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Recent Progress in Hypernuclear Physics

Tohoku University
H. Tamura

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1. Introduction

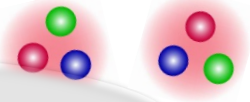
Role of Strangeness in Nuclear Physics

Quarks/gluons

How are hadrons formed from quarks and gluons?

s, c, b quarks play essential roles

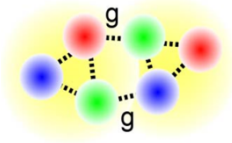
Constituent quarks, other quasi particles



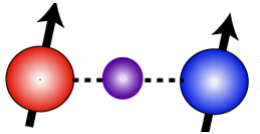
Hadrons

How are nuclei formed from hadrons?

s quarks play essential roles

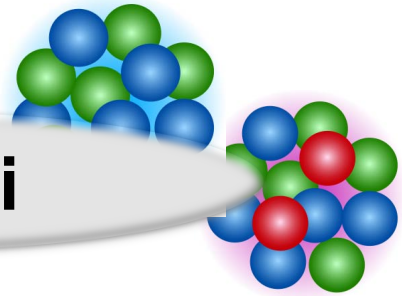


Baryon-baryon interactions



Short range force by quark picture

Meson exchange picture



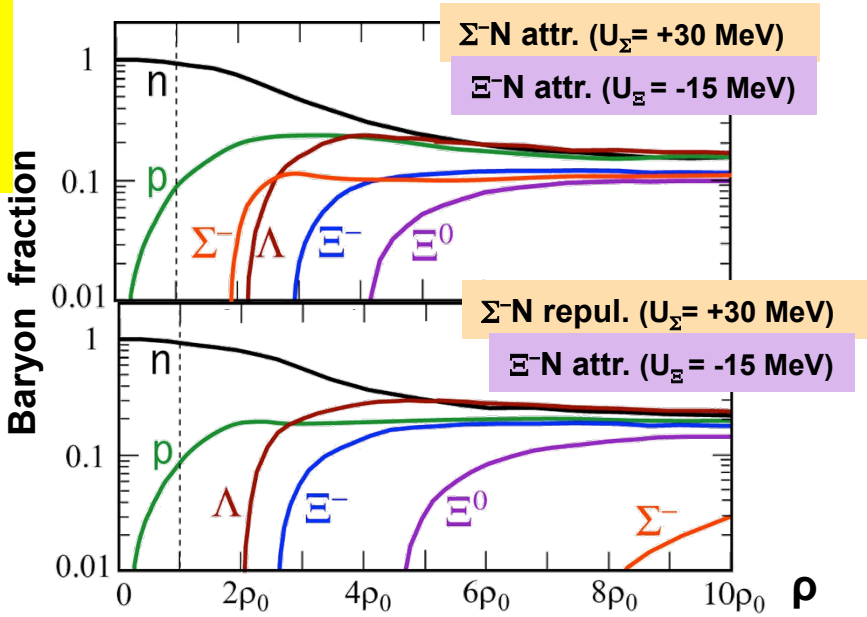
Nuclei

Test lattice QCD calculations

BB interactions and high density matter

Attractive ΛN interaction (U_Λ= -30 MeV)
=> at least Λ should appear at 2-2.5ρ_0

We need YN, YY int. both in free space and in nuclear matter



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

- ΛN: Same in pure neutron matter? ΛN-ΣN mixing?
- ΣN: How repulsive?
- ΞN: Attractive or repulsive?
- ΛΛ: How weakly attractive?
- Unbound H dibaryon exists?
- $K^{bar}N$: How strongly attractive in nuclear matter?
- YNN, YYN strongly repulsive? Can solve the hyperon puzzle?

Recent results and plans of hypernuclear experiments

S=-1 systems: *more accuracy*

- γ spectroscopy of Λ hypernuclei — J-PARC
  - *$^{4}_{\Lambda}$He γ-ray observed* *$^{4}_{\Lambda}$H γ-ray, $^{7}_{\Lambda}$Li B(M1), …*
- Λ hypernuclear spectroscopy via (e,e'K^{+}) — JLab
  - *$^{7}_{\Lambda}$He, $^{10}_{\Lambda}$Be, $^{12}_{\Lambda}$B high res. spectra* *$^{40}_{\Lambda}$K, $^{48}_{\Lambda}$K* — MAMI
- Decay pion spectroscopy of Λ hypernuclei
  - *$^{4}_{\Lambda}$H mass from $^{4}_{\Lambda}$H -> ^{4}He + π^{-}* — GSI, STAR, ALICE
- Lifetime of light Λ hypernuclei via HI beams
  - *Surprisingly short $^{3}_{\Lambda}$H lifetime*
- Σ$^{\pm}$p scattering — J-PARC

S=-2 systems: *more strangeness*

- Emulsion experiments — J-PARC
  - *Ξ^{-} ^{14}N bound state observed* — KEK
- Ξ hypernuclear spectroscopy
  - *$^{12}_{\Xi}$Be observed* — J-PARC
- Ξ atom X rays — J-PARC
- *Unbound H dibaryon search* — J-PARC

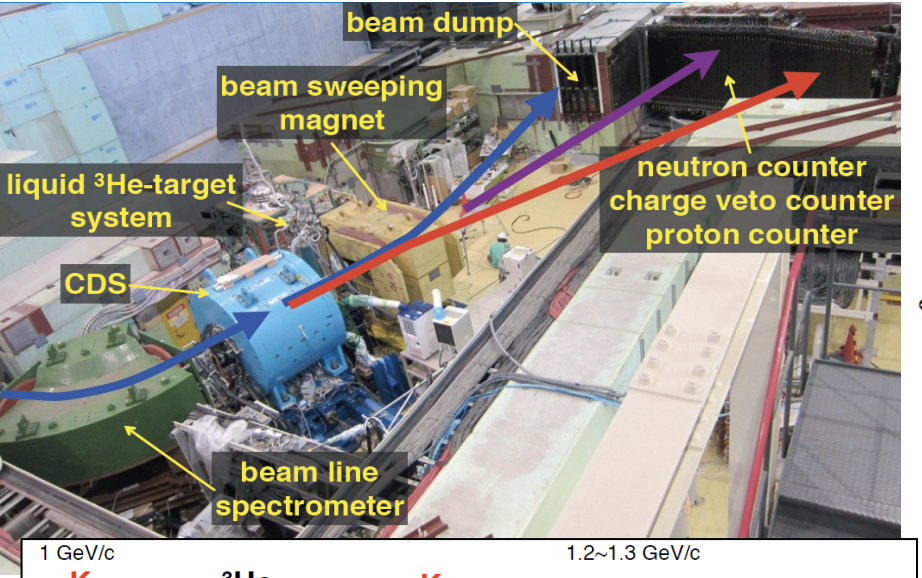
K^{bar}-nuclear systems

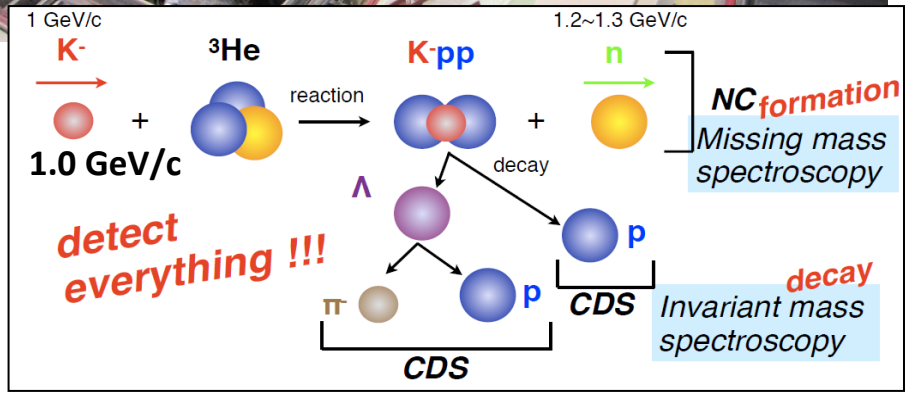
- K^{-}pp via ^{3}He(K^{-},n) *K-pp spectrum measured* — J-PARC
- K^{-}pp via d(π^{+},K^{+}) *K-pp like bump observed* — J-PARC
- K-pp studies at GSI-HADES — GSI
- K-d, K-He atom X rays — J-PARC

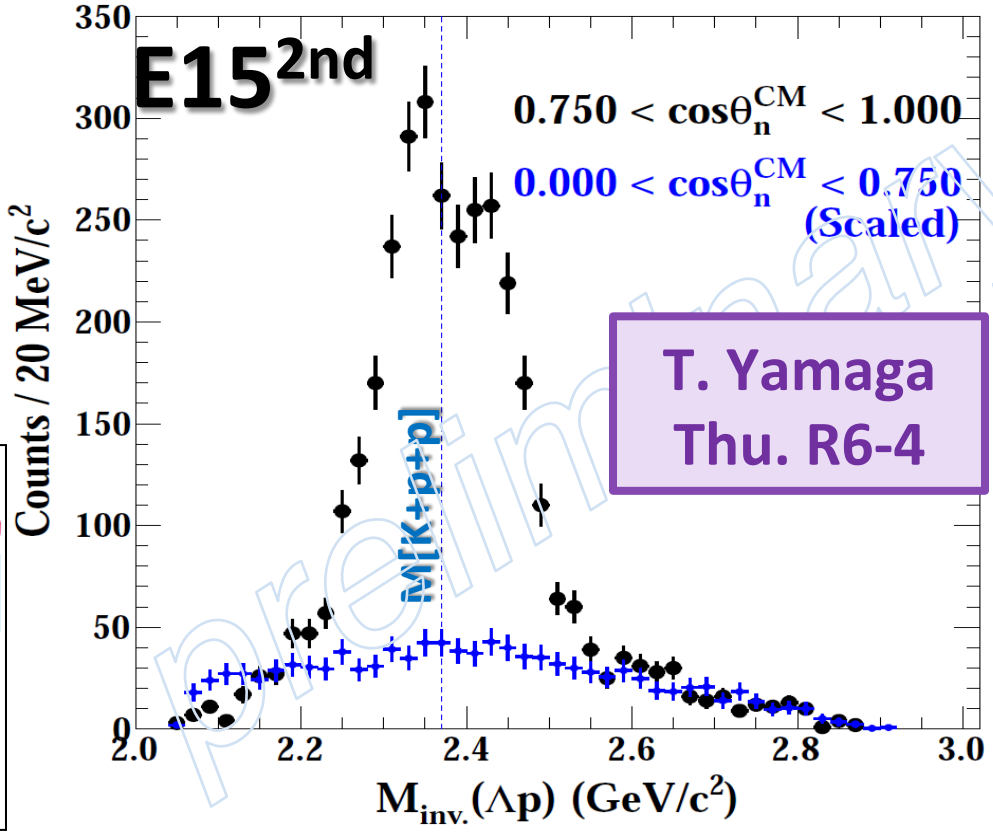
■ *(Partly) took data*
■ *running*
■ *Under preparation*

K^{bar}NN search: ^{3}He(K$^-$,Λp)n spectrum

J-PARC E15
Iwasaki et al.



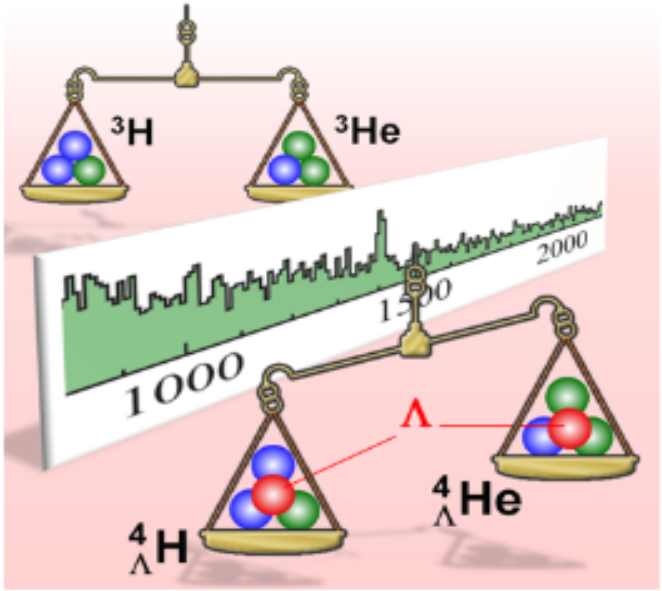




T. Yamaga
Thu. R6-4

2. S = -1 Systems

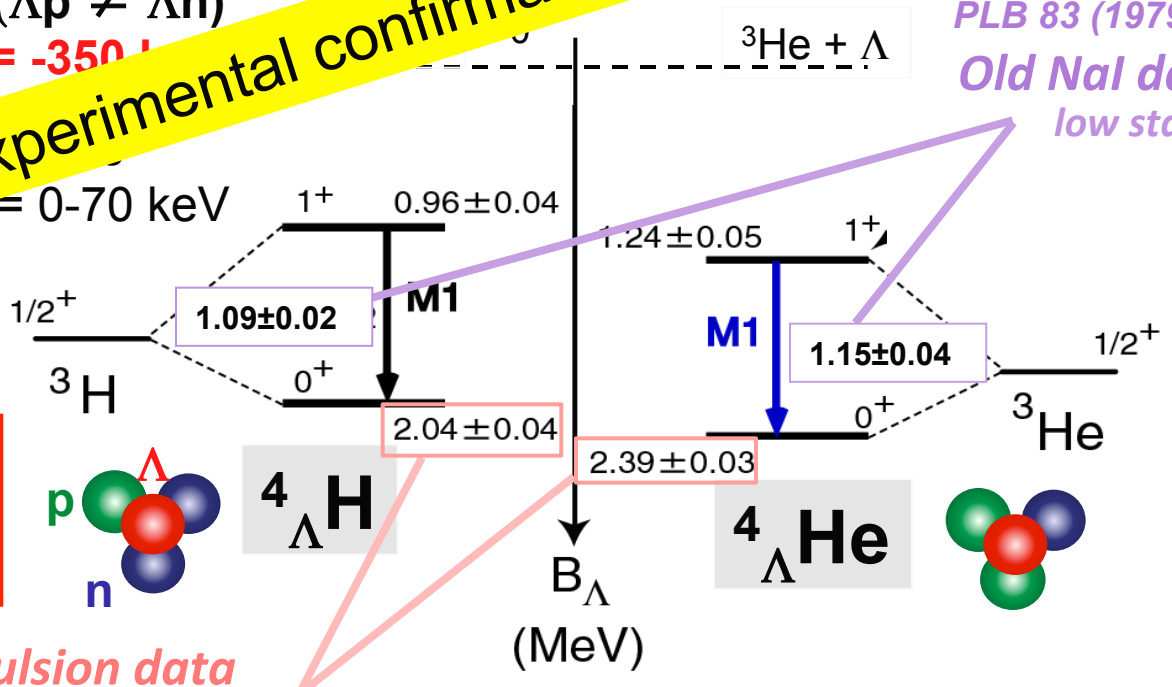
Charge symmetry breaking in Λ hypernuclei



Charge Symmetry Breaking (CSB) in A=4 hypernuclei

- CSB in NN force (**pp ≠ nn**)
  => B(^{3}H) - B(^{3}He) – EM effect ~70 keV
- CSB in ΛN force (**Λp ≠ Λn**)
  $B_\Lambda(^4_\Lambda H) - B_\Lambda(^4_\Lambda He) = -350$!
- YN interaction
  $B_\Lambda(^4_\Lambda H) - B_\Lambda(^4_\Lambda He)$ = 0-70 keV

Experimental confirmation awaited



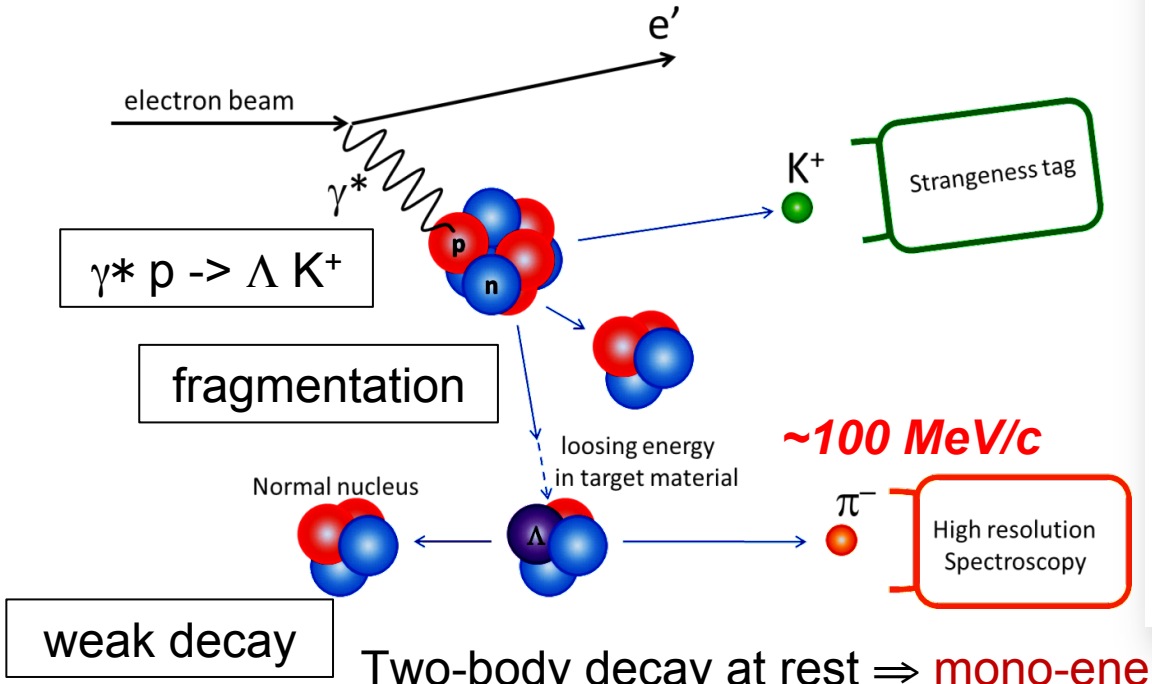
Measure using weak decay pion

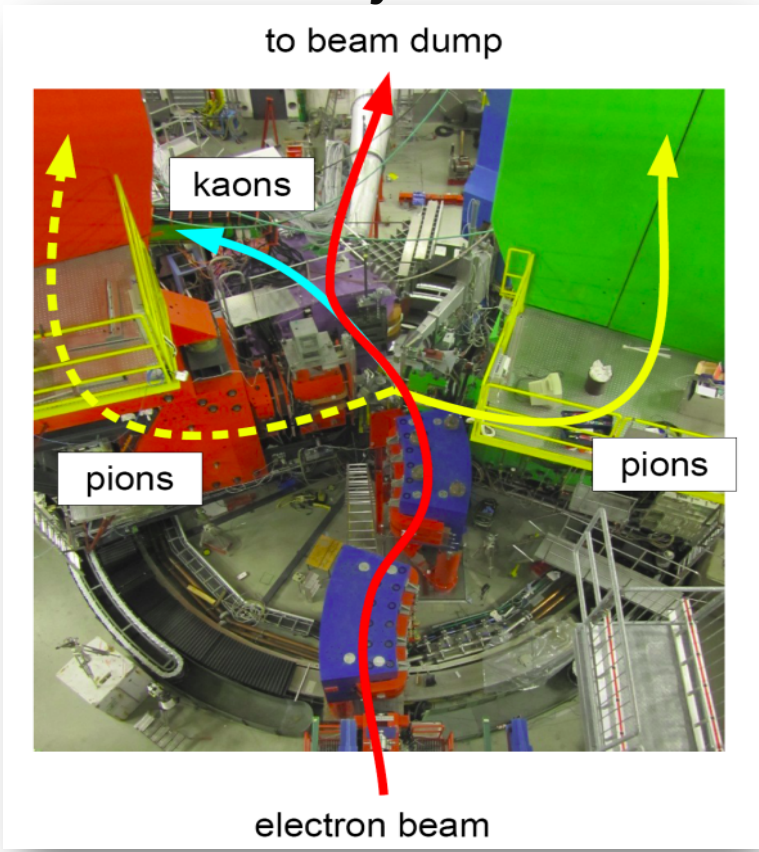
Bedjidian et al.
PLB 62 (1976) 467
PLB 83 (1979) 252
Old NaI data
low statistics

Old emulsion data
no systematic error
M. Juric et al. NPB 52 (1973) 1

Slide by P. Achenbach

Decay-pion spectroscopy of hyperfragments with electron beams

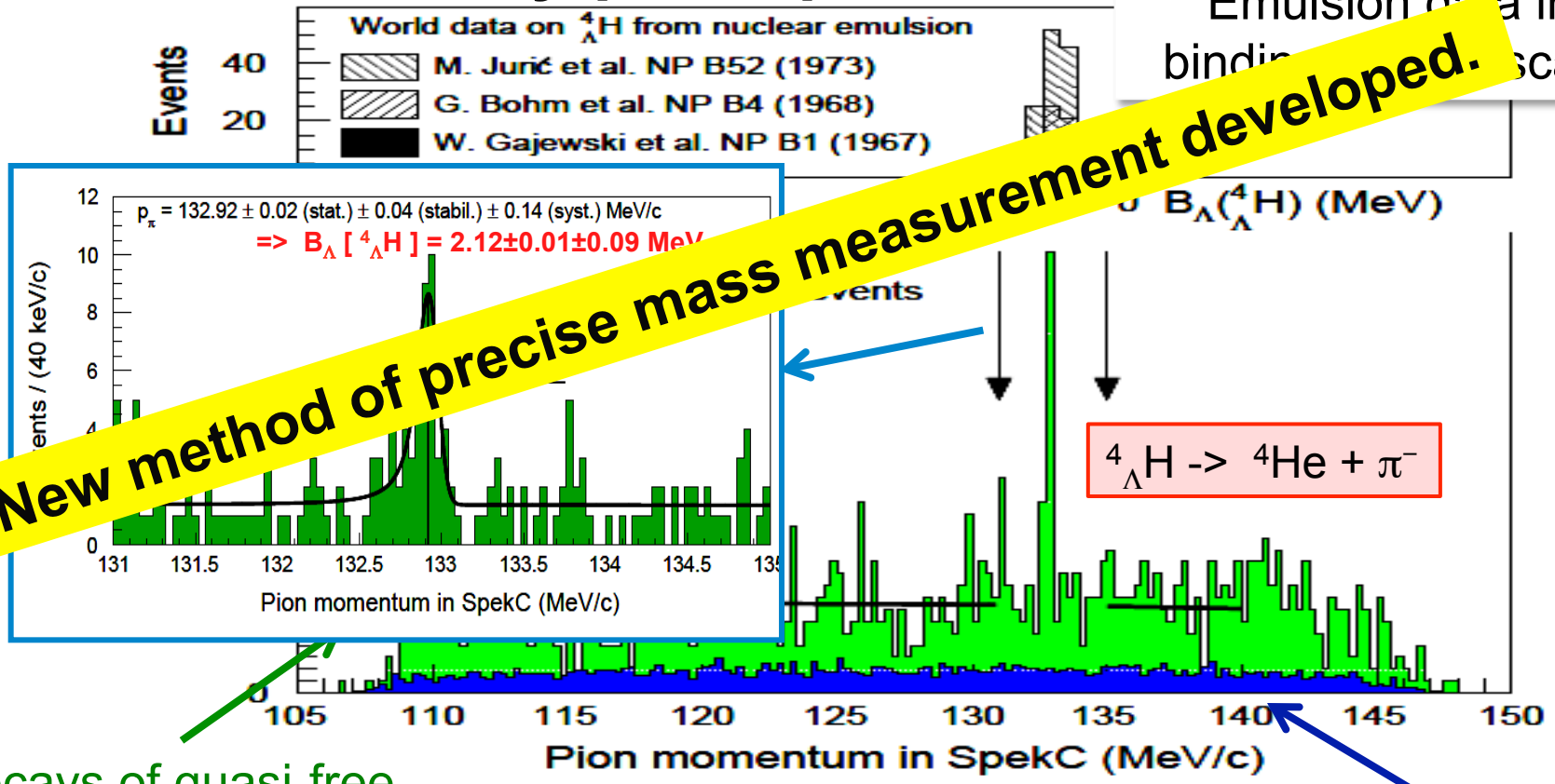




Two-body decay at rest ⇒ mono-energetic pions

An independent method for precise mass measurement

Decay-pion spectrum



Emulsion data in binding scale

New method of precise mass measurement developed.

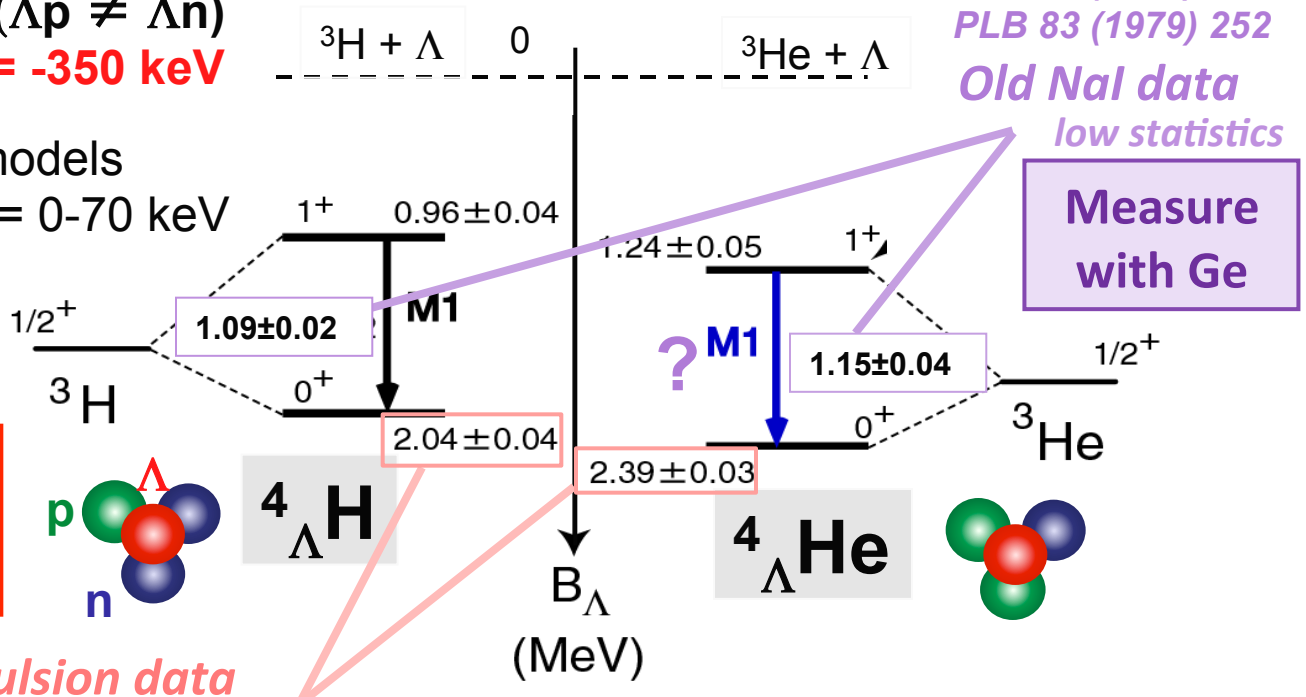
decays of quasi-free produced hyperon

accidental background

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

Charge Symmetry Breaking (CSB) in A=4 hypernuclei

- CSB in NN force (**pp ≠ nn**)
  => B(^{3}H) - B(^{3}He) – EM effect ~70 keV
- CSB in ΛN force (**Λp ≠ Λn**)
  $B_\Lambda(^4_\Lambda H) - B_\Lambda(^4_\Lambda He) = -350$ keV
- YN interactions models
  $B_\Lambda(^4_\Lambda H) - B_\Lambda(^4_\Lambda He) = 0$-70 keV



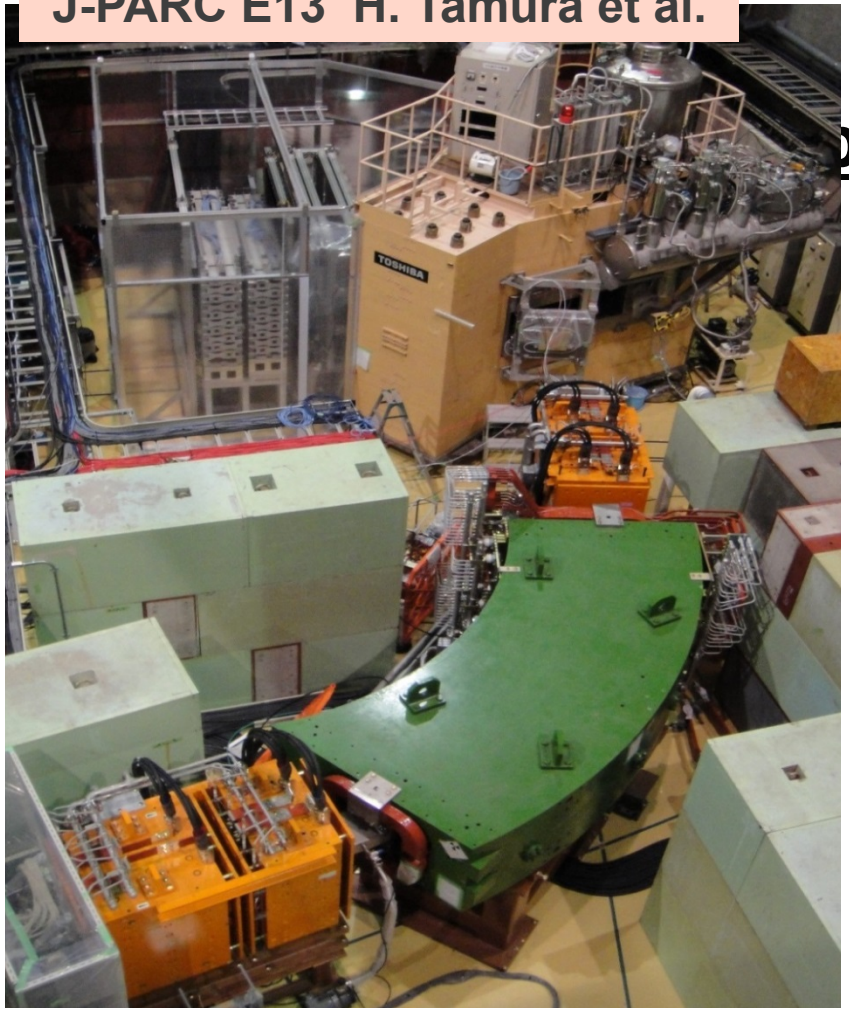
Bedjidian et al.
PLB 62 (1976) 467
PLB 83 (1979) 252
Old NaI data
low statistics

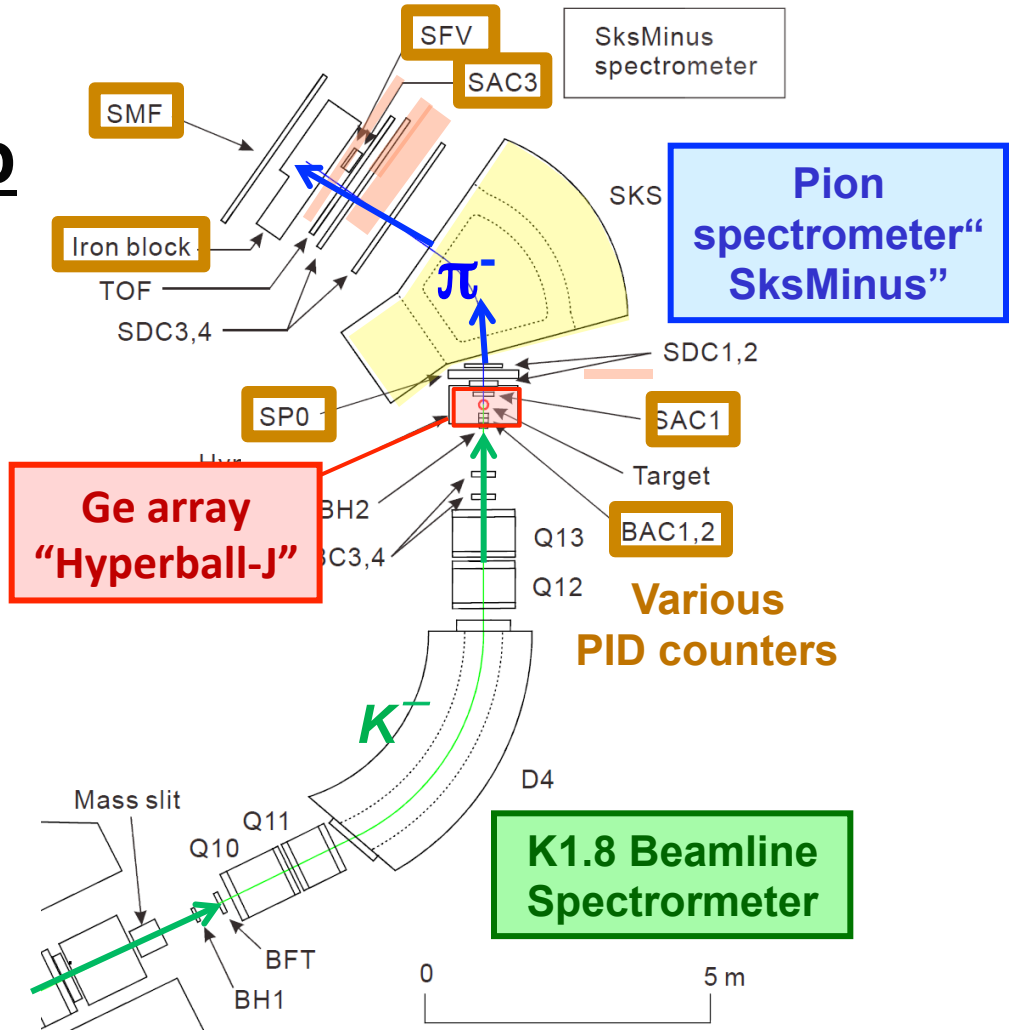
Measure with Ge

Measure using weak decay pion

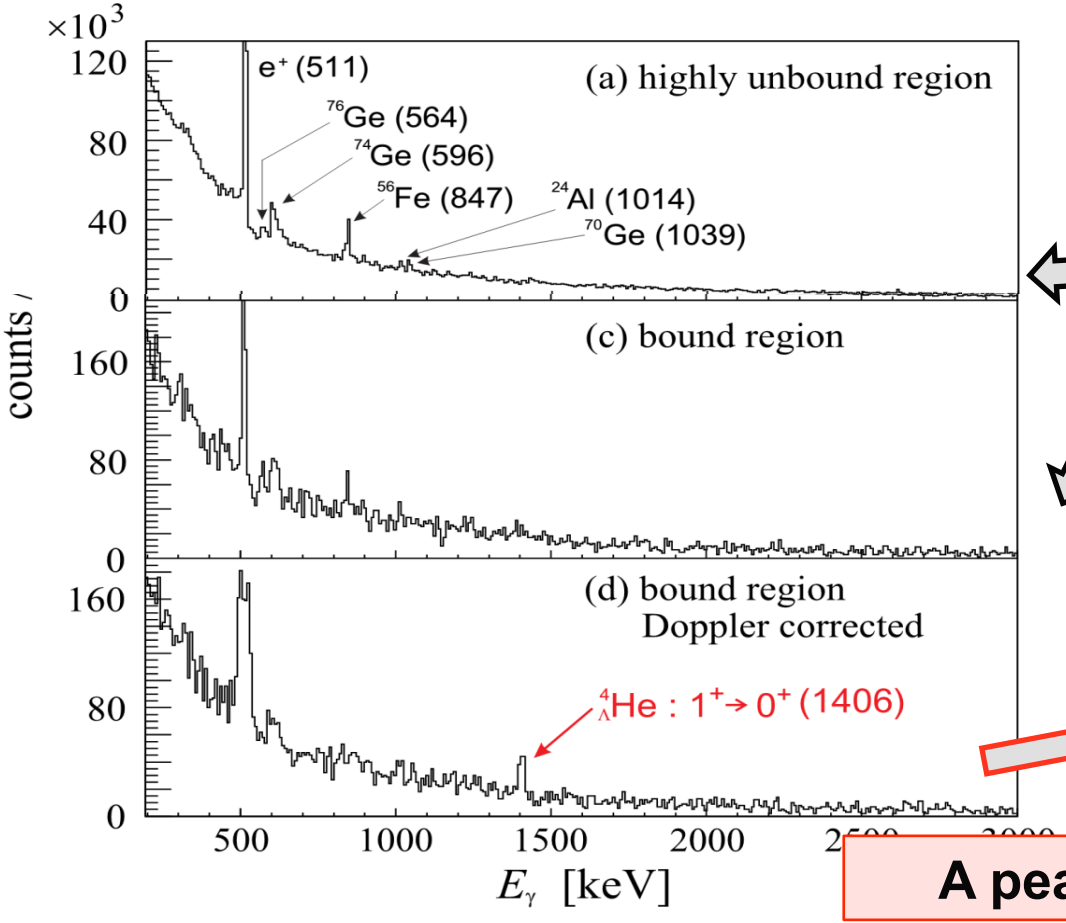
Old emulsion data
no systematic error
M. Juric et al. NPB 52 (1973) 1

J-PARC E13 H. Tamura et al.

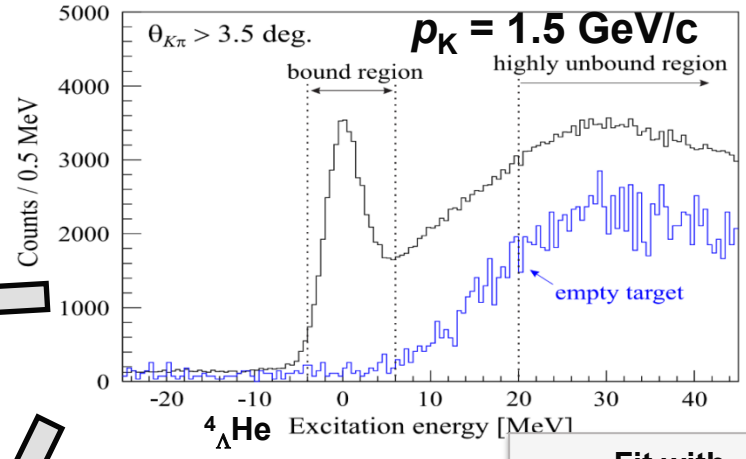


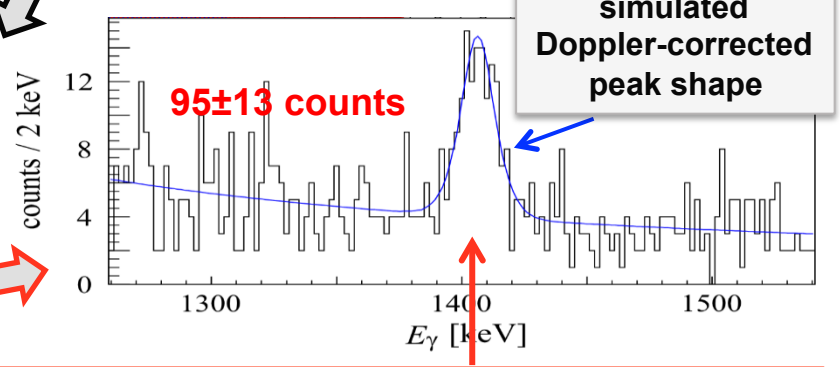


$^{4}_{\Lambda}$He γ-ray spectrum



Missing mass of ^{4}He(K$^-$,π$^-$)



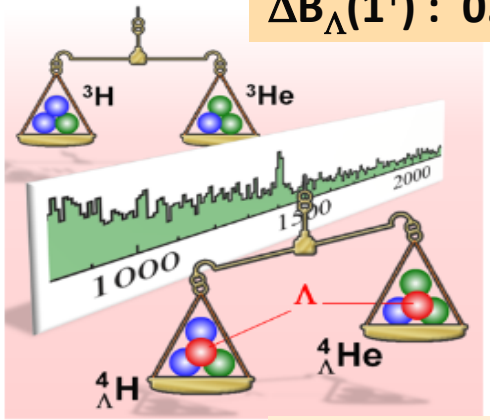


Fit with simulated Doppler-corrected peak shape

A peak observed at 1406±2±2 keV

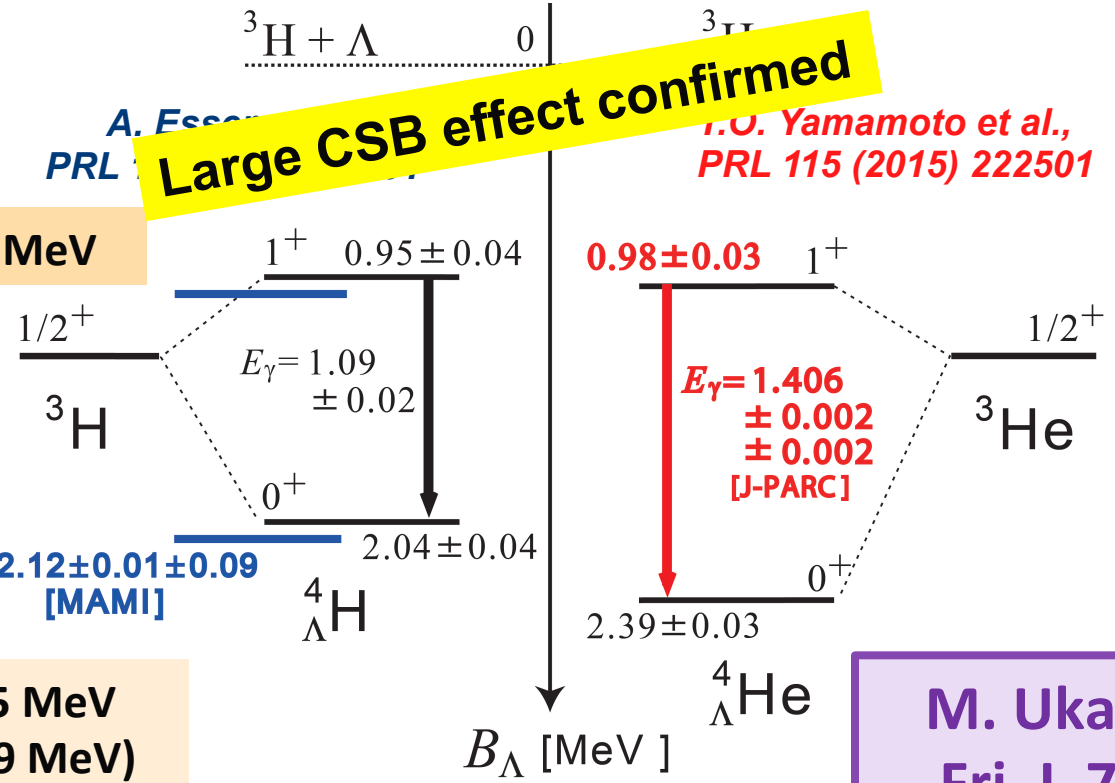
Results

Large CSB effect confirmed



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

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

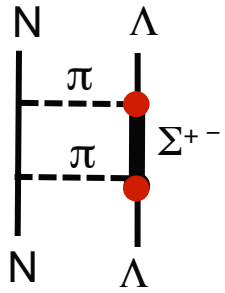


M. Ukai
Fri. L-7

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

What is the origin of the large CSB effect?

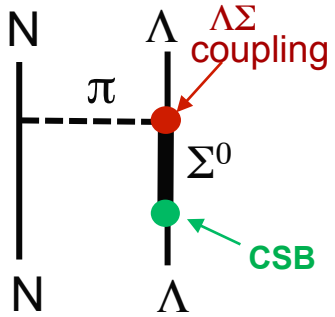
u/d quark mass difference + EM effects
=> CSB in hadrons and hadron-hadron interactions



∗ $\Sigma^+\Sigma^-$ mass difference + CSB in BB forces (Nijmegen **SC97e**)
=> $\Delta B_\Lambda(0^+)$ ~70 keV at maximum.
SC: tensor dominated $\Lambda\Sigma$ coupling *Nogga et al., PRL 88 (2002) 172501*

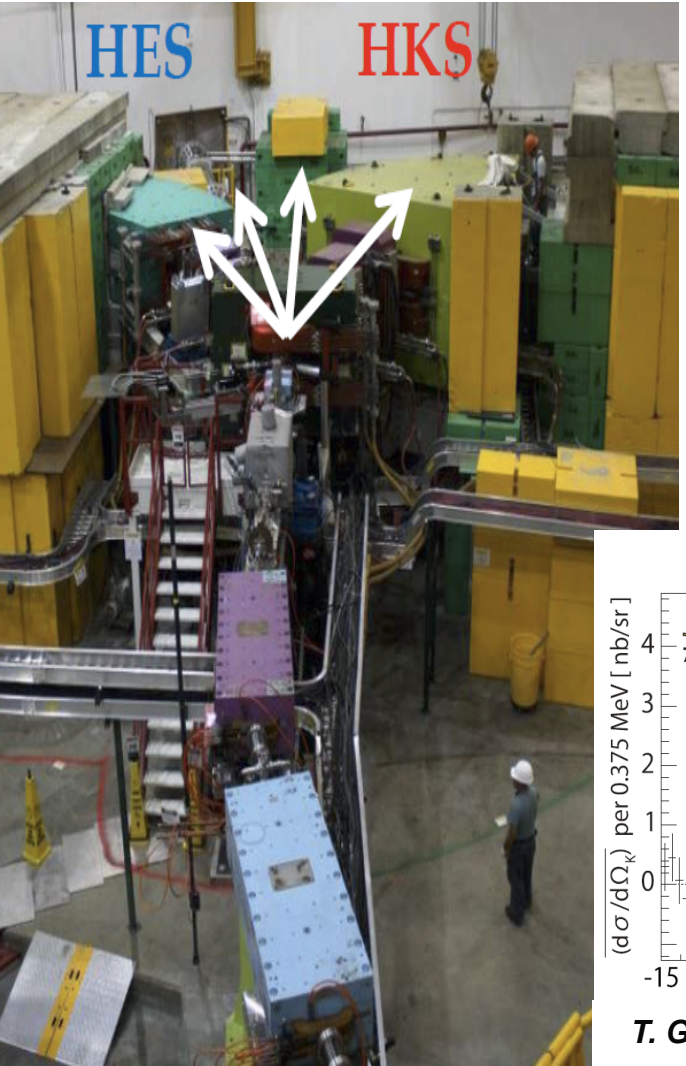
∗ Shell model calc. using **D2** => $\Delta B_\Lambda(0^+)$ ~200 keV. *A. Gal, PLB 744 (2015) 352*
D2: central-only $\Lambda\Sigma$ coupling *Akaishi et al., PRL 84 (2000) 3539*

∗ Ab initio calc. with **Bonn-Juelich EFT force (LO)**
=> $\Delta(B_\Lambda(0^+) - \Delta B_\Lambda(1^+))$ ~0.3 MeV. *= central dominated $\Lambda\Sigma$ coupling*
D. Gazda and A. Gal, PRL 116 (2016) 122501



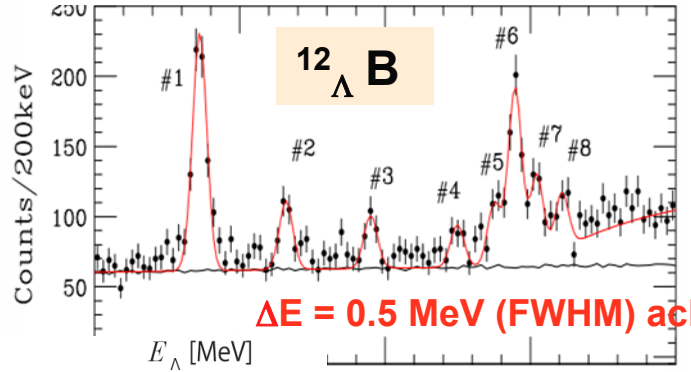
The observed CSB effect is sensitive to ΛN-ΣN coupling.

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



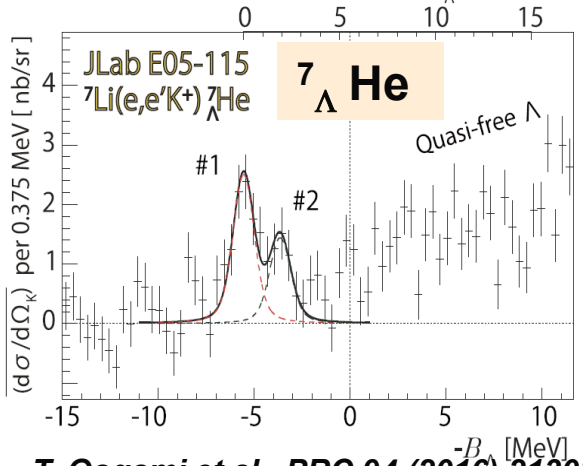
Jlab E05-115

JLab (e,e'K⁺) spectroscopy

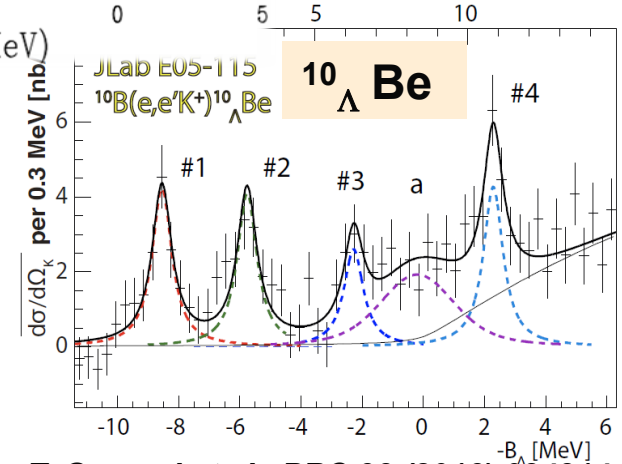


L. Tang et al., PRC90 (2014) 034320

ΔE = 0.5 MeV (FWHM) achieved



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



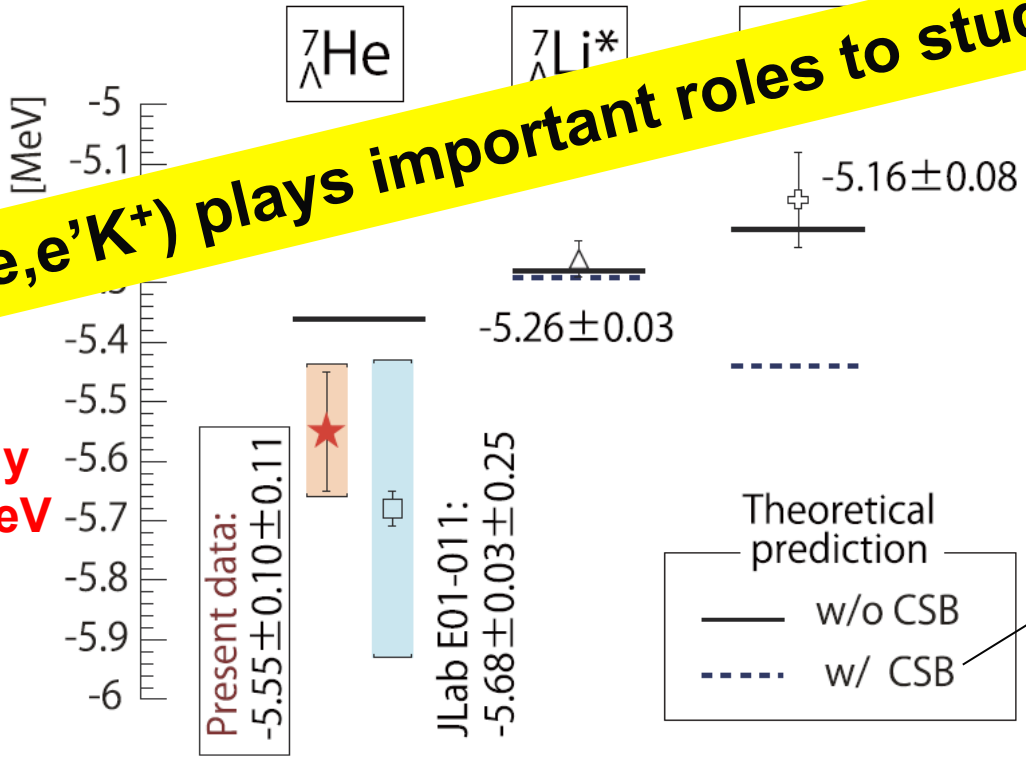
T. Gogami et al., PRC 93 (2016) 034314

(e,e'K$^+$) spectroscopy and CSB in p-shell hypernuclei

JLab (e,e'K$^+$) plays important roles to study CSB

Accuracy of absolute energy (e,e'K$^+$) ~ 100 keV

(π^+,K$^+$), (K$^-$,π^-) ~ 1 MeV

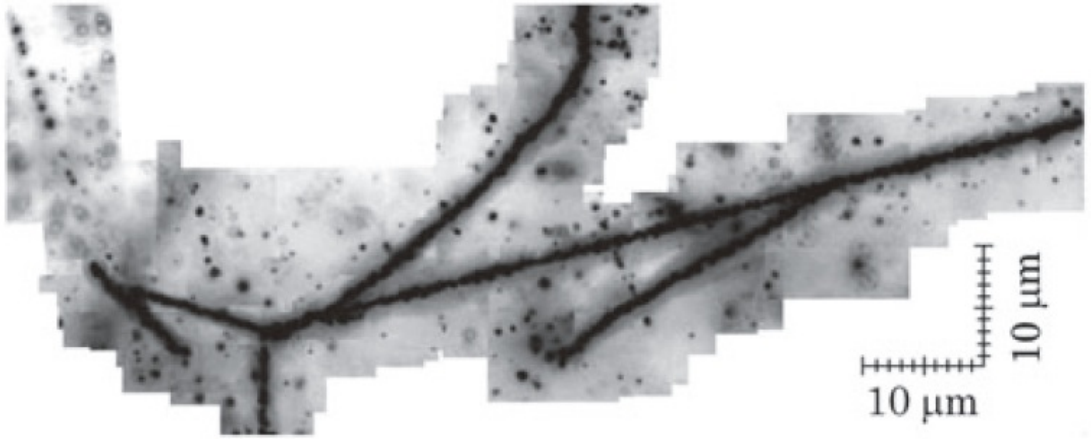


Phenom. CSB int. which accounts for A=4 (Hiyama et al.)

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

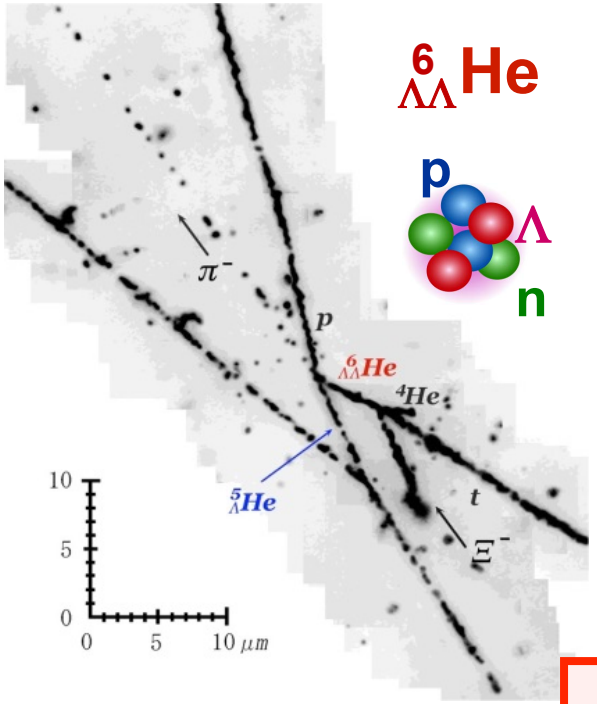
3. S = -2 Systems

Ξ-nuclear bound states



S=−2 World

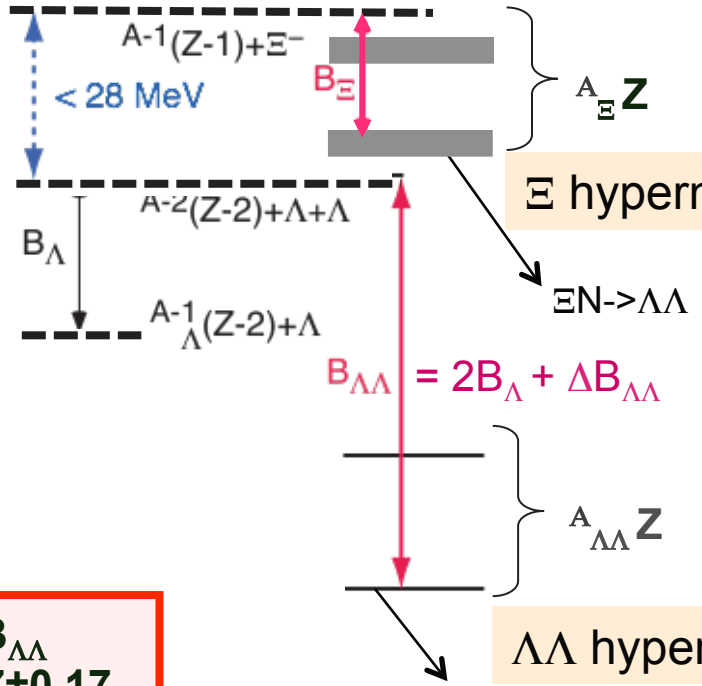
Nagara event (KEK E373)

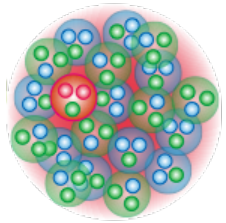


$^{6}_{\Lambda\Lambda}$He

J.K. Ahn et al., PRC 88 (2013) 014003.

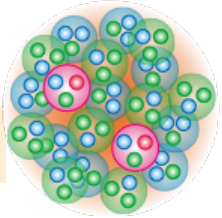
$\Delta B_{\Lambda\Lambda}$ = 0.67±0.17 MeV





ΞN-ΛΛ coupling

3-8%? mixing



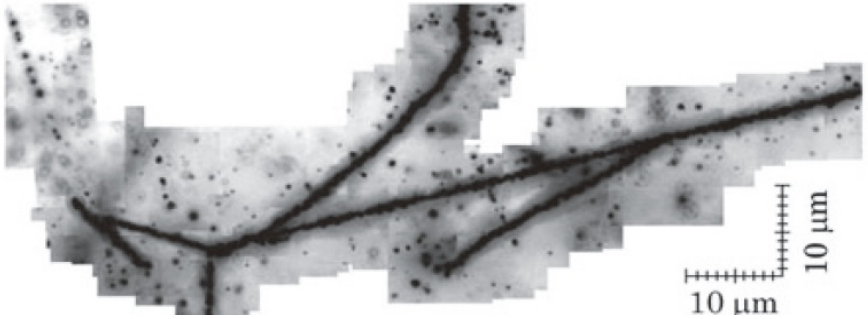
T.Nagae

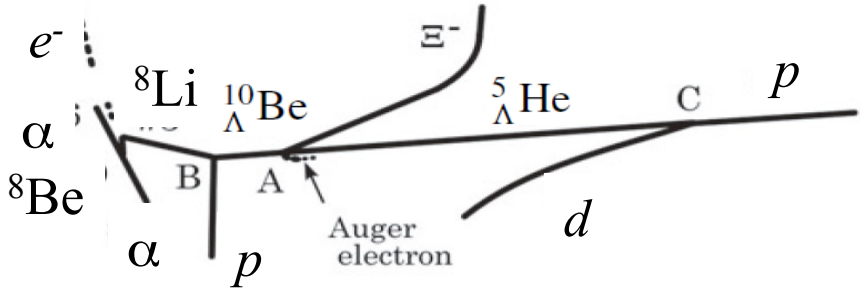
KEK E373
K. Nakazawa et al.

“Kiso event”

found by overall scanning method

K. Nakazawa et al. PTEP 2015, 033D02





uniquely identified as

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

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

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

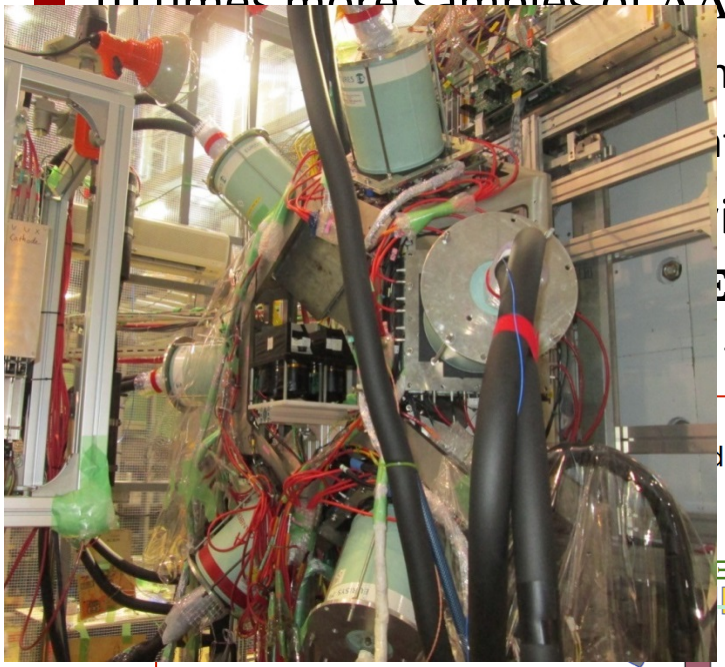
: $3D$ atomic state of the $\Xi^- - {}^{14}\mathrm{N}$ system (0.17 MeV)

The first evidence for a deeply bound Ξ state -> Ξ⁻-nucleus is attractive

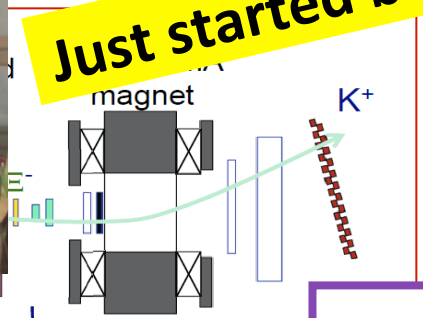
J-PARC E07
K. Nakazawa et al.

More S=-2 events with emulsion

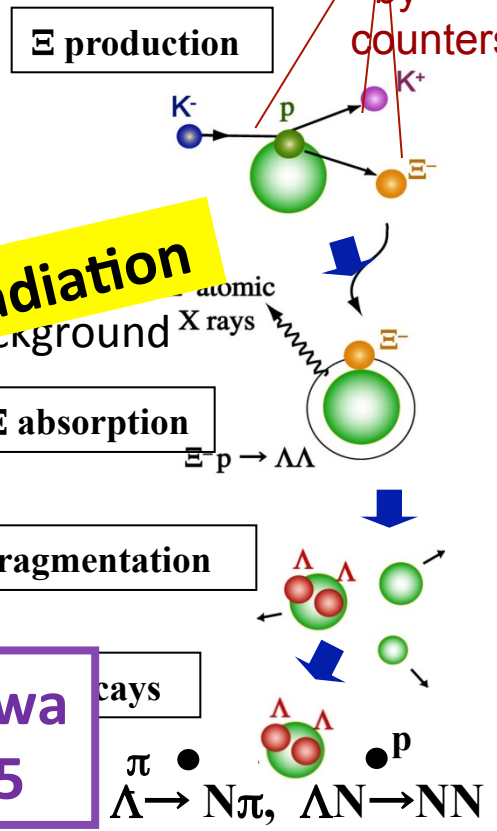
- 10 times more samples of ΛΛ hypernuclei and Ξ-nuclear bound states
  - ngth (nuclear dependence)
  - teraction
  - ith Ge detectors
  - Ξ-nuclear potential at the nu
  - from emulsio ckground



Just started beam irradiation



Measure tracks by counters



K. Nakazawa
Thu, R6-5

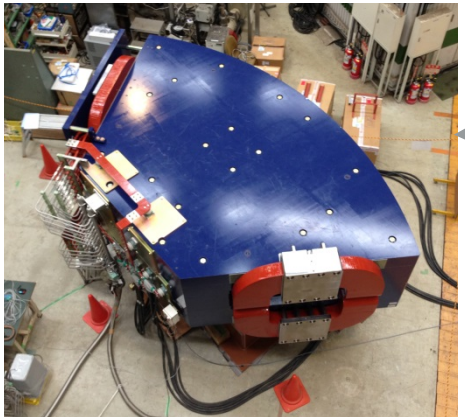
Spectroscopic Study of Ξ-Hypernucleus, $^{12}_{\Xi}$Be, via the ^{12}C(K^-,K^+) Reaction

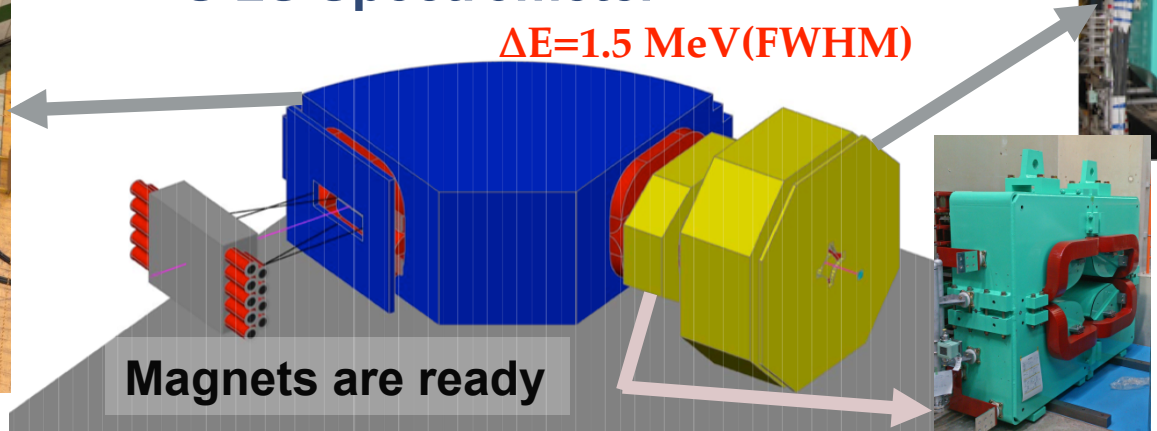
J-PARC E05
Nagae et al.

S. Kanatsuki
Mon. L3-4

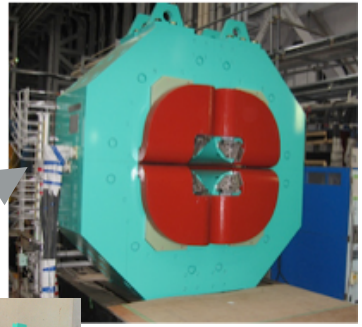
- Discovery of Ξ−hypernuclei as a peak(s)
- Measurement of Ξ−nucleus potential depth and width
- Coupling between Ξ−nucleus and Λ Λ−nucleus

D1, 86t, 1.5 T





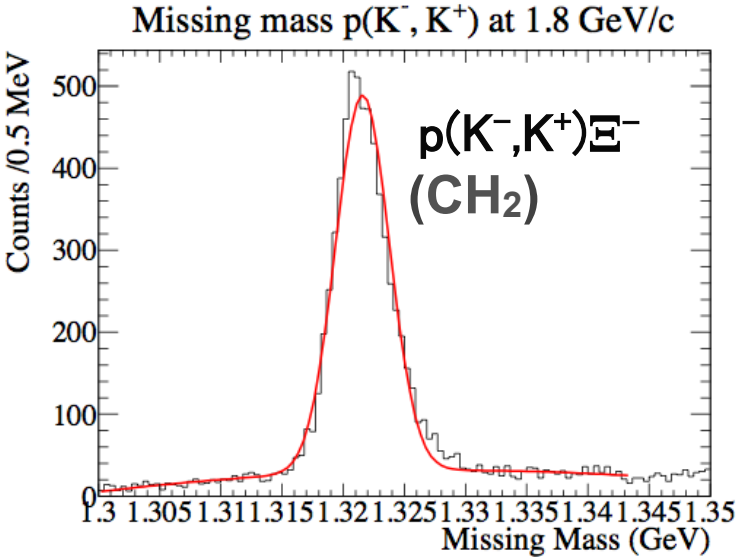
Q1, 37t, 8.7 T/m

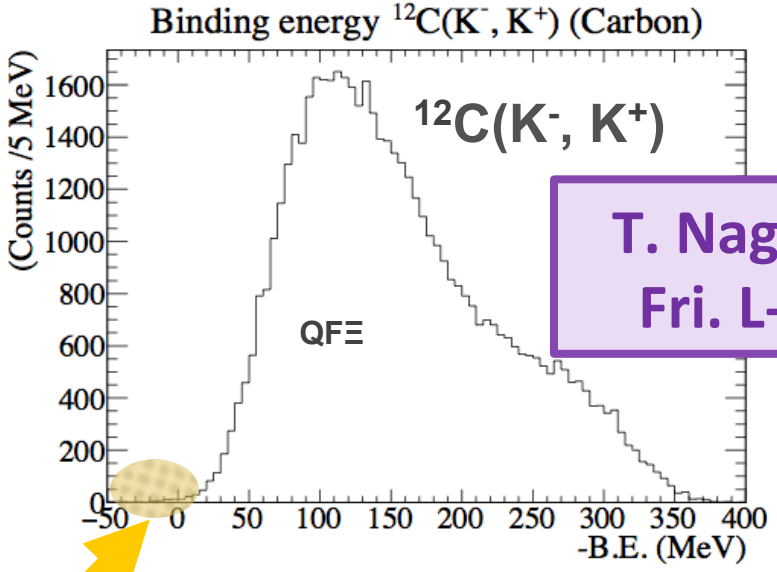


Q2, 12t, 5 T/m

Results of the pilot run (2015)

Using the existing SKS spectrometer (110 msr)



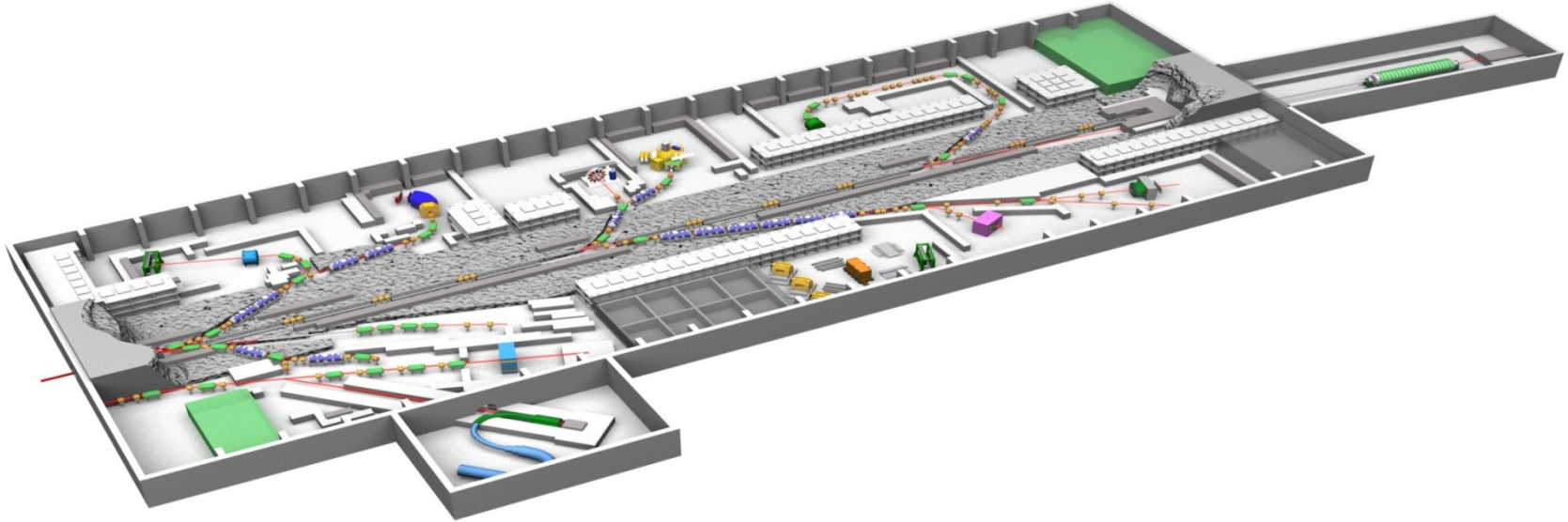


T. Nagae
Fri. L-6

ΔE ~ 5.4 MeV fwhm

~ 50 events in the Ξ bound region
Details will be discussed by T. Nagae on Fri at Hall L.

4. Future Plans

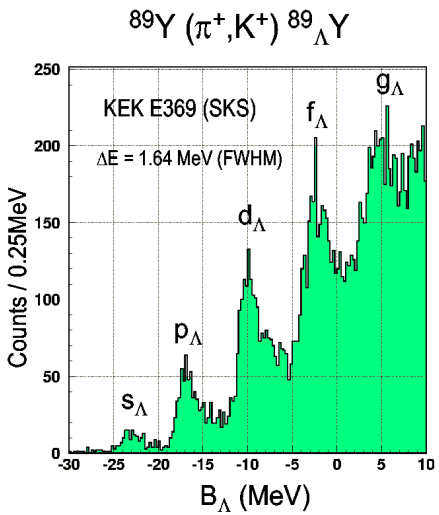


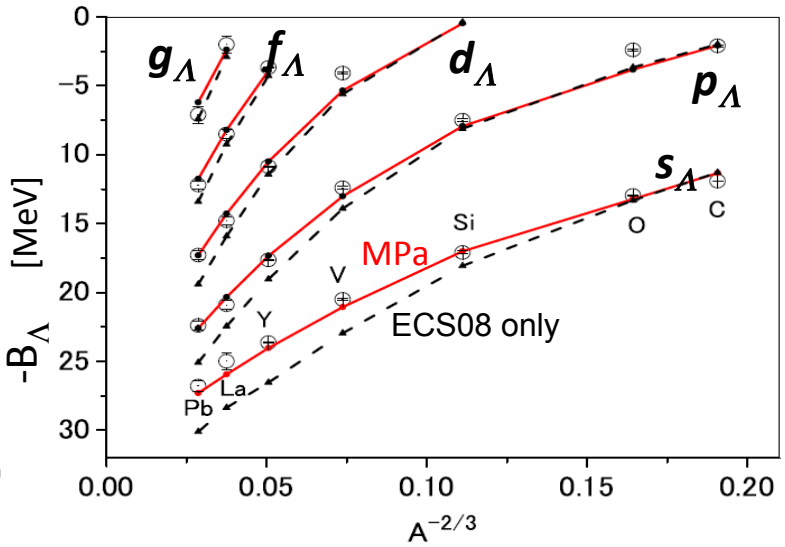
Density dependence of ΛN interaction in matter

To solve the hyperon puzzle, BB forces in high density ($\rho > \rho_0$) matter necessary

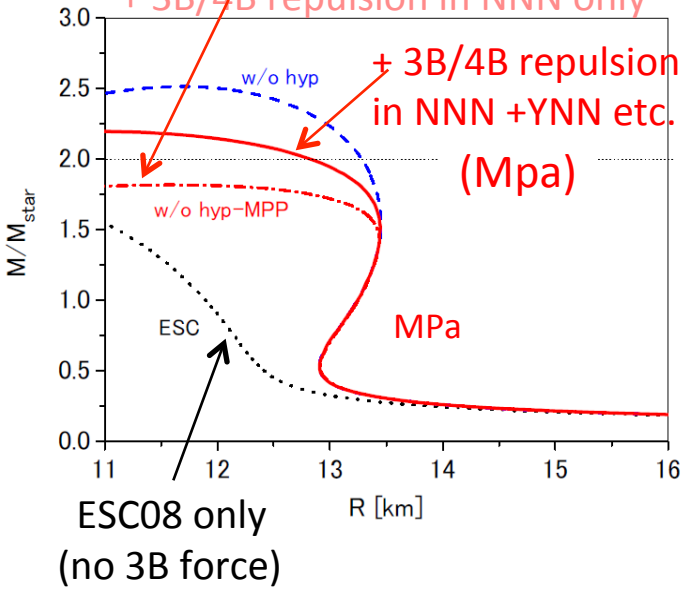
Ab-initio calc. of nuclear binding energies => NNN repulsion necessary
Similar YNN (YYN, YYY) repulsive forces?

Precise B_Λ data for wide A of Λ hypernuclei
0.1 MeV accuracy is necessary



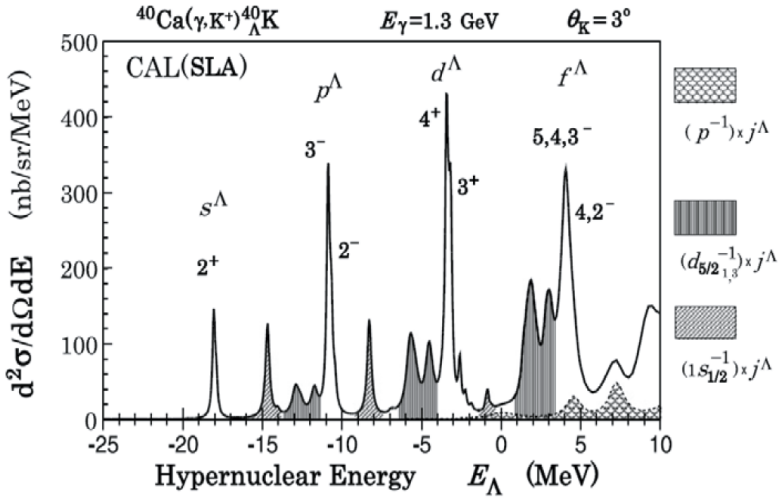


Yamamoto, Furumoto, Rijken et al.
PRC88 (2013) 2, 022801
PRC90 (2014) 045805
+ 3B/4B repulsion in NNN only

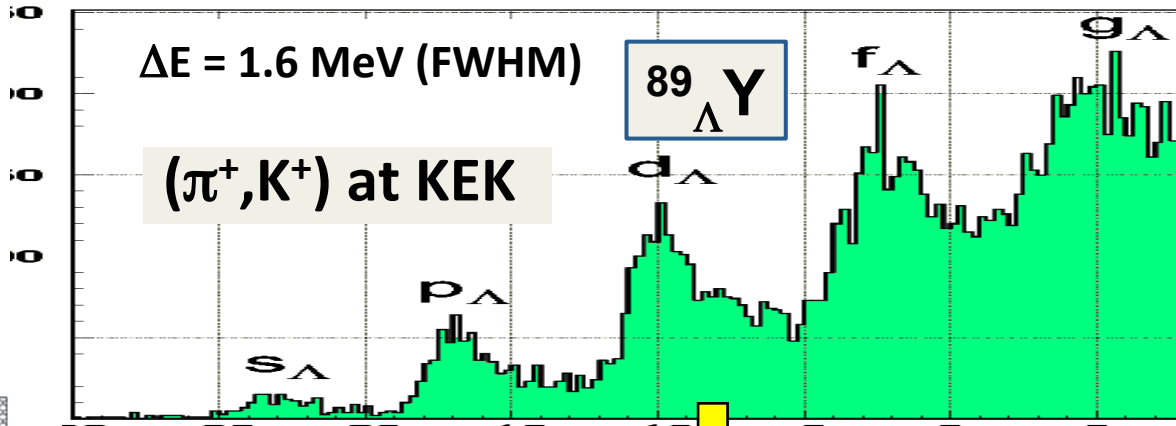


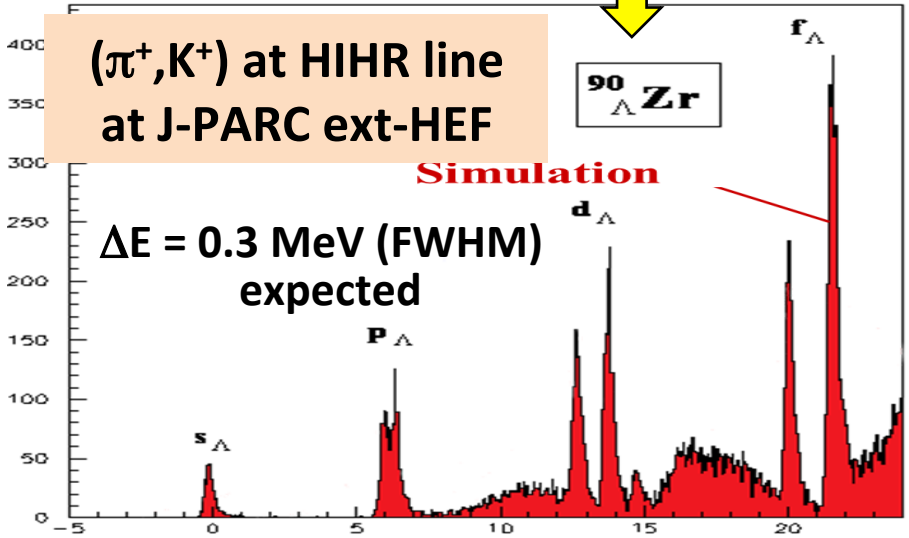
Λ single particle energies in future

(e,e'K⁺) at JLab

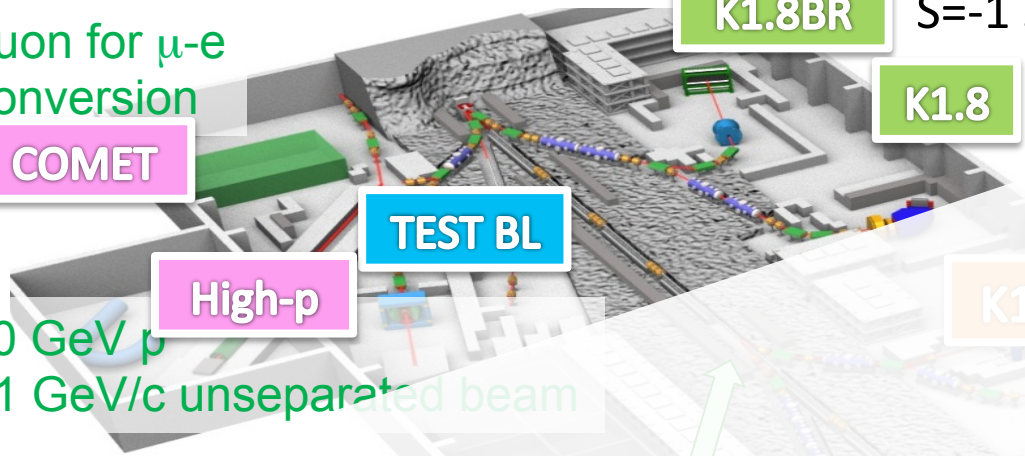


$^{40}_{Λ}$K, $^{48}_{Λ}$K experiment approved





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


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"
Δp/p ~ 1/10000
< 2.0 GeV/c
HIHR
2nd production target
J-PARC
Hadron Hall
Extension Plan
K10
Charm/ S=-3 systems
<10 GeV/c
Separated beam
3rd production target
5 deg extraction
~5.2 GeV/c K0
KL
K. Tanaka
Tue. L3-1

5. Summary

Highlights in Strangeness NP experiments

S=-1

Large CSB effect in A=4 confirmed.

- ${}^{4}_{\Lambda}$H mass measurement via ${}^{4}_{\Lambda}$H-> ^{4}He + π^-
- ${}^{4}_{\Lambda}$He γ-ray measurement

S=-2

Ξ^-nucleus bound systems confirmed.

- Ξ^-14N bound system observed in emulsion (Kiso event).
- A pilot run spectrum for ^{12}C(K-,K+) ${}^{12}_{\Xi}$Be shows bound state events.

Future

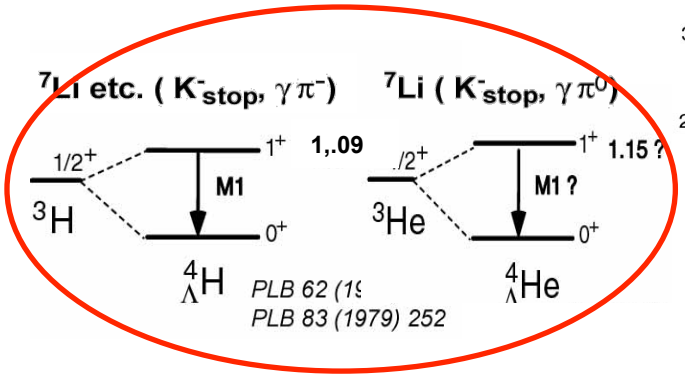
New experiments at JLab/J-PARC + Hadron Hall extension

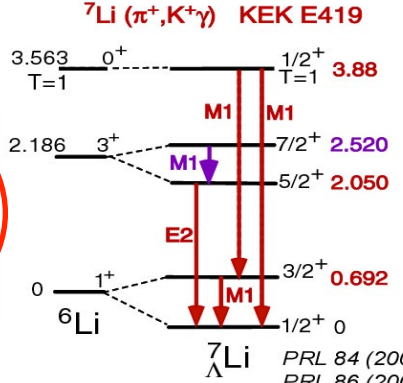
=> YN interaction in nuclear matter => solve hyperon puzzle

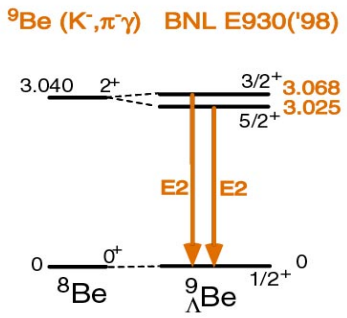
Backup

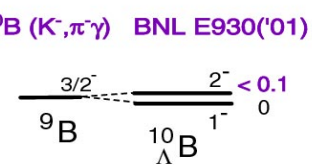
Hypernuclear γ-ray data (2014)

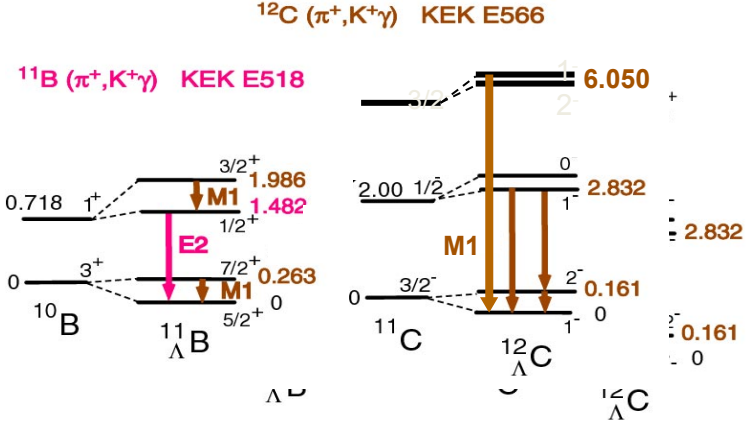
Old NaI data

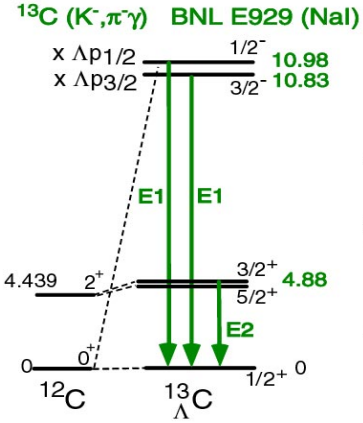


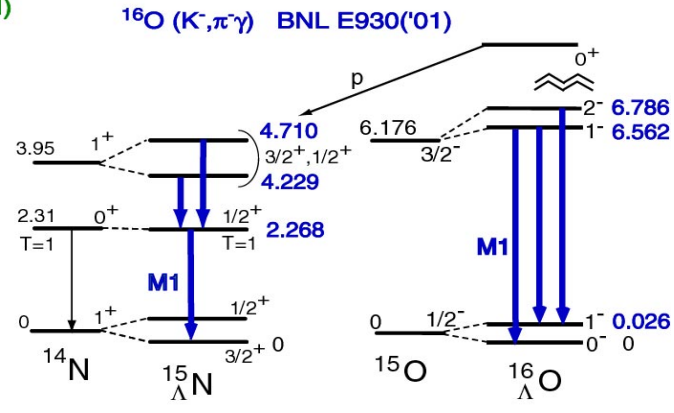




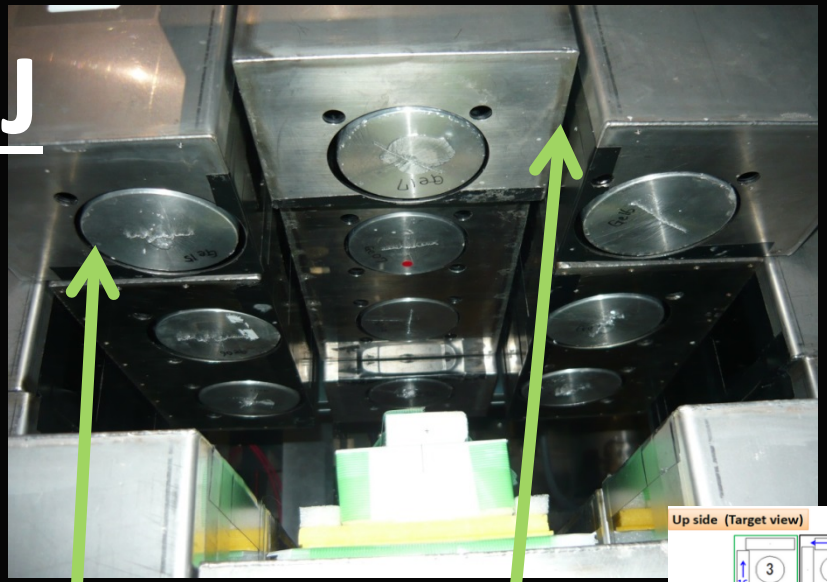








Hyperball-J

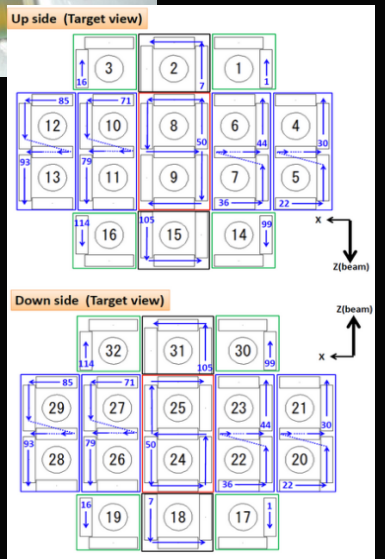


Ge cooled down to ~70K
(c.f. 92K w/LN2) to reduce
radiation damage

T. Koike et al., Nucl. Instr. Meth. A 770 (2015) 1

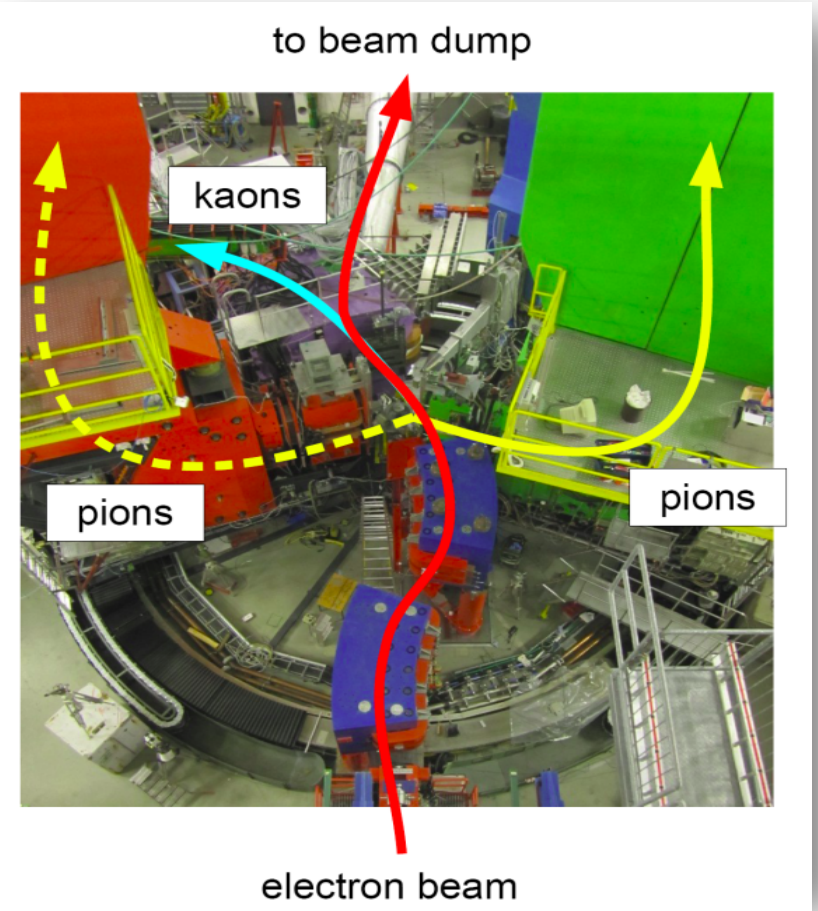
Pulse-tube
refrigerator

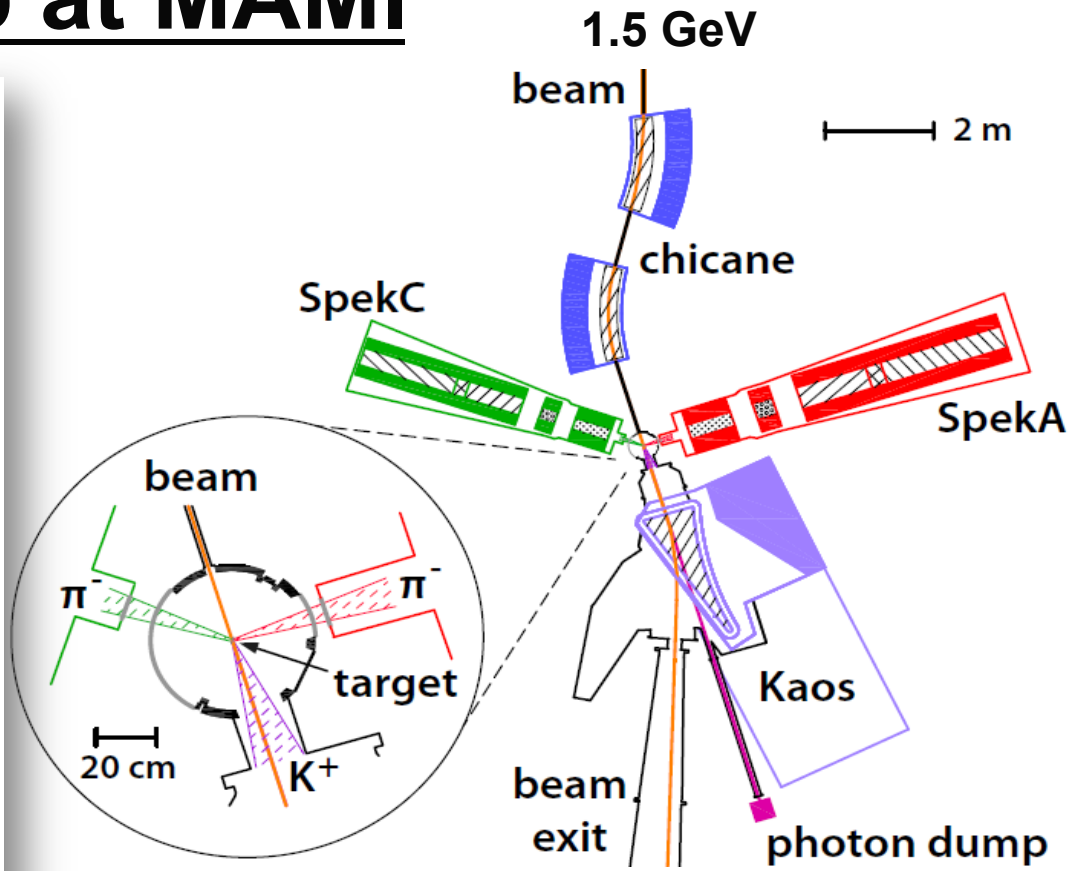
+ fast PWO counters
Eff. = 5.4% @1 MeV
with 28 Ge(re=60%)



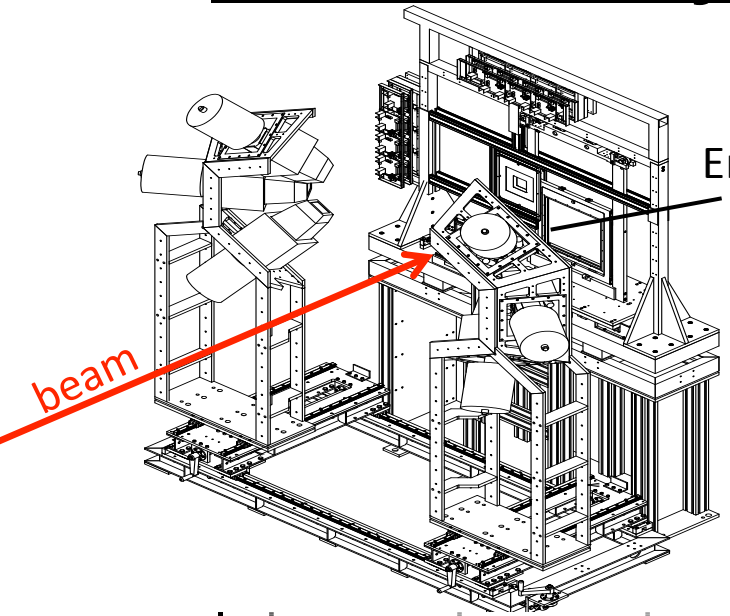
Setup at MAMI

Slide by P. Achenbach





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



Clover Ge
(4 segments)

BGO counters
for background
suppression

emulsion

10cm

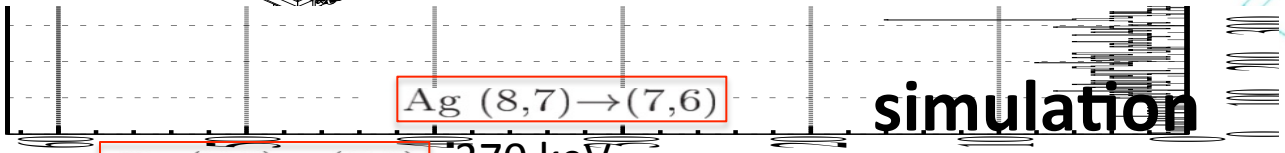
beam

SSD

^{12}C target
for Ξ production

Expected shift :
0.1– 3 keV

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



simulation

370 keV

316 keV

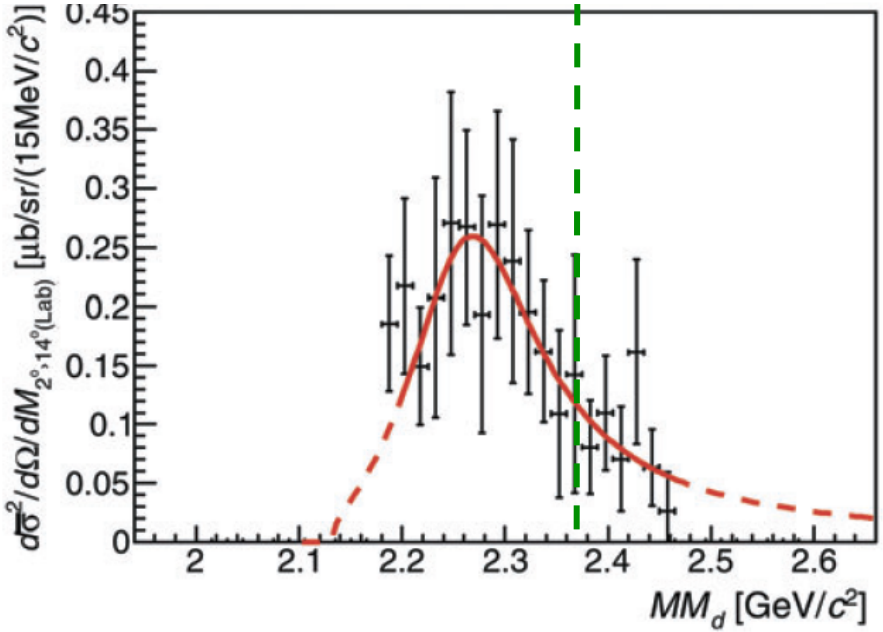
511 keV
(from π^0)

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

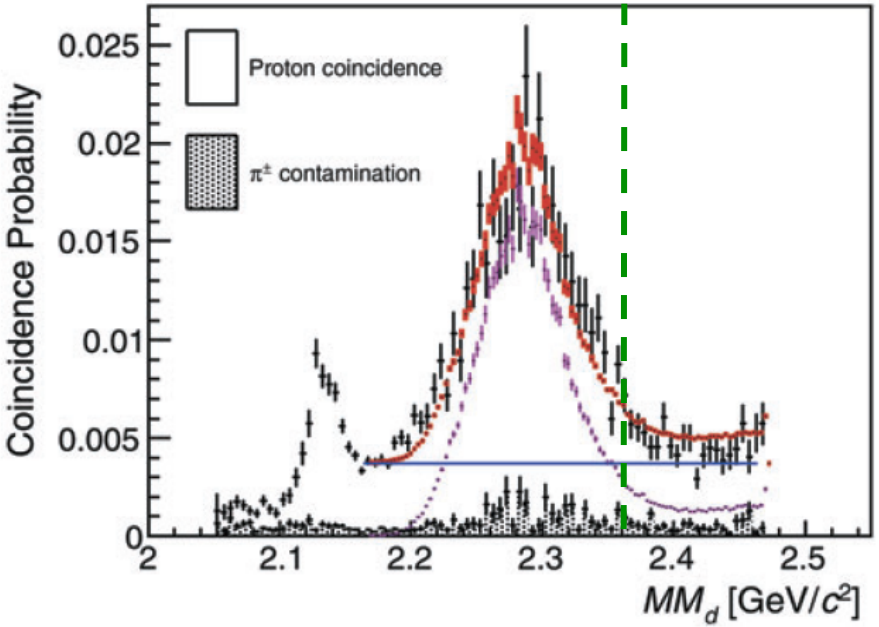
J-PARC E27
Nagae et al.

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

Two proton coincidence spectrum



One-proton coin. spectrum / inclusive spectrum

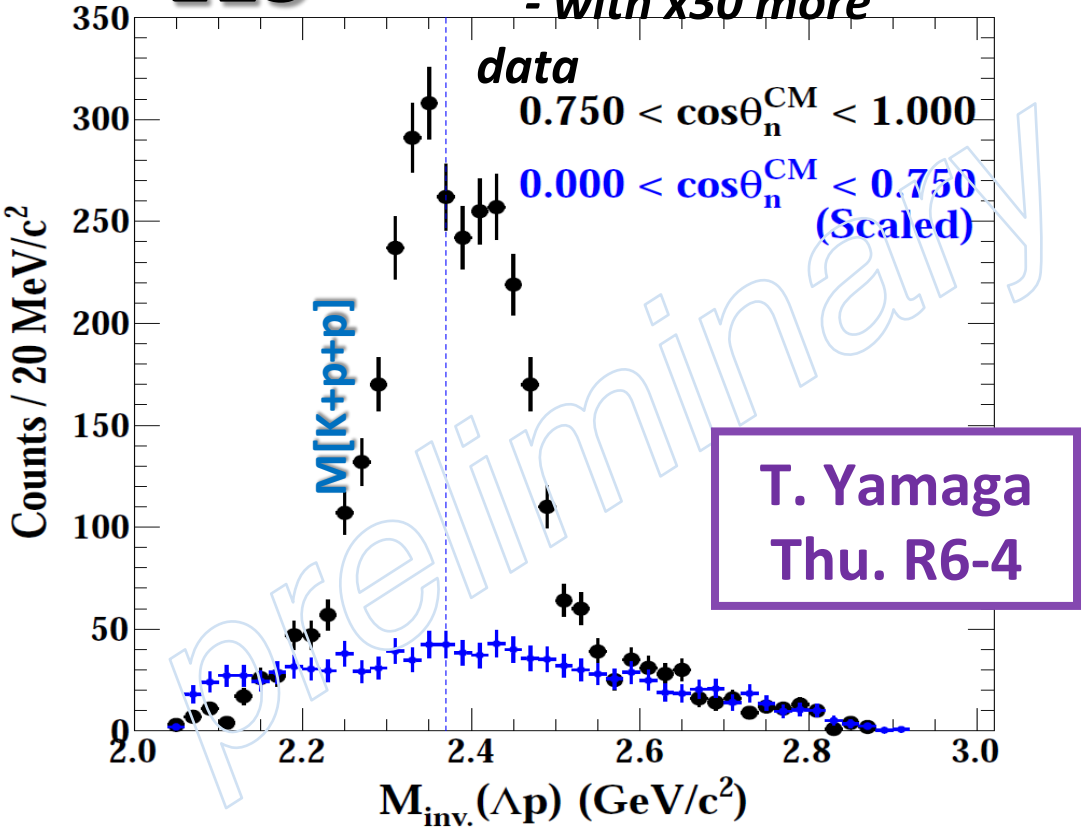


B(Kpp) = 95 $^{+18}_{-17}$ (stat) $^{+30}_{-21}$ (syst) MeV

Similar to DISTO / FINUDA results

The latest result: ^{3}He(K^-,Λp)n

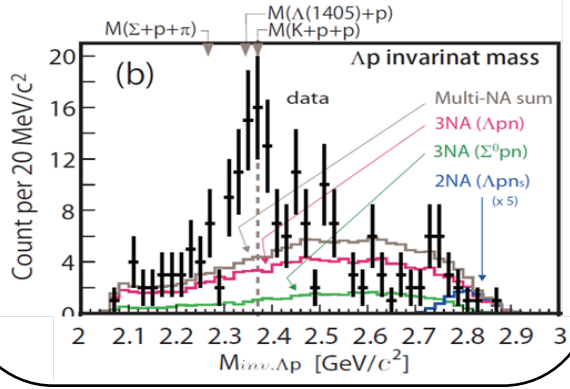
E15^{2nd} *performed in 2015 - with x30 more*



T. Yamaga
Thu. R6-4

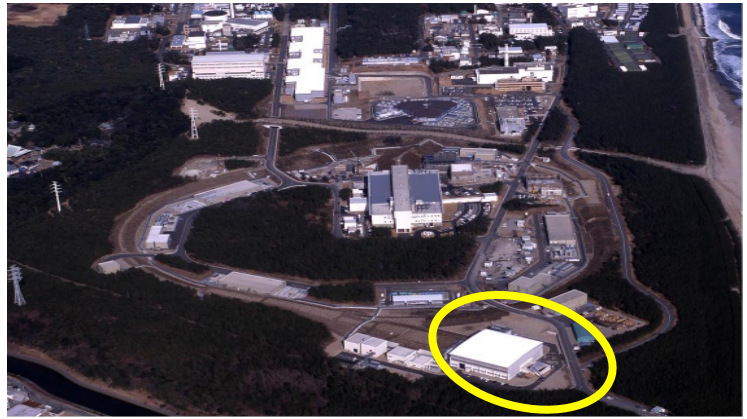
E15^{1st} *performed in 2013*

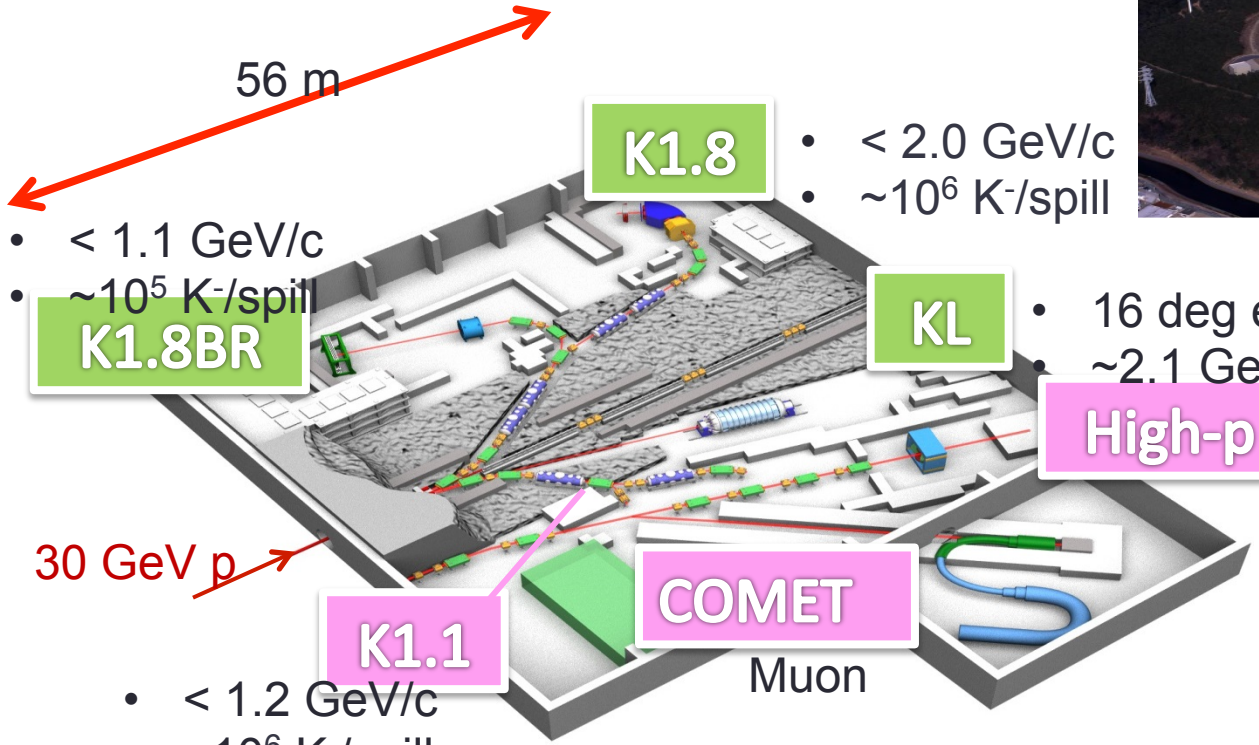
Y. Sada, et al,
Prog. Theor. Exp. Phys. (2016) 051D01



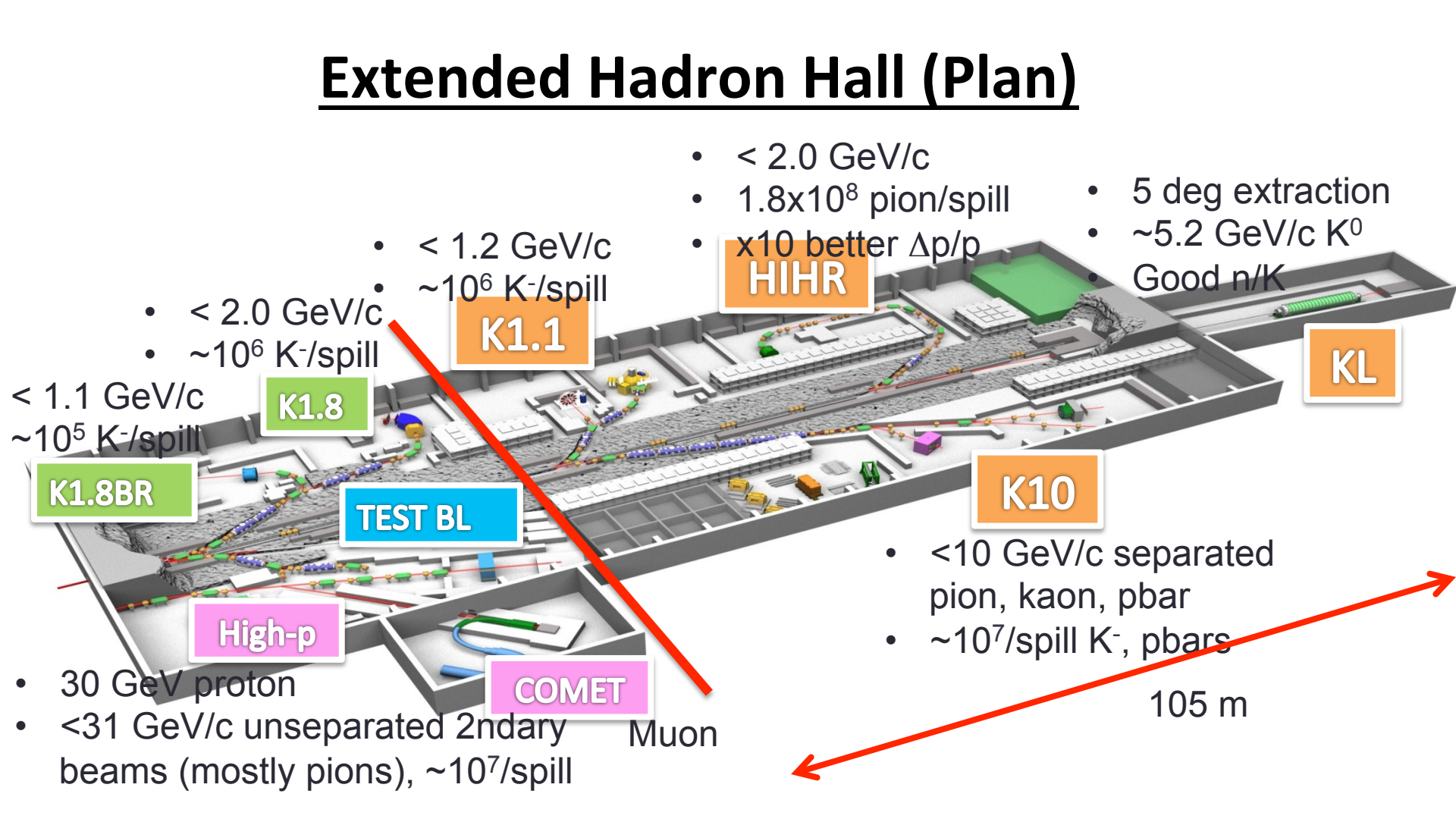
- Consistent with the E15-1st result
  - within statistics
- **Peak(s) around M_{K^-pp} can be seen**

Present Hadron Hall

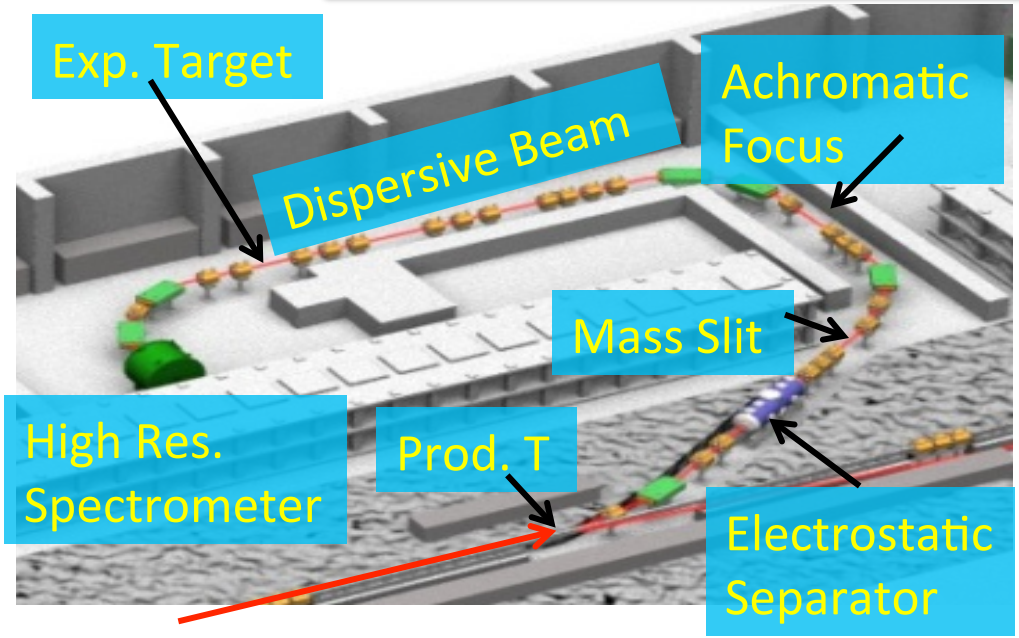


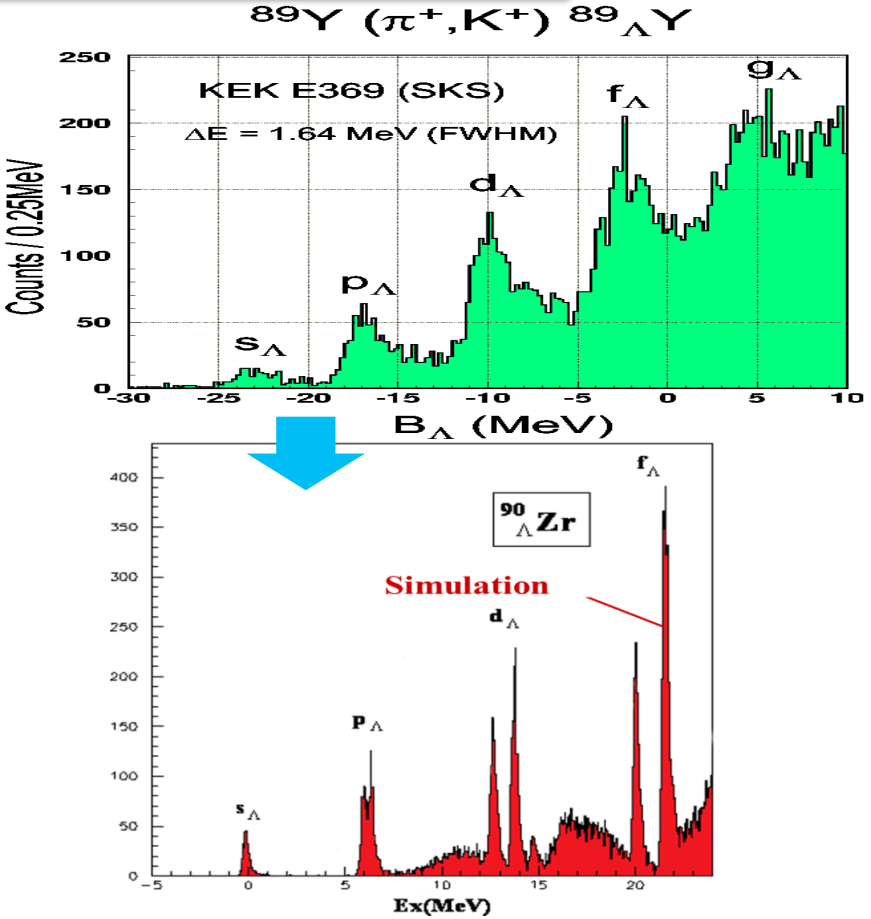


Extended Hadron Hall (Plan)



High-Intensity High-Resolution line (HIHR)





Intensity: ~ 1.8x10^8 pion/pulse
(1.2 GeV/c, 50 m, 1.4msr*%,
100kW, 6s spill, Pt 60mm)
Δp/p ~ 1/10000 (Δm~200 keV)