Status of the hyperon-nucleon scattering experiment at J-PARC

Koji Miwa (Tohoku Univ.)
on behalf of J-PARC E40, E86 collaboration, HEF ex TF

EMMI Workshop, Feb. 13th – 17th, 2023

TOHOKU UNIVERSITY

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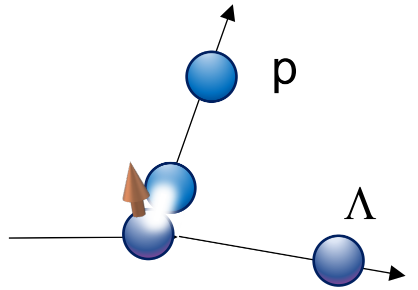
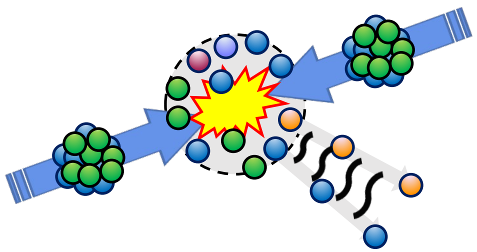
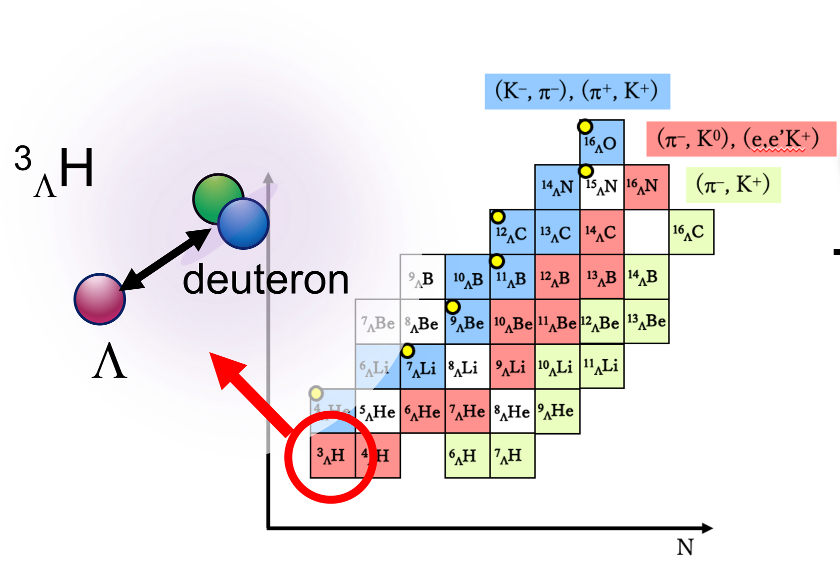
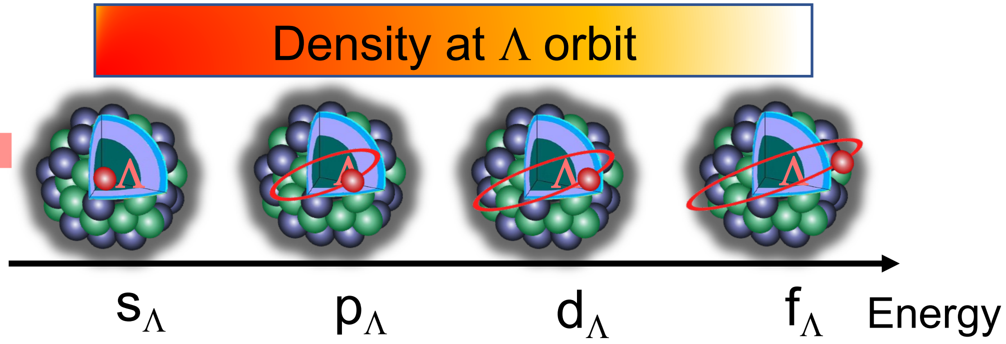
Hypernuclear physics

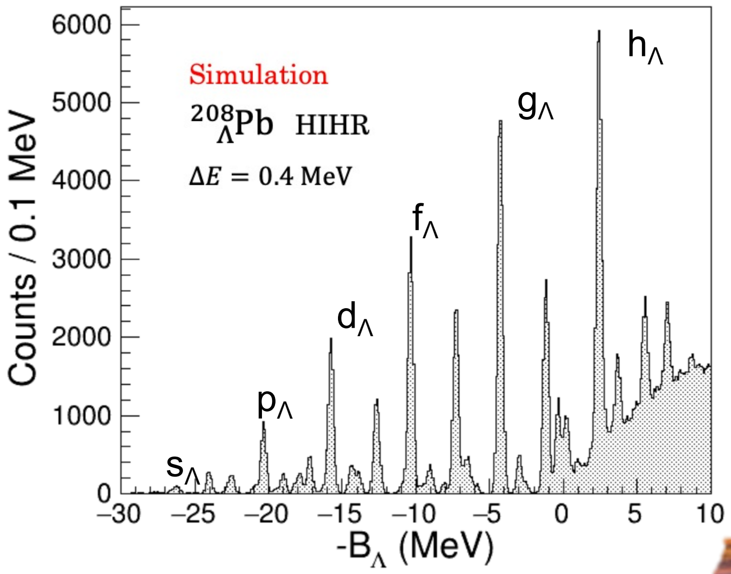
Baryon-Baryon interaction **Study of light Λ, Ξ hypernuclei** **Spectroscopy of heavy hypernuclei**



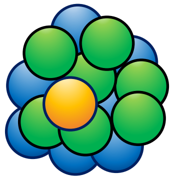




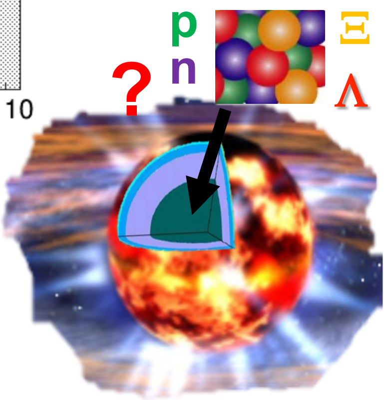




Ξ hypernuclei



Neutron star



Two-body YN int.

ΛN-ΣN coupling, ΛNN int., ΛΛ, ΞN int.

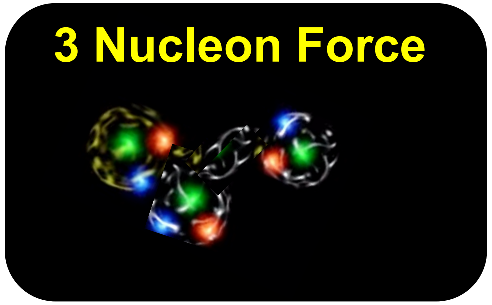
Density dependent ΛN int., ΛNN int.

Realistic nuclear force : base for nuclear physics

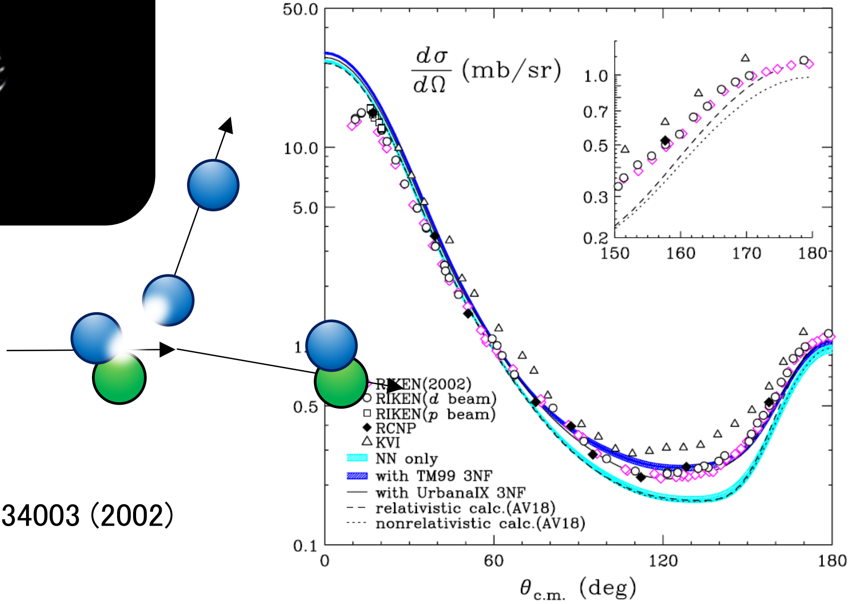
Realistic Nucleon-Nucleon Potential (CD Bonn, AV18, Nijmegen I, II)

Updated based on a lot of scattering observables of NN scattering

Solid base for nuclear studies

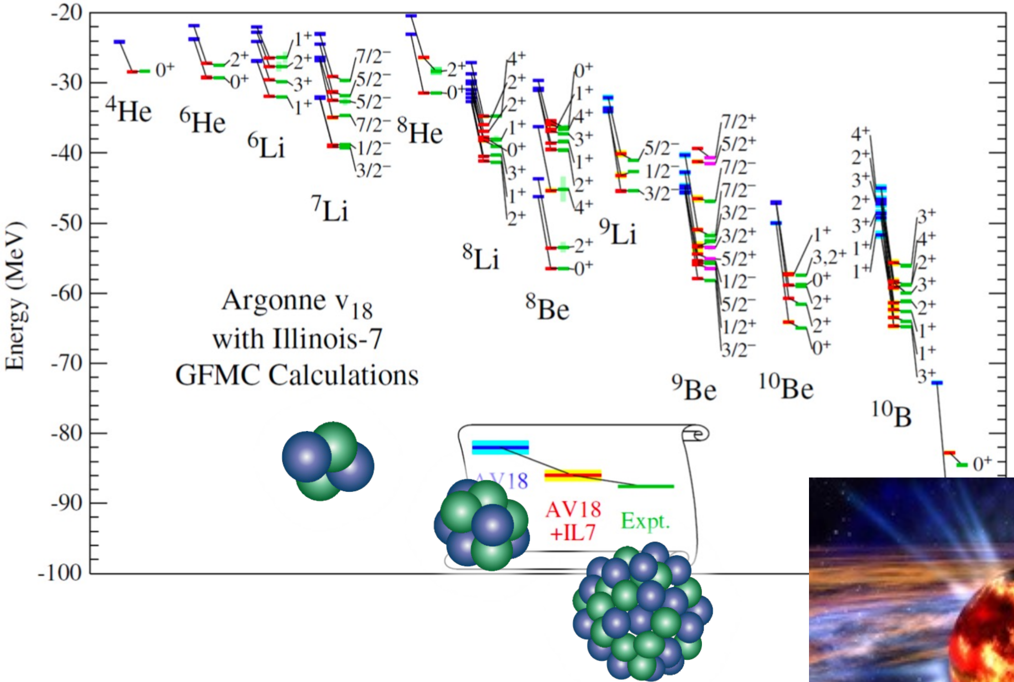


Nucleon-Deuteron scattering



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

Nuclear binding energy

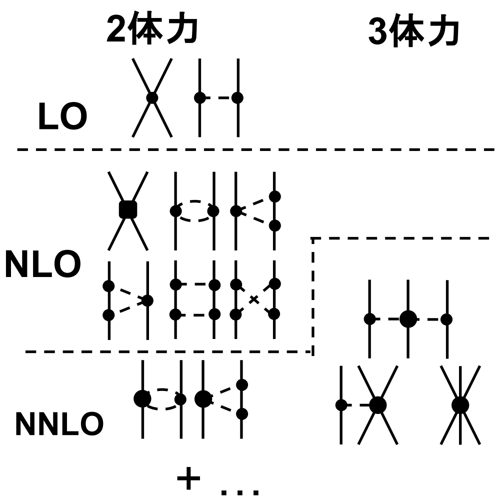


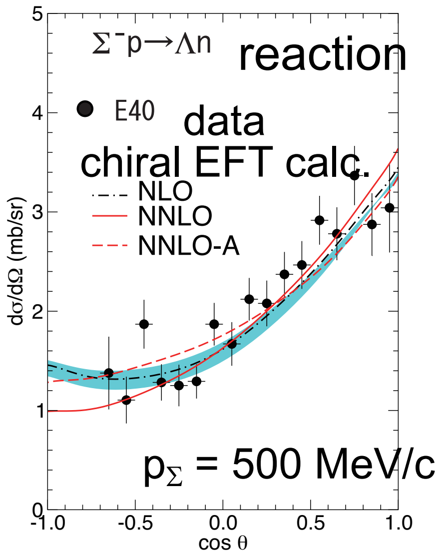
Equation of State of Nuclear Matter

Progress of theory & experiment of BB int. study

Theoretical progress

Hyperon-Nucleon int. w/ chiral effective field theory
(J. Haidenbauer et al.)

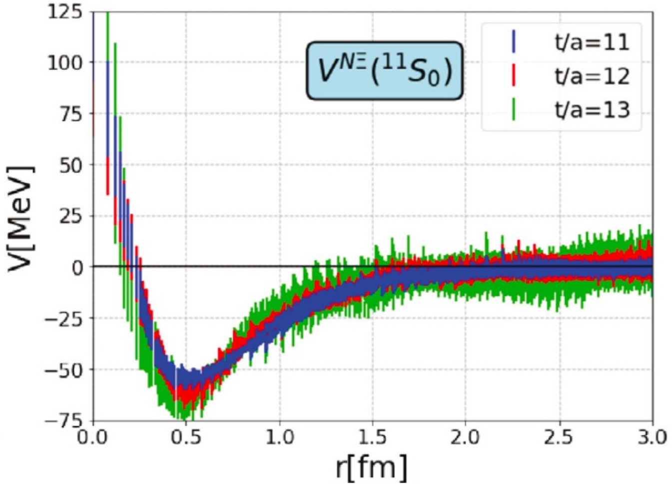




Improving accuracy w/ our new data

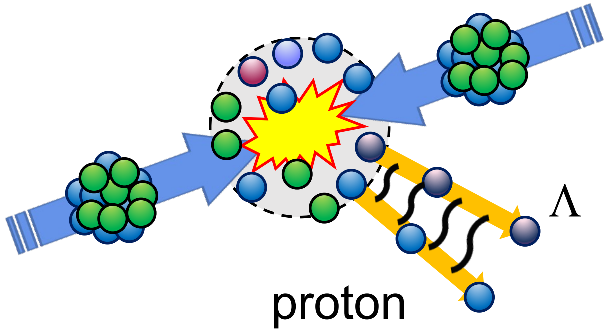
Hyperon potential by Lattice QCD

BB interaction at almost physical point for multi-strangeness sector



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

Experimental progress



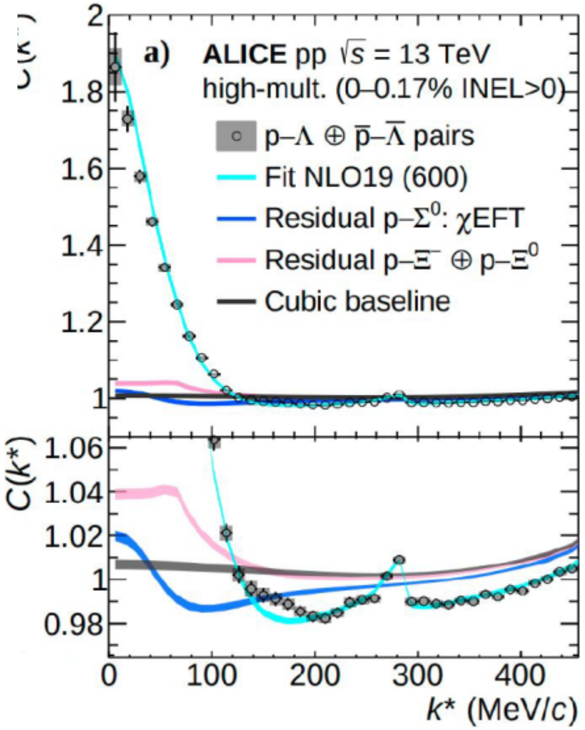
BB interaction from femtoscopy

ALICE Collaboration, Phys. Lett. B 833 (2022) 137272

$$c(k^*) = \int S(r^*) \left|\Psi(\vec{k^*}, \vec{r^*})\right|^2 d^3 r^*$$

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

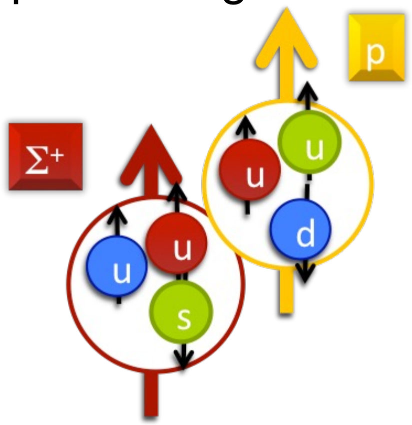
Particle correlation between Λ and p



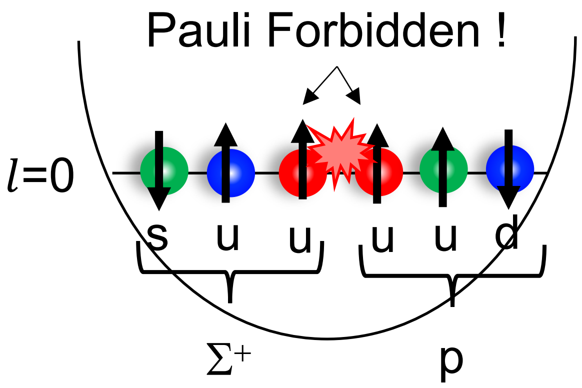
J-PARC E40 : Measurement of dσ/dΩ of Σp scatterings

Verification of quark Pauli repulsion

$\Sigma^{+}p$ scatterng



6 quarks can stay in s state in normal case



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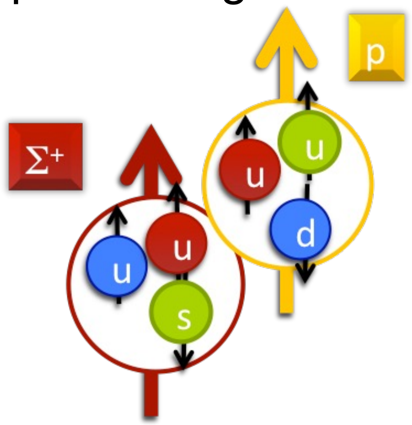

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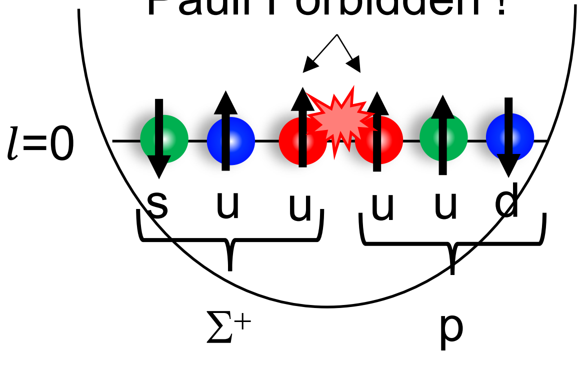
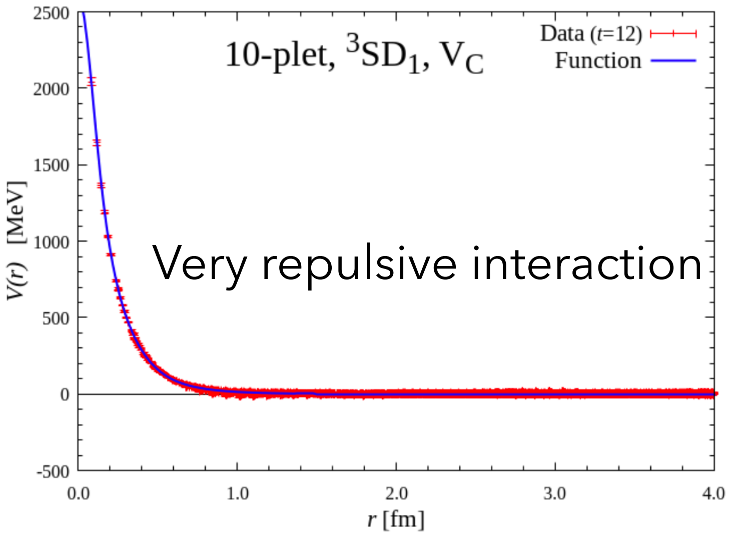


Lattice QCD calculation

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



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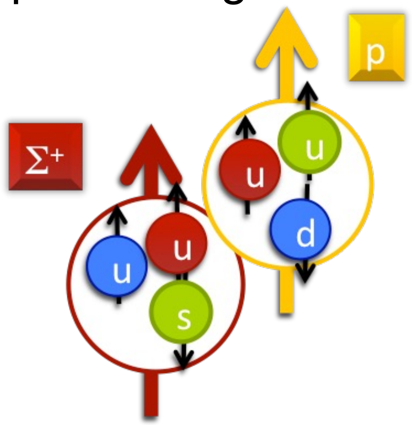

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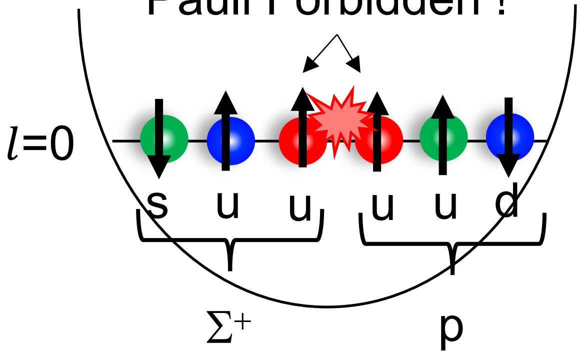
Pauli Forbidden !



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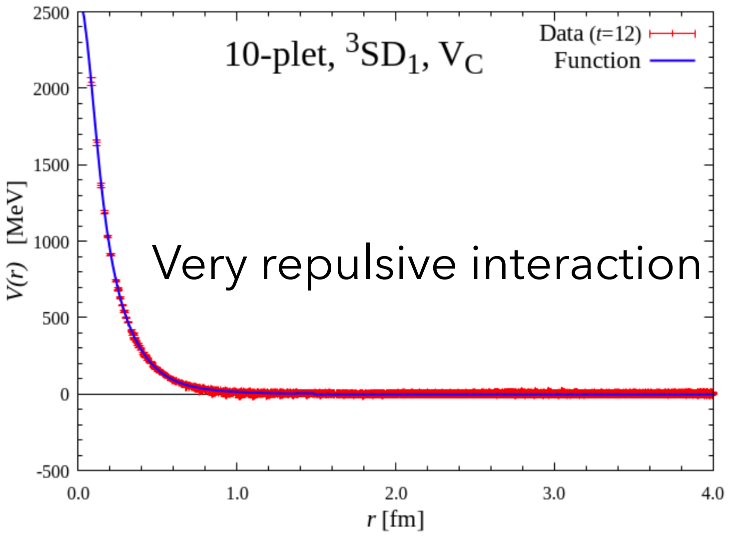


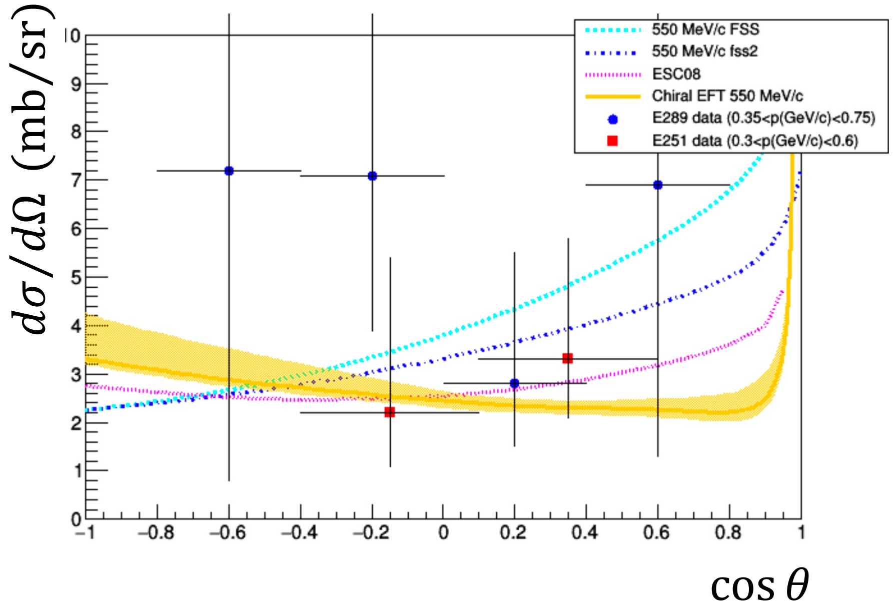
Constraint for BB int. theories

Quark Cluster model (FSS, fss2)

Nijmegen model

Chiral EFT (NLO)

Σ^+p (0.5 < p (GeV/c) < 0.6)



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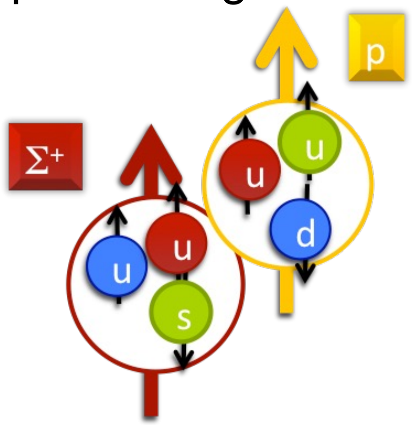

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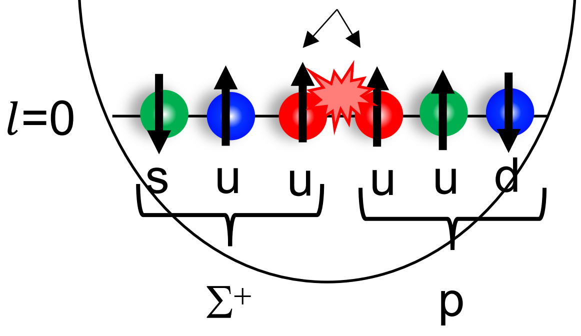

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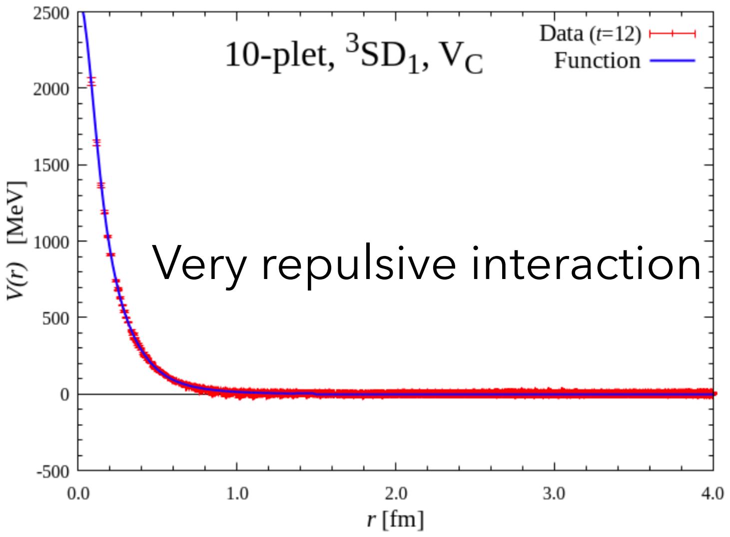
T. Inoue, AIP Conf. Proc. 2130, 020002 (2019)



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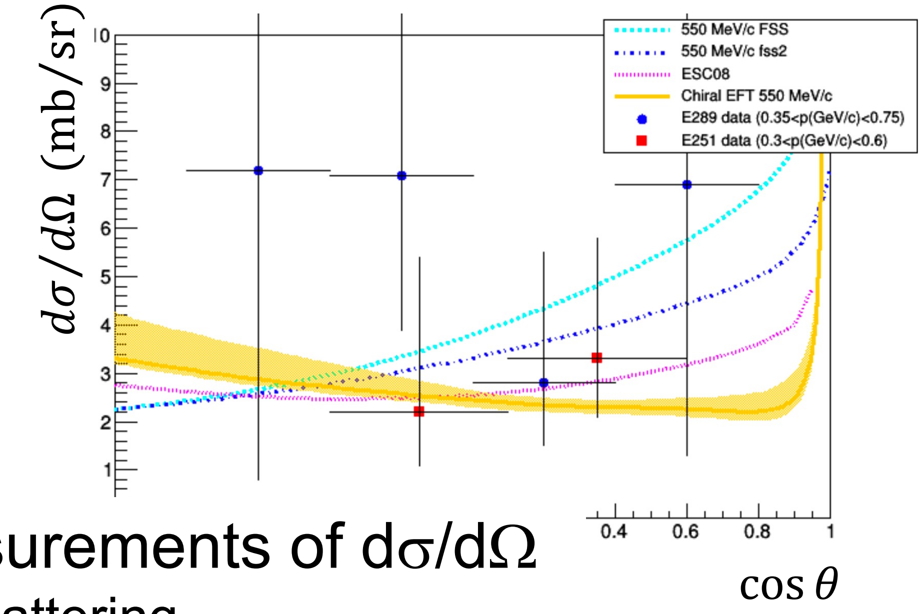
- Nijmegen model
- Chiral EFT (NLO)

Σ^{+}p (0.5 < p (GeV/c) < 0.6)



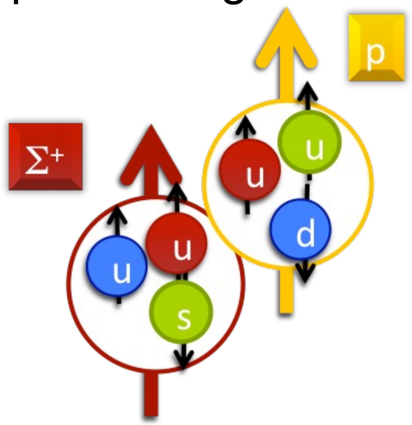
Systematic measurements of dσ/dΩ

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

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

Verification of quark Pauli repulsion

$\Sigma^+ p$ scatterng



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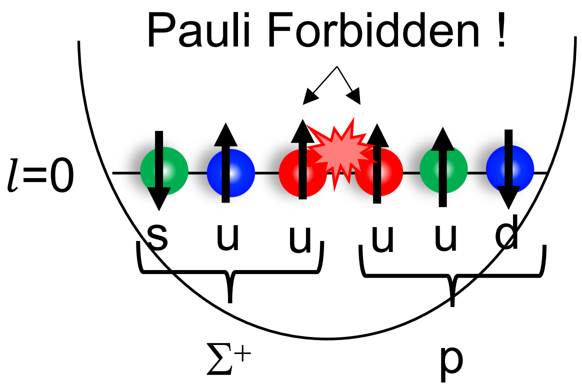
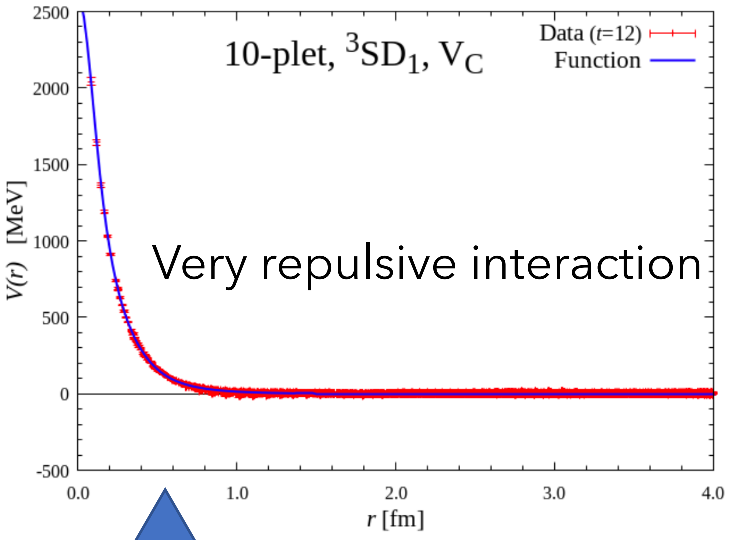


Lattice QCD calculation

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



Phase-shift measurement

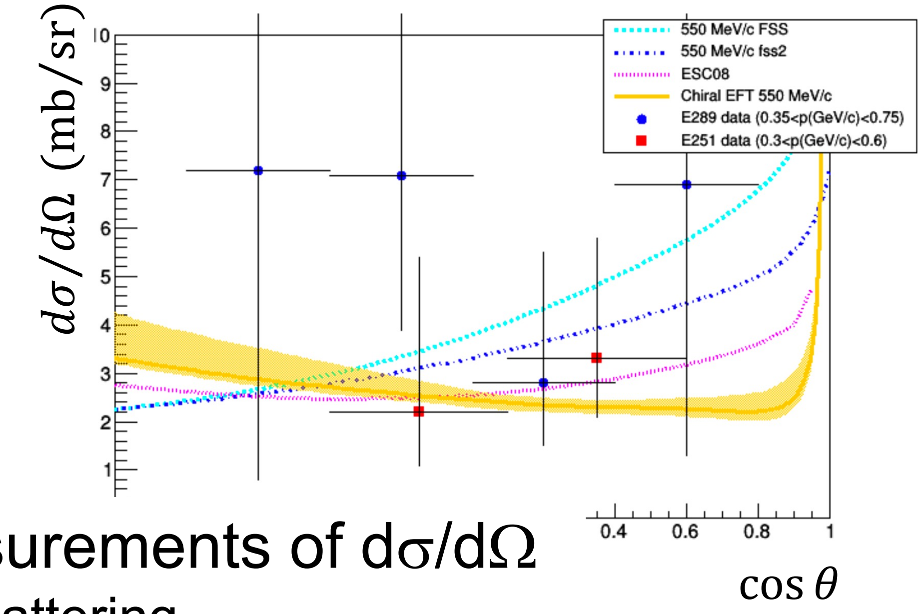
Constraint for BB int. theories

Quark Cluster model (FSS, fss2)

Nijmegen model

Chiral EFT (NLO)

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



Systematic measurements of dσ/dΩ

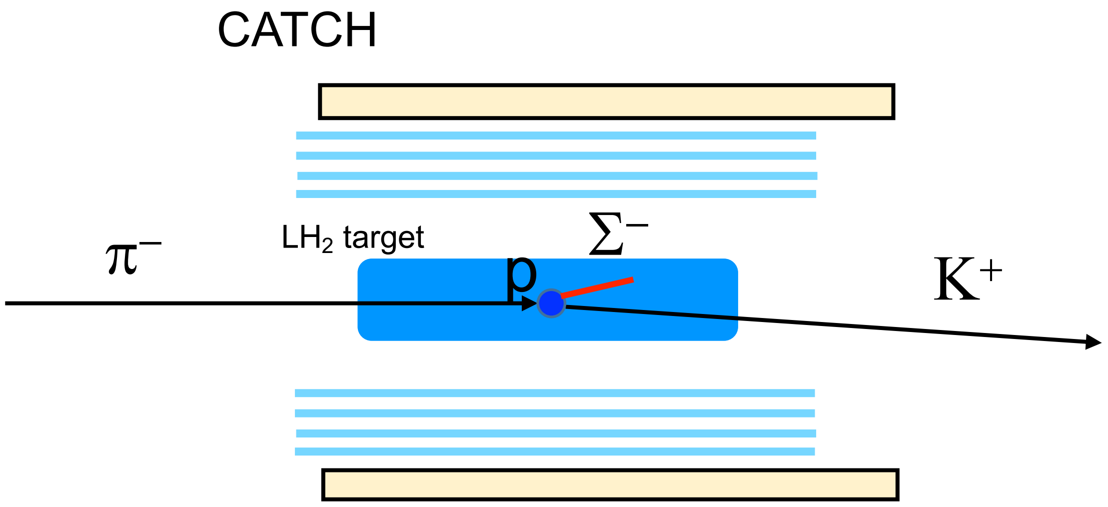
- $\Sigma^+ p$ elastic scattering
- $\Sigma^- p$ elastic scattering
- $\Sigma^- p \rightarrow \Lambda n$ inelastic scattering

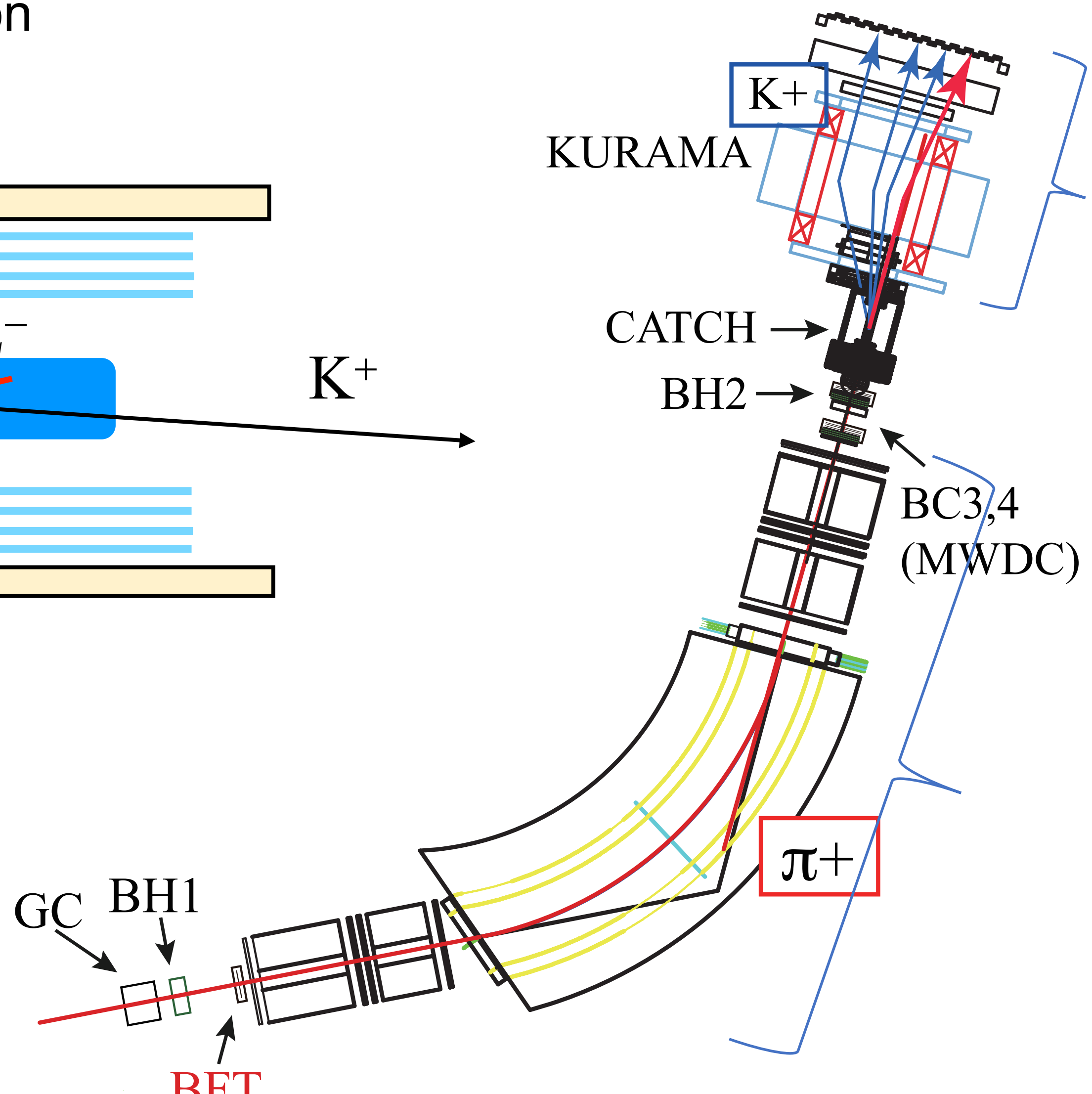
J-PARC E40 experimental setup

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

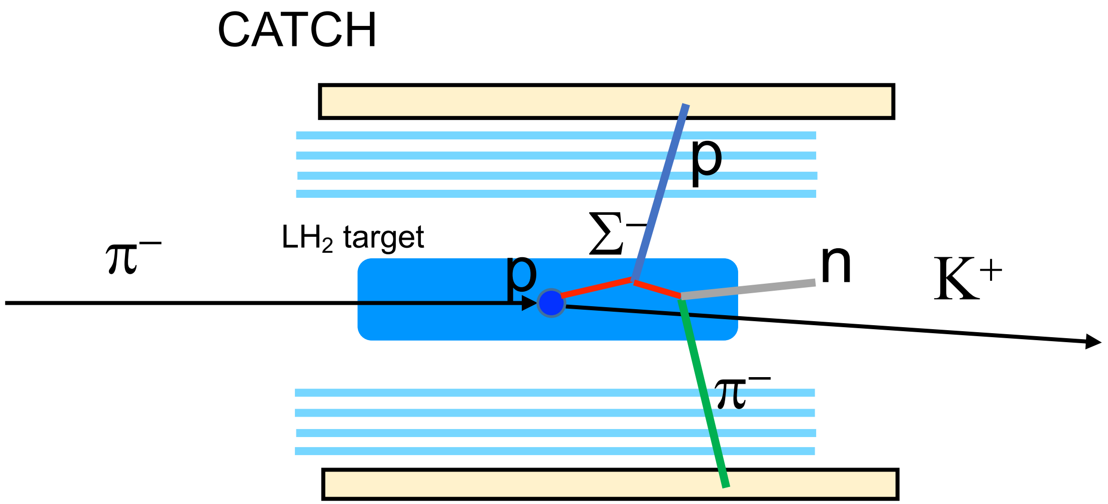
Momentum tagging of Σ beam

Beam-line spectrometer

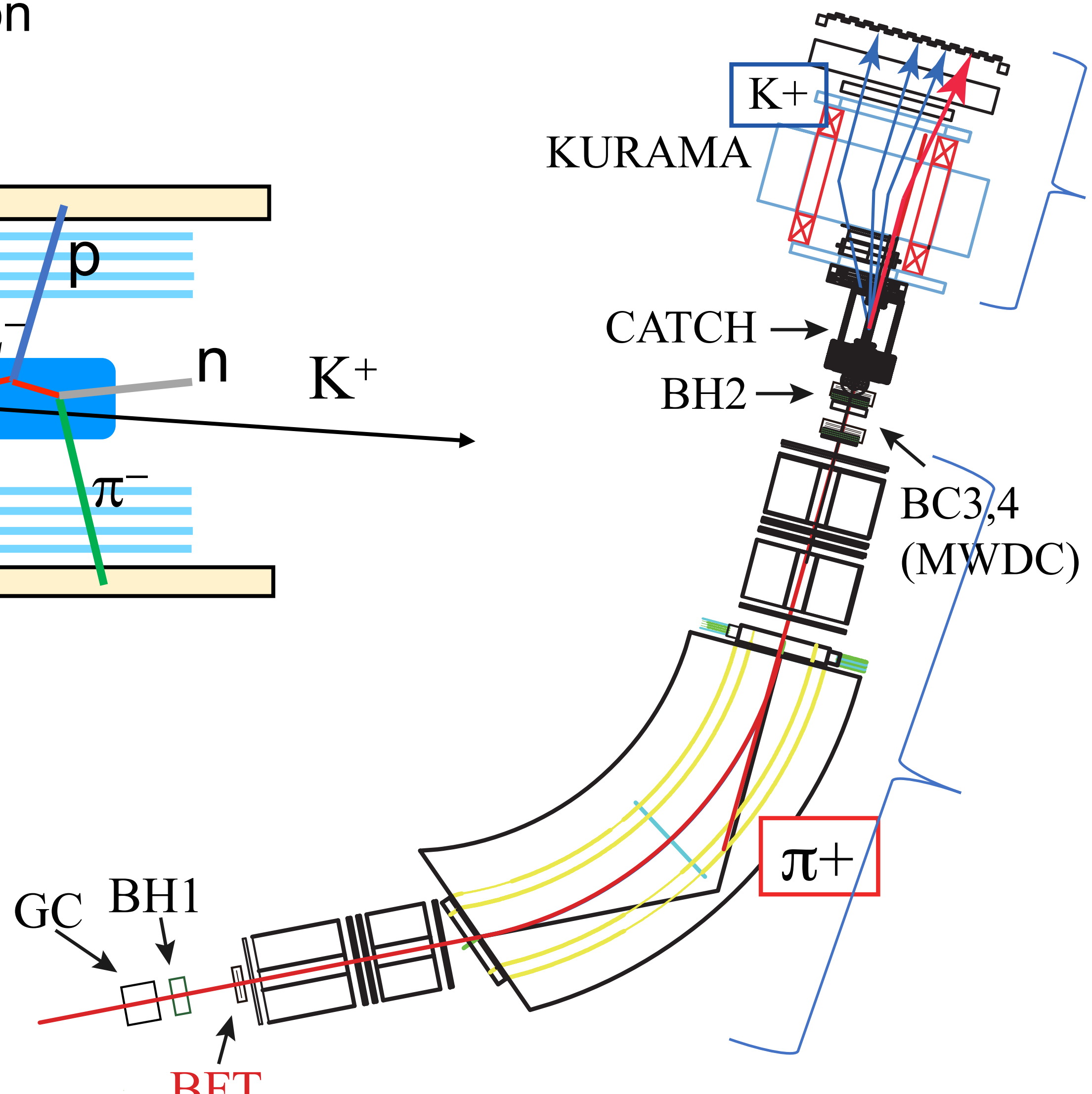
- Momentum analysis of π beam

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

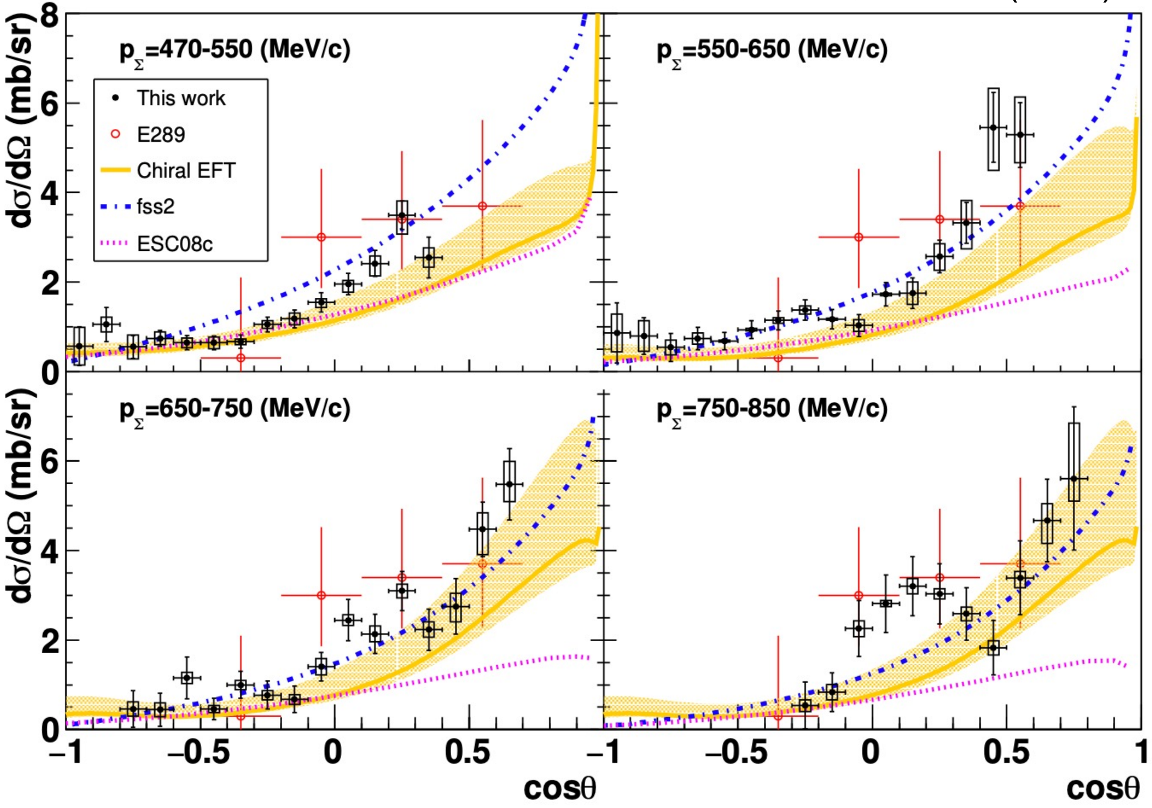
Momentum tagging of Σ beam

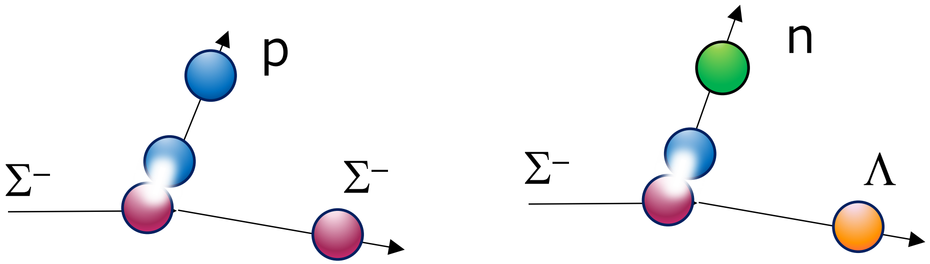
Beam-line spectrometer
- Momentum analysis of π beam

dσ/dΩ of Σ–p scattering channels

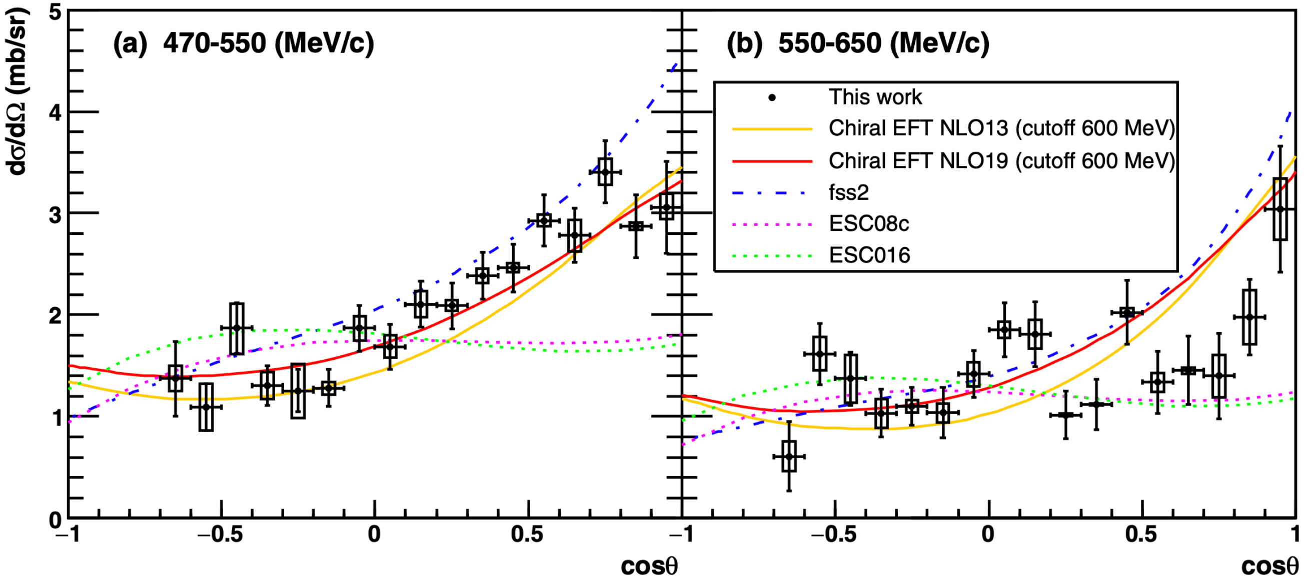
Σ⁻p elastic scattering

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

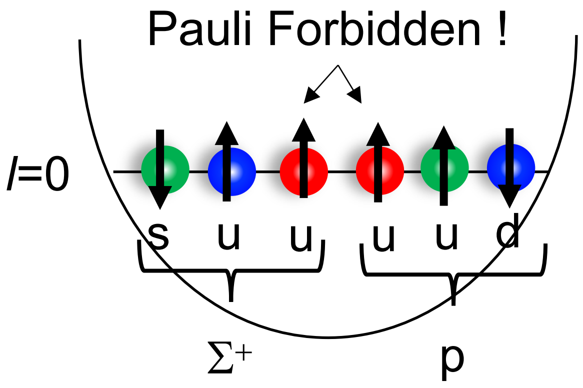
<u>Comparison with theories</u>

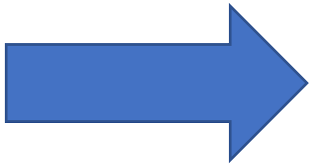
- fss2, Chiral EFT show a reasonable angular dependence.
- Nijmegen ESC models clearly underestimate the forward angle.

dσ/dΩ of Σ^+p elastic scattering

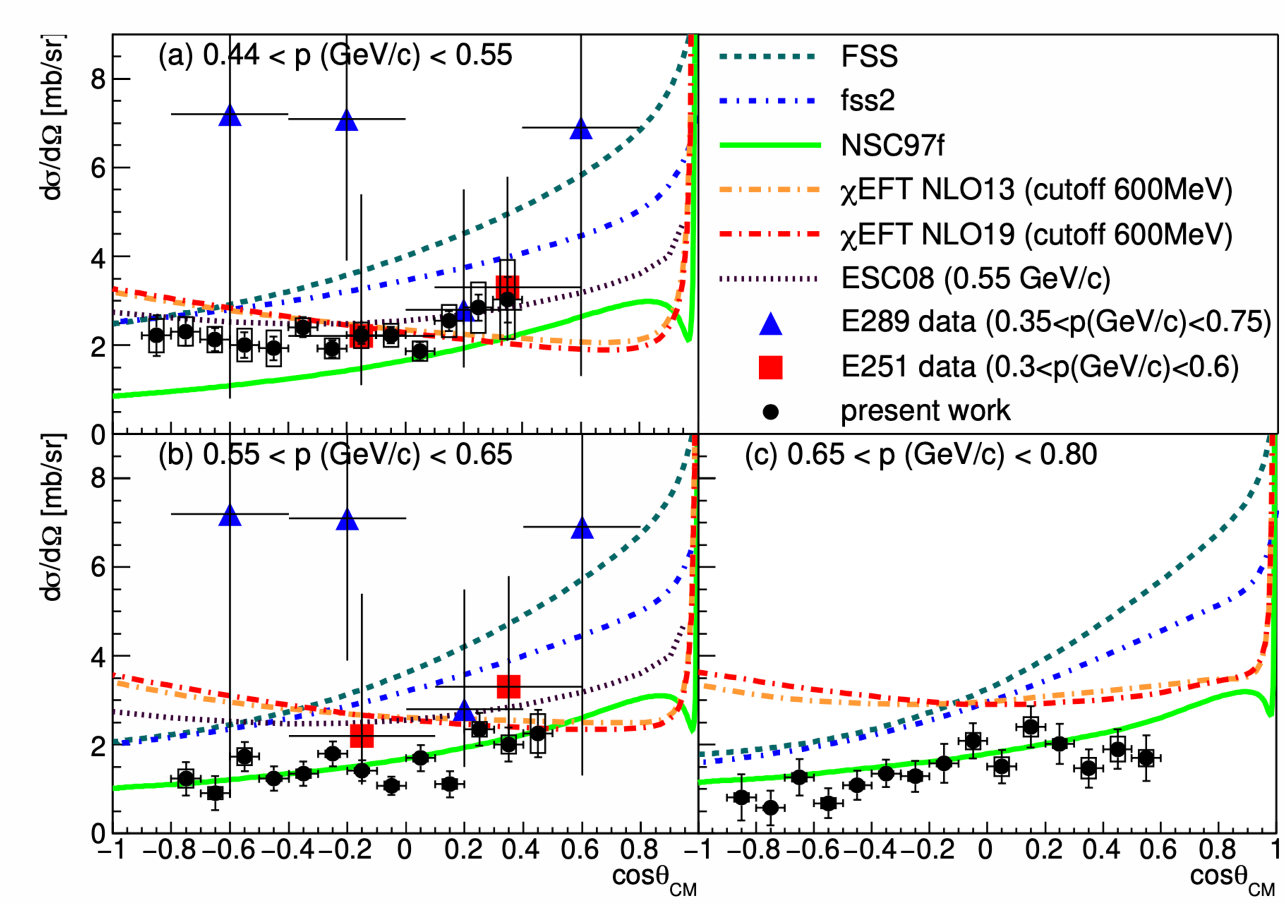
Σ^+p scatterng

6 quarks can stay in s state in normal case





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



The more repulsive potential in $^3S_1$

→ The larger dσ/dΩ (like fss2)

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

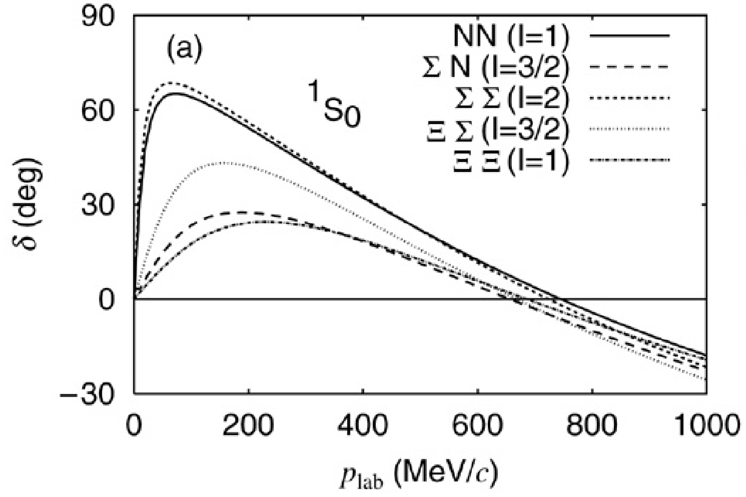
Phase shift analysis for Σ^+p $d\sigma/d\Omega$

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

  fixed on NSC97f, ESC16, pp scat

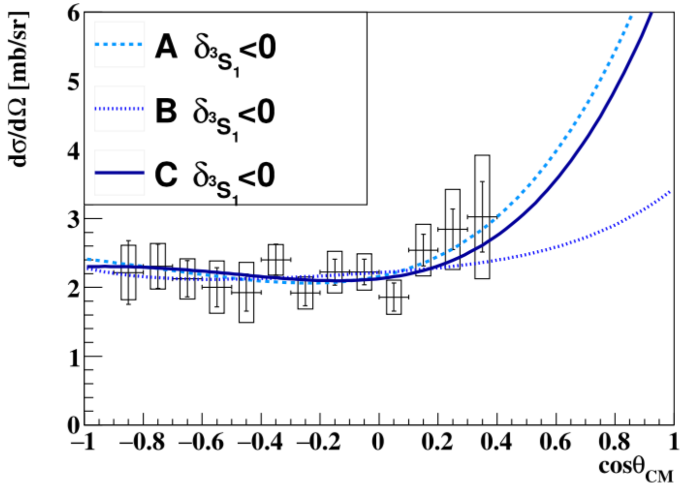
strangeness	BB channel (I)	^{1}Even or ^{3}Odd	^{3}Even or ^{1}Odd
0	NN($I=0$)	–	(**10***)
	NN($I=1$)	(**27**)	–
	$\Sigma N(I=\frac{3}{2})$	(**27**)	(**10**)

- Constrained from NN (I=1) channel
- Smaller uncertainty

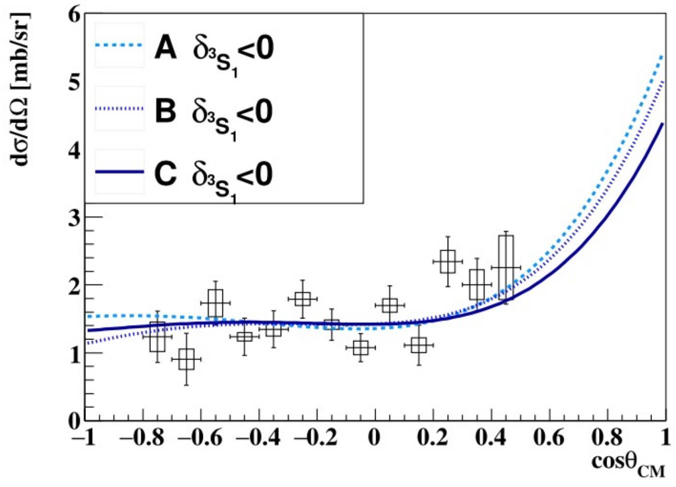


Fitting $d\sigma/d\Omega$ with sum of partial waves

0.44<p(GeV/c)<0.55



0.55<p(GeV/c)<0.65



Phase shift analysis

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

- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
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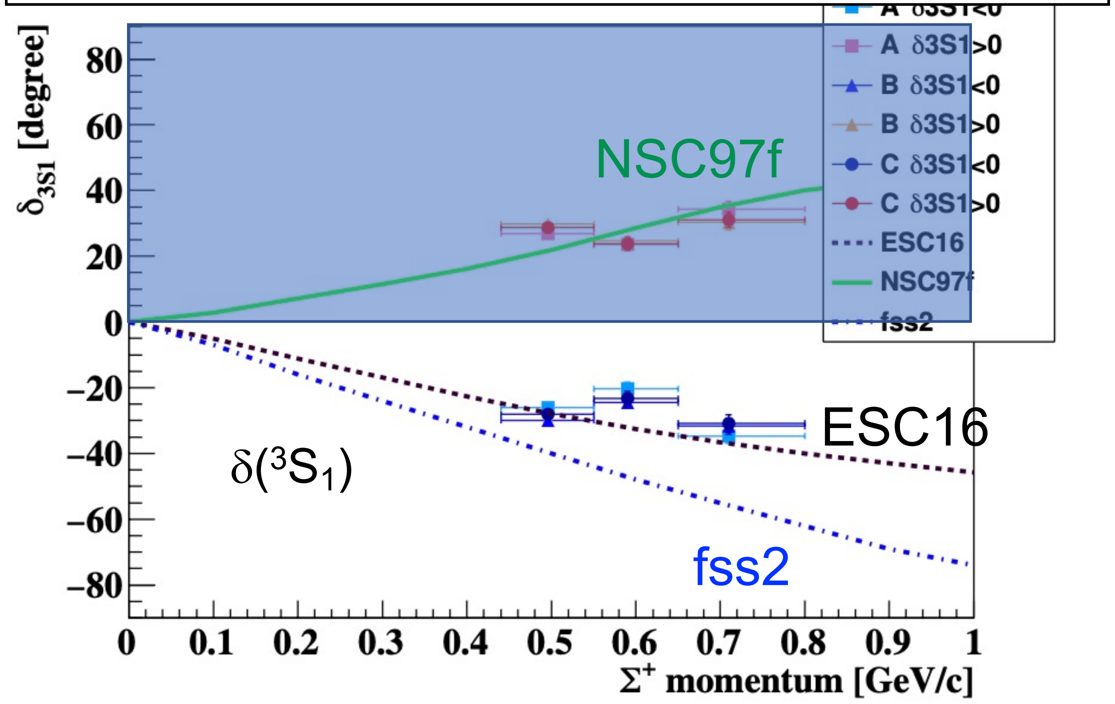
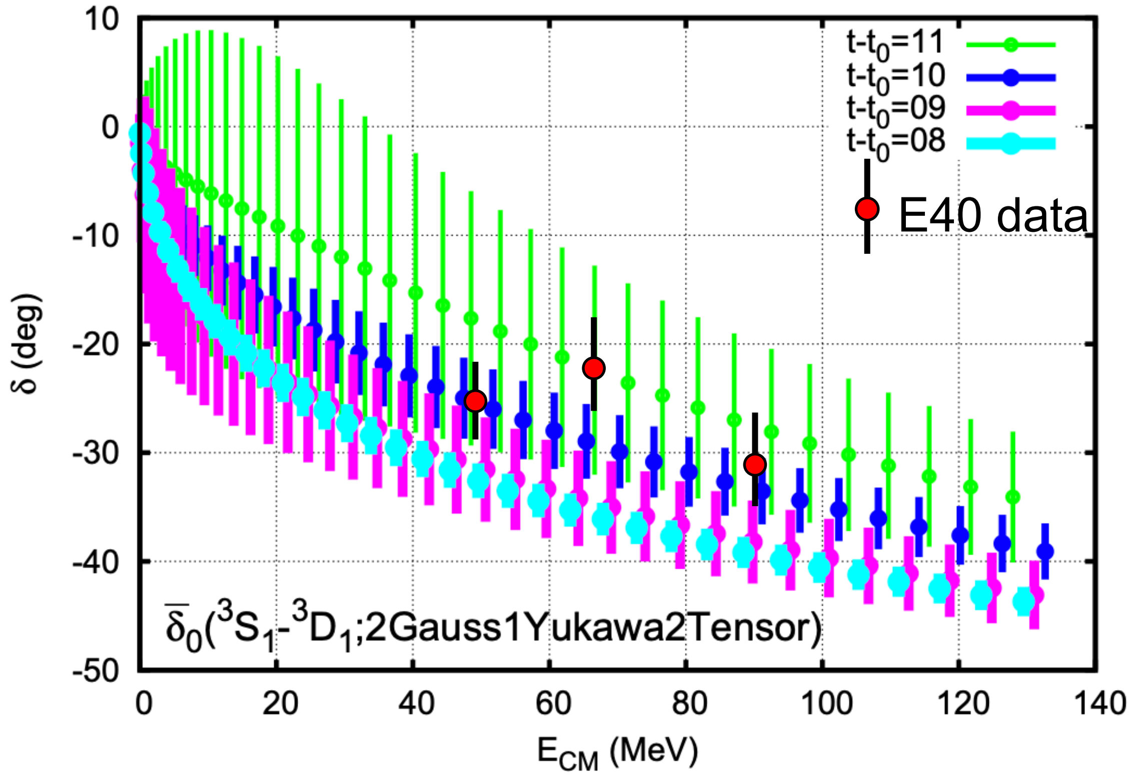
First experimental derivation of phase shift of $^3S_1$



Comparison with HAL QCD ΣN potential



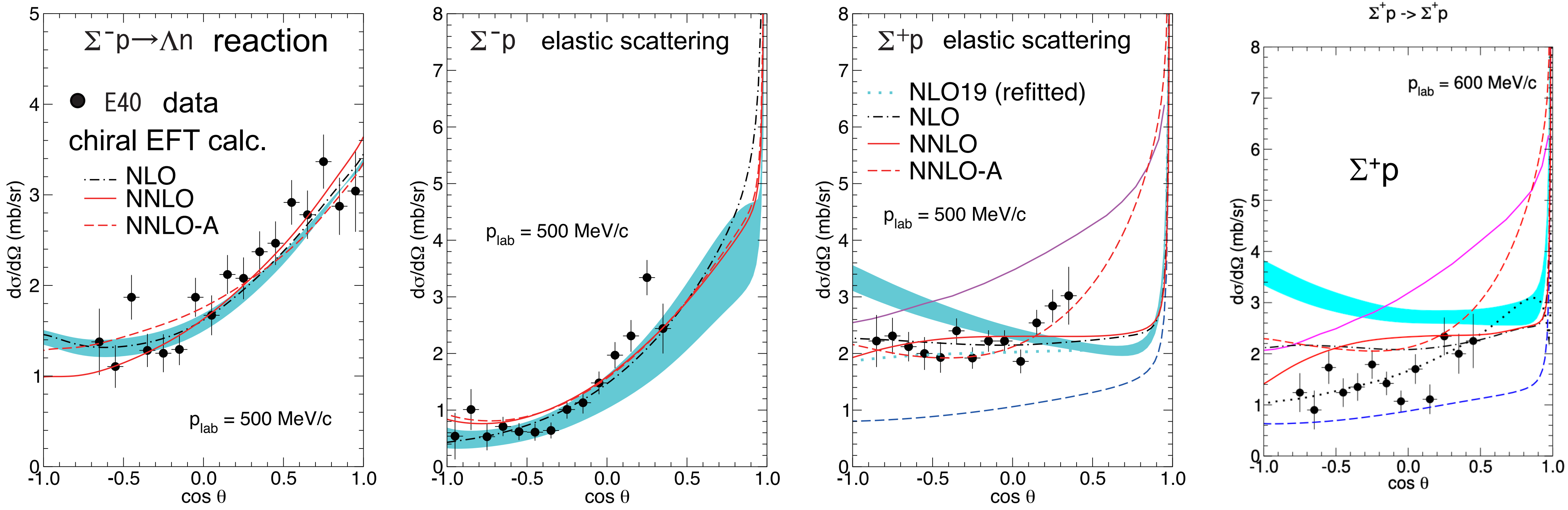
H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

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

Difficulty at higher momentum



J. Haidenbauer et al., arXiv:2301.00722

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⁻)

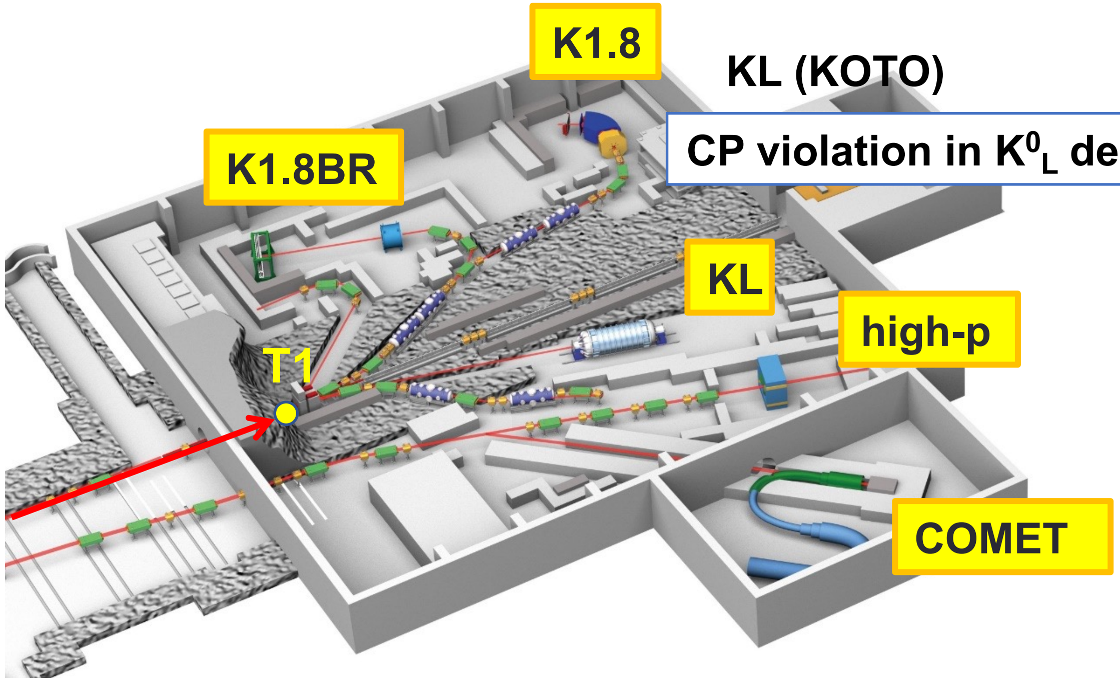
K^{bar} N interaction

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)

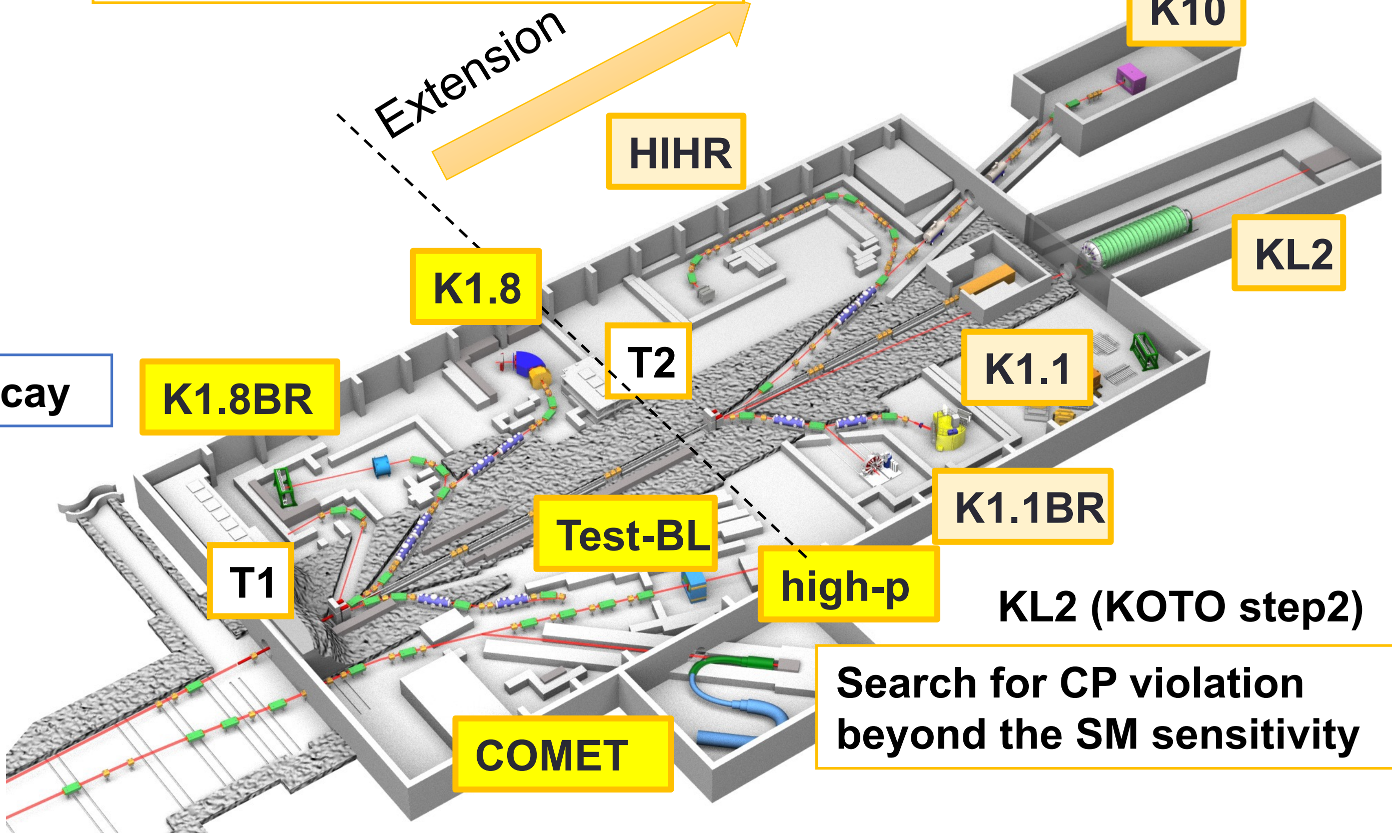
Hadron property in nuclear medium
Baryon spectroscopy

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)

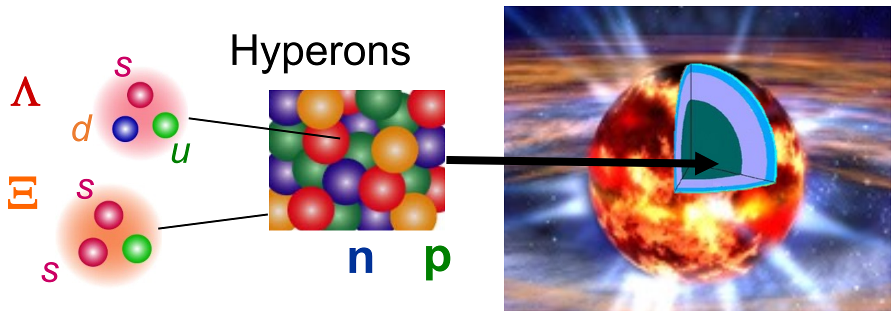
BB interaction (focusing on S=-1)

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 ?

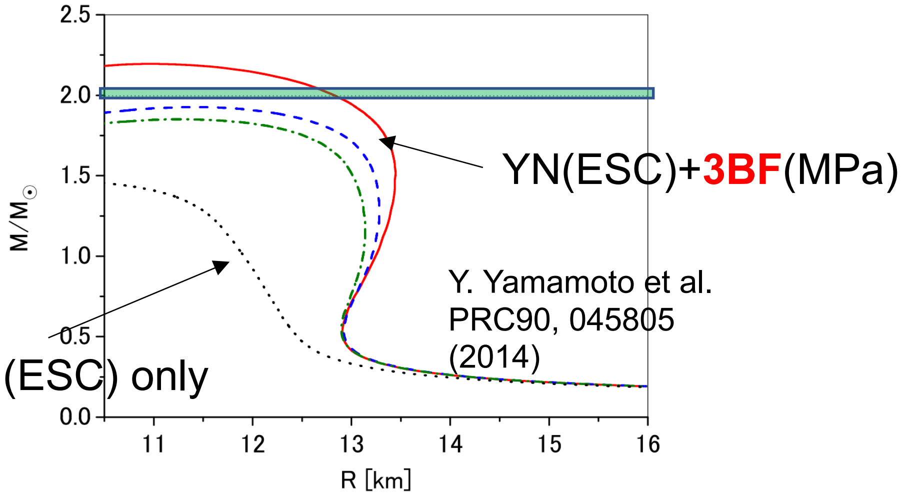
Hyperon's appearance is reasonable scenario because of the huge Fermi energy of neutrons in the inner core.



How can we reconcile ?

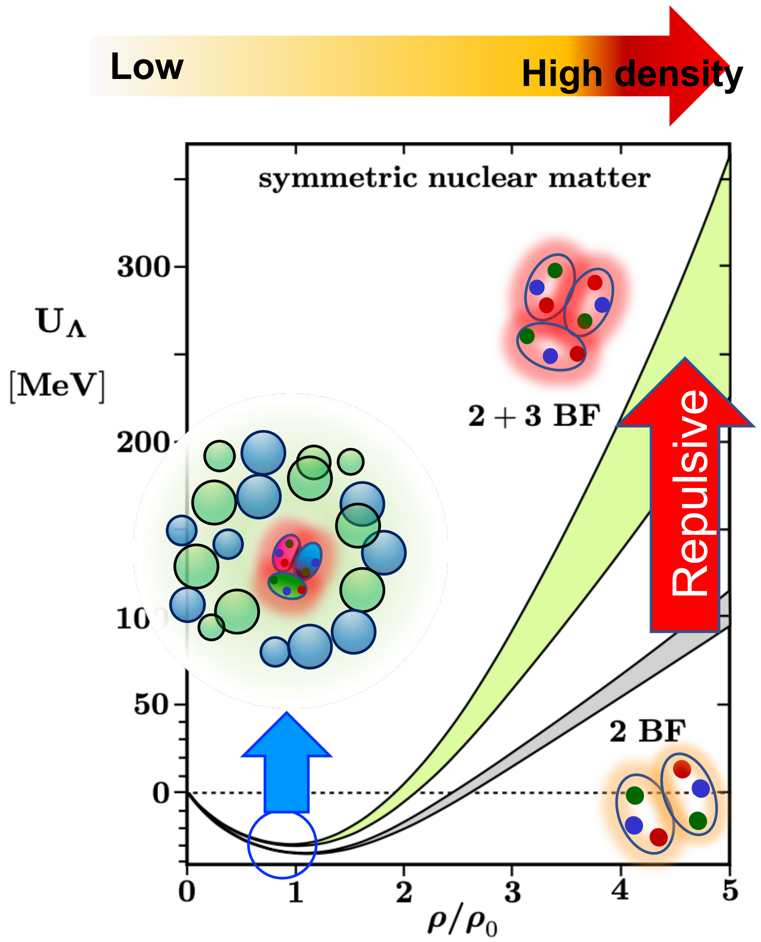
Hyperon appearance → **soften** EOS

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



3 Baryon Force (3BF):

Significant repulsive contribution at high density



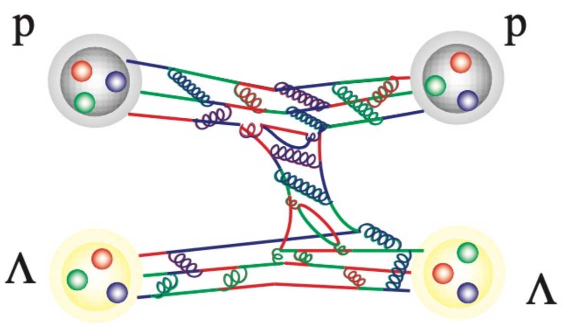
D. Gerstung et al., Eur. Phys. J. A(2020) 56:175

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

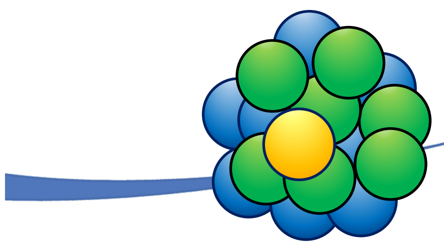
→ determine **the strength of the ΛNN force**

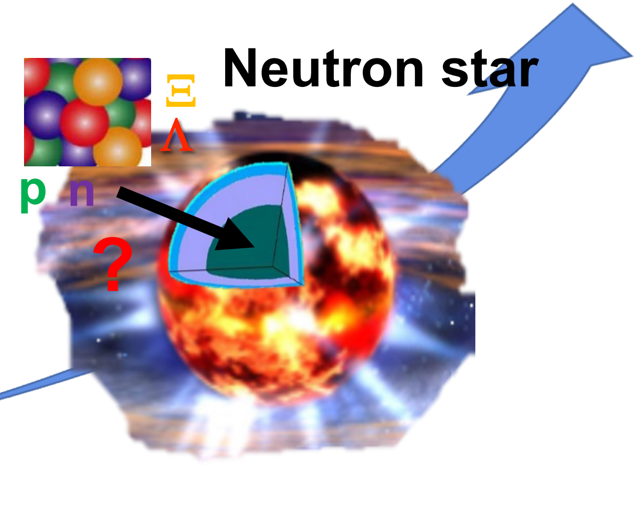
Toward Λp scattering

<u>Reliable ΛN two-body interaction :</u>
key to deepen Λ hypernuclear physics

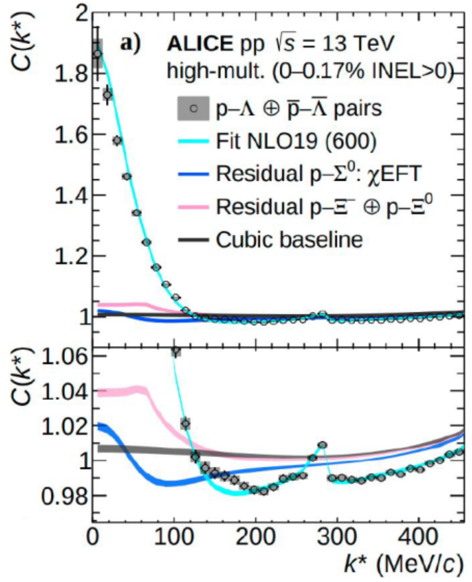


Λ hypernuclei
key to reveal ΛNN int.



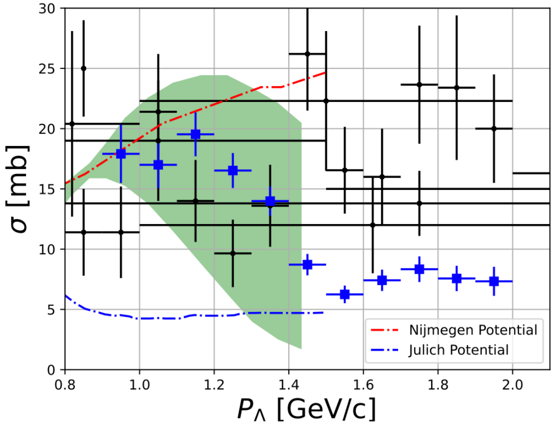


Femtoscopy from HIC



ALICE Collaboration, arXiv:2104.04427

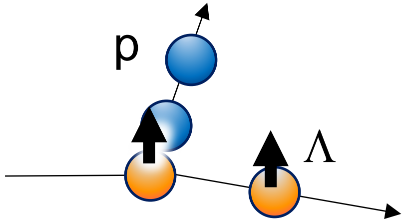
New cross section data
from Jlab CLAS



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

New project at J-PARC

Λp scattering w/ polarized Λ

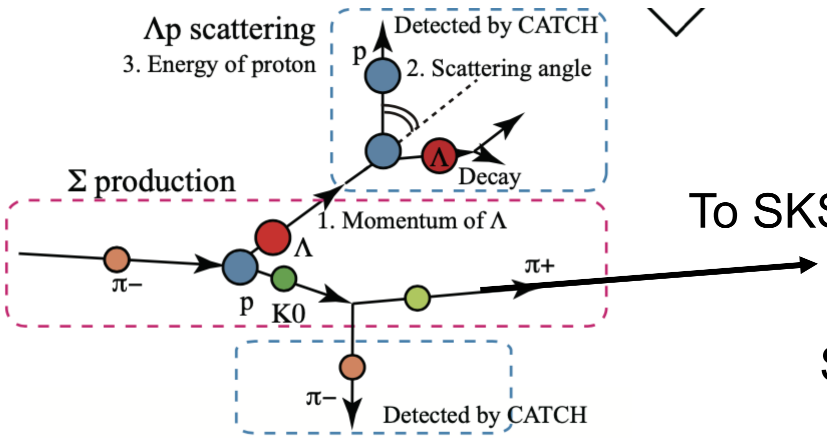


- Feasibility test w/ E40 data
- Expected results in new experiment

Λp scattering experiment with polarized Λ beam

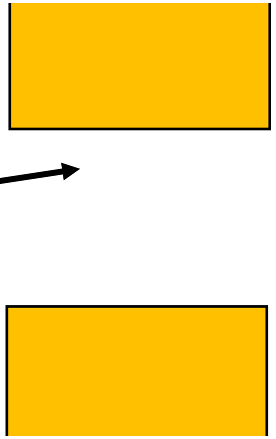
Λ beam identification

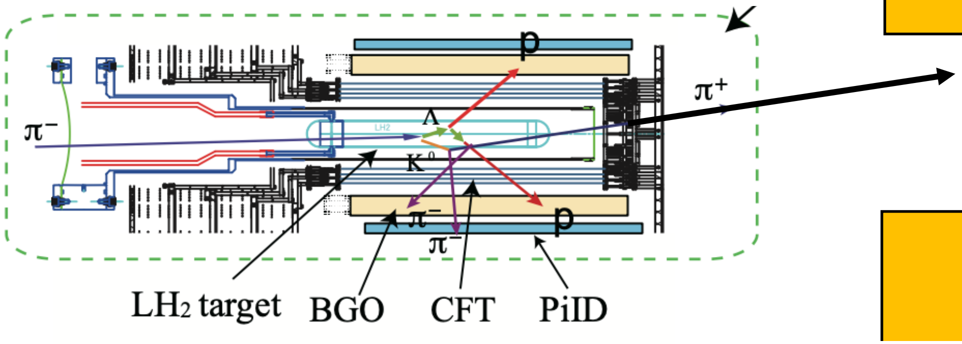
Tagged by $\pi^{-}p \rightarrow K^{0}\Lambda$ reaction at p=1.05 GeV/c



To SKS spectrometer

SKS spectrometer

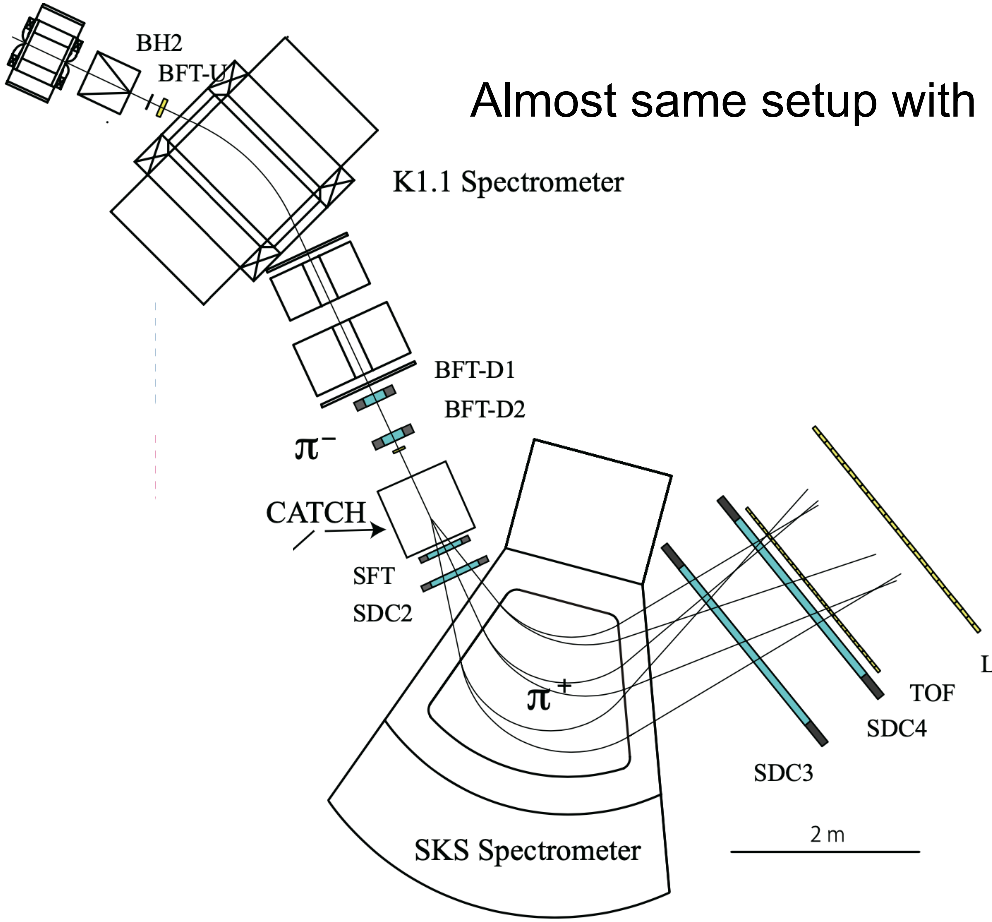




Λp scattering identification

Detected by CATCH

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

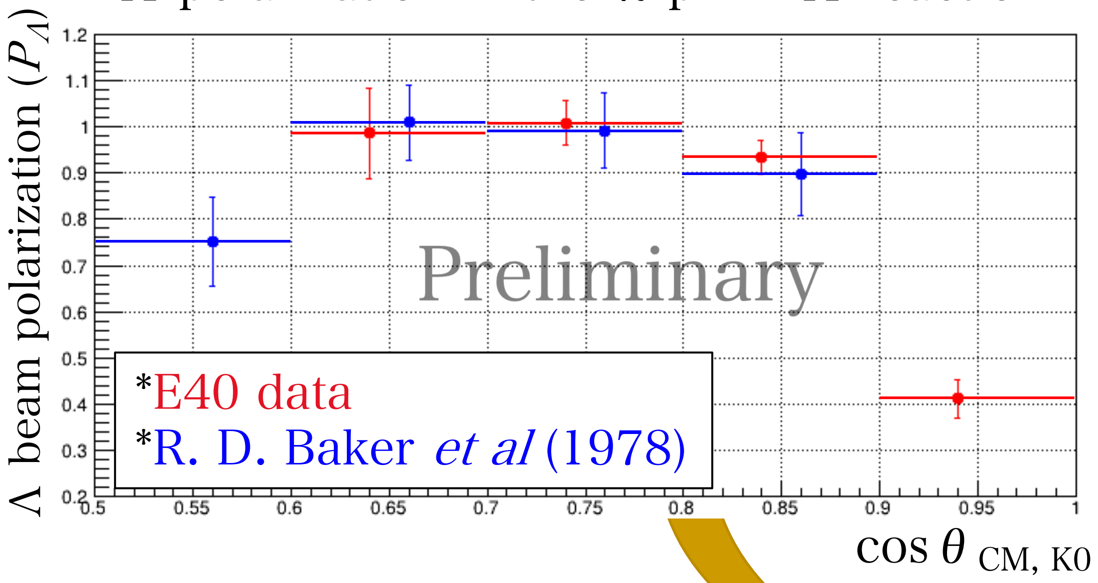


Almost same setup with E40

Λp scattering experiment with polarized Λ beam

High spin polarization of Λ

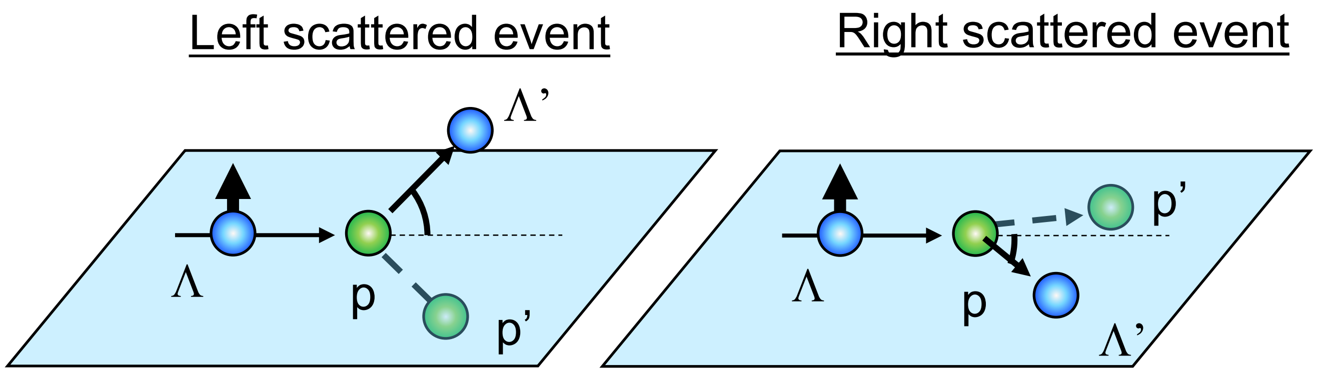
Λ polarization in the $\pi^- p \rightarrow K^0 \Lambda$ reaction



Realize spin observable measurement

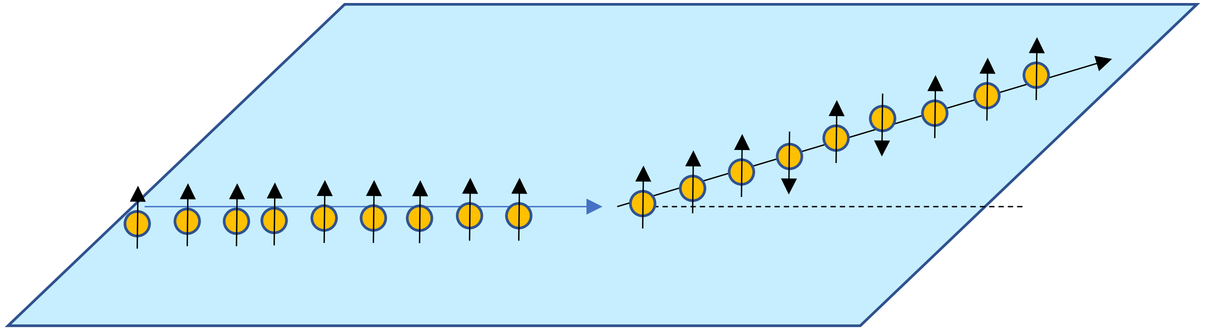
Analyzing power

Left/Right asymmetry of Λp scattering



Depolarization (D_y^y)

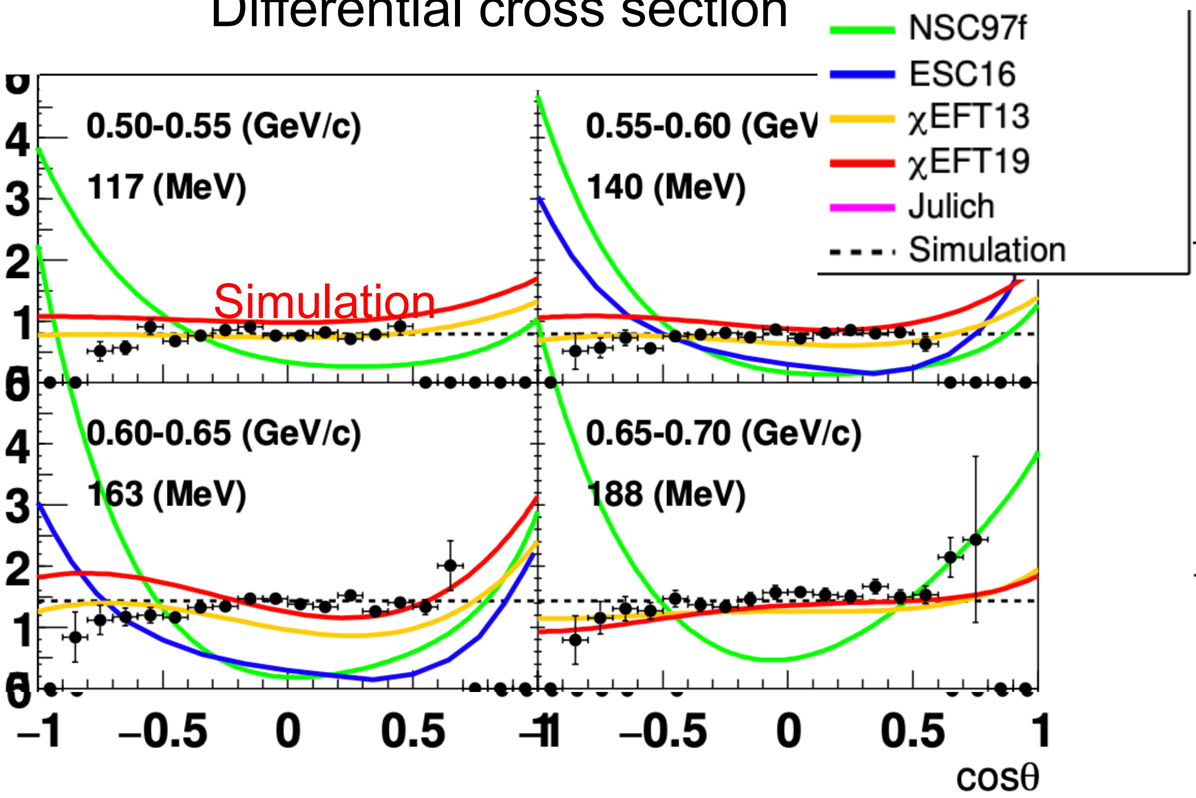
Change the spin polarization after the Λp scattering



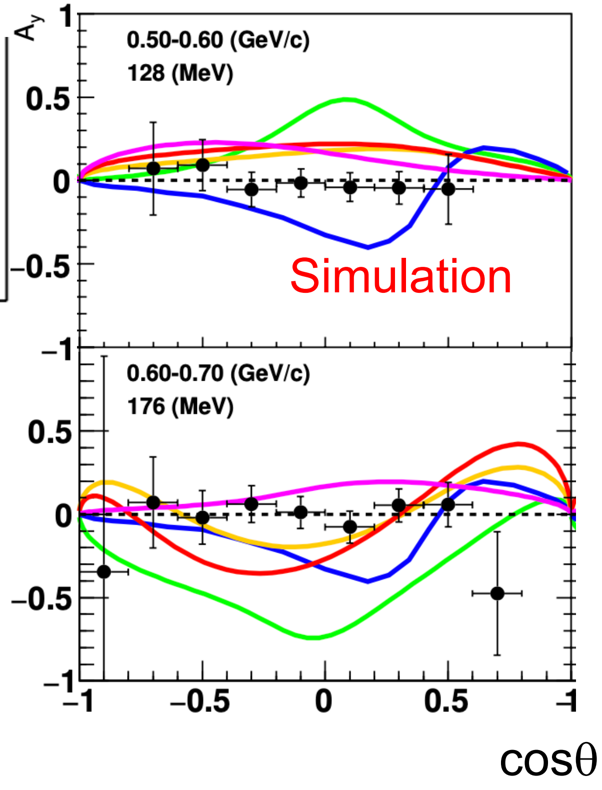
dσ/dΩ and Spin observables in Λp scattering

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

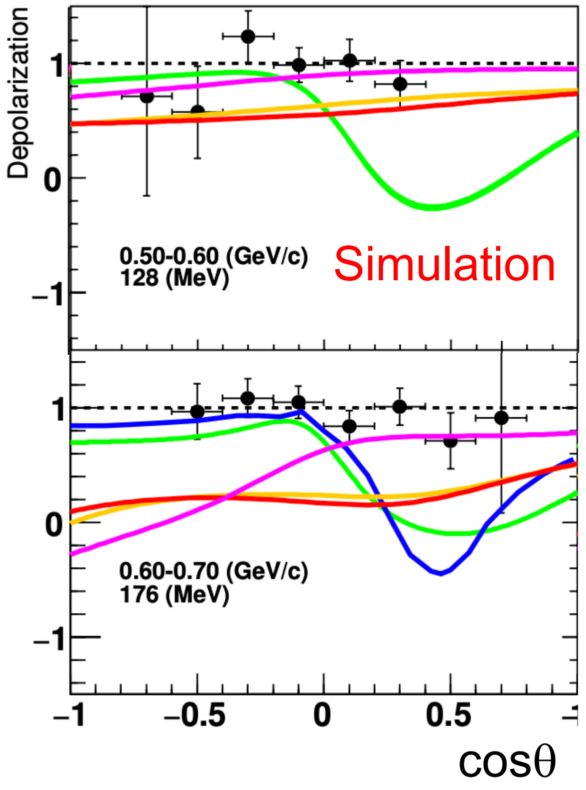
Differential cross section



Analyzing power



Depolarization (D_y^y)



Simulated results w/ 10^8 Λ

No differential observables of Λp scattering SO FAR

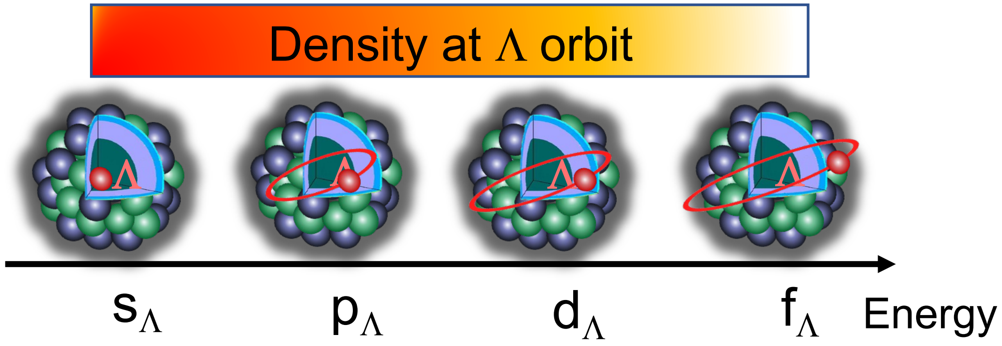
--> Large uncertainty in P-wave and higher-wave interaction.

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**

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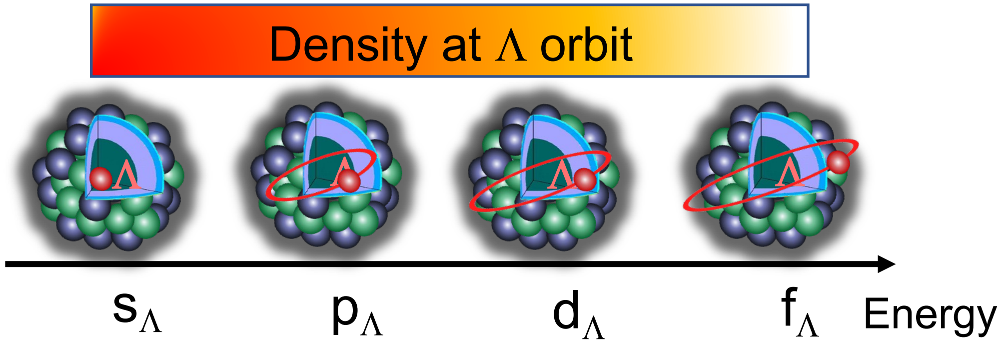

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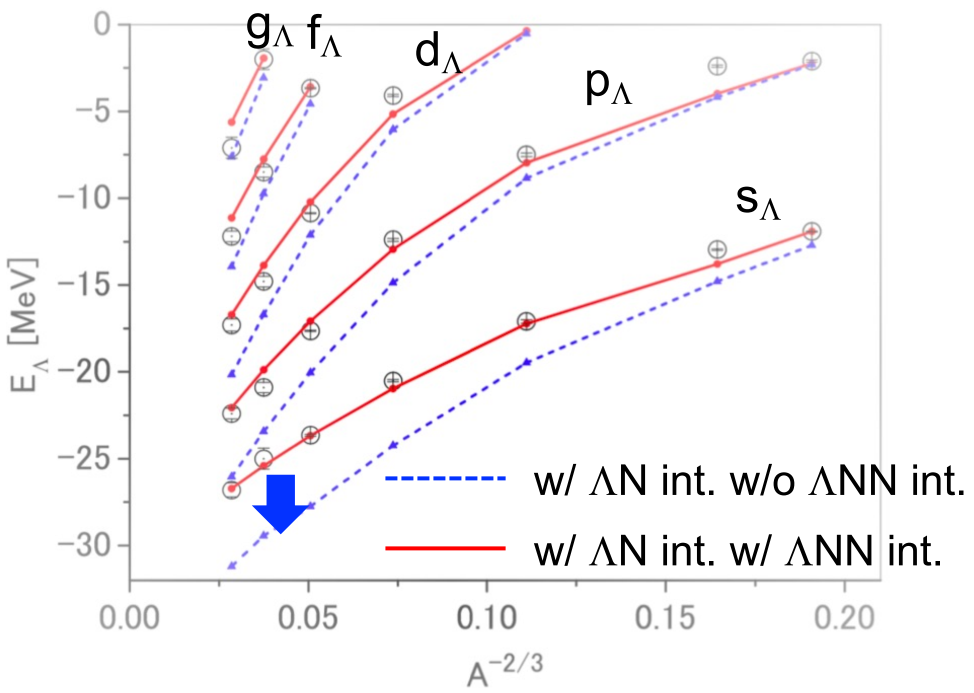
Energy spectra of $^{13}_{\Lambda}C$, $^{16}_{\Lambda}O$, $^{28}_{\Lambda}Si$, $^{51}_{\Lambda}V$, $^{89}_{\Lambda}Y$, $^{139}_{\Lambda}La$, $^{208}_{\Lambda}Pb$ with Nijmegen ESC16 model

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



Calculation w/ only ΛN int : Over bound

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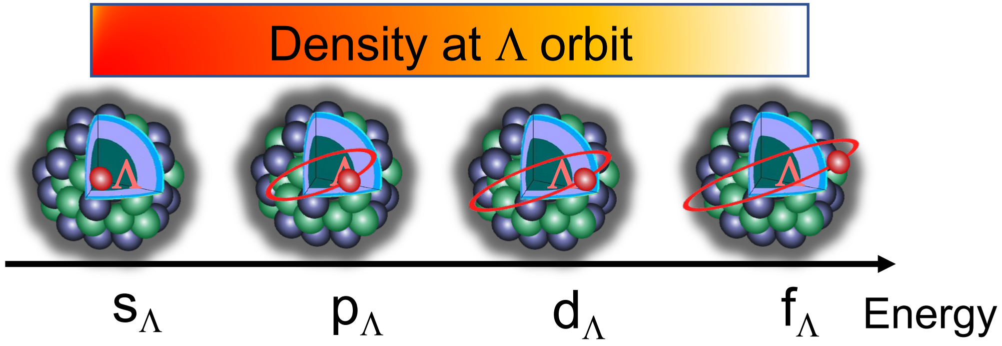

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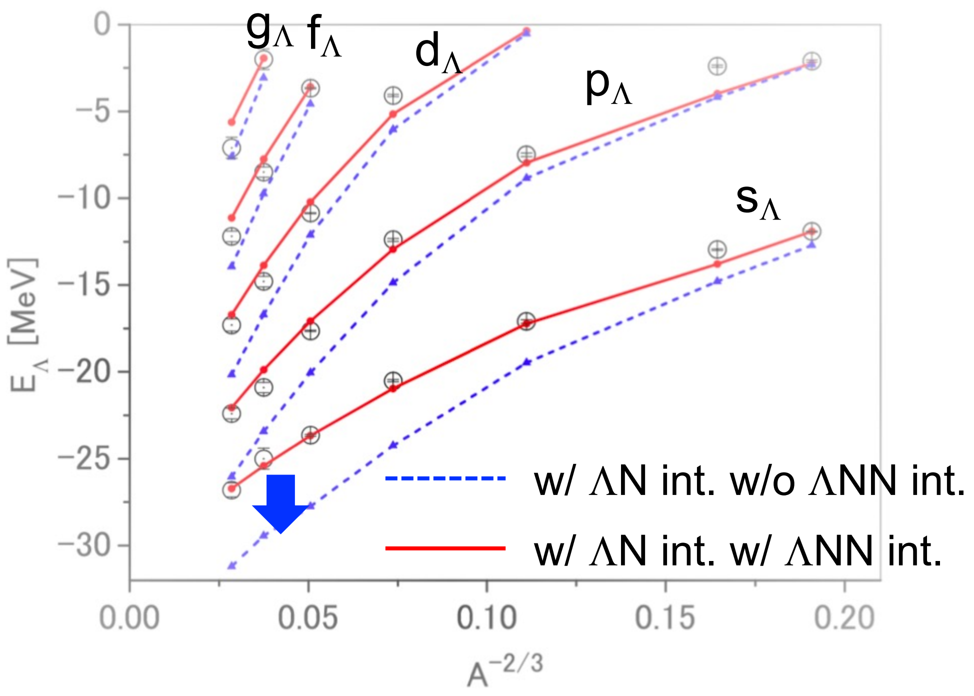
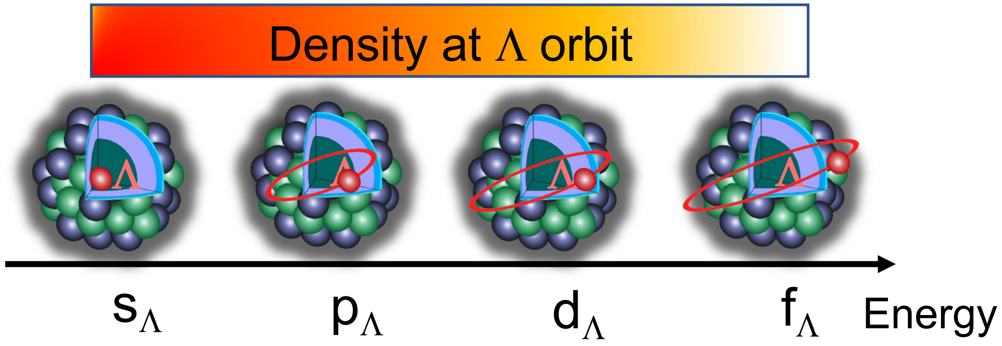


Accurate B_Λ measurement ⟵ **Difference** ⟶ **Calculation w/ only ΛN int : Over bound**

Effect of **density dependence of ΛN interaction**

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

Nuclear density is different for each Λ orbital state



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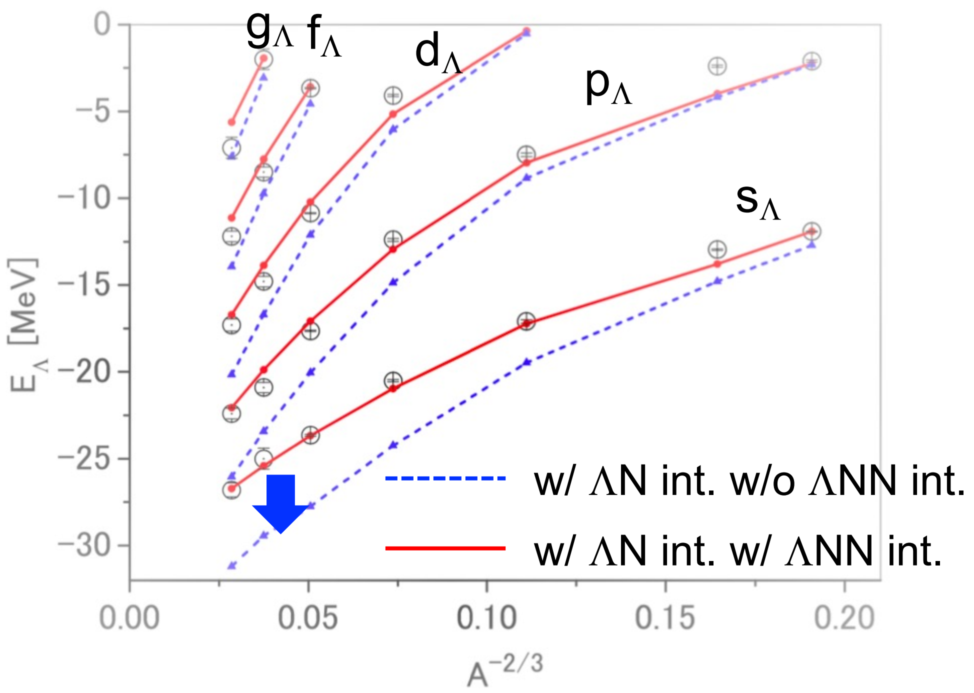


Accurate B_Λ measurement ⟷ **Difference** ⟷ **Calculation w/ only ΛN int : Over bound**

Effect of **density dependence of ΛN interaction**

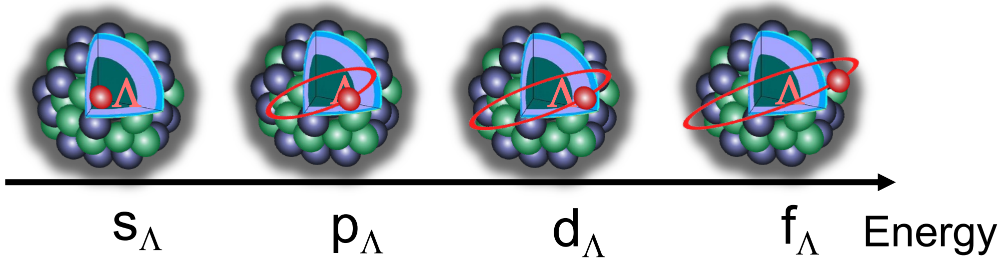
This density dependence should be explained from ΛNN force.

→ Predict ΛN int. in higher density nuclear matter.

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

Nuclear density is different for each Λ orbital state

Density at Λ orbit



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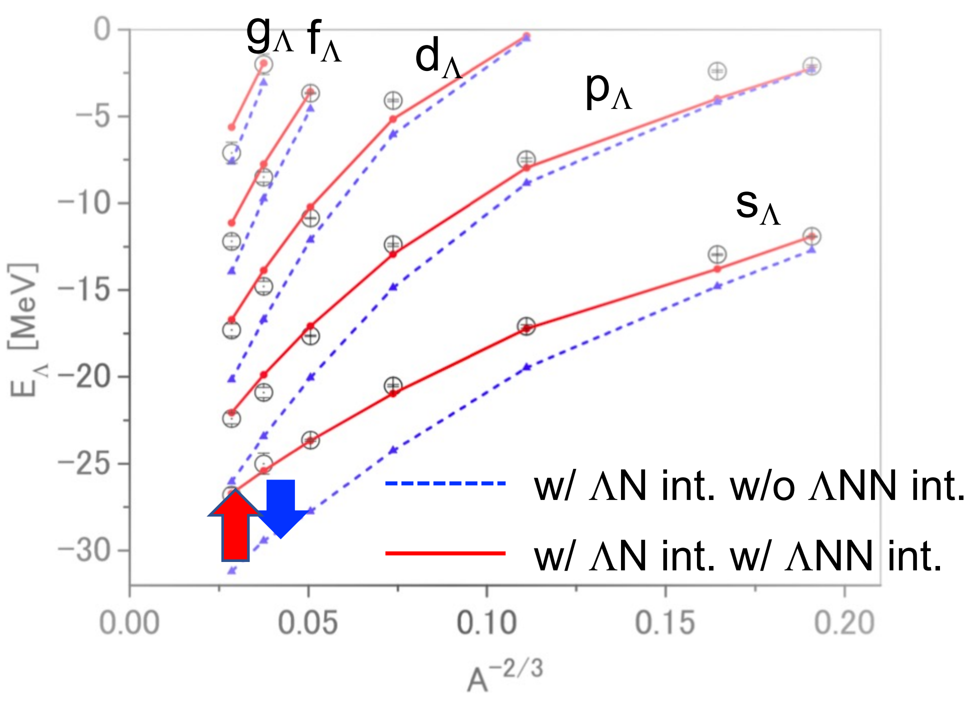


Difference

Accurate B_Λ measurement ⟷ **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

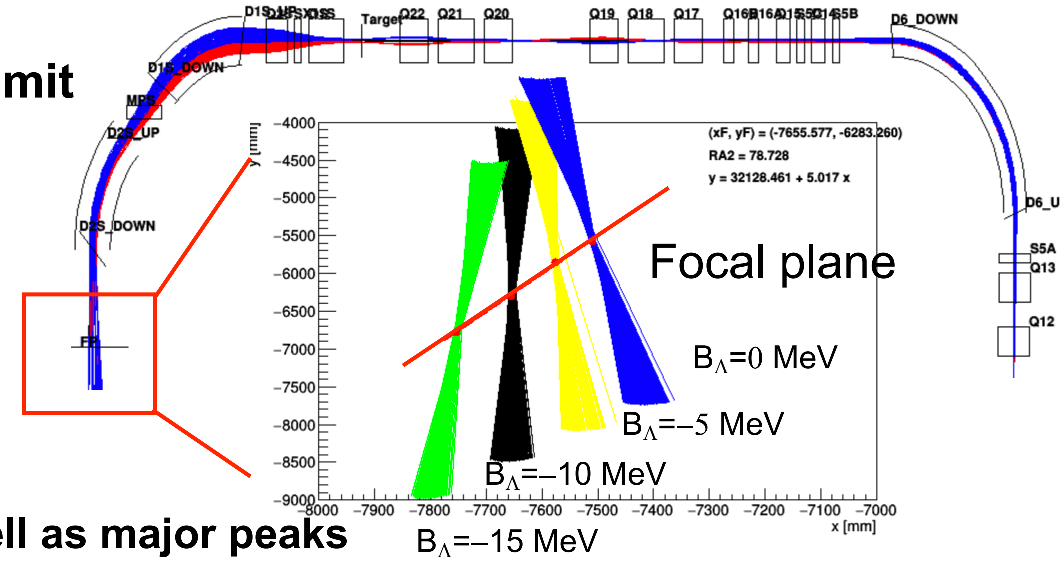
→ Realize **high-resolution** spectroscopy **without beam intensity limit**

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

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

- Thin target can be used

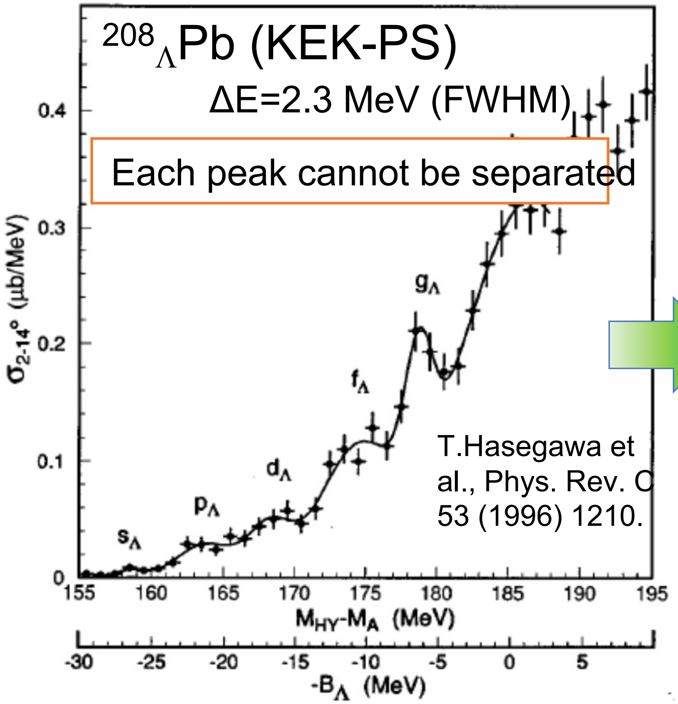
→ High resolution and various target options

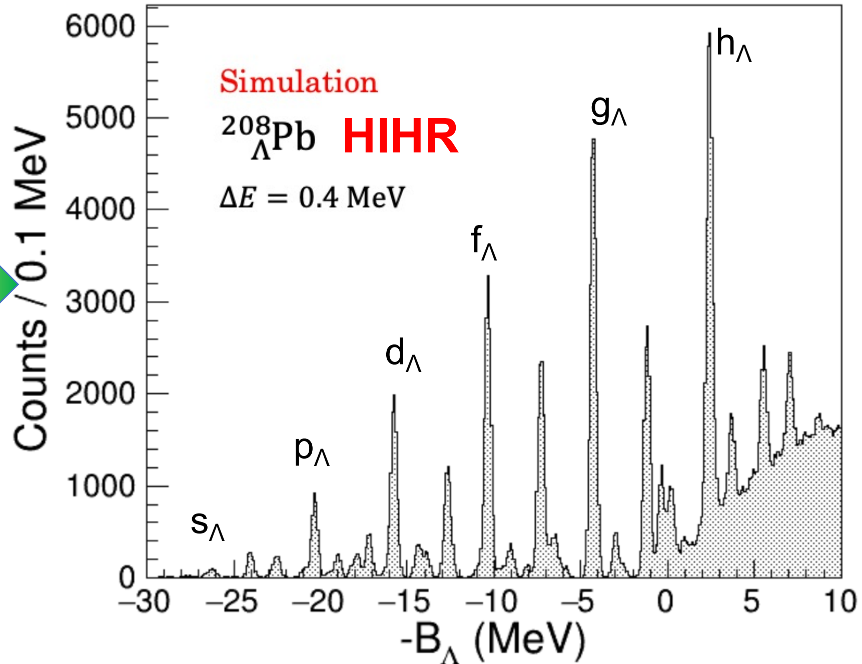


Impossible to separate peaks with a few MeV resolution

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)

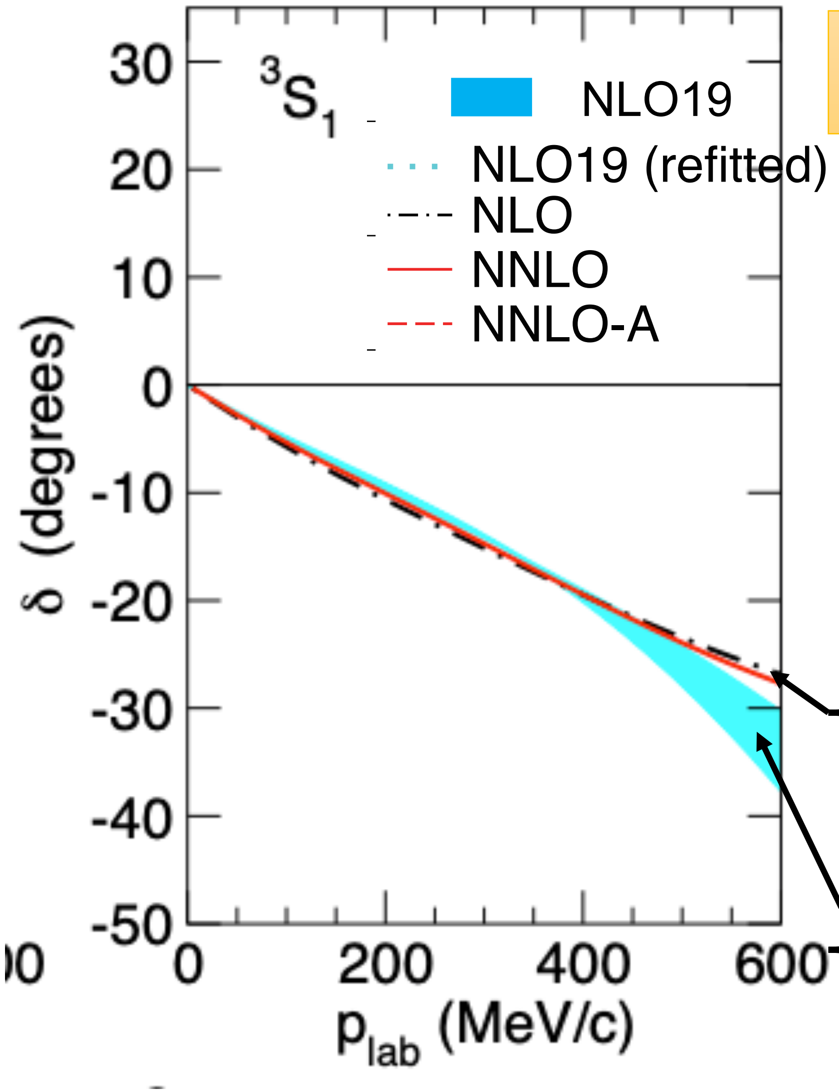
Calculate U_Λ at high density region

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, Σ^-p→Λn scatterings with ~10% level accuracy for fine angular pitch (dcosθ=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.

Phase shift in Chiral EFT NNLO and U_Σ



J. Haidenbauer et al., arXiv:2301.00722

Based on the E40 Σ^+p phase shift, U_Σ becomes less repulsive.

$^3_\Lambda H$

YN potential	B_Λ [MeV]	E [MeV]	P_Σ [%]	$U_\Lambda(0)$	$U_\Sigma(0)$
SMS N²LO(500)	0.147	−2.371	0.25	−33.1	6.4
SMS N²LO(550)[a]	0.139	−2.362	0.25	−38.5	2.5
SMS N²LO(550)[b]	0.125	−2.348	0.24	−35.9	2.5
SMS N²LO(600)	0.172	−2.395	0.22	−37.8	0.1
NLO13(600)	0.090	−2.335	0.25	−21.6	17.1
NLO19(600)	0.091	−2.336	0.21	−32.6	16.9

ΣN (I=3/2) phase shift in chiral EFT