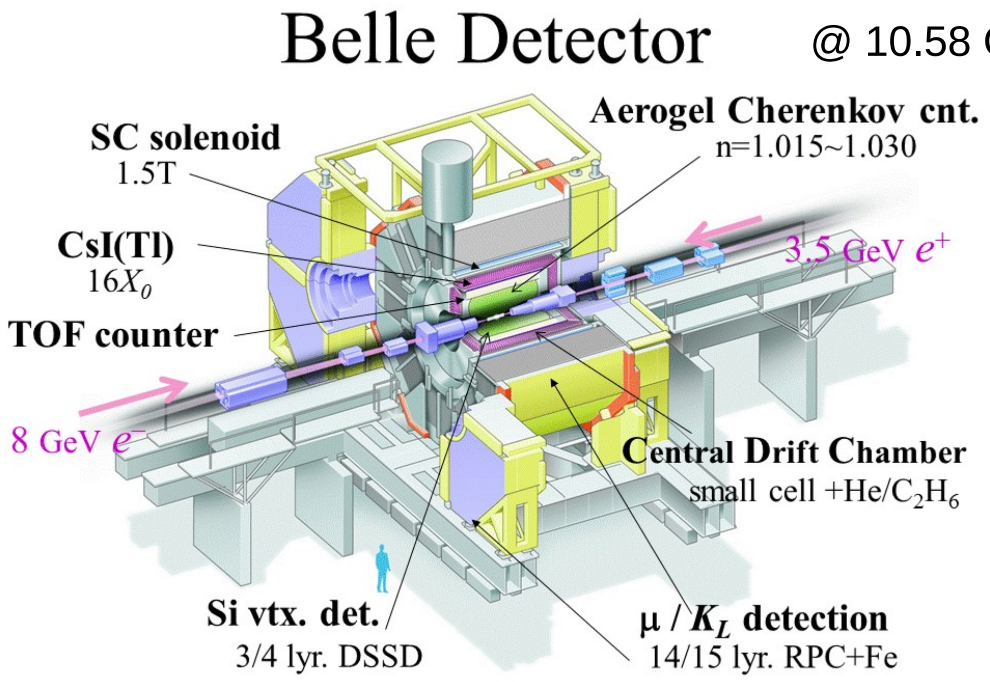
We have shown the importance of joint experimental and theoretical effort for studies on $\Omega(2012)^-$, excited hyperons in three body Λc decay,

Need interplay between theorists and experimentalists.

- Global fits to baryon and meson spectrum. [$^3P_0$ model for charmed baryon; light cone model for mesons]. The common bootstrap and fitting method in experiment is used. Output can guide future experimental search. [arXiv:2205.07049]
- Double charmed baryon production (ex. $\bar{\Lambda}_c\Lambda_c^*$) from e^+e^-; spin-parity study of excited baryon– the initial helicity of excited baryon is known, precise and powerful angular distributions.
- Theoretical predictions of masses and decay channels of exotic hadrons – ex: $\Lambda_c\bar{D}^0$ and $\Sigma_c D^-$ (hidden charm pentaquark); tetraquark and pentaquark with strangeness; collaboration with Italian group at INFN.

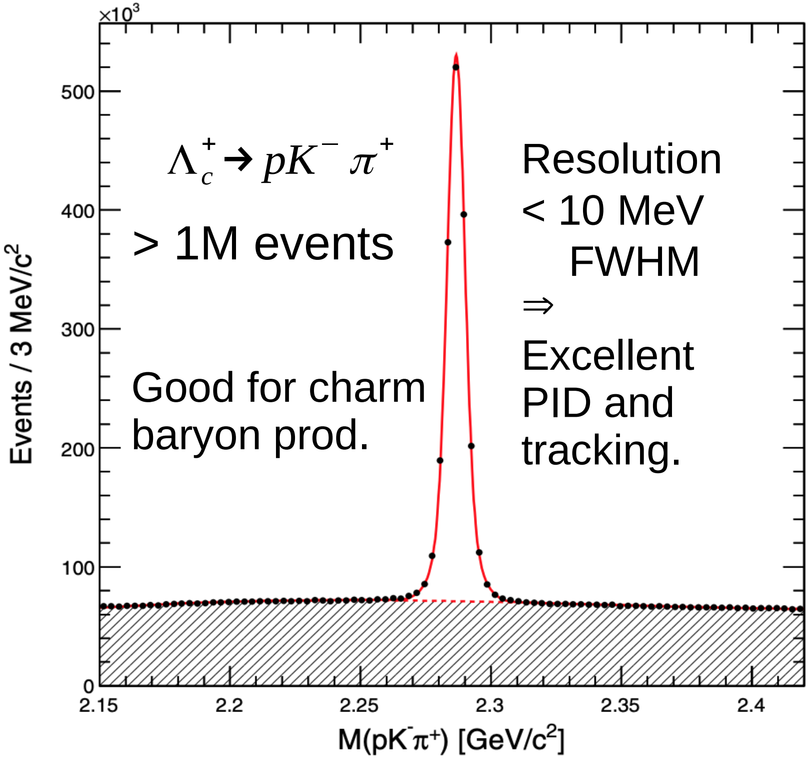
BACKUP

Belle Detector and charmed baryon production.



@ 10.58 GeV

$e^+e^- \to \Upsilon(4S): 1.1\,nb^{-1}$ $e^+e^- \to c\bar{c}: 1.3\,nb^{-1}$



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

> 1M events

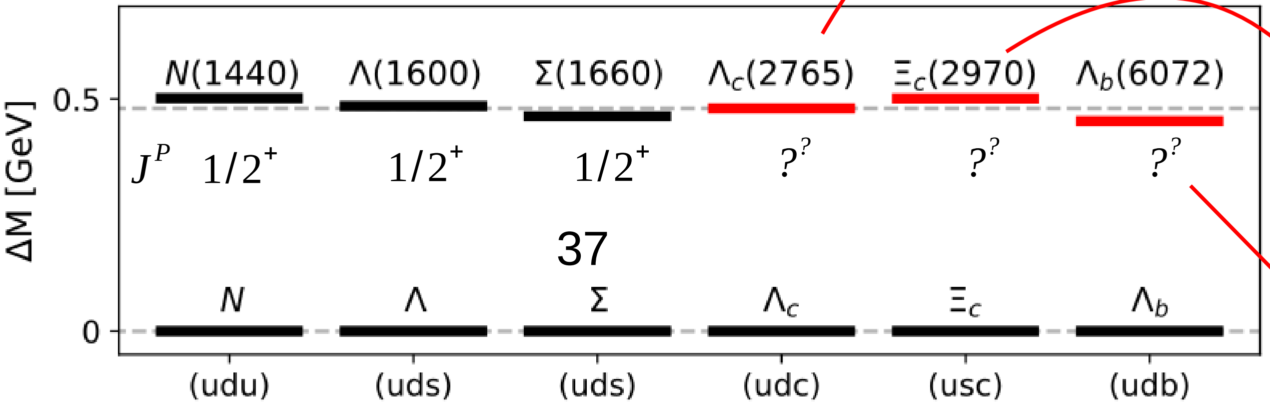
Good for charm baryon prod.

Resolution < 10 MeV FWHM ⇒ Excellent PID and tracking.

Total int. lumnosity ~ 1 ab^{-1}
⇒ used in all three studies

$\Xi_c(2970)^+$ in baryon family

First excited $J^P = ½^+$ baryons



Not been pinned down.
Theory prediction only.

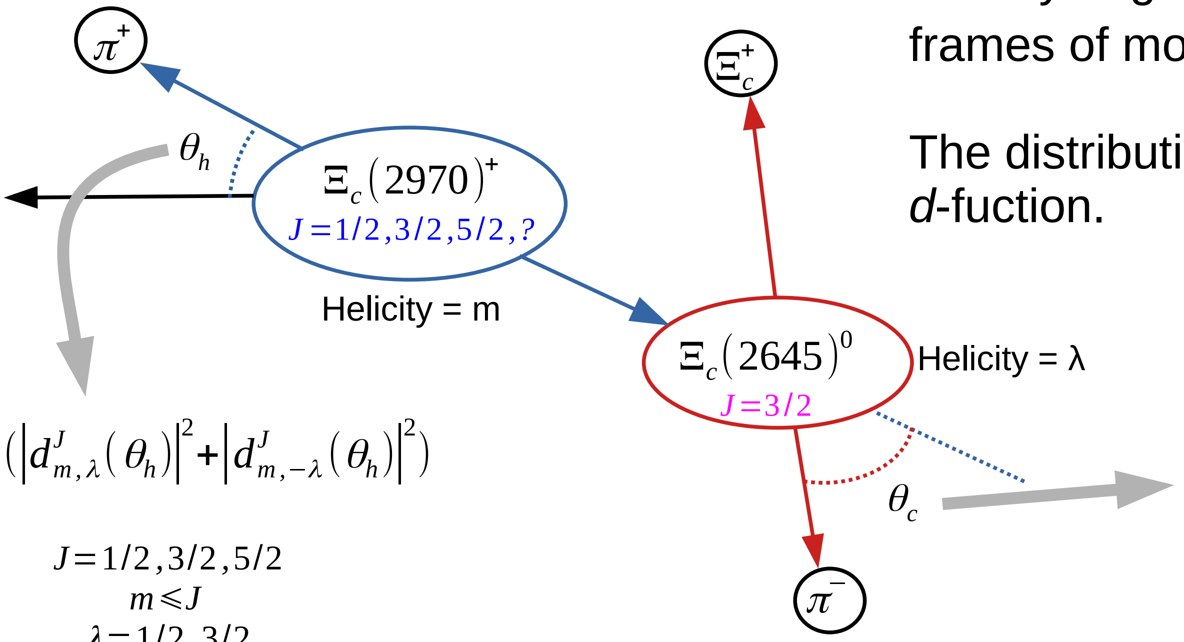
Nucl. Phys. Rev. 35, 1
Int J Theor Phys 59, 1129

Belle's work (this talk)
Phys. Rev. D 103, 111101

LHCb data suggest ½$^+$ assignment.
- Arifi, Hosaka, Nagahiro, and Tanida
Phys. Rev. D 101, 111502

Helicity angle θ$_h$ and θ$_c$ evaluated in rest frames of mother particle.

The distribution is related to Wigner's *d*-fuction.



$$\propto \rho_{mm}\left(\left|d^J_{m,\lambda}(\theta_h)\right|^2+\left|d^J_{m,-\lambda}(\theta_h)\right|^2\right)$$

$$\propto \left|d^{3/2}_{\lambda,1/2}(\theta_c)\right|^2+\left|d^{3/2}_{\lambda,-1/2}(\theta_c)\right|^2$$

$$J=1/2,3/2,5/2$$
$$m\leqslant J$$
$$\lambda=1/2,3/2$$

ρ_{mm}: Initial spin density of $\Xi_c(2970)^+$

Formula of angular distribution (θ_h and θ_c)

θ_h for $J \rightarrow 3/2(\Xi_c(2645))+0$

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

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

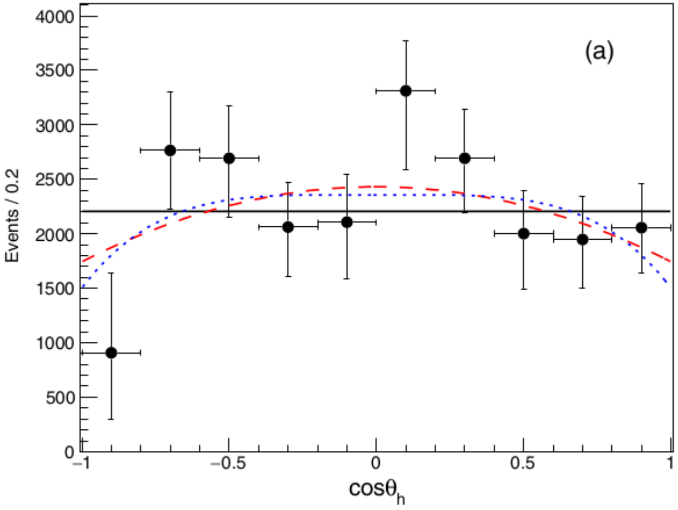
$$\begin{aligned} W_{\frac{5}{2}} = \frac{3}{32}[&\rho_{55}5\{(-\cos^4\theta_h - 2\cos^2\theta_h + 3) + T(-5\cos^4\theta_h + 6\cos^2\theta_h - 1)\} \\ &+ \rho_{33}\{(15\cos^4\theta_h - 10\cos^2\theta_h + 11) + T(75\cos^4\theta_h - 66\cos^2\theta_h + 7))\} \\ &+ \rho_{11}2\{(-5\cos^4\theta_h + 10\cos^2\theta_h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

Relative fraction of 3/2 polarization in Ξc(2645)

θ_c in $\Xi_c(2645)(3/2^-) \rightarrow \Xi_c(1/2^+) + \pi(0^-)$

J^P of $\Xi_c(2970)^+$	Partial Wave	Expected Angular Distribution
$1/2^+$	P	$1 + 3\cos\theta_c^2$
$1/2^-$	D	$1 + 3\cos\theta_c^2$
$3/2^+$	P	$1 + 6\sin\theta_c^2$
$3/2^-$	S	1
$5/2^+$	P	$1 + (1/3)\cos\theta_c^2$
$5/2^-$	D	$1 + (15/4)\sin\theta_c^2$

$\cos\theta_h$



1/2

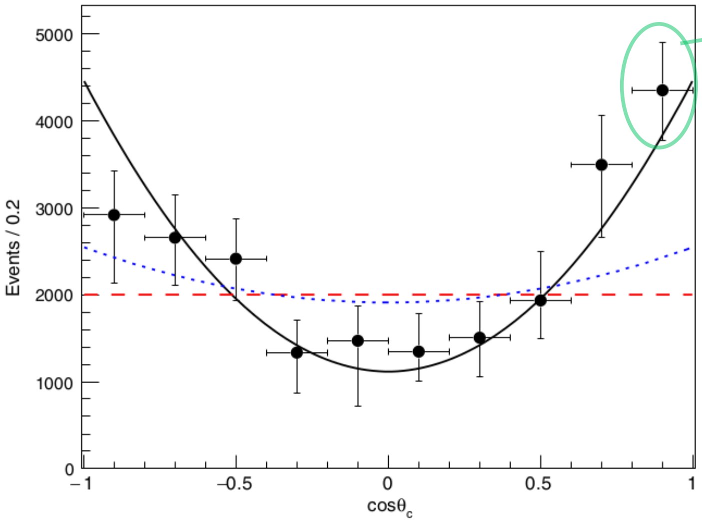
3/2

5/2

Inconclusive in $\cos\theta_h$

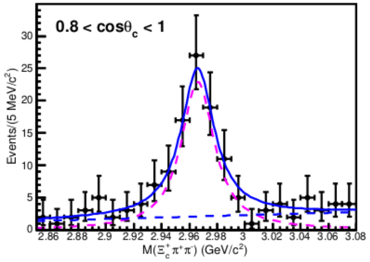
Exclusion Level 0.8 (0.5)σ for 3/2 (5/2) hypothesis

$\cos\theta_c$



$0.8<\cos\theta_c<1$

Yield=95±13
Eff.=2.46%
N=Yield/Eff.



Favors **J=1/2**
over 3/2 (5/2) at 5.1 (4.0)σ
- consistent with $\mathbf{1+3\cos^2\theta_c}$

- HQS doublet with brown-muck (light component) spin j=1: J=3/2 ($\Xi_c(2645)^0$) and 1/2($\Xi_c'^0$)
- The decay rate ratio $R=\dfrac{\Gamma\left(\Xi_c(2970)^+ \to \Xi_c(2645)^0 \pi^+\right)}{\Gamma\left(\Xi_c(2970)^+ \to \Xi_c'^0 \pi^+\right)}$ is calculable:

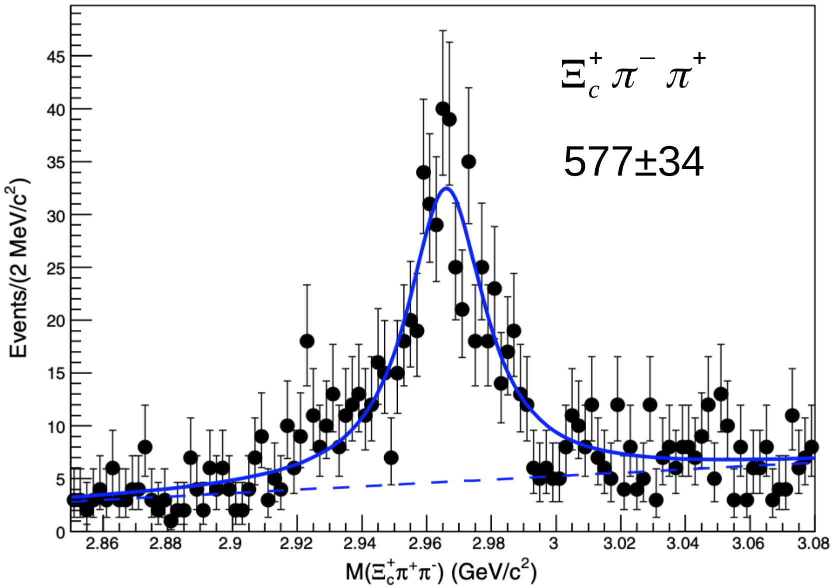
PRD 75 (2007) 014006

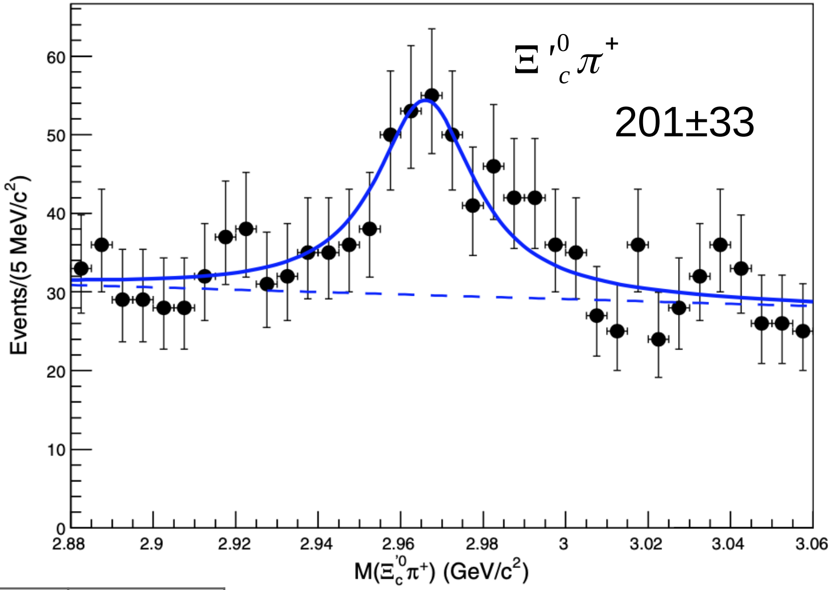
Parity	+	+	−	−
Brown-muck spin s_ℓ	0	1	0	1
R	1.06	0.26	0	$\ll 1$

Suppressed due to D-wave of $\Xi_c(2645)^0\pi^+$

Determination of Parity and s_l

Results of BR





s_l (P=+)	0	1
R	1.06	0.26

Favors

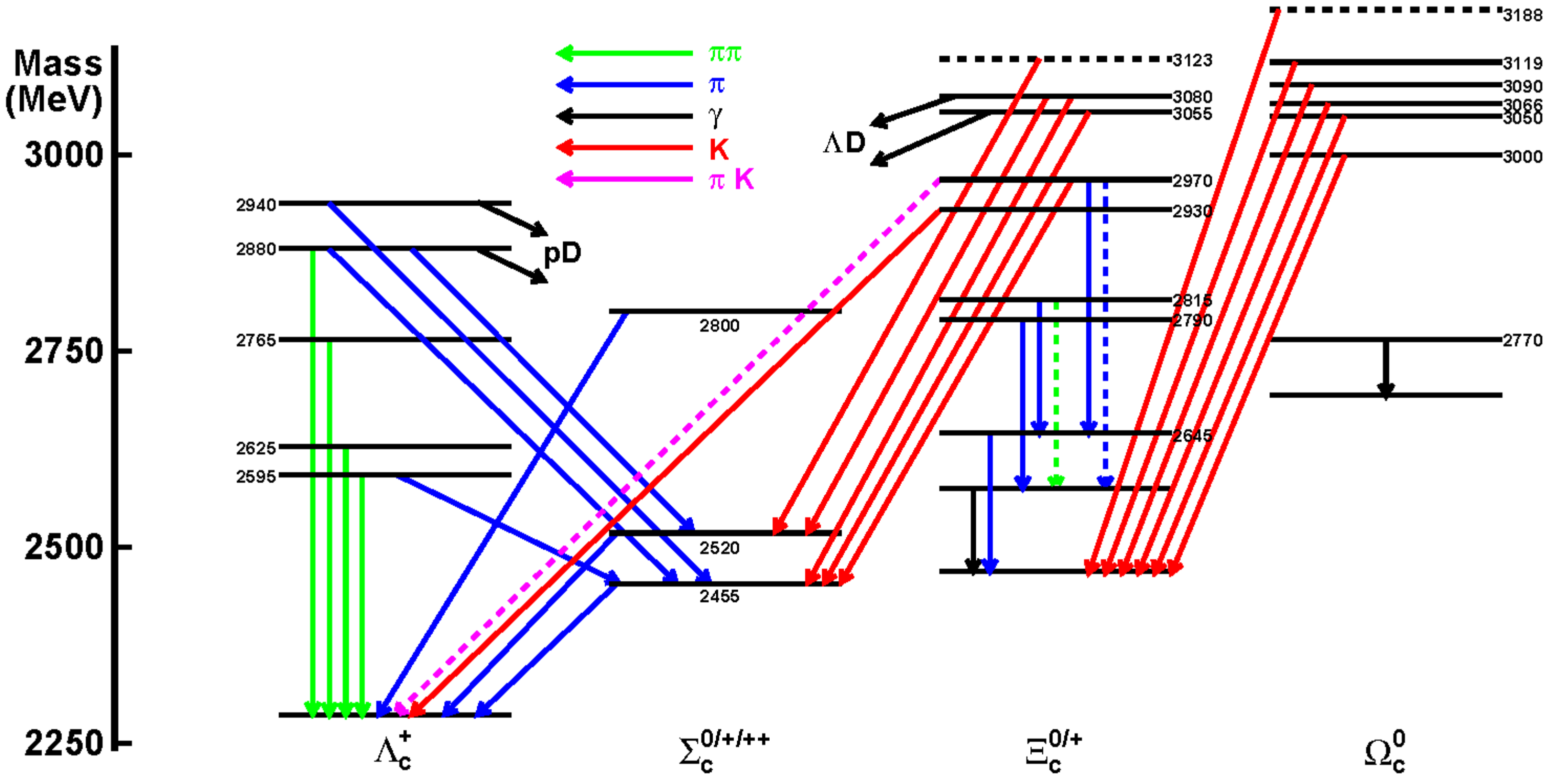
Final conclusion: $J^P(s_l) = 1/2^+(0)$

PRD 103, L111101 (2021)

$$R = \frac{\Gamma\left(\Xi_c(2970)^+ \to \Xi_c(2645)^0 \pi^+\right)}{\Gamma\left(\Xi_c(2970)^+ \to \Xi_c'^0 \pi^+\right)} = 1.67 \pm 0.29^{+0.18}_{-0.09} \pm 0.25$$

Due to isospin assumption in sub-BF calculation for $\Xi_c^{+/0}$

Transitions of charmed baryons



HFLAV

Only $\Xi_c' \rightarrow \Xi_c\gamma$ and $\Omega_c(2770) \rightarrow \Omega_c\gamma$ for electromagnetic decays.