# Hyperon-proton scattering experiment at J-PARC for better understanding of hyperon-nucleon interaction

APCTP Focus Program in NP2021 Part Ⅱ, July 23, 2021

Koji Miwa (Tohoku univ.)

# CONTENTS

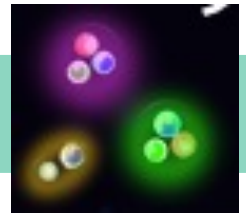
# From Quark to Neutron star

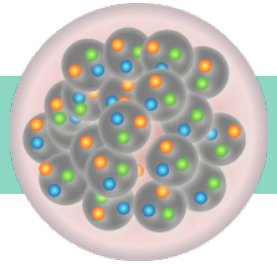
Bound system interacting by strong interaction with completely different scale.

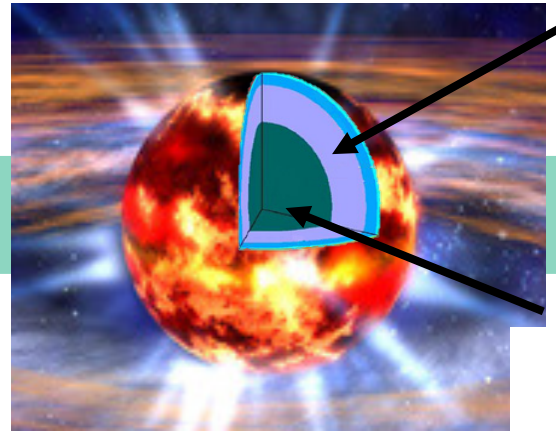
Hadron

Nucleus, Hypernucleus

Neutron star





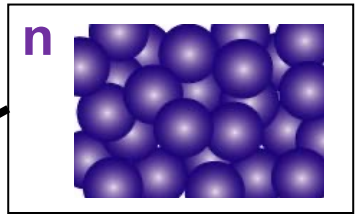


$10^{-15}$ m

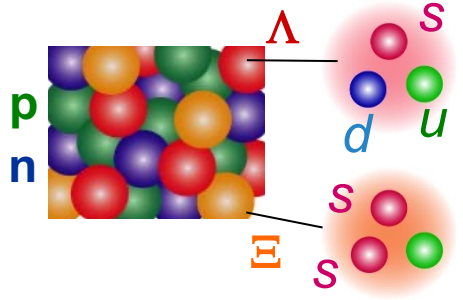
$10^{-14}$ m

$10^{4}$ m

Neutron matter




Strange hadronic matter ?




Hyperon

These system should be understood with the same framework based on the microscopic picture with strong interaction.

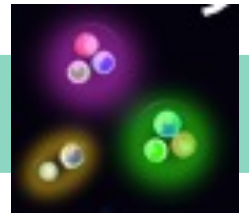
# From Quark to Neutron star

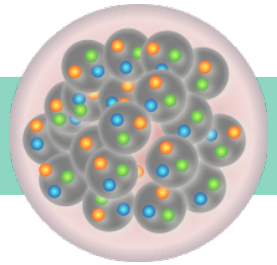
Bound system interacting by strong interaction with completely different scale.

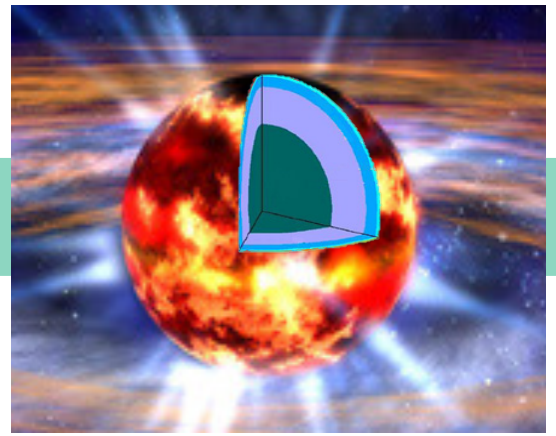
Hadron

Nucleus, Hypernucleus

Neutron star







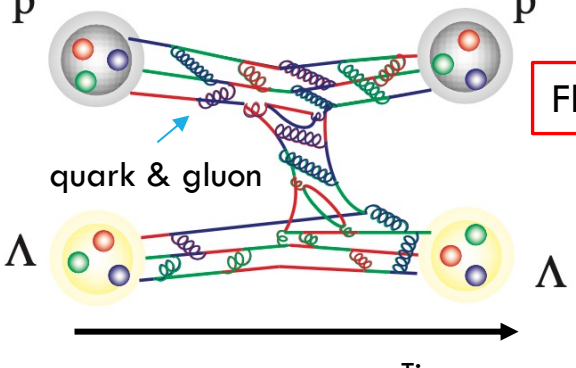
$10^{-15}$ m

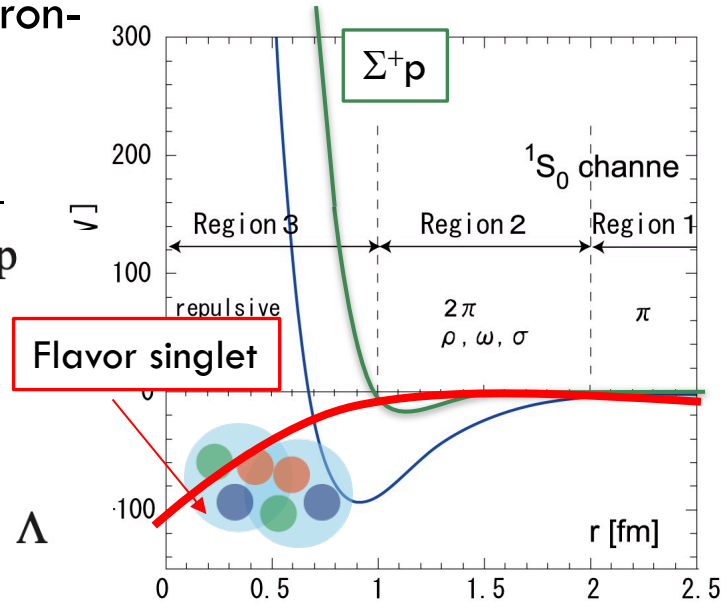
$10^{-14}$ m

$10^{4}$ m

## Understanding of hyperon-nucleon interaction

Quantum Chromo Dynamics (QCD)



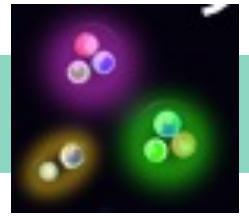
# From Quark to Neutron star

Bound system interacting by strong interaction with completely different scale.

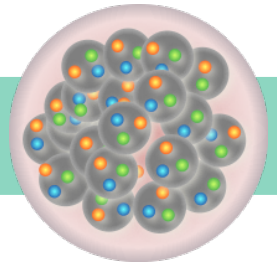
Hadron

Nucleus, Hypernucleus

Neutron star

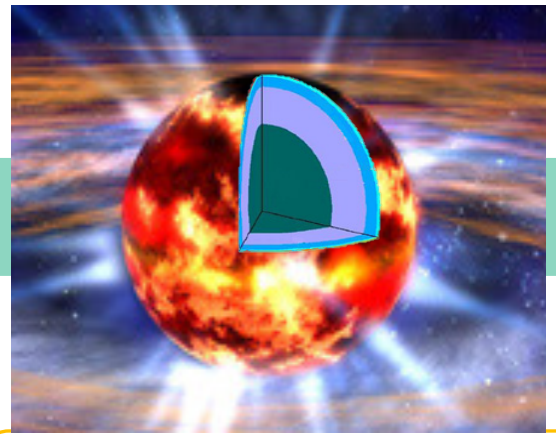


$10^{-15}$ m



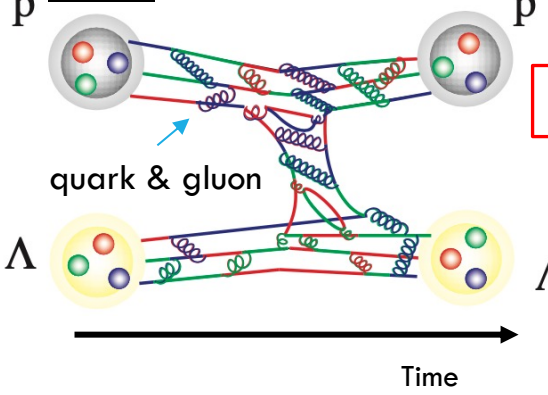
$10^{-14}$ m

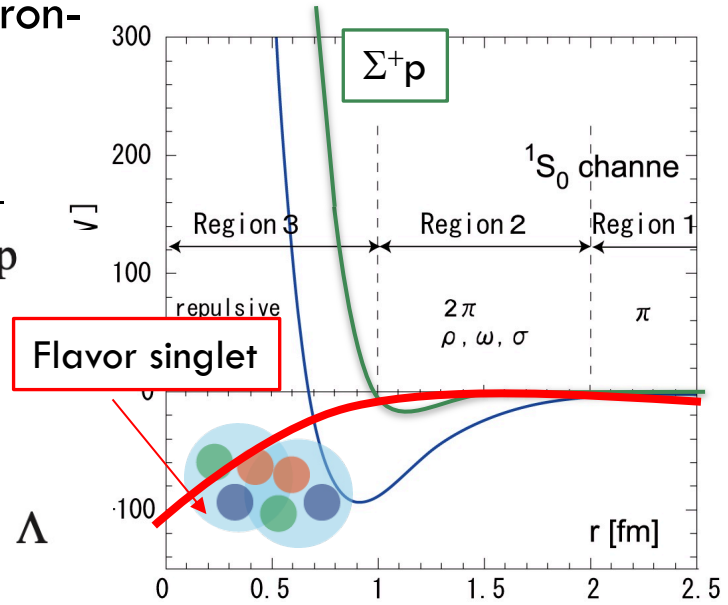
$10^{4}$ m

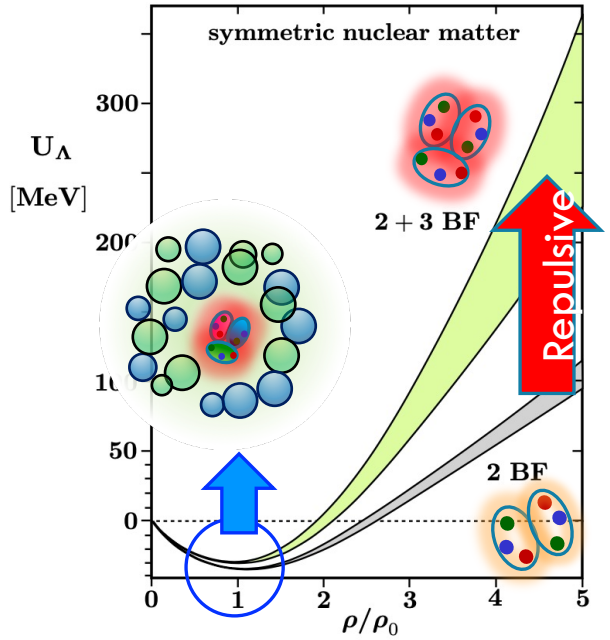


## Understanding of hyperon-nucleon interaction

Quantum Chromo Dynamics (QCD)

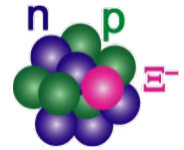



Λ hypernuclei (ΛNN interaction)

Ξ hypernuclei

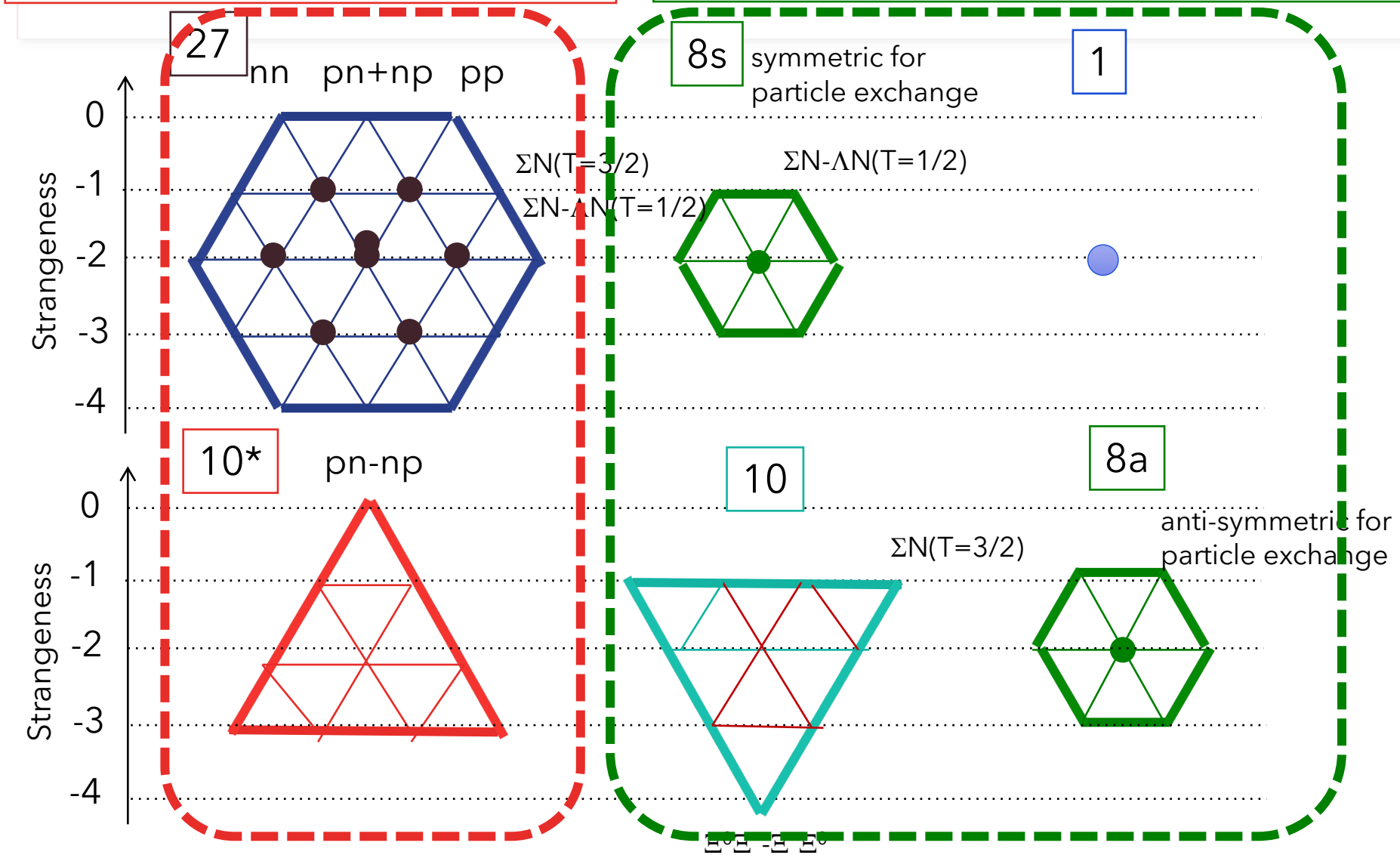



D. Gerstung et al., Eur. Phys. J. A(2020) 56:175

# Baryon-Baryon interaction in $SU_F(3)$ symmetry

Same multiplet with NN interaction

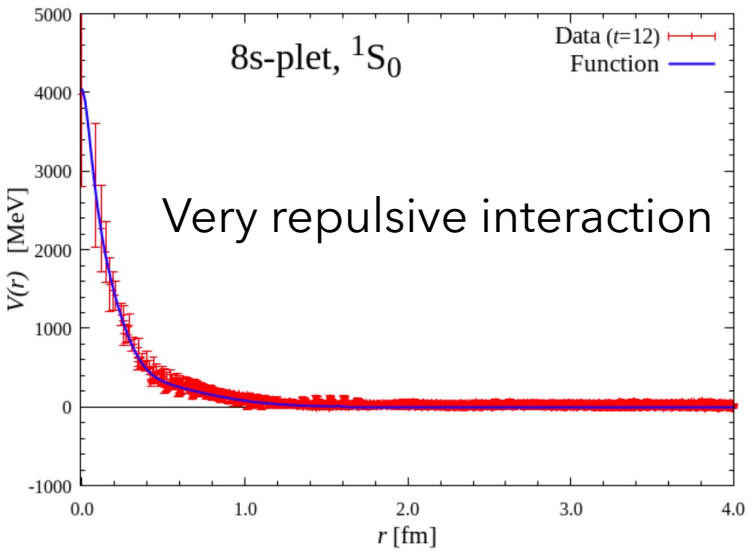
Newly appeared interaction in BB(YN, YY) interaction

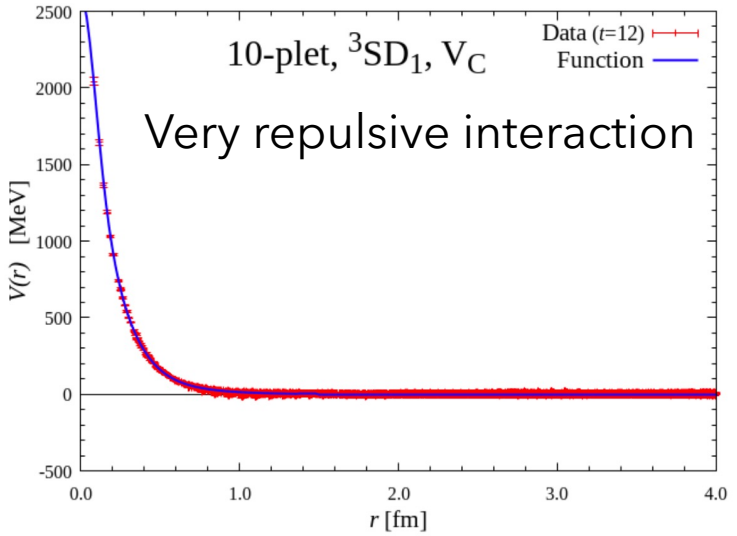


# Baryon-Baryon interaction in $SU_F(3)$ symmetry

Lattice QCD calculation
T. Inoue, AIP Conf. Proc. 2130, 020002 (2019)

Newly appeared interaction in BB(YN, YY) interaction



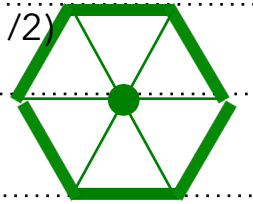

8s symmetric for particle exchange

1

T=3/2)

ΣN-ΛN(T=1/2)

-ΛN(T=1/2)

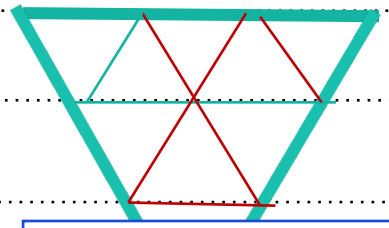


10

8a

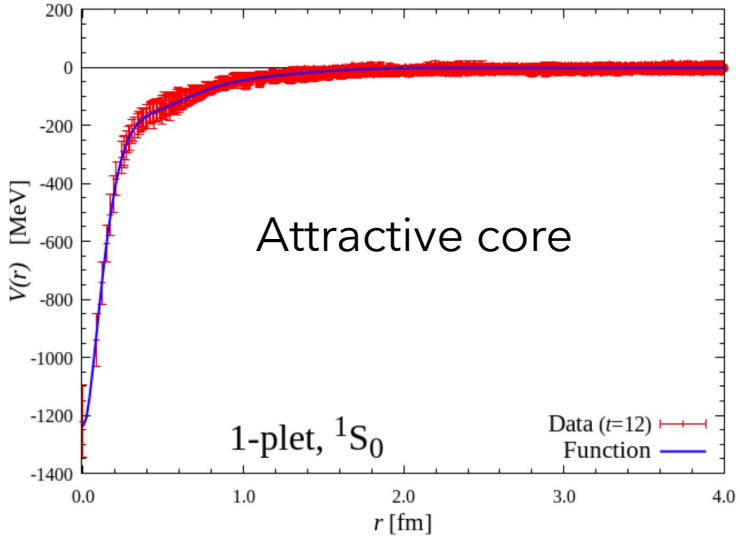
ΣN(T=3/2)

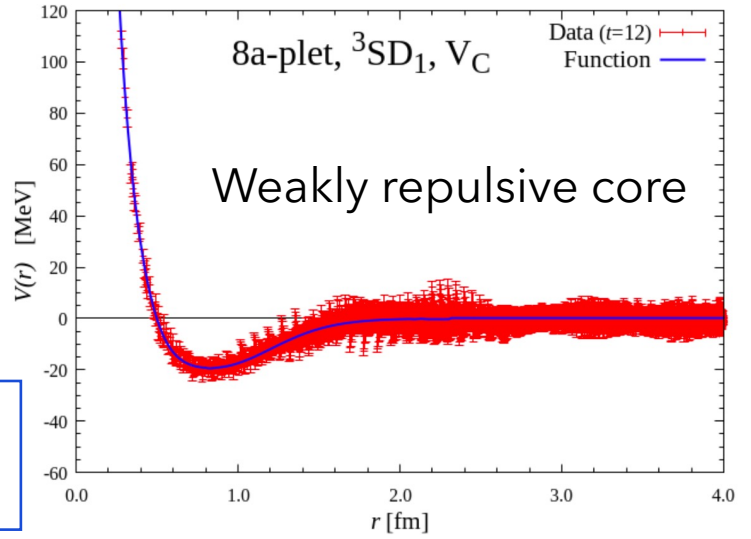
anti-symn
particle e





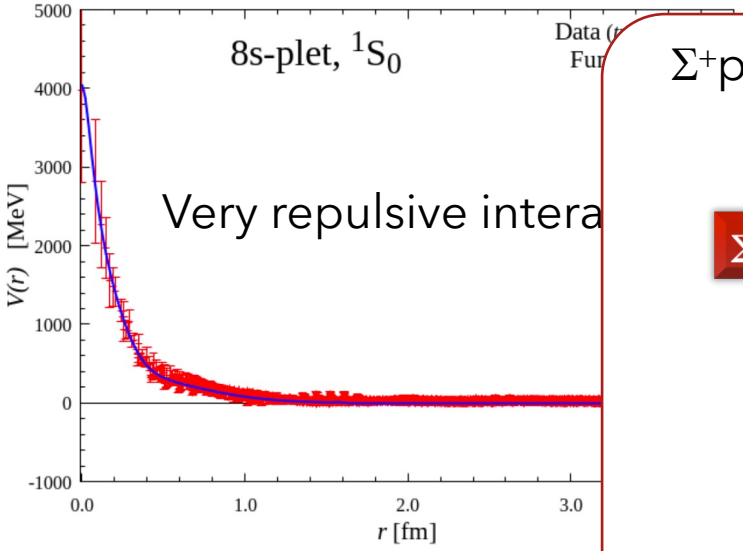
Rich aspect in YN, YY interaction
especially in short range region

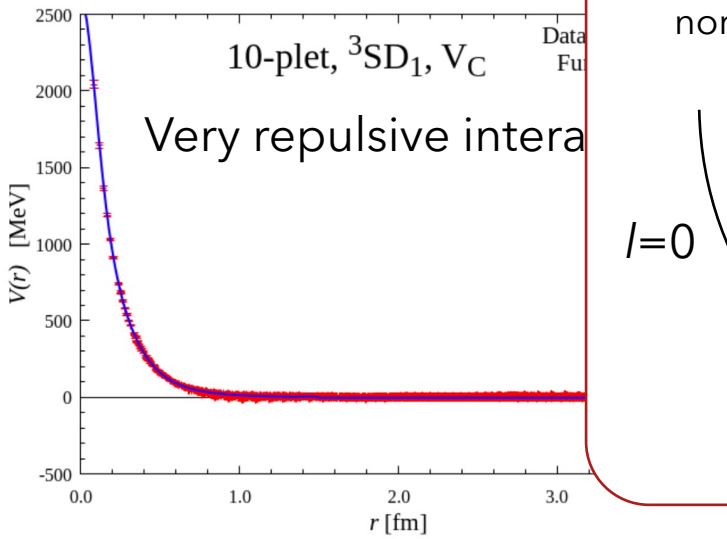


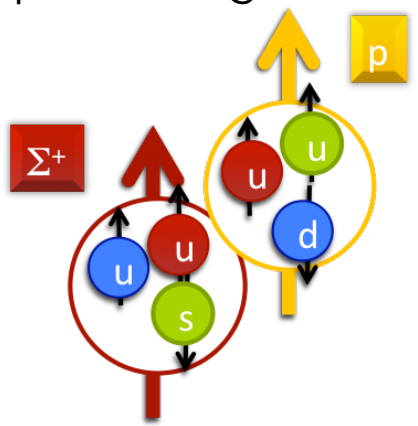
# Baryon-Baryon interaction in $SU_F(3)$ symmetry

Lattice QCD calculation
T. Inoue, AIP Conf. Proc. 2130, 020002 (2019)



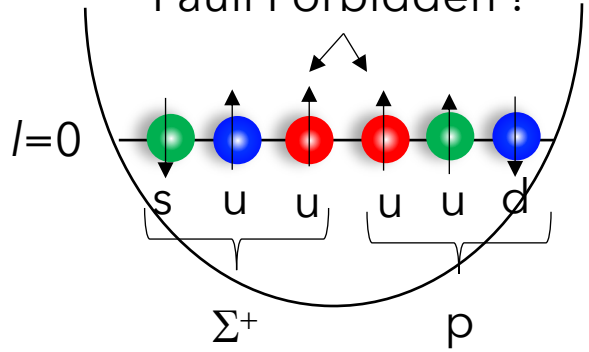




$\Sigma^+$p scatterng

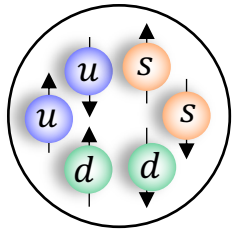



6 quarks can stay in s state in normal case

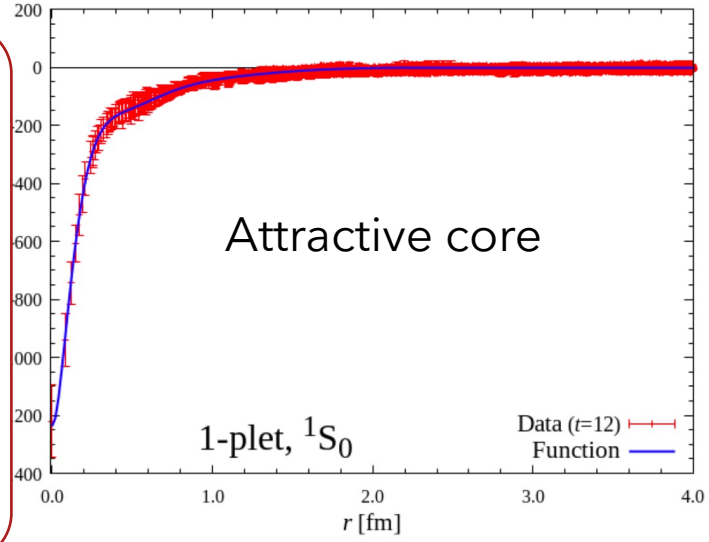
Pauli Forbidden !



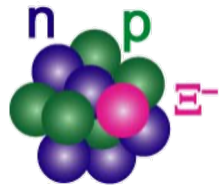

H-dibaryon



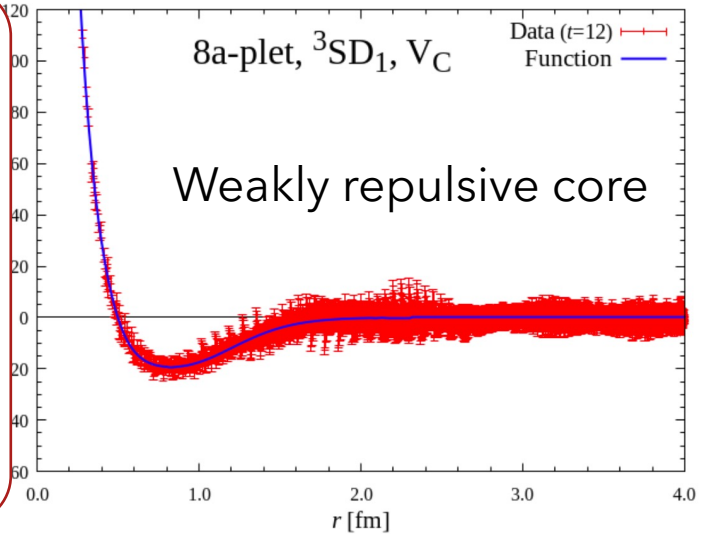

Attractive color-magnetic interaction




Ξ hypernuclei




ΞN (I=0) $^3S_1$ channel



# PRESENT HADRON EXPERIMENTAL FACILITY

Slow extraction of 30 GeV proton beam with ~65 kW (2021/June)

- High intensity 2ndary beam : $K^-, \pi^\pm$
- A part of primary proton beam

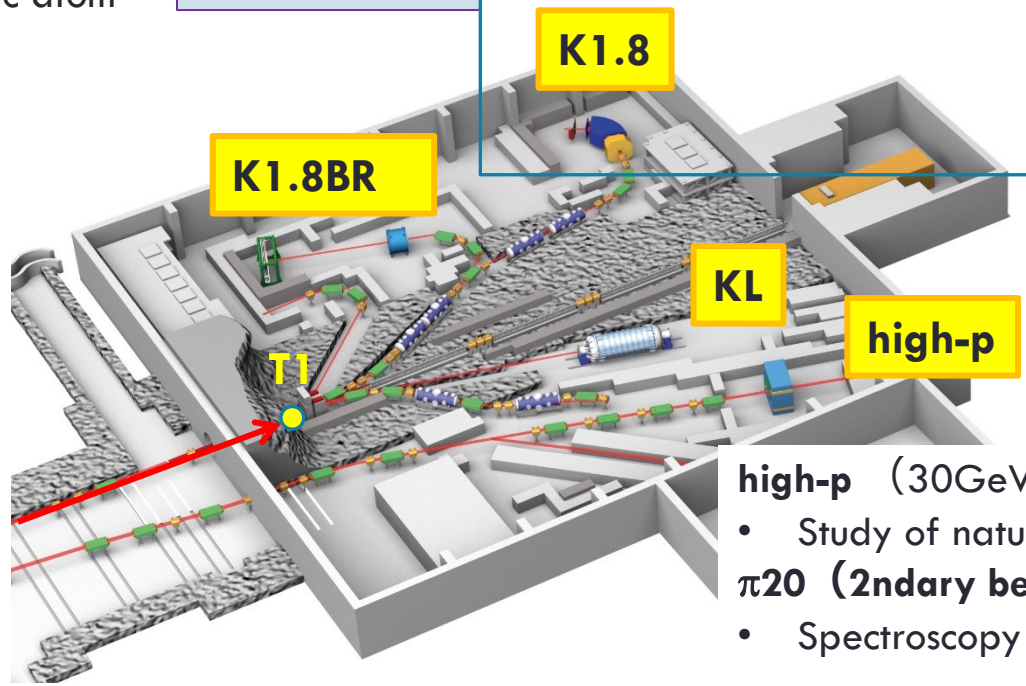
→ Strangeness nuclear physics, Hadron physics

**K1.8BR** (~1.0 GeV/c $K^-$ beam)
- Study of $\bar{K}N$ interaction
  - Kaonic nuclei
  - Kaonic atom

**$\bar{K}N$ interaction**

**K1.8** (~1.8 GeV/c $K^-$、 1.2 – 2.0 GeV/c $\pi^\pm$)
- Study of hypernuclei with S=–1,–2
- Hyperon-proton scattering experiment

**Baryon-Baryon interaction**
**(Especially focusing on S=–2)**




**Hadron in nuclear medium**
**Effective degree of freedom for hadron structure**

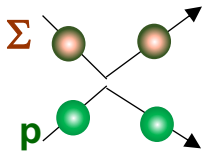
**high-p** (30GeV primary proton beam) constructed in 2019
- Study of nature of vector meson in nuclear medium

**π20 (2ndary beam up to 20GeV/c )** future program
- Spectroscopy of charm baryon

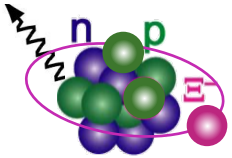
# Hierarchy of matter studied via strange hadron clusters

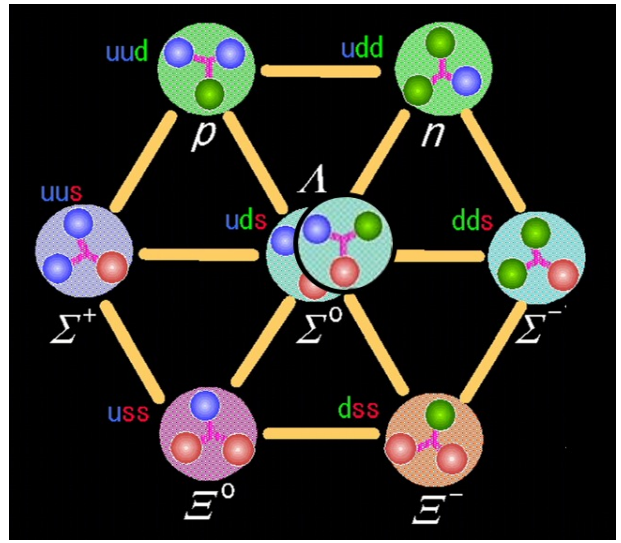
## (a) Baryon-Baryon forces from quark hierarchy

- Study of S=-2 system with hybrid emulsion method (E07)
  - Many S=-2 events are observed.
- $\Sigma^{\pm}$-p scattering experiment (E40)
  - Analysis to be finished soon.

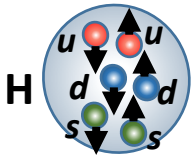



- Ξ-atomic X-rays (E03)
  - Finished successfully.

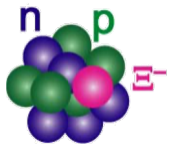



- H-dibaryon search (E42)
  - Just finish data taking at end of June 2021.

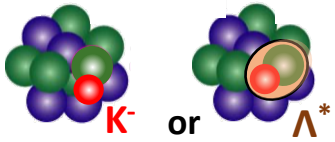



- Ξ-hypernuclear spectroscopy via $^{12}C(K^-,K^+)$ (E70)
  - Run in 2023.

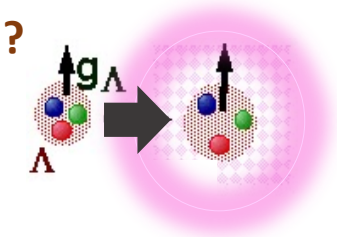



## (b) Why "nuclear hierarchy" exists?

- $K^-$nucleus = sub-hierarchy of Meson-Baryon systems
  - $^{12}C(K^-,p)$ E05 data -> Very-deeply-bound $K^-$-nucleus (or $\Lambda^*$-nucleus) ?
    - *Y. Ichikawa et al., PTEP 2020 (2020) 12, 123D01*




- Change of Λ's magnetic moment in a nucleus (E63)
  - Under preparation.



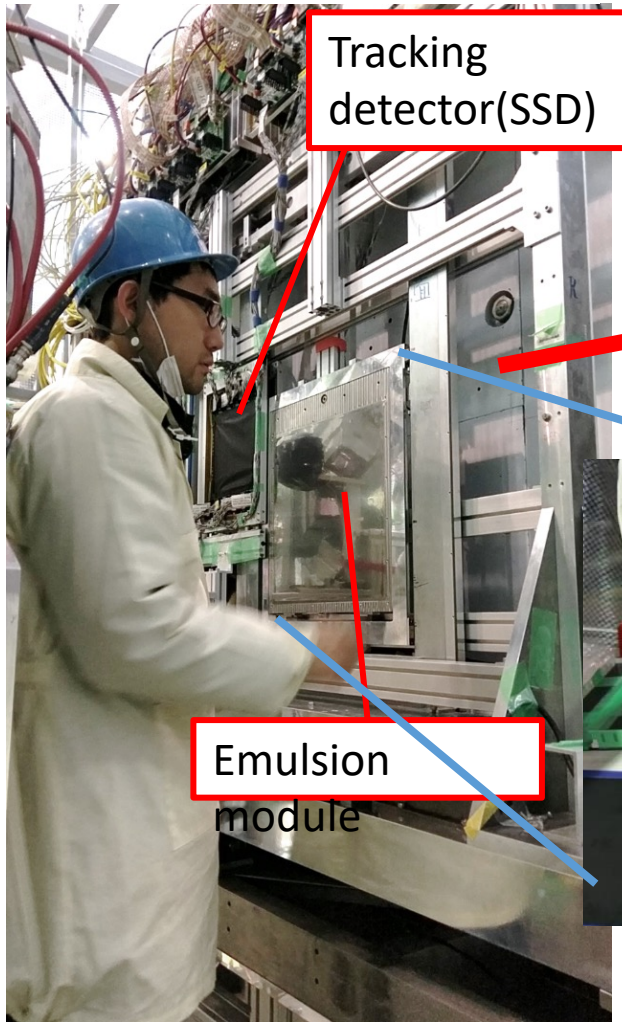
# Experimental apparatus of E07

2016-2017

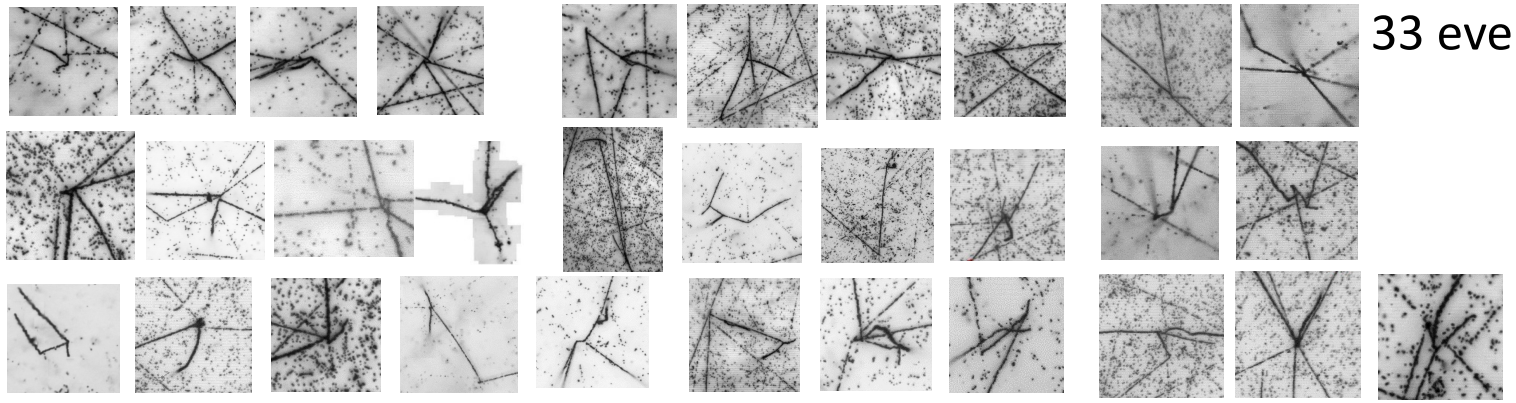
J-PARC, Ibaraki, Japan

Slide from J. Yoshida

## Emulsion module




# Observed events of double hypernuclei in J-PARC E07

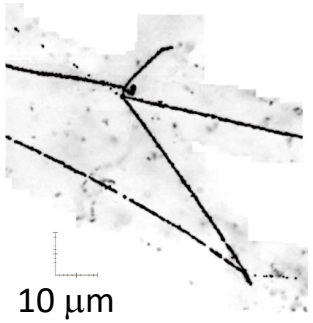


33 events

Slide from J. Yoshida

Published identified events:

H. Ekawa et al.,
Prog. Theor. Exp. Phys. 2019, 021D02 (2019)

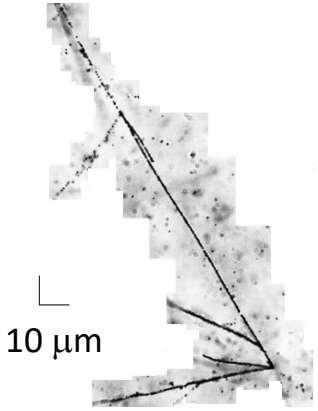



| Nuclide | $B_{\Lambda\Lambda}$ [MeV] |
|---|---|
| $_{\Lambda\Lambda}{}^{10}$Be | 15.05 +- 0.11 |
| $_{\Lambda\Lambda}{}^{11}$Be | 19.07 +- 0.11 |
| $_{\Lambda\Lambda}{}^{12}$Be | 13.68 +- 0.11 |

Where, $B_{\Xi^-}$ = 0.23 MeV

$$^{16}\mathrm{O} + \Xi^- \rightarrow (^{10}_{\Lambda\Lambda}\mathrm{Be},\ ^{11}_{\Lambda\Lambda}\mathrm{Be},\ ^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^5_{\Lambda}\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$

S. H. Hayakawa et al.,
Physical Review Letters, 126, 062501 (2021)

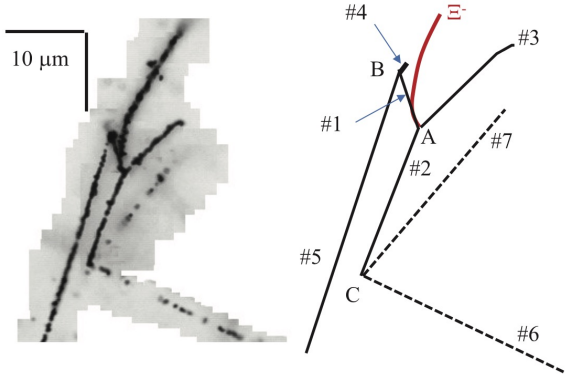



$\Xi^-$ – $^{14}$N system

$B_{\Xi^-}$ = 1.27 +- 0.21 MeV

$\Xi^-$ + $^{14}$N -> $_{\Lambda}{}^{10}$Be + $_{\Lambda}{}^{5}$He

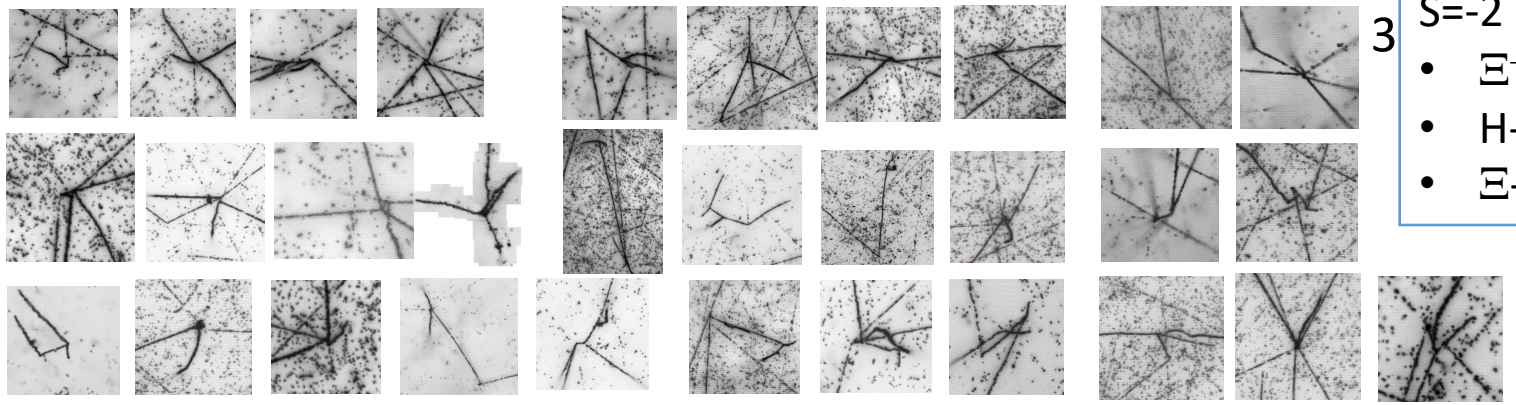
M. Yoshimoto et al.,
PTEP (https://doi.org/10.1093/ptep/ptab073)




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

$\Xi^-$ + $^{14}$N -> $_{\Lambda}{}^{5}$He + $_{\Lambda}{}^{5}$He+$^{4}$He+n

# Observed events of double hypernuclei in J-PAR



3

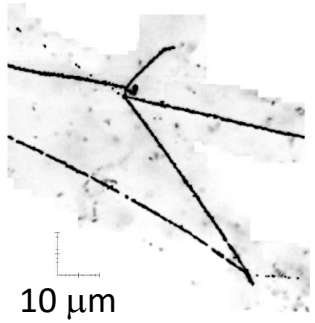
Current and Future program of S=-2 system

- $\Xi^-$ atomic X-ray measurement
- H-dibaryon resonance
- $\Xi$-hypernuclear spectroscopy

Deeper understanding of $\Xi$N interaction

Published identified events:

H. Ekawa et al.,
Prog. Theor. Exp. Phys. 2019, 021D02 (2019)

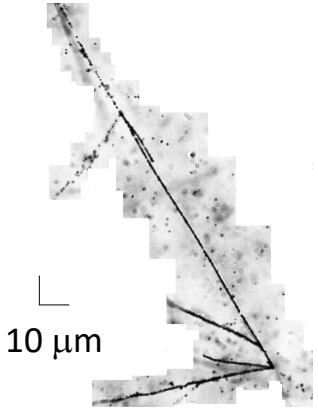



| Nuclide | $B_{\Lambda\Lambda}$ [MeV] |
|---|---|
| $^{\Lambda\Lambda}{}^{10}$Be | 15.05 +- 0.11 |
| $^{\Lambda\Lambda}{}^{11}$Be | 19.07 +- 0.11 |
| $^{\Lambda\Lambda}{}^{12}$Be | 13.68 +- 0.11 |

Where, $B_{\Xi^-}$ = 0.23 MeV

$$^{16}\mathrm{O} + \Xi^- \rightarrow (^{10}_{\Lambda\Lambda}\mathrm{Be},\ ^{11}_{\Lambda\Lambda}\mathrm{Be},\ ^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^5_{\Lambda}\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$

S. H. Hayakawa et al.,
Physical Review Letters, 126, 062501 (2021)

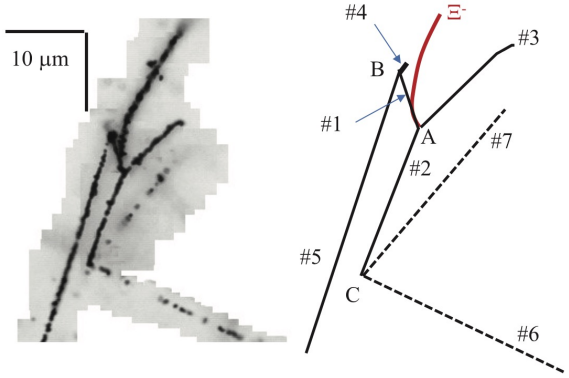



$\Xi^-$ – $^{14}$N system

$B_{\Xi^-}$ = 1.27 +- 0.21 MeV

$\Xi^-$ + $^{14}$N -> $_{\Lambda}{}^{10}$Be + $_{\Lambda}{}^{5}$He

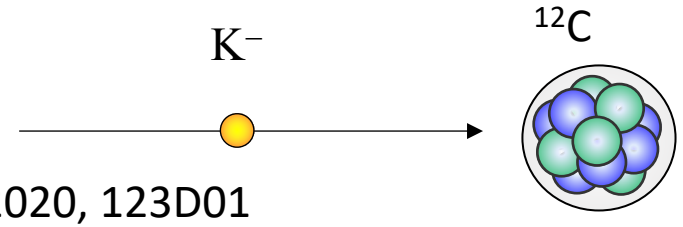
M. Yoshimoto et al.,
PTEP (https://doi.org/10.1093/ptep/ptab073)

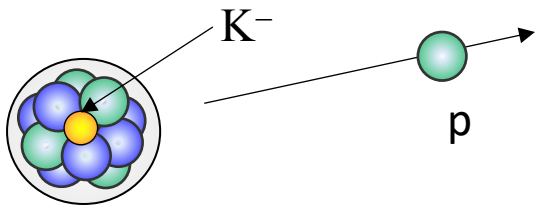



$B_{\Xi^-}$ = 6.27 +- 0.27 MeV

$\Xi^-$ + $^{14}$N -> $_{\Lambda}{}^{5}$He + $_{\Lambda}{}^{5}$He+$^{4}$He+n

# Study of $\bar{K}$ nucleus in J-PARC E05 $^{12}C(K^-, p)$ analysis



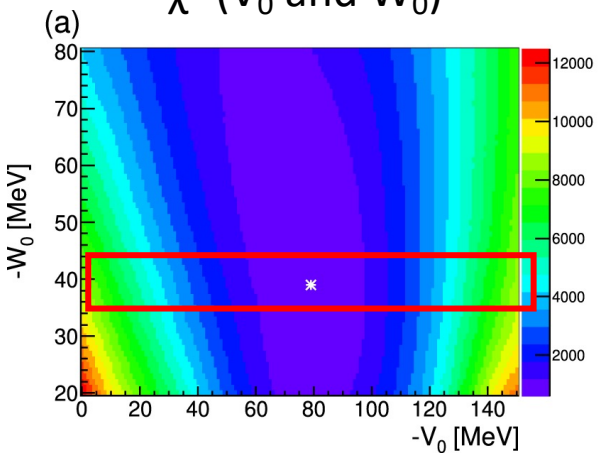




Y. Ichikawa et al., PTEP 2020, 123D01

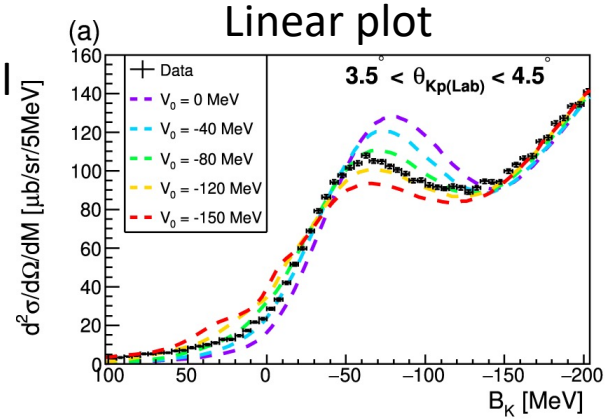
**K⁻ optical potential of $K^- + {}^{11}B$ system**

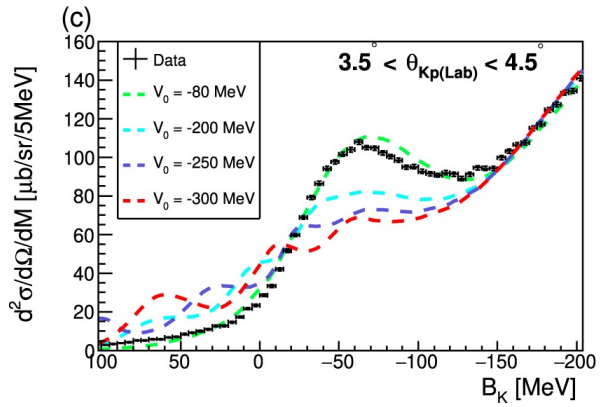
$(V_0, W_0) = (-80, -40)$ MeV corresponds to shallow potential

$\chi^2$ ($V_0$ and $W_0$)

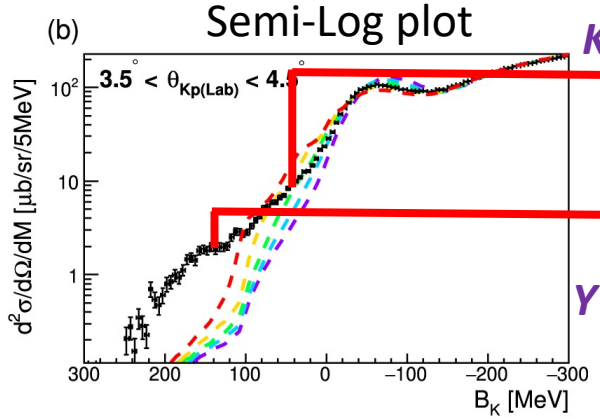


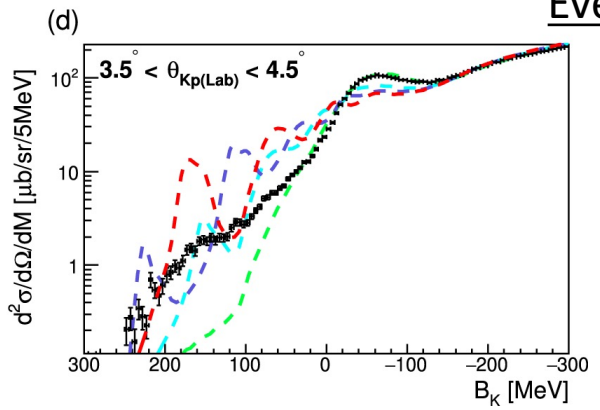

Linear plot



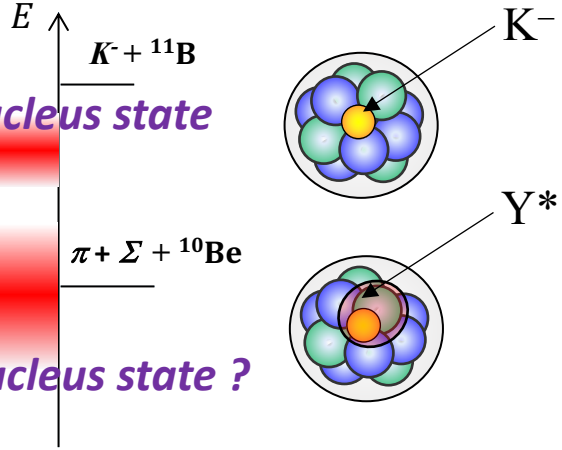




Semi-Log plot




**$K^-$ +$^{11}$B system**

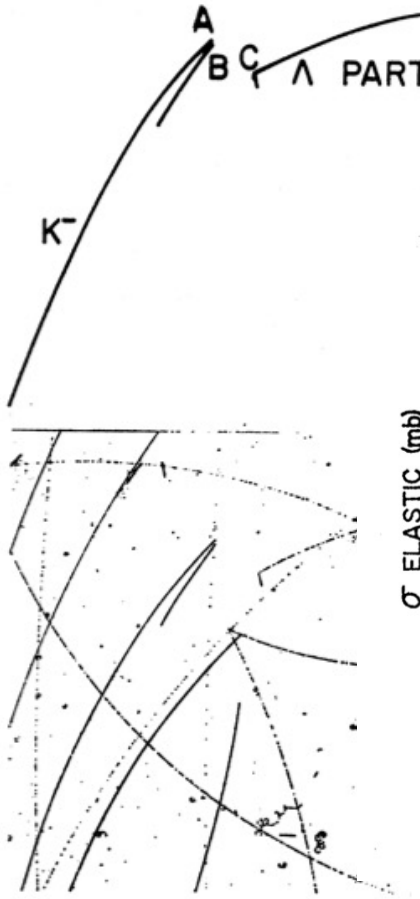



Event excess around $B_K$ ~ 100 MeV.

It may be the signal of Y* nucleus state.

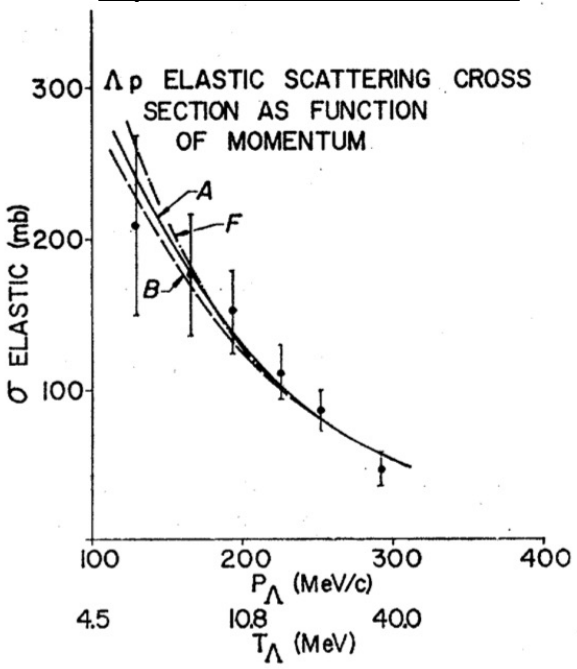
# Hyperon proton (Yp) scattering experiment and YN interaction

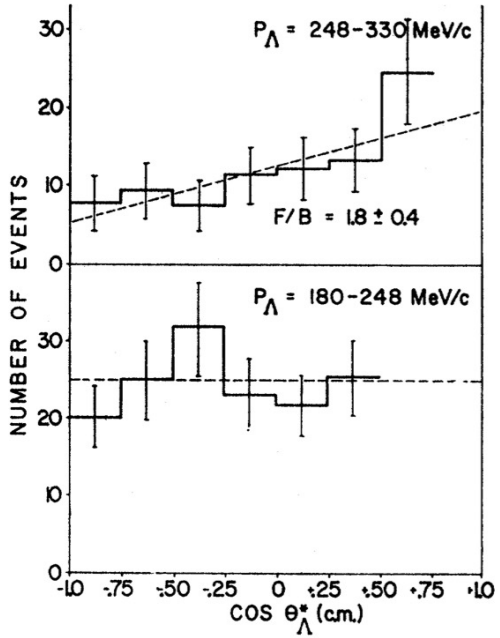
Experimental difficulty due to low intensity of hyperon beam and its short lifetime




B. Sechi-Zorn, et al. Phys. Rev. 175 (1968) 1735

Λp total cross section



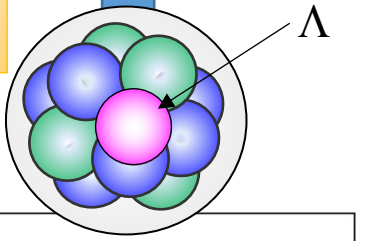



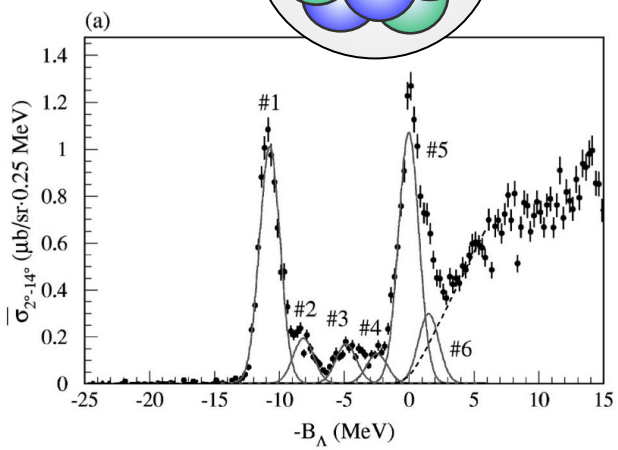

The Λ-$p$ elastic scattering angular distributio
different regions of Λ momentum.

Almost all data were limited in the low energy region (S-wave dominant).

YN interaction

Hypernuclei



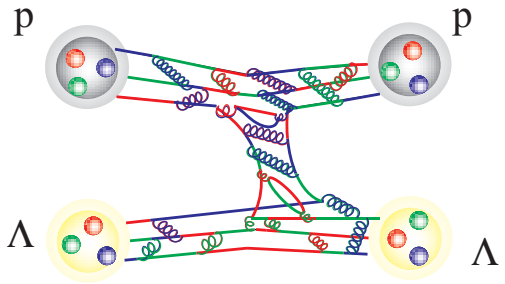

PRC 64 044302 (2001)

# Neutron star and YN interaction

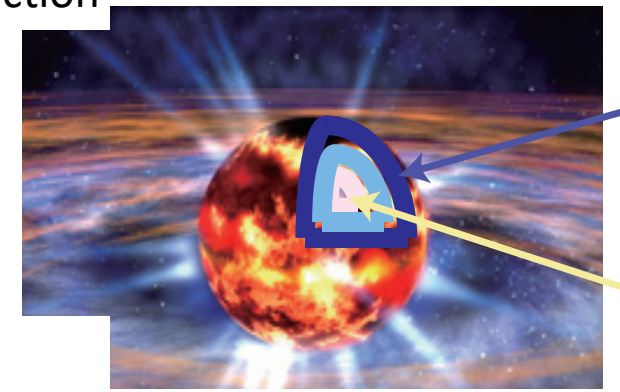
Two-body YN scattering is essential to understand the internal structure of neutron star.

- Interaction at short range
- Basic information to derive 3 body force from hypernuclear structure

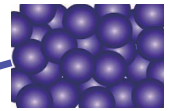
Hypernuclear physics based on Realistic YN interaction



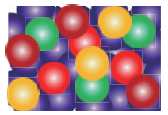

YN scattering experiment
Lattice QCD
Recent theoretical framework



neutron matter



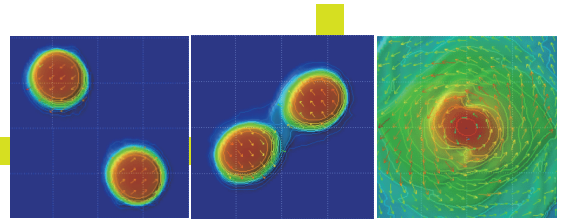
strange matter ?

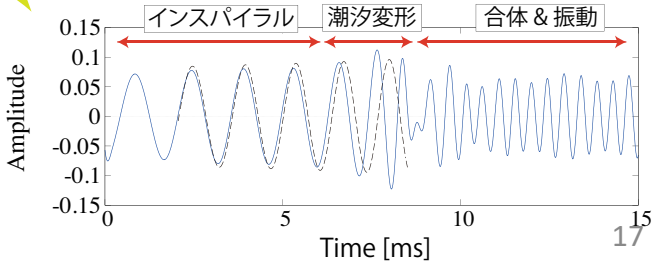


$p, n, \Lambda, \Xi^0, \Xi^-$

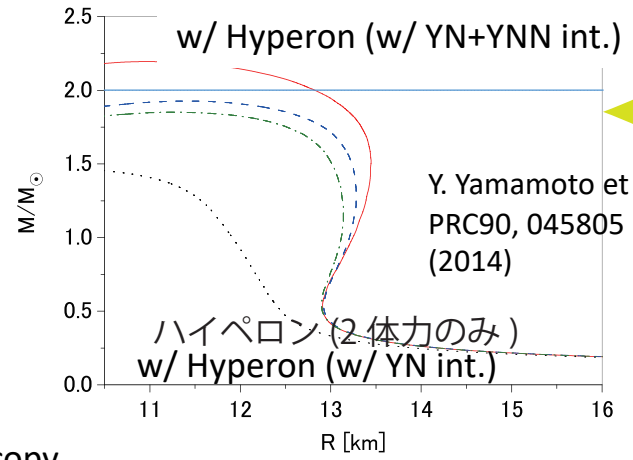
日本物理学会誌より
木内健太、関口雄一郎

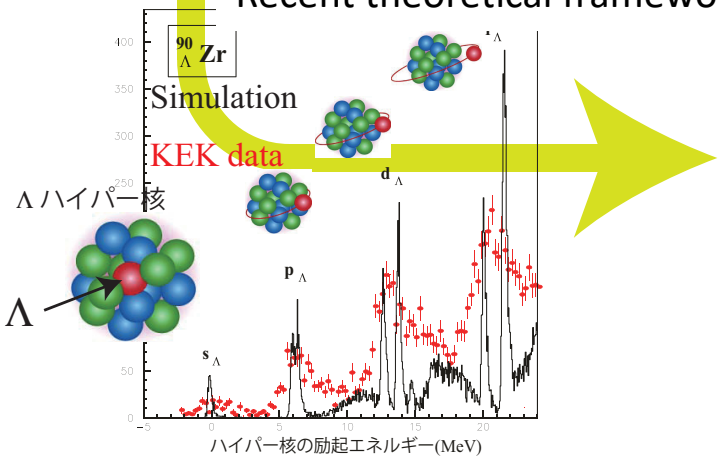
Gravitational wave from neutron star merger






EOS of neutron star



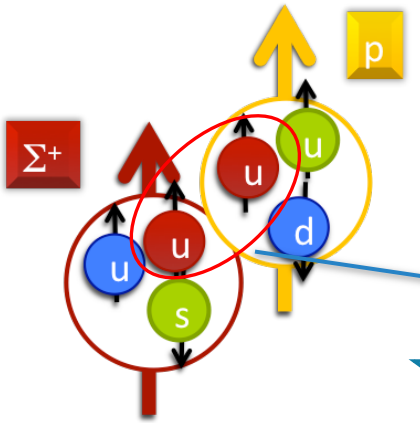




Ultra high-resolution Λ hypernuclear spectroscopy

# J-PARC E40 : Measurement of $d\sigma/d\Omega$ of $\Sigma p$ scatterings

Physics motivations

- Verification of repulsive force due to quark Pauli effect in the $\Sigma^+p$ channel
- Systematic study of the $\Sigma N$ interaction by separating isospin channel

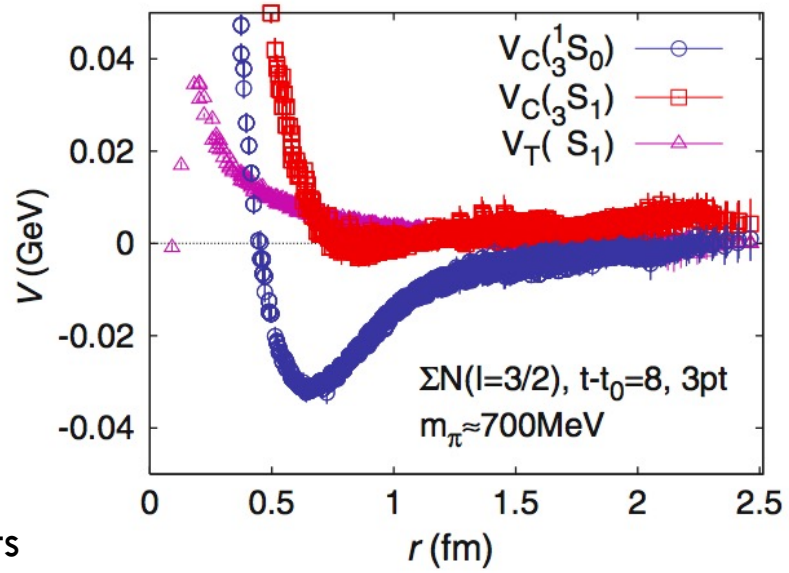



Pauli effect in quark level

Large repulsive core is expected in Lattice QCD

Large $d\sigma/d\Omega$ is predicted in $\Sigma^+p$ channel

$\Sigma^+p$ potential by Lattice QCD




H. Nemura et al.
Few-Body Syst (2013) 54:1223-1226

## Measurement of $d\sigma/d\Omega$

- $\Sigma^+p$ elastic scattering → 4,500 events
- $\Sigma^-p$ elastic scattering → 4,500 events
- $\Sigma^-p \rightarrow \Lambda n$ inelastic scattering → 2,700 events

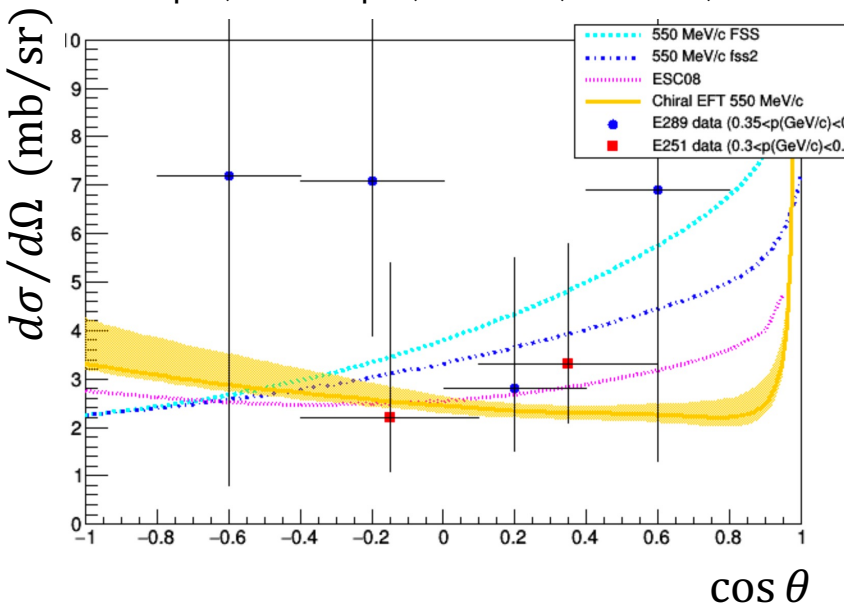
# Theoretical calculation of $d\sigma/d\Omega$ of $\Sigma p$ channels

- Quark Cluster model (FSS, fss2)
  - Y. Fujiwara et al., Prog. in Part. and Nucl. Phys. 58 (2007) 429
- Nijmegen model (ESC08c)
  - T. A. Rijken, Prog. of Theor. Phys. Suppl. 185 (2010) 14
- Chiral EFT (NLO)
  - J. Haidenbauer et al., Nucl. Phys. A 915 (2013) 24, and private communication

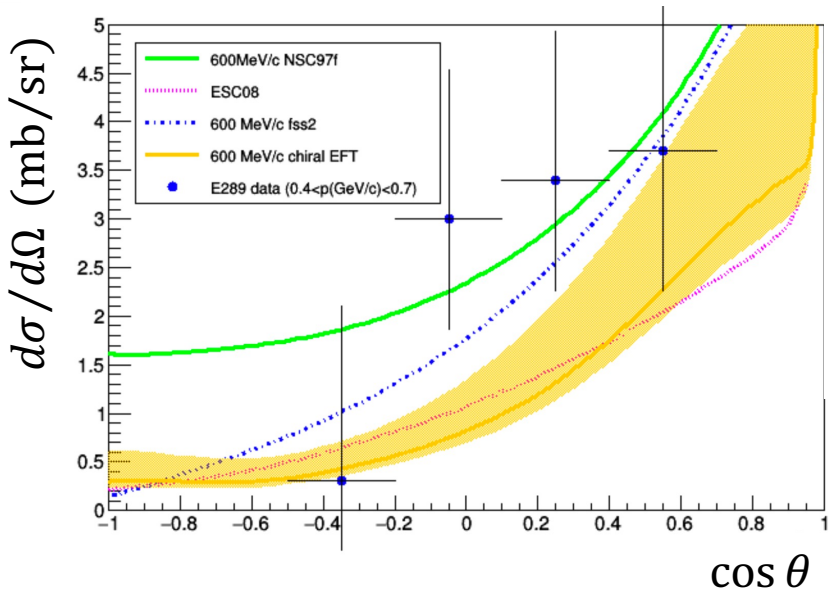
Past $\Sigma p$ scattering data

- KEK-PS E251 $0.3<p_\Sigma<0.6$ GeV/c
- KEK-PS E289 $0.4<p_\Sigma<0.7$ GeV/c

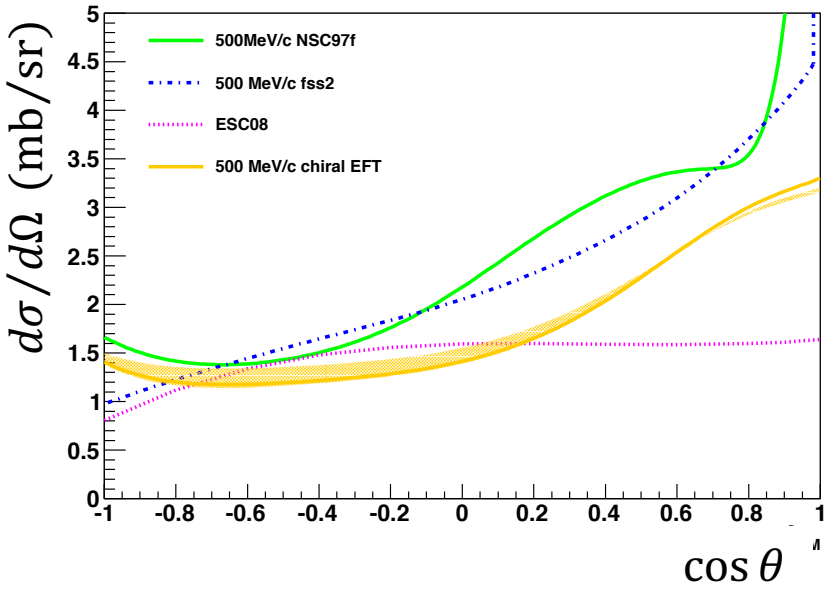
$\Sigma^+p$ $(0.5 < p\ (\mathrm{GeV/c}) < 0.6)$




$\Sigma^-p$ $(0.55 < p\ (\mathrm{GeV/c}) < 0.65)$

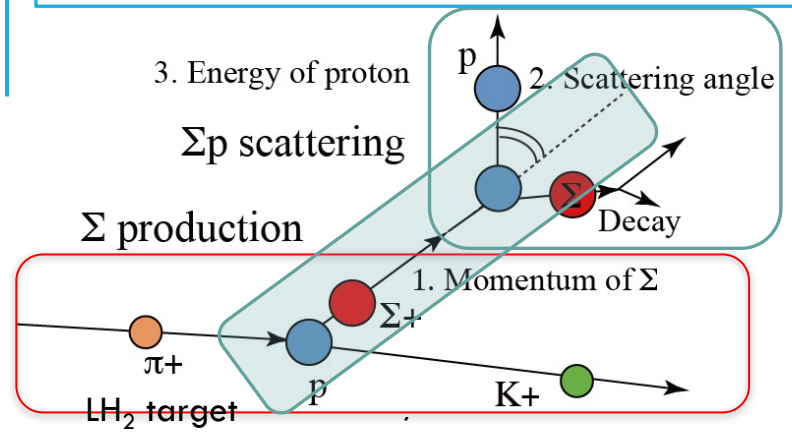



$\Sigma^-p \rightarrow \Lambda n$ $(0.55 < p\ (\mathrm{GeV/c}) < 0.65)$

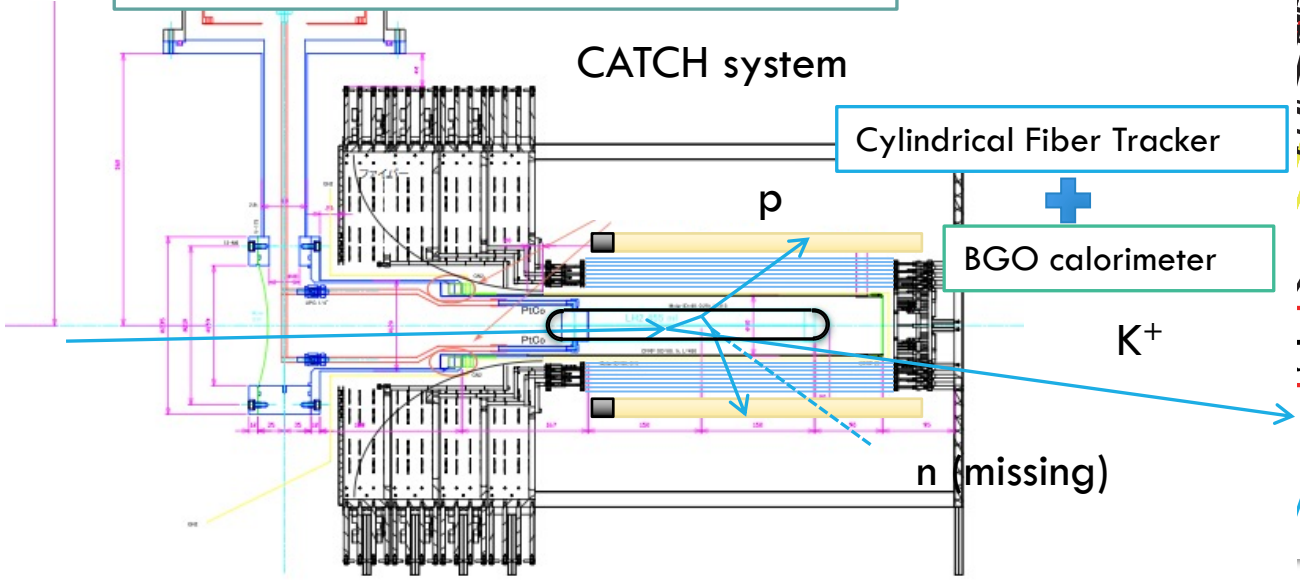


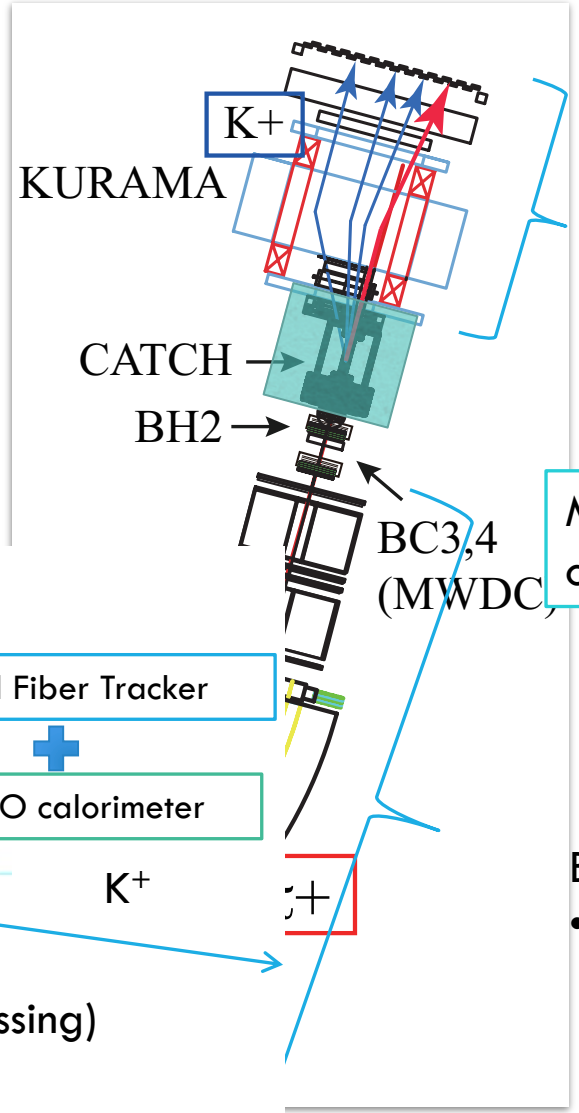
# E40 EXPERIMENTAL SETUP

Two successive two-body reactions




Detection of Σp scattering event by CATCH detector



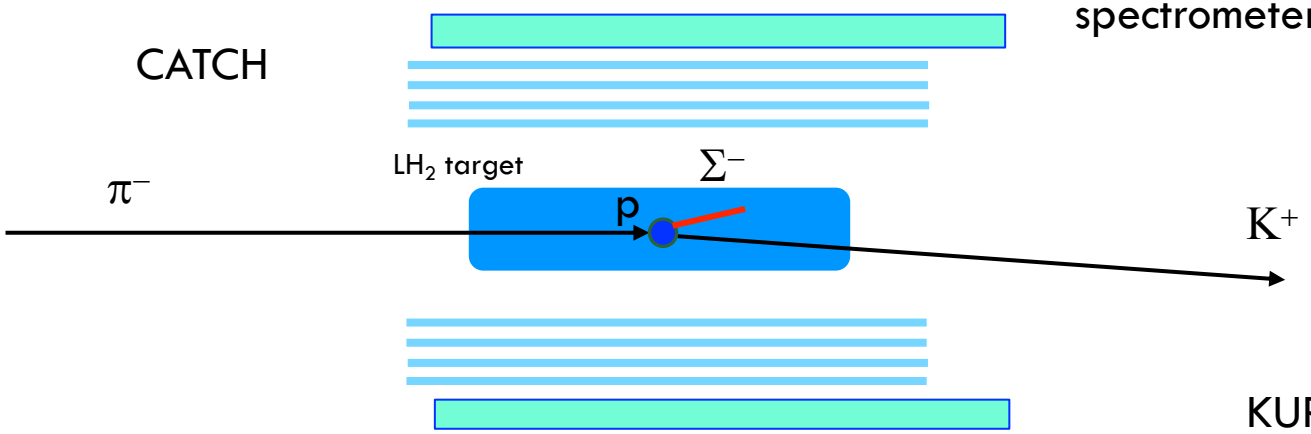

KURAMA spectrometer
- Identification of $K^+$
- Momentum analysis

Momentum reconstruction of Σ beam

Beamline spectrometer
- Momentum analysis of π beam

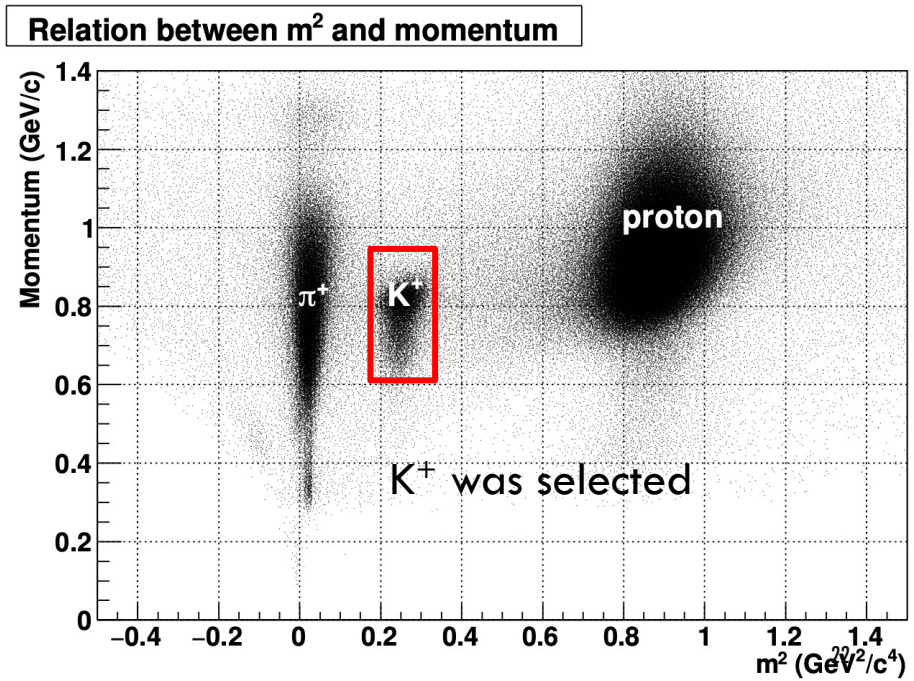
J-PARC K1.8 beamline

# Σ beam identification



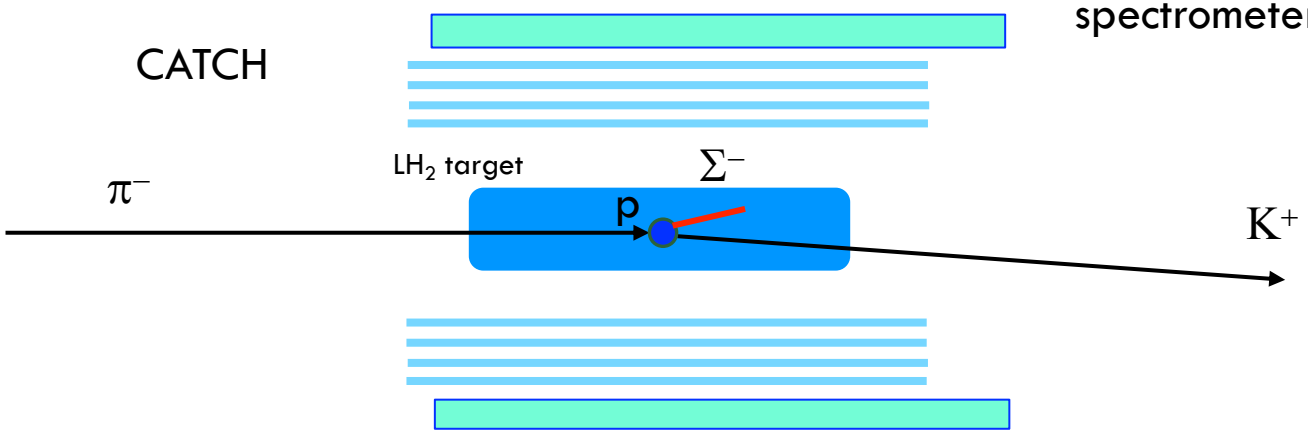

Σ beam in $LH_2$ target is tagged by the magnetic spectrometers

KURAMA spectrometer analysis

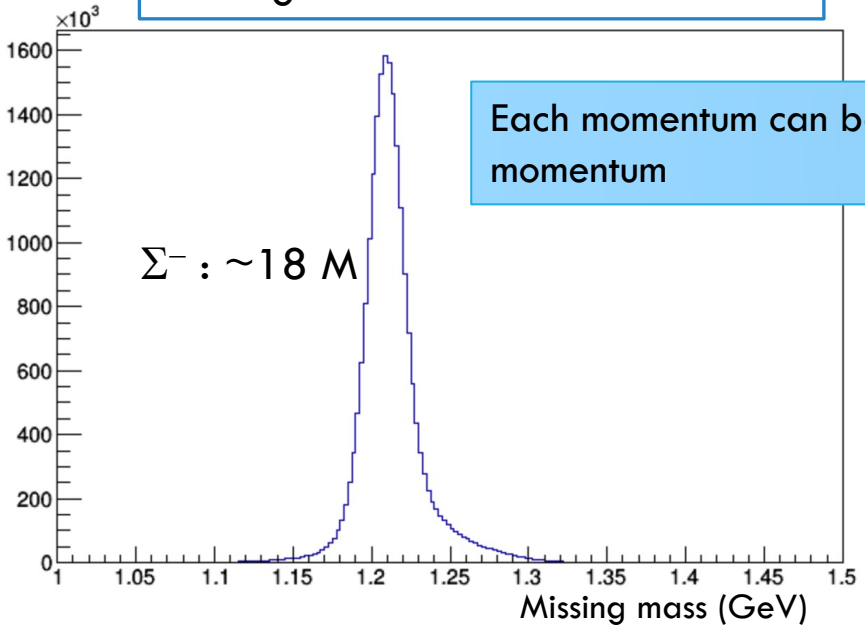


# Σ beam identification

Σ beam in $LH_2$ target is tagged by the magnetic spectrometers



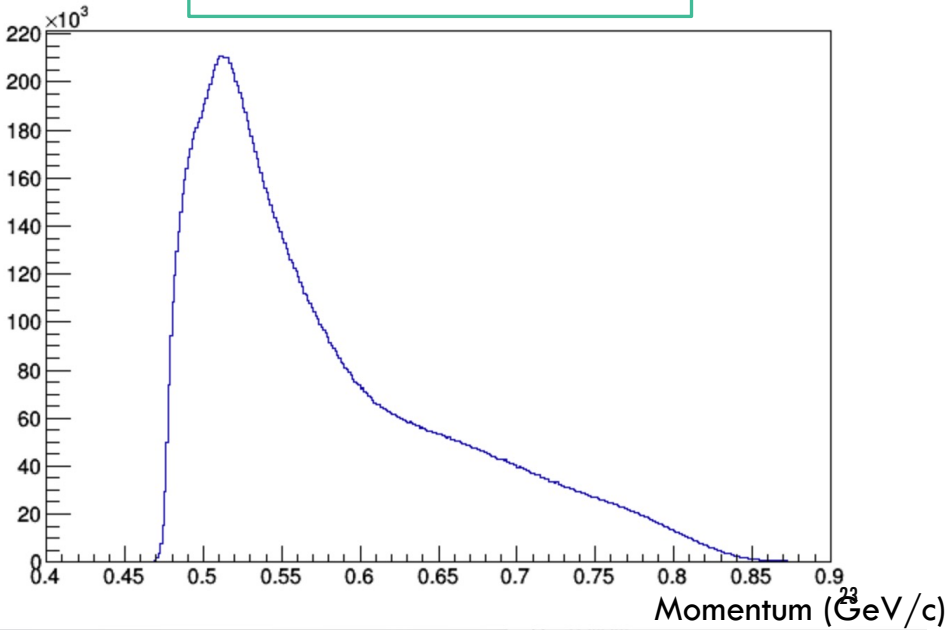

Missing mass from $\pi^-$ and $K^+$



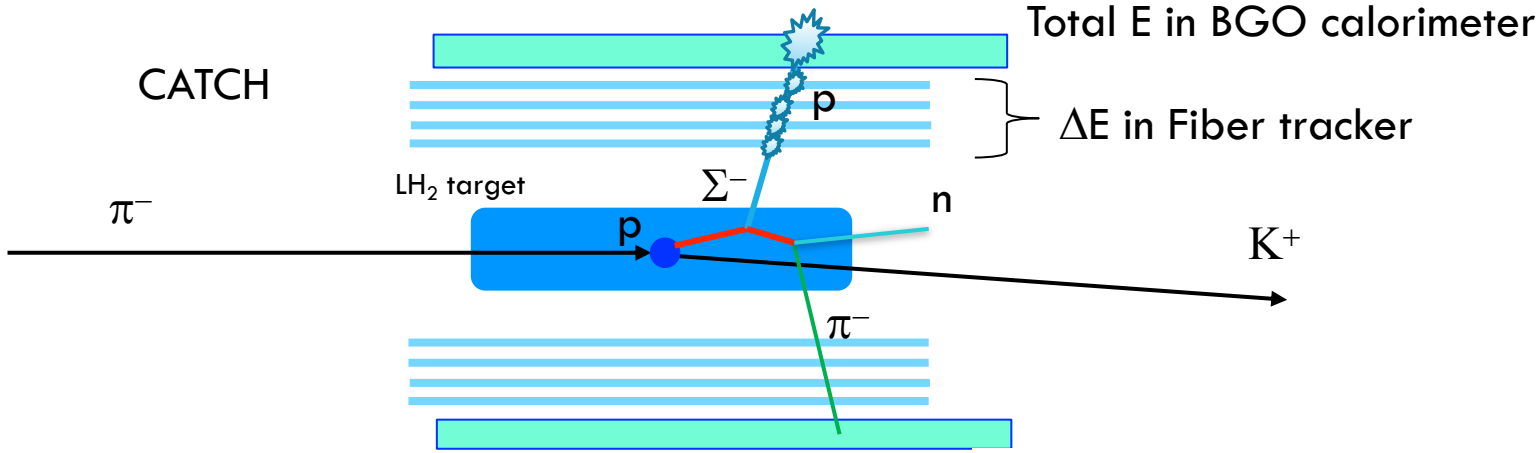

$\Sigma^-$ : ~18 M

Each momentum can be reconstructed from missing momentum

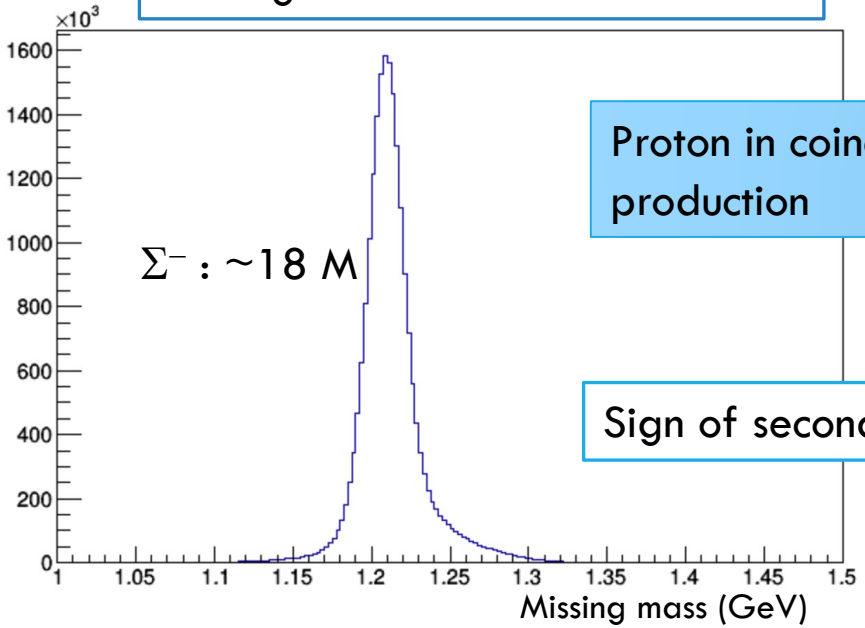
$\Sigma^-$ beam momentum



# Recoil proton identification



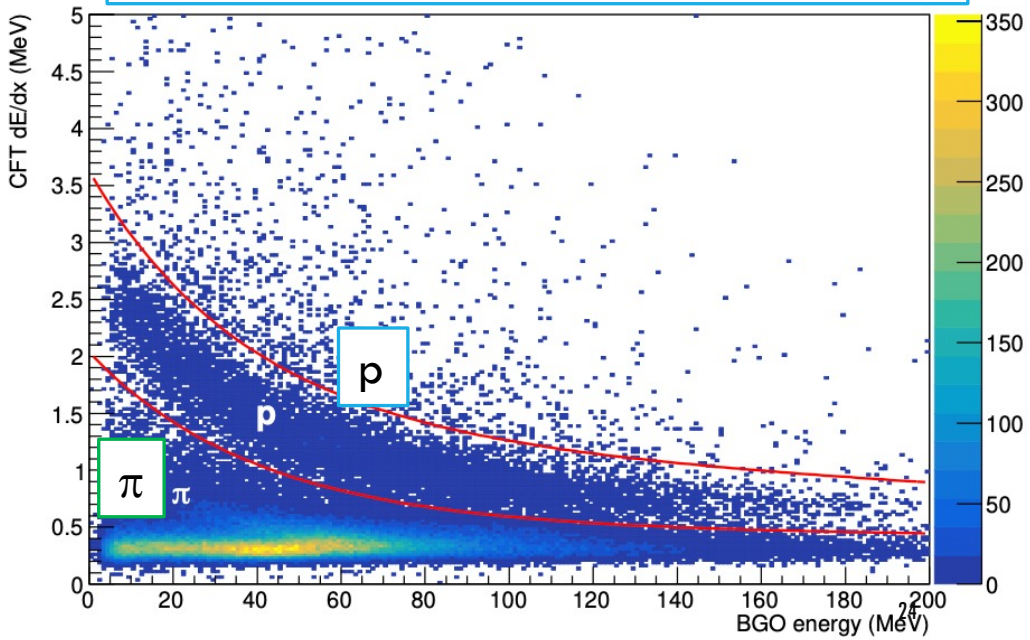

Missing mass from $\pi^-$ and $K^+$




Proton in coincidence with $\Sigma^-$ production

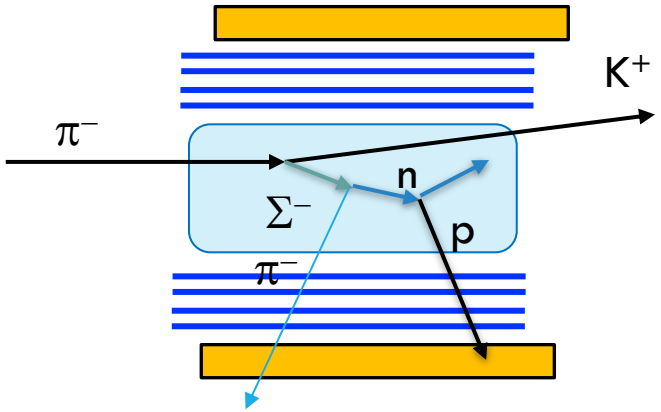
Sign of secondary reactions

Particle ID in CATCH ($\Delta$E-E method)



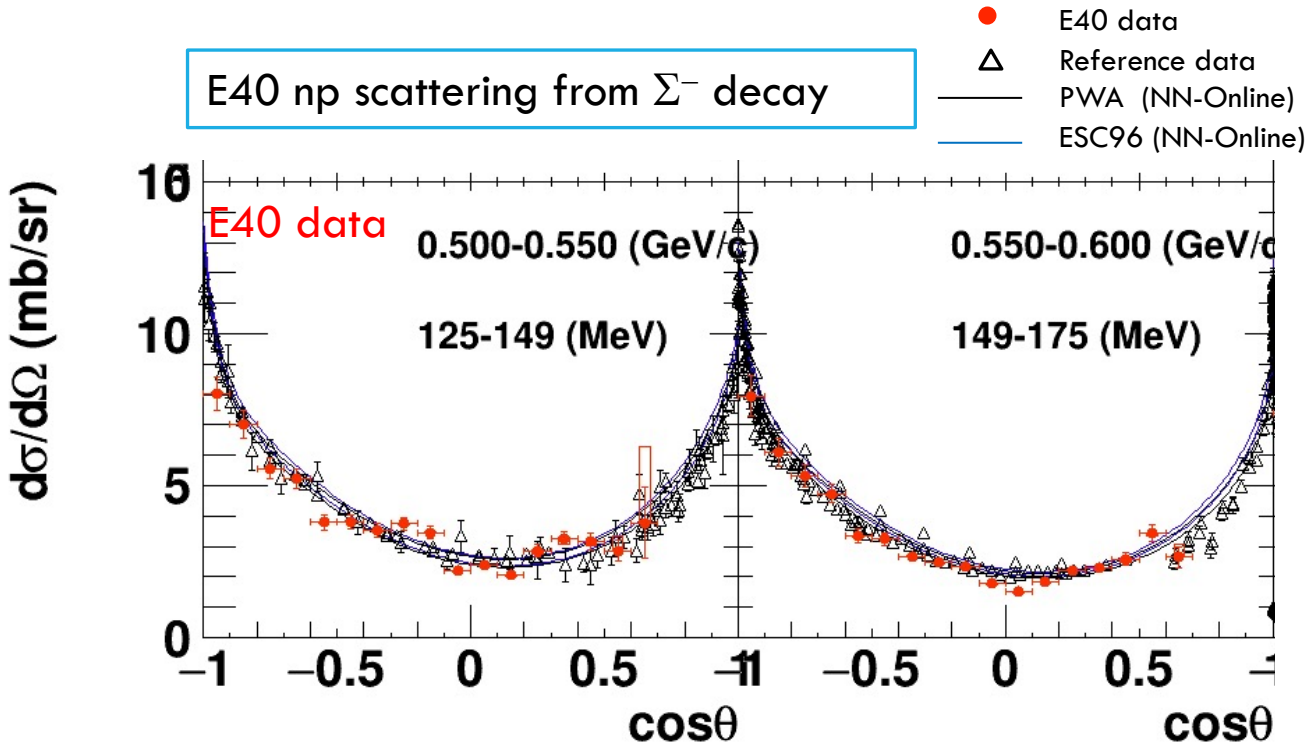
# dσ/dΩ of np scattering from $\Sigma^-$ decay

np scattering



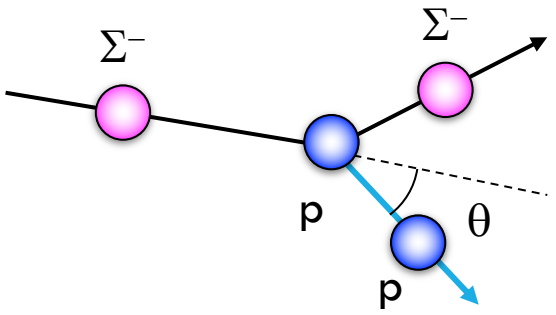

Good reaction to understand our systematics to measure dσ/dΩ

E40 np scattering from $\Sigma^-$ decay




The derived dσ/dΩ of np scattering are reasonable.

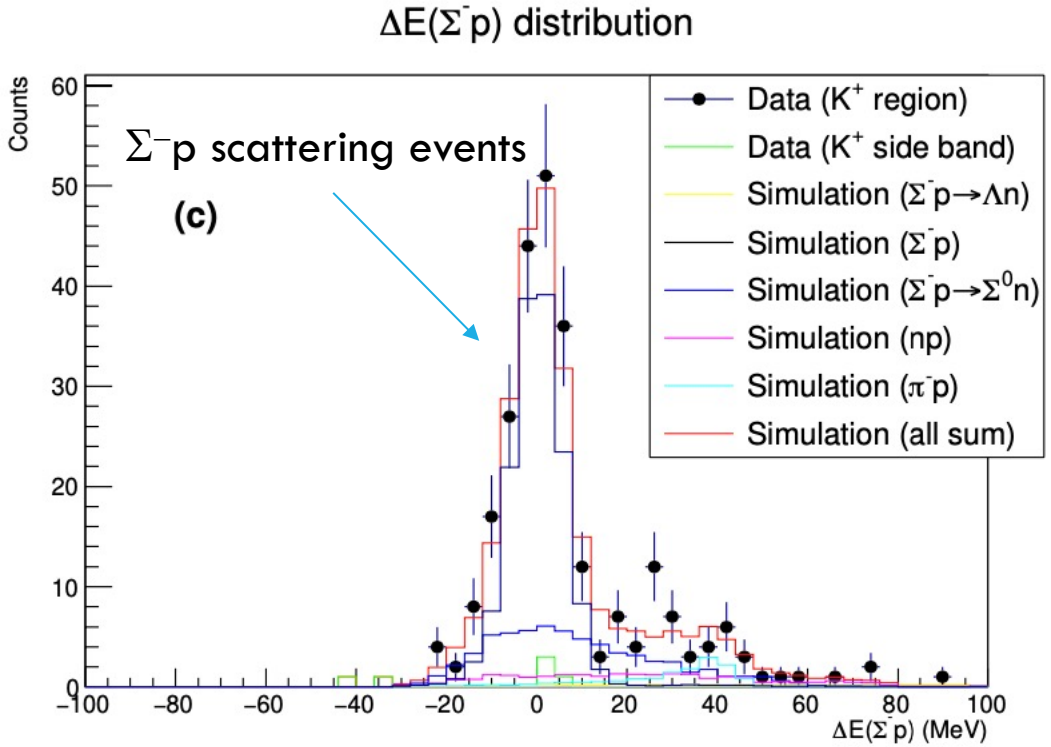
# Kinematical identification of $\Sigma^-$p scatterings

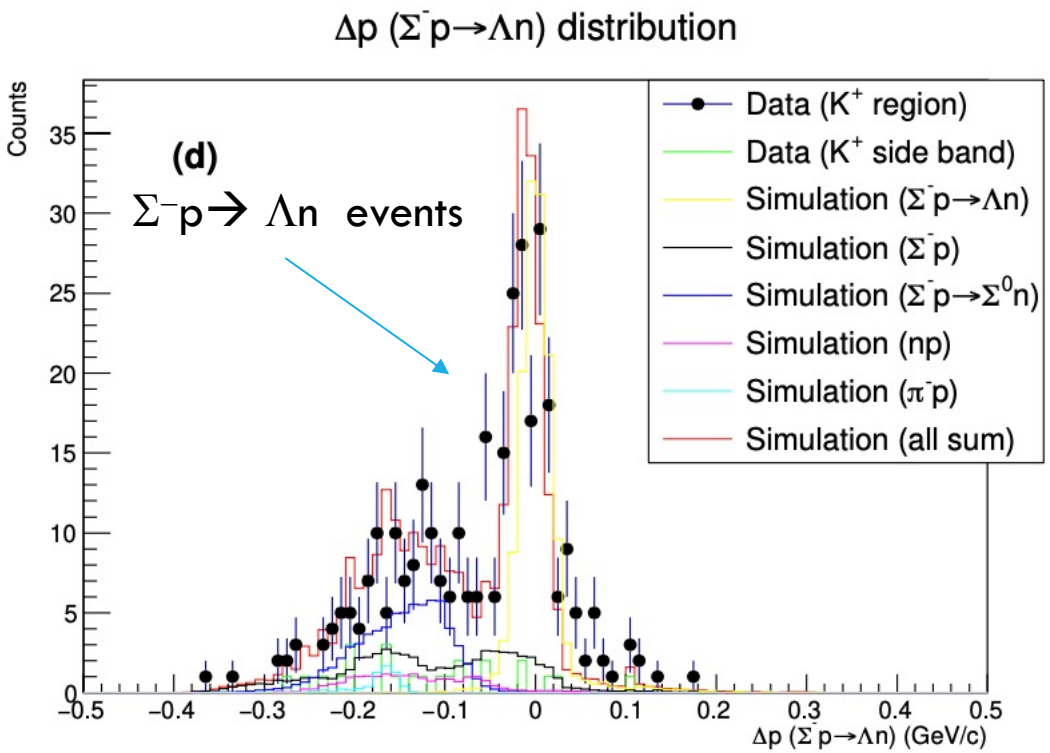



Check kinetic energy difference between

- $E_{measured}$ : measured energy
- $E_{calc}$ : calculated energy from scattering angle
  based on $\Sigma^-$p elastic scattering kinematics

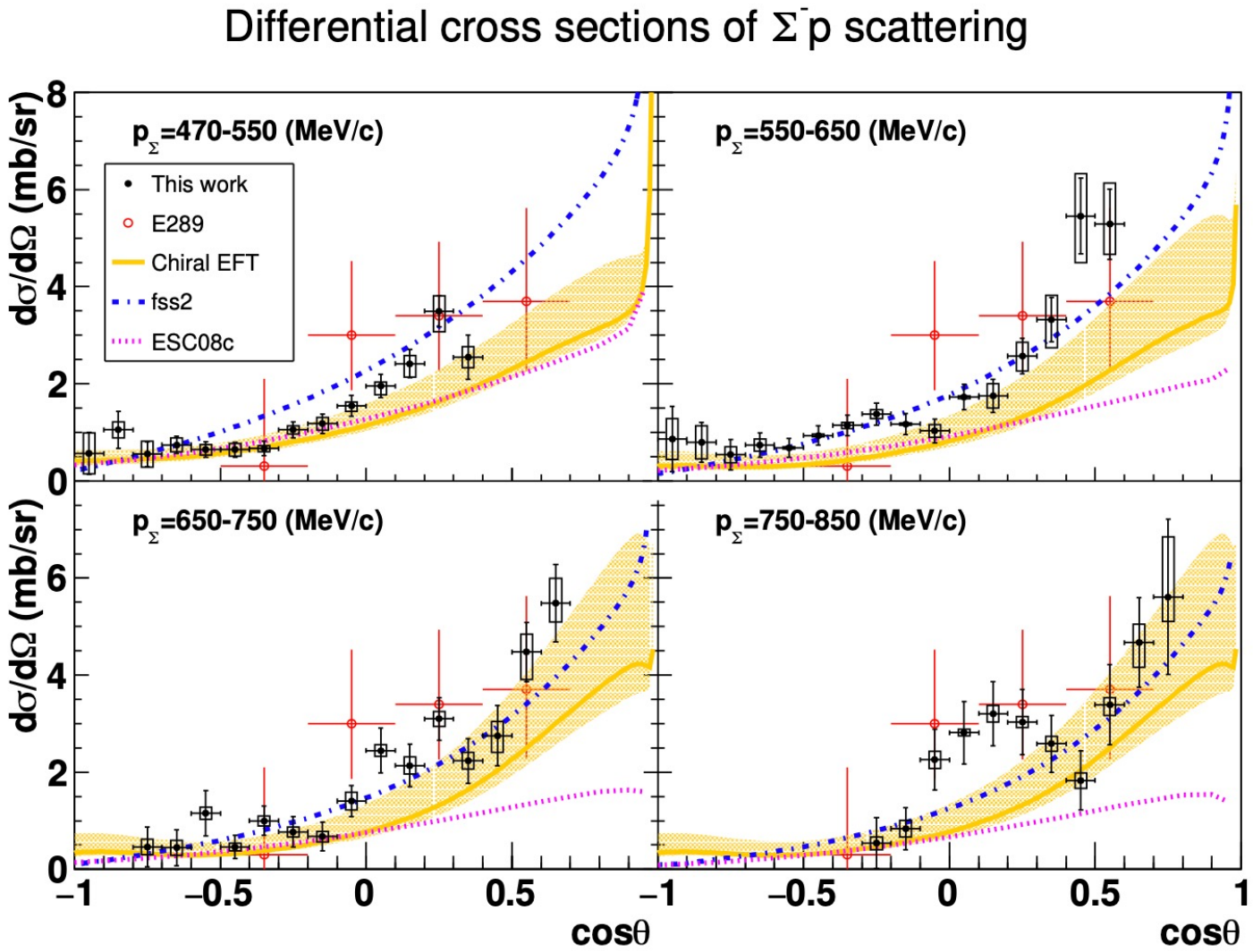
$$\Delta E(\Sigma^- p) = E_{measured} - E_{calc}$$



# $d\sigma/d\Omega$ of the $\Sigma^-p$ elastic scattering

K. Miwa et al., arXiv:2104.13608 [nucl-ex]




$d\sigma/d\Omega$ of the $\Sigma^-p$ scattering shows a clear forward peak structure.

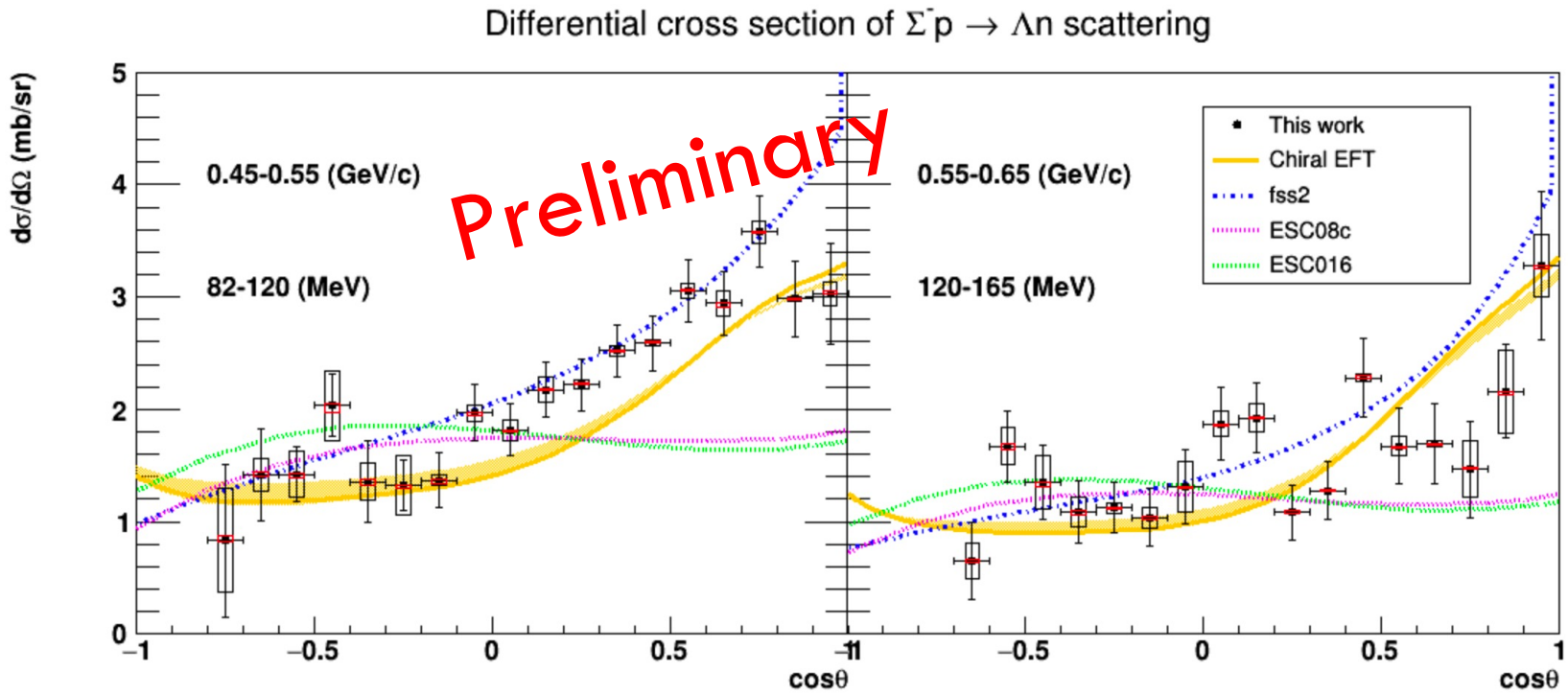
- Large higher (p, d, … ) wave contribution

Angular dependence of theoretical calculation seems to be consistent with our measurement.

- fss2 (quark model) reproduces the data for $0.55<p<0.65$ GeV/c
- Chiral EFT and ESC08 are smaller than our measurement.

This is the first accurate $d\sigma/d\Omega$ data in higher momentum region.
Our data can impose much stricter constraint on theories.

# $d\sigma/d\Omega$ of the $\Sigma^-p \rightarrow \Lambda n$ reactions




$d\sigma/d\Omega$ of the $\Sigma^-p \rightarrow \Lambda n$ scattering shows a moderate forward peak in $0.45 < p\ (GeV/c) < 0.55$. In the $0.55 < p\ (GeV/c) < 0.65$, $d\sigma/d\Omega$ looks flat, although the fluctuation in data is large.

- fss2 reproduces well in $0.45 < p\ (GeV/c) < 0.55$.
- Chiral EFT also shows the reasonable angular dependence.

# Discussion

Relationship between the isospin basis and the flavor SU(3) basis

| $S$ | $BB$ channel (I) | ${}^1E$ or ${}^3O$ | ${}^3E$ or ${}^1O$ |
|---|---|---|---|
| 0 | $NN(I=0)$ | $--$ | $(10^*)$ |
| Update ΛN | $NN(I=1)$ | $(27)$ | $--$ |
| interaction | $\Lambda N(I=1/2)$ | $\frac{1}{\sqrt{10}}[(8_s)+3(27)]$ | $\frac{1}{\sqrt{2}}[-(8_a)+(10^*)]$ |
| $-1$ | $\Sigma N(I=1/2)$ | $\frac{1}{\sqrt{10}}[3(8_s)-(27)]$ | $\frac{1}{\sqrt{2}}[(8_a)+(10^*)]$ |
| | $\Sigma N(I=3/2)$ | $(27)$ | $(10)$ |

ΣN (I=3/2) can be investigated from the $\Sigma^+$p channel.
- This channel will be also finalized in near future.

$\Sigma^-$p→Λn channel is pure ΣN (I=1/2) channel
- It also relates with the ΛN-ΣN coupling directly.

$\Sigma^-$p is superposition of ΣN (I=1/2) and ΣN (I=3/2)

By combining our data, all 3 multiplets should be constrained in P-wave momentum region.

- ✓ First constraint on LEC for Chiral EFT in p wave region
- ✓ ΛN-ΣN coupling parameter in Nijmegen model

First step to construct realistic YN interaction by the cooperation between theories and scattering experiment.

We expect
- the ΛN interaction will be also updated because it consists of the same multiplets.

Λ hypernuclear structure should be calculated by theoretical models which reproduce our Σp scattering data

# FUTURE PROSPECT

New project:
$\Lambda$p scattering experiment at K1.1 beam line with polarized $\Lambda$ beam

Submitted to J-PARC 32nd PAC

**Proposal for an experiment at the 50-GeV PS**

**Measurement of the differential cross section and spin observables of the $\Lambda p$ scattering with a polarized $\Lambda$ beam**


K. Miwa(spokesperson), S. H. Hayakawa, Y. Ishikawa, K. Itabashi, K. Kamada, T. Kitaoka, T. Morino, S. Nagao, S. N. Nakamura, F. Oura, T. Sakao, H. Tamura, H. Umetsu, S. Wada
*Tohoku University, Japan*

M. Fujita, Y. Ichikawa, T. O. Yamamoto
*Japan Atomic Energy Agency (JAEA), Japan*

R. Honda, M. Ieiri, T. Takahashi, M. Ukai
*High Energy Accelerator Research Organization (KEK), Japan*

T. Nanamura
*Kyoto University, Japan*

K. Shirotori
*Research Center for Nuclear Physics (RCNP), Osaka University, Japan*

P. Evtoukhovitch
*Joint Institute for Nuclear Research (JINR), Russia*

Z. Tsamalaidze
*Joint Institute for Nuclear Research (JINR), Russia*
*Georgian Technical University (GTU), Tbilisi, Georgia*

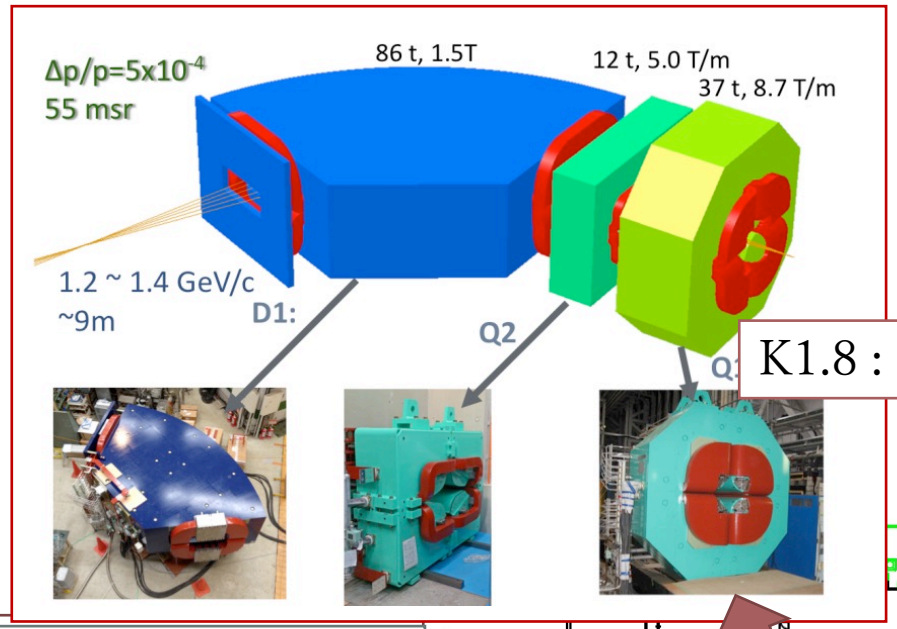
# Extend J-PARC Physics Capability



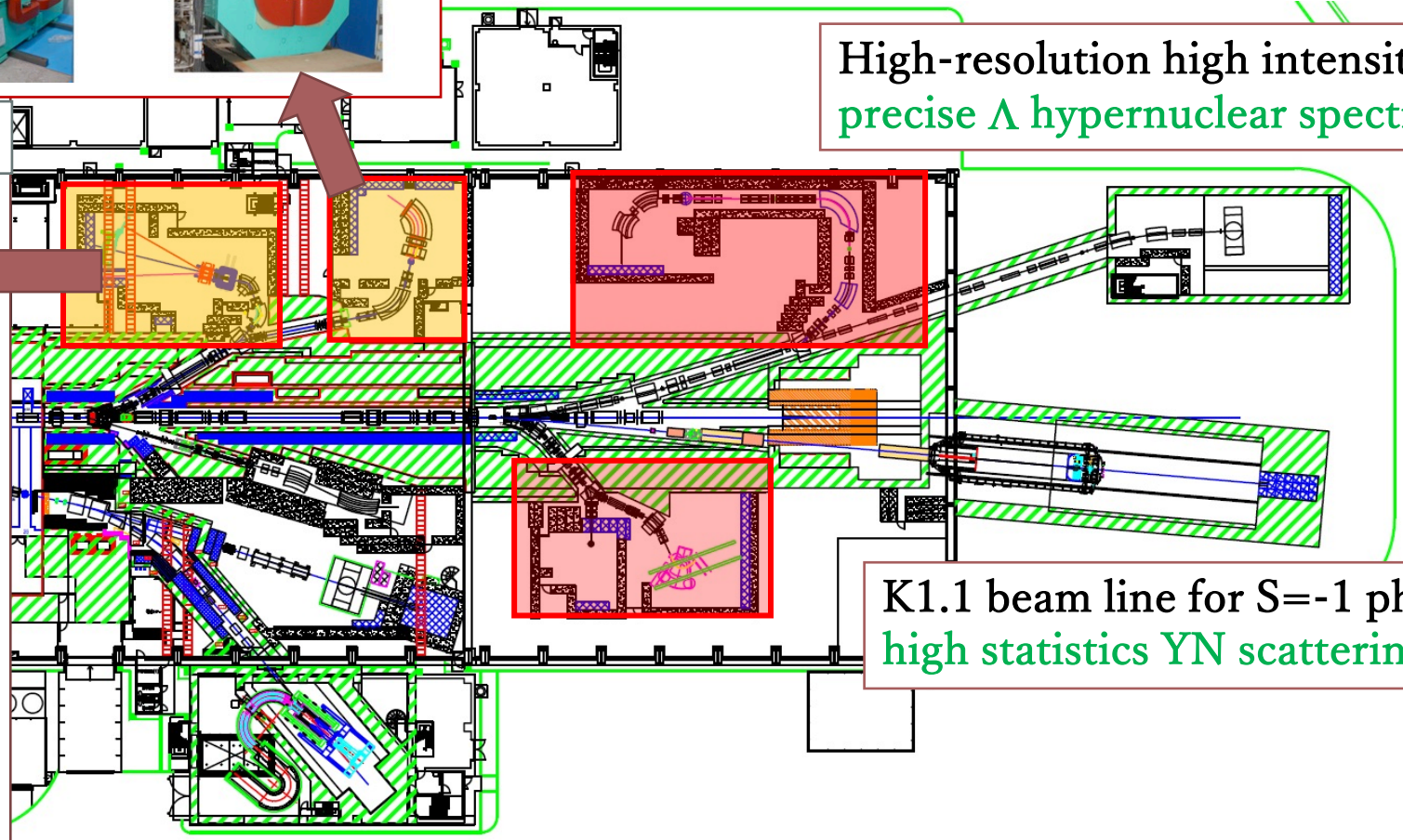
Our strategy at J-PARC

Go forward physics programs of S=-2 hypernuclei and Kaonic nuclei at existing beam lines

We need new beam lines for S=-1 physics



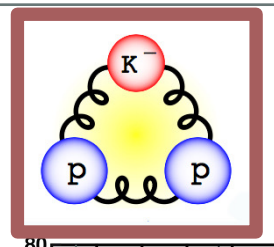

K1.8 : S=-2 physics

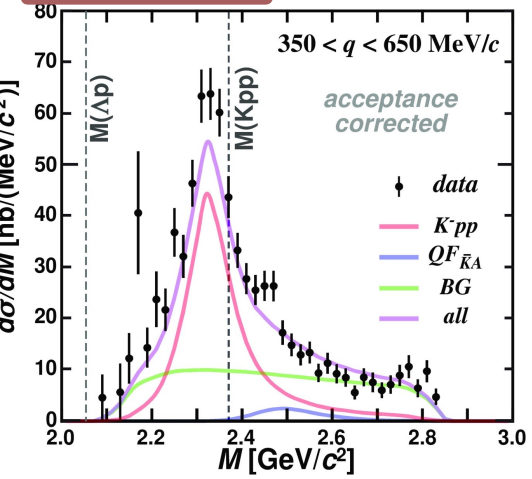


High-resolution high intensity beam line for precise Λ hypernuclear spectroscopy

K1.1 beam line for S=-1 physics and high statistics YN scattering

K1.8 BR : Kaon in nuclei



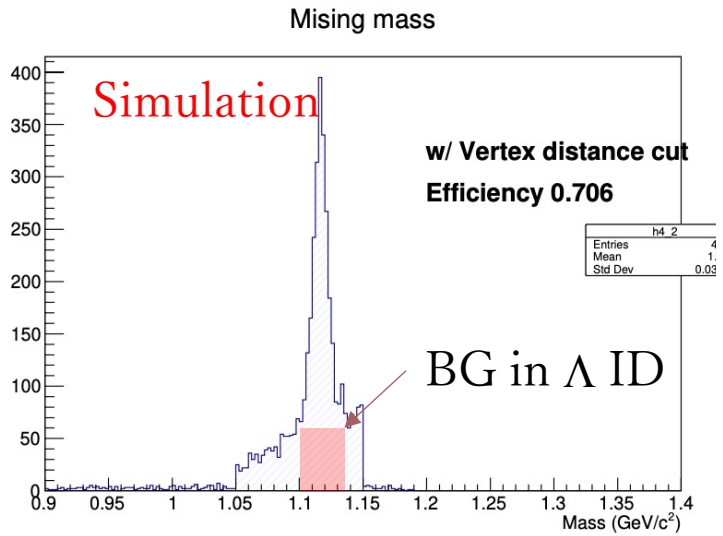



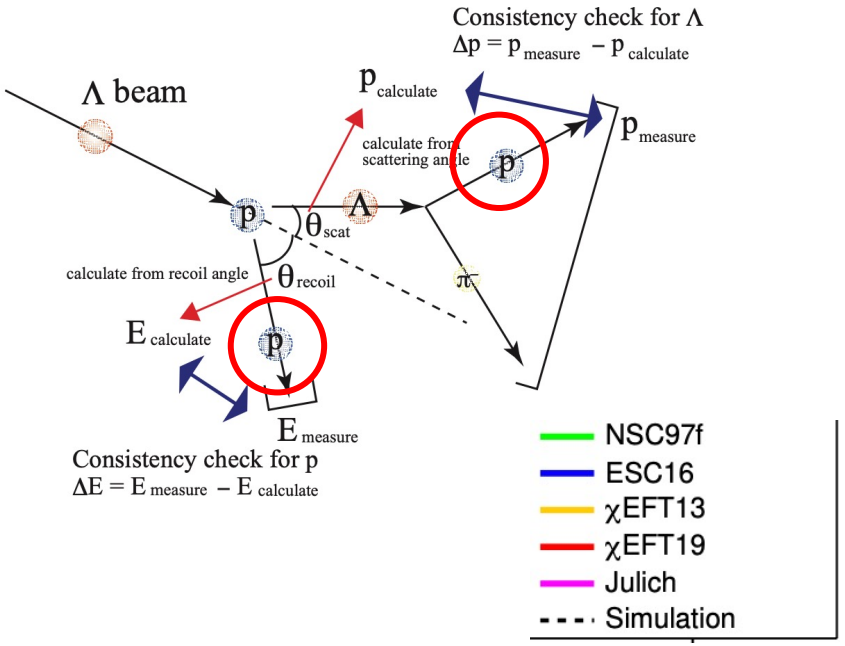
# Λp scattering with polarized Λ beam

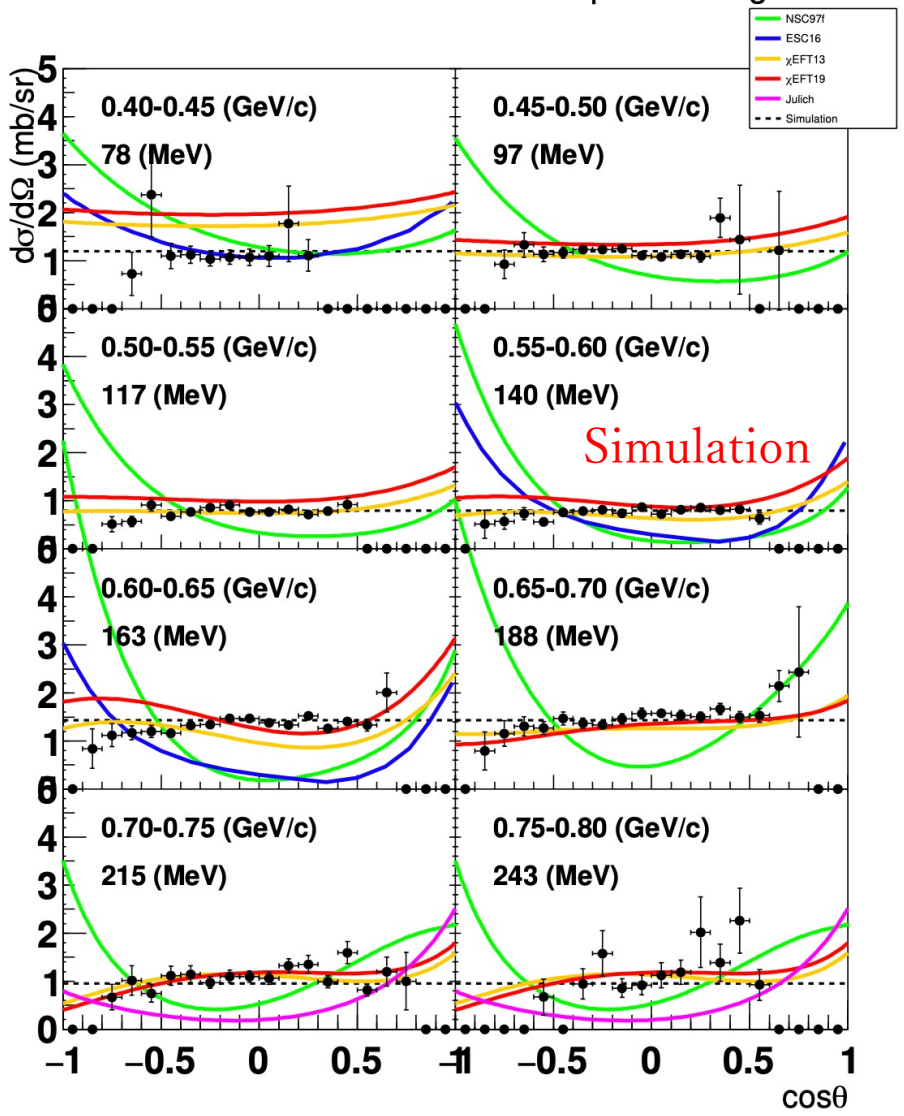
Simulated results w/ 100M Λ

To suppress B.G. in the Λ production,
we request at least 2 protons for scattering analysis

➡ Angular acceptance is limited



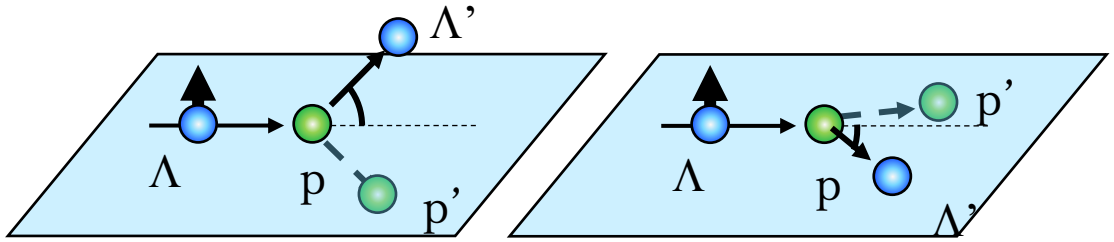

- ✓ Selection of model (chiral EFT, Nijmegen, Julich) is possible
- ✓ Selection in each model
  - ✓ NSC97f, ESC16 OK
  - ✓ ChiralEFT13, 19 OK

Simulated results w/ 100M Λ

# Spin observables in Λp scattering

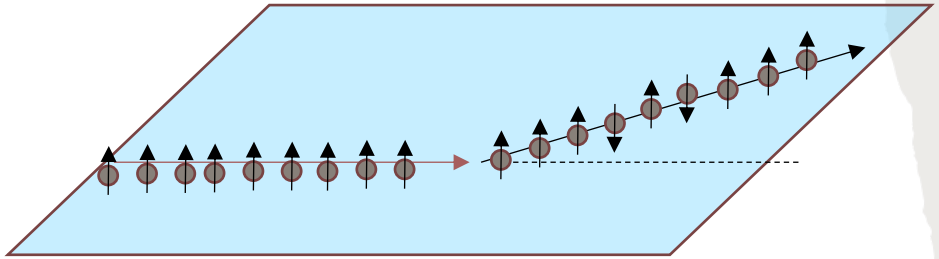
## Analyzing power

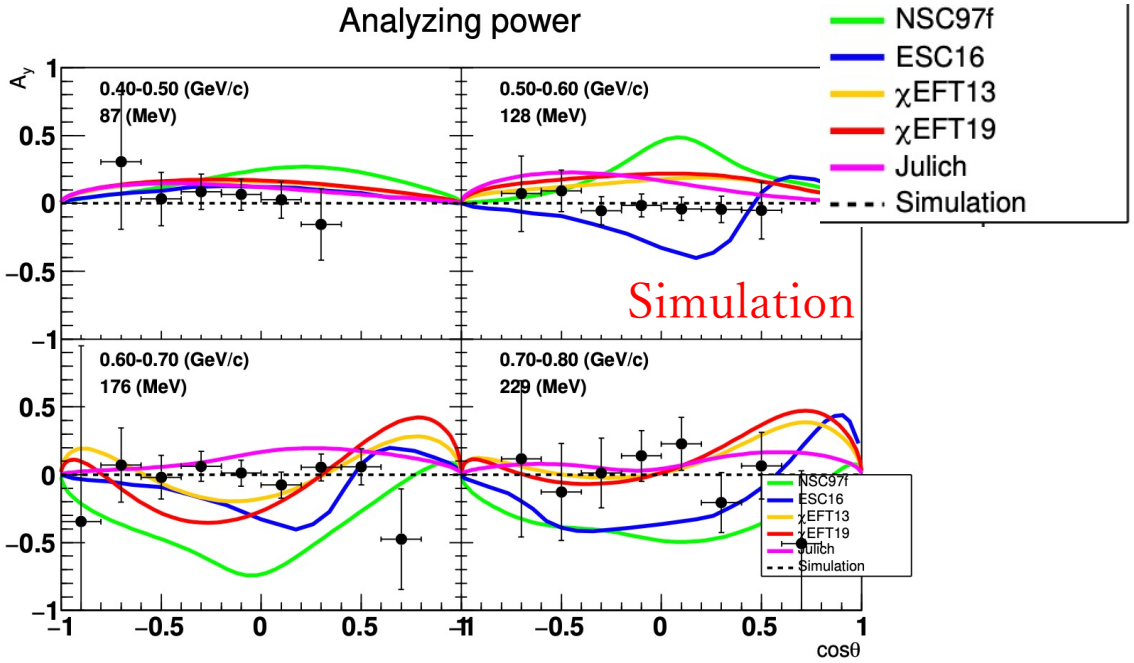
Left scattered event　　Right scattered event

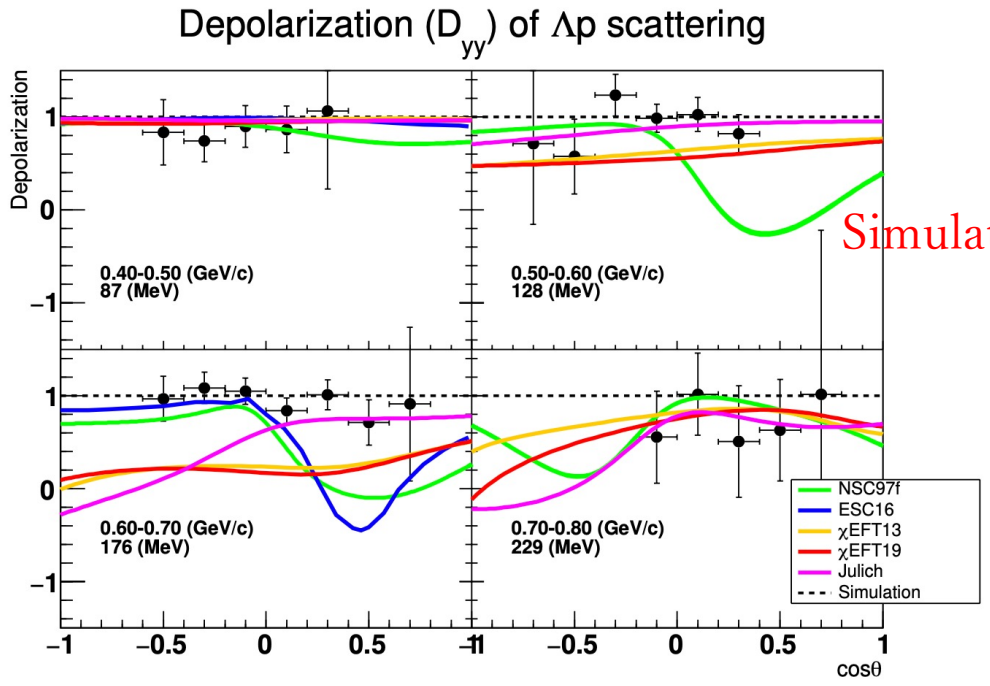



## Depolarization ($D_y^y$)

Change the spin polarization after the Λp scattering






Simulation

In the middle momentum range (0.5~0.7 GeV/c), 10% level accuracy can be achieved.

We believe that these new scattering data becomes important constraint to determine spin-dependent ΛN interaction

# Summary

- BB interactions are important to understand

  Generalized meson-exchange picture with (broken) $SU_F(3)$ symmetry

  Role of quarks at the short range

  Complicated dynamics of nuclear system with hyperon (hypernuclei, neutron star)as its basic interaction

- Scattering observables of Yp scattering are essential inputs for constructing realistic BB interaction models

  Now, Yp scattering experiment, which can impose a strong constraint on theoretical model, becomes possible

- Systematic measurement of Σp scattering was performed at J-PARC

  By accumulating 18M $\Sigma^-$ (70M $\Sigma^+$) beams, ~5,000 $\Sigma^-$p and $\Sigma^+$p elastic scatterings were identified. This enables us to provide $d\sigma/d\Omega$ with ~10% level accuracy for fine angular pitch ($d\cos\theta=0.1$)

  $d\sigma/d\Omega$ for $\Sigma^-$p elastic scattering for 0.45~0.8 GeV/c shows a clear forward-peaking structure due to P- and higher wave contribution

  $d\sigma/d\Omega$ for $\Sigma^-p \rightarrow \Lambda n$ scattering for 0.45~0.8 GeV/c shows rather moderate angular distribution

- Future project to measure $d\sigma/d\Omega$ and spin observables of Λp scattering w/ polarized Λ beam

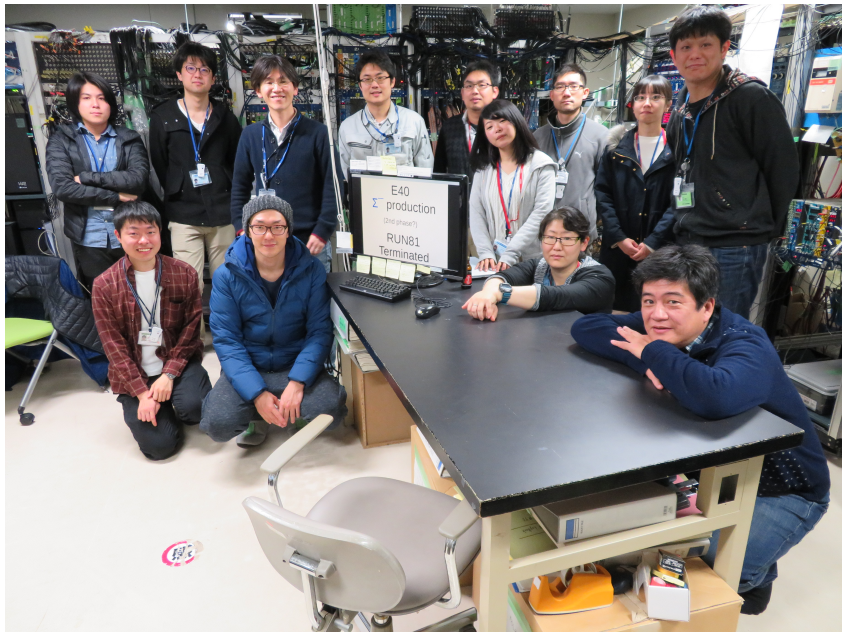
  These measurements are important to reinforce the current ΛN interaction for deepening hypernuclear physics.

We hope our data become important inputs to improve theoretical models

# Acknowledgement

Many thanks to

K1.8 group and E40 collaboration




J-PARC accelerator and hadron facility staffs

Continuous work for providing beam

CYRIC and ELPH staffs

Support for many test experiments