2019.12.1
EMMI workshop @Wraclow

Status and Perspective of Hypernuclear Physics at J-PARC

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Japan Atomic Energy Agency
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2. γ-ray spectroscopy of Λ hypernuclei
3. $\Sigma^{\pm}$p scattering
4. Double strangeness systems (Ξ and $\Lambda\Lambda$ hypernuclei)
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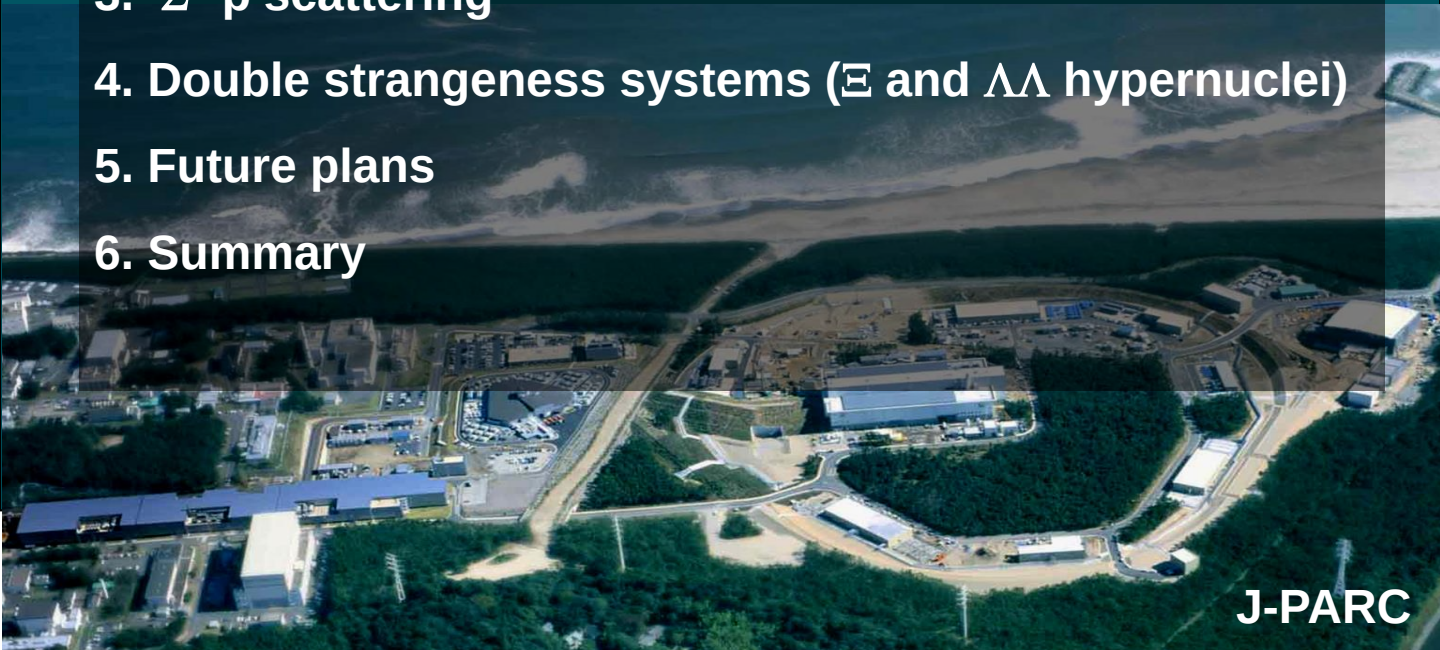


1. Introduction

Matter made of u, d, s quarks

Nu ~ Nd ~ Ns

metastable

Strange hadronic matter (A → ∞)

Compression by gravity => stable

p,n,Λ,Ξ^0,Ξ^-

3-dimensional nuclear chart

Matter made of u, d, s quarks

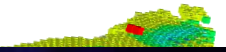
Nu ~ Nd ~ Ns

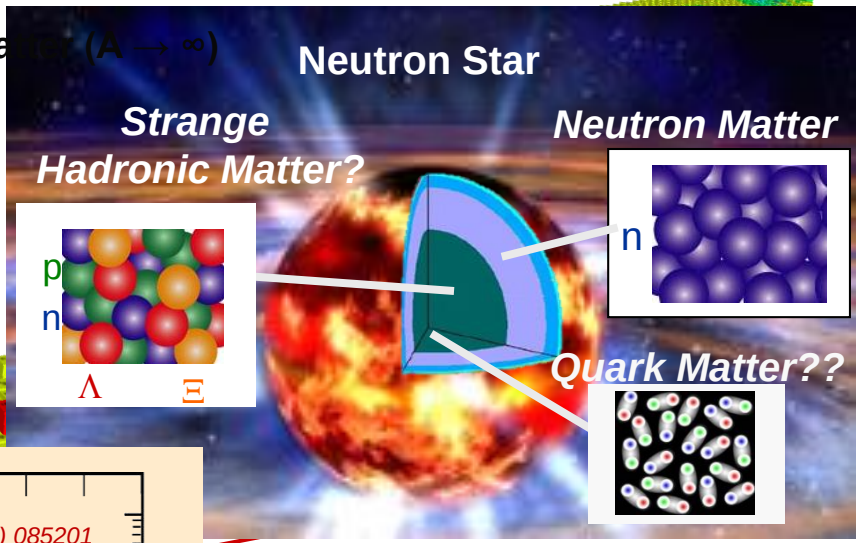
metastable

Strange hadronic ma… (A → ∞)

p,n,Λ,Ξ⁰,Ξ⁻

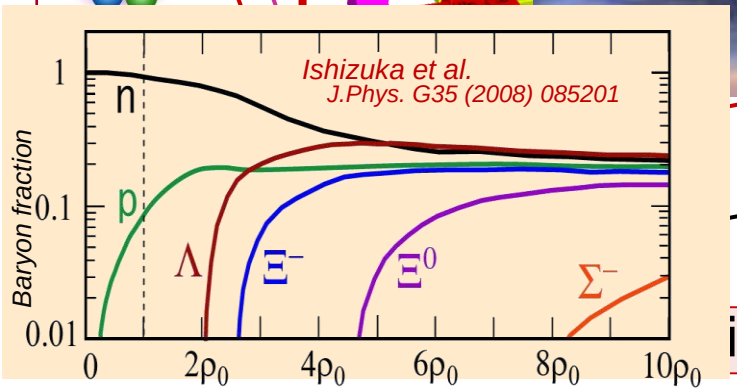
Compression by gravity => stable





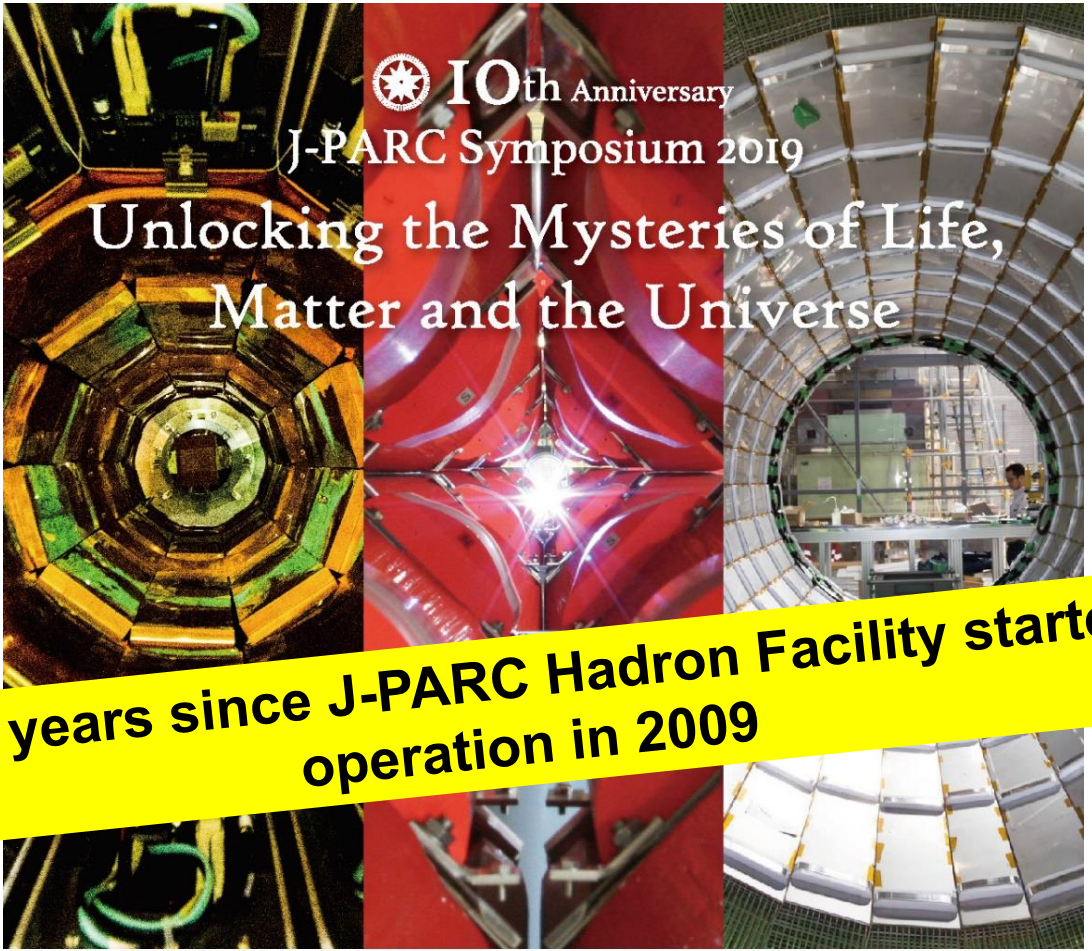
Strangeness

N



…ional nuclear chart

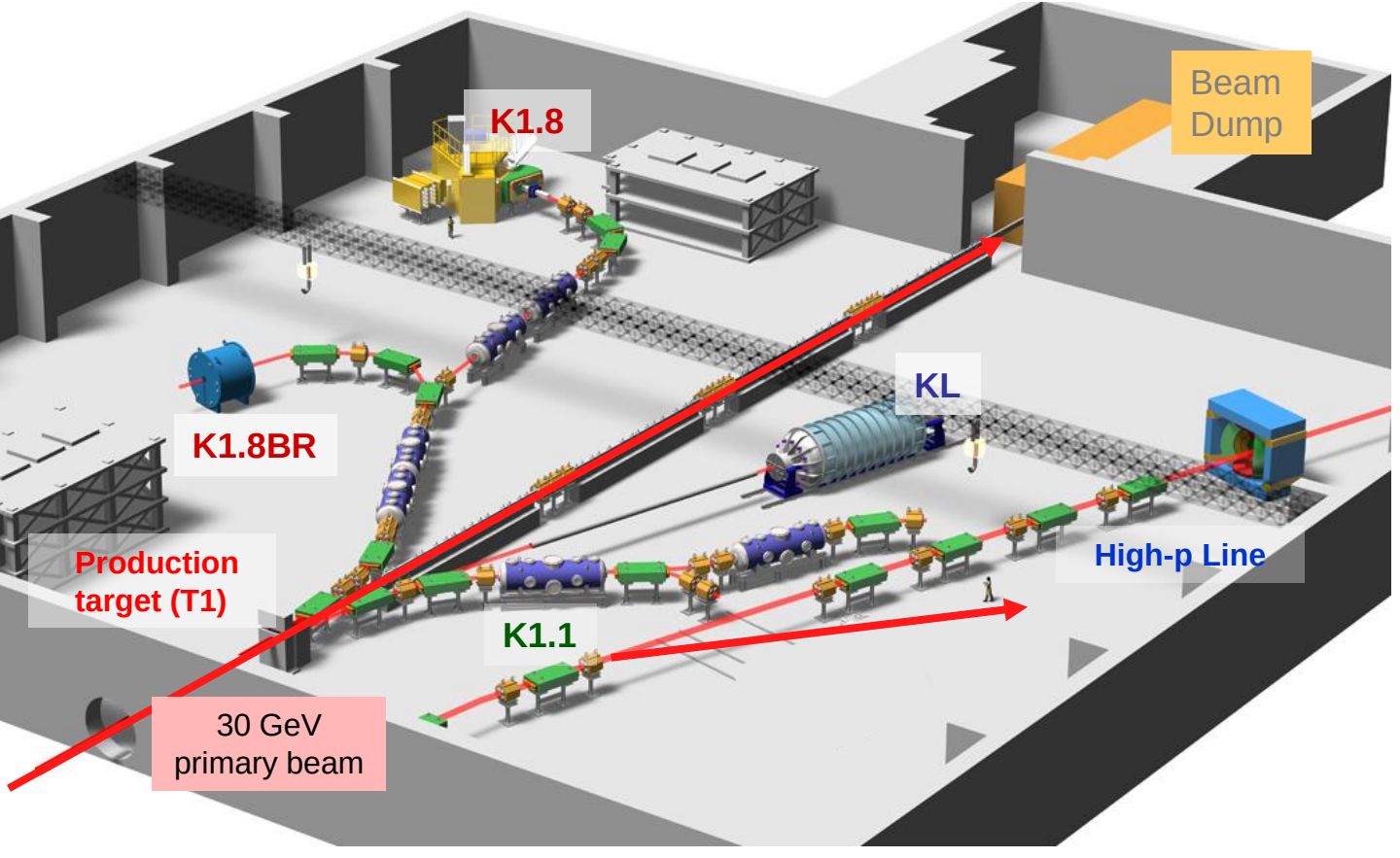
Depends on YN , YY int. Hyperon puzzle?



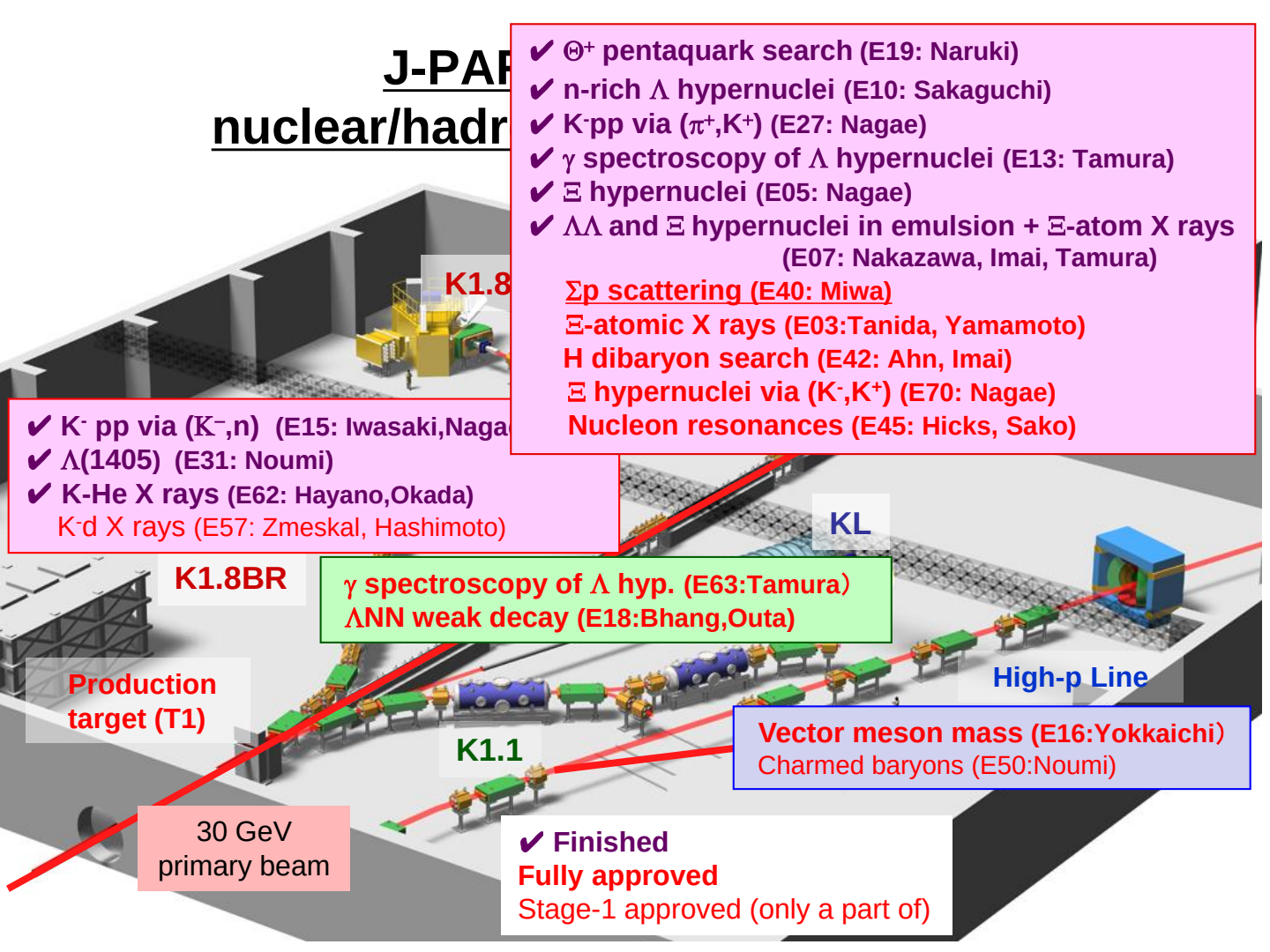
Ten years since J-PARC Hadron Facility started operation in 2009

The 3rd J-PARC Symposium (J-PARC2019)
September 23-26, 2019, Tsukuba, Japan

J-PARC Hadron Hall
nuclear/hadron experiments (2019)



J-PAR
nuclear/hadr



✔ Θ^+ pentaquark search (E19: Naruki)
✔ n-rich Λ hypernuclei (E10: Sakaguchi)
✔ K^-pp via (π^+,K^+) (E27: Nagae)
✔ γ spectroscopy of Λ hypernuclei (E13: Tamura)
✔ Ξ hypernuclei (E05: Nagae)
✔ $\Lambda\Lambda$ and Ξ hypernuclei in emulsion + Ξ-atom X rays (E07: Nakazawa, Imai, Tamura)

Σp scattering (E40: Miwa)
Ξ-atomic X rays (E03:Tanida, Yamamoto)
H dibaryon search (E42: Ahn, Imai)
Ξ hypernuclei via (K^-,K^+) (E70: Nagae)
Nucleon resonances (E45: Hicks, Sako)

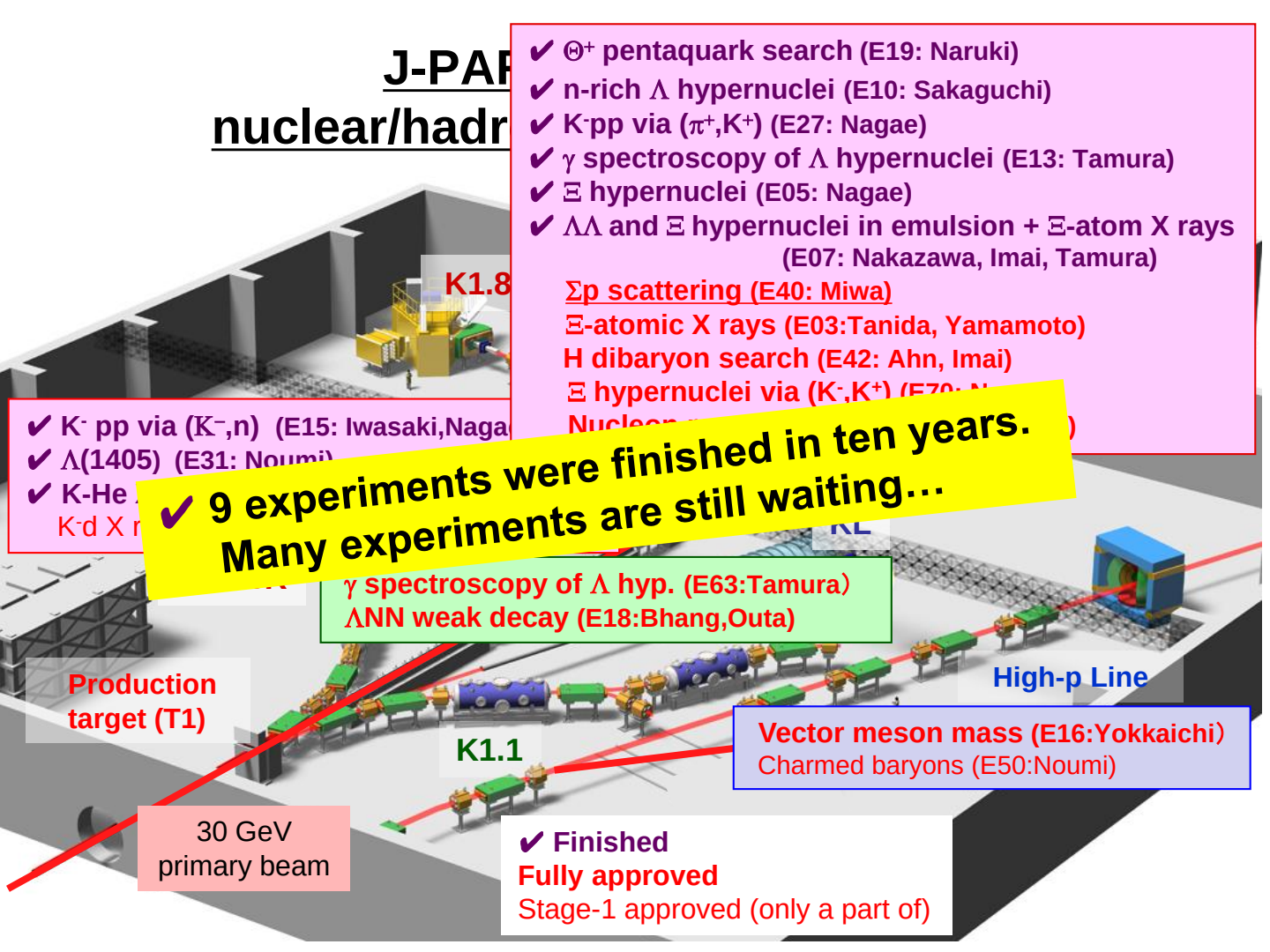
✔ K^- pp via (K^-,n) (E15: Iwasaki,Naga
✔ $\Lambda(1405)$ (E31: Noumi)
✔ K-He X rays (E62: Hayano,Okada)
K^-d X rays (E57: Zmeskal, Hashimoto)

γ spectroscopy of Λ hyp. (E63:Tamura)
ΛNN weak decay (E18:Bhang,Outa)

Vector meson mass (E16:Yokkaichi)
Charmed baryons (E50:Noumi)

✔ Finished
Fully approved
Stage-1 approved (only a part of)

J-PAR
nuclear/hadr



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✔ $\Lambda\Lambda$ and Ξ hypernuclei in emulsion + Ξ-atom X rays (E07: Nakazawa, Imai, Tamura)

Σp scattering (E40: Miwa)
Ξ-atomic X rays (E03:Tanida, Yamamoto)
H dibaryon search (E42: Ahn, Imai)
Ξ hypernuclei via (K^-,K^+) (E70: N
Nucleon

✔ K^- pp via (K^-,n) (E15: Iwasaki,Naga
✔ Λ(1405) (E31: Noumi)
✔ K-He
K^-d X r

✔ **9 experiments were finished in ten years.**
Many experiments are still waiting…

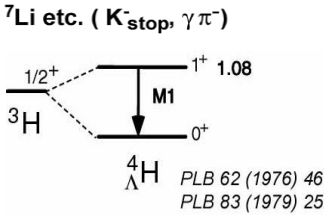
γ spectroscopy of Λ hyp. (E63:Tamura)
ΛNN weak decay (E18:Bhang,Outa)

Vector meson mass (E16:Yokkaichi)
Charmed baryons (E50:Noumi)

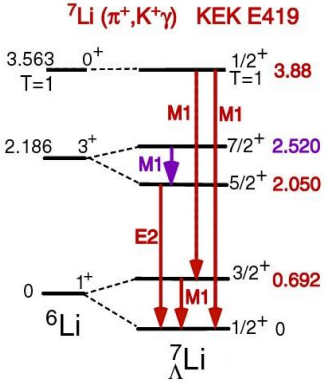
✔ Finished
Fully approved
Stage-1 approved (only a part of)

2. γ-ray spectroscopy of Λ hypernuclei

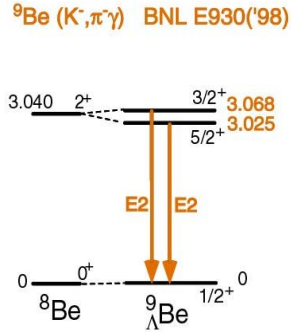
Hypernuclear γ-ray data (2019)



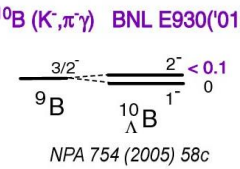
PLB 62 (1976) 46
PLB 83 (1979) 25



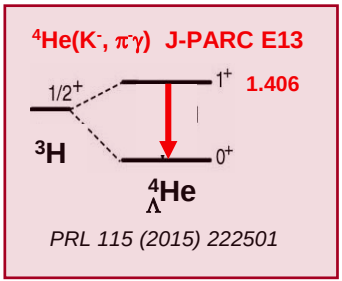
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501



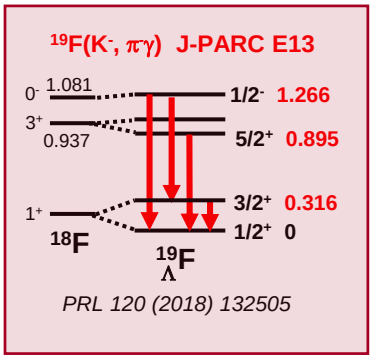
PRL 88 (2002) 082501
NPA 754 (2005) 58c



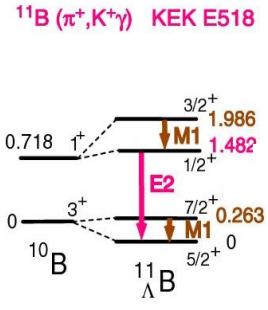
NPA 754 (2005) 58c



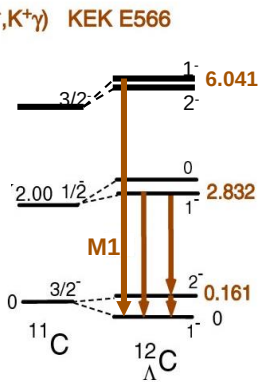
PRL 115 (2015) 222501



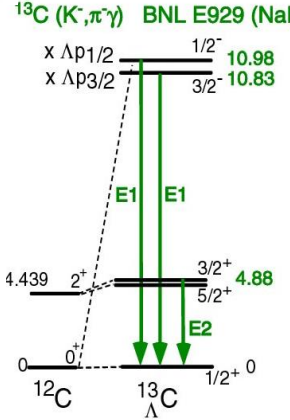
PRL 120 (2018) 132505



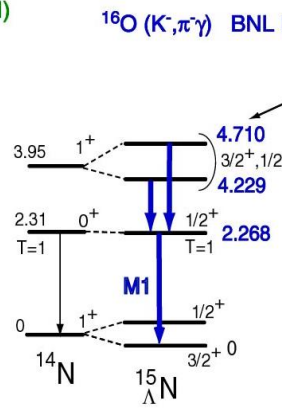
NPA835 (2010) 422



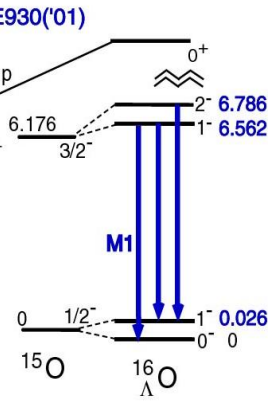
PTEP (2015) 081D01



PRL 86 (2001) 4255
PRC 65 (2002) 034607



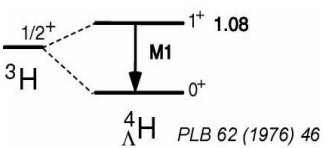
PRC 77 (2008) 054315



PRL 93 (2004) 232501
EPJ A33 (2007) 247

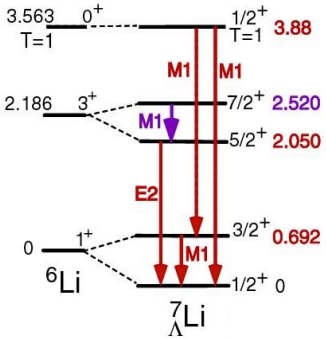
Hypernuclear γ-ray data (2019)

^{7}Li etc. (K^-_{stop}, $\gamma\pi^-$)



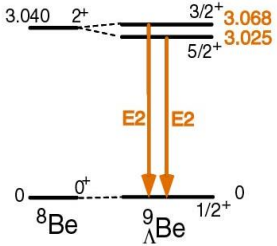
PLB 62 (1976) 46
PLB 83 (1979) 25

^{7}Li (π^+,$K^+\gamma$) KEK E419



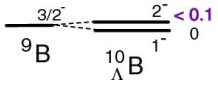
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501

^{9}Be (K^-,$\pi^-\gamma$) BNL E930('98)



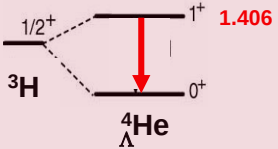
PRL 88 (2002) 082501
NPA 754 (2005) 58c

^{10}B (K^-,$\pi^-\gamma$) BNL E930('01)



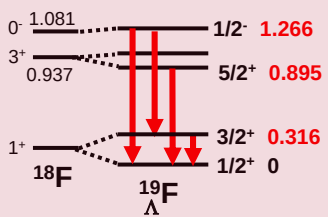
NPA 754 (2005) 58c

^{4}He(K^-, $\pi^-\gamma$) J-PARC E13



PRL 115 (2015) 222501

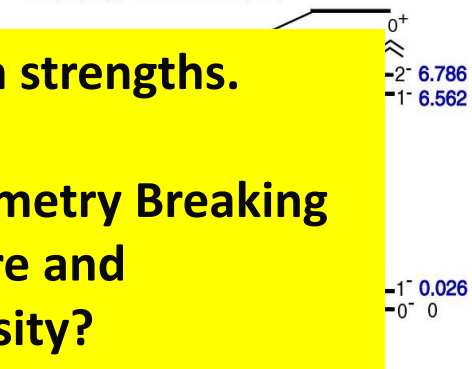
^{19}F(K^-, $\pi^-\gamma$) J-PARC E13



PRL 120 (2018) 132505

^{13}C (K^-,$\pi^-\gamma$) BNL E929 (NaI)

^{16}O (K^-,$\pi^-\gamma$) BNL E930('01)



^{12}C (π^+,$K^+\gamma$) KEK E566

p-shell: ΛN spin-dependent interaction strengths.

s-shell: Λ–Σ coupling and Charge Symmetry Breaking

sd-shell: Heavier hypernuclear structure and ΛN interaction in a larger density?

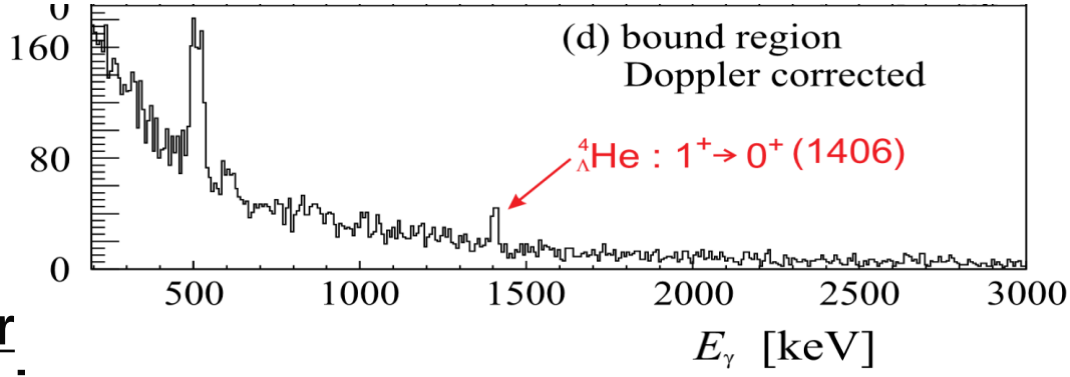
NPA835 (2010) 422

PTEP (2015) 081D01

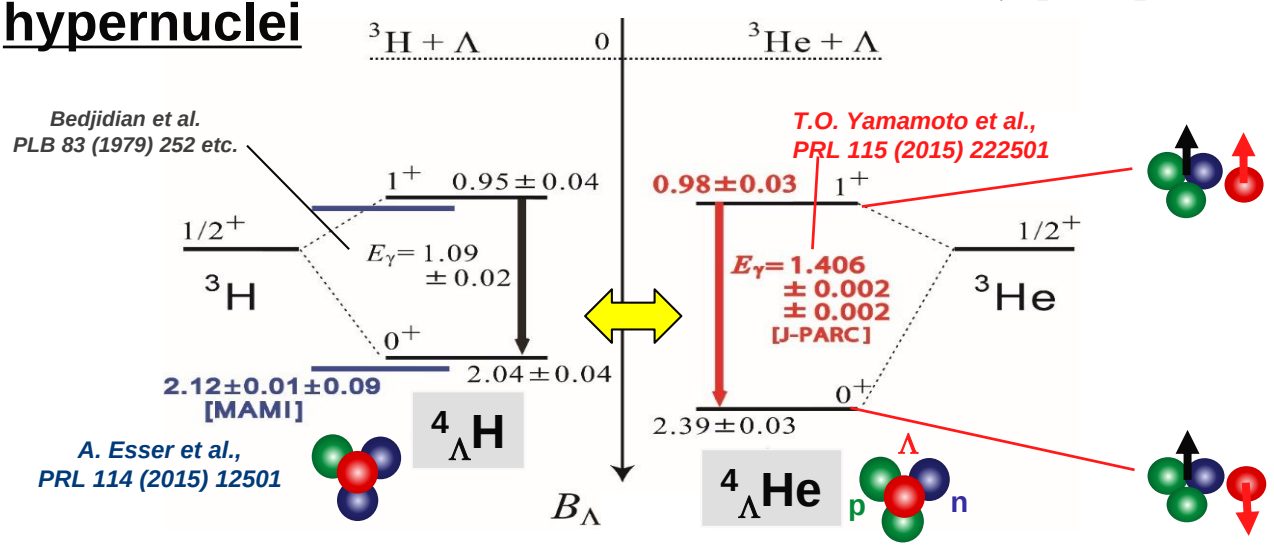
PRL 86 (2001) 4255
PRC 65 (2002) 034607

PRC 77 (2008) 054315

PRL 93 (2004) 232501
EPJ A33 (2007) 247



A=4 mirror hypernuclei

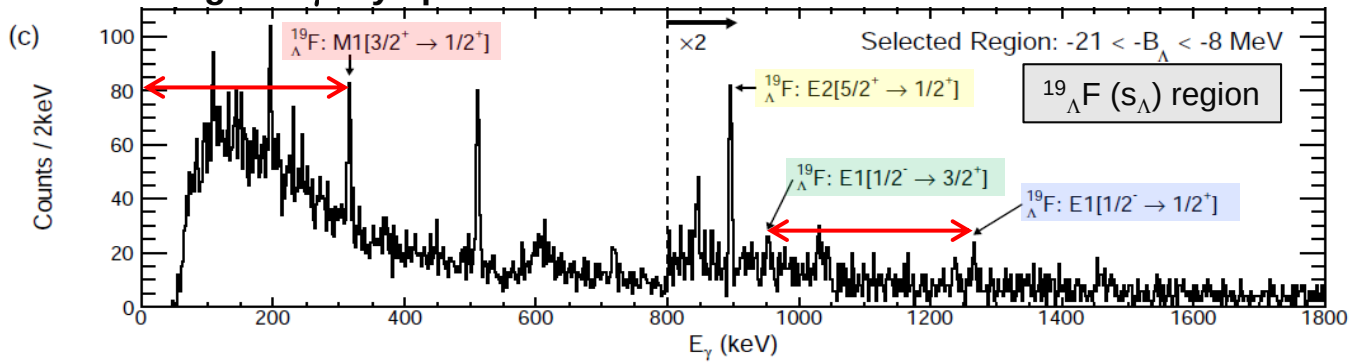


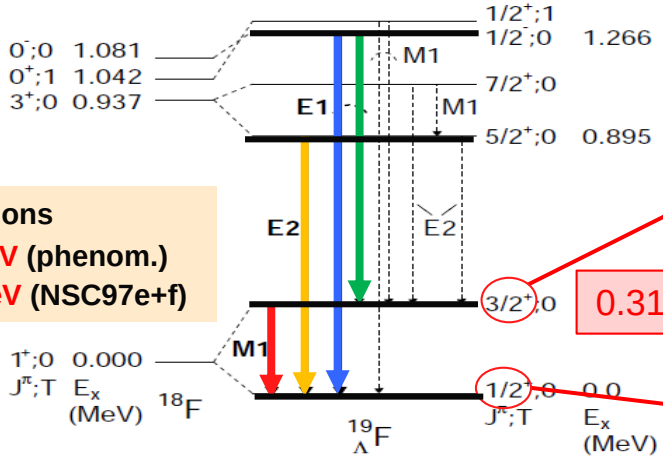
A large Charge Symmetry Breaking effect is confirmed!

$^{19}_{\Lambda}$F results

Mass-gated γ-ray spectra

S.B.Yang et al., PRL120 (2018) 132505



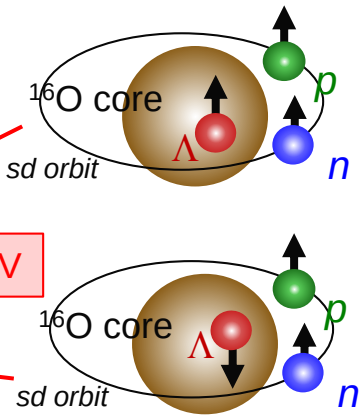


Predictions

Millener 305 keV (phenom.)

Umeya 346 keV (NSC97e+f)

0.315 MeV



ΛN interaction and theoretical framework work well for heavier hypernuclei.

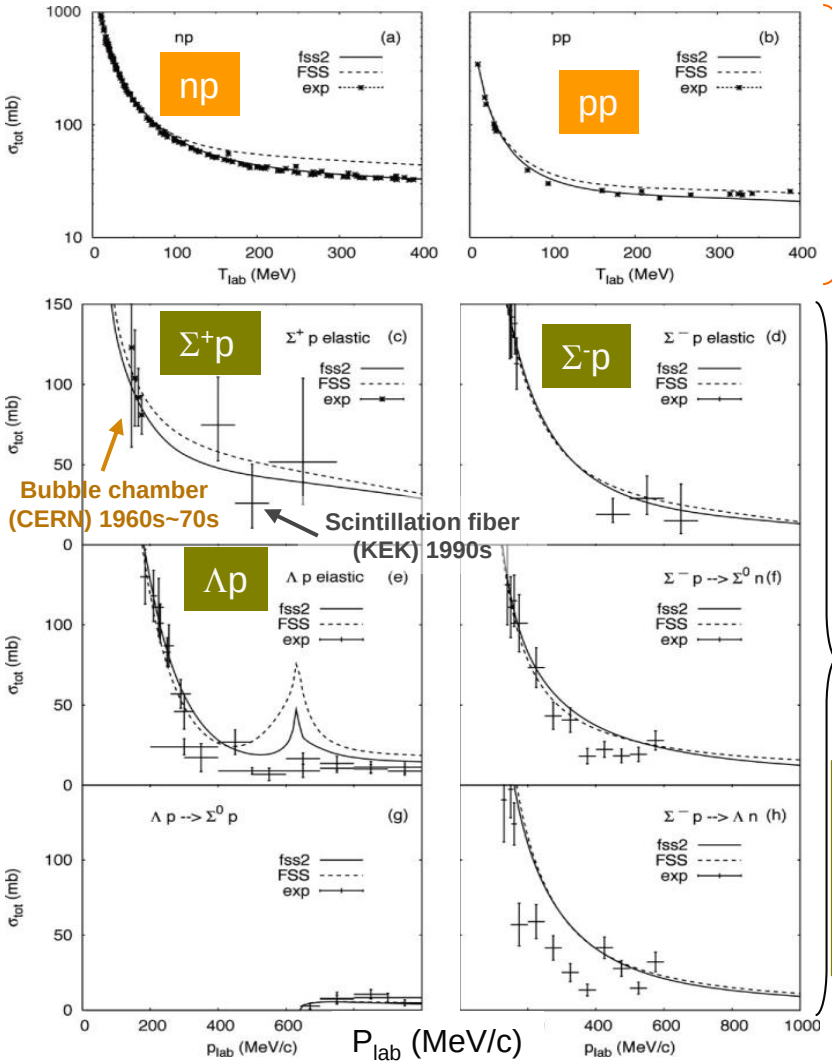
=> Hope to extract ΛNN force effect from heavy hypernuclear data.

Future plans of γ spectroscopy

- **Further study of CSB**
  - **Measure $^{4}_{\Lambda}$H(1^{+}->0^{+}) + hopefully $^{3}_{\Lambda}$H(T=1;$1/2^{+}$->T=0;$1/2^{+}$)**
  - **p-shell hypernuclei via (π^{-},K^{0}) reaction**
  - **E63 (approved)**
- **B(M1) measurement for g_{Λ} of a Λ in medium**
  - **→ possible modification of a baron in nuclear matter**
- **Structure of medium to heavy hypernuclei**
  - **E1(p_{Λ}->s_{Λ})**
    - **-> Density dependent ΛN interaction**
    - **-> Origin of spin-orbit splitting**
  - **Impurity effects in deformed hypernuclei**

3. $\Sigma^{\pm}$p scattering

NN and YN scattering data



total cross sections

NN
High statistics data in wide momentum range and with spin observables
-> phase shift analysis

YN
Statistically poor
Limited momentum region
$c\tau(\Lambda) = 7.9cm$, $c\tau(\Sigma^+) = 2.4$ cm

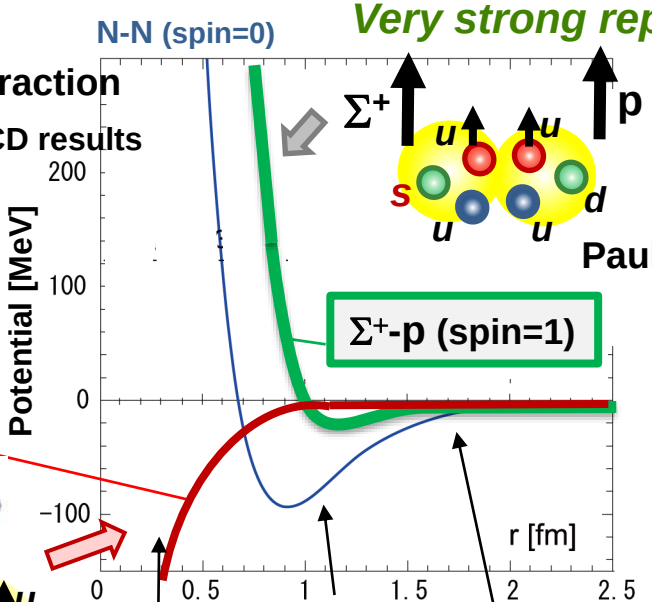
Info. on YN (and YY) forces from hypernuclear B.E. /structure data + NN force assuming $SU(3)_f$

Origin of the short range nuclear force?

Quark picture (Oka-Yazaki)

- Pauli in quark level
- Color magnetic interaction

-- consistent with HAL QCD results



Very strong repulsive core?

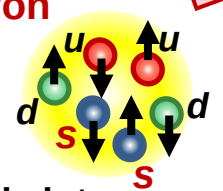
Pauli in quark level

Attractive core?

flavor singlet

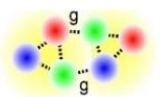
$$-\sqrt{\frac{1}{8}}|\Lambda\Lambda\rangle+\sqrt{\frac{4}{8}}|N\Xi\rangle+\sqrt{\frac{3}{8}}|\Sigma\Sigma\rangle$$

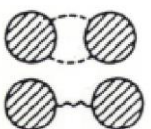
H dibaryon

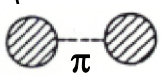


Color magnetic int.

No Pauli



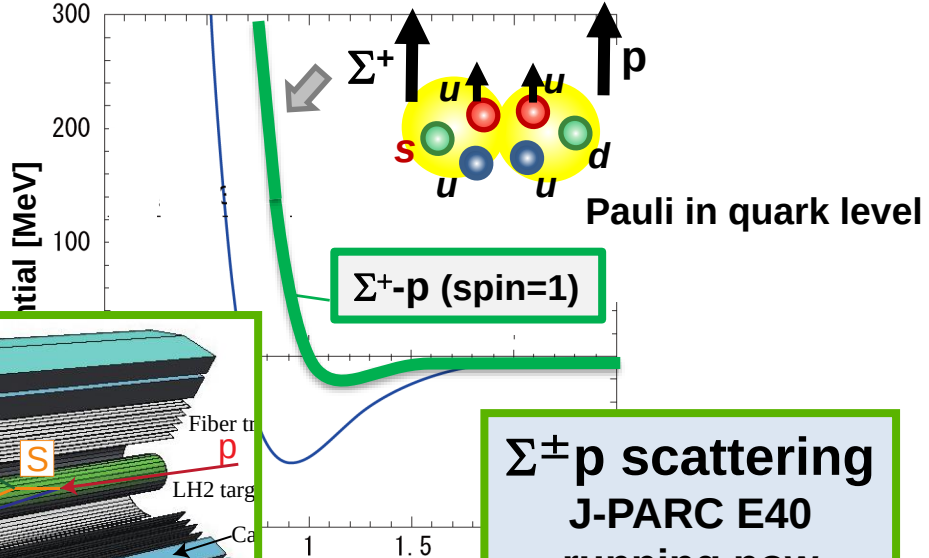


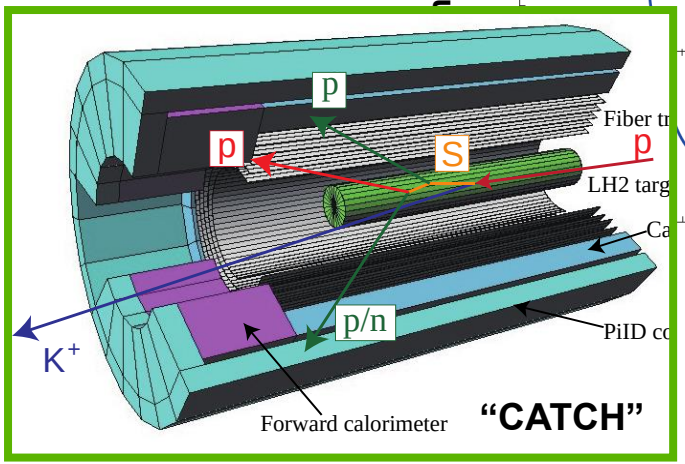


Meson picture

Origin of the short range nuclear force?

Very strong repulsive core?

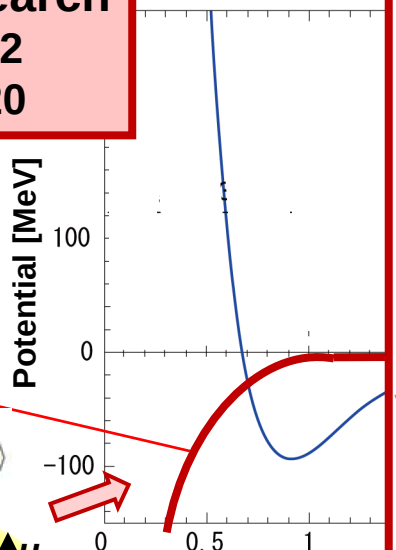




Σ±p scattering
J-PARC E40
running now

Origin of the short range nuclear force?

H dibaryon search
J-PARC E42
run in ~2020

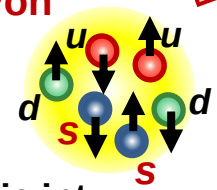


Attractive core?

flavor singlet

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

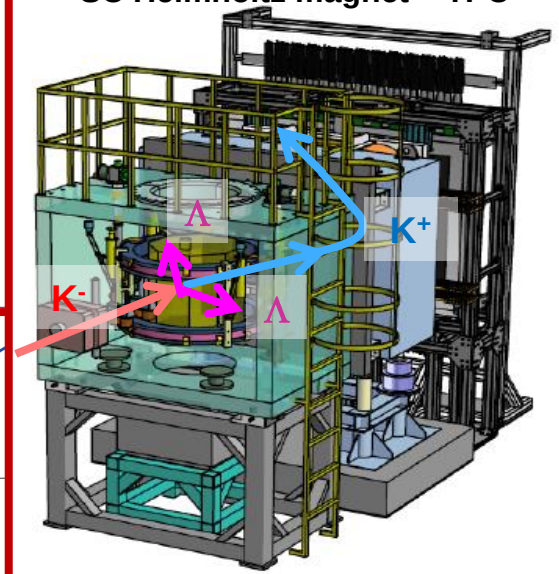
H dibaryon



color magnetic int.

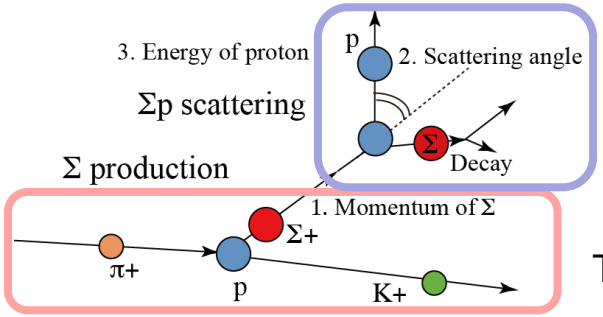
No Pauli

Hyperon Spectrometer
SC Helmholtz magnet + TPC



$\Sigma^{\pm}$p Scattering Experiment

J-PARC E40 (Miwa et al.)

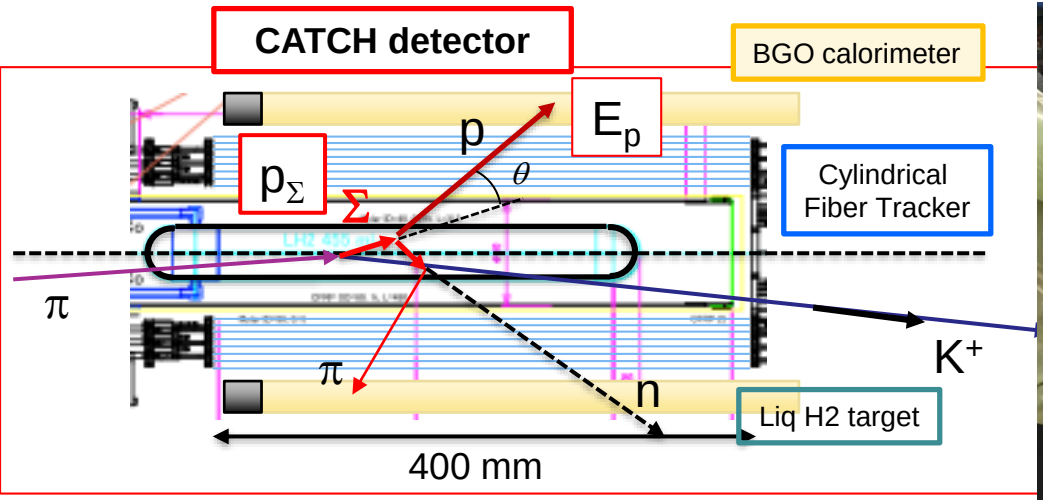


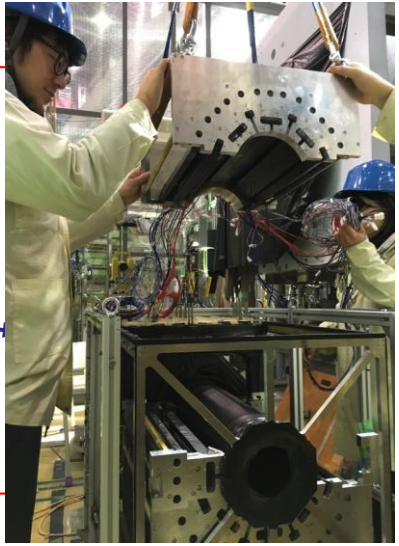
Σ production via $\pi^{\pm}p \rightarrow K^{+}\Sigma^{\pm}$

p_{Σ} = 0.4 ~ 0.8 GeV/c

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

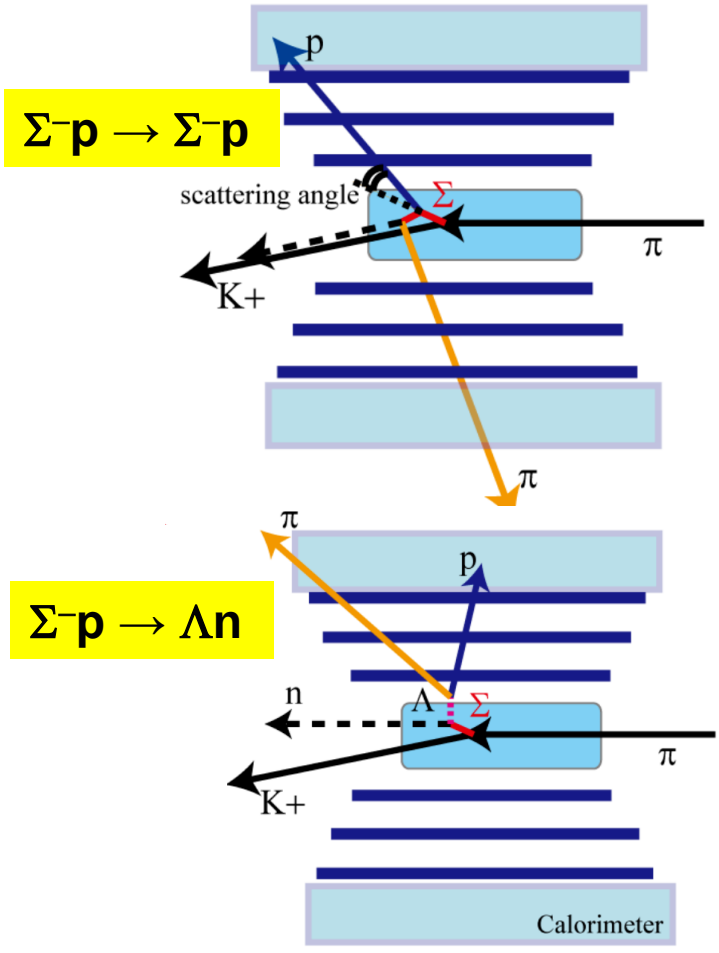
Take 10^4 scattering events (x100 than before)

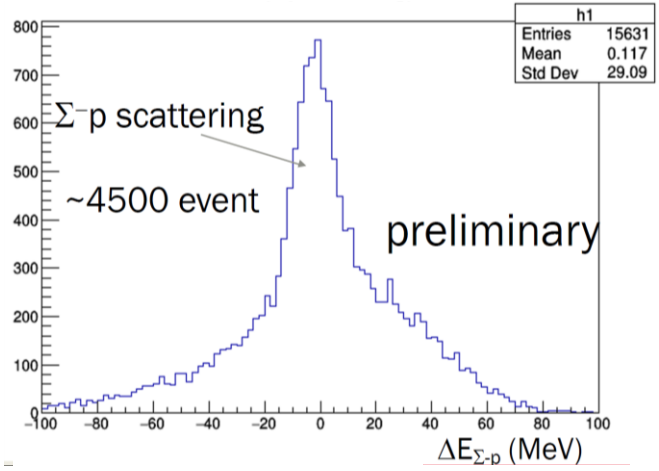


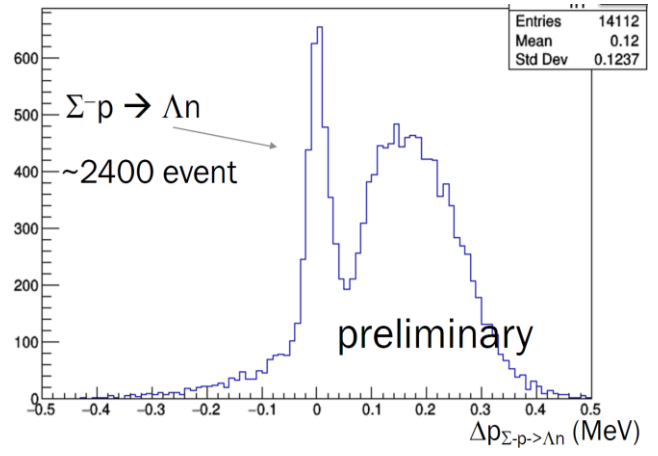


Slide by K. Miwa

Kinematical matching



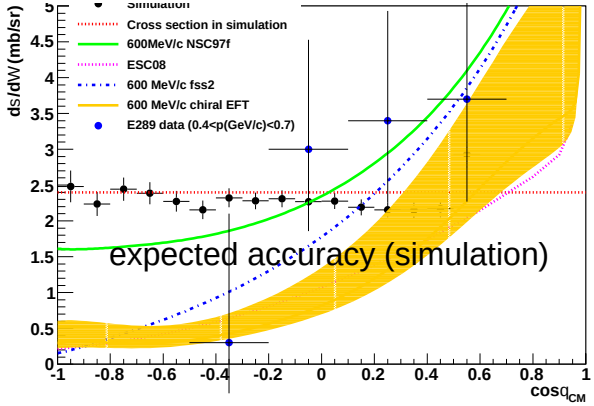




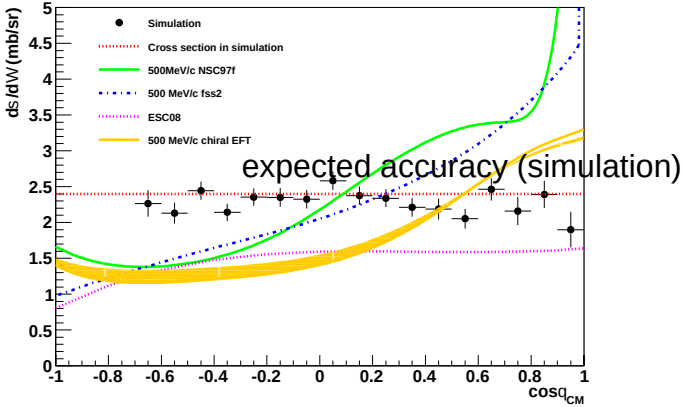
Slide by K. Miwa

Data (angular distribution)

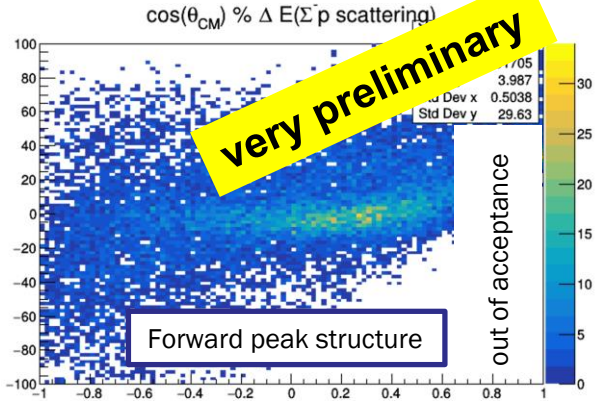
$\Sigma^- p \rightarrow \Sigma^- p$ (0.55 < p (GeV/c) < 0.65)

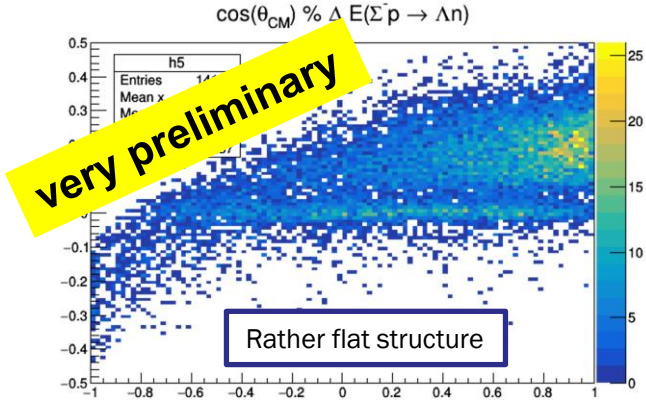


$\Sigma^- p \rightarrow \Lambda n$ (0.55 < p (GeV/c) < 0.65)



Data: Before acceptance and efficiency correction



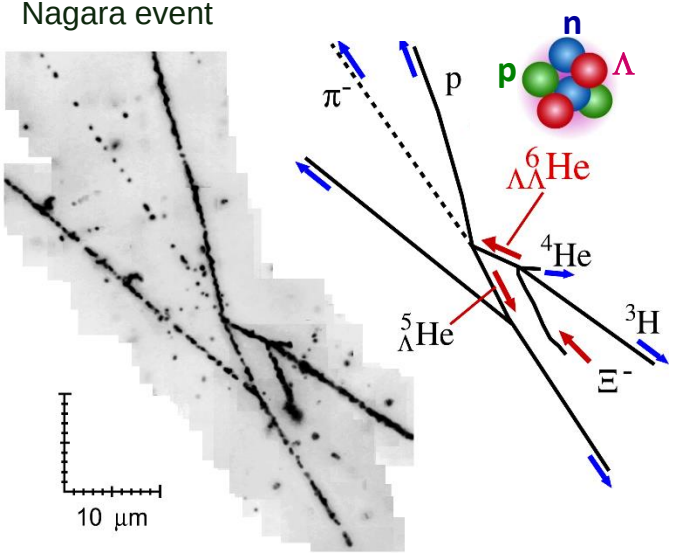


4. Double Strangeness Systems

(Ξ and $\Lambda\Lambda$ hypernuclei)

Previous Emulsion Results (KEK E373)

Nagara event



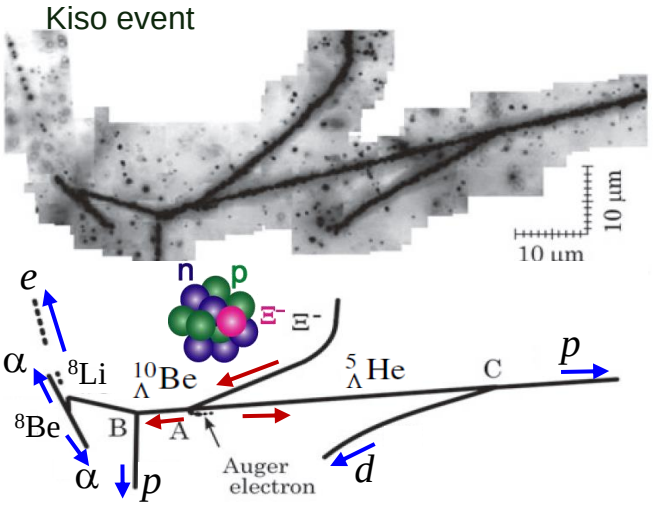
$^{6}_{ΛΛ}$He -> $^{5}_{Λ}$He + p + π⁻

$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

H. Takahashi et al., PRL 87 (2001) 212502

Λ-Λ is weakly attractive

Kiso event



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

The first clear Ξ hypernucleus

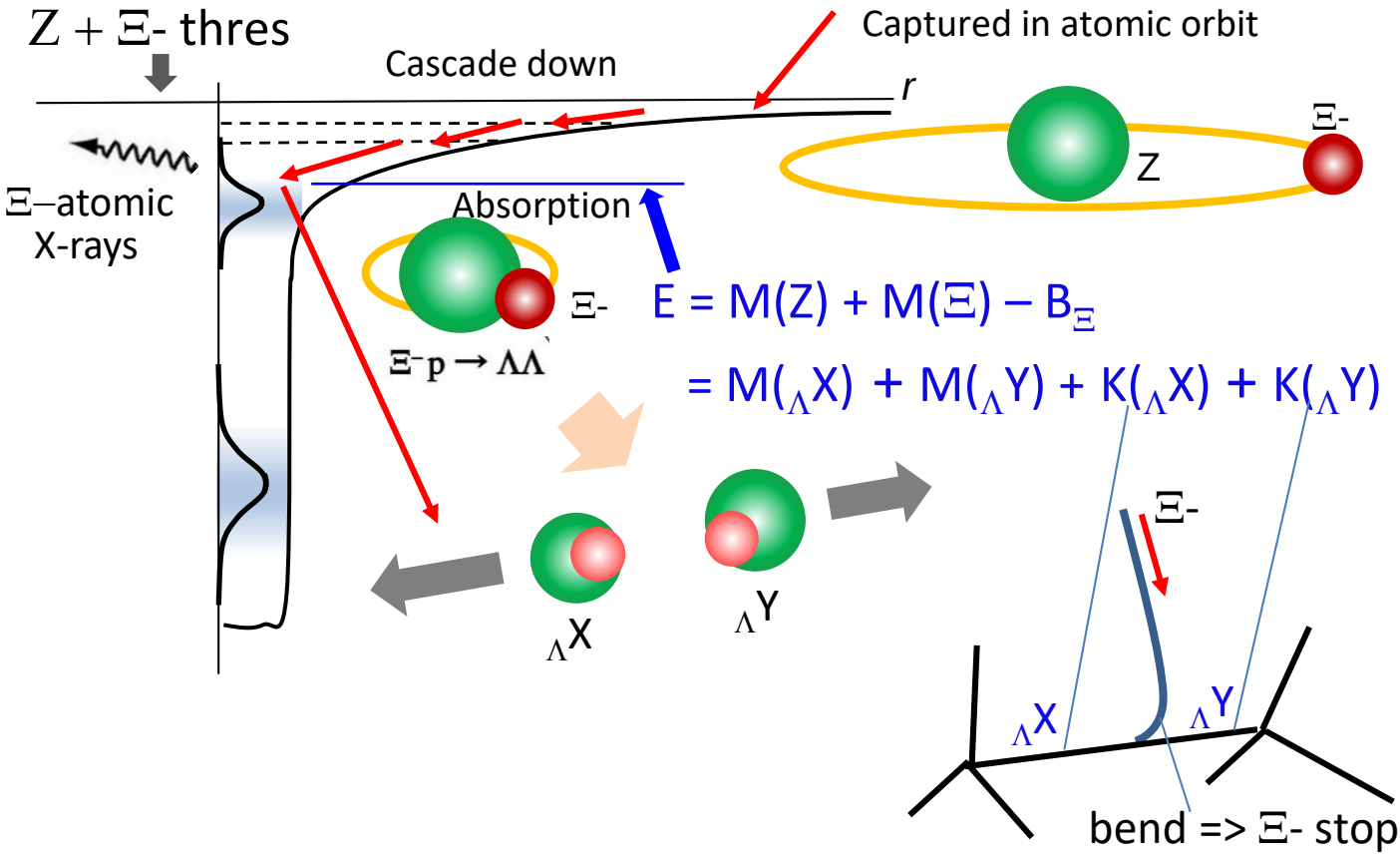
$B_{\Xi^-} = 4.38 \pm 0.25$ MeV,
or 1.11 ± 0.25 MeV

K. Nakazawa et al. PTEP 2015, 033D02

Ξ-N is attractive !

cf. Ξ⁻p attractive (ALICE)

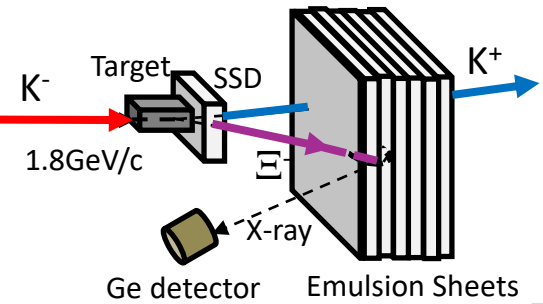
Twin Λ hypernuclear event

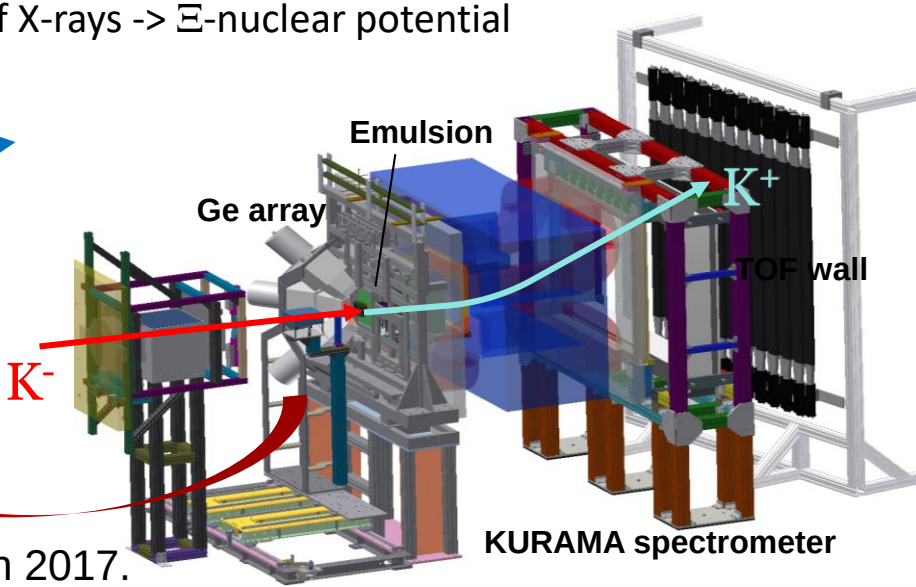


Hybrid emulsion experiment at J-PARC

J-PARC E07 (Nakazawa, Imai, Tamura et al.)

- **Collect ~100 double strange (ΛΛ and Ξ) hypernuclei**
  - Confirm ΛΛ and ΞN interactions
  - ΛΛ–ΞN interaction in nuclear matter
- **Measure Ξ^- -atomic X-rays for the first time**
  - Shift and width of X-rays -> Ξ-nuclear potential



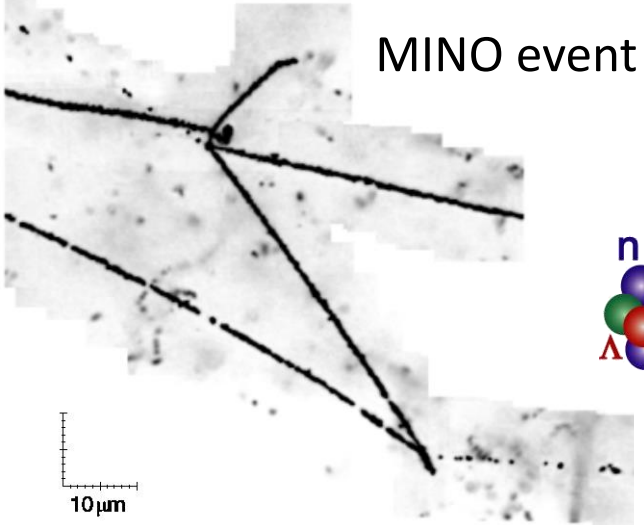


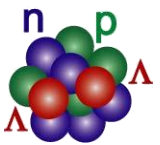
Beam exposure finished in 2017.
Emulsion analysis ~40% now.

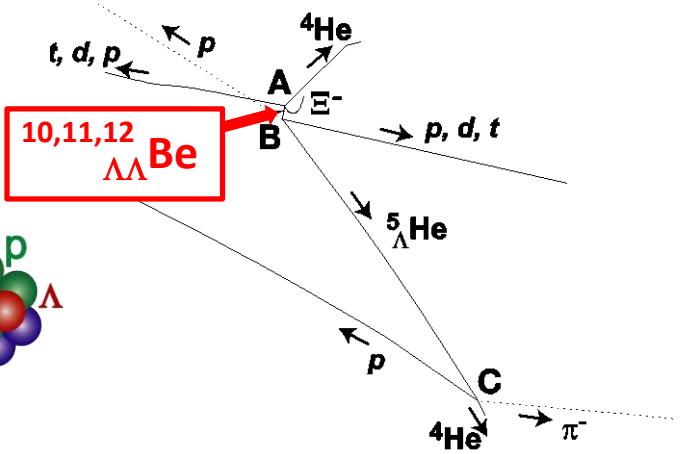
A new ΛΛ hypernuclear event

~30 events of ΛΛ / Ξ hypernuclei have been observed at present.

H. Ekawa et al., PTEP 2019 (2019) 021D02







$^{11}_{\Lambda\Lambda}$Be is most probable

$\Xi^- + {}^{16}O \rightarrow {}^{17}_{\Xi}N \rightarrow {}^{11}_{\Lambda\Lambda}Be + {}^{4}He + d$

$\rightarrow {}^{5}_{\Lambda}He + d + p$

$\rightarrow {}^{4}He + p + \pi^-$

$\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37$ MeV

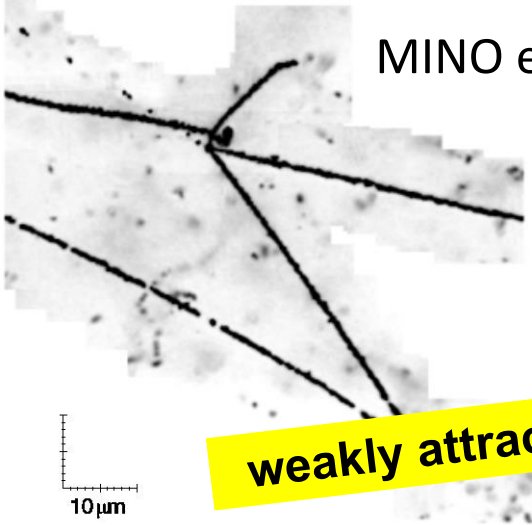
Slightly different from $\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV for $^{6}_{\Lambda\Lambda}$He

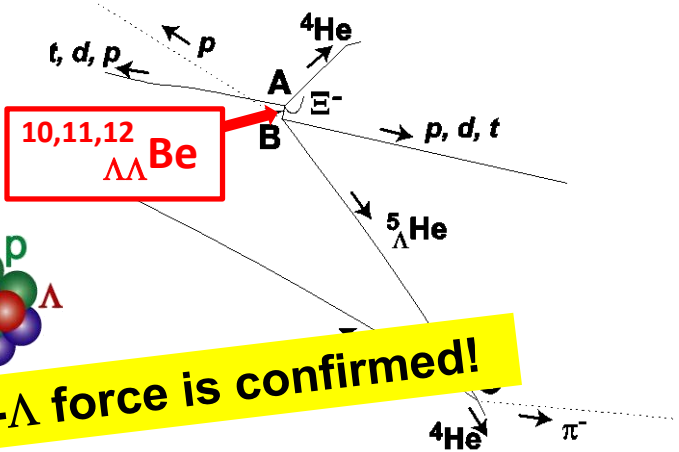
=> Binding effect? ΛΛ-ΞN effect?

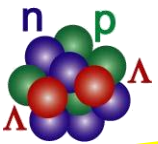
A new ΛΛ hypernuclear event

~30 events of ΛΛ / Ξ hypernuclei have been observed at present.

H. Ekawa et al., PTEP 2019 (2019) 021D02







weakly attractive Λ-Λ force is confirmed!

$^{11}_{\Lambda\Lambda}$Be is most probable

$\Xi^- + {}^{16}O \rightarrow {}^{17}_{\Xi}N \rightarrow {}^{11}_{\Lambda\Lambda}Be + {}^{4}He + d$

$\rightarrow {}^{5}_{\Lambda}He + d + p$

$\rightarrow {}^{4}He + p + \pi^-$

$\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37$ MeV

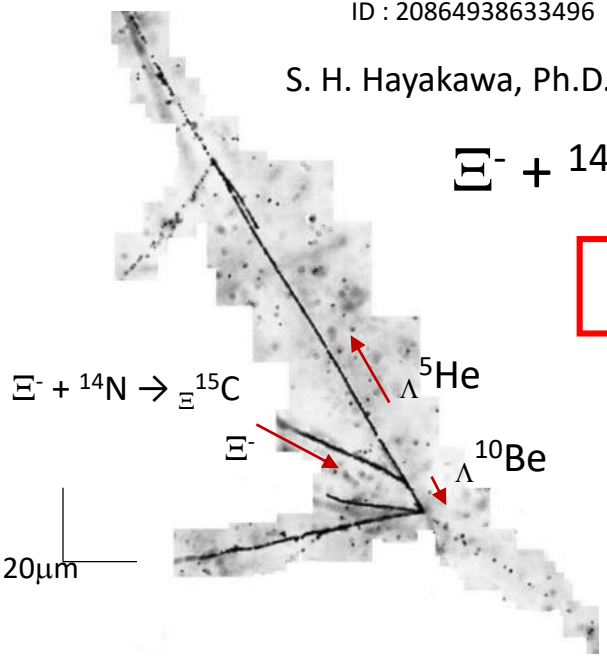
Slightly different from $\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV for ${}^{6}_{\Lambda\Lambda}He$

=> Binding effect? ΛΛ-ΞN effect?

A new Ξ hypernuclear event

IBUKI event

Mod#047 pl10
ID : 20864938633496



S. H. Hayakawa, Ph.D. Thesis, Osaka Univ. (2019), to be published

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

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

The same reaction as KISO

KISO

$$B_{\Xi^-} = 4.38 \pm 0.25\ \mathrm{MeV},$$

or $1.11 \pm 0.25\ \mathrm{MeV}$

This interpretation seems correct.

-> Suggesting that this state has a rather narrow width < 1 MeV

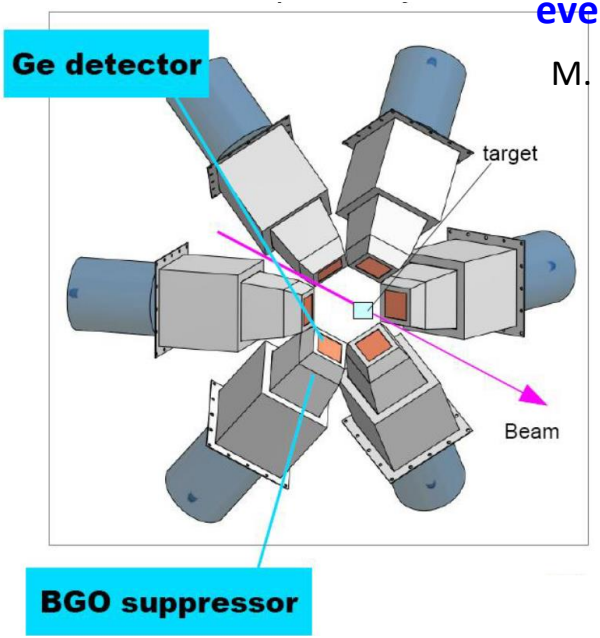
Preliminary X-ray spectrum

	(n,l)	X-ray Energy [keV]
Ag	(9,8)→(8,7)	254.7
	(8,7)→(7,6)	371.5
Br	(8,7)→(7,6)	206.0
	(7,6)→(6,5)	317.4

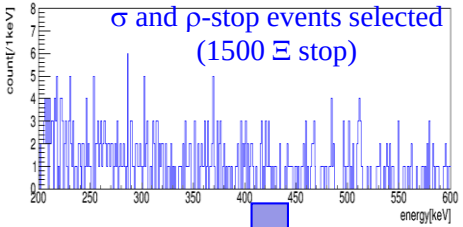
In-beam energy calibration of Ge detectors successfully done within ±100 eV accuracy using LSO scintillator (^{167}Lu) and ^{22}Na source

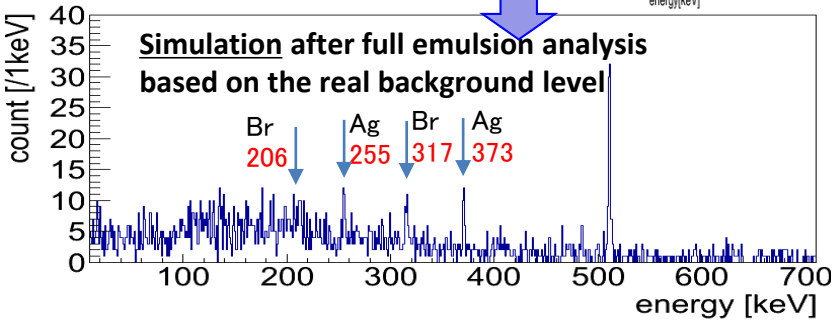
X-ray spectrum after selecting Ξ- absorption events from emulsion image

M. Fujita, Ph.D. Thesis, Tohoku Univ. (2019)



real data ~20%

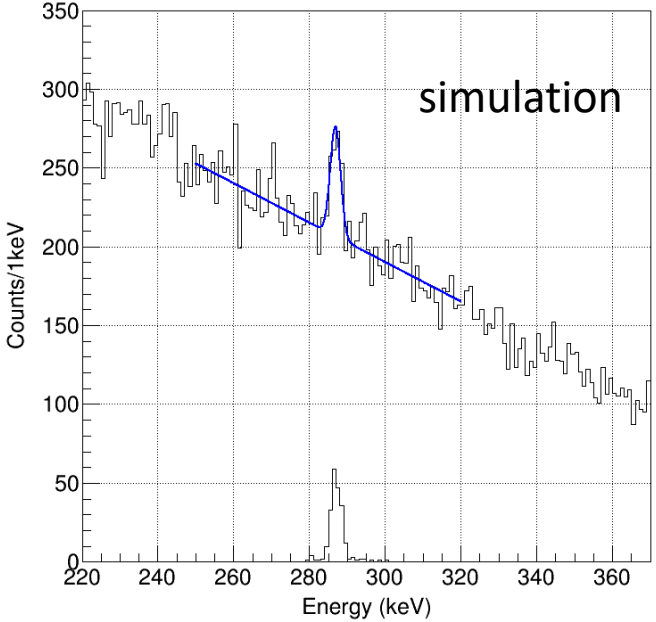


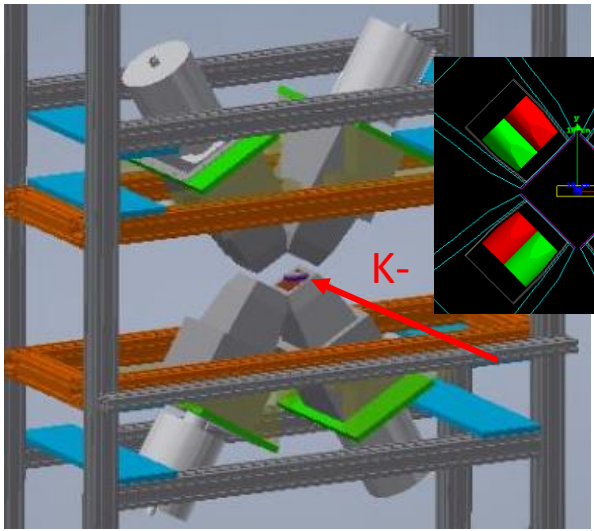


Near future: Ξ-atomic X-ray without emulsion

J-PARC E03 (Tanida, Yamamoto et al.)

- Fe (K-,K+) and select Ξ production in missing mass
- Phase 1 run in 2020 -> Observe Ξ-Fe(7->6) (no shift expected), Ξ-Fe(6->5) can be also observed if absorption width is small.



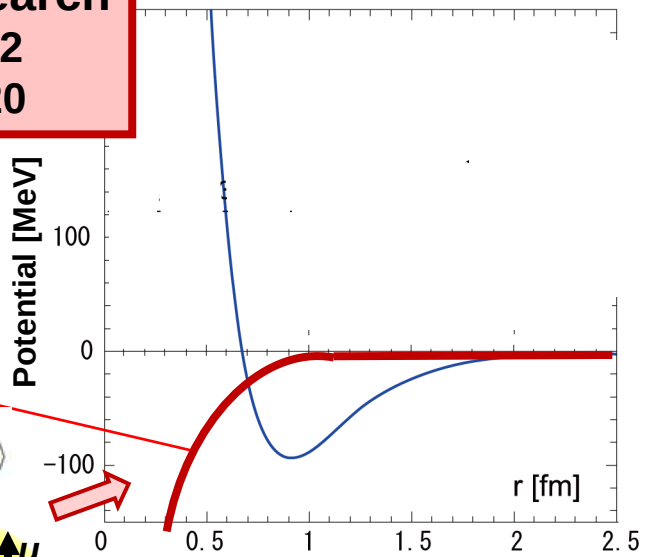


4 Clover Ge detectors close to the target

H dibaryon search via H->ΛΛ

J-PARC E42 (Ahn et al.)

H dibaryon search
J-PARC E42
run in ~2020

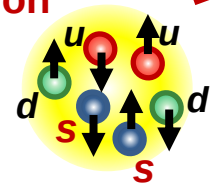


Attractive core?

flavor singlet

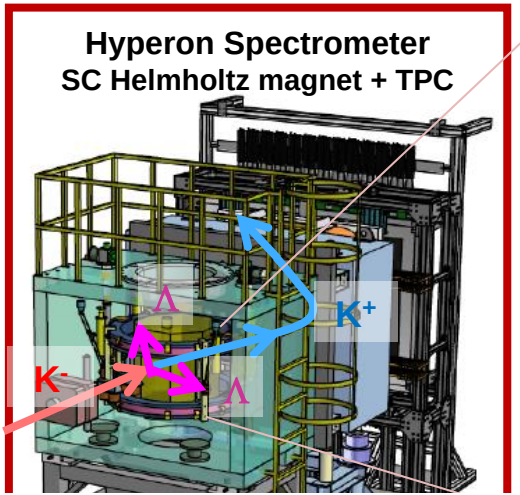
$$-\sqrt{\frac{1}{8}}|\Lambda\Lambda\rangle+\sqrt{\frac{4}{8}}|N\Xi\rangle+\sqrt{\frac{3}{8}}|\Sigma\Sigma\rangle$$

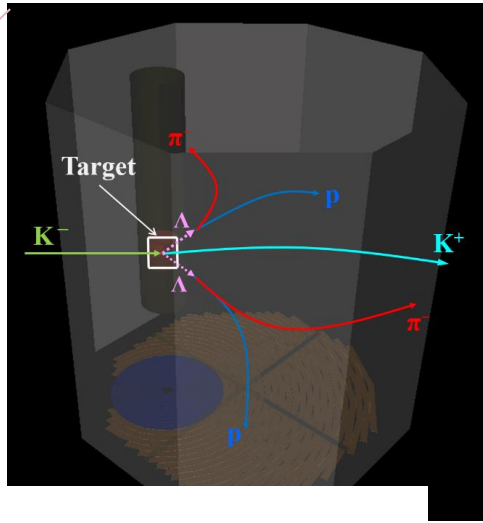
H dibaryon

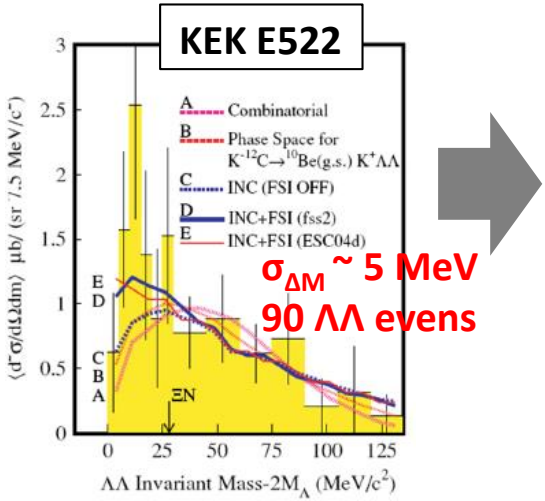


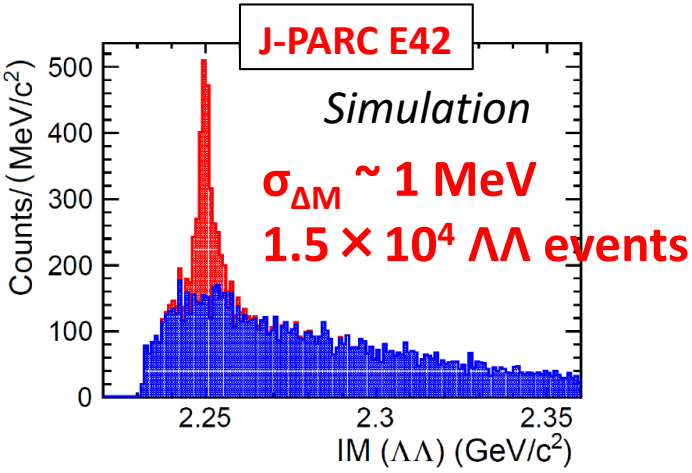
Lattice QCD suggesting:
Resonance near Ξ^-p thres.

J-PARC E42


Hyperon Spectrometer
SC Helmholtz magnet + TPC
K-
Λ
K+
Λ


Target
π
p
K−
K+
Λ
Λ
π
p


KEK E522
A Combinatorial
B Phase Space for K-12C→10Be(g.s.) K+ΛΛ
C INC (FSI OFF)
D INC+FSI (fss2)
E INC+FSI (ESC04d)
σΔM ~ 5 MeV
90 ΛΛ evens
ΞN
ΛΛ Invariant Mass-2MΛ (MeV/c2)


J-PARC E42
Simulation
σΔM ~ 1 MeV
1.5 × 10⁴ ΛΛ events
Counts/(MeV/c2)
IM (ΛΛ) (GeV/c2)

5. Future plans

Future plans for hypernuclei

- **Hypertriton lifetime**
  Two exp's, ^{3}He(π^-,K^0) and ^{3}He(K^-,π^0) are proposed
  => K1.8BR and K1.1 lines
- **Various S=-2 systems**
  Ξ-hypernuclei via ^{12}C,.. (K^-,K^+) $^{12}_{\Xi}$Be,.. spectroscopy
  => K1.8 line
- **More Σp, Λp scattering experiments**
  $d\sigma/d\Omega$ and spin observables
  => K1.1 line
- **Precise B_Λ and structure data of light to heavy Λ-hypernuclei via (π,K^+) and γ-ray spectroscopy**
  => HIHR line **=> K1.1 line**

Extension Plans of J-PARC Hadron Hall

S= -1 Systems

γ-ray spectroscopy
weak decays
ΛN scattering

- < 1.2 GeV/c
- ~10^6 K^-/spill

High precision
Λ hypernuclear spectroscopy

- < 2.0 GeV/c
- 1.8×10^8 pion/spill
- x10 better Δp/p

HIHR

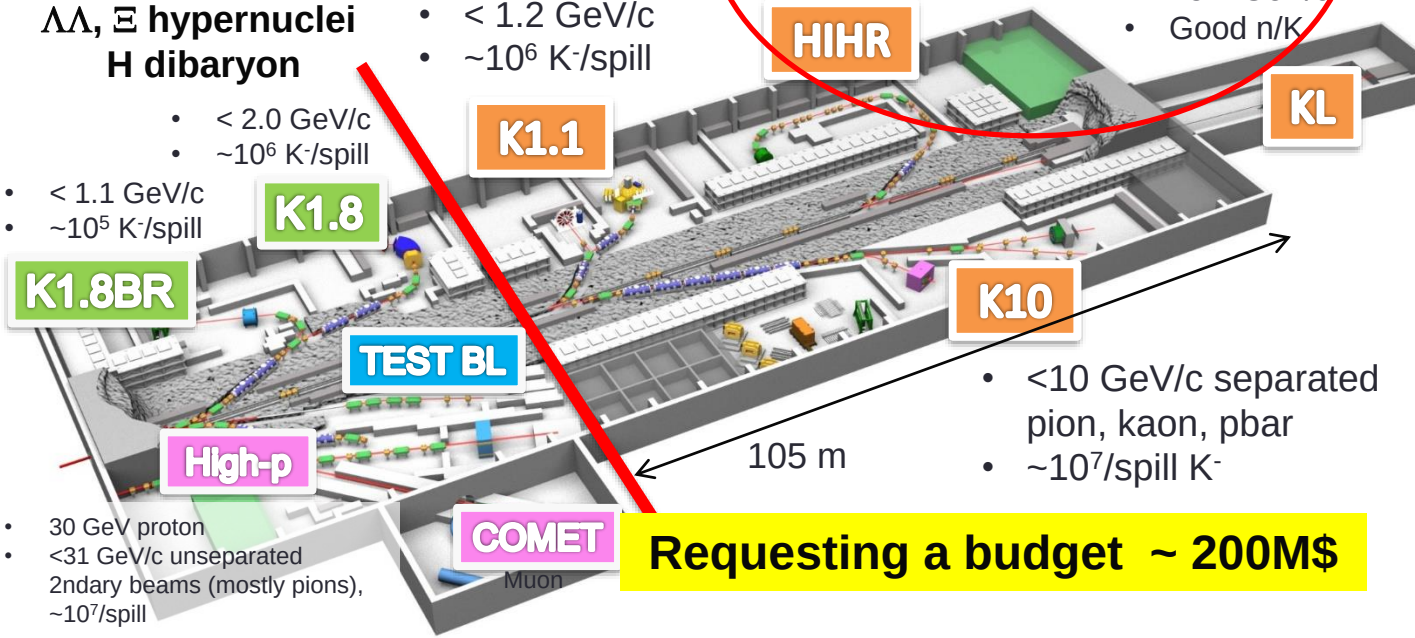
- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K

S= -2 Systems

ΛΛ, Ξ hypernuclei
H dibaryon

- < 2.0 GeV/c
- ~10^6 K^-/spill

- < 1.1 GeV/c
- ~10^5 K^-/spill



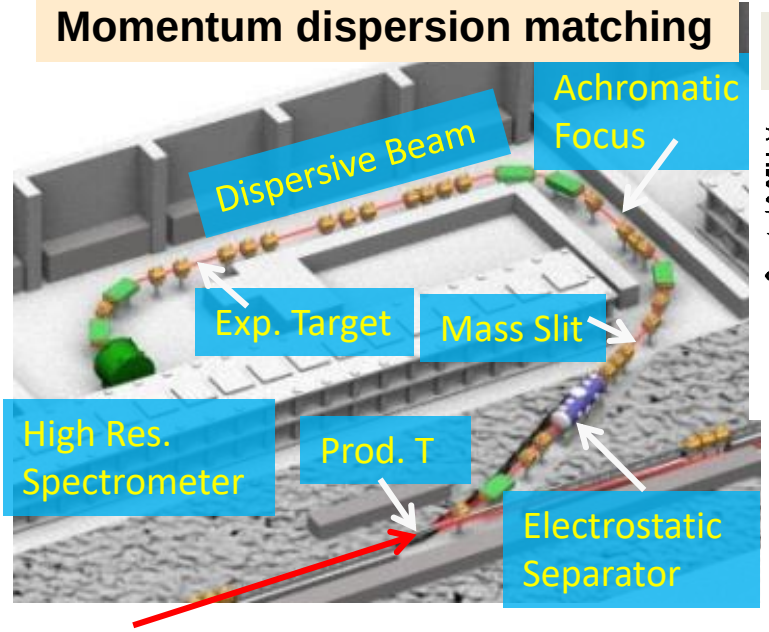
- <10 GeV/c separated pion, kaon, pbar
- ~10^7/spill K^-

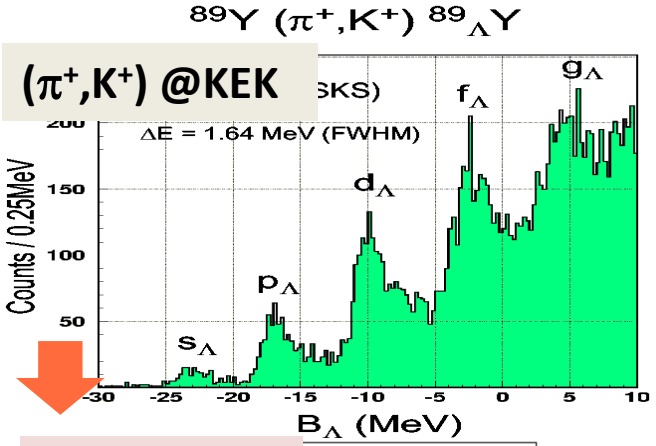
- 30 GeV proton
- <31 GeV/c unseparated 2ndary beams (mostly pions), ~10^7/spill

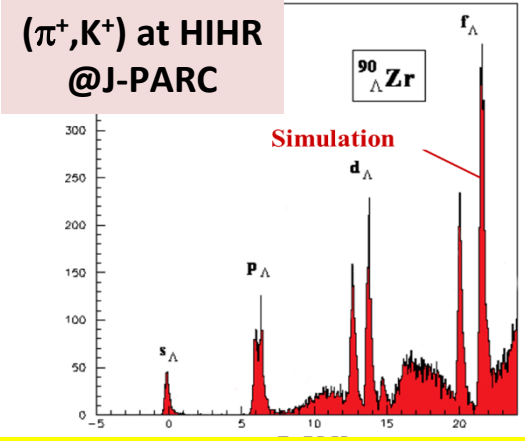
Requesting a budget ~ 200M$

High-Intensity High-Resolution line (HIHR)

Momentum dispersion matching







~ 1.8x10^8 pion/pulse, 1.2 GeV/c,
$\Delta p/p$~1/10000 ->Δm~200 keV

designed by H. Noumi

=> Density dependence of ΛN interaction => Hyperon puzzle

5. Summary

- J-PARC hadron hall has operated for 10 years and obtained various data for S=-1 and recently S=-2 hypernuclear systems.
- In γ-ray spectroscopy of Λ hypernuclei, ${}^{4}_{\Lambda}$He data confirmed a large CSB effect, and ${}^{19}_{\Lambda}$F data extended our understanding of Λ hypernuclear structure to a heavier system.
- A Σ-p scattering experiment is successfully running. It will get ~10^2 times more statistics than before.
- $\Lambda\Lambda$ and Ξ hypernuclear data in emulsion, including a recently observed ${}^{11}_{\Lambda\Lambda}$Be and ${}^{15}_{\Xi}$C, have confirmed attractive $\Lambda\Lambda$ and ΞN interactions.
- New S=-2 experiments on Ξ-atomic X-rays, H-dibaryon search, and (K-,K+) spectroscopy are being prepared.
- We will extend the J-PARC Hadron Hall at J-PARC and construct new beamlines, particularly for high-resolution Λ hypernuclear spectroscopy and ΛN/ΣN scattering.