# Weak Decay Studies with FINUDA

Stefania Bufalino
INFN-Sezione di Torino

# Summary

- Hypernuclear weak decay
- FINUDA @ DAΦNE LNF-INFN
- Hypernuclear decay study in FINUDA
- Mesonic weak decay (MWD)
- Non-Mesonic weak decay (NMWD)
- Conclusions

# Weak Decay modes of $\Lambda$ hypernuclei (1)

The two main decay mechanism inside a hypernucleus are

- Mesonic Weak decay
- Non Mesonic Weak Decay (NMWD)

- Mesonic weak decay like $\Lambda$ free weak decay:
  - $\Lambda \to p\pi^-$ B.R. 63.9% ($\Gamma_{\pi-}$)
  - $\Lambda \to n\pi^0$ B.R. 35.8% ($\Gamma_{\pi 0}$)

lifetime $\tau_\Lambda^{free}$= 263 ps nucleons emitted with a momentum $q \sim 100 MeV/c$

- Negligible semi-leptonic and weak radiative decay modes:
  - $\Lambda \to n\gamma$ B.R. $1.75\times10^{-3}$
  - $\Lambda \to p\pi^- \gamma$ B.R. $8.4\times10^{-4}$
  - $\Lambda \to pe^- \nu_e$ B.R. $8.32\times10^{-4}$
  - $\Lambda \to p\mu^- \nu_\mu$ B.R. $1.57\times10^{-4}$

# Weak Decay modes of $\Lambda$ hypernuclei (2)

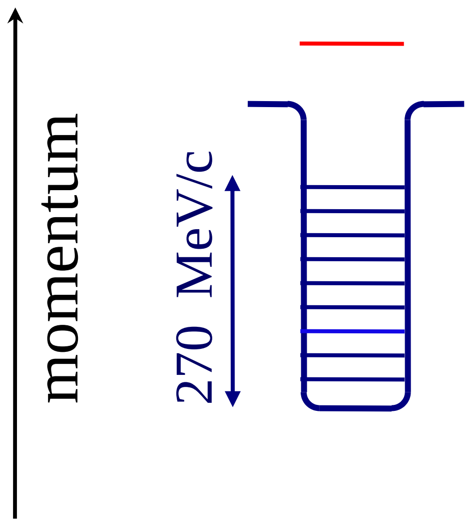
- $\Lambda$ embedded in a nucleus
  - $\Lambda n \rightarrow nn$ $(\Gamma_n)$ "neutron-induced decay"
  - $\Lambda p \rightarrow np$ $(\Gamma_p)$ "proton-induced decay"
  - $\Lambda NN \rightarrow nNN$ $(\Gamma_2)$ "two nucleons-induced decay"

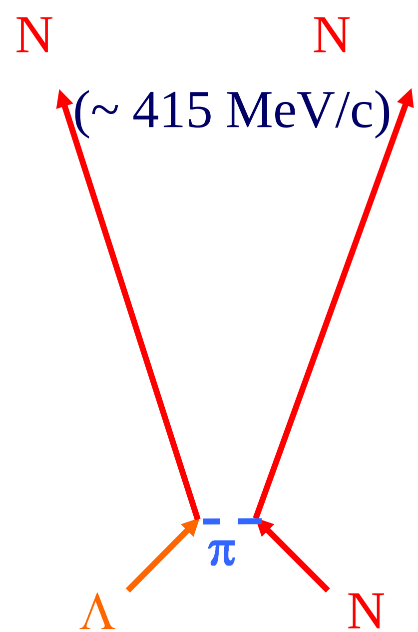
Total width decay $\Gamma_T = \Gamma_M + \Gamma_{NM}$

$\Gamma_M = \Gamma_{\pi^-} + \Gamma_{\pi^0}$

$\Gamma_{NM} = \Gamma_n + \Gamma_p + \Gamma_2$

$\boxed{Q = m_\Lambda - m_N \simeq 176 \text{ MeV}}$




The non mesonic decay in nuclear matter is not forbidden by Pauli blocking

Dominant decay channel for medium-heavy nuclei ($A \geq 12$)

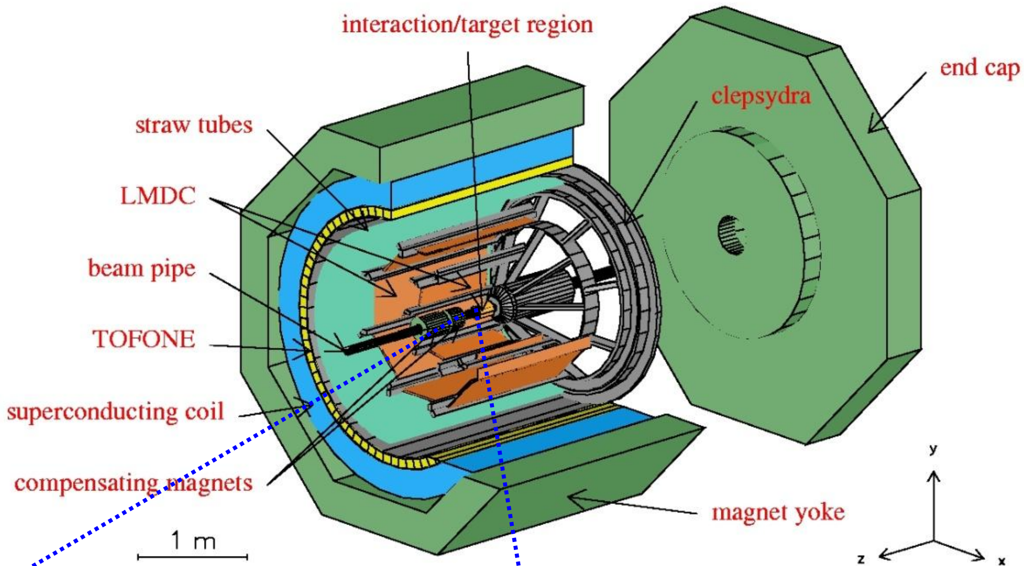
# Physics Motivations

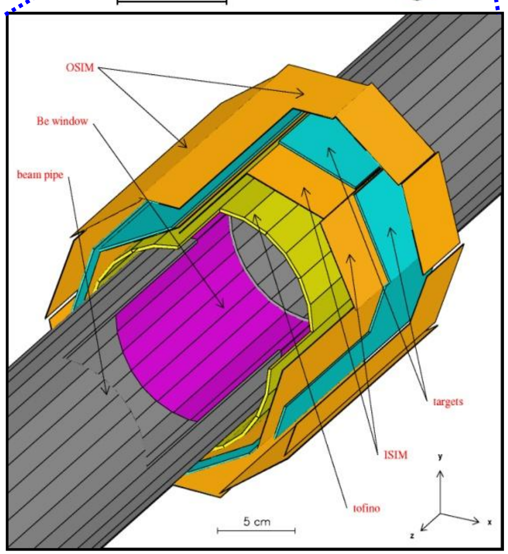
- MWD:
  - $J^\pi$ assignment
  - $\pi^-$-nucleus optical potential

- NMWD:
  - 4-baryon strangeness-changing weak interaction
  - $\Delta I=1/2$ from *s*-shell hypernuclei ($^4_\Lambda H$)
  - $\Gamma_n/\Gamma_p$ (? … systematics)
  - $\Gamma_{2N}$, FSI contributions

# FINUDA @ DAΦNE

$$e^+ + e^- \rightarrow \phi\,(1020) \rightarrow K^+ + K^-\ (127\ \mathrm{MeV/c})$$
$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$




Solenoid: B=1T

## Detector capabilities:

**Selective trigger** based on fast scintillation detectors (TOFINO, TOFONE)

**Clean $K^-$ vertex identification**

(ISIM P.ID.+ *x,y,z* resolution + $K^+$ tagging)

**π, K, p, d, … P.I.D.** (OSIM&LMDs d*E*/d*x*, TOF)

**High momentum resolution**

(6‰ FWHM for π- @270 MeV/c for spectroscopy)

(1% FWHM for π- @270 MeV/c for decay study)

(6% FWHM for π- @110 MeV/c for decay study)

(2% FWHM for p @400 MeV/c for decay study)

(tracker resolution + He bag + thin targets)

**Solid angle** ~ 2π srad

2003 data taking: 190 $pb^{-1}$ (2x$^{6}$Li, $^{7}$Li, 3x$^{12}$C, $^{27}$Al, $^{51}$V)
2006 data taking: 966 $pb^{-1}$ (2x$^{6}$Li, 2x$^{7}$Li, 2x$^{9}$Be, $^{13}$C, $D_2O$)
10 $pb^{-1}$/day

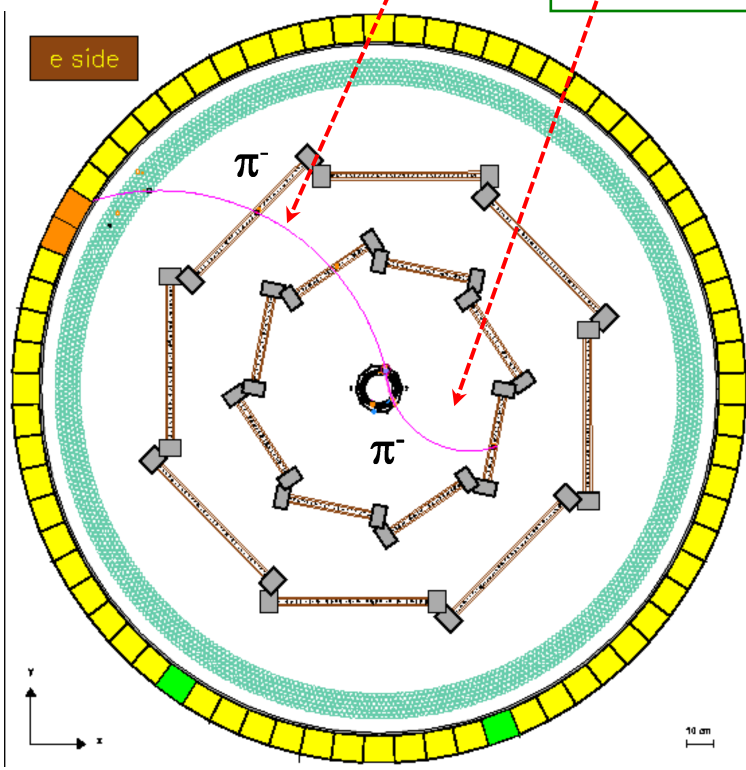
# Hypernuclear decay study in FINUDA
## Strategy: coincidence measurement

<u>charged Mesonic channel</u>

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

S-EX
260-280 MeV/c

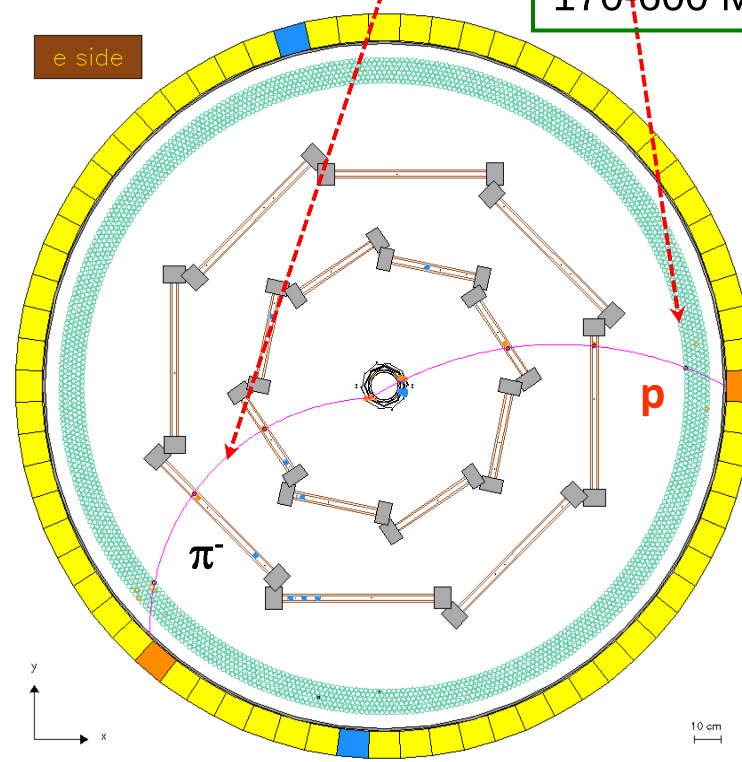
MVD
80-110 MeV/c




<u>charged Non-Mesonic channel</u>

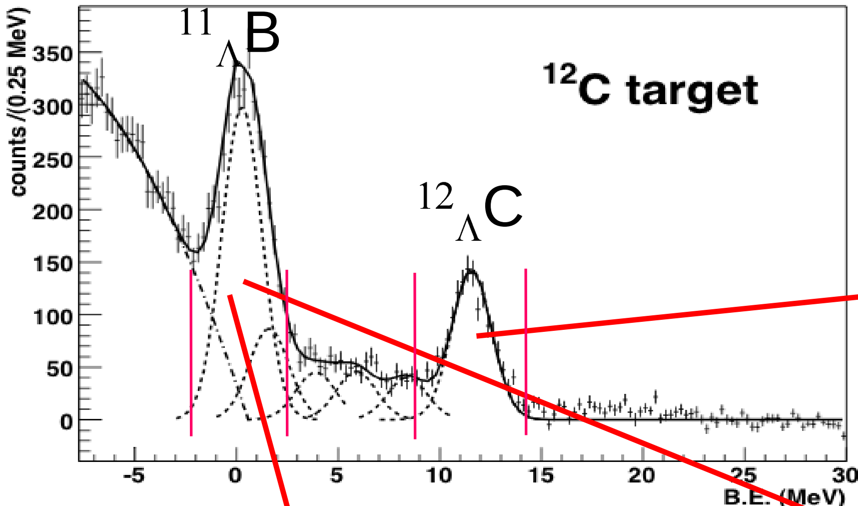
$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$
$$ {}^{A}_{\Lambda}Z \rightarrow {}^{A-2}(Z-1) + p + n$$

NMWD
170-600 MeV/c

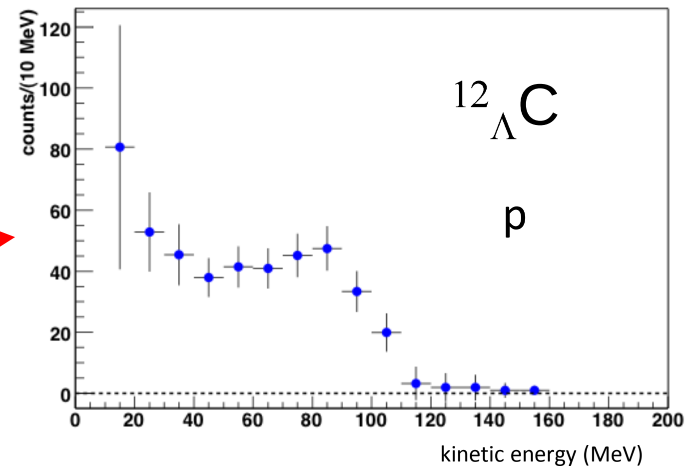


# Hypernuclear decay study in FINUDA: strategy

Inclusive production $\pi^-$ spectra
$K^-np$ background corrected

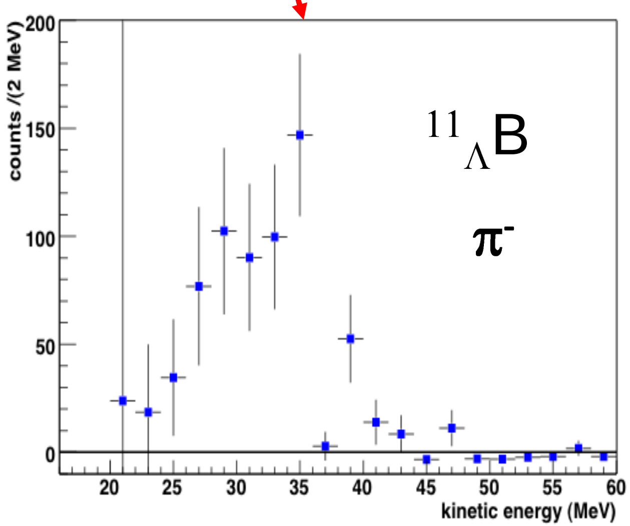


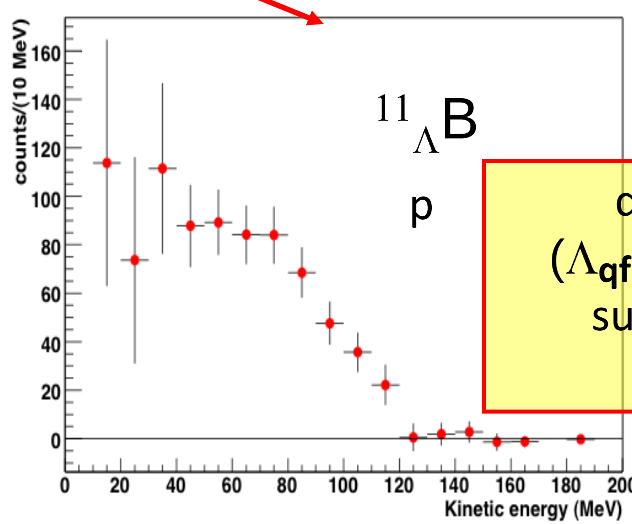

NMWD




MWD

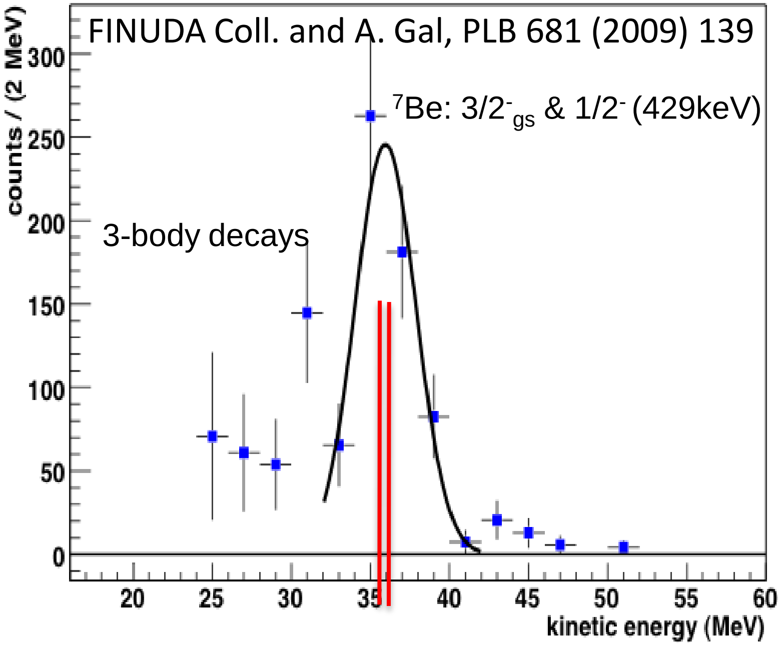
NMWD




decay $\pi^-$ and p spectra
($\Lambda_{qf}$ decay)/$K^-np$ background
subtracted & acceptance
corrected

# Mesonic weak decay spectra: $^{7}_{\Lambda}Li$




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

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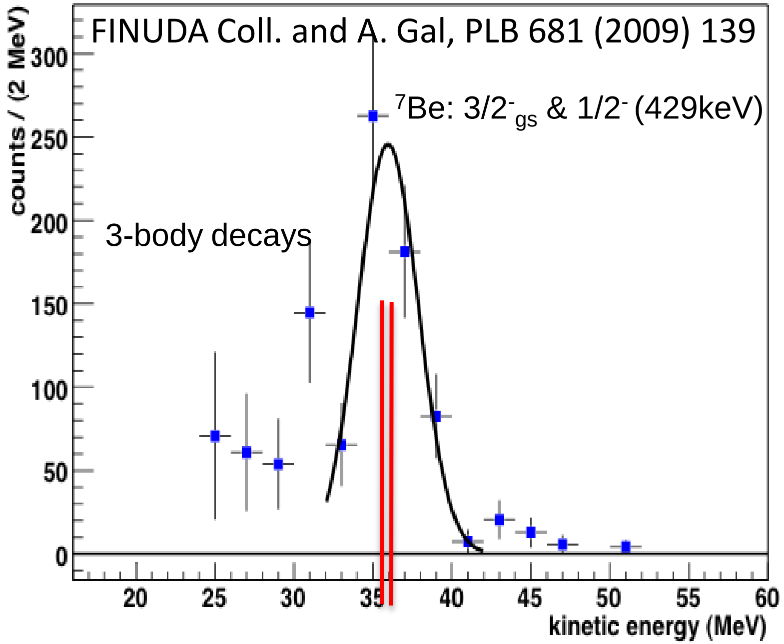


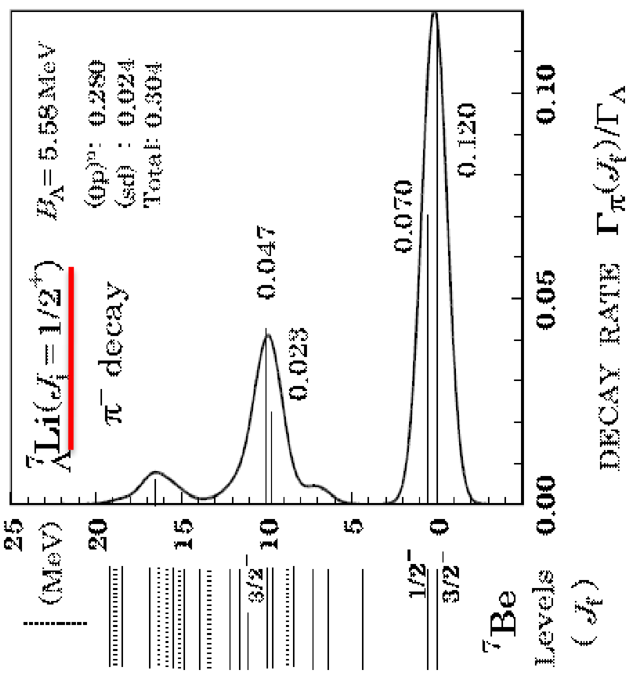


T. Motoba (Private Communication)

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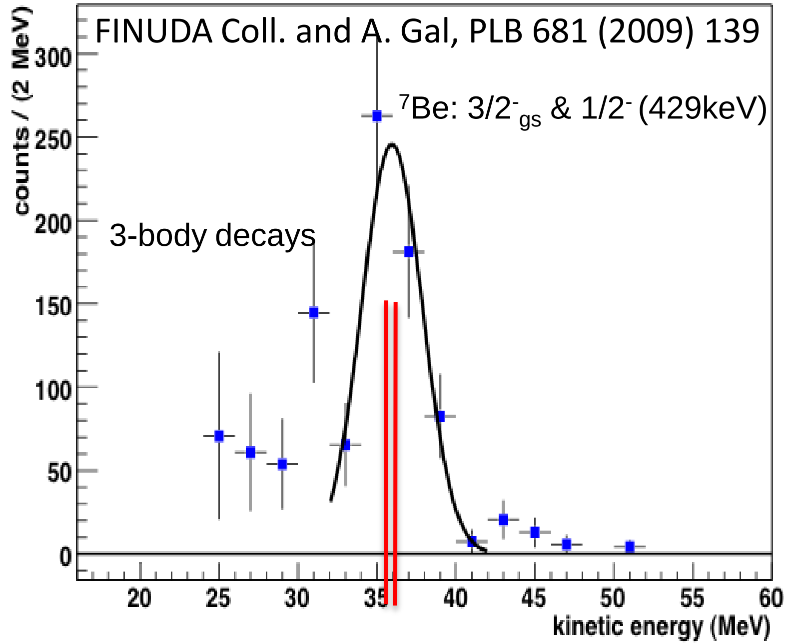


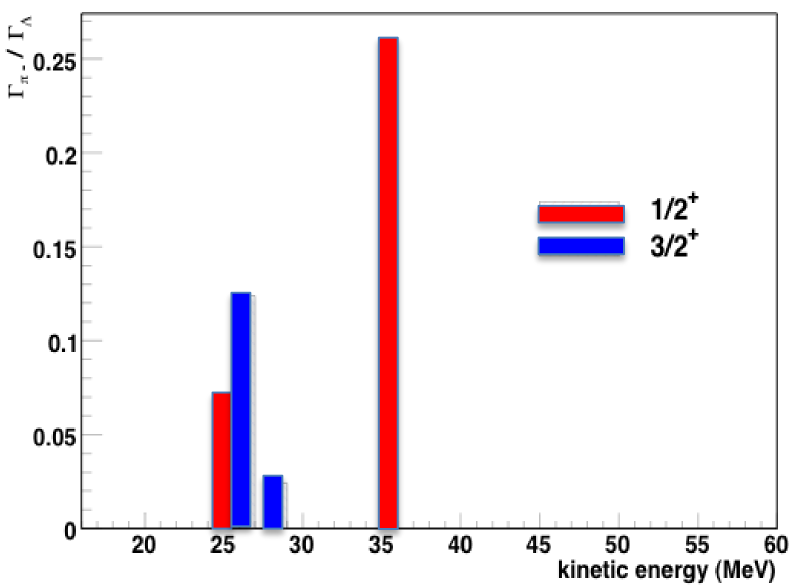


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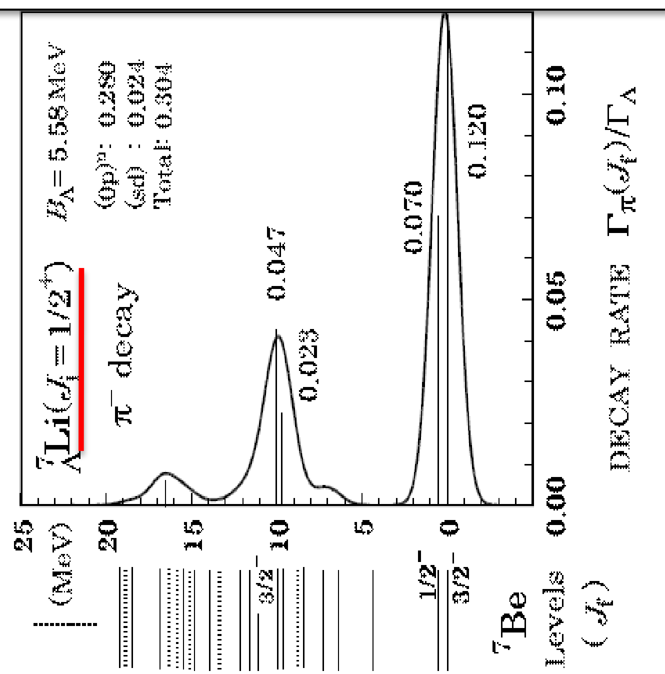


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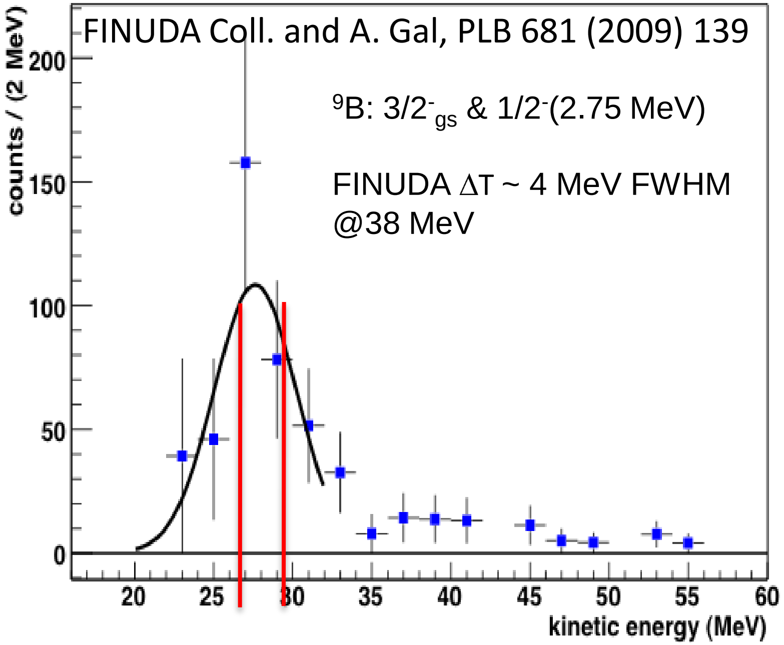
# Mesonic weak decay spectra: $^{9}_{\Lambda}$Be

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- Initial hypernucleus spin
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  O.Hashimoto NPA 639 (1998) 93c.

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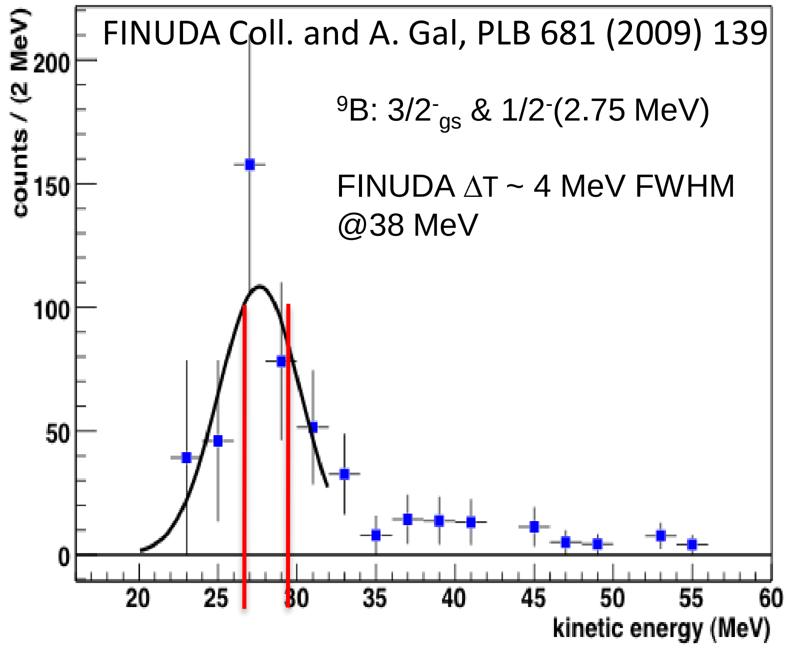


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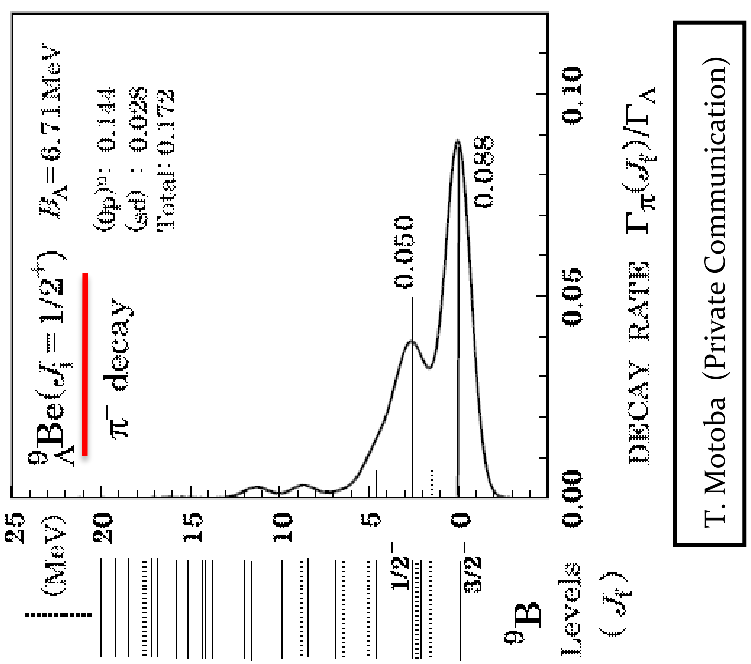

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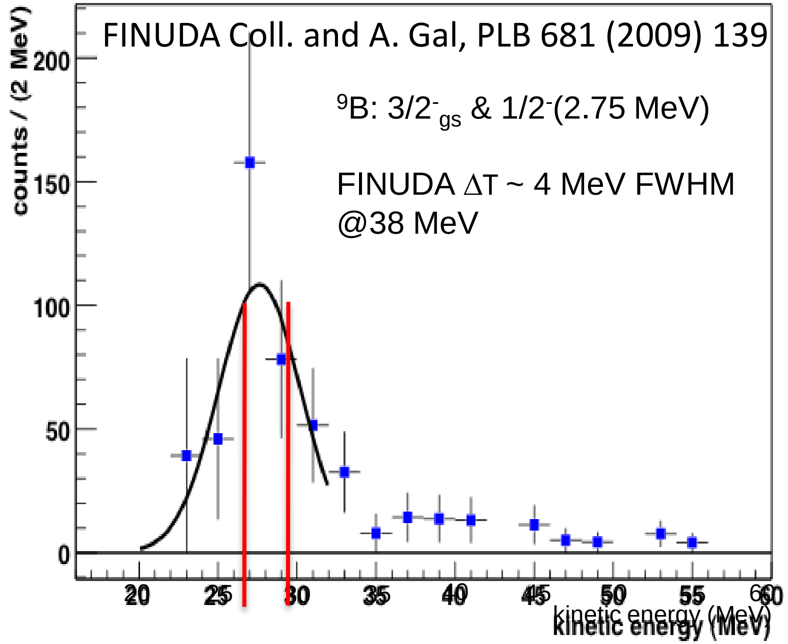


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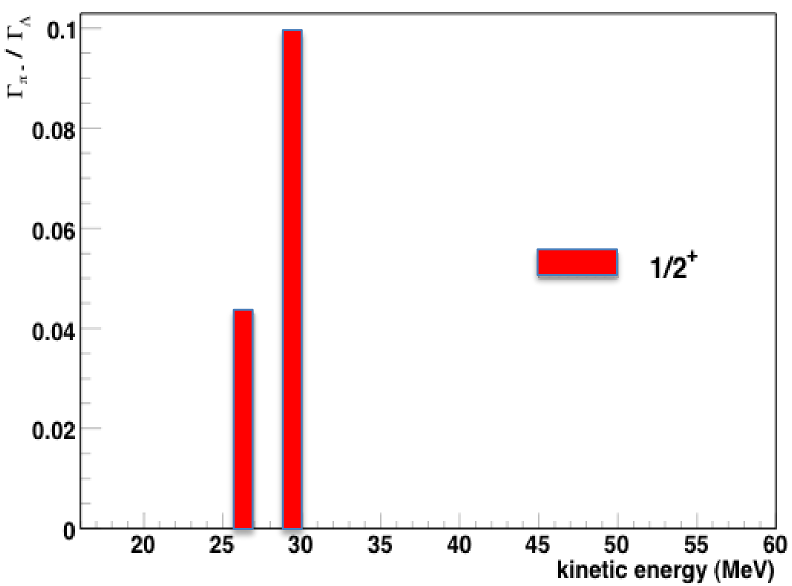


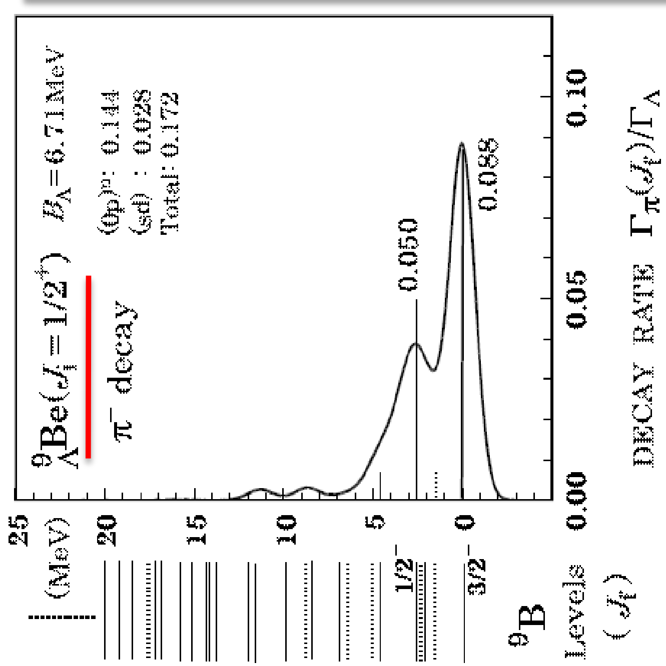


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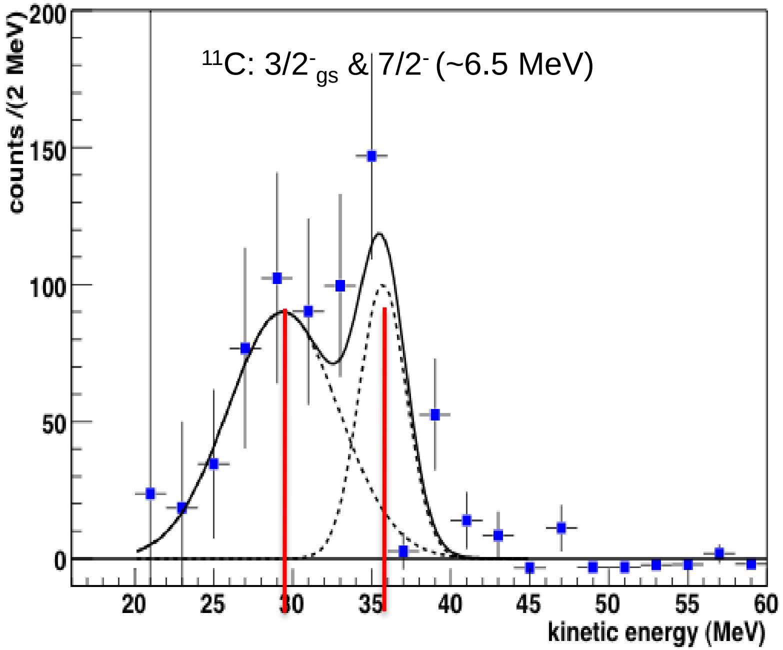
# Mesonic weak decay spectra: $^{11}{}_{\Lambda}B$




FINUDA Coll. and A. Gal, PLB 681 (2009) 139

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- Two contributions of the $^{11}C$ ground state $5/2^-$ and its $7/2^-$ excited state

- Initial hypernucleus spin
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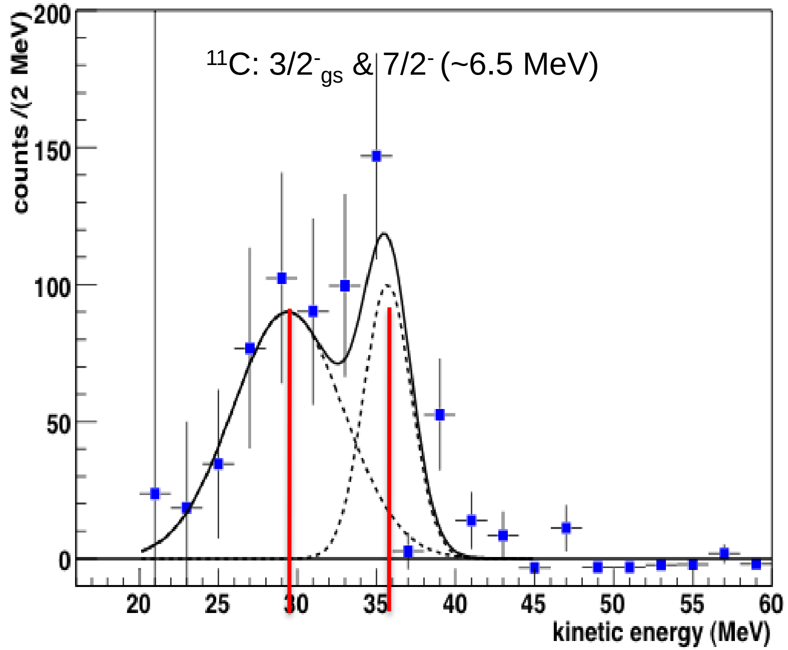


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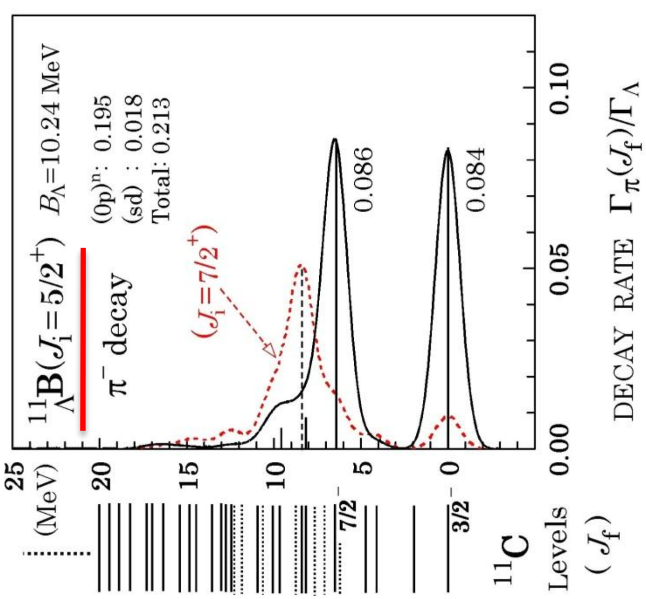


Motoba (Private Communication)

FINUDA Coll. and A. Gal, PLB 681 (2009) 139

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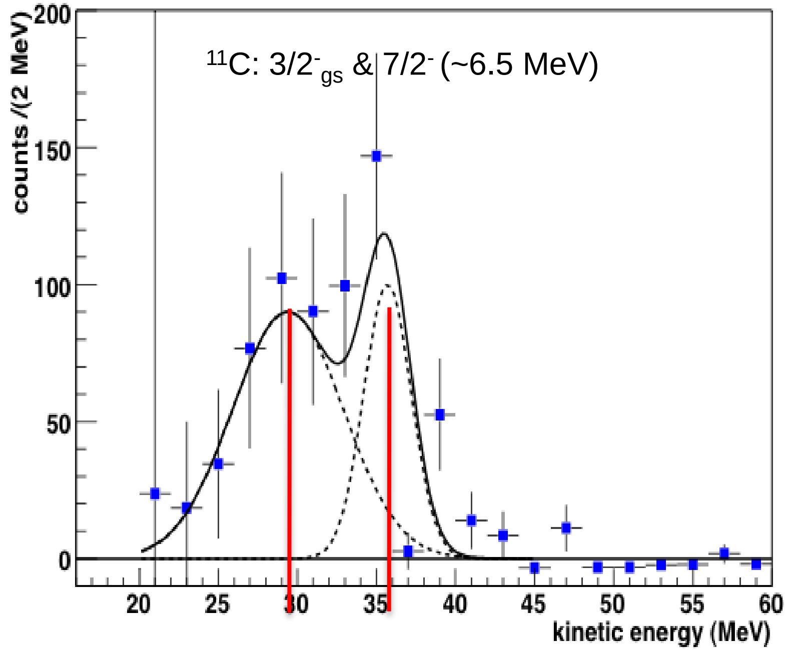


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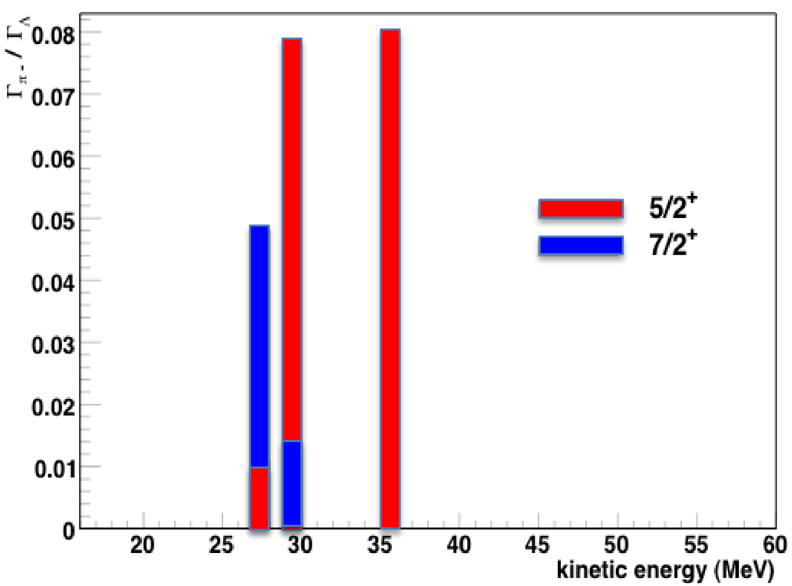


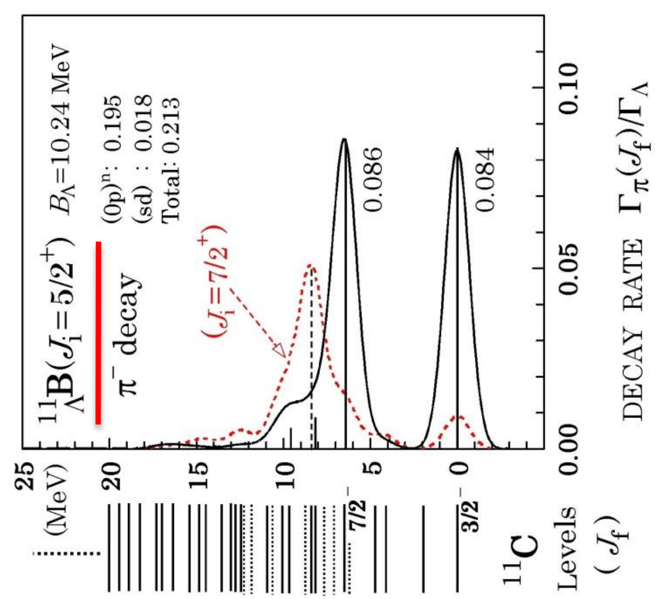


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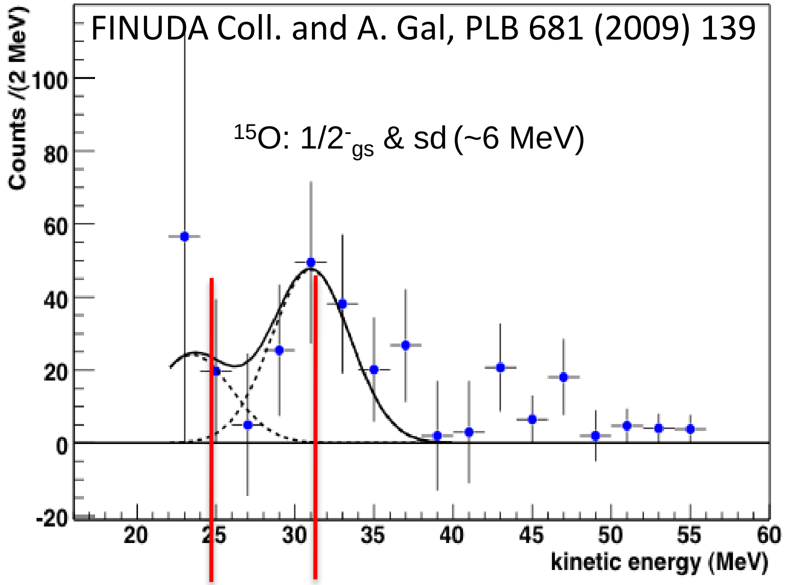
# Mesonic weak decay spectra: $^{15}_{\Lambda}N$

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  - ✓ A. Gal, Nucl. Phys. A 828 (2009) 72.

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D.J.Millener, A.Gal, C.B.Dover Phys. Rev. C 31 (1985) 499.
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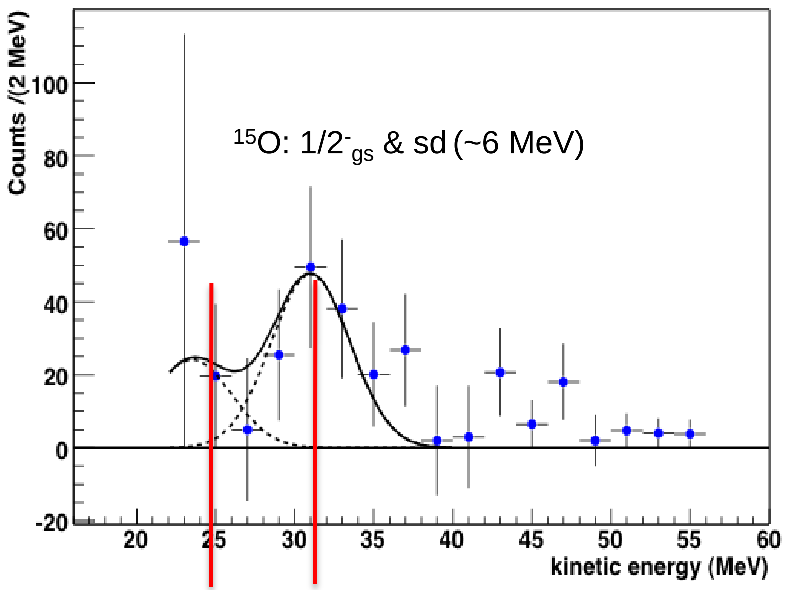


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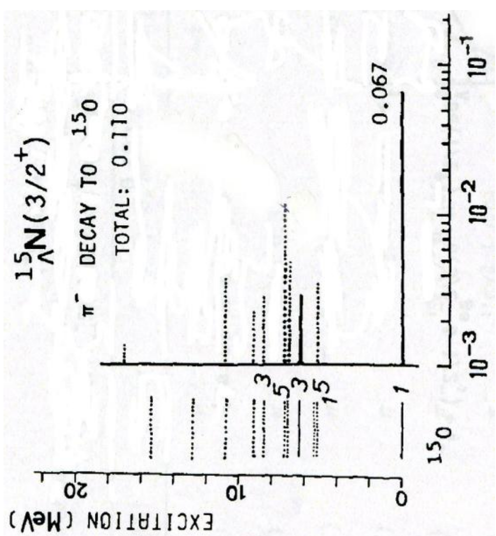


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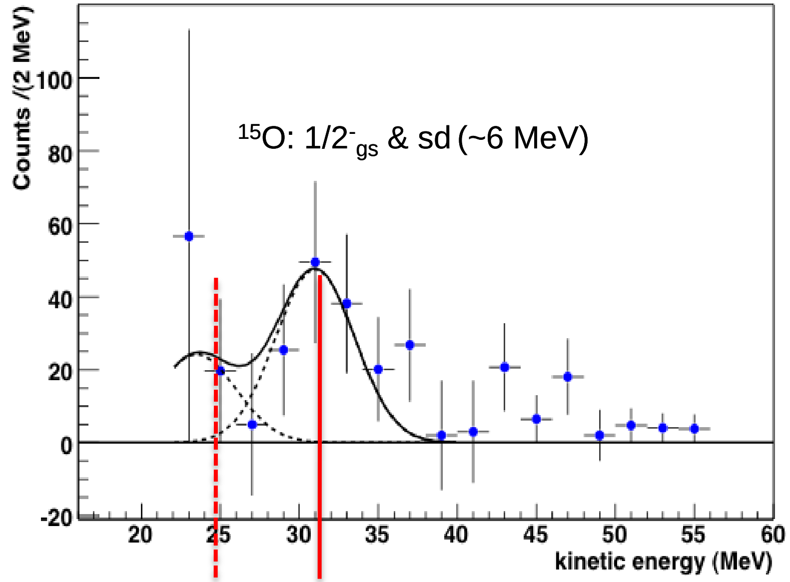


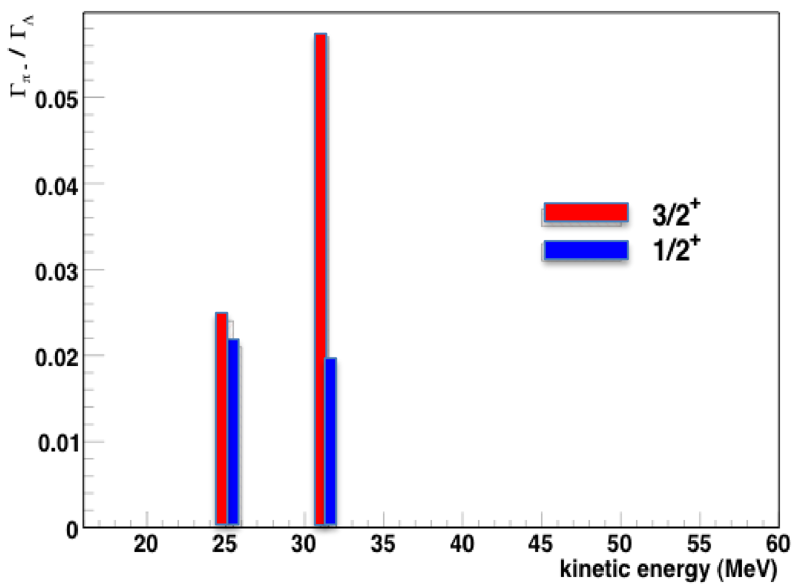


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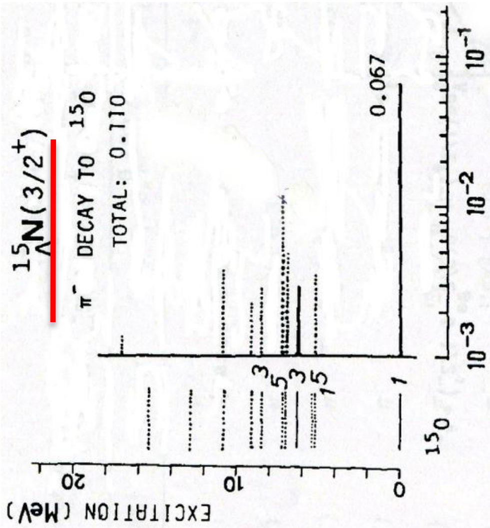
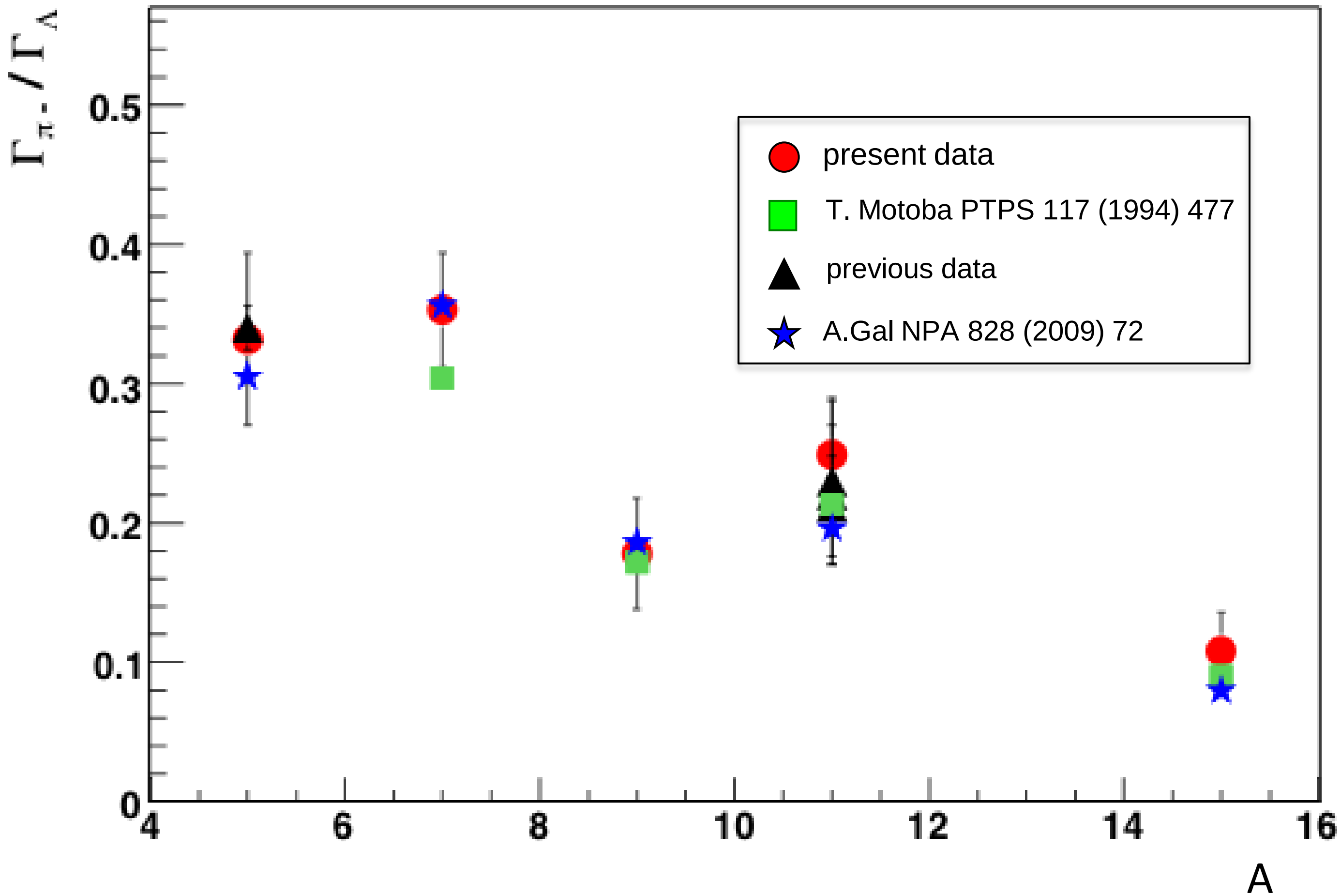



T. Motoba NPA 489 (1988) 683.

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

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

fit from measured values for A=4-12 hypernuclei




**strong nuclear structure effects**

# Mesonic decay: results

- MWD $\pi^-$ spectra for ${}^{7}_{\Lambda}Li$, ${}^{9}_{\Lambda}Be$, ${}^{11}_{\Lambda}B$ and ${}^{15}_{\Lambda}N$
- spin-parity assignment confirmed for ${}^{7}_{\Lambda}Li$, ${}^{9}_{\Lambda}Be$, ${}^{11}_{\Lambda}B$ g.s.
- new spin-parity assignment for ${}^{15}_{\Lambda}N$, based on decay rate (and spectrum shape)
- MWD decay rates calculated and compared with theoretical calculations and previous measurements
- nuclear structure effects

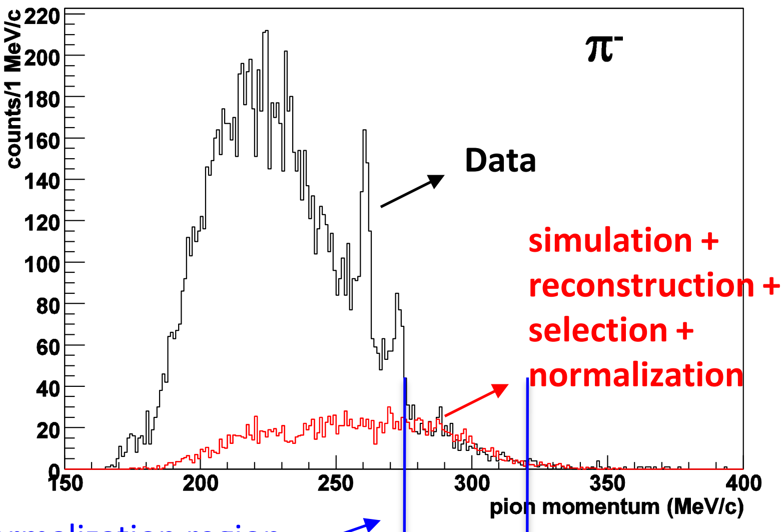
# Non Mesonic weak decay spectra: the method

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

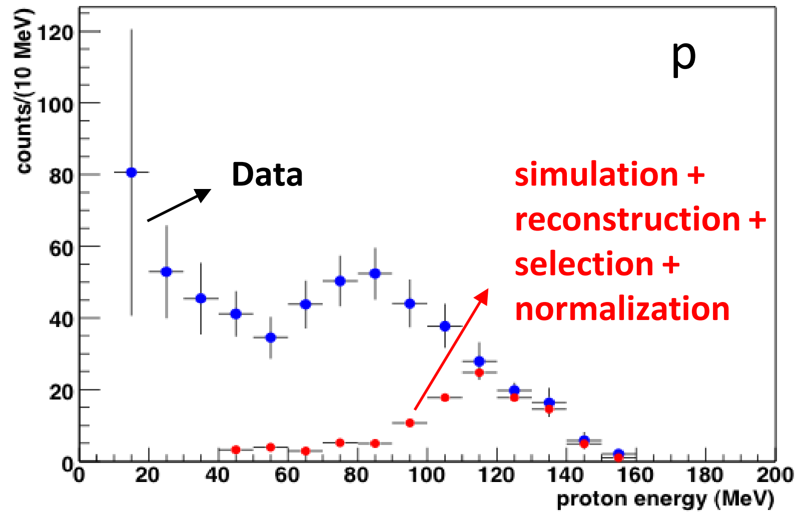
$\Sigma^- \rightarrow n \pi^-$

coincidence

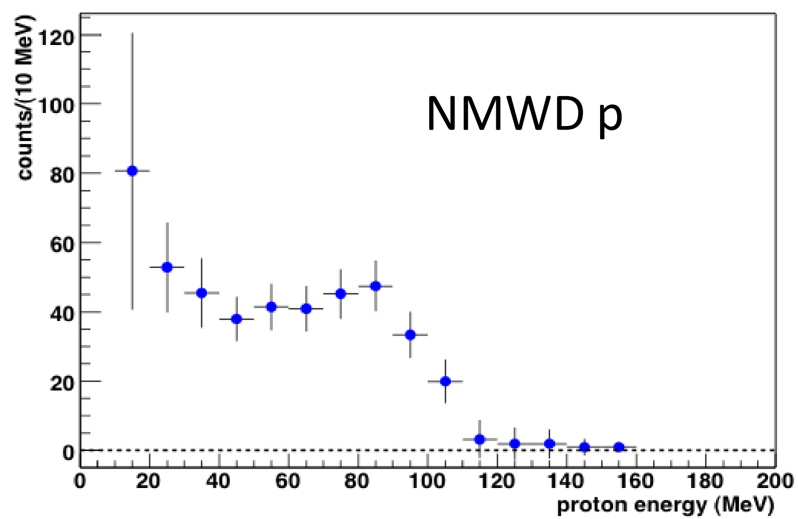
Coincidence spectra: $^{12}_{\Lambda}C$, all targets




normalization region




subtraction



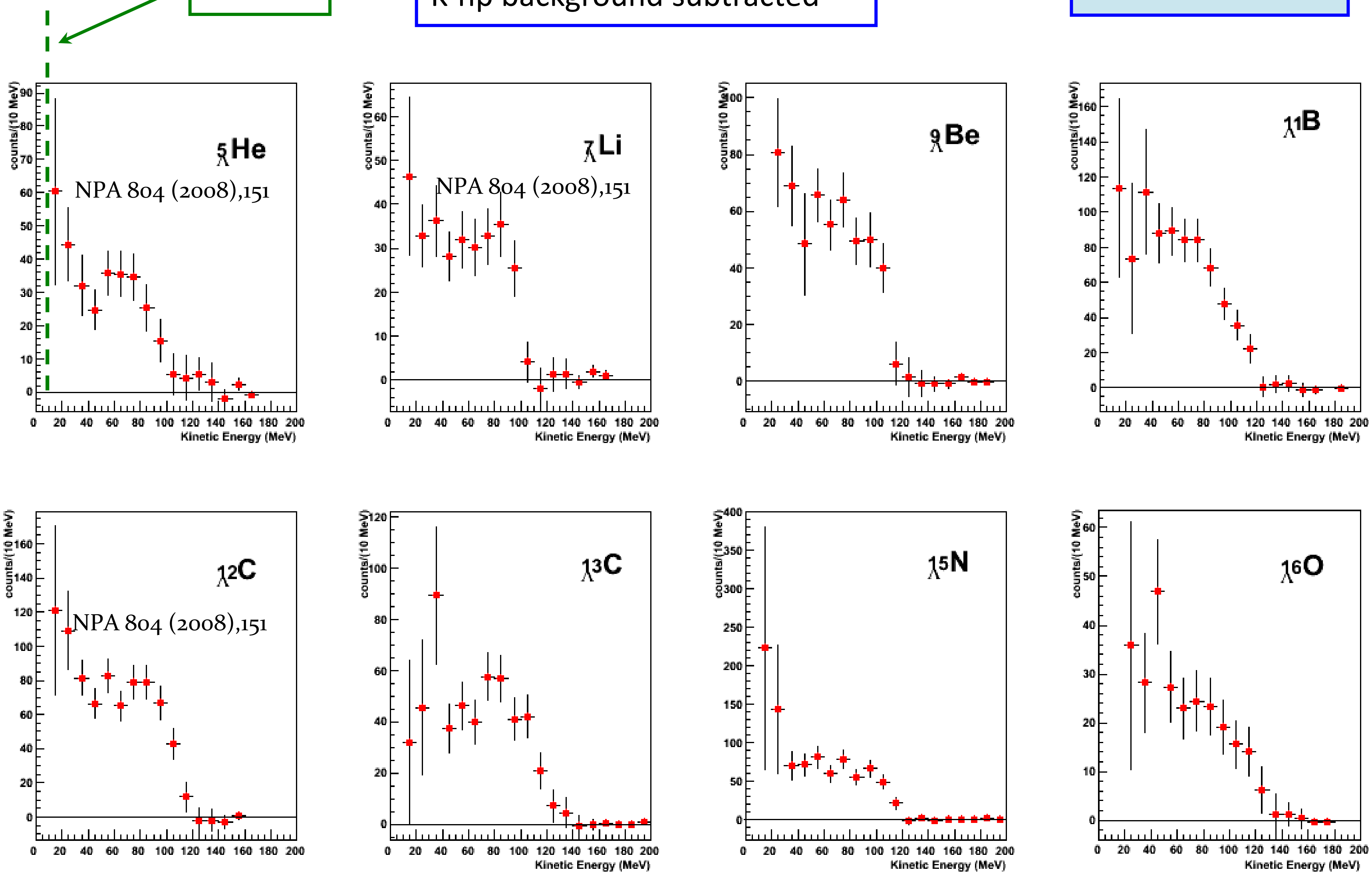

M. Agnello et al., NPA 804 (2008),151

# Non Mesonic Weak Decay spectra

15 MeV

$K^-np$ background subtracted

1N + 2N + FSI !!

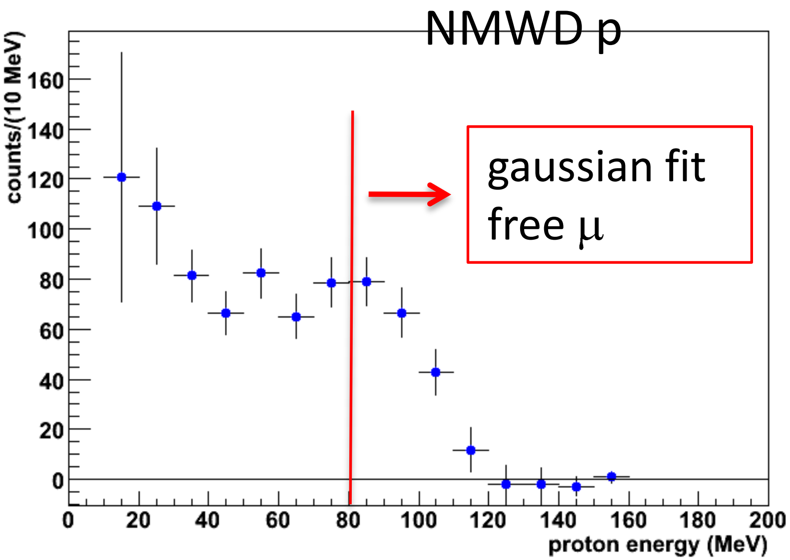


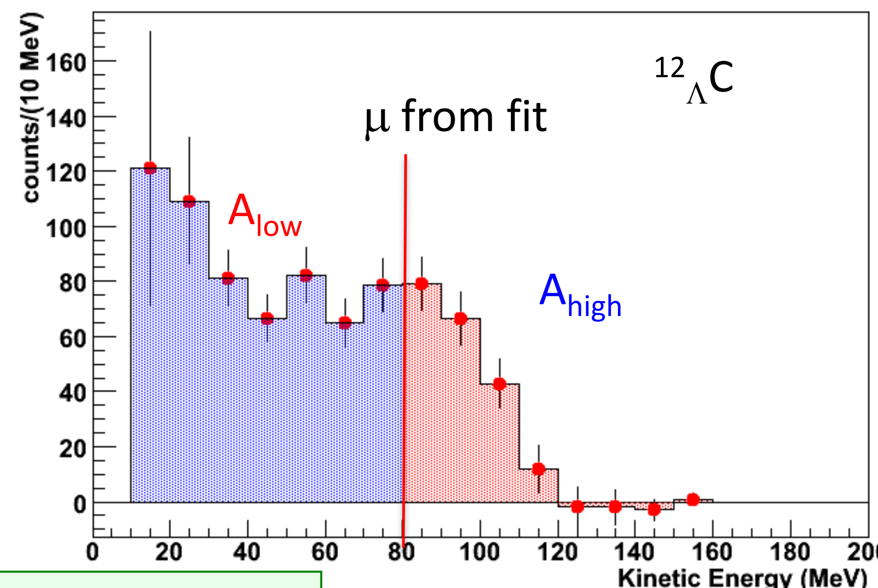

FINUDA Coll. and G. Garbarino, PLB 685 (2010) 247

# FSI & $\Lambda$NN contribution evaluation: the method

2N / NMWD independent on A ⟸ assumption

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




$A_{low}$: spectrum area below $\mu$

1N + 2N + FSI

$A_{high}$: spectrum area above $\mu$

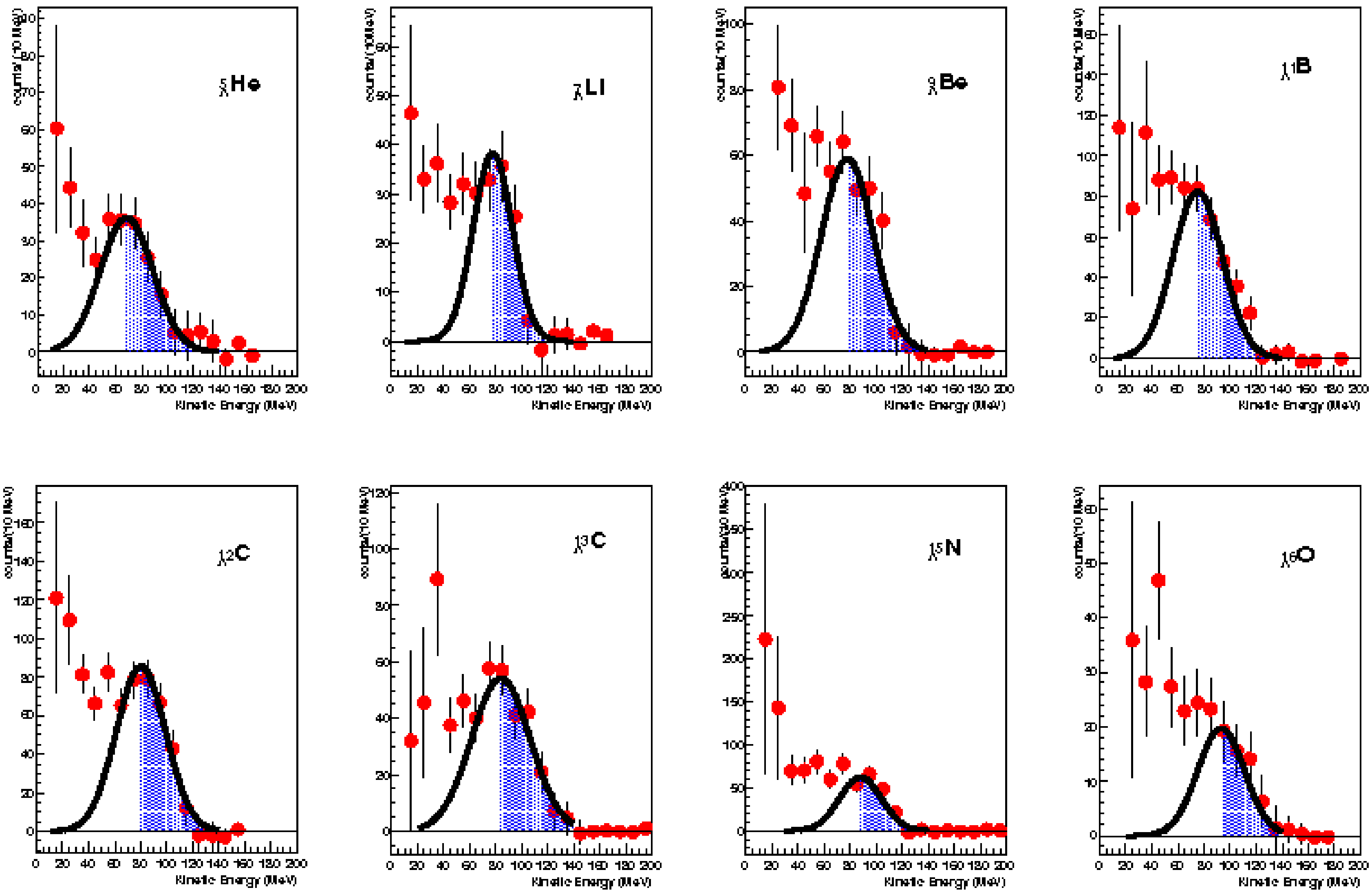
1N + FSI

2N(>70 MeV) ~ 5% $2N_{tot}$ ⟸ assumption

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

Phys.Rev. C 69 (2004) 054603.

# FSI & ΛNN contribution evaluation: systematics




FINUDA Coll. and G. Garbarino, PLB 685 (2010) 247

# FSI & $\Lambda$NN contribution evaluation

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

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

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

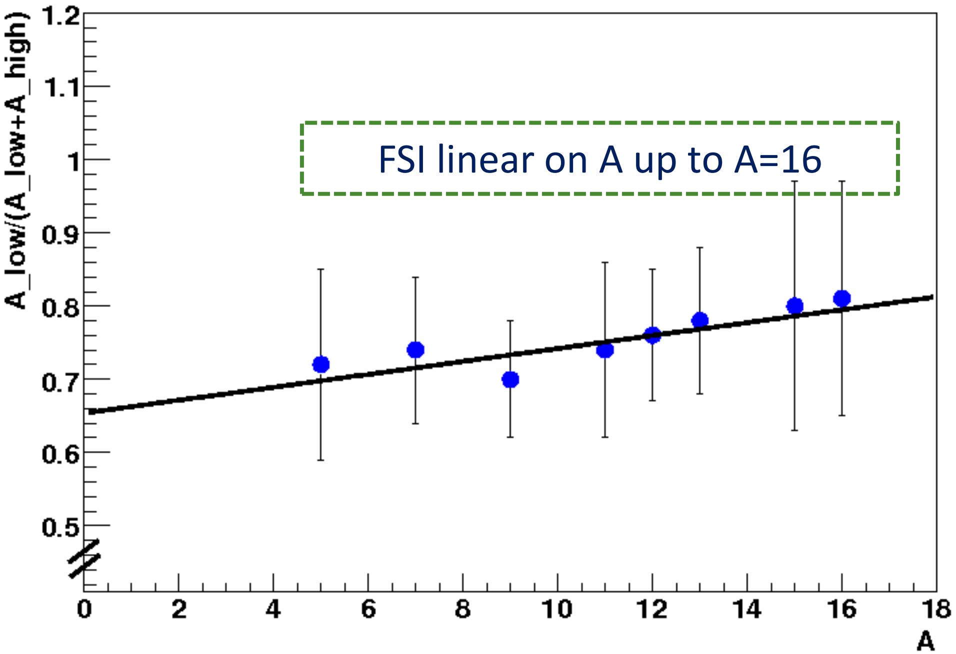
assumption

$\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$
E. Bauer and G.Garbarino,
Nucl.Phys. A 828 (2009), 29.

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

# Non-Mesonic Weak Decay

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

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$$\Gamma_2 = \Gamma_{np} + \Gamma_{pp} + \Gamma_{nn}$$

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

E. Bauer and G.Garbarino, NPA 828 (2009), 29.

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

$$R(A) = \frac{0.5 + \frac{\Gamma_2}{\Gamma_p}}{1 + \frac{\Gamma_2}{\Gamma_p}} + bA$$

Assumption: $\Gamma_2/\Gamma_1$ and $\Gamma_n/\Gamma_p$ indipendent from A→ supported by exp and the

$$\frac{\Gamma_2}{\Gamma_p} = 0.43 \pm 0.25$$

$$\frac{\Gamma_2}{\Gamma_{NMWD}} = 0.24 \pm 0.10$$

1

# NMWD, FSI & 2N: results

- p-induced NMWD proton spectra from ${}^{5}_{\Lambda}$He to ${}^{16}_{\Lambda}$O

- first experimental indication of the relevant rôle played by the two–nucleon induced mode in the NMWD of hypernuclei

- contribution as large as almost **24%** of all the non–mesonic weak decays

- **very large contributions from 2N suggested by theoretical calculation**

**W.Alberico, A.De Pace, G.Garbarino and A.Ramos, Phys. Rev. C 61 (2000) 044314.**

**G. Garbarino, A.Parreno and A.Ramos, Phys. Rev. C 69 (2004) 054603.**

**E. Bauer and G. Garbarino , NPA 828 (2009) 29.**

- $\Gamma_2/\Gamma_{NMWD}$ *experimental indications:*

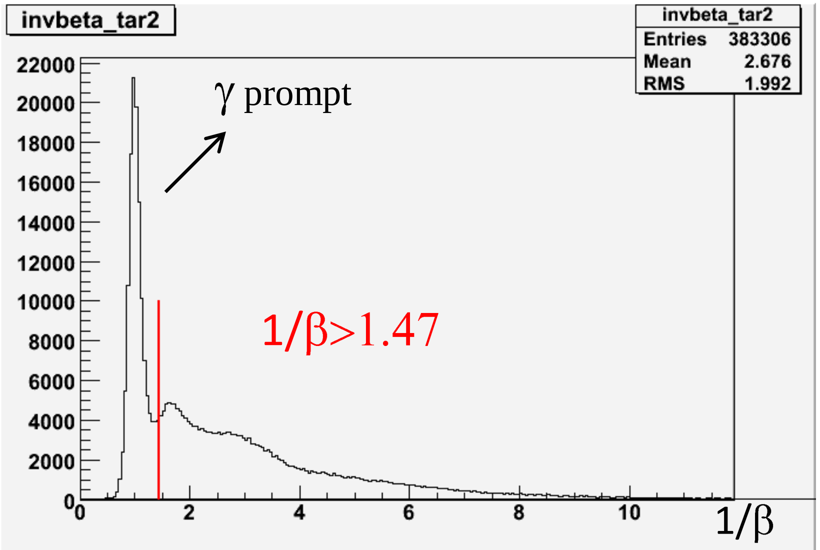
*FINUDA value: 0.24 ± 0.10*

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

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

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

# Triple coincidence analysis




Neutron detection efficiency ~10%

Neutron energy resolution ~9% at 80 MeV

TOF allows n/γ discrimination

Background prevails if no correlations or selections are imposed

Analysis of ($\pi$-,n,p) coincidence

**$N_n$ ($\cos\theta \geq$- 0.8, $E_p < \mu - 20$ MeV): 2N + FSI and small contribution of 1N**

$N_n$ = number of n in coincidence with ($\pi$-,p)

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

No spectra shape analysis (20 events for each target)

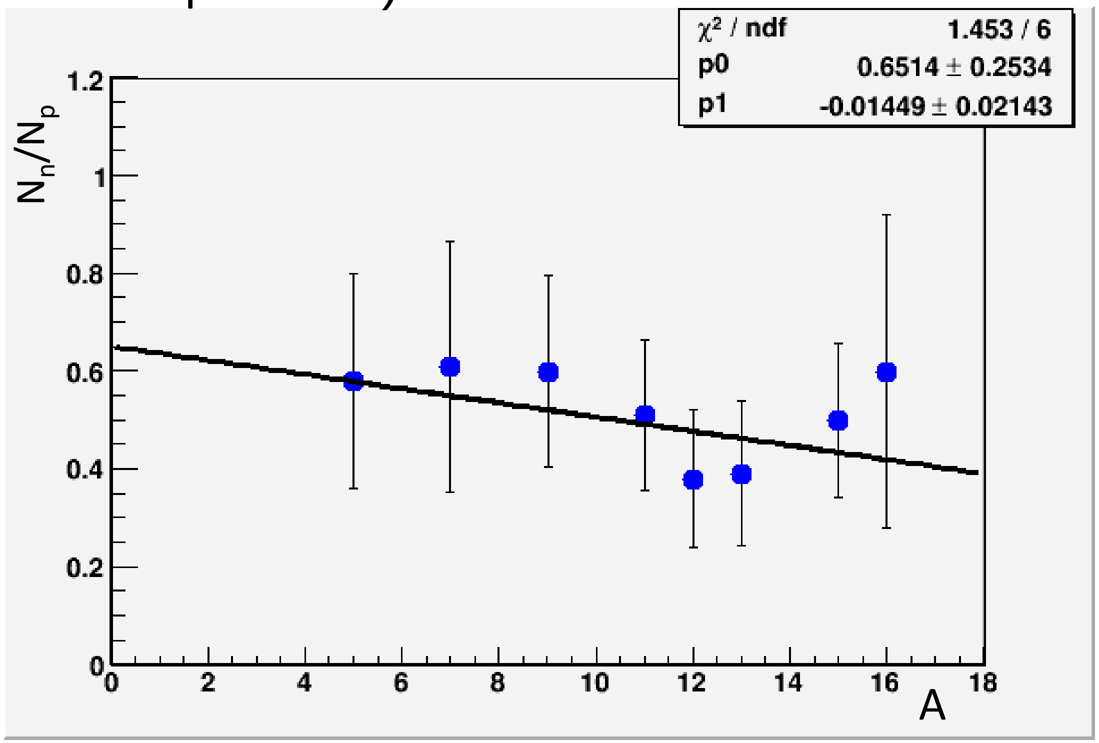
Background study (events from $K^-$np absorption)

Acceptance correction

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

# Non-Mesonic Weak Decay from np coincidence

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




$$R(A) = \frac{\Gamma_2}{0.5\Gamma_P} + bA$$

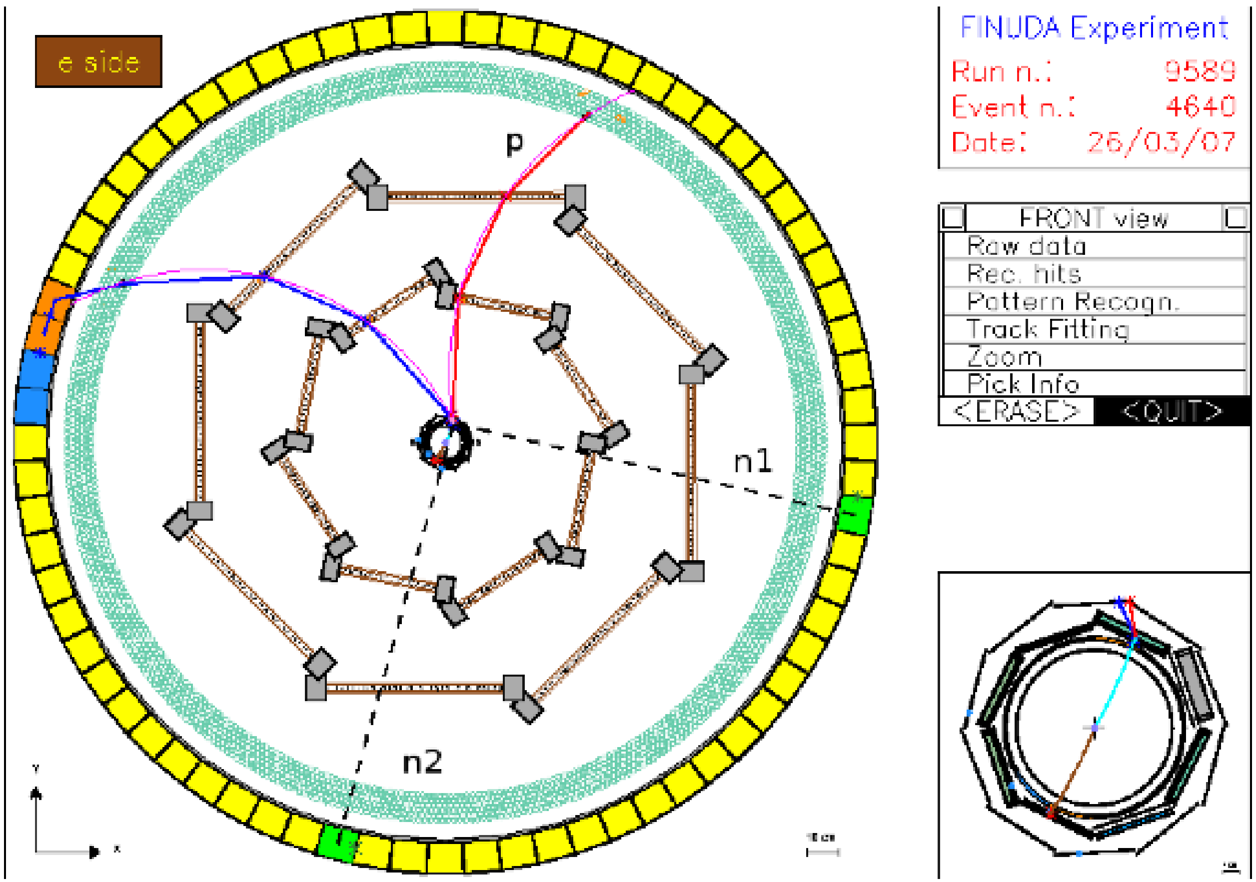
$$\frac{\Gamma_2}{\Gamma_p} = 0.33 \pm 0.07$$

$$\frac{\Gamma_2}{\Gamma_{NMWD}} = 0.18 \pm 0.03$$

Low statistic but direct measurement-→ error lowered by a factor 3

# 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 scattering

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

# Conclusions

- ✓ First systematic study of p-induced NMWD from ${}^{5}_{\Lambda}He$ to ${}^{16}_{\Lambda}O$
- ✓ Energy threshold never reached before: 15 MeV
- ✓ Evaluation of the FSI and 2N-induced NMWD: values in agreement with theoretical calculation and latest experimental results
- ✓ First direct evidence of the relevant contribution of the 2N stimulated NMWD
- ✓ Results confirmed with smaller errors by means of the analisys of (π-,n,p) coincidences
- ✓ First detection of clear events with pnn emitted from the 2N-induced NMWD

…… thank you!