Observation of $\Lambda\Lambda$ Production in the Reaction (K^-, K^+) with HypTPC at J-PARC

Double Strangeness Systems with E42 Detector

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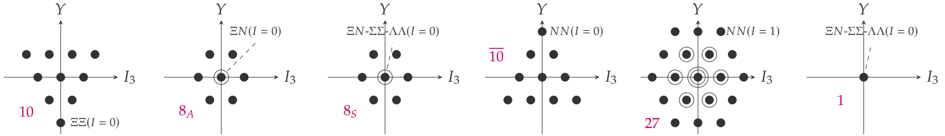
Doubly Strange Dibaryon Systems and H Particle

$$\underbrace{\Lambda\Lambda}_{I=0} \qquad \underbrace{\Xi N}_{I=0,\,1} \qquad \underbrace{\Lambda\Sigma}_{I=0,\,1} \qquad \underbrace{\Sigma\Sigma}_{I=0,\,1,\,2}$$



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

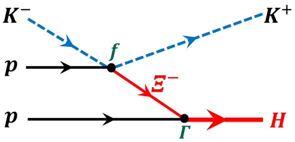
$$\mathscr{H}_{\text{eff}} \propto -\sum_{i\neq j}^{N} \{\vec{\lambda}\vec{\sigma}\}_i \cdot \{\vec{\lambda}\vec{\sigma}\}_j = 8N - \frac{1}{2}C_6^N + \frac{4}{3}S_N(S_N+1).$$

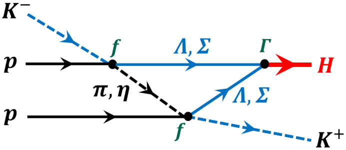
- For 6 quarks, the color-spin interaction energies are

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

The History of H-Dibaryon Searches

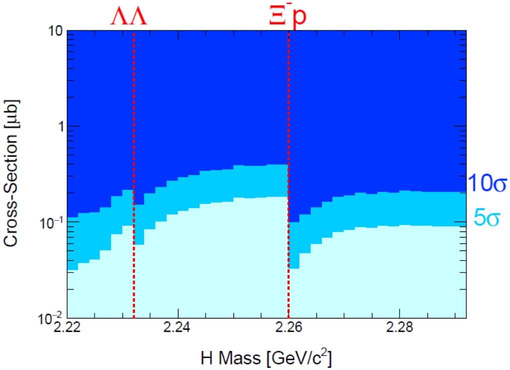
1977 • Deeply-bound di-hyperon predicted by R. Jaffe
1980-2000 • No evidence for the deeply-bound H from KEK, BNL,
• and CERN experimental efforts by more than 80 MeV
2001 • Mass constraint from observation of $^{6}_{\Lambda\Lambda}$He (E373)
1998,2007 • Enhanced $\Lambda\Lambda$ production near threshold was
• reported from E224 and E522 at KEK-PS.
2011 • LQCD calculations predict the H-dibaryon near $m_{\Lambda\Lambda}$
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 the H-dibaryon
• very close to ΞN threshold ($m_\pi \approx 146$ MeV)
2021 • **J-PARC E42 has successfully completed with HypTPC.**
2024 • We are about to see what we would see in the E42 dataset.



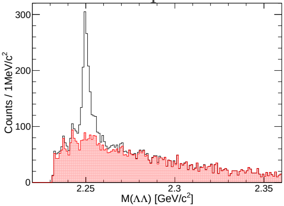


H-Dibaryon Search at J-PARC : E42

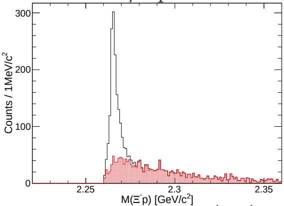
- E42 aims at searching for an H-dibaryon in $\Lambda p \pi^-$, $\Lambda\Lambda$, and $\Xi^- p$ from $^{12}\mathrm{C}(K^-, K^+)$ at 1.8 GeV/c.
- E42 has a good sensitivity over a broad range of the H mass.



Simulated $\Lambda\Lambda$ Spectrum for $H(2250)$



Simulated $\Xi^- p$ Spectrum for $H(2265)$



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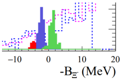
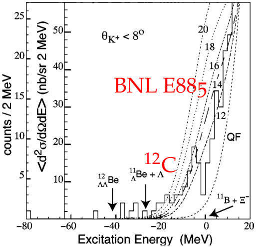
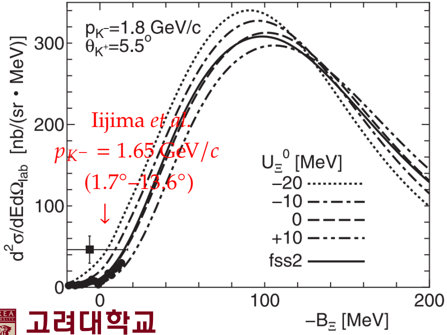
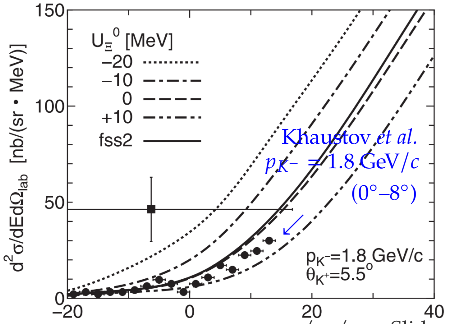
Ξ Nuclear Potential

- Spectral response of the $-B_\Xi$ spectrum for $^{12}C(K^-, K^+)$ provides some information on the WS potential depth V_0^Ξ, which ≈ −14 MeV (DWIA) but ≈ 0 MeV (SCDW) analyses.
- High-resolution Ξ^- nuclear state measurement 

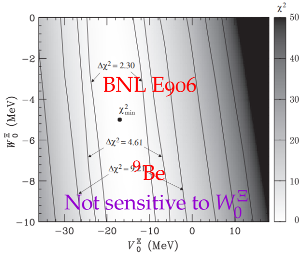
with E70 detector







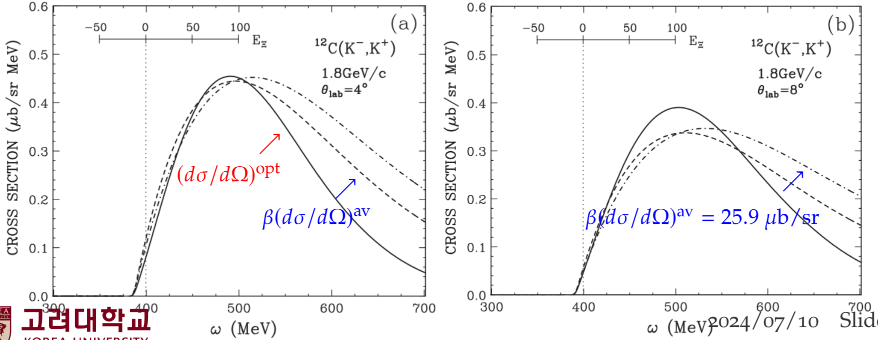
Ξ Nuclear Potential



- Ξ spectrum of $^9\mathrm{Be}(K^-, K^+)$ within DWIA using the optimal Fermi-averaged $K^- p \longrightarrow K^+ \Xi^-$ amplitude favors $V_0^\Xi \approx -17$ MeV[1].
- The same study on $^{12}\mathrm{C}(K^-, K^+)$ shows strong energy and angular dependencies[2].

[a] T. Harada and Y. Shirabayashi, Phys. Rev. C 103, 024605 (2021).

[b] T. Harada and Y. Shirabayashi, Phys. Rev. C 102, 024618 (2020).



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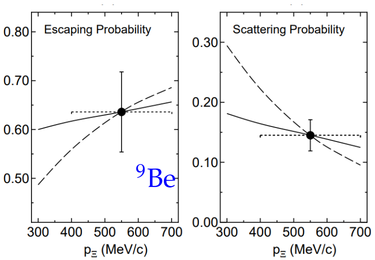
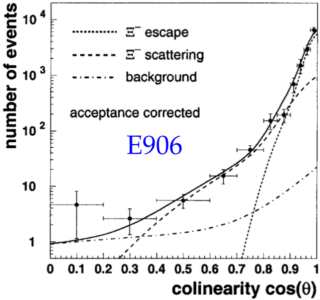
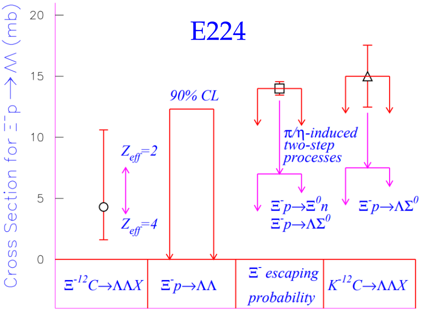
ΞN Interaction with ^{9}Be(K^-, K^+) and ^{12}C(K^-, K^+)





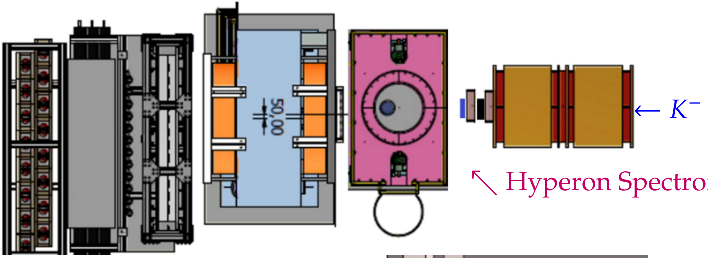


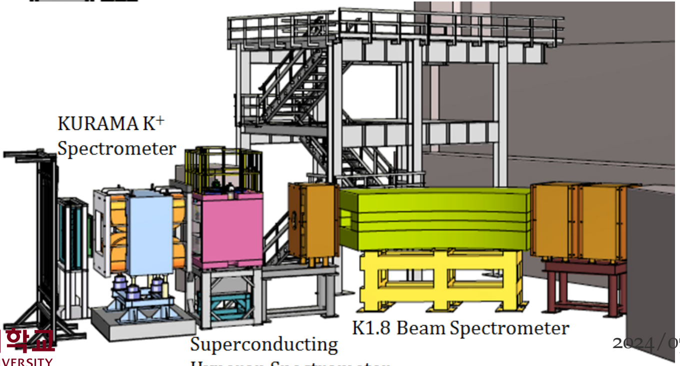
- $\Xi^- N$ elastic cross section $\sigma \approx 30$ mb at ~ 0.55 GeV$/c$ [1].
- $\sigma(\Xi^- p \to \Xi^- p) =$ 24 mb at 90% CL and $\sigma(\Xi^- p \to \Lambda\Lambda) = 4.3^{+6.3}_{-2.7}$ in $p_\Xi = 0.2$ to 0.8 GeV$/c^2$.

[a] T. Tamagawa *et al.*, Nucl. Phys. A 691, 234c (2001); Y. Yamamoto, T. Tamagawa, T. Fukuda, T. Motoba, PTP 106, 363 (2001).

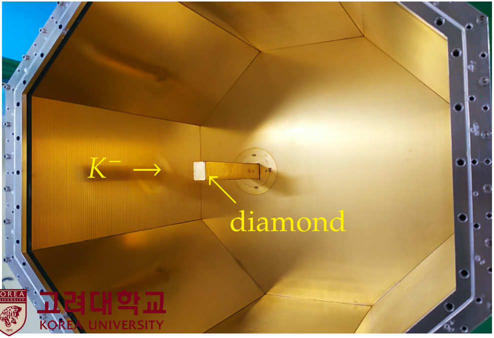
[b] J.K. Ahn *et al.*, Phys. Lett. B633, 214 (2006).

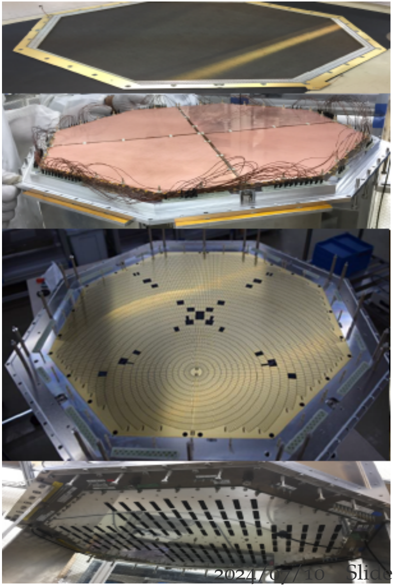
E42 Detector at J-PARC K1.8 Beamline





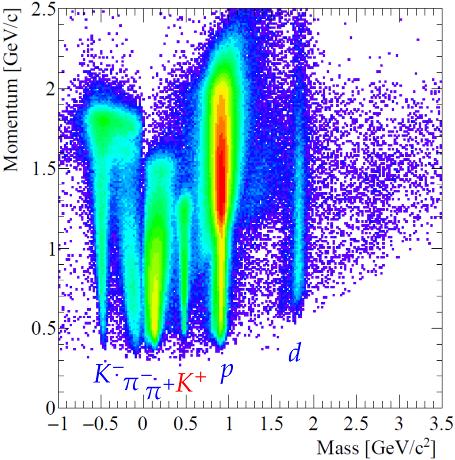
Superconducting Hyperon Spectrometer

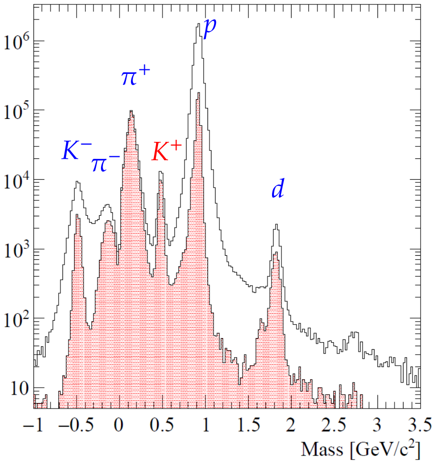




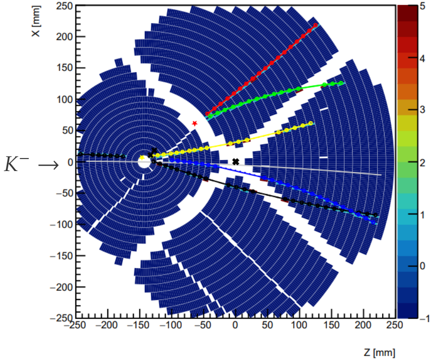
Scattered Particles at Forward Angles

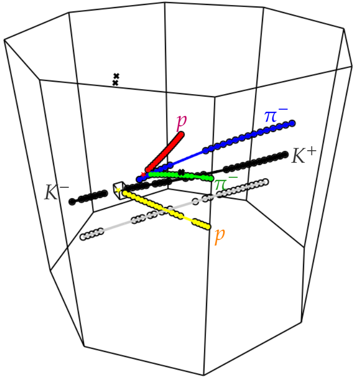
- We reconstructed the masses and momenta for scattered particles successfully with the forward K^+ spectrometer.

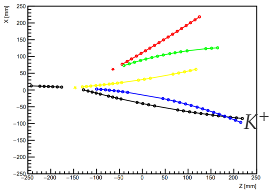


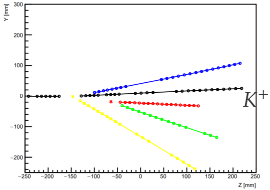


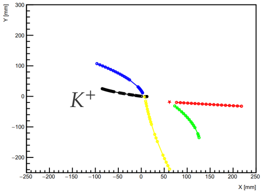
Charged Particles at Large Angles in HypTPC



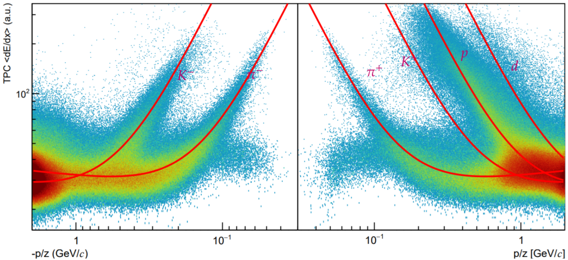


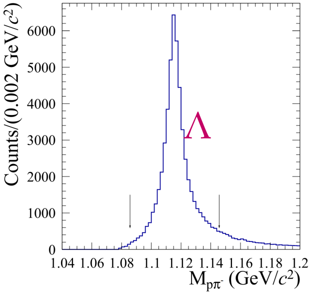


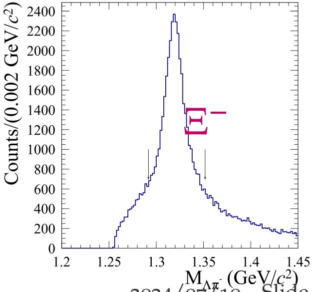




Particle Identification with HypTPC



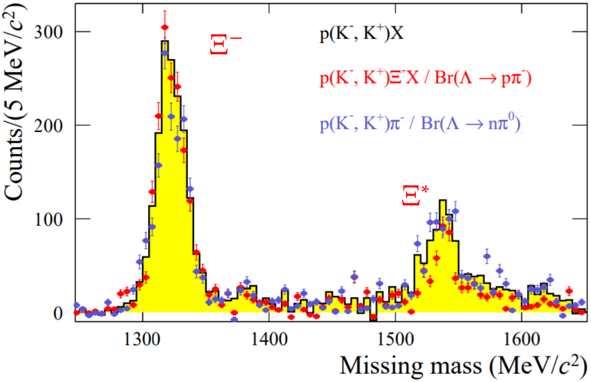


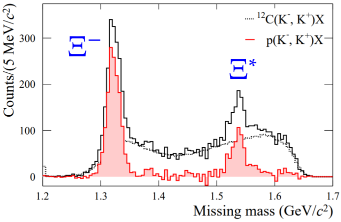


- $\langle dE/dx \rangle_{20\%\ \text{truncated}}$ vs p/z for reconstructed HypTPC tracks in the diamond target dataset (C(K^-, K^+)X reactions).
- $\sigma_{dE/dx}/\langle dE/dx \rangle \sim$ 20% for the range $0.40 < p_T < 0.45$ GeV/c.

Missing-Mass Spectrum for $p(K^-, K^+)X$ Reactions

- Missing-mass spectrum for $p(K^-, K^+)X$ reactions is reproduced by considering the reconstruction efficiencies for Ξ^- decays with visible and invisible Λ decays, which are obtained from an independent Monte Carlo simulation study.



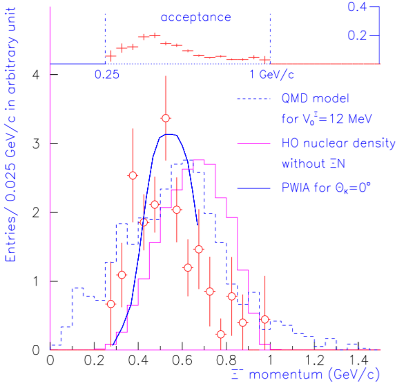


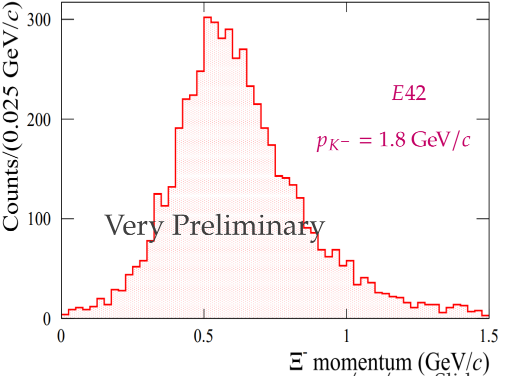
- ^{12}C contribution subtracted from the spectrum with a CH_2 target.

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

- The $\Xi^- \rightarrow \Lambda\pi^-$ and its subsequent $\Lambda \rightarrow p\pi^-$ visible decays are reconstructed using HypTPC track information.

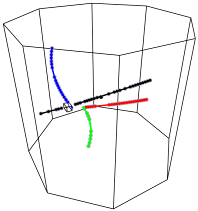
E224 $p_{K^-} = 1.65$ GeV/c



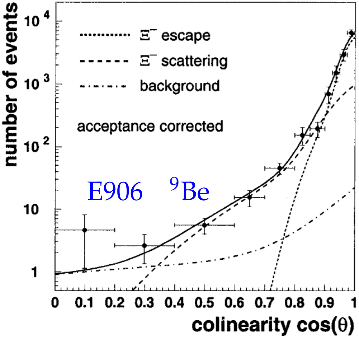


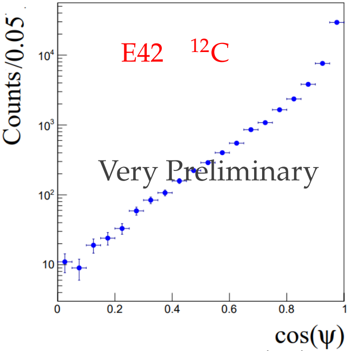
$\Xi^- N$ Scattering in the $^{12}C(K^-, K^+)$ Reaction

- Colinearity angle $\cos\psi = (\vec{p}_{K^-} - \vec{p}_{K^+}) \cdot \vec{p}_{\Xi}^{\,rec}$
- $\sigma_{\Xi^- N} = 30.7 \pm 6.7^{+3.7}_{-3.6}$ mb for $\langle p_\Xi \rangle = 0.55$ GeV$/c$ and $R(\sigma_{\Xi^- p}/\sigma_{\Xi^- n}) \approx 1.1$ in the eikonal approximation[a].



[a] T. Tamagawa *et al.*, Nucl. Phys. A 691, 234c (2001).





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Individual Elementary Processes in $^{12}\mathrm{C}(K^-, K^+)$

- One and two-step processes may contribute to the $^{12}\mathrm{C}(K^-, K^+)$ reactions but the previous intranuclear cascade model calculation[1] needs further improvements to reproduce the experimental data from E176[2].

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[a] Y. Nara, A. Ohnishi, T. Harada, A. Engel, Nucl. Phys. A 614, 433 (1997).
[b] T. Iijima *et al.*, Nucl. Phys. A 546, 588 (1992).

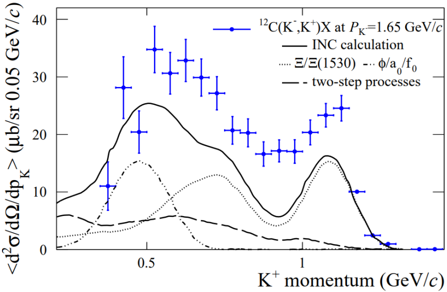
$$K^- p \to K^+ \begin{pmatrix} \Xi^- \\ \Xi(1535)^- \end{pmatrix}$$

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

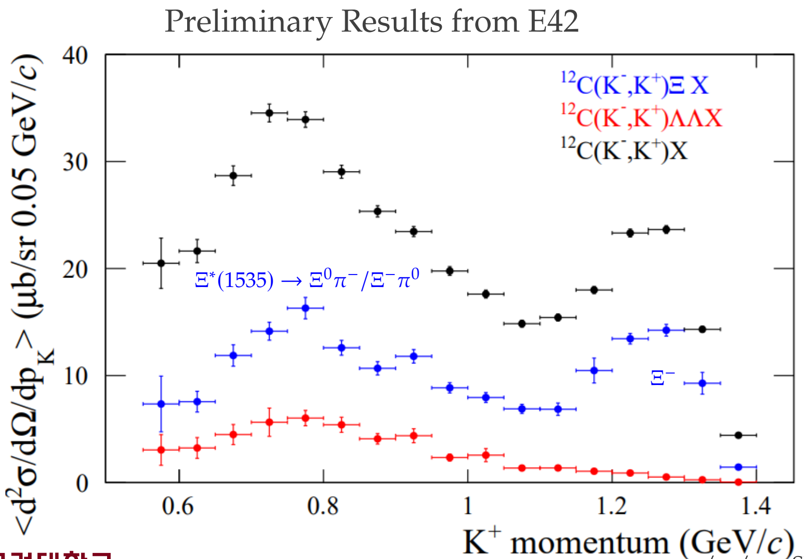
$$K^- p \to K^+ \Xi^- ; \underbrace{\Xi^- p \to}_{\mathbf{H}} \begin{pmatrix} \Lambda\Lambda \\ \Xi^- p \end{pmatrix}$$

$$K^- p \to \begin{pmatrix} \phi \\ a_0 \\ f_0 \end{pmatrix} \Lambda, \quad \text{where} \;\; \phi, a_0, f_0 \to K^+ K^-$$

E176 $(p_{K^-} = 1.65\ \mathrm{GeV}/c)$



Cross sections $d^2\sigma/d\Omega dp_{K^+}$ for $^{12}C(K^-, K^+)$ Reaction



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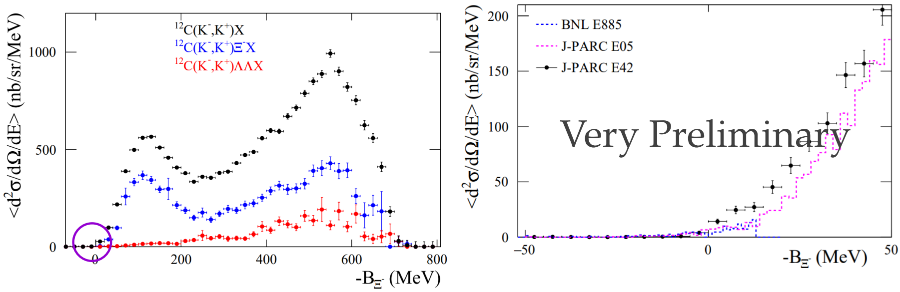
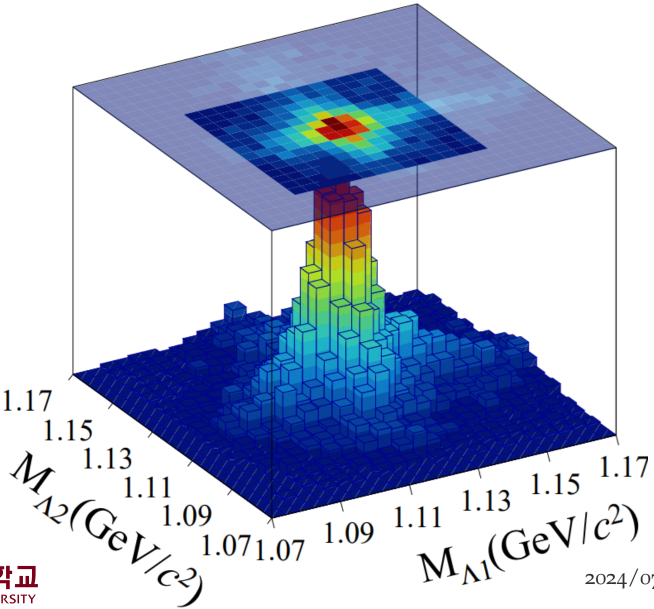
Binding Energy Spectrum for $^{12}C(K^-, K^+)X$

$$K^- + ^{12}C \rightarrow K^+ + (\Xi^- + ^{11}B)$$



- E42 can offer critical information on individual processes involved in the $^{12}C(K^-, K^+)$ reaction with large acceptance despite moderate energy resolution.
- The processes include reactions with the emission of Ξ^-, $\Xi^- p$, $\Lambda\Lambda$, and hypernuclear decay particles such as two pions.

$\Lambda\Lambda$ Production in the (K^-, K^+) Reactions



Summary

- E42 will soon open the box for the *H*-dibaryon search.
- E42 can also offer critical information on individual processes involved in the $^{12}C(K^-, K^+)$ reactions with large acceptance despite moderate energy resolution.
- Additionally, E42 has a good dataset for extensive studies of kaonic nuclei (F. Oura, Wed 14:40 M5) and K^* production in $^{12}C(K^-, p)$ reactions.

Proposal for J-PARC 50 GeV Proton Synchrotron

Double ϕ Production in $\bar{p}p$ Reactions near Threshold