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Baryon2022

Studies of baryon-baryon interaction at J-PARC

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1. Introduction

Emergence of “nuclear force”

How can we describe and understand Nuclear Force?

Strong interaction between colorless compound objects = complicated!

- **Meson exchange picture (Yukawa)**

  One Pion Exch for a long range (>2fm)

  -> OBE models (Bonn, Nijmegen,..)

  Phenom. models (AV18,…)

  "Realistic Nuclear Force"

- **Chiral Effective Field Theory**

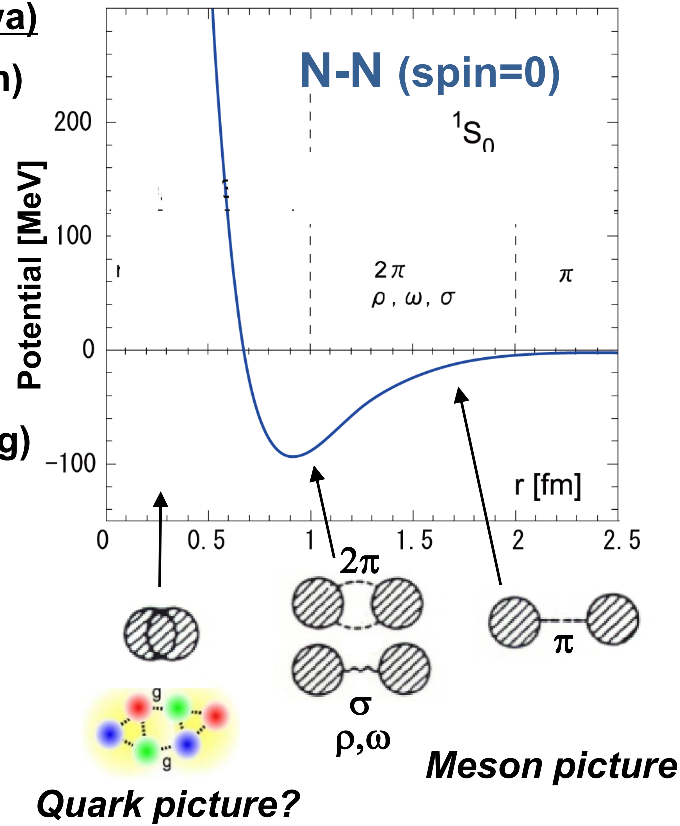
  Pion exch + contact terms (Weinberg)

- **Quark picture** for short ranges

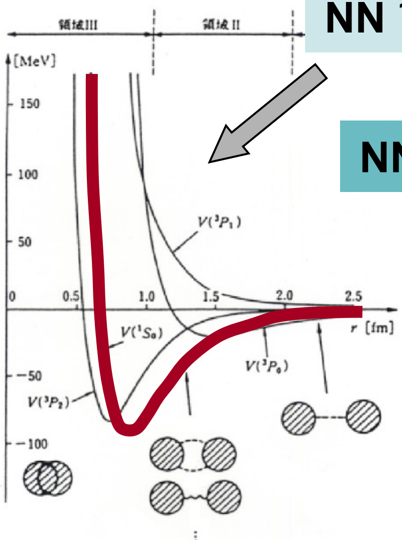
  Quark Cluster Model (Oka-Yazaki)

- **Lattice QCD** (HAL QCD, NPLQCD)

  Only 3 or 4 parameters



Extension of NN to BB interactions

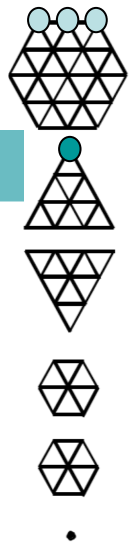


NN $^1S_0$

NN $^3S_1$

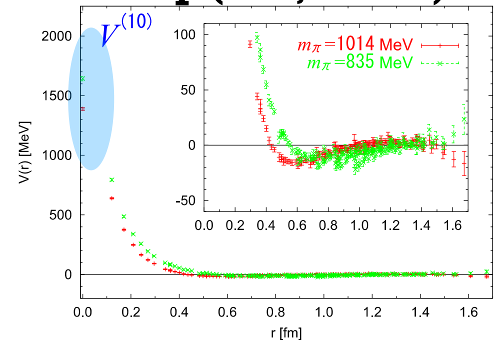
B_8B_8 forces

$8 \otimes 8 =$



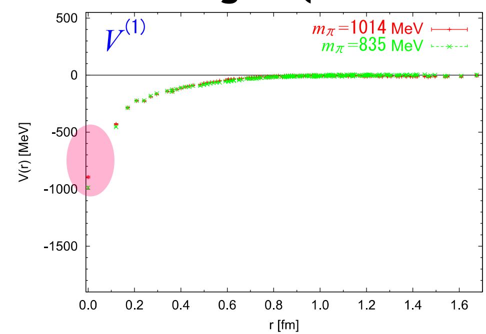
Strong repulsive core

Σ^+p (S=1, T=3/2)



Attractive Core

Flavor singlet (H-Channel)



HAL QCD (T. Inoue et al.)
Prog. Theor. Phys. 124 (2010) 4

Origin of the short range BB forces? J-PARC's challenge

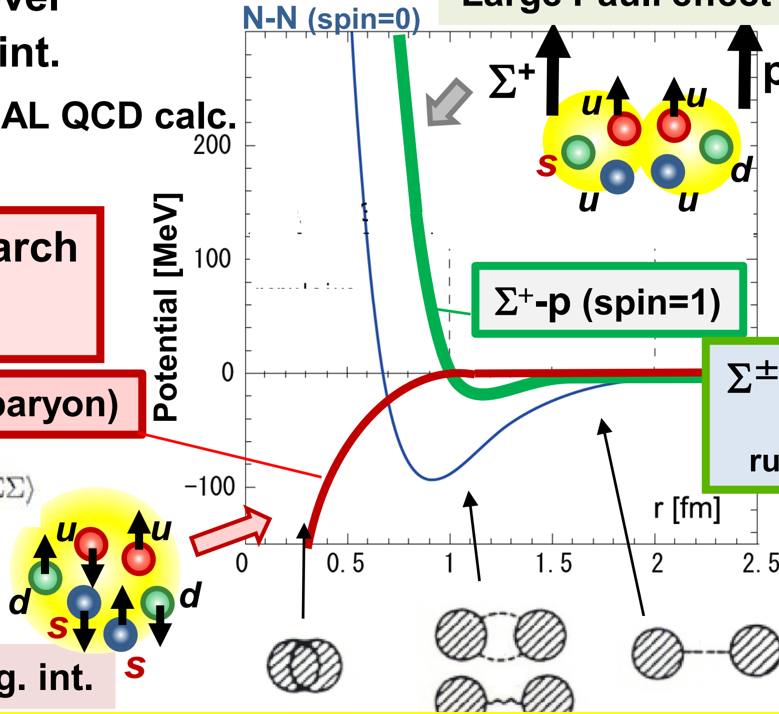
Quark Cluster Model (Oka-Yazaki)

- Pauli in quark level
- Color magnetic int.

→ consistent with HAL QCD calc.

Very strong repulsive core?

Large Pauli effect in quark level



H dibaryon search
J-PARC E42
run in 2021

flavor singlet (H-dibaryon)

$$-\sqrt{\frac{1}{8}}|\Lambda\Lambda\rangle + \sqrt{\frac{4}{8}}|N\Xi\rangle + \sqrt{\frac{3}{8}}|\Sigma\Sigma\rangle$$

Attractive core?

No Pauli

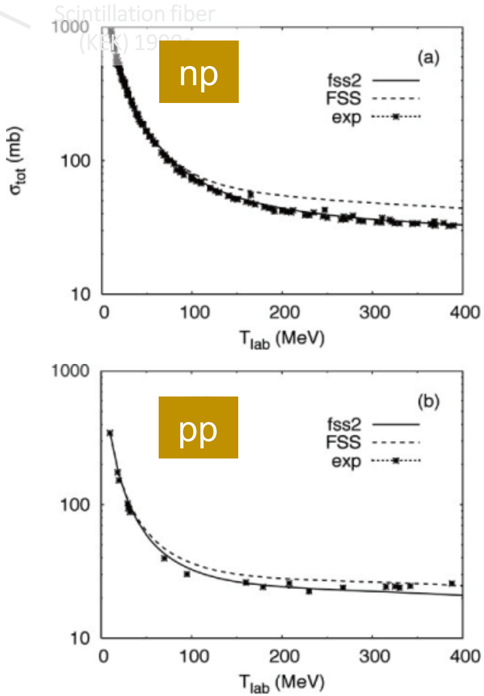
Attractive color mag. int.

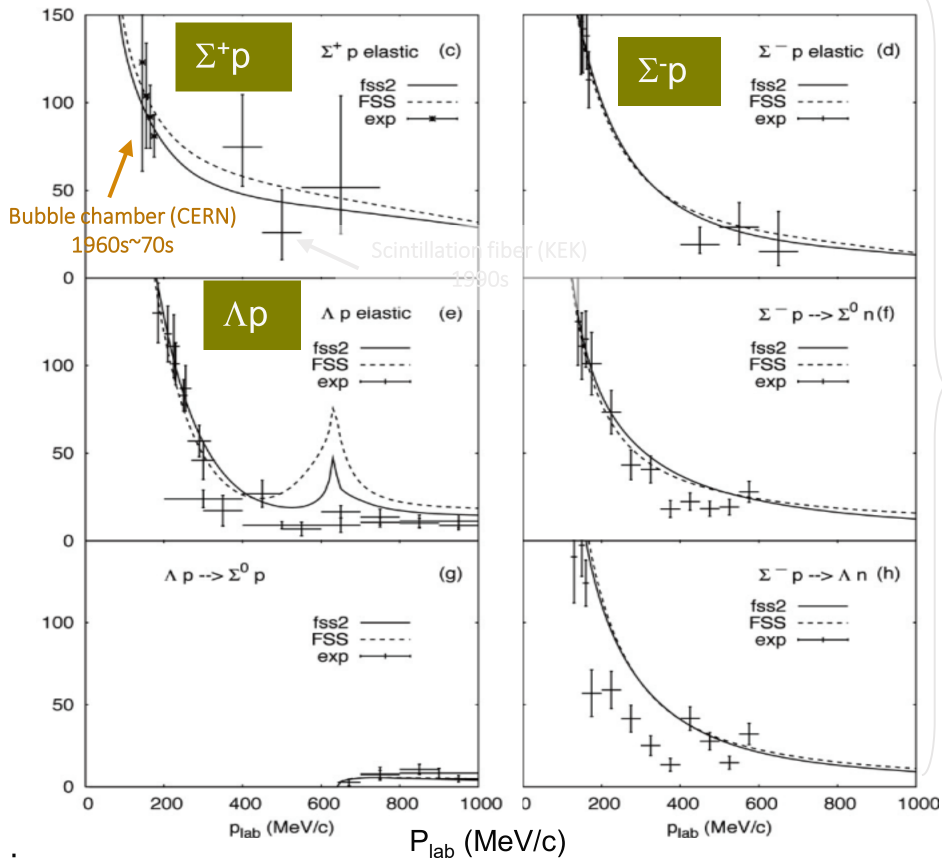
$\Sigma^{\pm}$p scattering
J-PARC E40
run in 2018-2019

Strange quarks provide clues to understand the short range force

NN and YN scattering data

Total cross sections





dσ/dΩ, spin observables
for wide momenta
-> precise phase shift analysis

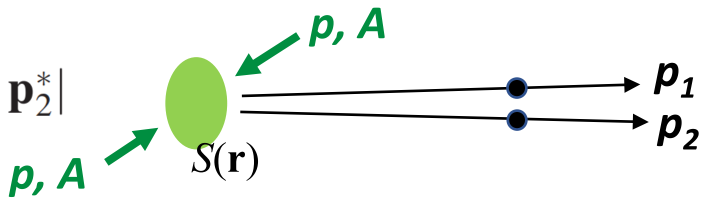
Almost no dσ/dΩ data -> No phase shifts

"Femtoscopy" : BB interaction from BB correlation

$$C(k^*) = \mathcal{N}\frac{A(k^*)}{B(k^*)}, \text{ where } k^* = \frac{1}{2}\left|\mathbf{p}_1^* - \mathbf{p}_2^*\right|$$

same event

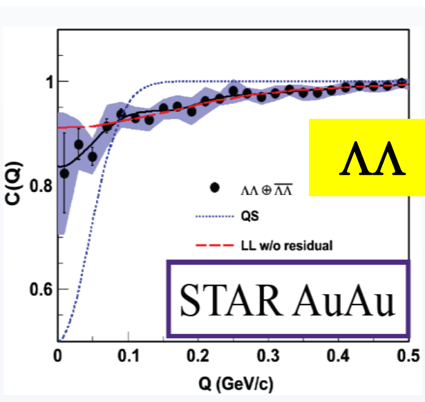
different event



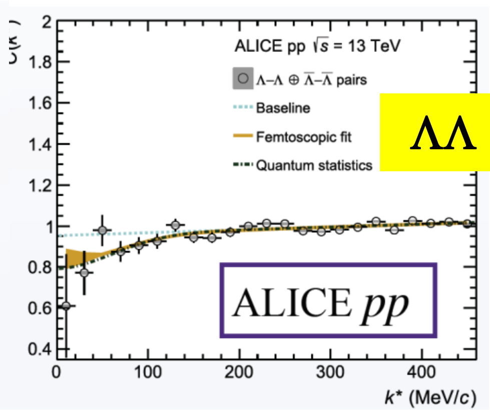
$$C(\mathbf{q}) = \int d^3r\, S(\mathbf{q},\mathbf{r}) \left|\psi_{12}^{(-)}(\mathbf{r};\mathbf{q})\right|^2$$ **int. → relative w.f.**

$$\simeq 1\left[-\frac{1}{2}\exp(-4q^2R^2)\right] + \frac{1}{2}\int d^3r S_{12}(\mathbf{r})\left[|\chi_0(r)|^2 - |j_0(qr)|^2\right]$$

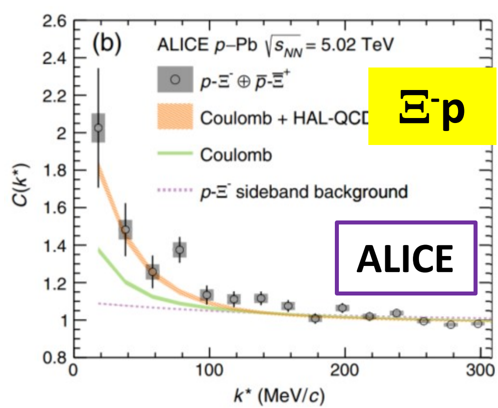
Fermion **Source** **w.f.** **free**



PRL 114 (2015) 022301



PLB 797 (2019) 13482



PRL 12 (2019) 112002

Experimental status of BB interactions

★ personal ratings

	NN	ΛN	ΣN	ΞN	ΛΛ
Scattering data	★★★★★ ~4000 points high stat. phase shifts	★★ poor stat. only σ_{tot} *PRL 127, 272303*	★ poor stat. ~only σ_{tot}	—	—
Nuclear data Indirect (many-body effects) Info. for low momenta	★★★★★ (~3000)	★★★ ~40	★ 1	★ ~2	★ 1
Femtoscopy data s-wave/ low momenta	(reference)	★★	★	★	★

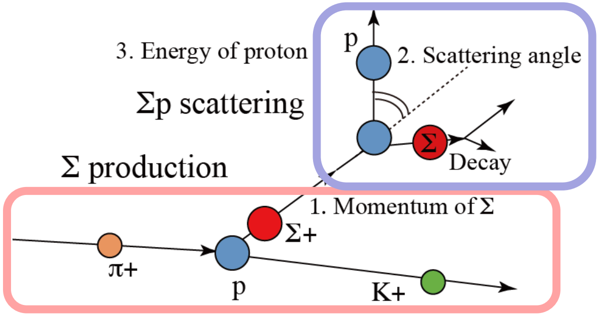
- Due to difficulties in YN scattering experiments, YN, YY interactions have been long studied based on SU(3)f + hypernuclear data -> not accurate
- For high density matter in neutron stars, YN, YY int. *in medium* should be understood. → Both **2-body data in free space + nuclear data** necessary

  YN scattering data -> phase shifts strongly required.

  Femtoscopy data : powerful for s-wave / low-momentum int. and YY int.

2. $\Sigma^{\pm}p$ scattering
(J-PARC E40)

$\Sigma^{\pm}$p Scattering J-PARC E40 (Miwa et al.)



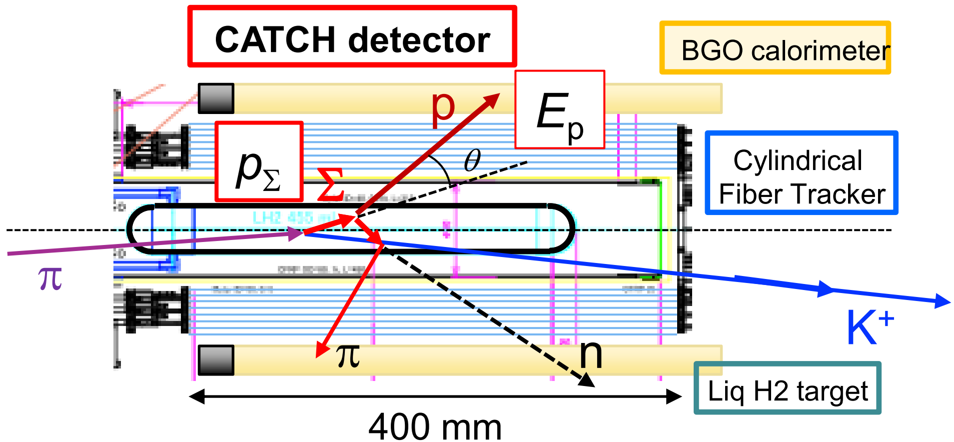
$\pi^{\pm}p \rightarrow K^{+}\Sigma^{\pm}$, p_{Σ} = 0.4--0.8 GeV/c

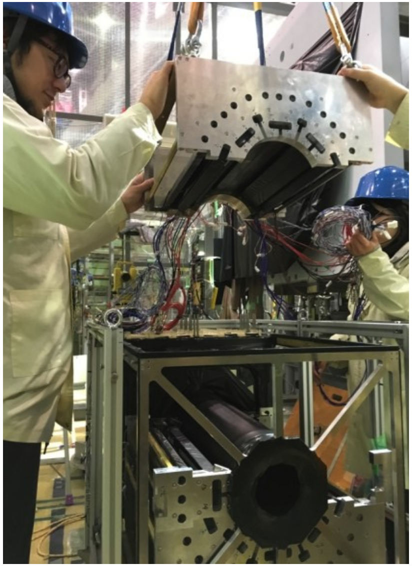
Event selection via kinematical matching

Measure $d\sigma/d\Omega$ for $\Sigma^{+}p$, $\Sigma^{-}p$, $\Sigma^{-}p \rightarrow \Lambda n$

10^{4} scattering events (x100 than before)

Dedicated "fast" detector system, CATCH
(scint. fiber + SiPM + fast DAQ)

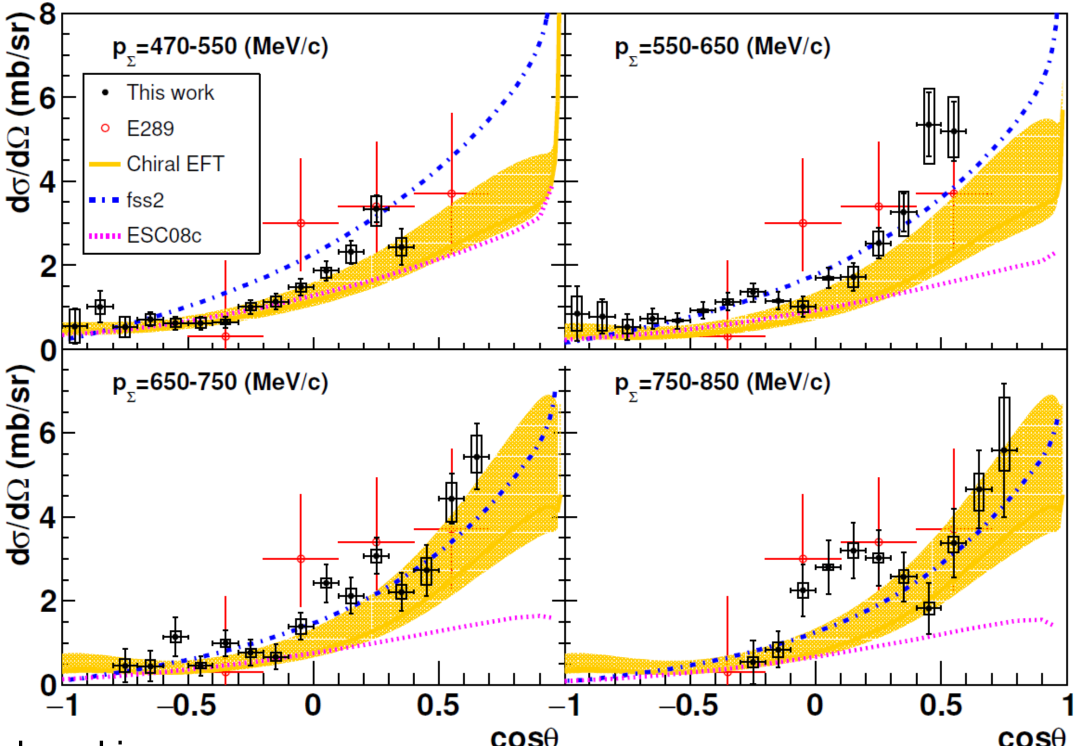




Σ^-p elastic scattering

$\Sigma^-p \to \Sigma^-p$

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

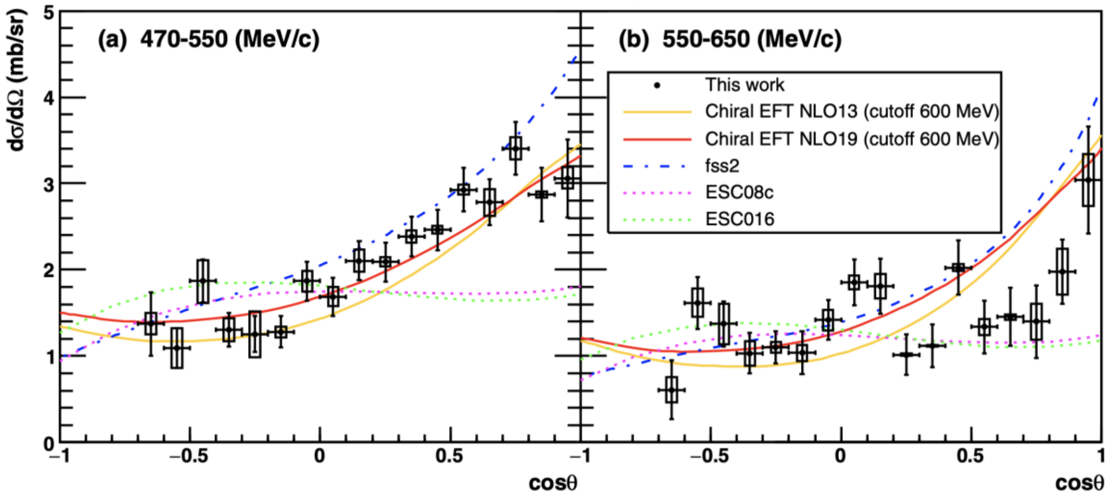


Forward peaking,
almost consistent with ChEFT (Haidenbauer et al.) and a quark model (fss2) but not with a Nijmegen model (ESC08c).

Σ⁻p→Λn inelastic scattering

$\Sigma^{-}p \rightarrow \Lambda n$

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



Moderately forward peaking,

almost consistent with ChEFT and a quark model (fss2)

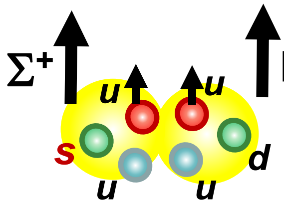
but not with a Nijmegen model (ESC08c).

Σ^+p elastic scattering

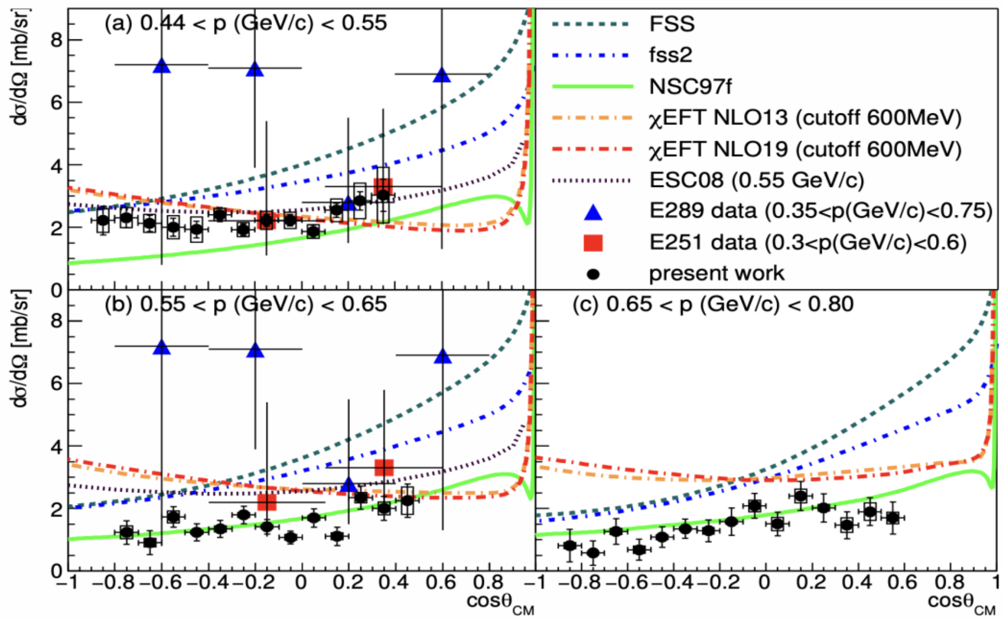
T. Nanamura et al., Prog. Theor. Exp. Phys. ***2022*** *093D01*

$\Sigma^+ p \rightarrow \Sigma^+ p$

Strong repulsion in 3S1 via **quark Pauli effect**
→ Larger $d\sigma/d\Omega$ (fss2)



Σ^+-p (spin=1)



- Quark models (fss2, FSS) overestimate $d\sigma/d\Omega$.
- ChEFT models do not agree for > 0.55 GeV/c.
- Nijmegen (ESC) models are rather consistent.

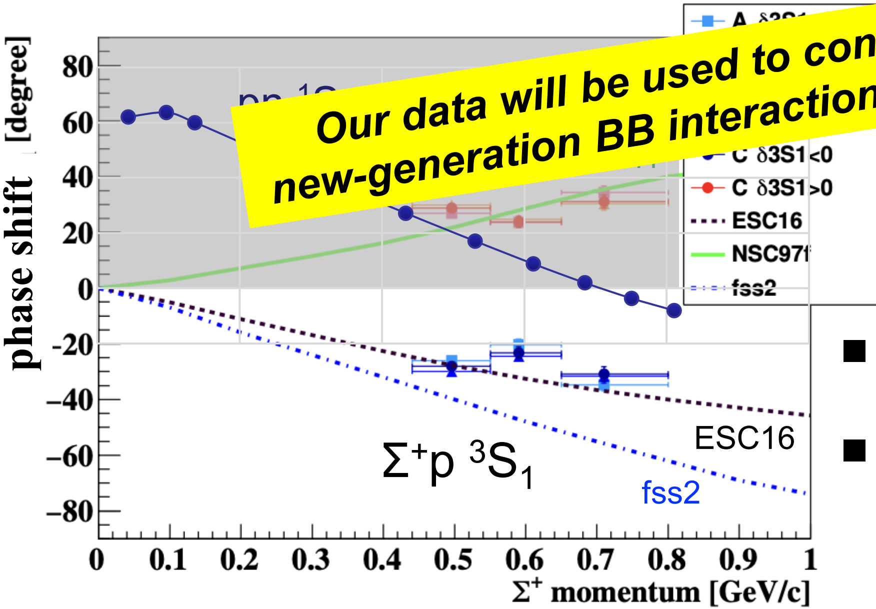
The first phase shift result in YN scattering

$\Sigma^+ p \rightarrow \Sigma^+ p$

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

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

- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
- $\delta(^1S_0)$ and other phase shifts up to D wave : fixed on pp scat. or NSC97f, ESC16
  27-plet, similar to pp



Our data will be used to construct new-generation BB interaction models.

Hypernuclear experiments
...rongly repulsive
...n-averaged ΣN

PRL 89 (2002) 072301
PRC 96 (2017) 014005

Large weight for (T,S)=(3/2,1)
(3/2,1):(3/2,0):(1/2,1):(1/2,0)
= 6:2:3:1

- **Stronger repulsive core than NN**
- **Not as repulsive as a quark model prediction (fss2)**

Consistent with HAL QCD calc.
=> Aoki's talk

The first phase shift result in YN scattering

$\Sigma^+p \to \Sigma^+p$

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

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

- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
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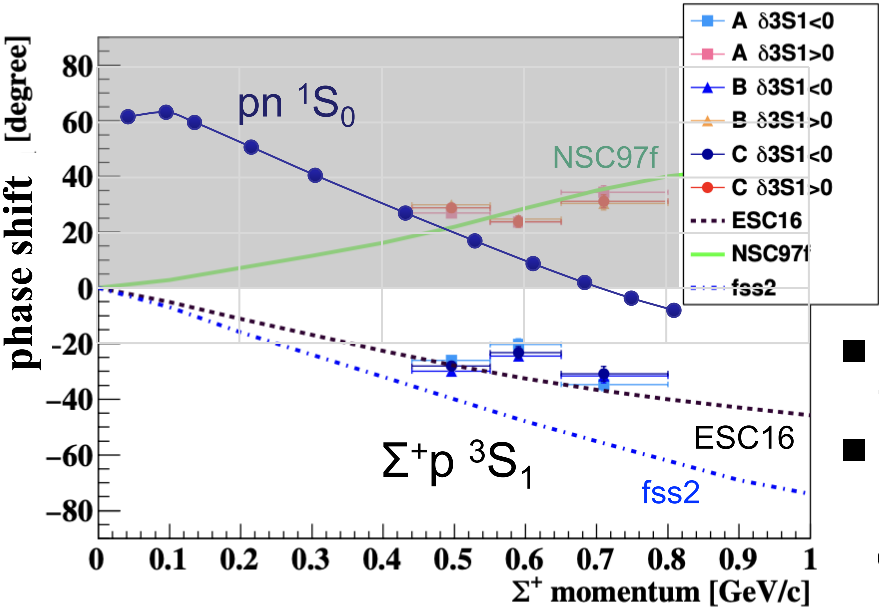


Hypernuclear experiments indicate strongly repulsive spin-isospin-averaged ΣN force

PRL 89 (2002) 072301

PRC 96 (2017) 014005

Large weight for (T,S)=(3/2,1)

(3/2,1):(3/2,0):(1/2,1):(1/2,0) = 6:2:3:1

- **Stronger repulsive core than NN**
- **Not as repulsive as a quark model prediction (fss2)**

Consistent with HAL QCD calc.
=> Aoki's talk

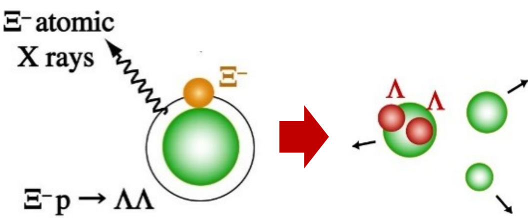
3. Doubly strange hypernuclei (J-PARC E07)

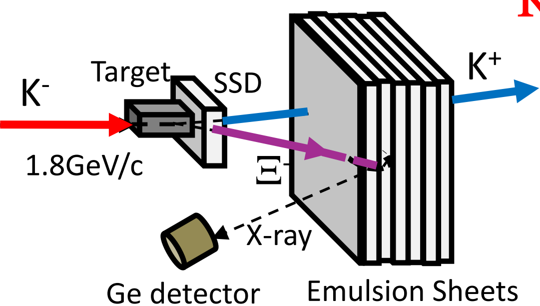
S=-2 emulsion experiment

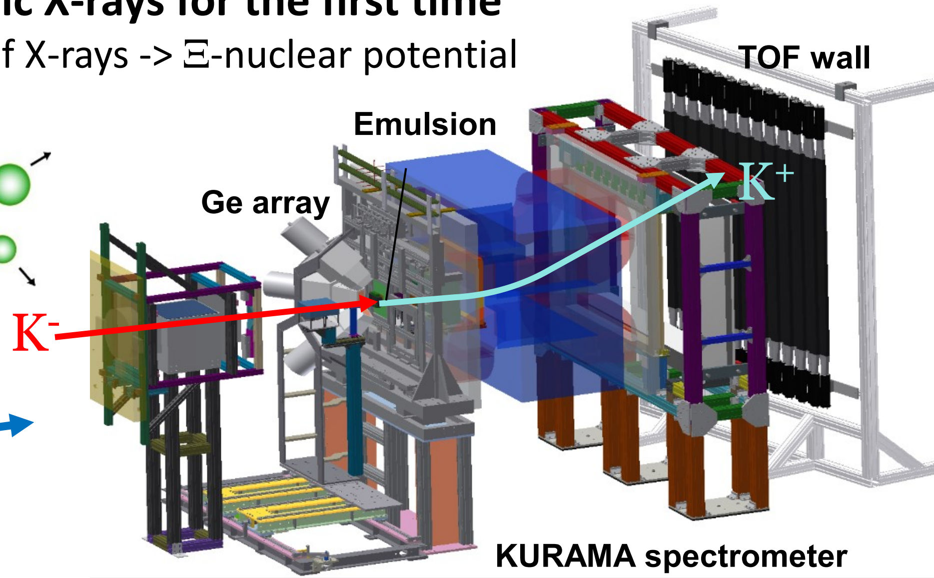
J-PARC E07 Nakazawa et al.

- **Emulsion-counter hybrid method**
- **Collect ~10^2 doubly strange ($\Lambda\Lambda$ and Ξ) hypernuclei**

  $\Lambda\Lambda$ and ΞN interactions, $\Lambda\Lambda$–ΞN interaction
- **Measure Ξ^- -atomic X-rays for the first time**
  - Shift and width of X-rays -> Ξ-nuclear potential





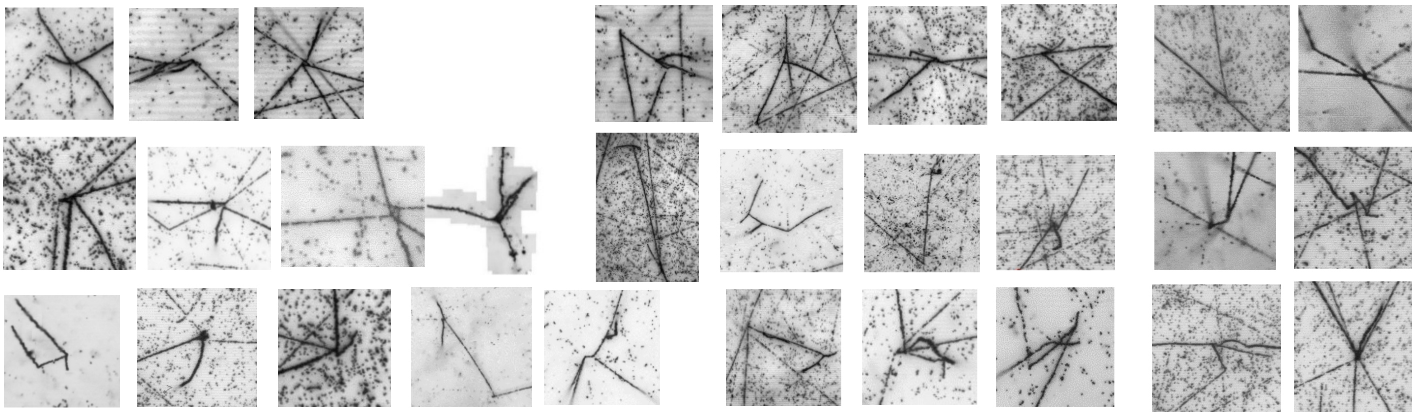


Beam exposure finished in 2017. The 1st stage emulsion analysis finished.

Observed doubly strange events

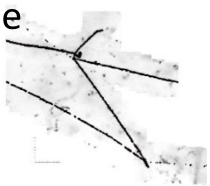
Slide by J. Yoshida

33 events in J-PARC E07 + 14 events in previous KEK experiments



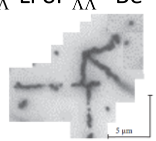
Double Λ hypernuclear events

${}_{\Lambda\Lambda}$Be



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

${}_{\Lambda\Lambda}^{8}$Li or ${}_{\Lambda\Lambda}^{10}$Be

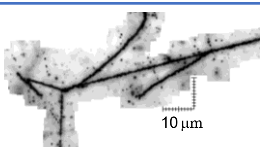


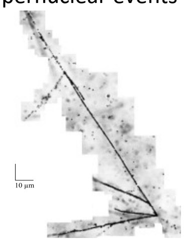
Nyaw, A. N. L. et al., Bull. Soc. Photogr. Imag. Japan 30, 22– 25 (2020)

Ξ hypernuclear events

${}_{\Xi}^{15}$C

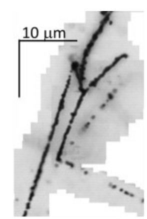
K. Nakazawa, et al., Prog. Theor. Exp. Phys. 2015, 033D02 (2015)

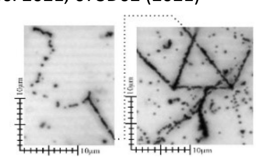




S. H. Hayakawa, et al., Phys. Rev. Let., 126, 062501 (2021)

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





Unambiguous determination of B_{Ξ} of Ξ hypernucleus

$\Xi^- + {}^{14}N \rightarrow {}^{15}_{\Xi}C \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$

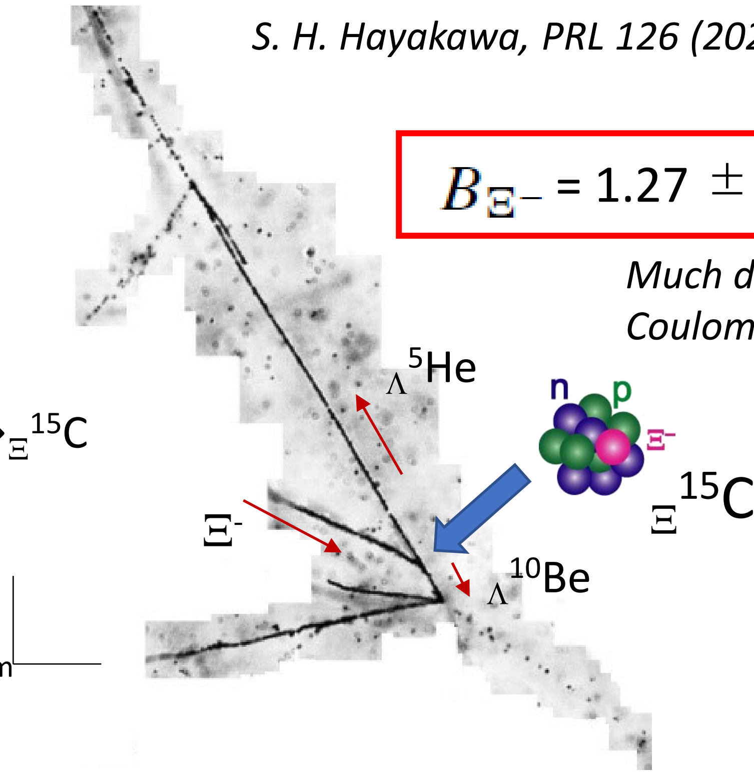
S. H. Hayakawa, PRL 126 (2021) 062501

IBUKI event
(J-PARC E07)

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

Much deeper than the Coulomb binding energy

$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$



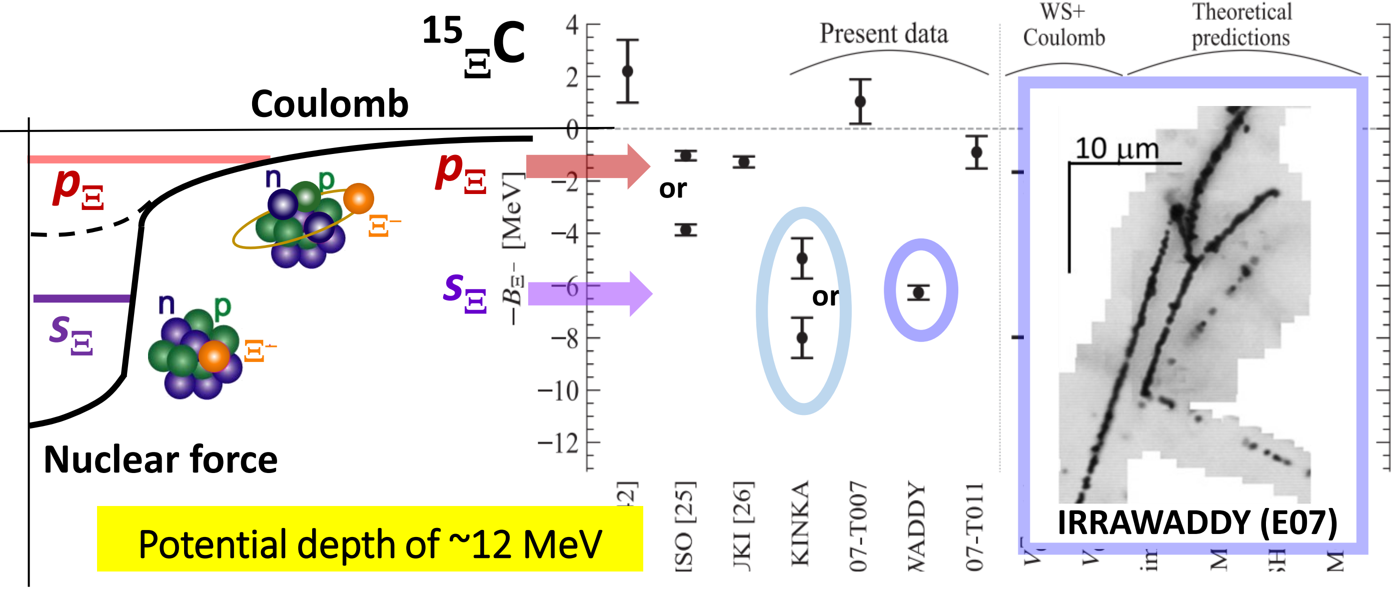
First observation of *s*-state Ξ hypernucleus

$\Xi^- + {}^{14}N \rightarrow {}^{15}{}_{\Xi}C$

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

IRRAWADDY (E07) ${}^{5}{}_{\Lambda}He + {}^{5}{}_{\Lambda}He + {}^{4}He + n$: 6.27 ± 0.27 MeV

KINKA (KEK E373) ${}^{9}{}_{\Lambda}Be + {}^{5}{}_{\Lambda}He + n$: 8.00 ± 0.77 or 4.96 ± 0.77 MeV



Potential depth of ~12 MeV

ΞN→ΛΛ strength in Nijmegen models = > Ξ absorption mainly at 3D orbit

Observation of s states suggests **a very weak ΞN→ΛΛ interaction**

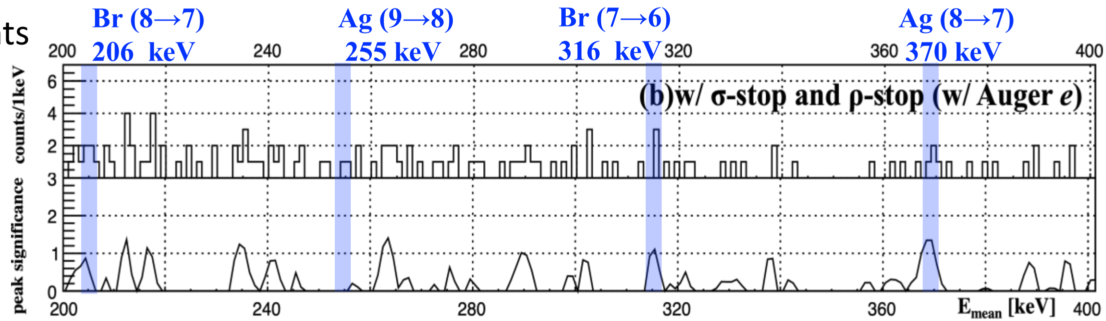
More S=-2 studies are going on at J-PARC

Ξ^- atomic X-rays (E07, E03, E96)

Two experiments done, under analysis, not yet observed

E07 "Reaction-Xray-Emulsion" triple-coincidence hybrid method

Ξ absorption events selected via emulsion image analysis



H dibaryon search via H->ΛΛ (E42)

Data successfully taken in 2021, under analysis

Spectroscopy of Ξ hypernuclei via $^{12}C(K^-,K^+)$ $^{12}_{\Xi}Be$ (E70)

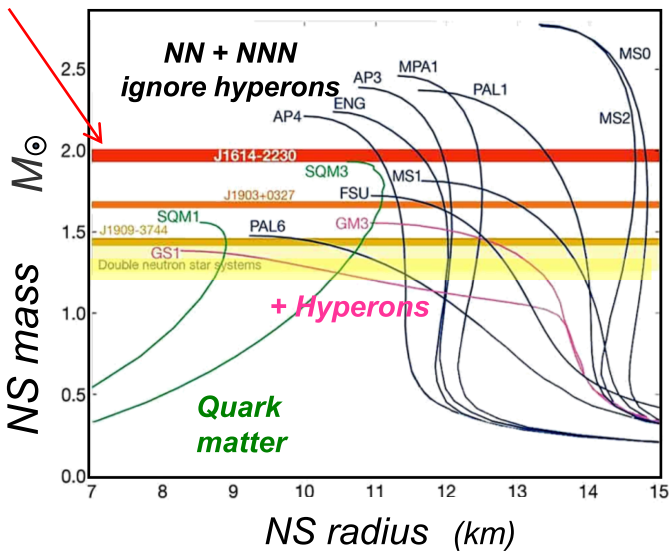
Run in 2023, a new spectrometer (S-2S) installed, under preparation

4. Future plans for ΛNN interaction and neutron stars

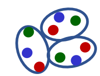
Hyperon puzzle in neutron stars

- Huge Fermi energy of neutrons + attractive $\Lambda N/\Xi N$ forces
  => Hyperons (Λ, Ξ^-) <u>should appear</u> at ρ ~ 2-3 ρ_0
- EOS's with hyperons too soft to support massive NS's of >1.5 M_{sun}

1.97±0.04 M_{sun} J1614-2230 (2010)
2.01±0.04 M_{sun} J0348-0432 (2013)
2.14±0.10 M_{sun} J0740-6620 (2020)



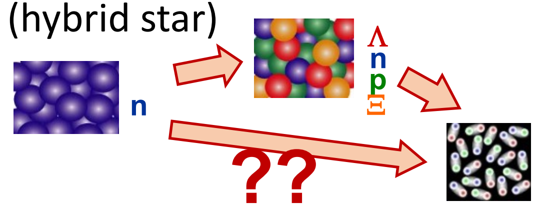
How to solve the puzzle?



- Strong repulsion at high ρ ?
  Repulsive three-body force in NNN
  => Also in <u>YNN, YYN, YYY</u> ?

  but no experimental evidence at all

- Phase transition to quark matter?
  (hybrid star)



We need YN, YY interactions both in <u>free space</u> + in <u>nuclear medium</u>

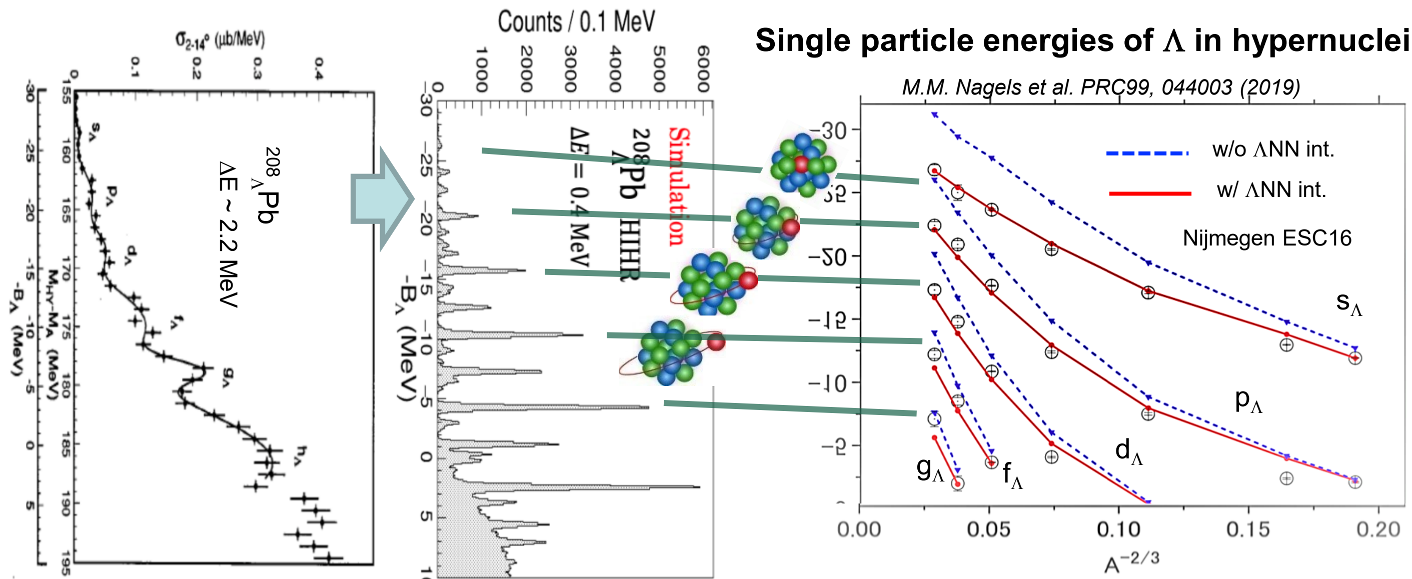
Our approach to the hyperon puzzle

High-quality ΛN scattering data -> Construct SU(3)f chiral EFT force

High-resolution Λ hypernuclear spectroscopy
-> Extract strength of ΛNN repulsion

- Λ is distinguishable from nucleons. No Pauli.
- We know the local density where the Λ is located.
- Different mass numbers, orbitals -> probe different densities

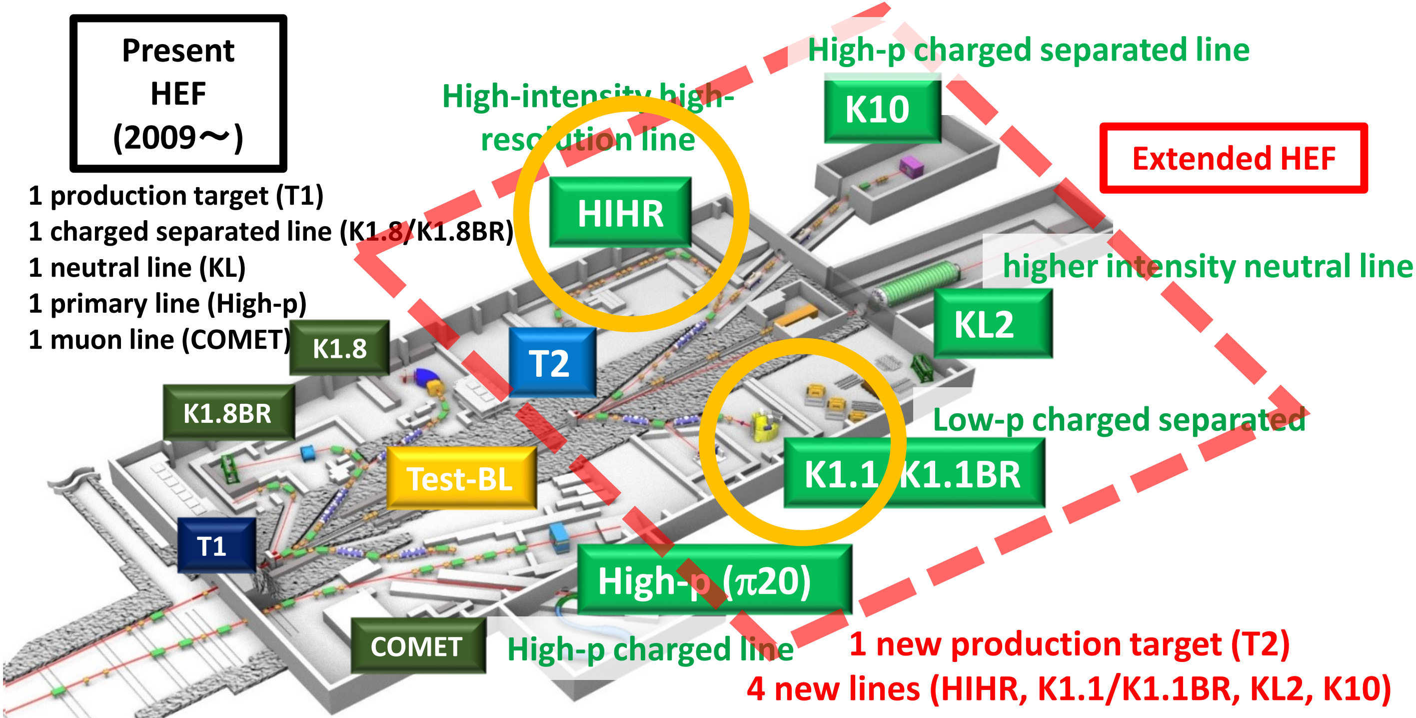
Hyperons are special in nuclear matter !



J-PARC Hadron Experimental Facility extension Project (HEF-ex)

Present HEF (2009～)

1 production target (T1)
1 charged separated line (K1.8/K1.8BR)
1 neutral line (KL)
1 primary line (High-p)
1 muon line (COMET)



1 new production target (T2)
4 new lines (HIHR, K1.1/K1.1BR, KL2, K10)
2 updated beamlines (High-p (π20), Test-BL)

Performance of HEF will be more than doubled

5. Summary

- $\Sigma^{\pm}$-p scattering experiment（J-PARC E40）
  - $d\sigma/d\Omega$ for $\Sigma^{-}p$ / $\Sigma^{+}p$ elastic, $\Sigma^{-}p \rightarrow \Lambda n$ with 10^2 times statistics
  - Phase shifts for $\Sigma^{+}p$ elastic scattering obtained. Strong repulsion confirmed but not as repulsive as a QM prediction.
- Doubly strange nuclei with emulsion (J-PARC E07)
  - $\Lambda\Lambda$ and Ξ hypernuclear data increased.
  - Several events of ${}^{15}_{\Xi}C$ observed, suggesting the first observation of s_{Ξ} states and a very weak $\Xi N \rightarrow \Lambda\Lambda$ interaction
- Other S=-2 experiments going on
  - Ξ-atomic X-rays, H search, (K^-,K^+)spectroscopy of Ξ hypernuclei
- Future plan to study ΛNN force for NS in the J-PARC Hadron Facility extension project