H-Dibaryon Search near the $\Lambda\Lambda$ and $\Xi^{-}p$ Thresholds at J-PARC

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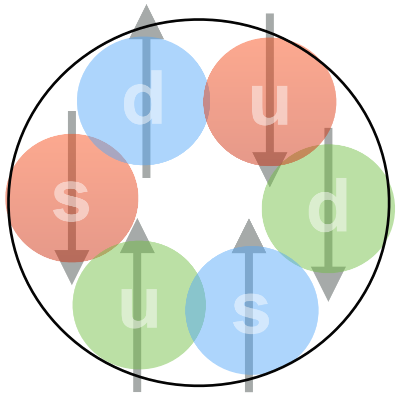
for the J-PARC E42 Collaboration

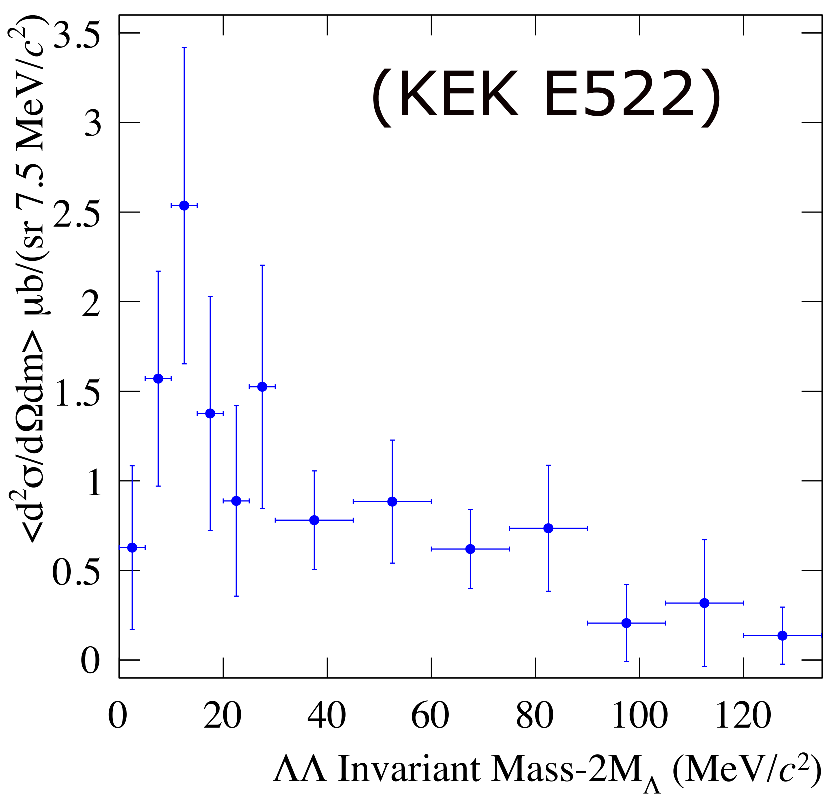
J-PARC HypTPC Collaboration

H-Dibaryon

- SU(3) flavor-singlet hexaquark state ($\mathbf{uuddss}, \mathbf{I}=\mathbf{0}, \mathbf{J^P}=\mathbf{0^+}$), which is the most promising hexaquark candidate due to QCD color magnetic force.



- $\Lambda\Lambda - \Xi N - \Sigma\Sigma$ coupled channel system
- A constraint on the mass: $M_H > 2M_{\Lambda\Lambda} - B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{6}\mathrm{He})$



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

- 72 ΛΛ events with a moderate mass resolution of $\sigma(M_{\Lambda\Lambda})$ = 5–15 MeV/c^2.
- The upper limit on the H-Dibaryon production cross section between ΛΛ and $\Xi^- p$ threshold is

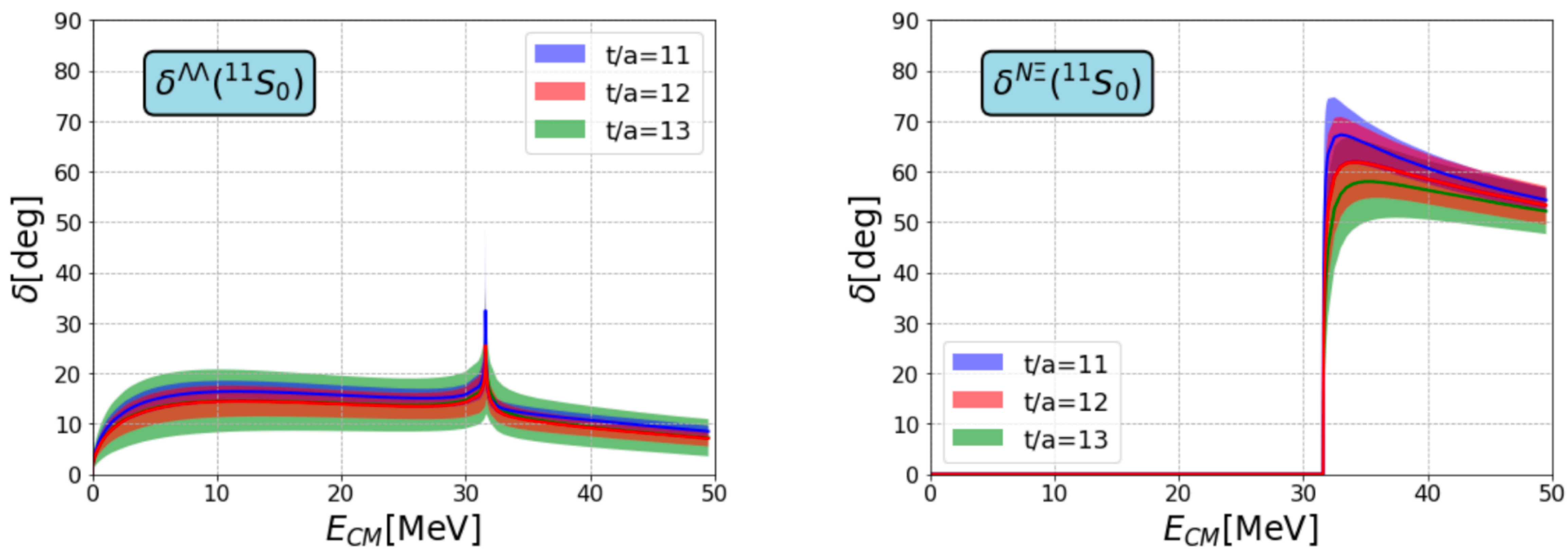
$$d\sigma/d\Omega_L(\mathbf{H}) = 2.1 \pm 0.6 \pm 0.1\ \mu\mathrm{b/sr}\ (90\,\%\ \mathrm{C.L.})$$

*C.J. Yoon et al., Phys. Rev. C 75 (2008) 022201

Recent Lattice QCD results

- Coupled channel ($\Lambda\Lambda$, ΞN) analysis with the flavor SU(3) breaking (n_f = 2+1, $m_\pi \simeq$ 146 MeV)

*K.Sasaki for the HALCollab.,NPA 998 (2020) 121737

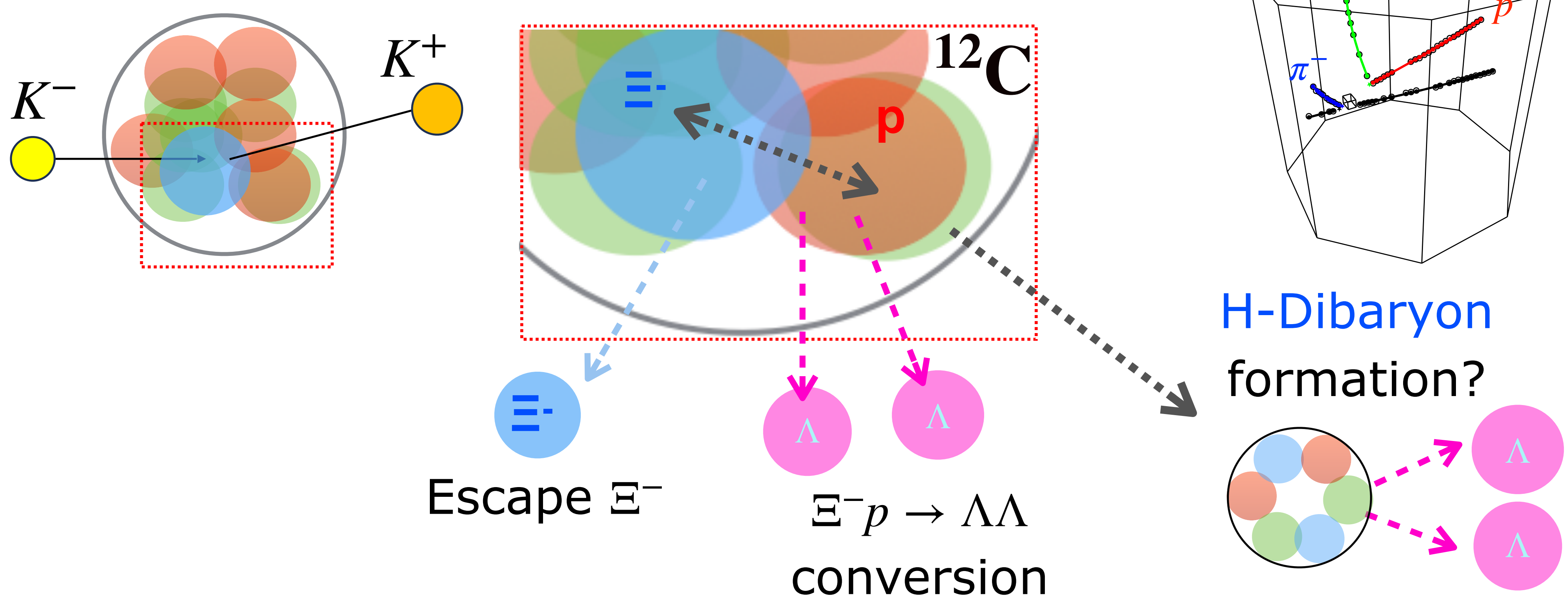


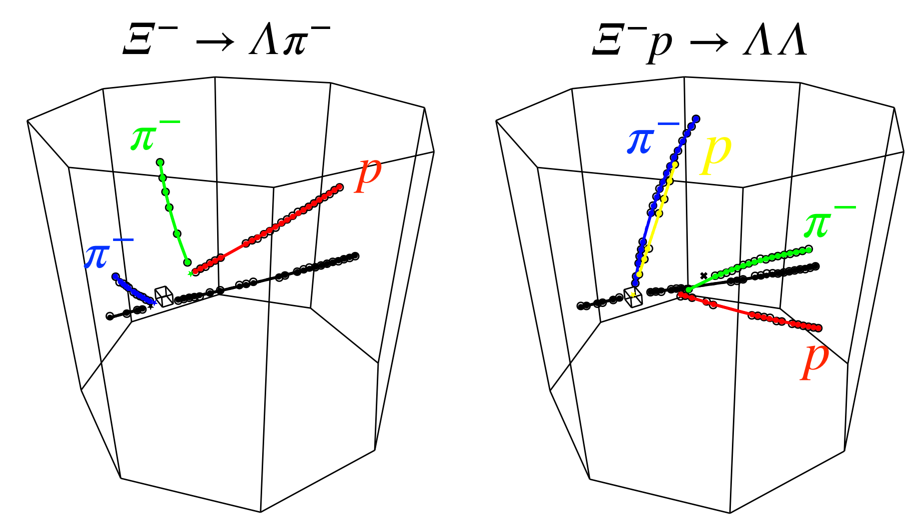
Sharp peak just before ΞN threshold

J-PARC E42: H-Dibaryon search via $^{12}\mathrm{C}(K^-, K^+)$ reaction

- Invariant-mass measurement of $\Lambda p\pi^-$, $\Lambda\Lambda$ and $\Xi^- p$ systems with HypTPC
- Measurement of double strangeness production in the $^{12}\mathrm{C}(K^-, K^+)X$ reaction at 1.8 GeV/c K^- beam.
- The ΞN interaction provides the essential doorway to H-dibaryon formation.

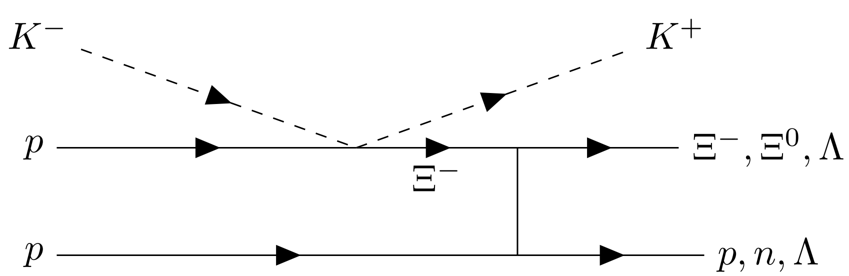
Processes following Ξ^- Production in $^{12}\mathrm{C}$

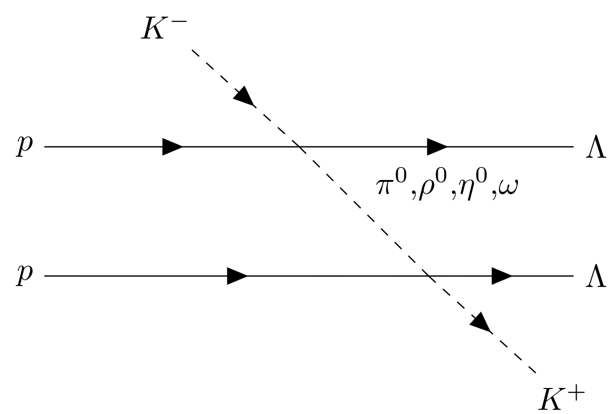


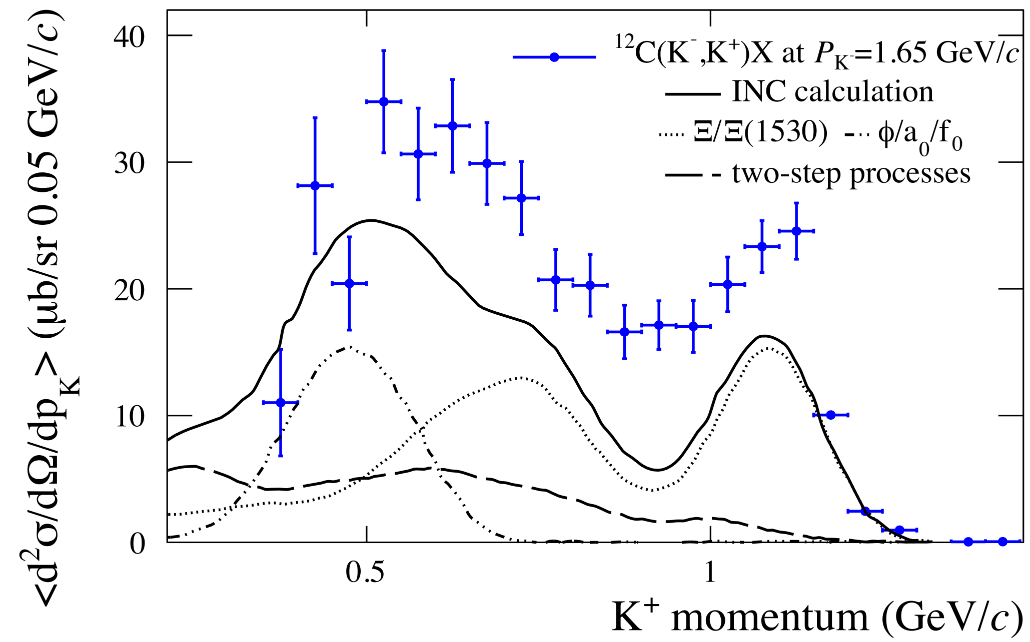


Individual Elementary Processes in $^{12}\mathrm{C}(K^-, K^+)$

- Processes of double-strangeness exchange in $^{12}\mathrm{C}(K^-, K^+)$ reaction







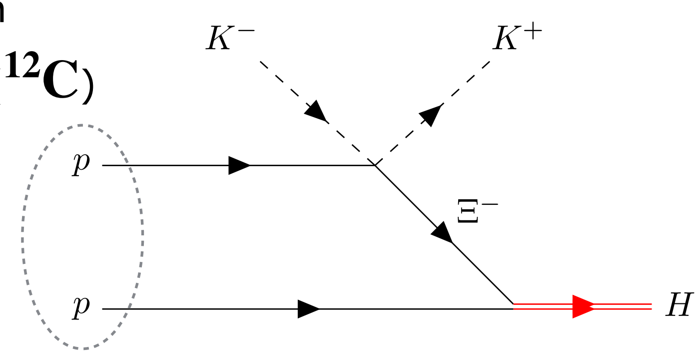
*T. Iijima et al., Nucl. Phys. A 546, 588 (1992)

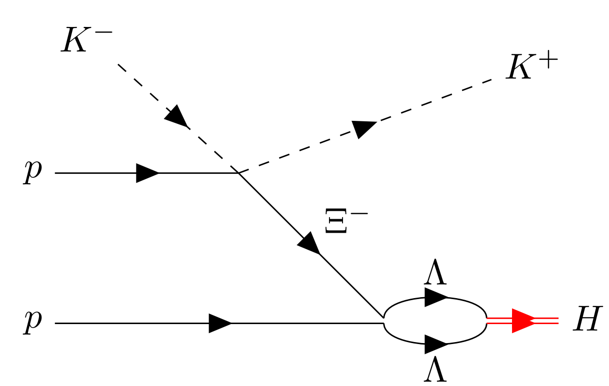
*Y. Nara, A. Ohnishi, T. Harada, A. Engel, Nucl. Phys. A 614, 433 (1997)

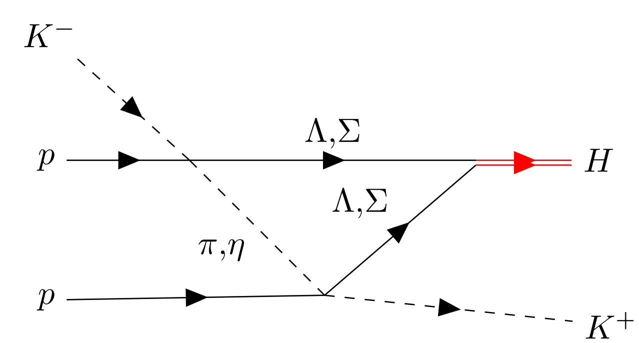
- Possible H production processes on a diproton pair via (K^-, K^+) reaction (Lowest order)

*A.T.M. Hertz and C.B. Dover, Phys. Rev. D28, 450 (1983)

Carbon target(^{12}C)





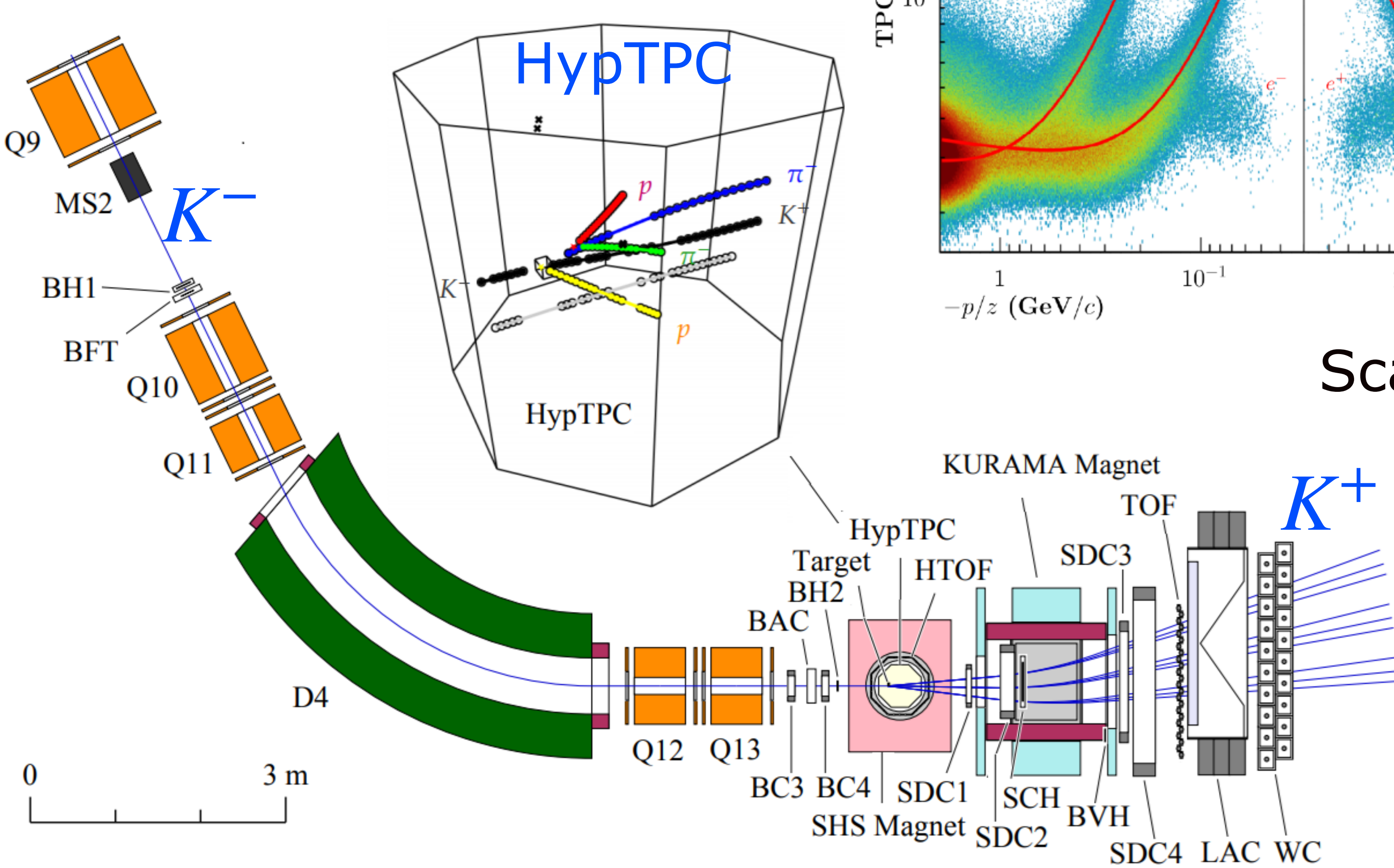


There is <u>no combinatorial background</u> in the E42 data!

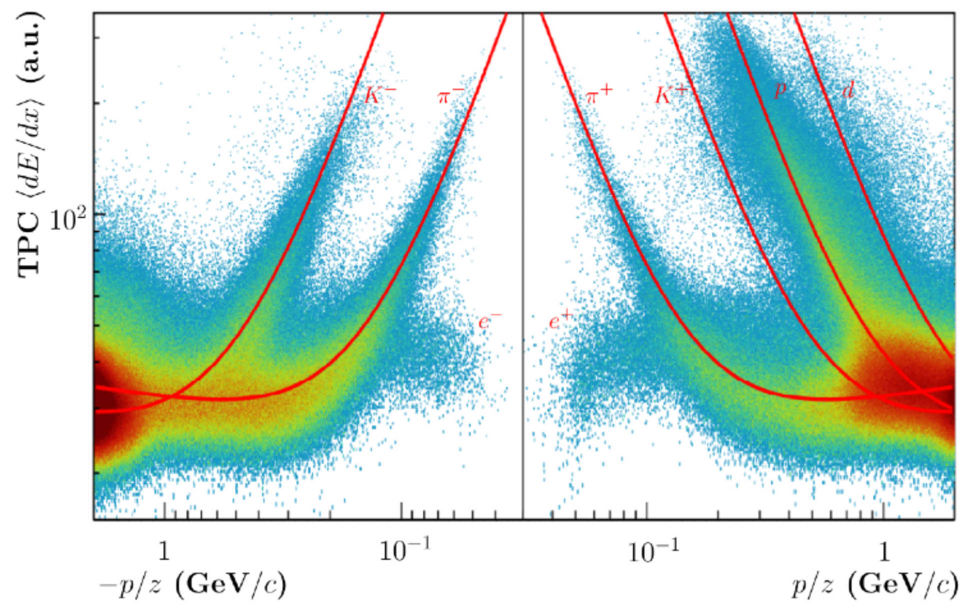
J-PARC E42 Detector and Particle Identification

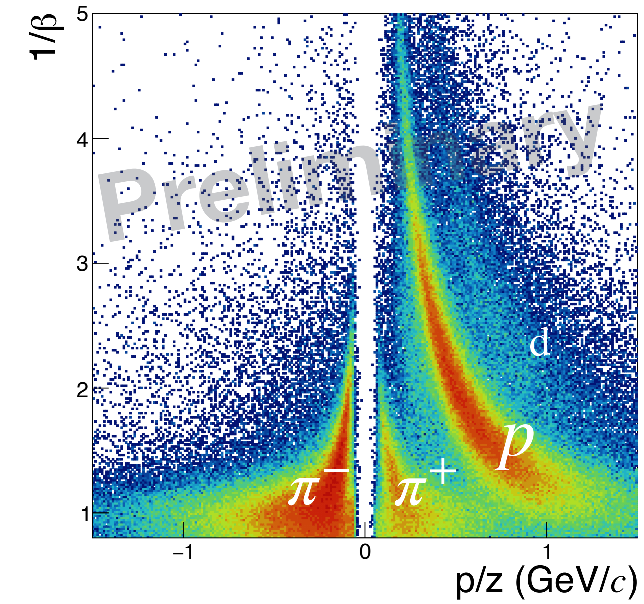
E42 detectors@

J-PARC K1.8 beamline

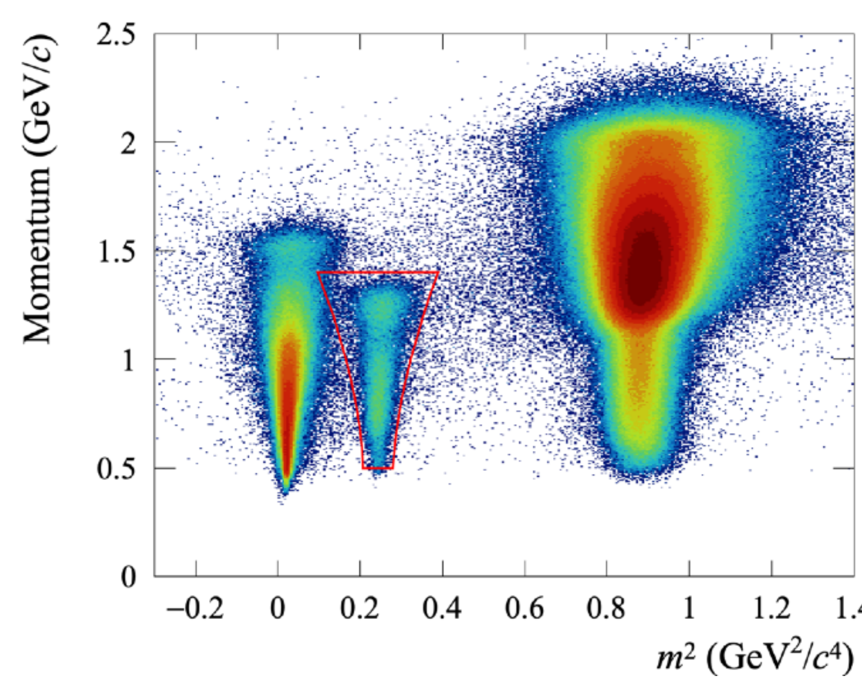


PID with HypTPC dE/dx and TOF





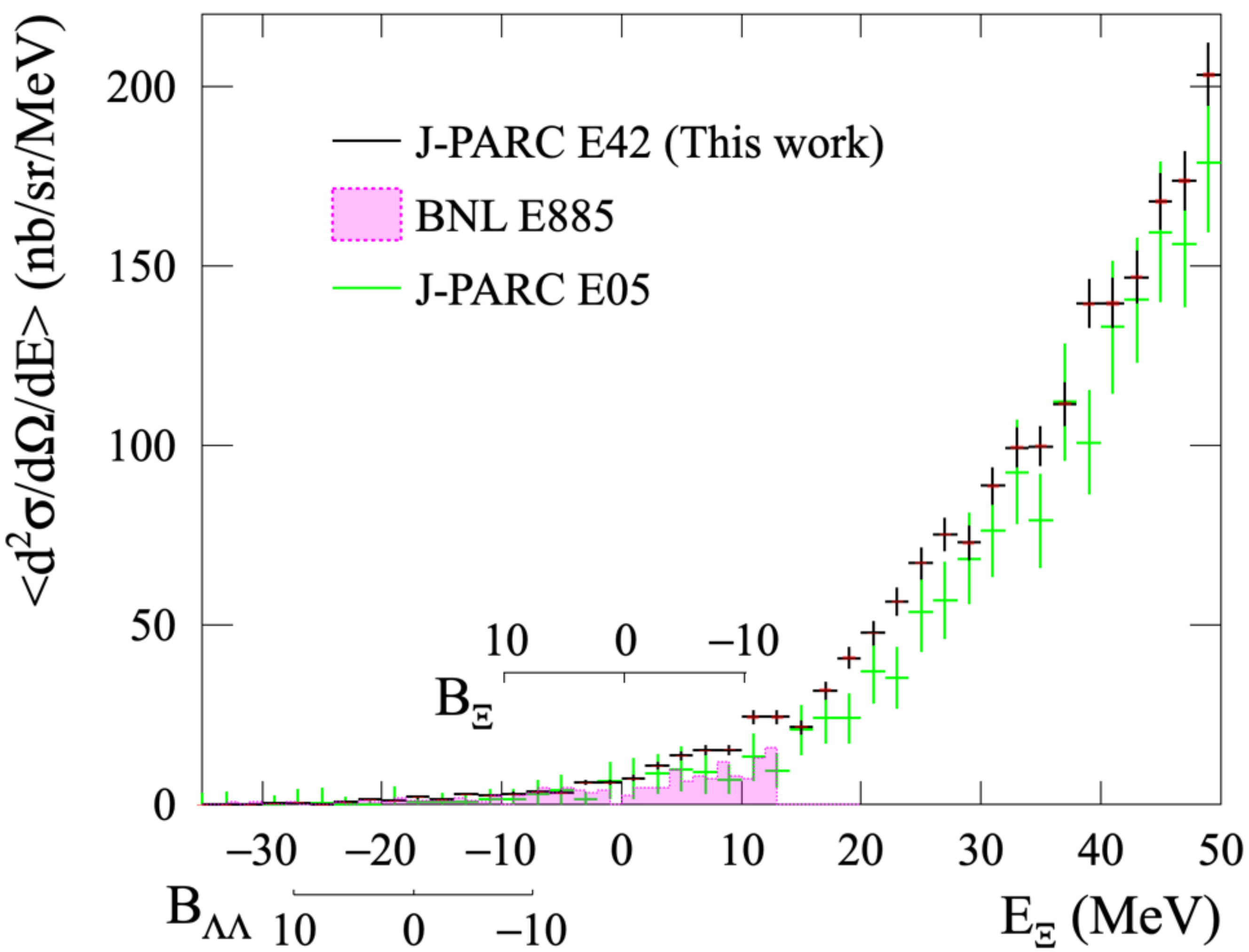
Scattered K^+ at forward angles

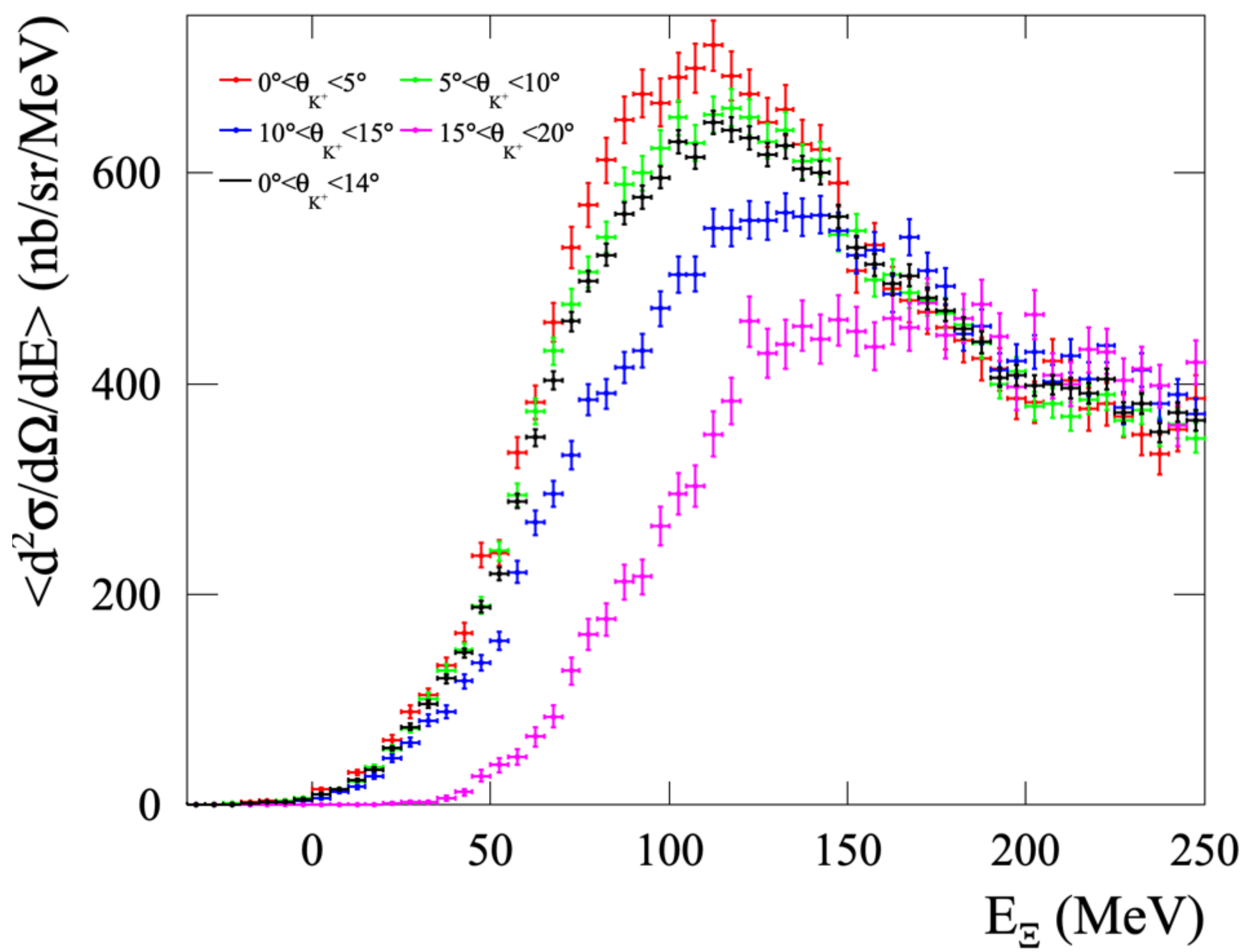


Ξ^- Excitation Energy Spectra for the inclusive ${}^{12}\mathrm{C}(K^-, K^+)$ reaction

$$\mathbf{E}_\Xi = \mathbf{M_X} - \mathbf{M}(\Xi^-) - \mathbf{M}({}^{11}\mathbf{B}) \text{ where } \mathbf{M_X} : {}^{12}\mathbf{C}(K^-, K^+)\mathbf{X}$$

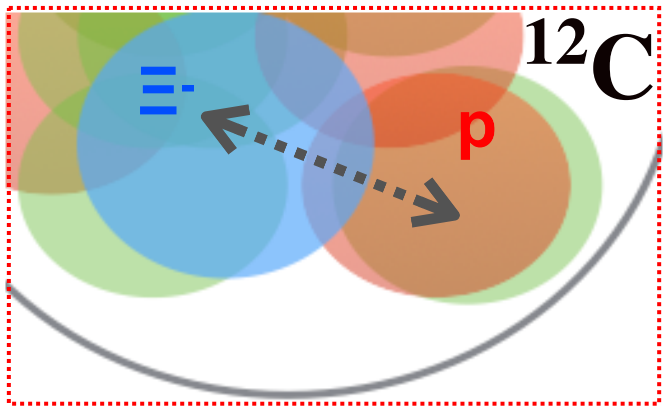
- **The inclusive** ${}^{12}\mathrm{C}(K^-, K^+)$ **spectrum** provides the reference for interpreting the exclusive the ΞN channels.

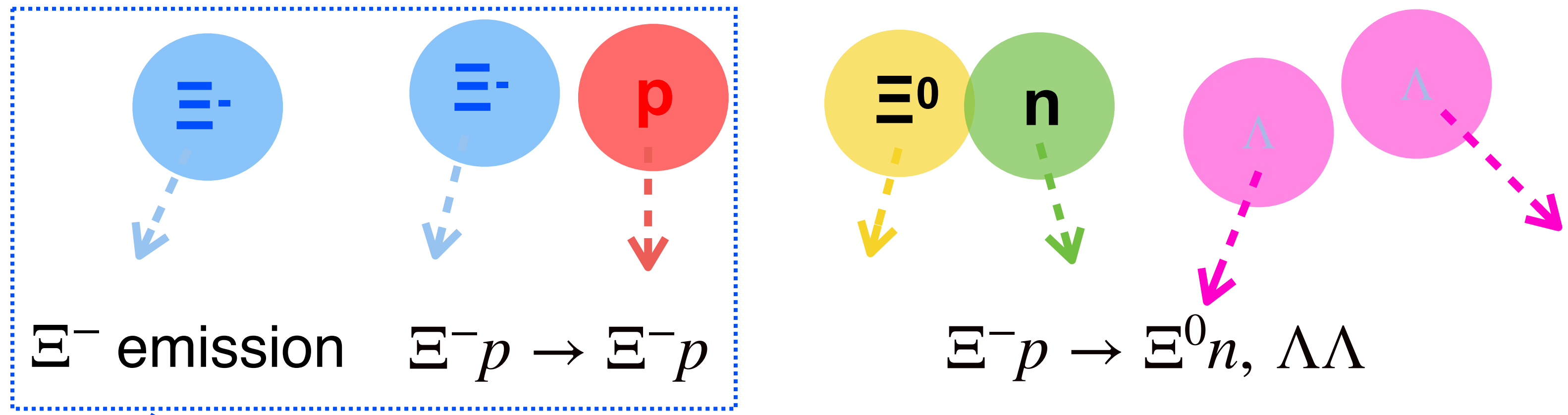


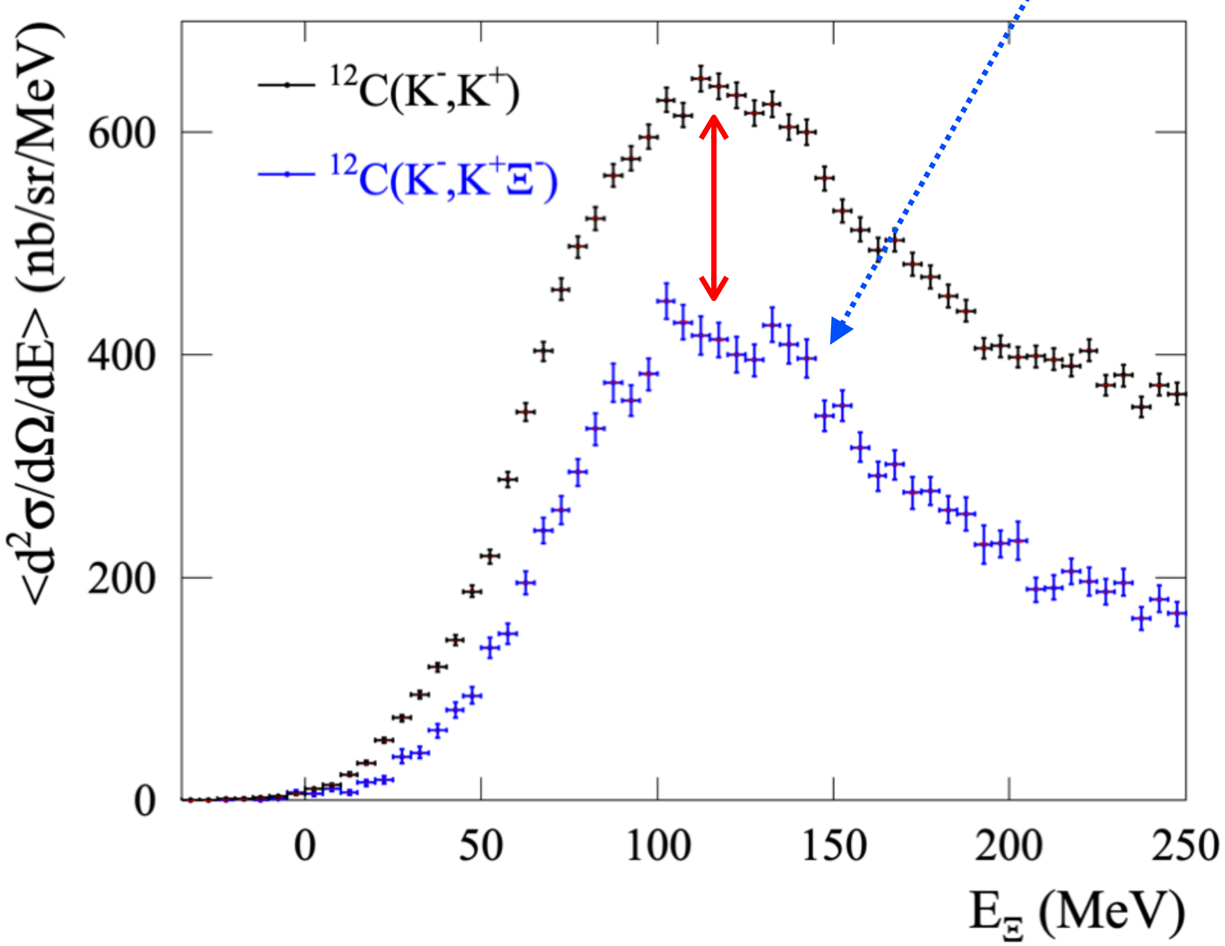


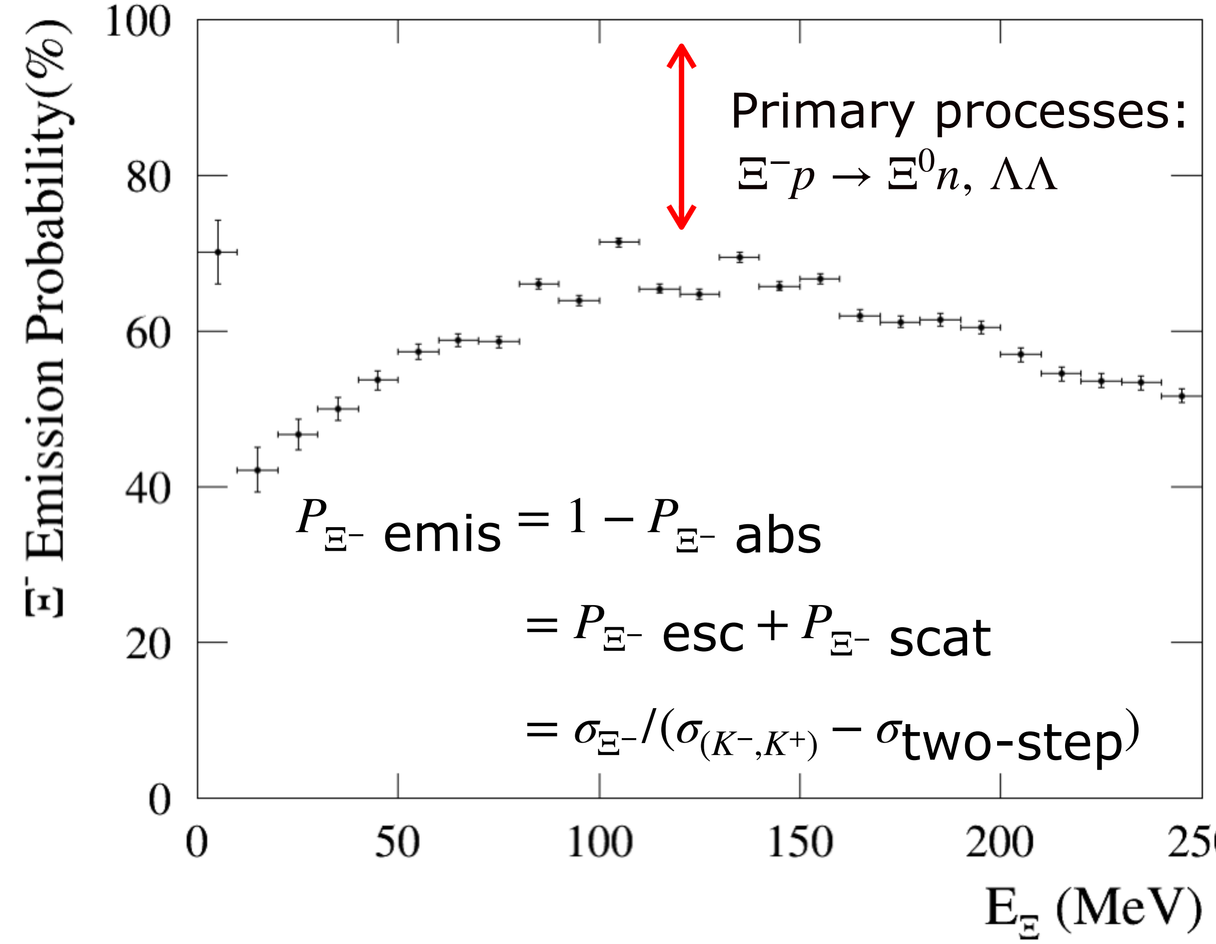
*W.S. Jung *et al.*, Prog. Theor. Exp. Phys. ptaf064 (2025).

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



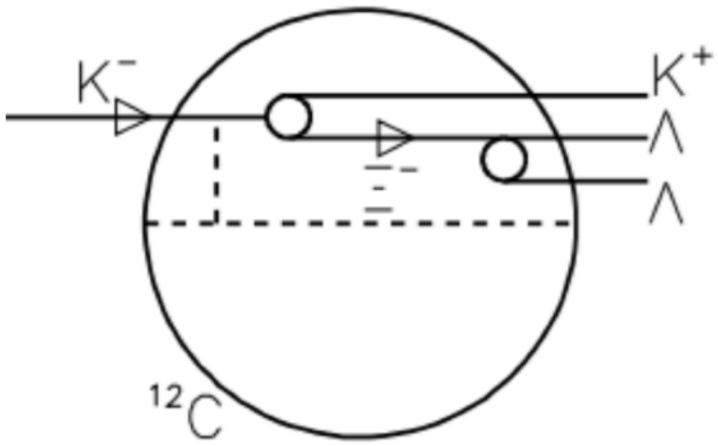






Ξ^- escaping probability and $\Xi^- p$ inelastic scattering cross section

- The effective number of the ΞN process calculated using a classical approach in the eikonal approximation.



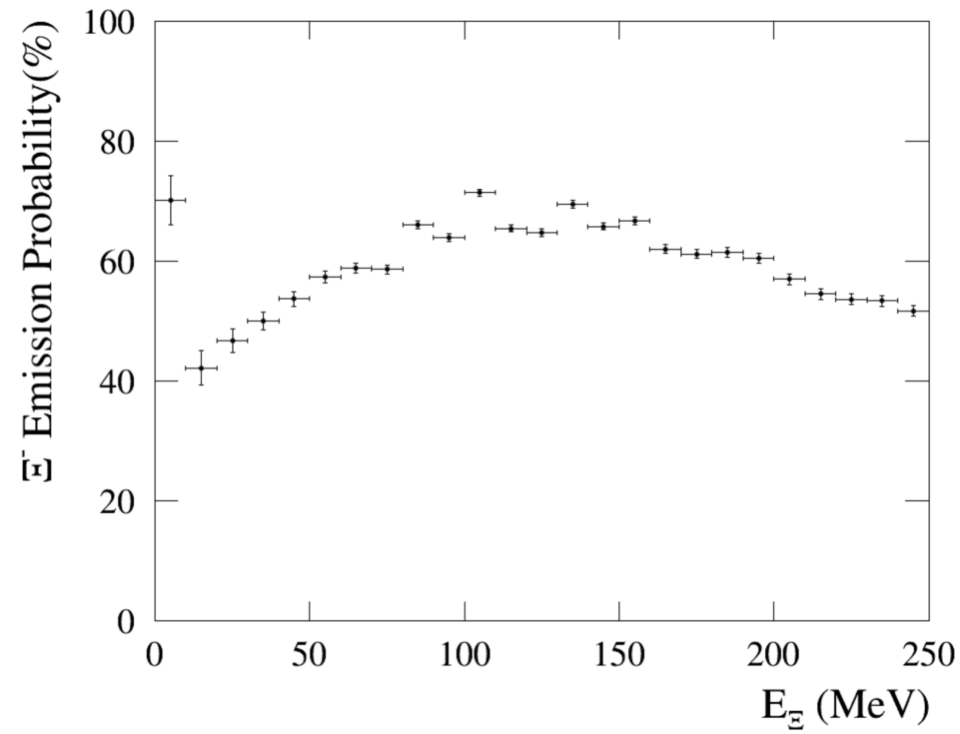
$$N_{\Xi N} = \int_0^\infty 2\pi b db \int_{-\infty}^{+\infty} dz \rho(\sqrt{b^2+z^2}) F(b,z) \left[1 - \exp\left\{ \bar{\sigma}_{\Xi N} \int_z^{+\infty} dz' \rho(\sqrt{b^2+z'^2} \right\} \right],$$

$$N_{KK} = \int_0^\infty 2\pi b db \int_{-\infty}^{+\infty} dz \rho(\sqrt{b^2+z^2}) F(b,z)$$

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

$\bar{\sigma}(K^-N) \; = \; 28.9\,\mathrm{mb},\; \bar{\sigma}(K^+N) \; = \; 19.4\,\mathrm{mb}.$

P_{Ξ^-} emis $= 1 - N_{\Xi N}/N_{KK}$

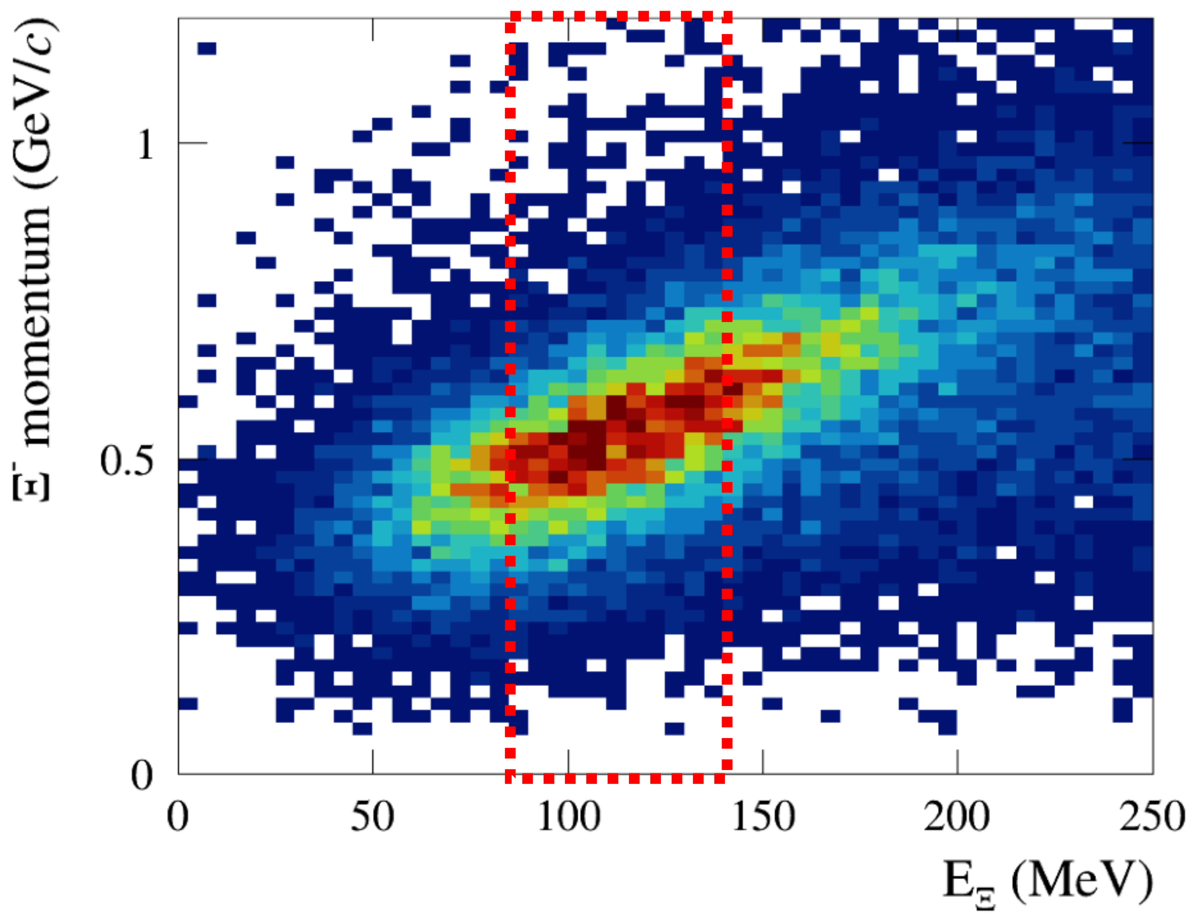


$\Xi^{-}p$ inelastic scattering in the $^{12}\mathrm{C}(K^{-}, K^{+})$ reaction

$\mathbf{E_{\Xi}} = \mathbf{M_X} - \mathbf{M}(\Xi^{-}) - \mathbf{M}(^{11}\mathbf{B})$ where $\mathbf{M_X}$: $^{12}\mathbf{C}(K^{-}, K^{+})\mathbf{X}$

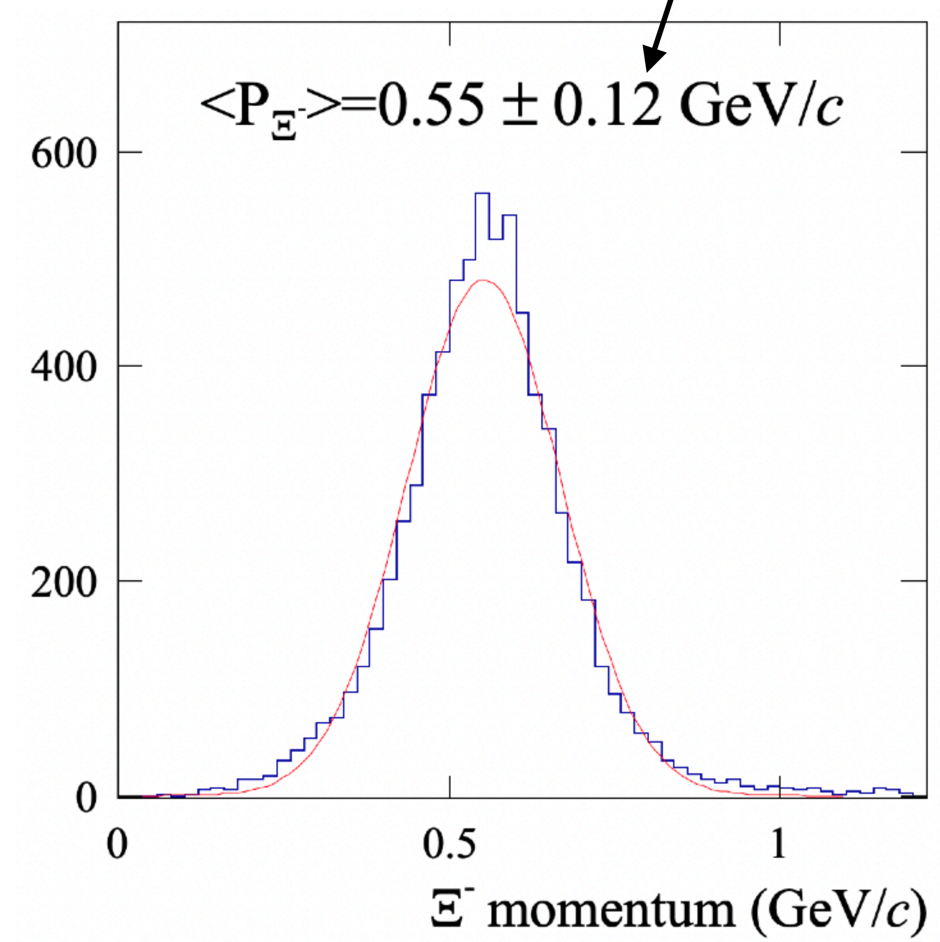
- Momentum of Ξ^{-}($\mathbf{P}_{\Xi^-}$) is measured as a function of Ξ^{-} energy($\mathbf{E_{\Xi}}$)

$\mathbf{P}_{\Xi^-}$ reconstructed using the HypTPC



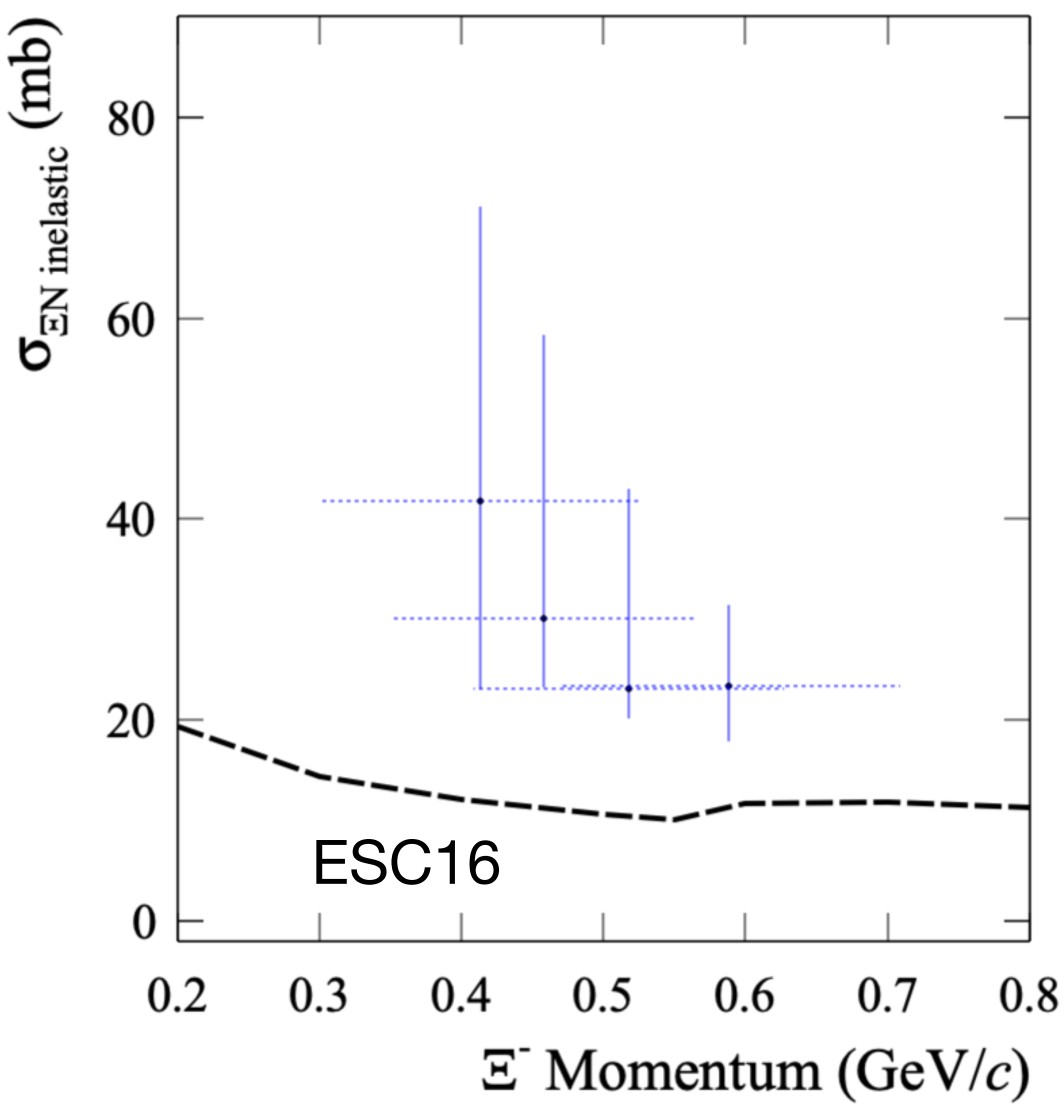
$\mathbf{E_{\Xi}}$ obtained from (K-,K+)
missing-mass spectroscopy

Momentum spread of Ξ^{-}(1σ)



$\Xi^- p$ inelastic scattering in the $^{12}\mathrm{C}(K^-, K^+)$ reaction

Dotted lines correspond to
momentum spread of Ξ^- (1σ)



- This work:42 - 23 mb($0.4 < p_{\Xi^-} < 0.6$ GeV/c)
- Nijmegen-D model calculation based on the BNL E906 data at p_{Ξ^-} = 0.55 GeV/c
  (α_{two}: a fraction of two-step processes)

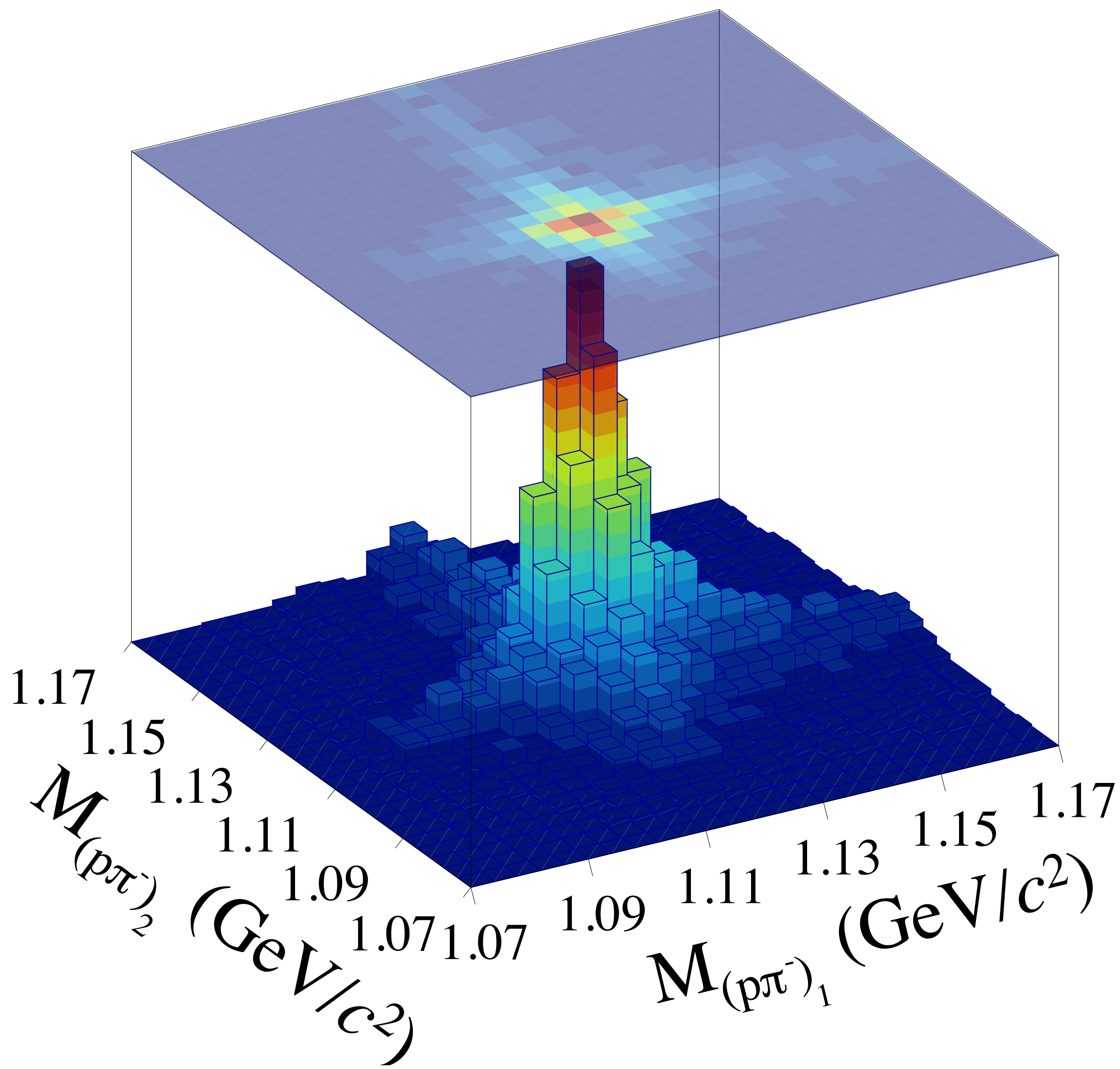
*Y.Yamamoto, et al., PTP106,363 (2001).

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

Primary processes: $\Xi^- p \rightarrow \Xi^0 n,\ \Lambda\Lambda$

Possible contribution from H-dibaryon formation

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



- J-PARC E42 accumulated ~9,000 $\Lambda\Lambda$ events which are two orders of magnitude more then ever in past experiments.
- 1,500 events in the region for Ξ^- production (E_Ξ < 250 MeV).

$$K^- p \to K^+ \Xi^-, \Xi^- p \to \Lambda\Lambda$$

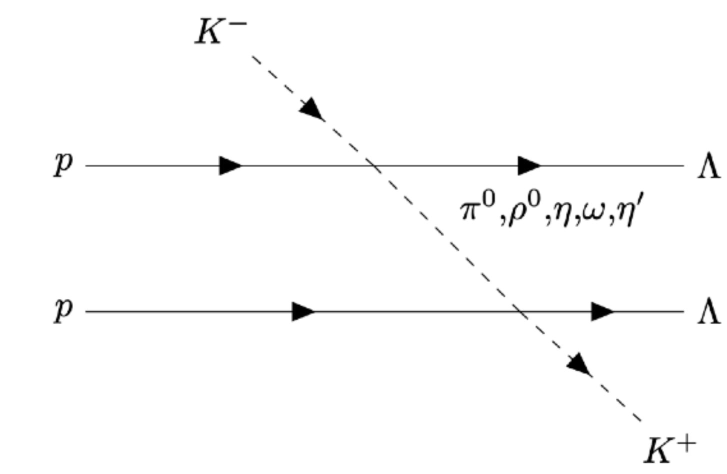
$$K^- p \to \begin{pmatrix} \pi^0 \\ \eta \\ \omega \\ \eta' \end{pmatrix} \Lambda, \quad \begin{pmatrix} \pi^0 \\ \eta \\ \omega \\ \eta' \end{pmatrix} p \to K^+ \Lambda,$$

$$K^- p \to \pi\Lambda, \quad \pi p \to K^+ \Sigma^0.$$

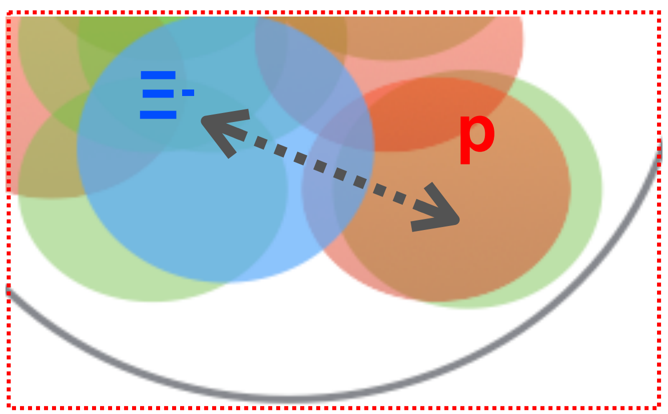
$\Lambda\Lambda$ production and $\Xi^- p \to \Lambda\Lambda$ contribution in the $^{12}\mathrm{C}(K^-, K^+)$ reaction

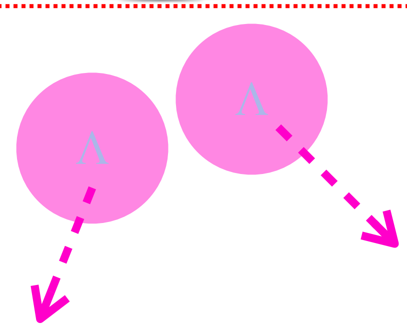
- $\Lambda\Lambda$ production yield is reproduced by considering two-step processes in $^{12}\mathrm{C}(K^-, K^+)$ reactions.
- J-PARC E42 data with intra-nuclear cascade model calculation for understanding the contribution of $\Xi^- p \to \Lambda\Lambda$ conversion(~2%).

Based on Ref. *"Y. Nara, A. Ohnishi, T. Harada, A. Engel, Nucl. Phys. A 614, 433 (1997)"*

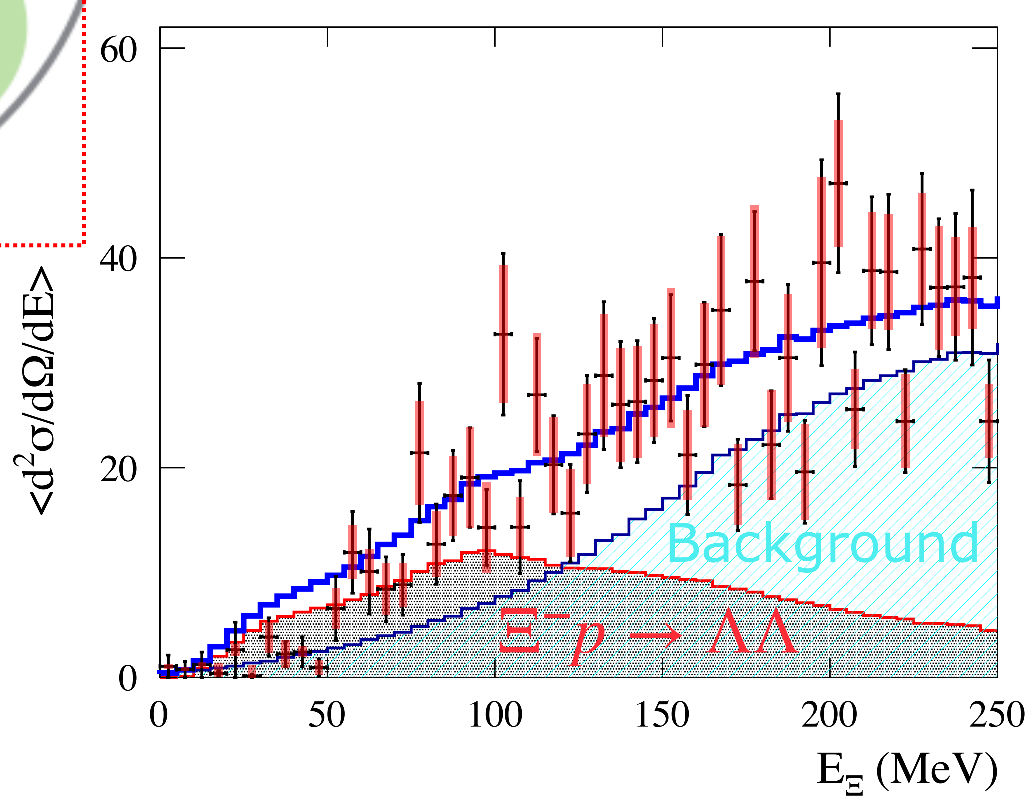


(Background processes)

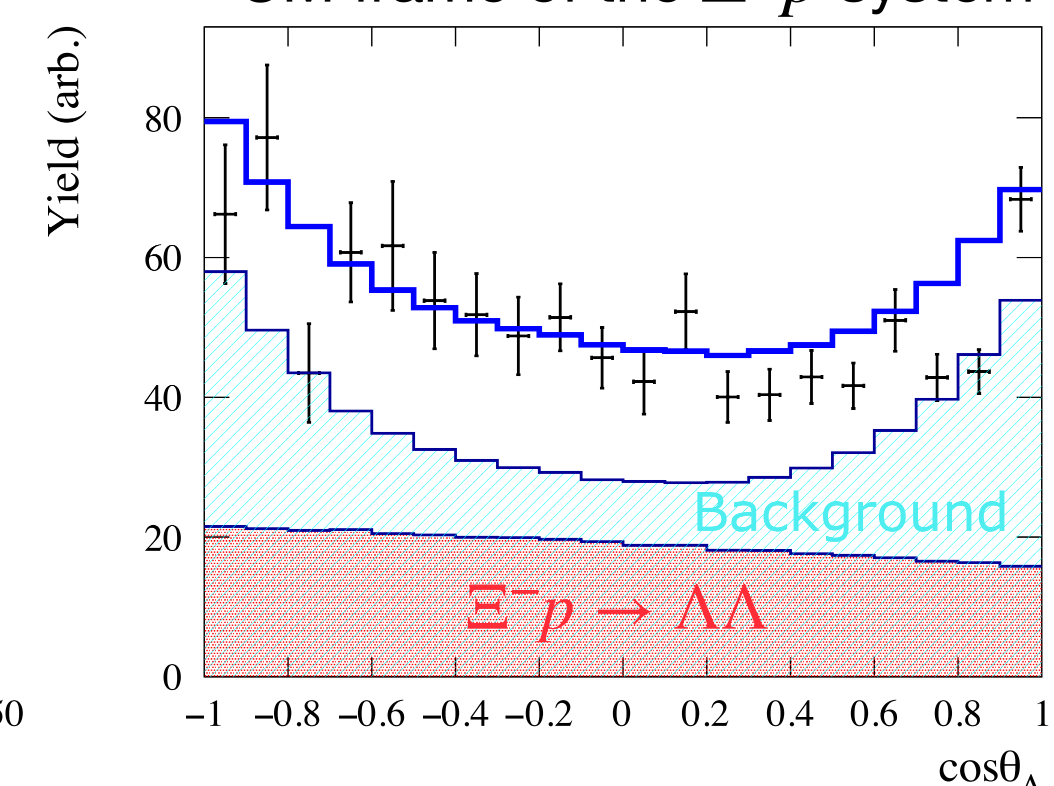




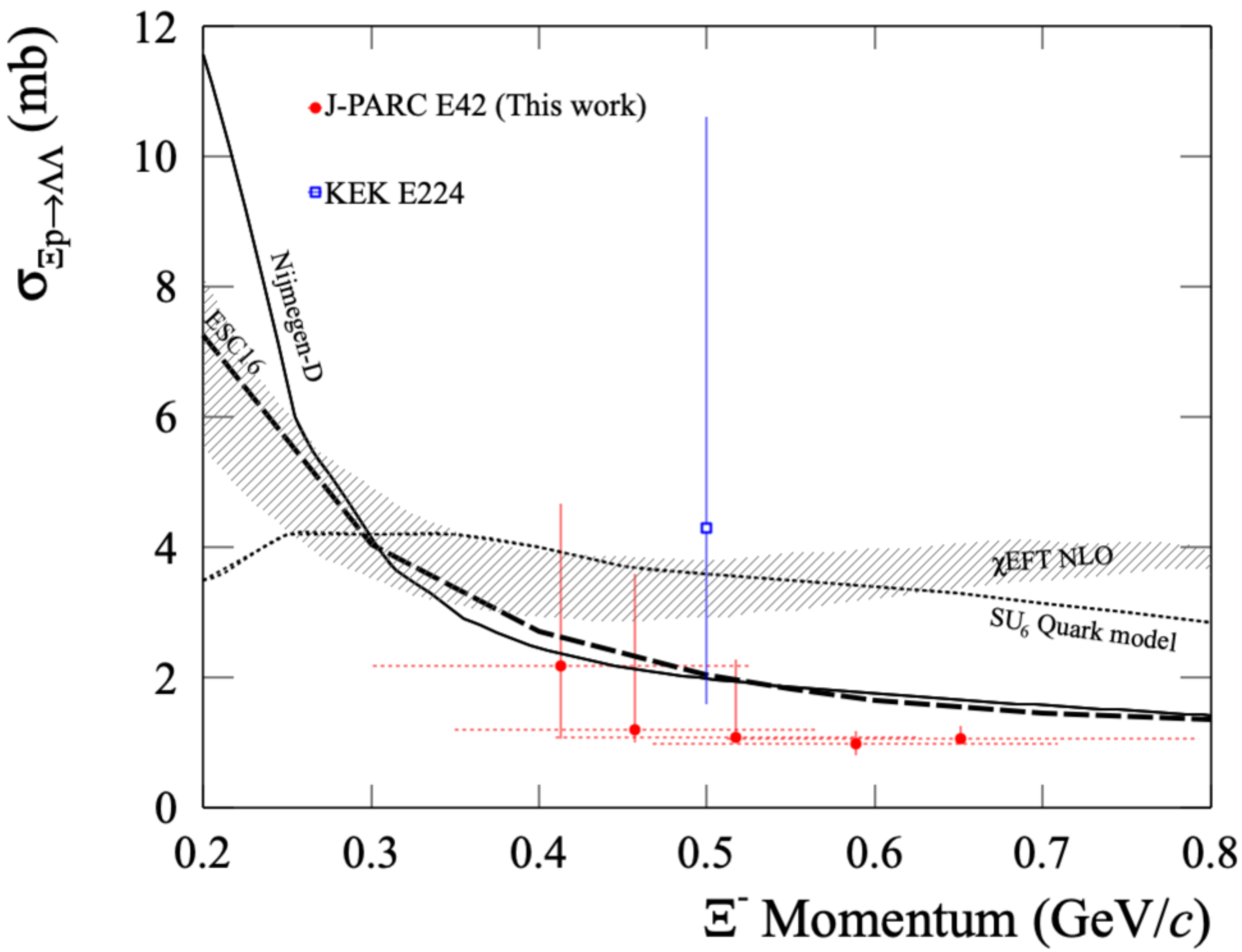
$\Xi^- p \to \Lambda\Lambda$



Λ angular distribution in the CM frame of the $\Xi^- p$ system



Total cross-section for $\Xi^- p \rightarrow \Lambda\Lambda$ conversion process



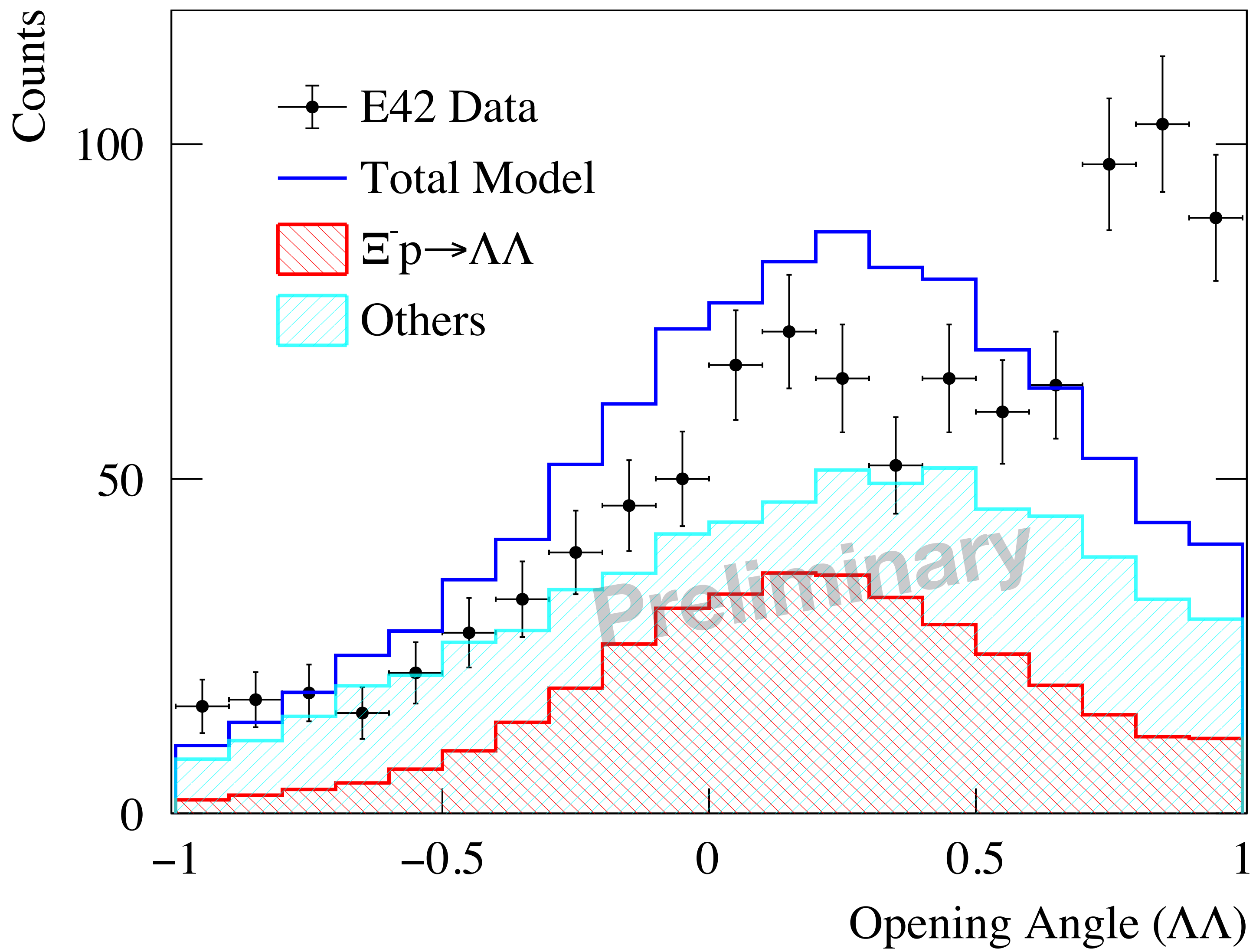
Dotted lines correspond to momentum spread of Ξ^- (1σ)

- $\Xi^- p \rightarrow \Lambda\Lambda$ cross section is $1.0^{+1.3}_{-0.8}$ mb at $0.5 < P_{\Xi^-} < 0.6$ GeV/c.
- This result constraints $\Gamma_{\Xi^-} < \sim 0.6$ MeV in nuclear matter, by the relation of $\Gamma_{\Xi} \sim (\rho_0/2) \cdot (v\sigma)_{\Xi^- p \rightarrow \Lambda\Lambda}$ where, $\rho_0/2 \sim 0.08\ fm^{-3}$.

*C. B. Dover, A. Gal, and D. J. Millener, Nucl. Phys. A 572, 85 (1994)

This result indicates very weak ΞN-ΛΛ coupling

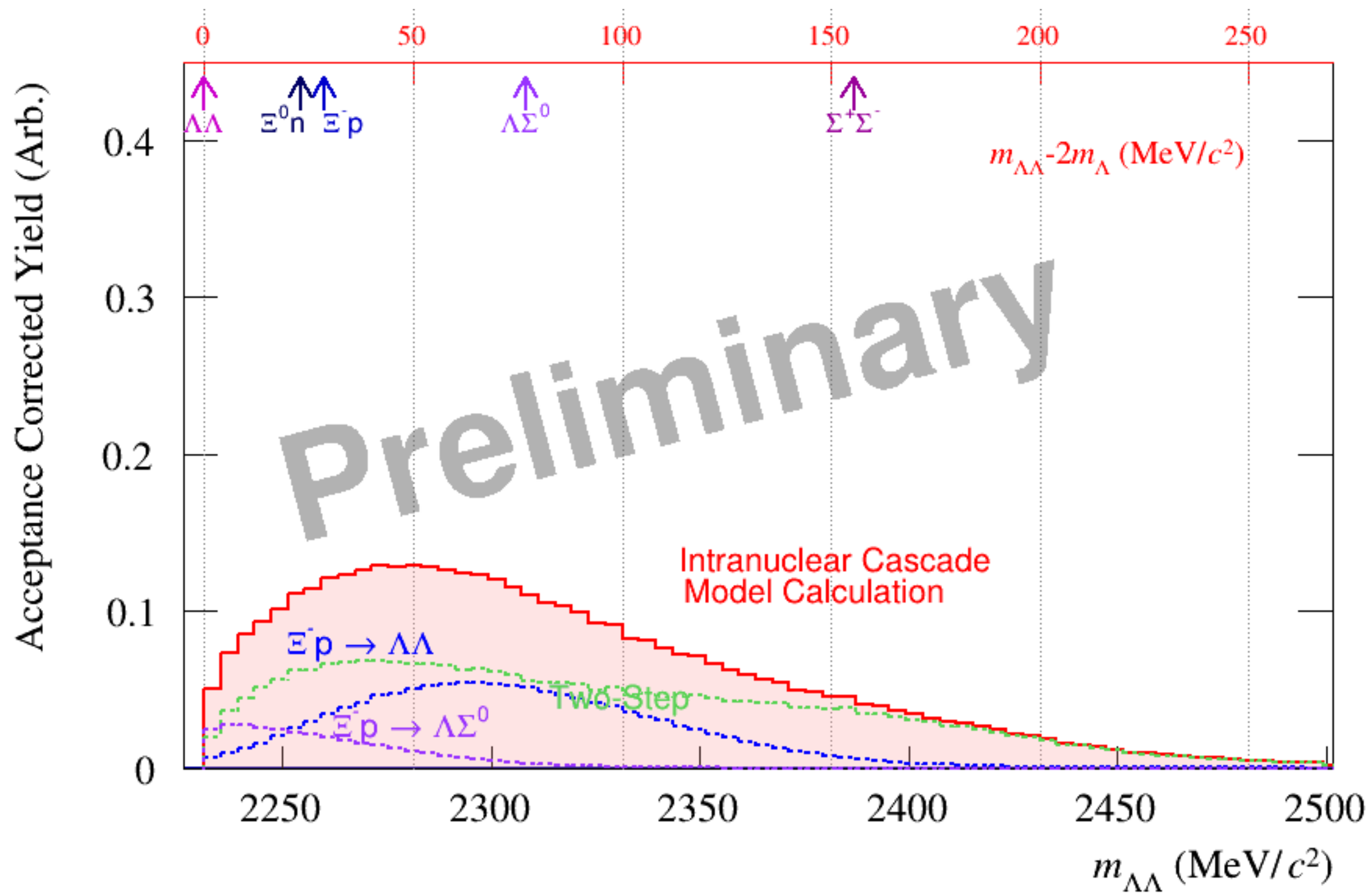
ΛΛ opening angle distribution



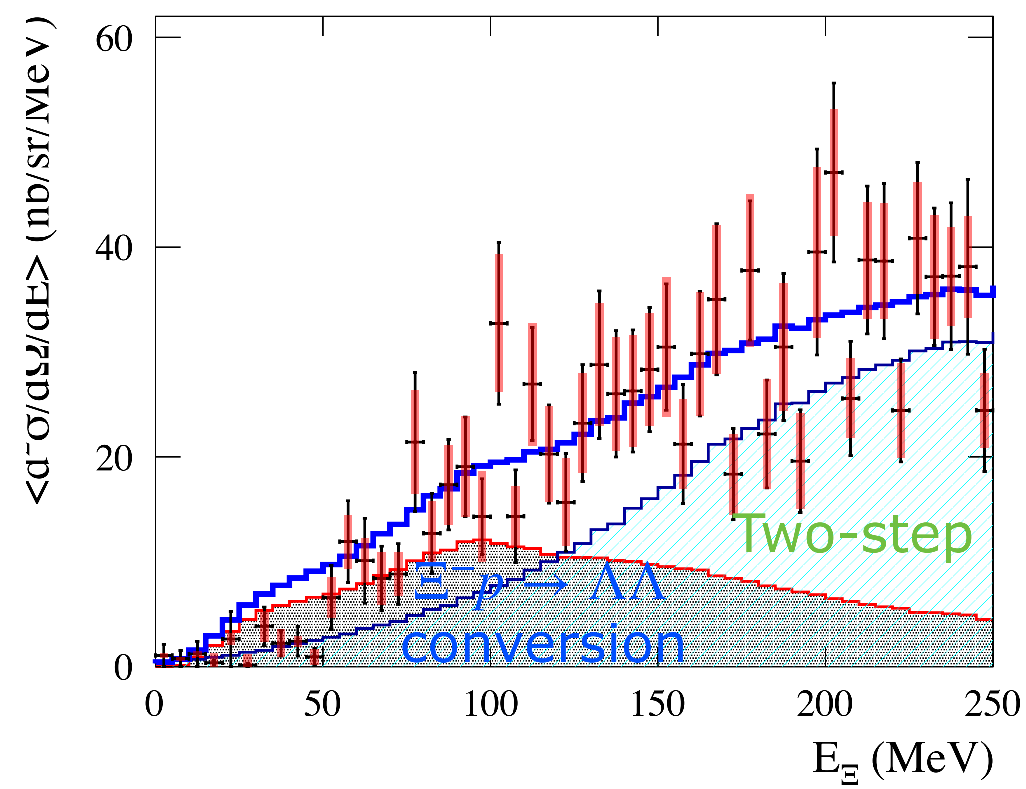
- A clear small opening angle enhancement is observed.
- It may give us insights into the ΛΛ mass structure.

$\Lambda\Lambda$ Invariant-Mass Spectra in the $^{12}\mathrm{C}(K^-, K^+)$ Reaction

Expected m(ΛΛ) spectra for each process based on the INC calculation



Events with E_Ξ < 250 MeV



$$K^-p \to K^+\Xi^-, \Xi^-p \to \Lambda\Lambda$$
$$\Xi^-p \to \Sigma^0\Lambda$$

$$K^-p \to \begin{pmatrix} \pi^0 \\ \eta \\ \omega \\ \eta' \end{pmatrix} \Lambda, \quad \begin{pmatrix} \pi^0 \\ \eta \\ \omega \\ \eta' \end{pmatrix} p \to K^+\Lambda,$$

$$K^-p \to \pi\Lambda, \quad \pi p \to K^+\Sigma^0.$$

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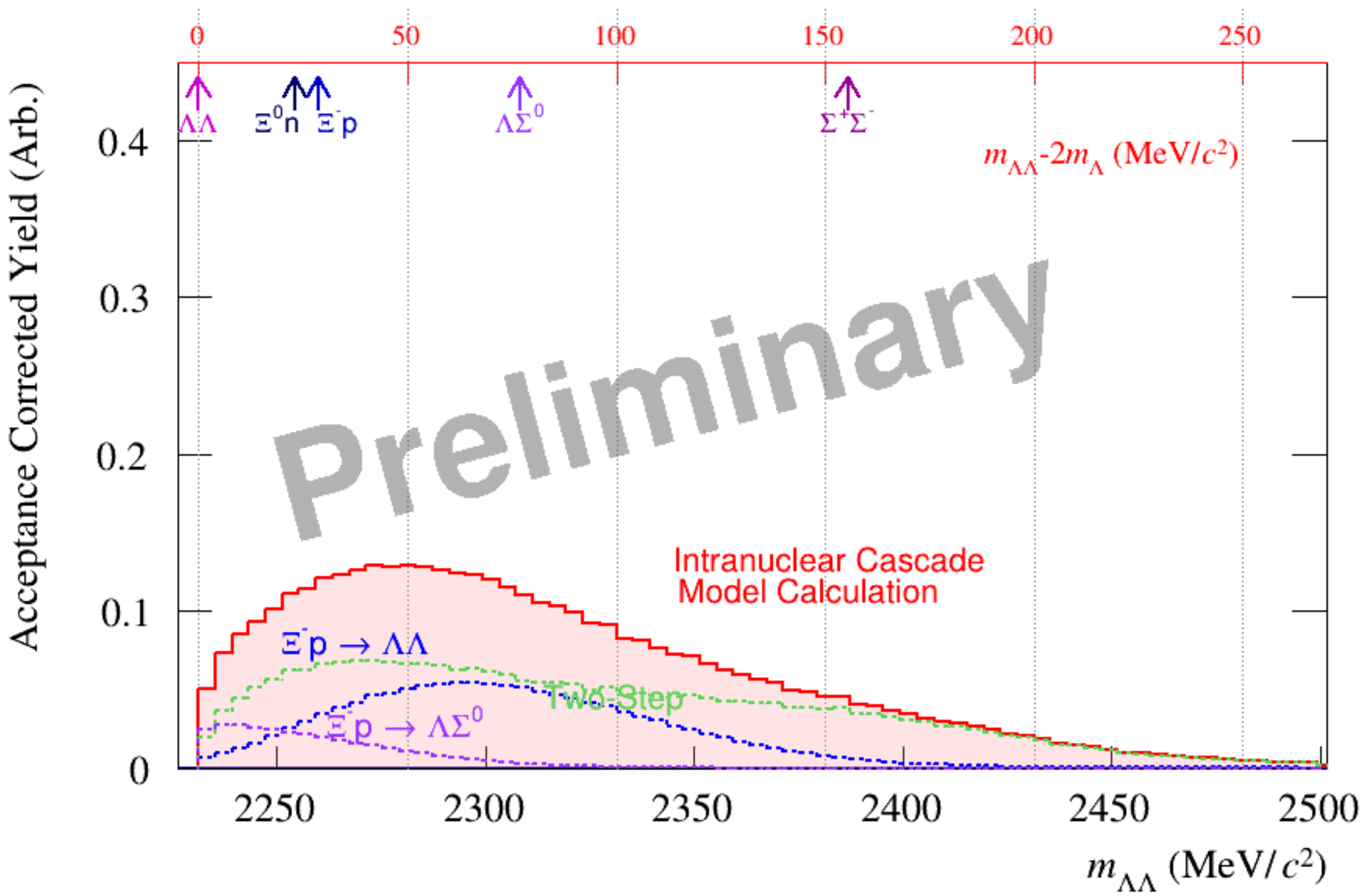
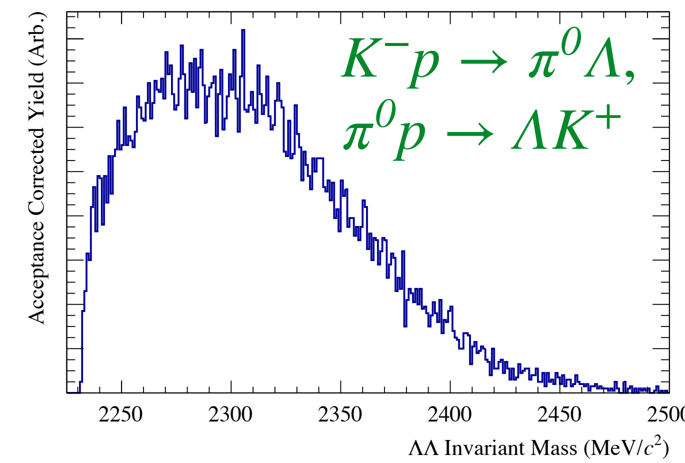
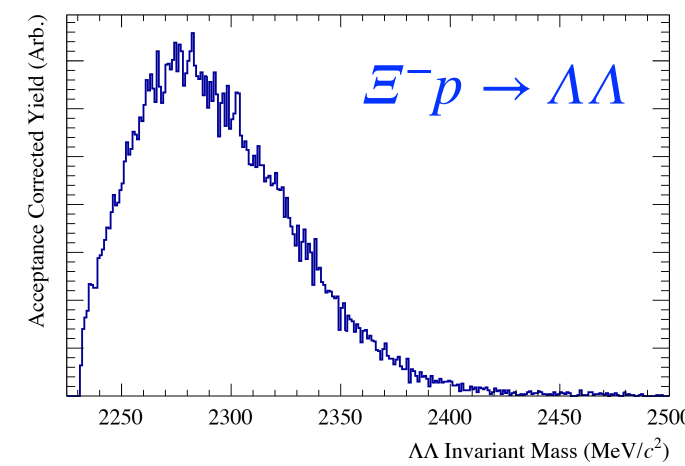
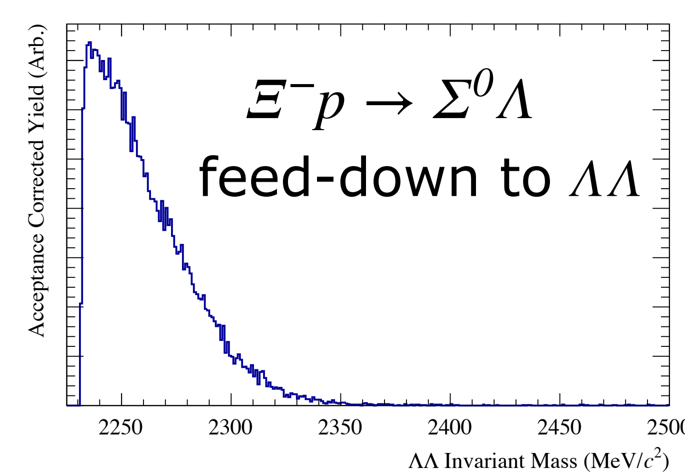








$$K^-p \to K^+\Xi^-, \Xi^-p \to \Lambda\Lambda$$
$$\Xi^-p \to \Sigma^0\Lambda$$

$$K^-p \to \begin{pmatrix}\pi^0\\ \eta\\ \omega\\ \eta'\end{pmatrix}\Lambda, \quad \begin{pmatrix}\pi^0\\ \eta\\ \omega\\ \eta'\end{pmatrix}p \to K^+\Lambda,$$

$$K^-p \to \pi\Lambda, \quad \pi p \to K^+\Sigma^0.$$

J-PARC HypTPC Collaboration

Summary

- J-PARC E42 reports the preliminary results from our search for the H-dibaryon near the $\Lambda\Lambda$ and $\Xi^- p$ Thresholds, together with a detailed study of the ΞN interactions using the $^{12}\mathrm{C}(K^-, K^+)$ reaction.
- We report the $\Xi^- p$ inelastic scattering cross section 22^{+14}_{-7} mb and $\Xi^- p \to \Lambda\Lambda$ cross section $1.0^{+1.3}_{-0.8}$ mb at $< \mathrm{P}_{\Xi^-} > = 0.55$ GeV/c.
- This result can provide crucial information for the $\Xi^- N$ interaction. We report a upper bound of Ξ^- decay width in nuclear matter is $\Gamma_{\Xi^-} < \sim 0.6$ MeV.
- The clear peak-like structure observed between the $\Lambda\Lambda$ and $\Xi^- p$ thresholds in $\Lambda\Lambda$ mass spectrum.

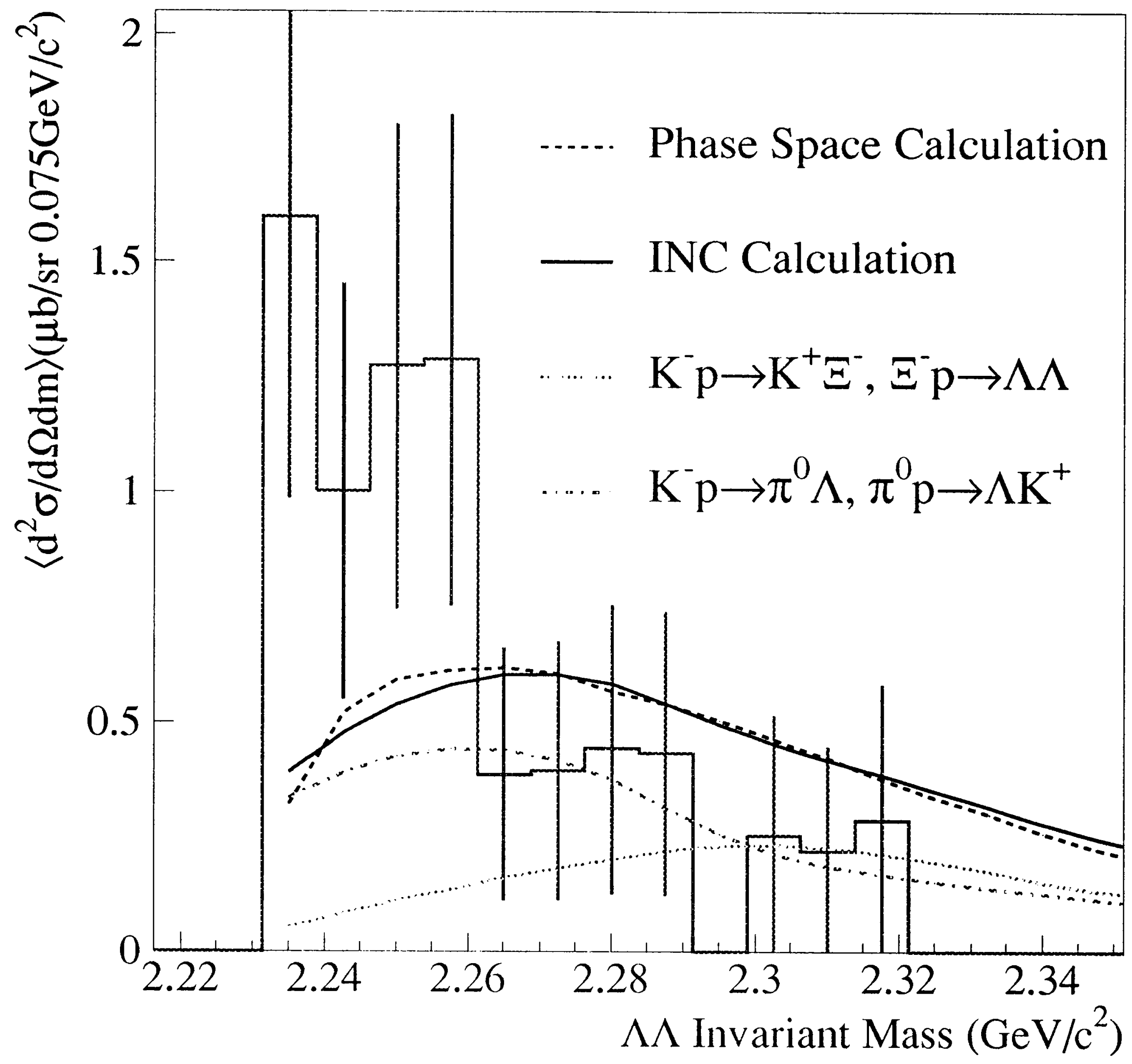
BACKUP

J-PARC HypTPC Collaboration

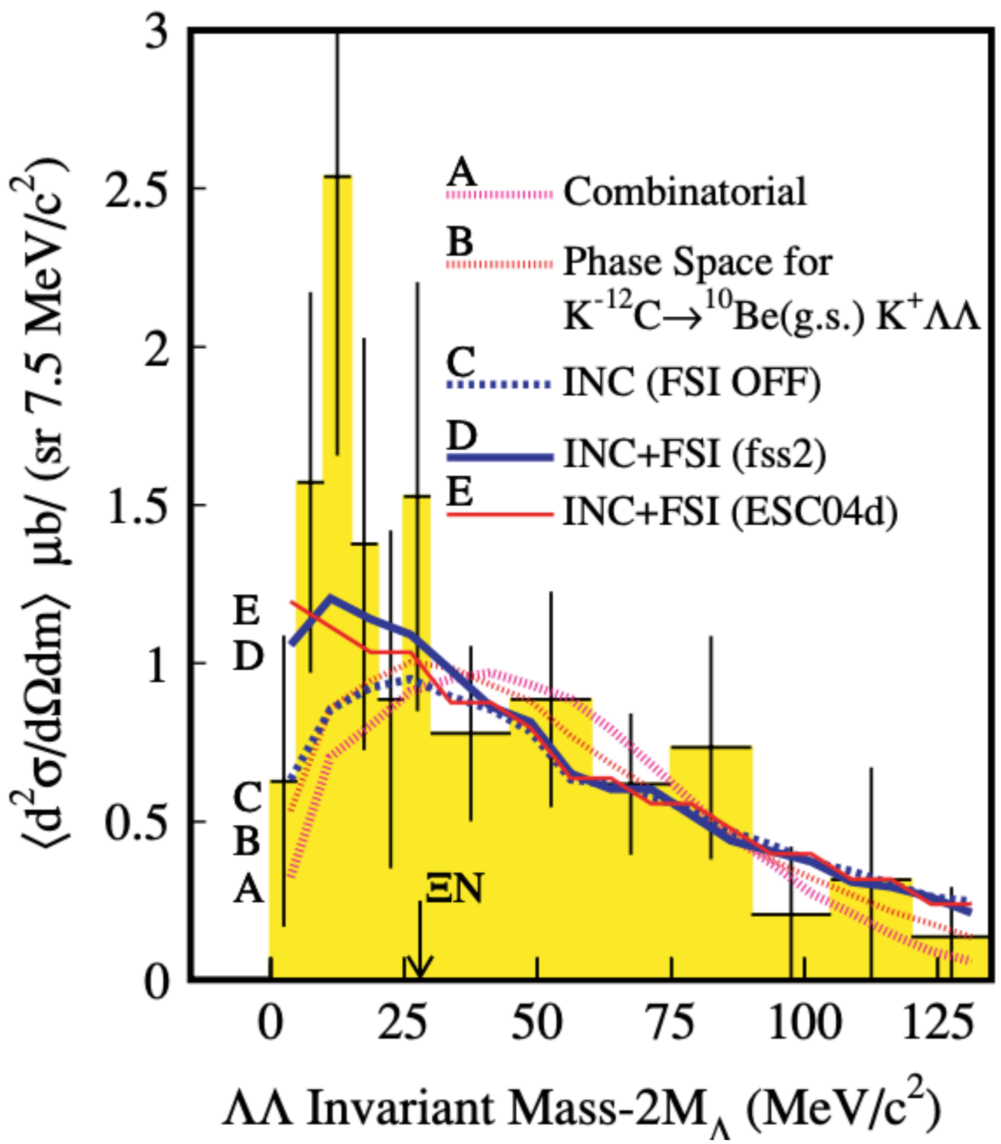
Past H-Dibaryon Searches

$^{12}\mathrm{C}(K^-, K^+)$ reaction at 1.65 GeV/c

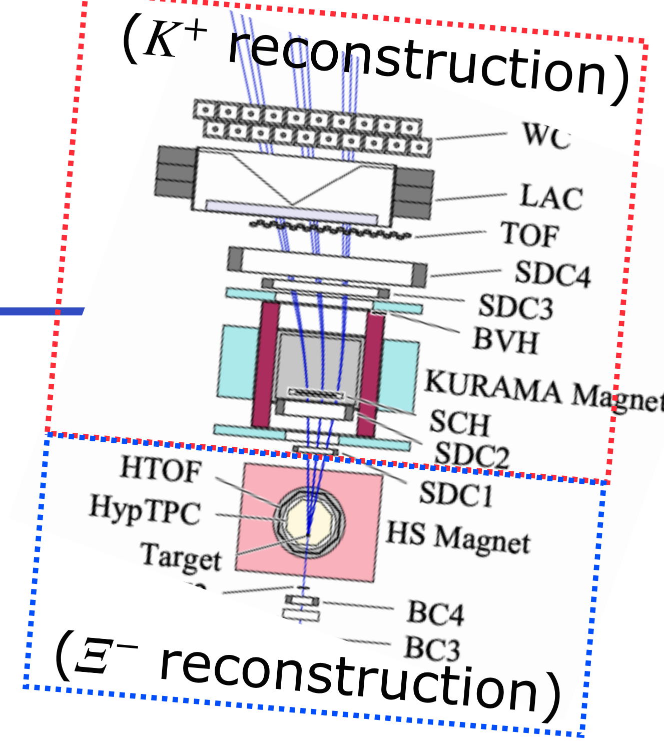
KEK-E224



KEK-E522



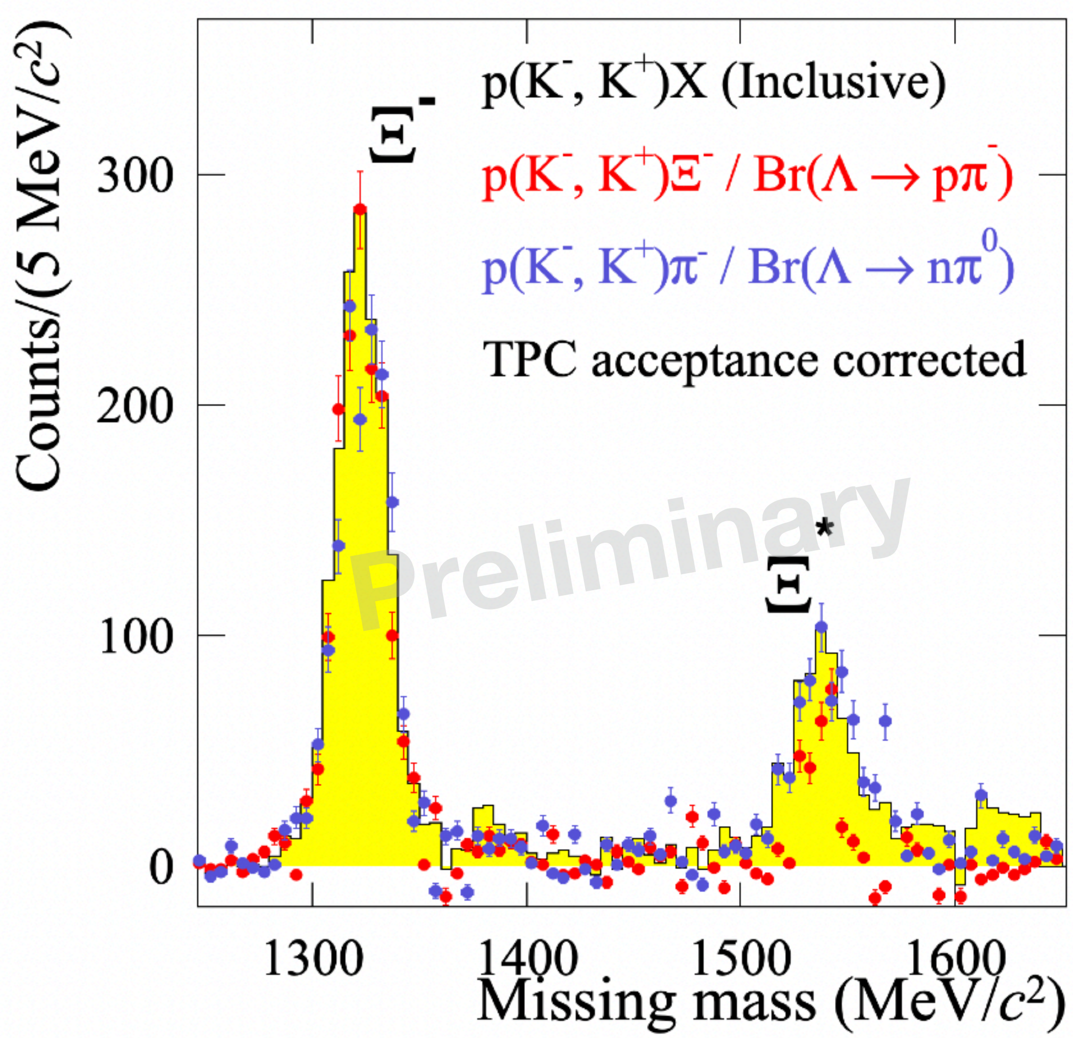
Missing-Mass Spectrum for $p(K^-, K^+)X$ reactions



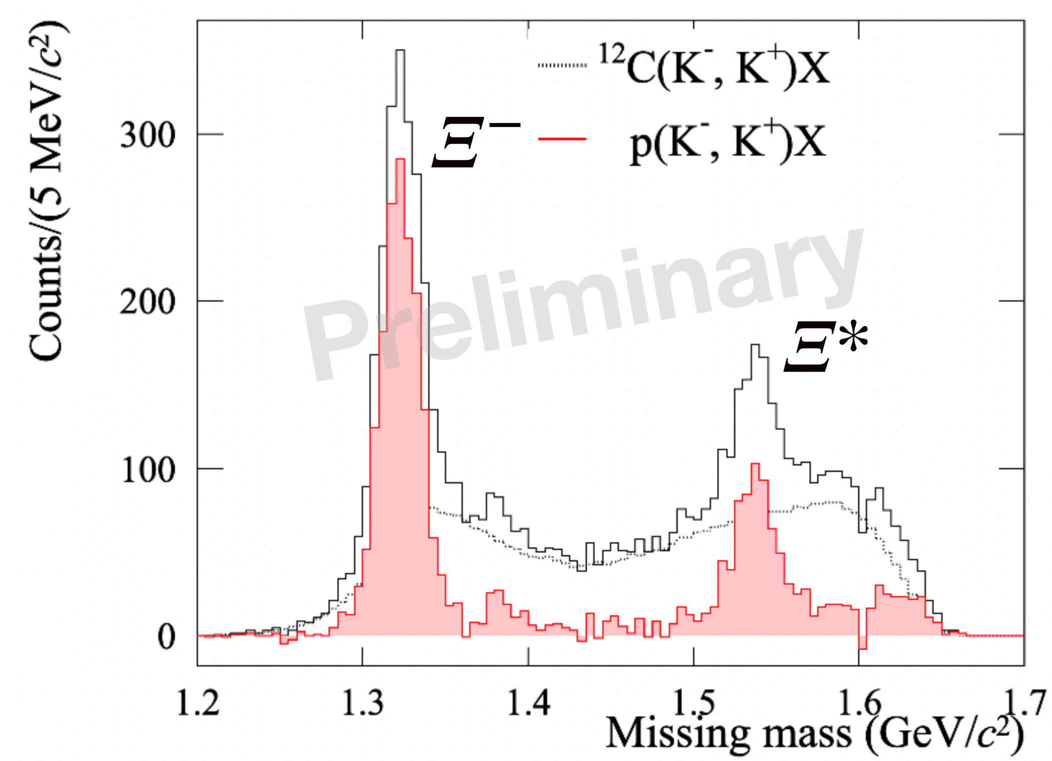
The missing-mass spectrum for $p(K^-, K^+)X$ reactions is reproduced with Ξ^- reconstructed events for

1. visible Λ decays 2. invisible Λ decays in the TPC.

The reconstruction efficiencies for Ξ^- decays are obtained by simulation



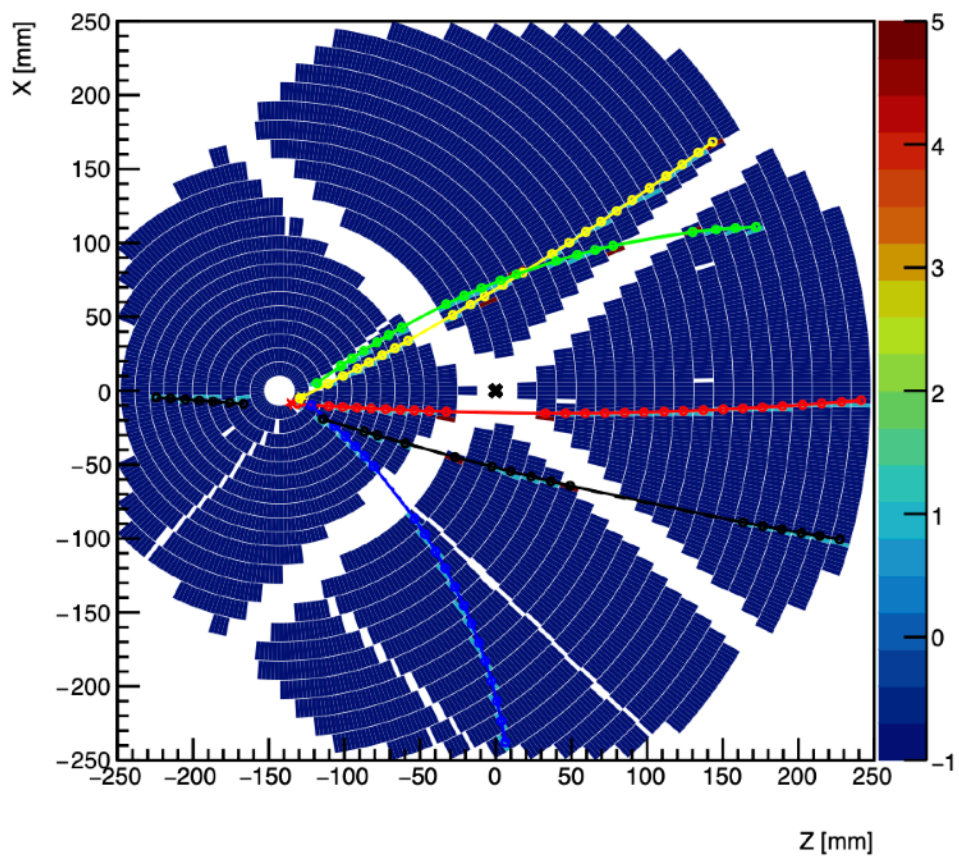
^{12}C contribution subtracted from the spectrum with a CH_2 target



J-PARC HypTPC Collaboration

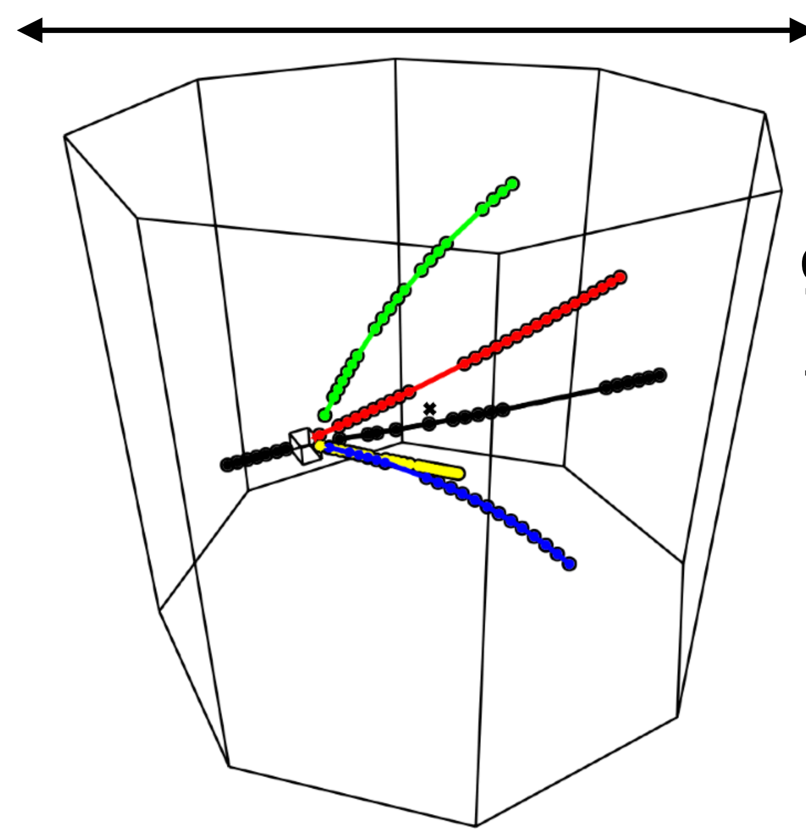
Hyperon Reconstruction using HypTPC

- A Time Projection Chamber (TPC) is a 3D charged-particle tracker that records ionization electrons drifting in gas.
- HypTPC enables precise reconstruction of particle trajectories and decay vertices.



Ionization electrons drift to the readout pads

The active area~0.5 m



gas: Ar(90%) +CH_4(10%)

2D hit pattern & electron drift time → 3D space points

Hyperon Reconstruction using HypTPC

Reconstruction of invariant mass distributions for Ξ^- and its sequential decays.