High resolution missing-mass spectroscopy of Ξ hypernuclei at J-PARC

ELPH研究会

1. 京都大学大学院理学研究科
2. 原子力研究開発機構先端基礎研究センター

江端健悟[1,2](Kengo EBATA) for J-PARC E70 collaboration

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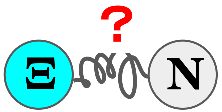
Introduction : Strangeness Physics

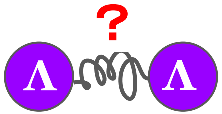
- S = −1 (one s-quark)

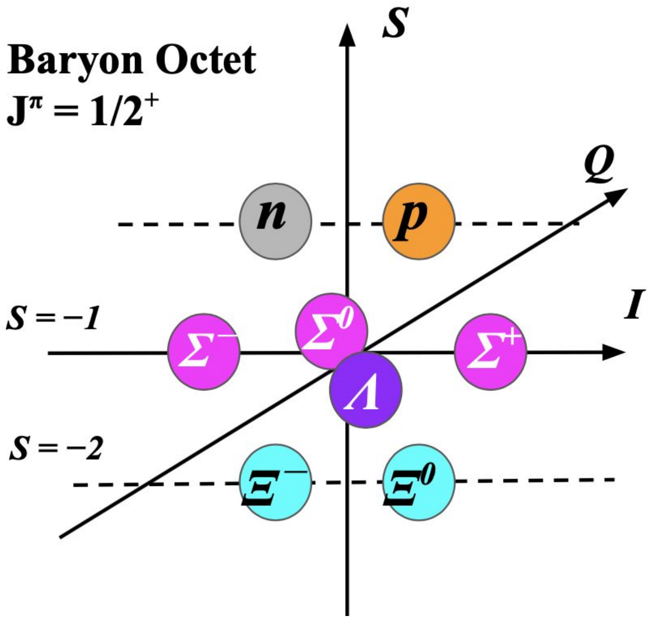
  → ・Spectroscopy for Λ, Σ hypernuclei
  ・deexcited γ-ray spectroscopy
  ・Σp scattering (J-PARC E40)

- S = −2 (two s-quarks)

  ・ΛΛ, ΞN interaction





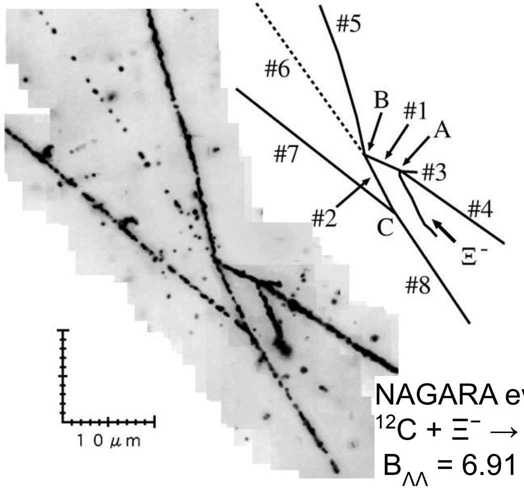


→ more general Baryon-Baryon interaction

S=−2 Physics Experiments

・Emulsion

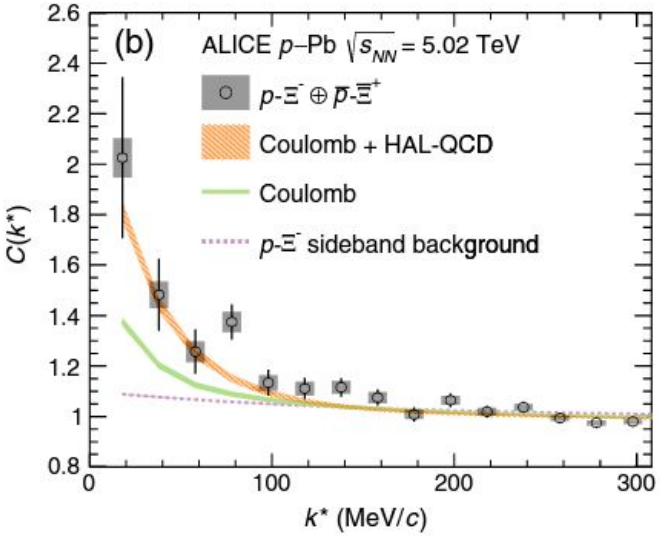
(NAGARA[1]、KISO, IRRAWADDY(^{14}N-Ξ), ...)



NAGARA event
$^{12}C + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}He + \alpha + t$
$B_{\Lambda\Lambda} = 6.91 \pm 0.16$ MeV

・Femtoscopy in heavy ion collision [3]

→ p-Ξ is attractive.

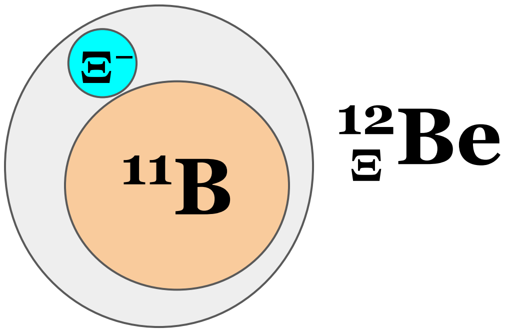


isospin and spin dependent interaction ?

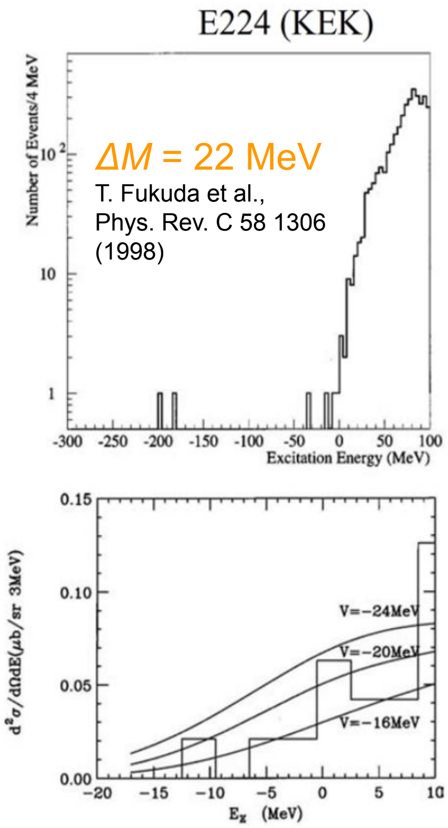
→ **High statistical & high resolution spectroscopy for Ξ hypernuclei**

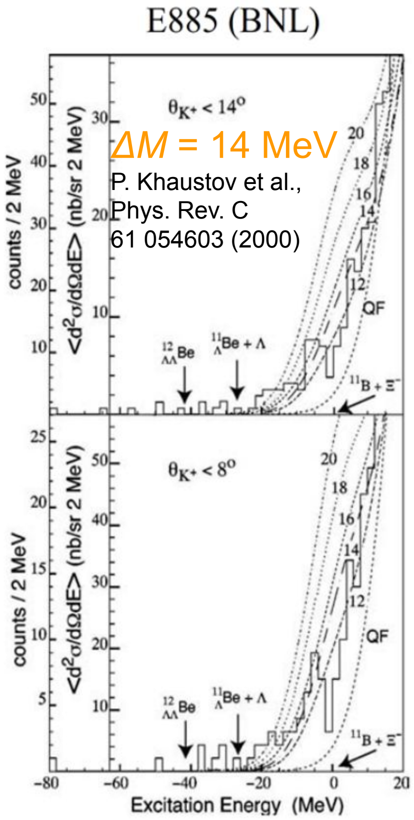
[1] H. Takahashi *et al*., Phys. Rev. Lett. **87**, 212502 (2001). [2] K. Nakazawa *et al*., Prog. Theor. Exp. Phys. **2015** 033D02 (2015).
[3] S. Acharya *et al*., (ALICE collaboration) Phys. Rev. Lett. **123**, 112002 (2019).

Missing-Mass Spectroscopy for Ξ hypernuclei



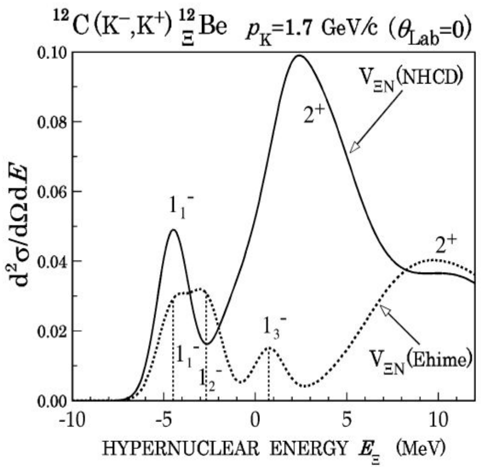
resolution	KEK E224	BNL E885	J-PARC E05	J-PARC E70
FWHM MeV/c^2	22	14	6	2

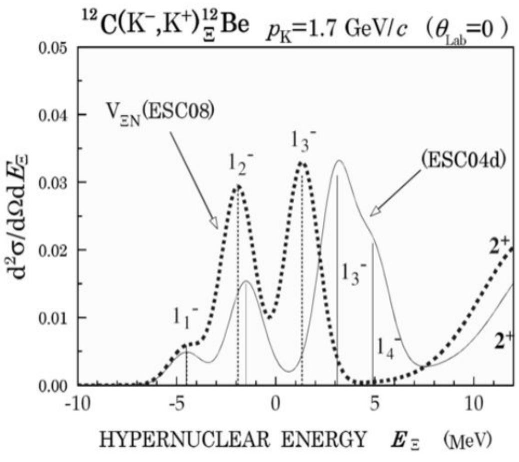


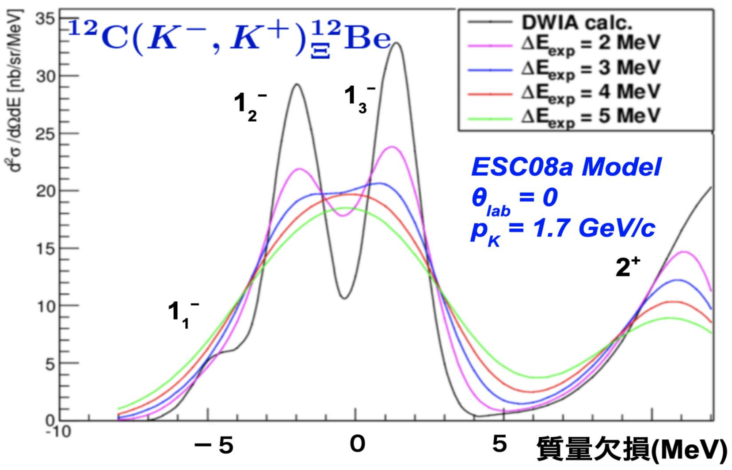


Missing-Mass Spectroscopy for Ξ hypernuclei

T. Motoba, S. Sugimoto, Nuclear Physics A **835**, 223 – 230 (2010).





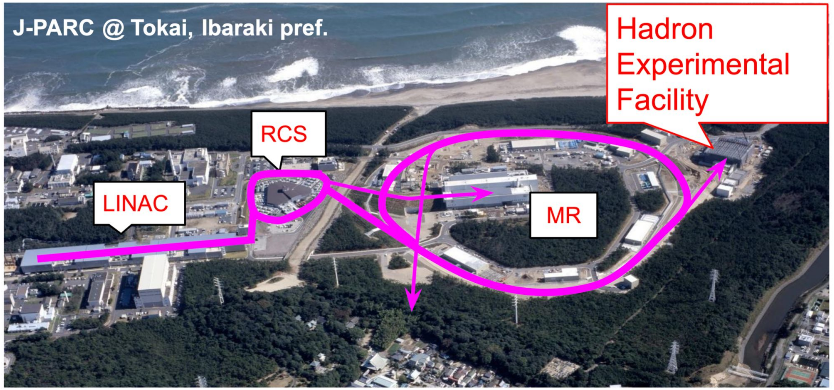


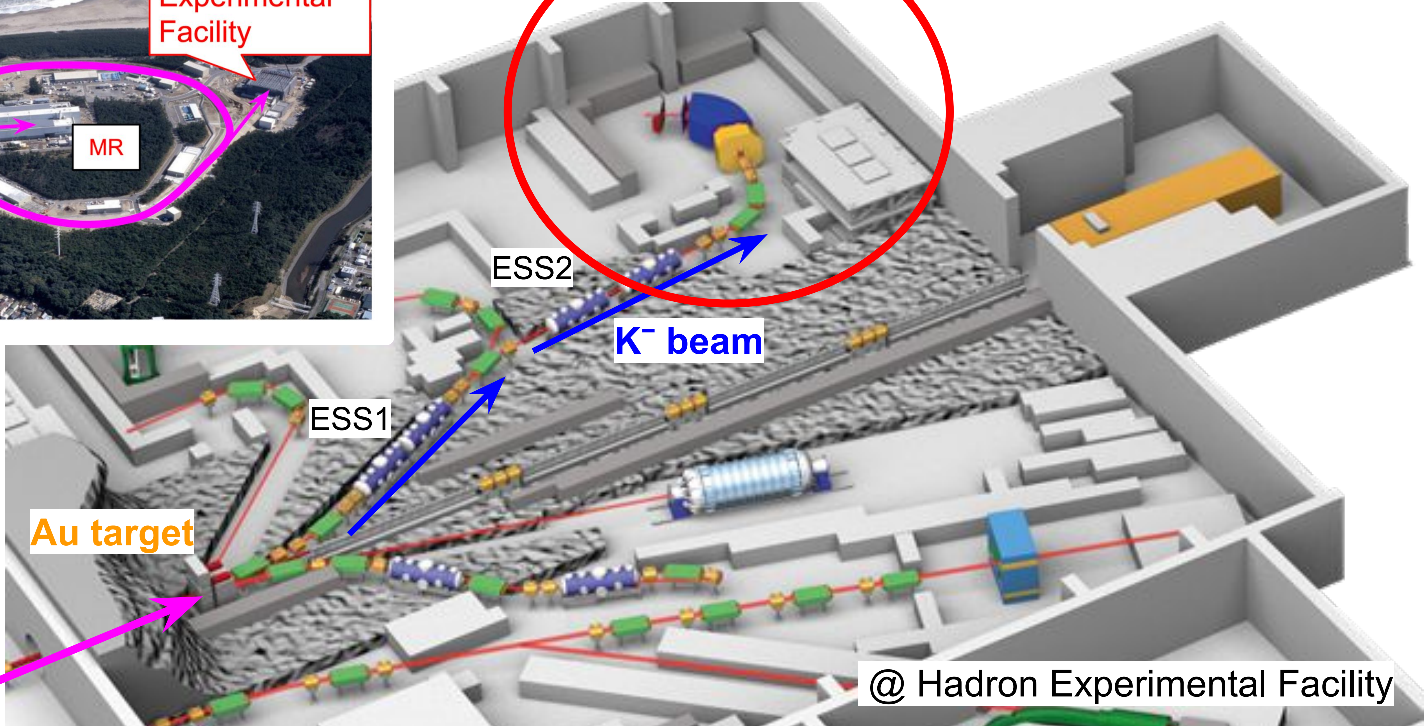
in J-PARC E70,
ΔM **< 2 MeV** (FWHM)

accuracy of peak position → ~100 keV,
decay width → a few hundred keV

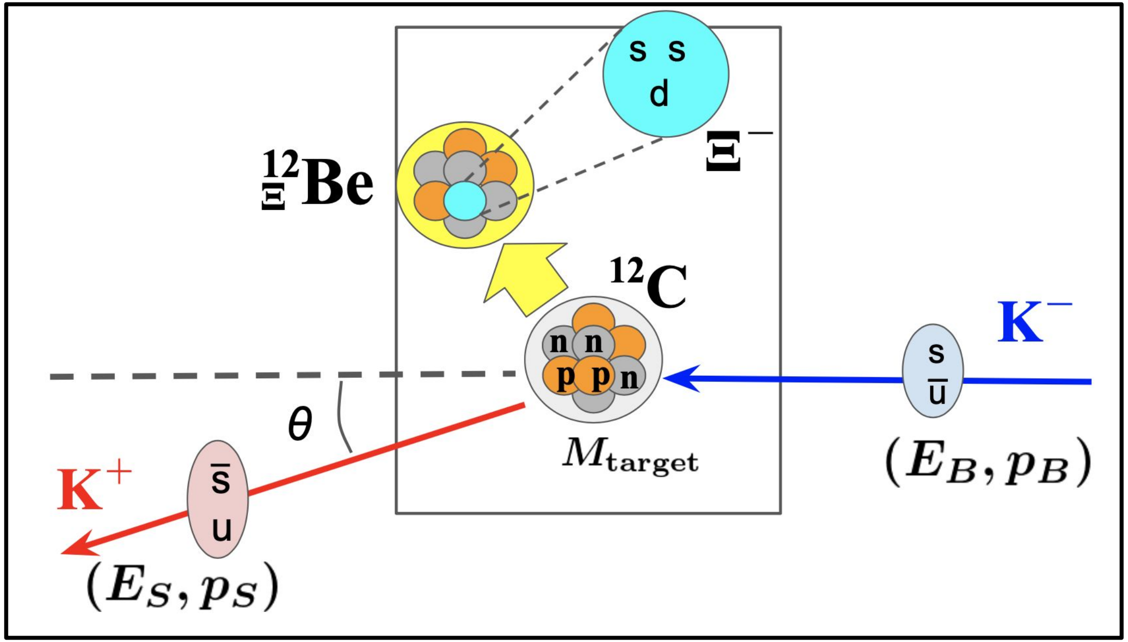
→ Establish spectroscopy for Ξ hypernuclei

K1.8 beamline in J-PARC





J-PARC E70 Experiment

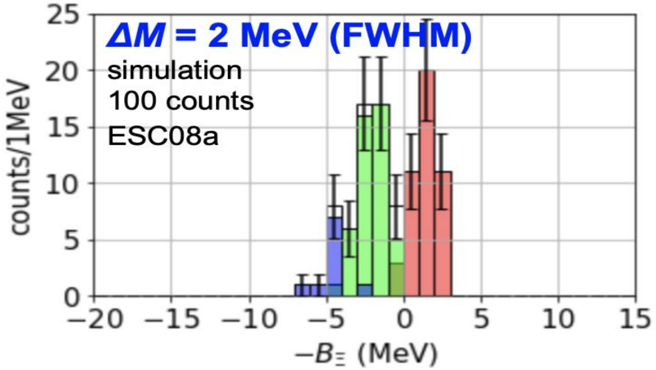


K⁻ momenta : p_B
K⁺ momenta : p_S

Missing-Mass

$$M_{\rm HYP} = \sqrt{(E_B + M_{\rm target} - E_S)^2 - (p_B^2 + p_S^2 - 2p_B p_S \cos\theta)}$$

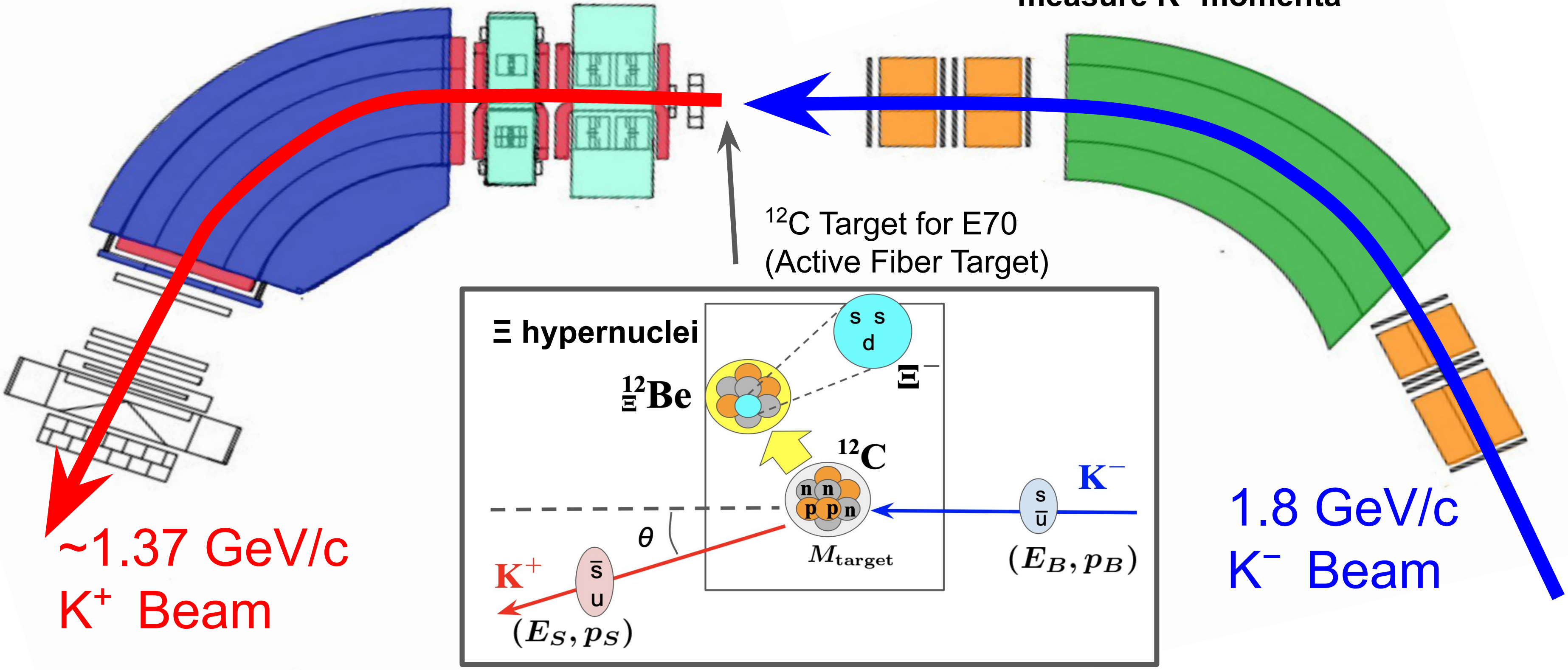
Peak Structure of Ξ hypernuclei



S-2S detectors @ K1.8 area

S-2S magnetic spectrometer
measure K⁺ momenta

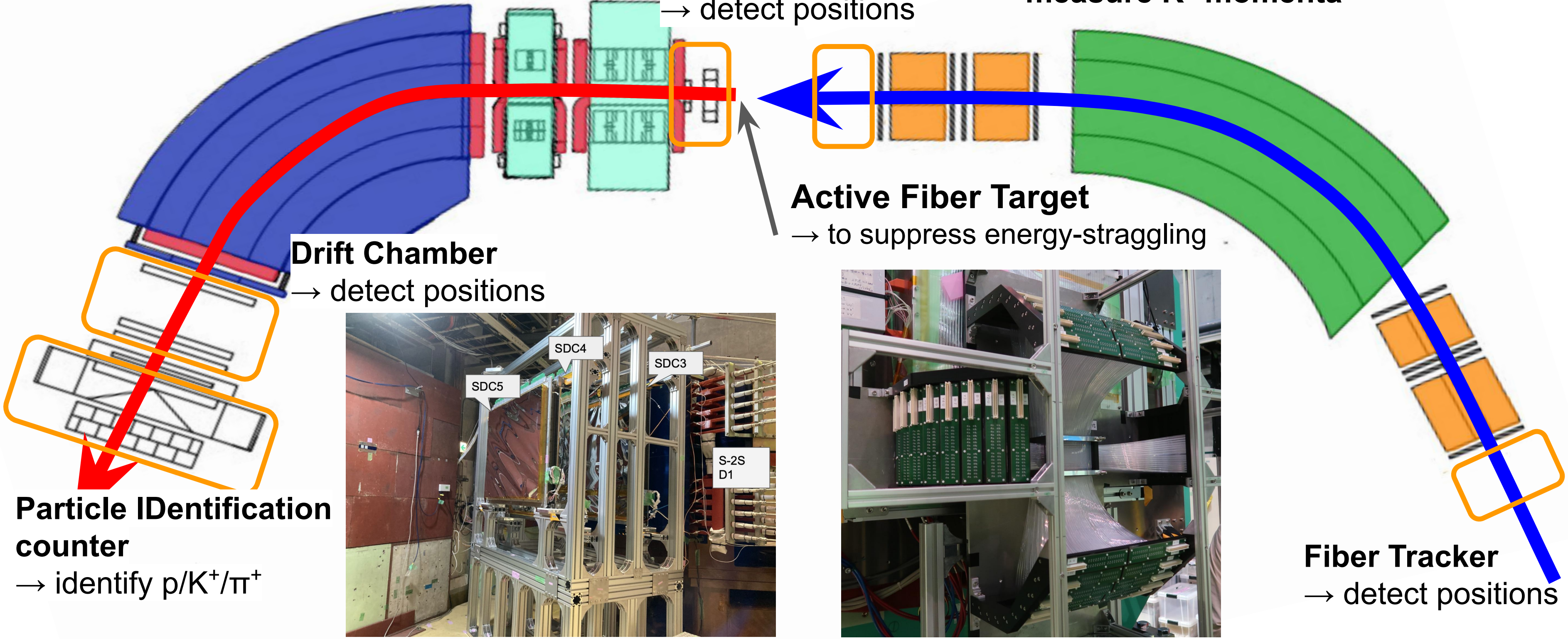
K1.8 beamline spectrometer
measure K⁻ momenta



S-2S detectors @ K1.8 area

S-2S magnetic spectrometer
measure K^+ momenta

K1.8 beamline spectrometer
measure K^- momenta



Drift Chamber
→ detect positions

Active Fiber Target
→ to suppress energy-straggling

Drift Chamber
→ detect positions

Particle IDentification counter
→ identify p/K^+/π^+

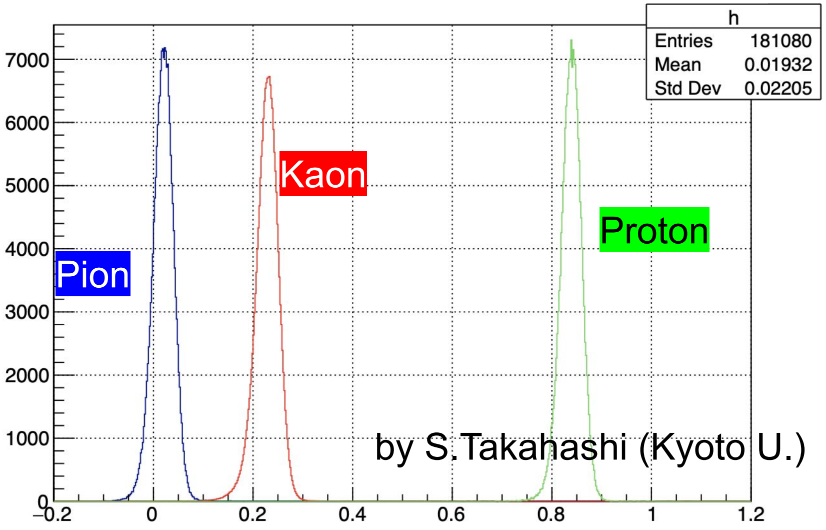
Fiber Tracker
→ detect positions

First Commissioning for S-2S

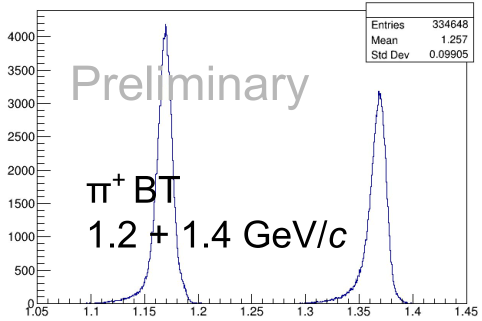
in June 2023, we had first commissioning.

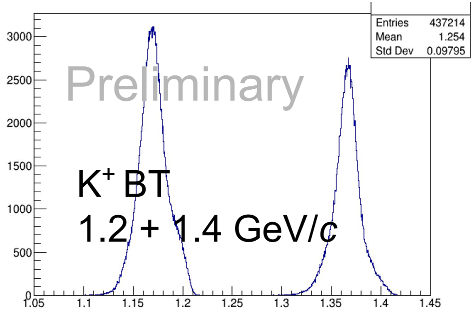
- detector check (PID counters, AFT)
- Beam through (1.2, 1.4 GeV/*c*, K^+ / π^+)

mass (mass squared) distribution

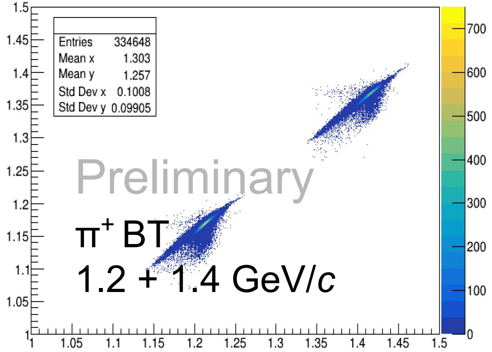


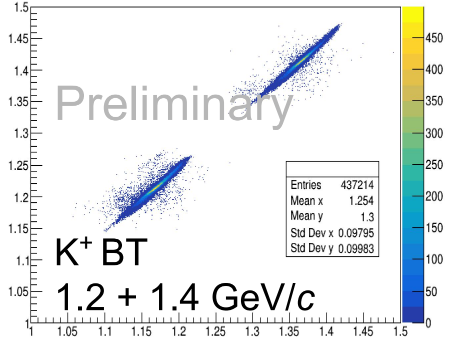
Beam Through w/ S-2S tracking (Runge-Kutta)





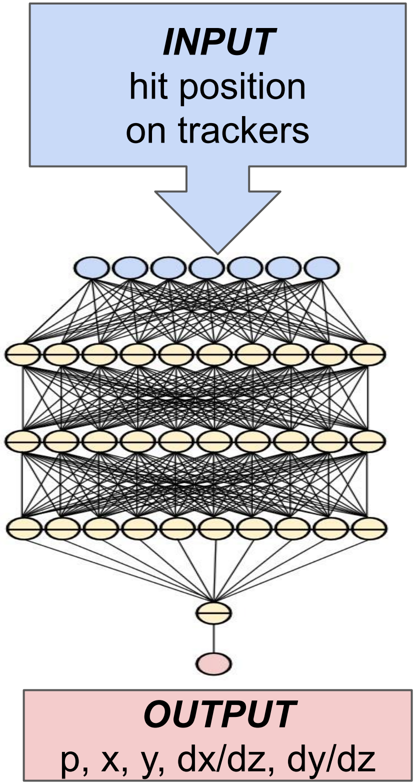
K1.8 tracking vs S-2S tracking (Matrix, Runge-Kutta)

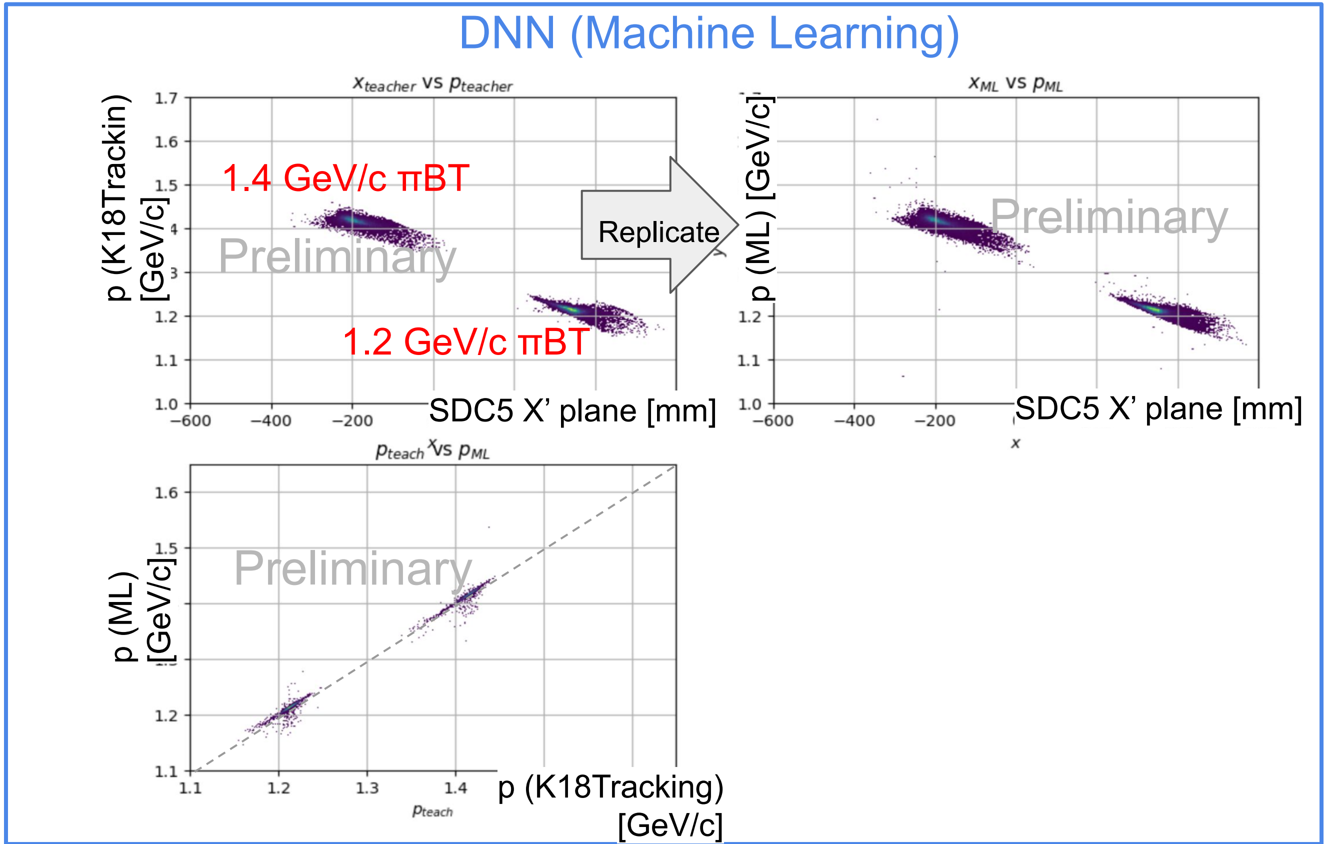




First Commissioning for S-2S

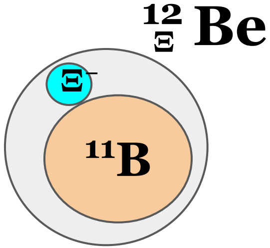
Beam through data analysis w/ DNN (Machine Learning)

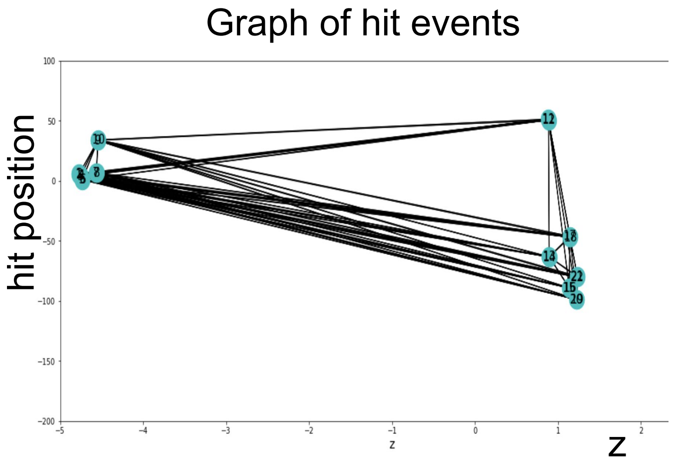




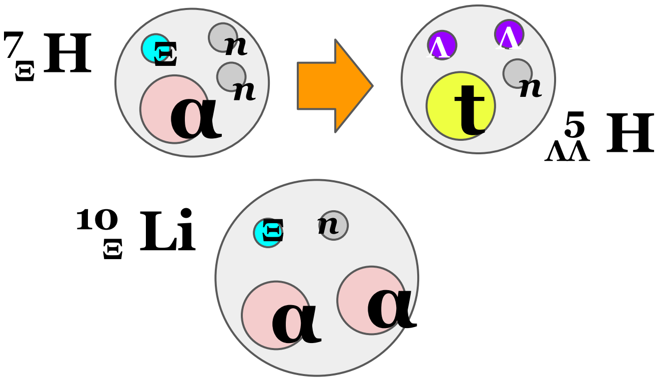
Outlook

- J-PARC E70
  - Second Commissioning (From 2024 Mar)
  - Physics run → 20 days,
    - Ξ hypernuclei ~ 100 events
  - Machine Learning analysis for momentum
    - DNN → GNN





- After E70 (12ΞBe)
  - E75 (7ΞH, Phase1 -> 5ΛΛH, Phase2)
  - 10ΞLi

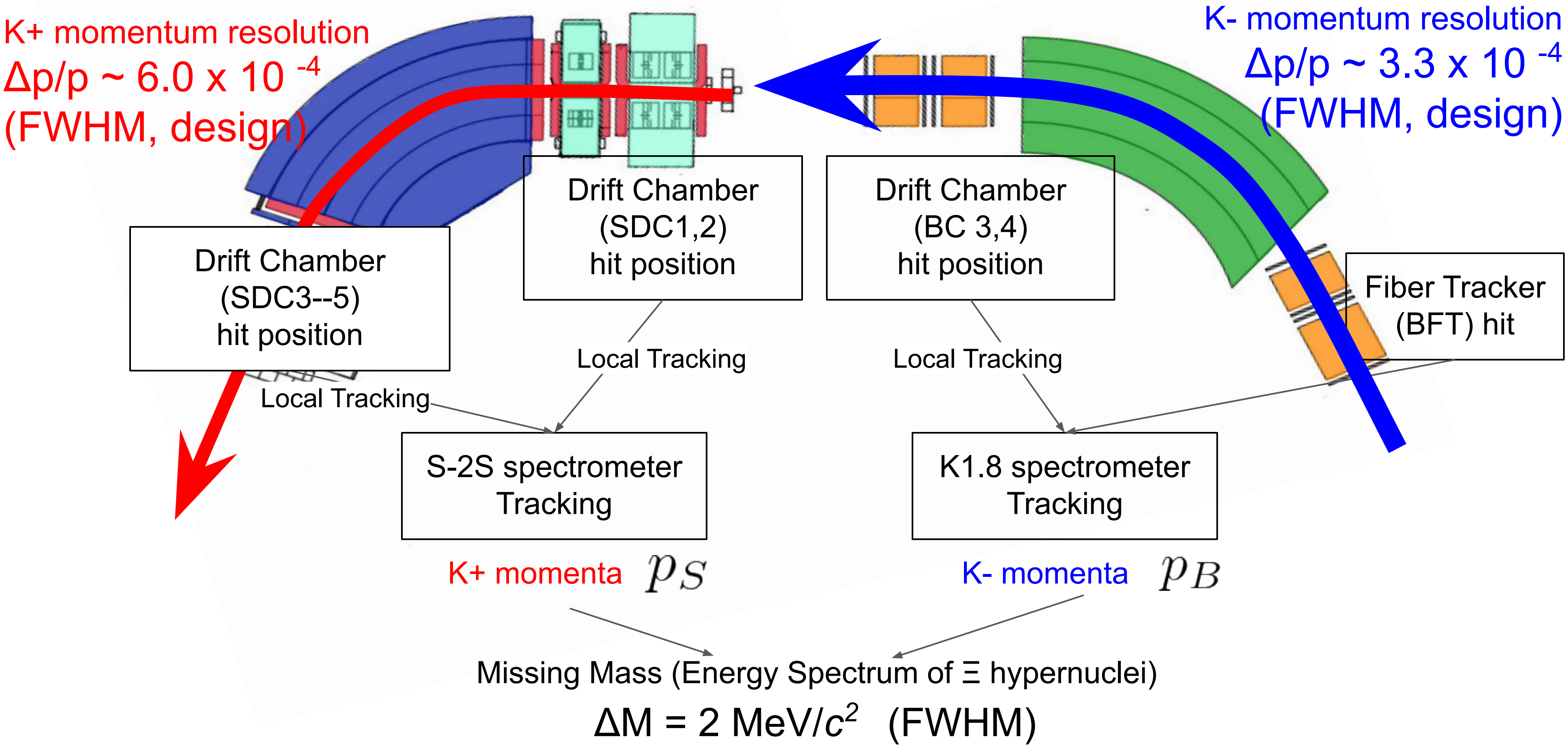


Summary

- S = −2 Physics → ΞN, ΛΛ int., more general baryon interactions.
- J-PARC E70 = Spectroscopy of Ξ hypernuclei (12ΞBe)
  - ΔM ~ 2 MeV/c^2
  - Establish Spectroscopy for Ξ hypernuclei for the future
  - June in 2023, First Commissioning in S-2S.
    We got detectors commissioning and beam through data.
- After E70 (12ΞBe)
  - E75 (7ΞH → 5ΛΛH)
  - 10ΞLi
  - spin & isospin dependent interaction of ΞN

BACK UP

Momentum analysis of K1.8 & S-2S spectrometer



Backward Transfer Matrix Method for Momentum analysis

How is momentum measured ?

By Using Optical Transfer Matrix, we get momentum from x, y (positions), u, v (angles).
One of conventional method -> K1.8 Spectrometer

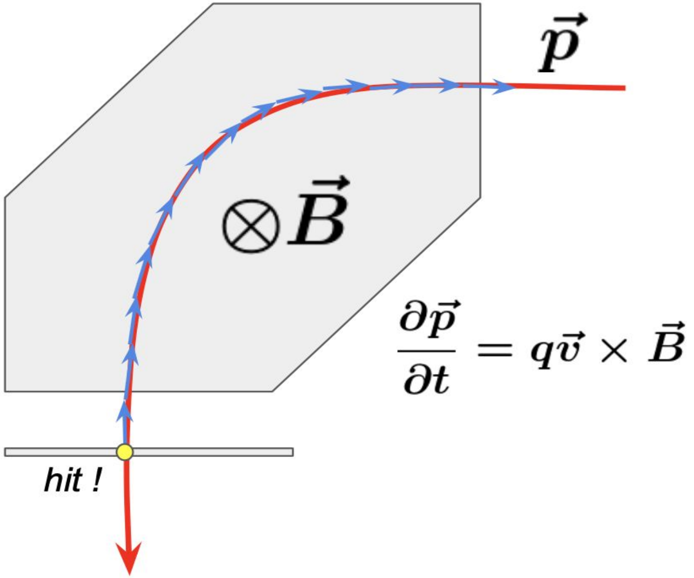
$$\begin{pmatrix} x_1 \\ y_1 \\ u_1 \\ v_1 \\ \delta_1 \end{pmatrix} = \begin{pmatrix} \cos\theta & \rho\sin\theta & 0 & 0 & (1-\cos\theta)\rho \\ -\sin\theta/\rho & \cos\theta & 0 & 0 & \sin\theta \\ 0 & 0 & 1 & \rho\theta & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ y_0 \\ u_0 \\ v_0 \\ \delta_0 \end{pmatrix} \begin{matrix} \\ \\ \leftarrow \dfrac{dx}{dz} \\ \leftarrow \dfrac{dy}{dz} \\ \leftarrow \dfrac{p-p_0}{p_0} \end{matrix}$$

Runge-Kutta Method for Momentum analysis

<u>Runge-Kutta method</u>

One of conventional method

Tracking according to the EOM on magnetic field of spectrometer, momenta are calculated.



Momentum analysis for S-2S with Machine Learning

Momentum Reconstruction : hit position → momentum

Conventional methods

- Runge-Kutta method → Correction by phenomenological functions after reconstruction.
- Backward Transfer Matrix method → Difficult in large momentum acceptances.

Machine Learning (ML method)

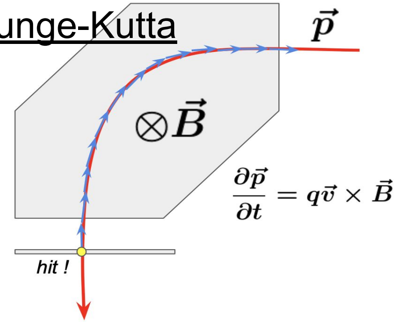
→ ・automatical correction. (especially higher order correction)

・more flexible analysis,

which for example, reconstruct momentum directly from hit of drift chambers.

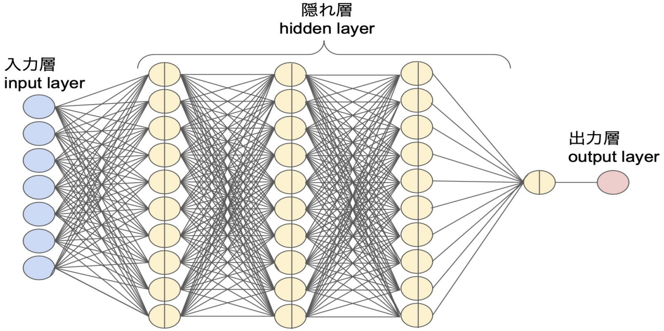
→ High efficiency & High resolution momentum analysis.

Runge-Kutta



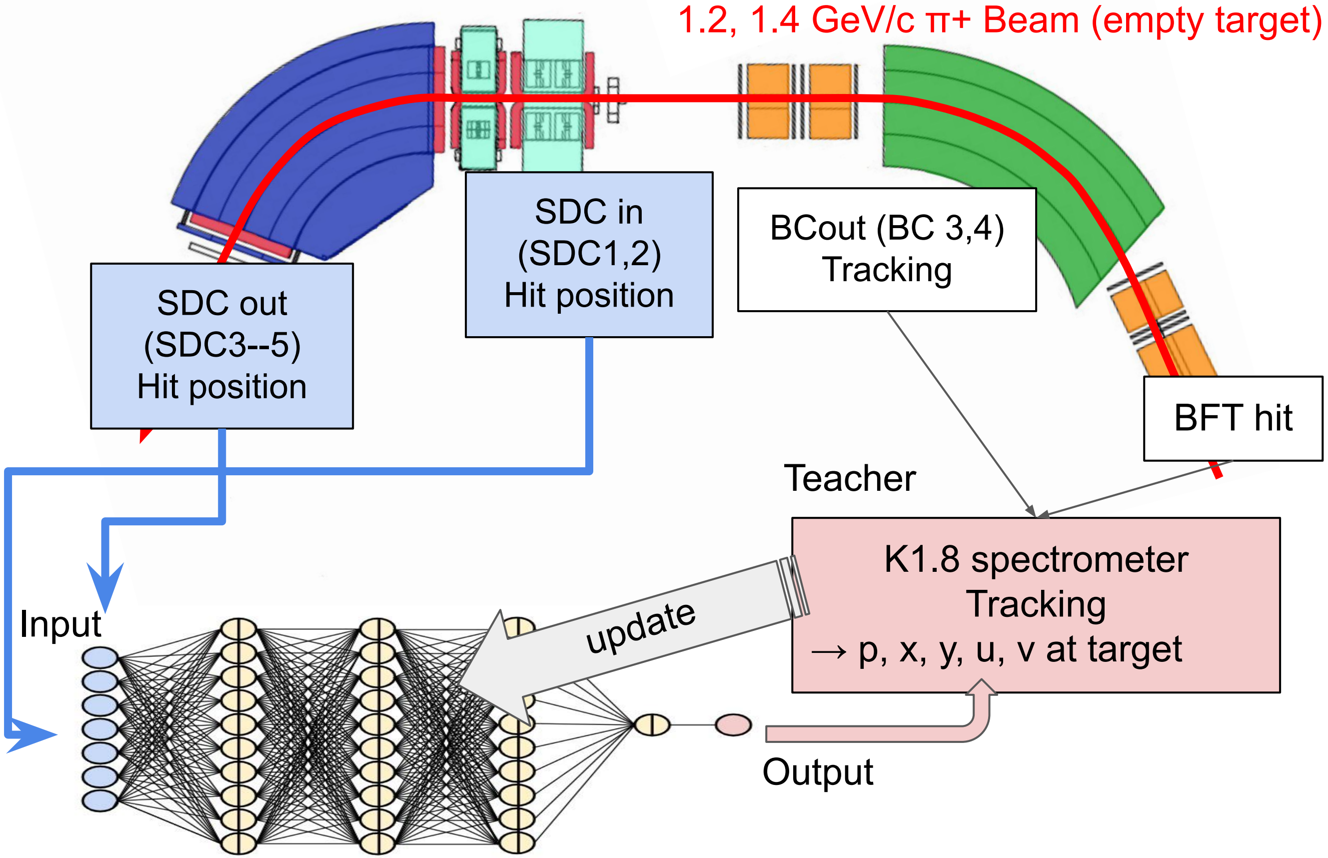
Matrix

$$M_D = \begin{pmatrix} \cos\theta & \rho\sin\theta & 0 & 0 & (1-\cos\theta)\rho \\ -\sin\theta/\rho & \cos\theta & 0 & 0 & \sin\theta \\ 0 & 0 & 1 & \rho\theta & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$



S-2S Deep Neural Network (DNN) analysis

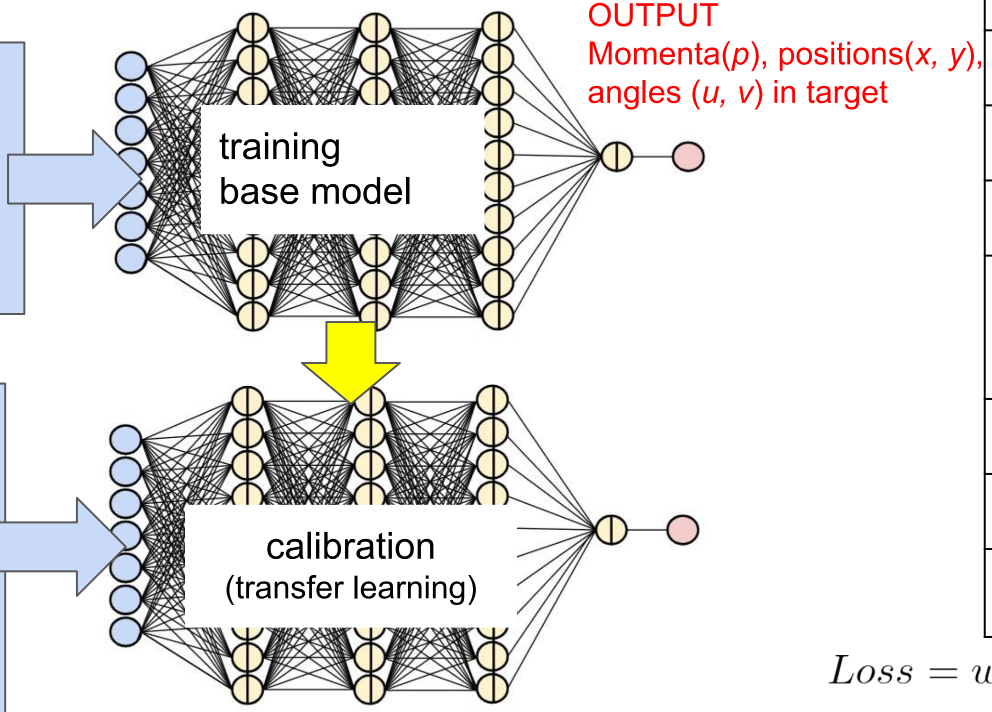
ML analysis for real data is feasible ??? → use Beam Through events of commissioning run in June 2023



S-2S Deep Neural Network (DNN) analysis

1.1 ~ 1.6 GeV/c
events from
GEANT4
= 2×10^{6} events

1.2, 1.4 GeV/c
BT events
= 4×10^{5} events



Used hyper parameters	
activation function	swish
# node / layer	32
# hidden layer	3
Loss function	MAE (p, x, y, u, v)
optimizer	Adam
input dim	22
statistics	2×10^{5}

$$Loss = w_p Loss_p + w_x Loss_x + w_y Loss_y + w_u Loss_u + w_v Loss_v$$

Divide to Training data, Validation data, Test data.

J-PARC E75 Experiment (Phase-1)

Phase-1 product $^{7}_{\Xi}H$ via $^{7}Li(K^{-}, K^{+})$ reaction and measures cross section of $^{7}_{\Xi}H$.

decay π^{-} spectroscopy for $^{5}_{\Lambda\Lambda}H$. (Phase-2)