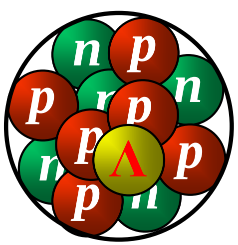
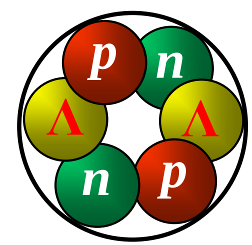
Terzo Incontro Nazionale di Fisica Nucleare
INFN2016

Laboratori Nazionali di Frascati, 14-16 novembre 2016

CSN3 | fisica nucleare   CSN4 | fisica teorica   CSN5 | fisica delle tecnologie



Experiments on hypernuclei



Istituto Nazionale di Fisica Nucleare

Alessandro Feliciello

I.N.F.N. - Sezione di Torino

Outline

- The FINUDA experiment @ LNF
- The Hall-A and Hall-C @ JLab
- The HypHI experiment @ GSI
- The STAR experiment @ BNL

past

- The ALICE experiment @ CERN/LHC
- The ULYSSES experiment @ J-PARC
  - S = -1 Λ-hypernuclei:
    - E10: search for neutron-rich Λ-hypernuclei (Dec 12 / Jan 13)
    - E13: γ-ray spectroscopy of Λ-hypernuclei (May/Jun 2015)
  - S = -2 Ξ-hypernuclei:
    - E05: search for Ξ-hypernuclei (Oct-Nov 2015)
- The A1 experiment @ MaMi-C
- The $\bar{\text{P}}$ANDA experiment @ FAIR

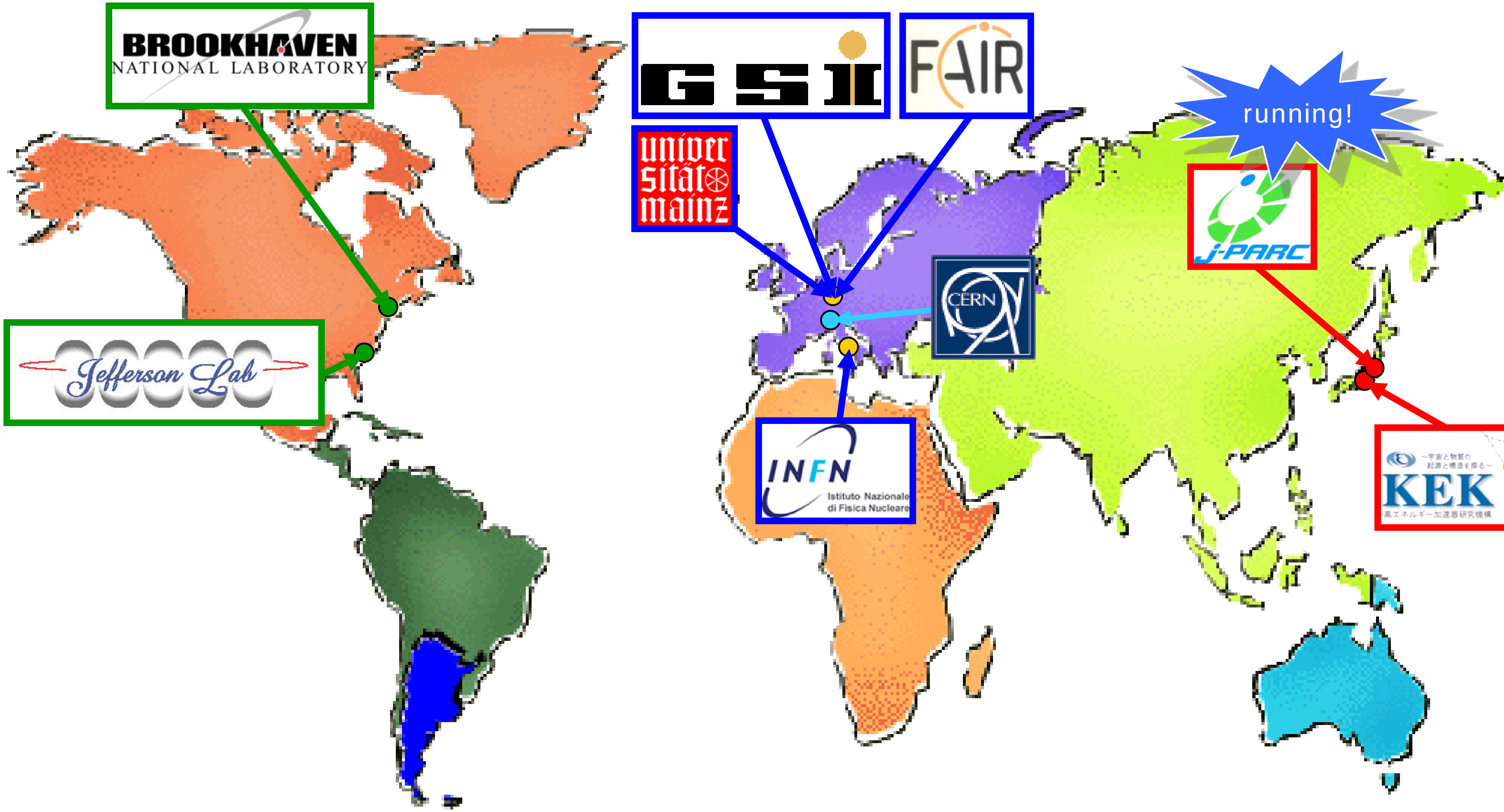
present & short term future

- future perspectives:
  - JLab hypernuclear program
  - J-PARC Hadron Hall Extension
    - Hydrogen hyperisotopes ($^3H_\Lambda$ and $^4H_\Lambda$) lifetime measurement
    - hypernuclear weak decay further studies (determination of some missing decay widths)

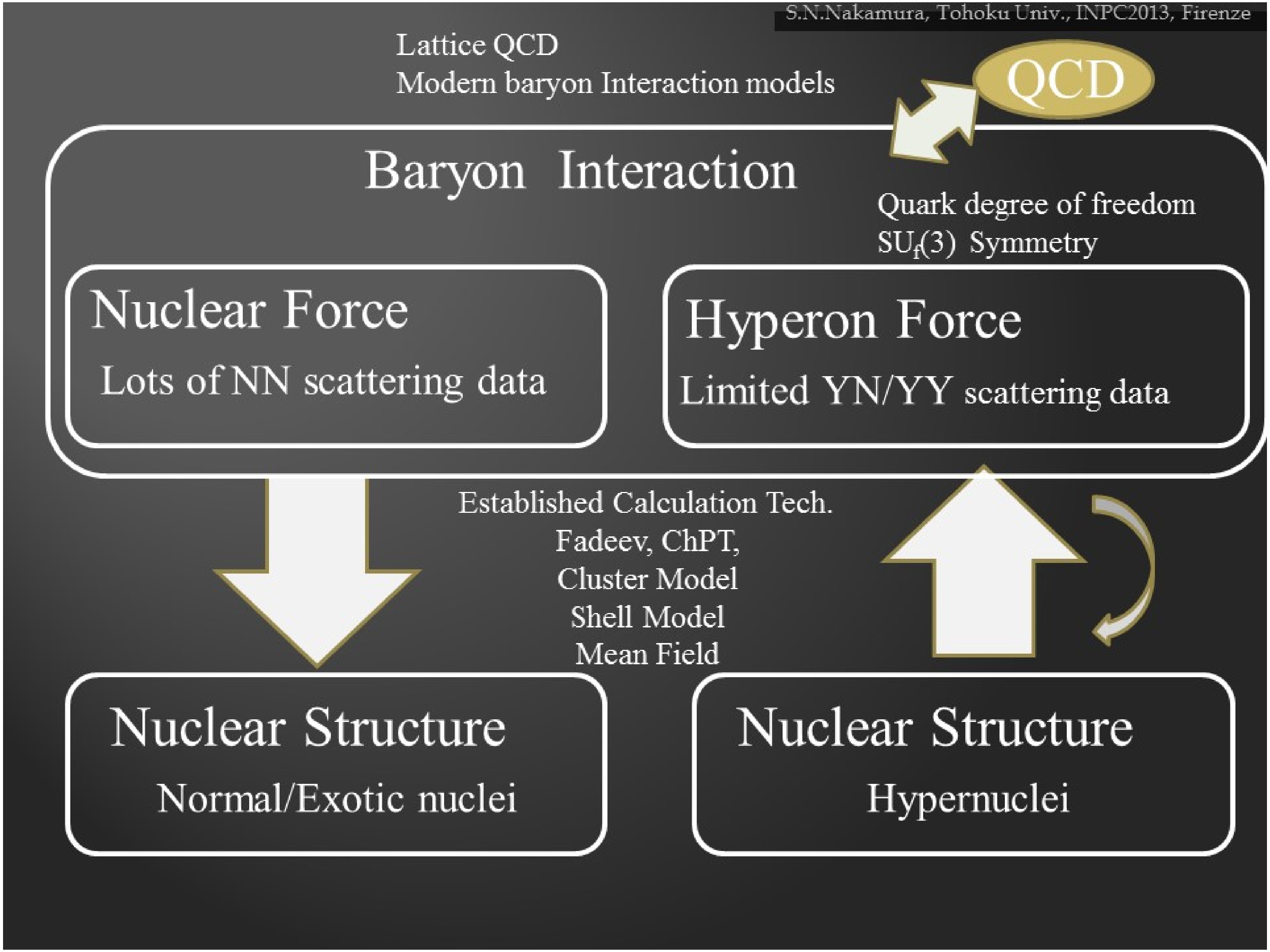
see P. Rossi's talk (Tuesday)

the JJ roadmap

A worldwide interest

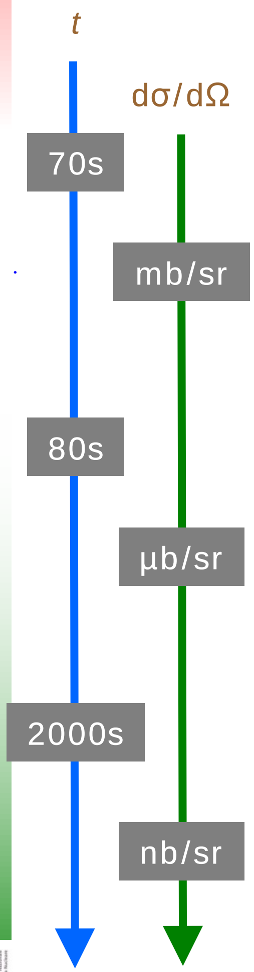


Physics motivations



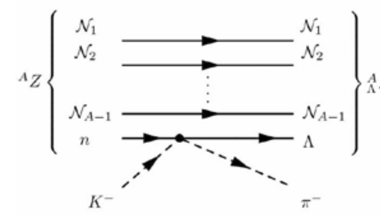
Hypernuclear physics in a nutshell

A hypernucleus is the outcome of a genetic engineering manipulation applied to the nuclear physics domain



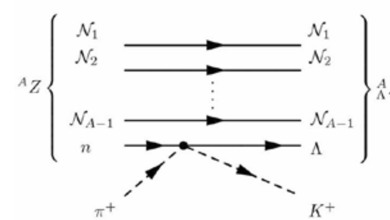
1) strangeness exchange (both in flight and at rest):

$$K^- + {}^AZ \to {}^A_\Lambda Z + \pi^-$$



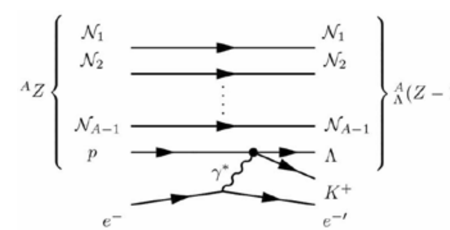
2) associated strangeness production:

$$\pi^+ + {}^AZ \to {}^A_\Lambda Z + K^+$$



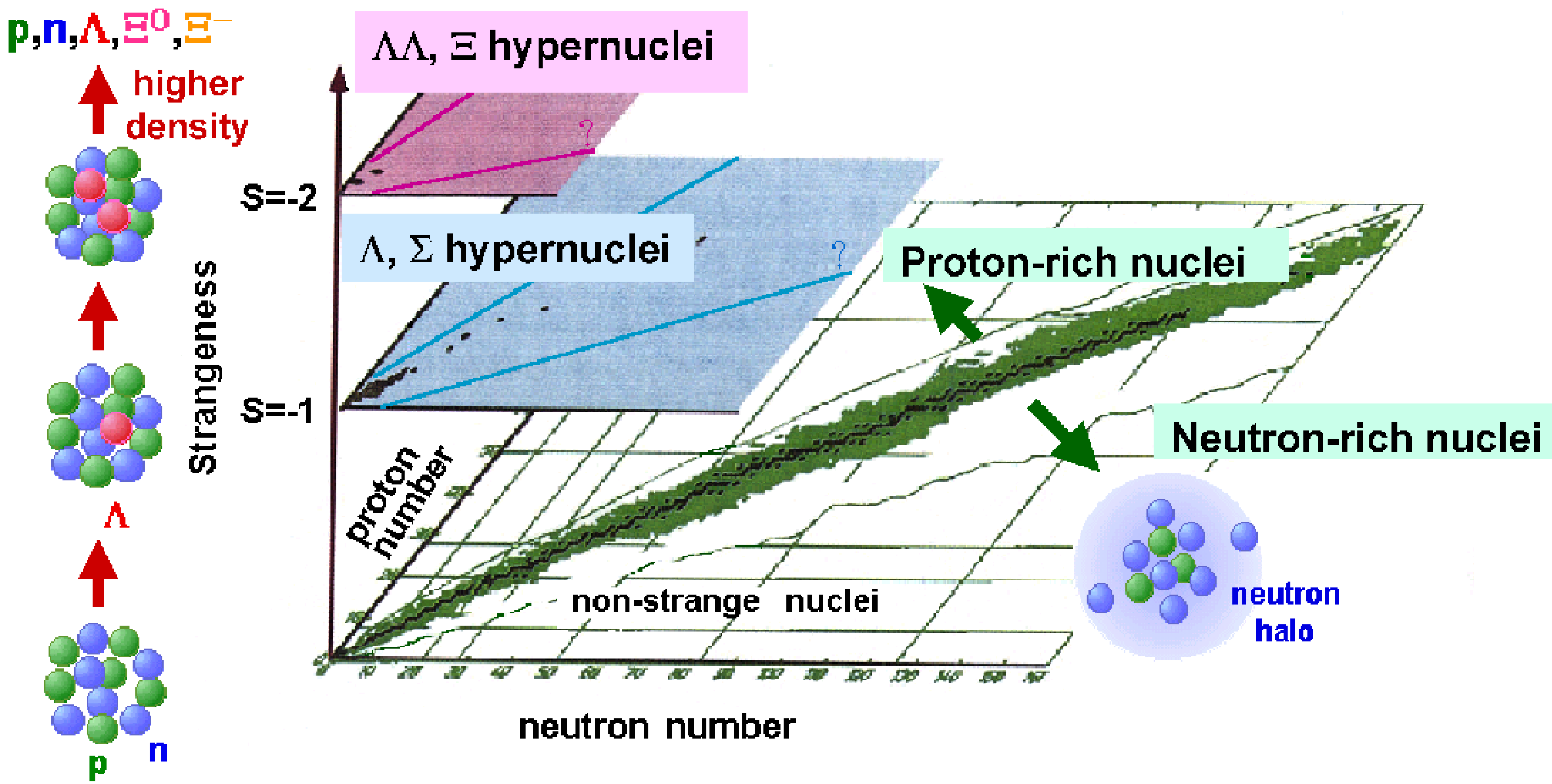
3) "electro-production":

$$e^- + {}^AZ \to e^{-'} + K^+ + {}^A_\Lambda(Z-1)$$



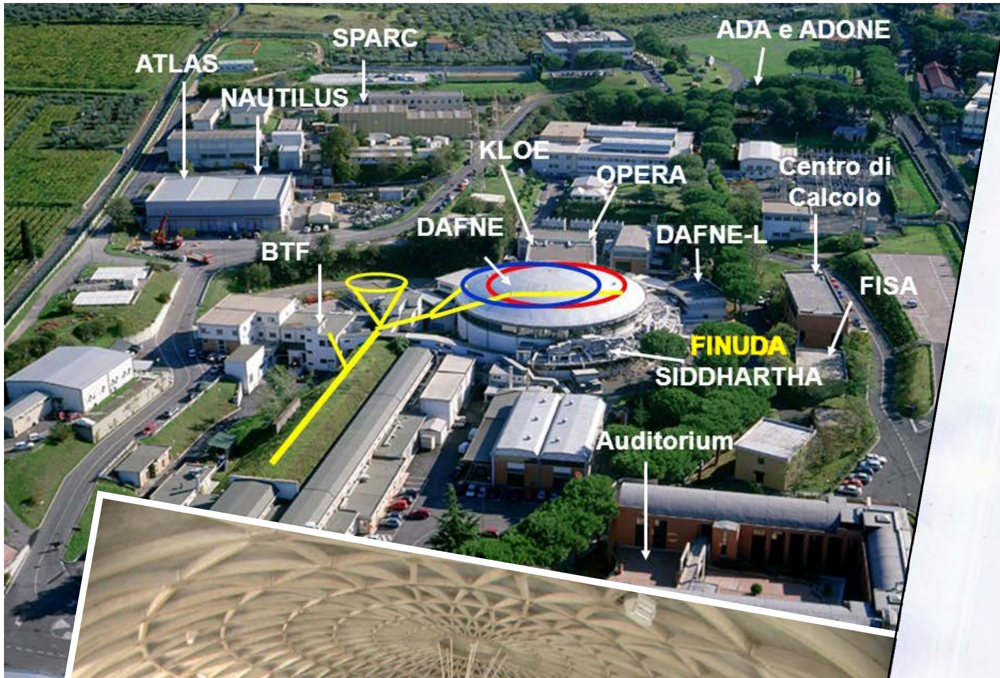
Hypernuclei's chart

Alessandro Feliciello / III Incontro Nazionale di Fisica Nucleare, INFN/LNF, Frascati (RM), 14-16 novembre 2016



courtesy of H. Tamura

The FINUDA experiment at

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Laboratori Nazionali di Frascati

LNF–93/021 (IR)
11 Maggio 1993

The FINUDA Collaboration:

FINUDA
A DETECTOR FOR NUCLEAR PHYSICS AT DAΦNE

PACS.: 21.80.+a ; 25.80.Nv ; 13.30.Eg

Servizio Documentazione
dei Laboratori Nazionali di Frascati

The FINUDA way

$e^- + e^+ \rightarrow \phi$ σ = 3.26 μb $\mathscr{L} \approx 1 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$ ≈ 300 Hz

B.R. ≈ 49% $K^- + K^+$ $T_{K^-} \approx 16.1\ \mathrm{MeV}$ ≈ 150 Hz

$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$

high resolution spectroscopy

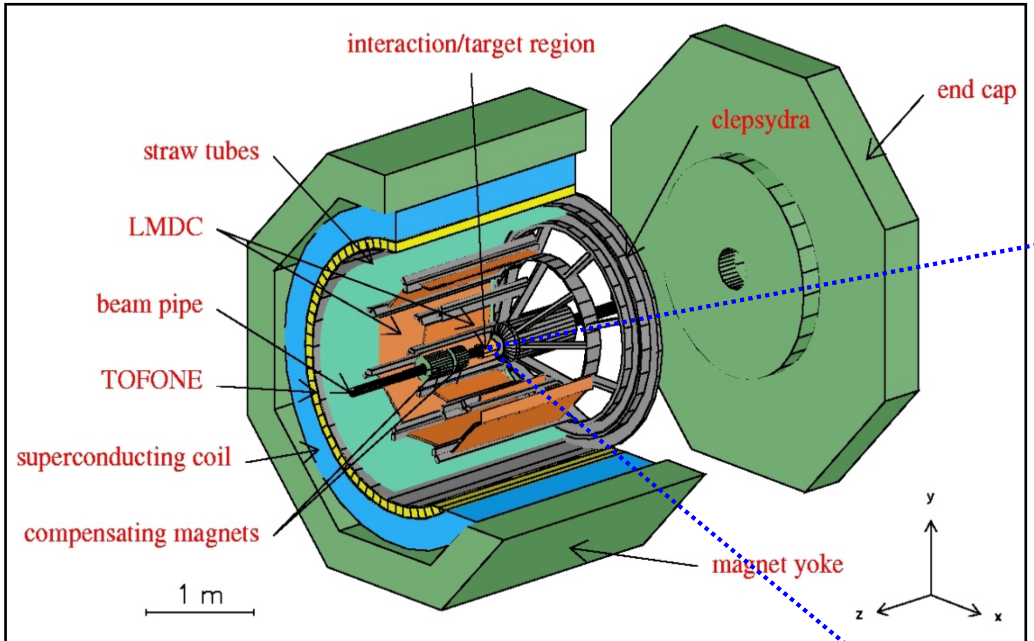
$$\frac{\Delta T_\pi}{T_\pi} = \frac{\sqrt{p_\pi^2 + m_\pi^2} + m_\pi}{\sqrt{p_\pi^2 + m_\pi^2}} \cdot \frac{\Delta p_\pi}{p_\pi} \equiv f(p_\pi)\frac{\Delta p_\pi}{p_\pi}$$

systematic study of decay modes

coincidence measurement

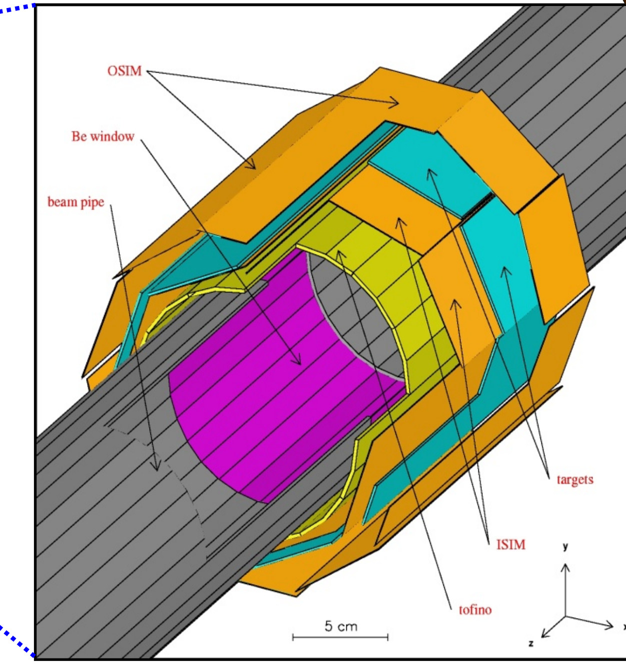
$$ {}^{A}_{\Lambda}Z \rightarrow \begin{cases} {}^{A}(Z+1) + \pi^- \\ {}^{(A-2)}(Z-1) + p + n \\ {}^{(A-2)}Z + n + n \end{cases} $$

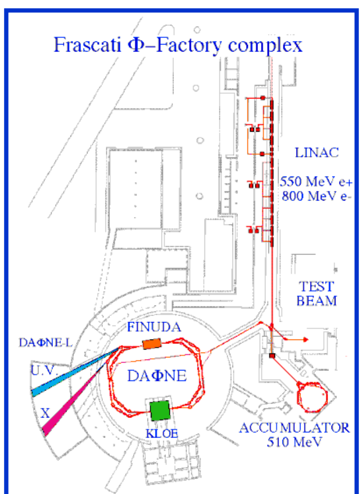
FINUDA @ DAΦNE



$$e^- + e^+ \rightarrow \phi \rightarrow K^- K^+$$

$$K^-_{stop} + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$$





energy	510 MeV
luminosity	$5\ 10^{32}\ cm^{-2}\ s^{-1}$
σ_x (rms)	2.11 mm
σ_y (rms)	0.021 mm
σ_z (rms)	35 mm
bunch length	30 mm
crossing angle	12.5 mrad
frequency (max)	368.25 MHz
bunch/ring	up to 120
part./bunch	$8.9\ 10^{10}$
current/ring	5.2 A (max)

$${}^A_\Lambda Z \rightarrow \begin{cases} {}^A(Z+1) + \pi^- \\ {}^{(A-2)}(Z-1) + p + n \\ {}^{(A-2)}Z + n + n \end{cases}$$

Physics output (S = -1)

possible thanks to apparatus performance and stability

1. M. Agnello *et al.*, *PLB* 640 (2006) 145
2. M. Agnello *et al.*, *PRL* 108 (2012) 042501
3. M. Agnello *et al.*, *NPA* 881 (2012) 269
4. M. Agnello *et al.*, *PRC* 86 (2012) 057301

nuclear models

neutron-rich Λ-hypernuclei

4B weak interaction

spectroscopy

(weak) decay

1. M. Agnello *et al.*, *PLB* 622 (2005) 35
2. M. Agnello *et al.*, *PLB* 681 (2009) 139
3. M. Agnello *et al.*, *NPA 835* (2010) 414
4. M. Agnello *et al.*, *PLB* 698 (2011) 219

medium effect

quark substructures

low-energy $\mathcal{N}$-Y interaction

deeply bound $\bar{K}$ states

\> 300 citations!!!

1. M. Agnello *et al.*, *PRL* 94 (2005) 212303
2. M. Agnello *et al.*, PLB 654 (2007) 80

1. M. Agnello *et al.*, *NPA* 804 (2008) 151
2. M. Agnello *et al.*, *PLB* 681 (2009) 139
3. M. Agnello *et al.*, *NPA* 835 (2010) 439
4. M. Agnello *et al.*, *PLB* 685 (2010) 247
5. M. Agnello *et al.*, *PLB* 701 (2011) 556
6. M. Agnello *et al.*, *NPA* 881 (2012) 322
7. M. Agnello *et al.*, *PLB* 738 (2014) 499
8. E. Botta *et al.*, *PLB* 748 (2015) 86

Search for neutron-rich hypernuclei

central issue in hypernuclear physics

- historical paper: R.H. Dalitz and R. Levi Setti, Nuovo Cimento 30 (1963) 489

1. Pauli effect not effective for Λ
2. Λ extra binding energy

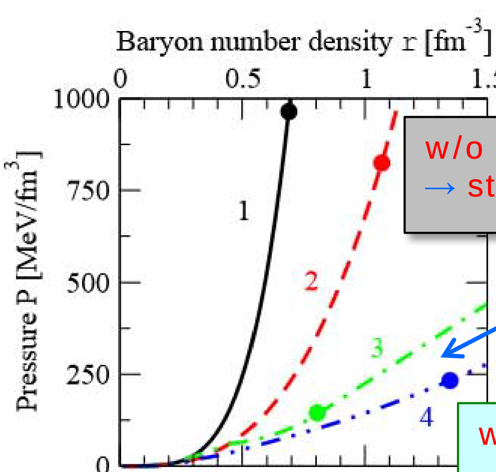
⇒ existence of hypernuclei with core nucleus near (or even beyond) the neutron drip line

- unique opportunity to study:
  - effect of 3-body forces (Λ𝒩𝒩)
  - Λ𝒩- Σ𝒩 coupling contribution to binding en.
  - hyperon behaviour in n-rich environment

⇓

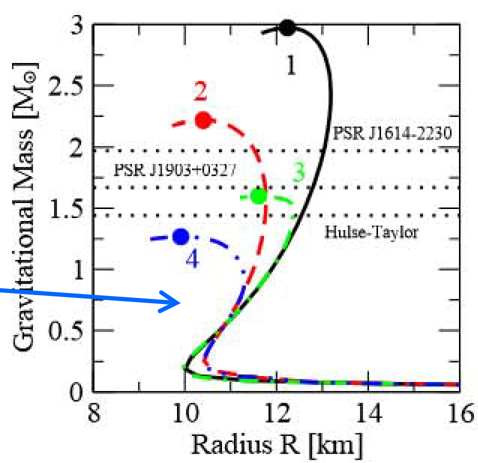
direct influence on neutron star EoS

prediction of neutron star main parameters



w/o hyperons → stiff EoS

w/ hyperons → soft EoS



I. Vidaña *et al.*, *EPL* 94 (2011) 11002

The status of art (as of 2011)

$$K^-_{stop} + {}^AZ \rightarrow {}^A_\Lambda(Z-2) + \pi^+$$

- $K^- + p \rightarrow \pi^0 + \Lambda$, $\pi^0 + p \rightarrow \pi^+ + n$: 2-step (S-EX + C-EX)
- $K^- + p \rightarrow \bar{K}^0 + n$, $\bar{K}^0 + p \rightarrow \Lambda + \pi^+$: 2-step (C-EX + S-EX)
- $K^- + p \rightarrow \pi^+ + \Sigma^-$, $\Sigma^- + p \rightarrow \Lambda + n$: 1-step (S-EX)

experimental results

KEK

- ${}^9_\Lambda He({}^9Be): u.l. = 2.3\cdot10^{-4} / K^-_{stop}$
- ${}^{12}_\Lambda Be({}^{12}C): u.l. = 6.1\cdot10^{-5} / K^-_{stop}$
- ${}^{16}_\Lambda C({}^{16}O): u.l. = 6.2\cdot10^{-5} / K^-_{stop}$

K. Kubota *et al.*, *NPA* 602 (1996) 327

INFN-LNF

- ${}^6_\Lambda H({}^6Li): u.l. = (2.5\pm1.4)\cdot10^{-5} / K^-_{stop}$
- ${}^7_\Lambda H({}^7Li): u.l. = (4.5\pm1.4)\cdot10^{-5} / K^-_{stop}$
- ${}^{12}_\Lambda Be({}^{12}C): u.l. = (2.0\pm0.4)\cdot10^{-5} / K^-_{stop}$

M. Agnello *et al.*, *PLB* 640 (2006) 145

theoretical predictions

$10^{-6} \div 10^{-7} / K^-_{stop}$

T.Y. Tretyakova *et al.*, *NPA* 691 (2001) 51c

$$\pi^- + {}^AZ \rightarrow {}^A_\Lambda(Z-2) + K^+$$

- $\pi^- + p \rightarrow \pi^0 + n$, $\pi^0 + p \rightarrow K^+ + \Lambda$: 2-step (C-EX + AP)
- $\pi^- + p \rightarrow K^0 + \Lambda$, $K^0 + p \rightarrow K^+ + n$: 2-step (AP + C-EX)
- $\pi^- + p \rightarrow K^+ + \Sigma^-$, $\Sigma^- + p \rightarrow \Lambda + n$: 1-step (AP)

experimental results

KEK

${}^{10}_\Lambda Li({}^{10}B): d\sigma/d\Omega = 11.3\pm1.9\ nb/sr$

P.K. Saha *et al.*, *PRL* 94 (2005) 052502

theoretical predictions

T.Y. Tretyakova *et al.*, *PAT* 66 (2003) 1681

The new NRH search strategy

$\mathcal{L}_{int} \approx 1156\ pb^{-1}$ → **coincidence measurements**

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

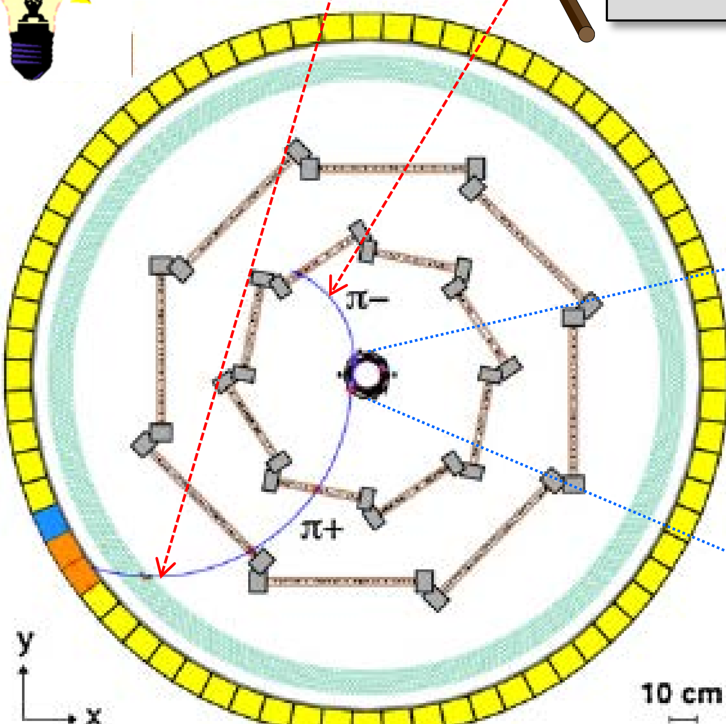
double C-EX
p ~ 252 MeV/c

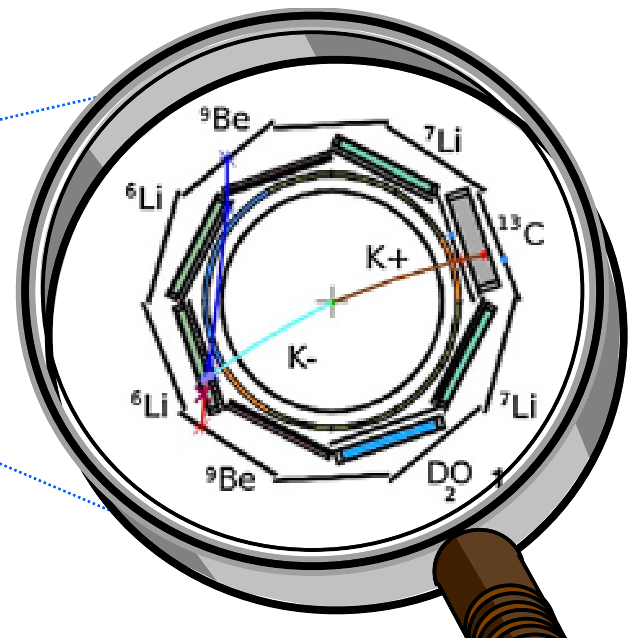
$$ {}^6_\Lambda\text{H} \rightarrow {}^6\text{He} + \pi^- $$

n.m. decay
p ~ 134 MeV/c

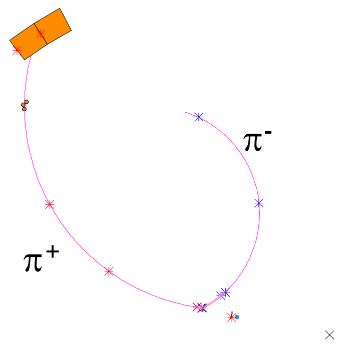
apparatus capabilities:

- selective trigger
  (based on fast scintillator detectors)
- precise K^- vertex identification < 1 mm^3
  (PID + spatial resolution + K^- tagging)
- π, K, p, d, ... separation (OSIM & LMDC dE/dx)
- high momentum resolution
  6 ‰ FWHM π^- @ 270 MeV/c
  6% FWHM π^- @ 110 MeV/c
  (tracker performance + He bag + thin target)



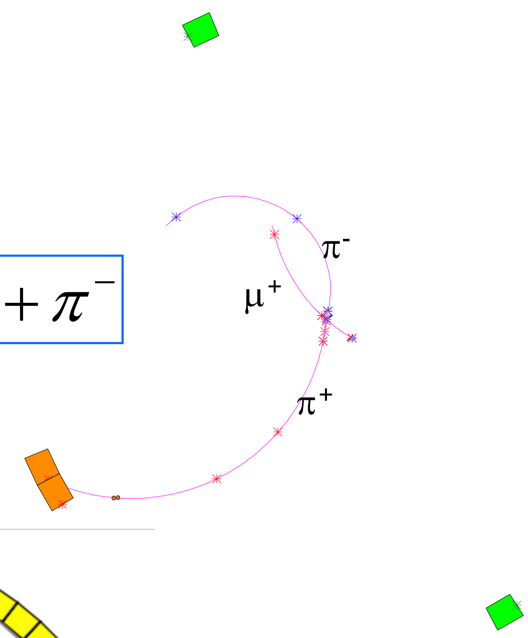


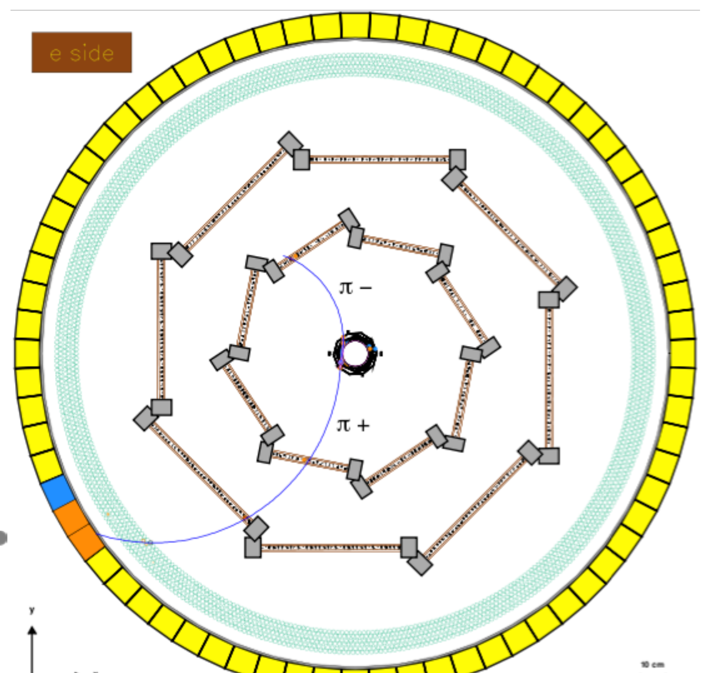
Experimental evidence for $^6H_\Lambda$ (2012)



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

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





FINUDA Coll. and A. Gal, *PRL* 108 (2012) 042501
FINUDA Coll. and A. Gal, *NPA* 881 (2012) 269

The $^6H_\Lambda$ puzzle

T_{tot} (MeV)	p_{π^+} (MeV/c)	p_{π^-} (MeV/c)	$M({}^6_\Lambda H)$ prod. (MeV)	$M({}^6_\Lambda H)$ decay (MeV)	$M({}^6_\Lambda H)$ mean (MeV)	$\Delta M({}^6_\Lambda H)$ (MeV)
202.6 ± 1.3	251.3 ± 1.1	135.1 ± 1.2	5802.33 ± 0.96	5801.41 ± 0.84	5801.87 ± 0.96	0.92 ± 1.28
202.7 ± 1.3	250.1 ± 1.1	136.9 ± 1.2	5803.45 ± 0.96	5802.73 ± 0.84	5803.09 ± 0.96	0.72 ± 1.28
202.1 ± 1.3	253.8 ± 1.1	131.2 ± 1.2	5799.97 ± 0.96	5798.66 ± 0.84	5799.32 ± 0.96	1.31 ± 1.28

$$(N+Y)/Z({}^6_\Lambda H) = 5 >> N/Z({}^8He) = 3$$

formation mass values systematically higher than the ones from decay

(0.98 ± 0.74) MeV

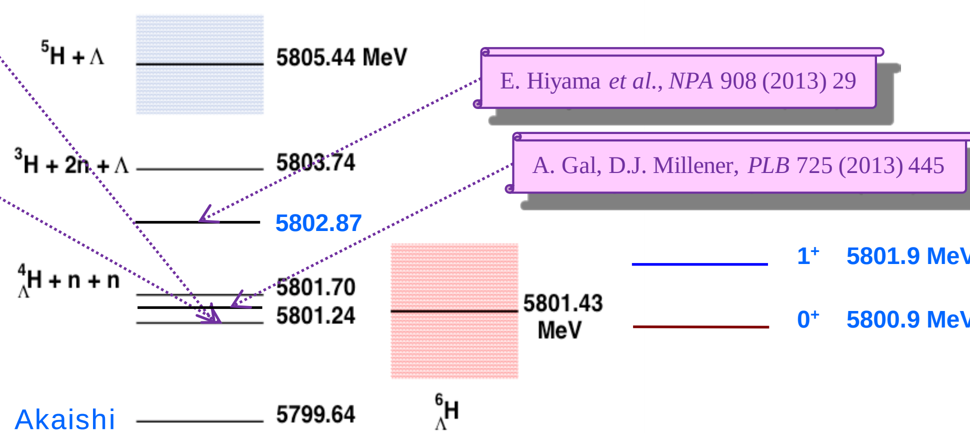
excited state production

theoretical predictions

- B_Λ = 4.2 MeV — R.H. Dalitz and R. Levi Setti, *NC* 30 (1963) 489
- B_Λ = 4.2 MeV — L. Majling, *NPA* 585 (1995) 211c

B ${}^4_\Lambda$He 2.39 Λ	${}^5_\Lambda$He 3.12 Λ	◇ ${}^6_\Lambda$He 4.18 n 0.17 xxx	◇ ${}^7_\Lambda$He 5.23 α 2.92 halo	${}^8_\Lambda$He 7.16 n 1.49 xxx	♠ ${}^9_\Lambda$He (8.5) n 3.9 halo
${}^3_\Lambda$H 0.13 Λ	◇ ${}^4_\Lambda$H 2.04 Λ	${}^5_\Lambda$H (3.1) n -1.8 xxx	♠ ${}^6_\Lambda$H (4.2) 2n -5 xxx	♠ ${}^7_\Lambda$H (5.2) 3n 0.4 xxx	

$\bar{M}$ = (5801.4 ± 1.1) MeV



B_Λ = (4.0 ± 1.1) MeV (⁵H + Λ)

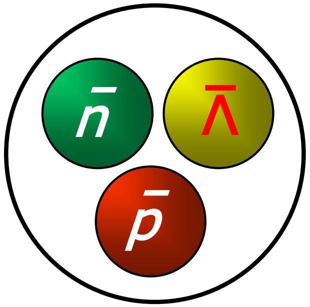
~~B_Λ = 5.8 MeV (⁵H + Λ)~~
~~ΛNN force ≡ 1.4 MeV~~

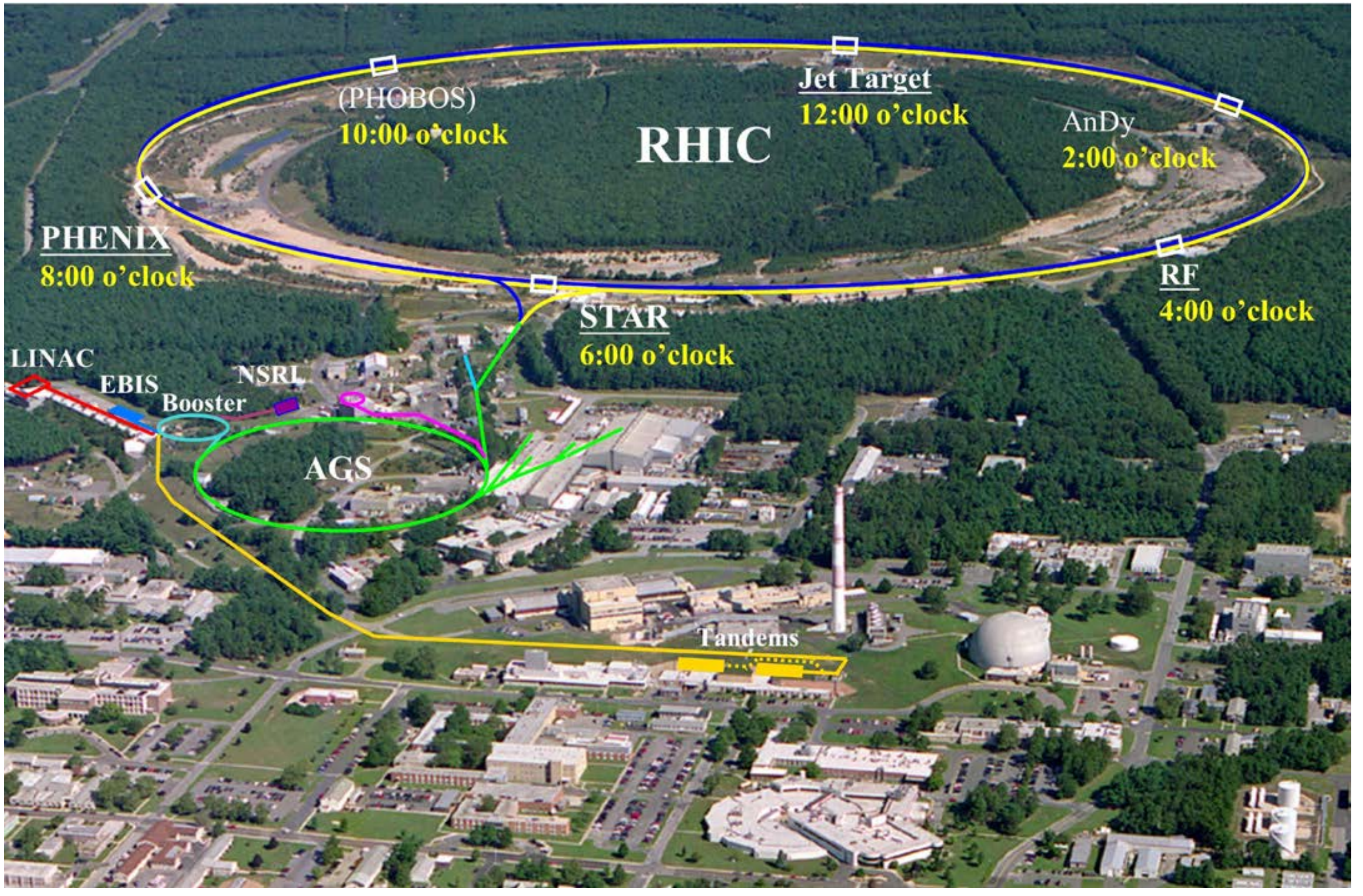
FINUDA Coll. and A. Gal, *PRL* 108 (2012) 042501
FINUDA Coll. and A. Gal, *NPA* 881 (2012) 269

nrh prod. rate: ~10^{-2} hyp. prod. rate in (K^-_{stop}, π^-)

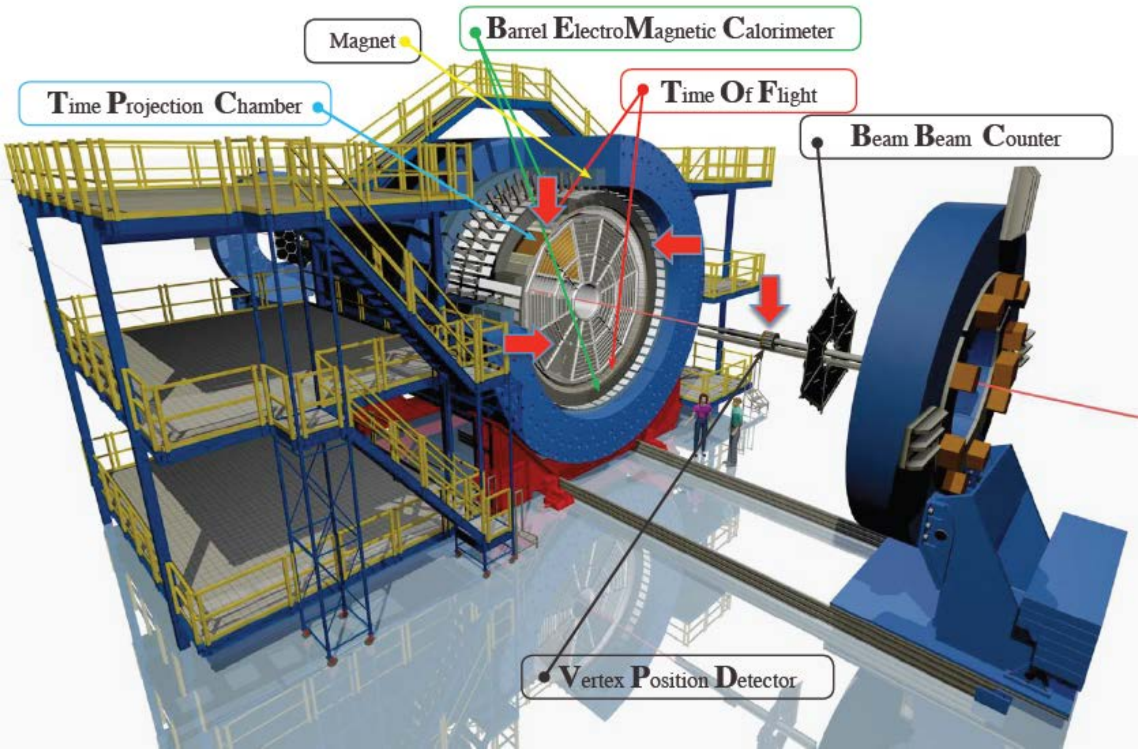
BROOKHAVEN NATIONAL LABORATORY

The STAR experiment at RHIC





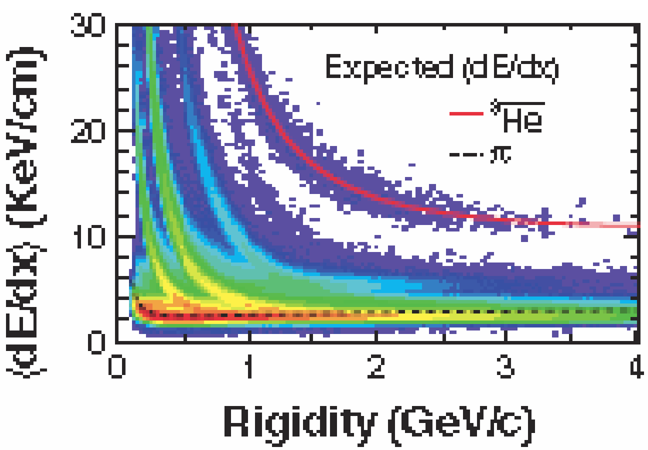
STAR $^{3}\bar{H}_{\bar{\Lambda}}$ signal

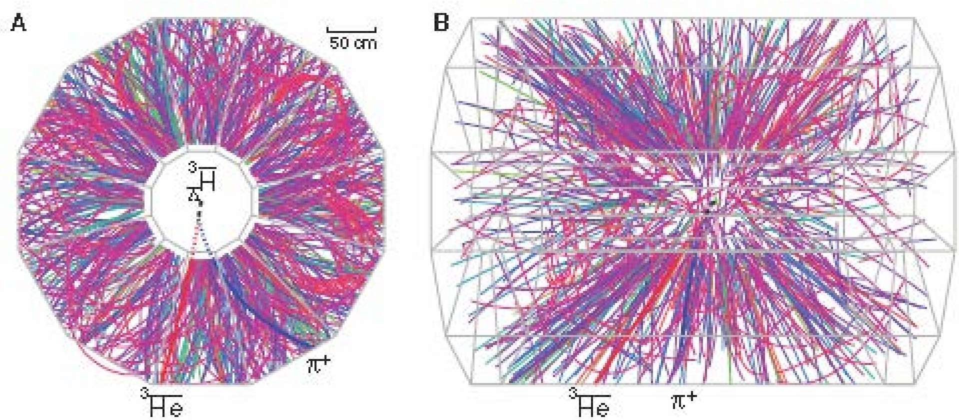


$$Au + Au @ 200\ GeV$$

$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

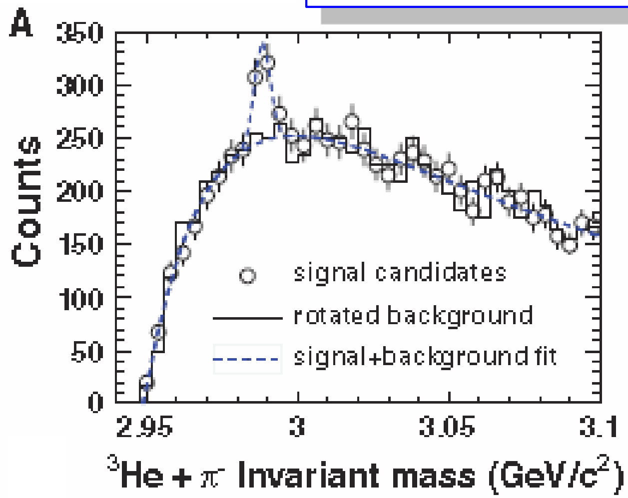
$$^{3}_{\bar{\Lambda}}\bar{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$$

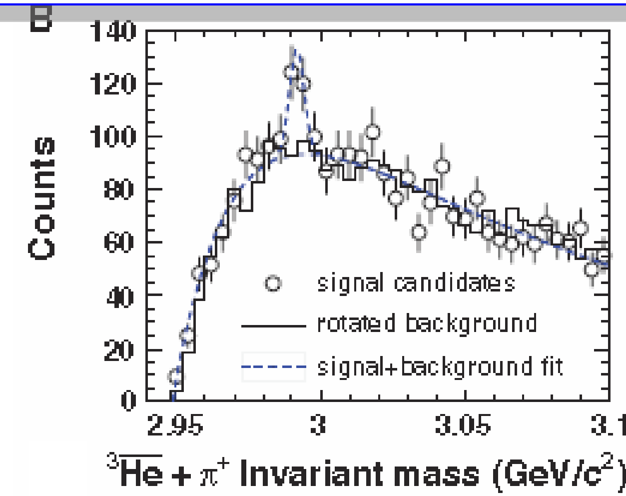




B.I. Abelev *et al.*, *Science* 328 (2010) 58.

Hypernuclei in HI collisions

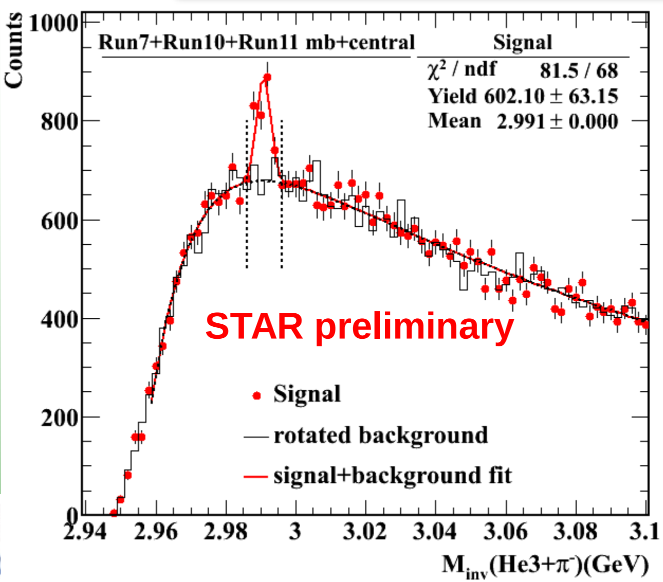




- μ = 2.989 ± 0.001 ± 0.002 GeV/c^2
- σ ≡ 0.0025 GeV/c^2
- significance = 5.2 σ

- μ = 2.991 ± 0.001 ± 0.002 GeV/c^2
- σ ≡ 0.0025 GeV/c^2
- significance = 4.1 σ

B.I. Abelev *et al.*, *Science* 328 (2010) 58.



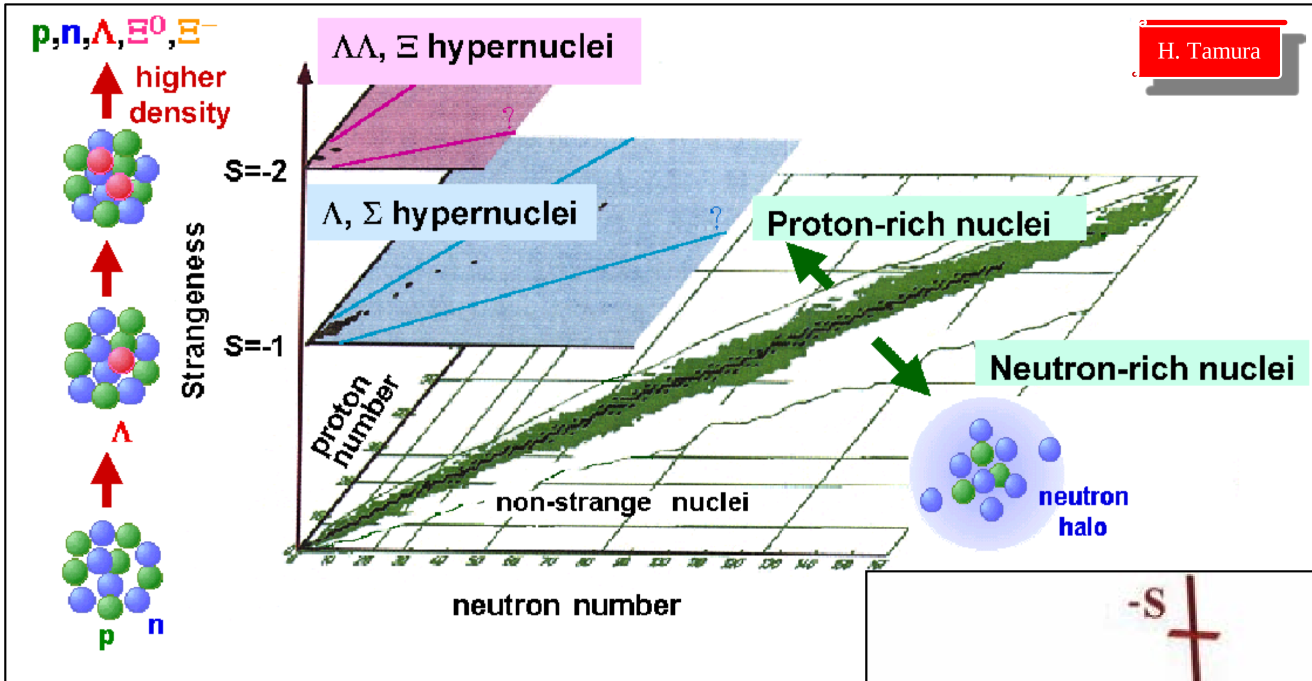
~610 × 10^6 events

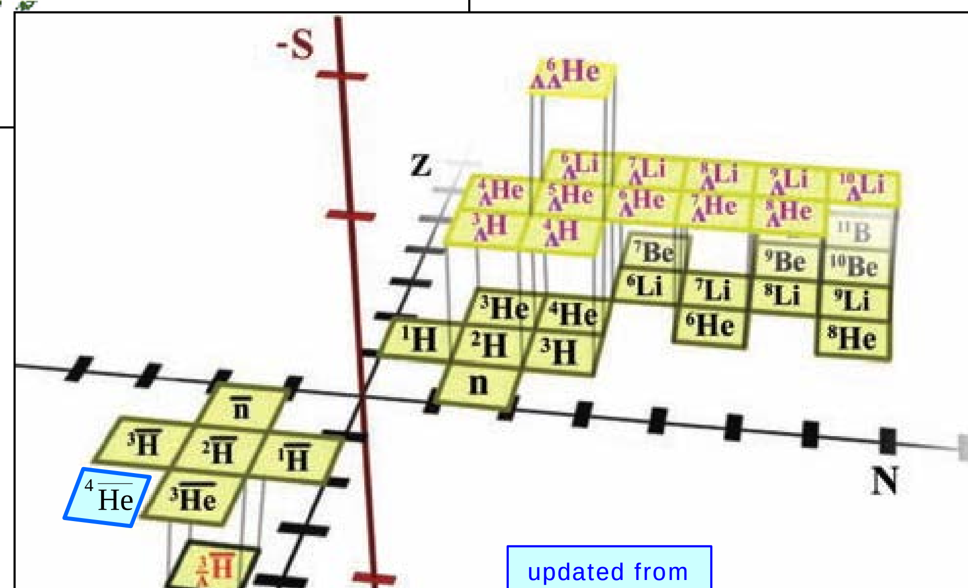
★ Signal observed from the data (bin-by-bin counting [2.986,2.996] GeV): **602±63**, significance: **9.6σ**

★ Background estimation: rotated background

J.H. Chen @ HYP 2012.
Y. Zhu, *NPA* 904-905 (2013) 551c.

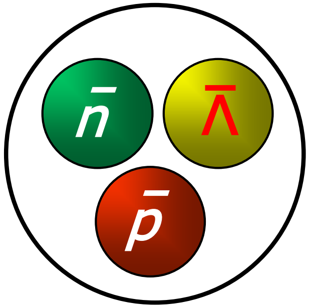
Expanding the horizon…

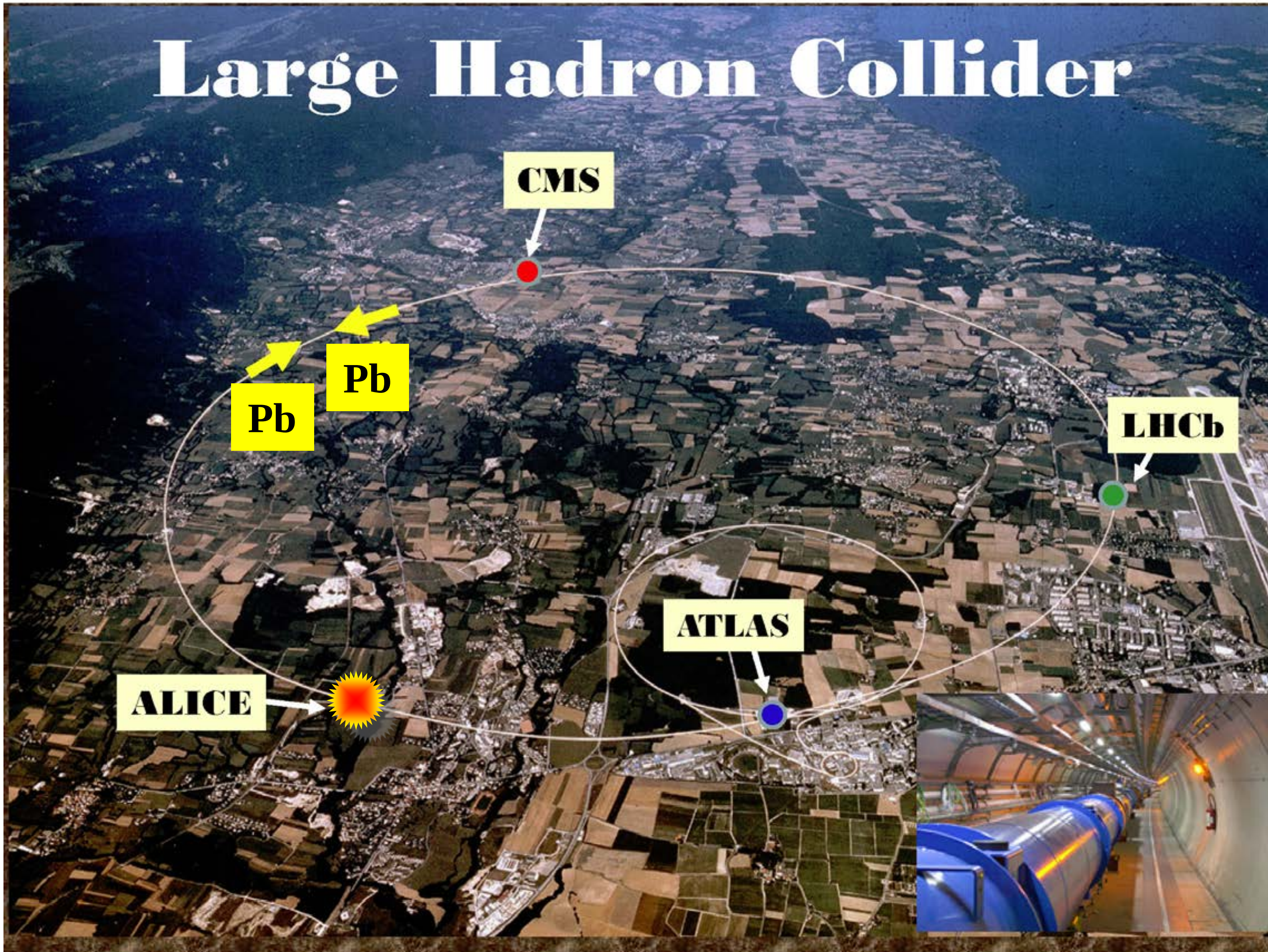




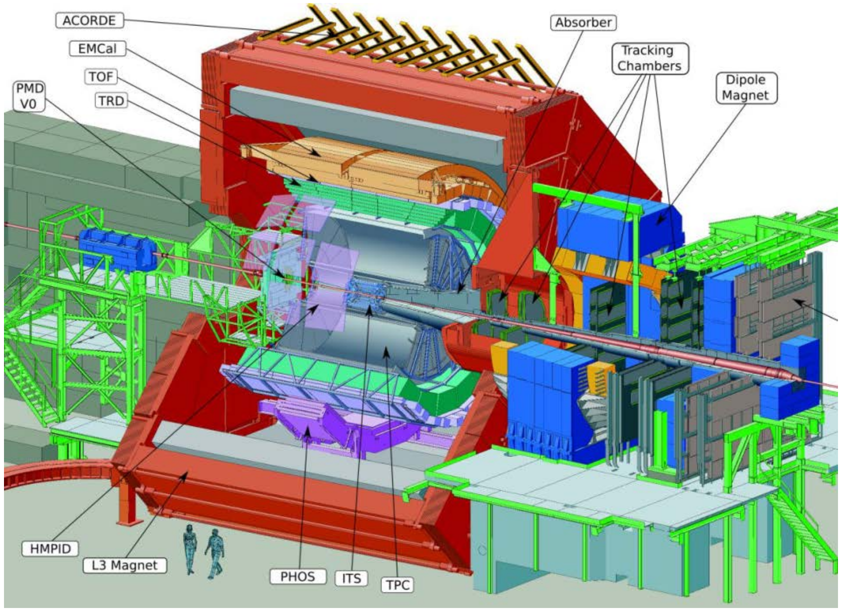
B.I. Abelev *et al.*, *Science* 328 (2010) 58.

The ALICE experiment at LHC





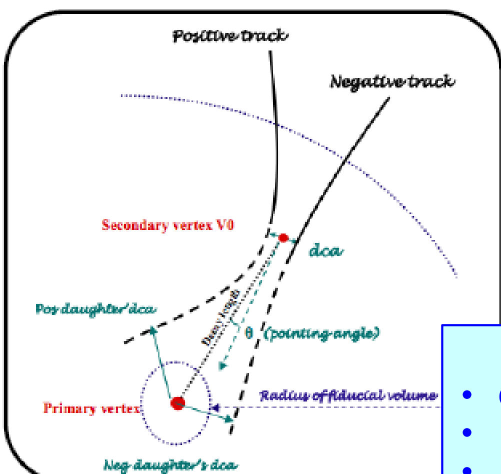
Hypernuclei in HI collisions



$$\mathrm{Pb+Pb} @ \sqrt{S_{NN}} = 2.76\ \mathrm{TeV}$$

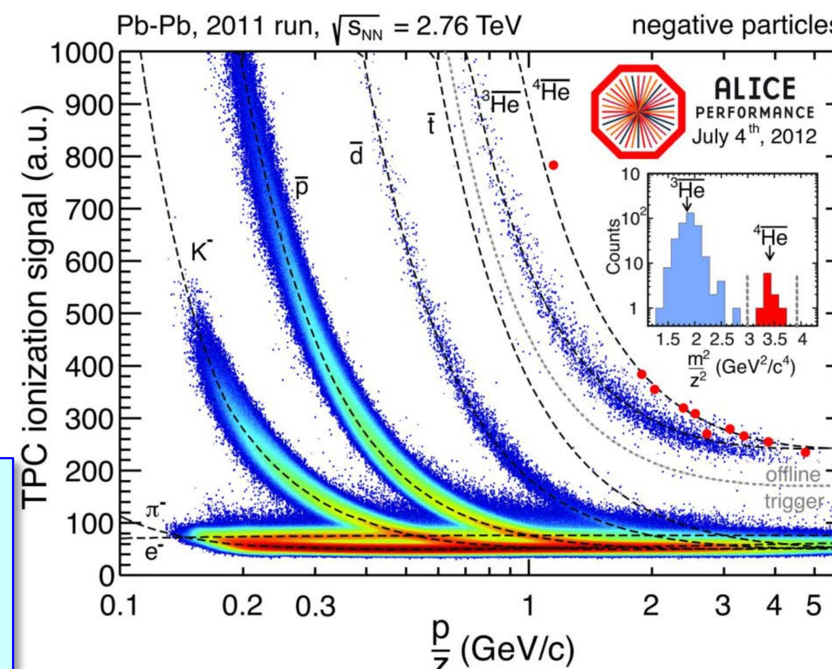
$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$$

$$^{3}_{\Lambda}\overline{\mathrm{H}} \rightarrow {}^{3}\overline{\mathrm{He}} + \pi^{+}$$



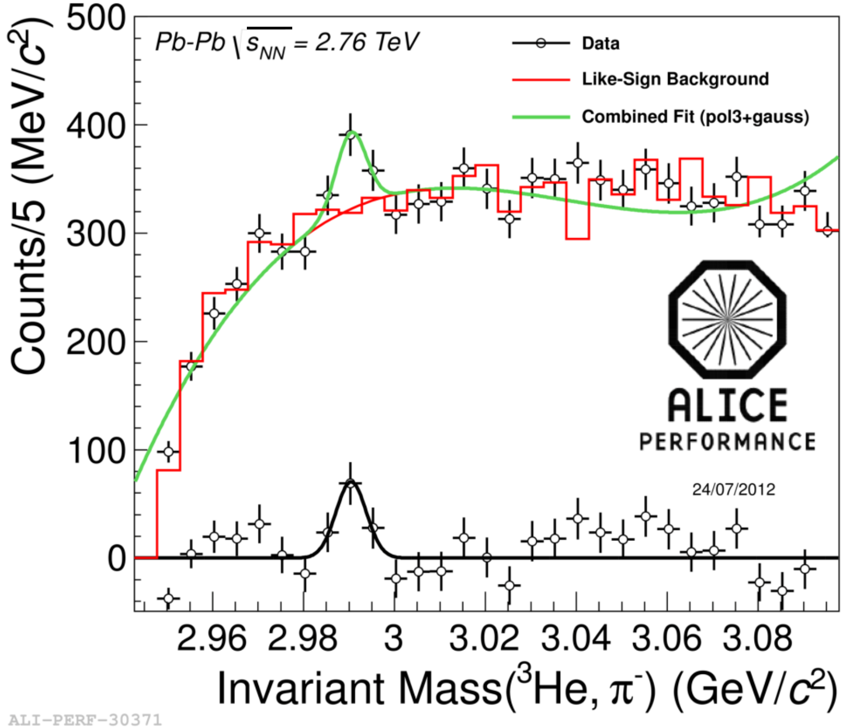
topological cuts

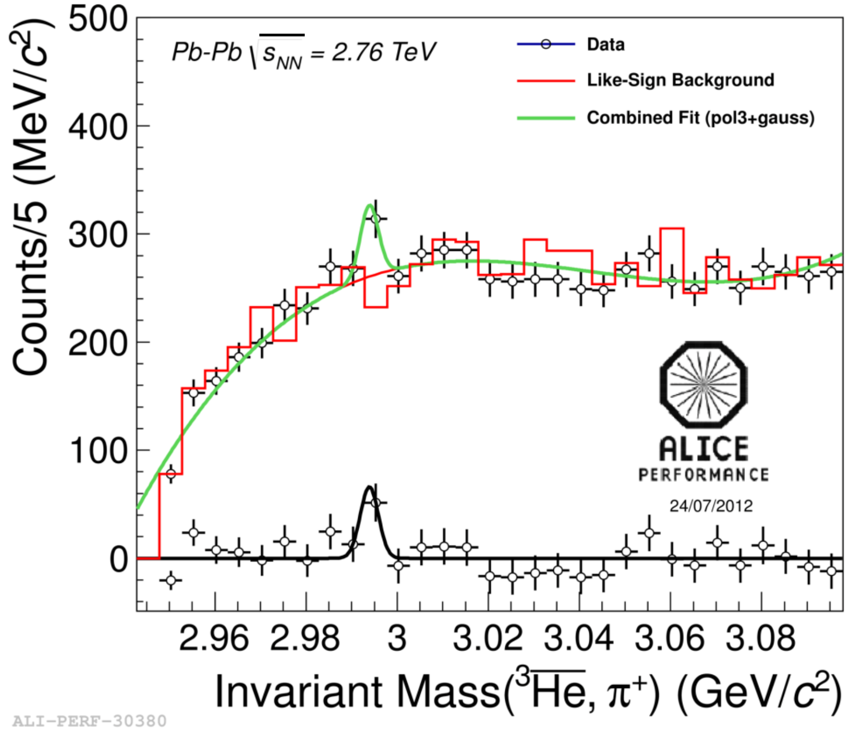
- cos(pointing angle) > 0.9
- DCA π track to PV > 0.4 cm
- DCA between tracks < 0.7 cm
- $p_T(^3\mathrm{He},\pi)$ > 1 GeV/c
- $c\tau$ > 1 cm



R. Lea, *NPA* 914 (2013) 415.

Hypernuclei in HI collisions





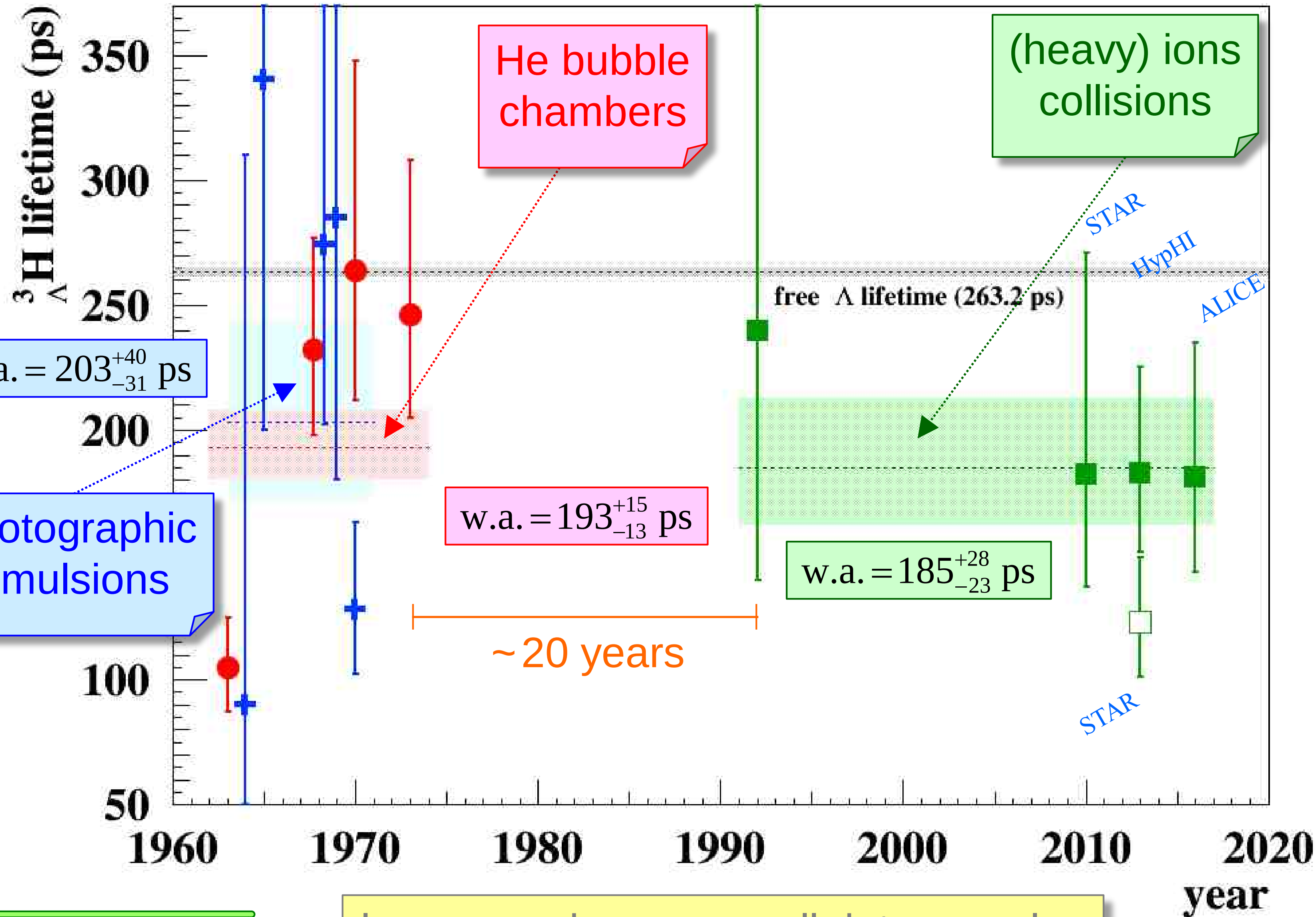
- μ = 2.990 ± 0.001 GeV/c^2
- σ = (3.35 ± 0.70) × 10^{-3} GeV/c^2
- N_{raw} = 119 ± 35
- $S/\sqrt{(S+B)}$ = 4.6

- μ = 2.993 ± 0.001 GeV/c^2
- σ = (2.00 ± 1.20) × 10^{-3} GeV/c^2
- N_{raw} = 77 ± 22
- $S/\sqrt{(S+B)}$ = 3.6

~23 × 10^6 events

R. Lea, *NPA* 914 (2013) 415.

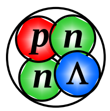
The light hypernuclei lifetime puzzle

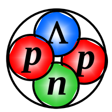


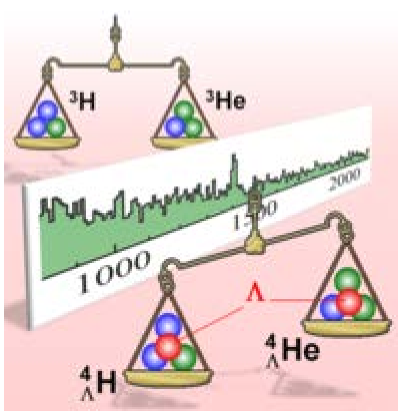
M. Agnello *et al.*, *NPA* 954 (2016) 176.

large error bars ↔ small data samples

The J-PARC E13 experiment

$^{4}_{\Lambda}$H


$^{4}_{\Lambda}$He




Proposal for J-PARC 50 GeV Proton Synchrotron

Gamma-ray spectroscopy of light hypernuclei

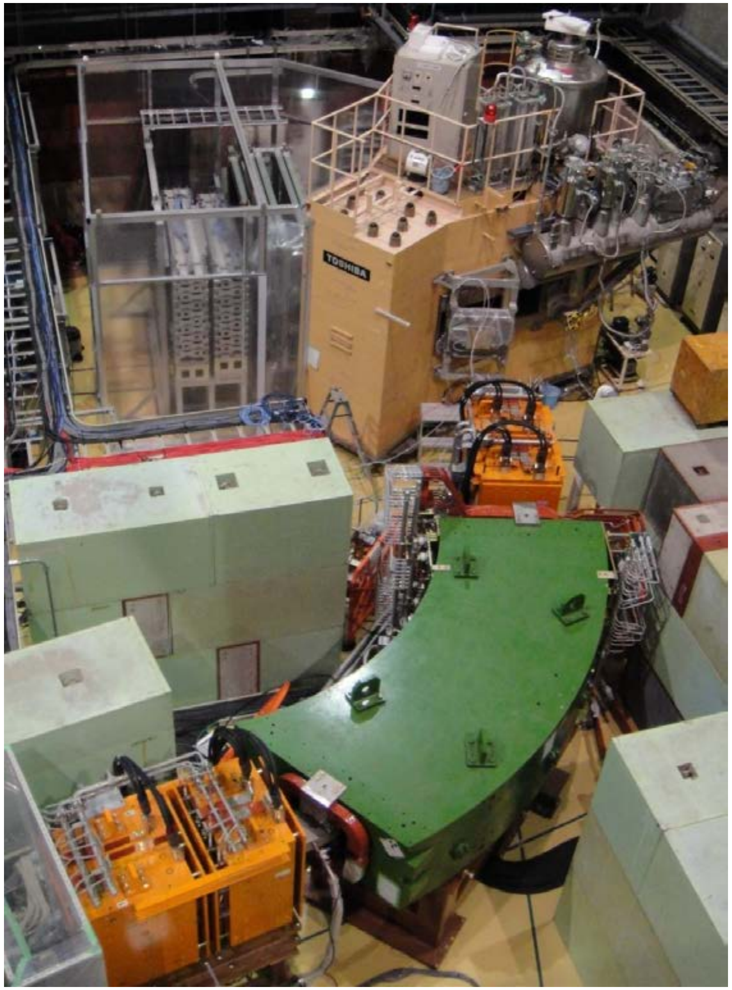
Y. Fujii, K. Futatsukawa, O. Hashimoto, K. Hosomi, H. Kanda, M. Kaneta, T. Koike, Y. Ma, K. Maeda, A. Matsumura, M. Mimori, S.N. Nakamura, K. Nonaka, Y. Okayasu, T. Suzuki, K. Shirotori, H. Tamura(spokesperson), K. Tsukada, M. Ukai
Tohoku University, Japan
K. Aoki, Y. Kakiguchi, T. Nagae, H. Noumi, Y. Sato, M. Sekimoto, H. Takahashi, T. Takahashi, A. Toyoda
High Energy Accelerator Research Organization (KEK), Japan
P. Evtoukhovitch, V. Kalinnikov, W. Kallies, N. Kravchuk, A. Moiseenko, D. Mzhavia, V. Samoilov, Z. Tsamalaidze, O. Zaimidoroga
Joint Institute for Nuclear Research, Russia
Y.Y. Fu, C.B. Li, X.M. Li, J. Zhou, S.H. Zhou, L.H. Zhu
China Institute of Atomic Energy, China
E. V. Hungerford, A. Lan (+ a postdoc and 2 graduate students)
University of Houston, U.S.A.
T. Bressani, S. Bufalino, L. Busso, D. Faso, A. Feliciello, S. Marcello,
University of Torino and INFN, Sezione di Torino, Italy
S. Kamigaito, K. Imai, K. Miwa, K. Tanida
Kyoto University, Japan
H. Fujioka, D. Nakajima, T.N. Takahashi
University of Tokyo, Japan
P. Markowitz, J. Reinhold
Florida International University, U.S.A.
K. Nakazawa, T. Watanabe
Gifu University, Japan
S. Minami, T.R. Saito
GSI, Germany
A. Krutenkova, V. Kulikov
Institute for Theoretical and Experimental Physics, Russia

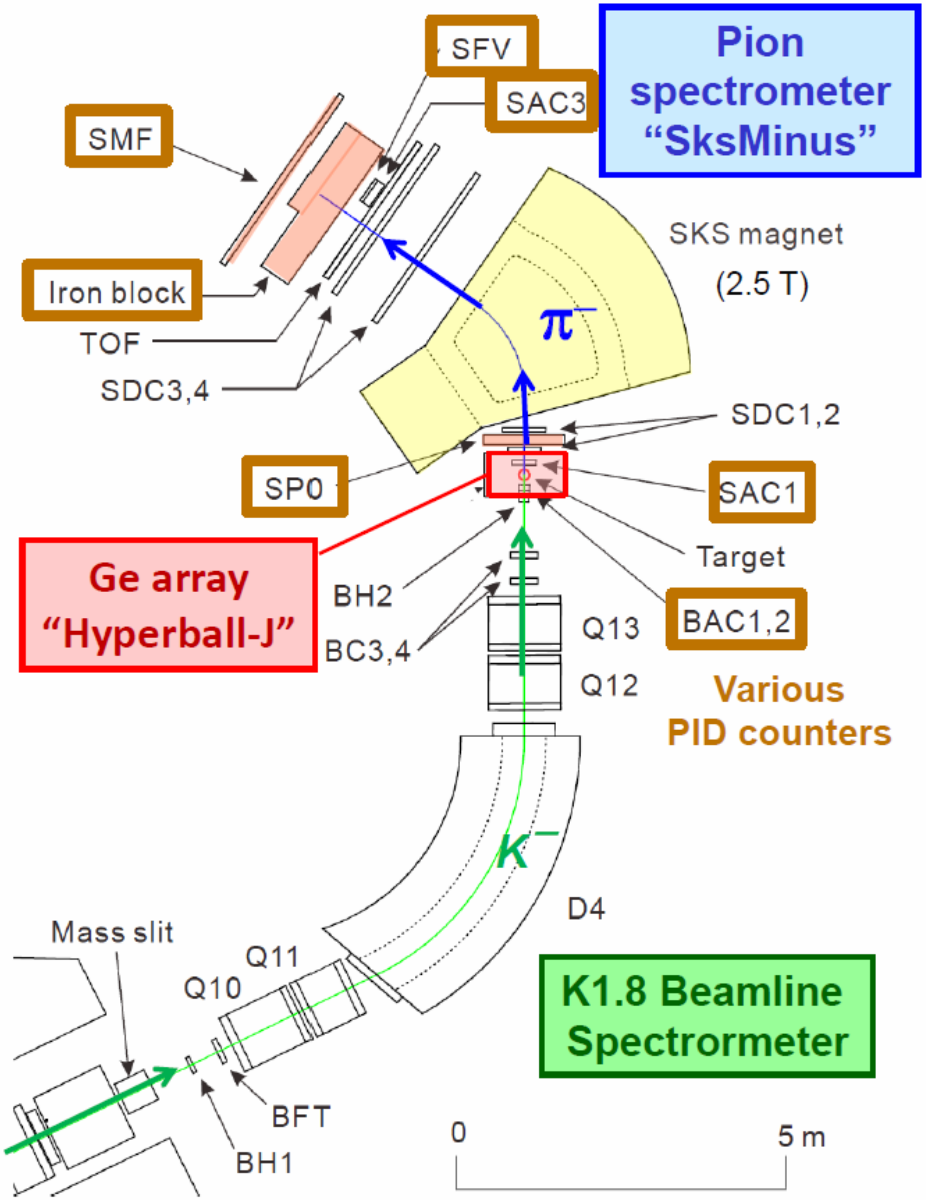
1

E13: physics motivations

- to explore the *s*-shell Λ–hypernuclei ($^{4}He_{\Lambda}$)
  - doorway to investigate the CSB effect in A = 4 systems
- to explore the *sd*-shell Λ–hypernuclei ($^{19}F_{\Lambda}$)
  - study of radial dependence of ΛN interaction
- to measure B(M1) in order to evaluate g_{Λ} in nuclear matter

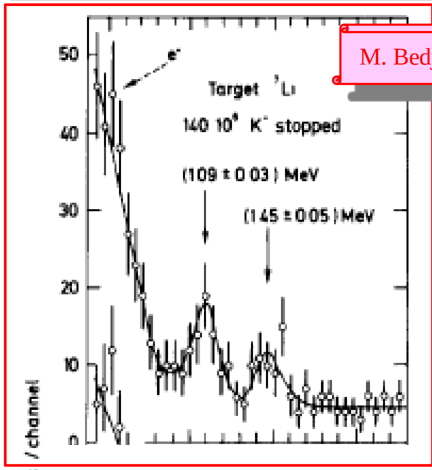
E13: experimental setup



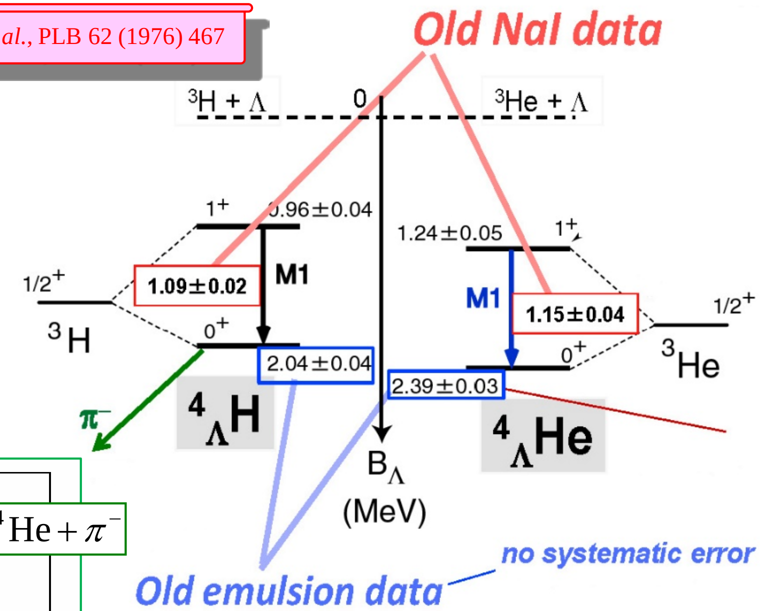


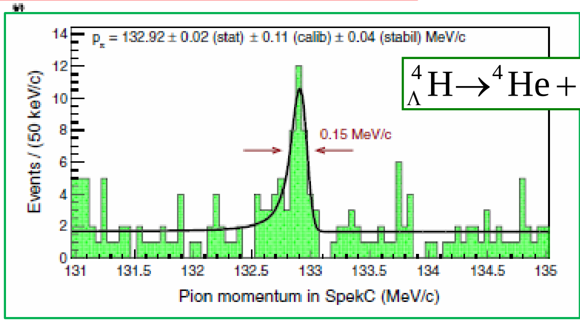
$$^{A}Z\,(K^-,\pi^-)\,^{A}_{\Lambda}Z^*$$
$$\rightarrow\ ^{A}_{\Lambda}Z+\gamma$$

CSB in A = 4 systems



M. Bedjidian *et al.*, PLB 62 (1976) 467





$^4_\Lambda\mathrm{H} \to {}^4\mathrm{He} + \pi^-$

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

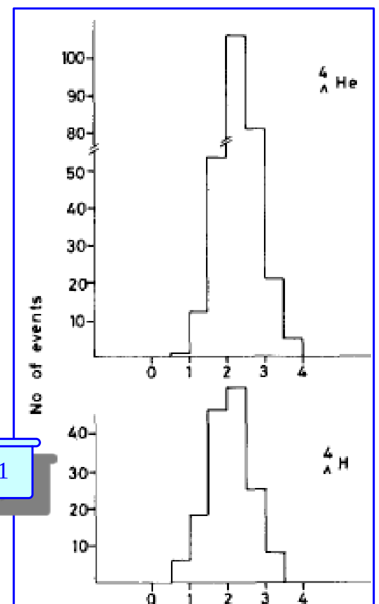
B_Λ = (2.12 ± 0.01 ± 0.09) MeV

origin:

- ???

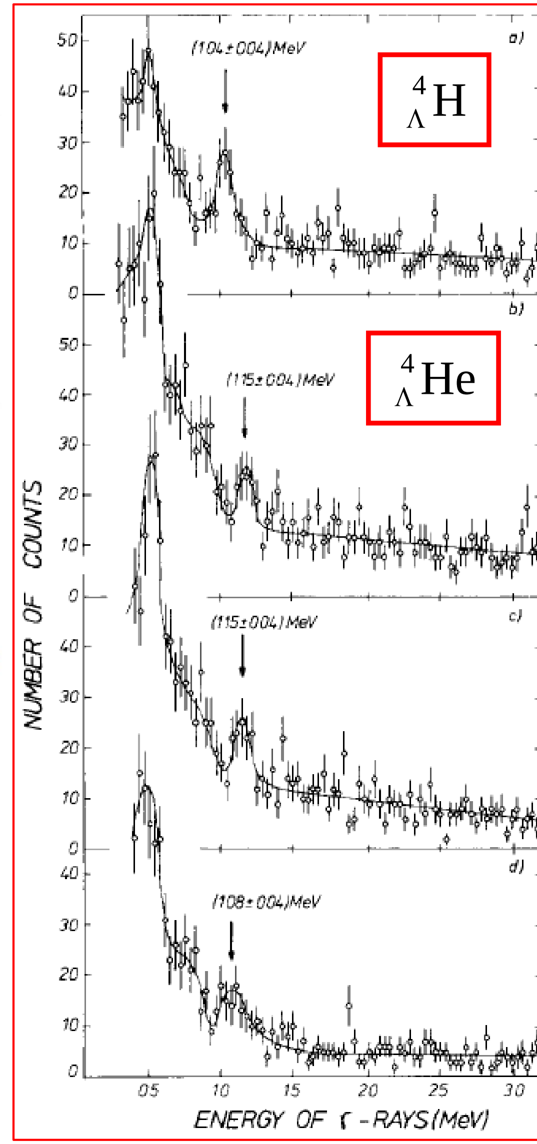
possible explanations:

- ΛΣ mixing
- ΛN-ΣN coupling



B_Λ (MeV)

M. Jurić *et al.*, NPB 52 (1973) 1

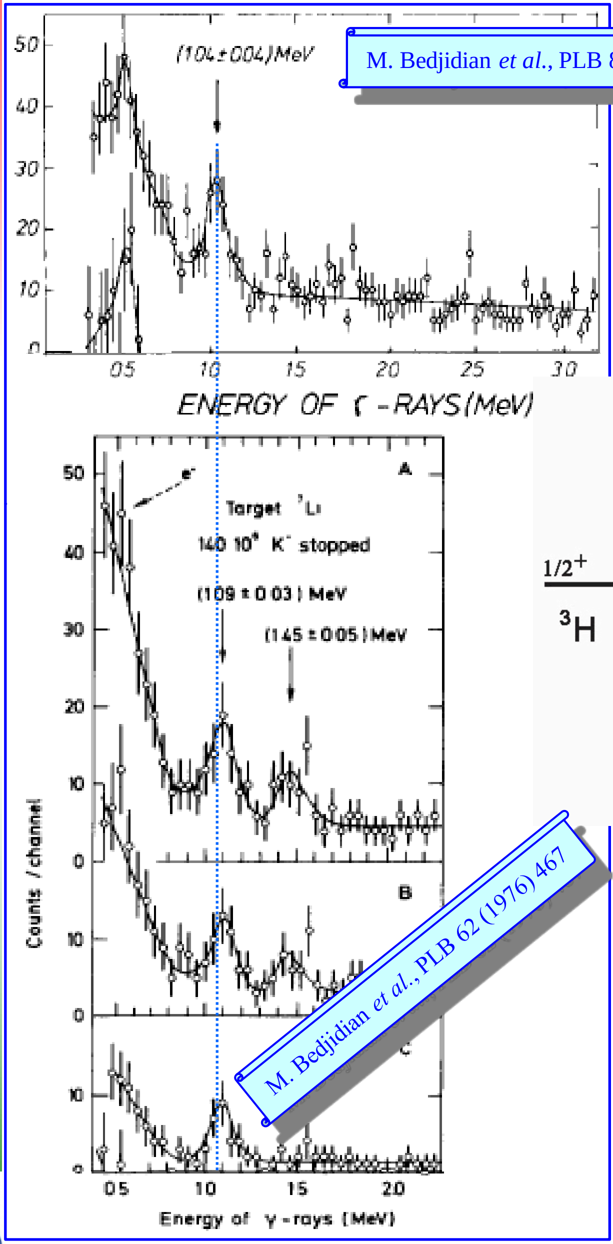


$^4_\Lambda\mathrm{H}$

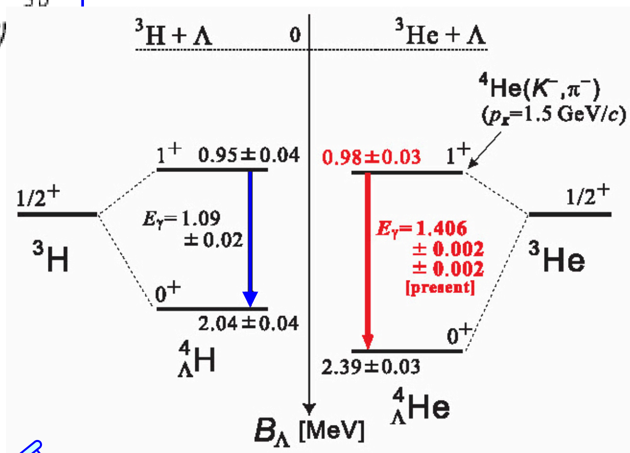
$^4_\Lambda\mathrm{He}$

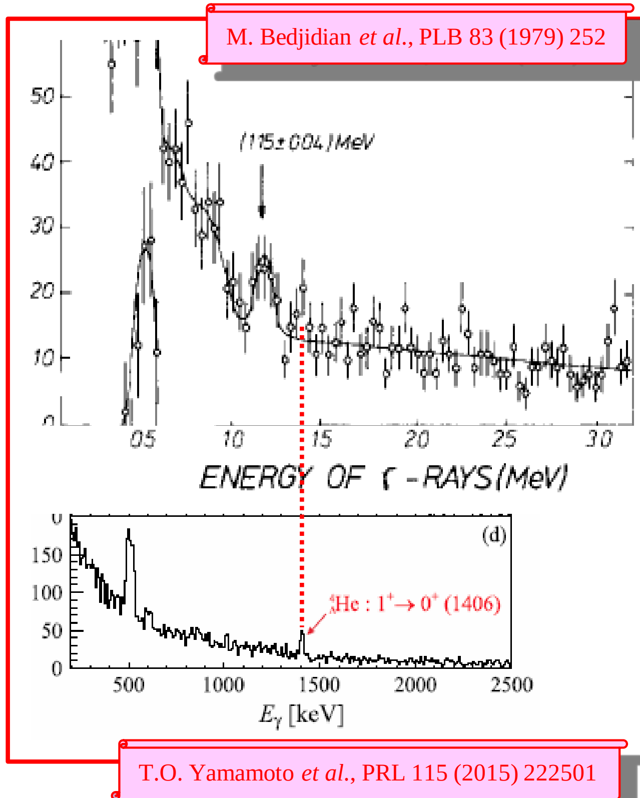
M. Bedjidian *et al.*, PLB 83 (1979) 252

E13: experimental results on $^4He_\Lambda$



$$^4\mathrm{He}(K^-,\pi^-)^4_\Lambda\mathrm{He}$$





$\Delta B_\Lambda(1^+) = (0.03 \pm 0.05)$ MeV

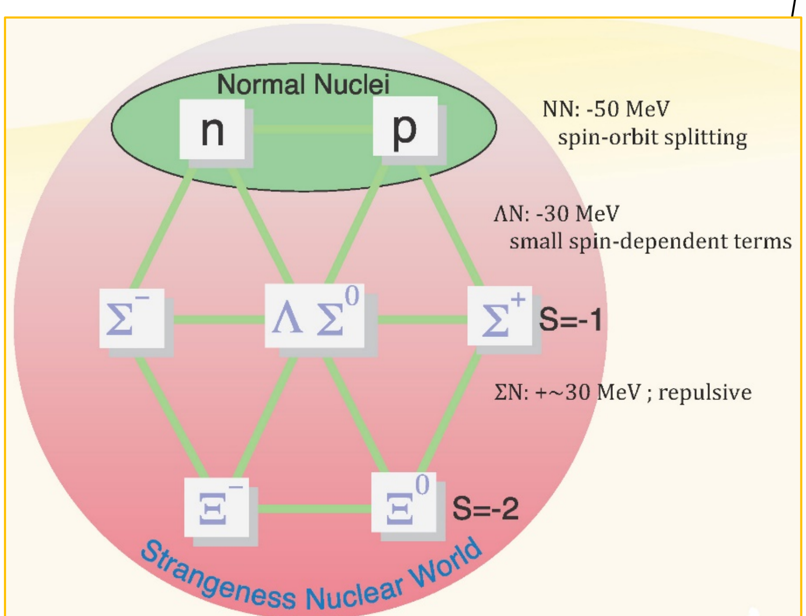
$\Delta B_\Lambda(0^+) = (0.35 \pm 0.05)$ MeV

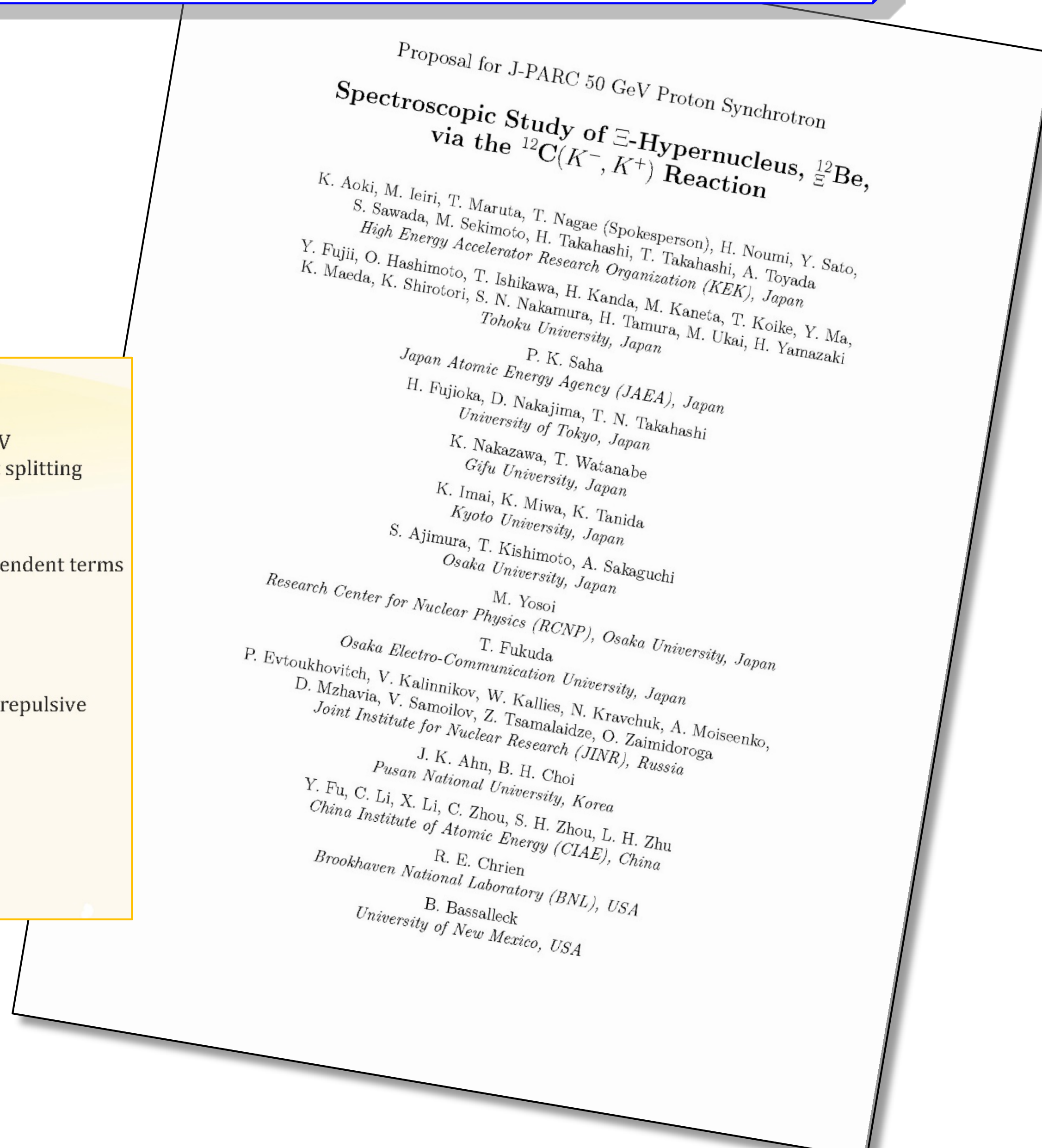
strong spin dependence

by combining E13 results with emulsion data

The J-PARC E05 experiment

AXiS with SKS+





Proposal for J-PARC 50 GeV Proton Synchrotron

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

K. Aoki, M. Ieiri, T. Maruta, T. Nagae (Spokesperson), H. Noumi, Y. Sato, S. Sawada, M. Sekimoto, H. Takahashi, T. Takahashi, A. Toyada
High Energy Accelerator Research Organization (KEK), Japan
Y. Fujii, O. Hashimoto, T. Ishikawa, H. Kanda, M. Kaneta, T. Koike, Y. Ma, K. Maeda, K. Shirotori, S. N. Nakamura, H. Tamura, M. Ukai, H. Yamazaki
Tohoku University, Japan
P. K. Saha
Japan Atomic Energy Agency (JAEA), Japan
H. Fujioka, D. Nakajima, T. N. Takahashi
University of Tokyo, Japan
K. Nakazawa, T. Watanabe
Gifu University, Japan
K. Imai, K. Miwa, K. Tanida
Kyoto University, Japan
S. Ajimura, T. Kishimoto, A. Sakaguchi
Osaka University, Japan
M. Yosoi
Research Center for Nuclear Physics (RCNP), Osaka University, Japan
T. Fukuda
Osaka Electro-Communication University, Japan
P. Evtoukhovitch, V. Kalinnikov, W. Kallies, N. Kravchuk, A. Moiseenko, D. Mzhavia, V. Samoilov, Z. Tsamalaidze, O. Zaimidoroga
Joint Institute for Nuclear Research (JINR), Russia
J. K. Ahn, B. H. Choi
Pusan National University, Korea
Y. Fu, C. Li, X. Li, C. Zhou, S. H. Zhou, L. H. Zhu
China Institute of Atomic Energy (CIAE), China
R. E. Chrien
Brookhaven National Laboratory (BNL), USA
B. Bassalleck
University of New Mexico, USA

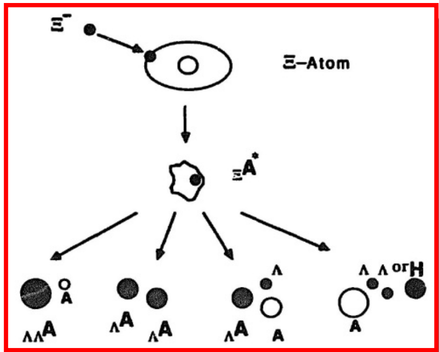
ΛΛ- and Ξ-hypernucleus production

Ξ^- atomic capture reaction at rest
is one of the most effective way to look for double Λ-hypernuclei

- compound double Λ state:

$$\Xi^- + {}^{A}Z \rightarrow {}^{(A-1)}(Z-1) \oplus \Lambda \oplus \Lambda$$

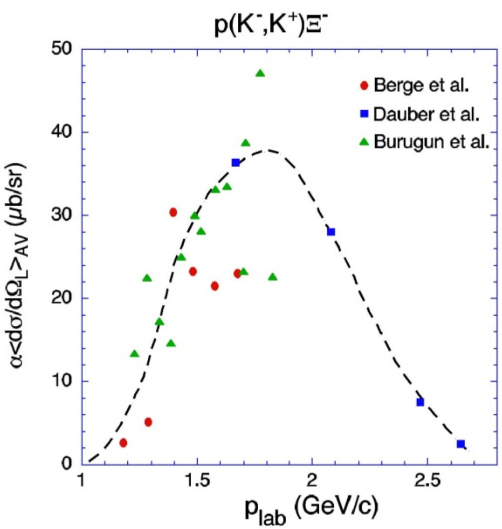
$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28\ \mathrm{MeV}$$



- quasi deuteron model:

$$\Xi^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda\Lambda}(Z-1) + n$$ ← high energy

$$\Xi^- + \text{“d”} \rightarrow \text{“}\Lambda\Lambda\text{”} + n$$ ← high energy



$$K^- + {}^{A}Z \rightarrow {}^{A}_{\Xi}(Z-1) + K^+$$

$$K^- + p \rightarrow \Xi^- + K^+$$ q.f.

K^- beams:

@ BNL	1.88 GeV/c
@ KEK	1.66 GeV/c
@ J-PARC	1.80 GeV/c

S = -2 systems study is not just a simple extension of what has been done for S = -1 system

The status of art for Ξ-hypernuclei

previous experiment: BNL-E885

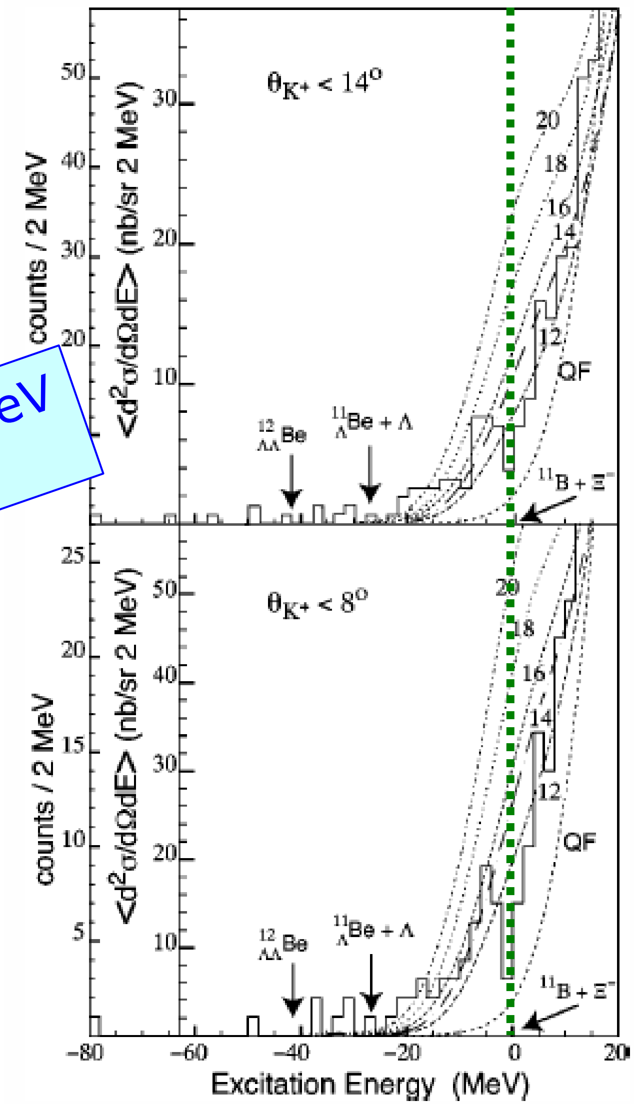
$$^{12}\mathrm{C}(K^-,K^+)\mathrm{X}$$

- evidence for Ξ-hypernuclear bound state (not definitive because of limited mass resolution)

ΔM_{exp} = 14 MeV (FWHM)

- signal shape analysys and counts in bound region, compared with DWIA calculations, suggest a weakly actractive Ξ*N* potential ~-14 MeV deep (B_{Ξ} ~ 4.5 MeV)

- production cross section:
  - dσ/dΩ = 89 ± 14 nb/sr (< 8 deg.)
  - dσ/dΩ = 42 ± 5 nb/sr (< 14 deg.)

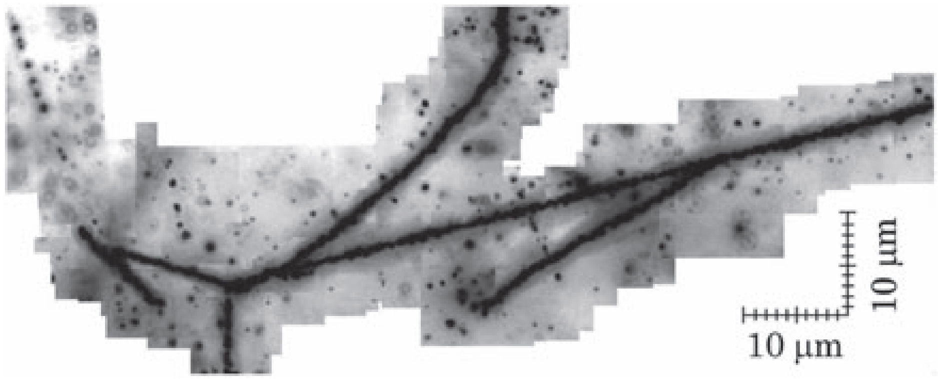


P. Khaustov *et al.*, PRC 61 (2000) 054603

The status of art for Ξ-hypernuclei

The "KISO" event

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



observation of a bound state of the Ξ^{-}-^{14}N system the by E-373 experiment

- $\Xi^{-} + {}^{14}N \rightarrow {}^{10}Be_{\Lambda} + {}^{5}He_{\Lambda}$
- B_{Ξ} = (4.38 ± 0.25) ÷ (1.11 ± 0.25) MeV

well beyond the atomic binding of 0.17 MeV!

☛ Ξ-hypernuclei do exist!

measurement of:

? $Re(V_{\Xi})$

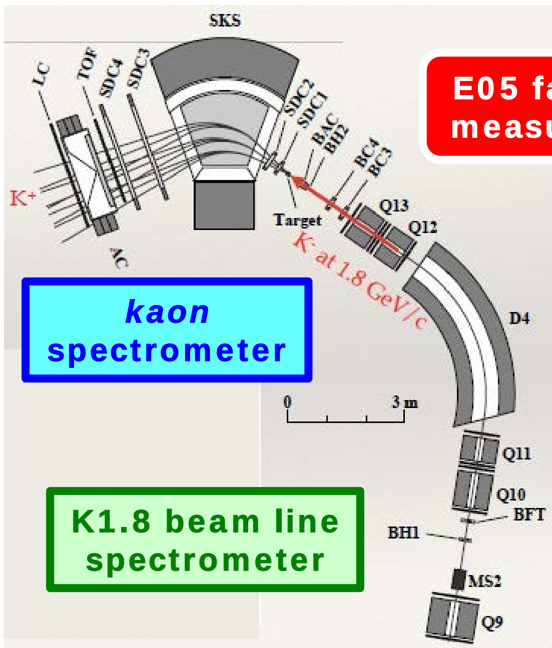
? $\Gamma_{\Xi N-\Lambda\Lambda}$

E05: physics motivations

- First spectroscopic study of $S = -2$ systems via the (K^-, K^+) reaction
  - Ξ-hypernuclei (⇒ double ΛΛ-hypernuclei)
  - Ξ*p*-ΛΛ mixing
  - first step for multistrangeness baryon systems
- Ξ*N* interactions: essentially no information
  - actractive or repulsive? ⇒ potential depth
  - Ξp-ΛΛ conversion? ⇒ conversion width
  - isospin dependence? ⇒ Lane term $(\tau_\Xi \cdot \tau_C/A_C)$

Observation of Ξ bound states

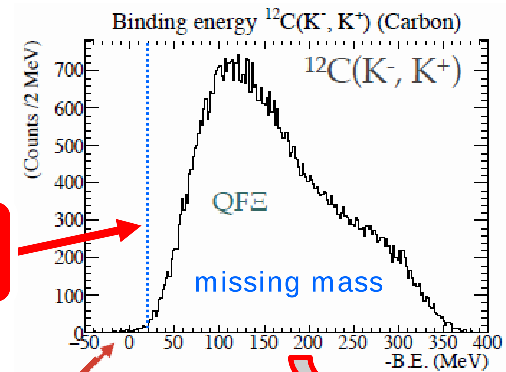
Search for Ξ–hypernuclei ($^{12}Be_{\Xi}$)



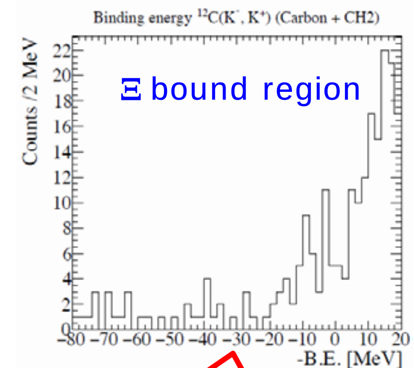
***kaon* spectrometer**

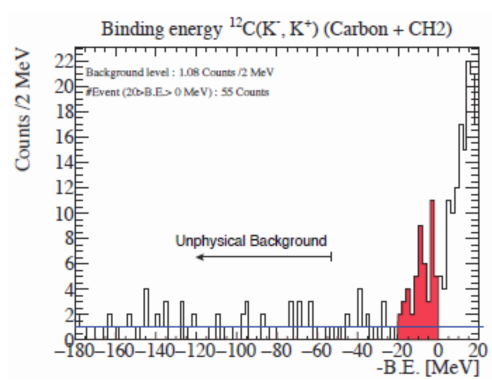
K1.8 beam line spectrometer

E05 fall 2015 measurement

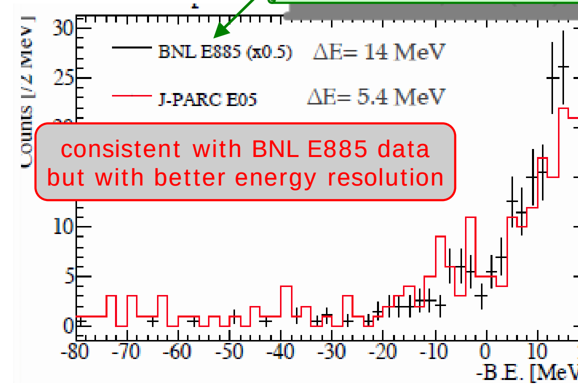


focus on this region





P. Khaustov *et al.*, PRC 61 (2000) 054603



consistent with BNL E885 data but with better energy resolution

$-20 < -B.E. < 0$ MeV { T = S + B = 55 counts; B = 10.8 counts ⇒ S/ΔS = 5.5

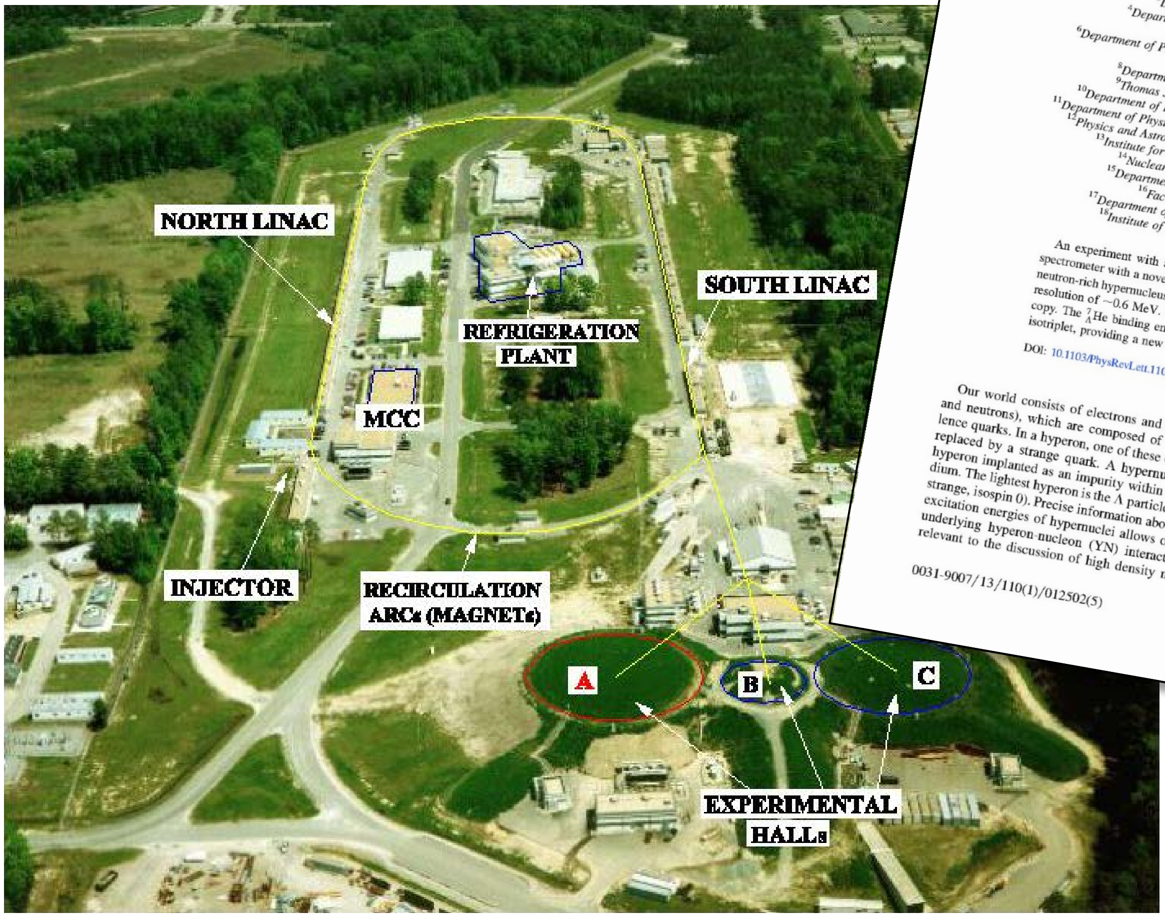
two signals resolved with ΔE = 5.4 MeV (FWHM) for the first time!!! (-B.E.: -9.1 and -2.1 MeV)

Jefferson Lab

The JLab experiments

Hall A: E94-107

Hall C: E01-011



PRL 110, 012502 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

Observation of the $^{7}_{\Lambda}$He Hypernucleus by the $(e, e'K^+)$ Reaction

S. N. Nakamura,[1] A. Matsumura,[1] Y. Okayasu,[1] T. Seva,[2] V. M. Rodriguez,[3] P. Baturin,[4] L. Yuan,[5] A. Acha,[4] A. Ahmidouch,[6] D. Androic,[2] A. Asaturyan,[7] R. Asaturyan,[7] O. K. Baker,[5] F. Benmokhtar,[8] P. Bosted,[9] R. Carlini,[9] C. Chen,[5] M. Christy,[5] L. Cole,[5] S. Danagoulian,[6] A. Daniel,[3] V. Dharmawardane,[9] K. Egiyan,[7] M. Elaasar,[10] R. Ent,[9,5] H. Fenker,[9] Y. Fujii,[1] M. Furic,[2] L. Gan,[11] D. Gaskell,[9] A. Gasparian,[6] E. F. Gibson,[12] T. Gogami,[1] P. Gueye,[5] Y. Han,[5] O. Hashimoto,[1,*] E. Hiyama,[13] D. Honda,[1] T. Horn,[8] B. Hu,[14] Ed V. Hungerford,[3] C. Jayalath,[5] M. Jones,[9] K. Johnston,[15] N. Kalantarians,[3] H. Kanda,[1] M. Kaneta,[1] F. Kato,[1] S. Kato,[16] D. Kawama,[1] C. Keppel,[5,9] K. J. Lan,[3] W. Luo,[14] D. Mack,[9] K. Maeda,[1] S. Malace,[5] A. Margaryan,[7] G. Marikyan,[7] P. Markowitz,[4] T. Maruta,[1] N. Maruyama,[1] T. Miyoshi,[3] A. Mkrtchyan,[7] H. Mkrtchyan,[7] S. Nagao,[1] T. Navasardyan,[7] G. Niculescu,[17] M.-I. Niculescu,[17] H. Nomura,[1] K. Nonaka,[1] A. Ohtani,[1] M. Oyamada,[1] N. Perez,[4] T. Petkovic,[2] S. Randeniya,[3] J. Reinhold,[4] J. Roche,[9] Y. Sato,[18] E. K. Segbefia,[5] N. Simicevic,[15] G. Smith,[9] Y. Song,[14] M. Sumihama,[1] V. Tadevosyan,[7] T. Takahashi,[1] L. Tang,[5,9] K. Tsukada,[1] V. Tvaskis,[5] W. Vulcan,[9] S. Wells,[15] S. A. Wood,[9] C. Yan,[9] and S. Zhamkochyan[7]

(HKS (JLab E01-011) Collaboration)

[1]Graduate School of Science, Tohoku University, Sendai, Miyagi 980-8578, Japan
[2]Department of Physics and Department of Applied Physics, University of Zagreb, HR-41001 Zagreb, Croatia
[3]Department of Physics, University of Houston, Houston, Texas 77204, USA
[4]Department of Physics, Florida International University, Miami, Florida 33199, USA
[5]Department of Physics, Hampton University, Virginia 23668, USA
[6]Department of Physics, North Carolina A&T State University, Greensboro, North Carolina 27411, USA
[7]Yerevan Physics Institute, Yerevan 0036, Armenia
[8]Department of Physics, University of Maryland, College Park, Maryland 20742, USA
[9]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
[10]Department of Physics, Southern University at New Orleans, New Orleans, Louisiana 70126, USA
[11]Department of Physics, University of North Carolina Wilmington, Wilmington, North Carolina 28403, USA
[12]Physics and Astronomy Department, California State University, Sacramento California 95819, USA
[13]Institute for Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan
[14]Nuclear Physics Institute, Lanzhou University, Lanzhou, Gansu 730000, China
[15]Department of Physics, Louisiana Tech University, Ruston, Louisiana 71272, USA
[16]Faculty of Science, Yamagata University, Yamagata 990-8560, Japan
[17]Department of Physics, James Madison University, Harrisonburg, Virginia 22807, USA
[18]Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan

(Received 2 July 2012; published 2 January 2013)

An experiment with a newly developed high-resolution kaon spectrometer and a scattered electron spectrometer with a novel configuration was performed in Hall C at Jefferson Lab. The ground state of a neutron-rich hypernucleus, $^{7}_{\Lambda}$He, was observed for the first time with the $(e, e'K^+)$ reaction with an energy resolution of ~0.6 MeV. This resolution is the best reported to date for hypernuclear reaction spectroscopy. The $^{7}_{\Lambda}$He binding energy supplies the last missing information of the $A = 7$, $T = 1$ hypernuclear isotriplet, providing a new input for the charge symmetry breaking effect of the ΛN potential.

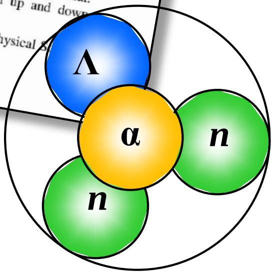
DOI: 10.1103/PhysRevLett.110.012502 PACS numbers: 21.80.+a, 13.75.Ev, 21.60.Gx, 25.30.Rw

Our world consists of electrons and nucleons (protons and neutrons), which are composed of up and down valence quarks. In a hyperon, one of these original quarks is replaced by a strange quark. A hypernucleus contains a hyperon implanted as an impurity within the nuclear medium. The lightest hyperon is the Λ particle (up + down + strange, isospin 0). Precise information about the mass and excitation energies of hypernuclei allows one to infer the underlying hyperon-nucleon (YN) interaction, which is relevant to the discussion of high density nuclear matter such as neutron stars. Precise nucleon-nucleon potentials have been derived from the rich data set of nucleon scattering experiments as well as from the masses and excitation energies of nuclei. In contrast, YN scattering experiments are technically difficult and data is very limited. Therefore, hypernuclear spectroscopy is a more realistic method to study the YN interaction.

The study of hypernuclei seeks to extend our knowledge of the nuclear force and baryon-baryon forces in general. While the strange quark is heavier than up and down

0031-9007/13/110(1)/012502(5)

$^{7}_{\Lambda}$He

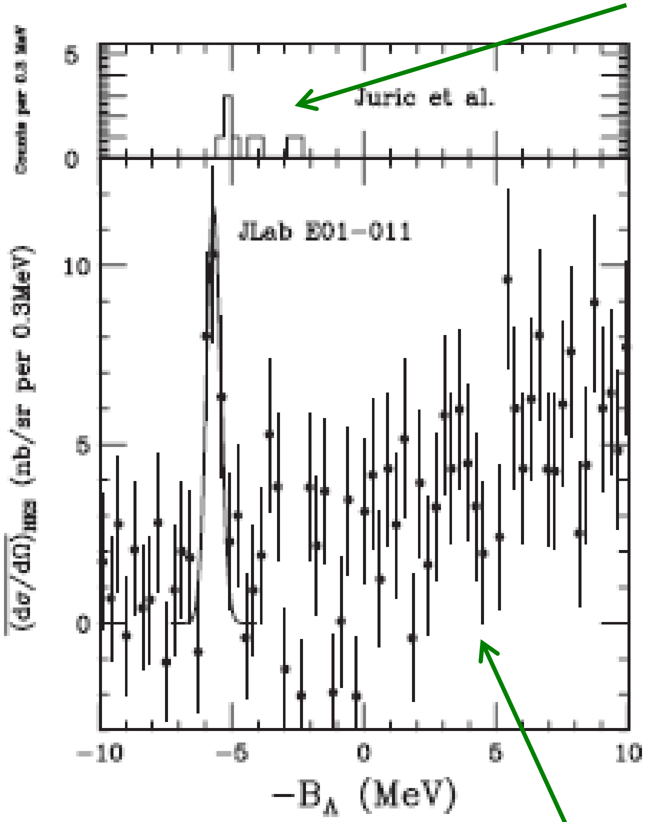


Jefferson Lab

A=7, T=1 triplet

E01-011 HKS

M. Jurić *et al.*, NPB 52 (1973) 1

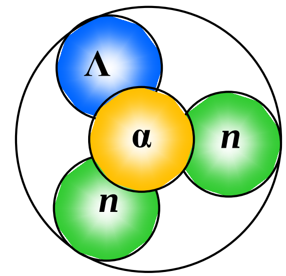


S.N. Nakamura *et al.*, PRL 110 (2013) 012502

$$\left(\frac{d\sigma}{d\Omega}\right) = 26 \pm 5.1 \pm 9.9 \text{ nb/sr}$$

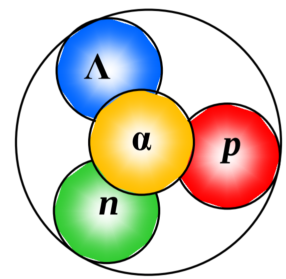
B_Λ [MeV]

${}^{7}_{\Lambda}\mathrm{He}$



5.68 ± 0.03 ± 0.25

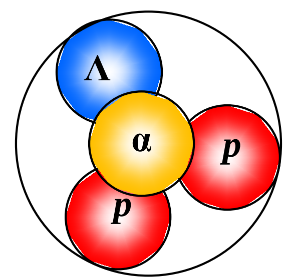
${}^{7}_{\Lambda}\mathrm{Li}^*$



5.26 ± 0.03

M. Jurić *et al.*, NPB 52 (1973) 1

${}^{7}_{\Lambda}\mathrm{Be}$

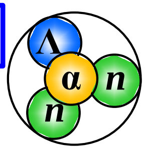


5.16 ± 0.08

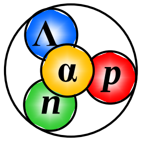
M. Jurić *et al.*, NPB 52 (1973) 1
H. Tamura *et al.*, PRL 84 (2000) 5963

CSB in A = 7 systems (?)

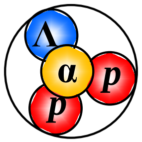
$^{7}_{\Lambda}\mathrm{He}$



$^{7}_{\Lambda}\mathrm{Li}^{*}$



$^{7}_{\Lambda}\mathrm{Be}$



$B_\Lambda(\mathrm{th.}+\mathrm{CSB}) = 5.16\ \mathrm{MeV}$

$B_\Lambda(\mathrm{th.}) = 5.36\ \mathrm{MeV}$

$B_\Lambda(^{7}_{\Lambda}\mathrm{He}, 1/2^{+}) = 5.68 \pm 0.03\ \mathrm{MeV}$

$B_\Lambda(^{7}_{\Lambda}\mathrm{Li}^{*}, 1/2^{+}) = 5.26 \pm 0.03\ \mathrm{MeV}$

$B_\Lambda(\mathrm{th.}) = 5.28\ \mathrm{MeV}$

$B_\Lambda(\mathrm{th.}+\mathrm{CSB}) = 5.29\ \mathrm{MeV}$

$B_\Lambda(^{7}_{\Lambda}\mathrm{Be}, 1/2^{+}) = 5.16 \pm 0.08\ \mathrm{MeV}$

$B_\Lambda(\mathrm{th.}) = 5.21\ \mathrm{MeV}$

$B_\Lambda(\mathrm{th.}+\mathrm{CSB}) = 5.44\ \mathrm{MeV}$

exp.
th.
th. + CSB

E. Hiyama *et al.*, PRC 80 (2009) 054321

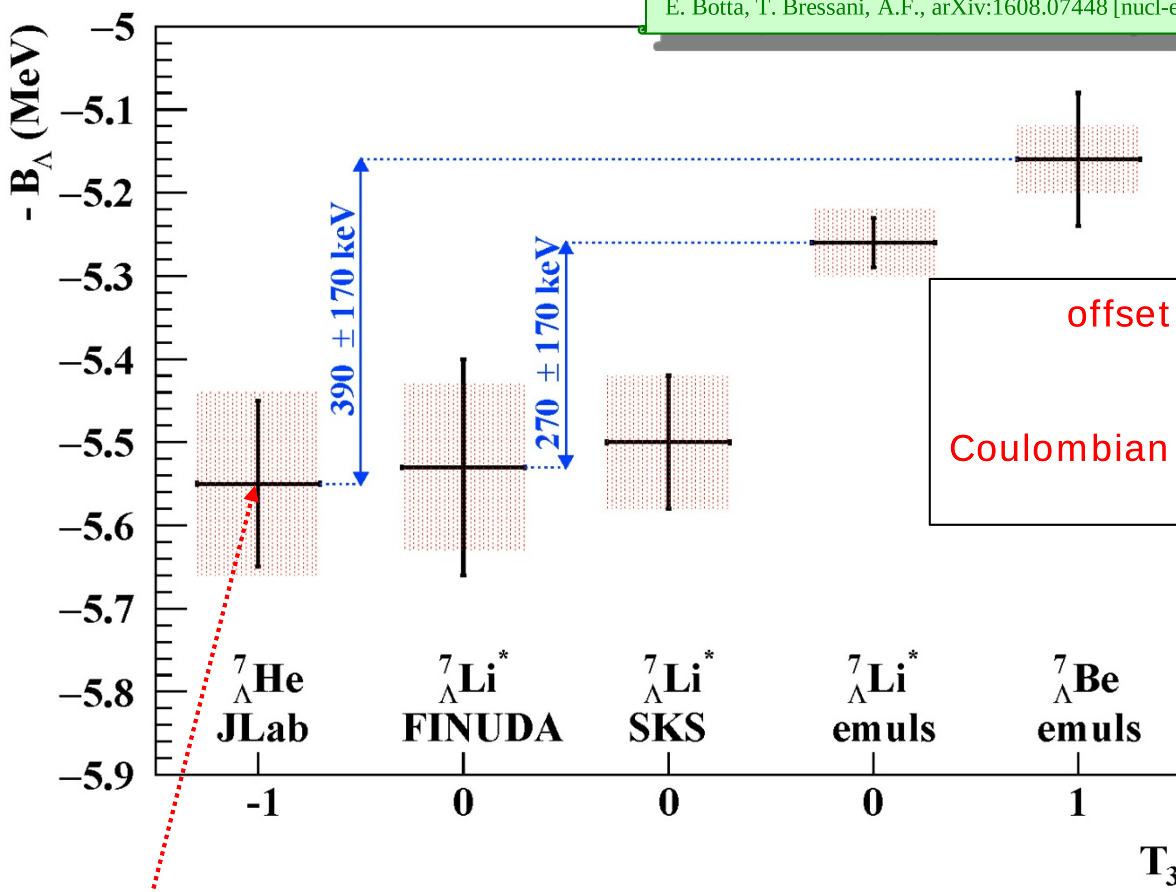
S.N. Nakamura *et al.*, PRL 110 (2013) 012502

M. Jurić *et al.*, NPB 52 (1973) 1

M. Jurić *et al.*, NPB 52 (1973) 1
H. Tamura *et al.*, PRL 84 (2000) 5963

CSB in A = 7 systems (?)

E. Botta, T. Bressani, A.F., arXiv:1608.07448 [nucl-ex]



offset between emulsions and counters experiments values

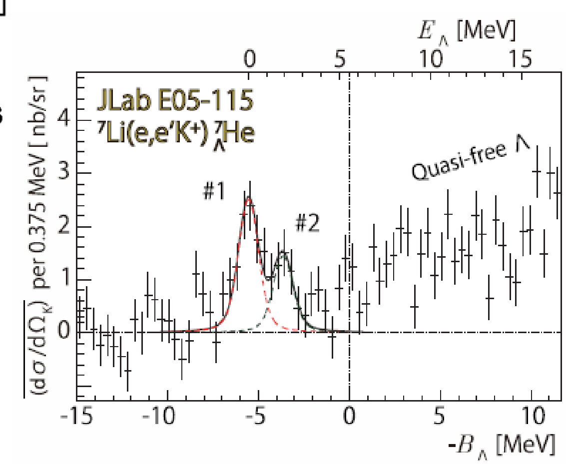
Coulombian differential shrink of $^{7}He_\Lambda$ and $^{7}Be_\Lambda$ cores (~150 keV)

E. Hiyama *et al.*, PRC 80 (2009) 054321

updated value from:

T. Gogami *et al.*, PRC 94 (2016) 021302

Hall C: E05-115



Future perspectives at the Jefferson Lab

Proposal to JLab PAC44 June 3 2016

An iso-spin dependence study of the ΛN interaction through the high precision spectroscopy of Λ-hypernuclei with electron beam

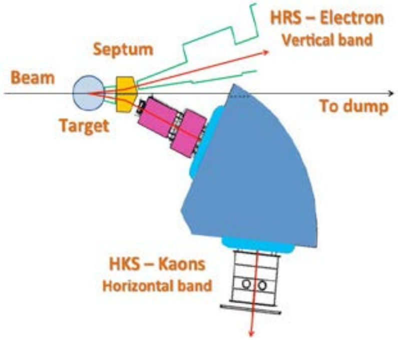
(update of the conditionally approved C12-15-008)

JLab Hypernuclear Collaboration

Spokespersons:
F. Garibaldi[1], P.E.C. Markowitz[2], S.N. Nakamura[3*], J.Reinhold[2], L. Tang[4,5], G.M. Urciuoli[1]

Goal of the experiment:
understanding neutron stars by solving the
hyperon puzzle

Precise hypernuclear spectroscopy on medium to heavy hypernuclei with electron beams is only possible with the CEBAF electron beam, due to equipment, beam quality constraints, and above all the possibility to calibrate absolute energy scale by the $p(e,e'K^+)_\Lambda$ and $p(e,e'K^+)_{\Sigma^0}$ reactions, impossible with hadron beams due to lack of pure neutron targets.



except the FINUDA experiment!

credit to G.M. Urciuoli

JLAB Theoreticians' comment

The neutron star puzzle born of the observation of two-solar mass specimens is indicative of a stiffer EOS than expected if hyperon components become active at the resulting densities.
Models where the *YN* interactions are only two-body have shown to lead to a soft EOS for which a neutron star cannot be heavier than about 1.5 solar masses.
Three or more body interactions seem to be necessary, but unfortunately at this stage close to nothing can be said about them.
In addition, the neutron star's large isospin density requires that the isospin dependencies of the Y N interactions be known.
The proposed experiment has the best potential to give information about both the three body Y N interactions as well as the dependency on isospin.
The latter has been recently illuminated in light hypernuclei by Mainz and J-PARC experiments, but much more information is needed especially for heavier hypernuclei.
It seems that the proposed experiment should be a first one in a program that hopefully continues with the goal of establishing hypernuclear physics which is crucial for understanding important problems, such as the neutron star puzzle.

~~Conclusions~~

The starting point!

- interesting results have already been achieved
- several open questions on fundamental issues
- stimulating discovery potential
- perspectives look promising
- active and well motivated physicists' community
  - experimental activity definitively started at J-PARC
  - extension of the J-PARC Hadron Experimental Facility
  - call for new ideas and proposals
    (light hypernuclei lifetime, further decay mode)
  - Jefferson Lab — JLab hypernuclear physics program