Physics highlights from the FINUDA experiment

from the point of view of an experimentalist

Alessandro Feliciello

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

Outline

1) Introduction

2) the experimental setup

- the DAΦNE machine
- the FINUDA apparatus

3) the strangeness nuclear physics program

- high-resolution spectroscopy of Λ-hypernuclei
- Λ-hypernucleus decay
  - neutron-rich Λ-hypernuclei
  - $K^+\mathcal{N}$ charge exchange reaction
- (deeply) bound kaon-nuclear states

DAΦNE hypernuclear physics program

International Workshop
on
the Spectroscopy of Hypernuclei

Tohoku University,
Sendai, Japan,
January 8 - 10, 1998

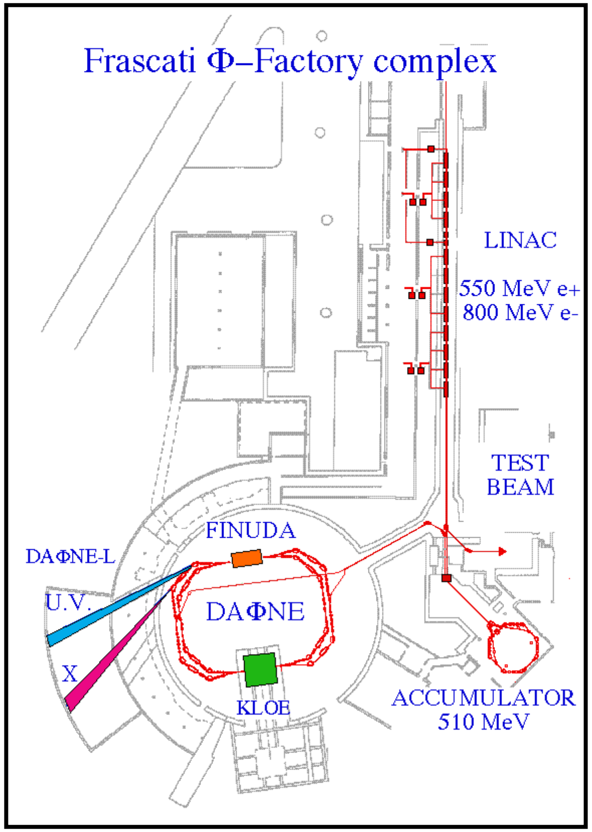
Alessandro Feliciello / I.N.F.N. - Sezione di Torino

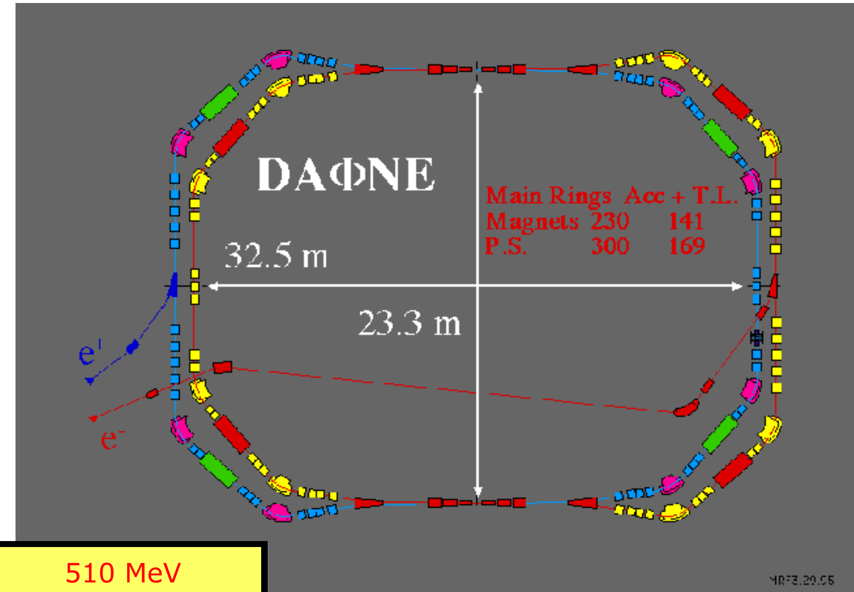
The DAΦNE machine

The DAΦNE Φ-factory

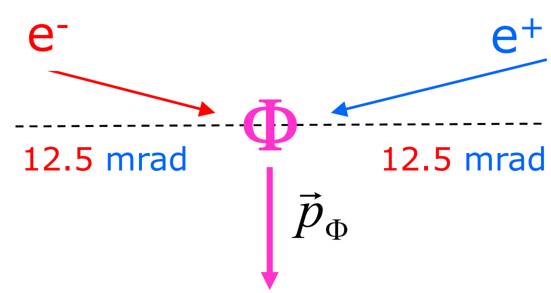
INFN
Istituto Nazionale di Fisica Nucleare

The DAΦNE e^+e^- collider





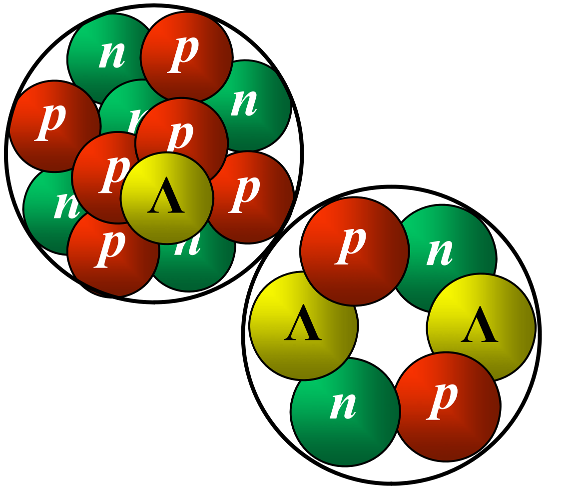
energy	510 MeV
luminosity	$\leq 5 \times 10^{32}$ cm^{-2} s^{-1}
σ_x (rms)	2.11 mm
σ_y (rms)	0.021 mm
σ_z (rms)	35 mm
bunch length	30 mm
crossing angle	12.5 mrad
frequency (max)	368.25 MHz
bunch/ring	up to 120
part./bunch	8.9 10^{10}
current/ring	5.2 A (max)



Hypernuclear physics

What is a hypernucleus?

- bound system of nucleons and one or more iperons

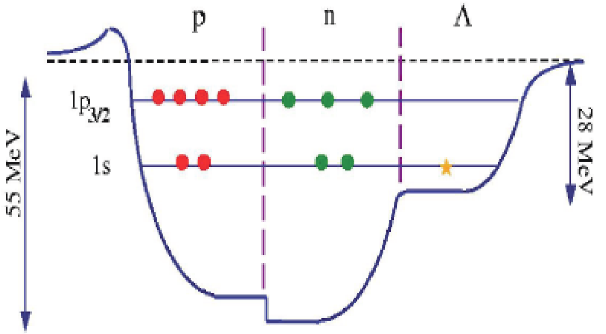


- M_Λ = 1115,68 MeV M_n = 939,57 MeV
  Λ(uds) n(udd)
  $q_\Lambda = 0$ $q_n = 0$

Λ is a "fat" n

strangeness makes it distinguishable

inner nuclear shell
are not Pauli-blocked to Λ

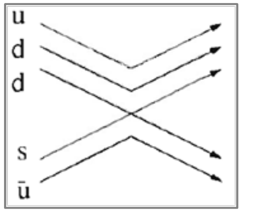


Single Λ-hypernucleus production

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

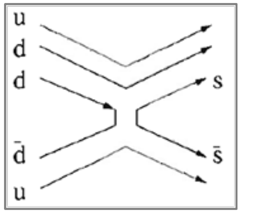
1) strangeness exchange (both in flight and at rest):

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



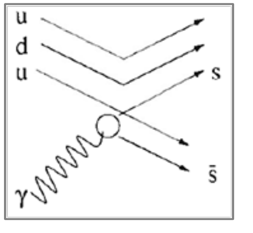
2) associated strangeness production:

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



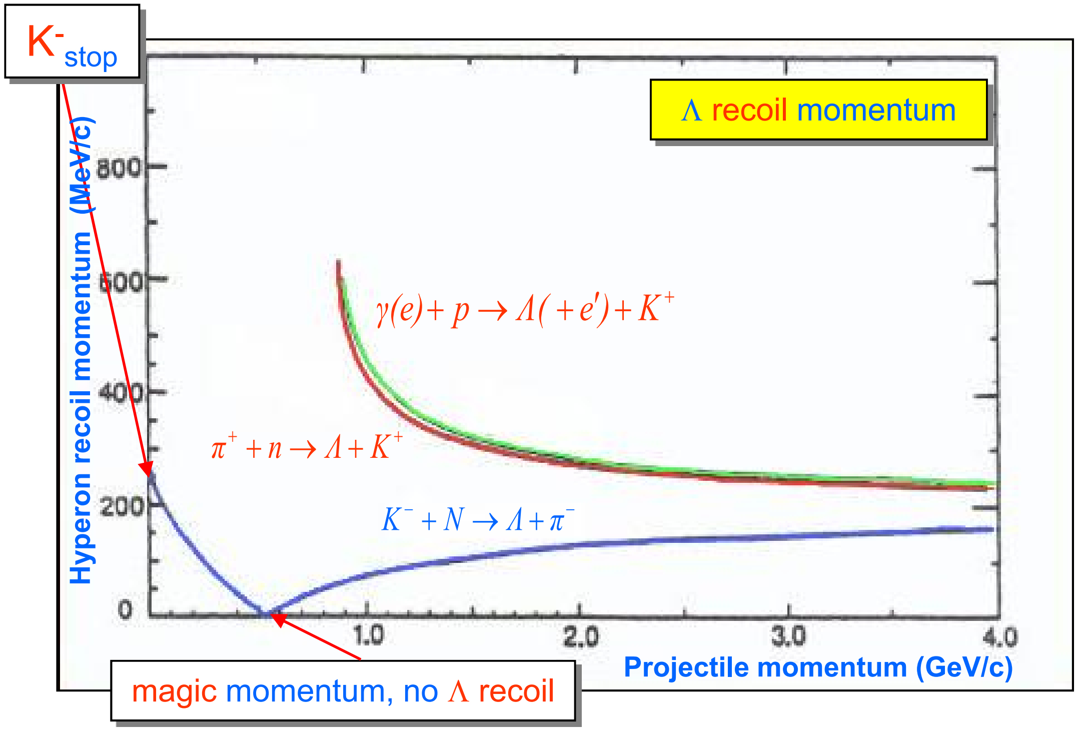
3) "electro-production":

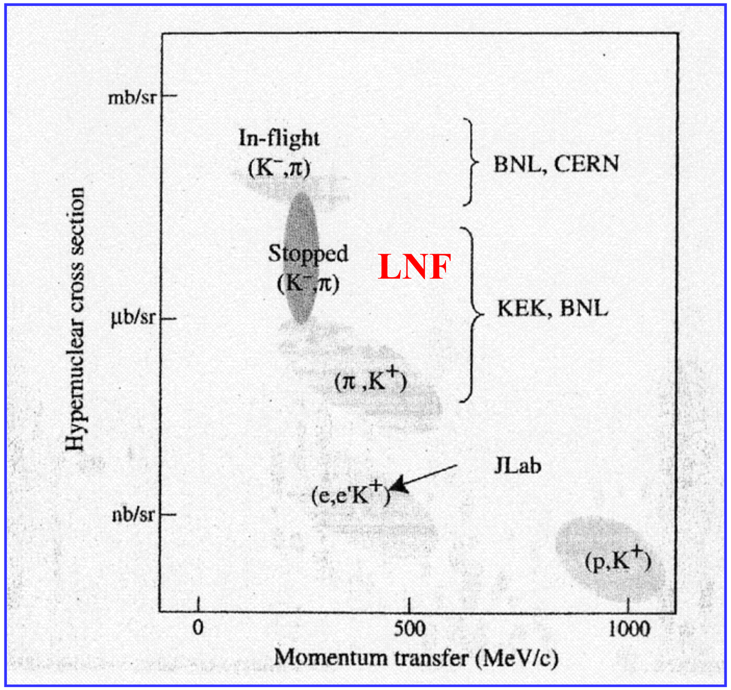
$$e^- + {}^AZ \to e^{-\prime} + K^+ + {}^A_\Lambda(Z-1)$$



Single Λ-hypernucleus production

two body reactions





What one can do with a Φ-factory?

source of (nearly) monochromatic, collinear, background free, tagged neutral and charged kaons

KLOE
CP, CPT violation
chiral dynamics
and more...

FINUDA
hypernuclear physics

$K_S K_L$
(34%)

$\rho\pi$
(13%)

K^+K^-
(49%)

DEAR/SIDDHARTA
exotic atoms

Double
Annular
Φ-factory for
Nice
Experiments

The FINUDA way

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

$K^- + K^+$ $T_{K^-} \approx 16.1$ MeV ≈ 150 Hz

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

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

coincidence measurement

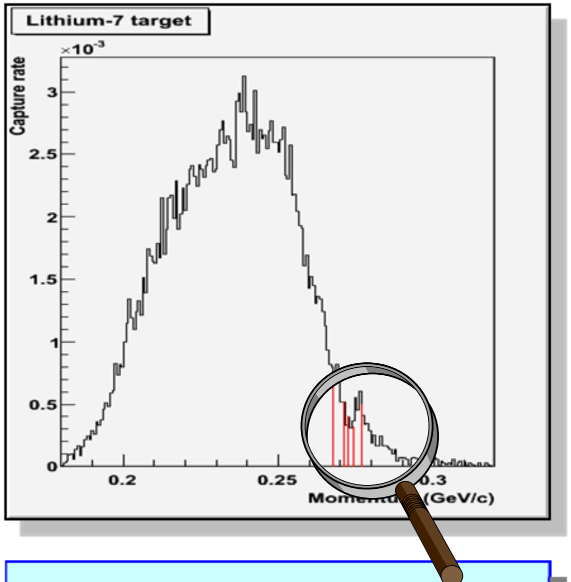
$${}^{A}_{\Lambda}Z \rightarrow \begin{cases} {}^{A}(Z+1) + \pi^- \\ {}^{(A-2)}(Z-1) + p + n \\ {}^{(A-2)}Z + n + n \end{cases}$$

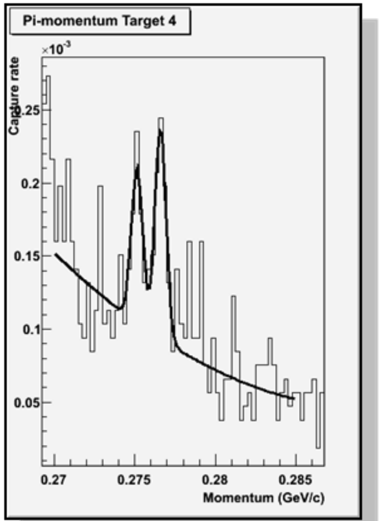
Open questions

- (low-energy) YN interaction
  - detailed knowledge of the hypernuclear fine structure
    → evaluation of the spin dependent terms of the ΛN interaction
  - measurement of angular distribution of γ–rays
    → determination of spin and parity of each observed level
- Impurity nuclear physics
  - measurement of transition probability B(E2)
    → information on the size and deformation of hypernuclei
    → measurement of nucleus core shrinking → glue-like role of Λ
- Properties of hyperons in nuclear matter (medium effect)
  - measurement of transition probability B(M1)
    → g-factor value for Λ in nuclear matter

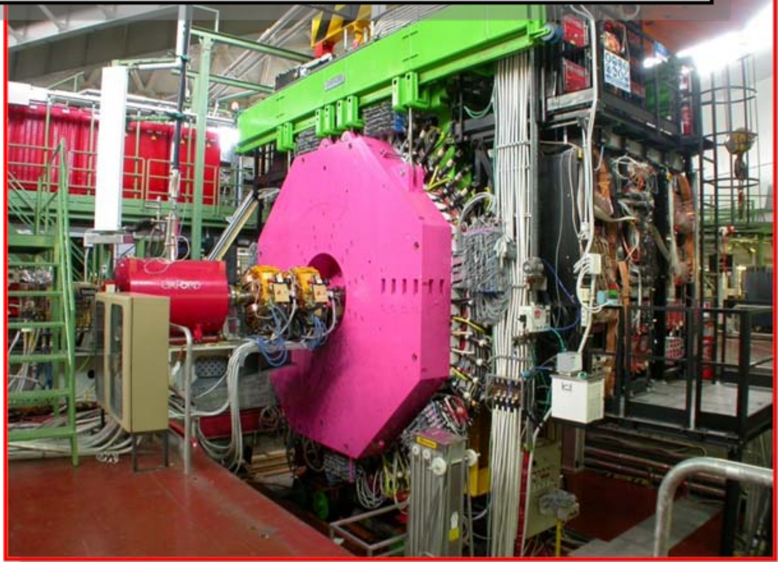
One step beyond

$^{7}Li(K^{-}_{stop},\pi^{-})\ ^{7}_{\Lambda}Li$





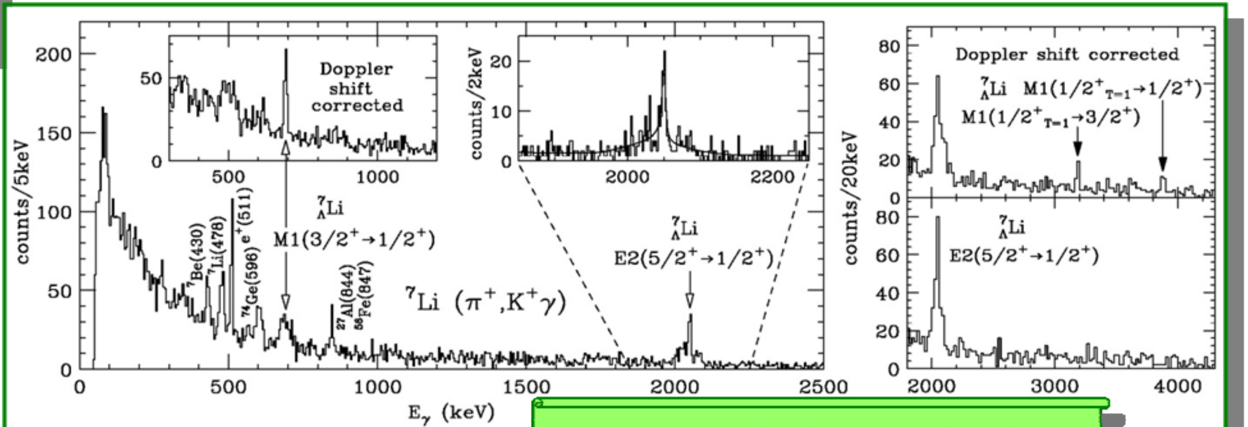
The FINUDA spectrometer @ DAΦNE



ΔE ~ 1.9 MeV FWHM

KEK E419

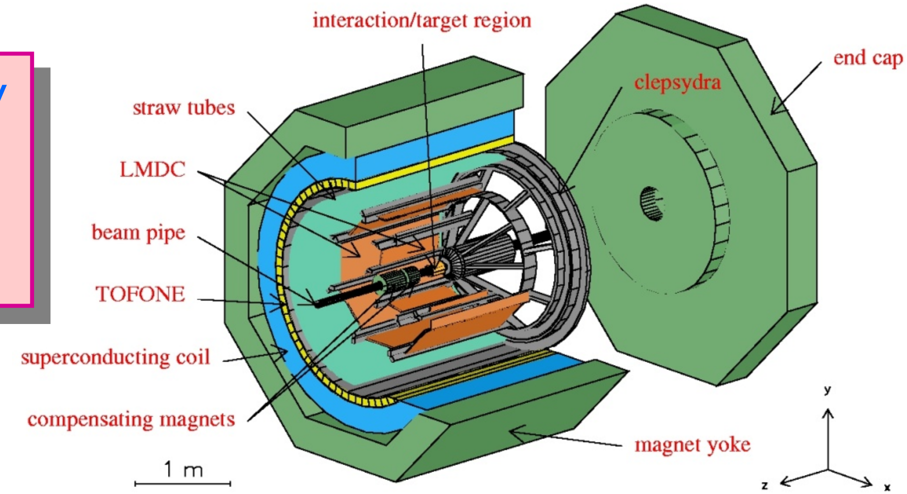
ΔE ~ 2 keV FWHM

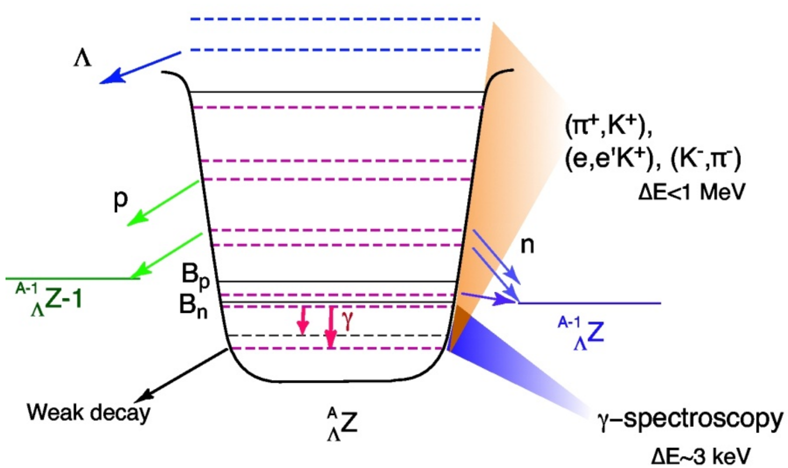


H. Tamura, *Nucl, Phis.* A 691 (2001) 86c

The γ-ray spectroscopy domain

The region of high excitation energy
in heavy Λ-hypernuclei
cannot be explored
with γ-spectroscopy





The FINUDA apparatus

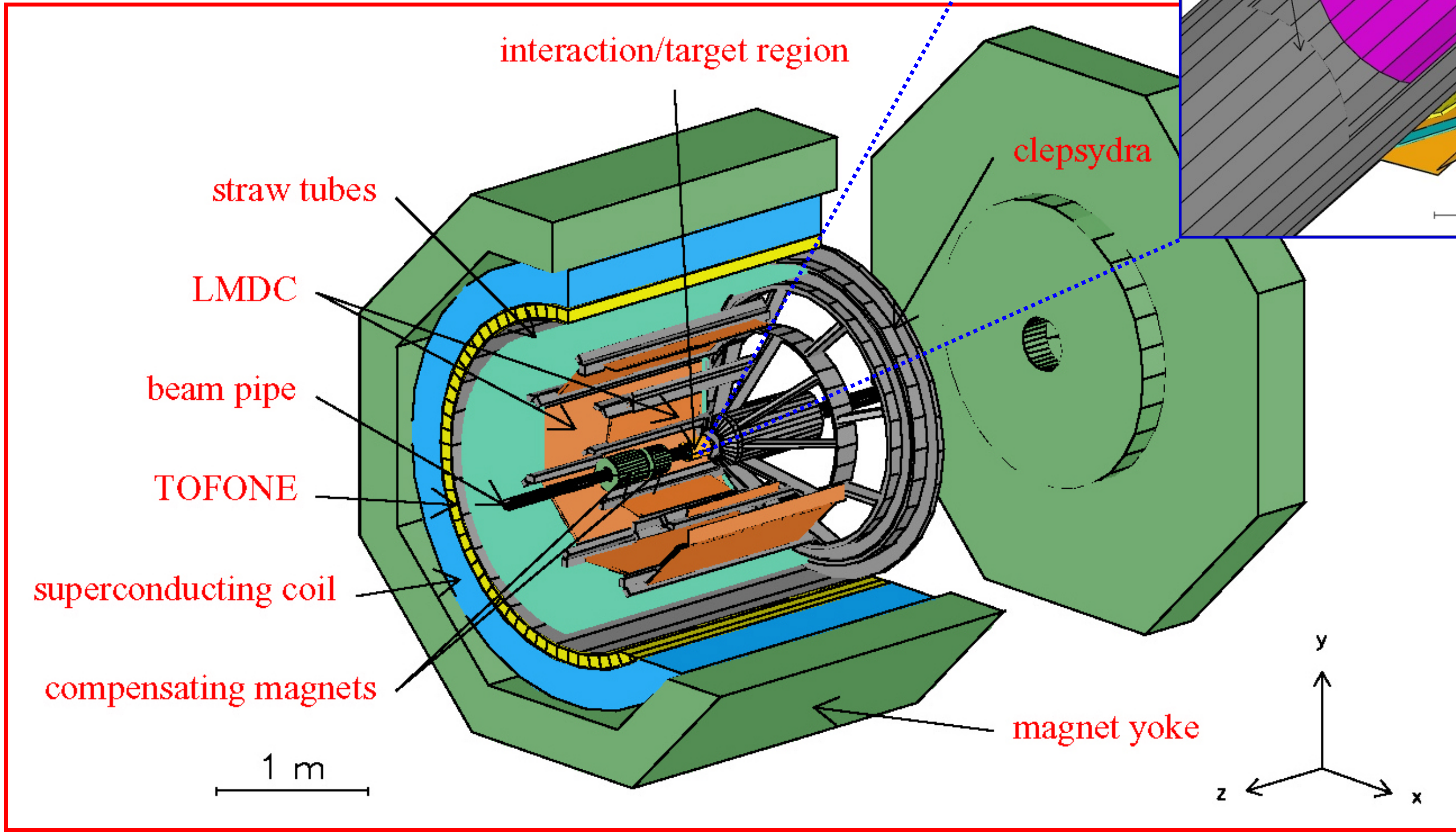
… nothing by chance

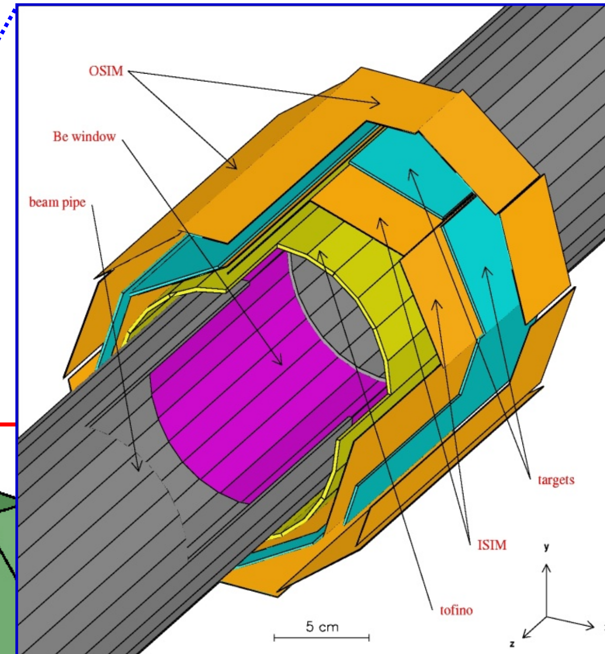
The FINUDA apparatus

- high resolution
- high acceptance

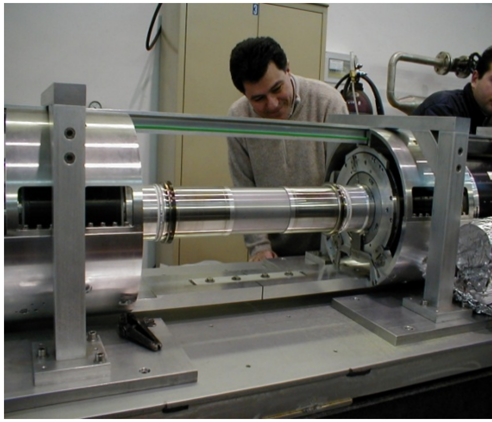
} magnetic spectrometer

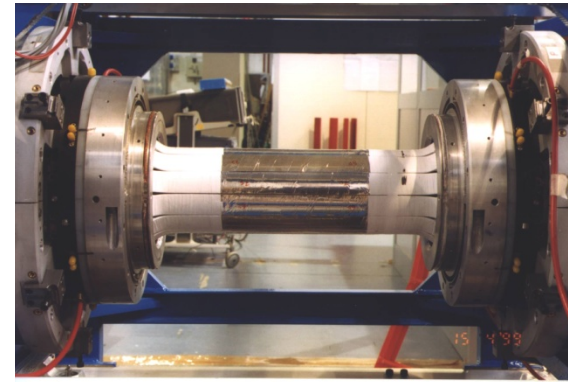
- realistic (feasible)
- reasonable cost





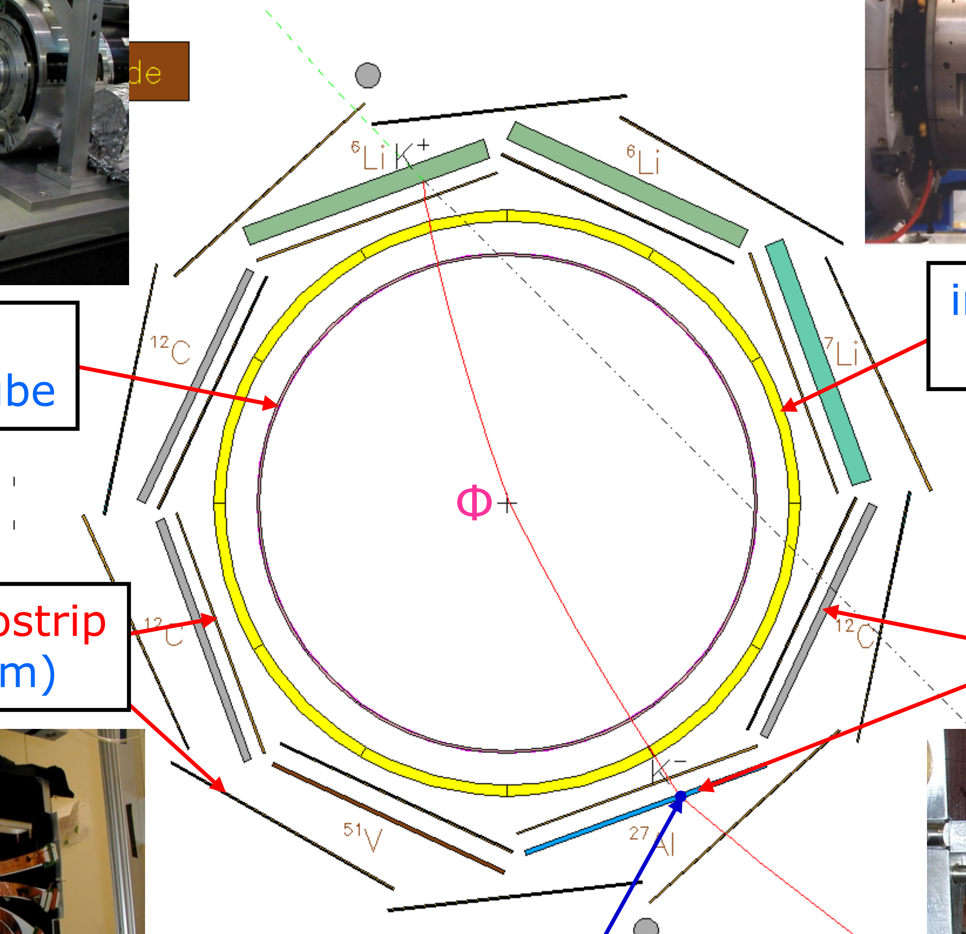
Interaction-target region





beam pipe
500 μm Be tube

internal scintillator
barrel (2.3 mm)



double Si microstrip
array (400 μm)

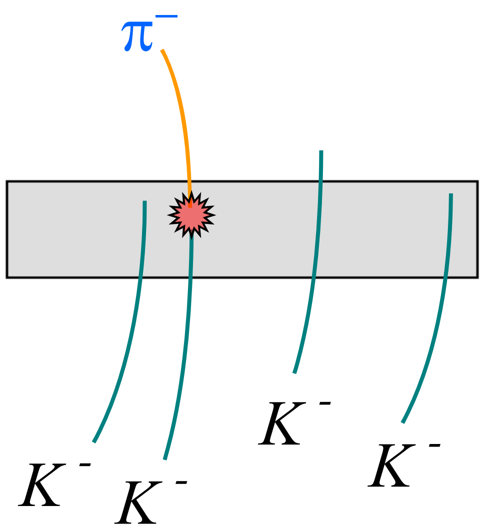
target modules
(0.1 – 0.3 g/cm²)

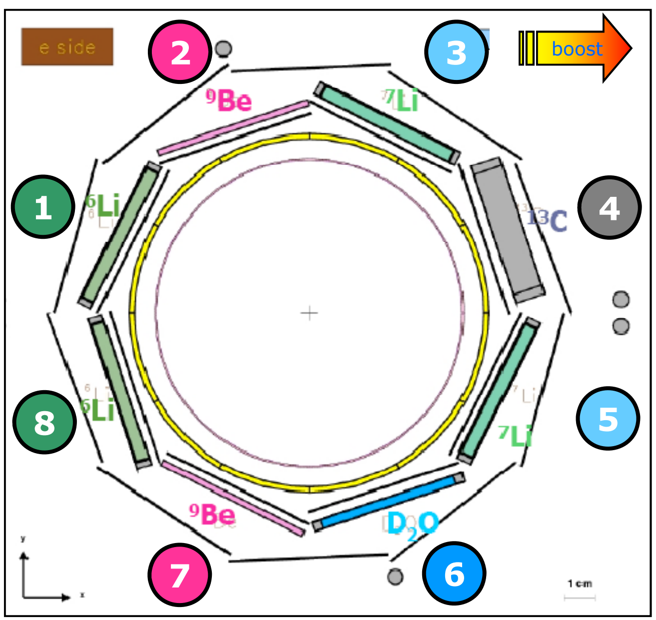
kaon stop point
in the target

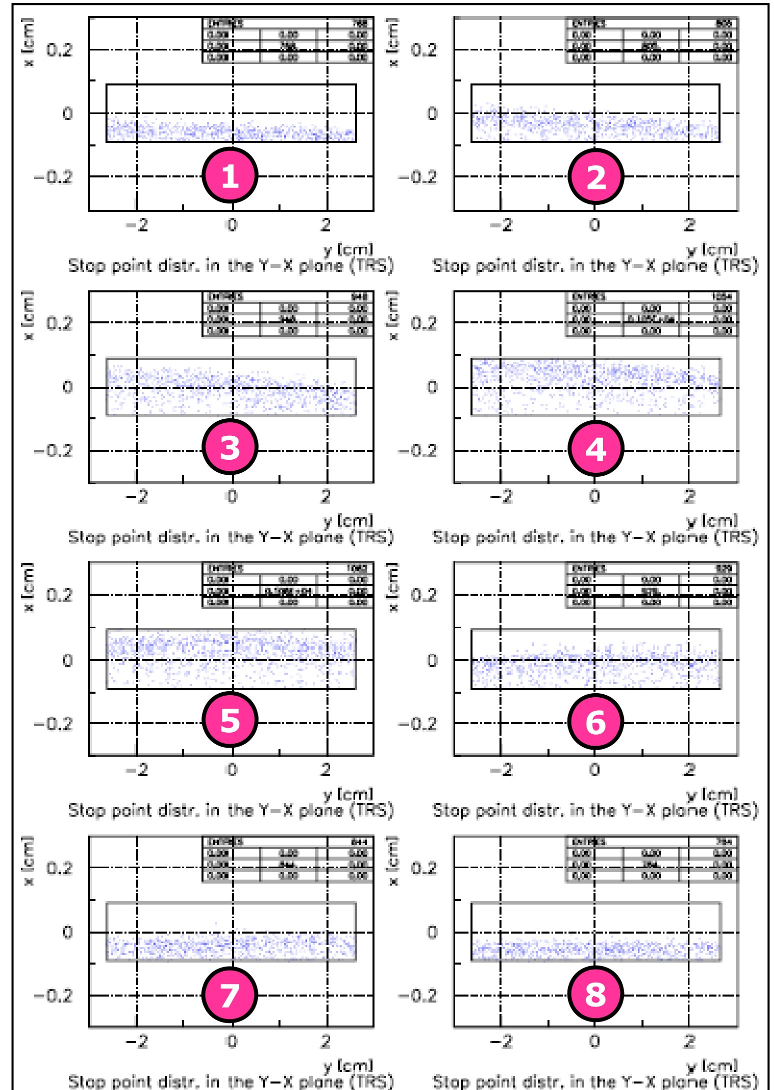
Target design study

MC study

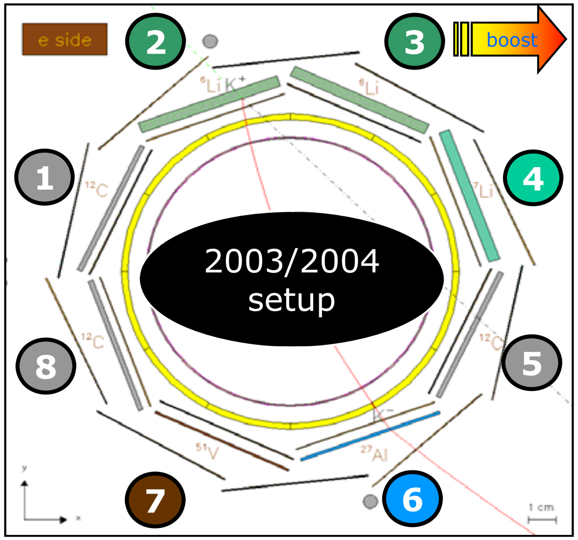
^{9}Be target
thickness: 1.8 mm

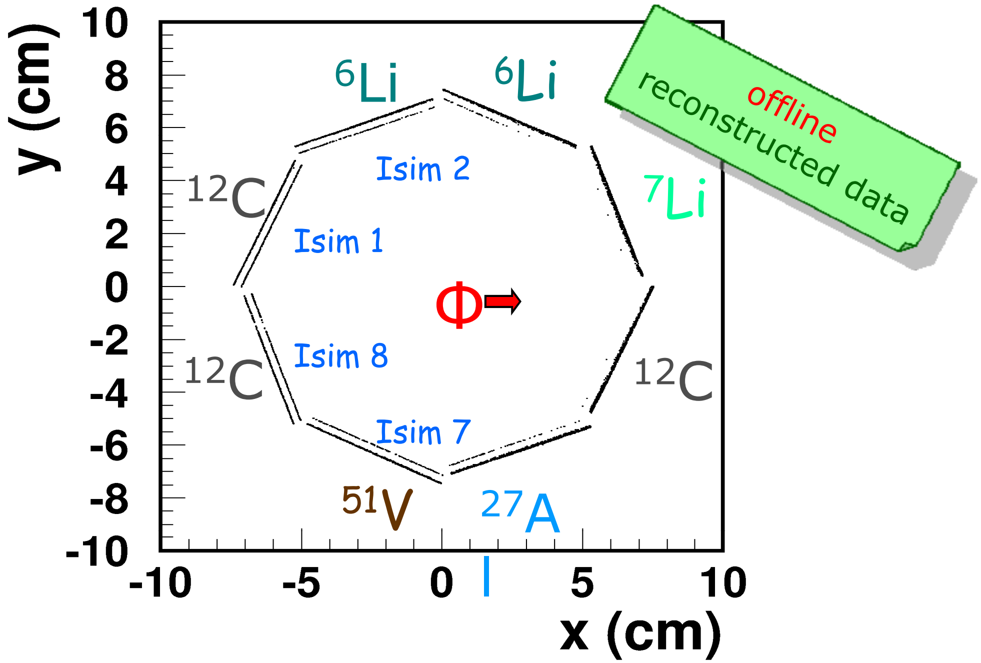


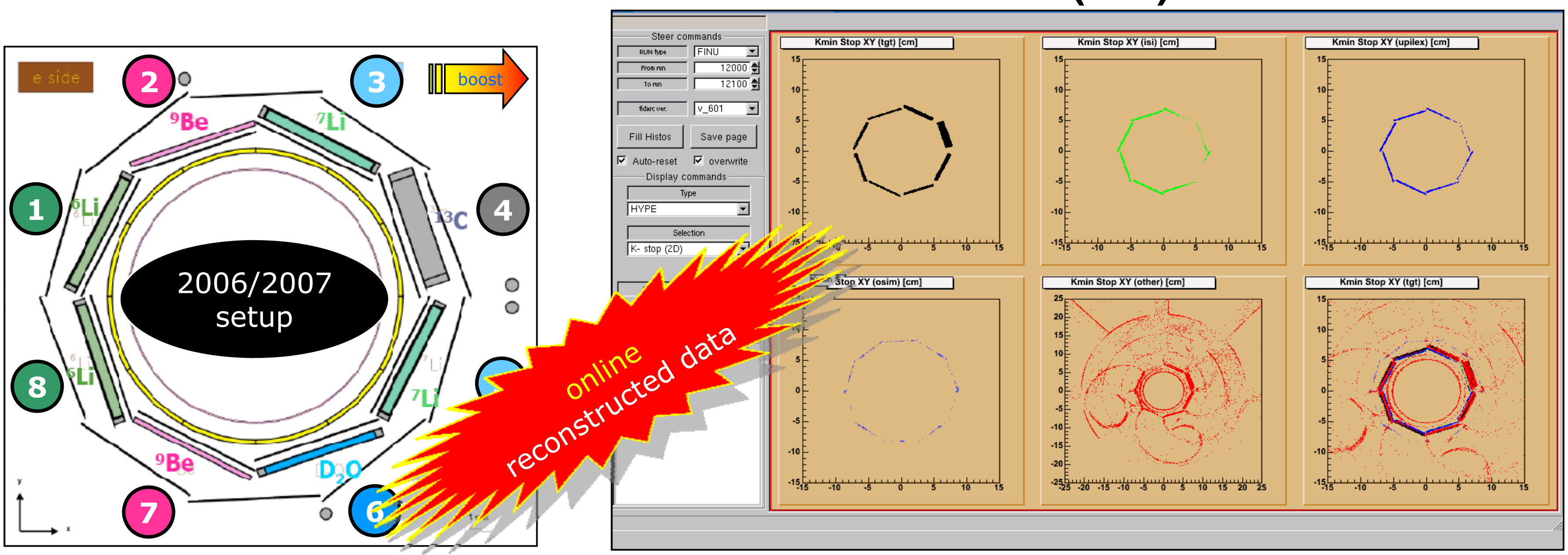




Target envelope by K^- stopping points



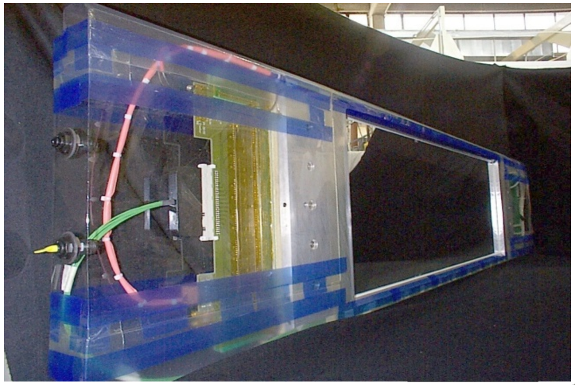




A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

Tracking system + neutron detector

A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.



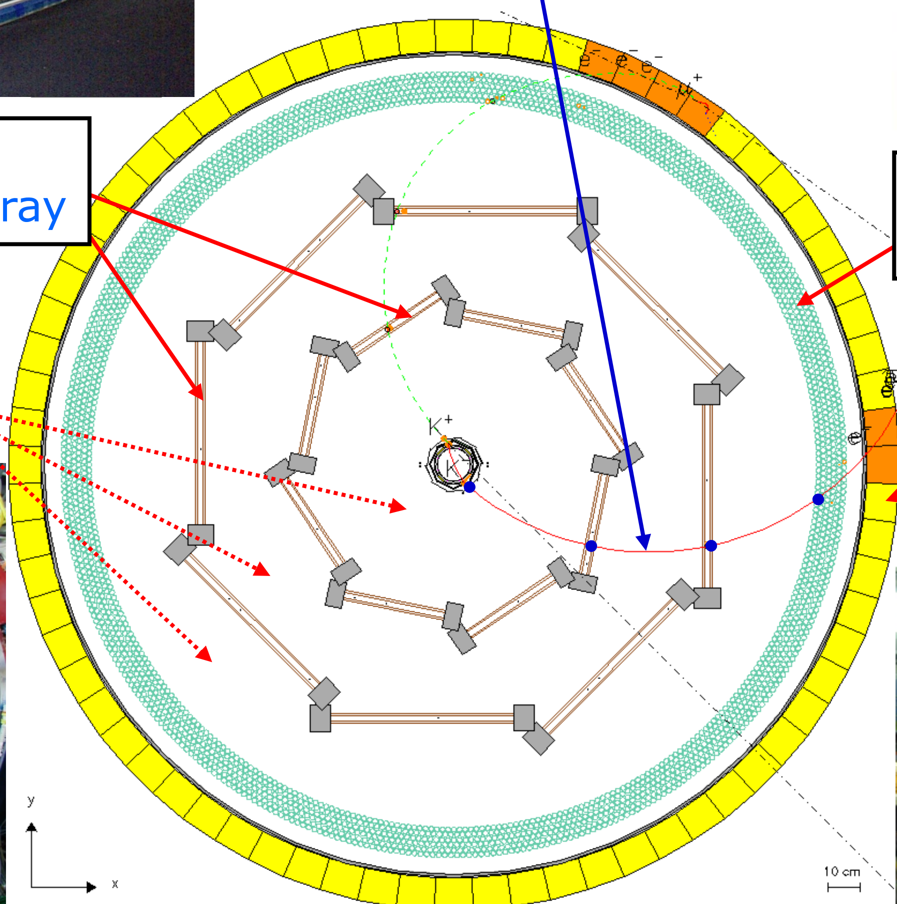
trajectories are measured in 4 points

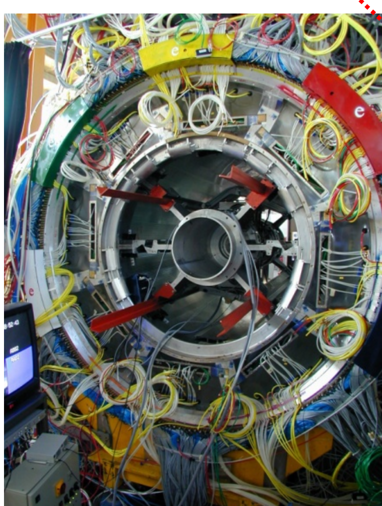
2 low-mass drift chamber array

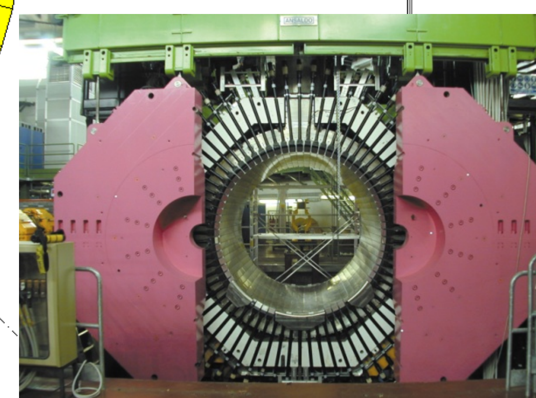
longitudinal and stereo straw tube arrays

8 m³ He bag

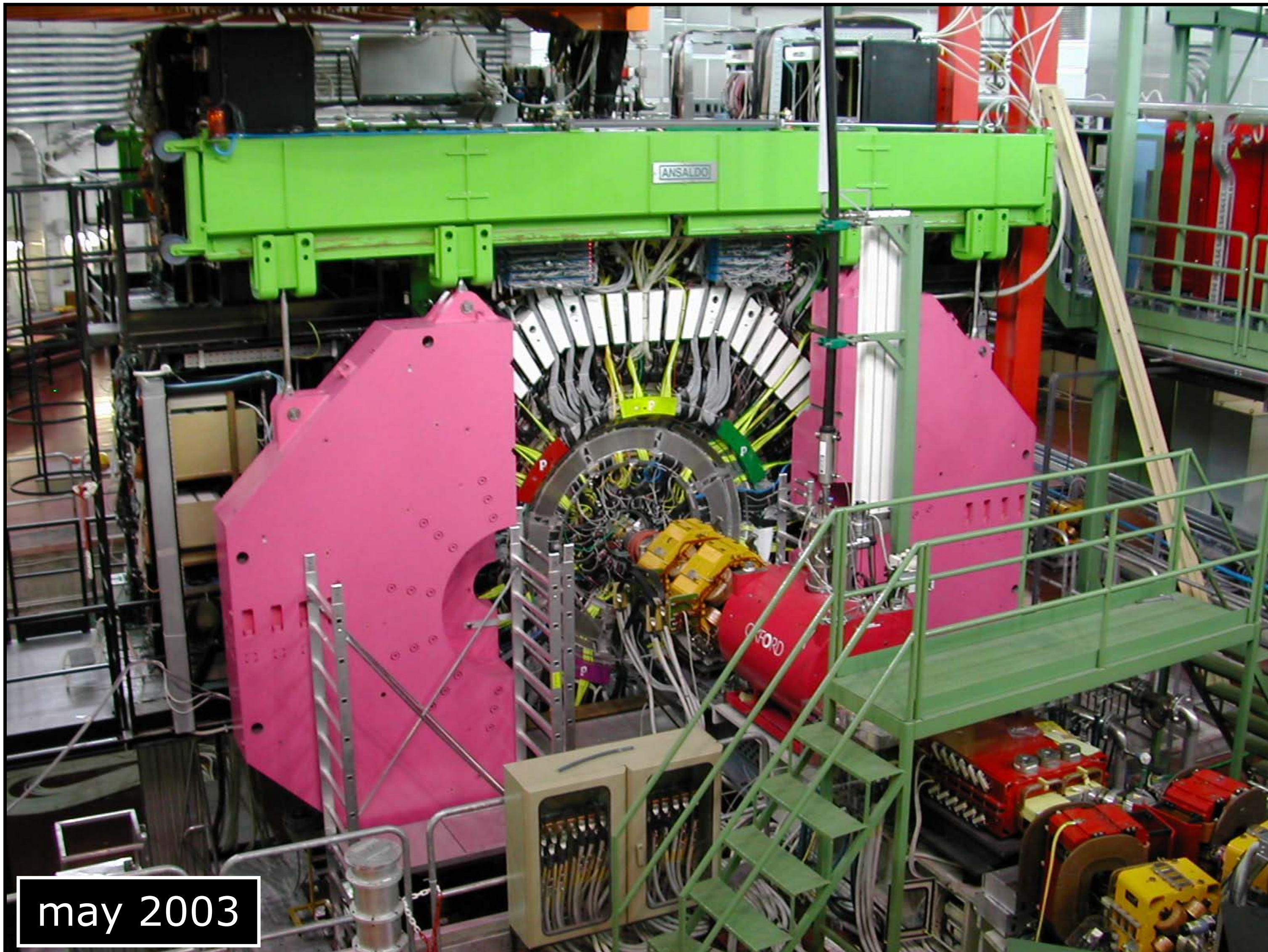
outer scintillator barrel (10.0 cm) neutron counter







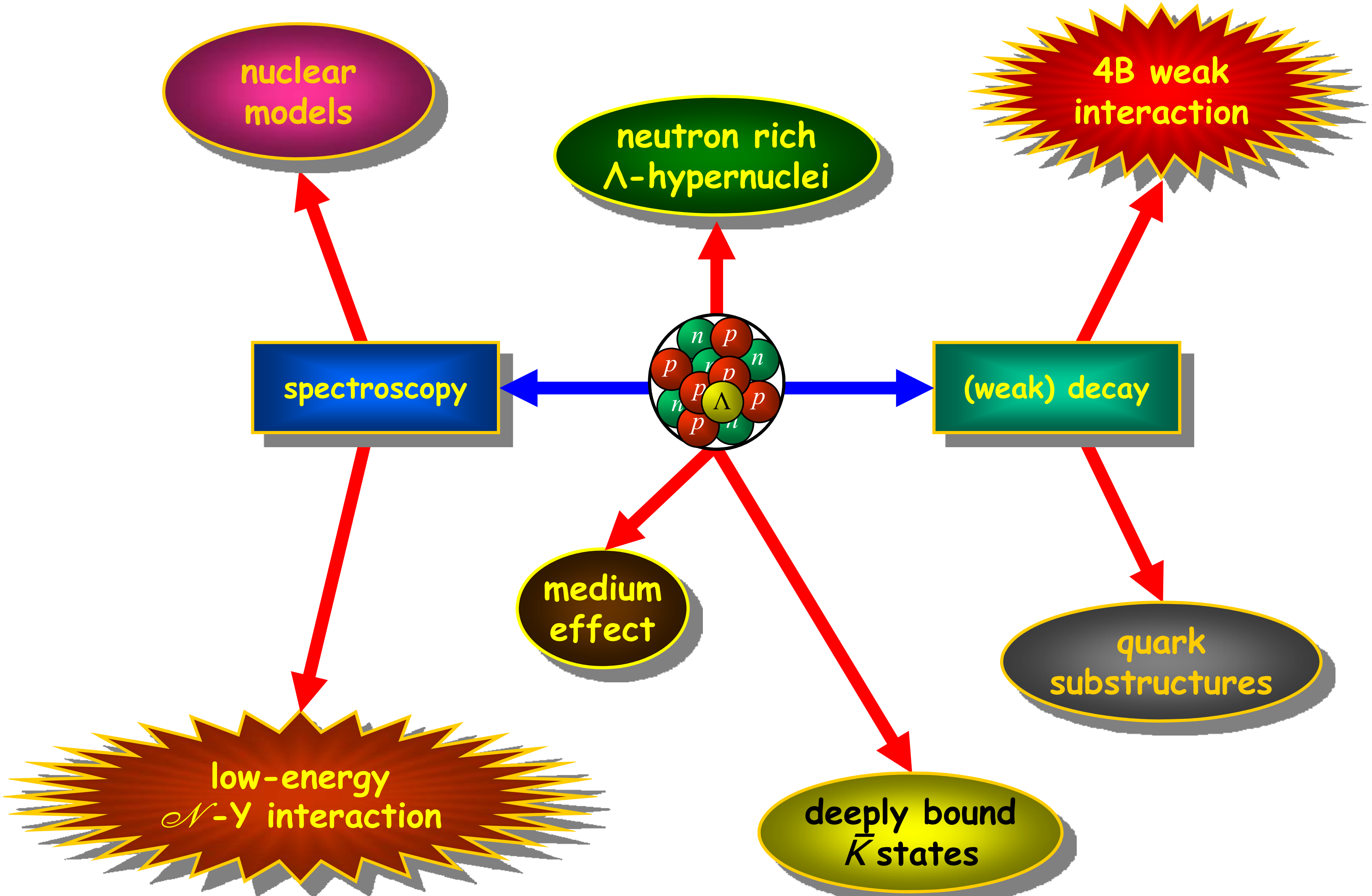
Concept becomes reality



FINUDA key features

- very thin nuclear targets ($0.1 \div 0.3$ g/cm^2)
  - → high resolution spectroscopy
- coincidence measurement with large acceptance
  - → decay mode study
- irradiation of different targets in the same run
  - → systematic error reduction

Physics output (S = -1)



Spectroscopy of Λ-hypernuclei

The fight against background

How did we detect an hypernucleus?

the measurement of the π^- momentum is possible thanks to the FINUDA capabilities of tracking and resolution

by conserving energy and momentum

$$m_{hyp} = \sqrt{(m_{K^-} + m_{^AZ} - E_{\pi^-})^2 - p_\pi^2}$$

$$-B_\Lambda = m_{hyp} - (m_{^AZ-1n} + m_\Lambda)$$

strangeness exchange reaction

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

$$K^- + n \rightarrow \Lambda + \pi^-$$

$$(\bar{u}s) + (udd) \rightarrow (uds) + (\bar{u}d)$$

the "strangeness exchange" reaction **it is not** the only possible way in which a **negative pion** can be present in the interaction K-N **final state**

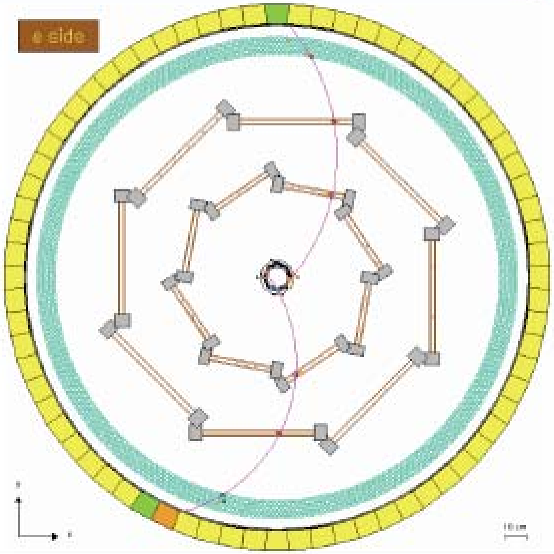
1 $K^- + n \rightarrow \Lambda + \pi^-$

2 $K^- + p \rightarrow \Sigma^- + \pi^+$

3 $K^- + (np) \rightarrow \Sigma^- + p$

(from 2 and 3:) $\Sigma^- \rightarrow n + \pi^-$

4 $K^- \rightarrow \mu^- + \overline{\nu}_\mu$



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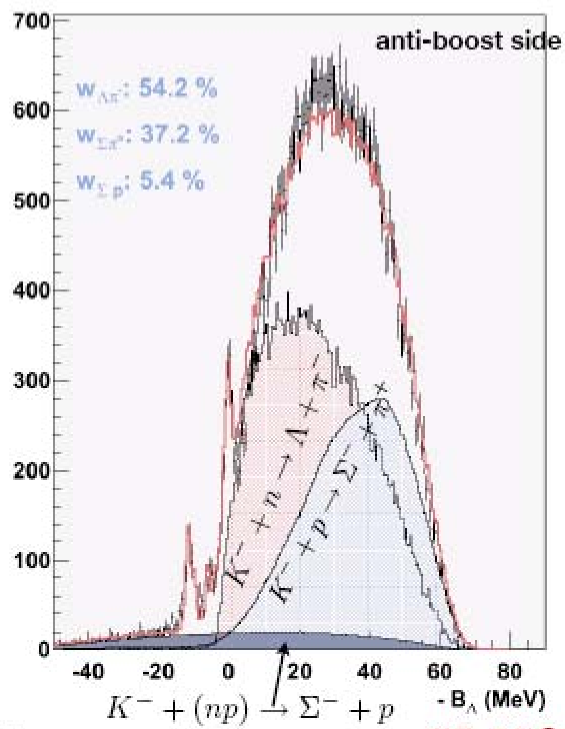
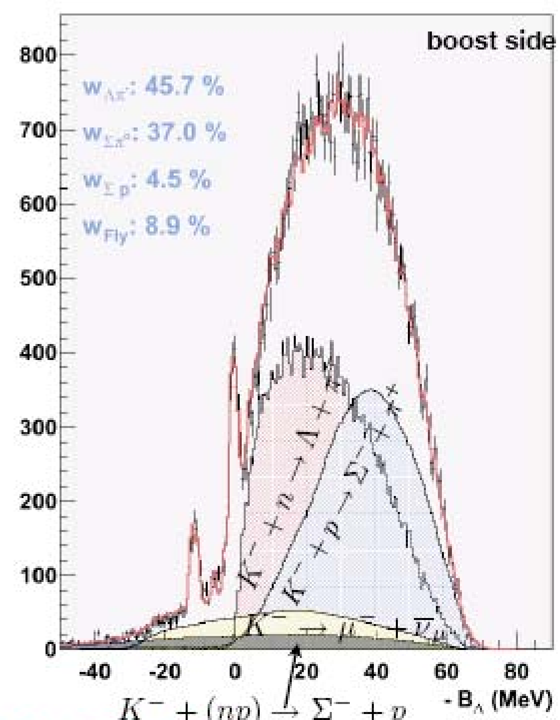
The fight against background

FITTING THE DATA | SIGNAL + BACKGROUND FIT

1) we fit the experimental distribution with the sum of N gaussians (for the signal) and 4 histograms for the background
   - the mean of the gaussians are free to move around the input values

2) we repeat the fit with a more sophisticated fit tool fixing also the mean values and the sigma of the gaussians (*)



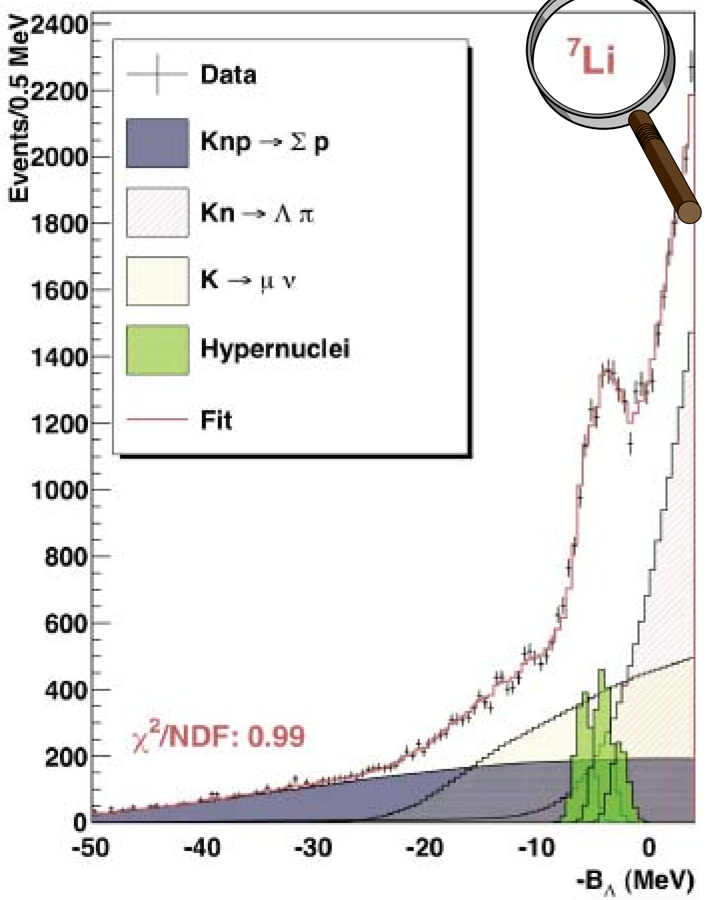


*ROOT TFractionFitter

WE KNOW THE BACKGROUND

Fits MC fractions to data histogram (a la HMCMLL, see R. Barlow and C. Beeston, Comp. Phys. Comm. 77 (1993) 219-228, and http://www.hep.man.ac.uk/~roger/hfrac.f).

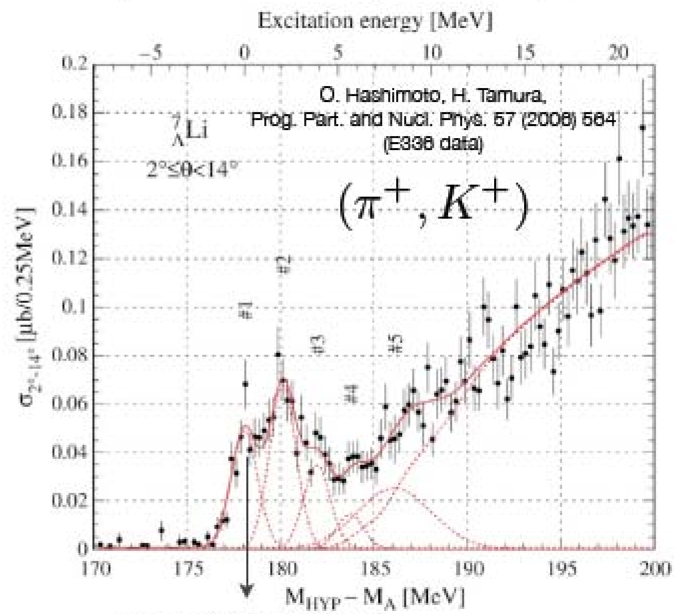
HYPERNUCLEAR SPECTROSCOPY | FROM THE NEW DATA TAKING: ^{7}Li ^{9}Be, ^{13}C, D_2O



^{7}Li	$-B_\Lambda$ (MeV)	E_X (MeV)	Formation probability per stopped K^- (10^{-3})
1	-5.8 ± 0.4	-	$0.37 \pm 0.04 \pm 0.05$
2	-4.1 ± 0.4	1.7	$0.46 \pm 0.05 \pm 0.06$
3	-2.6 ± 0.4	3.2	$0.21 \pm 0.03 \pm 0.03$

the ground state from emulsion data $B_\Lambda = -5.58 \pm 0.03$ MeV

[M. Juric et al. Nucl. Phys. B 52 (1973) 1]



$B_\Lambda = -5.22 \pm 0.08$ MeV

strangeness in nuclei | trento, 4-8 october 2010 13 germano bonomi | FINUDA hypernuclear spectroscopy

comparison with:

M. Agnello et al., FINUDA @ HYP2006

KEK E336 esperiment: g.s. @ lower energy

emulsion experiment: g.s. energy value within 1σ

boost

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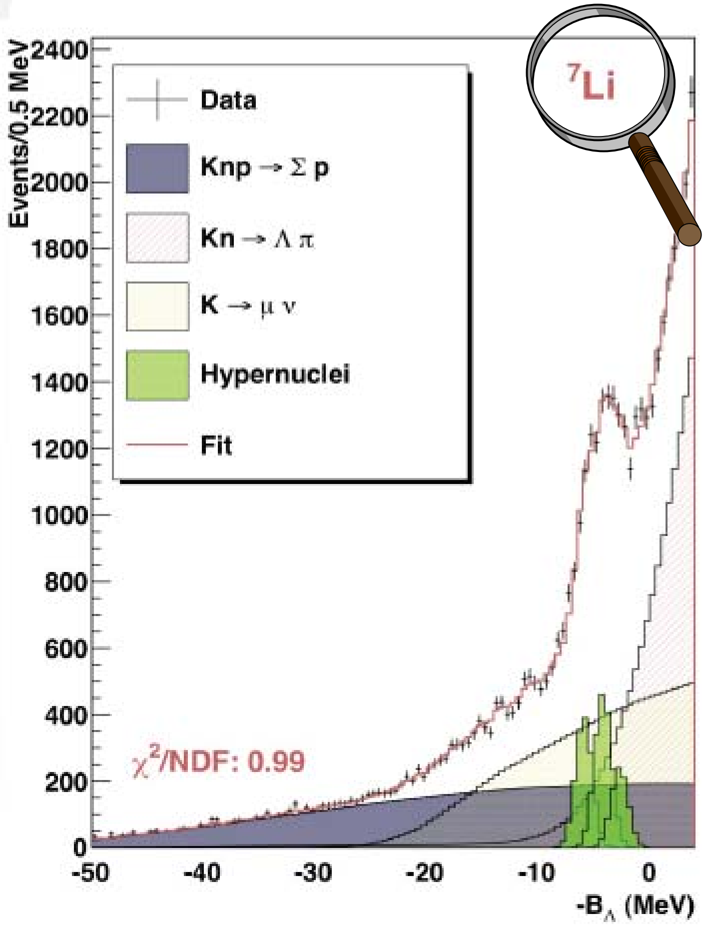
HYPERNUCLEAR SPECTROSCOPY | FROM THE NEW DATA TAKING: ^{7}Li ^{9}Be, ^{13}C, D_2O



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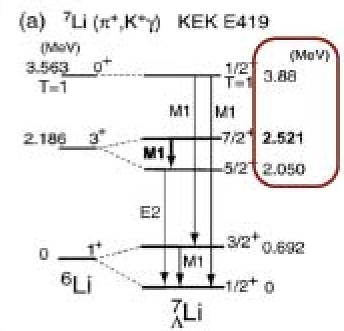
3	-2.6 ± 0.4	3.2	$0.21 \pm 0.03 \pm 0.03$

$(1.04 \pm 0.12 \pm 0.14) \times 10^{-3}$

FIRST WORLD MEASUREMENT of FORMATION PROBABILITY



H. Tamura et al. Nucl. Phys. A **754** (2005) 58c

boost

comparison with:

H. Tamura et al., Nucl. Phys. A 754 (2005) 58c (γ-ray): excited states

spin-flip amplitude ≈ 0 → ❶ ≡ $1/2^+$, ❷ ≡ $5/2^+$

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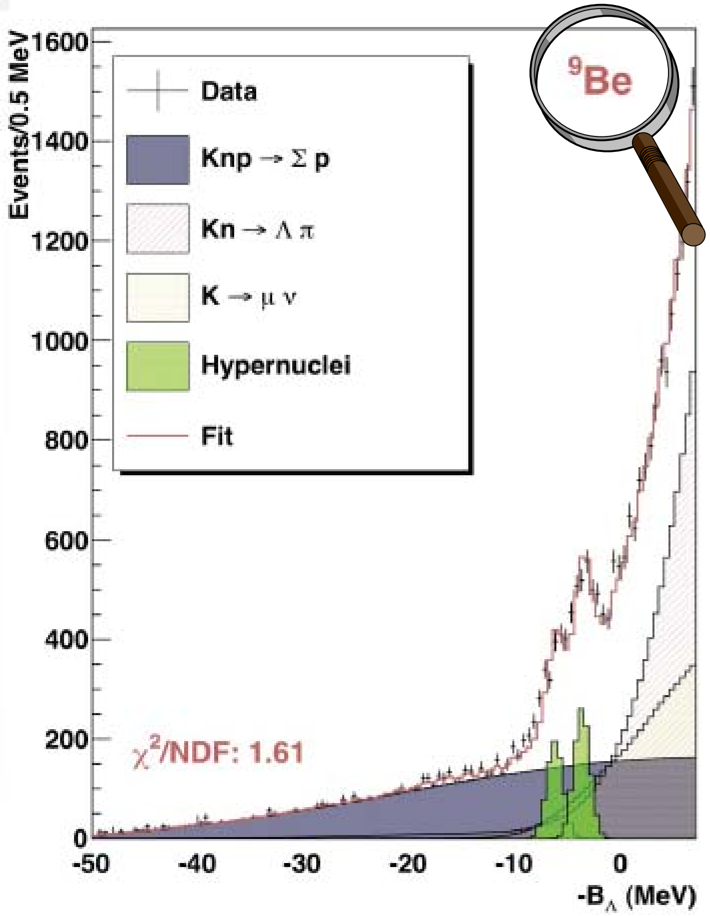
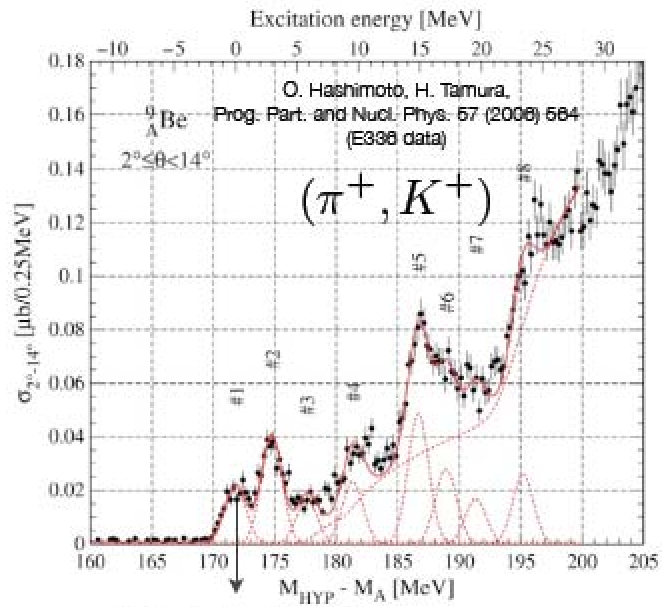
HYPERNUCLEAR SPECTROSCOPY — FROM THE NEW DATA TAKING: ^{7}Li, ^{9}Be, ^{13}C, D_2O



^{9}Be	$-B_\Lambda$ (MeV)	E_X (MeV)	Formation probability per stopped K^- (10^{-3})
1	-6.2 ± 0.4	-	$0.16 \pm 0.02 \pm 0.02$
2	-3.7 ± 0.4	2.5	$0.21 \pm 0.02 \pm 0.03$

the ground state from emulsion data $B_\Lambda = -6.71 \pm 0.04$ MeV
[M. Juric et al. Nucl. Phys. B 52 (1973) 1]

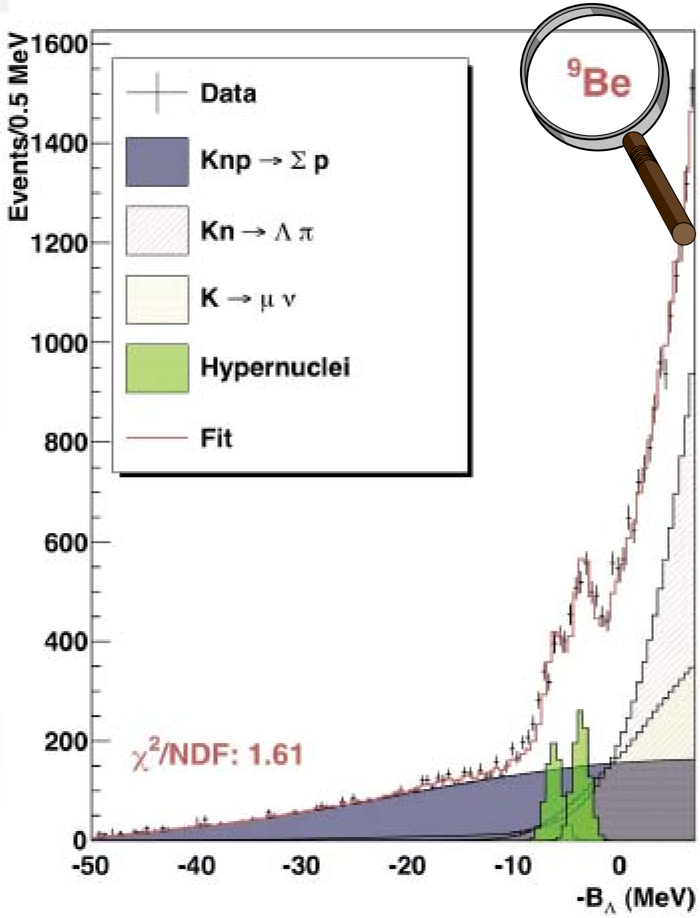


$B_\Lambda = -5.99 \pm 0.07$ MeV

comparison with:

KEK E336 esperiment: 2 signals vs. 8; first 2 in agreement
emulsion experiment: g.s. @ higher energy

no boost



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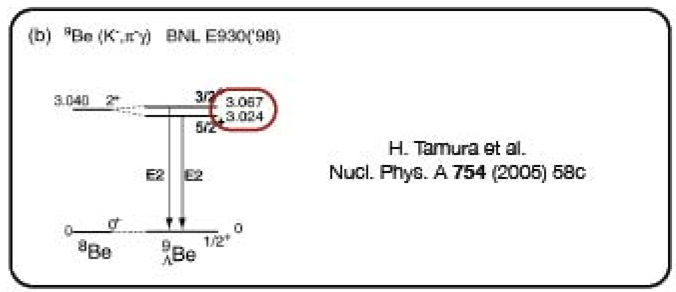
1	-6.2 ± 0.4	-	$0.16 \pm 0.02 \pm 0.02$
2	-3.7 ± 0.4	2.5	$0.21 \pm 0.02 \pm 0.03$

$(0.37 \pm 0.04 \pm 0.05) \times 10^{-3}$

FIRST WORLD MEASUREMENT of FORMATION PROBABILITY



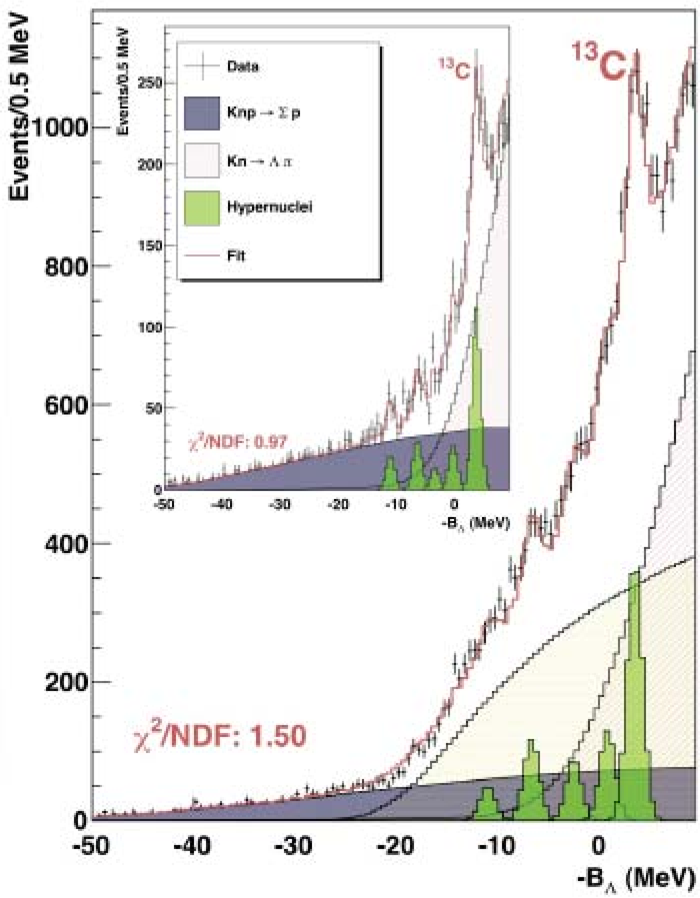
comparison with:

H. Tamura et al., Nucl. Phys. A 754 (2005) 58c (γ-ray): excited state compatible

no boost

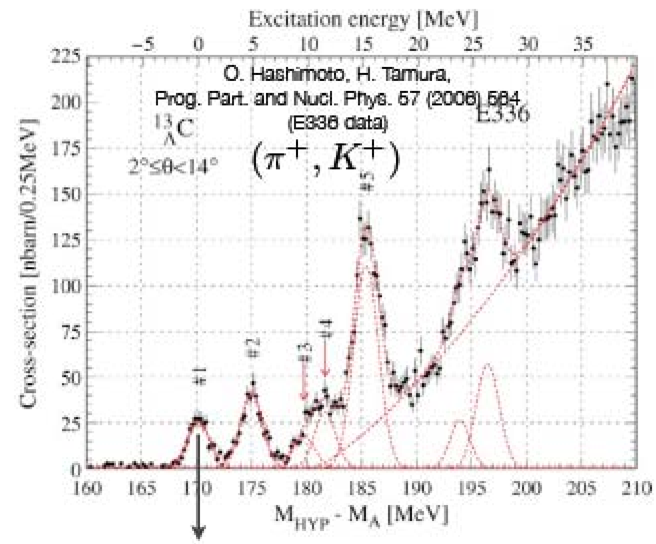
A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

HYPERNUCLEAR SPECTROSCOPY | FROM THE NEW DATA TAKING: ^{7}Li, ^{9}Be, ^{13}C, D_2O



^{13}C	$-B_\Lambda$ (MeV)	E_X (MeV)	Formation probability per stopped K^- (10^{-3})
1	-11.0 ± 0.4	-	$0.10 \pm 0.02 \pm 0.01$
2	-6.5 ± 0.4	4.5	$0.19 \pm 0.02 \pm 0.03$
3	-3.4 ± 0.4	7.6	$0.16 \pm 0.02 \pm 0.02$
4	-0.3 ± 0.4	10.7	$0.17 \pm 0.02 \pm 0.02$
5	$+3.7 \pm 0.4$	14.7	$0.49 \pm 0.04 \pm 0.07$

the ground state from emulsion data $B_\Lambda = -11.22 \pm 0.08$ MeV
[M. Juric et al. Nucl. Phys. B 52 (1973) 1]



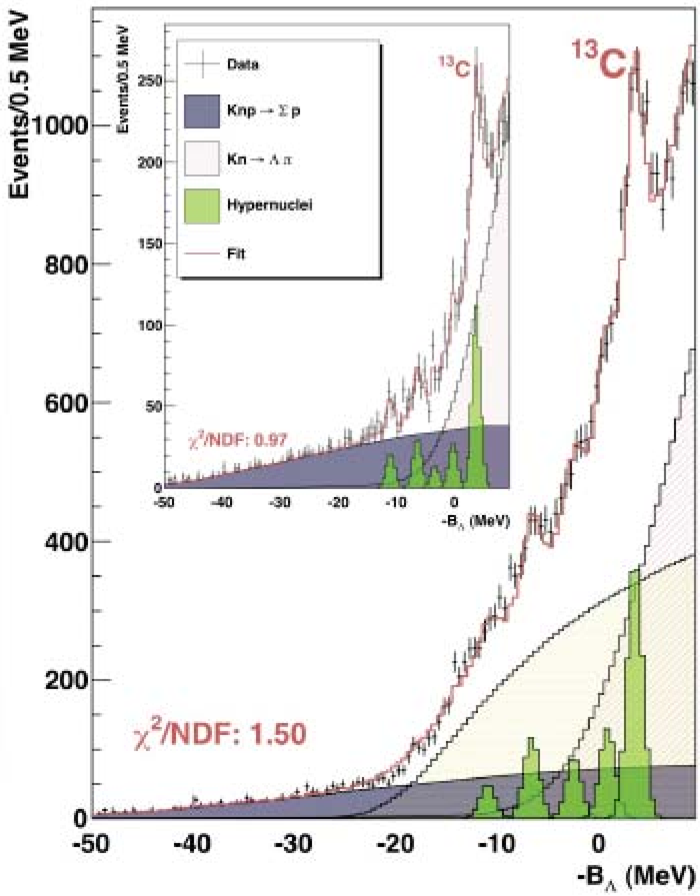
$B_\Lambda = -11.38 \pm 0.07$ MeV

comparison with:

KEK E336 esperiment: similar situation
emulsion experiment: g.s. within 2 σ

boost

HYPERNUCLEAR SPECTROSCOPY — FROM THE NEW DATA TAKING: ^{7}Li, ^{9}Be, ^{13}C, D$_2$O



^{13}C	$-B_\Lambda$ (MeV)	E_X (MeV)	Formation probability per stopped K^- (10^{-3})
1	-11.0 ± 0.4	-	$0.10 \pm 0.02 \pm 0.01$
2	-6.5 ± 0.4	4.5	$0.19 \pm 0.02 \pm 0.03$
3	-3.4 ± 0.4	7.6	$0.16 \pm 0.02 \pm 0.02$
4	-0.3 ± 0.4	10.7	$0.17 \pm 0.02 \pm 0.02$
5	$+3.7 \pm 0.4$	14.7	$0.49 \pm 0.04 \pm 0.07$

$(0.62 \pm 0.08 \pm 0.08) \times 10^{-3}$

FIRST WORLD MEASUREMENT of FORMATION PROBABILITY

PHYSICAL REVIEW C, VOLUME 65, 034607

$^{13}_{\Lambda}$C hypernucleus studied with the ^{13}C($K^-,\pi^-\gamma$) reaction

ceeded in measuring γ rays from the $1/2^-$ and $3/2^-$ states, which have predominantly a $[^{12}C_{g.s.}(0^+)\otimes p_\Lambda]$ configuration, to the GS in $^{13}_{\Lambda}$C by using NaI detectors. The splitting was found to be $\Delta E(1/2^- - 3/2^-) = +152 \pm 54$(stat) ± 36(syst) keV which was almost 20–30 times smaller than that of single particle states in nuclei around this mass region. The excitation energies of the $1/2^-$ and $3/2^-$ states were obtained as 10.982 ± 0.031(stat)± 0.056(syst) and 10.830 ± 0.031(stat)± 0.056(syst) MeV, respectively. The $j_\Lambda = \ell_\Lambda - 1/2[(p_{1/2})_\Lambda]$ state appeared higher in energy, as in normal nuclei, which is consistent with theoretical predictions. We also observed γ rays from the $3/2^+$ state to the GS in $^{13}_{\Lambda}$C, and the excitation energy of the state was obtained as 4.880 ± 0.010(stat)± 0.017(syst) MeV.

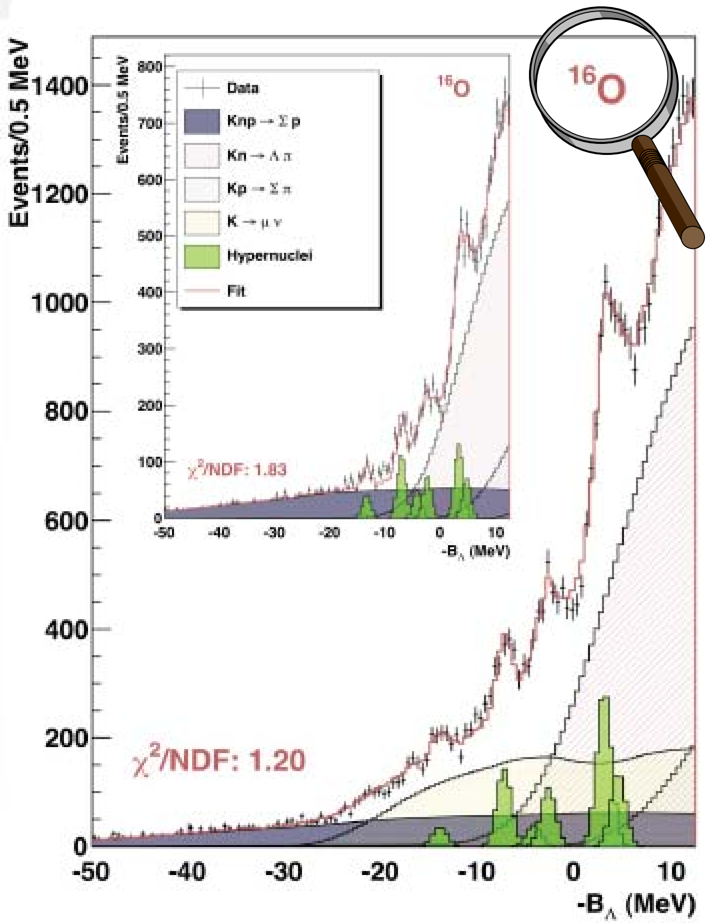
strangeness in nuclei | trento, 4-8 october 2010 18 germano bonomi | FINUDA hypernuclear spectroscopy

boost

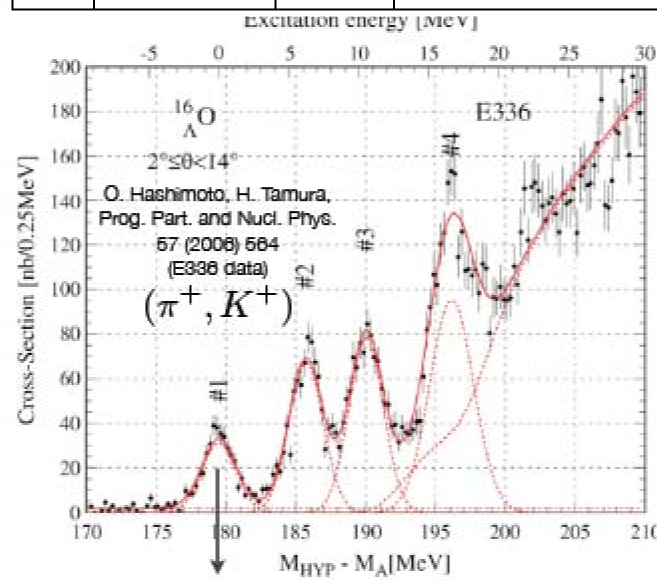
comparison with:

H. Kohri et al., Phys. Rev. C 65 (2002) 034607 (γ-ray): excited states compatible with peaks #2 and # 4

HYPERNUCLEAR SPECTROSCOPY | FROM THE NEW DATA TAKING: ^{7}Li, ^{9}Be, ^{13}C, D_2O



^{16}O	$-B_\Lambda$ (MeV)	E_X (MeV)	Formation probability per stopped K^- (10^{-3})
1	-13.4 ± 0.4	-	$0.10 \pm 0.02 \pm 0.01$
2	-7.1 ± 0.4	6.3	$0.26 \pm 0.04 \pm 0.04$
3	-4.3 ± 0.4	9.1	$0.13 \pm 0.03 \pm 0.02$
4	-2.4 ± 0.4	11.0	$0.15 \pm 0.03 \pm 0.02$
5	$+3.3 \pm 0.4$	16.7	$0.55 \pm 0.07 \pm 0.08$
6	$+4.7 \pm 0.4$	18.1	$0.28 \pm 0.06 \pm 0.04$



$B_\Lambda = -12.42 \pm 0.05$ MeV

strangeness in nuclei | trento, 4-8 october 2010 19 germano bonomi | FINUDA hypernuclear spectroscopy

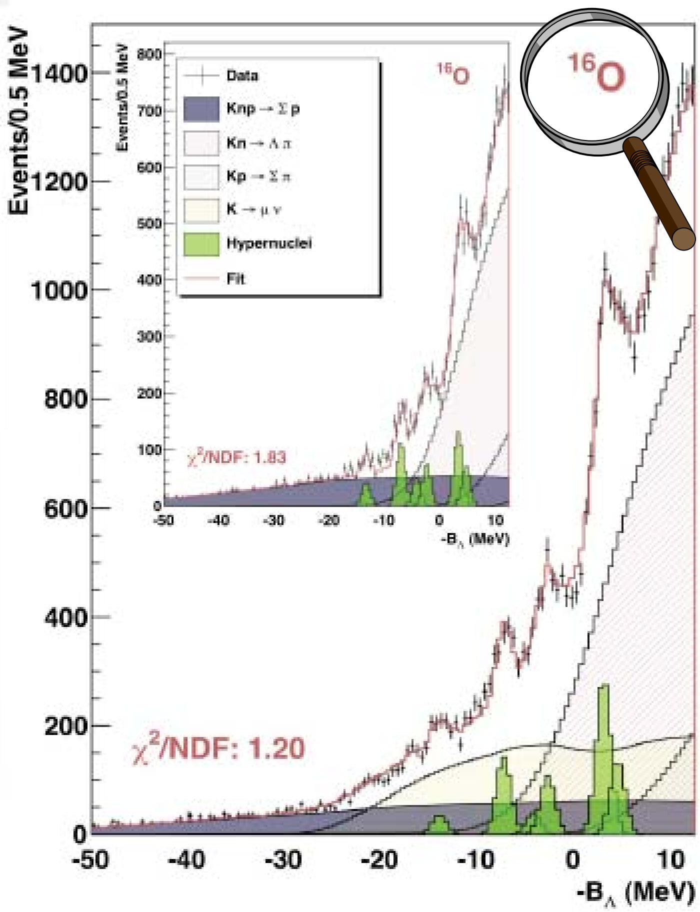
boost

comparison with:

- KEK E336 esperiment: g.s. not compatible
- H. Tamura et al. Prog. Theor. Phys. Suppl. 117 (1994) 1 (stopped K^-): g.s. in agreement
- F. Cusanno et al., Phys. Rev. Lett. 103 (2009) 202501 (electroproduction): g.s. in agreement

A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

HYPERNUCLEAR SPECTROSCOPY | FROM THE NEW DATA TAKING: ^{7}Li, ^{9}Be, ^{13}C, D_2O



^{16}O	$-B_\Lambda$ (MeV)	E_X (MeV)	Formation probability per stopped K^- (10^{-3})
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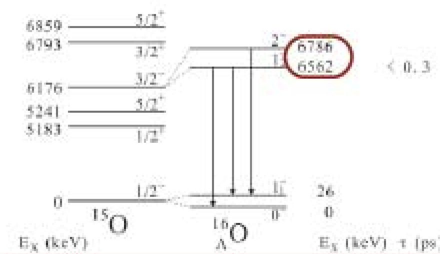
6	$+4.7 \pm 0.4$	18.1	$0.28 \pm 0.06 \pm 0.04$

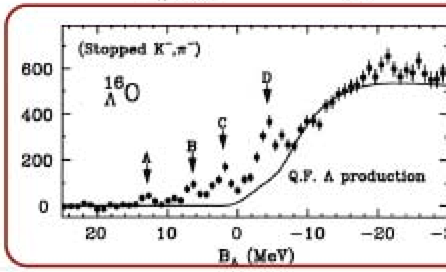
$^{16}O_\Lambda$ (rows 1–2)

$^{15}N_\Lambda$ (rows 3–6)

$(0.36 \pm 0.06 \pm 0.05) \times 10^{-3}$

PHYSICAL REVIEW C 77, 054315 (2008)





H. Tamura et al.
Prog. Theor. Phys. Suppl.
117 (1994) 1

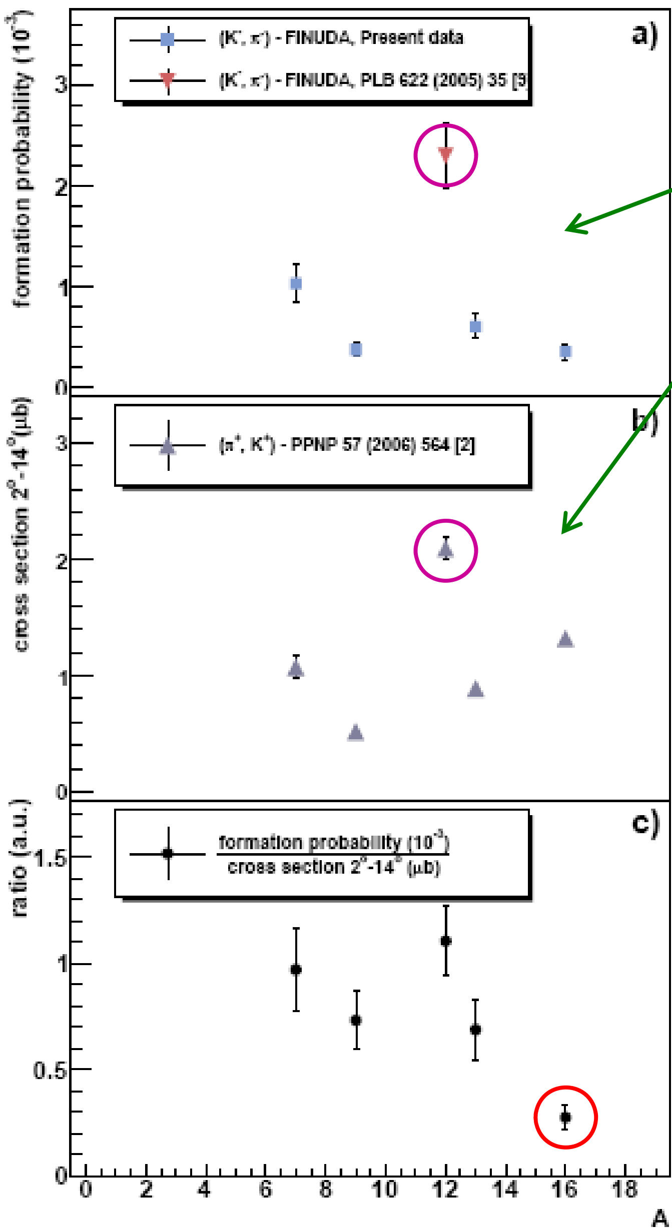
strangeness in nuclei | trento, 4-8 october 2010 | 20 | germano bonomi | FINUDA hypernuclear spectroscopy

boost

comparison with:

H. Tamura et al., Prog. Theor. Phys. Suppl. 117 (1994) 1 (stopped K^-): excited state @ 6.3 MeV in agreement

Un unsatisfactory summary



particle (p) stable levels only

formation probability: decreasing trend vs. A

however:

different measurements
for the same g.s.
formation probability
give different value

need for a coherent picture

systematics on A is a helpful tool

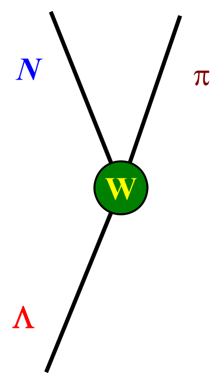
Λ-hypernucleus decay

A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

Λ-hypernucleus decay

free Λ decay

$p_N \sim$ 100 MeV/c



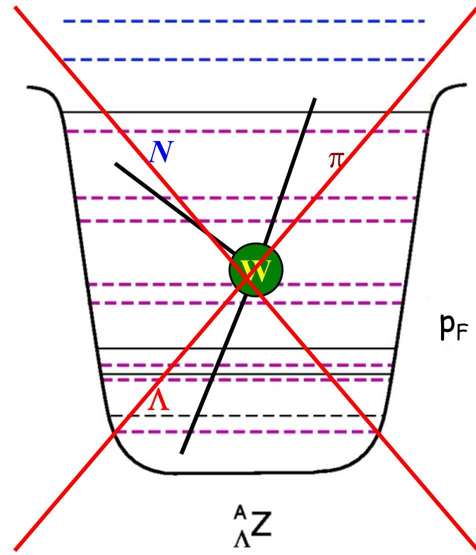
$\Lambda \rightarrow n + \pi^0 + 41$ MeV (36%)

$\Lambda \rightarrow p + \pi^- + 38$ MeV (64%)

$\tau_\Lambda = 263$ ps

ΔI = ½ rule
(not understood)

hypernucleus mesonic decay

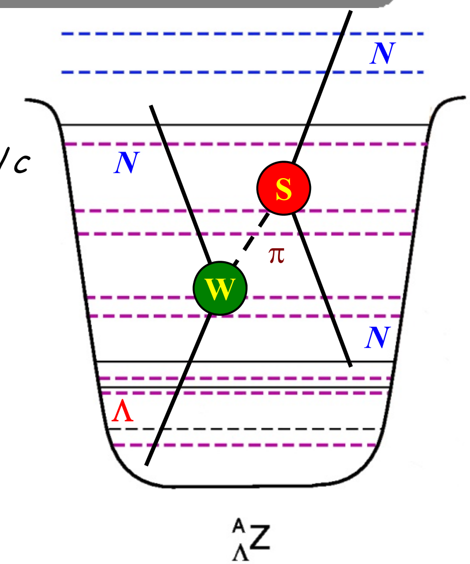


$p_F \sim$ 270 MeV/c

suspressed by Pauli blocking

hypernucleus non-mesonic decay

$p_N \sim$ 400 MeV/c



$\Lambda + n \rightarrow n + n + 176$ MeV

$\Lambda + p \rightarrow n + p + 176$ MeV

dominant in all but the lightest hypernuclei

Some notations

- $\Gamma_{tot} = \Gamma_{MWD} + \Gamma_{NMWD}$
  - $\Gamma_{MWD} = \Gamma_{\pi 0} + \Gamma_{\pi -}$ $(\Lambda \to n + \pi^0) + (\Lambda \to p + \pi^-)$
  - $\Gamma_{NMWD} = \Gamma_{1N} + \Gamma_{2N}$
    - $\Gamma_{1N} = \Gamma_n + \Gamma_p$ $(\Lambda n \to nn) + (\Lambda p \to np)$
    - $\Gamma_{2N} = \Gamma_{np} + \Gamma_{pp} + \Gamma_{nn}$ $(\Lambda np \to nnp) + (\Lambda pp \to npp) + (\Lambda nn \to nnn)$
- $\Gamma_{tot} = \Gamma_{\pi 0} + \Gamma_{\pi -} + \Gamma_n + \Gamma_p + \Gamma_{np} + \Gamma_{pp} + \Gamma_{nn}$

Physics motivations & open questions

- Experimental observables

τ, $\Gamma_{\pi^-,\pi^0}/\Gamma_\Lambda$, (single) particle decay spectra, $\Gamma_{n,p,2N}/\Gamma_\Lambda$, Γ_n/Γ_p

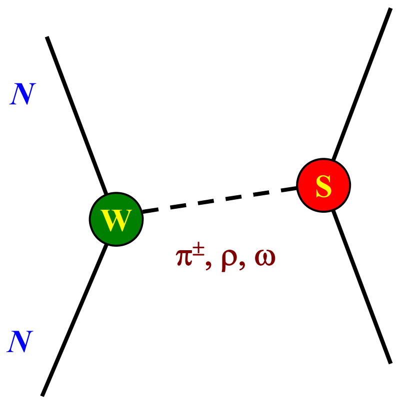
- MWD
  - J^π assignment: new indirect spectroscopic tool
  - ΛN interaction potential
  - π^--nucleus optical potential
- NMWD
  - 4-baryon strangeness-changing weak interaction
  - $\Delta I=1/2$ from *s*-shell ($^4_\Lambda H$) and heavy hypernuclei
  - Γ_n/Γ_p puzzle (solved ? … systematics)
  - Γ_{2N}, FSI contributions

KEK & LNF results

4 baryon weak interaction

The hypernucleus non-mesonic decay provides primary means of studying the baryon-baryon weak interaction

N-N scattering

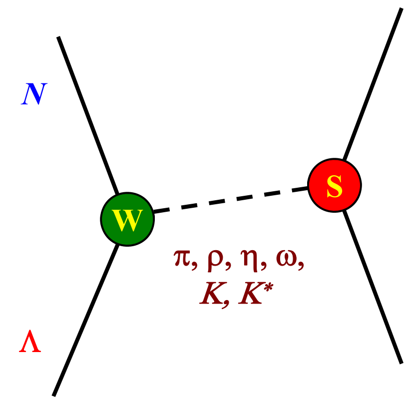


ΔS = 0

- only information on the parity violating part of weak interaction is accessible
- parity conserving part is masked by strong interaction

Λ + N → N + N

in nuclear medium only



ΔS = 1

- both information on the parity violating and parity conserving parts of weak interaction can be extracted
- q ~ 400 MeV/c ⇒ probes short distance

☛ Δ = ½ rule applies also to non-mesonic weak decay?

☛ The role of explicit quark/gluon substructures can be put in evidence?

MWD & NMWD studies in FINUDA

Coincidence measurement

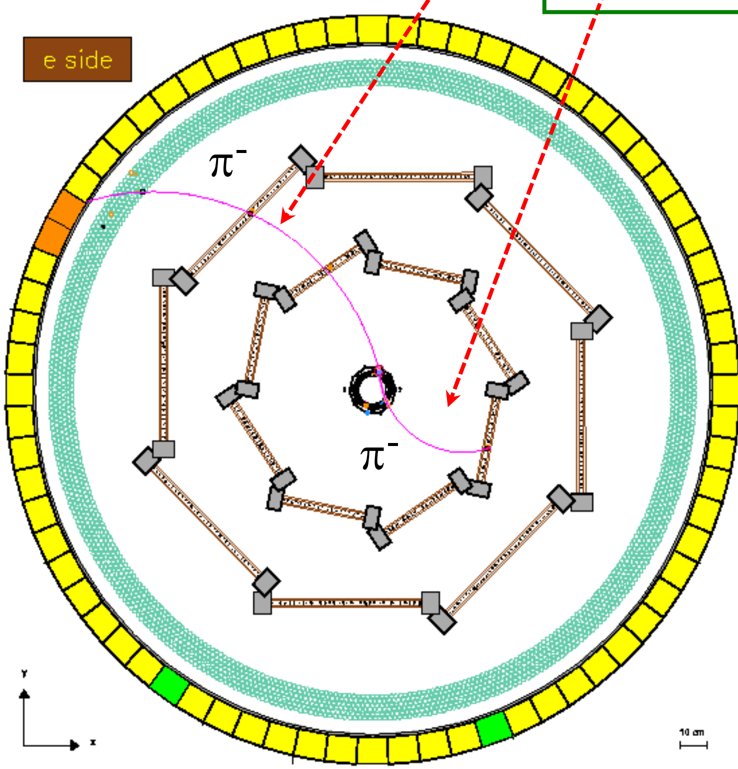
A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

charged Mesonic channel

$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$
$$ {}^{A}_{\Lambda}Z \rightarrow {}^{A}(Z+1) + \pi^-$$

S-EX
260-280 MeV/c

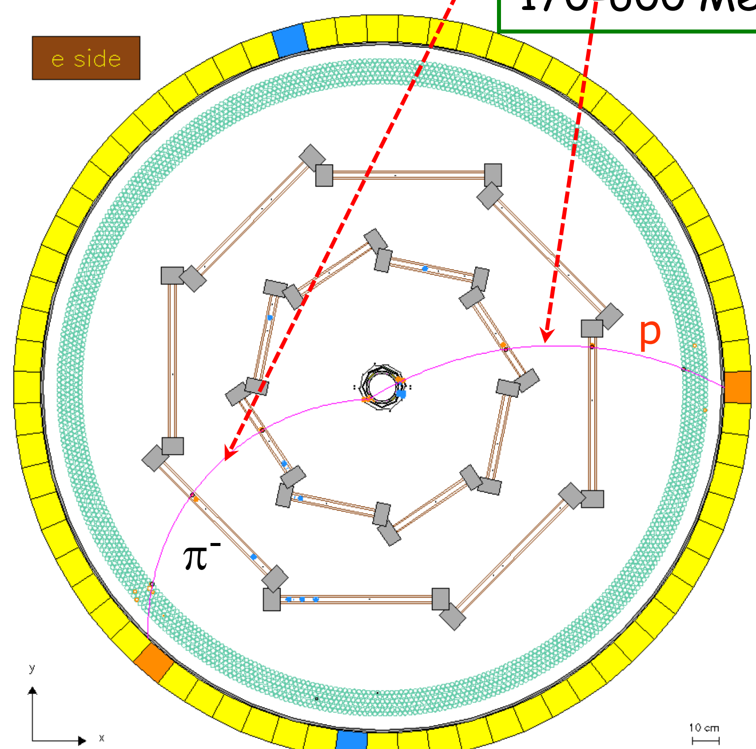
MWD
80-110 MeV/c



charged Non-Mesonic channel

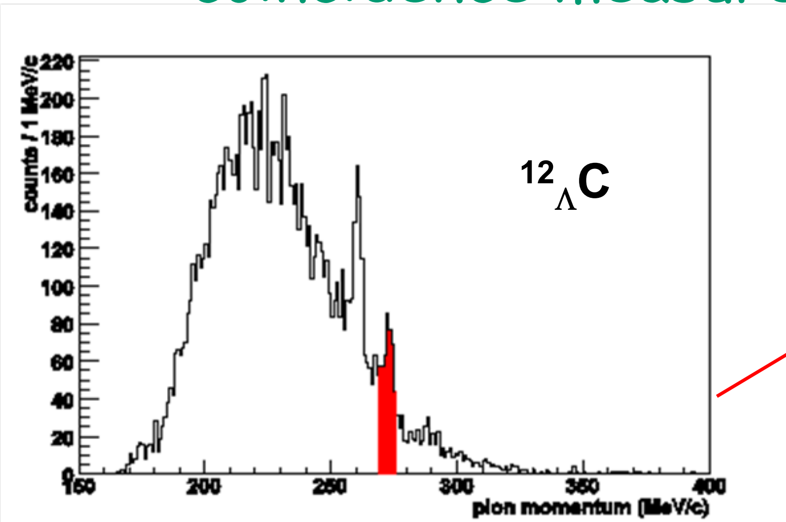
$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$
$$ {}^{A}_{\Lambda}Z \rightarrow {}^{A-2}(Z-1) + p + n$$

NMWD
170-600 MeV/c



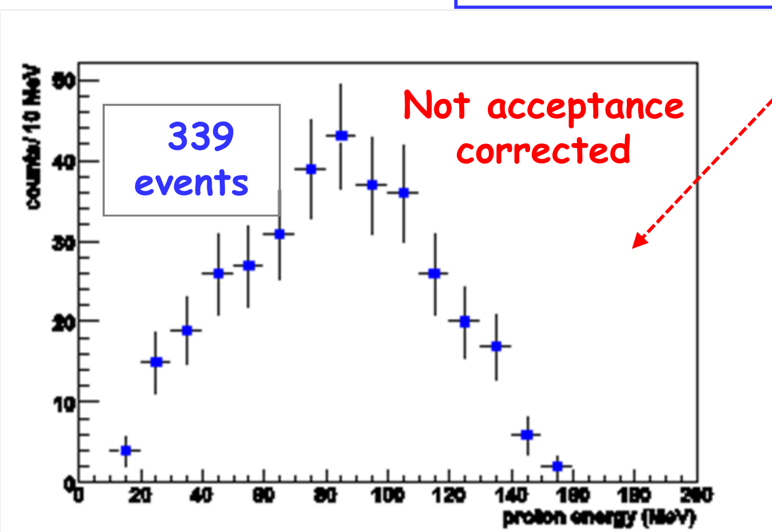
non-mesonic weak decay

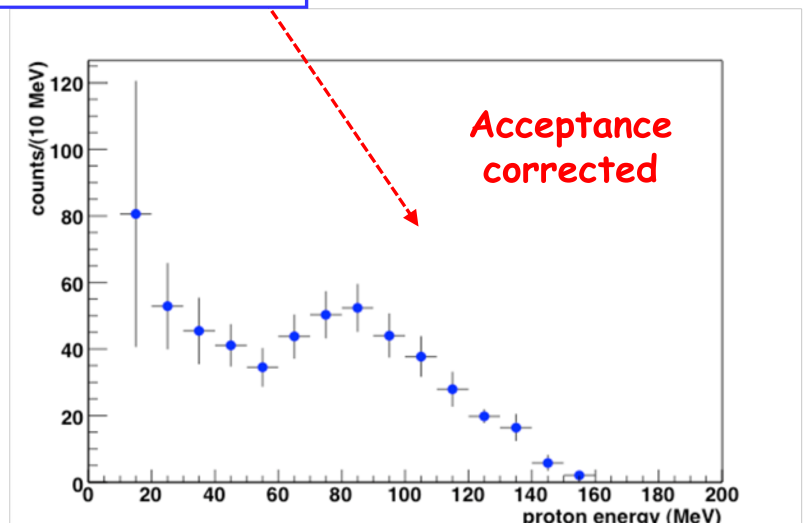
NMWD: p spectra @ LNF
coincidence measurement: method



- Spectrum of negative pions for events in which a proton is detected in coincidence with a π^-
- Asking for the proton coincidence a clear peak emerges at 272 MeV/c (ground state)

Proton energy spectrum from $^{12}_{\Lambda}C$ p-induced NMWD before and after the acceptance correction





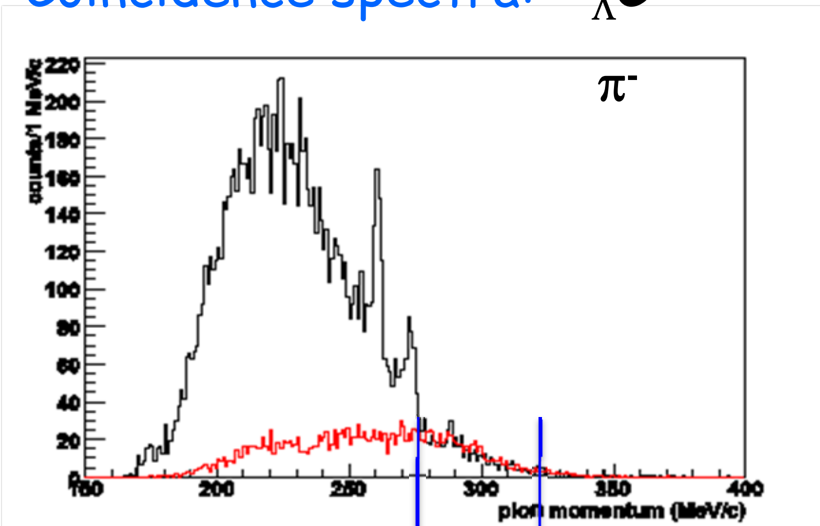
Coincidence measurement: FINUDA method

background reaction: $K^- np \to \Sigma^- p$

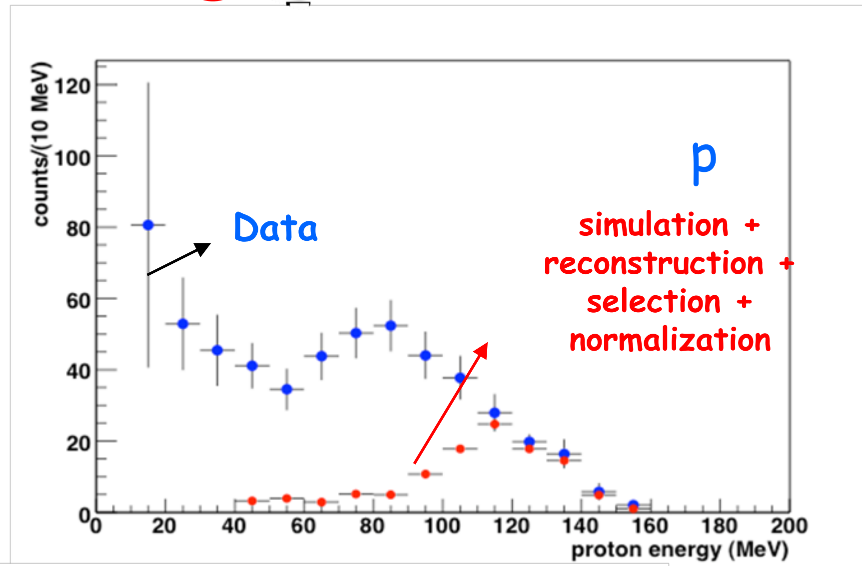
$\Sigma^- \to n \pi^-$

coincidence

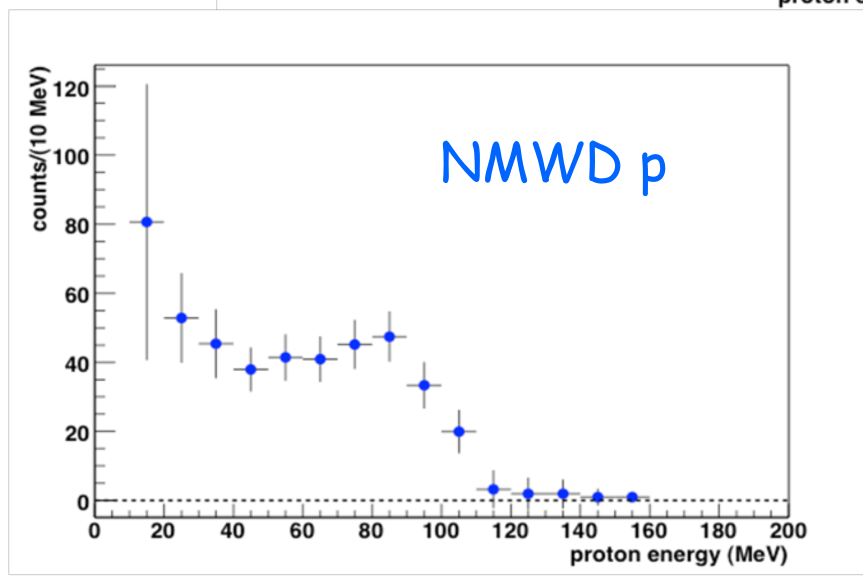
Coincidence spectra: $^{12}{}_{\Lambda}C$



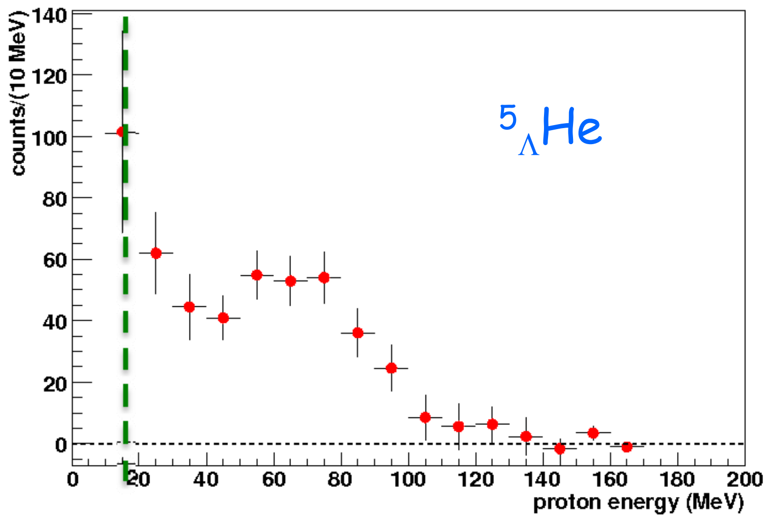
normalization region

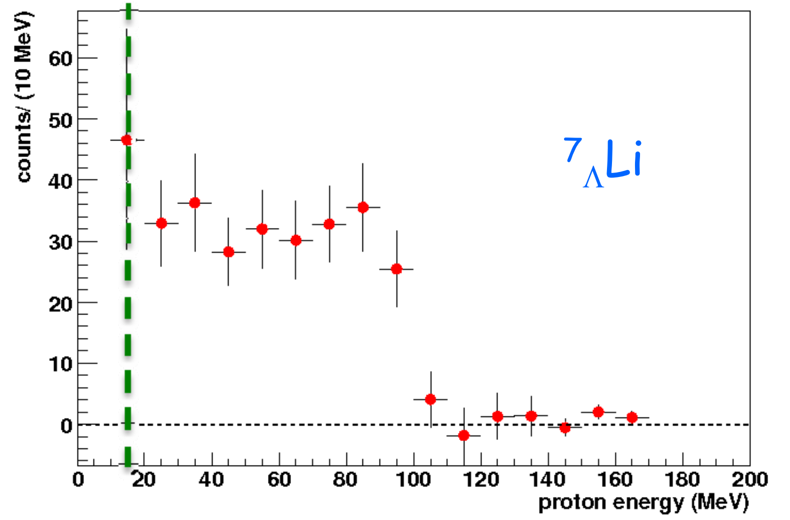


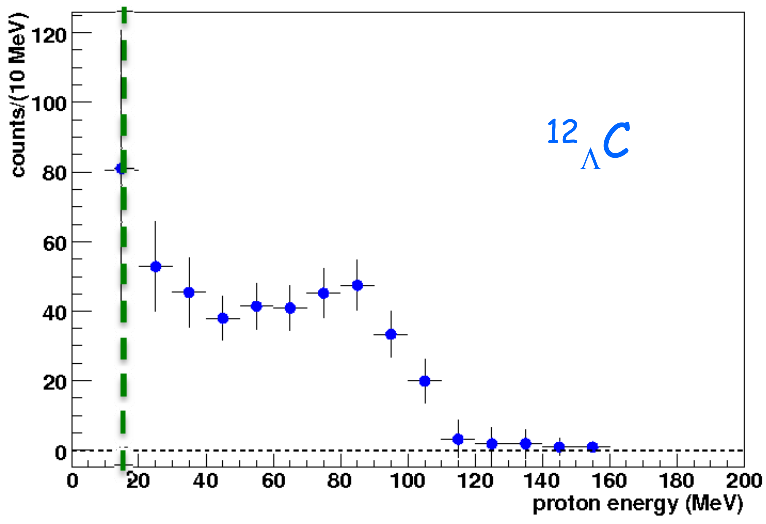
subtraction



M. Agnello et al., NPA 804 (2008) 151



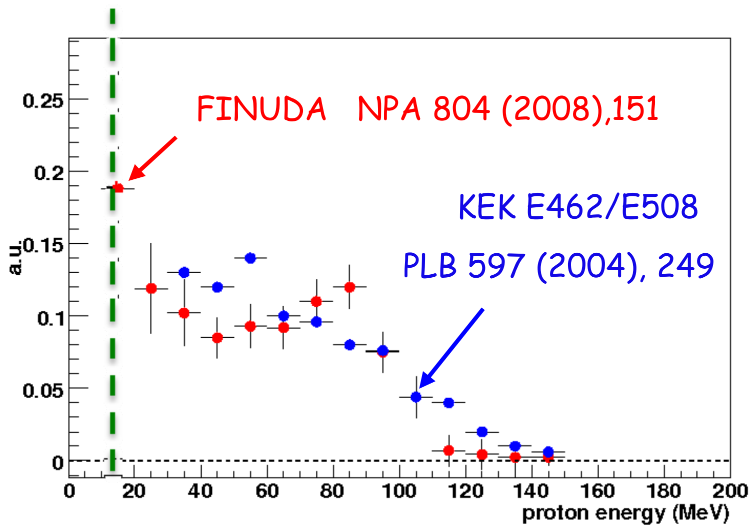




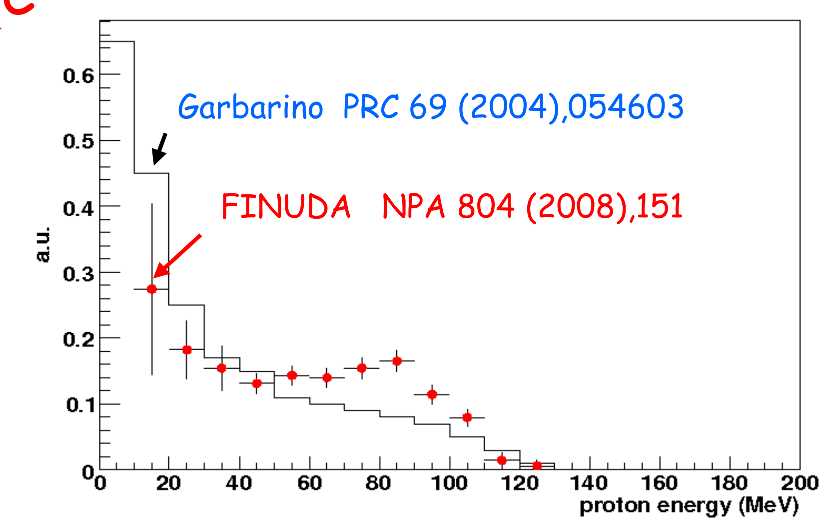
✓ Similar shape for $^5{}_\Lambda$He, $^7{}_\Lambda$Li and $^{12}{}_\Lambda$C
✓ Peak at ~ 80 MeV (Q/2 value), broadened by N Fermi motion, visible even for $^{12}{}_\Lambda$C → no strong FSI effect in low energy region
✓ FSI & 2N contribution in the low energy region?

Comparisons with theory and KEK results

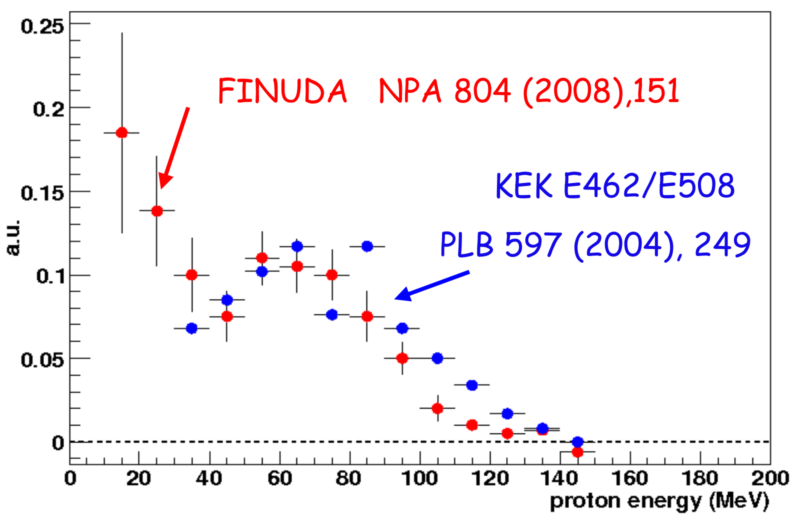
15 MeV threshold !

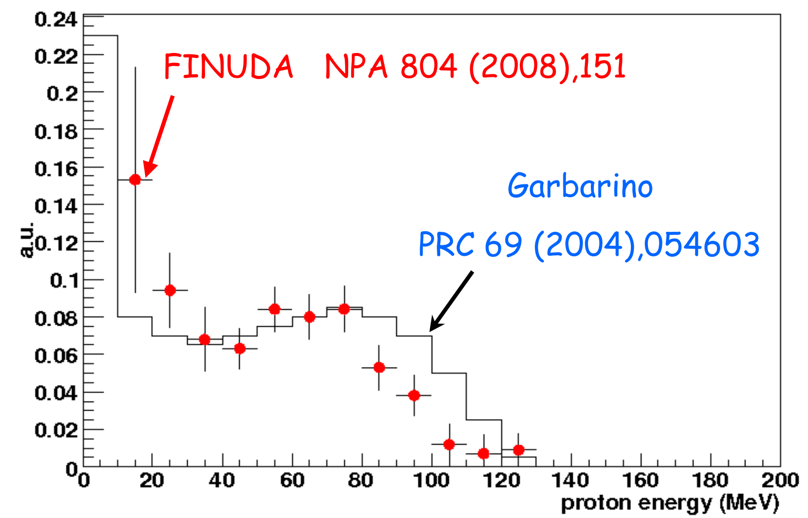


$^{12}{}_{\Lambda}C$



$^{5}{}_{\Lambda}He$





Comparisons with theory and KEK results

- Comparison between FINUDA and KEK data: normalization beyond 35 MeV (KEK data threshold)
- Kolmogorov-Smirnov test: 75% compatibility for $^{5}_{\Lambda}$He, 20% for $^{12}_{\Lambda}$C

- Comparison between FINUDA and theory: normalization beyond 15 MeV (FINUDA data threshold)
- Kolmogorov-Smirnov test: 80% compatibility for $^{5}_{\Lambda}$He, 5% for $^{12}_{\Lambda}$C

Strong disagreement between experiments and with theory

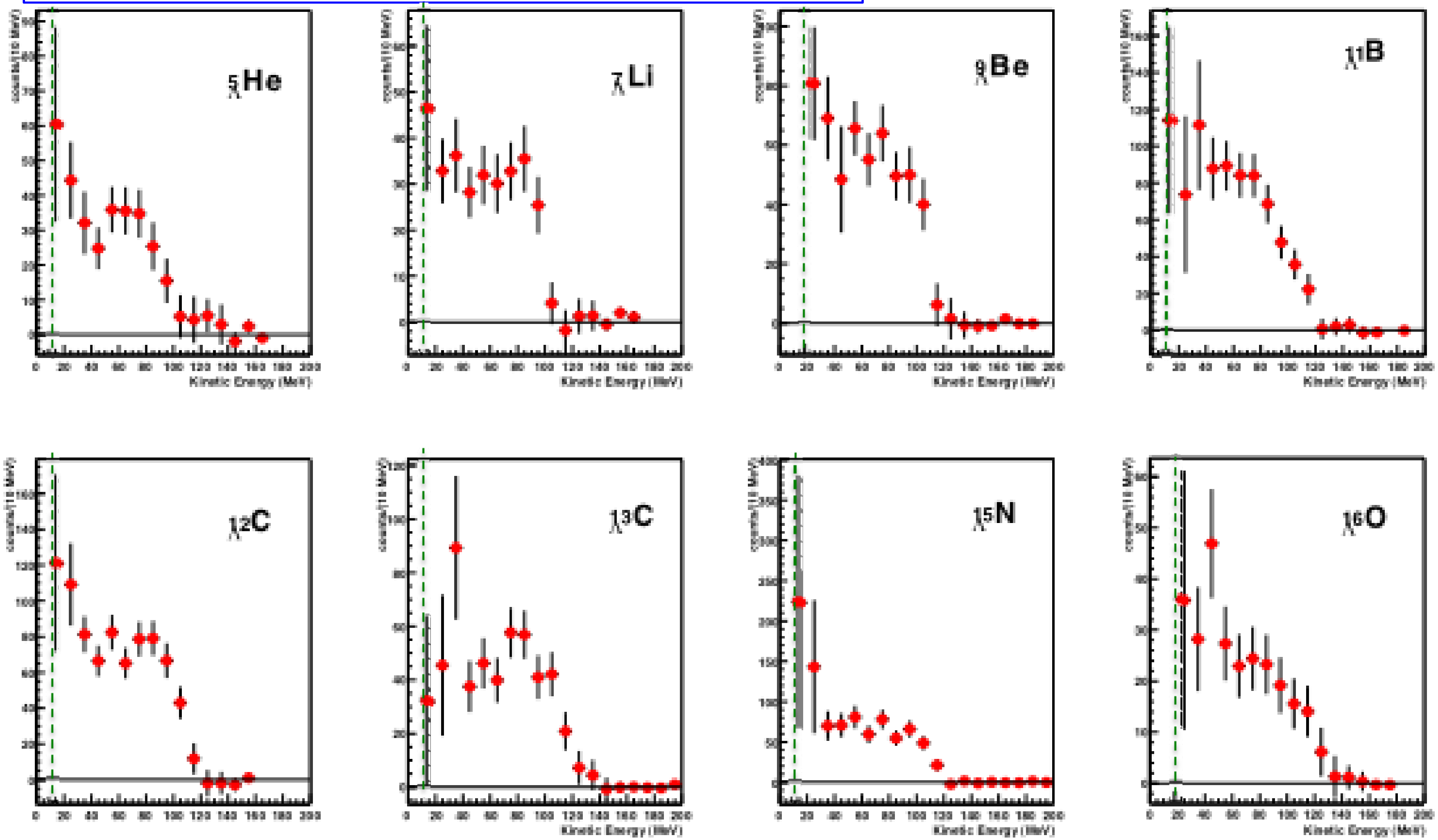
- KEK: thick targets $\rightarrow$ strong correction
  FINUDA: thin targets & transparent detectors
- KEK: p energy from TOF and range + dE/dx $\rightarrow$ poor energy resolution above 100 MeV, distortion
  FINUDA: p momentum from magnetic analysis, 2% energy resolution FWHM @ 80 MeV, no distortion

- Inputs of calculations

NMWD p spectra p-shell hypernuclei

LNF FINUDA – M.Agnello et al., PLB 685 (2010) 247

Background subtracted & acceptance corrected

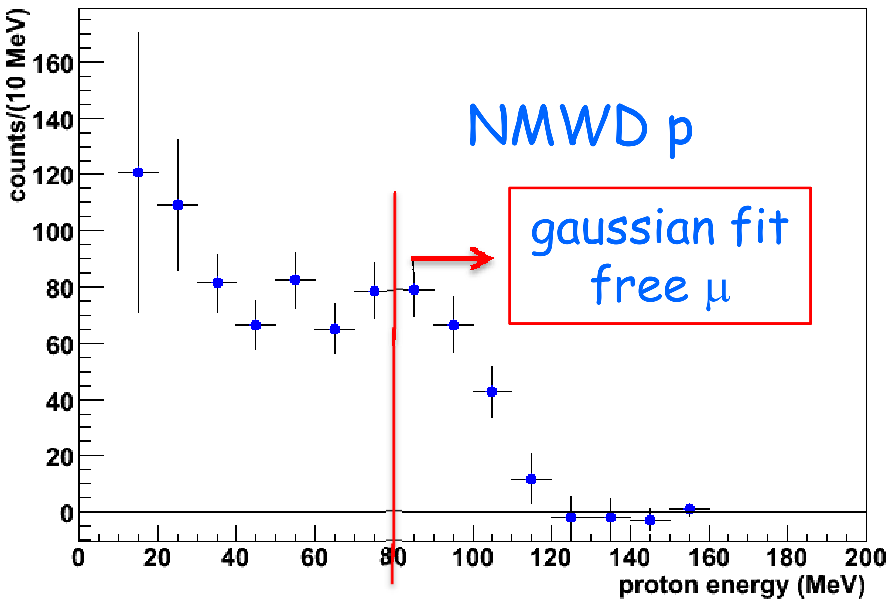


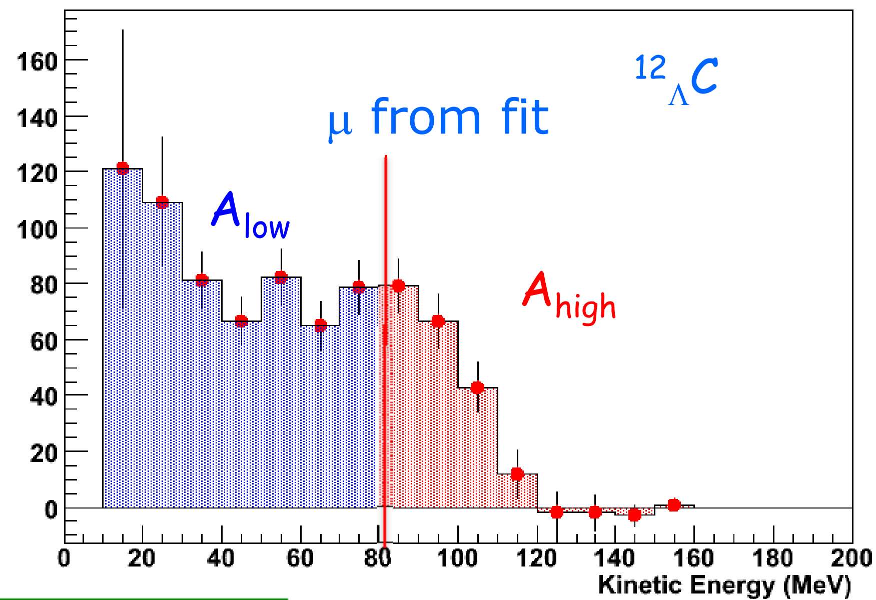
NMWD: Γ_{2N}

LNF – FINUDA M.Agnello et al., PLB 685 (2010) 247

$\Gamma_{2N}/\Gamma_{NMWD}$ & Γ_n/Γ_p independent on A ⇐ assumption

W. Alberico and G. Garbarino, Phys. Rev. 369 (2002) 1.





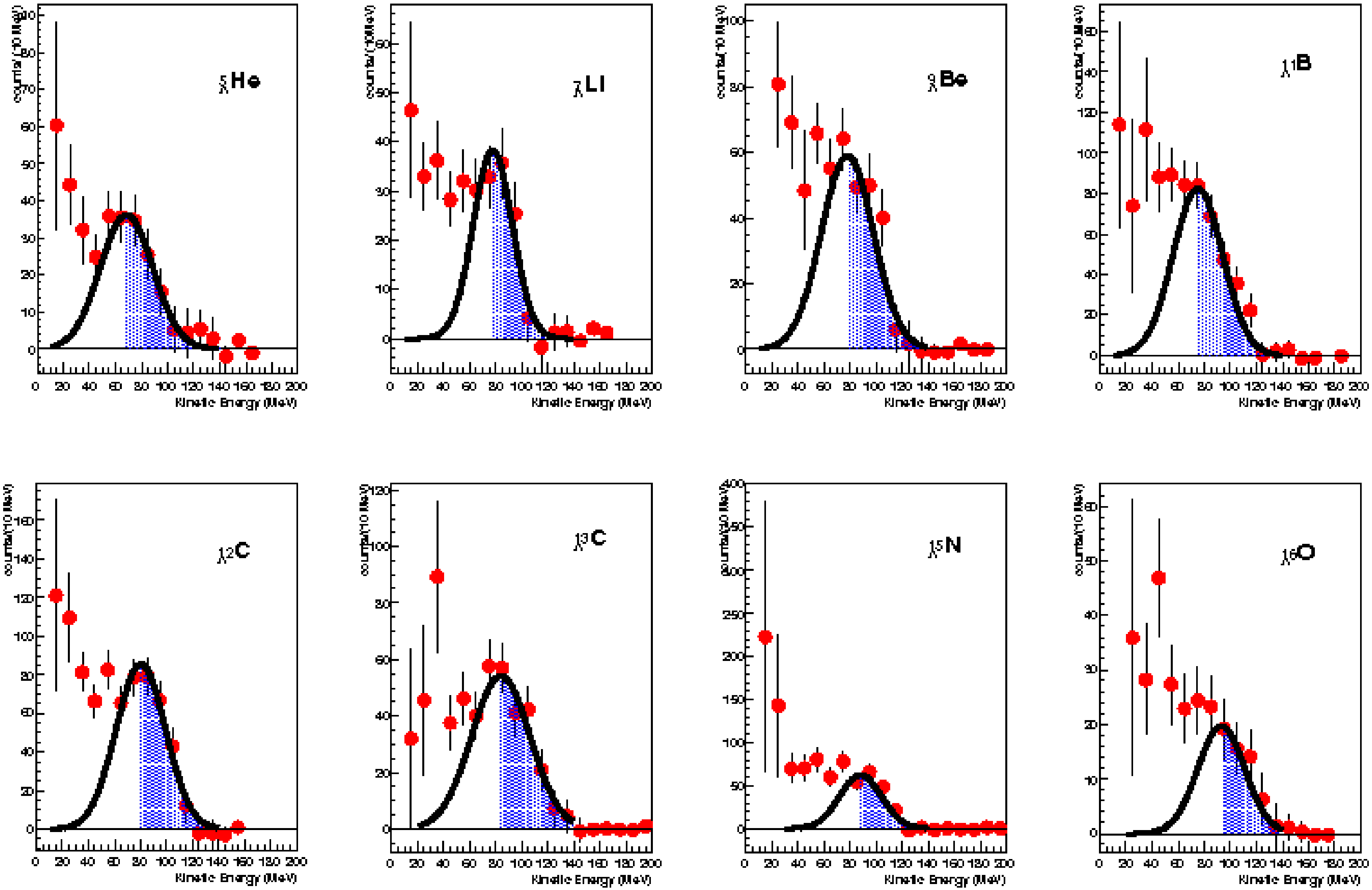
A_{low}: spectrum area below μ
1N + 2N + FSI

A_{high}: spectrum area above μ
1N + FSI ⇐ assumption
2N (>70 MeV) ~ 5% $2N_{tot}$

G. Garbarino, A. Parreno and A. Ramos, Phys.Rev.Lett. 91 (2003) 112501.
Phys.Rev. C 69 (2004) 054603.

NMWD: Γ_{2N}

FSI & ΛNN contribution evaluation: systematics



A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

NMWD: Γ_{2N}

FSI & ΛNN contribution evaluation

$$A_{low} = 0.5\, N_p(\Lambda p \to np) + N_p(\Lambda np \to nnp) + N_p^{FSI\text{-}low}$$

$$A_{high} = 0.5\, N_p(\Lambda p \to np) + N_p^{FSI\text{-}high}$$

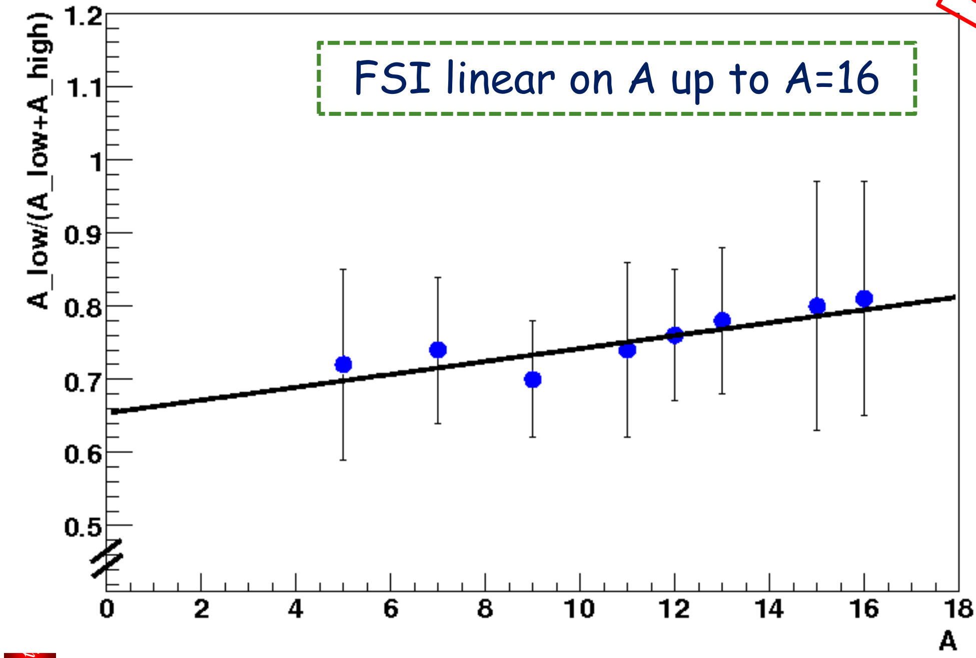
$$\frac{N_p(\Lambda np \to nnp)}{N_p(\Lambda p \to np)} = \frac{\Gamma_{np}}{\Gamma_p} \approx \frac{\Gamma_2}{\Gamma_p}$$

⇐ assumption

$$\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$$

E. Bauer and G. Garbarino,
Nucl. Phys. A 828 (2009) 29.

$$R = \frac{A_{low}}{A_{low} + A_{high}} = \frac{0.5\, N_p(\Lambda p \to np) + N_p(\Lambda np \to nnp) + N_p^{FSI\text{-}low}}{N_p(\Lambda p \to np) + N_p(\Lambda np \to nnp) + N_p^{FSI\text{-}low} + N_p^{FSI\text{-}high}}$$



systematics: all p-shell

$$R(A) = a + b\,A = \frac{0.5 + \Gamma_2/\Gamma_p}{1 + \Gamma_2/\Gamma_p} + b\,A$$

Assumption: Γ_2/Γ_1 and Γ_n/Γ_p independent from A→ supported by exp and theory

$$\frac{\Gamma_2}{\Gamma_p} = \frac{[R(A) - bA] - 0.5}{1 - [R(A) - bA]} = 0.43 \quad 0.25$$

weighted mean

$$\frac{\Gamma_2}{\Gamma_{NM}} = \frac{\Gamma_2/\Gamma_p}{\Gamma_n/\Gamma_p + 1 + \Gamma_2/\Gamma_p} = 0.24 \quad 0.10$$

Bhang et al., EPJ A33 (2007) 259.

Bauer et al., NPA 828 (2009) 29

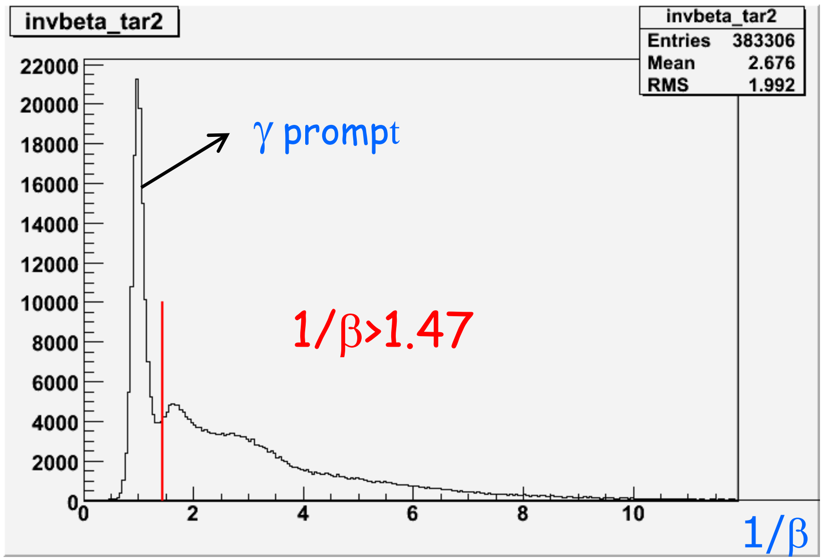
Bhang et al., EPJ A33 (2007) 259: ~ 0.4 $^{12}_{\Lambda}C$

M. Kim et al., PRL 103 (2009) 182502: 0.29 0.13 $^{12}_{\Lambda}C$

J.D.Parker et al., PRC 76 (2007), 035501: ≤ 0.24 (95% CL) $^{4}_{\Lambda}He$

NMWD: Γ_{2N}

NMWD: n+p coincidence @ FINUDA



n detection efficiency ~10%

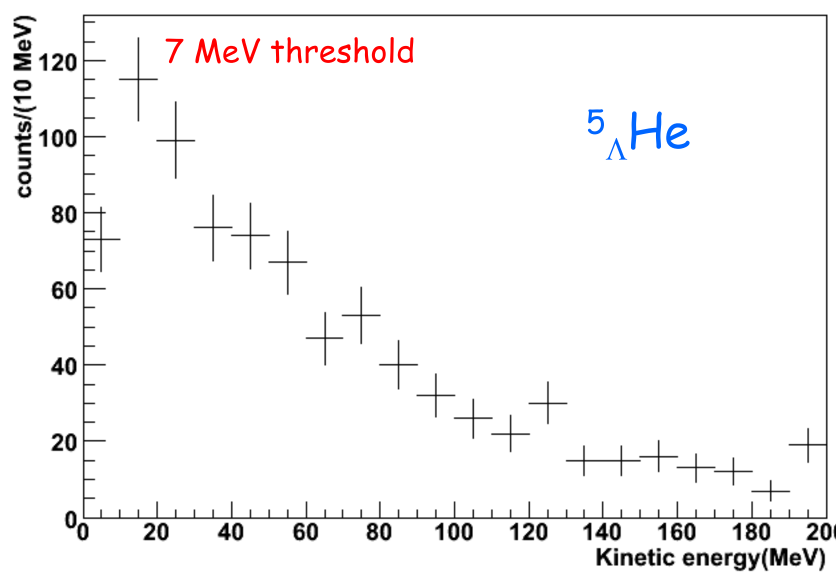
n energy resolution ~9% at 80 MeV

TOF allows n/γ discrimination

background prevails if no correlations or selections are imposed

$n + \pi^-_{bound}$

single n spectra shape cannot be directly analyzed due to background



Triple coincidence analysis

Analysis of (π-,n,p) coincidence

N_n (cosθ≥ - 0.8, E_p< μ–20 MeV): 2N + FSI and small contribution of 1N

N_n = number of n in coincidence with (π-,p)

Number of neutrons for all targets (from A=5 to A=16)

No spectra shape analysis (20 events for each target)

Background study (events from K^-np absorption)

Acceptance correction

Normalization to the number of protons with energy greater than the μ value of the gaussian fits of the proton spectra from FINUDA Coll. and G. Garbarino, PLB 685 (2010) 247

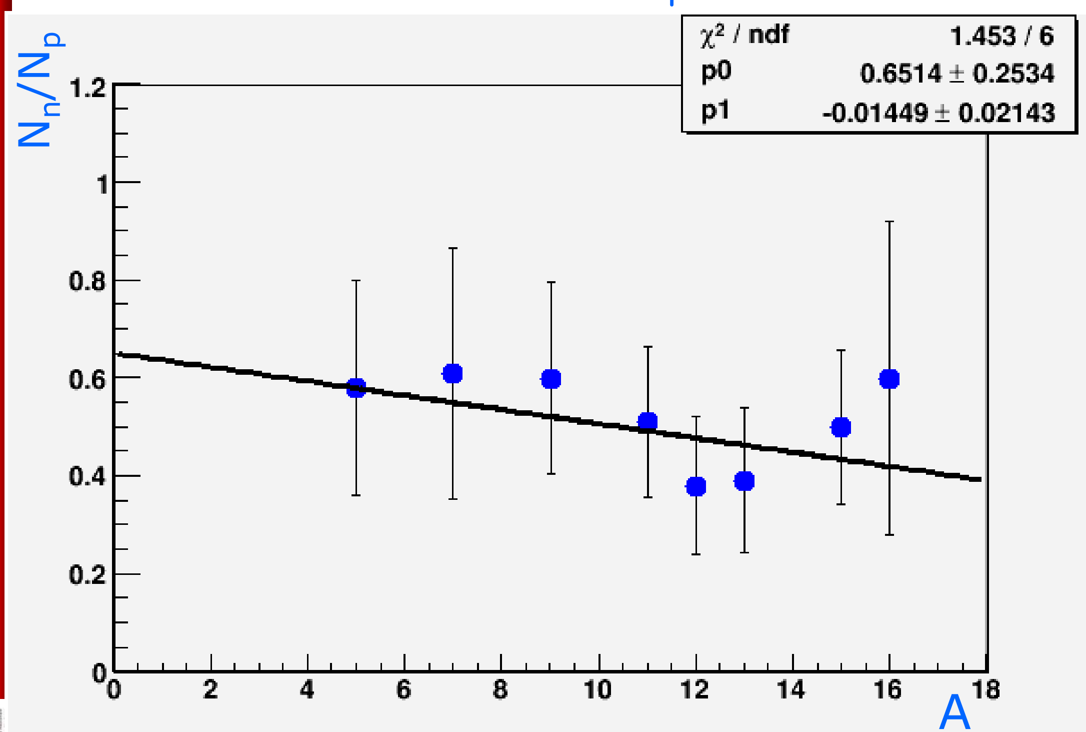
NMWD: Γ_{2N}

systematics: all *p*-shell

$$R(A) = \frac{N_n\,(\cos\theta \geq -0.8,\ E_p < \mu - 20\ \text{MeV})}{N_p\,(E_p > \mu\ \text{p single spectra fit})} = \frac{N_n(\Lambda np \rightarrow nnp) + N^{FSI}}{0.5\,N_p(\Lambda p \rightarrow np) + N^{FSI}}$$

$$R(A) = a + b\,A = \frac{\Gamma_2}{0.5\,\Gamma_p} + b\,A$$

Γ_2/Γ_p not dependent on *A*



weighted mean

$\Gamma_2/\Gamma_p = 0.36\ \ 0.07$

$\Gamma_2/\Gamma_{NM} = 0.20\ \ 0.03$

8% due to systematics

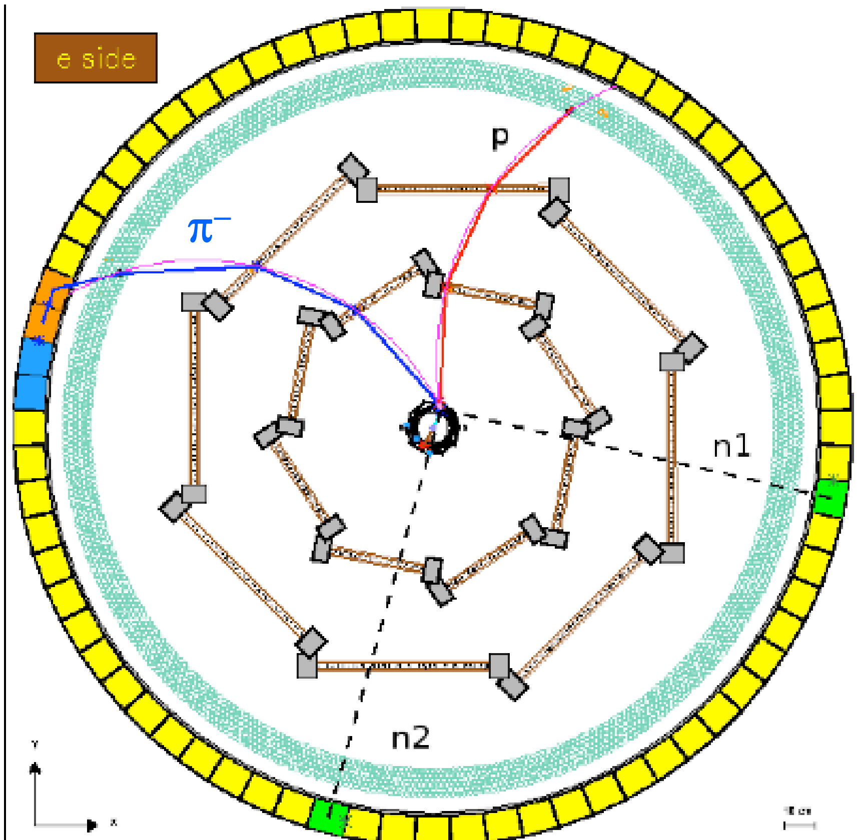
- direct measurement
- error lowered by a factor 3

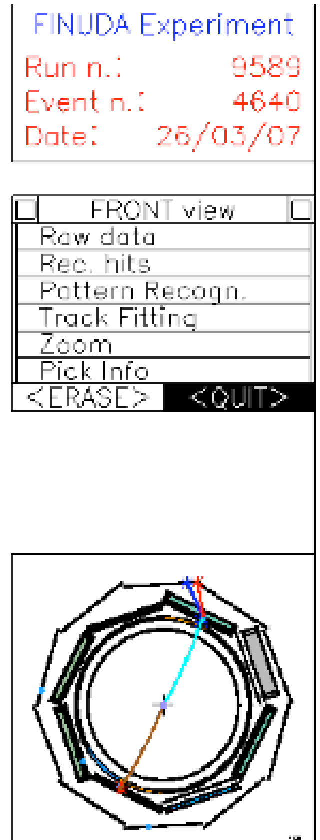
A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

NMWD: Γ_{2N}

Triple coincidence (n+n+p) events @ FINUDA

exclusive $\Lambda np \rightarrow nnp$ $^{7}_{\Lambda}Li \rightarrow {}^{4}He + p + n + n$ decay event





$p_{\pi-}$ = 276.93 MeV/c
E_{tot} = 178.3 MeV
Q-value = 167 MeV
p miss = 216.6 MeV/c

E(n1) = 110.2 MeV
E(n2) = 16.9 MeV
E(p) = 51.0 MeV

θ (n1 n2) = 95°
θ(n1 p) = 102°
θ(n2 p) = 154°
no n-n or p/n scattering

First direct experimental evidence of 2N-induced NMWD !!!

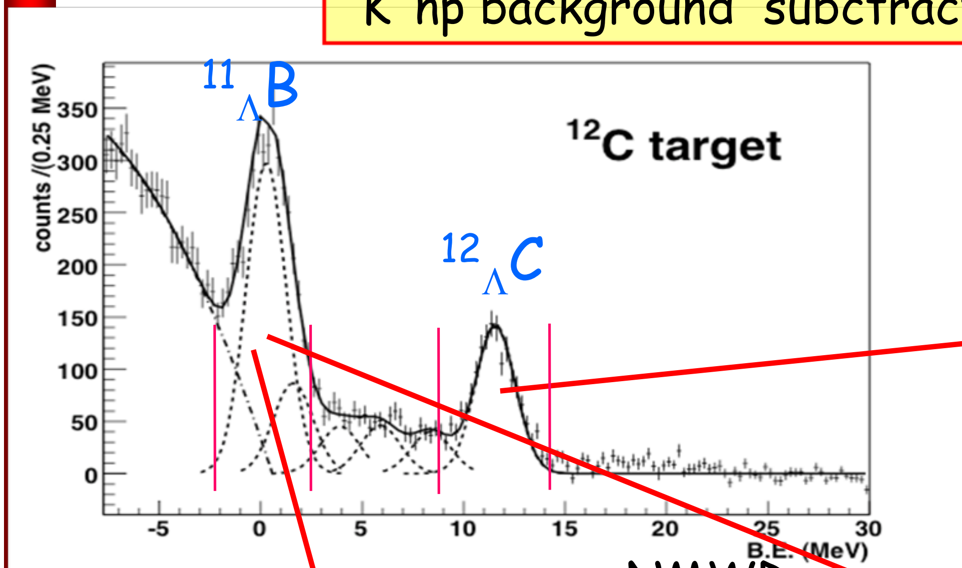
mesonic weak decay

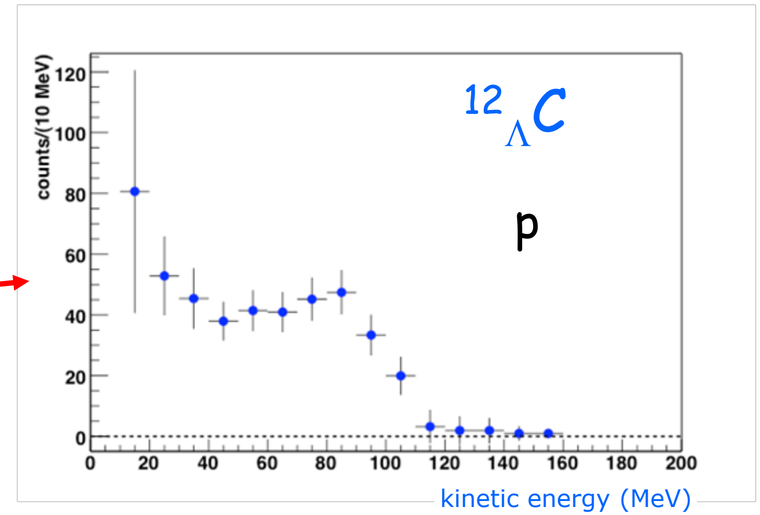
MWD: p-shell hypernuclei

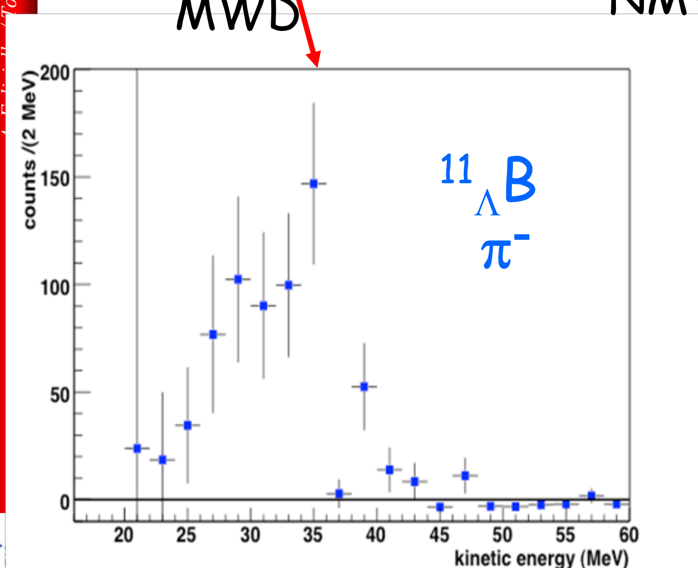
- MWD Pauli forbidden (p_N~100 MeV/c)
- theoretical calculations with pion distorted wave predict MWD to be less suppressed for p-shell (A~10)
- π feels attraction in nuclear medium due to the p-wave part of the optical potential → dispersion relation modified inside the nucleus → pion carries lower energy for fixed momentum q: $\omega(q) = (q^2+m_\pi^2)^{1/2}$ → energy conservation increases the final nucleon chance to come out above the Fermi surface
- Enhancement of MWD:
  - Bando et al., Progr. Theor. Phys. Suppl. 72 (1984) 109
  - Oset et al., NPA 443 (1985) 704
- Extensive calculations:
  - Motoba et al., Progr. Theor. Phys. Suppl. 117 (1994) 477
  - Gal Nucl. Phys. A 828 (2009) 72.

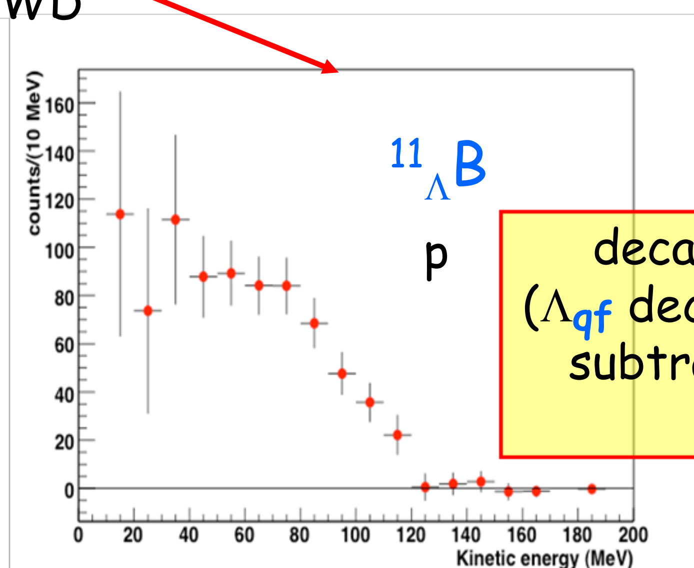
MWD & NMWD in FINUDA: strategy

inclusive production π^- spectra
K^-np background subctracted





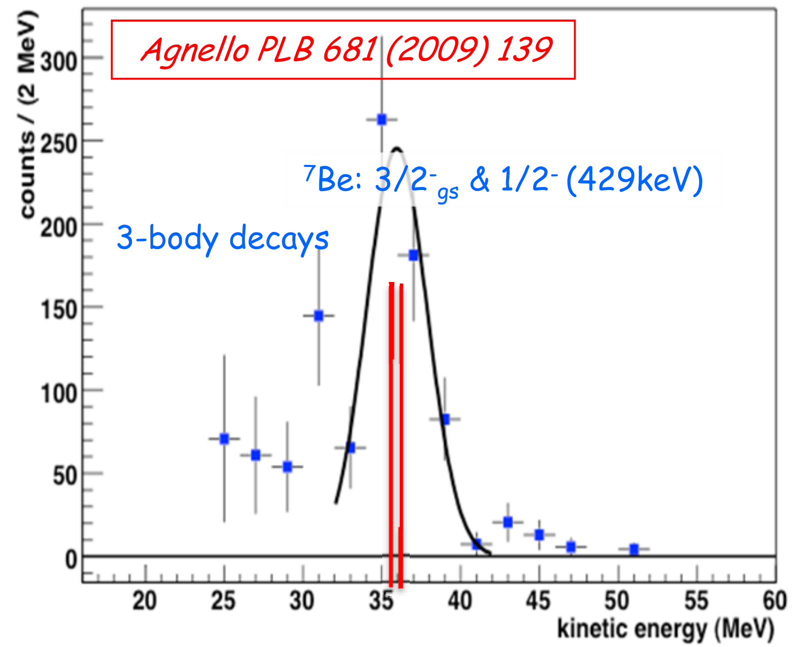


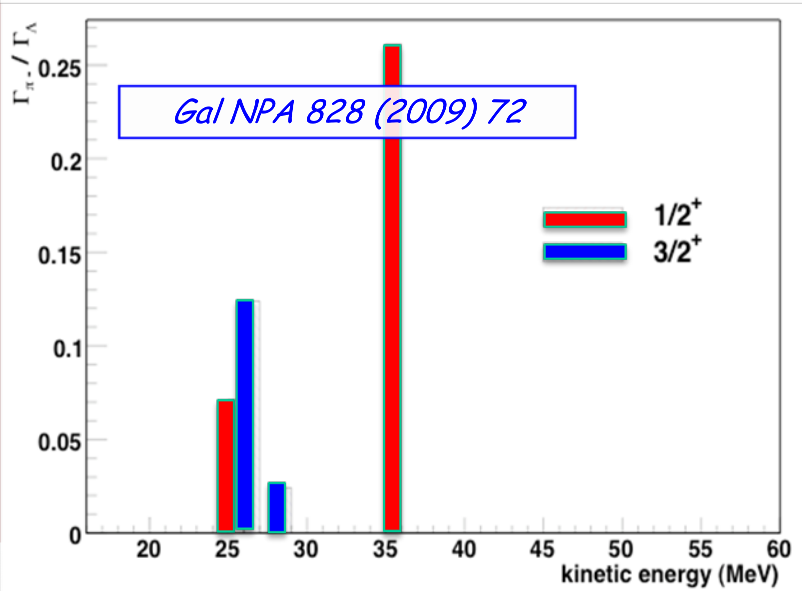


decay π^- and p spectra
(Λ_{qf} decay)/K^-np background
subtracted & acceptance
corrected

J^{π} assignment: $^{7}_{\Lambda}Li$

A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

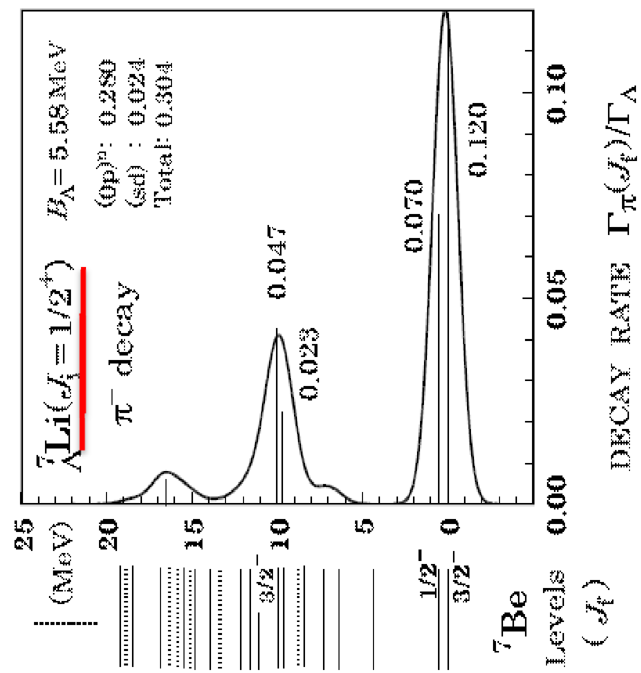




- Correspondence with the calculated strenght functions
- ✓ T. Motoba et al, Progr. Theor. Phys. Suppl. 117 (1994) 477.
- ✓ A. Gal, Nucl. Phys. A 828 (2009) 72.

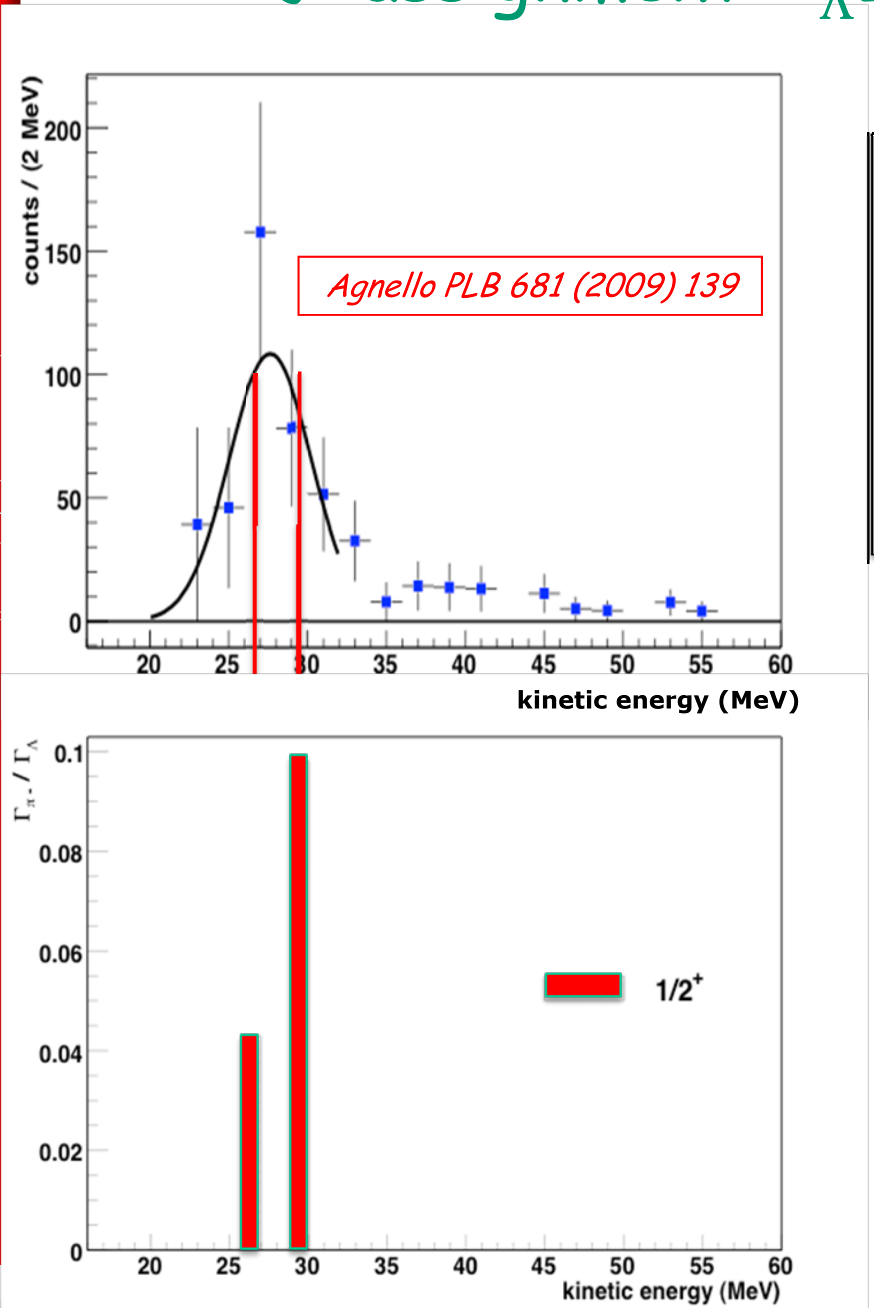
- Formation of different excited states of the daughter nucleus

- Initial hypernucleus spin $J^{\pi}(^{7}_{\Lambda}Li_{g.s.}) = 1/2^{+}$ (Sasao, PLB 579 (2004) 258).



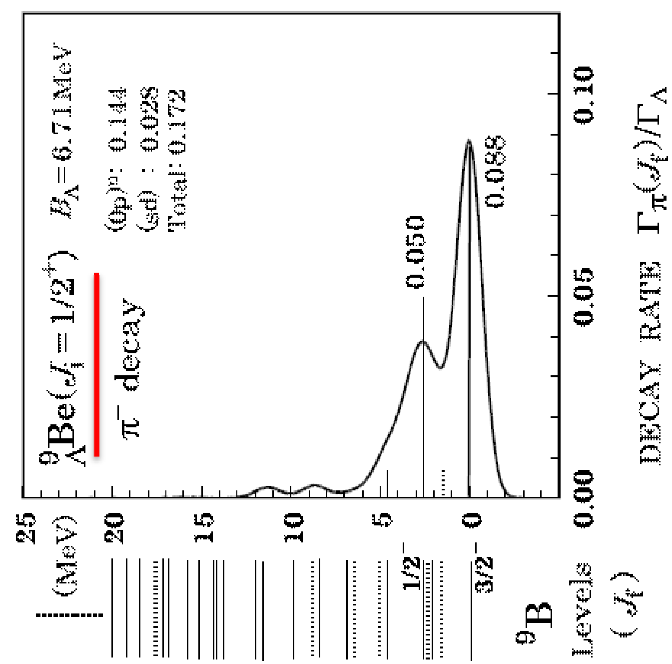
T. Motoba (Private Communication)

J^{π} assignment: $^{9}_{\Lambda}Be$



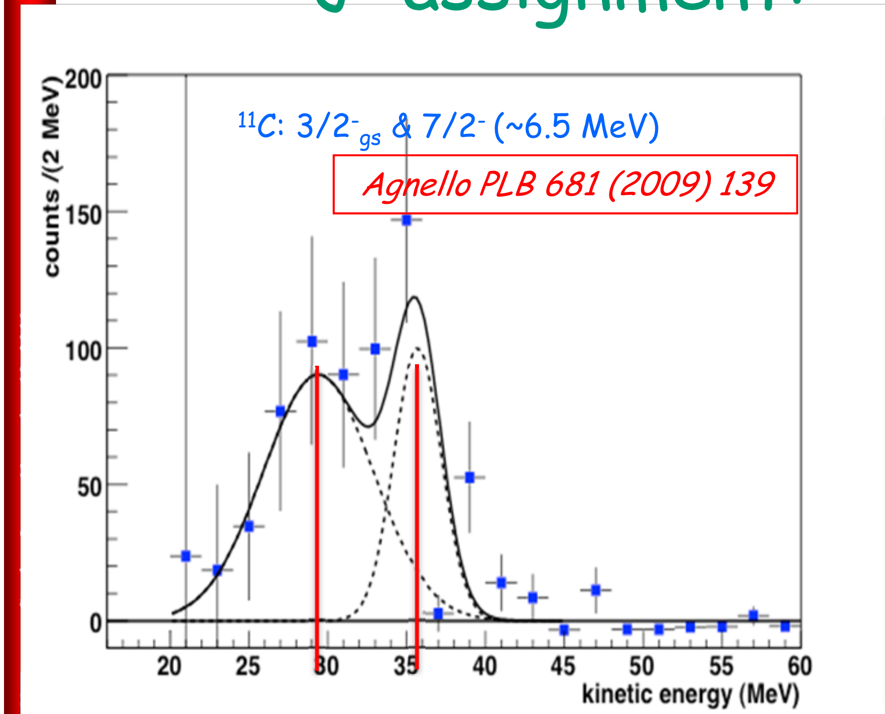
- Correspondence with the calculated strenght functions
  - ✓ T. Motoba et al, Progr. Theor. Phys. Suppl. 117 (1994) 477.
  - ✓ A. Gal, Nucl. Phys. A 828 (2009) 72.

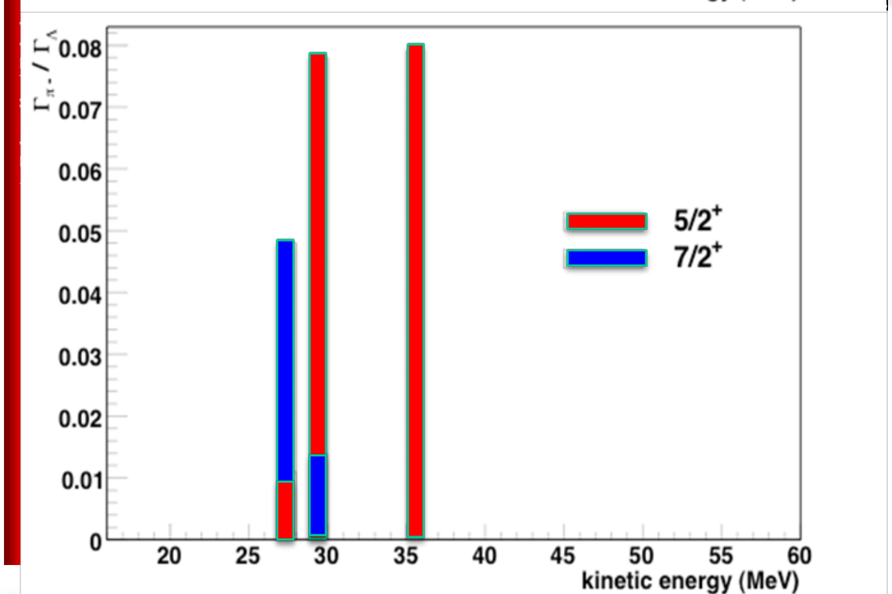
- Initial hypernucleus spin
  $J^{\pi}(^{9}_{\Lambda}Be_{g.s.}) = 1/2^{+}$
  O. Hashimoto NPA 639 (1998) 93c.



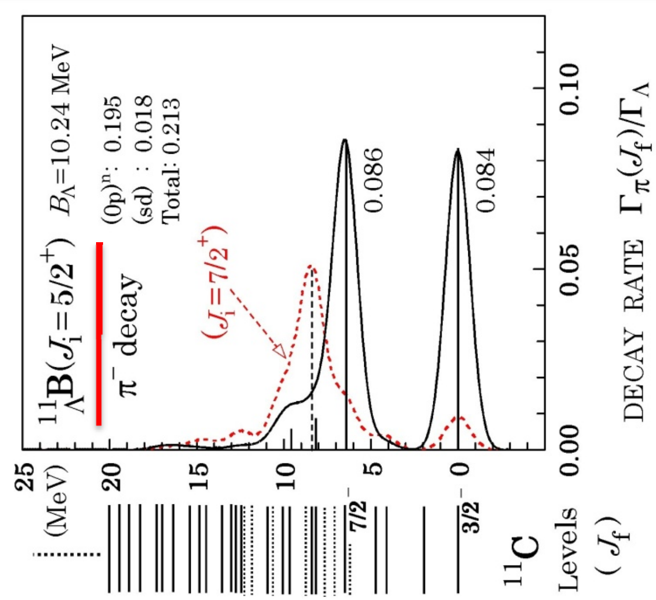
T. Motoba (Private Communication)

J^{π} assignment: $^{11}{}_{\Lambda}B$



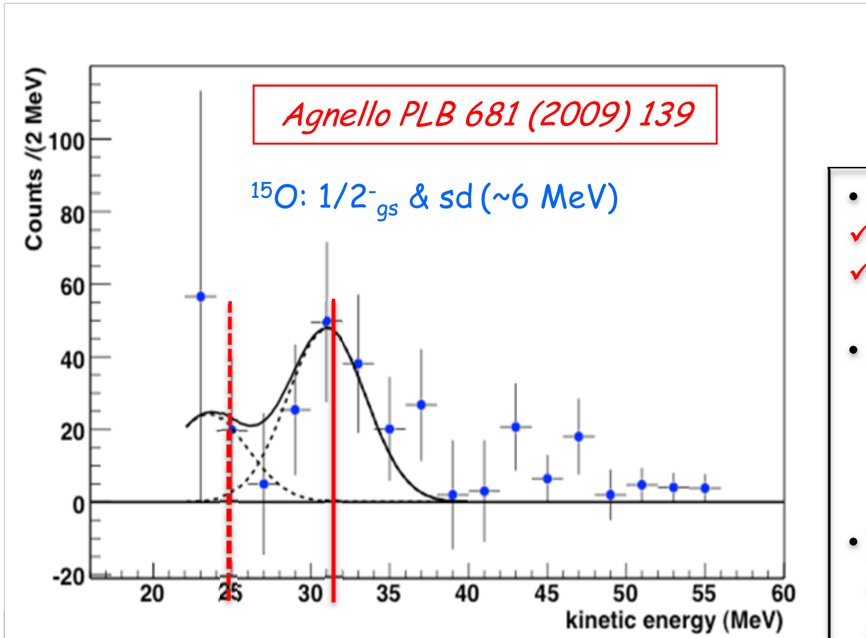


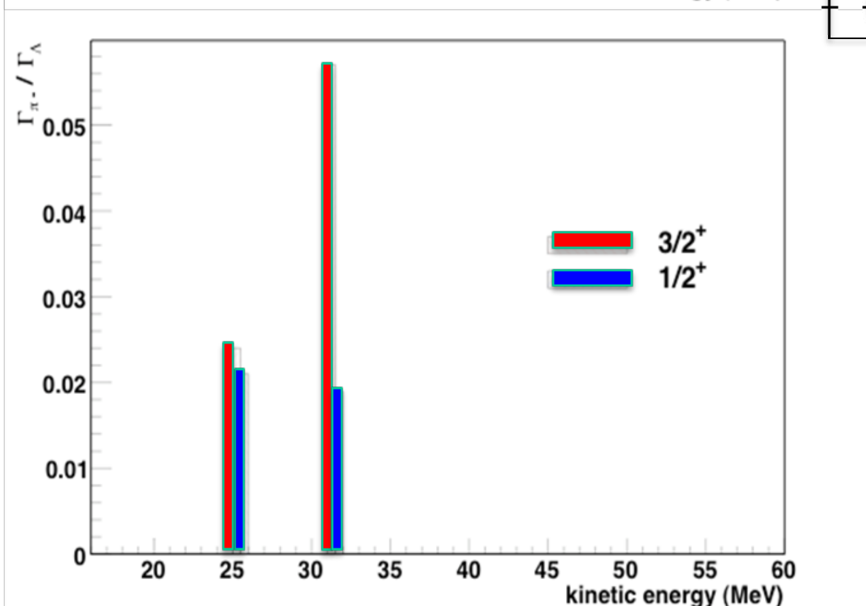
- Correspondence with the calculated strenght functions
  - ✓ H. Bando et al, Pers. Meson Science (1992) p.571
  - ✓ A. Gal, Nucl. Phys A 828 (2009) 72.
- Two contributions of the ^{11}C ground state $5/2^-$ and its $7/2^-$ excited state
- Initial hypernucleus spin $J^{\pi}(^{11}{}_{\Lambda}B_{g.s.}) = 5/2^+$: experimental confirmation (Sato et al., PRC 71 (2005) 025203) by different observable
-



. Motoba (Private Communication)

J^{π} assignment: $^{15}{}_{\Lambda}N$

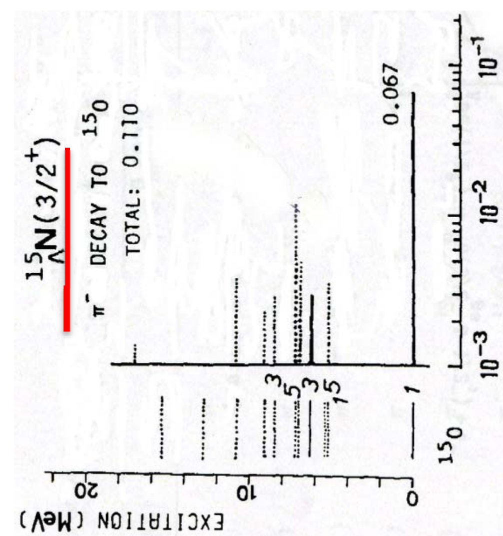




- Correspondence with the calculated strenght functions
  - ✓ T. Motoba et al, Nucl. Phys. A 489 (1988) 683.
  - ✓ A. Gal, Nucl. Phys. A 828 (2009) 72.

- $^{15}{}_{\Lambda}N_{g.s}$ spin not known. $J^{\pi}(^{15}{}_{\Lambda}N_{g.s.}) = 3/2^+$
  D.J.Millener, A.Gal, C.B.Dover Phys. Rev. C 31 (1985) 499.
  Spin ordering not obtained from γ-rays of $^{16}{}_{\Lambda}O$
  M.Ukai et al. Phys. Rev.C 77 (2008) 054315.

- First experimental determination of
  $J^{\pi}(^{15}{}_{\Lambda}N_{g.s.}) = 3/2^+$ from decay rate value
  (and spectrum shape)



T. Motoba NPA 489 (1988) 683.

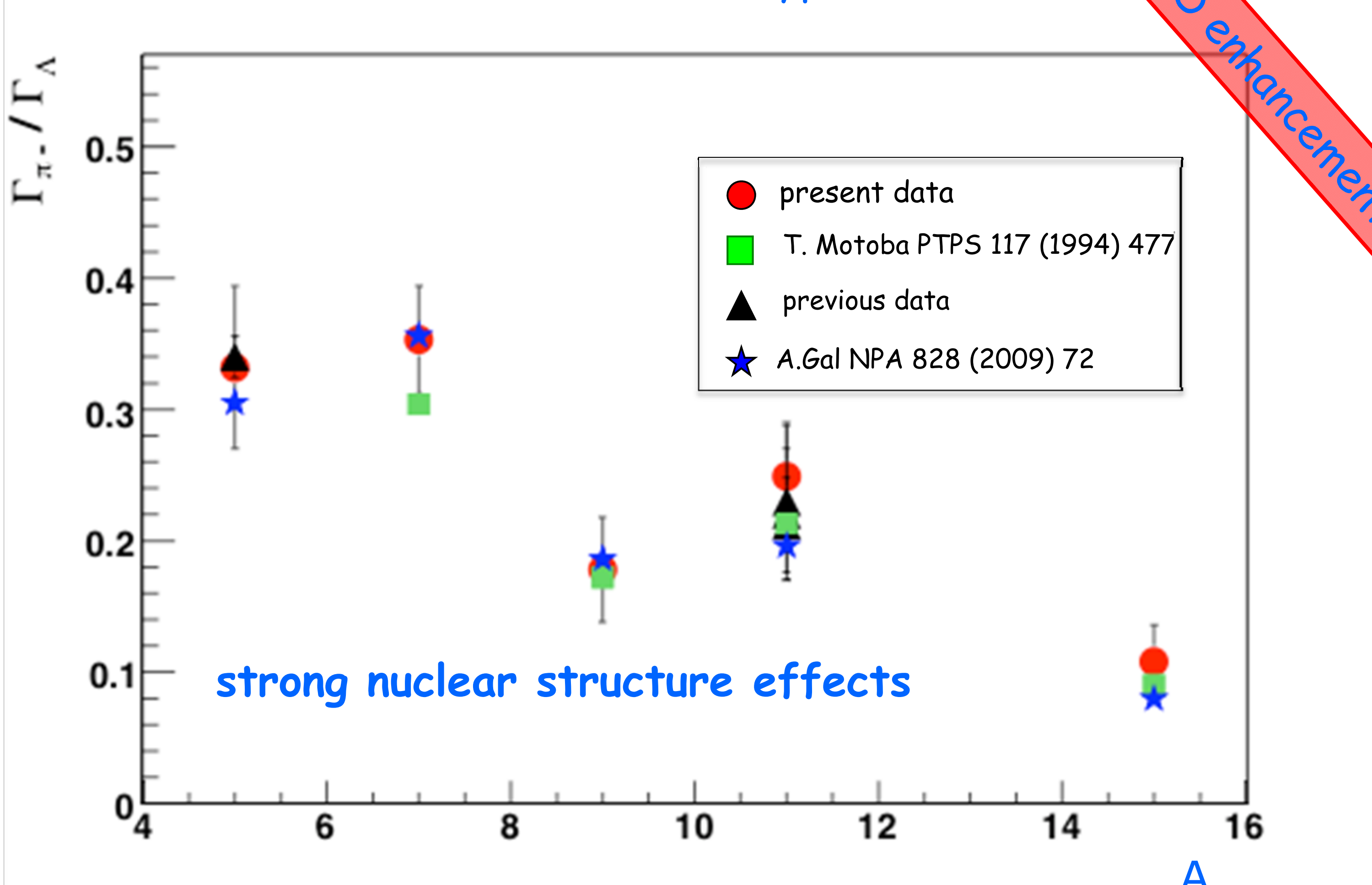
Mesonic decay ratio: $\Gamma_{\pi-} / \Gamma_{\Lambda}$

$$\Gamma_{\pi-} / \Gamma_{\Lambda} = \Gamma_{tot} / \Gamma_{\Lambda} \bullet \ BR_{\pi-}$$

$$\Gamma_{tot} / \Gamma_{\Lambda} = (0.990 \ \ 0.094) + (0.018 \ \ 0.010) \bullet A$$

fit from measured values for A=4-12 hypernuclei

π distortion, MWD enhancement proved !

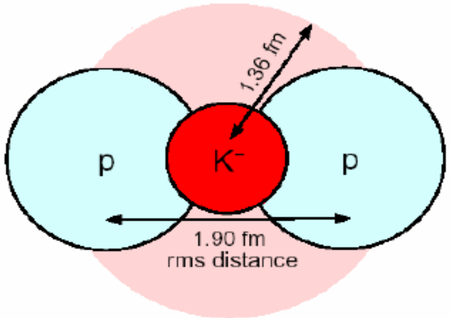


Search for $\bar{K}$ nuclear bound states

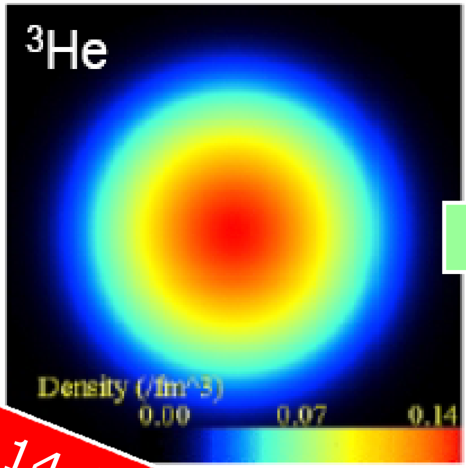
$\bar{K}$ nuclear bound states

few nucleon clusters
gathered together by a $\bar{K}$

☛ deeply bound?



nuclear density



0.14 / fm³

+ $\bar{K}$

medium effect

- ❖ hadron's mass and properties change
- ❖ (partial) chiral symmetry restoration

astrophysical interest

- ★ condensed strange nuclear matter
- ★ constituent of neutron star cores

A.Doté *et al.*, Phys. Rev. C 70 (2004) 044313

$\bar{K}$ nuclear bound states: theoretical debate

deep or shallow $\bar{K}$-nucleus potential?

- $\bar{K}\mathcal{N}$ scattering lengths
- energy level shift and width of kaonic hydrogen (x-ray measurements)
- Λ(1405) binding energy and width

deep:
- strong B ≈ 150–200 MeV
- small Γ ≈ 10–20 MeV

shallow:
- weak B ≈ 50–75 MeV
- large Γ ≈ 80–100 MeV

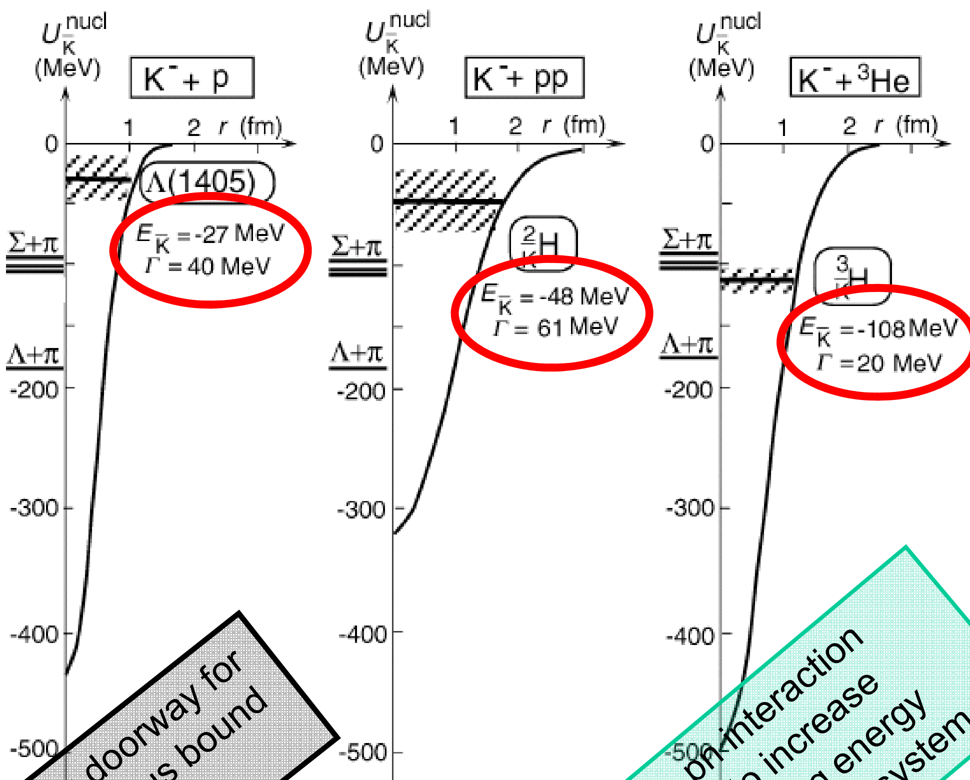
density dependent:
- strong B ≈ 100-200 MeV
- small Γ ≥ 50 MeV

width is critical for detection!

$\bar{K}$ –nucleus bound states: theoretical expectations

I = 0 $\bar{K}N$ interaction very attractive

The $\bar{K}N^{(I=0)}$ strong interaction stabilizes the nuclear matter attracting the surrounding nucleons



Λ(1405): doorway for the K-nucleus bound states?

The pn interaction helps to increase the binding energy of the K⁻ppn system

Simpler system (*strange dibaryon*):
K^-pp ($^2_{\bar{K}}H$)
the presence of the $\bar{K}$ attracts the two unbound protons to form a bound state with B=48 MeV and Γ= 61 MeV

The binding energy increases with the increase of the number of I=0 pairs, and the decrease of I=1 ones

A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

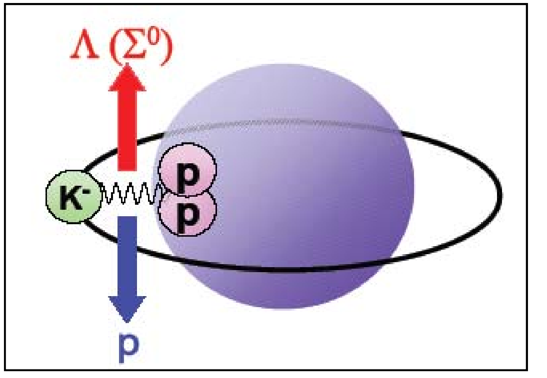
Search methods for deeply bound $\bar{K}$-states

- **Invariant mass spectroscopy**
  - Based on the kaonic nuclear states feature of decaying into hyperons
    - $(K^{-}pp) \rightarrow \Lambda + p$
    - $(K^{-}ppn) \rightarrow \Lambda + d$
    - Typically:
      - $p_{\Lambda,p} \sim 500$ MeV/c
      - $p_{\pi} < 200$ MeV/c
      - $p_{decay\ p} \sim 500$ MeV/c

  – Necessary to fully reconstruct all the particles emitted in the decay

  – The decay occurs at rest: angular correlation between the emitted particles

FINUDA @ DAΦNE



- **Missing mass spectroscopy**
  - Measurement of the momentum of the monochromatic recoiling particle in a A(K,N)X reaction

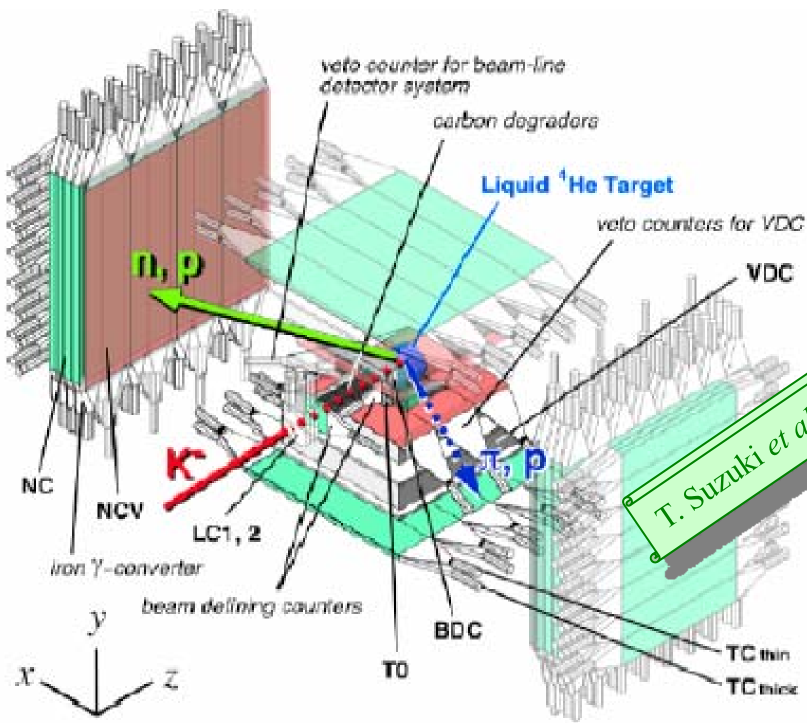
•With stopped K^{-}:
  •KEK-PS E471, E549
  •FINUDA @ DAΦNE
•With in flight K^{-}:
  •BNL-AGS E930
  •KEK-PS E548

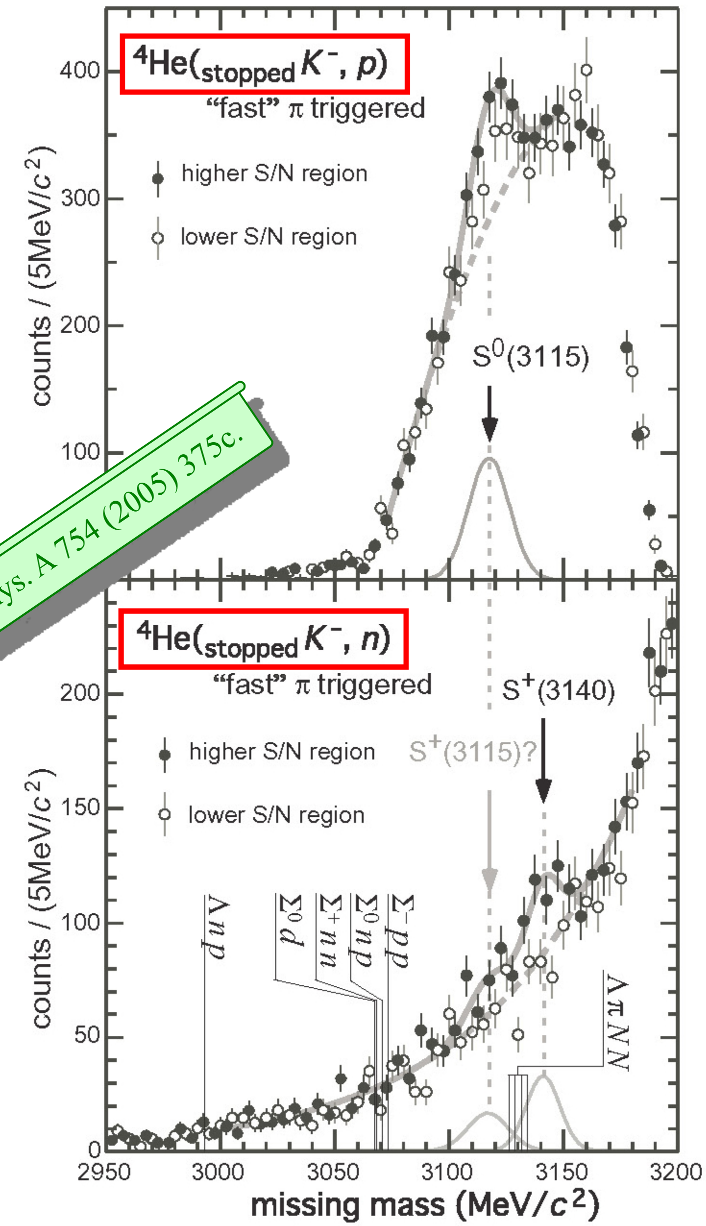
KEK-PS-E471 evidence for strange tribaryons

$$^4He(K^-_{stop}, p)S^0(3115) \equiv K^- pnn$$

I = 1

B = 193 MeV
$\Gamma \leq 21$ MeV





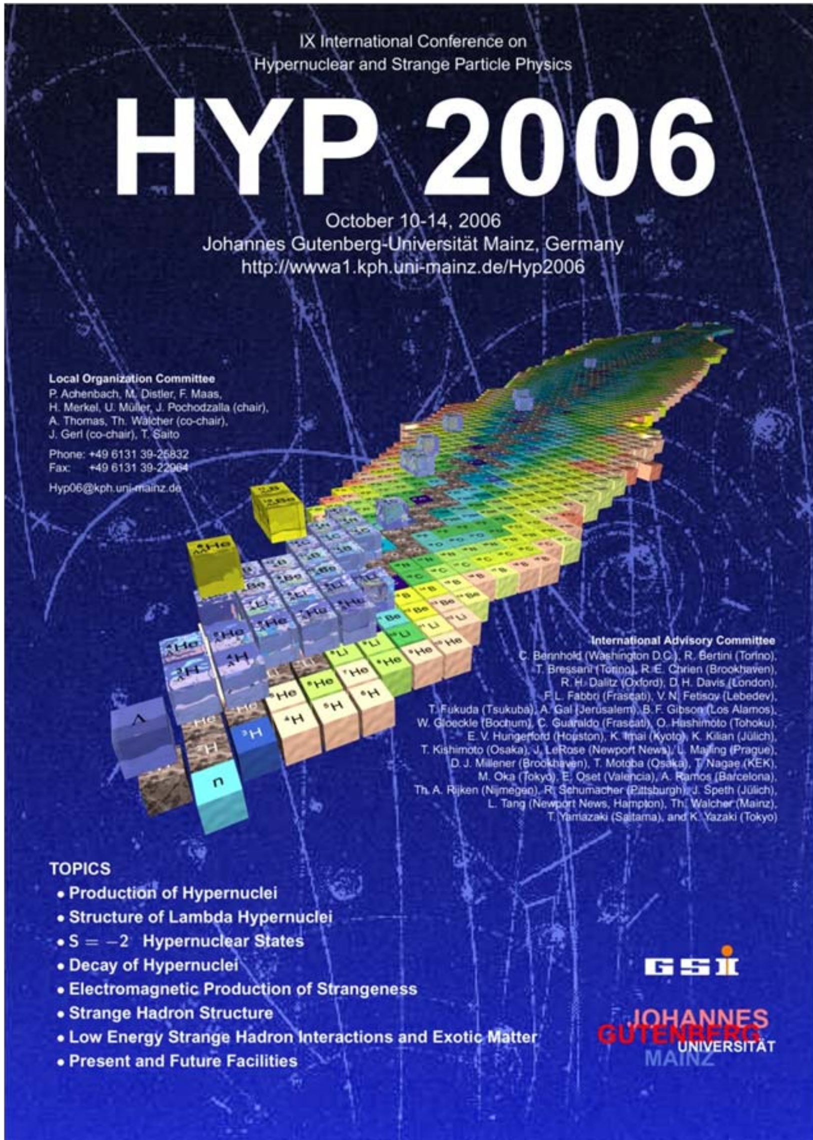
T. Suzuki *et al.*, Nucl. Phys. A 754 (2005) 375c.

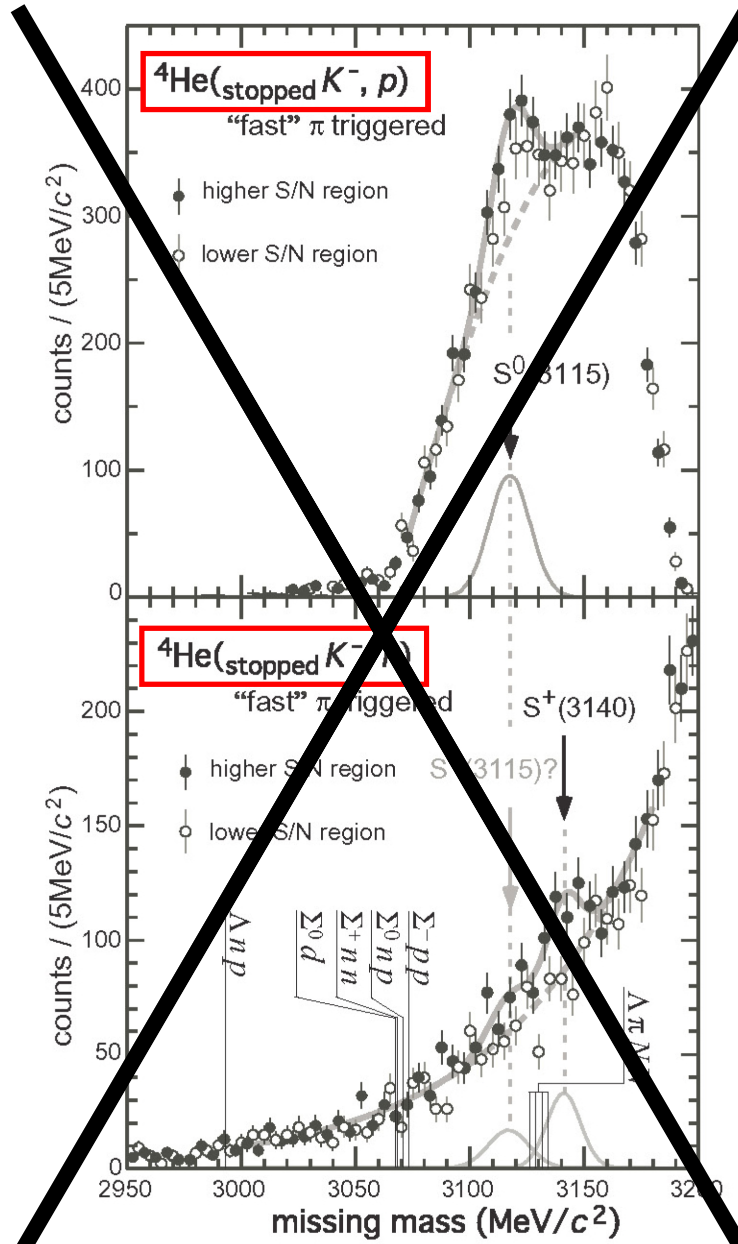
$$^4He(K^-_{stop}, n)S^+(3140) \equiv K^- ppn$$

I = 1

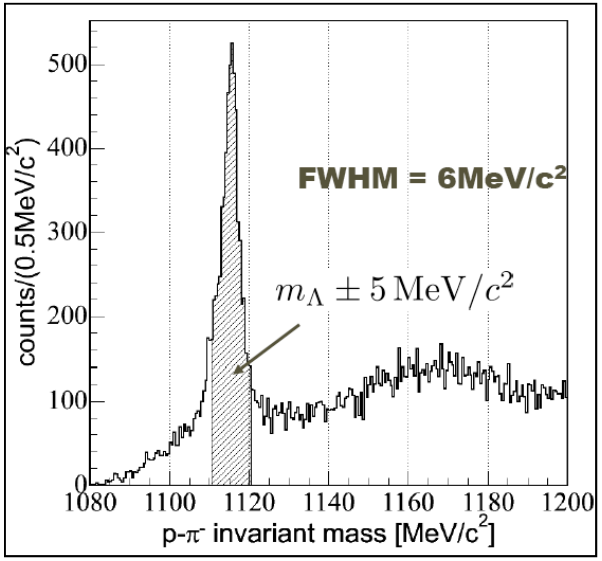
B = 169 MeV
$\Gamma \leq 21$ MeV

KEK-PS-E471 evidence for strange tribaryons





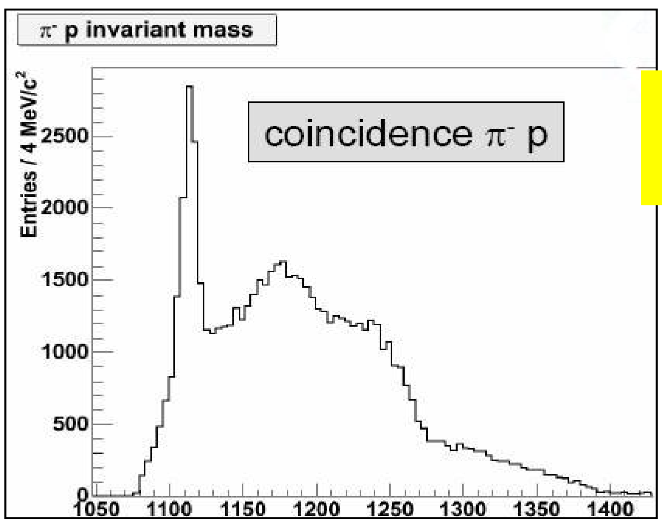
FINUDA search for B=2 kaon-nuclear states
- 1st step:direct observation of a Λ



Invariant mass spectrum for a proton and a negative pion system

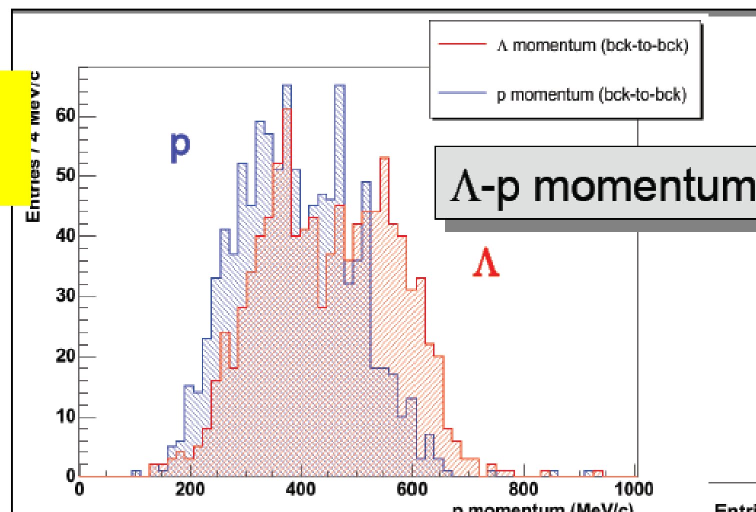
LONG TRACKS, higher resolution

the acceptance of the apparatus cuts the Λ's with momentum less than 300 MeV/c, due to the momentum threshold for π^-

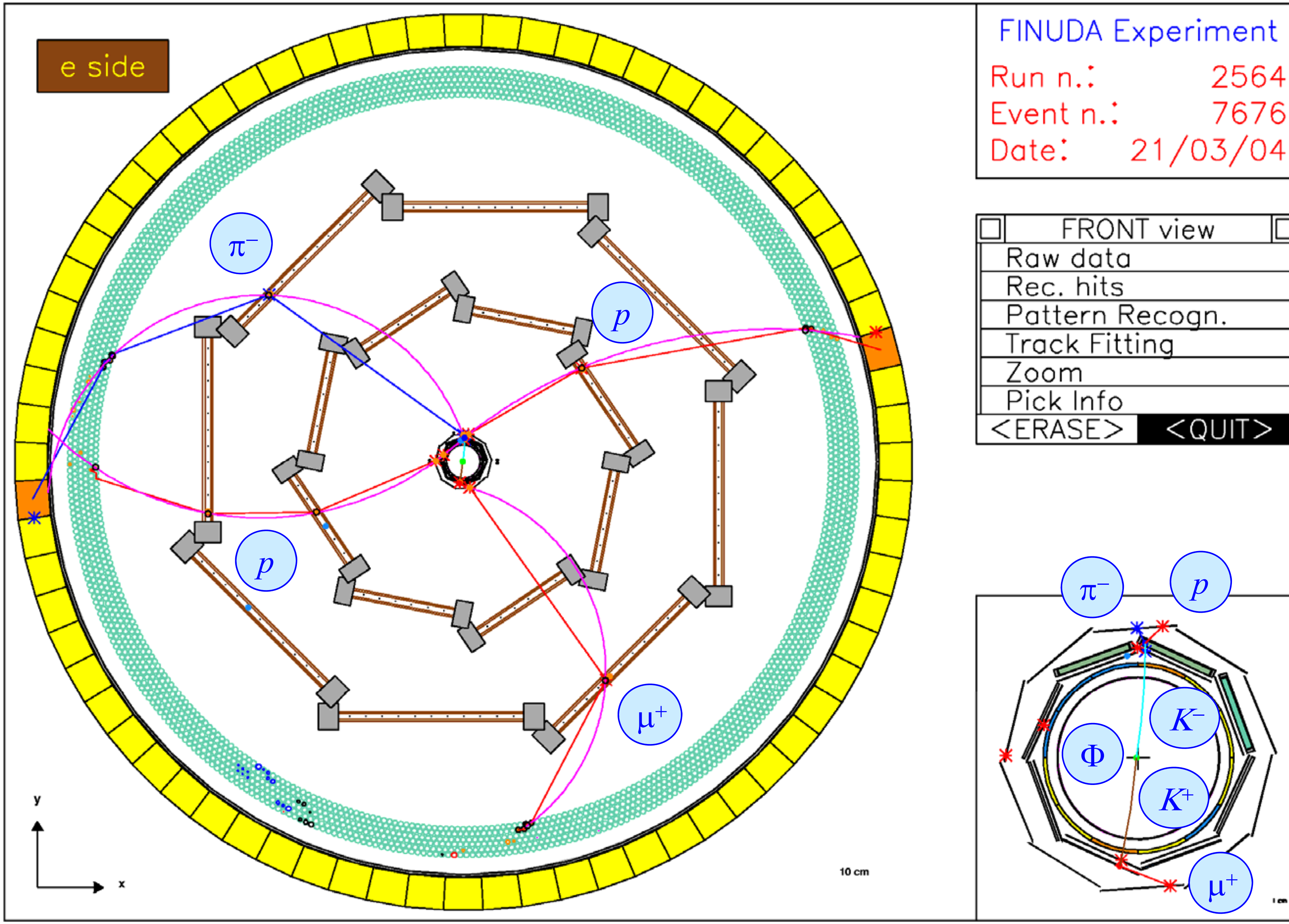


SHORT TRACKS, larger acceptance

Less resolution but higher statistics

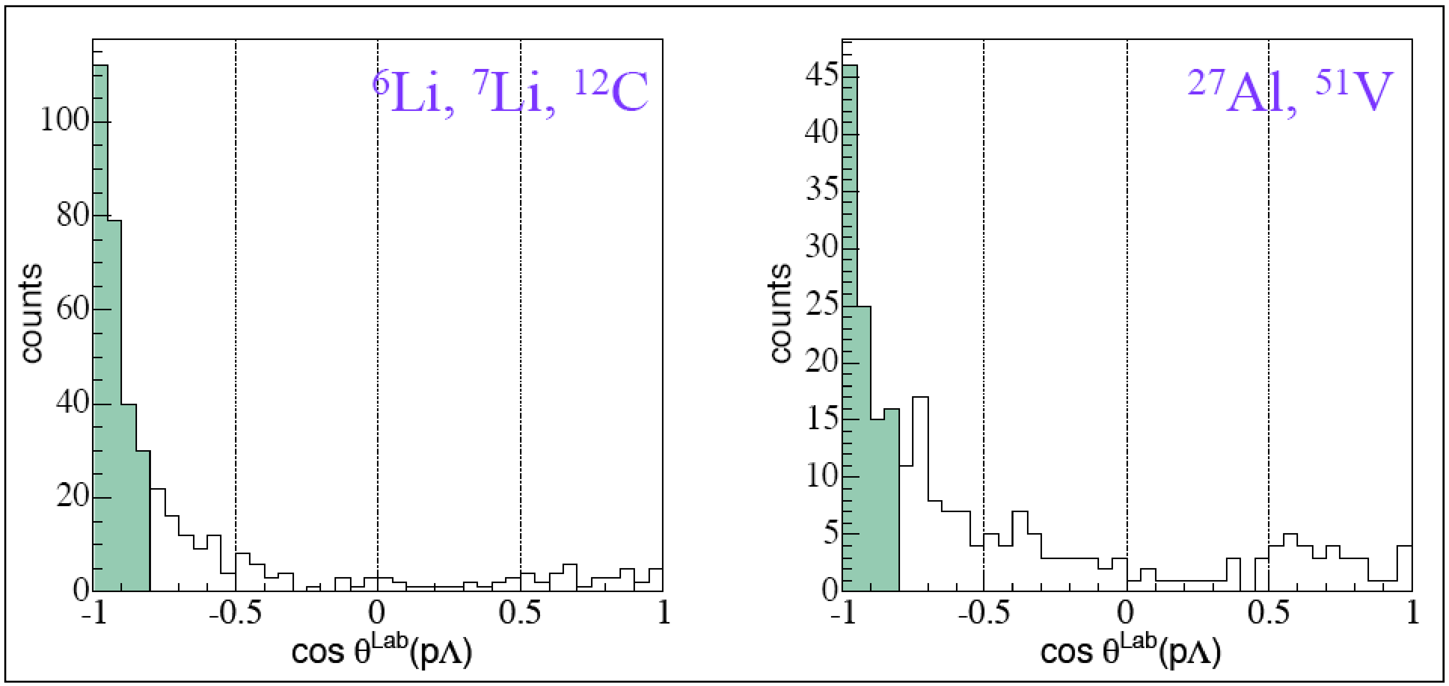


"$K^{-}pp$" → Λp → $pp\pi^{-}$ candidate event



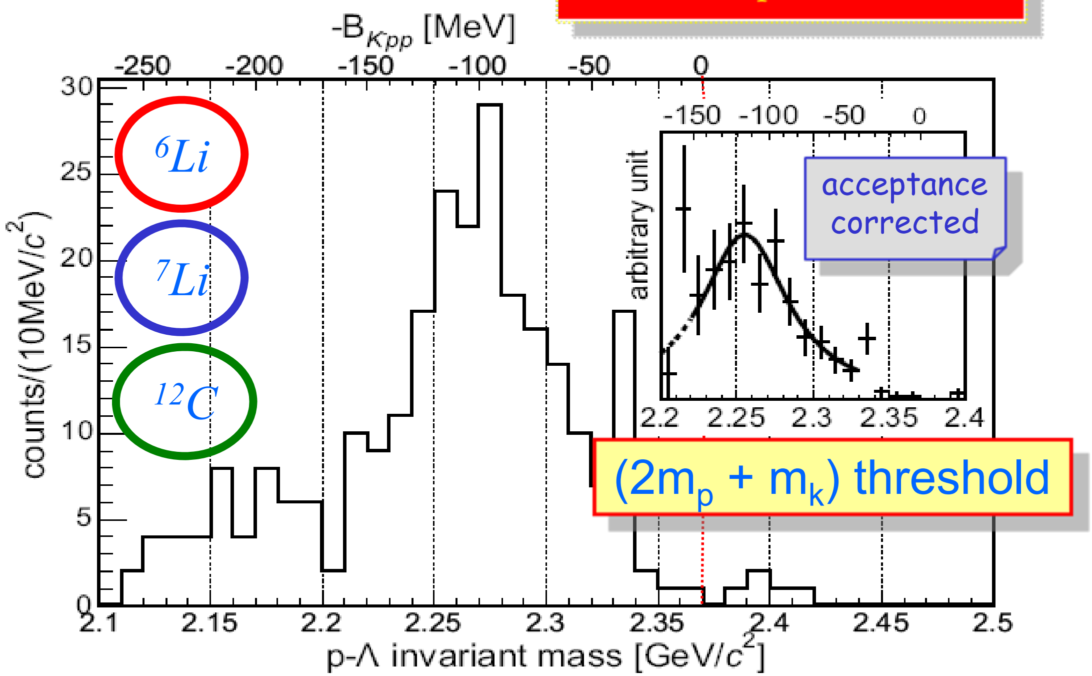
FINUDA search for B=2 kaon-nuclear states - 2nd step: back-to-back Λp events

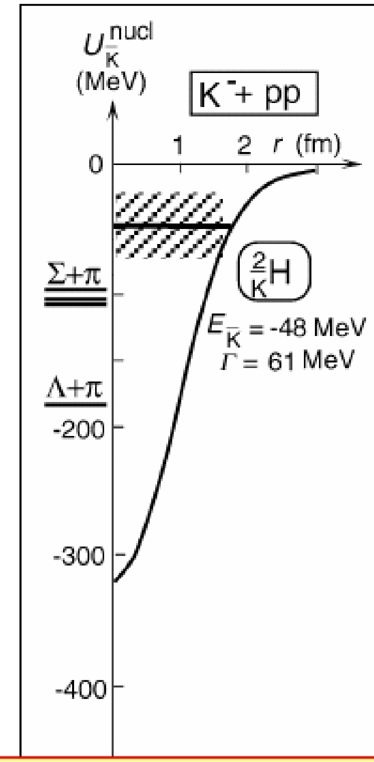
- When a kaon interacts with two nucleons and a hyperon-nucleon pair (Λp, Σ^0p, Σ^+n) is produced, they are expected to be emitted in opposite directions, ignoring a F.S.I. inside the nucleus
- About the 5% of events in FINUDA have a (Λp) coincidence
- Seen indeed, on every FINUDA target! (be it light or heavy: two nucleon absorption on the nucleus surface?)
- Event selection: $\cos\theta_{YN} < -0.8$



FINUDA search for B=2 kaon-nuclear states

$$A(K^-_{stop}, \Lambda p)A'$$





$$B = 115\,^{+6}_{-5}\,^{+3}_{-4}\,\mathrm{MeV}$$

$$\Gamma = 67\,^{+14}_{-11}\,^{+2}_{-3}\,\mathrm{MeV}$$

$$M = 2255 \pm 9\,\mathrm{MeV}/c^2$$

$$Y \approx 0.1\%/K^-_{stop}$$

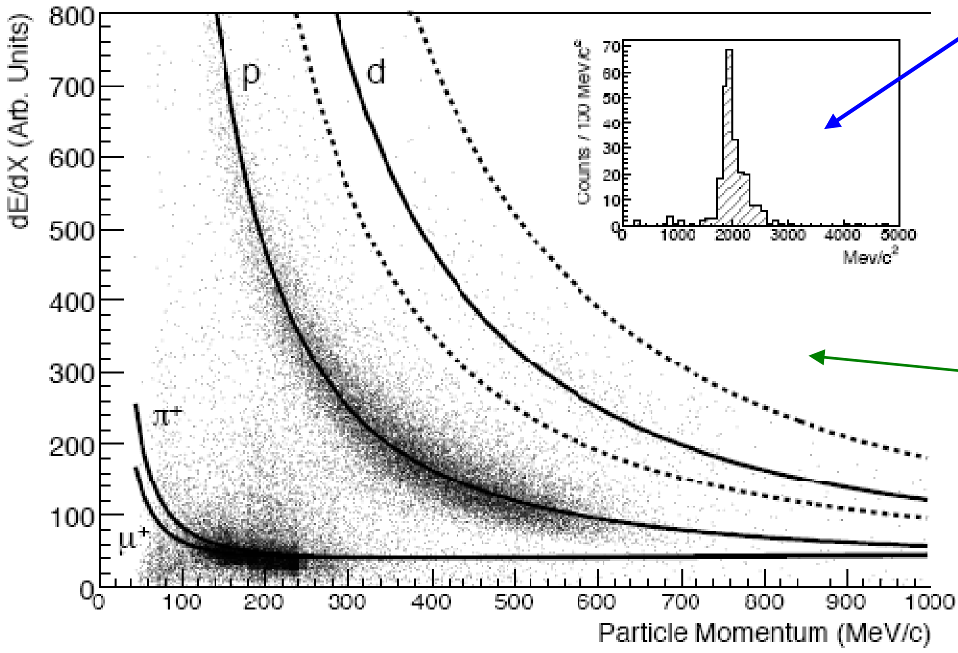
M. Agnello *et al.*, Phys. Rev. Lett. 94 (2005) 212303

FINUDA search for B=3 kaon-nuclear states

$$A(K^-_{stop}, \Lambda d)A'$$

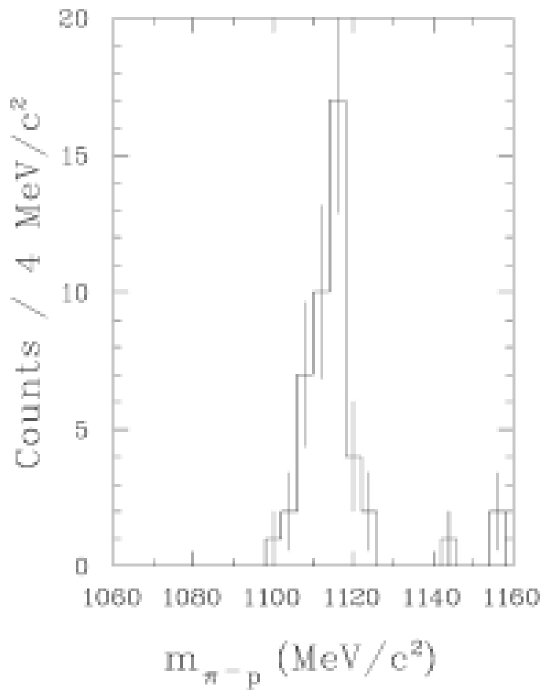
$$A \equiv {}^6Li,\ {}^{12}C$$
$$A' \equiv A - 3$$

reconstructed by T.O.F.



PID by OSIM

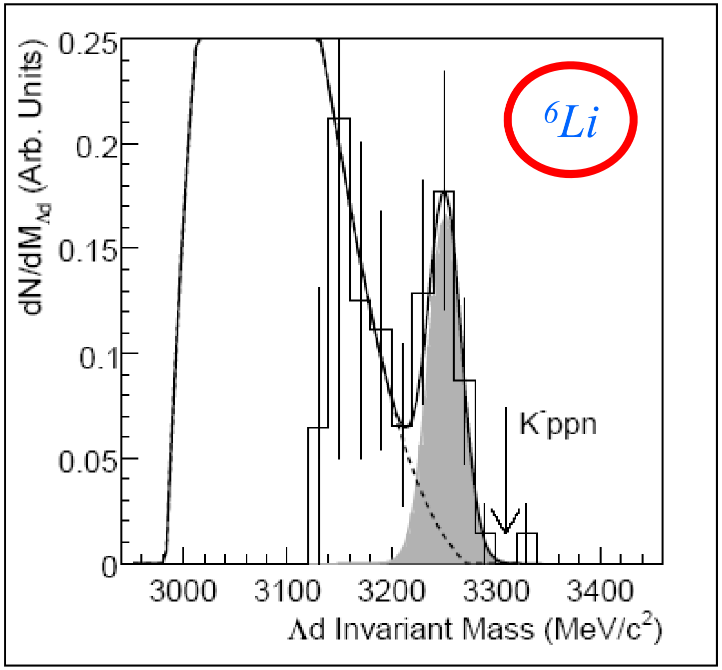
FINUDA search for B=3 kaon-nuclear states
- 1st step:direct observation of a Λ

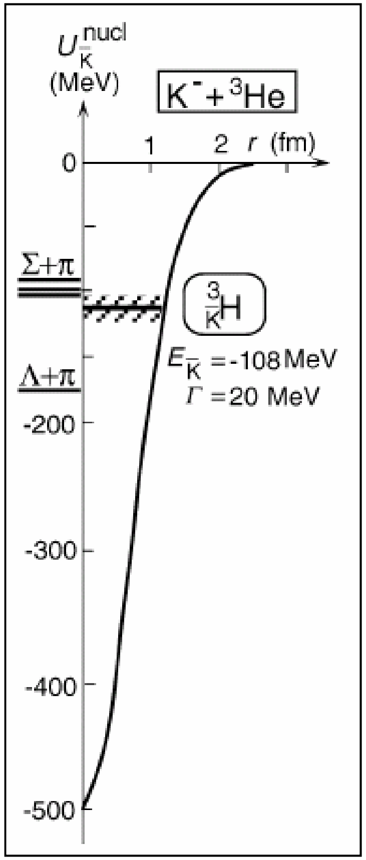


Invariant mass spectrum for a proton and a negative pion system in coincidence with a deuteron

background free

FINUDA search for B=3 kaon-nuclear states





$$B = 58 \pm 6 \text{ MeV}$$

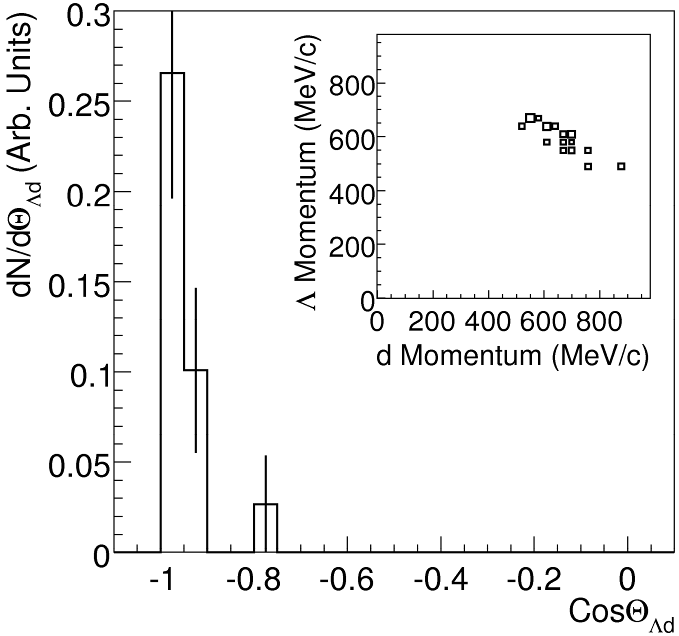
$$\Gamma = 36.6 \pm 14.1 \, \text{MeV}/c^2$$

M. Agnello *et al.*, Phys. Lett. B 654 (2007) 80

$$M = 3251 \pm 6 \, \text{MeV}/c^2$$

$$Y = (4.4 \pm 1.4) \times 10^{-3} / K^-_{stop}$$

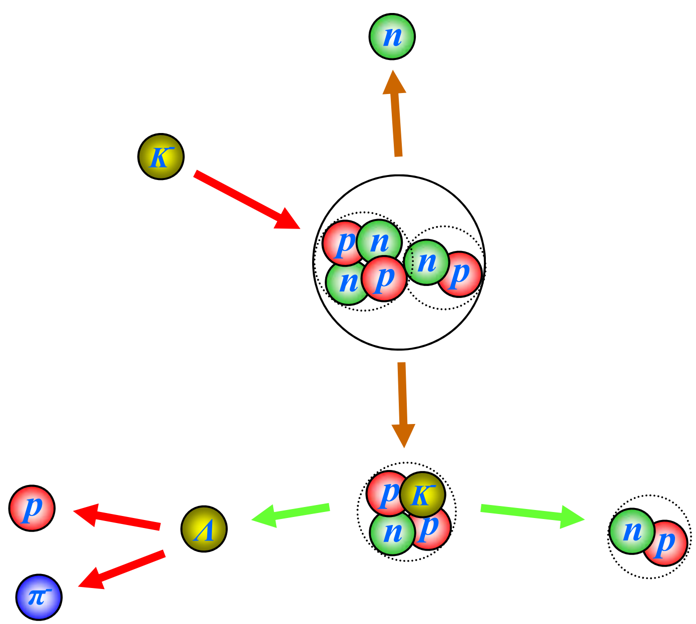
FINUDA search for B=3 kaon-nuclear states
- 2nd step: angular correlation



$^{6}Li(K^{-}_{stop},\ \Lambda d)pnn$

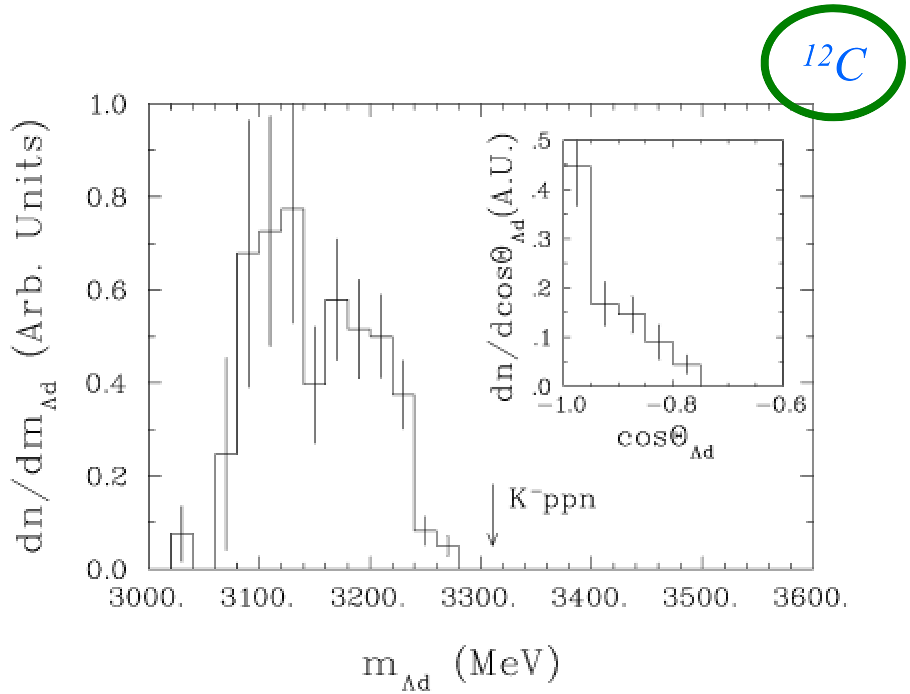
$^{6}Li(K^{-}_{stop},\ \Lambda d)dn$

$^{6}Li(K^{-}_{stop},\ \Lambda d)t$



FINUDA search for B=3 kaon-nuclear states

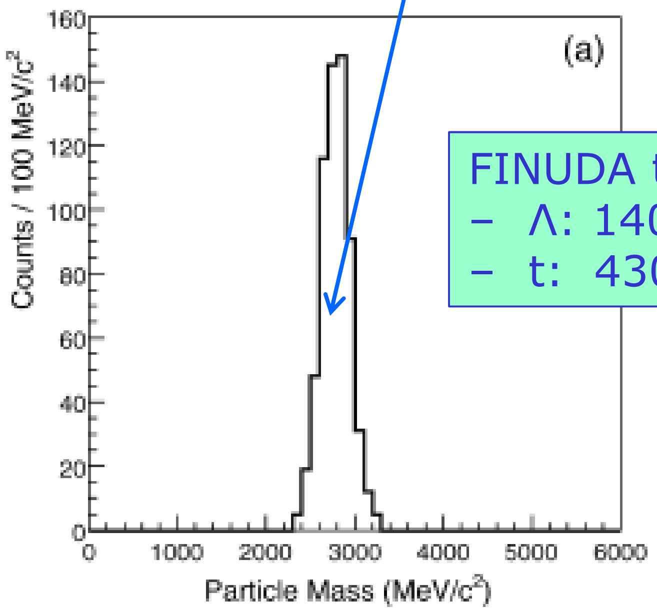
A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.



FINUDA search for B=4 kaon-nuclear states

$$A(K^-_{stop}, \Lambda t)A'$$

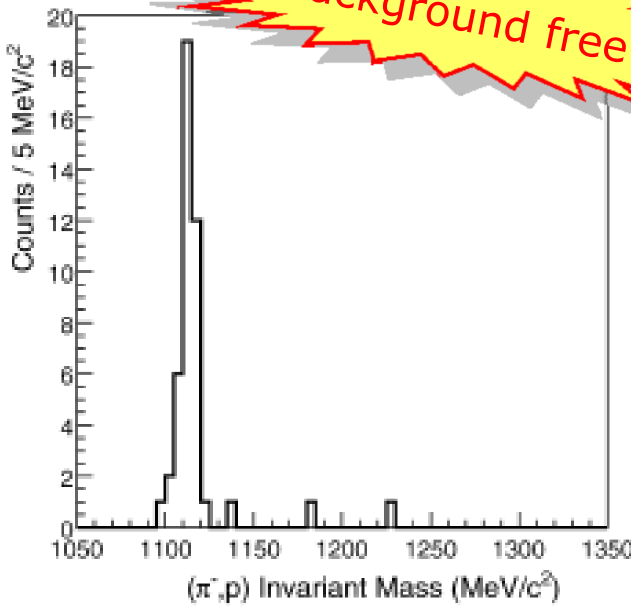
$$A \equiv {}^6Li,\ {}^7Li,\ {}^9Be$$
$$A' \equiv A - 4$$



FINUDA thresholds:
- Λ: 140 MeV/c
- t: 430 MeV/c

- particle identification

background free

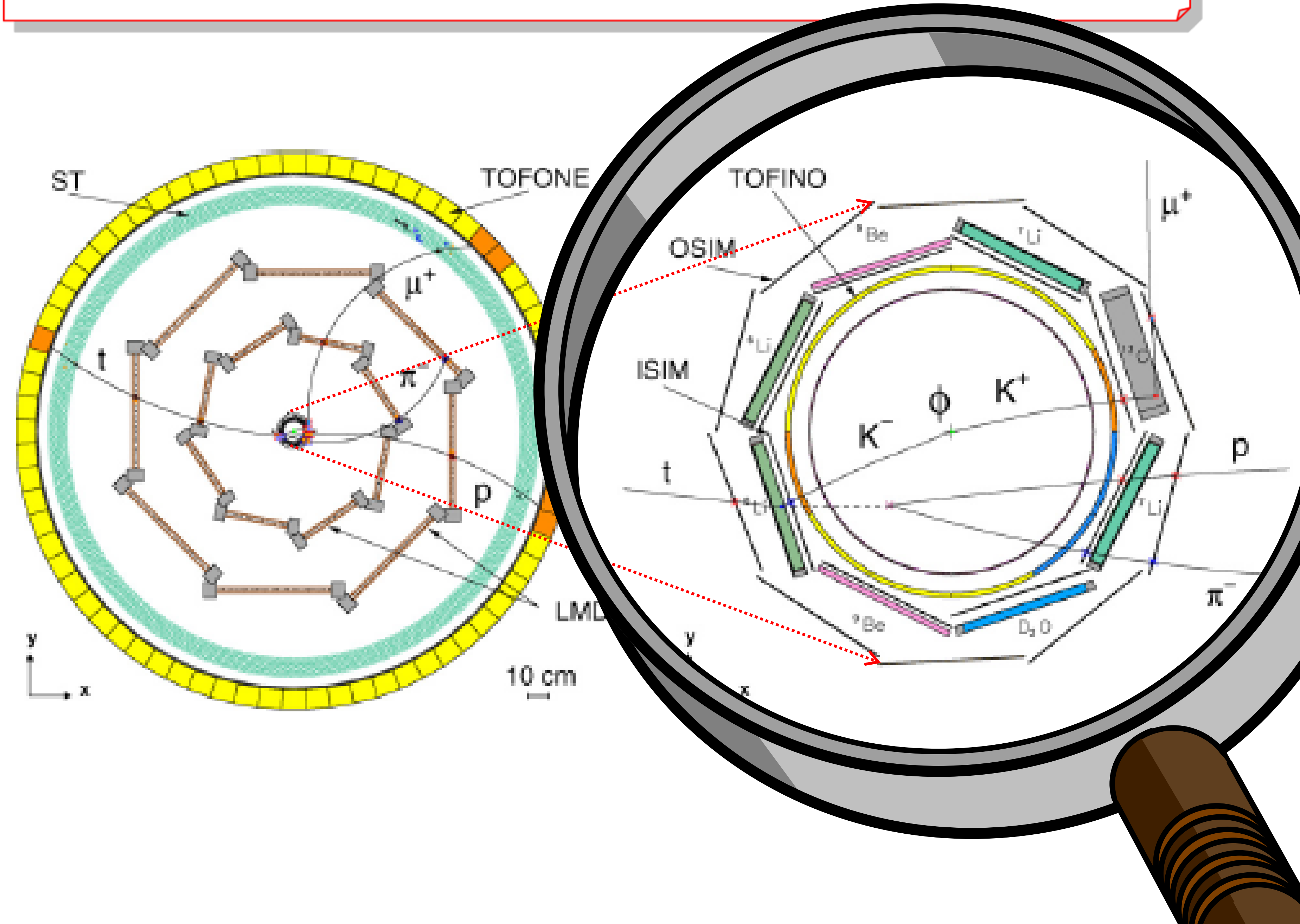


-1st step:direct observation of a Λ
(in coincidence with t)

Direct measurement of
K^- absorption on ^4He

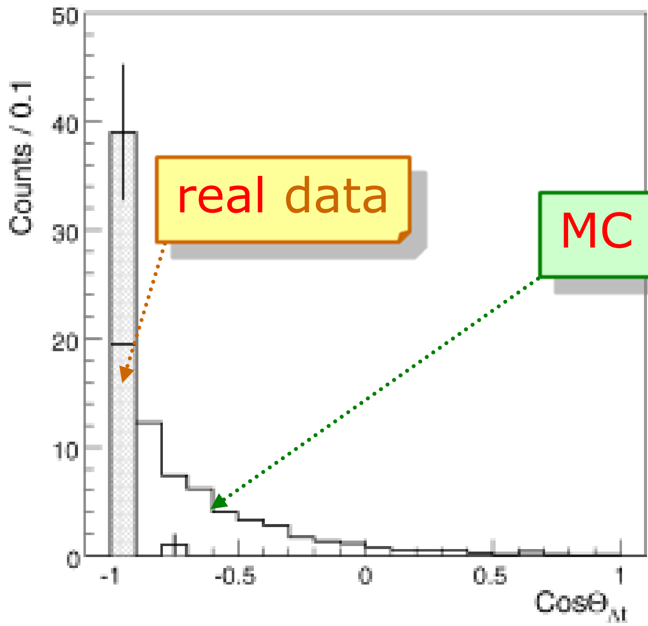
Only one measurement exists,
from bubble chamber:
3 events by kin fit
40 events observed in FINUDA

$K^{-6}Li \rightarrow \Lambda t + X$ candidate event



A. Feliciello / Tohoku University, Sendai, Japan, November 18, 2010.

FINUDA search for B=4 kaon-nuclear states - 2nd step: angular correlation

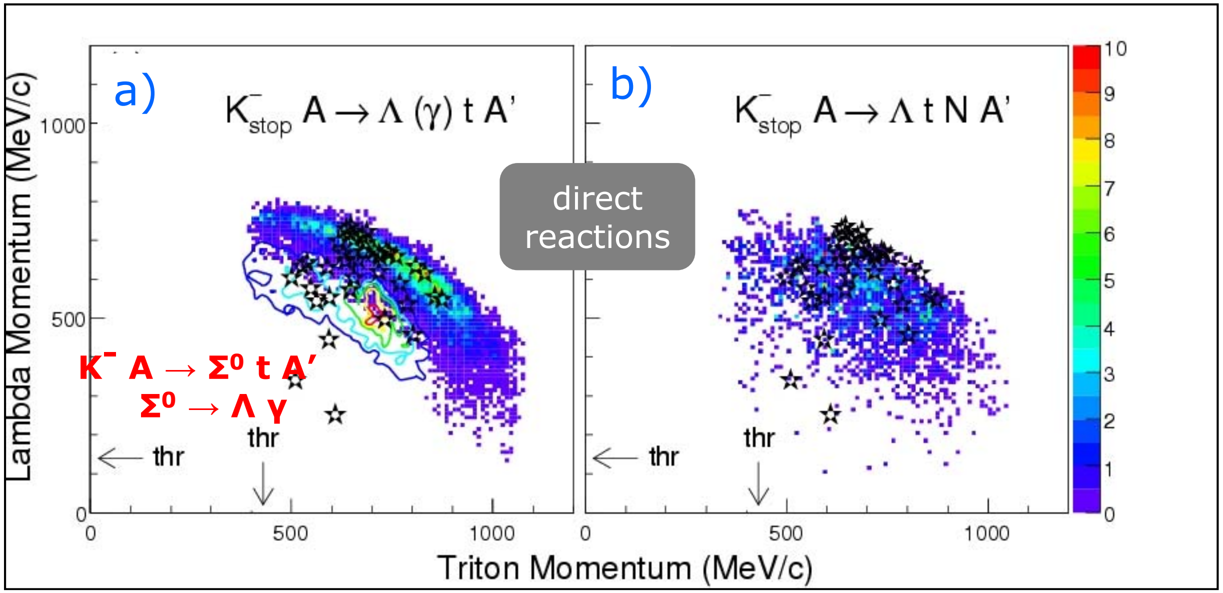


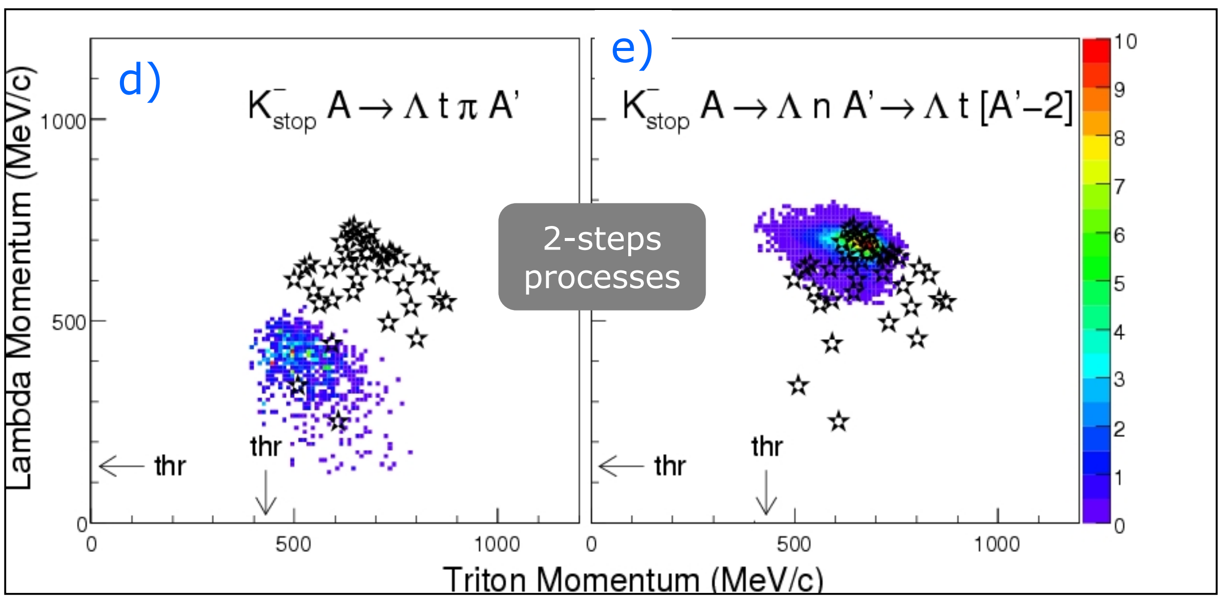
Λ, t pairs emitted back-to-back

M. Agnello *et al.*, Phys. Lett. B 669 (2008) 229

Nucleus	Absorption rate $[\times 10^{-4}/K^-_{stop}]$
^{6}Li	$7.1 \pm 3.4(stat)^{+1.2}_{-0.7}(syst)$
^{7}Li	$12.7 \pm 3.7(stat)^{+2.1}_{-1.3}(syst)$
^{9}Be	$11.1 \pm 2.9(stat)^{+1.8}_{-1.1}(syst)$
^{6}Li + ^{7}Li + ^{9}Be	$10.1 \pm 1.8(stat)^{+1.7}_{-1.0}(syst)$

Study of $A(K^-,\Lambda t)X$ ($A={}^6Li, {}^7Li, {}^9Be$)





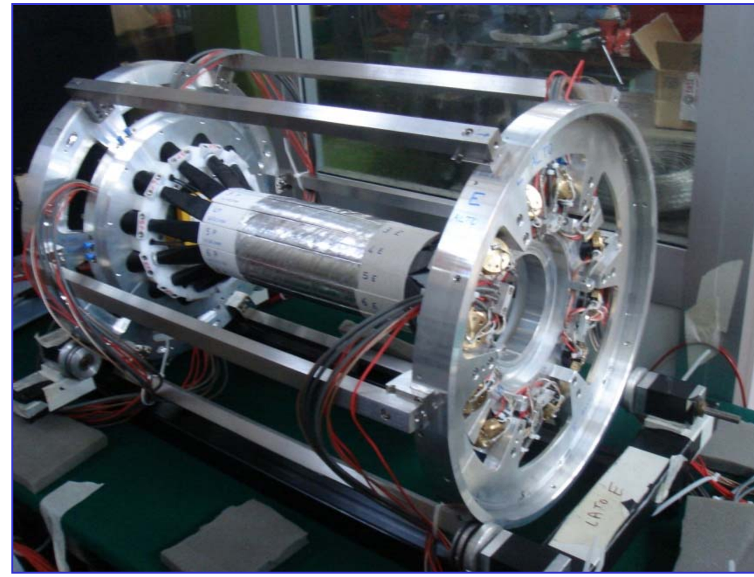
Many body K^- absorption role

- Simulations of different phase space reactions with $\cos(\Theta_{\Lambda t})<-0.9$ (filtered through apparatus acceptance)
- Λ and t momentum distribution compatible with:
  - a) 4-nucleon absorption with (Λt) or (Σt) emission
  - b) 4-nucleon absorption with (Λt)N emission
  - c) NOT with (Λt)π: too small Λ momentum
  - d) 2-step pickup reaction (suppressed?)

The FINUDA Collaboration

- I.N.F.N. Bari and Bari University
- Brescia University
- KEK
- L.N.F. / I.N.F.N. Frascati
- I.N.F.N. Pavia and Pavia University
- RIKEN
- Seoul National University
- Teheran Shahid Beheshty University
- I.N.F.N. Torino and Torino University
- Torino Polytechnic
- Trieste University and I.N.F.N. Trieste
- TRIUMF

A paradigmatic example of collaboration



Thank you!

どうも　ありがとう