Weak decay of hypernuclei with FINUDA

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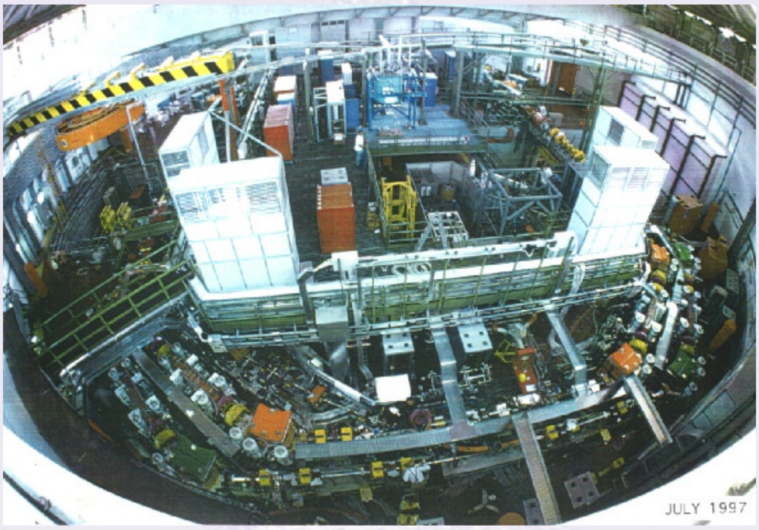
Outlook

- Introduction
- The FINUDA experiment
- Weak decay of hypernuclei
  - mesonic
  - nucleon stimulated
  - rare decay channels
- Conclusions

Physical motivations

- see B.F. Gibson's talk
- see E. Oset's talk
- see H. Bhang's talk
- see W.M. Alberico's talk
- see C. Bennhold's talk
- see H. Outa's talk
- see R.L. Gill's talk

Hypernuclear physics at DAΦNE



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

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

FINUDA
hypernuclear physics

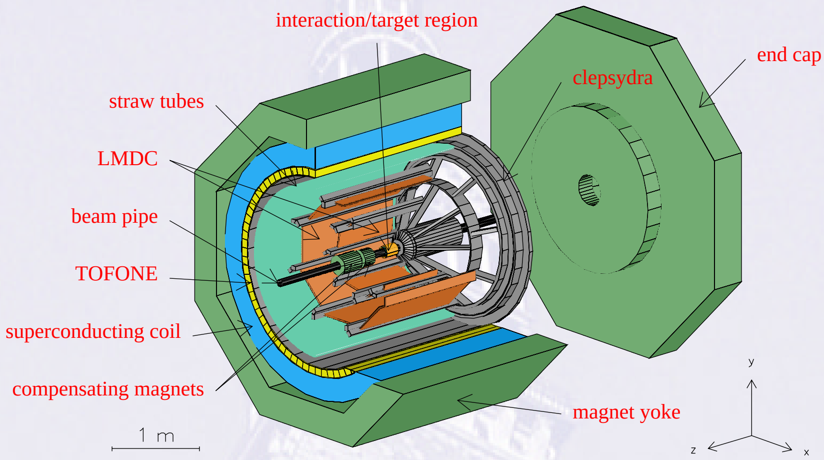
$K_S K_L$ (34%)

$\rho\pi$ (13%)

K^+K^- (49%)

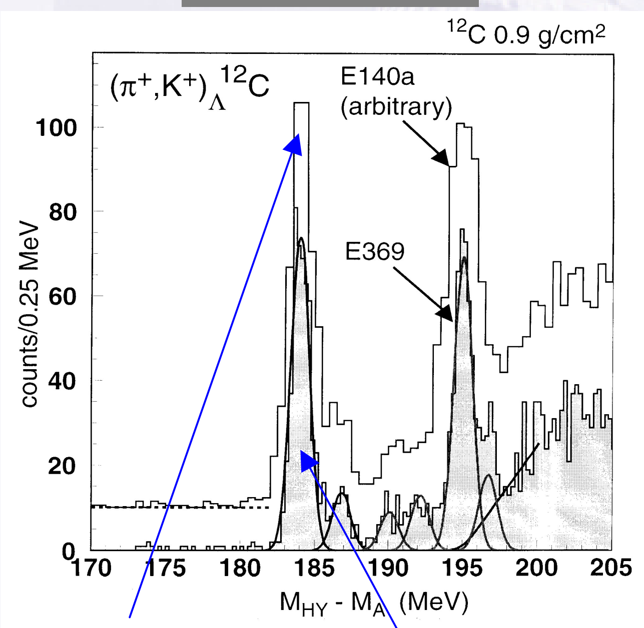
DEAR
K-N scattering

The FINUDA experiment at DAΦNE



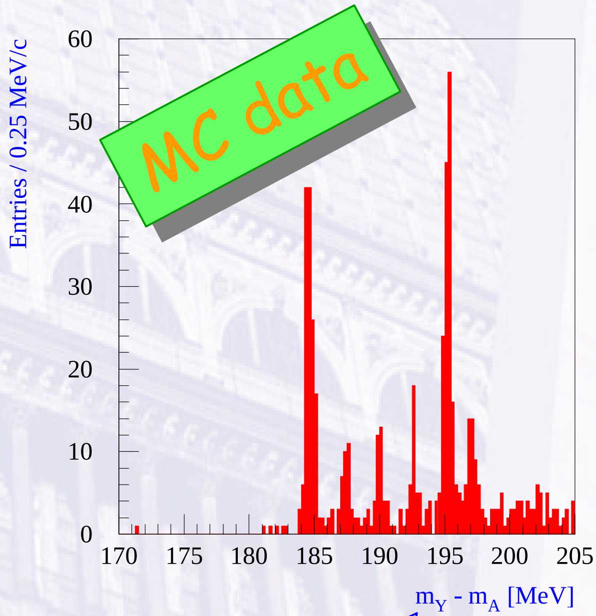
$^{12}C(K^-_{stop}, \pi^-)^{12}_{\Lambda}C$

KEK data



~ 2 MeV res.

~ 1.5 MeV res.



~ 0.7 MeV res.

Hypernucleus decay

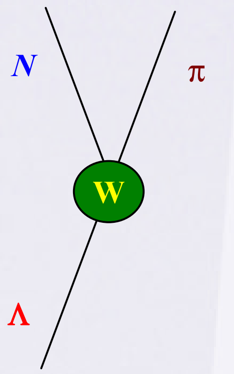
• mesonic

Pauli blocked in medium-heavy hypernuclei*

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

* A ≥ 5

partial rate	transition
Γ_{π^0}	$\Lambda \rightarrow n + \pi^0$
Γ_{π^-}	$\Lambda \rightarrow p + \pi^-$



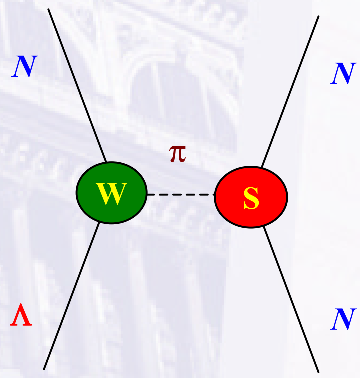
• non-mesonic

Dominant in medium-heavy hypernuclei*

* A ≥ 5

$$\Gamma_{nm} = \Gamma_n + \Gamma_p + \Gamma_{3N}$$

partial rate	transition
Γ_n	$\Lambda + n \rightarrow n + n$
Γ_p	$\Lambda + p \rightarrow n + p$
$\Gamma_{3N}{}^*$	$\Lambda + N + N \rightarrow N + N + N$



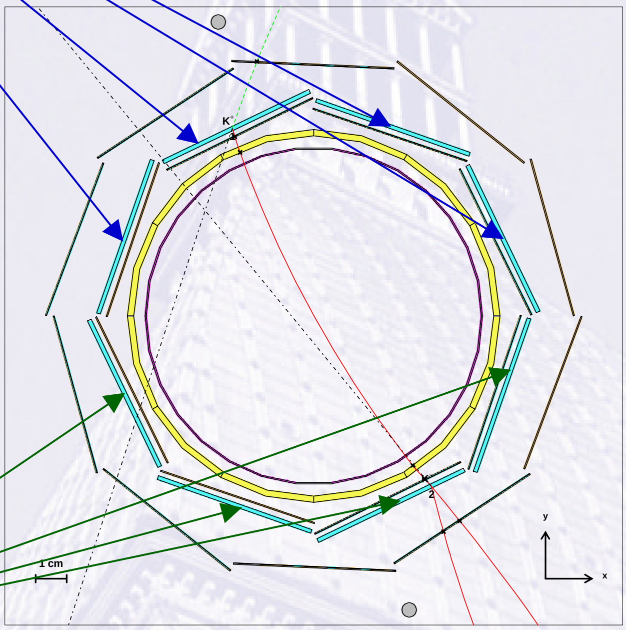
*not taken into account in the following evaluations

The FINUDA strategy

4 Carbon targets

$$K^-_{stop} + {}^{12}C \rightarrow {}^{12}_{\Lambda}C + \pi^-$$

reference mark



4 Lithium targets

a good opportunity
to study light hypernuclear systems

$$K^-_{stop} + {}^{6}Li \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$$

$$K^-_{stop} + {}^{6}Li \rightarrow {}^{4}_{\Lambda}He + p + n + \pi^-$$

$$K^-_{stop} + {}^{6}Li \rightarrow {}^{4}_{\Lambda}H + p + p + \pi^-$$

How to distinguish the different hypernuclei ($^{4}_{\Lambda}H$, $^{4}_{\Lambda}He$, $^{5}_{\Lambda}He$)

the excellent momentum resolution ($\Delta p/p$ 0.3% FWHM at 270 MeV/c) on the π^- from HY formation will allow to clearly identify $^{5}_{\Lambda}He$

more difficult will be the recognition between $^{4}_{\Lambda}He$ and $^{4}_{\Lambda}H$

however

the abundant production (Coulomb assisted) allows to search for rare decays channels

$$^{4}_{\Lambda}He \rightarrow \begin{cases} d + d \\ p + {}^{3}H \\ \pi^{+} + n + {}^{3}H \end{cases}$$

$^{4}_{\Lambda}He$ will be identified through its decay mode

mesonic decay

kinematic features:

★ 2-body decay

$${}^{A}_{\Lambda}Z \to {}^{A}(Z+1) + \pi^{-}$$

$${}^{A}_{\Lambda}Z \to {}^{A}Z + \pi^{0}$$

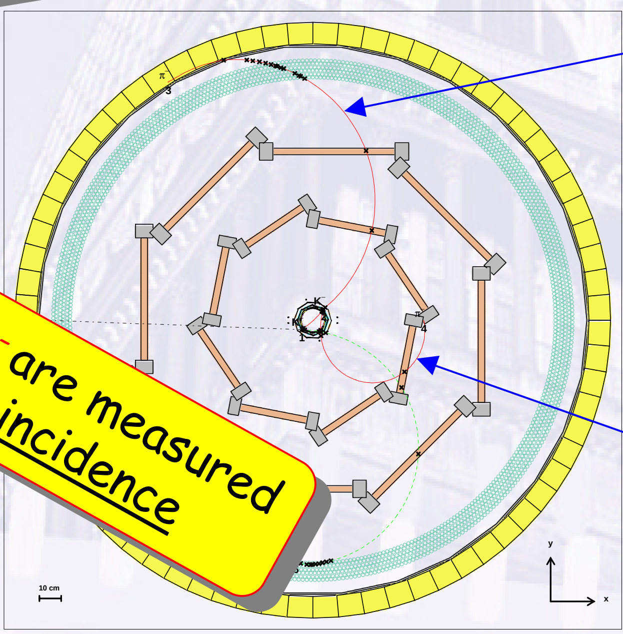
monochromatic
p ~ 100 MeV/c

★ n-body decay

$${}^{A}_{\Lambda}Z \to {}^{A'}Z' + \pi + xN \qquad x \geq 1$$

π spectrum is peaked
around 100 MeV/c

The FINUDA spectrometer
is not designed
to study mesonic decay...

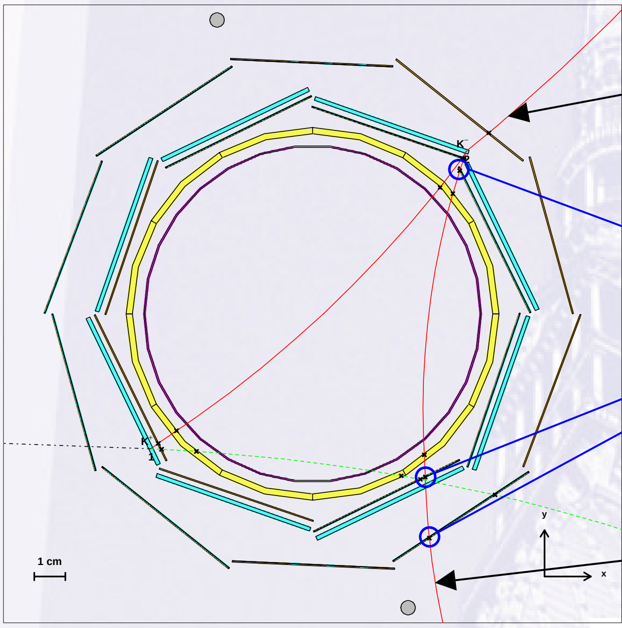


both π^- are measured
in coincidence

π^- from HY formation
p = 270 MeV/c
ρ_{max} = 80 cm

π^- from HY decay
p = 100 MeV/c
ρ_{max} = 30 cm

… anyway FINUDA can measure π^- from mesonic decay by means of two μstrip arrays

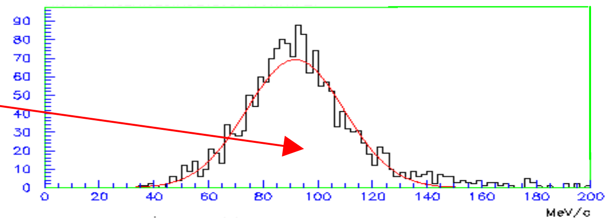


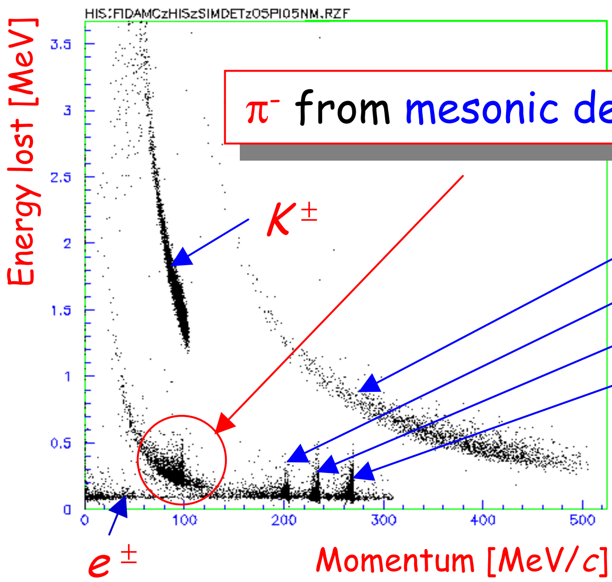
π^- from HY formation
p = 270 MeV/*c*

3 hits
on μstrip

π^- from HY decay
p = 100 MeV/*c*

poor
momentum resolution
Δp/p 40% (FWHM)
due to
multiple scattering





π^- from mesonic decay

good pid
by means of dE/dx
in μstrip

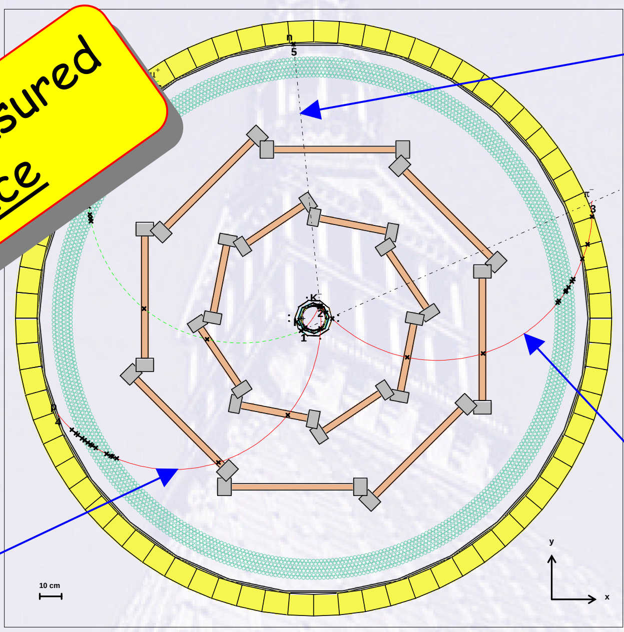
- *p* from non-mesonic decay
- π^+ from $K^+ \to \pi^+\pi^0$
- μ^+ from $K^+ \to \mu^+\nu$
- π^- from HY formation

Acceptance is 20%
(3 hits on μstrip)

p-induced decay

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

π^-, p and n are measured in coincidence



n is detected in thick scintillators

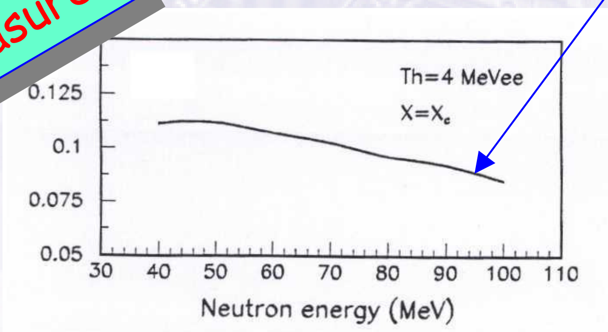
π is tracked

p is tracked

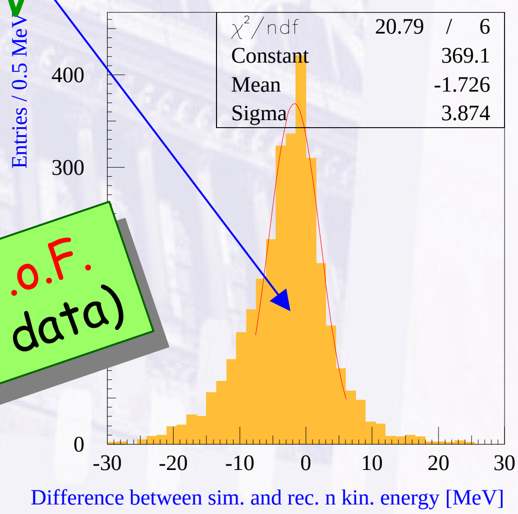
reconstruction:

- proton
  - acceptance 30%
  - energy resolution 1.3 MeV (at 80 MeV)
  - T.o.F. 500 ps (FWHM)
- neutron
  - acceptance 71%
  - energy resolution ~ 10 MeV
  - detection efficiency 10%

measured

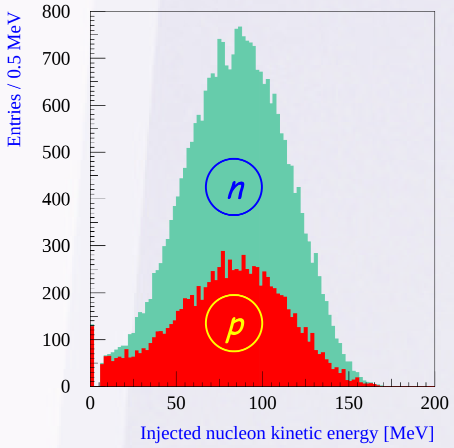


by T.o.F. (MC data)



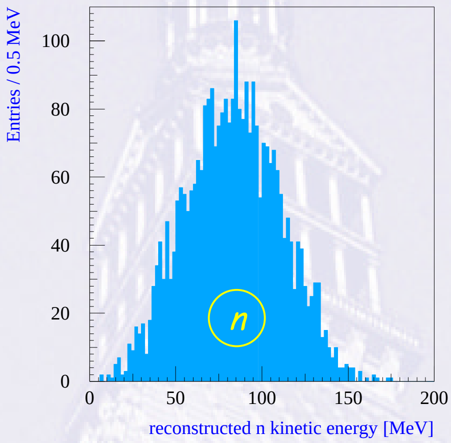
p-induced decay

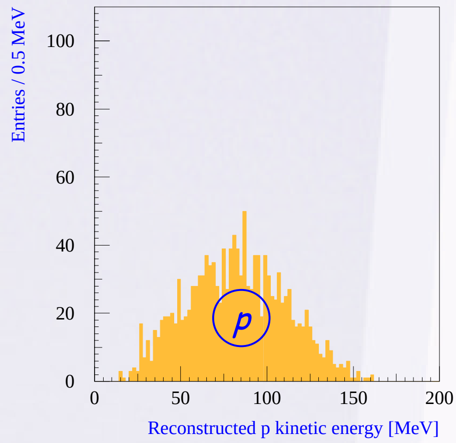
injected*



*A. Ramos et al., *Phys. Rev. C* (1997) 735

reconstructed





both *n* and *p* spectra from HY decay can be obtained!

main background:

$\pi^0 \rightarrow \gamma\gamma$ from $K^+ \rightarrow \pi^+\pi^0$ (21%)

$K^+ \rightarrow \pi^+\pi^0\pi^0$ (2%)

$$\frac{signal}{background} \approx 0.6$$ without any selection

$$\frac{signal}{background} \approx 20$$

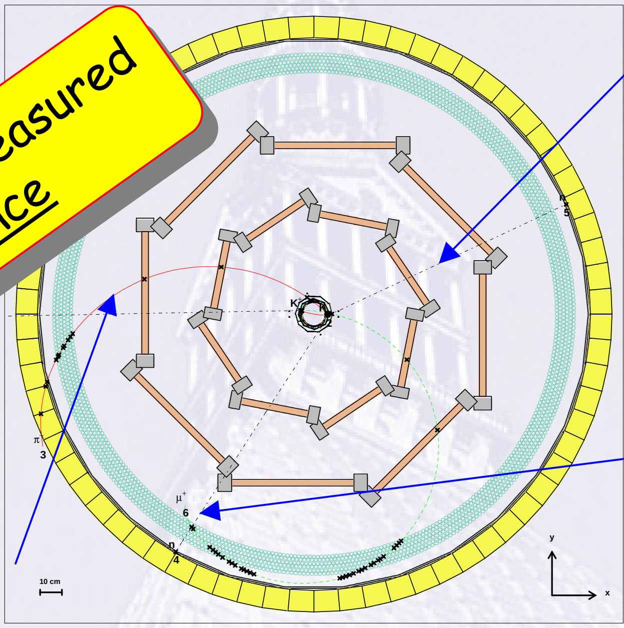
selection criteria on candidate events:

- *n* T.o.F.
- *p*-*n* angular correlation
- *p*-*n* total energy

signal	↓	80%
background	↓	2.5%

n-induced decay

$$^{A}_{\Lambda}Z \rightarrow {}^{(A-2)}Z + n + n$$



π⁻ and 1 (2) n are measured in coincidence

π is tracked

n is detected in thick scintillators

n is detected in thick scintillators

main background:

$\pi^0 \rightarrow \gamma\gamma$ from $K^+ \rightarrow \pi^+\pi^0$ (21%)

$K^+ \rightarrow \pi^+\pi^0\pi^0$ (2%)

$$\frac{signal}{background} \approx 0.2$$

without any selection

$$\frac{signal}{background} \approx 11$$

selection criteria on candidate events:

- n T.o.F.
- n-n angular correlation
- n-n total energy

signal	↓	93%
background	↓	1.5%

What FINUDA may do with 50 pb^{-1}

(2 sets of targets)

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

observable	B.R. (%)	collected events	statistical error (%)
high resolution hyp. spectr.		5.60 10^3 for $^{12}_{\Lambda}C$ g.s.	
τ_{hyp} (Γ_{tot})		1.09 10^3	~ 3
$\Gamma_{\pi-}/\Gamma_{\Lambda}$	0.14[1]	3.50 10^2	~ 5
$\Gamma_p/\Gamma_{\Lambda}$ only *p* detect	0.31[1]	1.09 10^3	~ 3
$\Gamma_p/\Gamma_{\Lambda}$ both *p* and *n* detected	0.31[1]	93	~ 10
$\Gamma_n/\Gamma_{\Lambda}$ both *n* detected	0.58[1]	48	~ 14
Γ_n/Γ_p			~ 14

[1] H. Noumi et al., *Phys. Rev.* C52 (1995) 2936

$^{11}_{\Lambda}B$

an equivalent number of events for $^{11}_{\Lambda}B$

($^{12}_{\Lambda}C$ excited states at ~ 10 MeV)

Hypernuclear decay observables

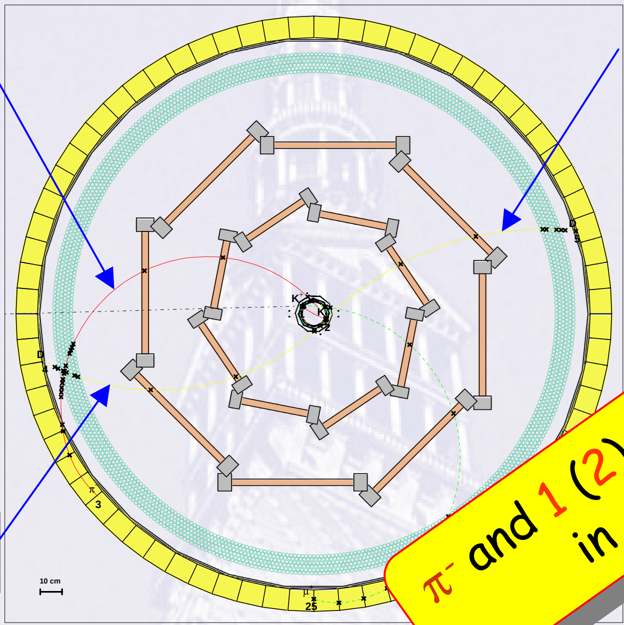
		${}^{12}_{\Lambda}C$
$\Gamma_{tot}/\Gamma_{\Lambda}$	total decay rate (lifetime) (strength of the interaction)	$1.25 \pm 0.18^{(4)}$
$\Gamma_{p}/\Gamma_{\Lambda}$	proton induced decay rate	$0.31 \pm 0.07^{+0.11(2)}_{-0.04}$
$\Gamma_{n}/\Gamma_{\Lambda}$	neutron induced decay rate	
$\Gamma_{nm}/\Gamma_{\Lambda}$	total non-mesonic decay rate	$1.14 \pm 0.20^{(1)}$ $0.89 \pm 0.15 \pm 0.03^{(2)}$
$\Gamma_{\pi^-}/\Gamma_{\Lambda}$	mesonic (π^-) decay rate (pion nucleus distortion)	$0.14 \pm 0.07 \pm 0.03^{(2)}$ $0.052^{+0.063(1)}_{-0.035}$
Γ_{n}/Γ_{p}	n/p induced decay rate (isospin structure of interaction)	$1.33^{+1.12(1)}_{-0.81}$ $1.87 \pm 0.59^{+0.32(2)}_{-1.00}$ $0.70 \pm 0.3^{(3)}$ $0.52 \pm 0.16^{(3)}$

Few measurements with large errors

(1) J.J. Szymansky et al. Phys. Rev. C43, (1991) 849
(2) H. Noumi et al., Phys. Rev. C52 (1995) 2936
(3) A. Montwill et al., Nucl. Phys. A234 (1974) 413
(4) R. Grace et al., Phys. Rev. Lett. 55(1985) 1055

$^{4}_{\Lambda}He \rightarrow d + d$ decay

π is tracked



d is tracked

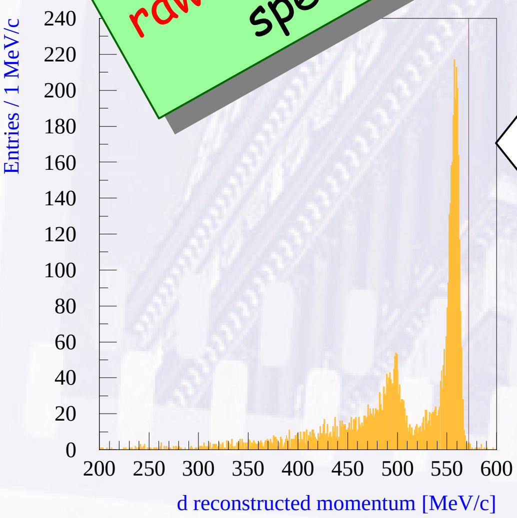
d is tracked

π^- and 1 (2) d are measured in coincidence

reconstruction:

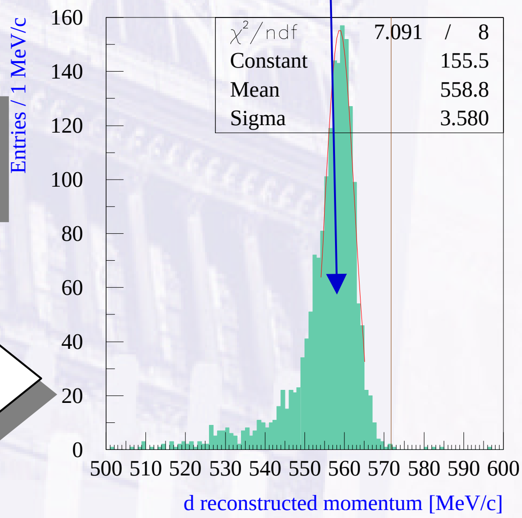
- deuteron
  - acceptance 32%
  - momentum resolution 2% (at ~ 570 MeV/c)
  - T.o.F. 500 ps (FWHM)

raw reconstructed spectrum



"forward" and "backward" d

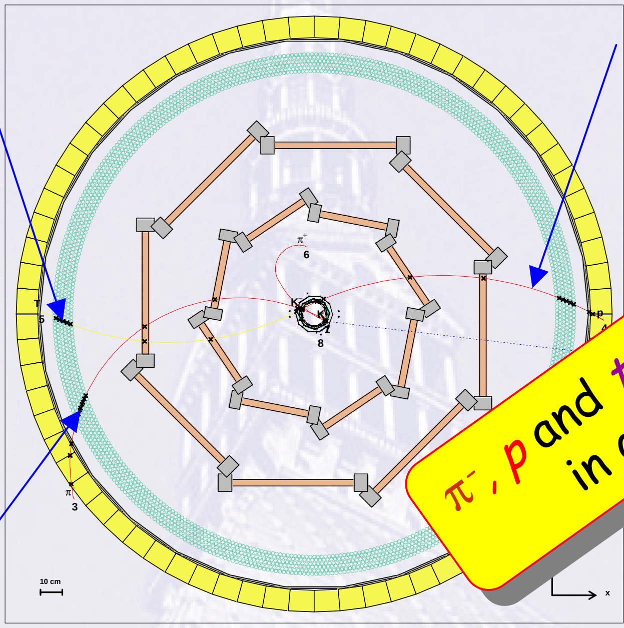
"forward" d



${}^{4}_{\Lambda}He \to p + {}^{3}H$ decay

t is tracked

p is tracked

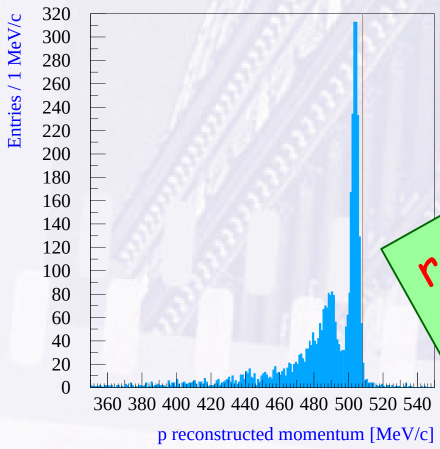


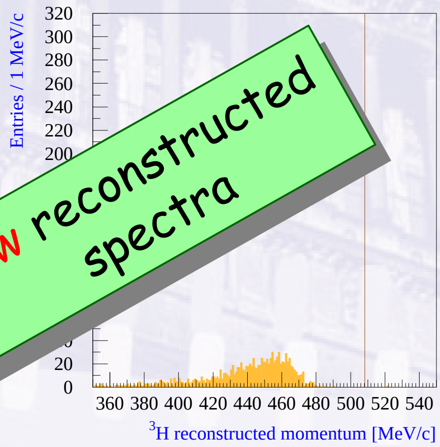
π is tracked

π^-, *p* and *t* are measured in coincidence

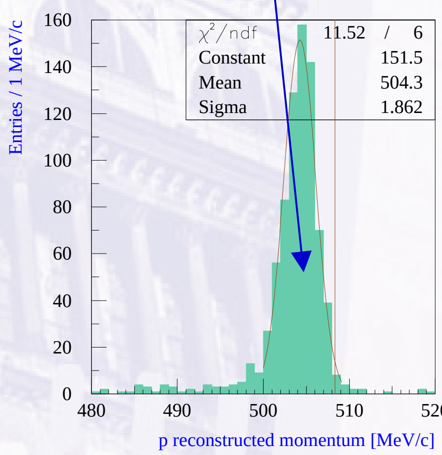
reconstruction:

- proton
  - acceptance 38%
  - momentum resolution 1% (at ~ 510 MeV/*c*)
  - T.o.F. 500 ps (FWHM)
- triton
  - acceptance 15%
  - poor momentum resolution





raw reconstructed spectra

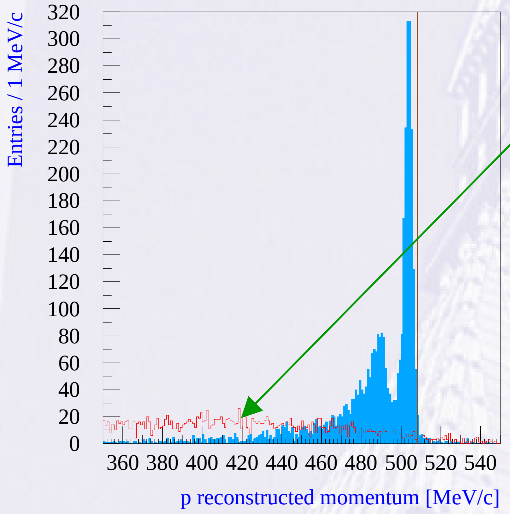


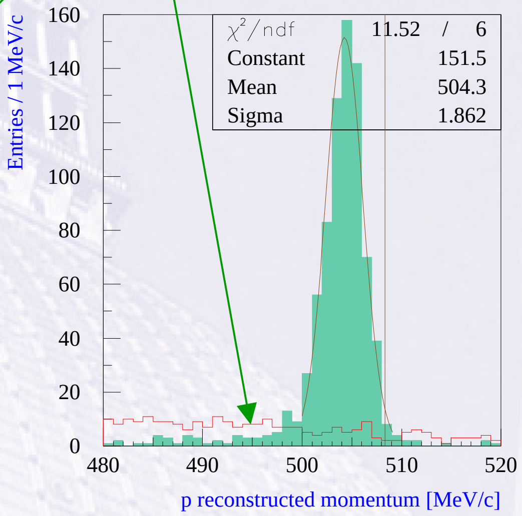
${}^{4}_{\Lambda}He \rightarrow p + {}^{3}H$ decay

main background:

p from hypernuclei non-mesonic decay

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





What FINUDA may do with 50 pb^{-1}

(2 sets of targets)

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

observable	B.R. (%)	collected events	statistical error (%)
τ_{hyp} (Γ_{tot})		3.81 10^3	~ 2
$\Gamma_{\pi-}/\Gamma_\Lambda$	0.44[1]	5.50 10^3	~ 1
Γ_p/Γ_Λ only *p* detect	0.21[1]	3.81 10^3	~ 2
Γ_p/Γ_Λ both *p* and *n* detected	0.21[1]	3.28 10^2	~ 6
Γ_n/Γ_Λ both *n* detected	0.20[1]	82	~ 11
Γ_n/Γ_p			~ 11

[1] J.J. Szymansky et al. Phys. Rev. C43, (1991) 849

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

observable	B.R. (%)	collected events	statistical error (%)
Γ_d/Γ_Λ both *d* detected	10^{-3}	32	~ 18
Γ_t/Γ_Λ both *p* and ${}^3H$ detected	10^{-3}	19	~ 23

Hypernuclear decay observables

Measured decay properties of light hypernuclei. *

Decay ratios	This work	Outa et al. [22]	Older results	References
$^{4}_{\Lambda}$H				
$\Gamma_{tot}/\Gamma_{\Lambda}$		$1.36^{+0.21}_{-0.15}$		
$\Gamma_{nm}/\Gamma_{\pi^-}$			0.26 ± 0.13	[23]
$\Gamma(\pi^- + {}^4\mathrm{He})/\Gamma_{\pi^-}$			$0.69^{+0.12}_{-0.09}$	[25]
$^{4}_{\Lambda}$He				
$\Gamma_{tot}/\Gamma_{\Lambda}$	1.07 ± 0.11	$1.03^{+0.12}_{-0.10}$	1.15 ± 0.48	[4]*
$\Gamma_{\pi^0}/\Gamma_{tot}$	0.57 ± 0.09	0.515 ± 0.035		
$\Gamma_{\pi^0}/\Gamma_{\Lambda}$	0.61 ± 0.08	0.53 ± 0.07		
$\Gamma_{\pi^-}/\Gamma_{\Lambda}$	0.26 ± 0.03	0.33 ± 0.05		
$\Gamma_{\pi^0}/\Gamma_{\pi^-}$	2.3 ± 0.4	1.59 ± 0.20	2.49 ± 0.34	[23]
			2.20 ± 0.39	[24]
$\Gamma_{\pi^+}/\Gamma_{\pi^-}$			0.043 ± 0.017	[18]
$\Gamma_{p}/\Gamma_{\Lambda}$	0.16 ± 0.02	0.16 ± 0.02		
$\Gamma_{n}/\Gamma_{\Lambda}$	0.04 ± 0.02	0.01 ± 0.05		
$\Gamma_{nm}/\Gamma_{\pi^-}$	0.77 ± 0.15	0.51 ± 0.16	0.56 ± 0.09	[4]*
Γ_{n}/Γ_{p}	0.25 ± 0.13	0.06 ± 0.40	0.40 ± 0.15	[23]
	< 0.40		0.29 ± 0.13	[24]
$^{5}_{\Lambda}$He				
$\Gamma_{tot}/\Gamma_{\Lambda}$			1.03 ± 0.08	[21]
$\Gamma_{\pi^0}/\Gamma_{\Lambda}$			0.18 ± 0.20	"
$\Gamma_{\pi^-}/\Gamma_{\Lambda}$			0.44 ± 0.11	"
$\Gamma_{p}/\Gamma_{\Lambda}$			0.21 ± 0.07	"
$\Gamma_{n}/\Gamma_{\Lambda}$			0.20 ± 0.11	"
$\Gamma_{nm}/\Gamma_{\pi^-}$			0.92 ± 0.31	"
Γ_{n}/Γ_{p}			0.93 ± 0.55	"

* reanalysis of many older measurements.

* from V.J. Zeps, *Nucl. Phys.* A639 (1998) 261c
[18] G. Keyes *et al.*, *Il Nuovo Cim.* 31A (1976) 401
[21] J.J. Szymanski *et al.*, *Phys. Rev. C* 43 (1991) 849

The case of ${}^4_\Lambda He$ π^+ decay

$${}^4_\Lambda He \to \pi^+ + n + {}^3H$$

experimentally: $\Gamma_{\pi^+} / \Gamma_{\pi^-} \approx 5\%$

G. Keyes *et al.*, *Il Nuovo Cim.* 31A (1976) 401
C. Mayeur *et al.*, *Il Nuovo Cim.* 44 (1966) 698
G. Bohm *et al.*, *Nucl. Phys.* B 9 (1969) 1

no $\Lambda\ \pi^+$ decay mode!

possible mechanisms:

Dalitz & von Hippel

$$\Lambda \to \pi^0 + n$$
$$\pi^0 + p \to \pi^+ + n$$

$$\Lambda + p \to \Sigma^+ + n$$
$$\Sigma^+ \to \pi^+ + n$$

$\Gamma_{\pi^+} / \Gamma_{\pi^-} \leq 1\%$

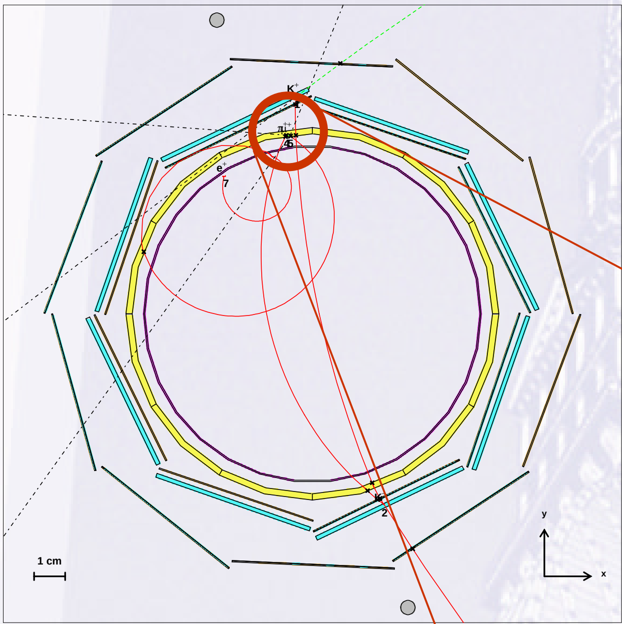
Gibson & Timmermans

$$\Lambda + p \to \Sigma^+ + n$$
$$\Sigma^+ + N \to \pi^+ + n + N$$

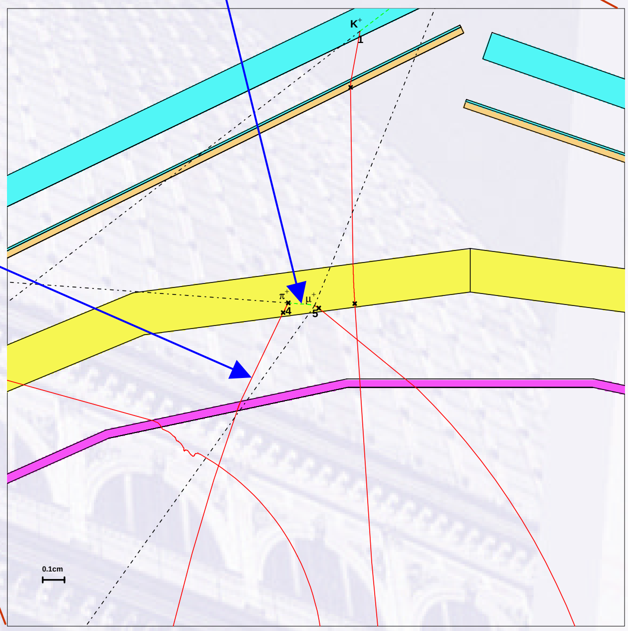
- π^+ emission is a s-wave process
- π^+ energy spectrum flat

FINUDA could potentially collect a large number of events (~ 4.04 10^3)

The case of $^{4}_{\Lambda}He$ π^{+} decay



μ^{+} stops
and decays
τ ~ 2.20 μs



π^{+} stops
and decays
τ ~ 26 ns

- 29 < $p_{\pi+}$ < 95 MeV/c: hard to be tracked
- $p_{\mu+}$ = 30 MeV/c: impossible to be tracked

We need a clever strategy
to filter the events

Conclusions

- FINUDA is ready to be installed
- errors on measurements of some observables related to hypernuclei weak decay are 1 order of magnitude lower than for the existing data
- some rare decay channels can be measured for the first time
- the success of the FINUDA hypernuclear program depends on the DAΦNE luminosity

DAΦNE luminosity & FINUDA