Study of hyperon-nucleon interactions for understanding the hierarchical structure of matter with hyperons

Koji Miwa (Tohoku Univ.)
on behalf of J-PARC E40 collaboration, HEF ex TF

B01 group : Hierarchy of matter studied via strange hadron clusters

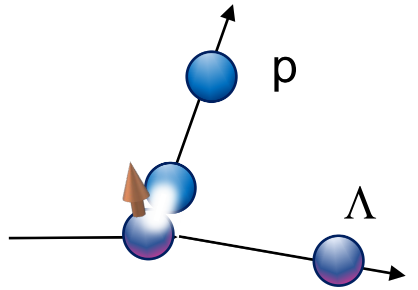
CLUSHIQ2022, Oct. 31st – Nov. 3rd, 2022

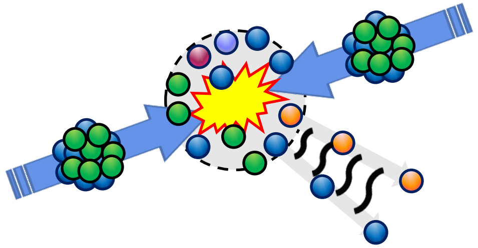
Clusters & Hierarchies

TOHOKU UNIVERSITY

Hypernuclear physics

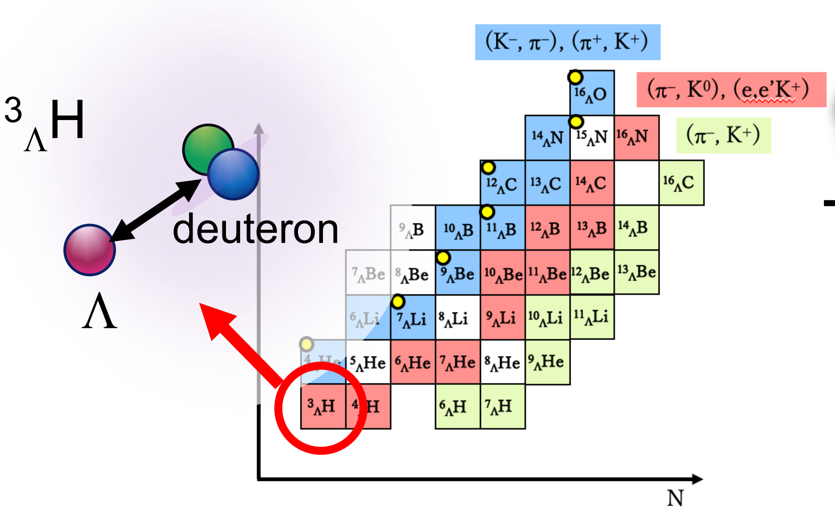
Baryon-Baryon interaction



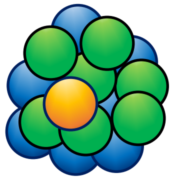


Two-body YN int.

Study of light Λ, Ξ hypernuclei

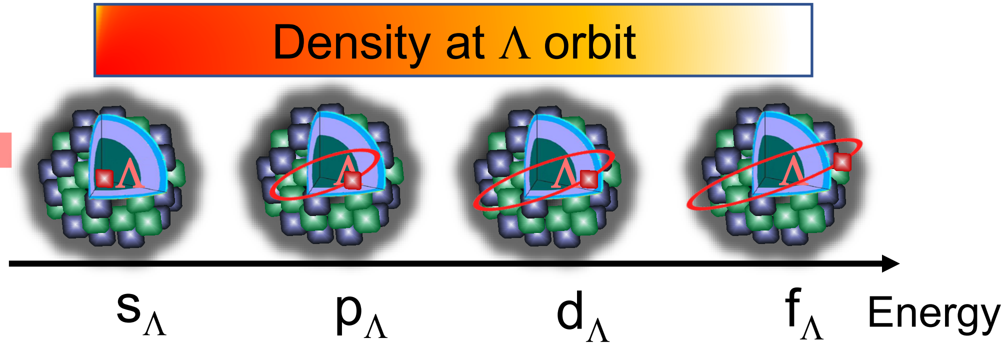


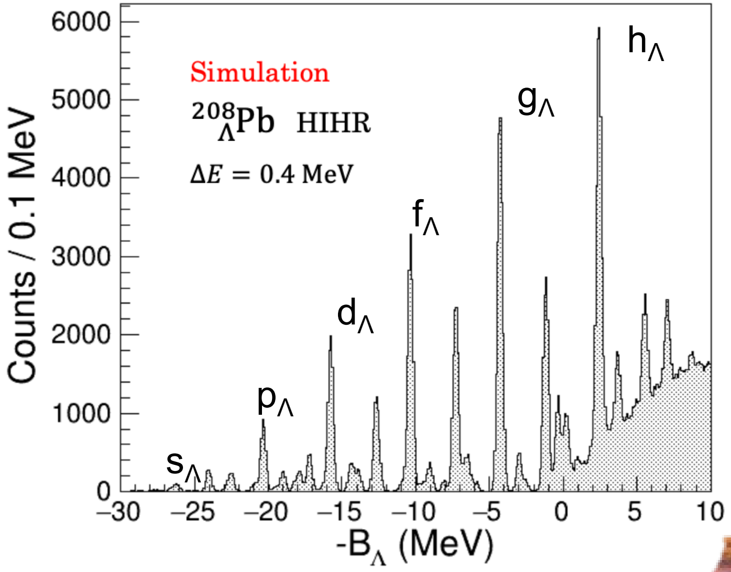
Ξ hypernuclei

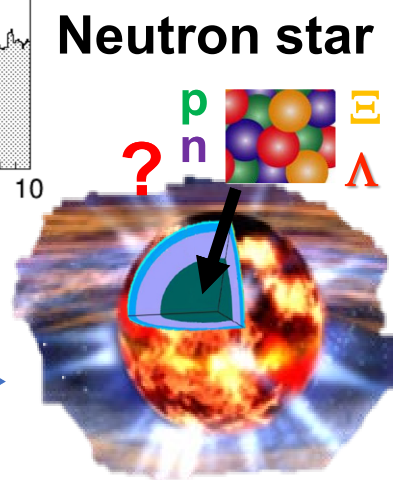


ΛN-ΣN coupling, ΛNN int., ΛΛ, ΞN int.

Spectroscopy of heavy hypernuclei







Density dependent ΛN int., ΛNN int.

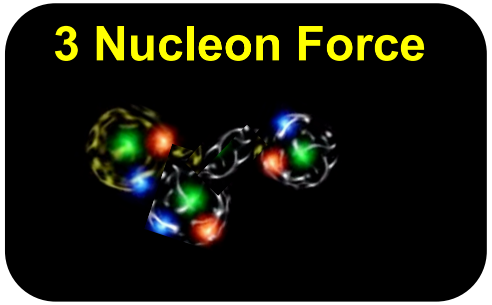
Contents

Realistic nuclear force : base for nuclear physics

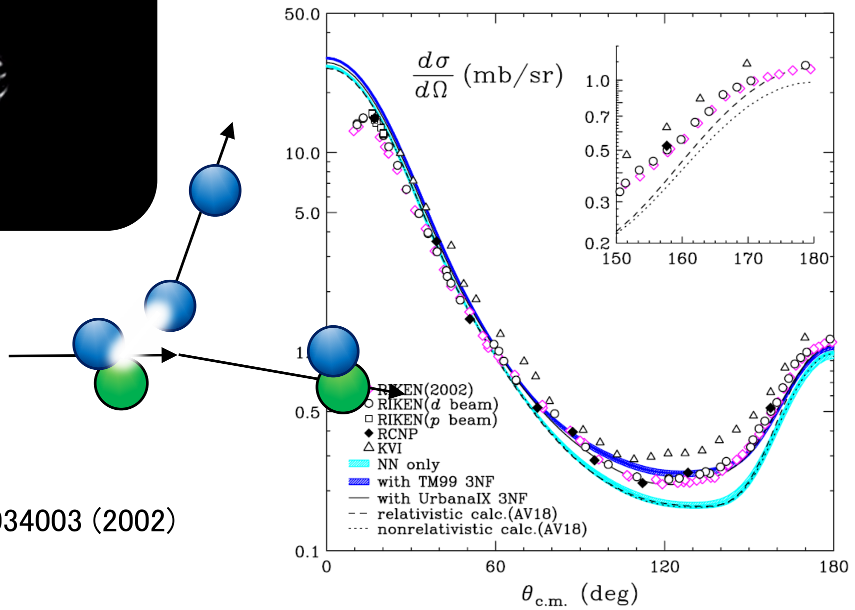
Realistic Nucleon-Nucleon Potential (CD Bonn, AV18, Nijmegen I, II)

Updated based on a lot of scattering observables of NN scattering

Solid base for nuclear studies

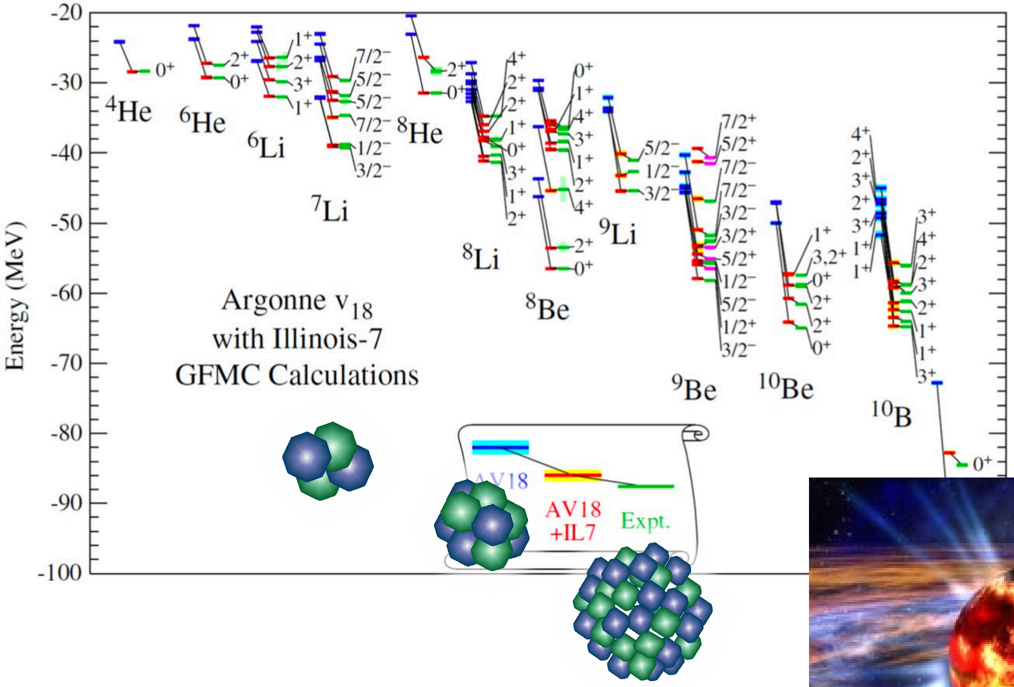


Nucleon-Deuteron scattering



K. Sekiguchi et al.
Phys. Rev. C 65, 034003 (2002)

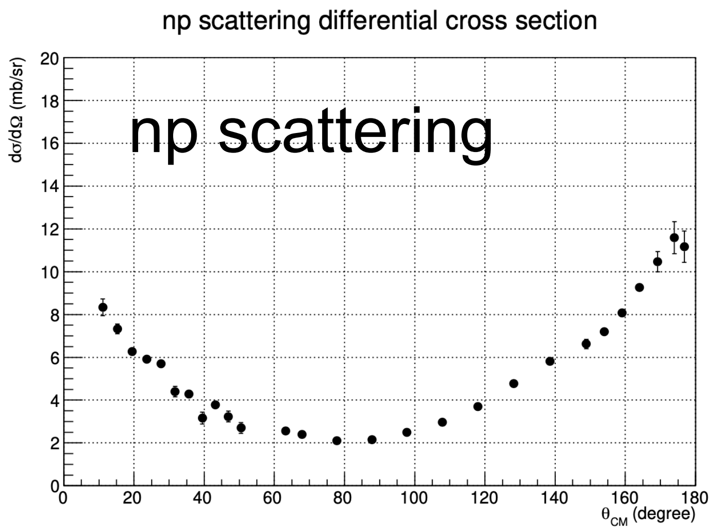
Nuclear binding energy

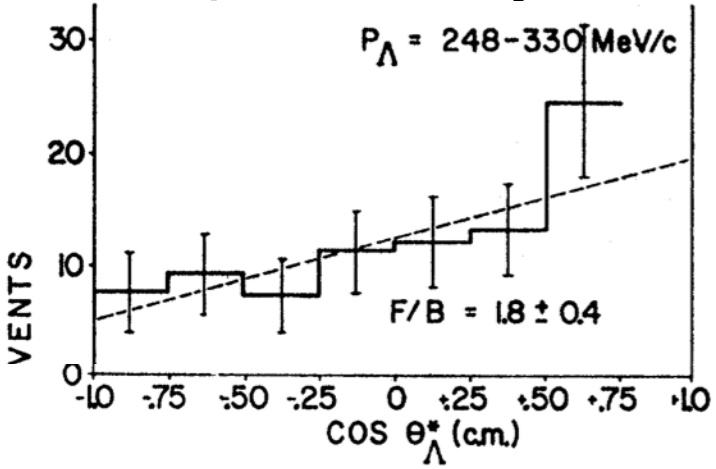


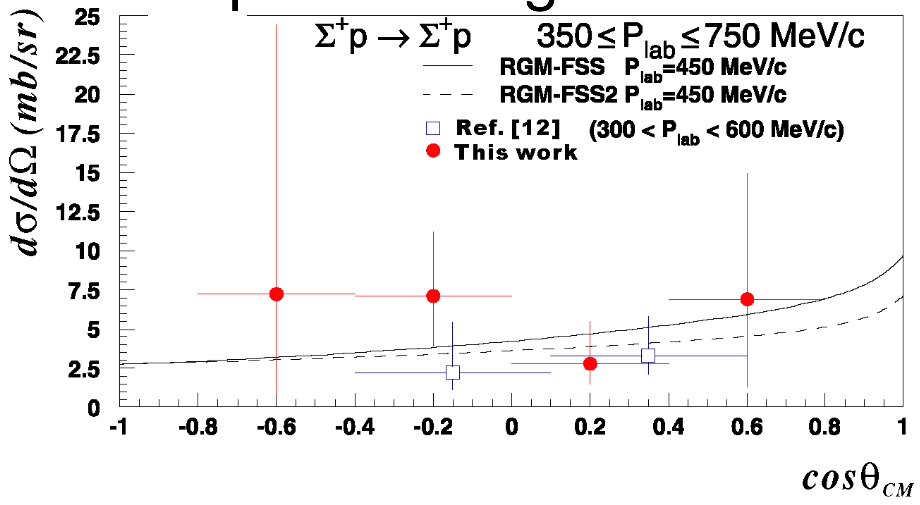
Equation of State of Nuclear Matter

NN scattering and hyperon-nucleon (YN) scattering

Clearly there is a big difference in data quality between NN and YN scatterings





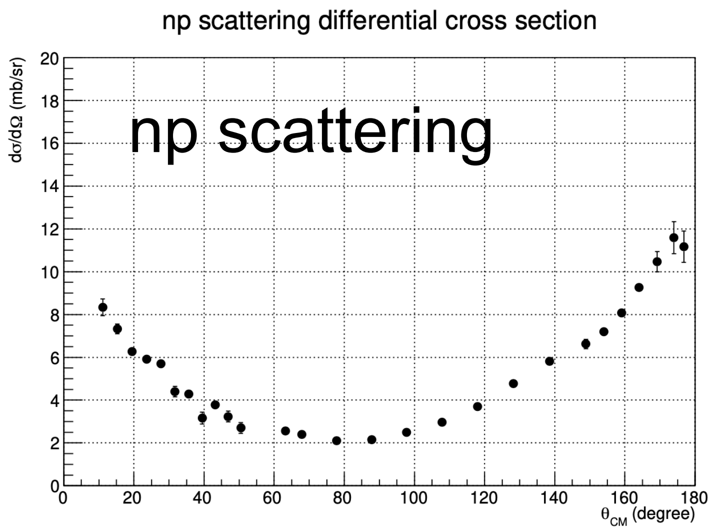


YN scattering experiment was regarded as impossible experiment

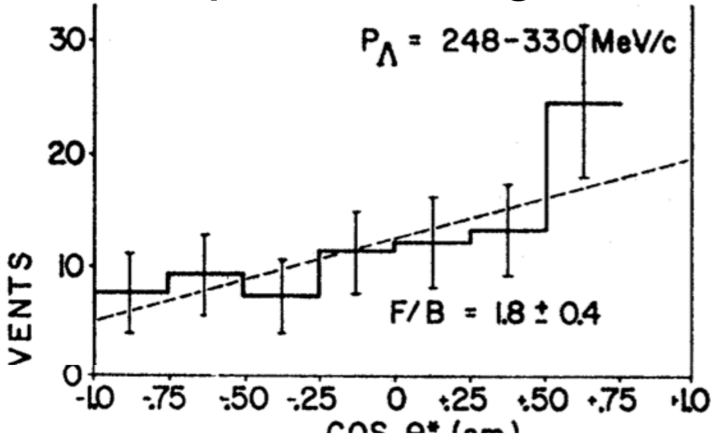
1. *Introduction* Spectroscopic studies of hypernuclei have played remarkable roles in our understanding of hyperon–nucleon (YN) and hyperon–hyperon (YY) interactions, since the short lifetimes of hyperons make YN and YY scattering experiments technically difficult, unlike the nucleon–nucleon (NN) case. For investigation of Λ hypernuclei structure, two types of spectroscopic techniques, one reaction based and the other γ-ray based, have made active progress in recent years.

NN scattering and hyperon-nucleon (YN) scattering

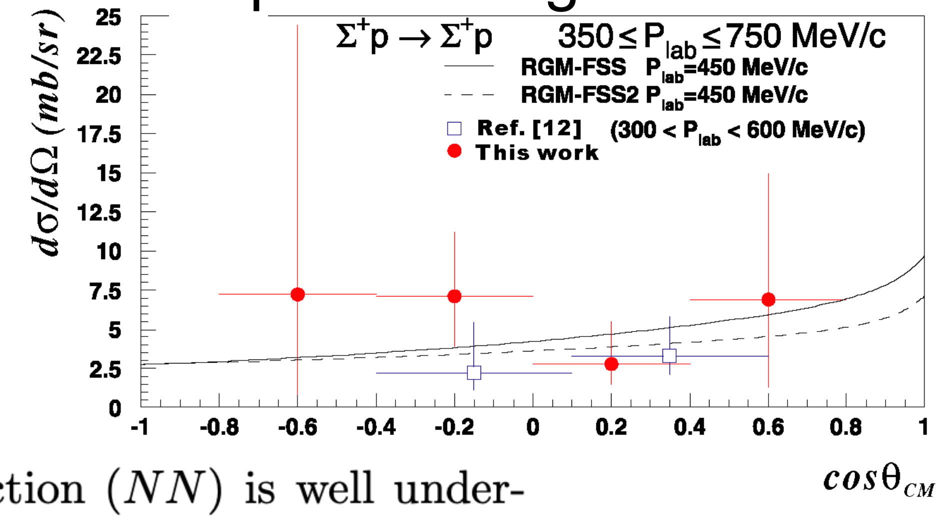
Clearly there is a big difference in data quality between NN and YN scatterings



Λp scattering



Σ^+p scattering



YN scattering exp

In prin
ied by ba
su Ex
ce YY s
lif peron
hy the Y

1. Intr
understa
lifetimes
nucleon-
techniqu

A precise measurement
ing is a powerful and reali
ΛN scattering experime
depe
with
(Ge)
γ-ra
spin
time.

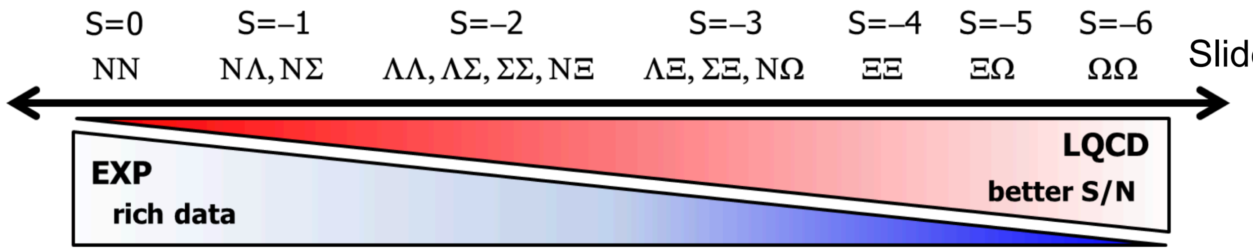
the core nucleus
such doublet spa
ΛN spin-depend
ficult to study by

The nucleon-nucleon interaction (NN) is well understood thanks to the rich data set from scattering and nuclear spectroscopy experiments. On the other hand, hyperon-nucleo
teractions are le
for the strange
iments are diffi
times. Data fr
still limited [1]
ment was recen

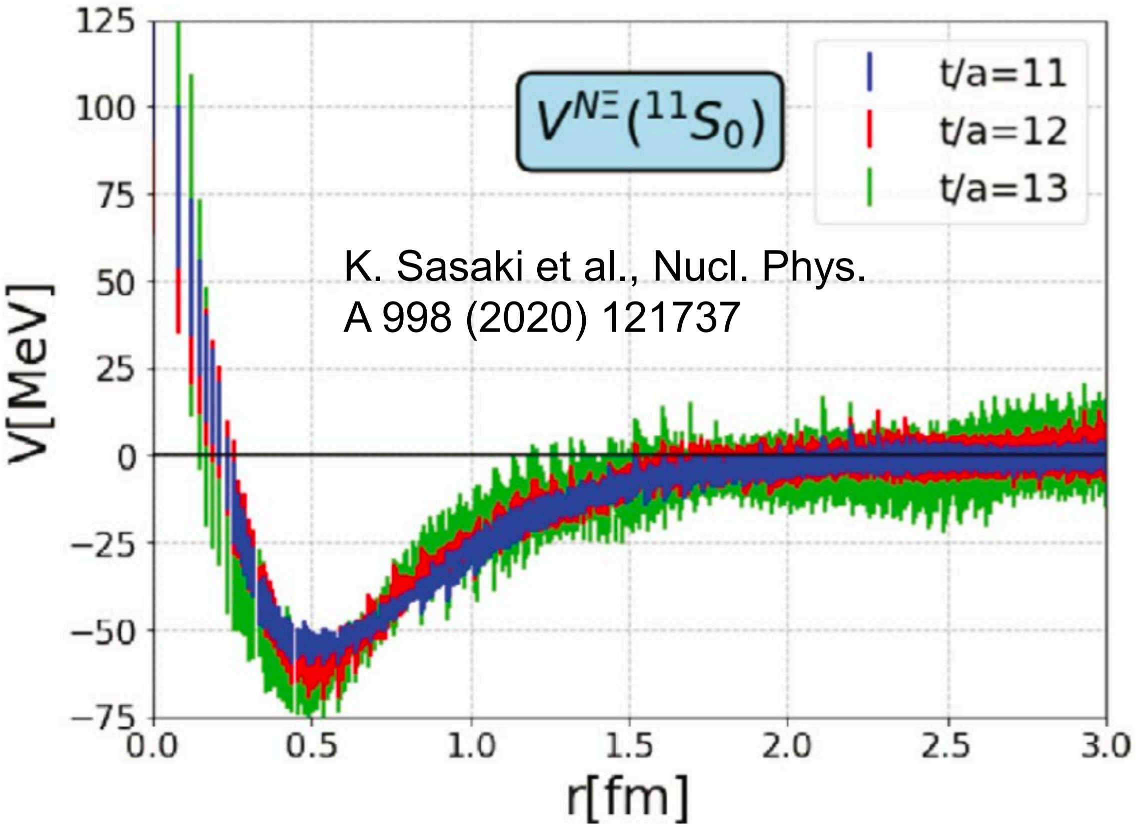
tions. On the other hand, the two-body potentials for the hyperon-nucleon interaction, YN, are not determined as well as those for NN, due to the experimental difficulties of producing and detecting hyperons in free scattering experiments. However, embedding a hyperon within the nuclear medium (hypernucleus) does allow extraction of

Recently, many achievements in two-body BB interaction study has been realized both theoretically and experimentally.

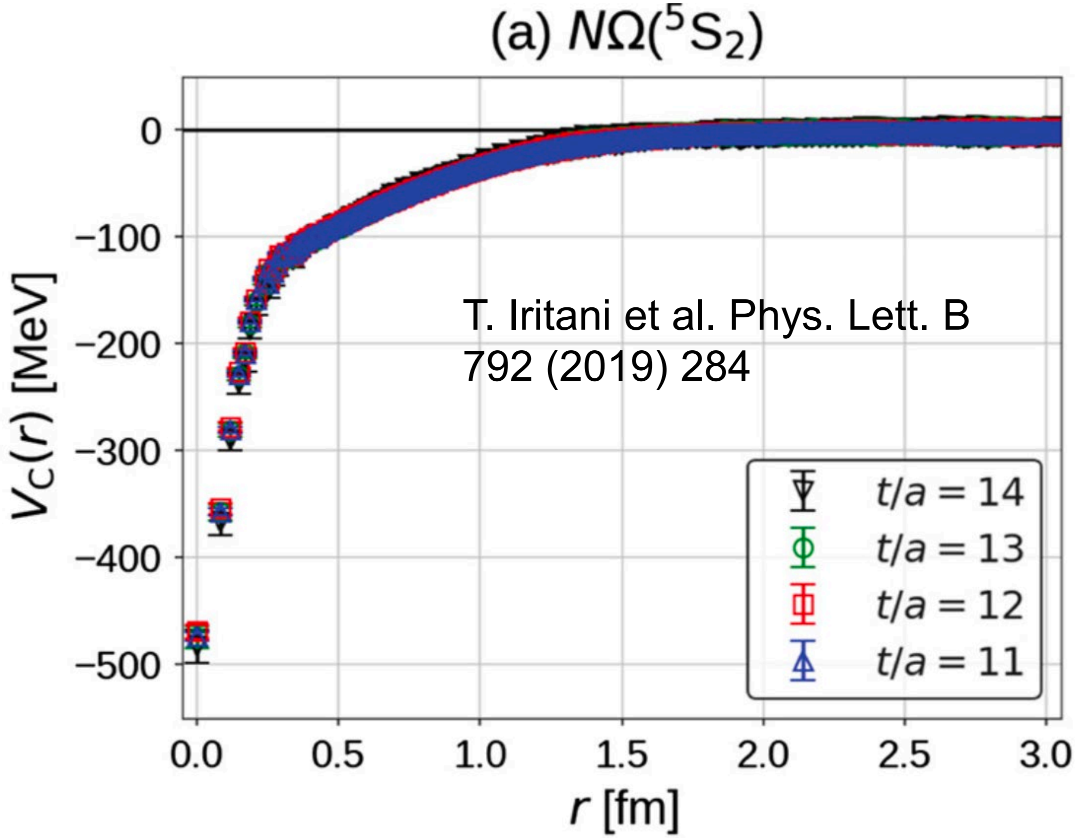
Lattice QCD



Slide from Doi-san



K. Sasaki et al., Nucl. Phys. A 998 (2020) 121737



T. Iritani et al. Phys. Lett. B 792 (2019) 284

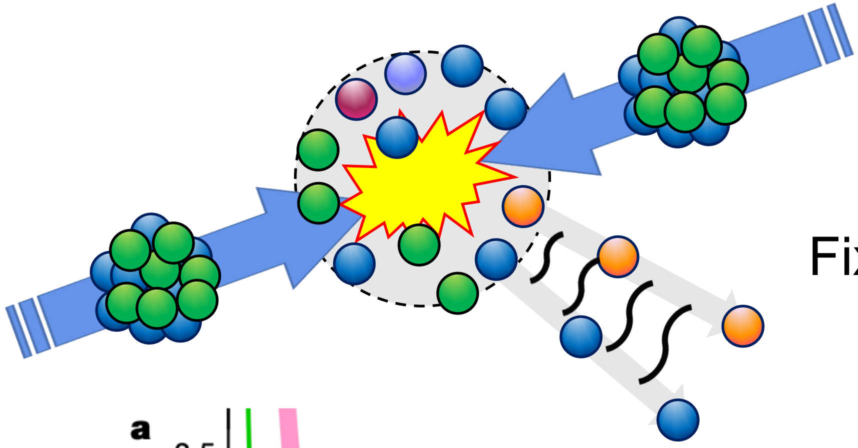
ΞN potential close to physical point
$^{11}S_0$ ΞN is most attractive among spin-isospin configurations

Attractive potential w/ NO Pauli exclusion
Decay suppression to ΛΞ, ΣΞ with D-wave

<u>S=-1 system</u>

Theoretical improvement with Misner's method (T. Miyamoto et al. Phys.Rev. D 101 (2020) 074514) is ongoing.

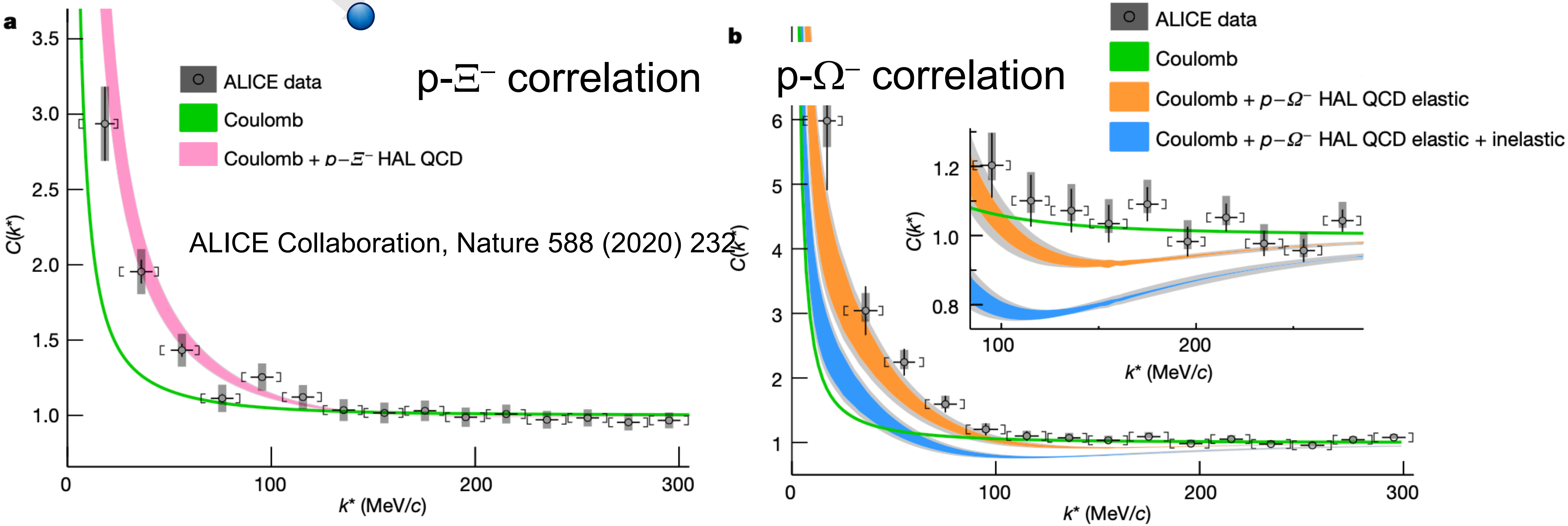
BB interaction from femtoscopy



$$c(k^*) = \frac{N\,(same\ event\ sample)}{N(mixed\ event\ sample)} = \int S(r^*)\,\left|\Psi(\vec{k^*}, \vec{r^*})\right|^2 d^3r^*$$

Fix source size(S(r*)) → Study interaction from wave function ($\Psi(\vec{k^*}, \vec{r^*})$)

Powerful method to test BB int. theories

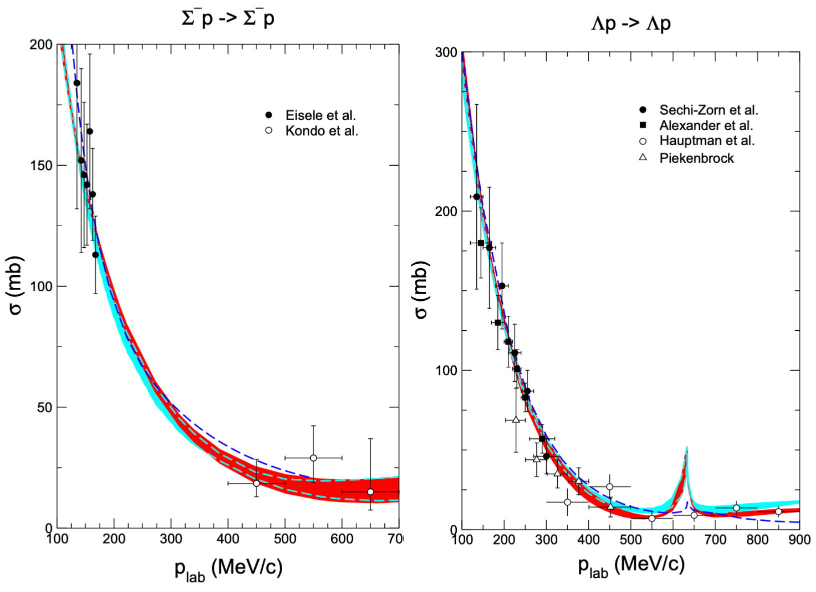


and more correlation data !

Chiral EFT in strangeness sector

- Underlying chiral symmetry in QCD
- Power counting feature to improve calculation systematically by going to higher order
- Multi baryon force appear naturally and automatically

YN interaction at NLO

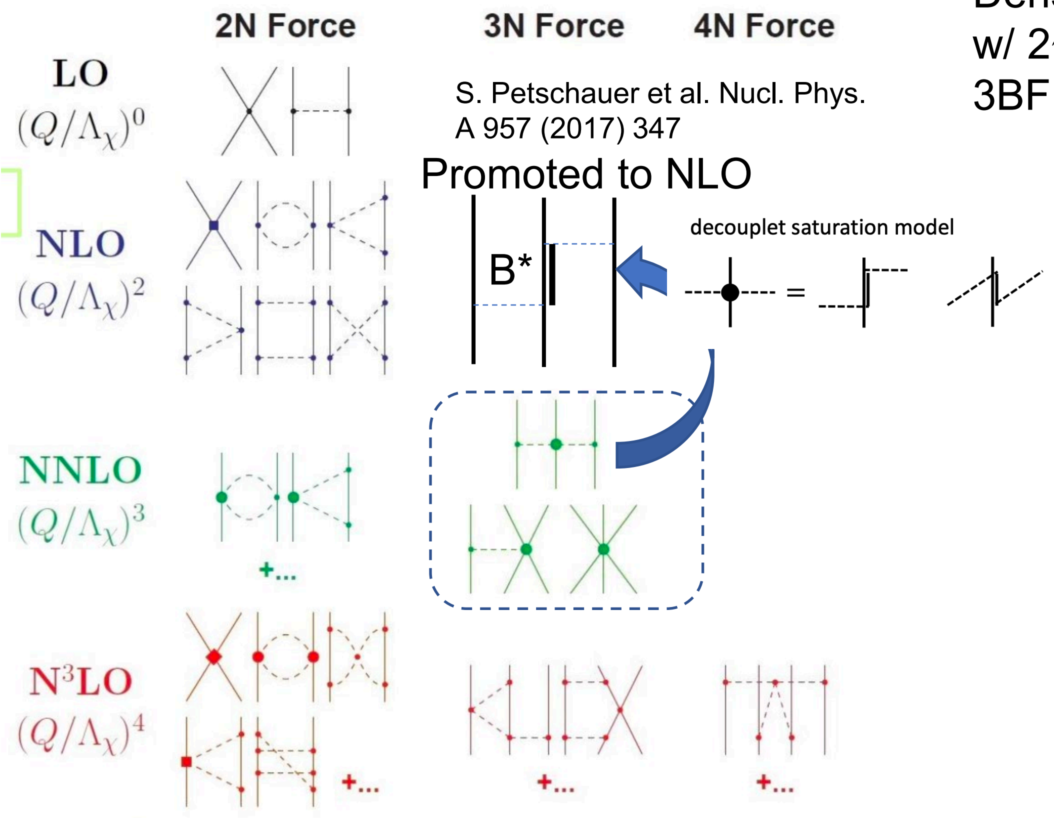


J. Haidenbauer et al., Eur. Phys. J. A (2020) 56:91

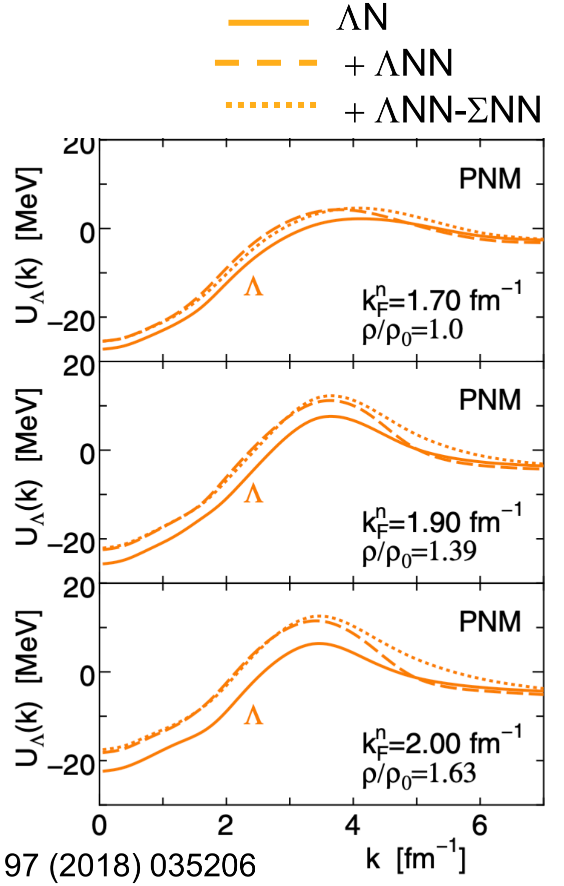
J. Haidenbauer et al., Nucl. Phys. A 915 (2013) 24

S. Petschauer et al. Nucl. Phys. A 957 (2017) 347

Promoted to NLO



Density-dependent effective potential w/ 2π-exchange ΛNN and ΛNN-ΣNN 3BF



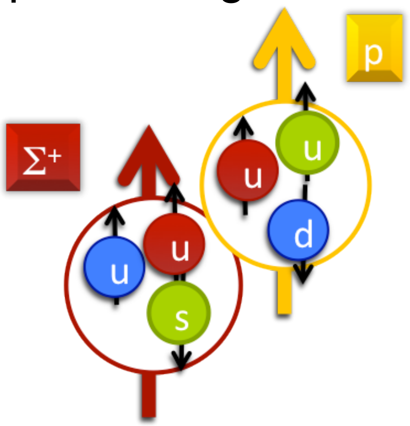
M. Kohno, Phys. Rev. C 97 (2018) 035206

New and accurate YN scattering data are also essential to construct realistic BB interaction models.

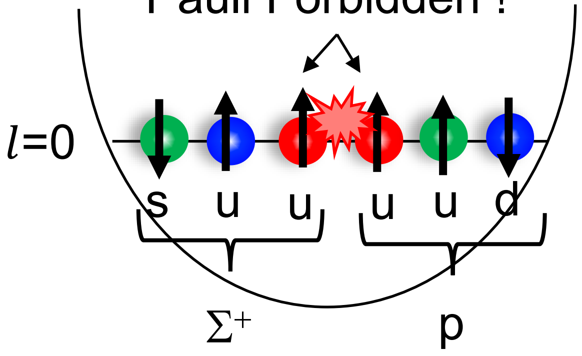
J-PARC E40 : Measurement of dσ/dΩ of Σp scatterings

Verification of quark Pauli repulsion

Σ^+p scatterng

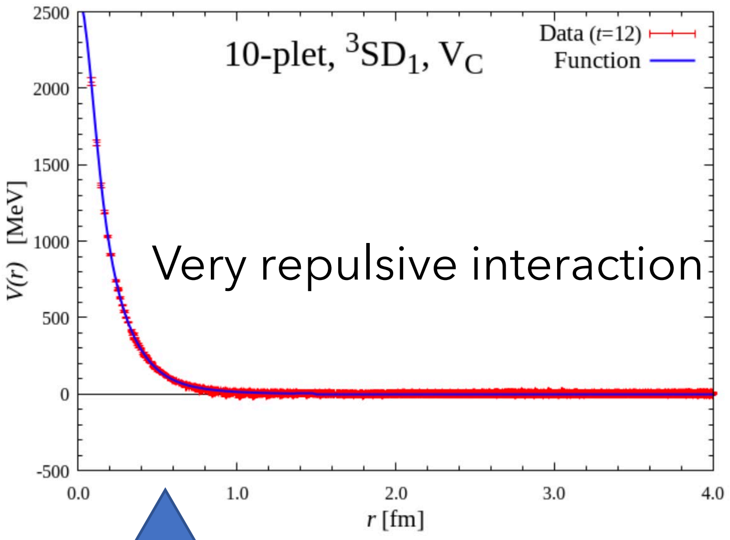


6 quarks can stay in s state in normal case



Lattice QCD calculation

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

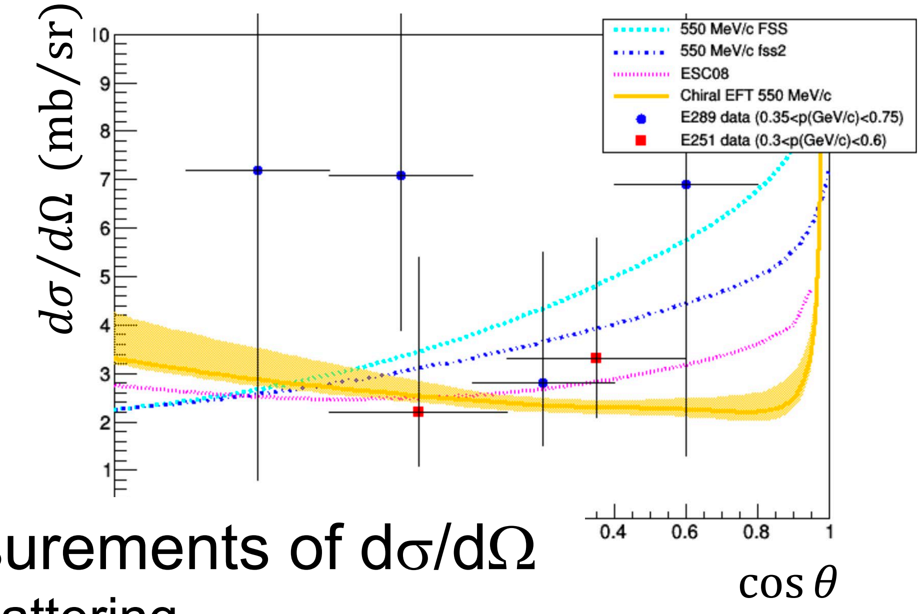


Phase-shift measurement

Constraint for BB int. theories

- Quark Cluster model (FSS, fss2)
- Nijmegen model
- Chiral EFT (NLO)

Σ^+p (0.5 < p (GeV/c) < 0.6)

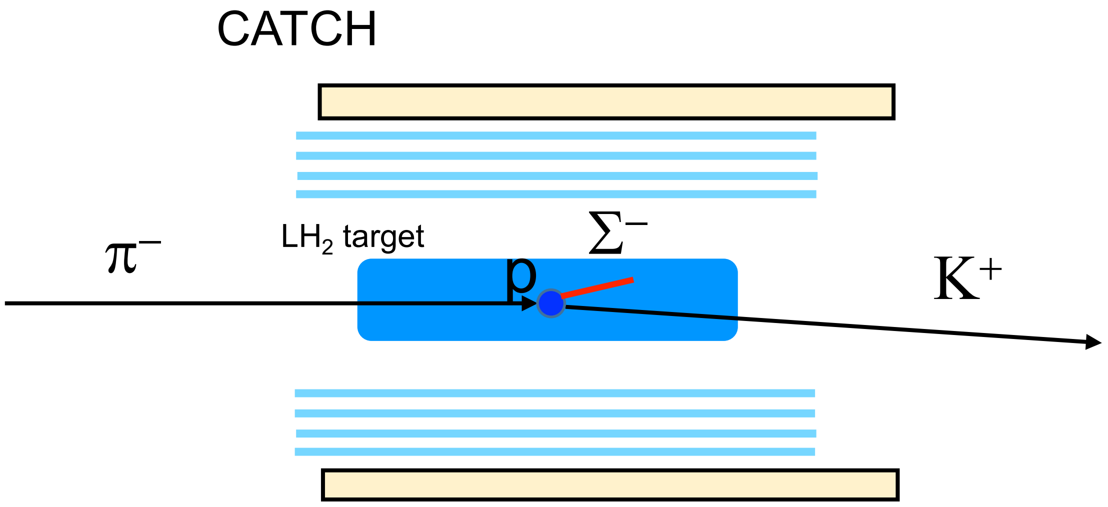


Systematic measurements of dσ/dΩ

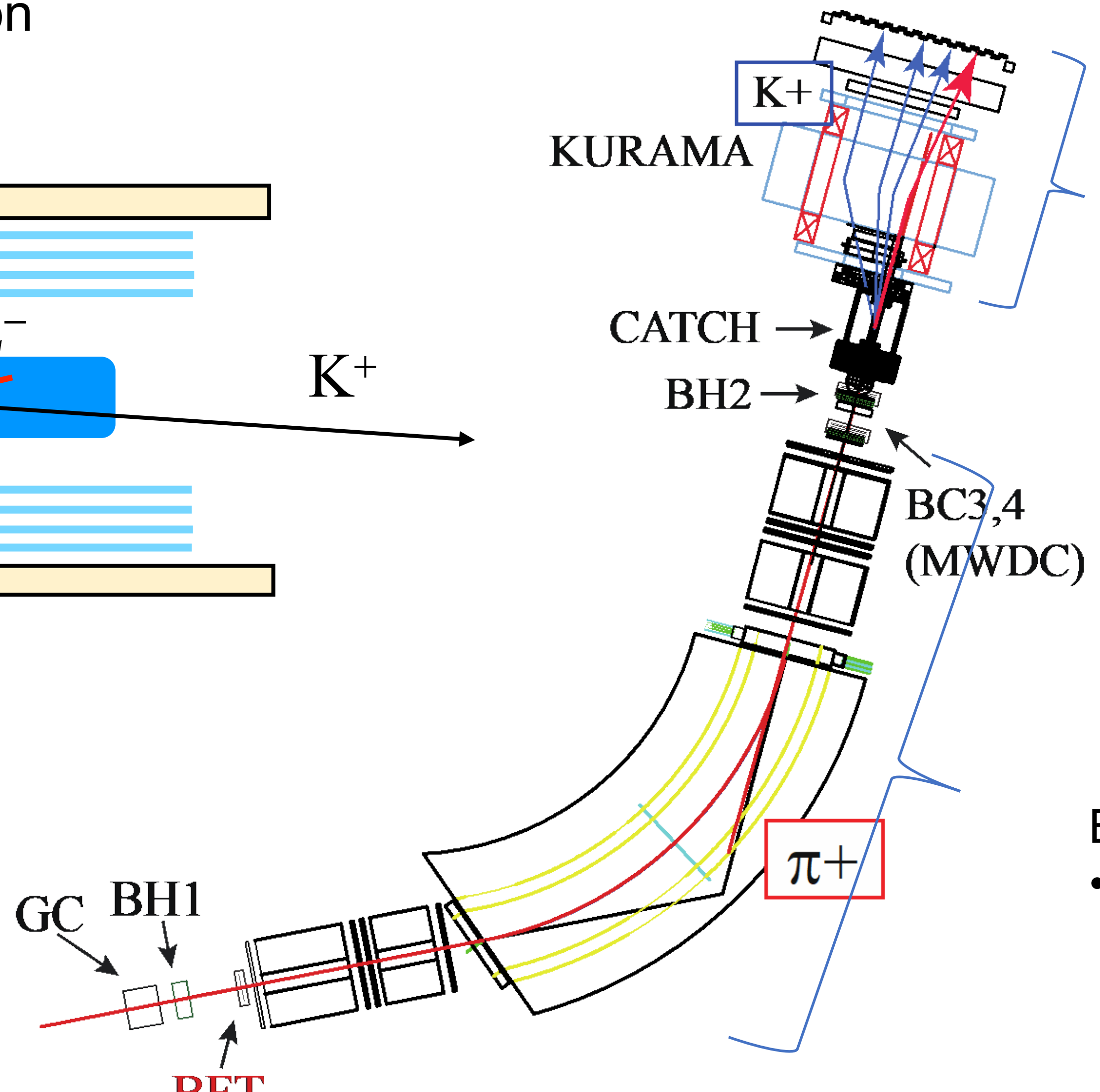
- Σ^+p elastic scattering
- Σ^-p elastic scattering
- Σ^-p → Λn inelastic scattering

J-PARC E40 experimental setup

Two successive two-body reactions
- Σ production by $\pi p \rightarrow K^+\Sigma$ reaction
- Σp scattering reaction



@ J-PARC K1.8 beam line



KURAMA spectrometer
- Identification of K^+
- Momentum analysis

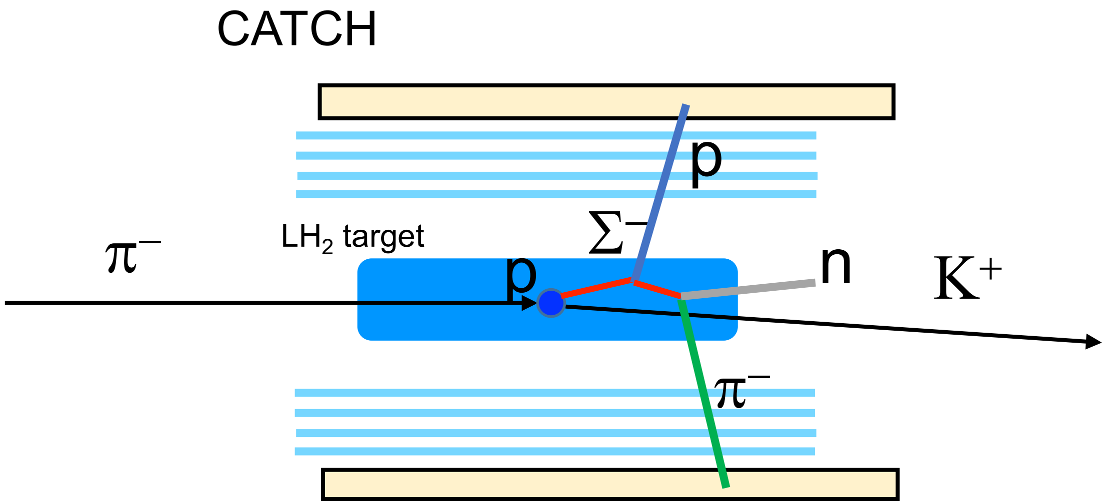
Momentum tagging of Σ beam

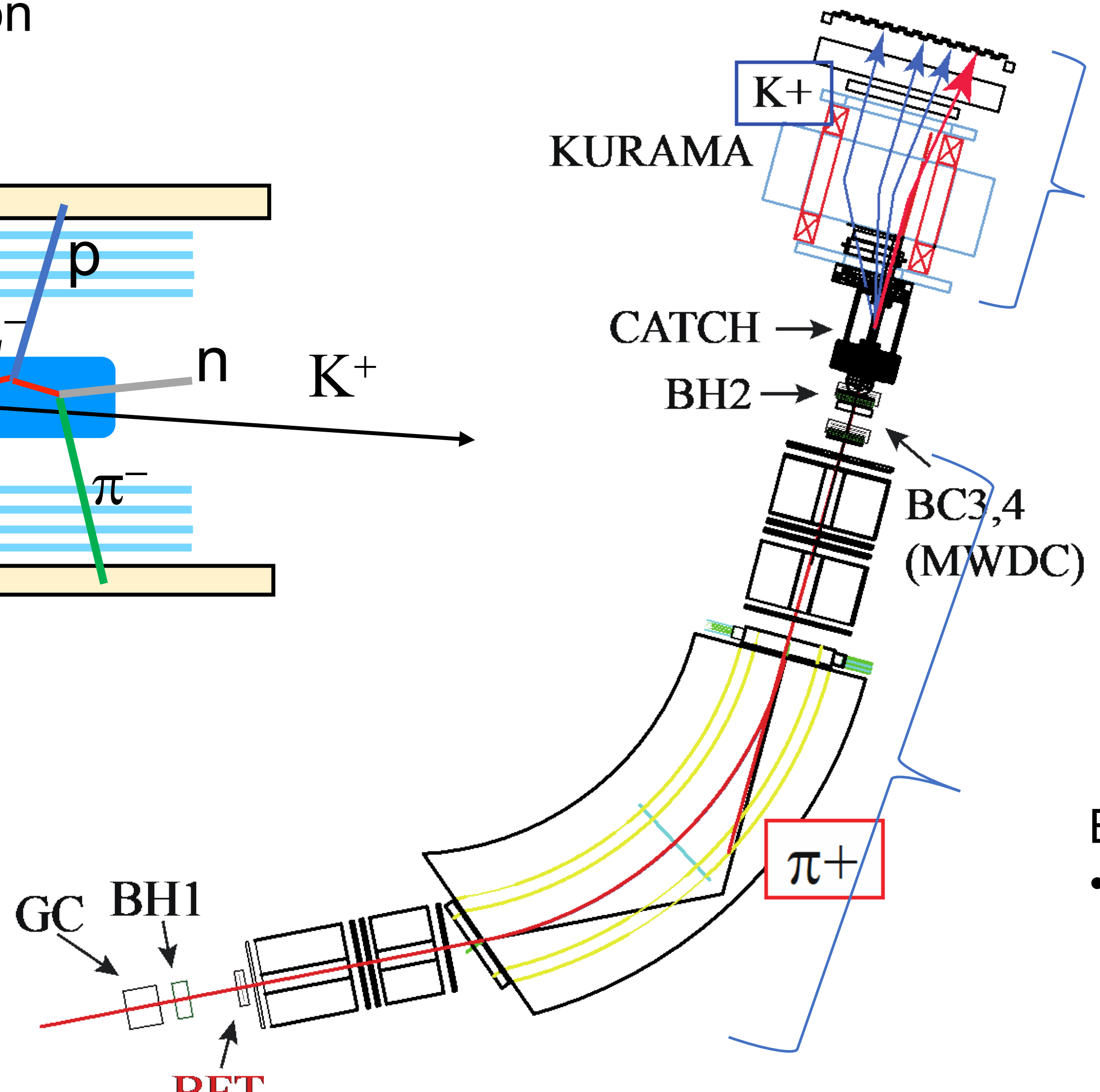
Beam-line spectrometer
- Momentum analysis of π beam

J-PARC E40 experimental setup

Two successive two-body reactions
- Σ production by πp→K⁺Σ reaction
- Σp scattering reaction

@ J-PARC K1.8 beam line





KURAMA spectrometer
- Identification of K⁺
- Momentum analysis

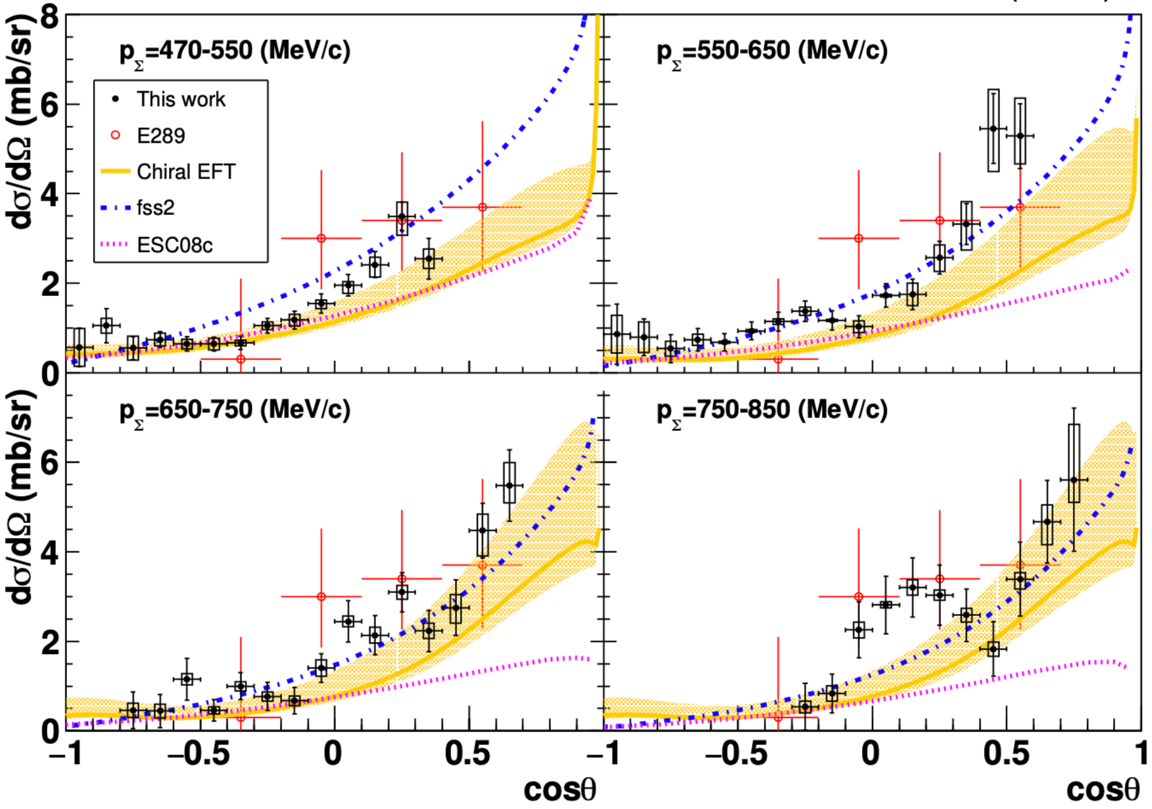
Momentum tagging of Σ beam

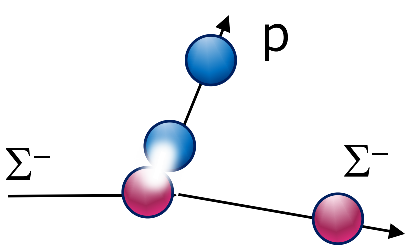
Beam-line spectrometer
- Momentum analysis of π beam

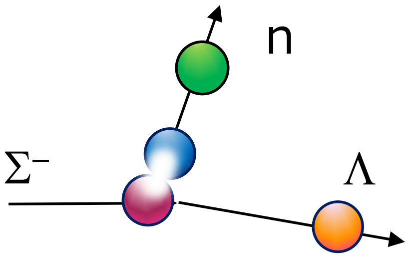
dσ/dΩ of Σ–p scattering channels

Σ^{-}p elastic scattering

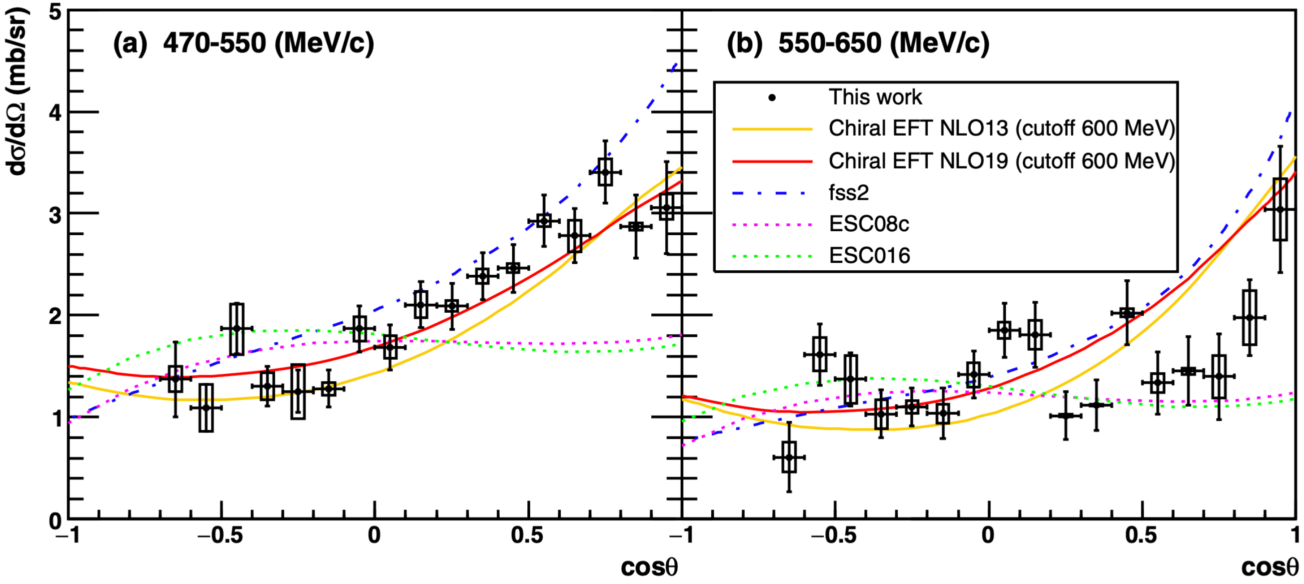
K. Miwa et al., PRC 104, 045204 (2021)







Σ^{-}p→Λn inelastic scattering



K. Miwa et al., PRL 128, 072501 (2022)

Clear forward peaking angular dependence

Moderate forward peaking dependence

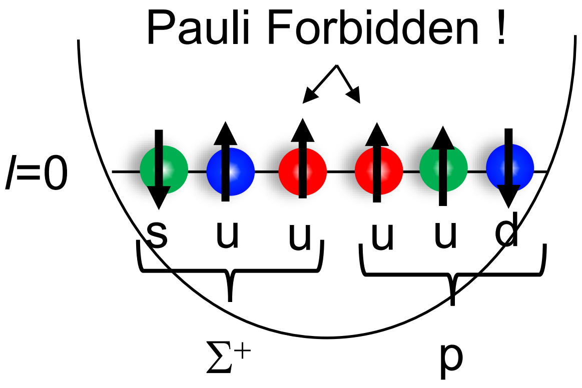
Comparison with theories

- fss2, Chiral EFT show a reasonable angular dependence.
- Nijmegen ESC models clearly underestimate the forward angle.

dσ/dΩ of Σ^+p elastic scattering

Σ^+p scatterng

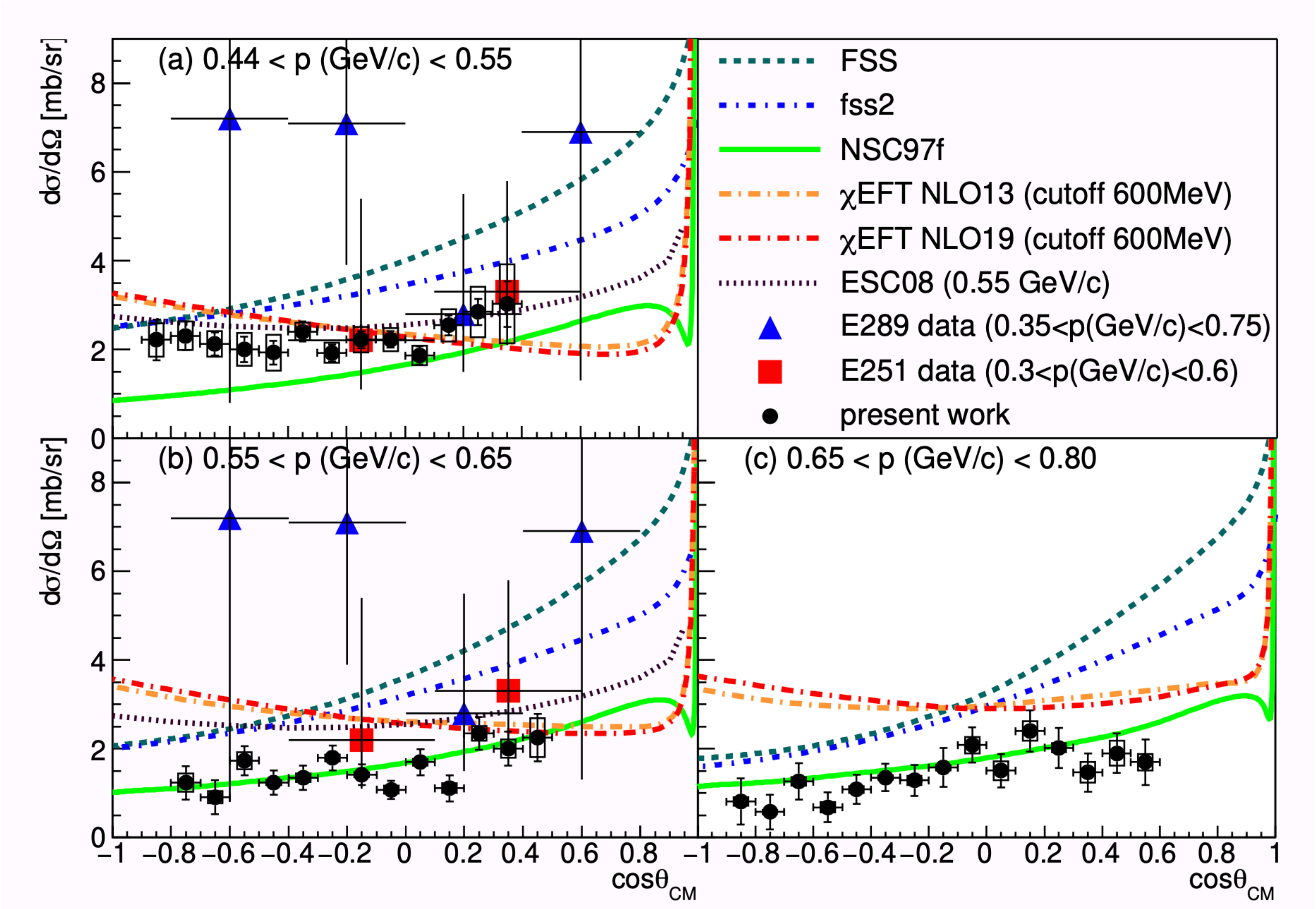
6 quarks can stay in s state in normal case



The more repulsive potential in $^3S_1$

→ The larger dσ/dΩ (like fss2)

T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01



E40 data : much smaller than fss2 prediction and E289 results

Comparison with theories

- fss2, FSS (quark model) are too large compared to data
- Chiral EFT's momentum dependence does not match with data
- Nijmegen (ESC) models are rather consistent.

Phase shift analysis

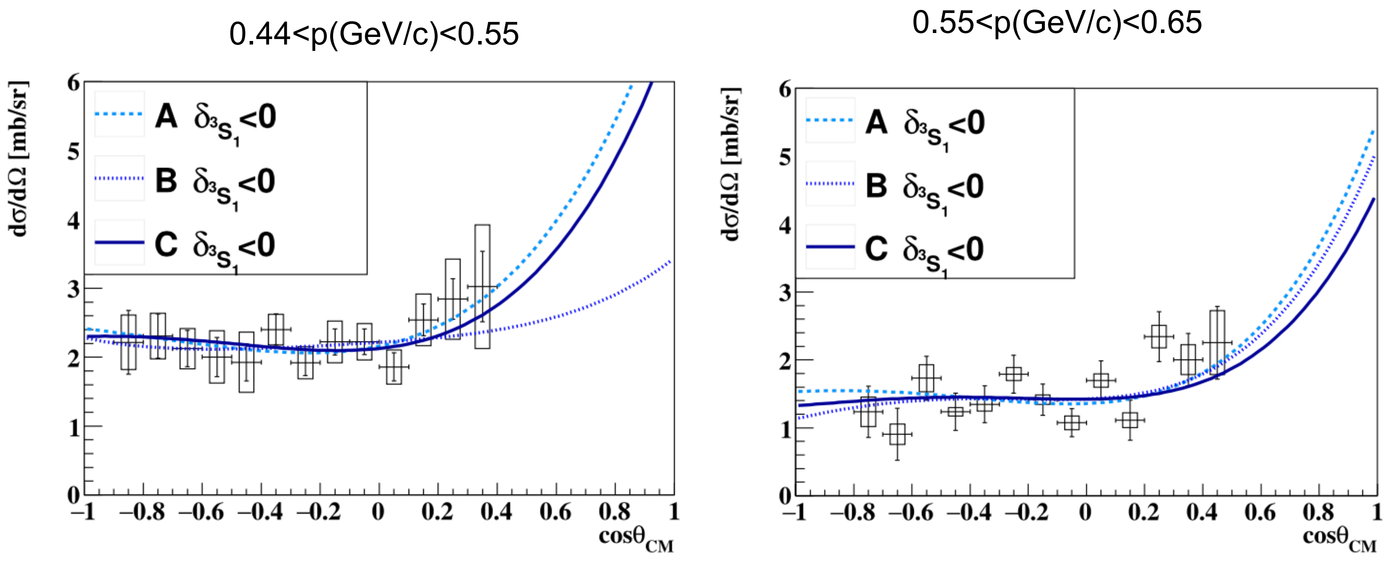
T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01

Phase shift analysis for Σ^+p $d\sigma/d\Omega$

- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
- Other phase shifts up to D wave :

fixed on NSC97f, ESC16, pp scat

Fitting $d\sigma/d\Omega$ with sum of partial waves



Phase shift analysis

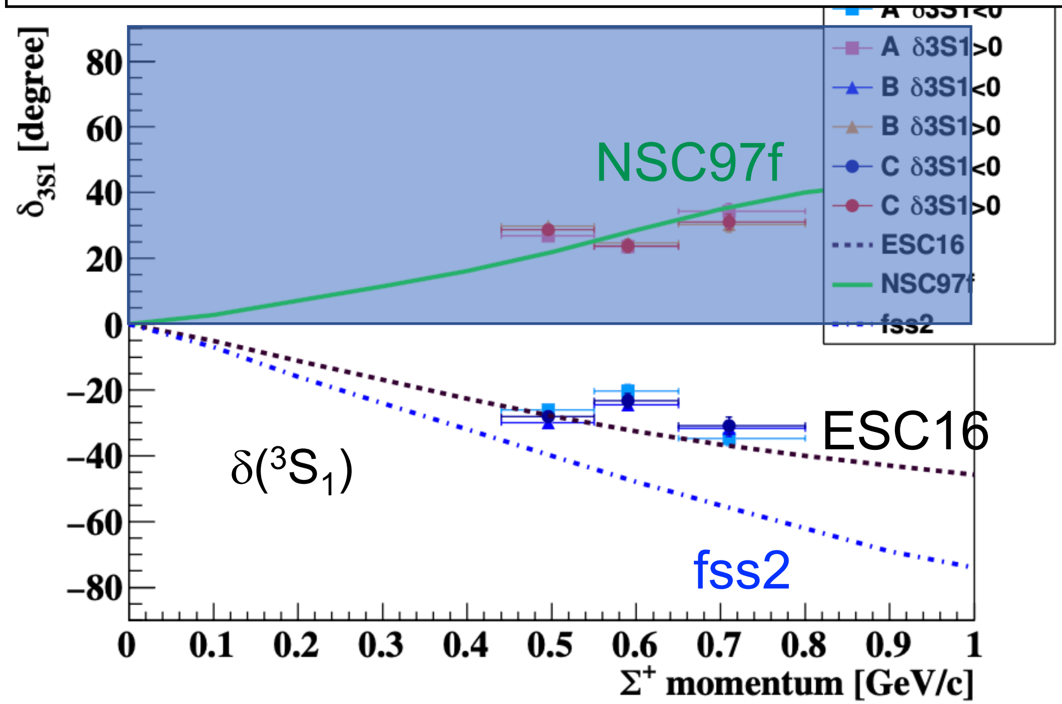
T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01

Phase shift analysis for Σ^+p $d\sigma/d\Omega$

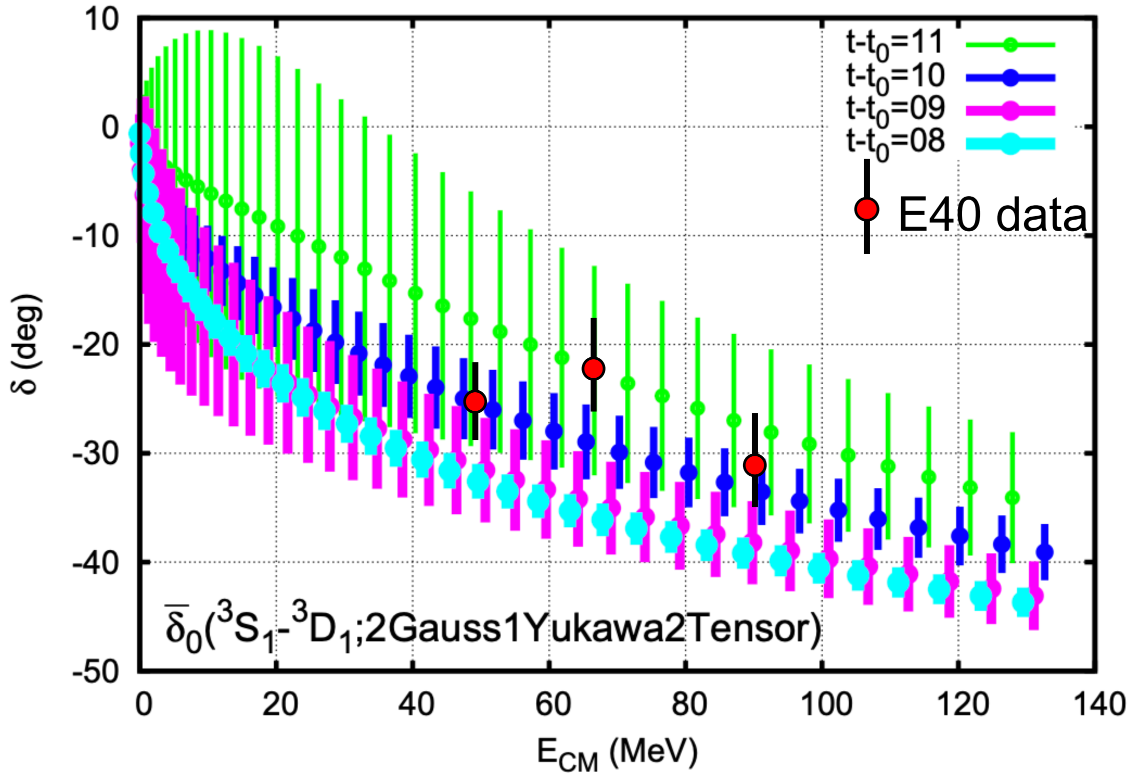
- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
- Other phase shifts up to D wave :

  fixed on NSC97f, ESC16, pp scat

First experimental derivation of phase shift of $^3S_1$



Comparison with HAL QCD ΣN potential

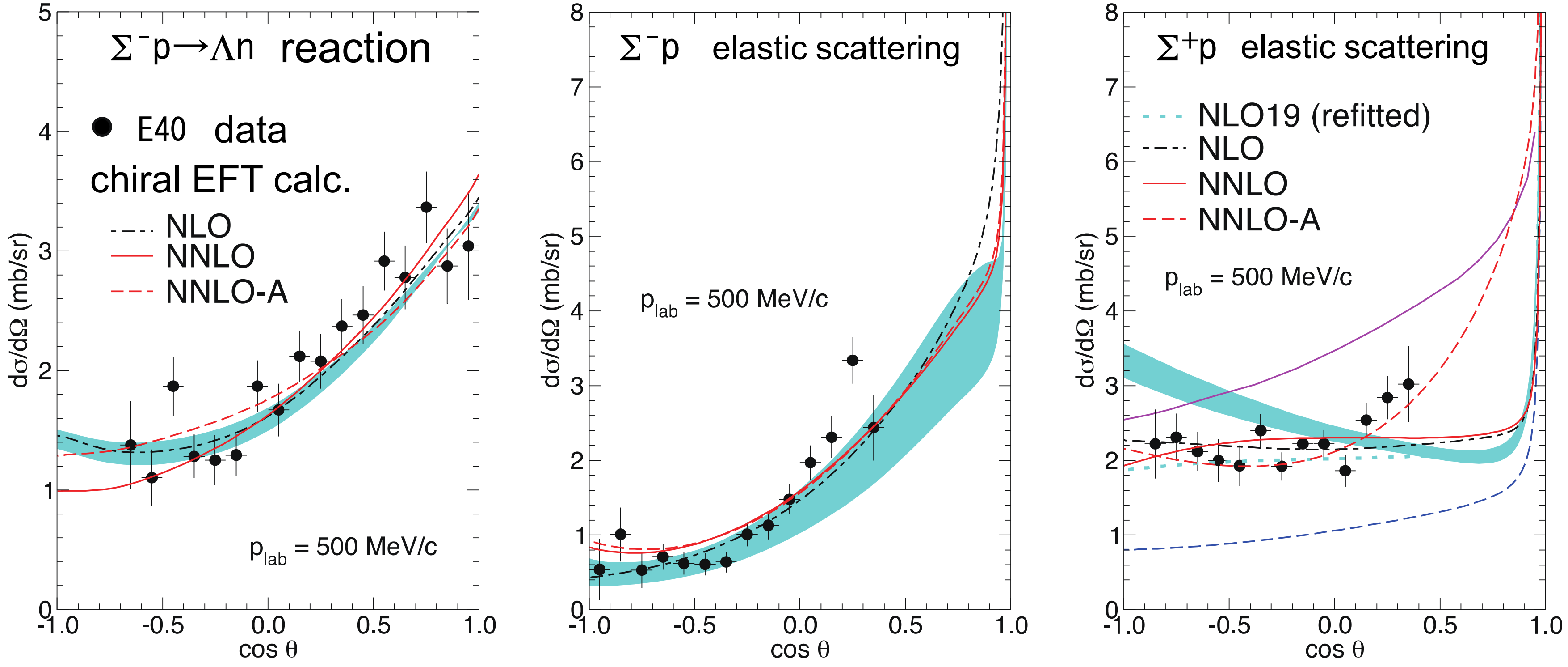


H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

Derived phase shift suggest that **the $^3S_1$ interaction is moderately repulsive**.

Chiral EFT is in progress w/ E40 data

Development of Chiral EFT at NNLO have got started with E40 data



Slide of J. Haidenbauer at HYP2022

But, still …

- no unique determination of all *P*-wave LECs possible
- one needs data from additional channels (Λp, $\Sigma^- p \to \Sigma^0 n$, ...)
- one needs additional differential observables (polarizations, ...)

Future project at J-PARC

J-PARC Hadron Experimental Facility Extension Project

Hadron Experimental Facility Extension (HEF−EX) project

K1.8BR
(~1.0 GeV/c K^-)

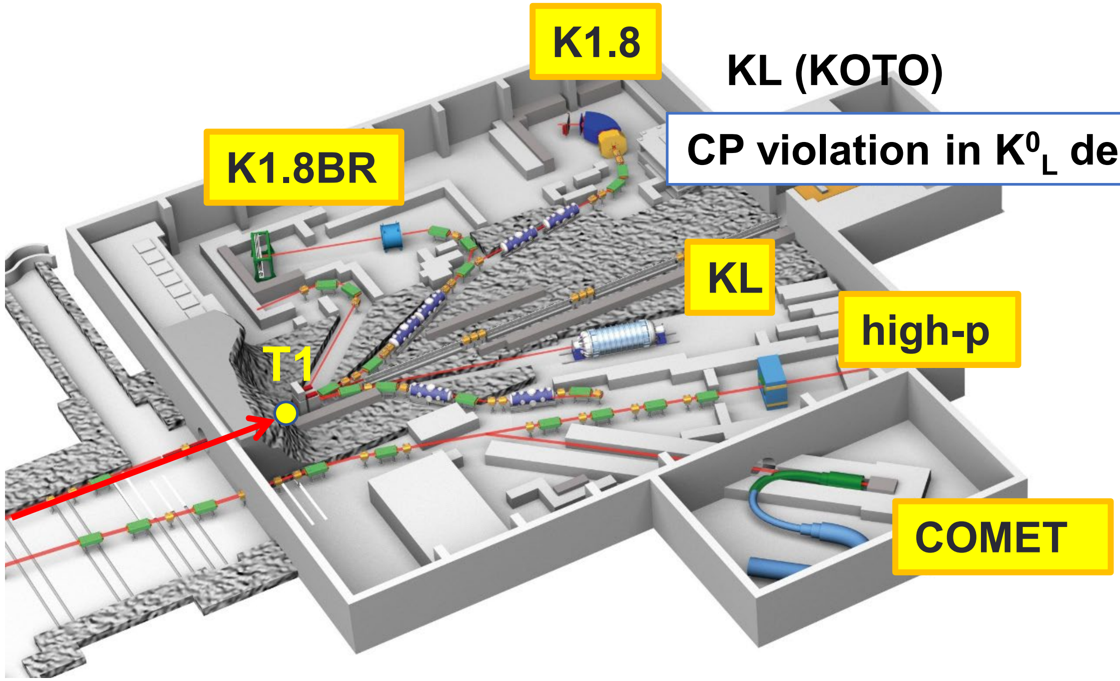
K^{bar} N interaction

K1.8 (~1.8 GeV/c K^-)

BB interaction (focusing on S=-2)

KL (KOTO)

CP violation in K^0_L decay



high-p (30GeV primary proton beam)
π20 (20GeV/c secondary beam)

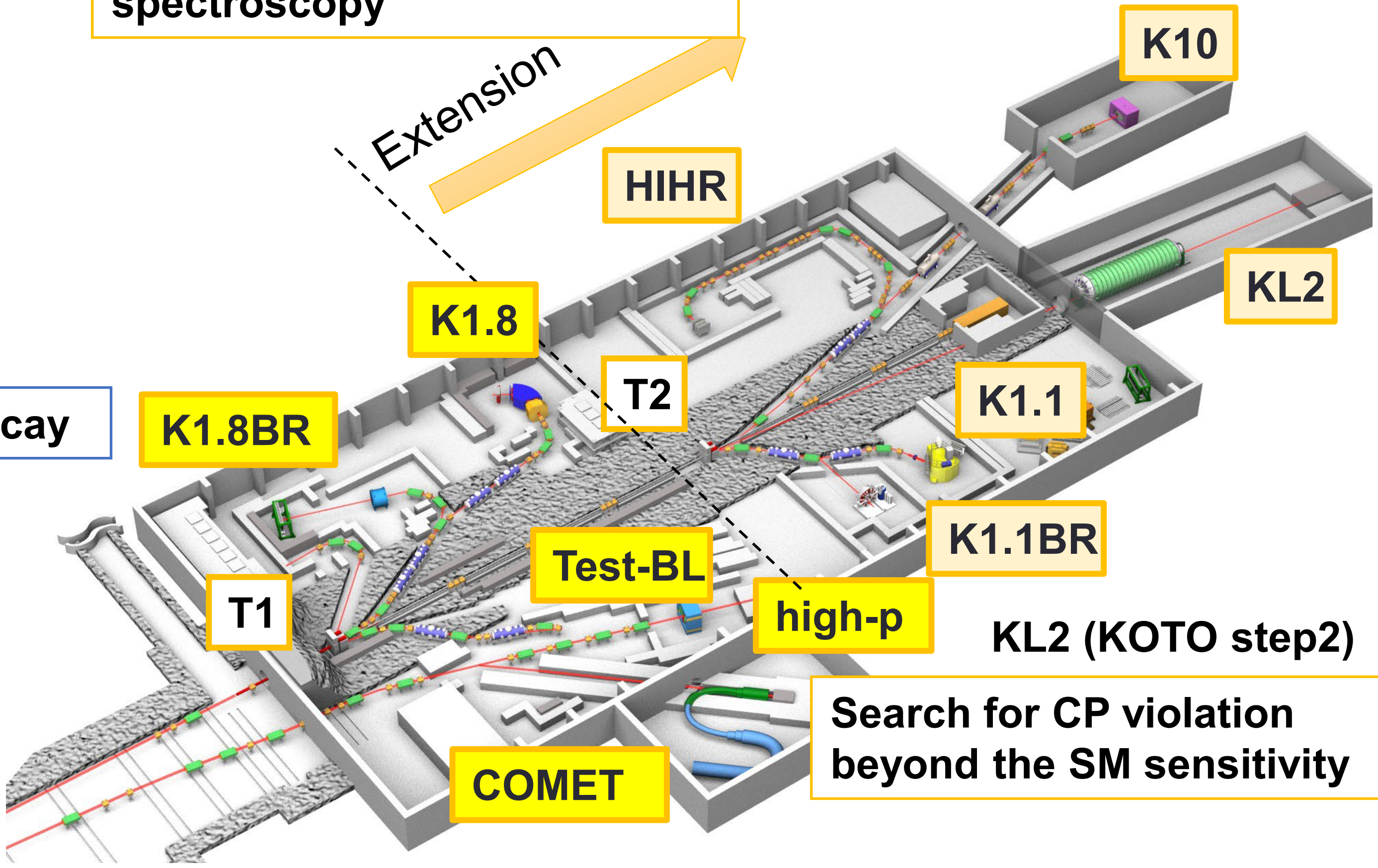
Hadron property in nuclear medium
Baryon spectroscopy

HIHR (~2 GeV/c π)

Ultra precise Λ hypernucler spectroscopy

K10 (~10 GeV/c K^-)

Ω baryon spectroscopy



KL2 (KOTO step2)

Search for CP violation beyond the SM sensitivity

K1.1BR (~0.8 GeV/c π/K)

Physics using a low energy Kaon

K1.1 (~1.2 GeV/c π/K)

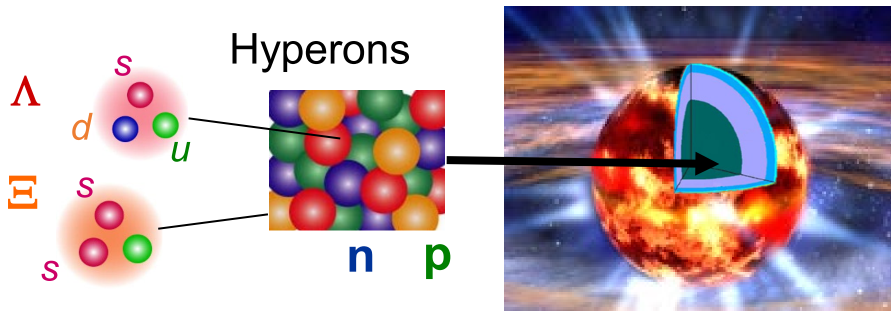
BB interaction (focusing on S=-1)

Perform physics not accessible in the present hadron hall
Perform physics programs in parallel with twice more beam lines

Hyperon puzzle in neutron star

Strange Hadronic Matter in neutron star ?

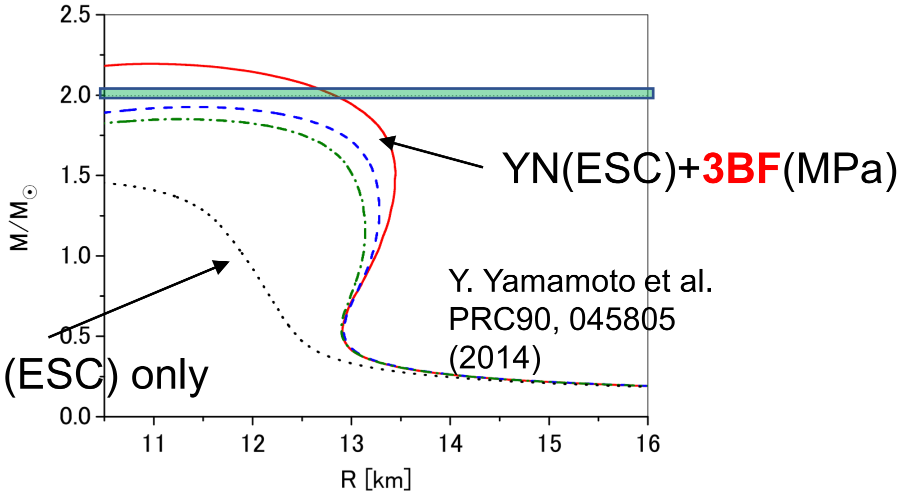
Hyperon's appearance is reasonable scenario because of the huge Fermi energy of neutrons in the inner core.



How can we reconcile ?

Hyperon appearance → **soften** EOS

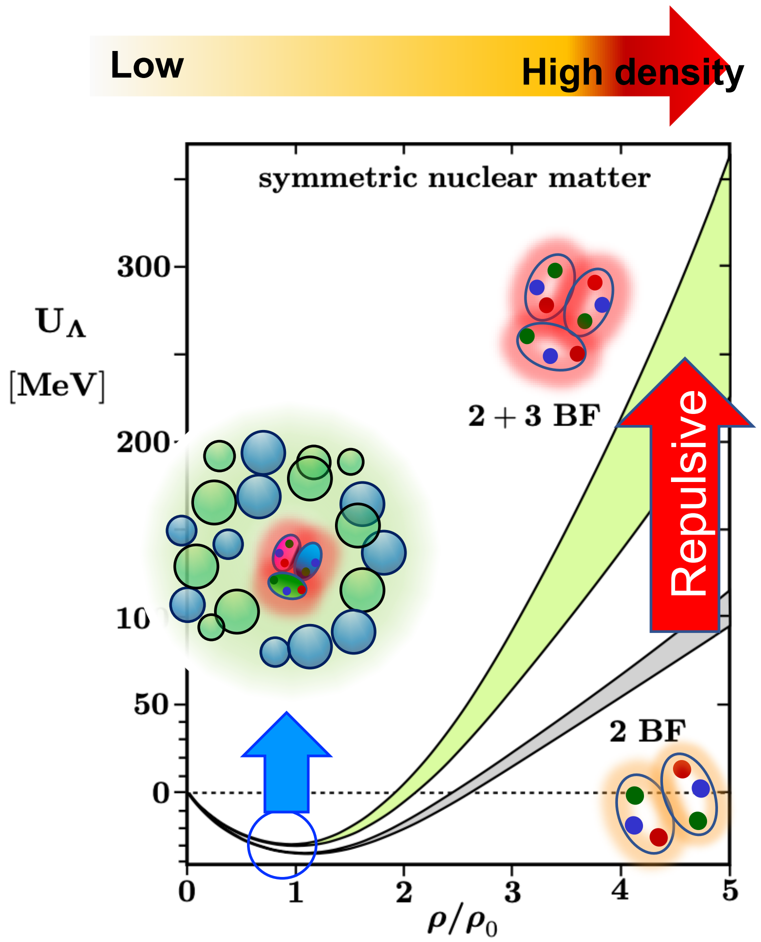
Two-solar-mass NS → require **stiff** EOS



Y. Yamamoto et al. PRC90, 045805 (2014)

3 Baryon Force (3BF):

Significant repulsive contribution at high density



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

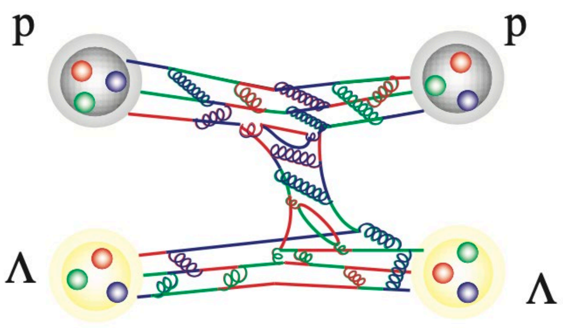
We have to understand the **density dependence of ΛN interaction** from **Λ binding energy data in hypernuclei.**

→ determine **the strength of the ΛNN force**

Toward Λp scattering

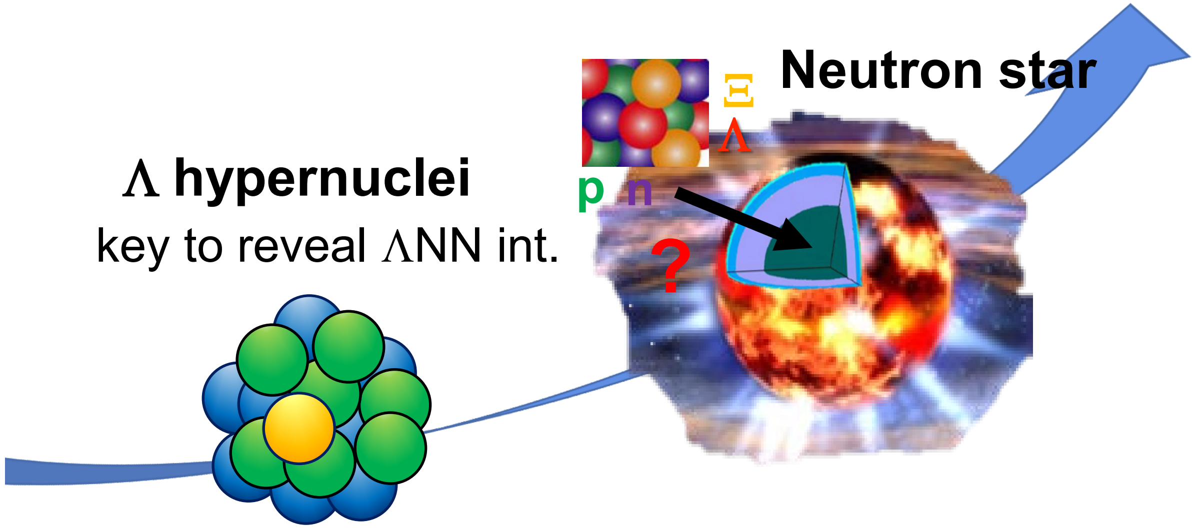
Reliable ΛN two-body interaction :

key to deepen Λ hypernuclear physics

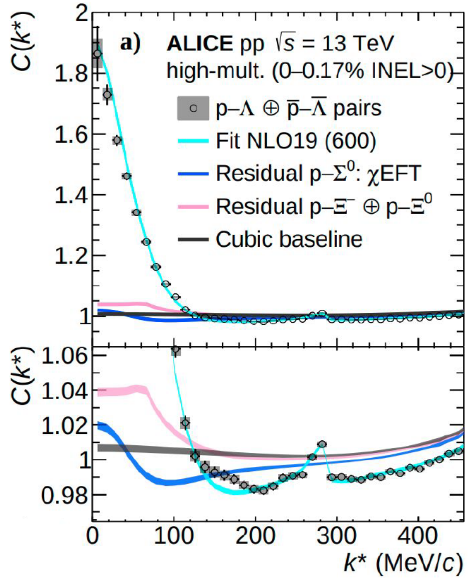


Λ hypernuclei

key to reveal ΛNN int.

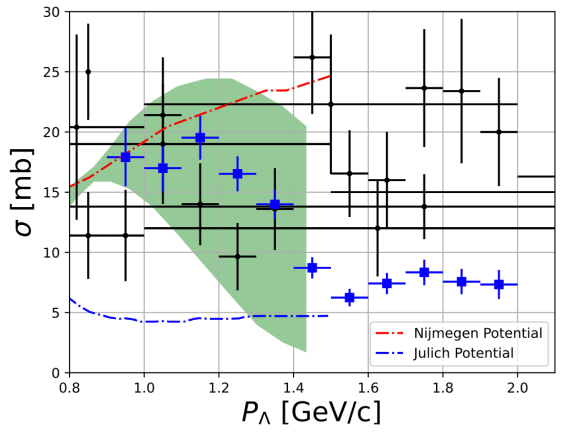


Femtoscopy from HIC



ALICE Collaboration, arXiv:2104.04427

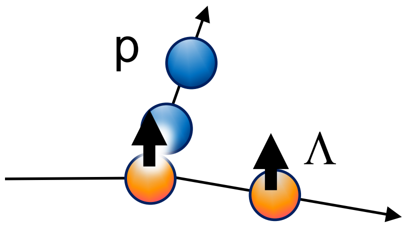
New cross section data from Jlab CLAS



J. Rowley et al. (CLAS), Phys. Rev. Lett. 127 (2021) 272303

New project at J-PARC

Λp scattering w/ polarized Λ



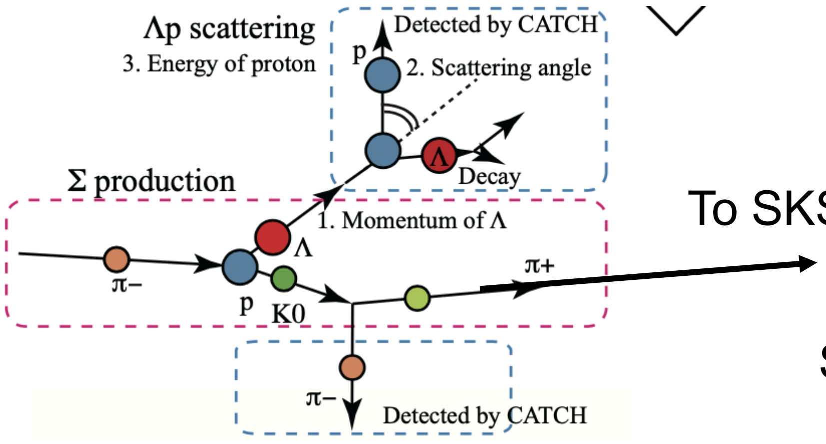
- Feasibility test w/ E40 data
- Expected results in new experiment

Λp scattering experiment with polarized Λ beam

J-PARC P86 (J-PARC EX project)
at K1.1 beam line

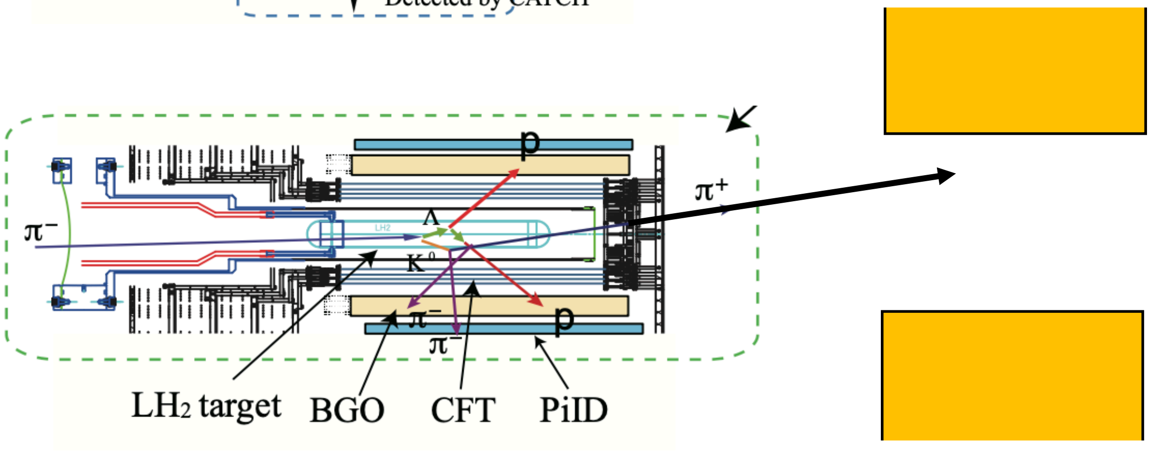
Λ beam identification

Tagged by $\pi^- p \rightarrow K^0 \Lambda$ reaction at p=1.05 GeV/c



To SKS spectrometer

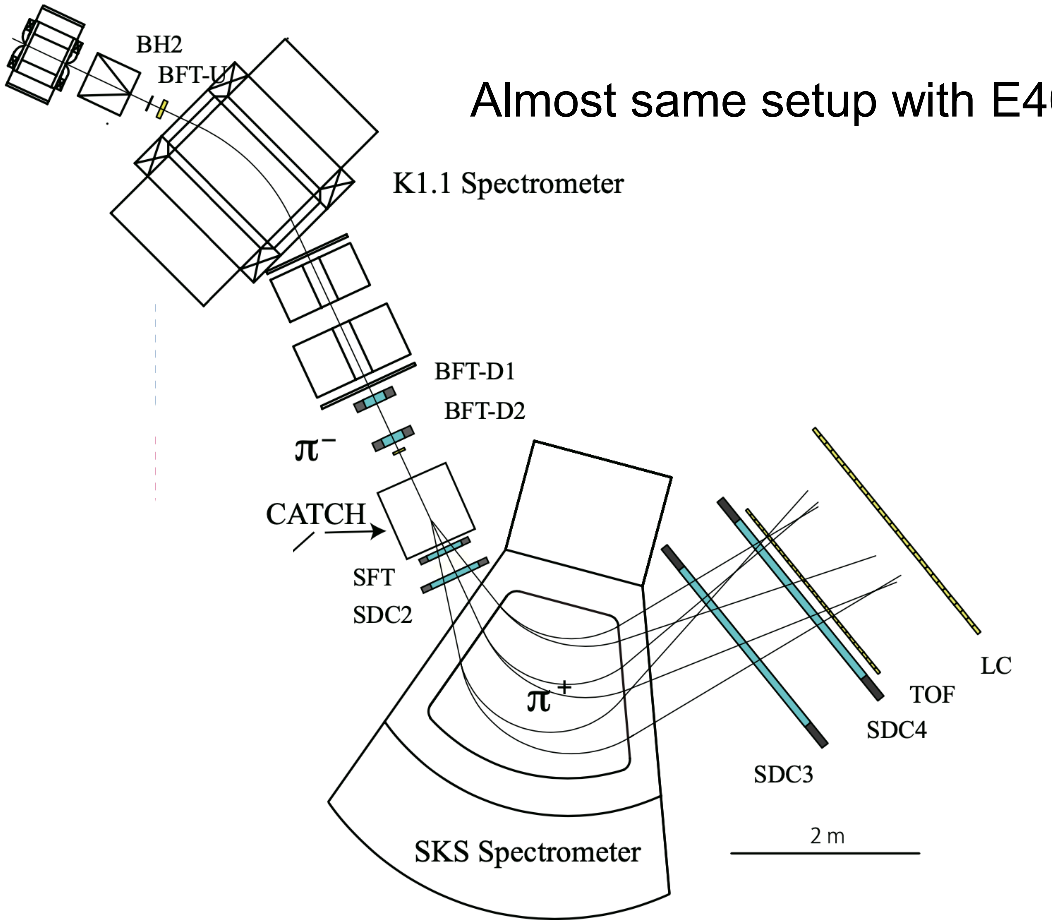
SKS spectrometer



Λp scattering identification

Detected by CATCH

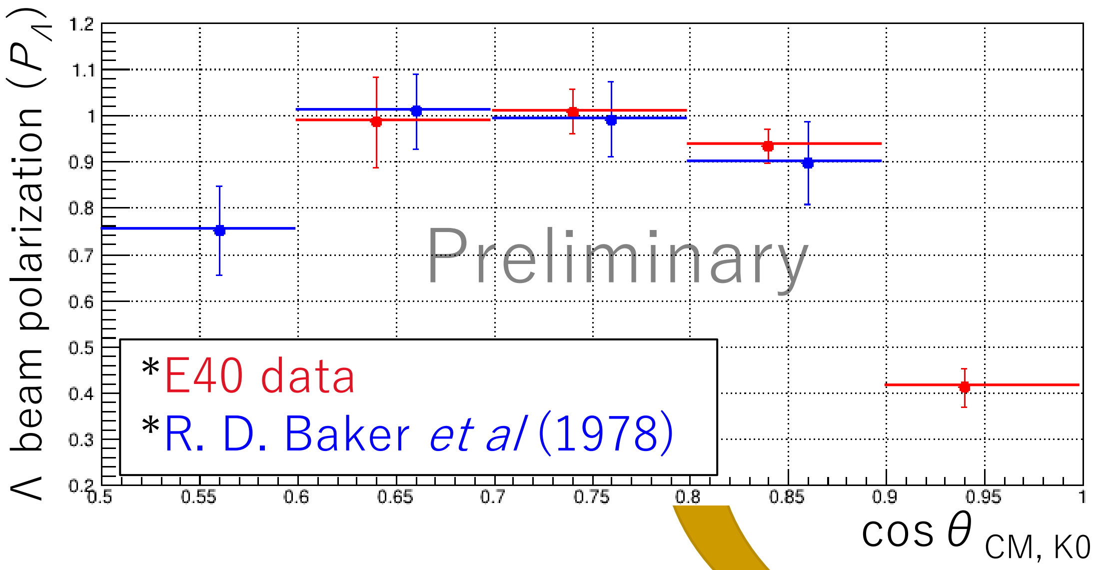
Almost same setup with E40



Λp scattering experiment with polarized Λ beam

High spin polarization of Λ

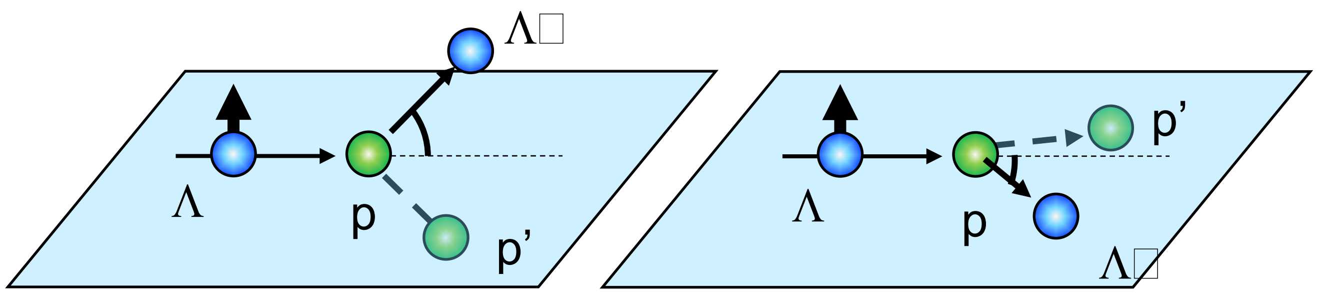
Λ polarization in the $\pi^- p \to K^0 \Lambda$ reaction



Realize spin observable measurement

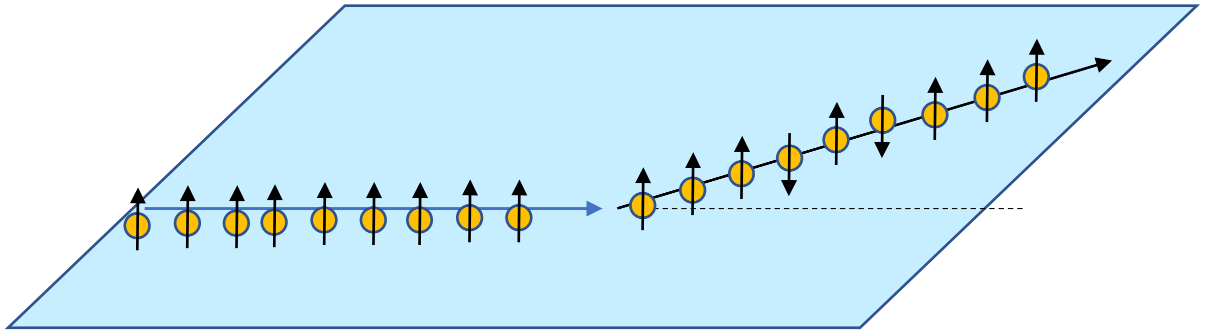
Analyzing power

Left/Right asymmetry of Λp scattering



Depolarization (D_y^y)

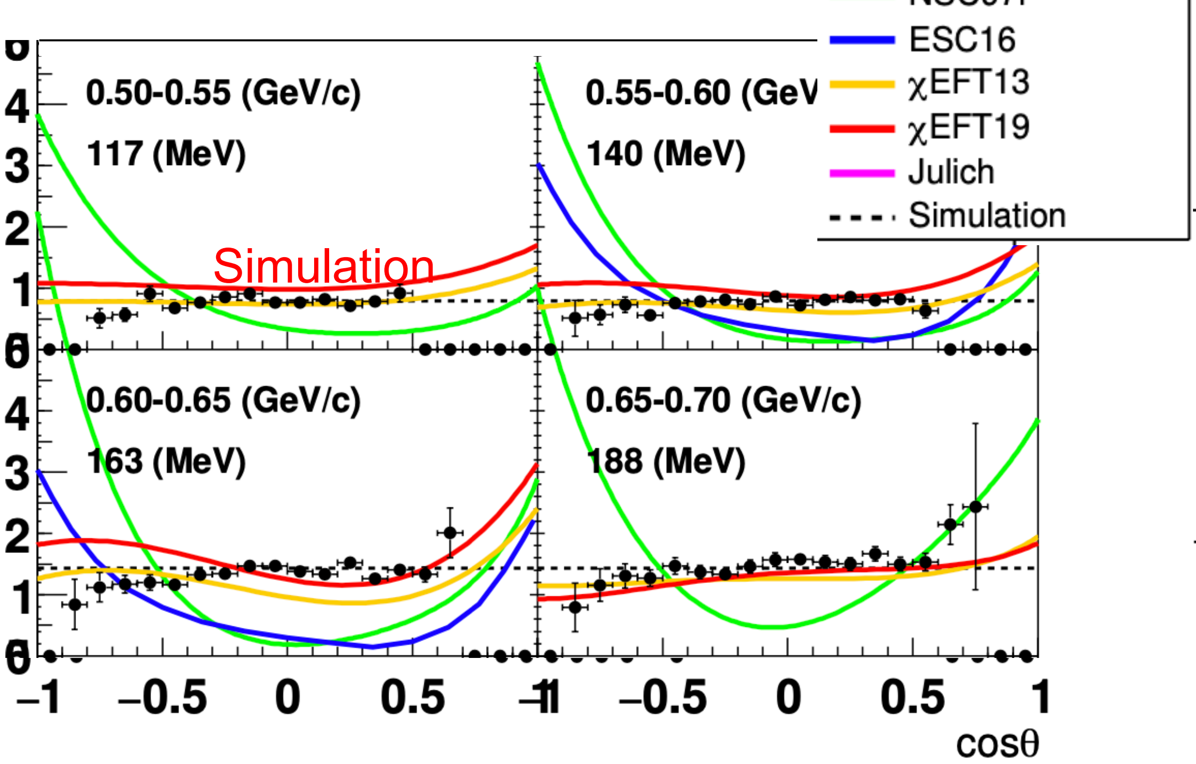
Change the spin polarization after the Λp scattering



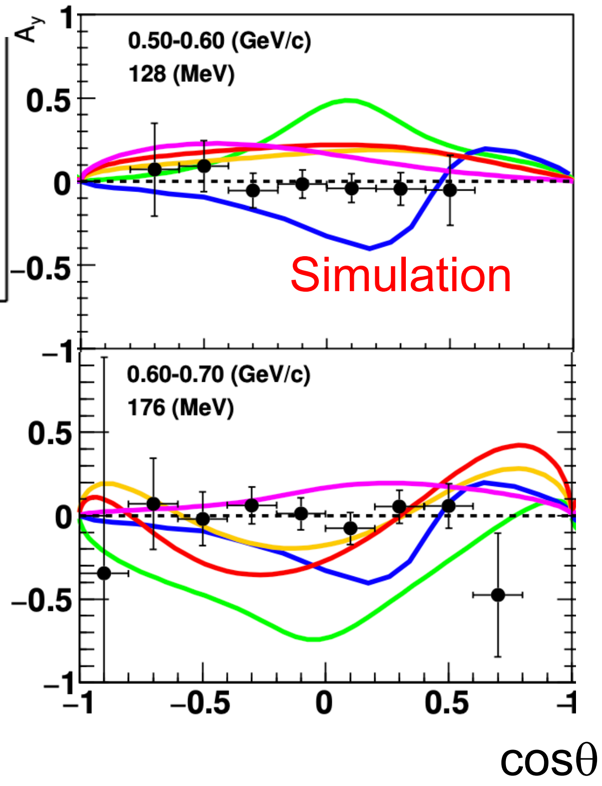
dσ/dΩ and Spin observables in Λp scattering

J-PARC P86 (J-PARC EX project) at K1.1 beam line

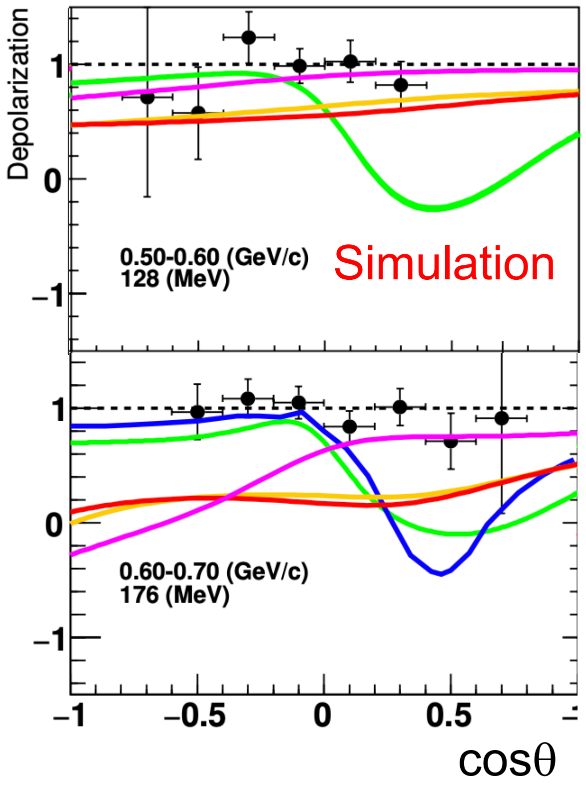
Differential cross section



Analyzing power



Depolarization (D_y^y)



No differential observables of Λp scattering SO FAR

Simulated results w/ 10^8 Λ

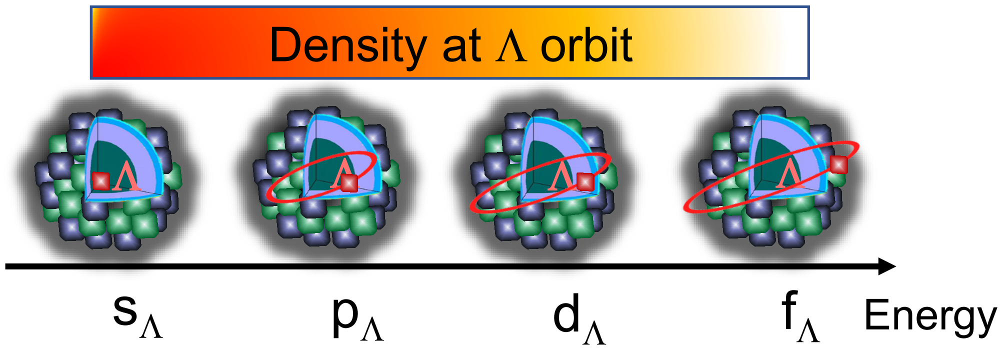
--> Large uncertainty in P-wave and higher-wave interaction.

Theoretical prediction shows quite different angular dependence in dσ/dΩ, A_y and D_y^y

These new scattering data become essential constraint to determine spin-dependent ΛN interaction

Λ binding energy measurement deep inside of nucleus : Unique for Λ hypernuclei

Nuclear density is different for each Λ orbital state

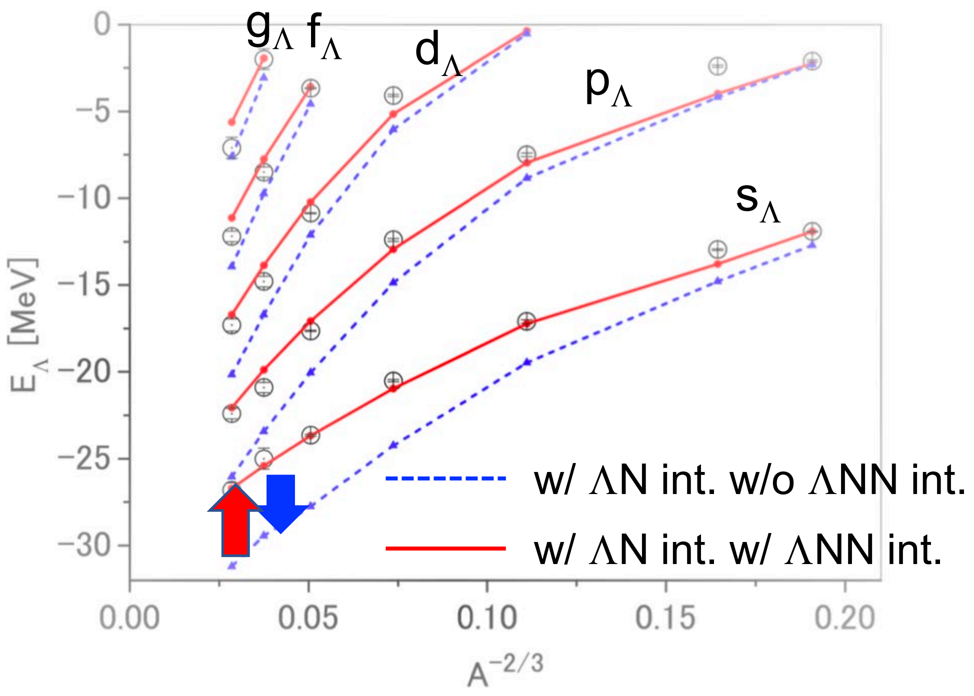


Two directions for study of the density dependence of ΛN interaction

- **Mass number dependence of B_Λ**
- **Λ orbital dependence of B_Λ**

Energy spectra of $^{13}_{\Lambda}$C, $^{16}_{\Lambda}$O, $^{28}_{\Lambda}$Si, $^{51}_{\Lambda}$V, $^{89}_{\Lambda}$Y, $^{139}_{\Lambda}$La, $^{208}_{\Lambda}$Pb with Nijmegen ESC16 model

M.M. Nagels et al. Phys. Rev. C99, 044003 (2019)



Accurate B_Λ measurement ⟷ **Difference** ⟷ **Calculation w/ only ΛN int : Over bound**

Effect of **density dependence of ΛN interaction**

ΛNN repulsive interaction is introduced to explain Λ hypernuclear binding energy

This density dependence should be explained from ΛNN force.
→ Predict ΛN int. in higher density nuclear matter.

High-resolution Λ hypernuclear spectroscopy at HIHR

HIHR : Dispersion-matching beam line

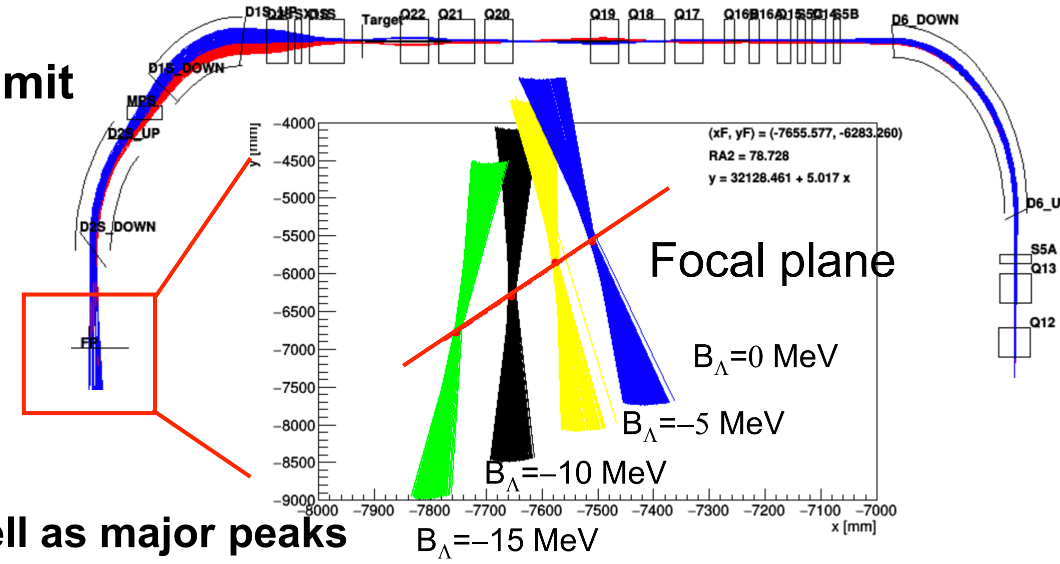
→ Realize **high-resolution** spectroscopy **without beam intensity limit**

High intensity π beam of **> 10^8 /pulse**

(**~100 times stronger** than KEK-PS)

- Thin target can be used

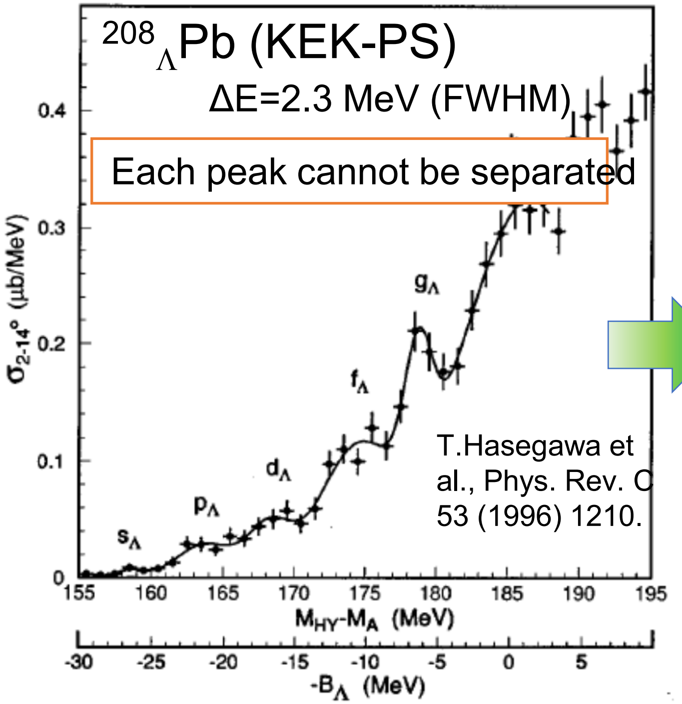
→ High resolution and various target options

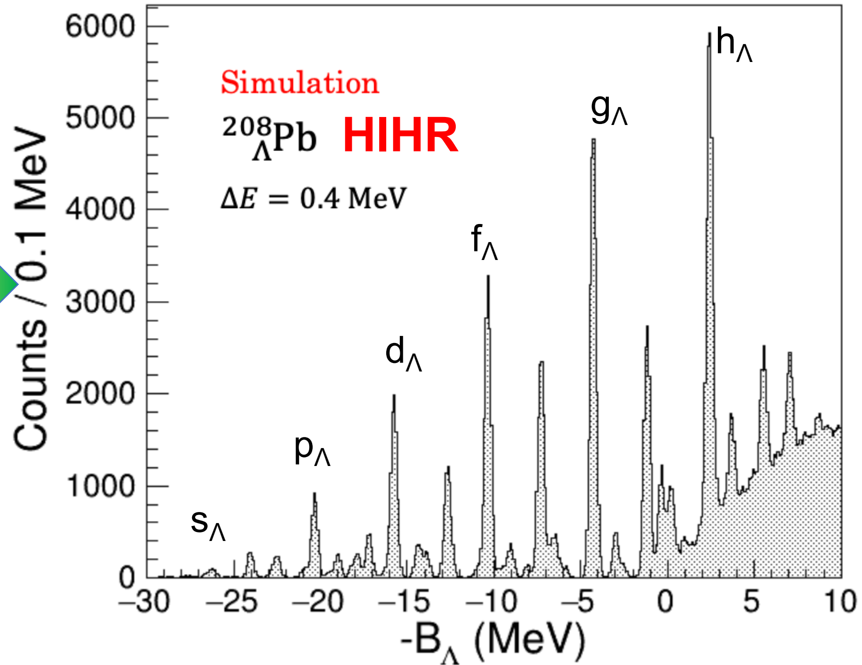


Impossible to separate peaks with a few MeV resolution

0.4 MeV (FWHM) resolution

Clear separation of sub-major as well as major peaks





Precise Λ binding energies for wide-mass range

Density dependence of ΛN interaction (ΛNN interaction)

Calculate U_Λ at high density region

Untangle hyperon puzzle in neutron star

Summary and future prospects

- Many progresses have been obtained in the BB interactions study.
  - Lattice QCD, Chiral EFT, …
  - Femtoscopy is successfully used for the hadron-hadron interaction study.
  - YN scattering experiment gets possible!
- Systematic measurements of Σp scattering at J-PARC
  - $d\sigma/d\Omega$ for Σ^+p, Σ^-p, $\Sigma^-p \rightarrow \Lambda n$ scatterings with ~10% level accuracy for fine angular pitch ($d\cos\theta$=0.1)
  - Momentum dependence of Σ^+p $\delta(^3S_1)$ channel was derived (–20 ~ −35 degrees)
- Future project : Λp scattering w/ polarized Λ beam
  - $d\sigma/d\Omega$ and spin observables (analyzing power, depolarization)
  - → reinforce the current ΛN interaction for deepening hypernuclear physics.
- High-resolution spectroscopy up to medium and heavy Λ hypernuclei
  - New HIHR beam line with dispersion-matching technique will open new era of unprecedent resolution of 400 keV (FWHM)
  - By using this high resolution, the ΛNN 3body interaction will be examined.