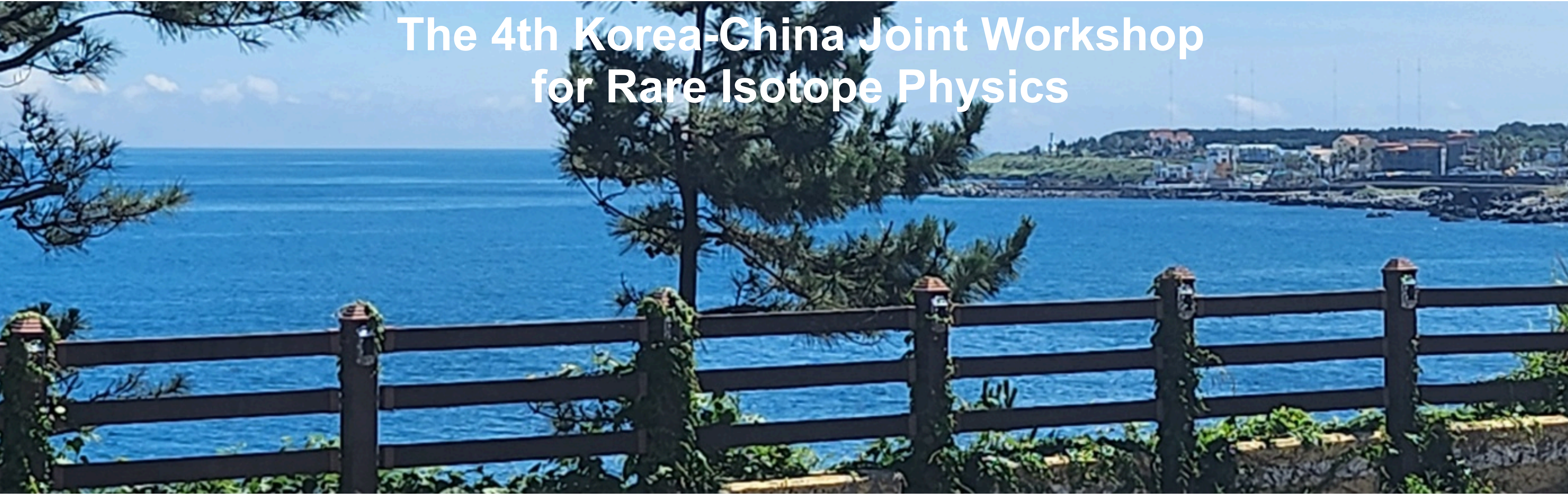
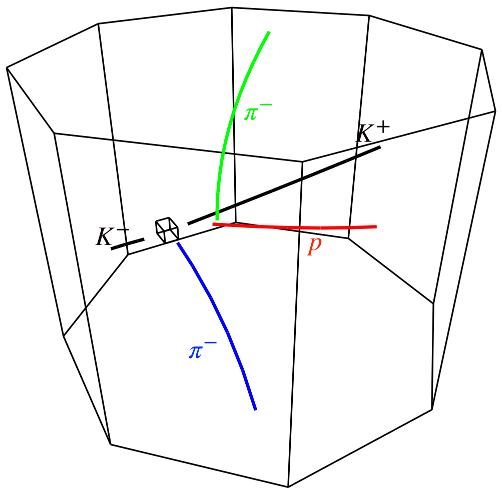


Study of Double-Strangeness Production in the $^{12}C(K^-, K^+)$ Reaction Using HypTPC

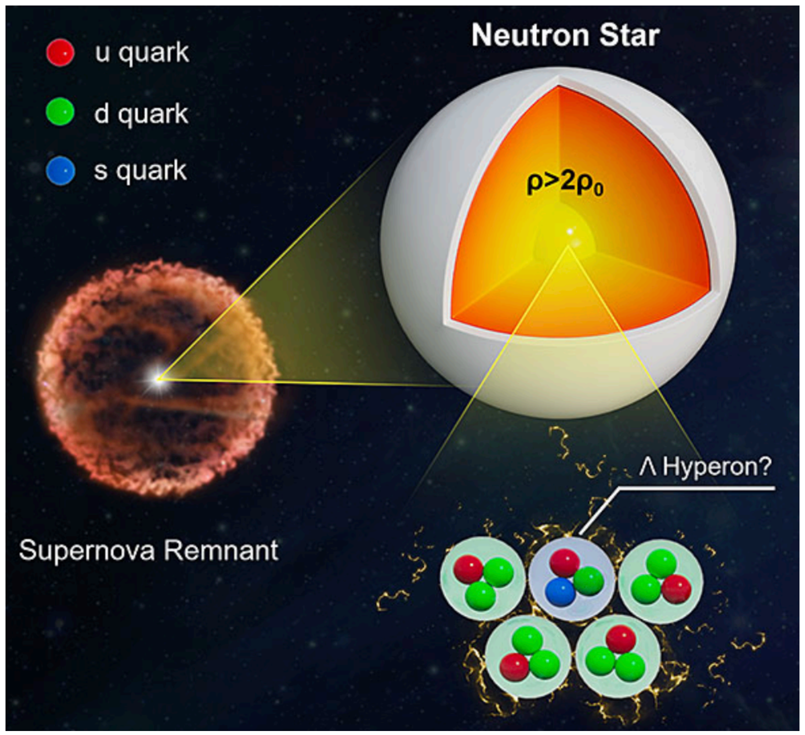
WooSeung Jung(Korea University)
for the J-PARC E42 Collaboration



J-PARC HypTPC Collaboration
KOREA UNIVERSITY
고려대학교
KOREA UNIVERSITY
Hadron & Nuclear Physics Lab

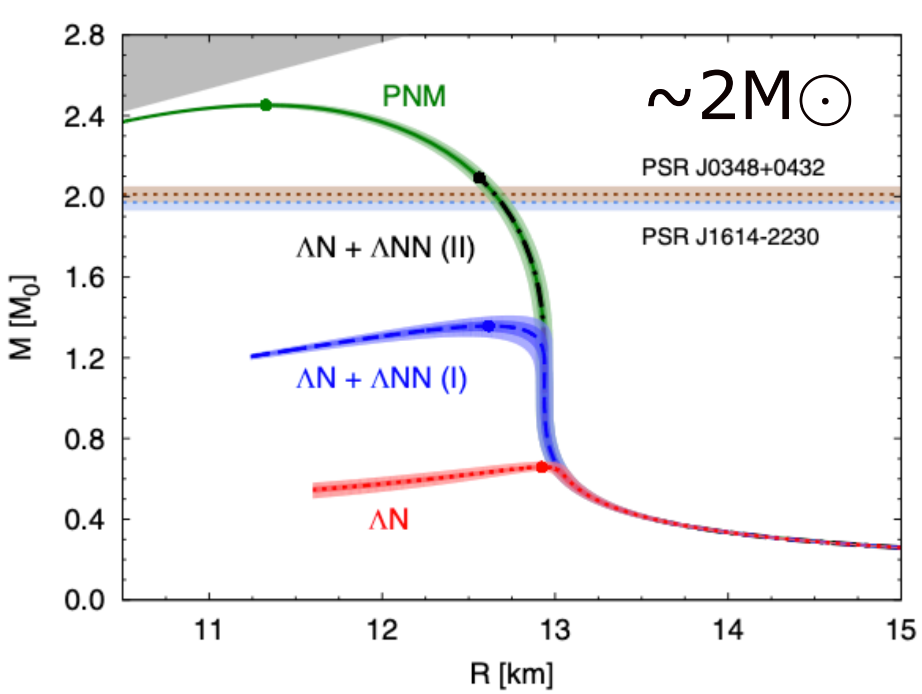
From Nuclei to Neutron Stars: What Baryon Interactions Can Tell Us

Hyperon Puzzle: A Mystery of Heavy Neutron Stars



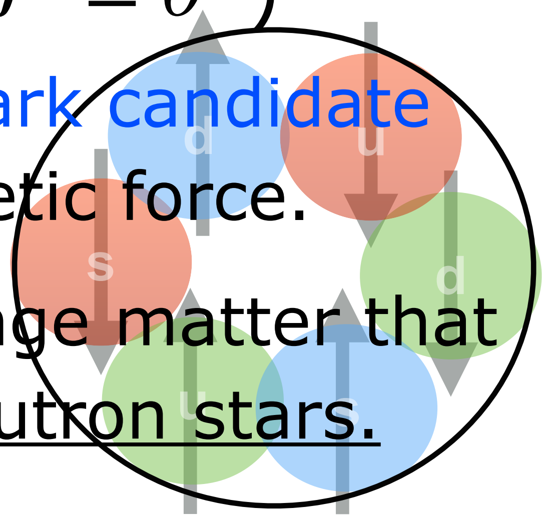
In the inner core of neutron star

- High chemical potential (neutron -> Hyperon)
  (u, d quarks)(u, d, s quarks)
- Pauli blocking prevents decay of hyperons.
  (lifetime on the order of 10^{-10} s)
- Equation of state softens due to hyperon onset
  <- Contradiction with observation of ~2M⊙ NS.



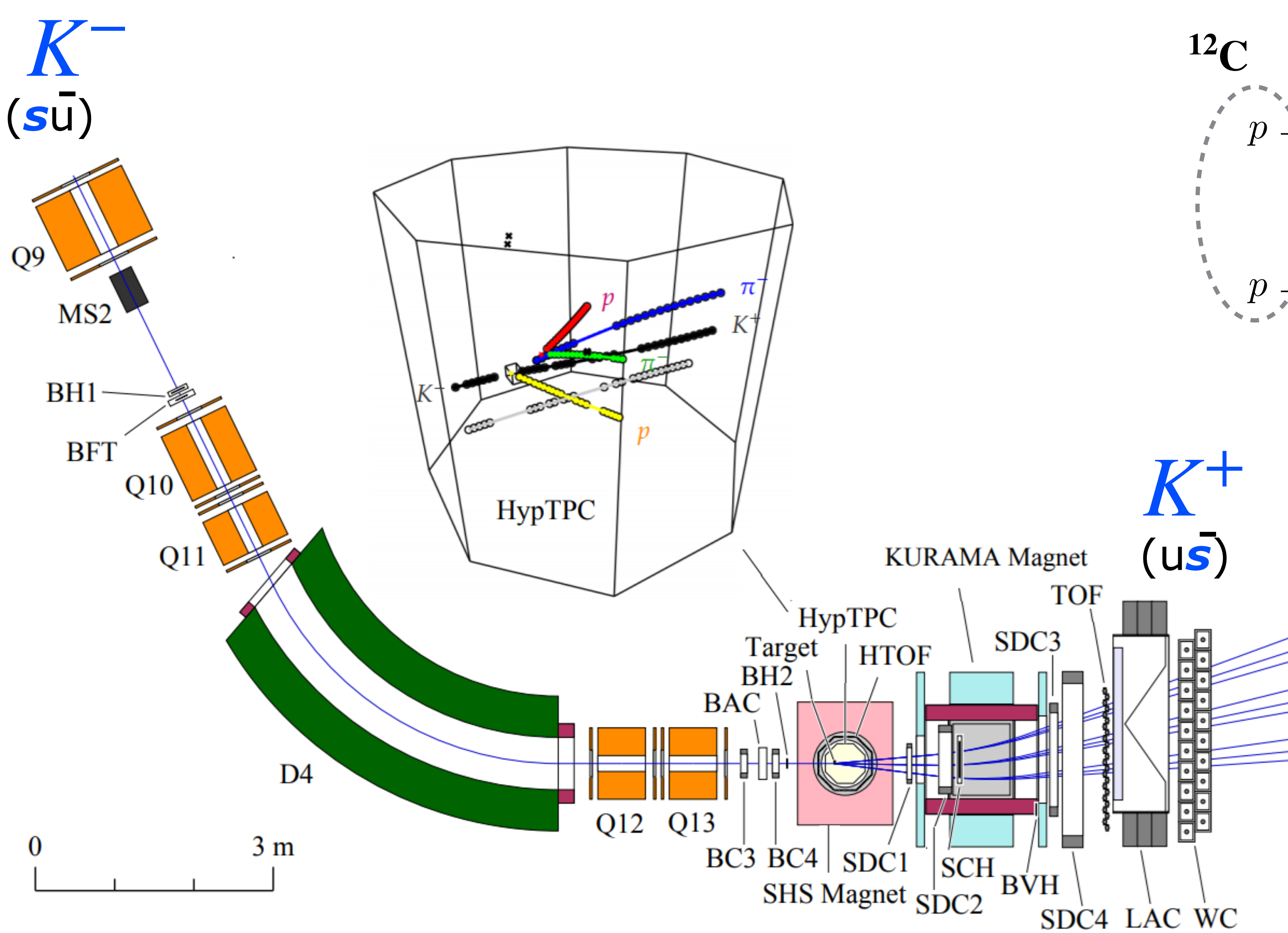
H-dibaryon(uuddss, $I = 0, J^P = 0^+$)

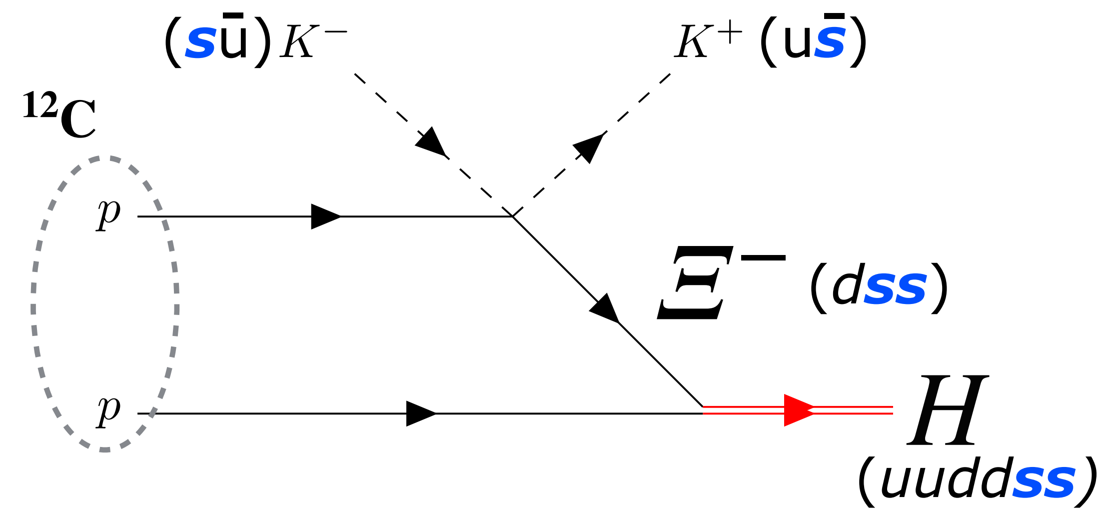
- the most promising hexaquark candidate due to the QCD color-magnetic force.
- It can be a doorway to strange matter that could exist in the core of neutron stars.

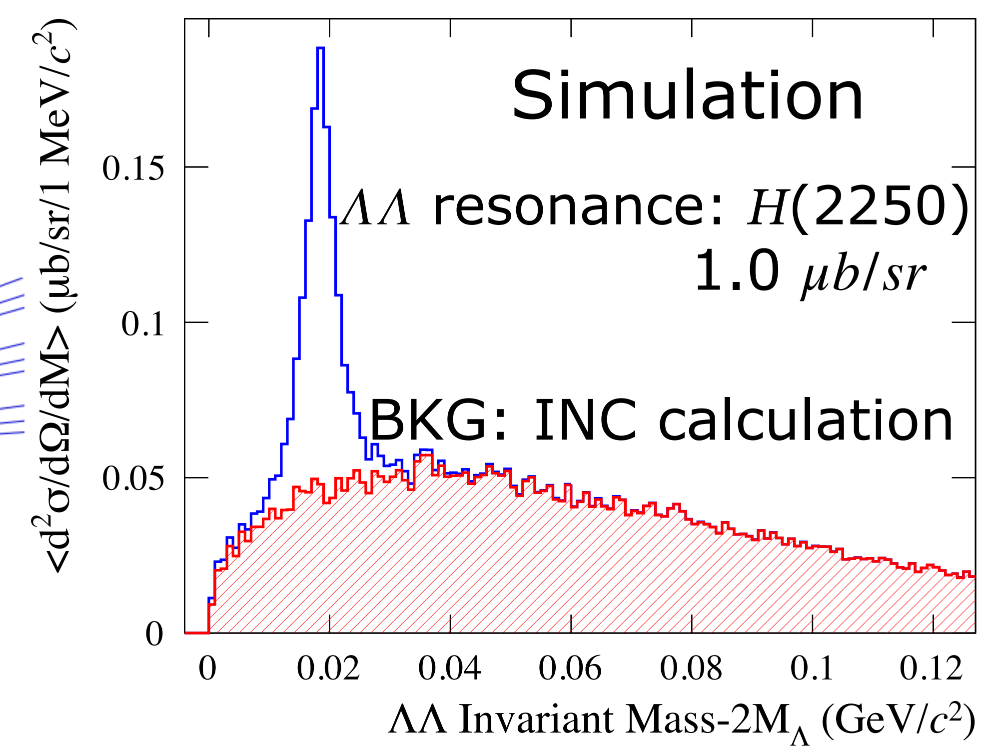


J-PARC E42 : Study of Double-Strangeness Production for $^{12}\mathrm{C}(K^-, K^+)$ Reaction

Measurement of all charged decays from $^{12}\mathrm{C}(K^-, K^+)X$ reaction at 1.8 GeV/c for ΞN Interaction study and H-dibaryon search







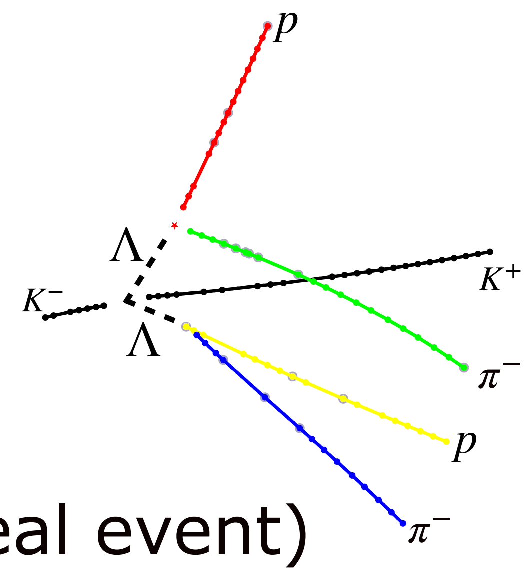
Hyperon Spectrometer for Hadron Experiment@J-PARC

HypTPC (Main tracking device for hadron experiments)

- A target is embedded inside for **large acceptance**.
- **~6000 pads with 32 layers**

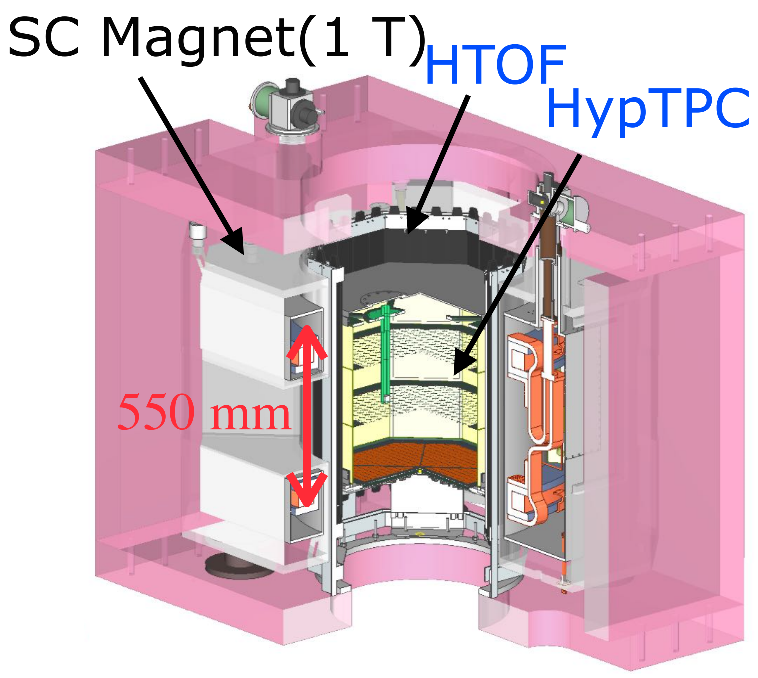
HTOF (Trigger detector)

- A counter **surrounding the TPC** with high-resolution timing measurement for particle identification

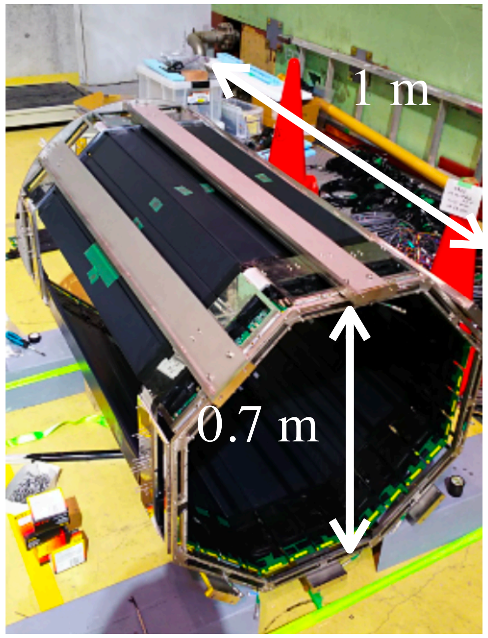


(real event)

Hyperon spectrometer



HTOF



Development of TPC Trigger Detector for J-PARC Hadron Experiments

Constraints and goal of R&D:

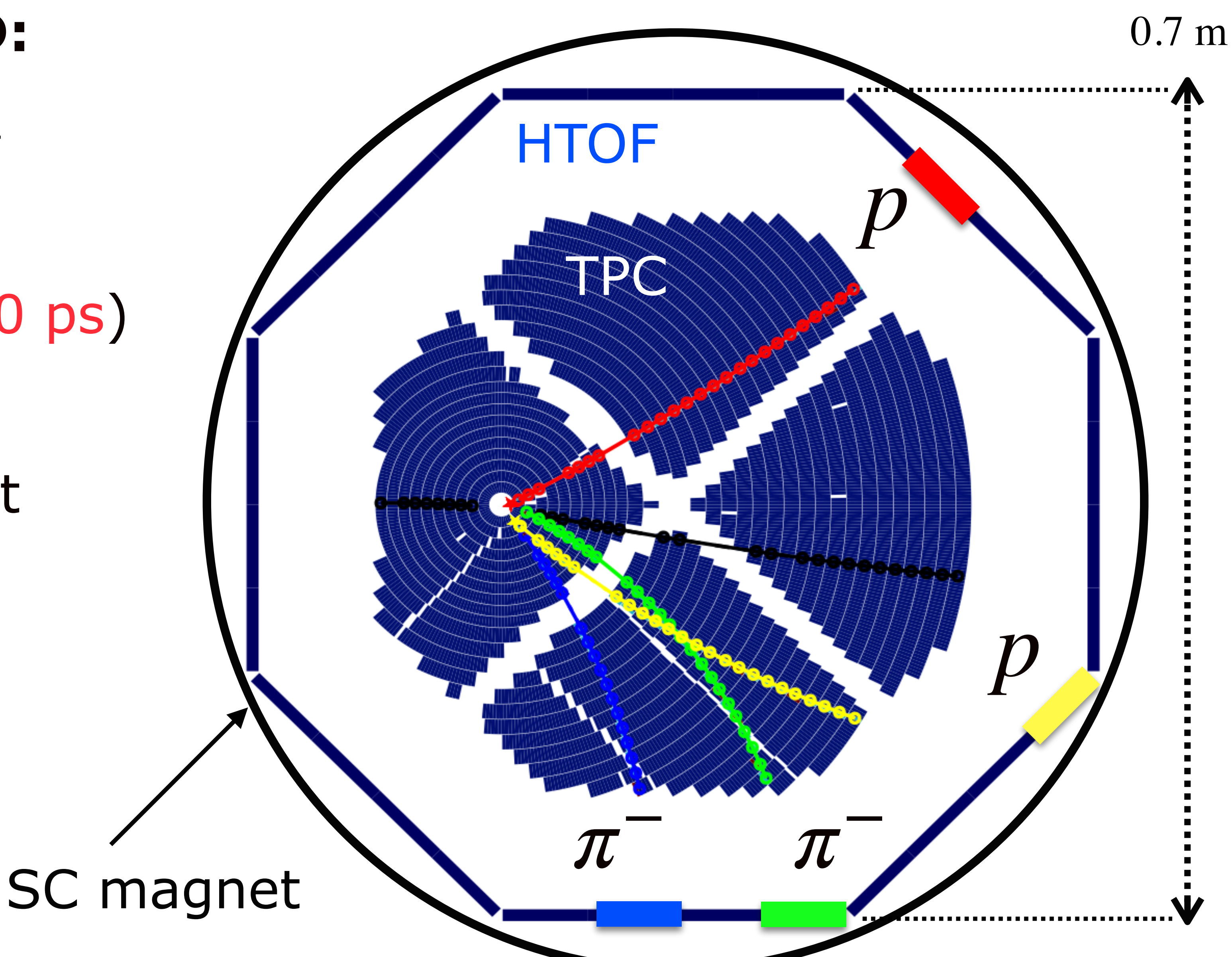
Operation in 1 T magnetic field

Space limitation (~5 cm)

Good time resolution($\sigma_t \sim 120$ ps)
—> **Achieved**

Developed signal readout circuit

*W.S. Jung, et al. / JPS Conf. Proc. , 011007 (2019)



HTOF will be used as **the primary trigger detector** in future J-PARC experiments.

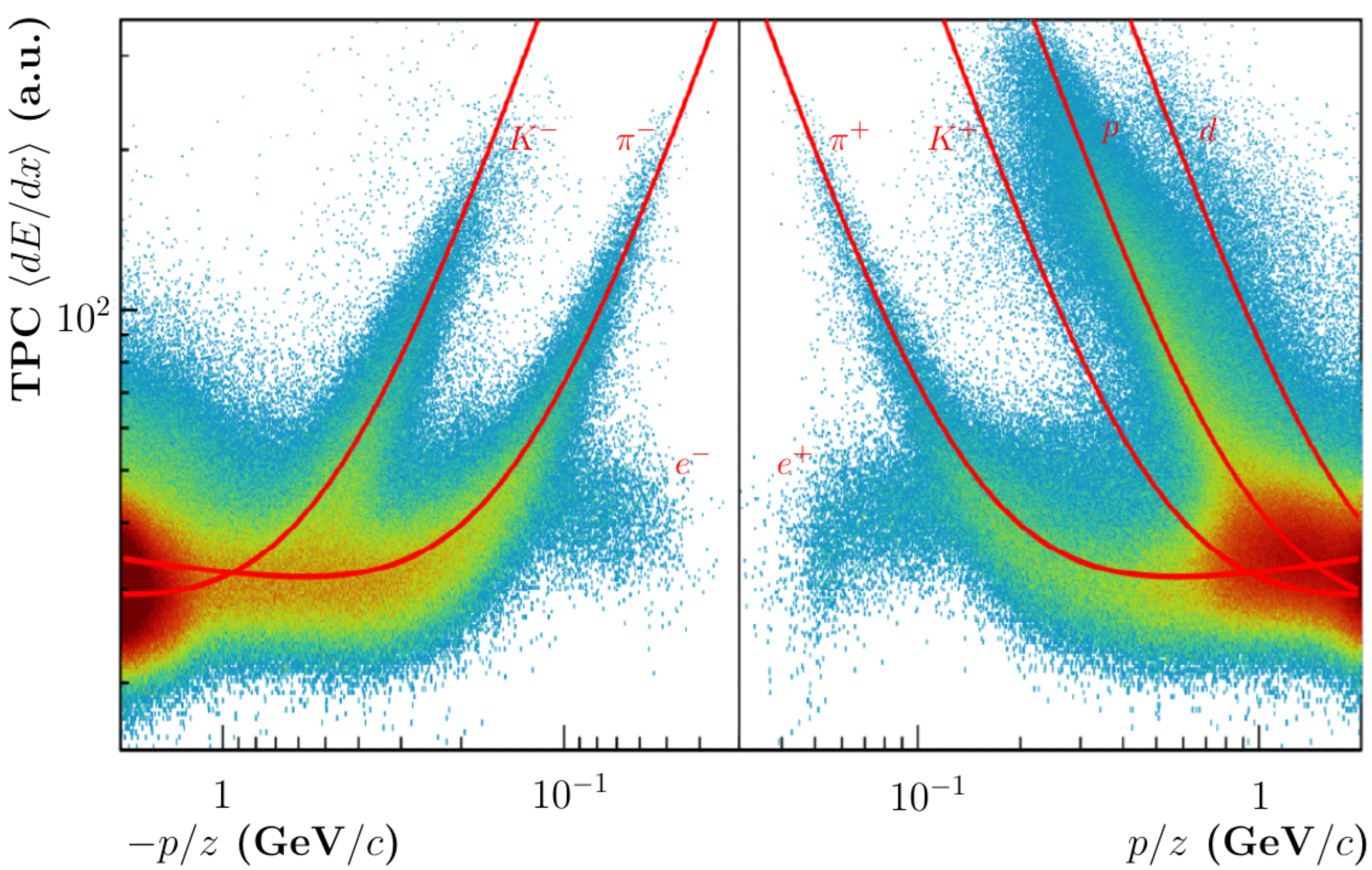
Particle Identification by Hyperon Spectrometer

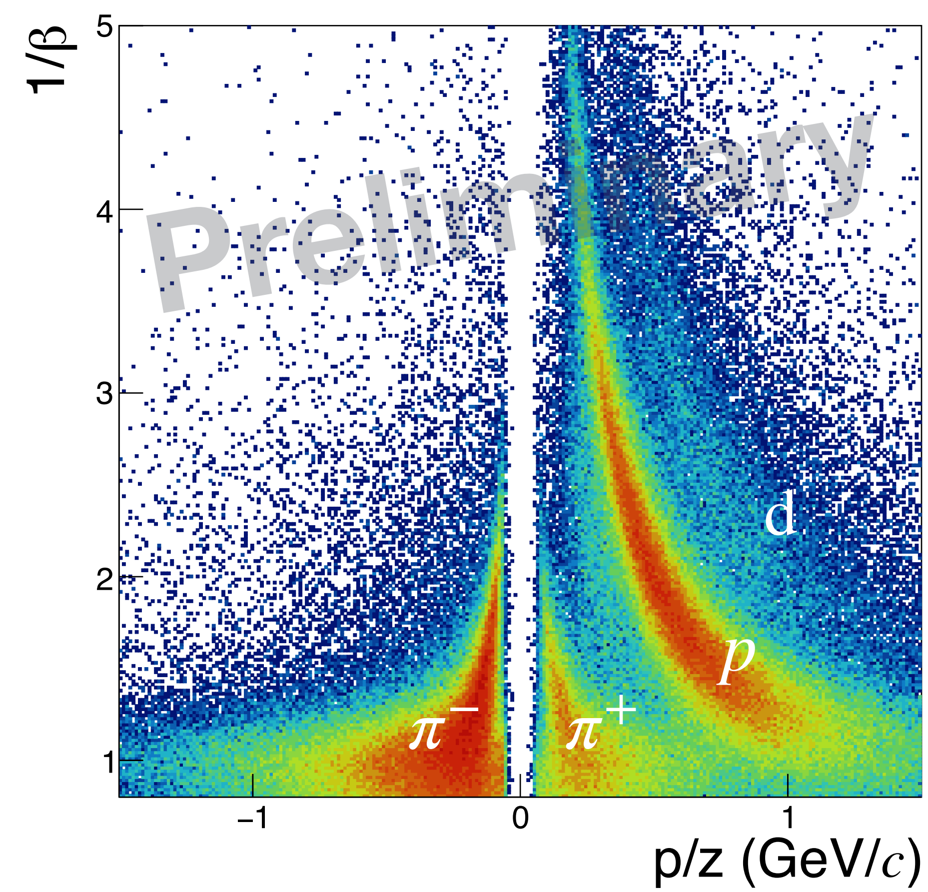
HypTPC dE/dx

- $< dE/dx >_{20\%\ truncated}$ vs p/z for reconstructed tracks of $^{12}C(K^{-}, K^{+})$ reactions
- $\sigma_{<dE/dx>} / < dE/dx >$ ~ 20% for the range 0.40 < p_T < 0.45 GeV/c

HTOF Time-of-flight

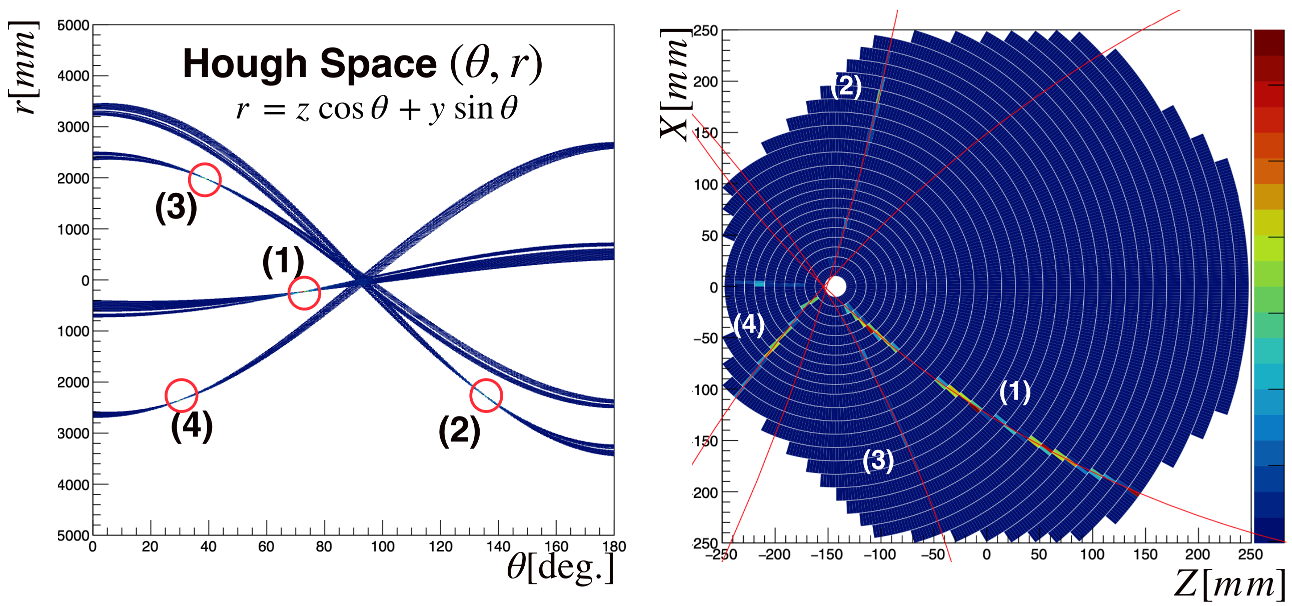
- Flight length about 200 ~ 500 mm, $\sigma_t \sim$ 120 ps for π^{-}



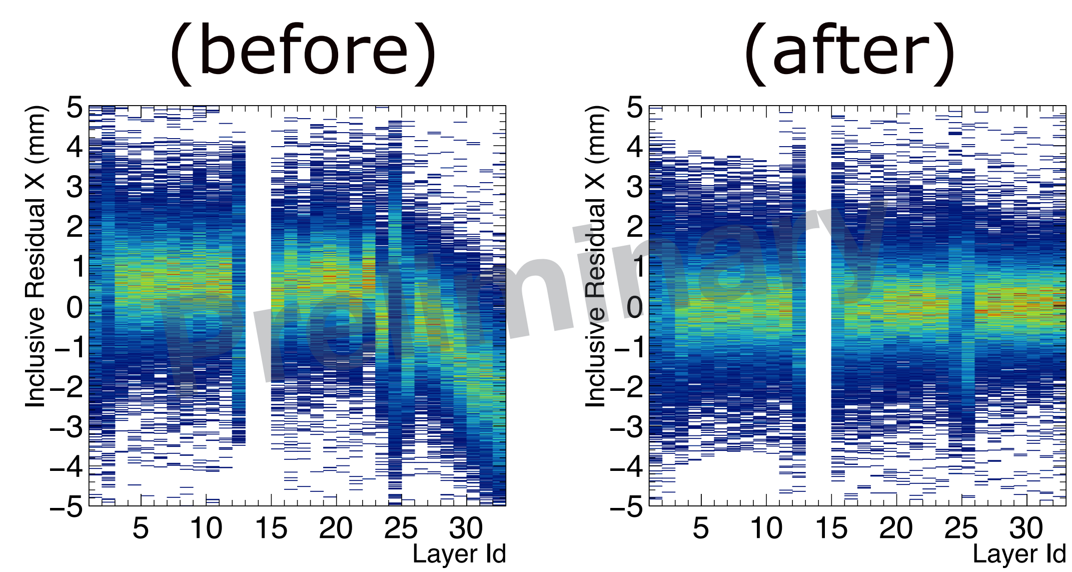


Calibrations and Measurements for J-PARC HypTPC

Track finding with Hough-Transform



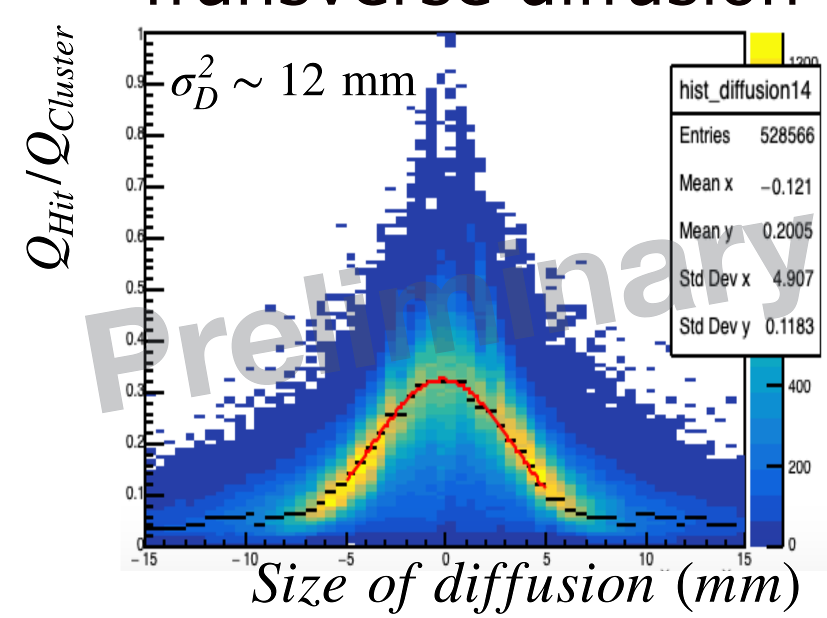
Systematic correction for track distortions due to field non-uniformity



Measurement of parameters of gas ionization

1. Drift velocity
2. Size of diffusion of electrons
3. Charge of electrons and deposit energy

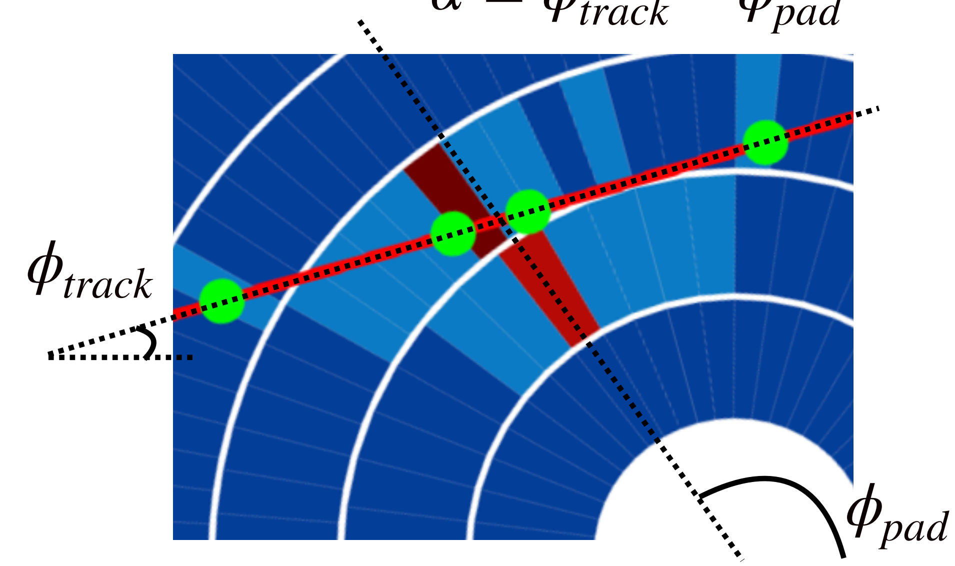
Transverse diffusion



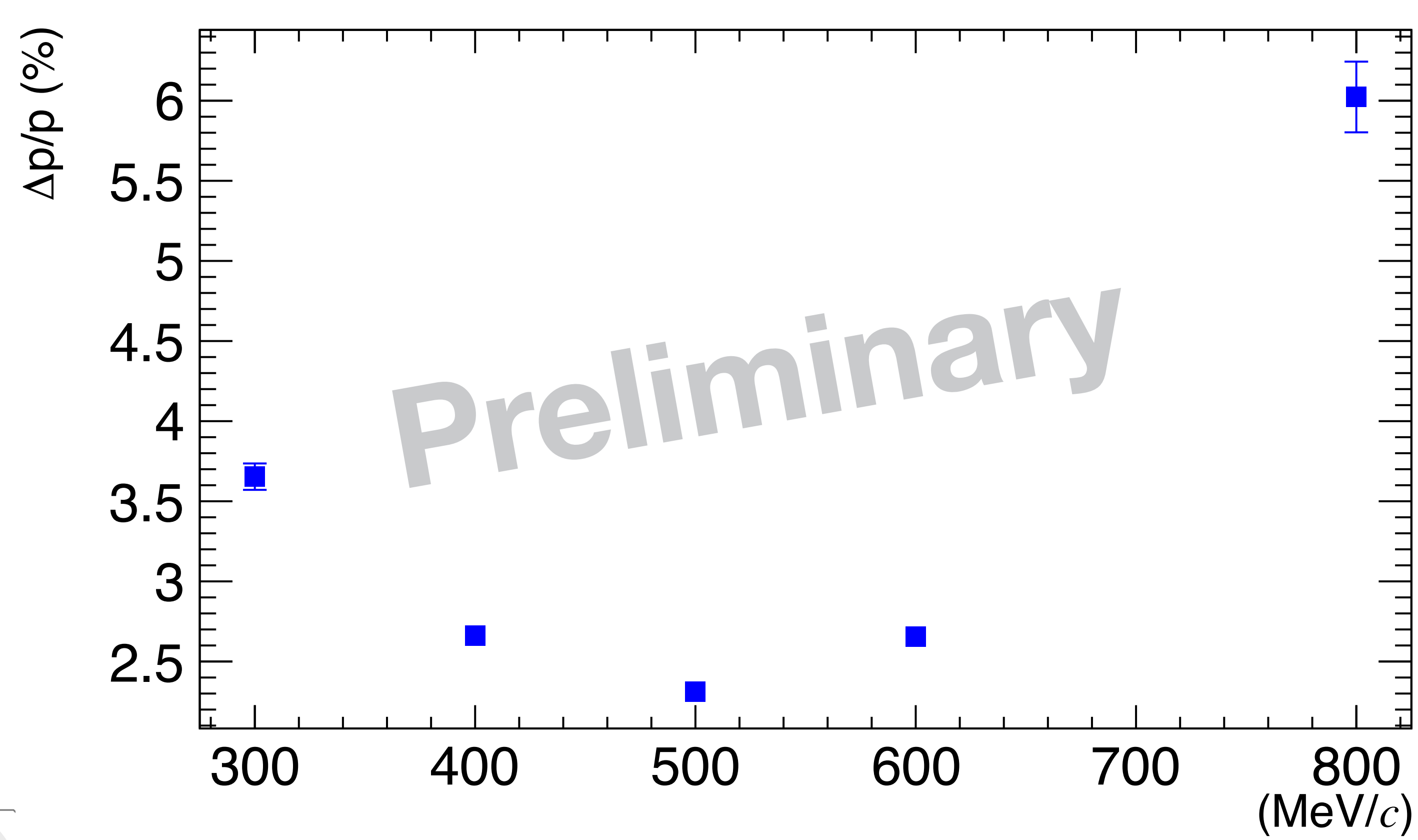
HypTPC Spatial and Momentum Resolution

- Momentum resolution was measured with π^- beam-through data at various momenta
- Spatial resolution is parameterized by intrinsic and angular-dependent terms.

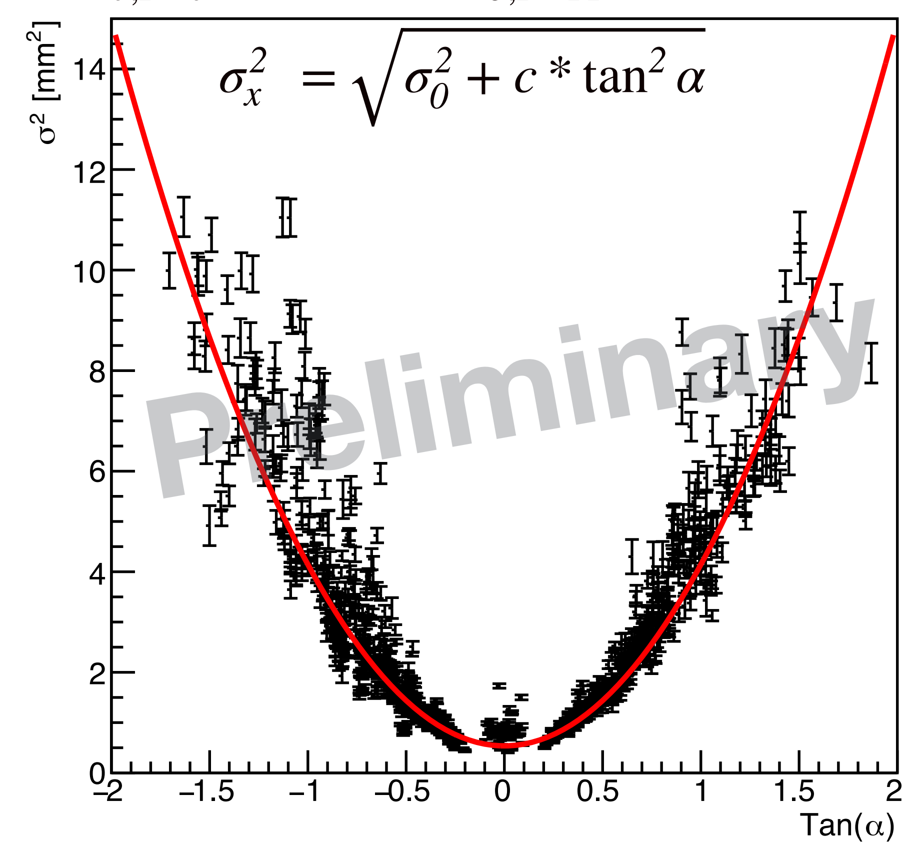
$$\alpha = \phi_{track} - \phi_{pad}$$



Momentum resolution for π^-

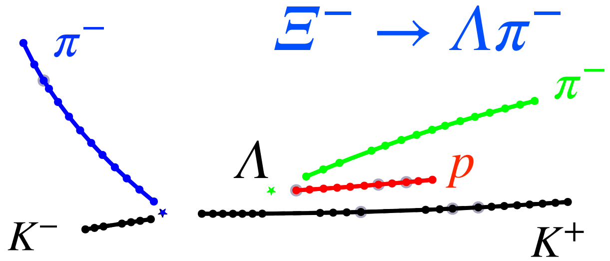


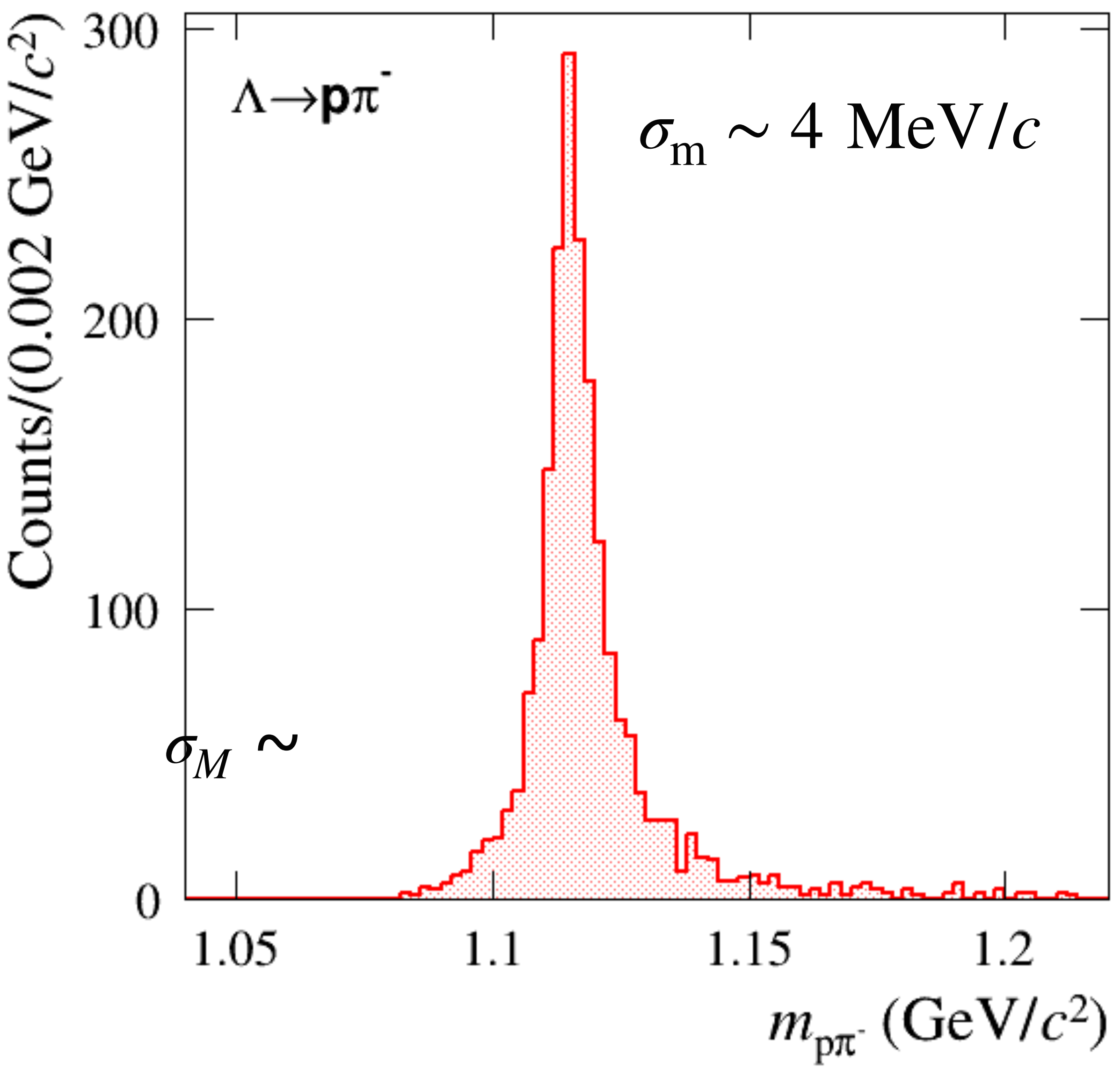
$\sigma_{0,B=0} \sim 730\ \mu m, \sigma_{o,B=1T} \sim 370\ \mu m$

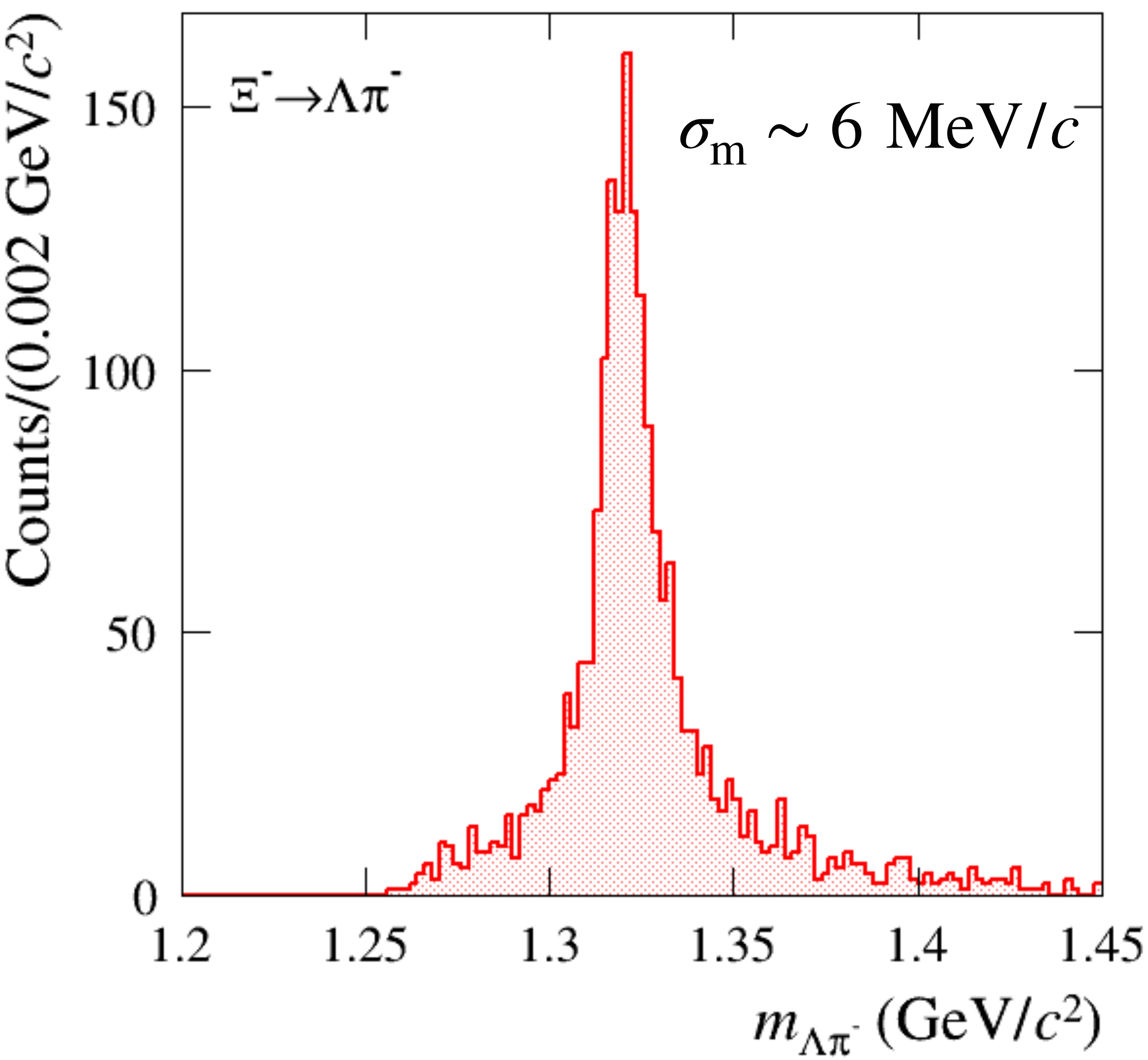


Ξ^- Hyperon Reconstruction using HypTPC

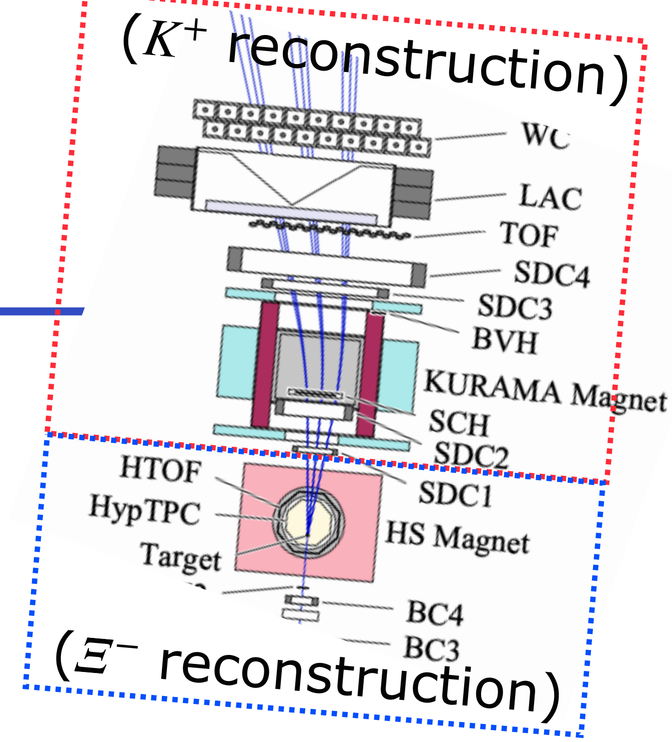
Reconstruction of invariant mass distributions
for Ξ^- and its sequential decays.







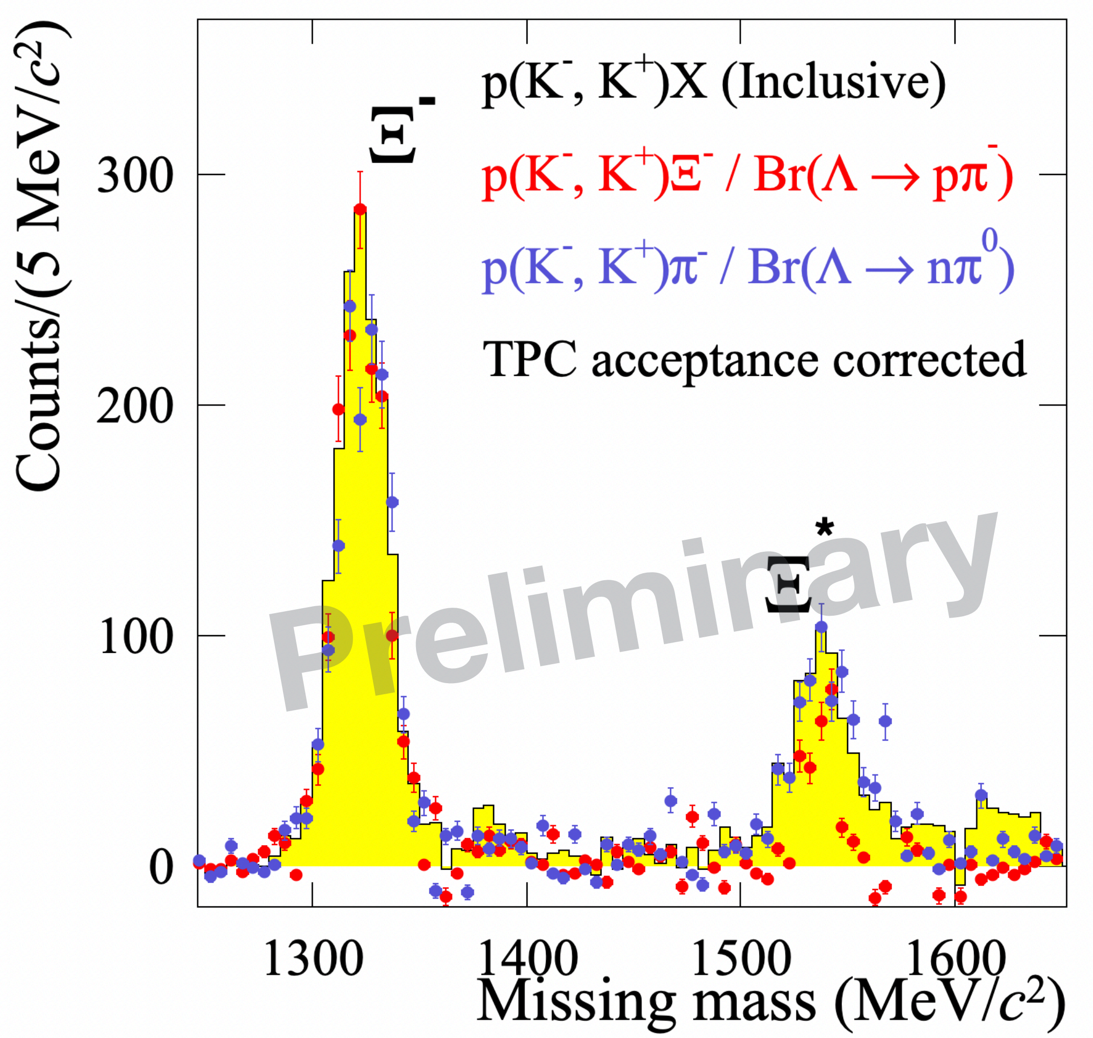
Validation for Ξ^- reconstruction with HypTPC



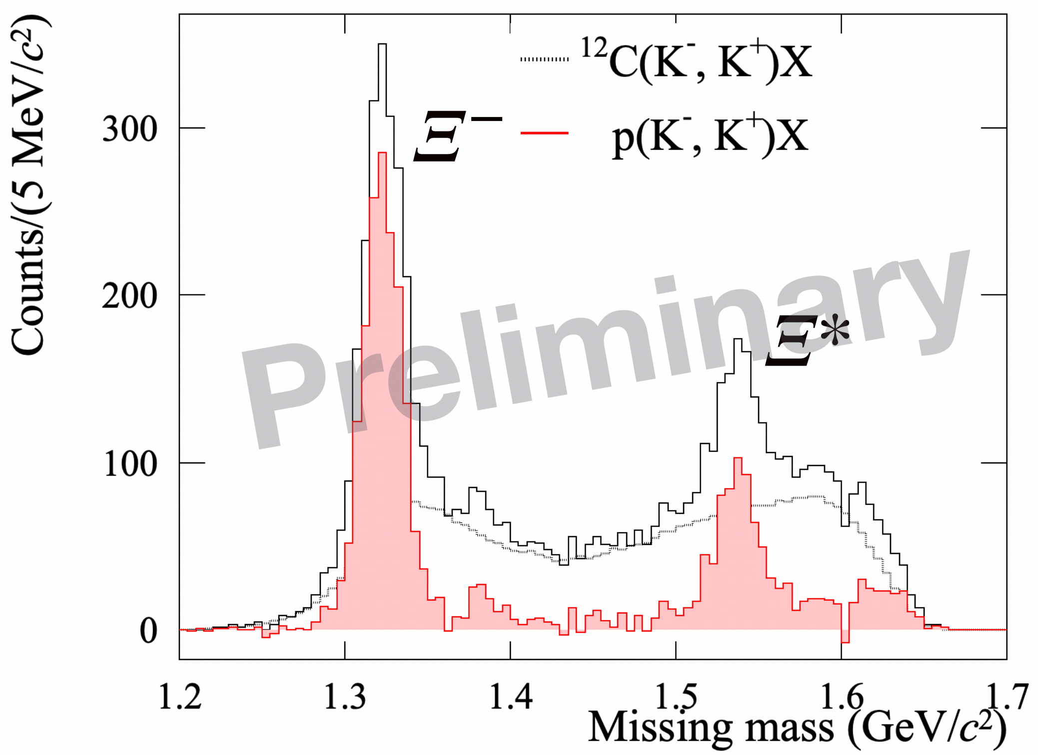
The missing-mass spectrum for $p(K^-, K^+)X$ reactions is reproduced with Ξ^- reconstructed events for

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

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

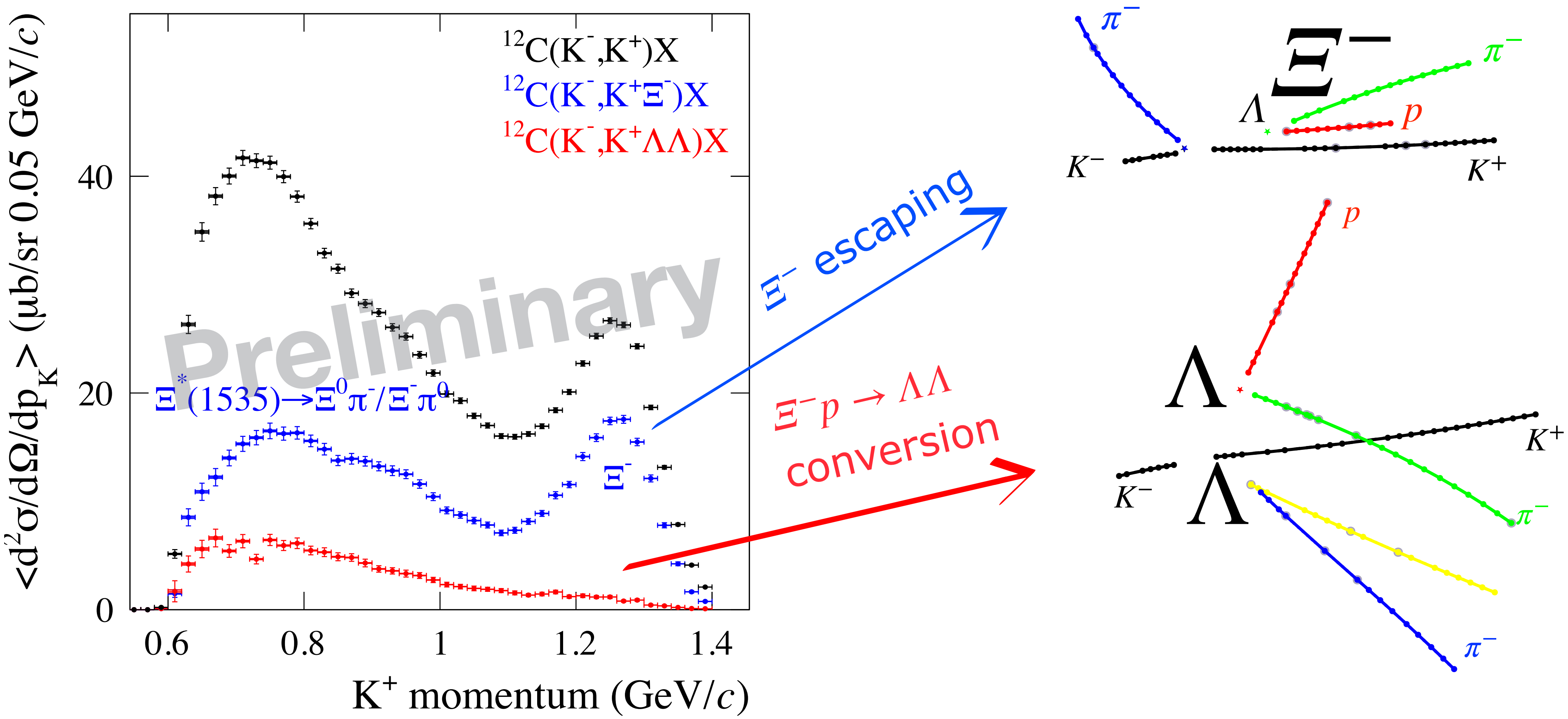


^{12}C contribution subtracted from the spectrum with a CH_2 target

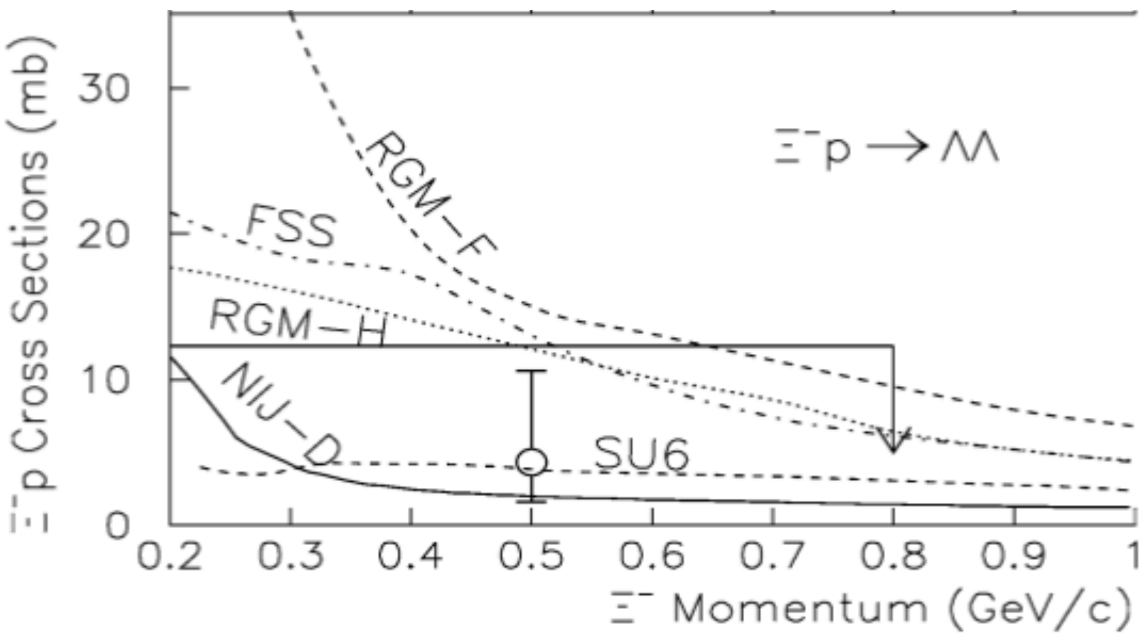


Results for Cross-section Measurement of $^{12}C(K^{-}, K^{+})$ Reactions

- The first physics analysis result using HypTPC at J-PARC.
- <u>The first statistically significant measurement</u> **X100 more data!**
- From the inclusive spectrum for $^{12}C(K^{-}, K^{+})$ reaction,
  Ξ^{-} escaping and $\Xi^{-}p \rightarrow \Lambda\Lambda$ conversion spectra were decomposed.



Definitive Measurement of the on $\Xi^{-}p \rightarrow \Lambda\Lambda$ Conversion Process

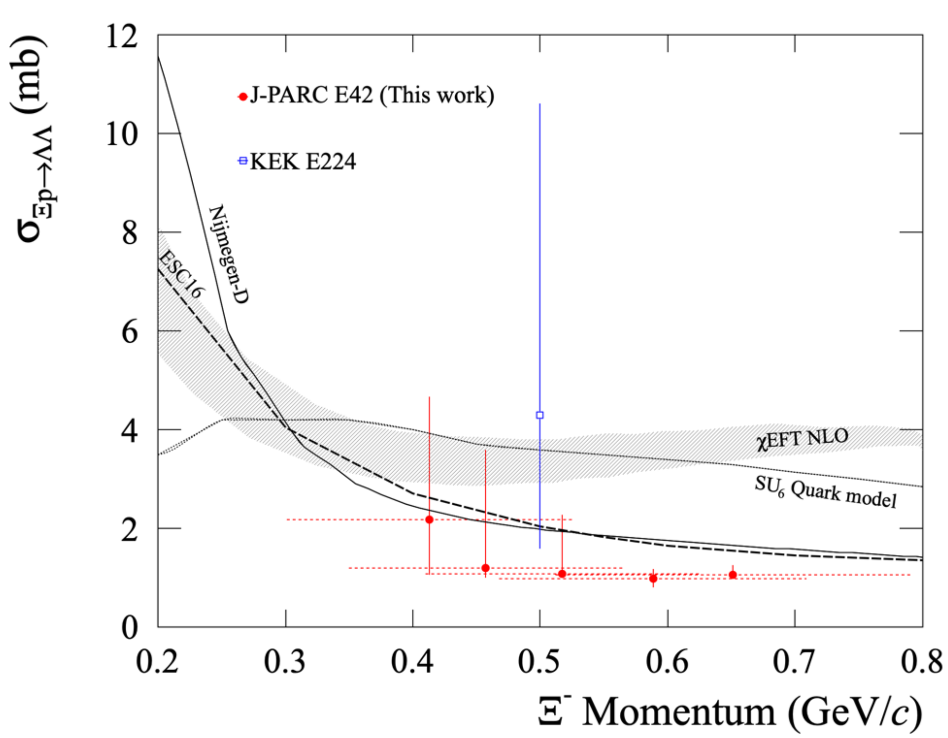


*J.K. Ahn et al. / Physics Letters B 633 (2006) 214–218

Past Data (KEK E224)

1. $\Xi^{-}p \rightarrow \Lambda\Lambda$ reaction: null event
   12 mb upper limit (90% C.L.)
2. $\Xi^{-11}\mathbf{B} \rightarrow \Lambda\Lambda^{10}\mathbf{Be}$ reaction: 3 events

These 3 events were only available data.



*W.S. Jung et al., In press, PTEP. (arXiv:2503.17614v2 [nucl-ex])

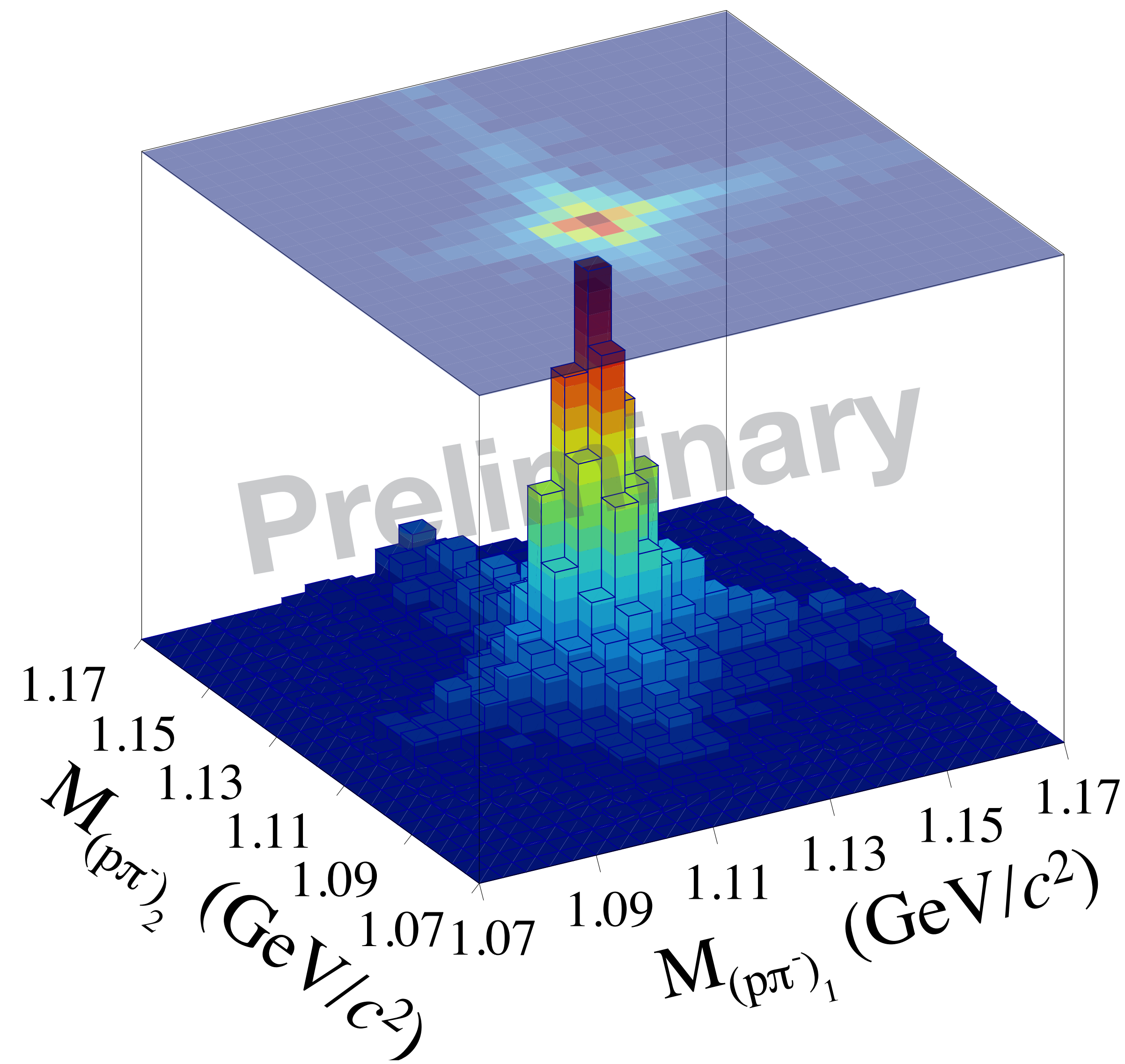
This work (J-PARC E42)

The first statistically significant measurement!

- $\Xi^{-}p \rightarrow \Lambda\Lambda$ cross section is $1.0^{+1.3}_{-0.9}$ mb at $0.5 < P_{\Xi^{-}} < 0.6$ GeV/c.
- This result constraints $\Gamma_{\Xi^{-}} < \sim 0.6$ MeV in nuclear matter.

Summary

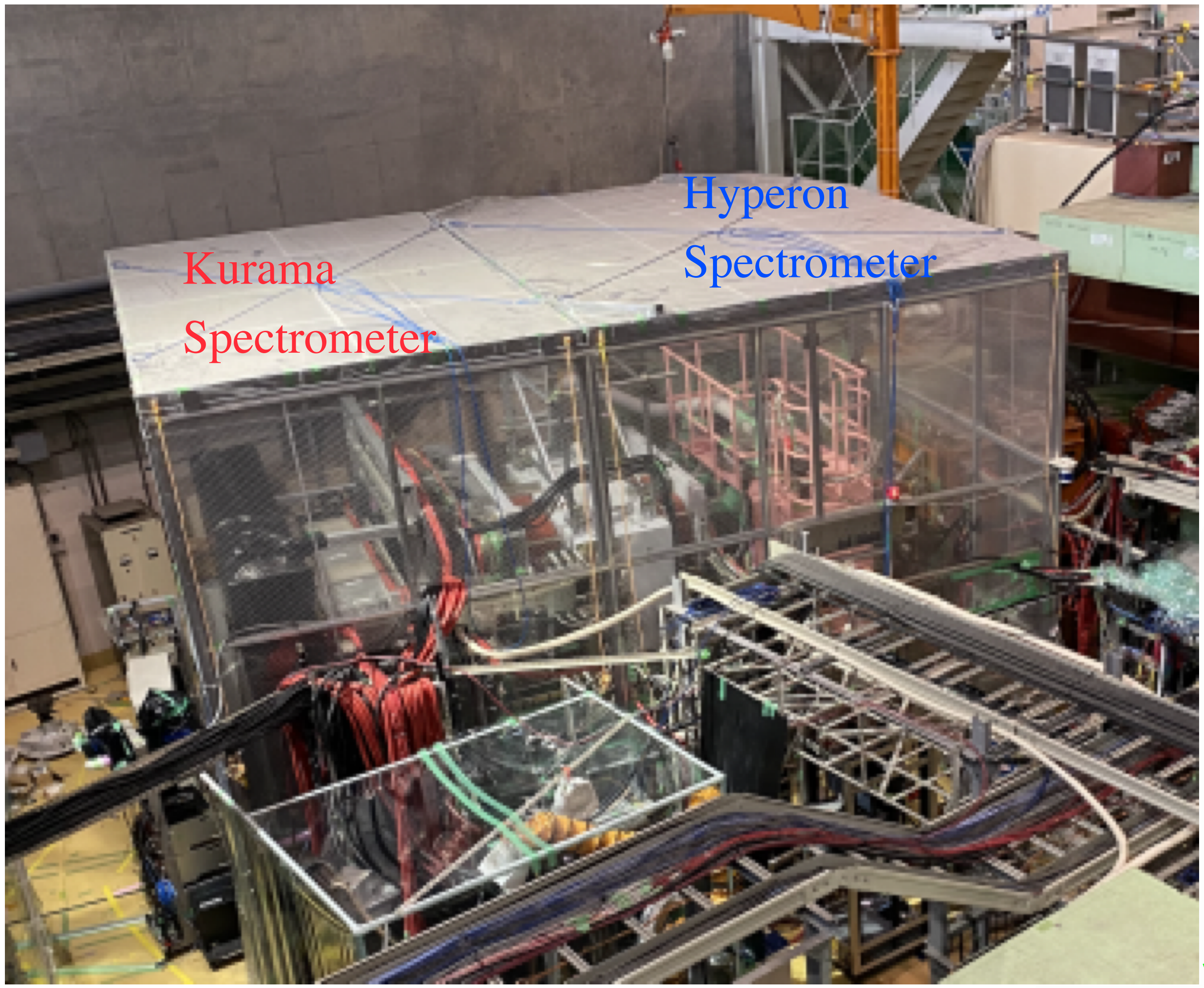
- We developed Hyperon Spectrometer for Hadron Experiments at J-PARC.
- J-PARC E42 for study on double-strangeness production for $^{12}\mathbf{C}(K^-, K^+)$ reaction was conducted successfully by using HypTPC.
- E42 report the results on differential cross-section measurement for $^{12}C(K^-, K^+)X$ reaction including $^{12}C(K^-, K^+\Xi^-)$ and $^{12}C(K^-, K^+\Lambda\Lambda)$.

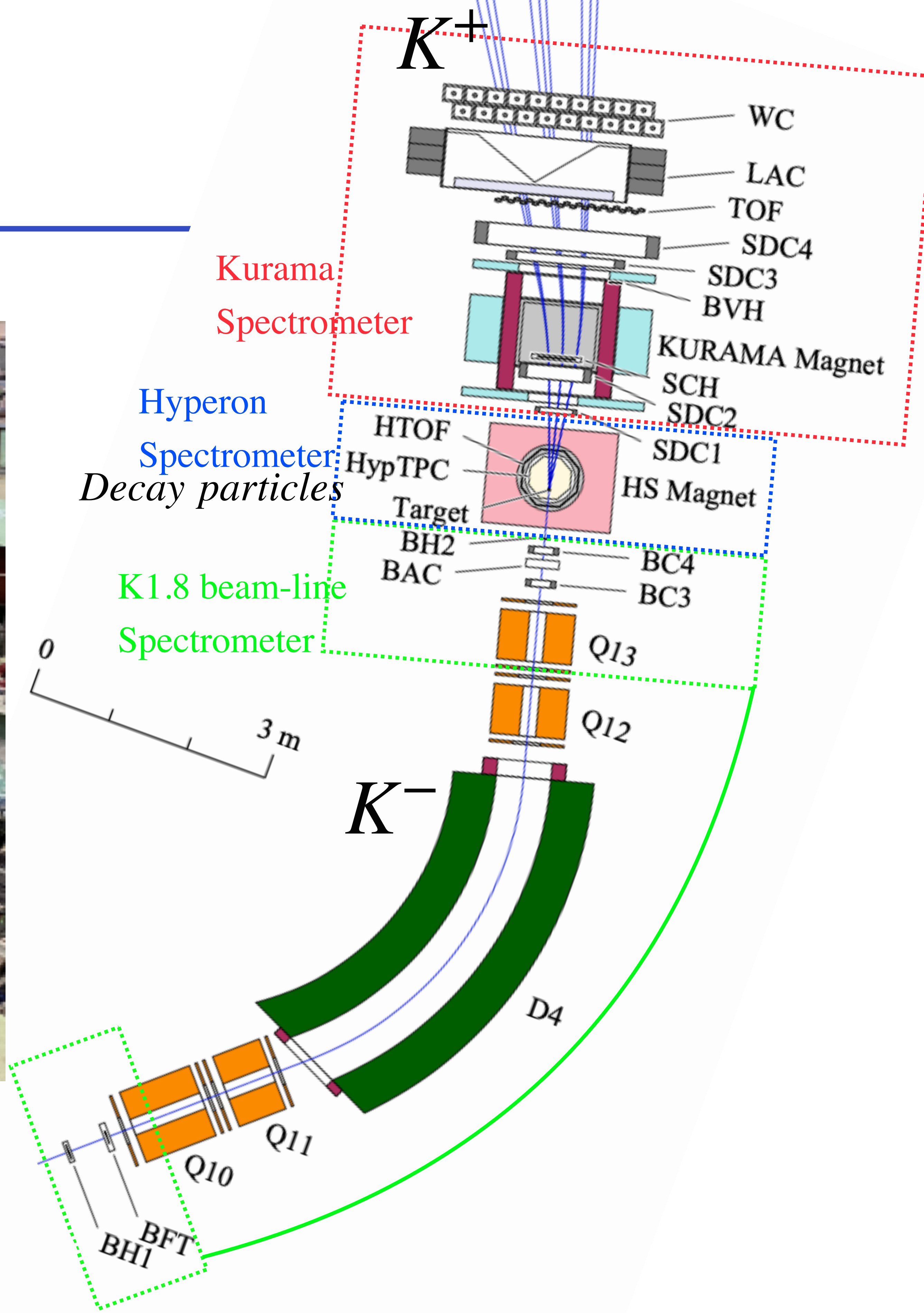


The preliminary results on H-search will be presented at HYP2025 on Sep.!

BACKUP

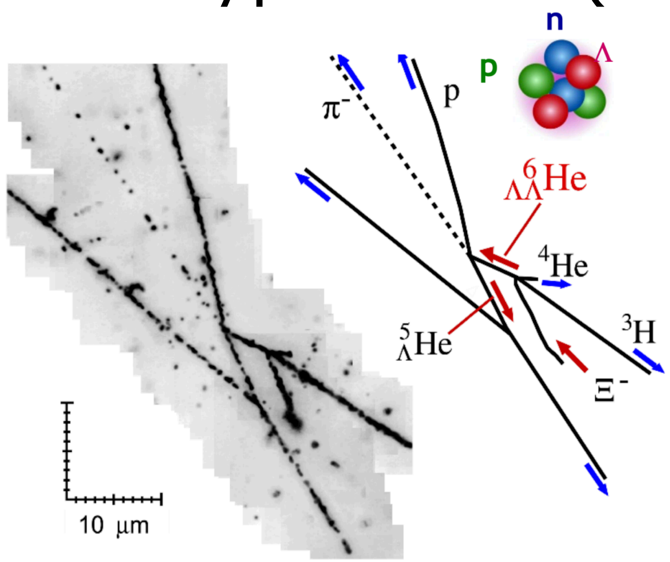
J-PARC E42 Detector





ΛΛ/Ξ Hypernuclei: Probes of The S=-2 Sector

1. ΛΛ Hypernuclei (Nagara event)



$$_{\Lambda\Lambda}{}^{6}\mathrm{He} \rightarrow {}_{\Lambda}{}^{5}\mathrm{He} + \mathrm{p} + \pi^{-}$$

$$B_{\Lambda\Lambda} = 6.91 \pm 0.16\ \mathrm{MeV},\ \Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17\ \mathrm{MeV}$$

*H. Takahashi et al., Phys. Rev. Lett. 87 (2001)212502

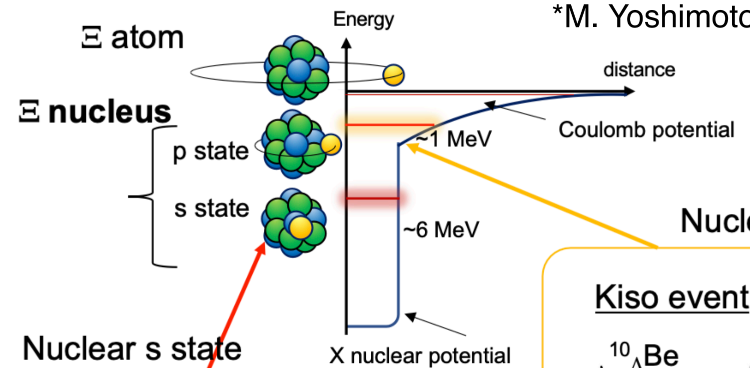
	(MeV)		
	2260	ΞN	$\updownarrow \Delta m : \Xi N - \Lambda\Lambda$
$B_{\Lambda\Lambda}\updownarrow$	2231	$\Lambda\Lambda$	
	2224		

$\Lambda\Lambda - \Xi N$ coupling

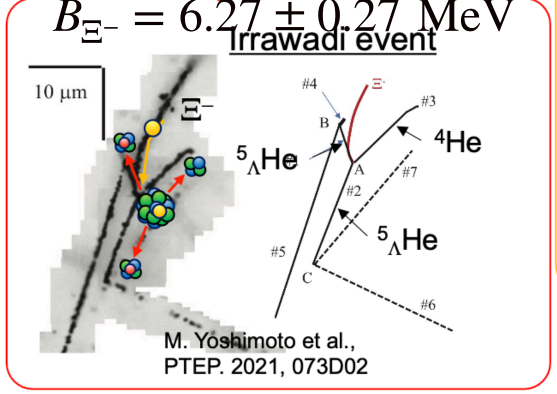
1. $_{\Lambda\Lambda}{}^{6}\mathrm{He}$ (suppressed) ⟷ $_{\Lambda\Lambda}{}^{4}\mathrm{H}, {}_{\Lambda\Lambda}{}^{5}\mathrm{H}$ no data (not suppressed)
2. Observation of p, s state Ξ Hypernuclei -> Weak!
3. X-ray yield ratio(width) of each absorption states

2. Ξ Hypernuclei

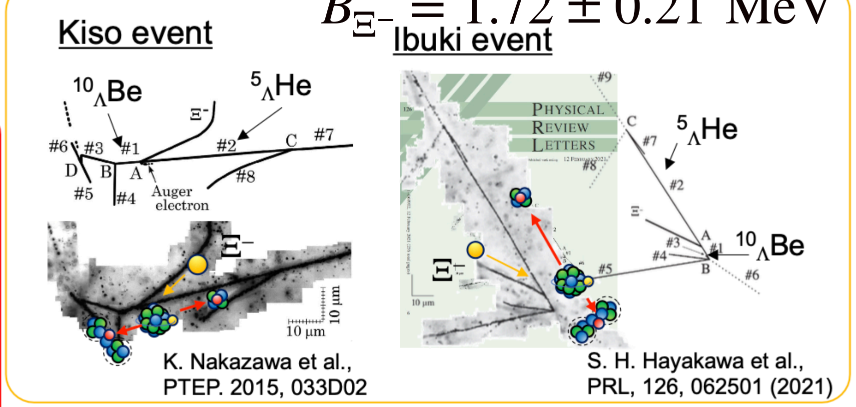
*M. Yoshimoto et al., Prog. Theor. Exp. Phys. 2021, 073D02



$B_{\Xi^-} = 6.27 \pm 0.27$ MeV



$B_{\Xi^-} = 1.72 \pm 0.21$ MeV

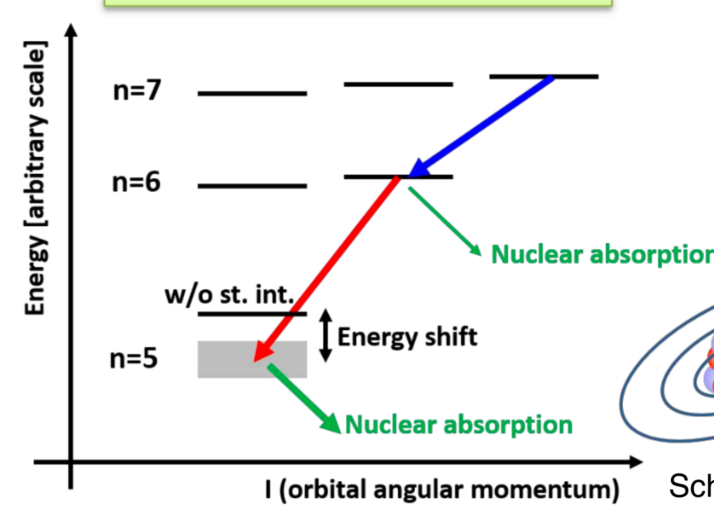


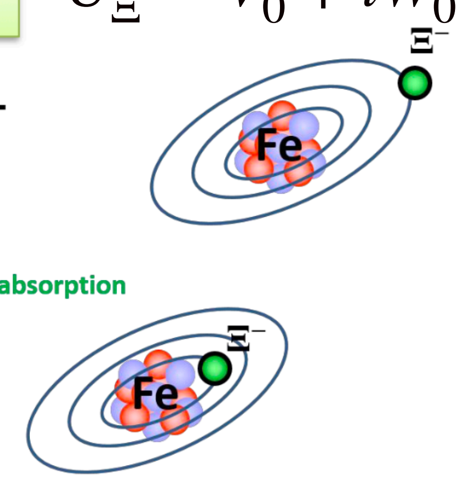
3D ~ 35%, 2P~4%, 1S<0.1%

3. Ξ atomic X-ray spectroscopy

Level scheme of Fe Ξ⁻-atom

$$U_{\Xi} = V_0 + iW_0$$





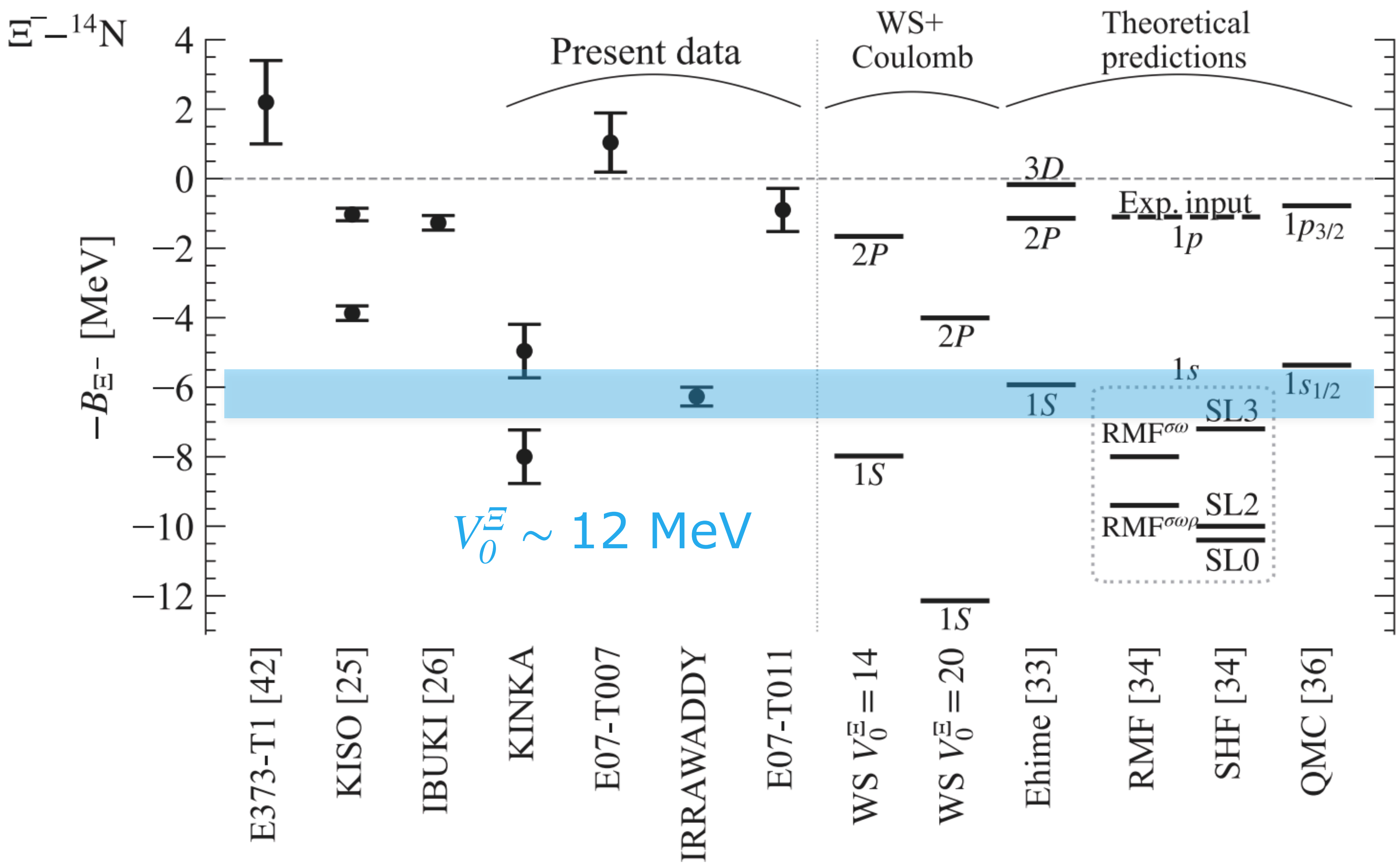
Schematic of J-PARC E03

Current Status of Ξ^-–nucleus Potential

How deep? How absorptive?

Constraints of the depth of the Ξ^- single-particle potential

*M. Yoshimoto et al., Prog. Theor. Exp. Phys. 2021, 073D02



Can we determine of W_Ξ^0 for absorption?

*T.Iijima et al, NPA 546 (1920) 588

cf.) E176 pK- : 1.65 GeV/c, nuclear target

12C integrated cross-section for K-K+ reaction

TABLE 1

Integrated cross section (μb/sr)

Target	K^+ momentum region (GeV/c) $0.95 < p_{K^+} < 1.30$ data [a)]	$0.95 < p_{K^+} < 1.30$ (calc.) [b)]	$0.35 < p_{K^+} < 0.95$ data [a)]	$0.35 < p_{K^+} < 0.95$ (calc.) [b)]	$0.35 < p_{K^+} < 1.30$ data [a)]
C	99 ± 4	(73)	289 ± 12	(65)	387 ± 13
Al	118 ± 11	(117)	472 ± 35	(107)	590 ± 37
Cu	190 ± 17	(178)	719 ± 50	(166)	908 ± 53
Ag	226 ± 15	(201)	1032 ± 53	(193)	1259 ± 55
Pb	296 ± 30	(224)	1357 ± 99	(219)	1653 ± 103

[a)] The normalization error (±6%) is not included in the error.
[b)] The calculation is made with the DWIA method described in sect. 5.1.

A-dependence

T. Iijima et al. / (K , K+) reaction 599

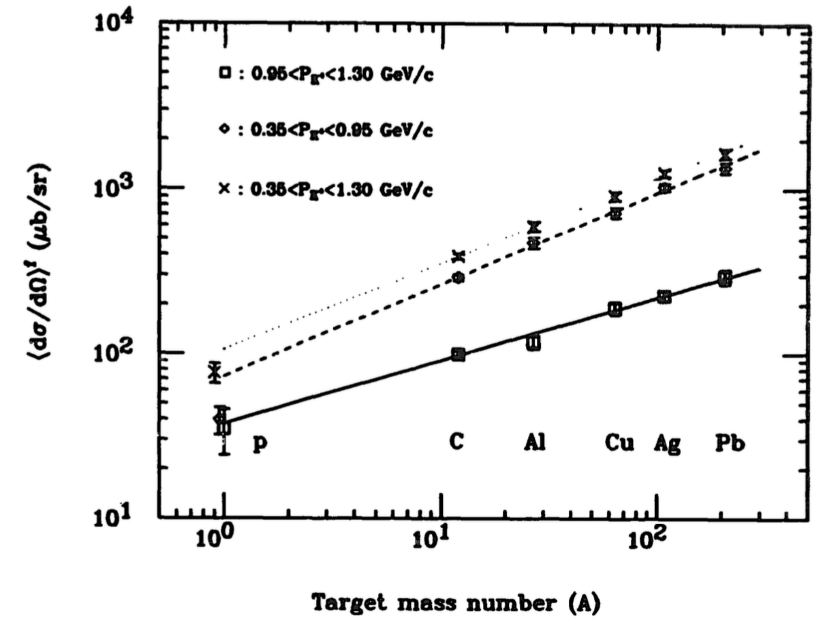


Fig. 6. Fitting of the A-dependence in the form of CA^{α}, for each K^+ momentum region (solid: $0.95 < p_{K^+} < 1.30$ GeV/c, dashed: $0.35 < p_{K^+} < 0.95$ GeV/c, dotted: $0.35 < p_{K^+} < 1.30$ GeV/c). The measured cross sections for the proton target are also shown but they are not included in the fitting. The normalization error of the cross section is not included in the error bar.

This work(J-PARC E42)

Diff. Cross-section

(K,K): ub/sr 99.72 +/- 0.32 (stat.) - 0.03 + 0.02(sys.)

$\Lambda\Lambda$: ub/sr 5.13 +/- 0.19 (stat.) - 0.16 + 0.16(sys.)

Ξ^-: ub/sr 59.55 +/- 0.44 (stat.) - 0.04 + 0.03(sys.)

Escaping Probabilities for (0 < $\mathbf{E}_{\Xi}$ < 250 MeV, 0.5 < P_{K+} < 1.4 GeV/c)

$\Lambda\Lambda$ conversion(%): 1.9 +/- 0.003 (stat.) - 0.01 + 0.01(sys.)

Ξ^- emission(%): 59.72 +/- 0.001 (stat.) - 0.02 + 0.02 (sys.)

12C escaping prob. x (12/9)^alpha (converted to 9Be):

66.62% with alpha=0.38 +/- 0.03 (0.95<pK<1.30 GeV/c T.Iijima et.al,)

*S. Aoki et al./Nuclear Physics A 644 (1998) 365-385

cf.) E176 P_{K-}=1.66 GeV/c, emulsion target

$73.9^{+4.5}_{-4.6}\%$

*T.Tamagawa/Nuclear Physics A691 (2001) 234c-237c

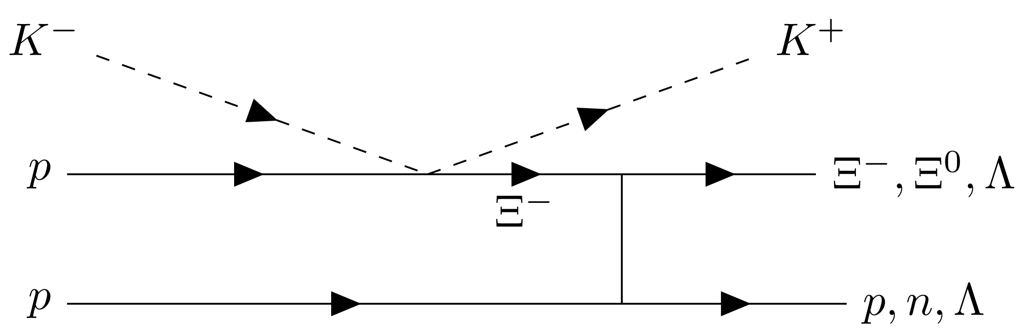
cf.) E906 P_{K-}=1.80 GeV/c, 9Be target

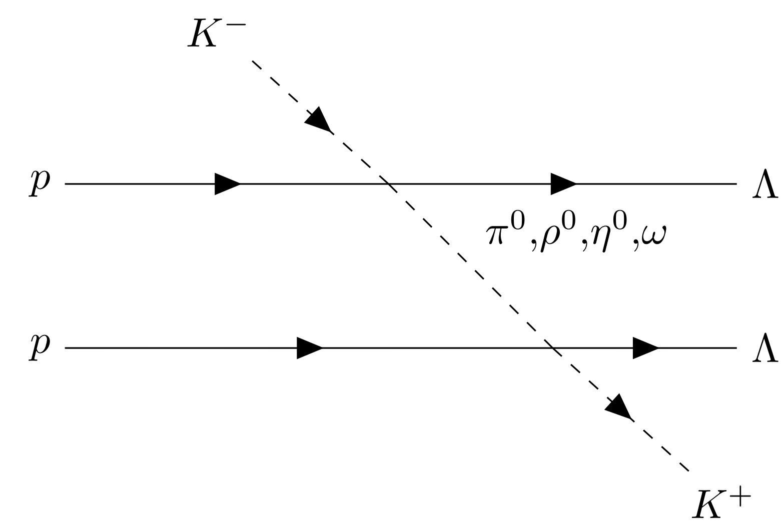
emission: $78.1 \pm 10.1\%$.

escaping: $63.6 \pm 8.2\%$

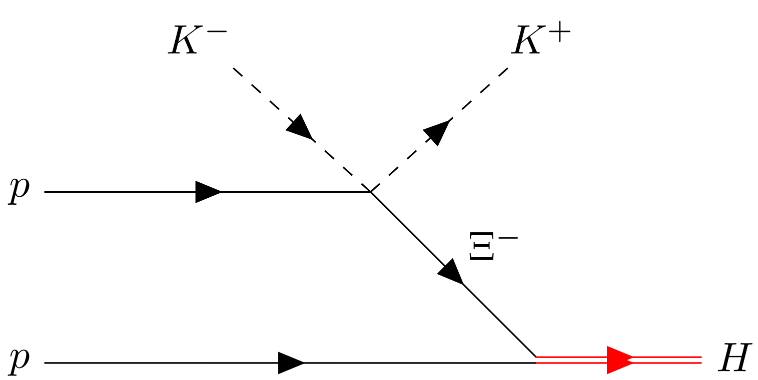
Possible H-dibaryon Formation via the $^{12}\mathrm{C}(K^-, K^+)$ Reaction

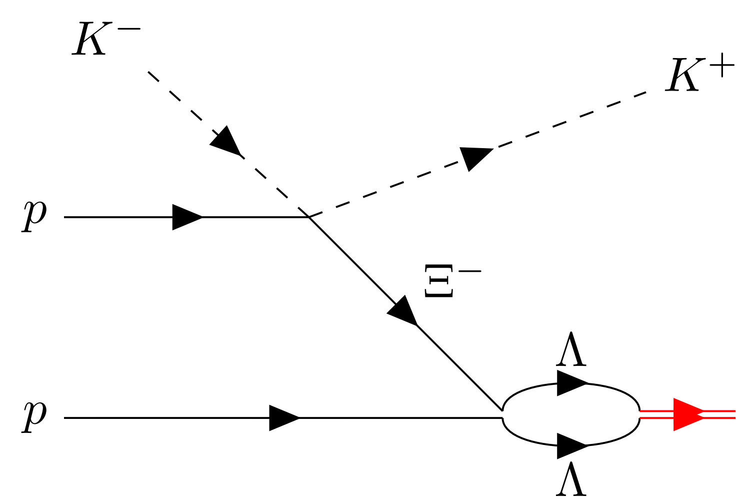
- Processes of double-strangeness exchange in $^{12}\mathrm{C}(K^-, K^+)X$ reaction

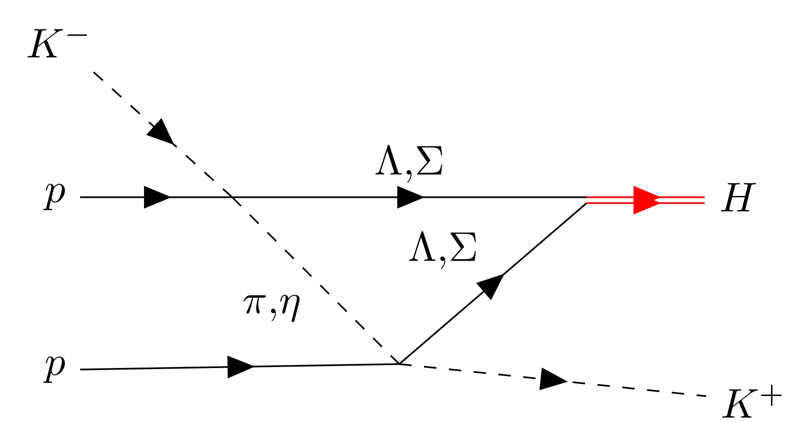




- Possible H production processes on a diproton pair via (K^-, K^+) reaction (Lowest order)







$\Xi N/\Lambda\Lambda$ interactions have a significant role in H-dibaryon formation

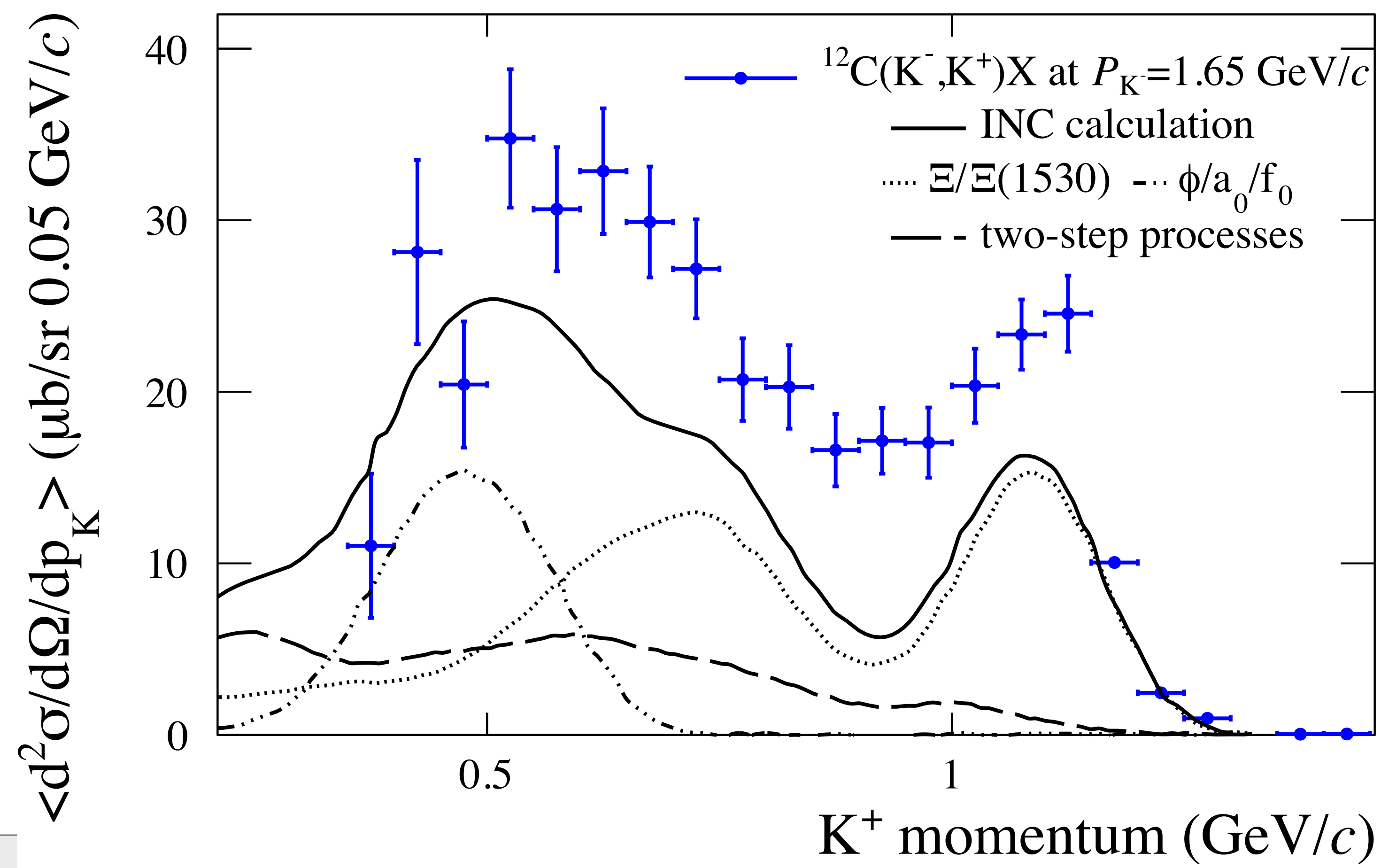
*A.T.M. Aerts and C.B. Dover, Phys. Rev. D28 450 (1983).

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

- One and two-step processes may contribute to the $^{12}C(K^-, K^+)X$ reactions.
- Past experimental data(KEK E176) with Intra-nuclear cascade model calculation

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

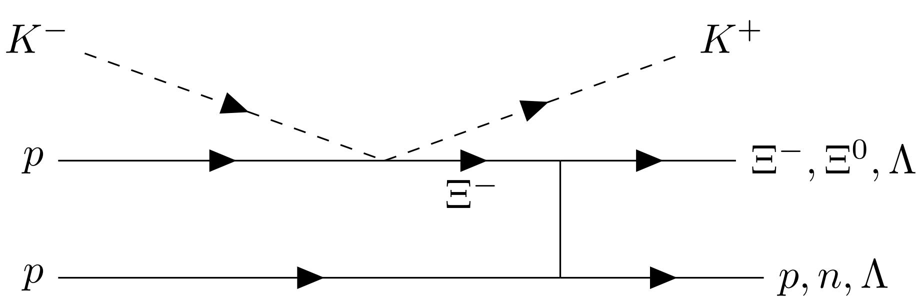
*Y. Nara, A. Ohnishi, T. Harada, A. Engel, Nucl. Phys. A 614, 433 (1997)

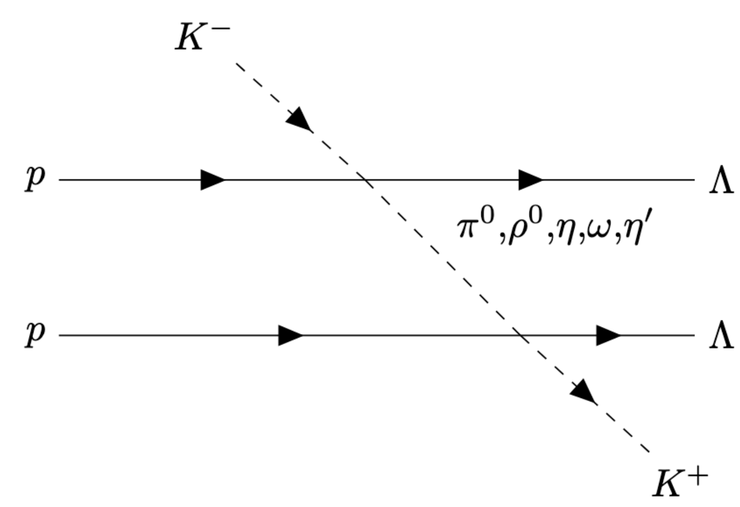


- One-step processes

$$K^-p \to K^+\Xi^-$$
$$K^-p \to K^+\Xi(1535)^-$$
$$K^-p \to \begin{pmatrix} \phi \\ a_0 \\ f_0 \end{pmatrix} \Lambda$$

- Two-step processes

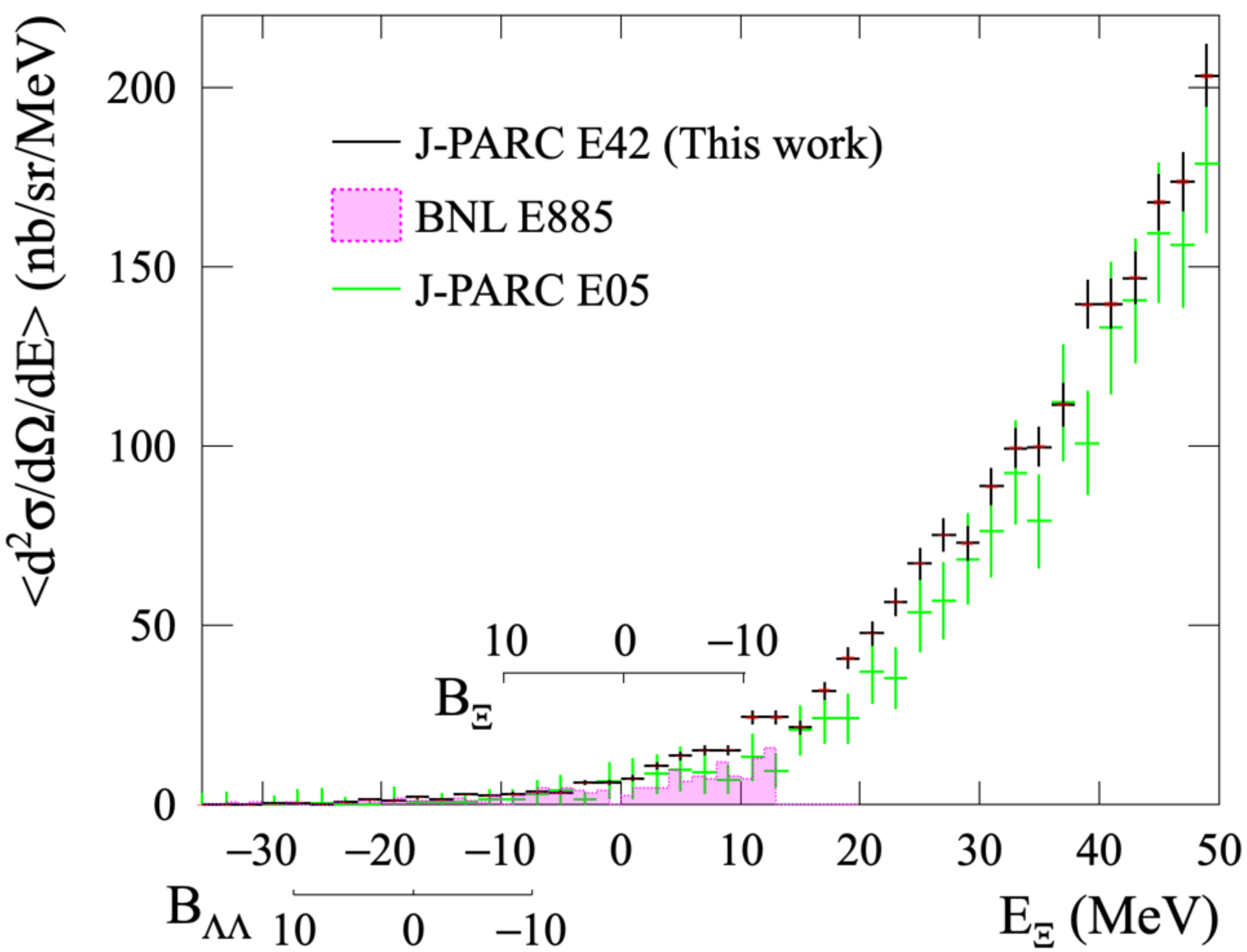


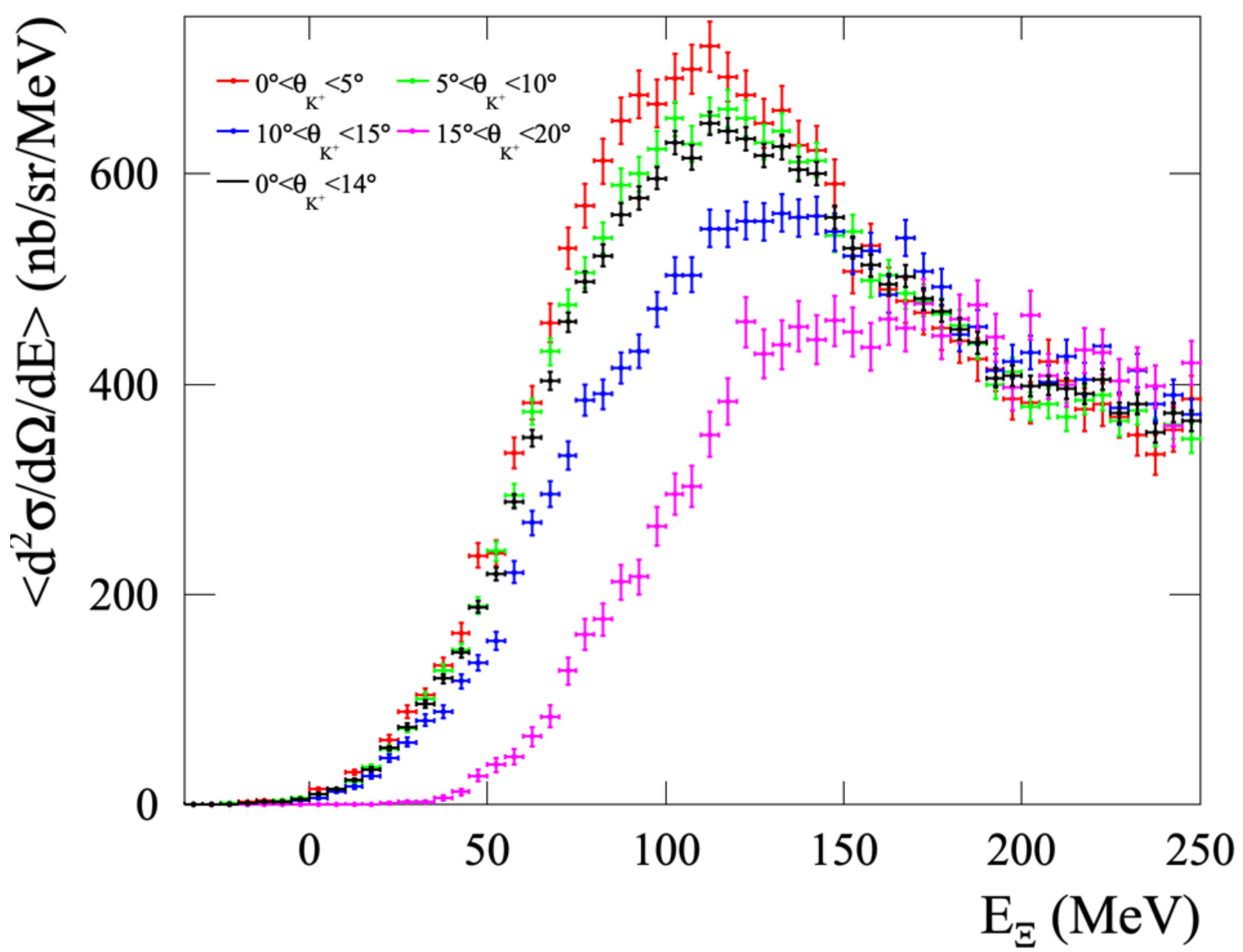


Ξ^- Excitation Energy Spectra for the inclusive $^{12}C(K^-, K^+)X$ reaction

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

$$\left\langle \frac{d^2\sigma}{d\Omega dE} \right\rangle = \frac{A}{N_A \rho x} \cdot \frac{N_{K^-K^+}}{N_{\text{beam}} \Delta\Omega_{\theta_1-\theta_2} \Delta E \varepsilon}$$



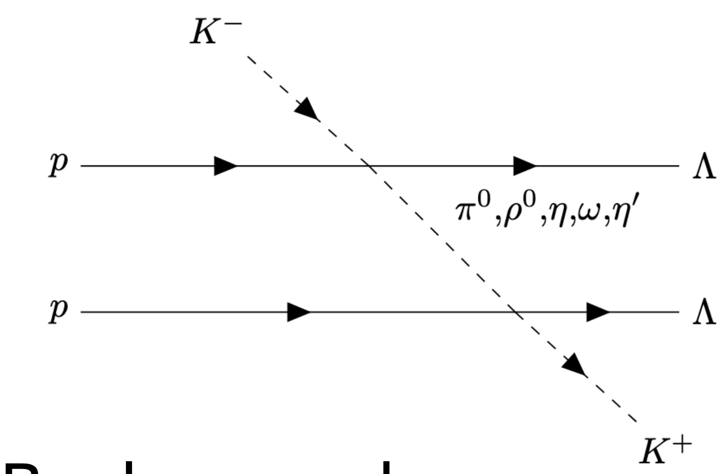


- J-PARC E42 measured double differential cross section for $^{12}C(K^-, K^+)X$ reaction.
- The result is consistent with previous experiments at BNL, J-PARC.
- W.S. Jung et al., (E42 Collab) In press, PTEP. (arXiv:2503.17614v2 [nucl-ex])

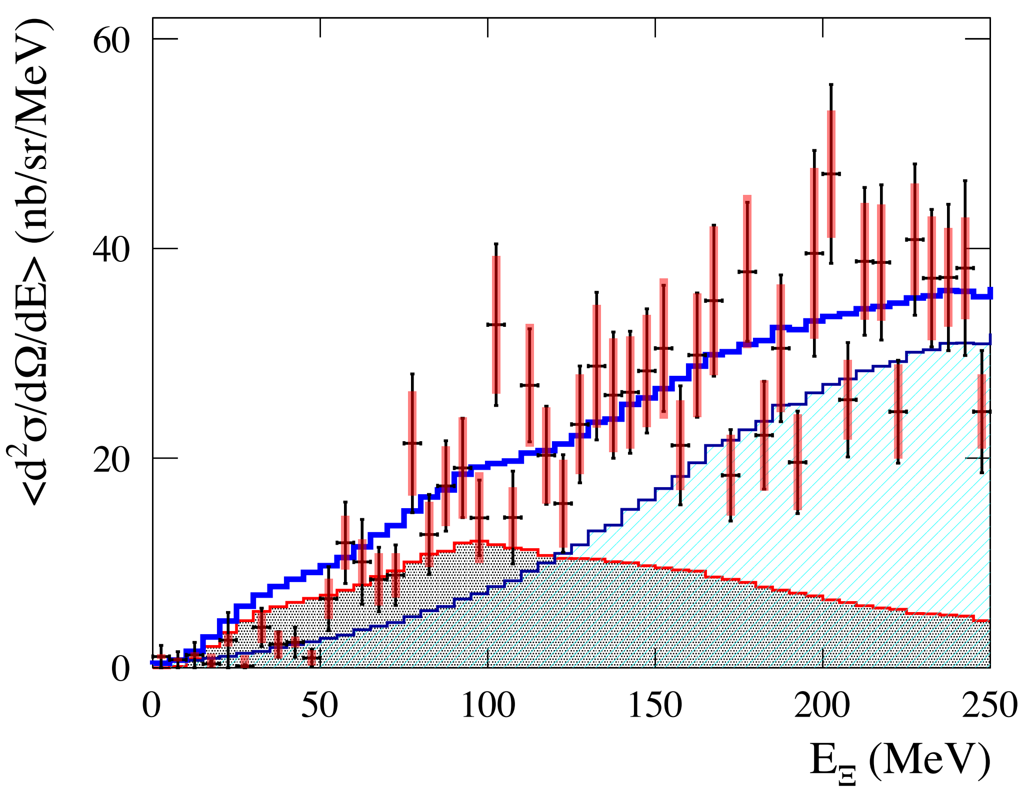
$\Lambda\Lambda$ production and $\Xi^- p \to \Lambda\Lambda$ contribution in the $^{12}\mathrm{C}(K^-, K^+)$ reaction

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

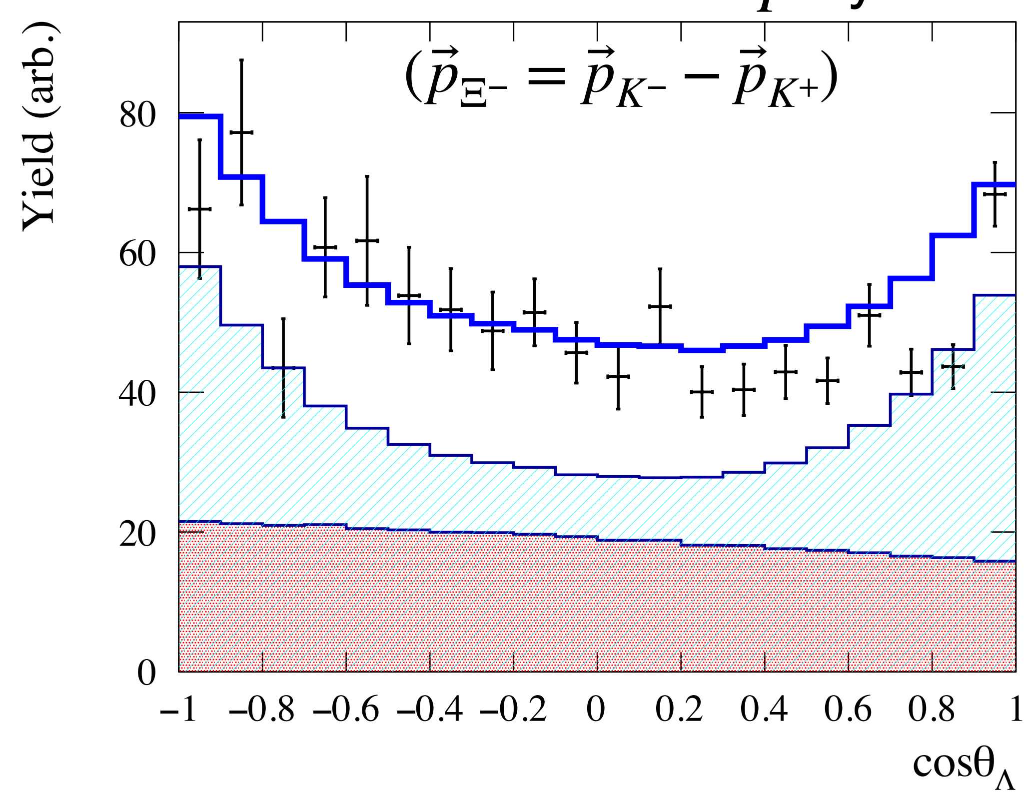
Based on Ref. *"Y. Nara, A. Ohnishi, T. Harada, A. Engel, Nucl. Phys. A 614, 433 (1997)"*



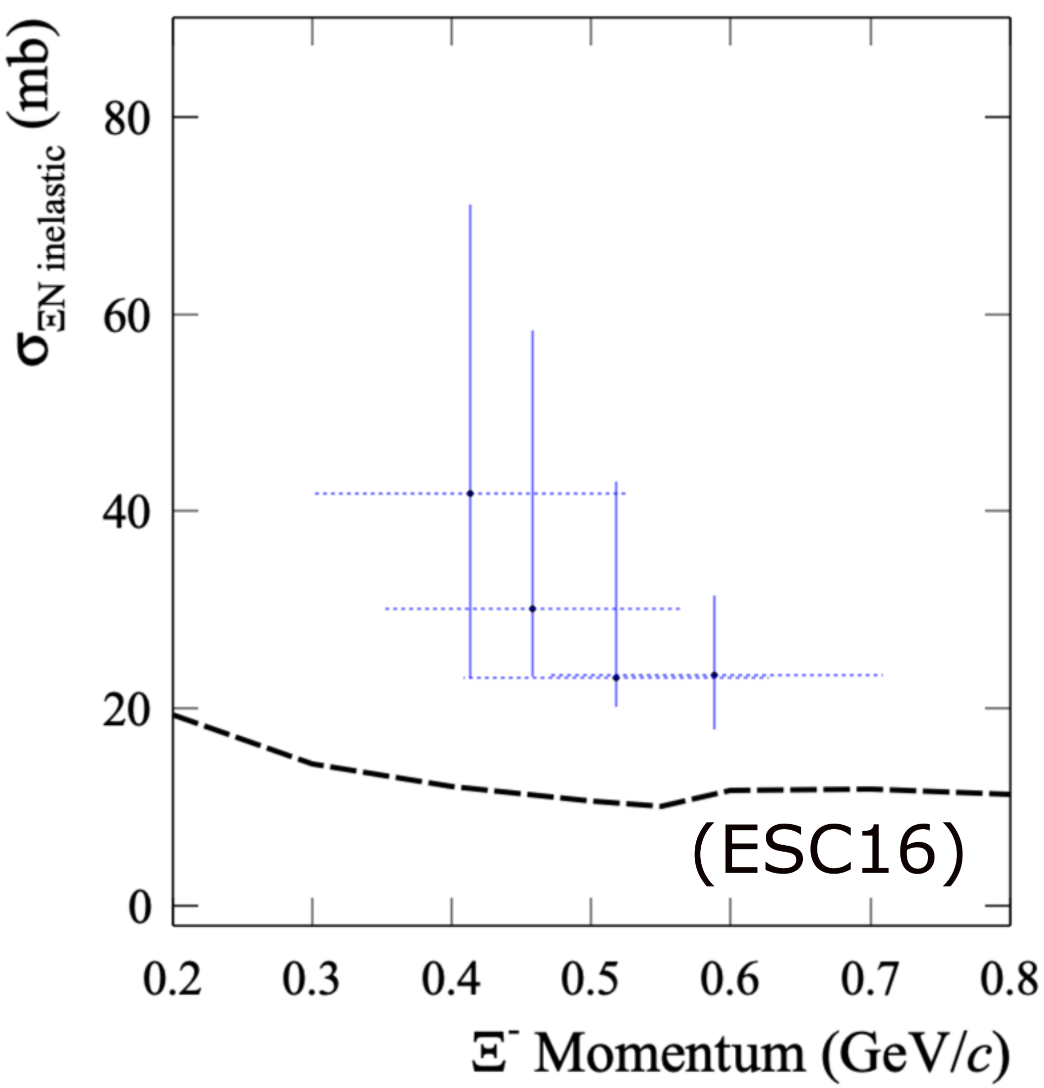
(Background processes)



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



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



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

- This work: 42 - 23 mb (0.4<p_{Ξ^-}<0.6 GeV/c)
- KEK E176: 12.7 mb (0.4<p_{Ξ^-}<0.6 GeV/c)
  *S. Aoki et al., NPA 644 (1998) 365-385
- BNL E906 at p_{Ξ^-} = 0.55 GeV/c (Nijmegen-D)
  (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

- Extended-soft-core Baryon Baryon model calculation (ESC16)

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