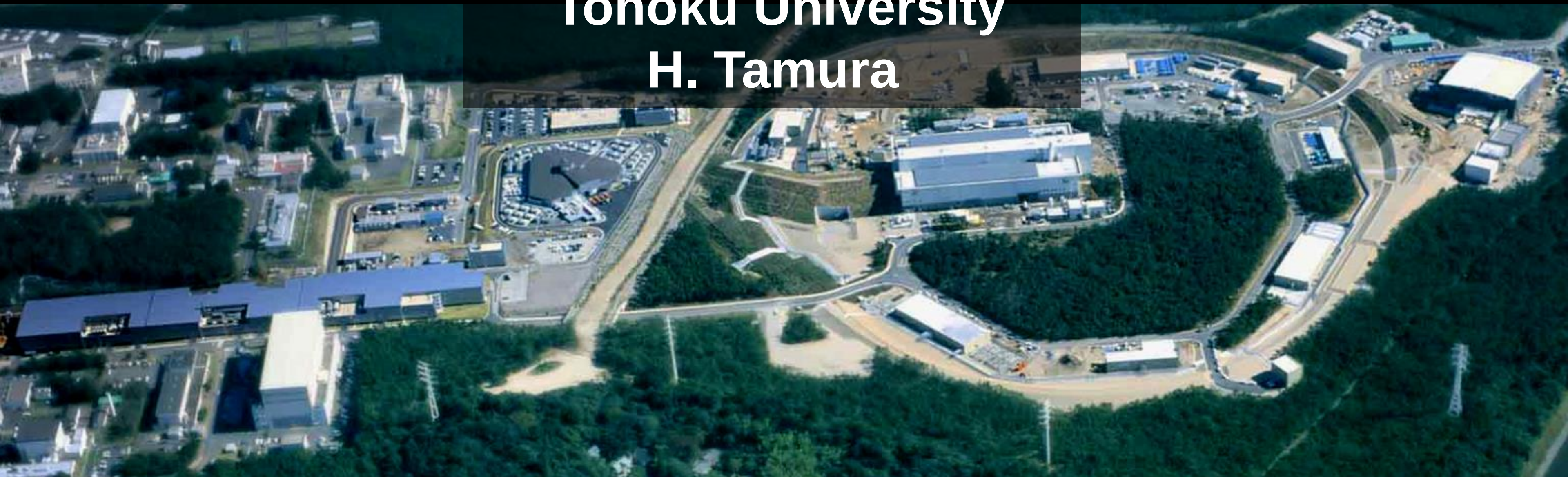
2016. 11. 2
Compact Stars and
Gravitational Waves

# Strangeness Nuclear Physics
# and
# Neutron Stars

Tohoku University
H. Tamura



## Contents

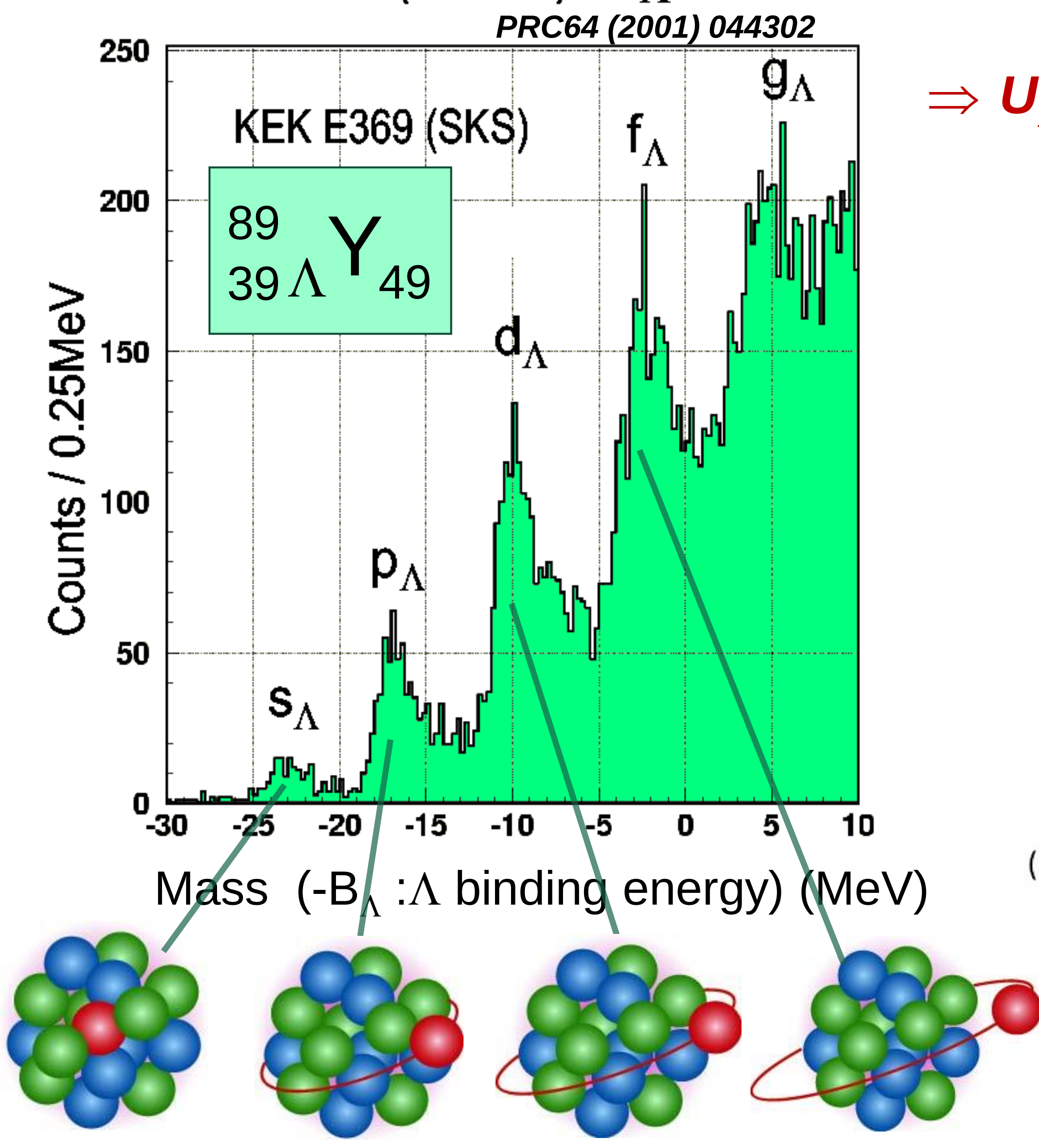


# 1. Introduction

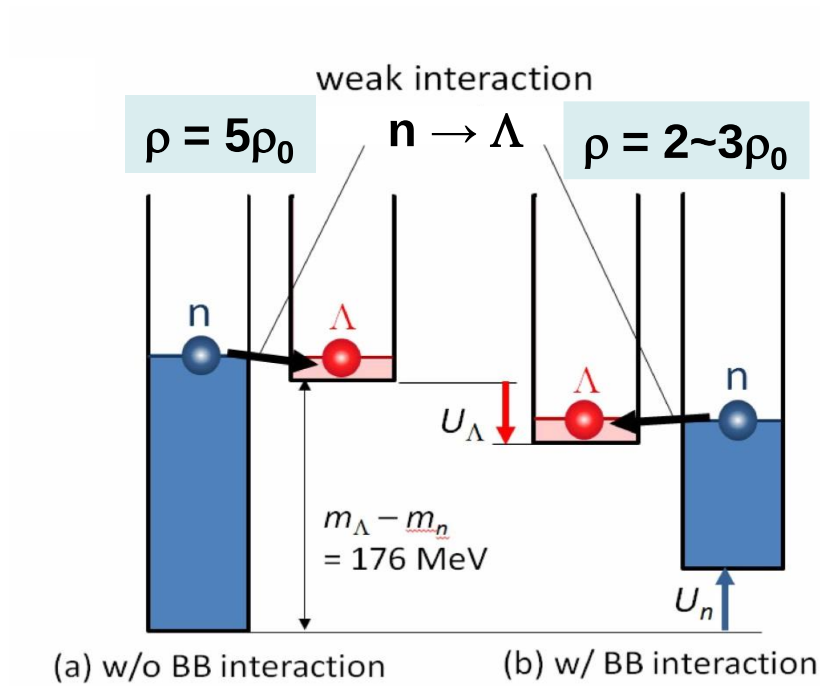
**Exotic flavors in NS?**

# Attractive ΛN interaction and hyperon mixing

$^{89}Y(\pi^+,K^+)\,^{89}_{\Lambda}Y$



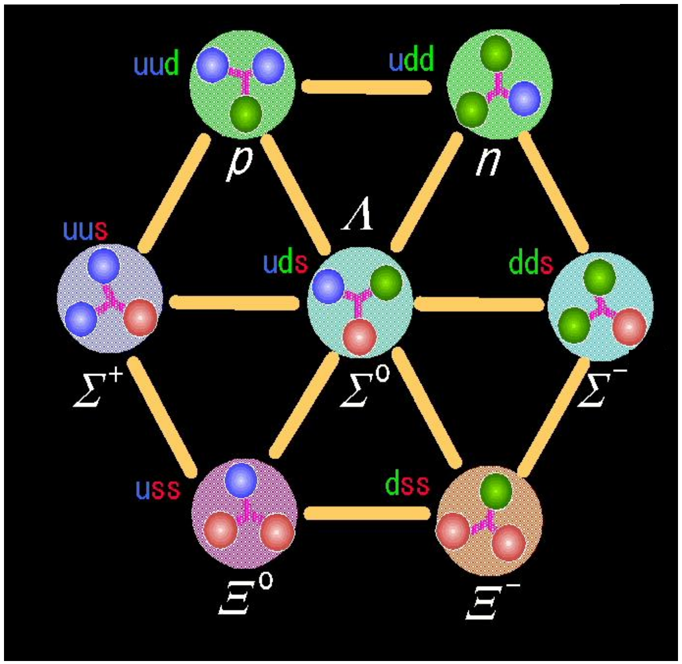

⇒ $U_\Lambda(\rho_0)$ = -30 MeV (~2/3 of $U_N$) well established.

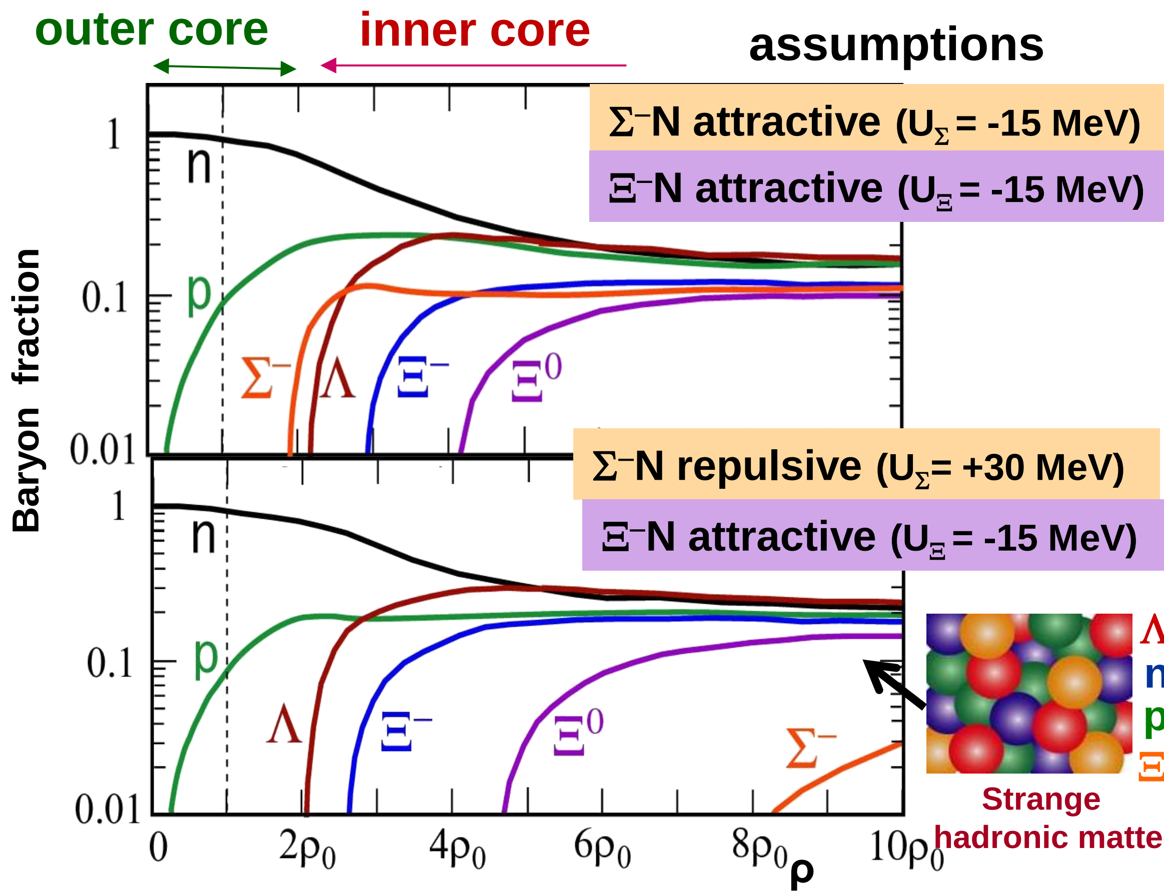



*Fermi gas model*

**Λ's must appear at ρ = 2~3 $\rho_0$**

# Baryon fractions in NS is sensitive to BB interactions




*C. Ishizuka et al., J.Phys. G35 (2008) 085201*

We need all the YN, YY interactions in free space and in nuclear matter (at high density...)

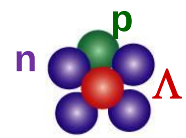
# Experimental status of YN, YY (+K$^{bar}$N) interactions

Poor $\Lambda$p, $\Sigma^{\pm}$p scattering data + **Various hypernuclear data**

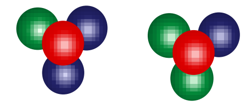
Experimentally known:

- $\Lambda$N int. attractive (U$_{\Lambda}$=-30 MeV)
  The same in neutron matter?
  Effect of $\Lambda$N-$\Sigma$N mixing?
- $\Sigma$N int. looks strongly repulsive.
  How large repulsion?
  -> No $\Sigma$'s in NS?
- $\Xi$N int. is unknown. Attractive or repulsive? -> $\Xi$'s in NS?
- $\Lambda\Lambda$ int. weakly attractive (B($\Lambda\Lambda$) =0.7 MeV). Need more data to confirm
  H dibaryon above $\Lambda\Lambda$ threshold?
- K$^{bar}$N interaction strongly attractive.
  How large attraction in nuclei?
  -> Kaon condensation in NS?

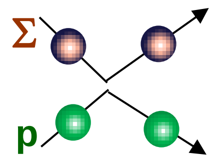
**Experiments running or planned**




**n-rich $\Lambda$ hypernuclei**

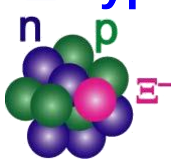


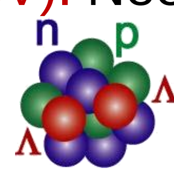
**Charge sym. breaking in $\Lambda$ hypernuclei**



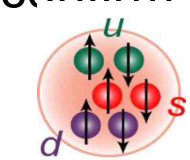

**$\Sigma^{\pm}$-p scattering**
**$\Lambda$-p scattering**

**$\Xi$ hypernuclei**

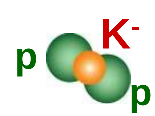



**$\Lambda\Lambda$ hypernuclei**




**H dibaryon**

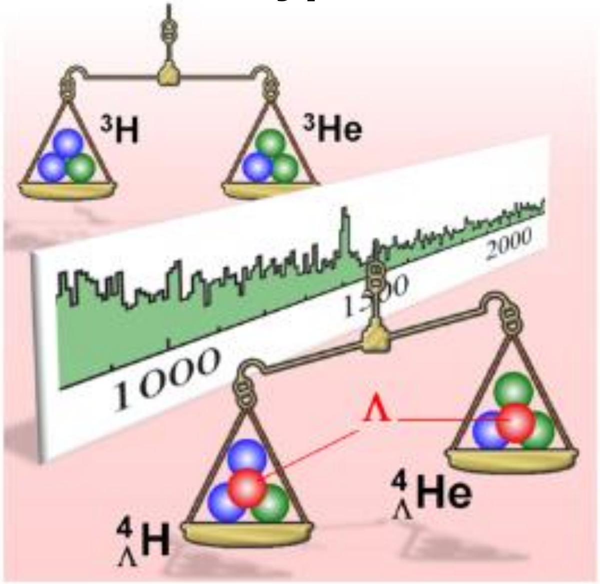



**K-nucleus**

Nijmegen ESC08 model reproduces most of the existing data well.

Also important to test Lattice QCD calculations.

Charge symmetry breaking
In A=4 Λ hypernuclei




# 2.1 S = -1 Systems

## ΛN interaction in neutron matter

**Charge symmetry breaking in Λ hypernuclei**

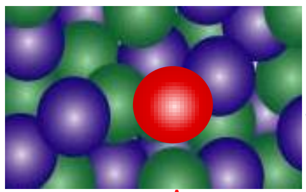
**Neutron–rich Λ hypernuclei**

**Isotope effect of Λ binding energies**

# ΛN interaction in neutron stars?

**Λ has no isospin => ΛN interaction should be the same in symmetric nuclear matter and in pure neutron matter**

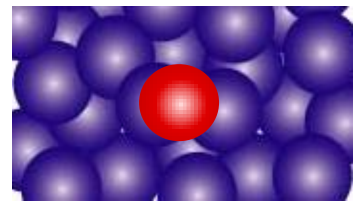
**Symmetric matter**



p
n
Λ

**=**
**?**

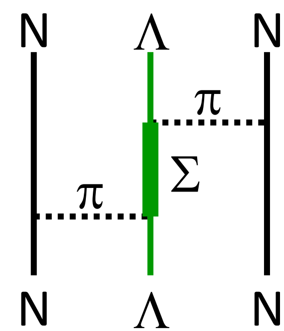
**Neutron matter**



n
Λ

**Known well from Λ hypernuclear data such as ${}^{12}_{\Lambda}C$, ${}^{28}_{\Lambda}Si$, ${}^{89}_{\Lambda}Y$, ${}^{208}_{\Lambda}Pb$**

**No data**




**Can be different due to**
**ΛNN(T=0) ≠ ΛNN(T=1) from Λ–Σ mixing and others**
**Charge symmetry breaking in ΛN (Λp ≠ Λn )**

**We need to study**

- **Charge symmetry breaking in Λ hypernuclei**
- **Neutron-rich Λ hypernuclei**
- **Isospin dependence of Λ binding energy (Λnn force)**

# Charge Symmetry Breaking (CSB) in Λ hypernuclei?

- CSB in NN force **(pp ≠ nn)**
  => $B(^3H) - B(^3He)$ – EM effect ~70 keV

**Experimental confirmation awaited**

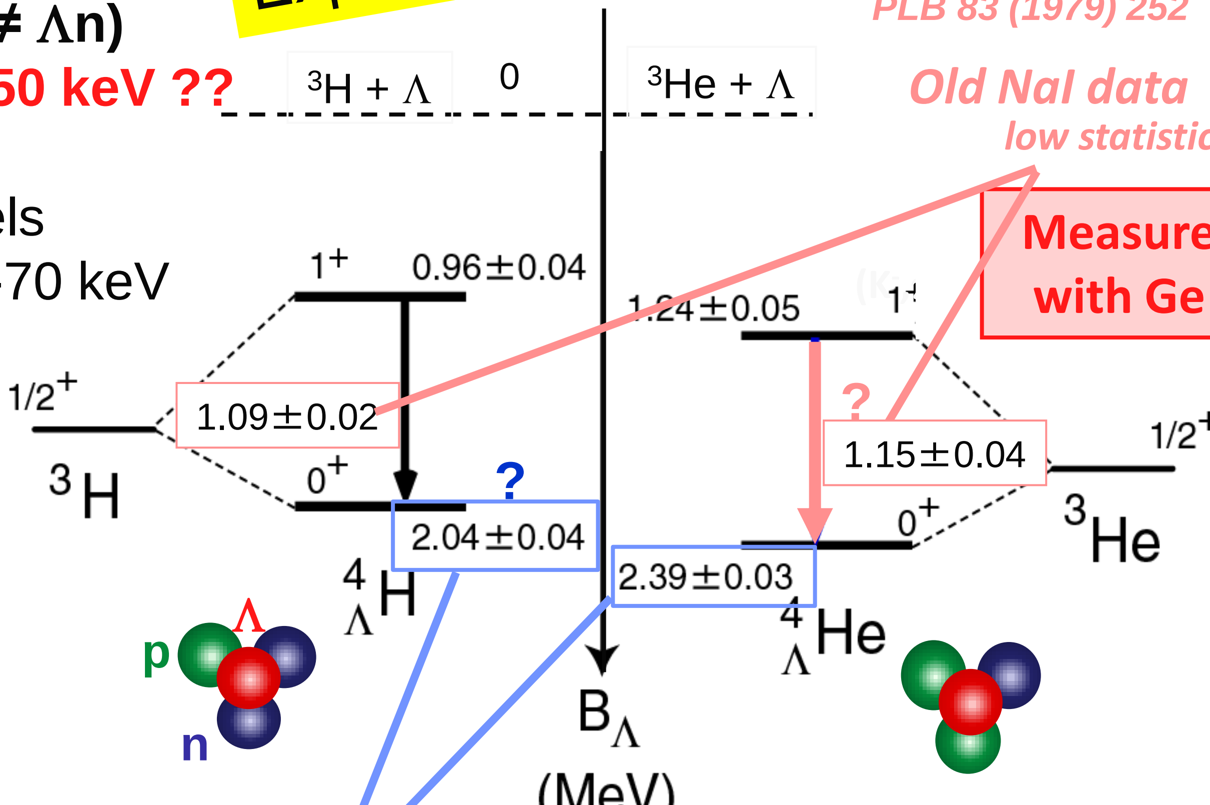
- CSB in ΛN force **(Λp ≠ Λn)**
  **$B_\Lambda(^4_\Lambda H) - B_\Lambda(^4_\Lambda He) = -350$ keV ??**

- YN interactions models
  $B_\Lambda(^4_\Lambda H) - B_\Lambda(^4_\Lambda He) = 0\text{-}70$ keV

*Bedjidian et al.*
*PLB 62 (1976) 467*
*PLB 83 (1979) 252*

***Old NaI data***
*low statistics*

**Measure with Ge**



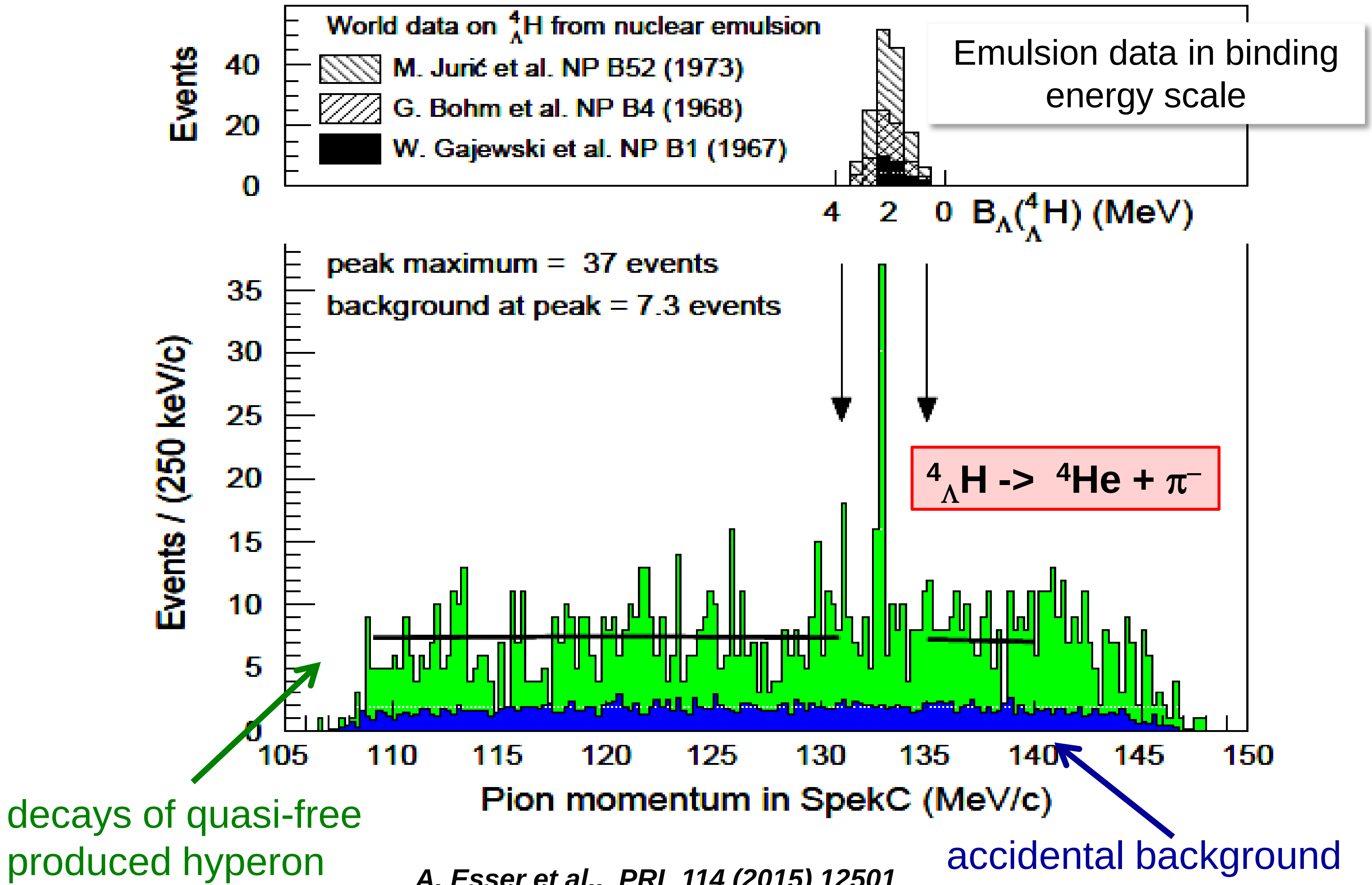

**Measure using weak decay pions**

***Old emulsion data***
*no systematic error*

*M. Juric et al. NPB 52 (1973) 1*

*Slide by P. Achenbach*

# Decay-pion measurement at Mainz

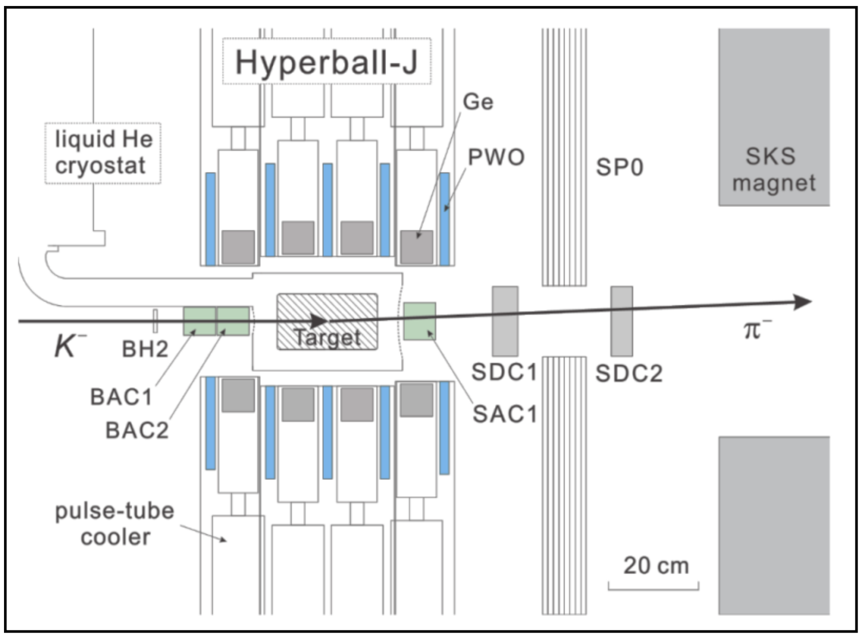


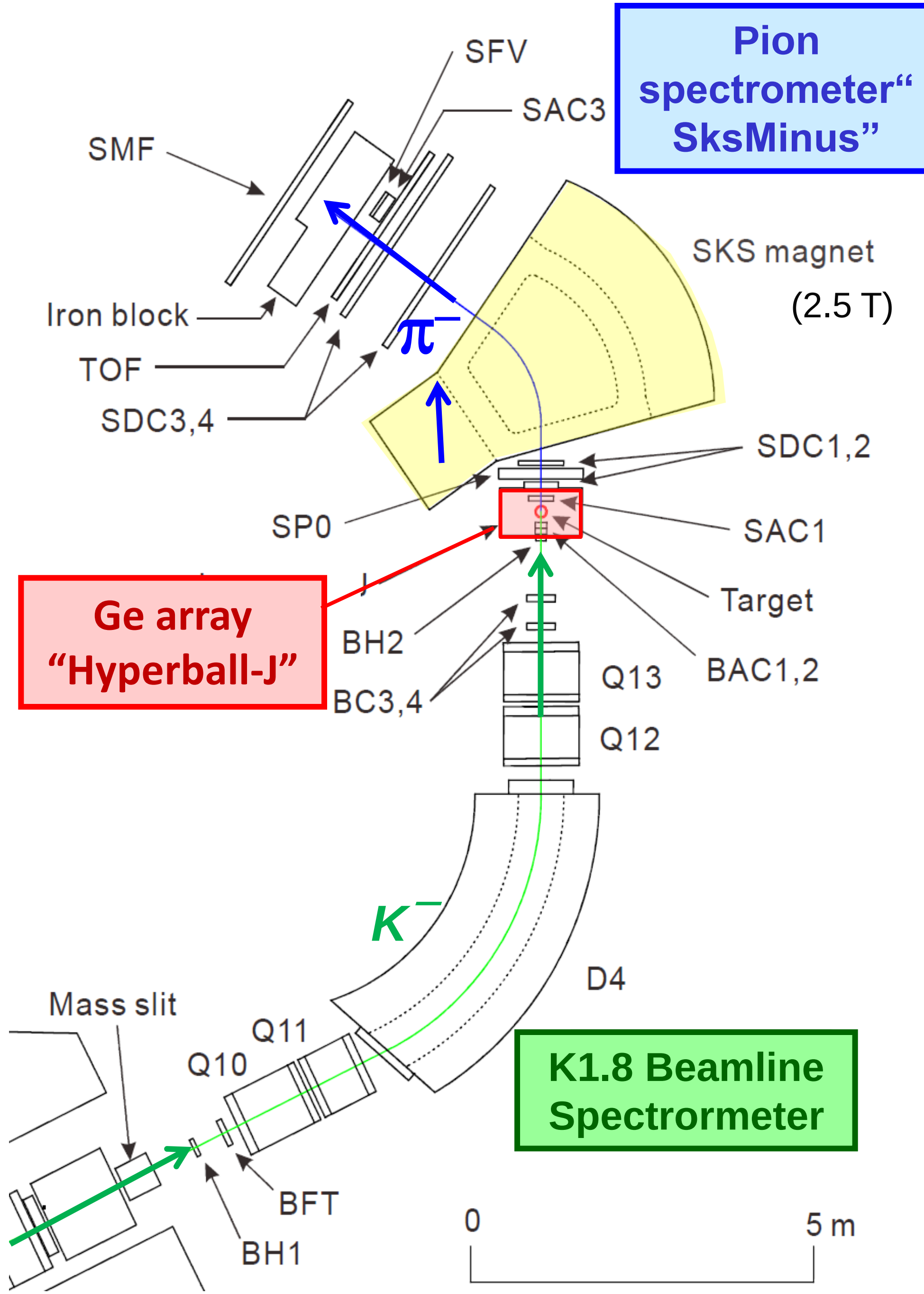

*A. Esser et al., PRL 114 (2015) 12501*

J-PARC E13 H. Tamura et al.

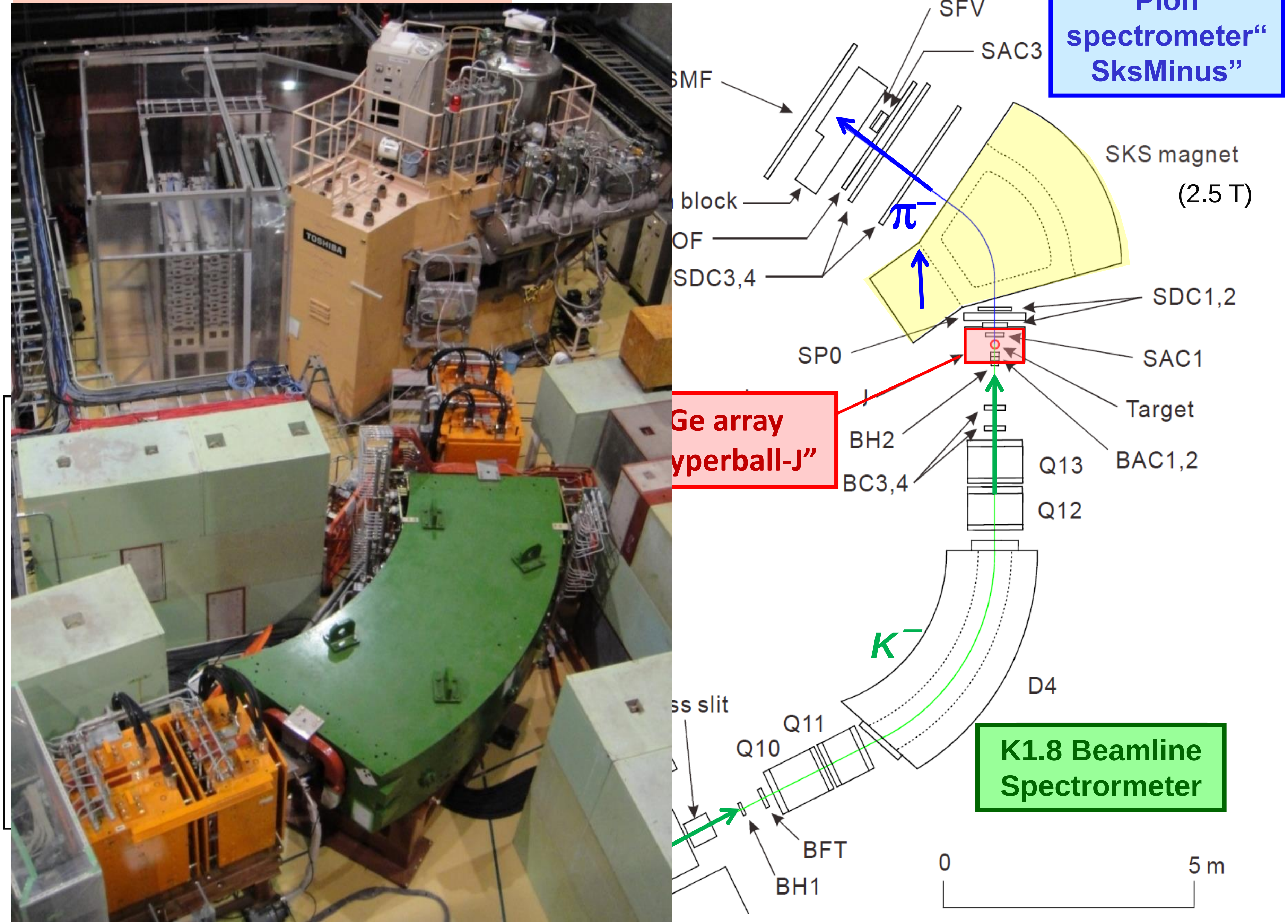
# γ spectroscopy of hyeprnuclei

$$ {}^{A}Z\,(K^-,\pi^-)\,{}^{A}_{\Lambda}Z^* \rightarrow {}^{A}_{\Lambda}Z+\gamma $$

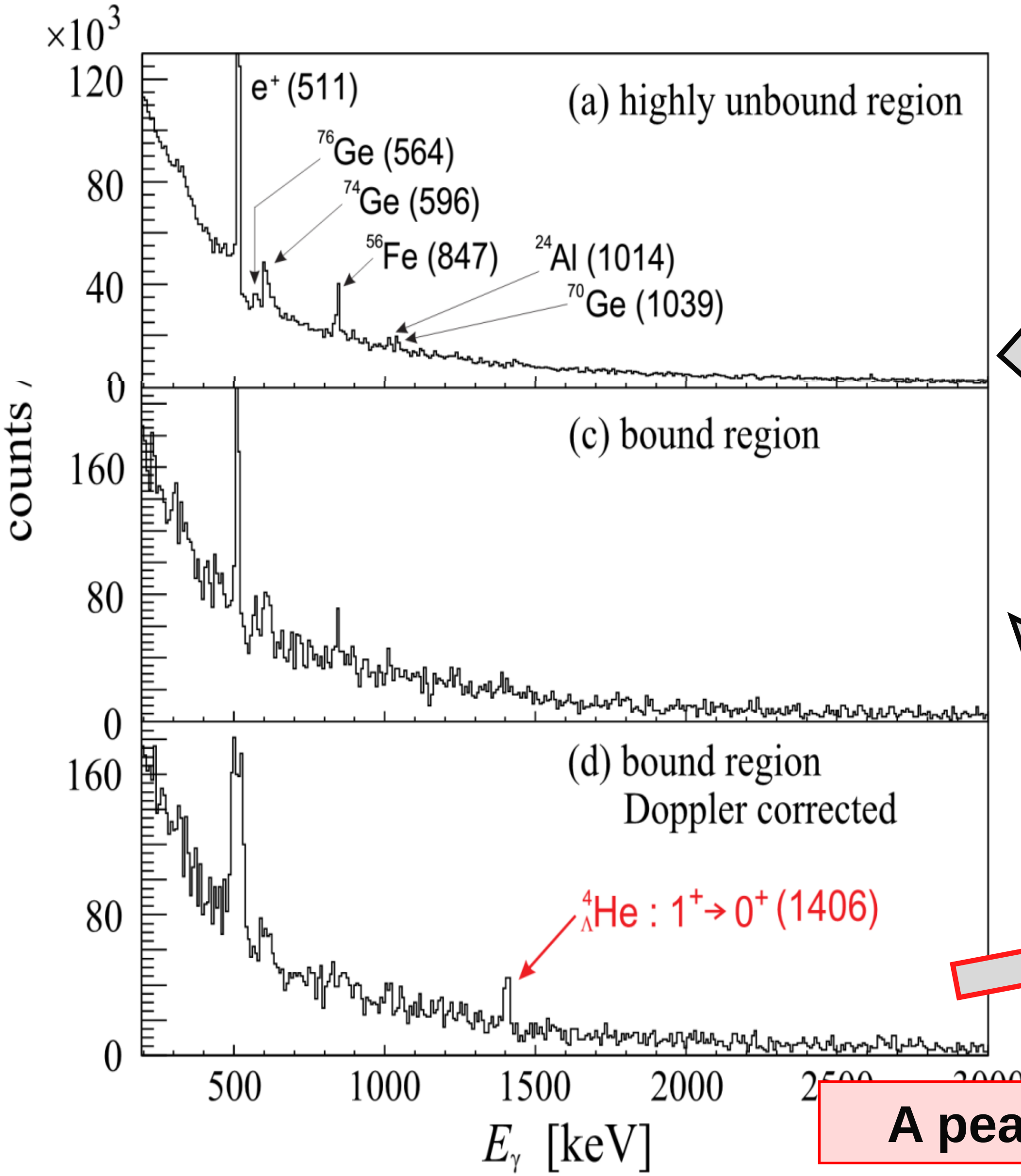


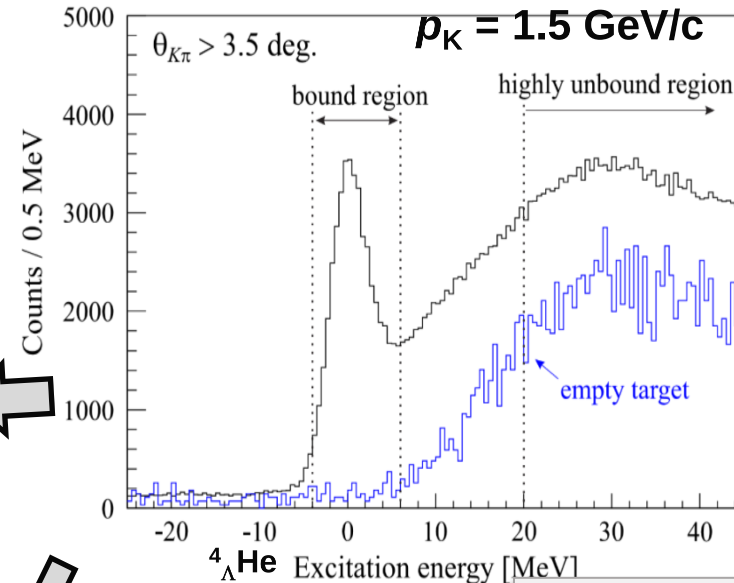
J-PARC E13 H. Tamura et al.

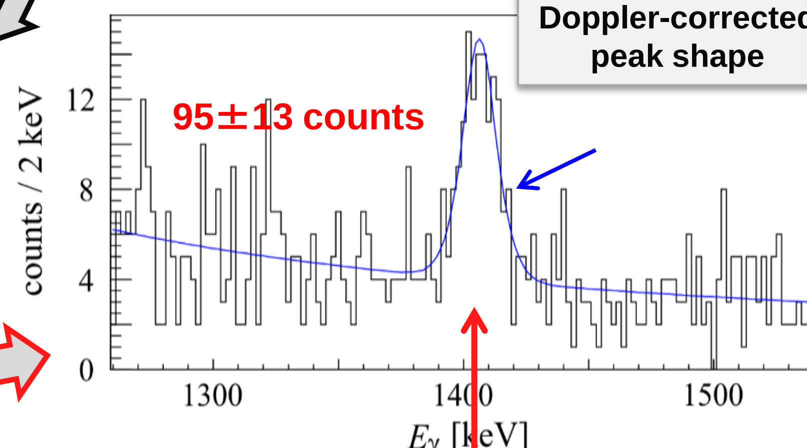


# $^{4}_{\Lambda}$He γ-ray spectrum




## Missing mass of $^4He(K^-,\pi^-)$



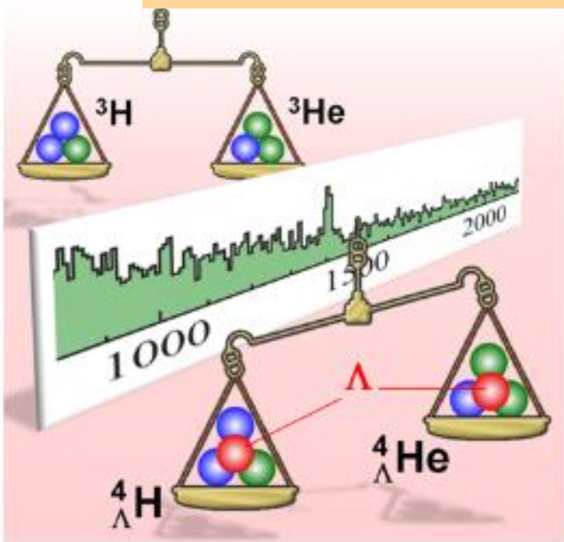



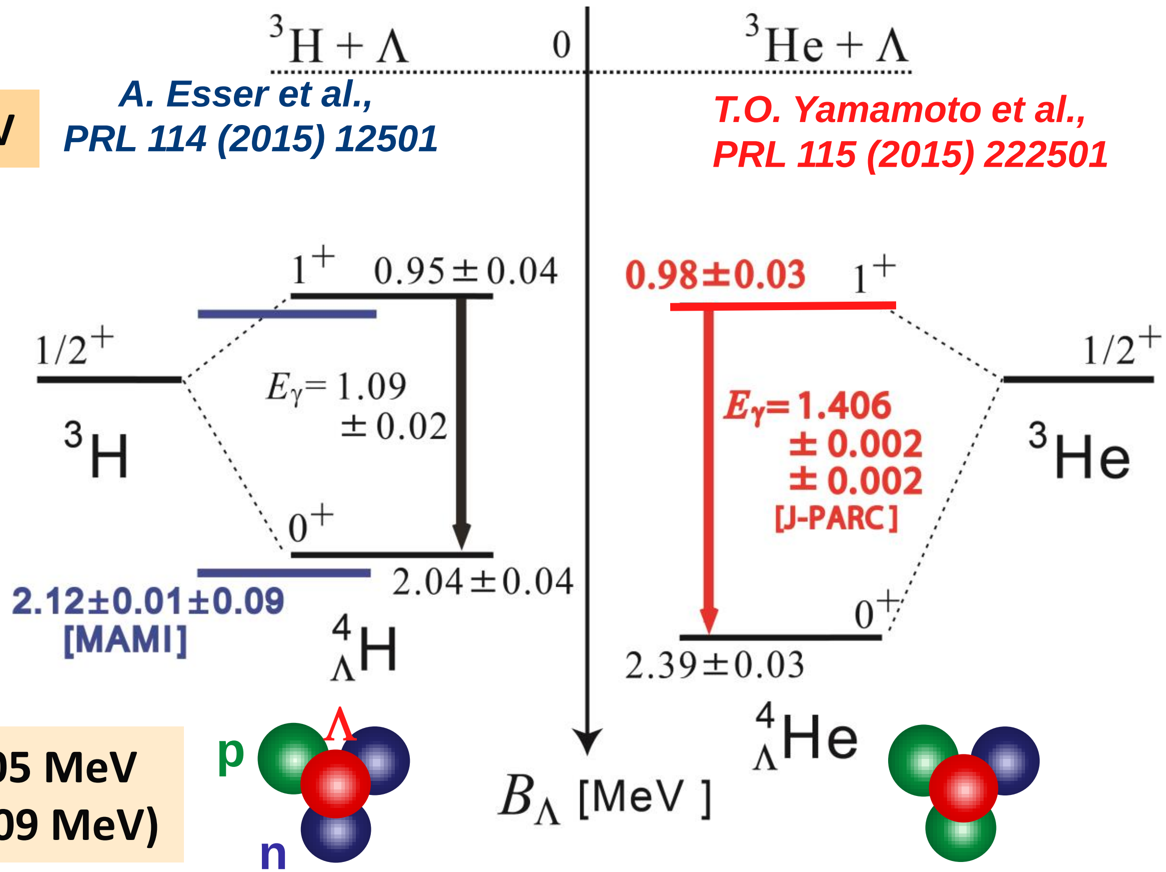

**Fit with simulated Doppler-corrected peak shape**

**A peak observed at 1406±2±2 keV**

# Charge Symmetry Breaking (CSB) in A=4 hypernuclei

**$\Delta B_\Lambda(1^+)$ : 0.03±0.05 MeV**

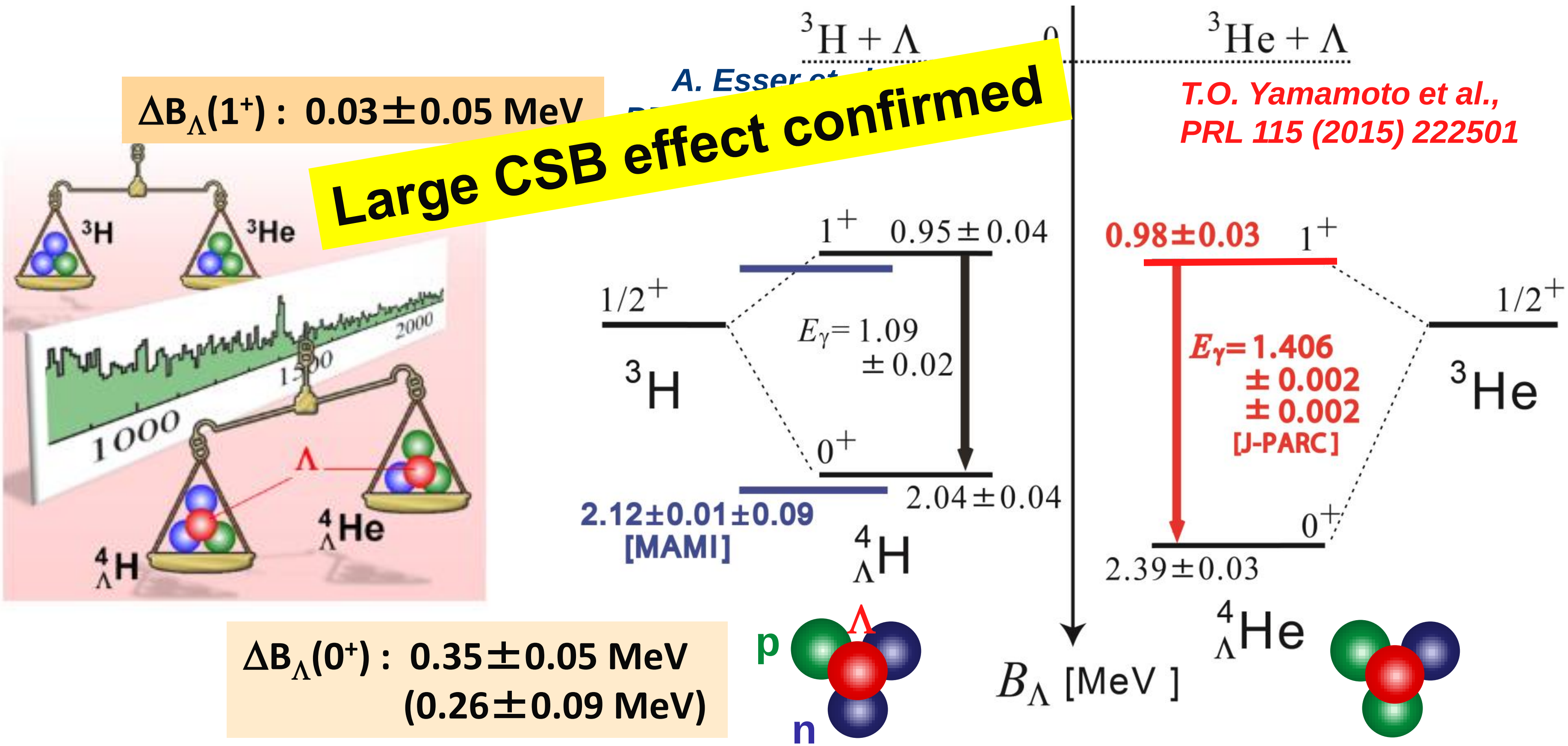



**$\Delta B_\Lambda(0^+)$ : 0.35±0.05 MeV**
**(0.26±0.09 MeV)**

- **Existence of a large CSB effect confirmed only by γ-ray data**
- **$B_\Lambda$ [ $^4_\Lambda$H($0^+$) ] confirmed via $^4_\Lambda$H -> $^4$He + $\pi^-$ decay , suggesting the emulsion $^4_\Lambda$He($0^+$) data also reliable**
- **Large spin dependence in CSB found by combining all the data**

# Charge Symmetry Breaking (CSB) in A=4 hypernuclei

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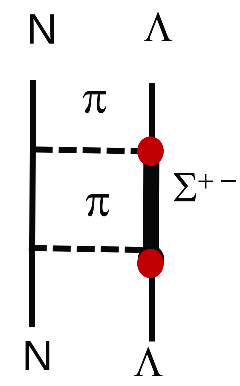
- Large spin dependence in CSB found by combining all the data

# What is the origin of the large CSB effect?




***u/d quark mass difference + EM effects***
***=> CSB in hadrons and hadron-hadron interactions***

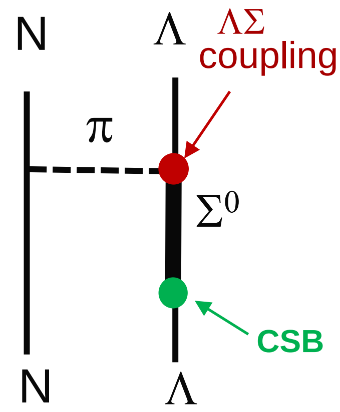
**∗ $\Sigma^+\Sigma^-$ mass difference + CSB in BB forces (Nijmegen SC97e)**
**=> $\Delta B_\Lambda(0^+)$ ~70 keV at maximum.**

*Nogga et al., PRL 88 (2002) 172501*

**∗ Shell model calc. using D2 => $\Delta B_\Lambda(0^+)$ ~200 keV.** *A. Gal, PLB 744 (2015) 352*

***D2: central-only ΛΣ coupling*** *Akaishi et al., PRL 84 (2000) 3539*

***(SC: tensor dominated ΛΣ coupling)***




**∗ Ab initio calc. with Bonn-Juelich EFT force (LO)**
**=> $\Delta(B_\Lambda(0^+)$- $\Delta B_\Lambda(1^+))$ ~0.3 MeV.** ***= central dominated ΛΣ coupling***

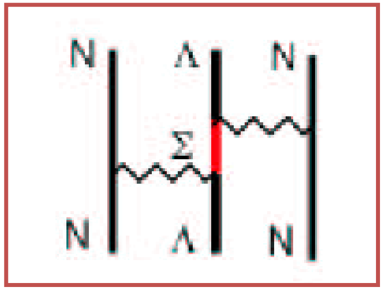
*D. Gazda and A. Gal, PRL 116 (2016) 122501*

**The CSB effect is sensitive to ΛN-ΣN coupling.**

**CSB effects in p-shell hypernuclei will confirm the origin.**

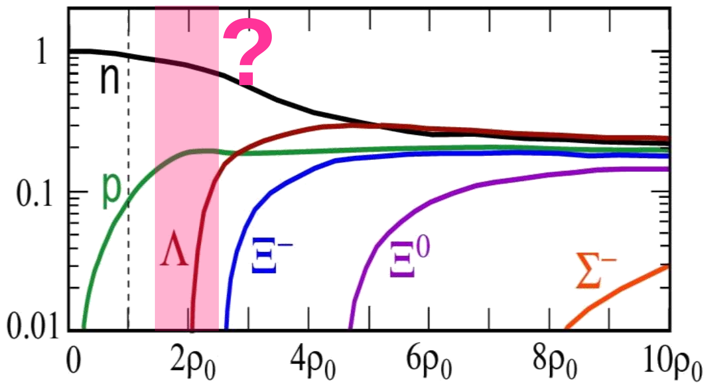
# Neutron-rich hypernuclei

- **Strong mixing of ΛN-ΣN** B.F. Gibson et al. PRC6 (1972) 741, etc
- **Coherent effect in proton/neutron-rich nuclei** Akaishi et al. PRL 84 (2000) 3539




Larger mixing in a host nucleus with larger I

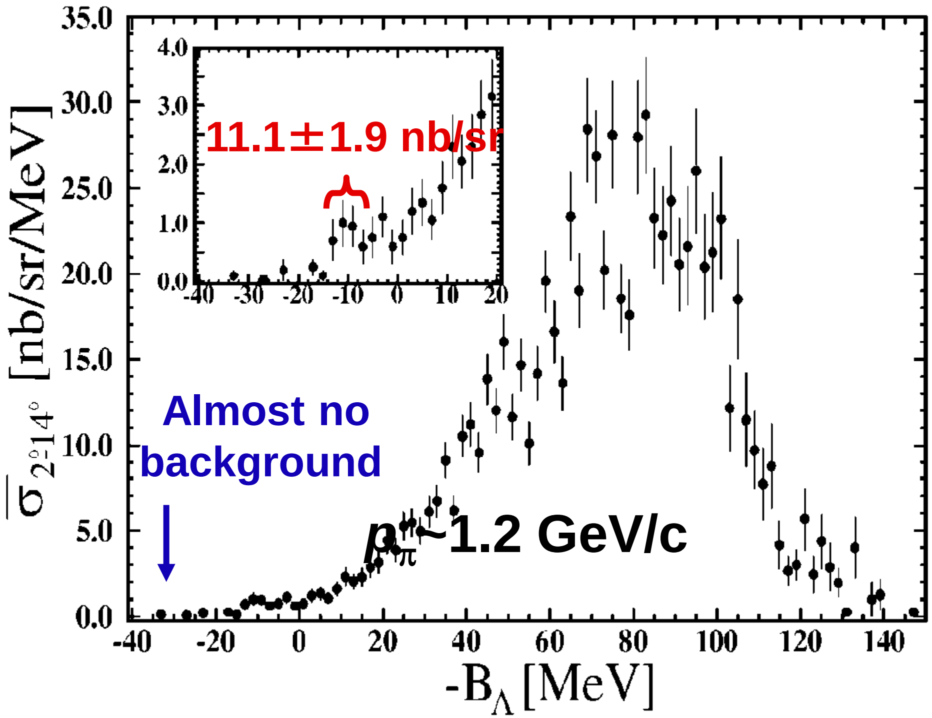
=> How large mixing in n-rich hypernuclei?



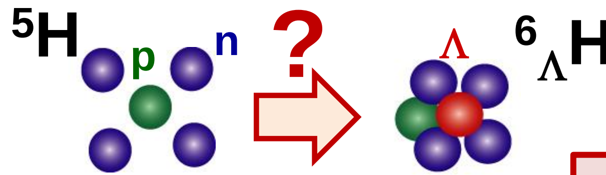

=> Effect to Λ appearance in n star?

**$^{10}B$ ($\pi^-$, $K^+$) $^{10}_{\Lambda}Li$**

***PRL 94 (2005) 052502***



# $^{6}_{\Lambda}$H is bound?



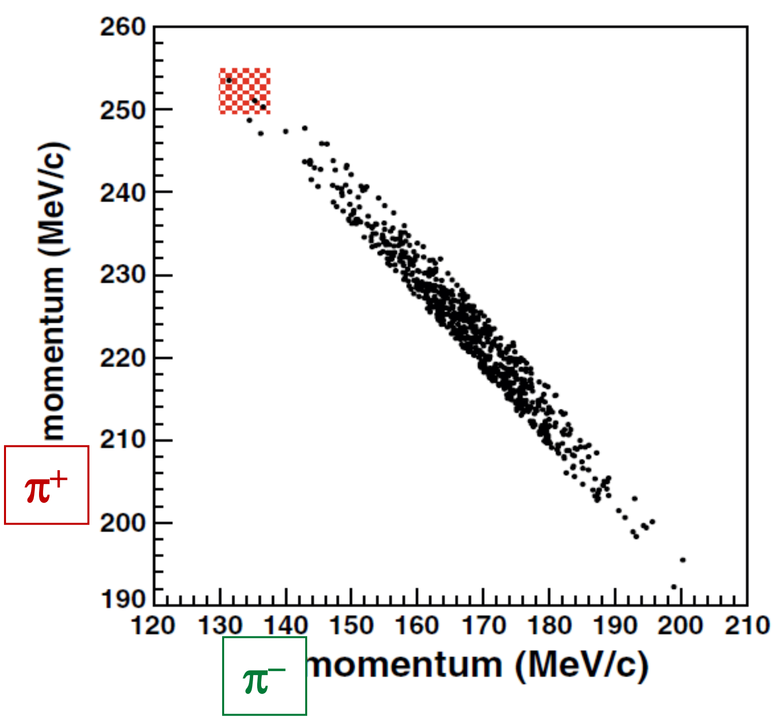

**FINUDA@DAΦNE**

*M. Agnello et al., PRL 108 (2012) 042501*

$K^-(stop) + {}^{6}Li \rightarrow {}^{6}_{\Lambda}H + \pi^+$

${}^{6}_{\Lambda}H \rightarrow {}^{6}He + \pi^-$

**3 events of bound $^{6}_{\Lambda}$H reported.**



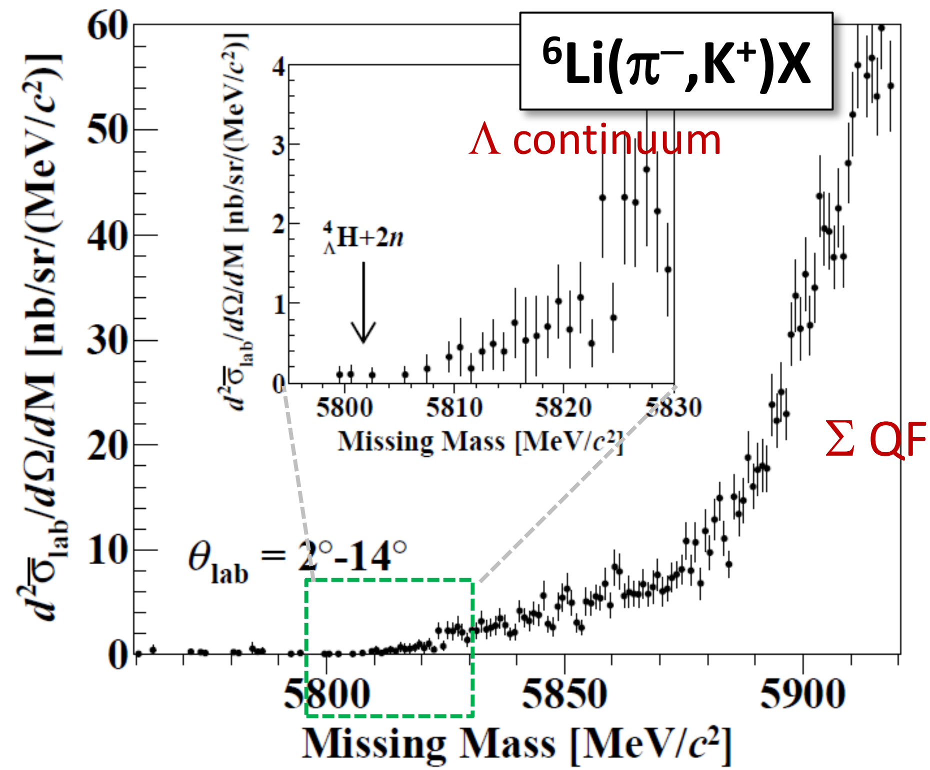

**E10@J-PARC**

*Sugimura et al. PLB 729 (2014) 39*

$\pi^- + {}^{6}Li \rightarrow {}^{6}_{\Lambda}H + K^+$

$(\pi^- p \rightarrow \Sigma^- K^+,\ \Sigma^- p \rightarrow \Lambda n$ etc.)

**No $^{6}_{\Lambda}$H peak observed.**

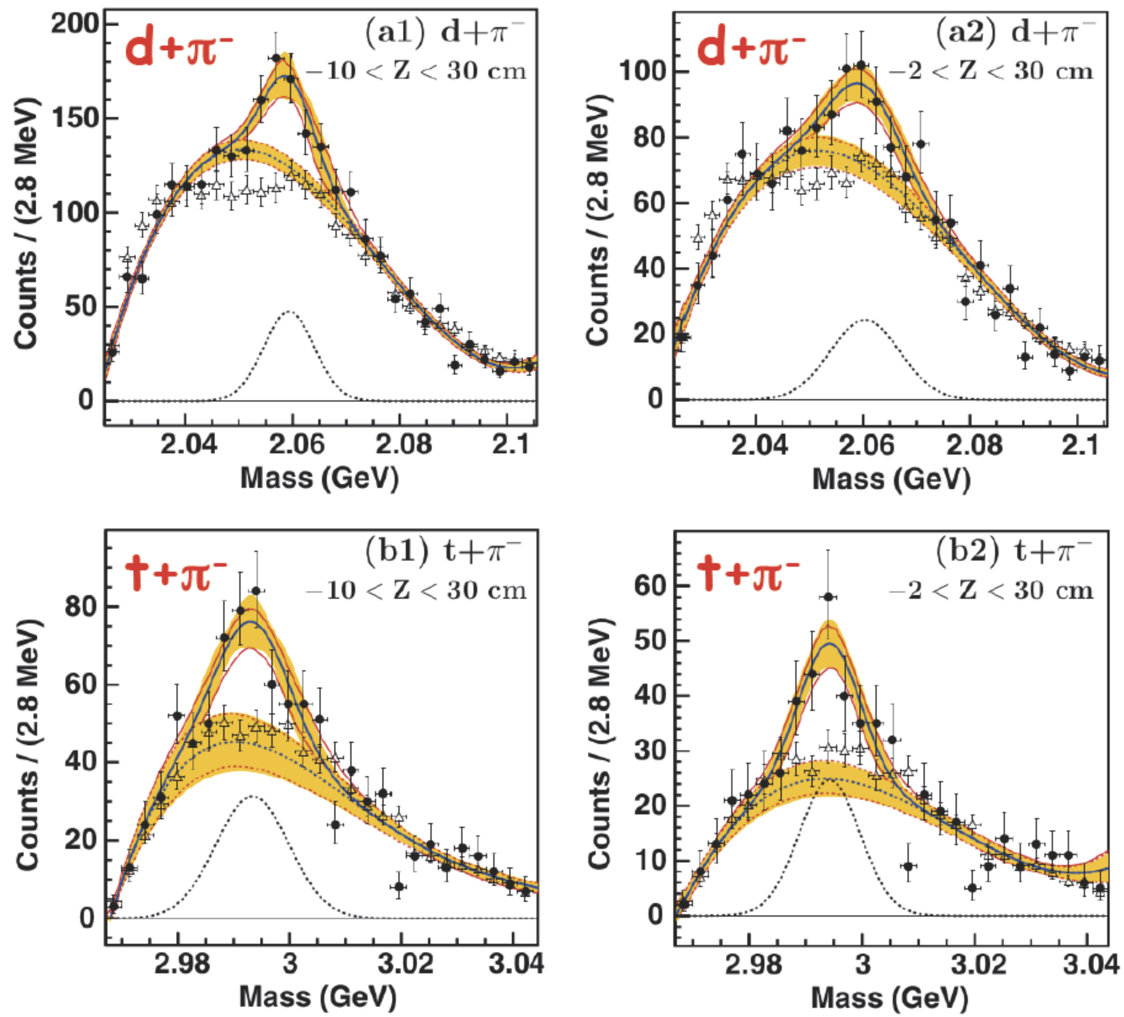


# Λnn bound state??

**HypHI@GSI**
*C. Rappold et al.*

PHYSICAL REVIEW C **88**, 041001(R) (2013)

**Search for evidence of ${}^{3}_{\Lambda}n$ by observing $d+\pi^-$ and $t+\pi^-$ final states in the reaction of ${}^{6}\mathrm{Li}+{}^{12}\mathrm{C}$ at 2$A$ GeV**




**The only interpretation is weak decays from a Λnn bound state.**

**But theoretically unlikely.**

**cf. ${}^{3}_{\Lambda}$H (=Λpn) is bound by $B_\Lambda$= 130 keV.**

**=> To be examined by a dedicated exp. at FRS@GSI.**

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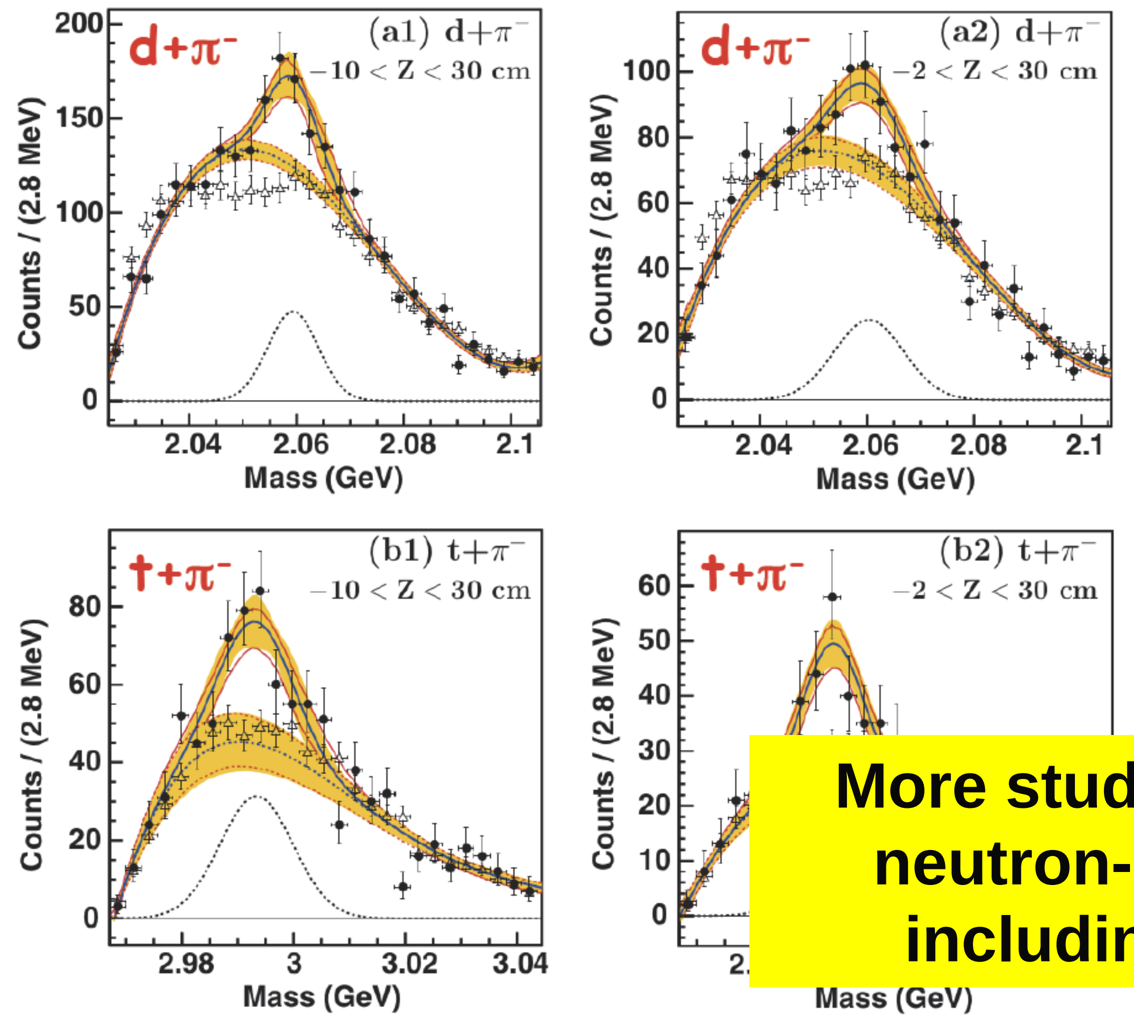


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**But theoretically unlikely.**
**cf.${}^{3}_{\Lambda}$H (=Λpn) is bound by $B_{\Lambda}$= 130 keV.**

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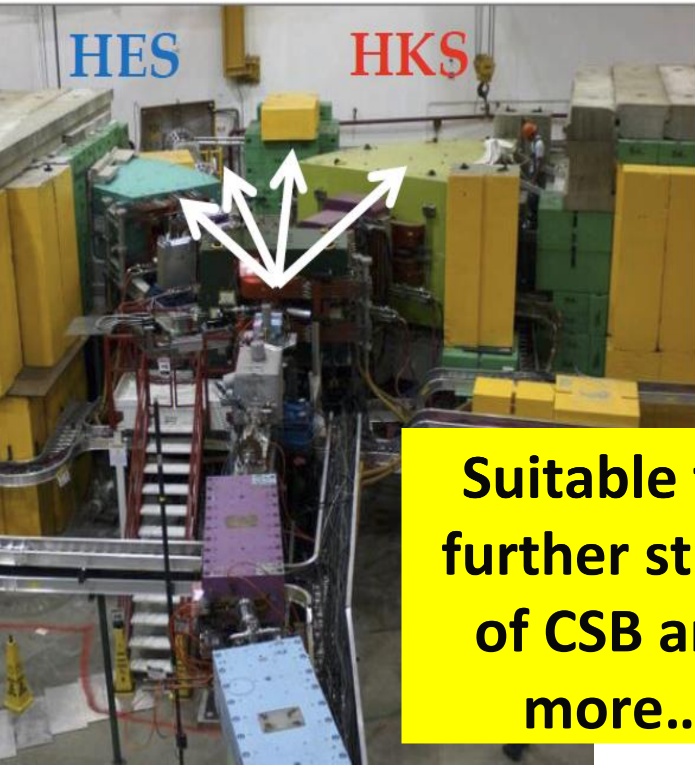
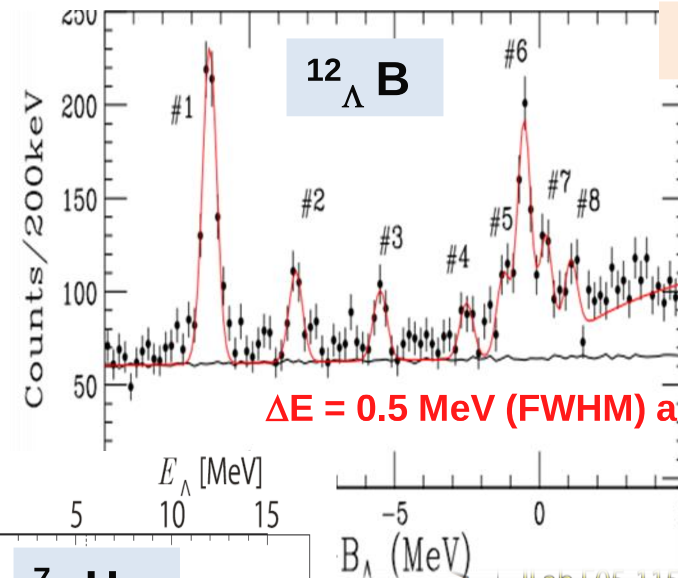
**More studies necessary for neutron-rich hypernuclei including ${}^{6}_{\Lambda}$H and Λnn.**

# High resolution (e,e'K$^+$) spectroscopy at JLab




**Suitable for further study of CSB and more…**

**Jlab E05-115**

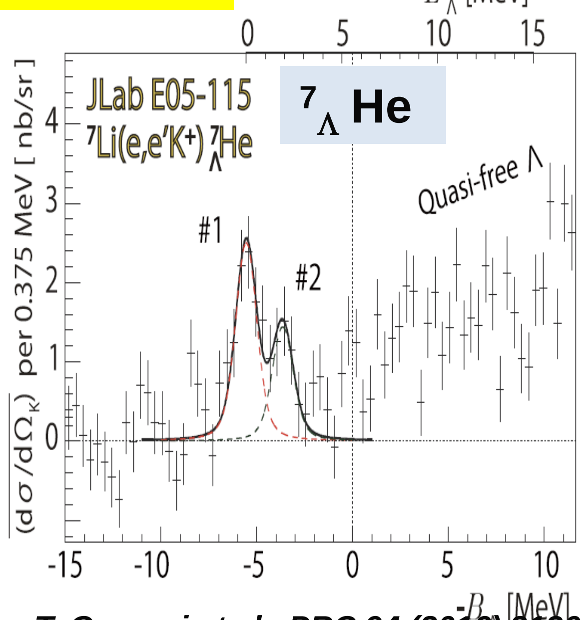



*L. Tang et al., PRC90 (2014) 034320*

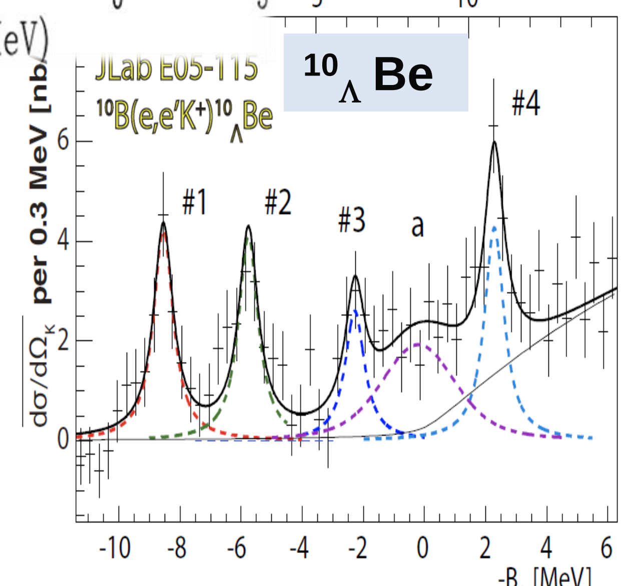
**ΔE = 0.5 MeV (FWHM) achieved**

**Mass resolution ~ 500 keV (FWHM)**
**⇔ > 1.5 MeV by ($\pi^+$,$K^+$), ($K^-$,$\pi^-$)**

**Accuracy of absolute mass ~ 100 keV**
**⇔ ~1 MeV by ($\pi^+$,$K^+$), ($K^-$,$\pi^-$)**




*T. Gogami et al., PRC 94 (2016) 21302(R)*




*T. Gogami et al., PRC 93 (2016) 034314*

# (e,e'K+) spectroscopy
# for isospin dependence in Λ binding energy

**Compare $^{40}$Ca (e,e'K$^+$) $^{40}{}_{\Lambda}$K and $^{48}$Ca (e,e'K$^+$) $^{48}{}_{\Lambda}$K**

$$\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j = -3P^{T=0} + C_T\, P^{T=1}$$

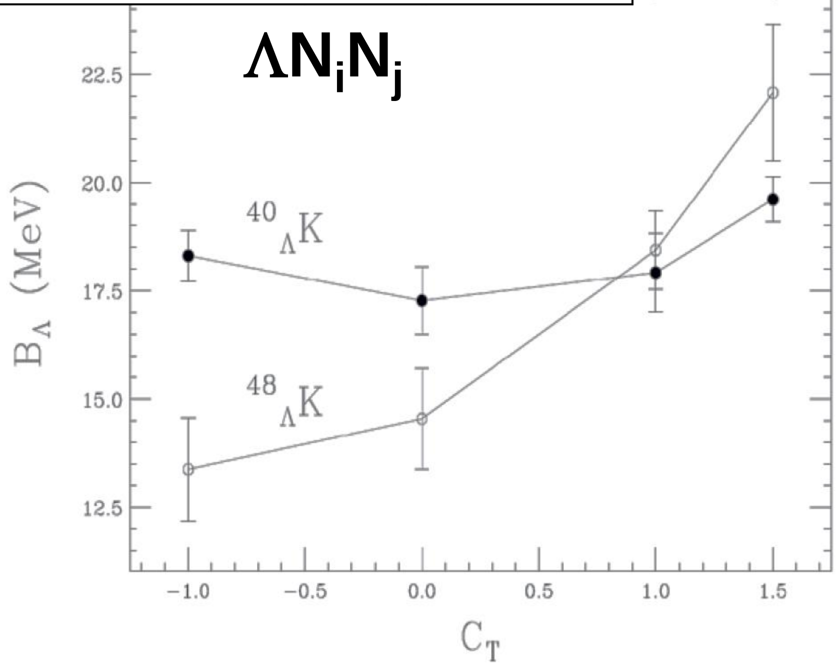
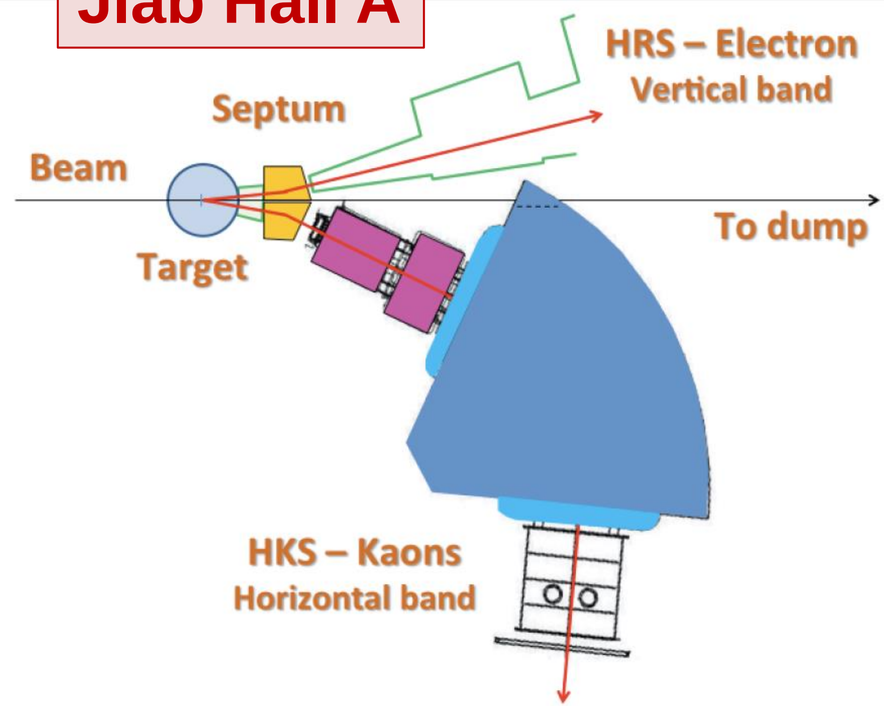



Figure 2-8: Latest results of Λ separation energies for $^{40}_{\Lambda}$K and $^{48}_{\Lambda}$K as a function of $C_T$ calculated with AFDMC. Errors are statistical errors in Monte Carlo calculation and future study will make them smaller.

*AFDMC calc. by D.Lonardoni, S.Gandolfi et al.*

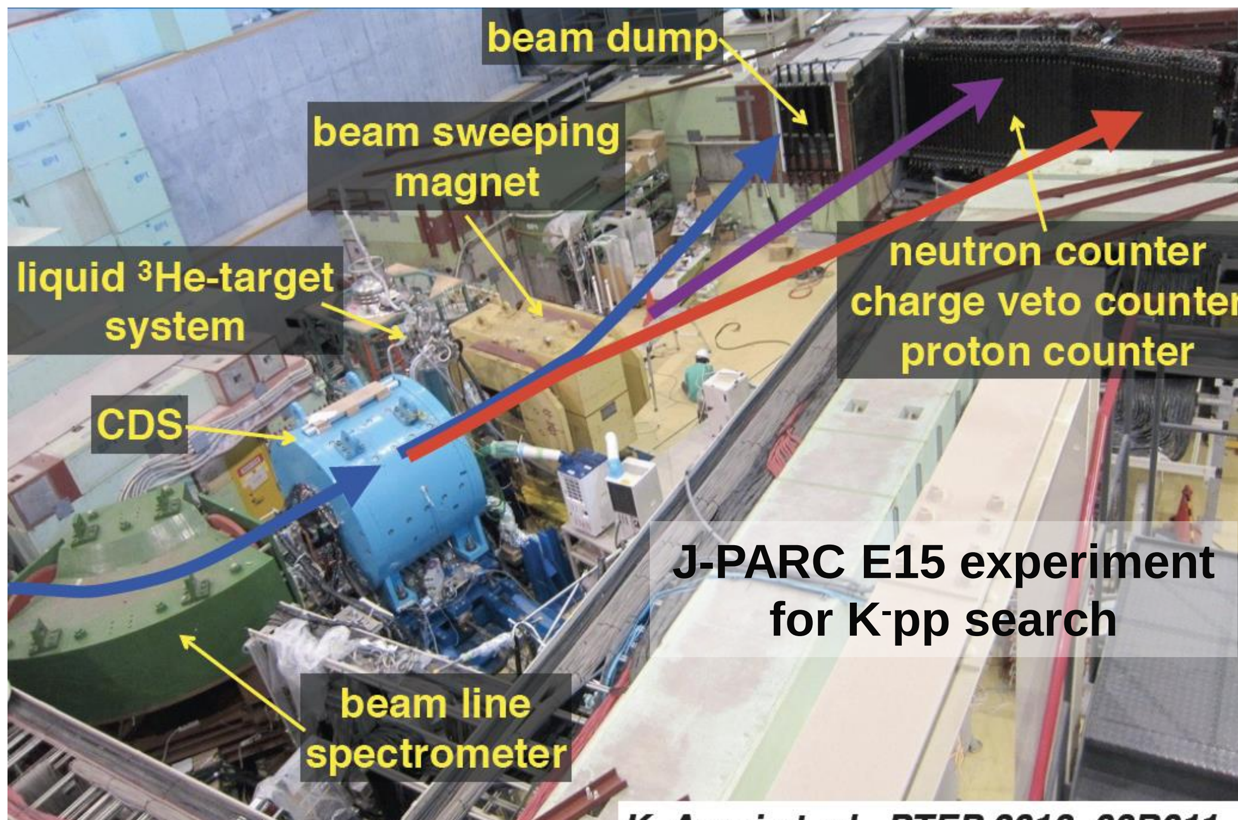
**Jlab Hall A**




*S.N. Nakamura (Tohoku) et al.*

**The experiment has been approved.**

# 2.2 S = -1 Systems
# $K^{-}pp$ and $K^{bar}N$ interaction



# $K^{bar}$-N interaction and $K^{bar}$ nucleus

- $\bar{K}$N interaction
  - Known to be strongly attractive from $K^-p$ atomic X-ray shift and low energy $K^-$ p scattering data
  - $\Lambda(1405)$ $(1/2^-)$ can be interpreted as a $K^-p$ bound state
- $K^-pp$ bound state  KNN (I=1/2) The simplest Kbar nucleus
  - Theoretical prediction of B.E. and Γ depend on the KN interaction and theoretical framework.
- $\bar{K}$ in matter
  - Clarify possible existence of $K^-$ condensation in neutron stars
  - Extremely high density nuclei can be produced?

Calculated $K^-pp$ binding energies $B$ and widths $\Gamma$ (in MeV). *A. Gal / Nuclear Physics A 914 (2013) 270–279*

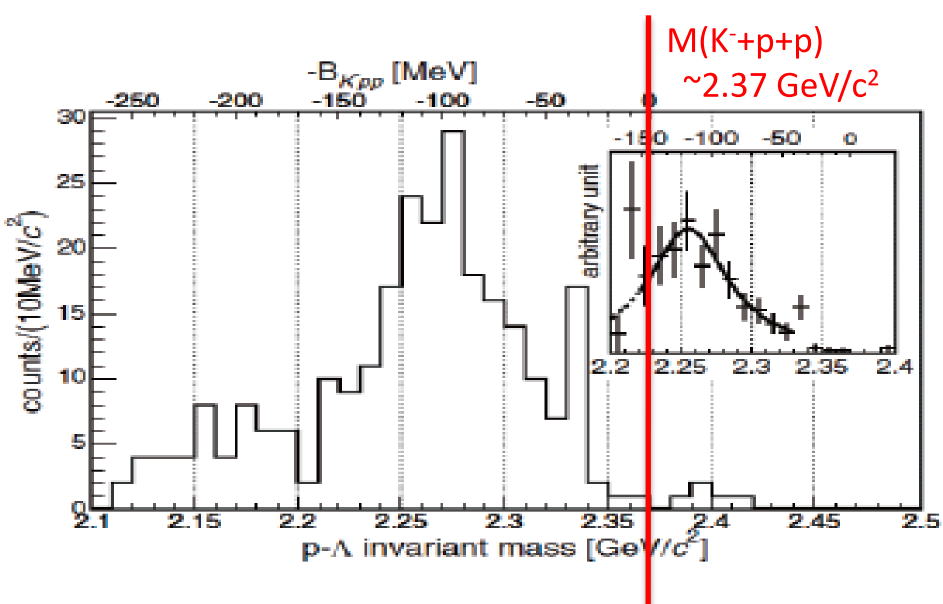
| | Chiral, energy dependent | | | Non-chiral, static calculations | | | |
|---|---|---|---|---|---|---|---|
| | var. [7] | var. [8] | Fad. [9] | var. [10] | Fad [11] | Fad [12] | var. [13] |
| $B$ | 16 | 17–23 | 9–16 | 48 | 50–70 | 60–95 | 40–80 |
| $\Gamma$ | 41 | 40–70 | 34–46 | 61 | 90–110 | 45–80 | 40–85 |


[7] N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B 712 (2012) 132.
[8] A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804 (2008) 197; A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79 (2009) 014003.
[9] Y. Ikeda, H. Kamano, T. Sato, Prog. Theor. Phys. 124 (2010) 533.
[10] T. Yamazaki, Y. Akaishi, Phys. Lett. B 535 (2002) 70.
[11] N.V. Shevchenko, A. Gal, J. Mareš, Phys. Rev. Lett. 98 (2007) 082301; N.V. Shevchenko, A. Gal, J. Mareš, J. Revai, Phys. Rev. C 76 (2007) 044004.
[12] Y. Ikeda, T. Sato, Phys. Rev. C 76 (2007) 035203; Y. Ikeda, T. Sato, Phys. Rev. C 79 (2009) 035201.
[13] S. Wycech, A.M. Green, Phys. Rev. C 79 (2009) 014001.

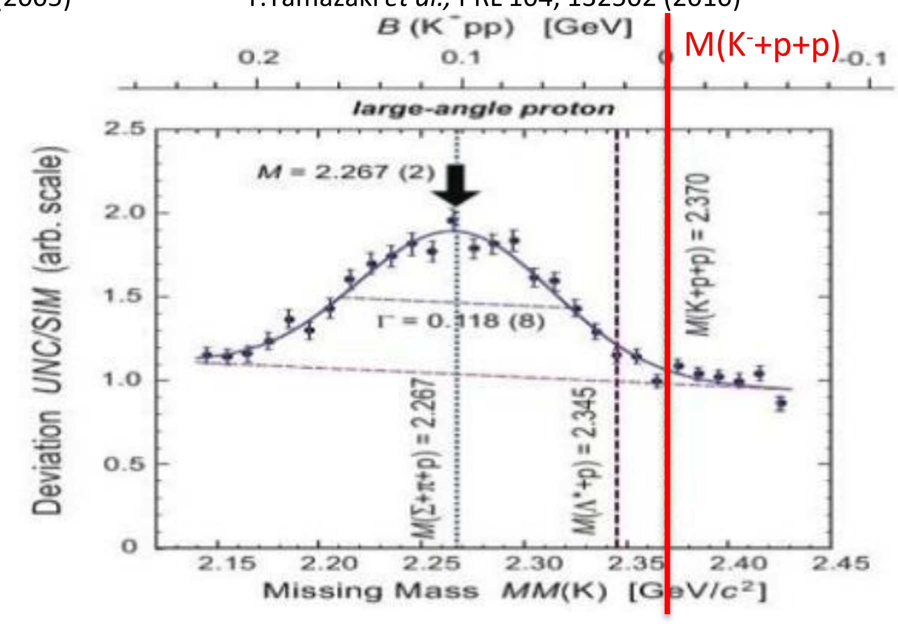
# Previous positive data for $K^-pp$

| | FINUDA | DISTO |
|---|---|---|
| reaction | Stopped $K^-$ absorption on $^{6,\,7}Li+^{12}C$ | p + p @ Tp=2.85GeV |
| method | Invariant mass of back-to-back Λp pairs | p+p→X+$K^+$（missing mass） X→Λ+p（invariant mass） |
| B.E | $115^{+6}_{-5}(stat)^{+3}_{-4}(syst)\quad MeV$ | 105 ± 5 MeV |
| Width | $67^{+14}_{-11}(stat)^{+2}_{-3}(syst)\quad MeV$ | 118 ± 8 MeV |

M.Agnello *et al.*, PRL 94, 212303 (2005)




T.Yamazaki *et al.*, PRL 104, 132502 (2010)



Slide by Y. Ichikawa

# $K^-pp$ search via $d(\pi^+,K^+)$

J-PARC E27
Nagae et al.

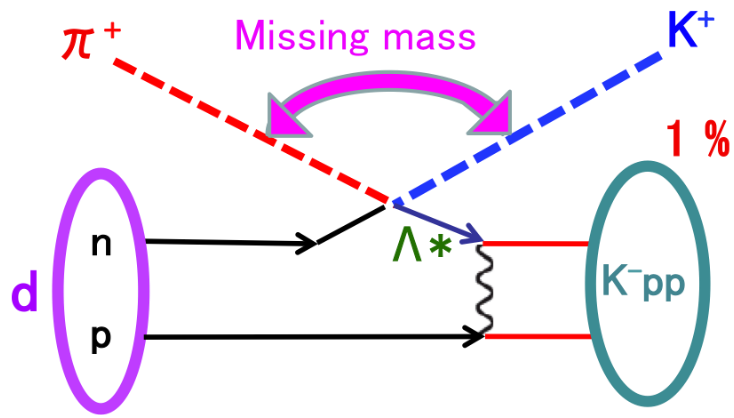
$d(\pi^+, K^+)X$ reaction ($P_\pi$ = 1.7GeV/c)

$K^-pp$ is produced via a Λ(1405) doorway.

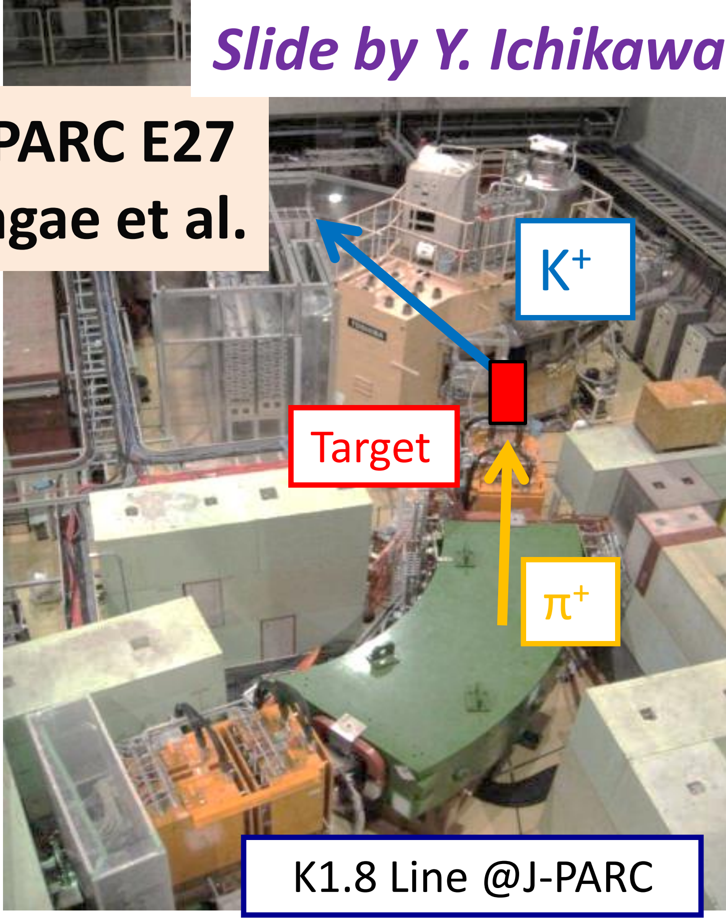
$\pi^+ + n \rightarrow \Lambda(1405) + K^+$

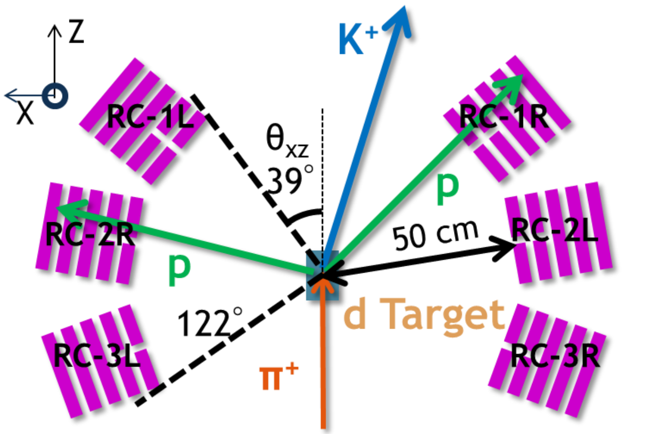
$\Lambda(1405) + p \rightarrow K^-pp$

(→quasi free Λ* )




Y.Akaishi, T.Yamazaki, Phys. Rev. C 76 045201 (2007)




Coincidence with protons

$d(\pi^+,K^+)K^-pp$

$K^-pp \rightarrow \Lambda + p$

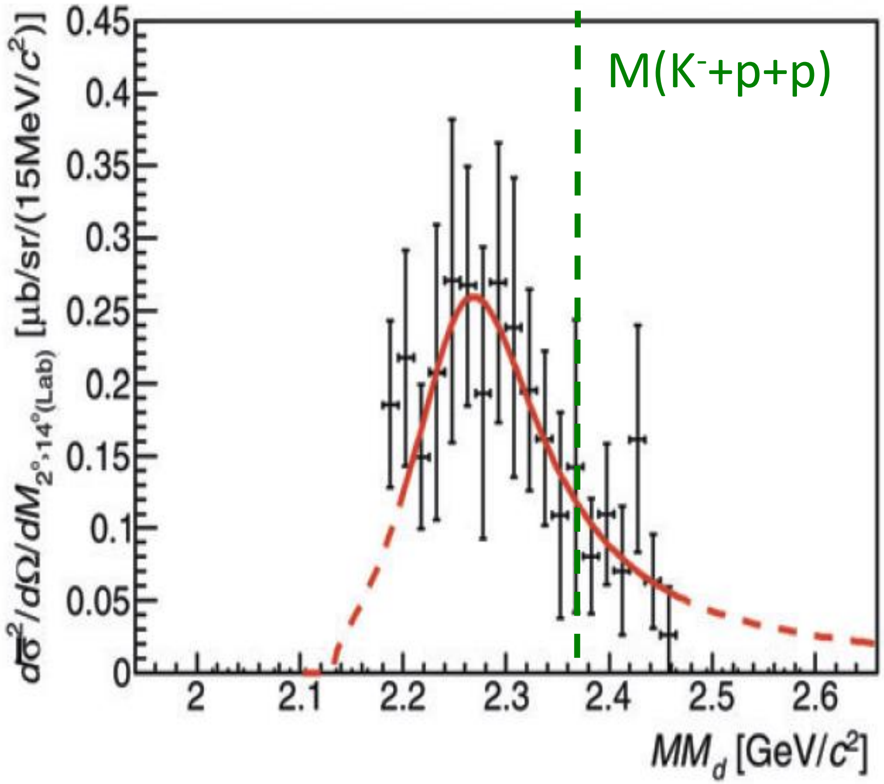
$\quad \hookrightarrow p+\pi^-$

# $K^-pp$ search via $d(\pi^+,K^+)$

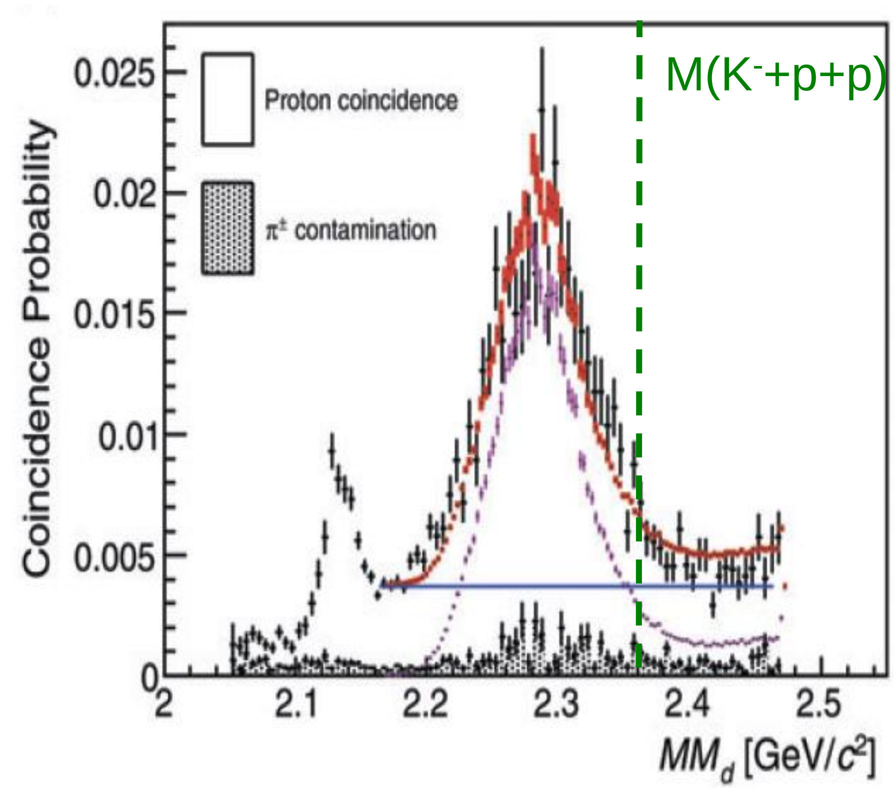
**J-PARC E27**
**Nagae et al.**

**1.69 GeV/c pion beam, $n(\pi^+,K^+)\,\Lambda(1405)$, $\Lambda(1405) + p \rightarrow K^-pp$**

**Two proton coincidence spectrum**




**One-proton coin. spectrum / inclusive spectrum**



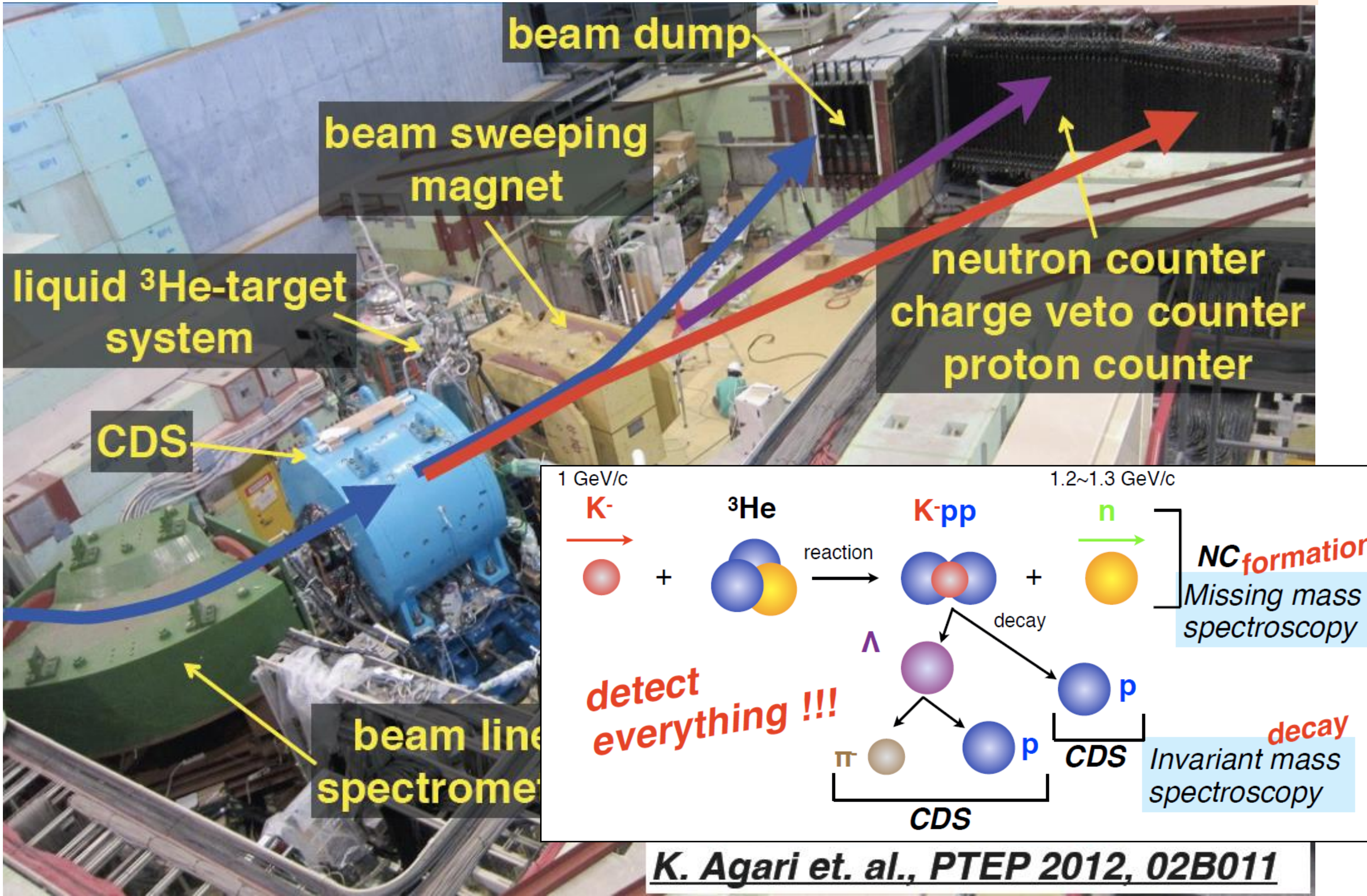

**B(Kpp) = 95 $^{+18}_{-17}$ (stat) $^{+30}_{-21}$ (syst) MeV**

**Similar to DISTO / FINUDA data**

*Y. Ichikawa et al., PTEP 2015 (2015) 021D01*

# Another K⁻pp search exp.

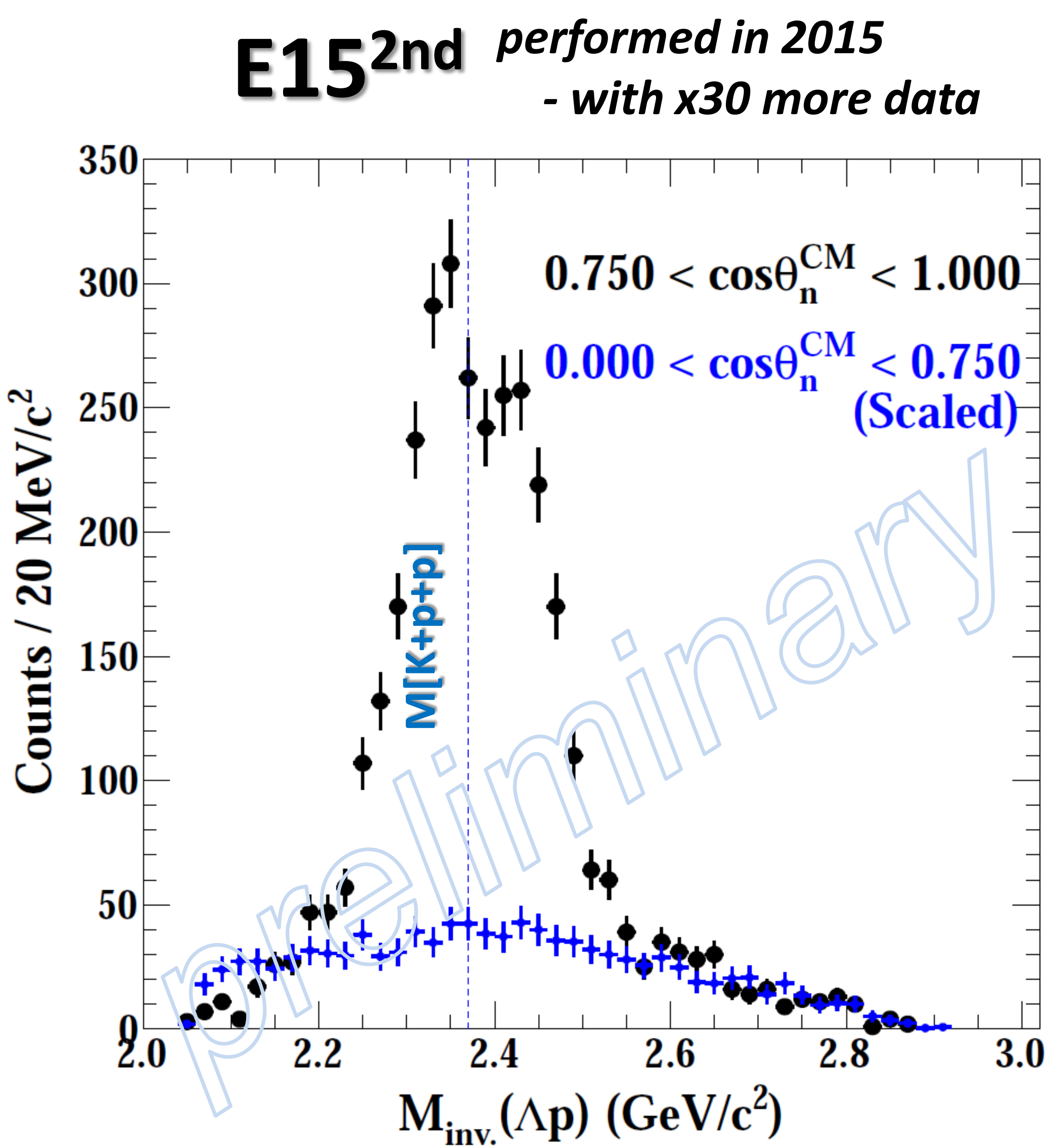
**J-PARC E15**
**Iwasaki et al.**

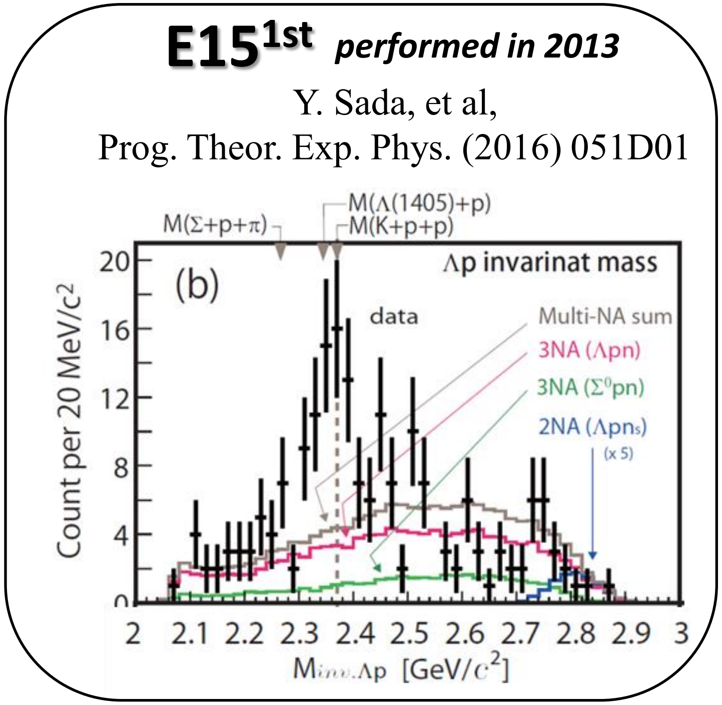



*K. Agari et. al., PTEP 2012, 02B011*

*Slide by T.Yamaga*

# The latest result: $^3$He(K$^-$,Λp)n



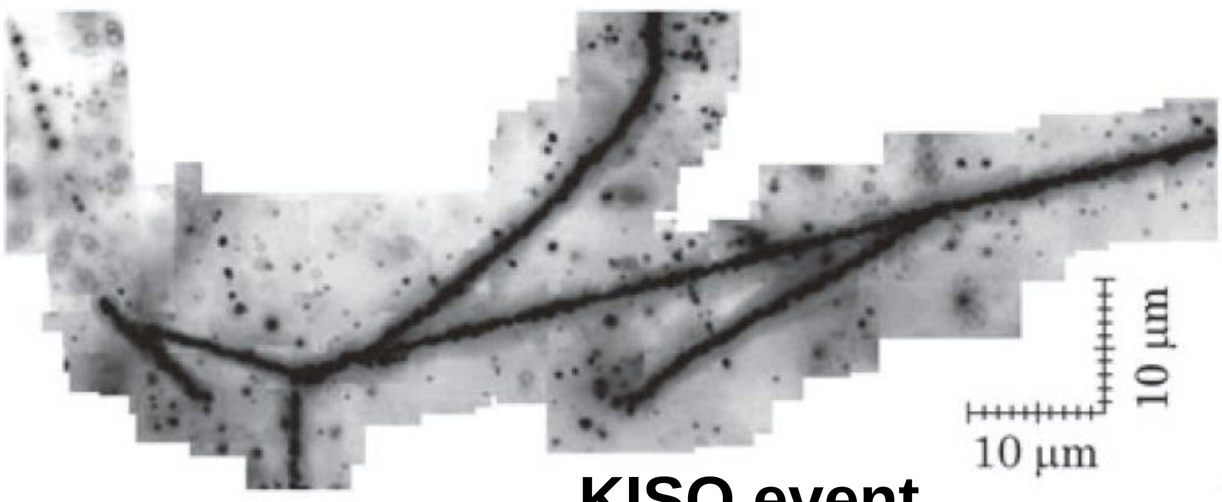




**Clear peak structure around M(K$^-$pp) thres. is seen.**

**Can be understood consistently with d(π$^+$,K$^+$) data?**

# 3. S = -2 Systems

# Ξ hypernuclei

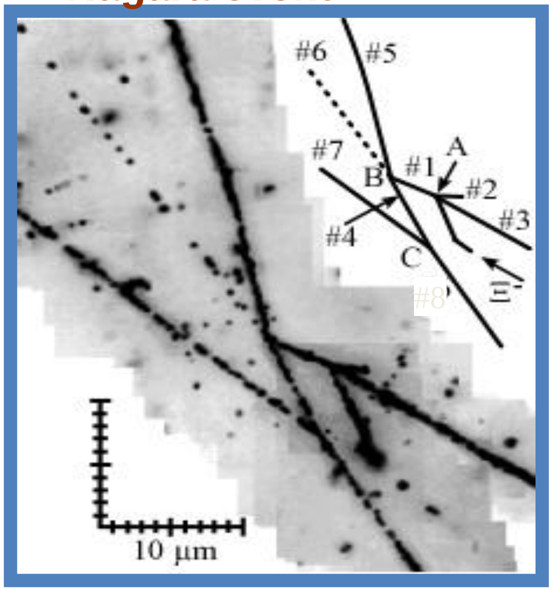



KISO event

Slide by Nakazawa

# ΛΛ hypernuclei from emulsion (KEK E373)

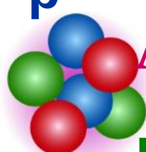
**Nagara event**



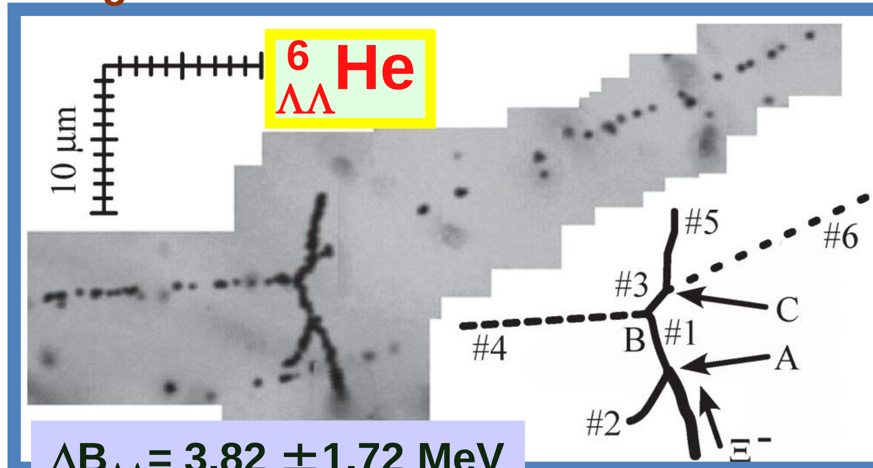

$^{6}_{\Lambda\Lambda}$He

(unique and accurate)

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

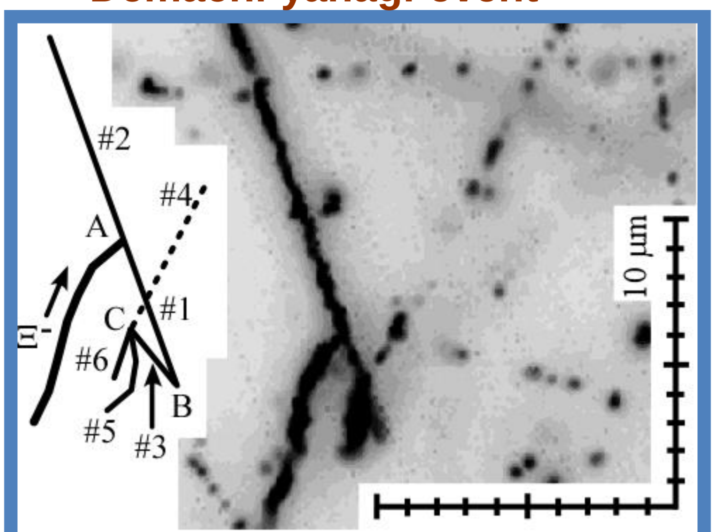



**Mikage event**




$\Delta B_{\Lambda\Lambda}$= 3.82 ±1.72 MeV

**Demachi-yanagi event**

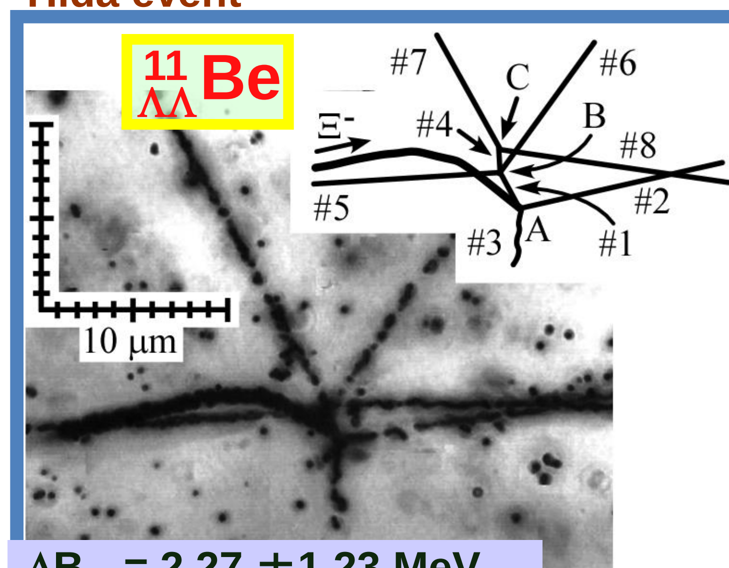



$^{10}_{\Lambda\Lambda}$Be*

(w/ theoretical help)

$\Delta B_{\Lambda\Lambda}$= -1.52 ±0.15 + 3.0(*Ex*)

**Hida event**

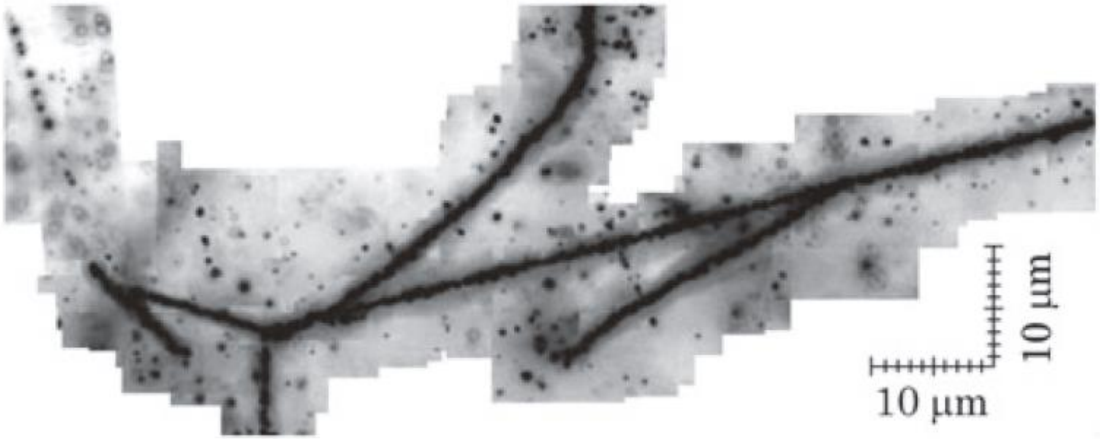


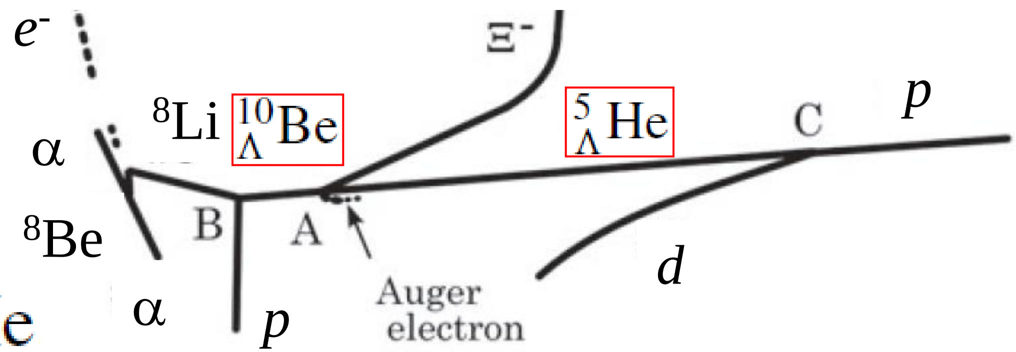

$\Delta B_{\Lambda\Lambda}$= 2.27 ±1.23 MeV

# “Kiso event”

## found by overall scanning method (E373)

*K. Nakazawa et al.*
*PTEP 2015, 033D02*




uniquely identified as

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

$$B_{\Xi^-} = 4.38 \pm 0.25\ \mathrm{MeV} \text{ --- } 1.11 \pm 0.25\ \mathrm{MeV}$$

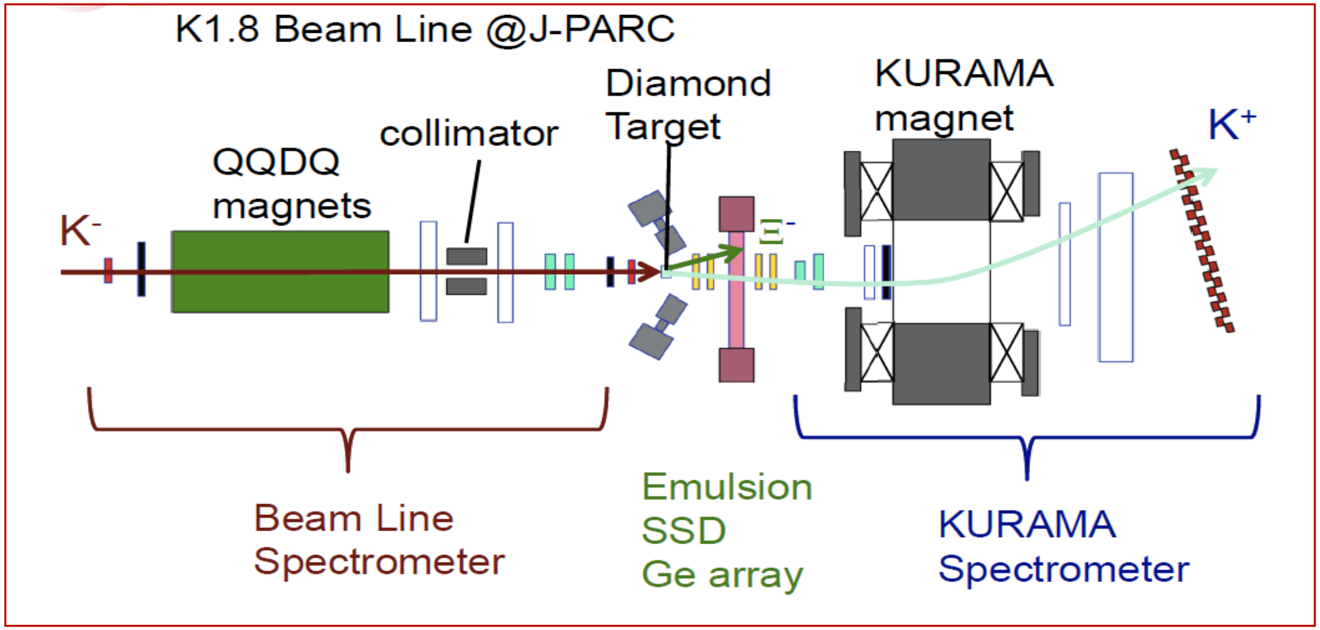
$^{10}_{\Lambda}$Be production: in the ground state — in the highest excited state

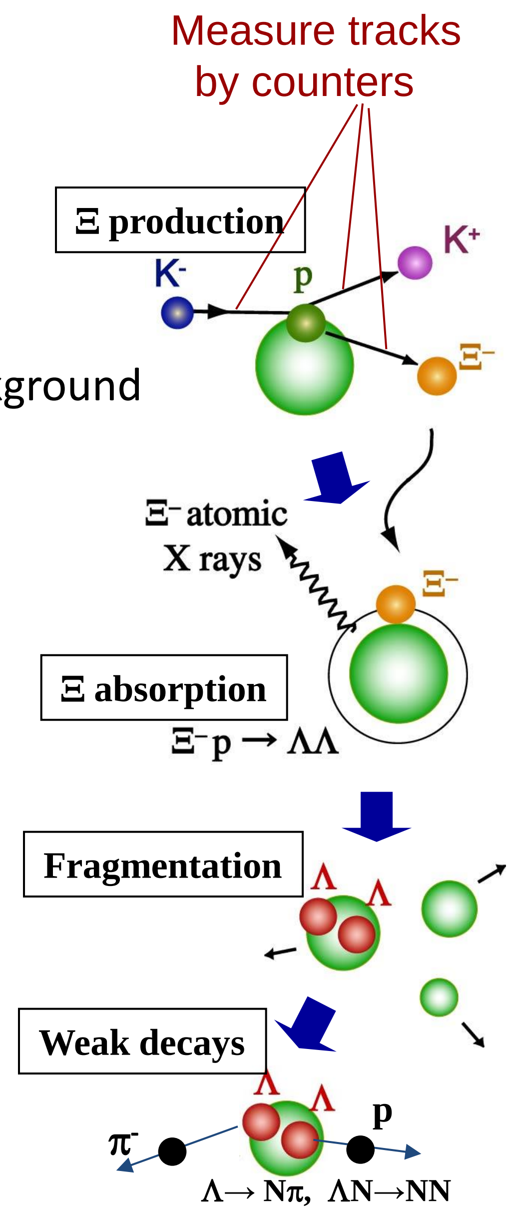
>> 3$D$ atomic state of the $\Xi^-$–$^{14}$N system (0.17 MeV)

**First evidence for a deeply bound Ξ state = Ξ-N attractive**
**-> Ξ⁻ can exist in neutron stars**

# J-PARC E07: S=-2 systems by emulsion

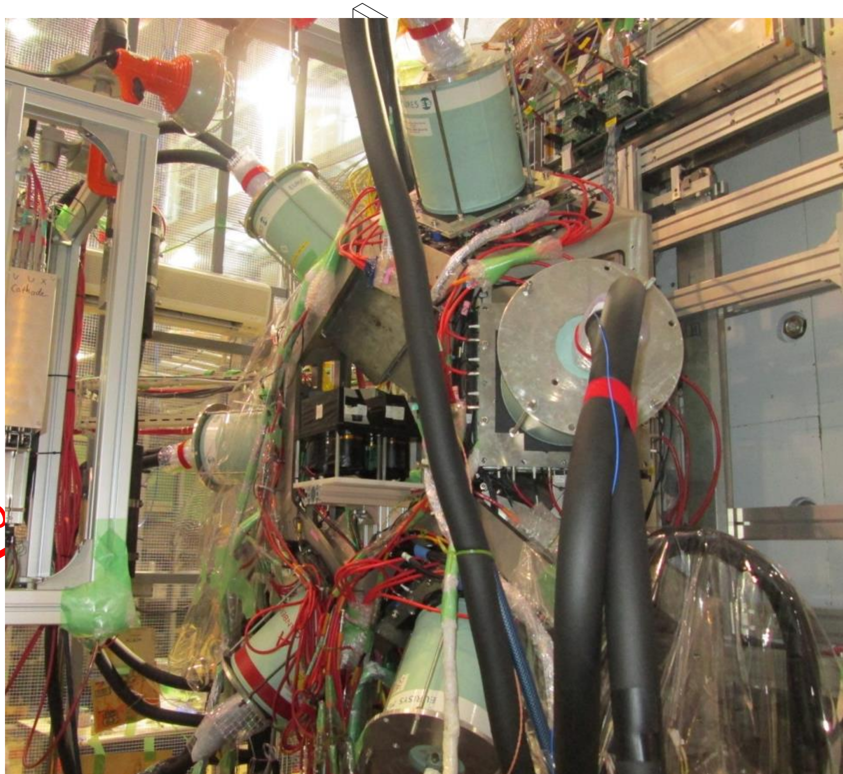
- Collect 10 times more S=-2 events
  - Confirm ΛΛ interaction strength (nuclear dependence)
  - More samples of Ξ-nuclear bound states
- Measure Ξ⁻ -atomic X-rays with Ge detectors
  - Shift and width of X-rays -> Ξ-nuclear potential
  - Stopped Ξ⁻ events identified from emulsion image -> no background

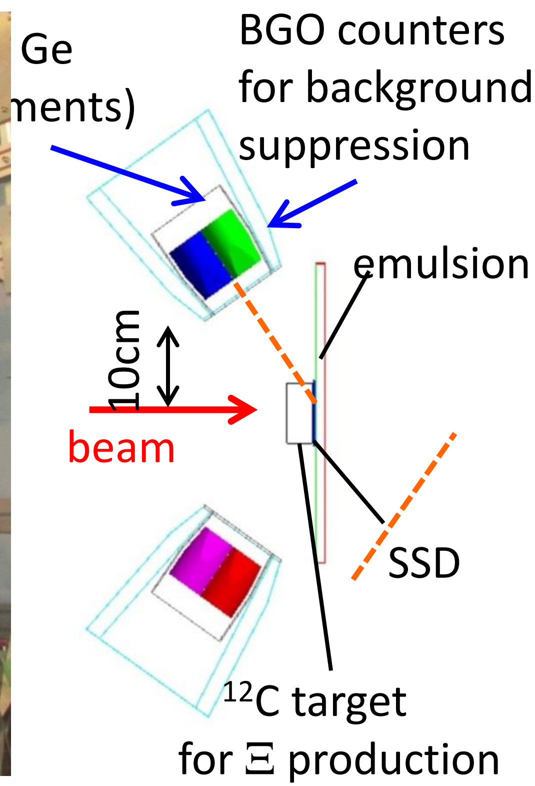


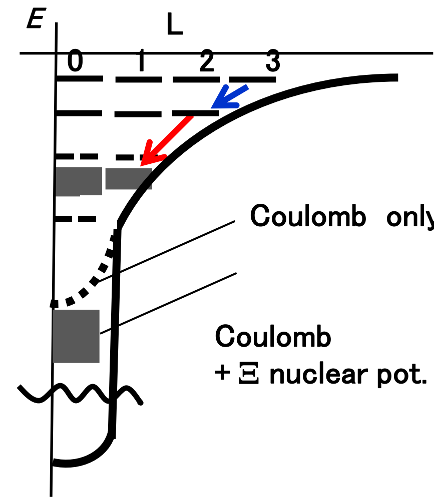




***The experiment just started this spring.***

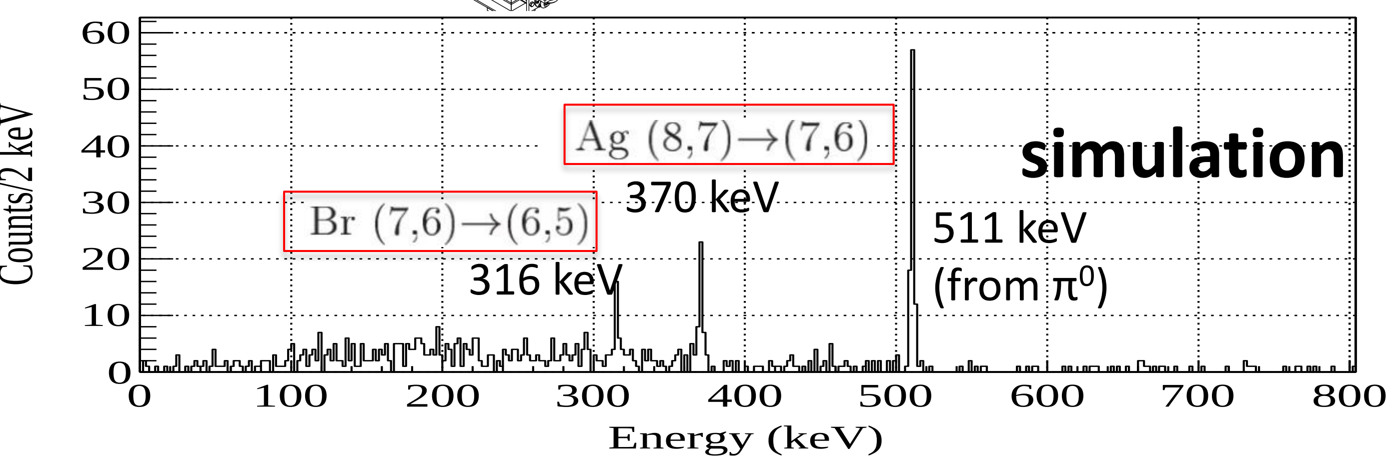
# Ξ-atomic X-rays via "Hyperball-X" (Ge array)






Expected shift :
0.1– 3 keV




$\varepsilon_{photo}$ = 2.3% @ 350 keV
sys. error < 0.1 keV (rms)
stat. error ~ 0.1 keV (rms)

# Spectroscopy of Ξ-hypernuclei via $(K^-,K^+)$ reaction

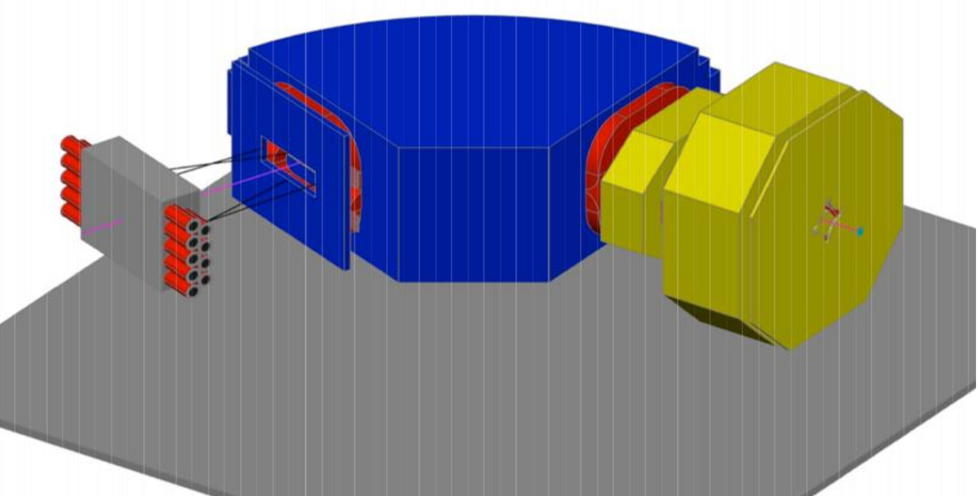
- Discovery of Ξ-hypernuclear states as a peak(s)
- Measurement of Ξ-nucleus potential depth and width
- Coupling between Ξ-nucleus and ΛΛ-nucleus

**J-PARC E05**
**Nagae et al.**

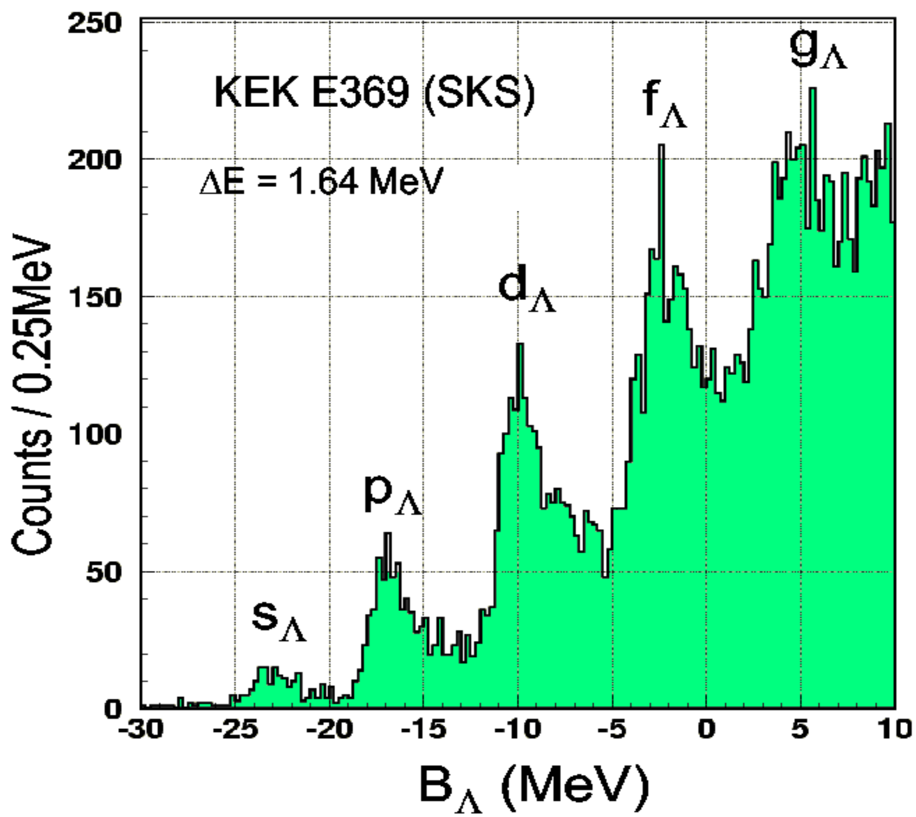
## Similar to

A new spectrometer (S-2S) is being built by Nagae et al.

**ΔE=1.5 MeV(FWHM)**



$^{89}Y\ (\pi^+,K^+)\ ^{89}_{\Lambda}Y$



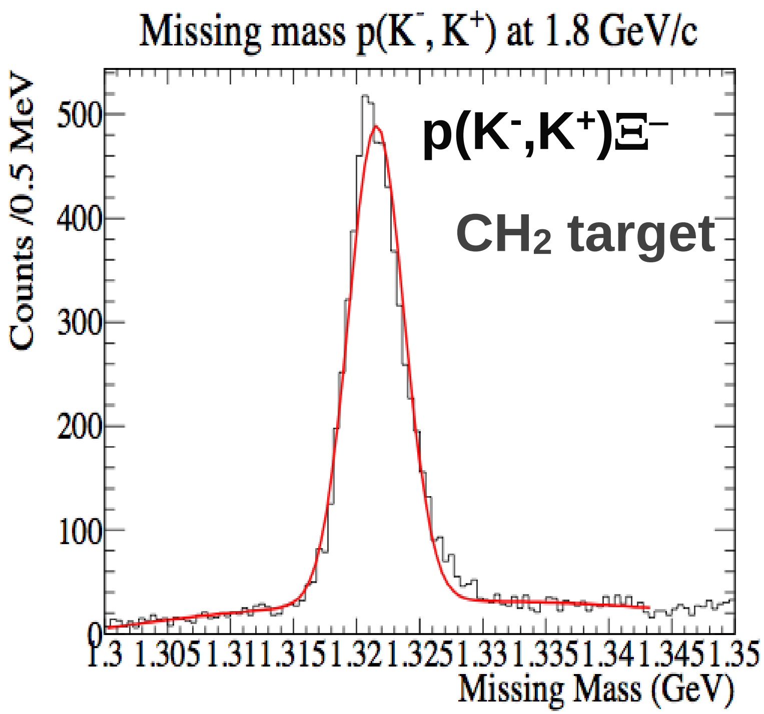
# Spectroscopy of Ξ-hypernuclei via $(K^-,K^+)$ reaction

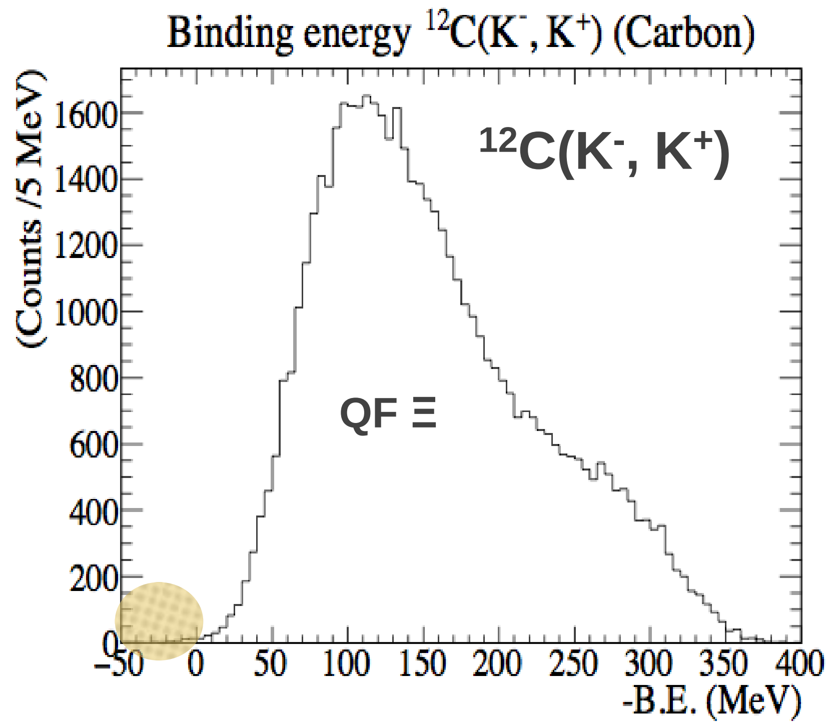
- **Discovery of Ξ-hypernuclear states as a peak(s)**
- **Measurement of Ξ-nucleus potential depth and width**
- **Coupling between Ξ-nucleus and ΛΛ-nucleus**

**J-PARC E05**
**Nagae et al.**

***Slide by T.Nagae***

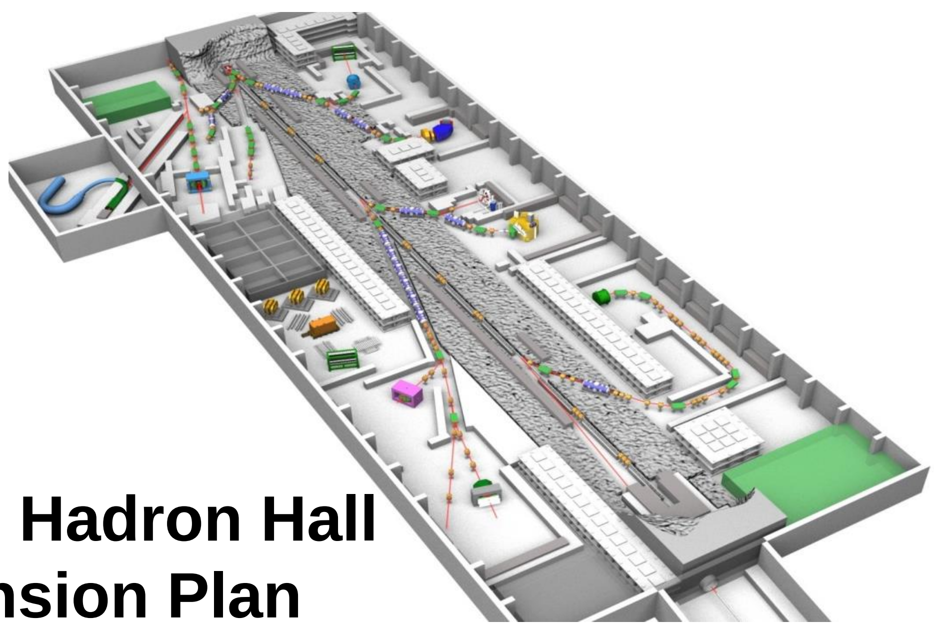
**Pilot run (2015) using the existing SKS spectrometer**




ΔE～5.4 MeV FWHM: much better than the previous BNL exp (～14 MeV)

# 4. Hyperon puzzle and future prospects for $\Lambda$NN interaction



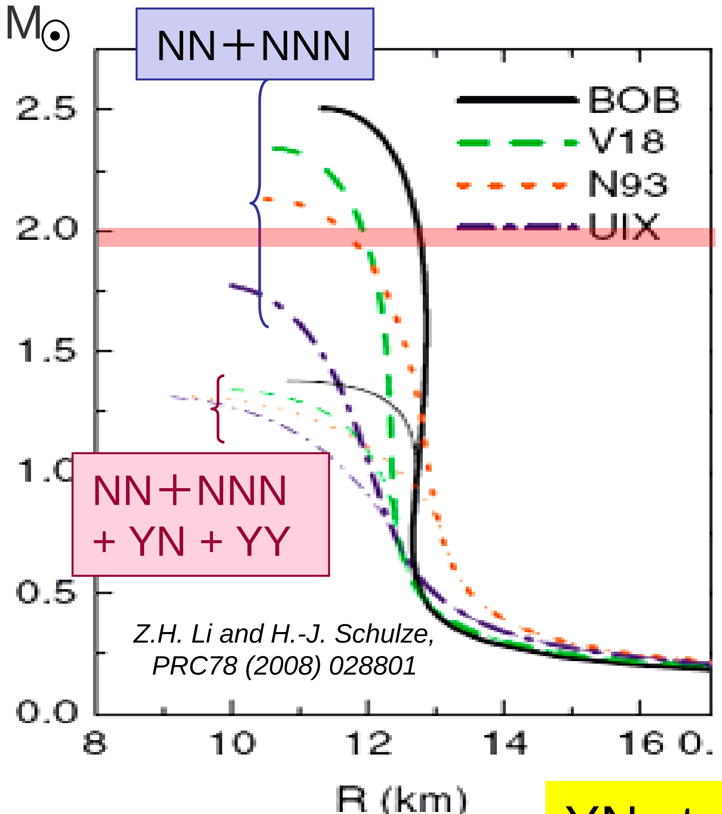
J-PARC Hadron Hall
Extension Plan

# Hyperon puzzle

- Hyperons (at least $\Lambda$'s) must appear at $\rho = 2\sim3\ \rho_0$
- EOS with hyperons (or kaons) too soft to support heavy ( >1.5 $M_{sun}$) NS's in "standard" frameworks

⇔ **2 reliable samples of ~2.0$M_\odot$ NS**

=> **Unknown repulsion** should exist at high $\rho$



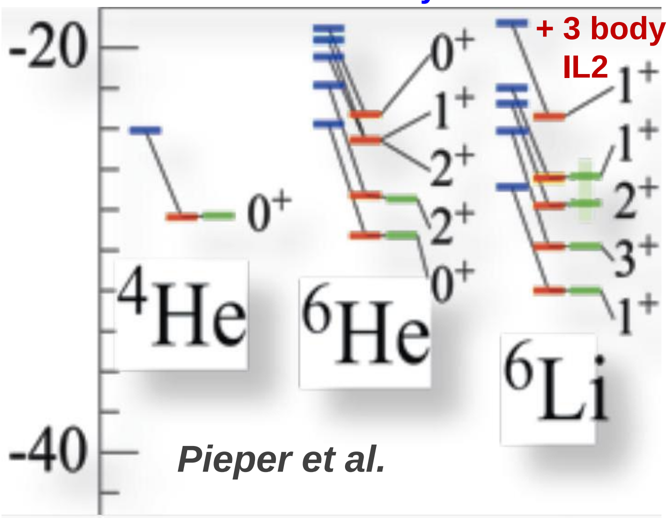
*Z.H. Li and H.-J. Schulze, PRC78 (2008) 028801*

Various models to support 2 $M_{sun}$ NS with hyperons

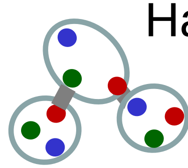
- Introduce strong repulsion in 3-body force (NNN, YNN, YYN, YYY)
- Quark Meson Coupling model
- Density dependence in coupling const., hadron mass, etc.
- Relativistic framework
- Lattice QCD
- Phase transition to quark matter = quark star or "crossover"

YN strong repulsion at high density really exists ?
Any experimental evidence for that?

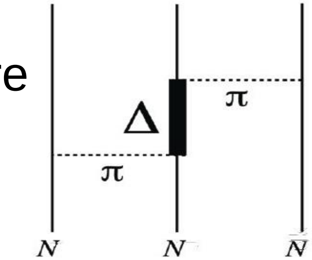
# 3-body nuclear force




IL2: Illinois 3BF



Hadrons have inner structure
-> 3 body force

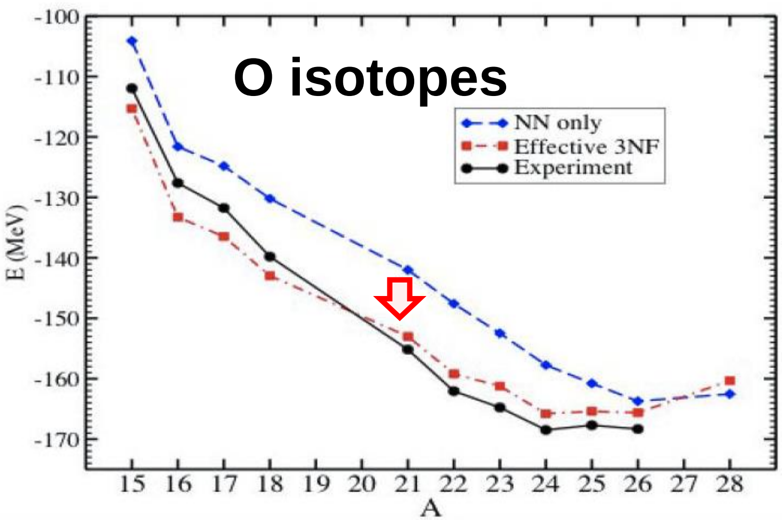


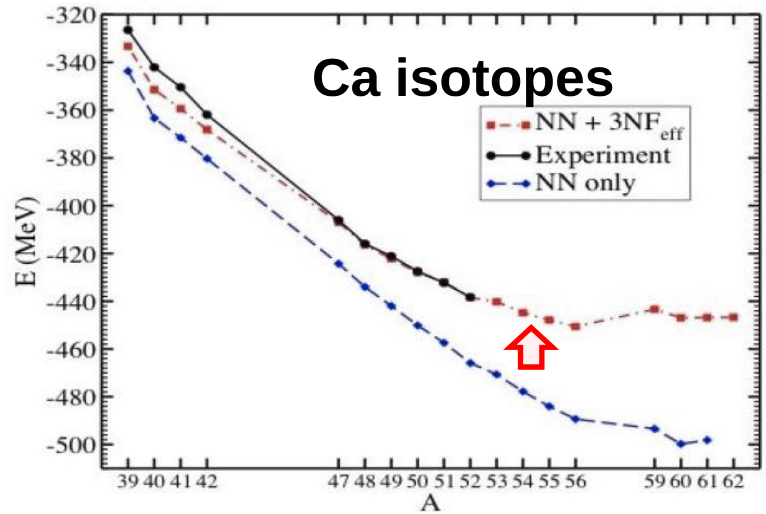

Light nuclei (low $\rho$): attractive
∼Fijita-Miyazawa's $2\pi$ exchange force

Heavy nuclei ($\sim\rho_0$): repulsive
+ relativistic effect (repulsive)

3-body force from chiral effective field theory

*G. Hagen et al., PRL 109 (2012) 032502*



# Density dependence of ΛN interaction affects Λ hypernuclear data?

We have almost no information on BB forces in high density ($\rho > \rho_0$) matter

Ab-initio calc. of nuclear binding energies => NNN repulsion necessary

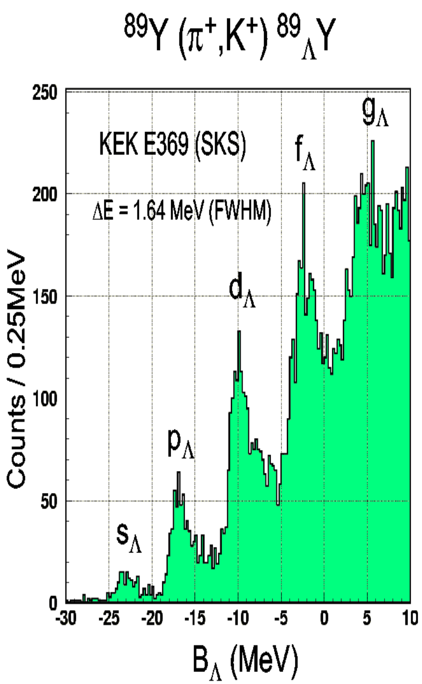
Similar YNN (YYN, YYY) repulsive forces? How large are they?

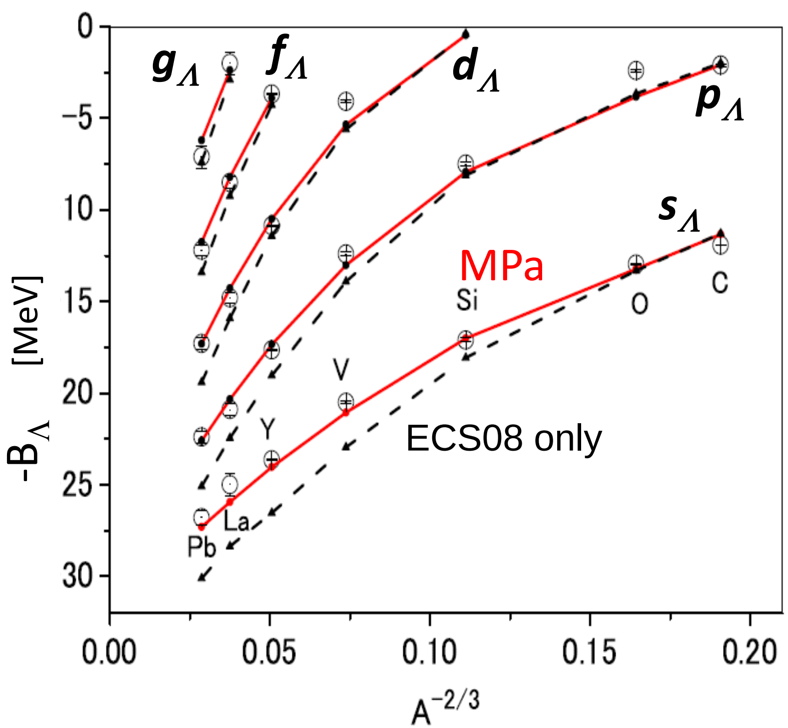
Experimentally approach:

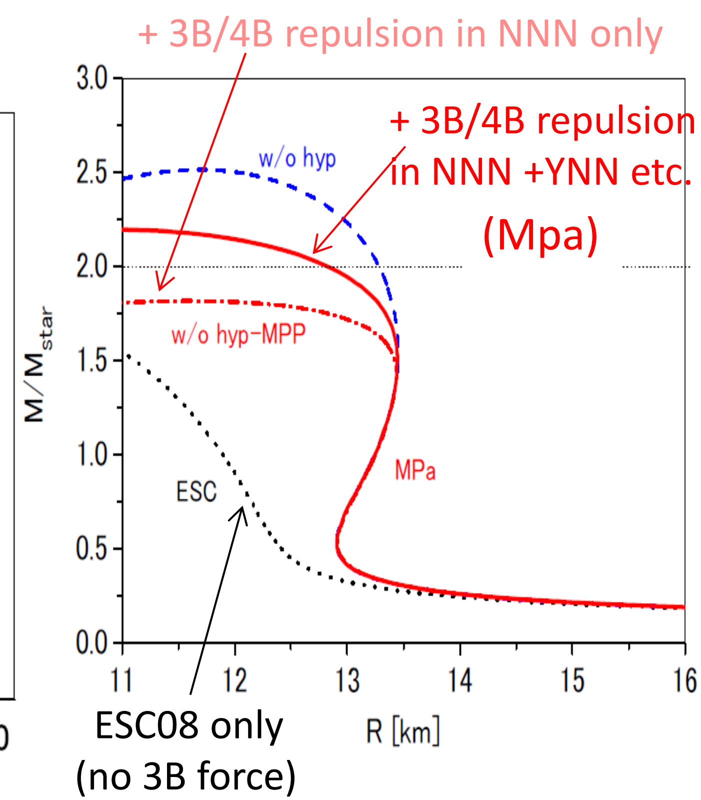
**Precise $B_\Lambda$ data for wide A of Λ hypernuclei**

**0.1 MeV accuracy is necessary**

*Yamamoto, Furumoto, Rijken et al.*
*PRC88 (2013) 2, 022801*
*PRC90 (2014) 045805*



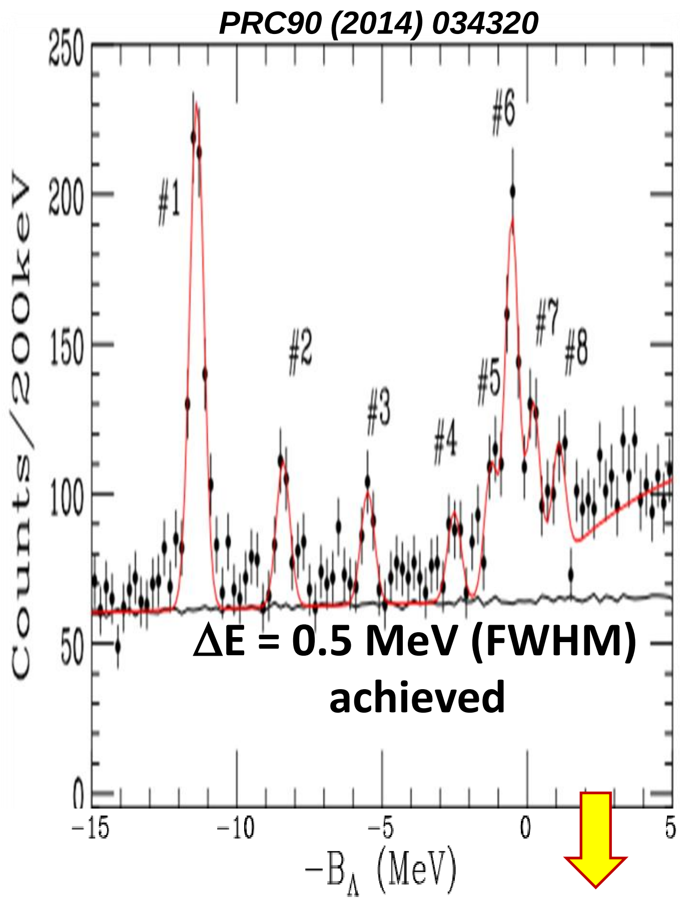



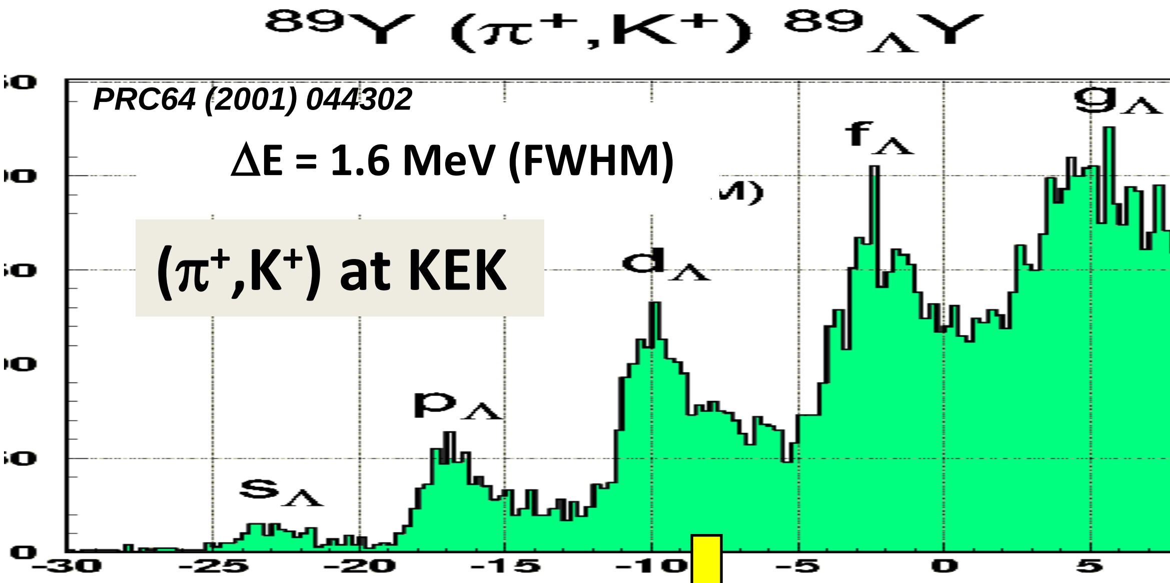



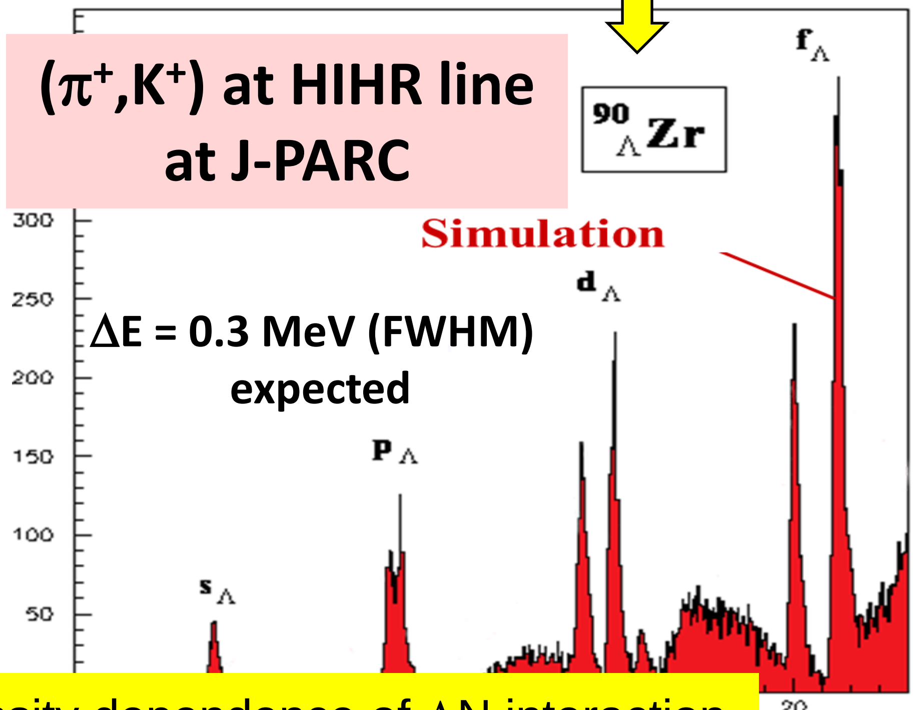
# High Resolution Spectroscopy

$(e,e'K^+)$ at JLab

*PRC90 (2014) 034320*

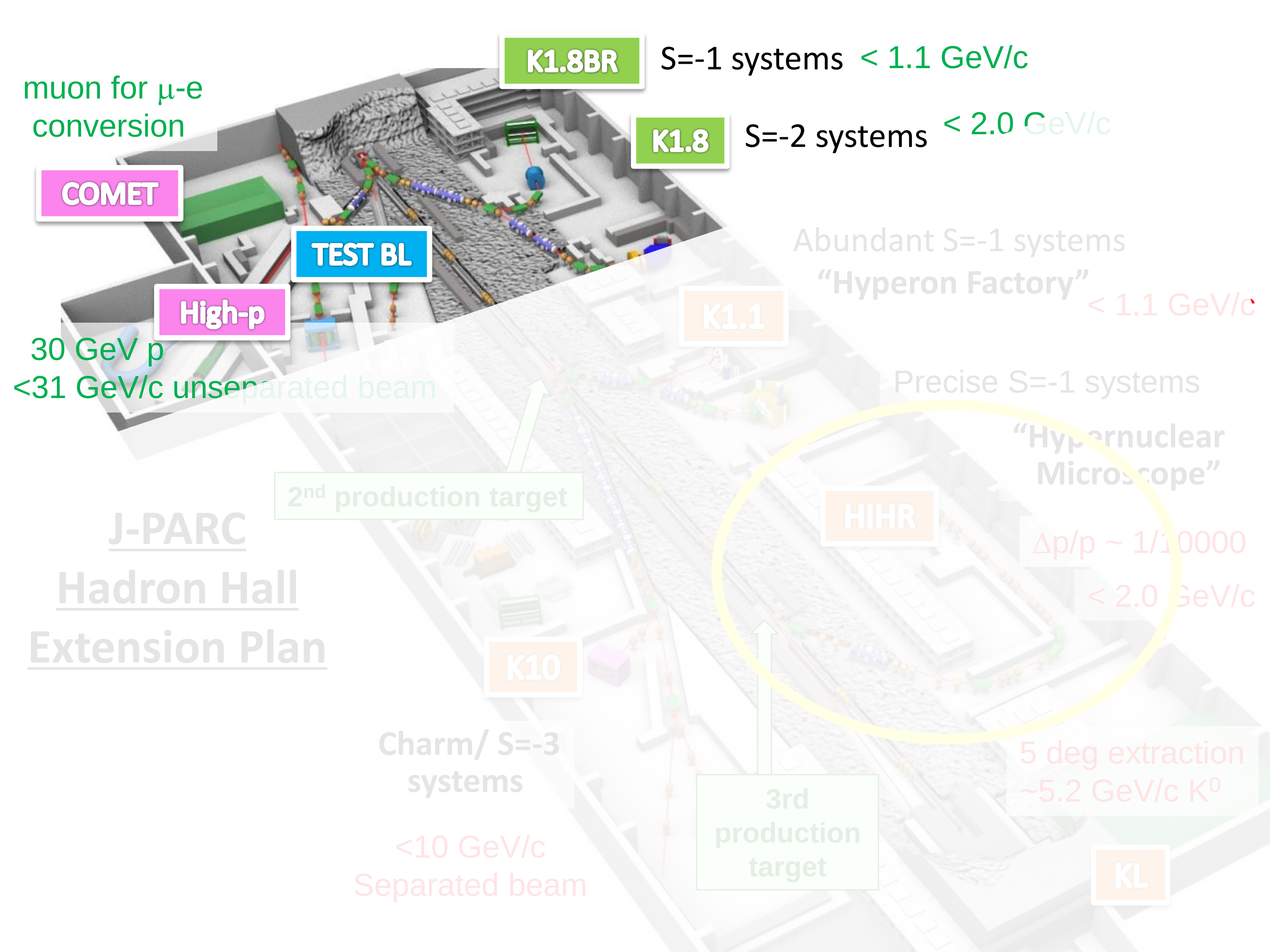


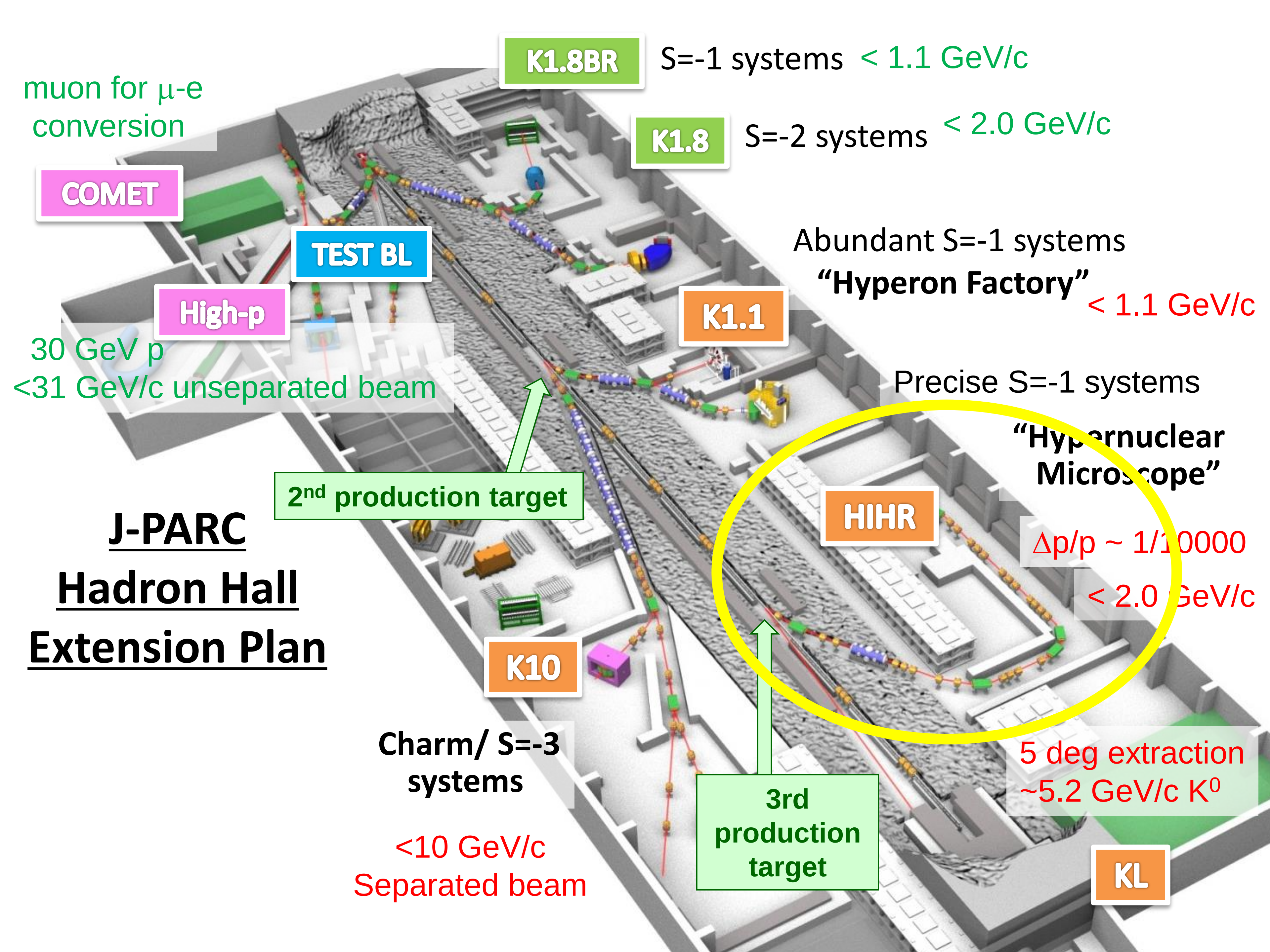




BE accuracy < 0.1 MeV => Density dependence of ΛN interaction

Theorists, can you extract it from precise Λ BE data?


K1.8BR
S=-1 systems
< 1.1 GeV/c
muon for μ-e conversion
K1.8
S=-2 systems
< 2.0 GeV/c
COMET
TEST BL
High-p
30 GeV p
<31 GeV/c unseparated beam
Abundant S=-1 systems
“Hyperon Factory”
K1.1
< 1.1 GeV/c
Precise S=-1 systems
“Hypernuclear Microscope”
2nd production target
J-PARC
Hadron Hall
Extension Plan
HIHR
Δp/p ~ 1/10000
< 2.0 GeV/c
K10
Charm/ S=-3 systems
<10 GeV/c
Separated beam
3rd production target
5 deg extraction
~5.2 GeV/c K0
KL


J-PARC
Hadron Hall
Extension Plan
muon for μ-e conversion
COMET
TEST BL
High-p
30 GeV p
<31 GeV/c unseparated beam
K1.8BR
S=-1 systems < 1.1 GeV/c
K1.8
S=-2 systems < 2.0 GeV/c
Abundant S=-1 systems
“Hyperon Factory”
< 1.1 GeV/c
K1.1
Precise S=-1 systems
“Hypernuclear Microscope”
HIHR
Δp/p ~ 1/10000
< 2.0 GeV/c
2nd production target
K10
Charm/ S=-3 systems
<10 GeV/c
Separated beam
3rd production target
5 deg extraction
~5.2 GeV/c K0
KL

# Summary

- YN, YY interactions in free space and in nuclear (neutron) matter should be studied to understand the inner core of NS.

**S=-1**

- A larger charge symmetry breaking effect in $\Lambda$N int. is confirmed for A=4 hypernuclei via $\gamma$-ray measurement.
- Exciting data for n-rich hypernuclei ($^{6}_{\Lambda}$H, $\Lambda$nn) should be confirmed.
- New data for $K^-$pp appeared, further investigation necessary.

**S=-2**

- A $\Xi$-nuclear bound system was discovered in emulsion, suggesting $\Xi$ to appear in NS. $\Xi$-atomic X-rays will be also measured.
- $^{12}_{\Xi}$Be hypernuclear state(s) were also observed in (K-,K+) reaction, indicating a rather deep $\Xi$-nuclear potential.

**Future**

- $\Lambda$'s binding energies in wide mass numbers will be precisely measured at Jlab and J-PARC to approach the $\Lambda$NN force.