H-Dibaryon near $\Lambda\Lambda$ and $\Xi^- p$ Thresholds

from J-PARC E42

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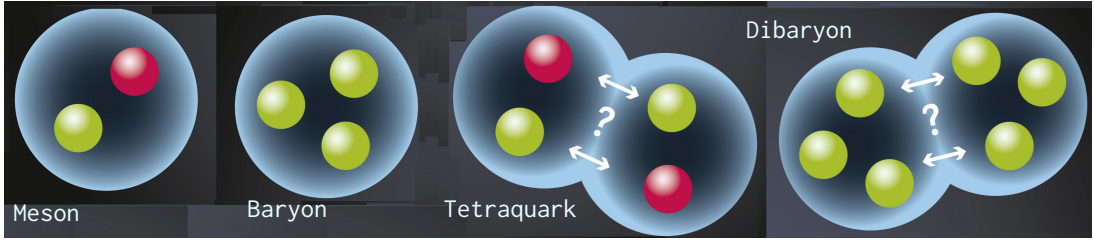
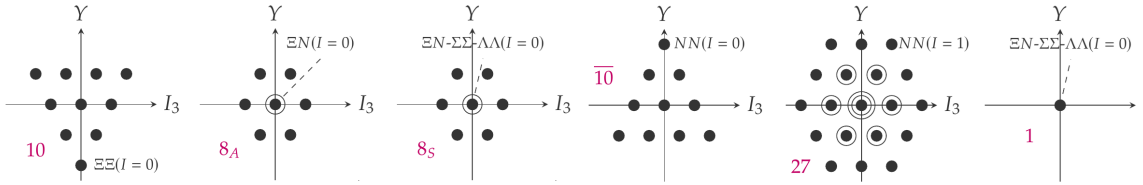
H-Dibaryon

Toward Drip Line of Multiquark States

- The observation of many multiquark candidates (such as T_{cc}, $T_{c\bar{c}}$, T_{cs}, $P_{c\bar{c}}$ and P_{cs} states) poses a question on the dripline of further multiquark states: hexaquark state.



Dibaryon Systems and the H Dibaryon



- For N quarks, the QCD color magnetic interaction can be summarized by an effective Hamiltonian acting on the quarks' spin and color indices;

$$\mathscr{H}_{\text{eff}} \propto -\sum_{i\neq j}^{N} \{\vec{\lambda}\vec{\sigma}\}_i \cdot \{\vec{\lambda}\vec{\sigma}\}_j = 8N - \frac{1}{2}C_6^N + \frac{4}{3}S_N(S_N+1).$$

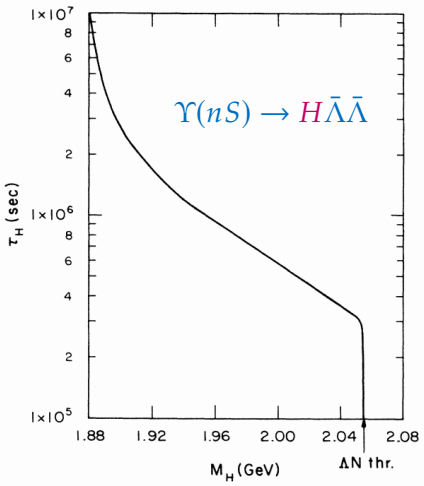
- For 6 quarks, the color-spin interaction energies are

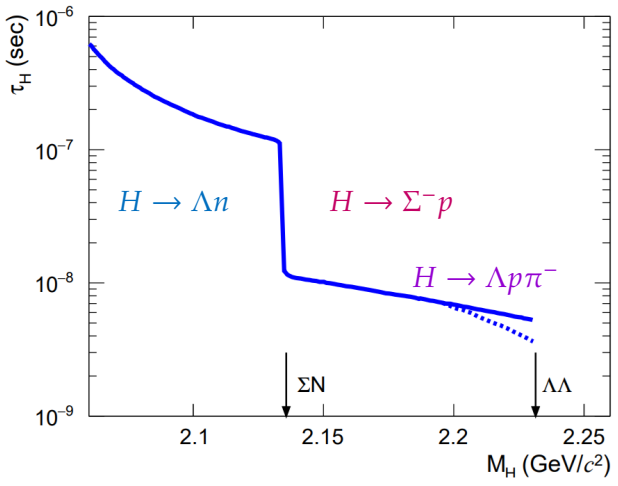
$$\langle\mathscr{H}_{\text{eff}}\rangle_1 = -24, \quad \langle\mathscr{H}_{\text{eff}}\rangle_8 = -28/3, \quad \langle\mathscr{H}_{\text{eff}}\rangle_{\overline{10}} = +8/3, \quad \langle\mathscr{H}_{\text{eff}}\rangle_{27} = +3$$

The History of H-Dibaryon Searches

1977	Deeply-bound di-hyperon predicted by R. Jaffe
1980-2000	No evidence for the deeply-bound H from KEK, BNL, and CERN
	experimental efforts by more than 80 MeV
2001	Mass constraint from observation of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ (E373)
1998,2007	Enhanced $\Lambda\Lambda$ production near threshold was reported from
	E224 and E522 at KEK-PS
2011	LQCD calculations predict the H-dibaryon near the $\Lambda\Lambda$ mass threshold.
2013-2015	No evidence for $H \to \Lambda p \pi^-$ and $H \to \Lambda\Lambda$ in high-energy
	e^+e^-, pp and AA experiments
2021	LQCD calculations point to the mass of the H-dibaryon
	very close to the ΞN mass threshold ($m_\pi \approx 146$ MeV)
2021	**J-PARC E42 has successfully completed with HypTPC.**
2025	The E42 is nearing the final stage of data analysis.

H-Dibaryon Searches below $\Lambda\Lambda$ Threshold

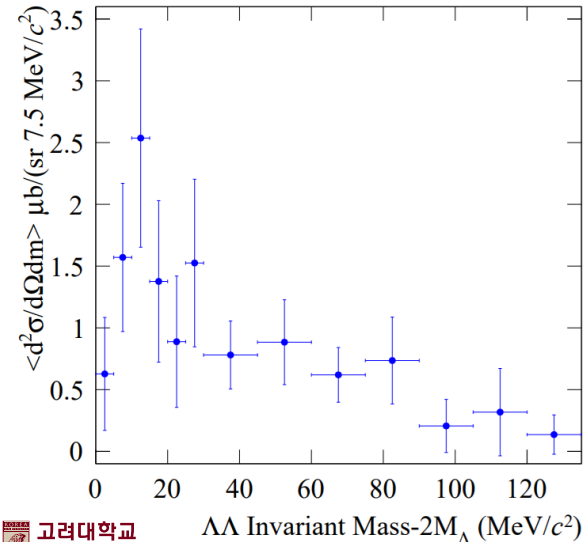




- A quark model calculation predicts the lifetimes for the weak decay of the H-dibaryon. [a]

[a] J.F. Donoghue, E. Golowich, and B.R. Holstein, Phys. Rev. D 34, 3434 (1986)

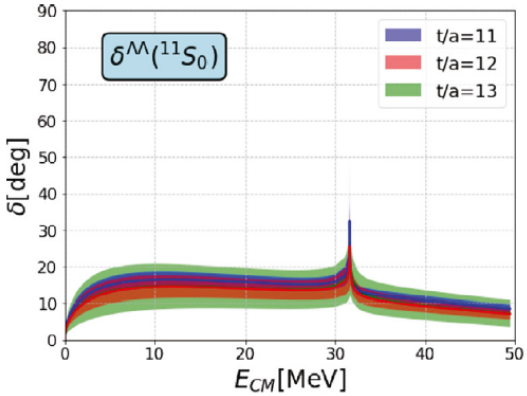
Previous H-Dibaryon Search via $^{12}C(K^-, K^+)$ Reaction

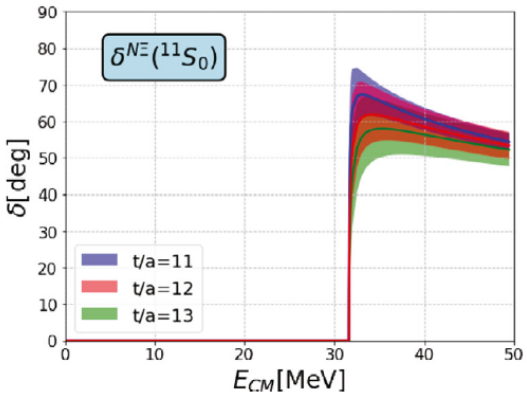


- Enhanced ΛΛ production is observed near the ΛΛ threshold in the $^{12}C(K^-, K^+\Lambda\Lambda)$ reaction. [a]
- The upper limit on the H dibaryon production cross section between ΛΛ and $\Xi^- p$ threshold is reported as $2.1 \pm 0.6 \pm 0.1$ μb/sr at a 90% C.L.
- 72 ΛΛ events and a moderate mass resolution of $\sigma(M_{\Lambda\Lambda}) = 5$–$15$ MeV/c^2.

[a] C.J. Yoon *et al.* (E522 Collab.), Phys. Rev. C 75, 022201(R) (2007).

Recent Lattice QCD Calculation Results





- LQCD calculation result predicts a sharp resonance just above $N\Xi$ threshold with $I = 0$ $^1S_0$ phase shifts at $m_\pi \approx 146$ MeV. [a]

[a] K. Sasaki for the HAL Collab., NPA 998 (2020) 121737

J-PARC E42

H Dibaryon Search with J-PARC E42

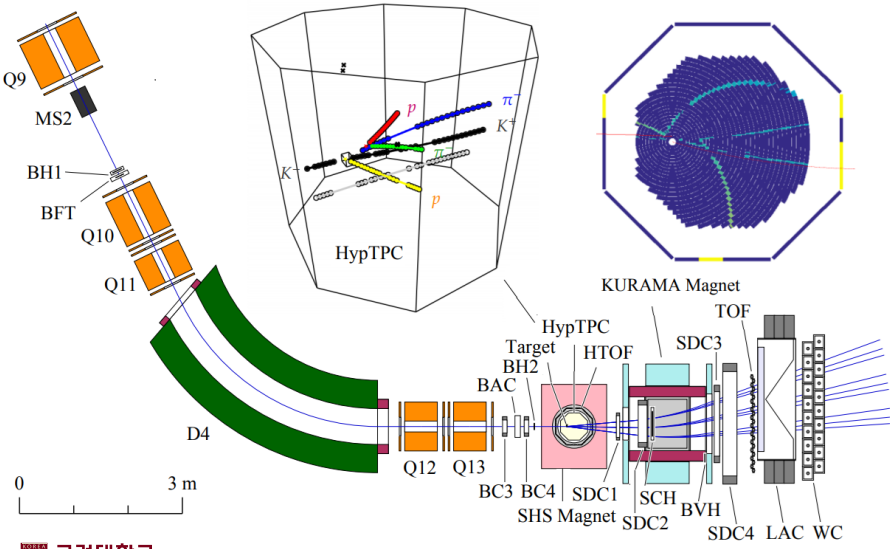
The existence of the H-dibaryon still awaits definitive experimental confirmation or exclusion.

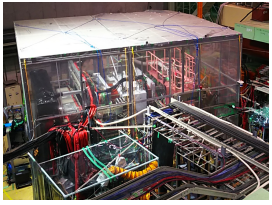
- Weakly-bound : $H \to \Lambda p \pi^-$, $(\Sigma^- p)$
- Virtual state : $\Lambda\Lambda$ or $\Xi^- p$ threshold effect
- Resonance : Breit-Wigner peak in $\Lambda\Lambda$ and $\Xi^- p$ mass thresholds

J-PARC E42

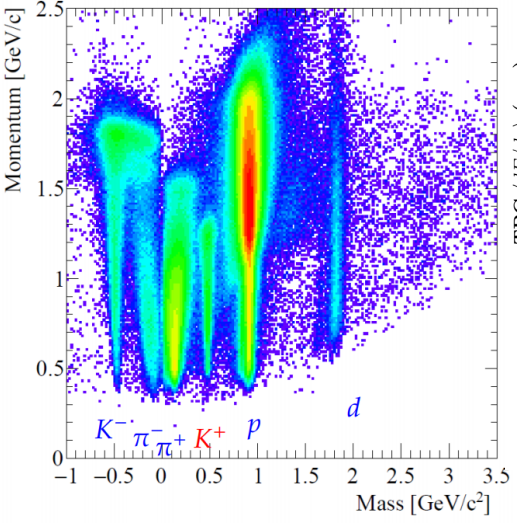
1. in $\Lambda p \pi^-$, $\Lambda\Lambda$ and $\Xi^- p$ channels
2. by tagging the $S = -2$ system production
3. via (K^-, K^+) reactions at 1.8 GeV/c with a diamond target
4. with a large-acceptance Hyperon Spectrometer

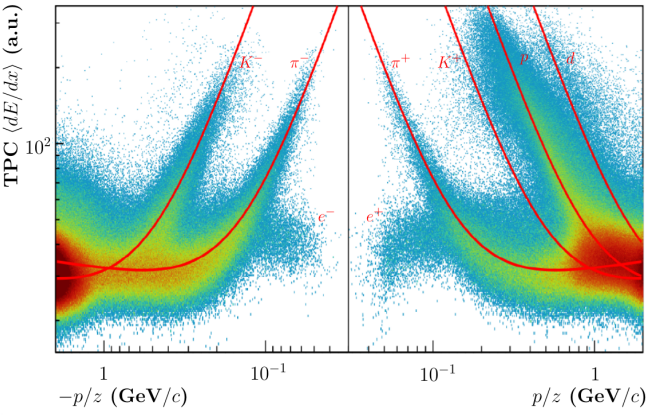
J-PARC E42 Detector



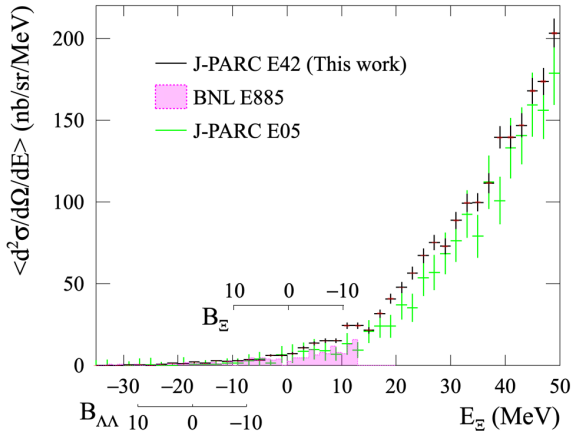


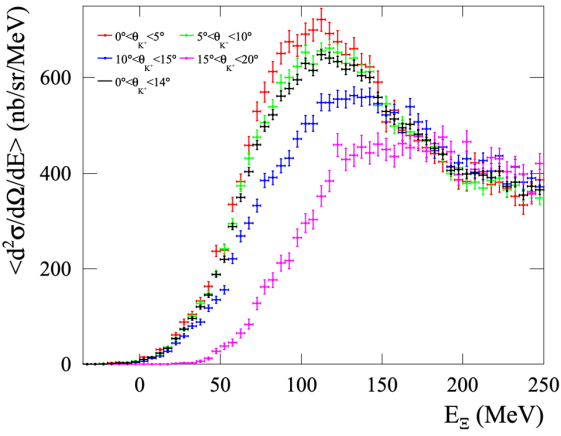
Track Reconstruction and Particle Identification





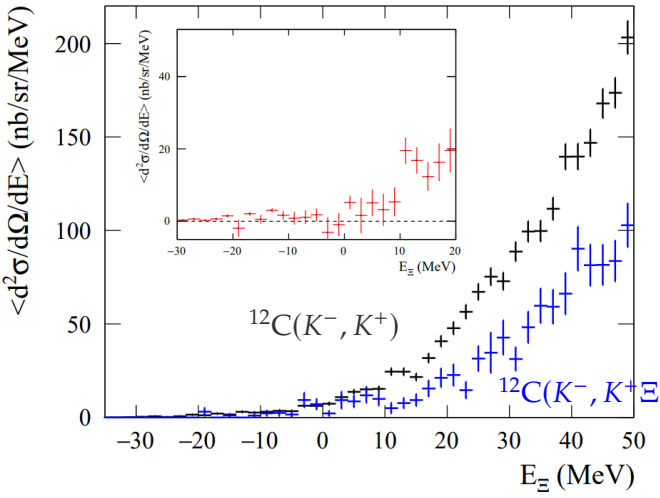
Differential Cross Sections for $^{12}C(K^-, K^+)$ Reaction





- The E42 results demonstrates similar lineshapes near the $-B_\Xi = 0$ energy to previous measurement results ($E_\Xi = -B_\Xi = M_X - m_\Xi - m_{^{11}\mathrm{Be}}$). [a]

Closer Look at the Bound Ξ^- Region

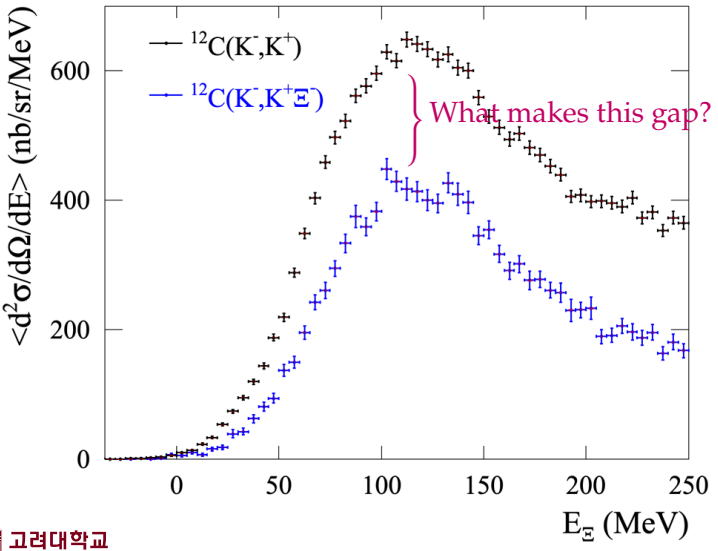


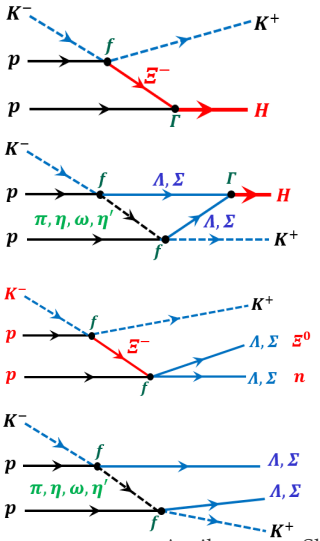
- The Ξ^- emission-subtracted cross sections from the inclusive $^{12}C(K^-, K^+)$ reaction cross sections :

$$\sigma = \sigma(^{12}C(K^-, K^+)) - \sigma(^{12}C(K^-, K^+\Xi^-)$$

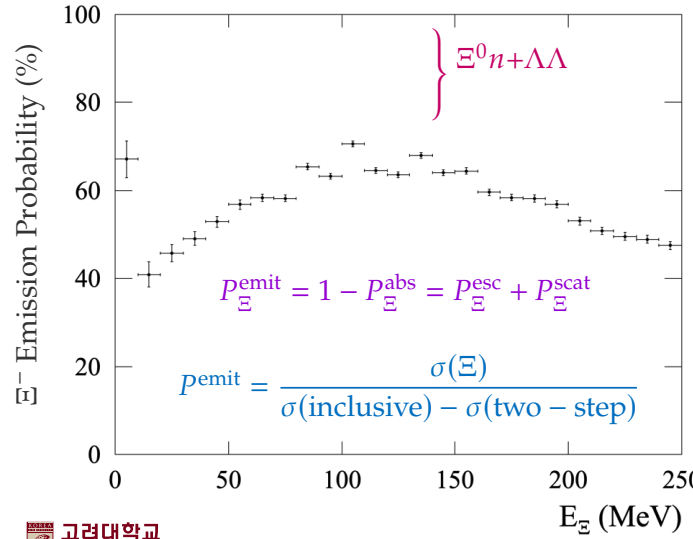
- J-PARC E42 can provide crucial information on the decays of double-hypernuclei by measuring Λ, p, and $\pi^\pm$ in coincidence.

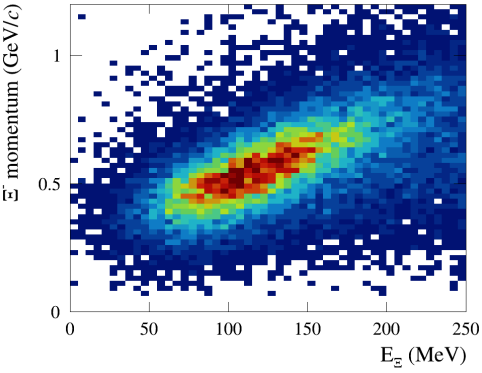
Ξ^- Production in $^{12}C(K^-, K^+)$ Reaction





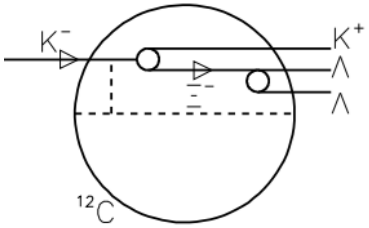
Ξ^- Emission Probability for $^{12}C(K^-, K^+)$ Reaction





- The Ξ^- absorption could primarily be associated with the $\Xi^- p \rightarrow \Xi^0 n$ and $\Xi^- p \rightarrow \Lambda\Lambda$ reactions.

Ξ^- Emission Probability and $\Xi^- N$ Inelastic Cross Section



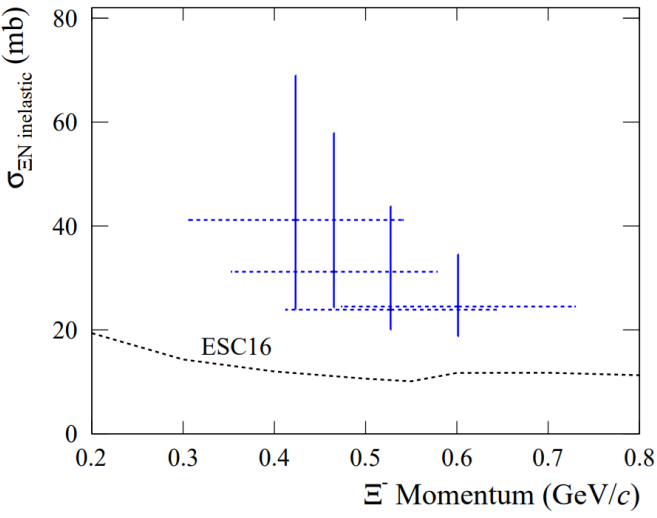
- Using a classical approach in the eikonal approximation the effective number of the ΞN process is calculated as

$$N_{\Xi N} = \int_0^\infty 2\pi b db \int_{-\infty}^{+\infty} dz \rho(\sqrt{b^2+z^2}) \cdot F(b,z) \times \left[1 - \exp\left\{\bar{\sigma}_{\Xi N} \int_z^{+\infty} dz' \rho(\sqrt{b^2+z'^2}\right\}\right]$$

$$F(b,z) = \exp\left[-\bar{\sigma}_{K^- N} \int_{-\infty}^{z} dz' \rho(\sqrt{b^2+z'^2}) - \bar{\sigma}_{K^+ N} \int_z^{+\infty} dz' \rho(\sqrt{b^2+z'^2}\right]$$

- $\rho(r) = (1 - wr^2/r_c^2)/(1 + \exp(r - r_c/a))$, where $w = 0.149$, $a = 0.5224$, $r_c = 2.355$ fm.
- $\bar{\sigma}(K^- N) = 28.9$ mb, $\bar{\sigma}(K^+ N) = 19.4$ mb, $N_{KK} = \int_0^\infty 2\pi b db \int_{-\infty}^{+\infty} dz \rho(\sqrt{b^2+z^2}) F(b,z)$.

Cross Sections for $\Xi^- N$ Inelastic Reactions



- Nijmegen-D model calculation based on the BNL E906 data at $p_\Xi = 0.55$ GeV/c (α_{two}: a fraction of two-step processes) [a]

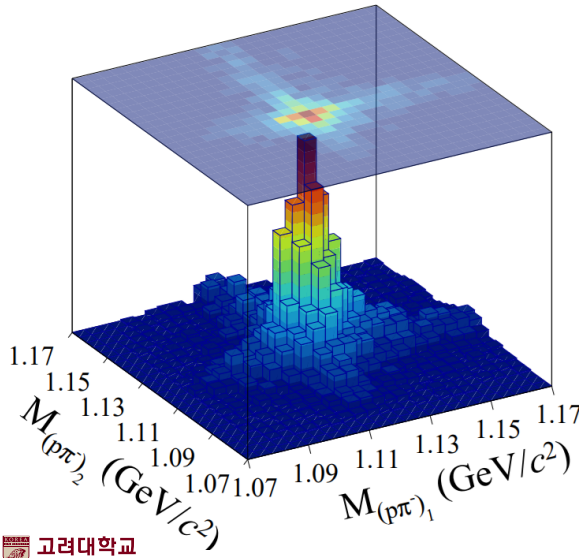
α_{two}	σ_{abs}	σ_{scat}
0.00	21.1 mb	21.6 mb
0.05	16.4 mb	20.3 mb
0.10	11.7 mb	19.1 mb

- Extended-soft-core baryon-baryon model (ESC16) [b]

[a] Y. Yamamoto, T. Tamagawa, T. Fukuda, T. Motoba, PTP 106, 363 (2001).

[b] M.M. Nagels, Th. A. Rijken, Y. Yamamoto, Phys. Rev. C 102, 054003 (2020).

$\Lambda\Lambda$ Production in $^{12}C(K^-, K^+)$ Reaction

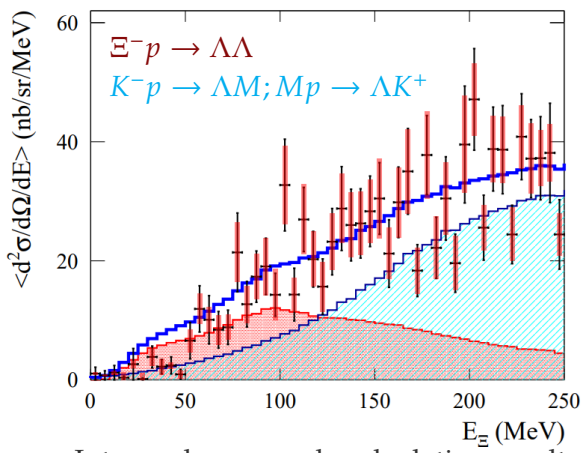


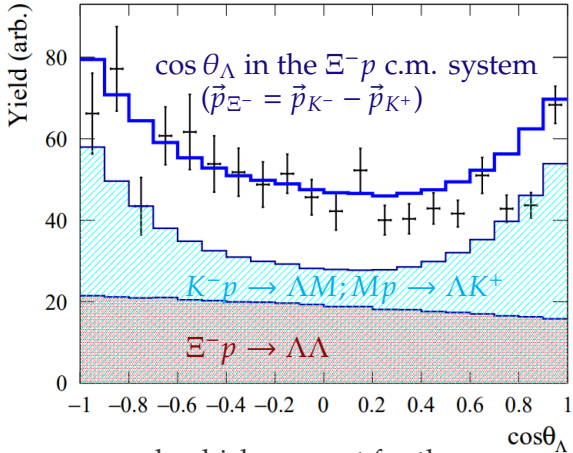
- E42 collected approximately 9×10^3 $\Lambda\Lambda$ events in the entire E_Ξ region and 1.5×10^3 events in the region associated with Ξ^- production ($E_\Xi < 250$ MeV).

$$K^- p \to \begin{pmatrix} \pi \\ \eta \\ \omega \\ \eta' \end{pmatrix} \begin{pmatrix} \Lambda \\ \Sigma \\ \Sigma^* \end{pmatrix} ; \begin{pmatrix} \pi \\ \eta \\ \omega \\ \eta' \end{pmatrix} N \to K^+ \begin{pmatrix} \Lambda \\ \Sigma \\ \Sigma^* \end{pmatrix}$$

$$K^- p \to K^+ \Xi^- ; \Xi^- p \to \begin{pmatrix} \Lambda\Lambda \\ \Xi^- p \end{pmatrix}$$

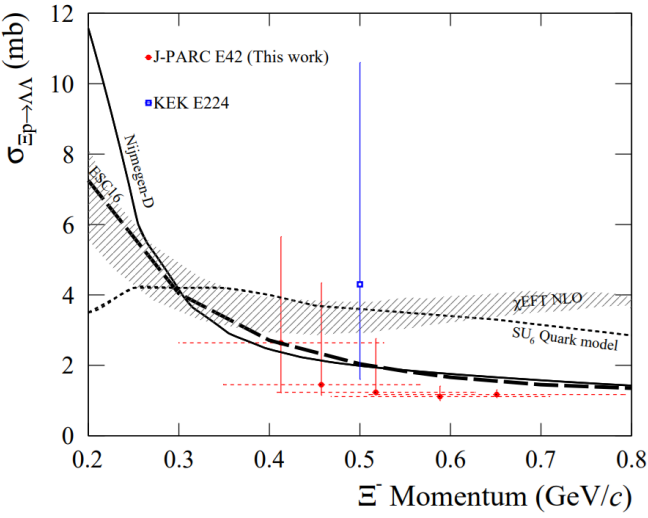
$\Lambda\Lambda$ Production in $^{12}C(K^-, K^+)$ Reaction





- Intranuclear cascade calculation results are compared, which account for the $\Xi^- p \to \Lambda\Lambda$ and two-step processes.

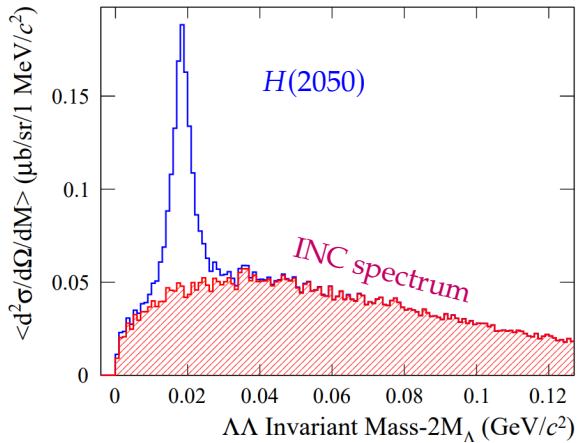
Cross Sections for $\Xi^- p \to \Lambda\Lambda$ Reaction

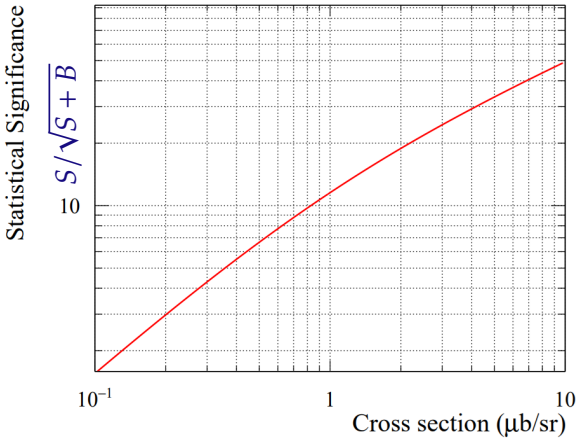


- These results agree with previous E224 results [a] and support theoretical predictions from Nijimegen-D, ESC16, [b] and SU_6 quark models.[c]
- $\bar{\sigma}$ = 1.1 mb 0.5 and 0.6 GeV/c imposes a constraint on the upper bound of the decay width of the Ξ^- particle in infinite nuclear matter, revealing $\Gamma_\Xi <\sim 0.7$ MeV ($\Gamma_\Xi \approx (v\sigma)_{\Xi^- p \to \Lambda\Lambda} \cdot (\rho_0/2)$).

[a] J. K. Ahn *et al.*, PLB 633, 214 (2006)
[b] M.M. Nagels, Th. A. Rijken, Y. Yamamoto, PRC 102, 054003 (2020).
[c] Y. Fujiwara, M. Kohno, C. Nakamoto, Y. Suzuki, PRC 64, 054001 (2001)

Simulated ΛΛ Mass Spectrum





- We are nearing the final step in opening the box.

We are hoping to open the box for our presentation at HYP25.