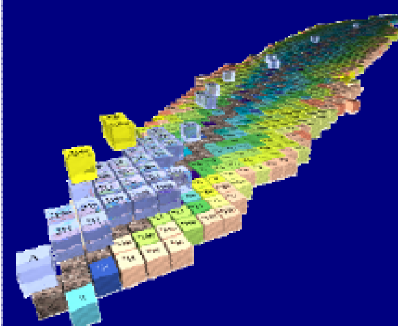
FINUDA: Hypernuclear Factory

HYP 2006

October 10 – October 14, Mainz, Germany

XI International Conference on Hypernuclear and Strange Particle Physics



- The FINUDA experiment
  - the physics program
  - the apparatus
  - next data taking
- The scientific results
  - hypernuclear spectroscopy
  - hypernuclear decays
  - search for neutron-rich hypernuclei
  - Sigma-hypernuclei
  - Kaon deeply-bound nuclear states

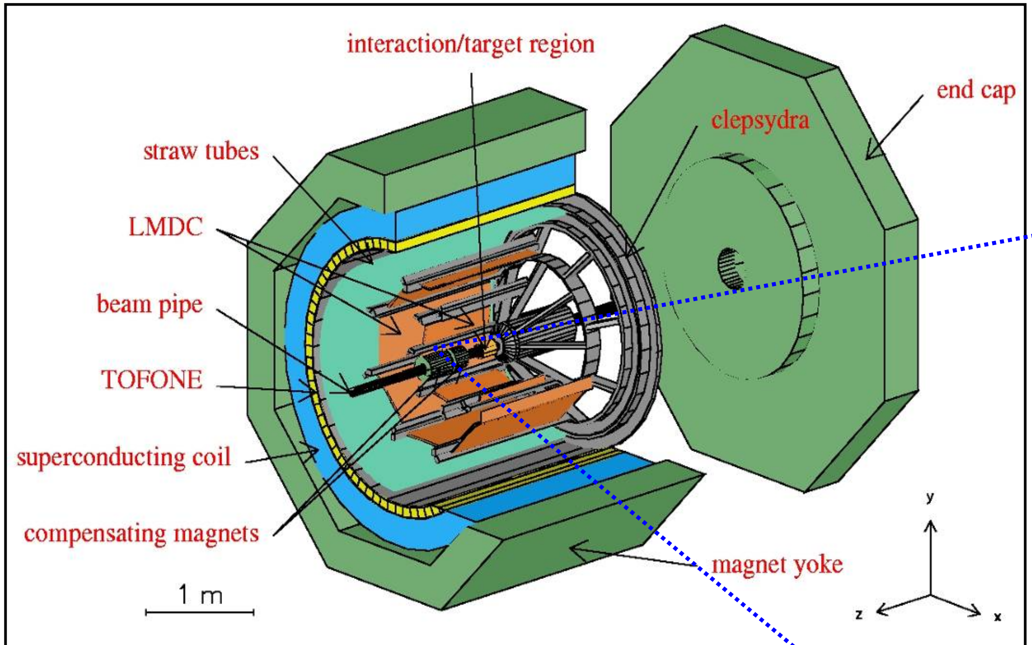
INFN Istituto Nazionale di Fisica Nucleare

Paola Gianotti For the FINUDA collaboration

The FINUDA Collaboration

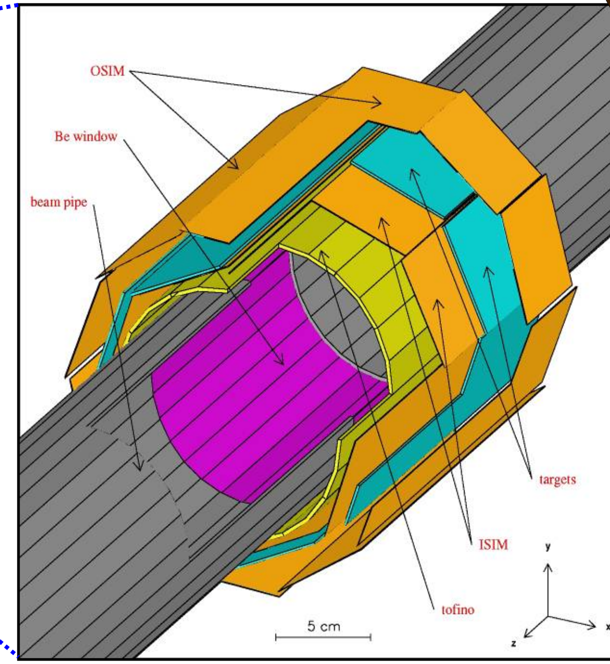
- Bari University and I.N.F.N. Bari
- Brescia University and I.N.F.N. Pavia
- KEK
- L.N.F. / I.N.F.N. Frascati
- Pavia University and I.N.F.N. Pavia
- RIKEN
- Seoul National University
- Teheran Shahid Beheshty University
- Torino University and I.N.F.N. Torino
- Torino Polytechnic and I.N.F.N. Torino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

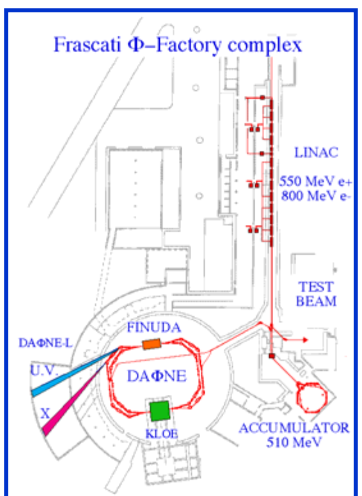
FINUDA @ DAΦNE



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

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

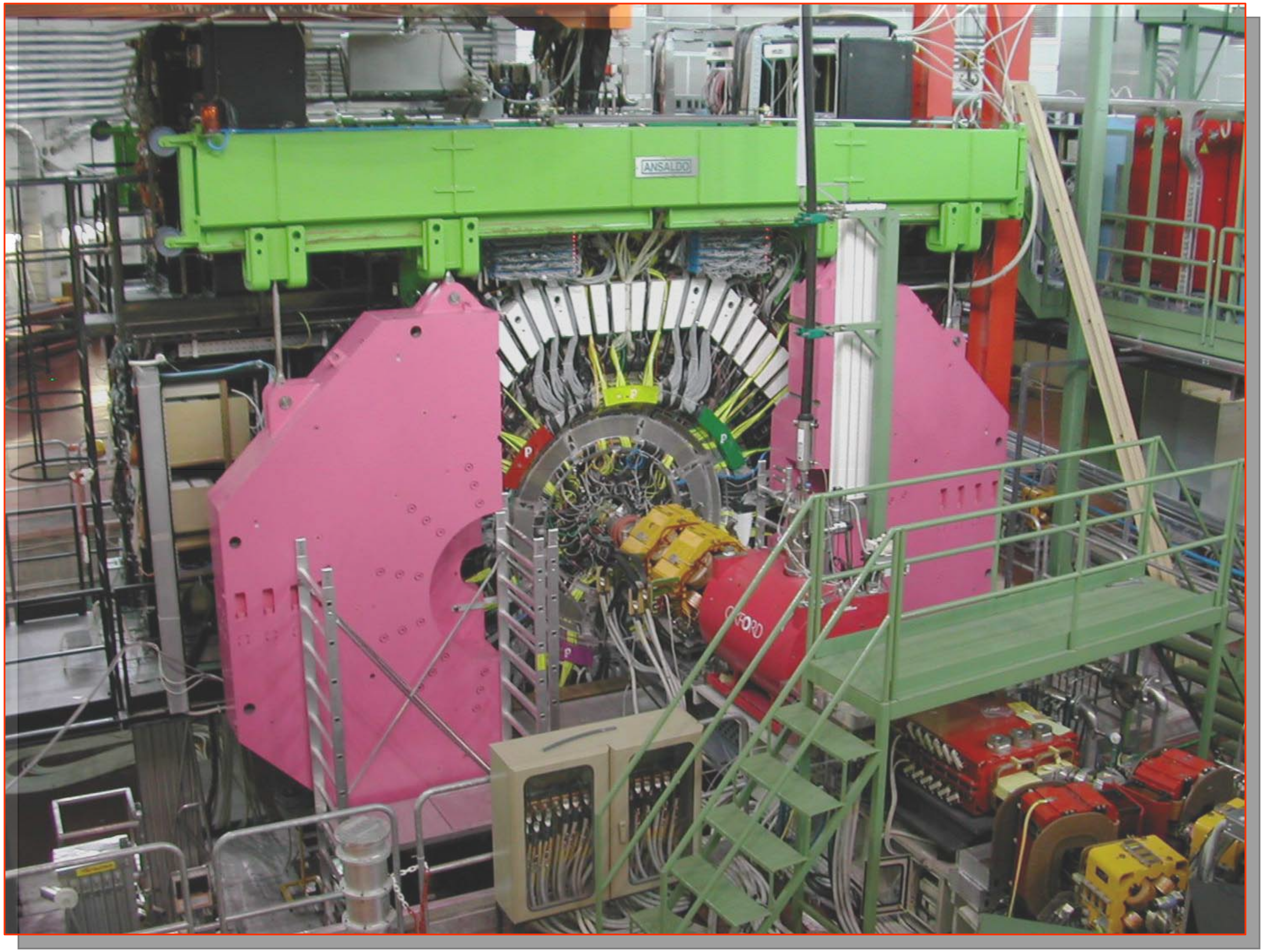




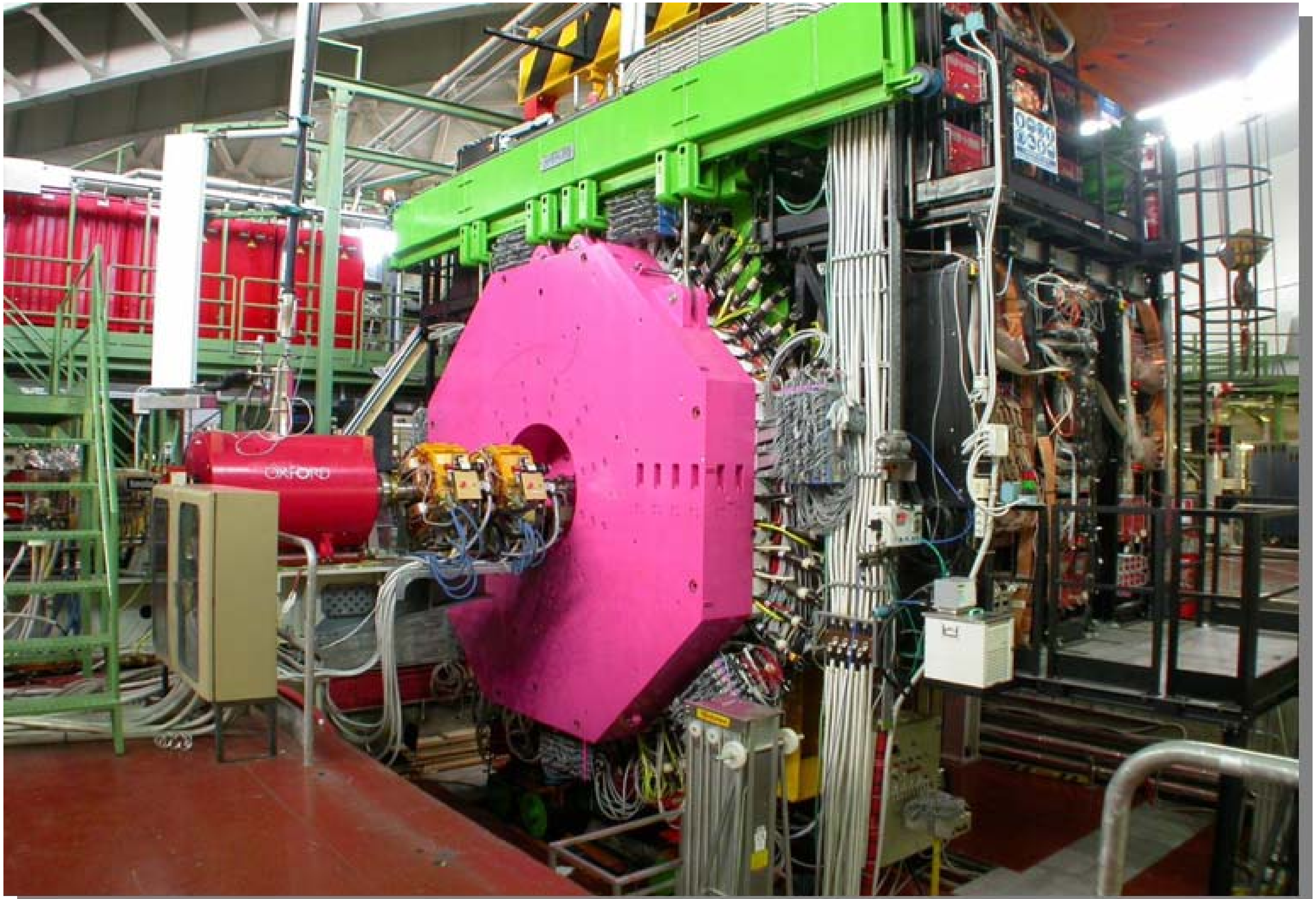
energy	510 MeV
luminosity	5 10^{32} cm^{-2} s^{-1}
σ_x (rms)	2.11 mm
σ_y (rms)	0.021 mm
σ_z (rms)	35 mm
bunch length	30 mm
crossing angle	12.5 mrad
frequency (max)	368.25 MHz
bunch/ring	up to 120
part./bunch	8.9 10^{10}
current/ring	5.2 A (max)

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

FINUDA @ DAΦNE



FINUDA @ DAΦNE



FINUDA detectors performances

- **s.c. solenoid**: B = 1.0 T; field homogeneity within 2%
- **interaction/target region**: K^+/K^- identification, hypernucleus production and detection

> VDET: σ_z = 30 μm; ΔE = 25% FWHM (K)
> TOF_{in}: σ_t = 250 ps

- **tracking devices**: measurement of trajectories and momenta of charged particles (Δp/p 5‰)

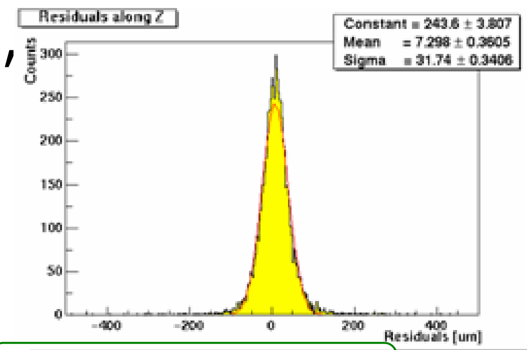
> LMDC: σ(ρ, φ) = 150 μm; $\sigma_z \leq$ 1% wire length
> STB: σ(ρ, φ) = 150 μm; σ_z 500 μm

- **external scintillator barrel**: trigger and neutron detection

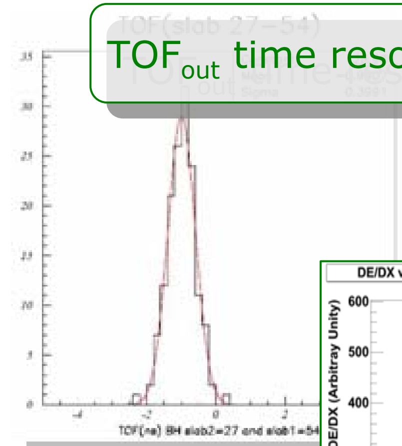
> TOF_{out}: σ_t = 500 ps FWHM
> efficiency ≥ 10%; ΔE = 8 MeV

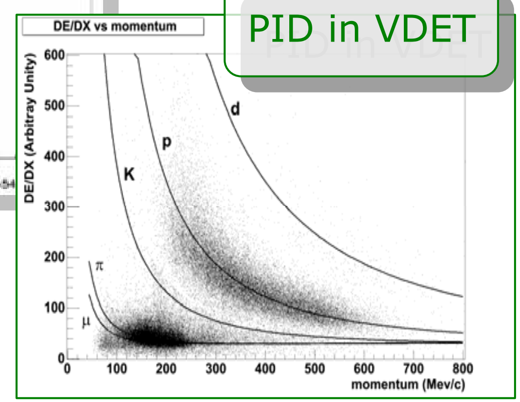
- **He chamber**: minimization of particle multiple scattering

> Δp/p: He atmosphere = 5‰
> air = 2%



VDET z resolution


TOF$_{out}$ time resolution



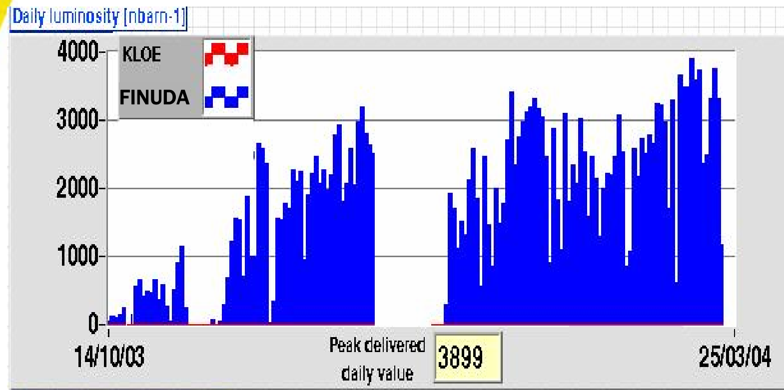
PID in VDET

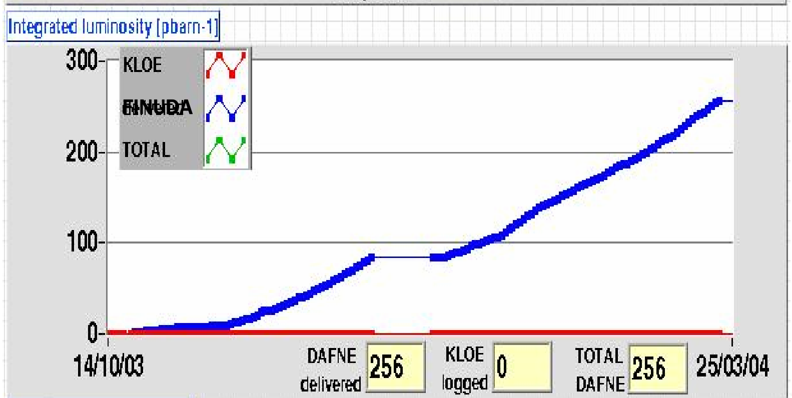
Articolo NIM

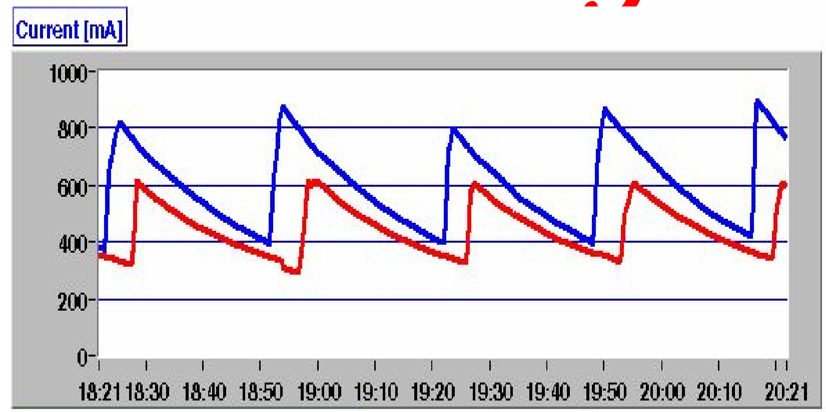
FINUDA key features

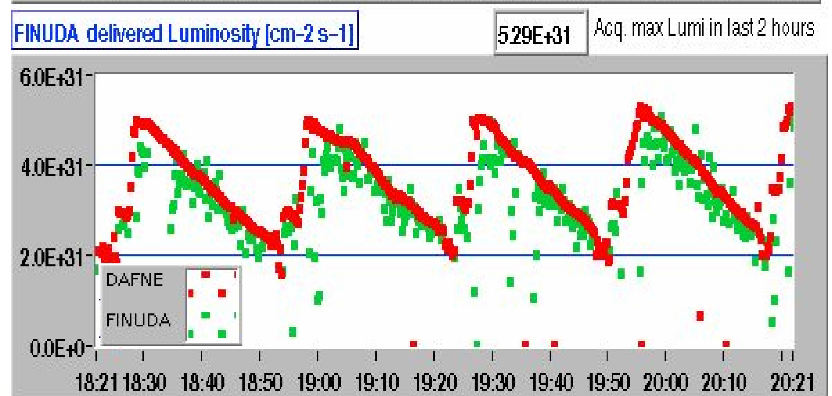
- ☺ very thin nuclear targets ($0.1 \div 0.3$ g/cm^2)
  - ⇒ high resolution spectroscopy
- ☺ coincidence measurement with large acceptance
  - ⇒ decay mode study
- ☺ different targets in the same run
  - ⇒ high degree of flexibility

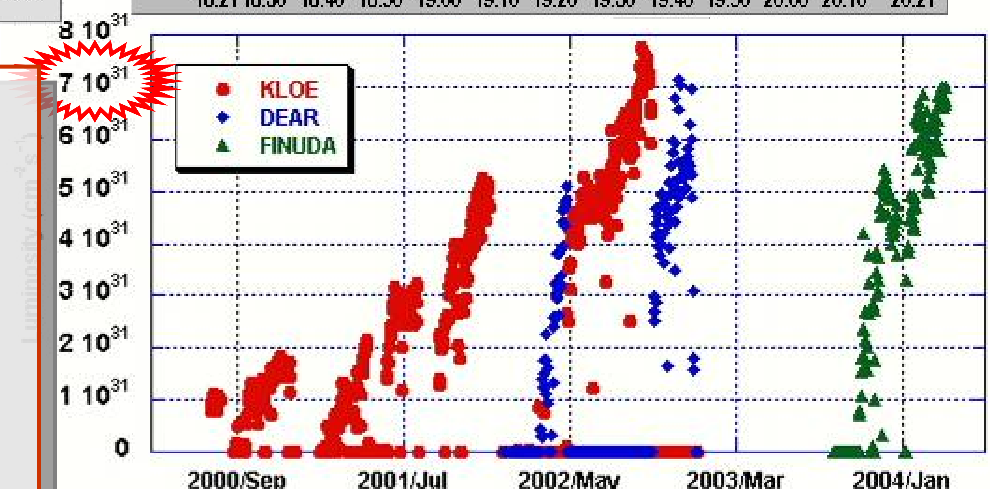
FINUDA first data taking









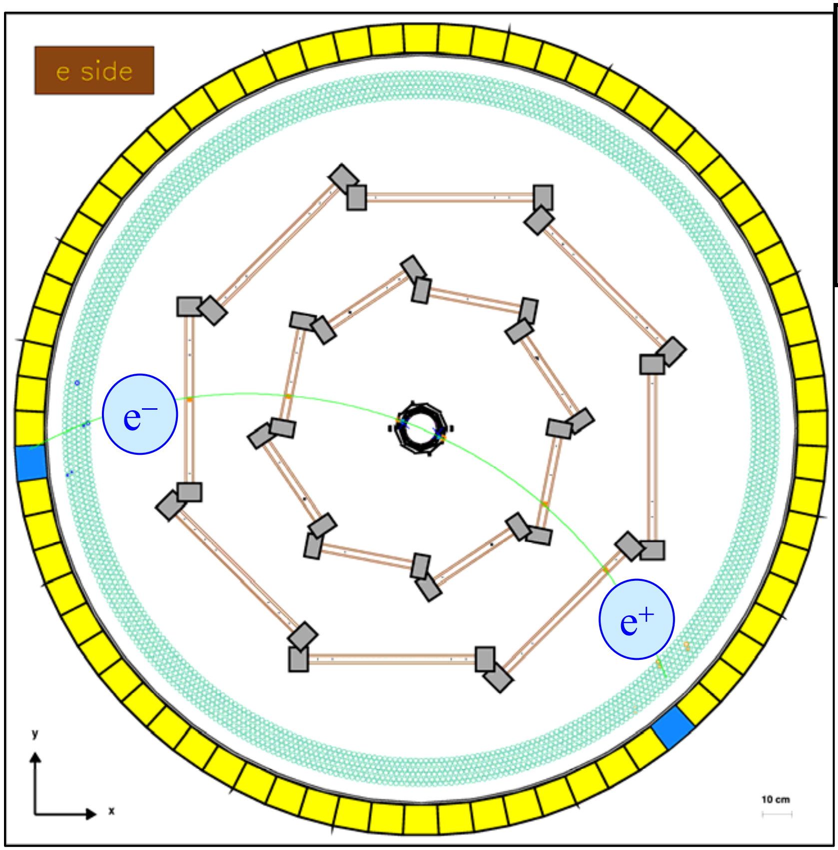


14-Oct-2003 to 22-Mar-2004:

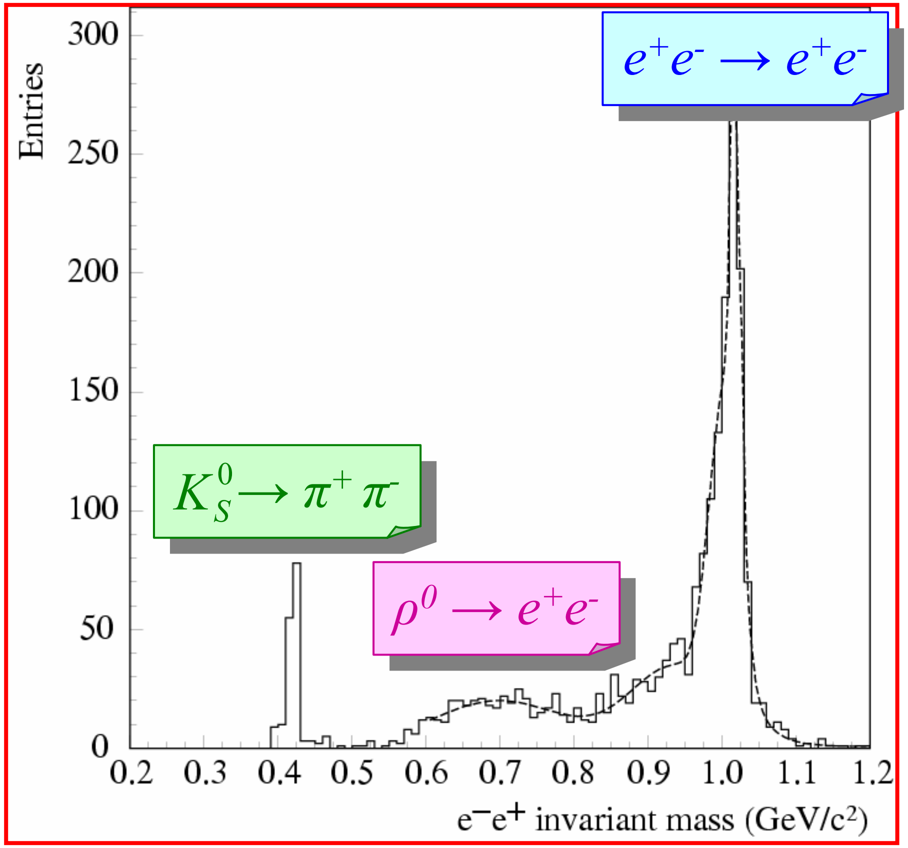
250 pb-1 delivered to FINUDA

- 33 pb-1 machine tuning
- 10 pb-1 FINUDA debug
- 190 pb-1 useful data taking

Luminosity monitor
Bhabha events



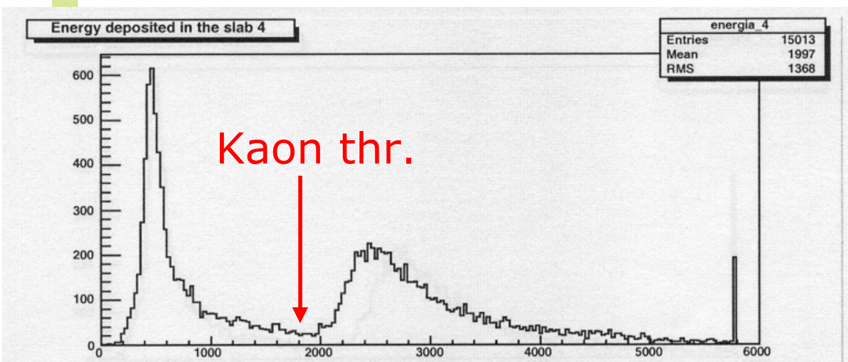
Bhabha trigger:
- 2 hits on tofino below threshold
- back to back topology
- multiplicity (=2) on tofone
- Time correlation tofino-tofone (<10ns)

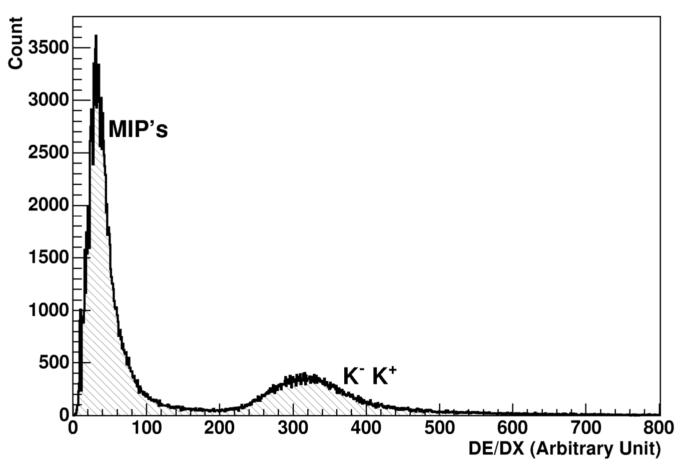


K + / K − identification

Hypernuclear trigger:

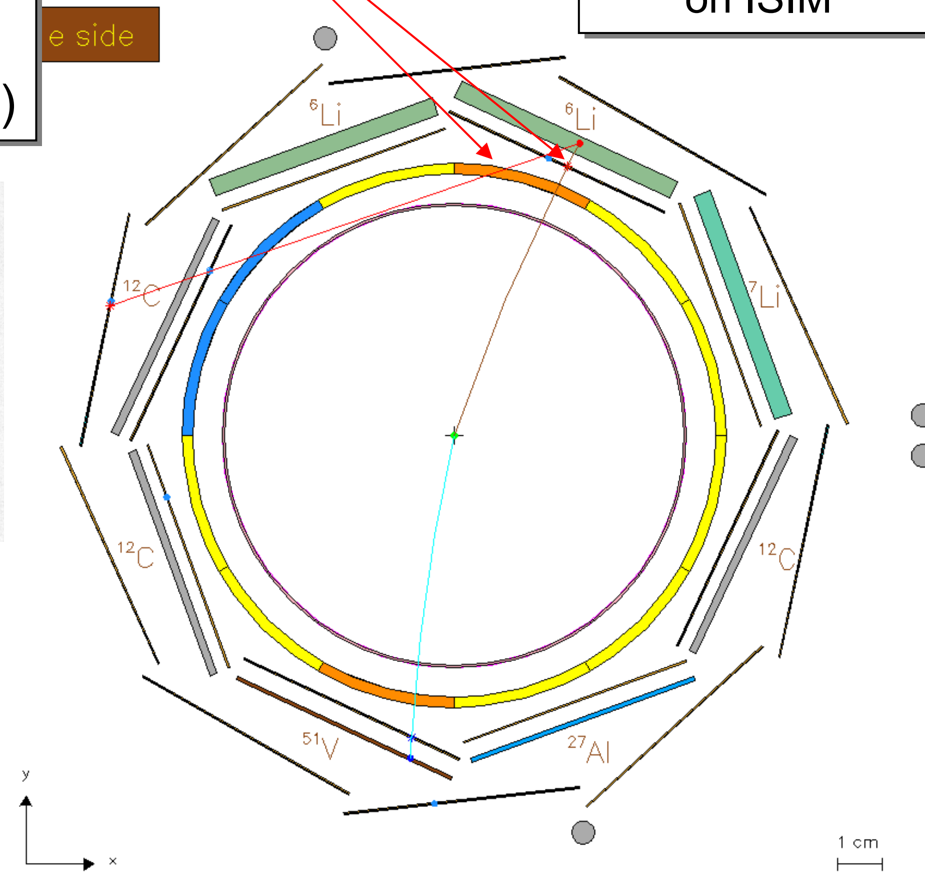
- 2 hits on tofino over threshold (kaon)
- extended back to back
- multiplicity (>2) on tofone
- Time correlation tofino-tofone (<10ns)





over threshold

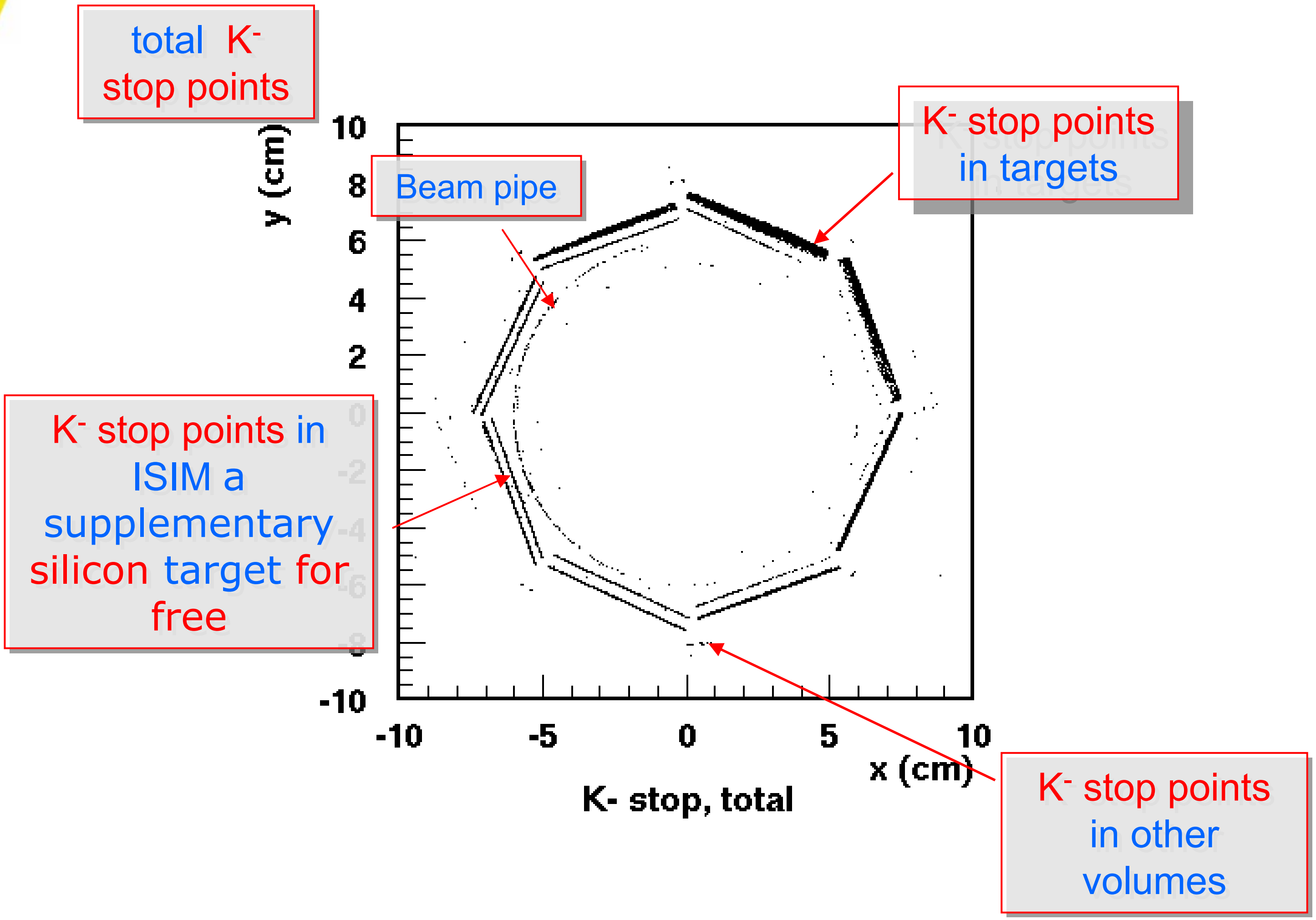
only two measured points on ISIM



very effective slow kaon recognition

K stop calculation GEANE tracking

K^+ / K^- stopping points



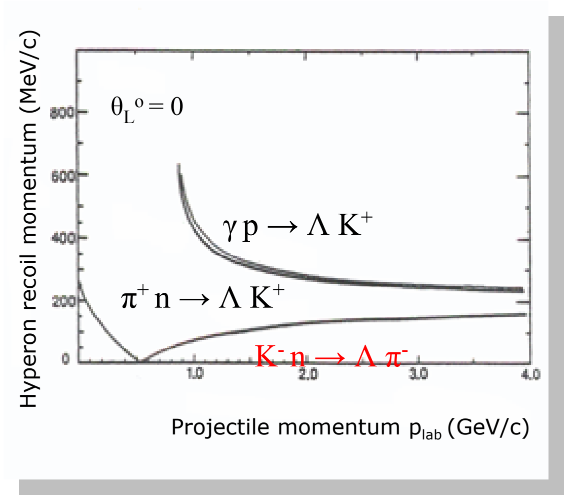
Due to the beam-crossing angle 12.5 mrad the Φ is produced in flight and the kaons do not have all the same momentum

Hypernuclear spectroscopy

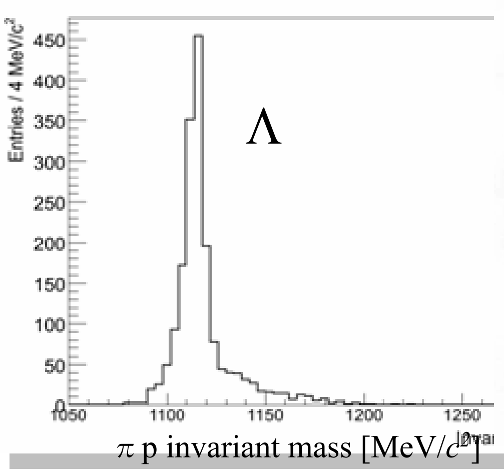
Hypernuclei are produced following Φ decay via strangeness exchange reaction

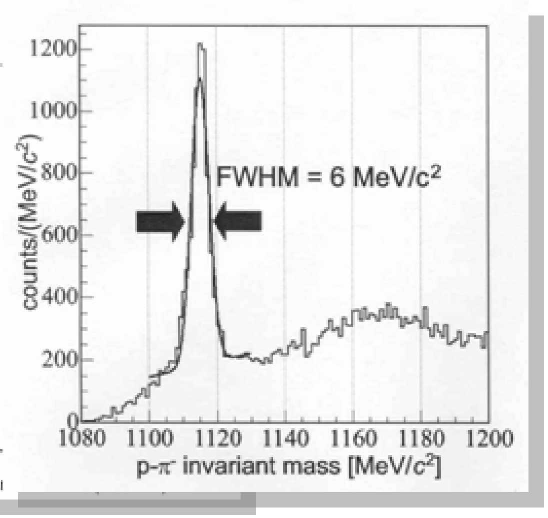
$$\Phi \to K^+ K^- \qquad (49\%)$$

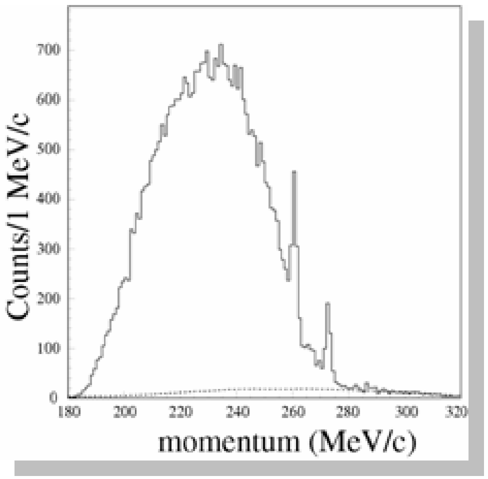
$$\hookrightarrow K^- + {}^{A}Z \to {}^{A}_{\Lambda}Z + \pi^- \qquad (\sim 10^{-3})$$



FINUDA, being a high acceptance magnetic spectrometer, can detect all the particles produced and following K^- interaction with the target

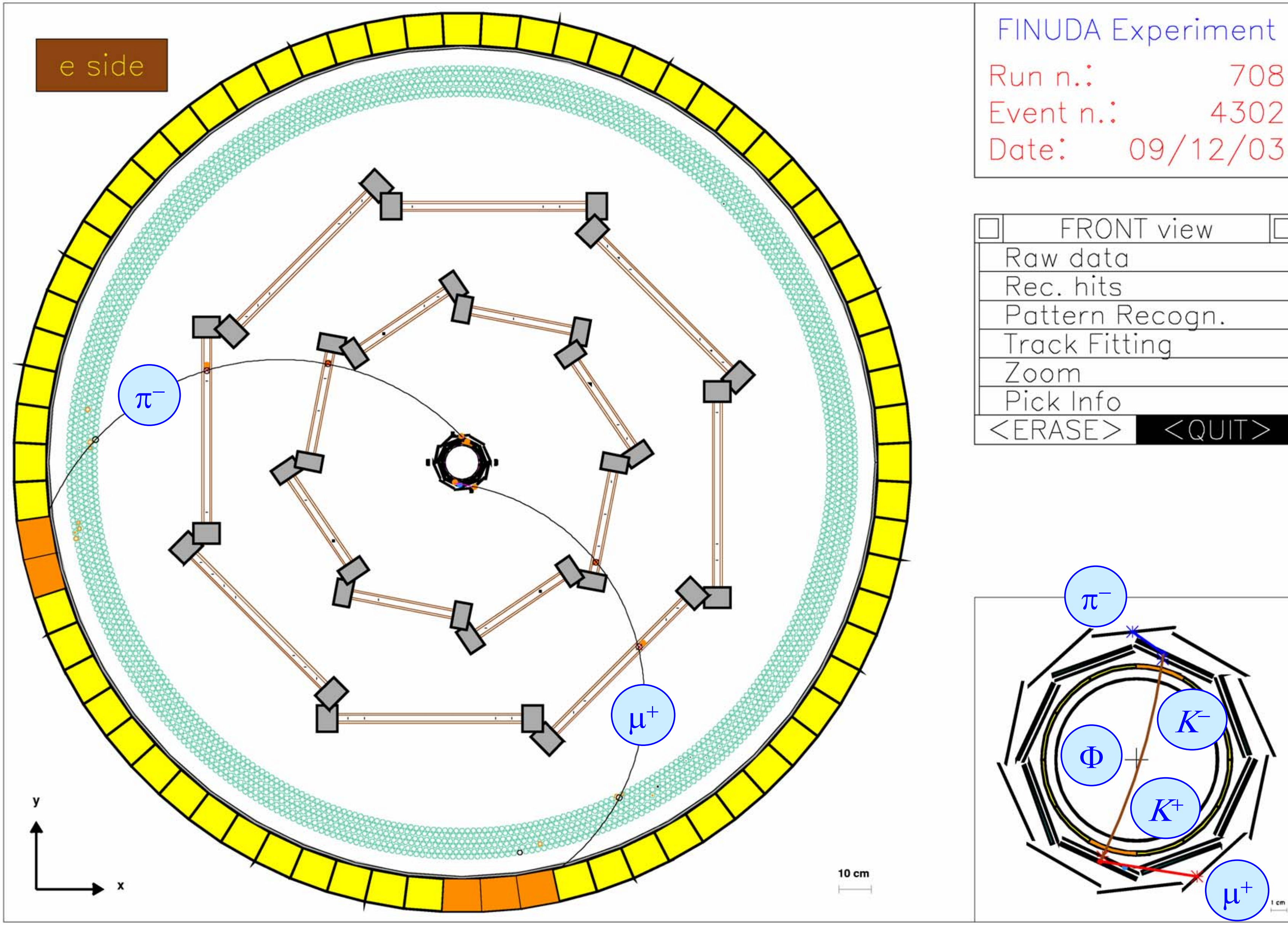






Not only hypernuclear systems can be studied

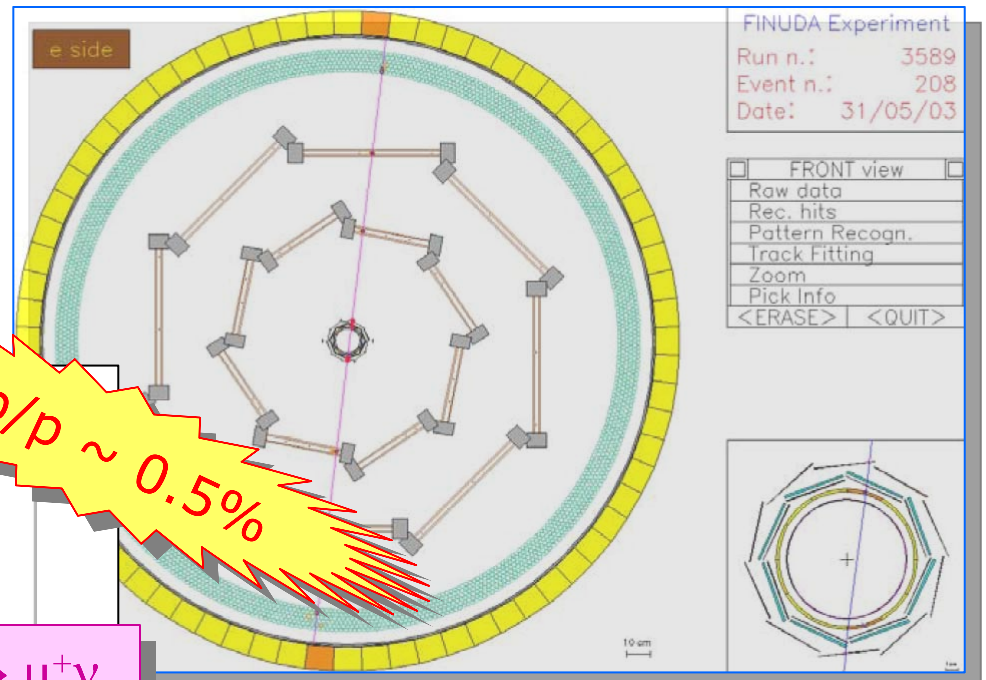
The hypernuclear event



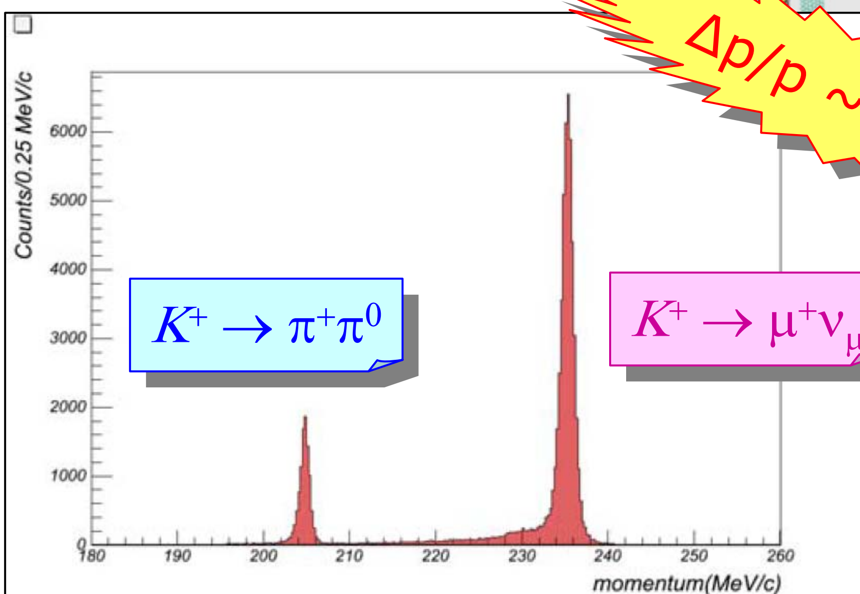
Momentum resolution

FINUDA is a composite detector ⇒ alignment procedure is crucial

- straight cosmic rays, collected during and after data taking, are used
- Iterative procedure



$\Delta p/p \sim 0.5\%$

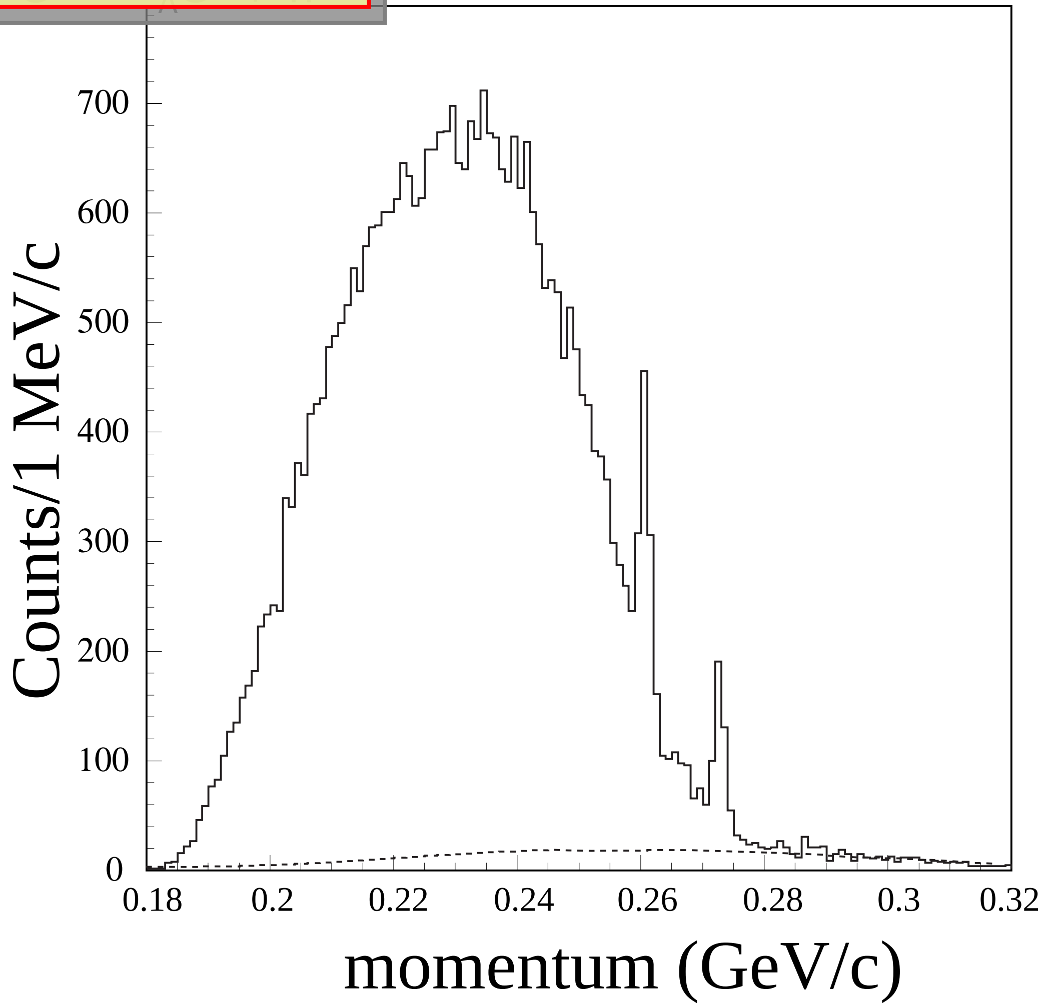


$K^+ \rightarrow \pi^+\pi^0$

$K^+ \rightarrow \mu^+\nu_\mu$

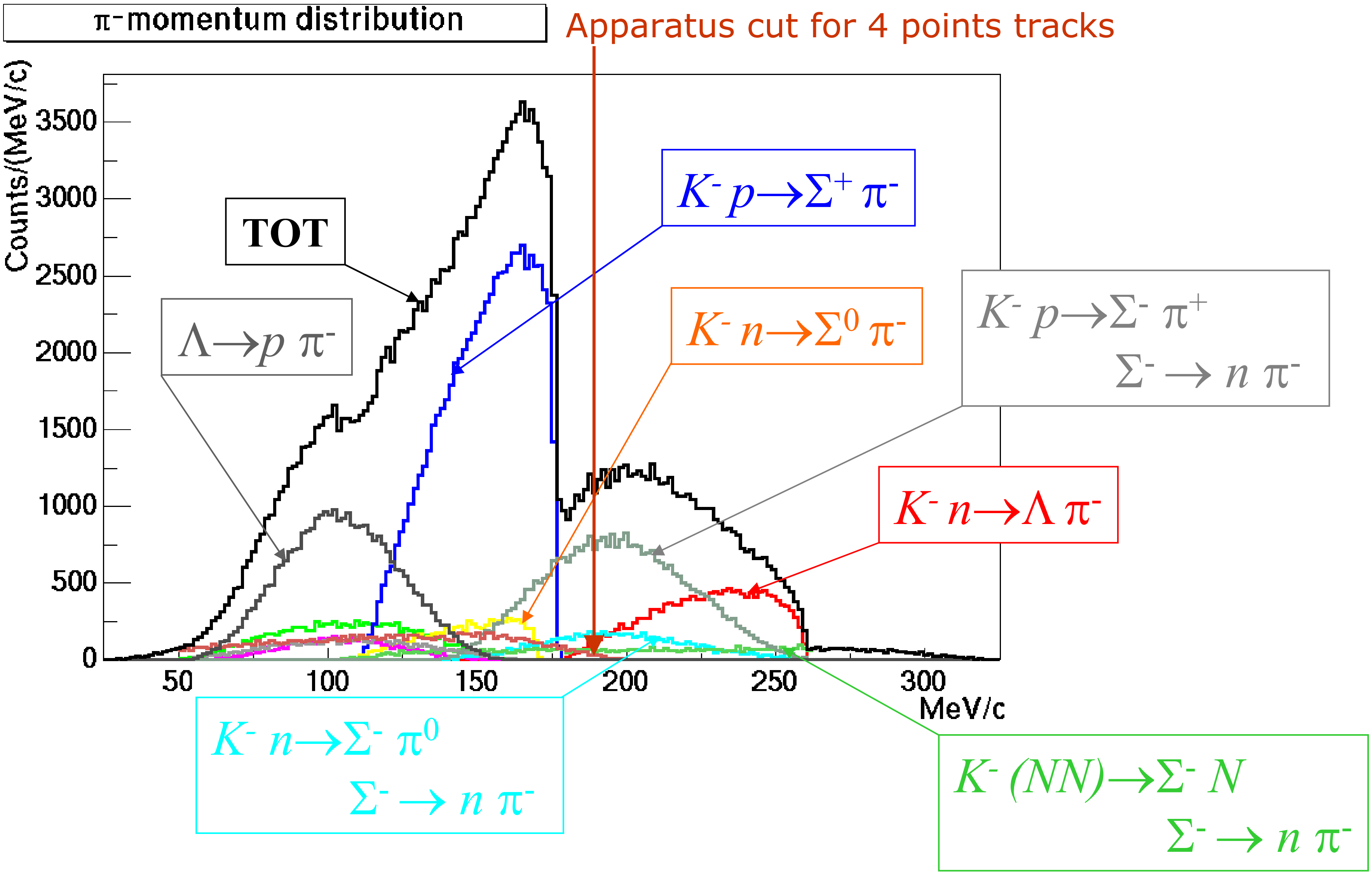
^{12}C (raw) excitation spectrum

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



Raw spectrum of negative pions coming out the ^{12}C targets. Hypernuclear peaks are visible already without any background subtraction

Background reactions: π^- spectrum

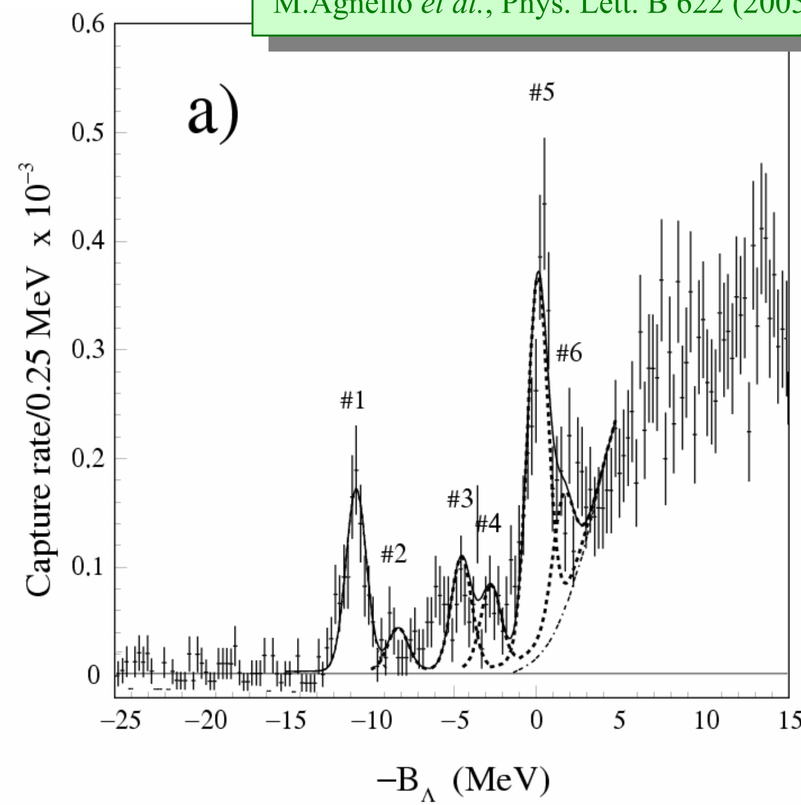


FINUDA vs. KEK-E369

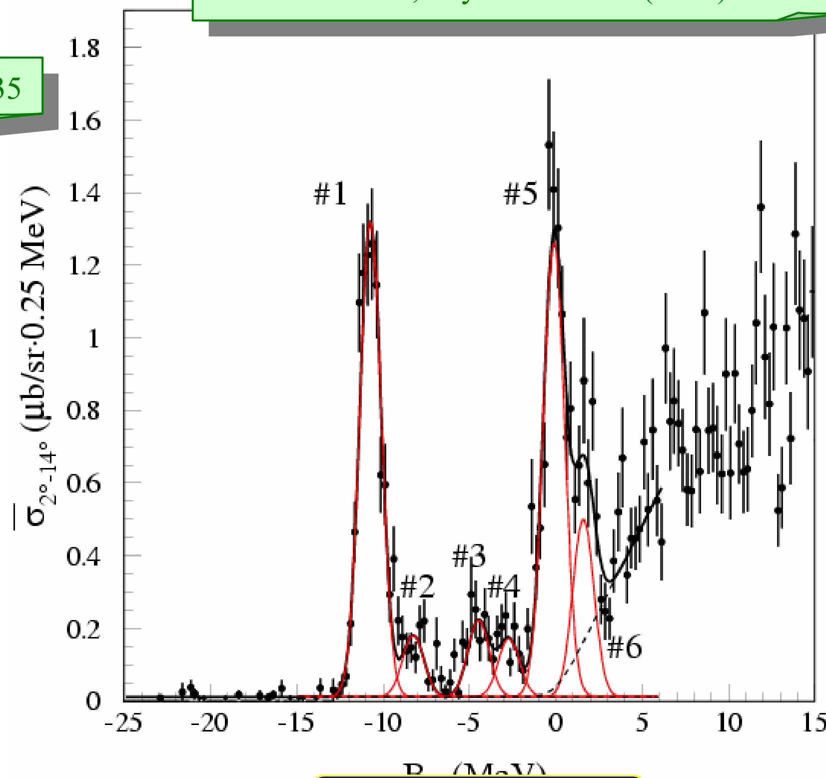
$^{12}C(K^-_{stop},\pi^-)^{12}_{\Lambda}C$

ΔE ~ 1.3 MeV FWHM

M.Agnello *et al.*, Phys. Lett. B 622 (2005) 35



H. Hotchi *et al.*, Phys. Rev. C 64 (2001) 044302

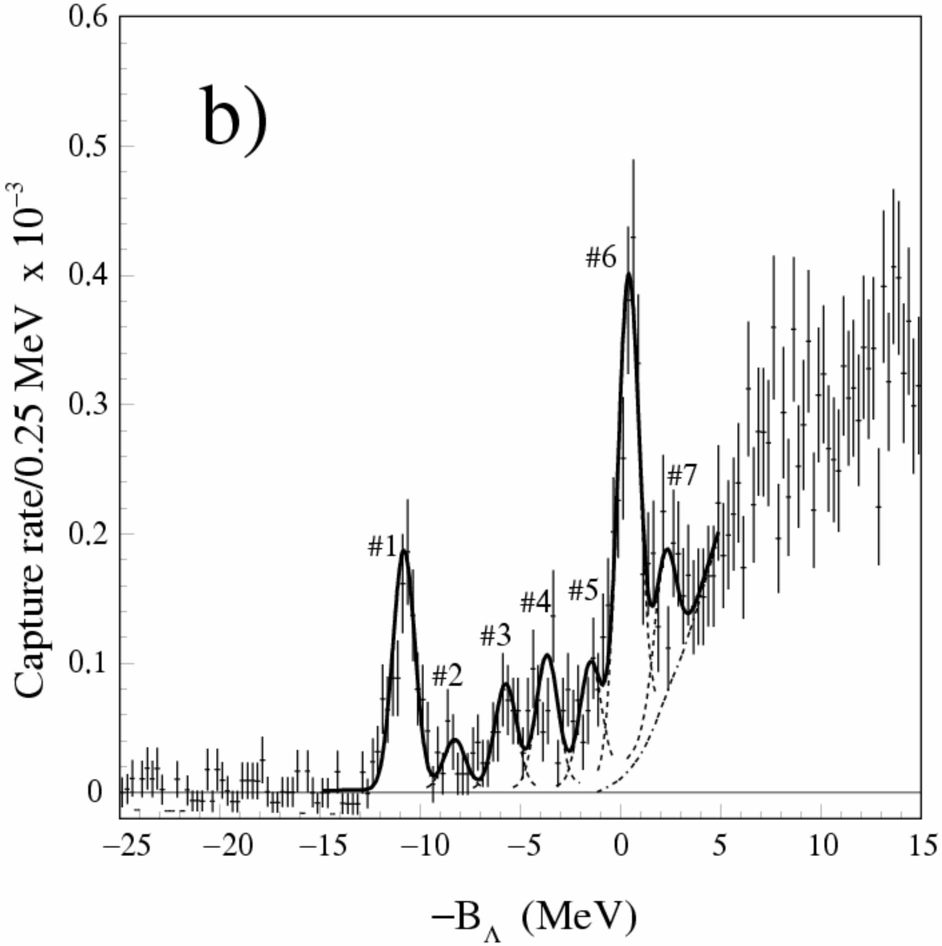


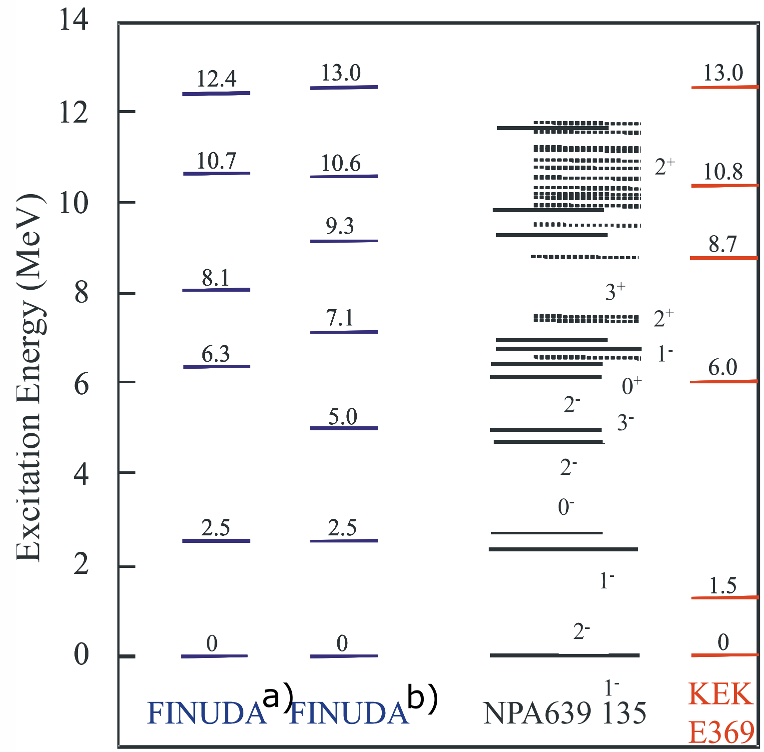
$^{12}C(\pi^+,K^+)^{12}_{\Lambda}C$

ΔE ~ 1.5 MeV FWHM

^{12}C excitation spectrum

Excitation Energy Ex = $B_\Lambda - B_{\Lambda\, g.s.}$





FINUDA fit with 7 peaks is more precise (better χ^2) and more similar to theoretical calculation

^7Li Spectroscopy

the signal

fit results (χ^2 and parameters):

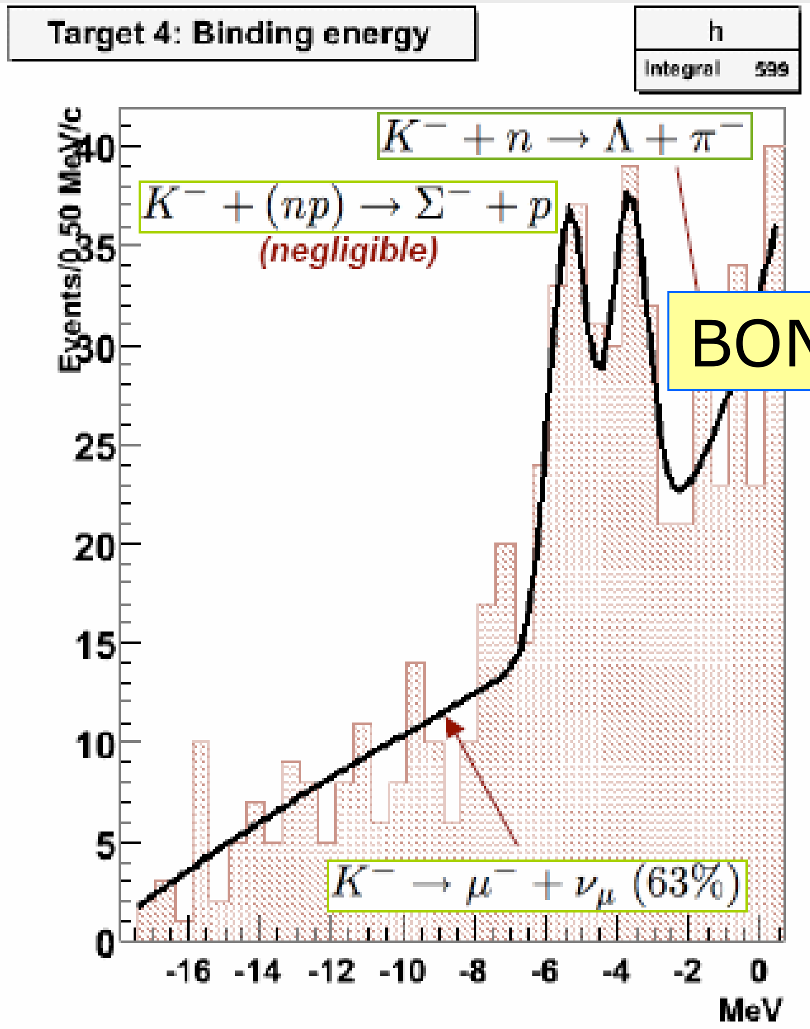
$\chi^2/d.o.f. \simeq 1.2$ $\quad$ $\sigma = 0.54\ MeV\ \ (fixed)$

$\mu_1 = -5.38 \pm 0.15\ MeV$ $\quad$ $Y_1 = 55 \pm 2$

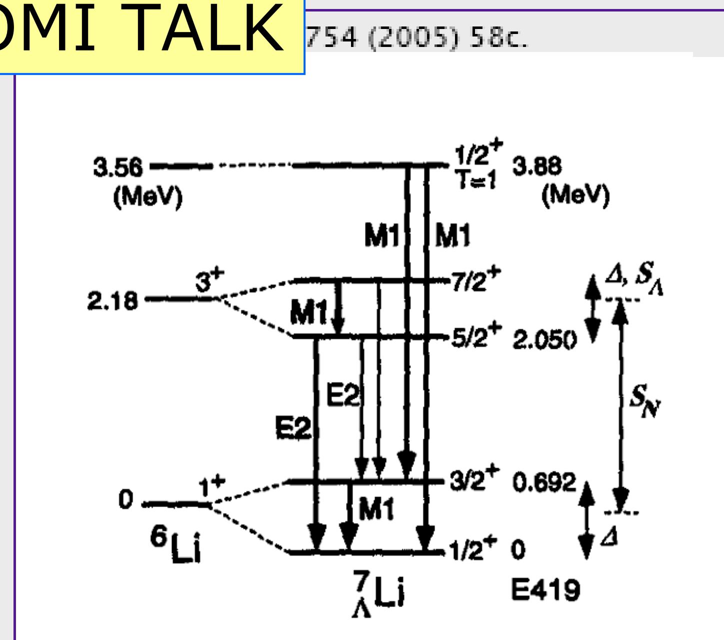
$syst. \simeq 0.18 MeV$ $\quad$ $\Delta = 1.69\ MeV$

$\mu_2 = -3.69 \pm 0.17\ MeV$ $\quad$ $Y_2 = 50 \pm 12$

the result is steady when varying binning, (size and limits) and fit interval

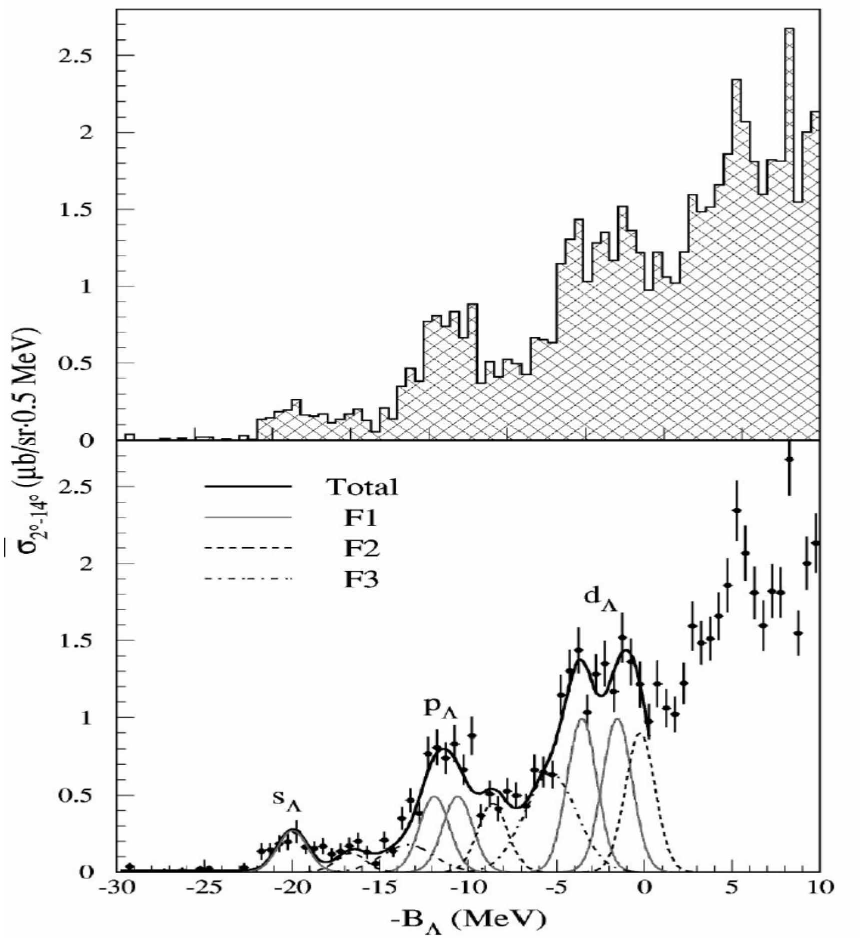


BONOMI TALK



"bound state" -5.58±0.03 MeV Juric et al., NPB 52 (1973) 1

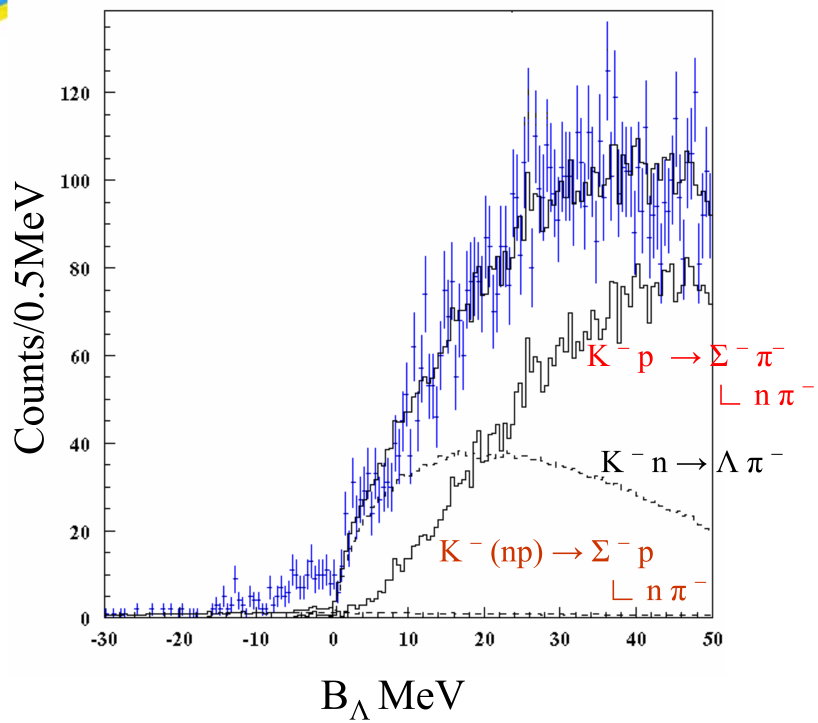
Vanadium spectroscopy



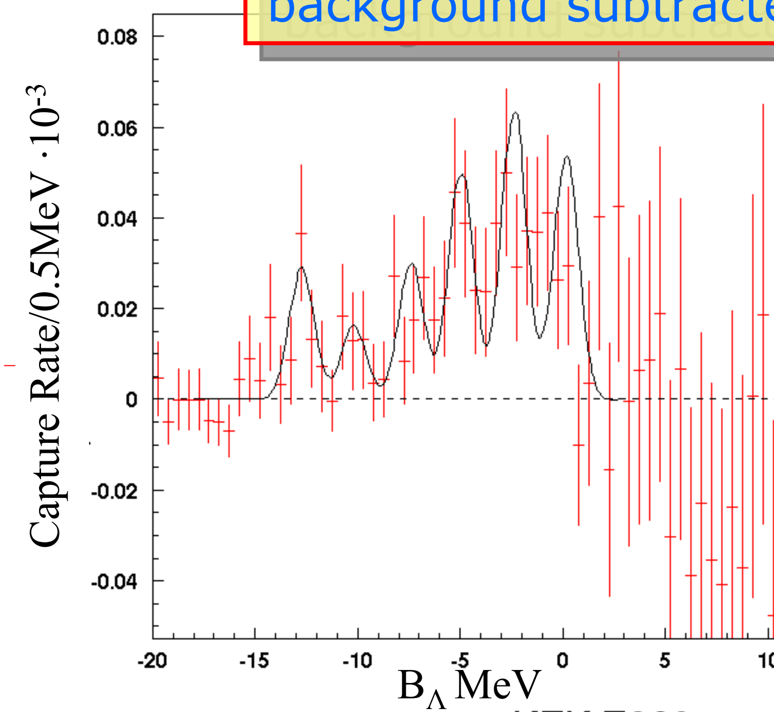
Peaks ($F1$)	B_Λ (MeV)	FWHM (MeV)	Cross sections (μb/sr)
$l=0$	19.97 ± 0.13	1.95(fixed)	1.15 ± 0.10
$l=1-L$	11.90 ± 0.17		4.20 ± 0.38(sum)
$l=1-R$	10.57 ± 0.15		$(L:R=1:1)$
$l=2-L$	3.55 ± 0.14		8.48 ± 0.83(sum)
$l=2-R$	1.55 ± 0.11		$(L:R=1:1)$
Peaks ($F2$)	Energy shift (δB) (MeV)	FWHM (MeV)	Ratio (A_l/a_l)
	3.31 ± 0.18	1.95(fixed)	0.45 ± 0.06
Peaks ($F3$)	Energy shift ($\delta B'$) (MeV)	FWHM (MeV)	Ratio (A'_l/a_l)
	6.57 ± 0.21	3.46(fixed)	1.13 ± 0.23

^{51}V spectrum measured by KEK E369 experiment via (π^+, K^+) associate production

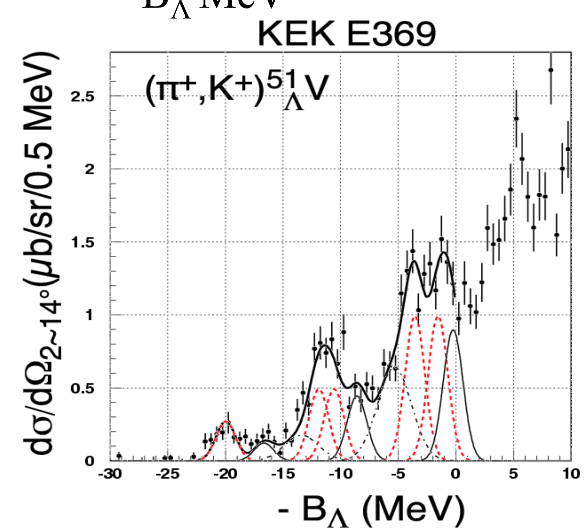
Vanadium spectroscopy



background subtracted

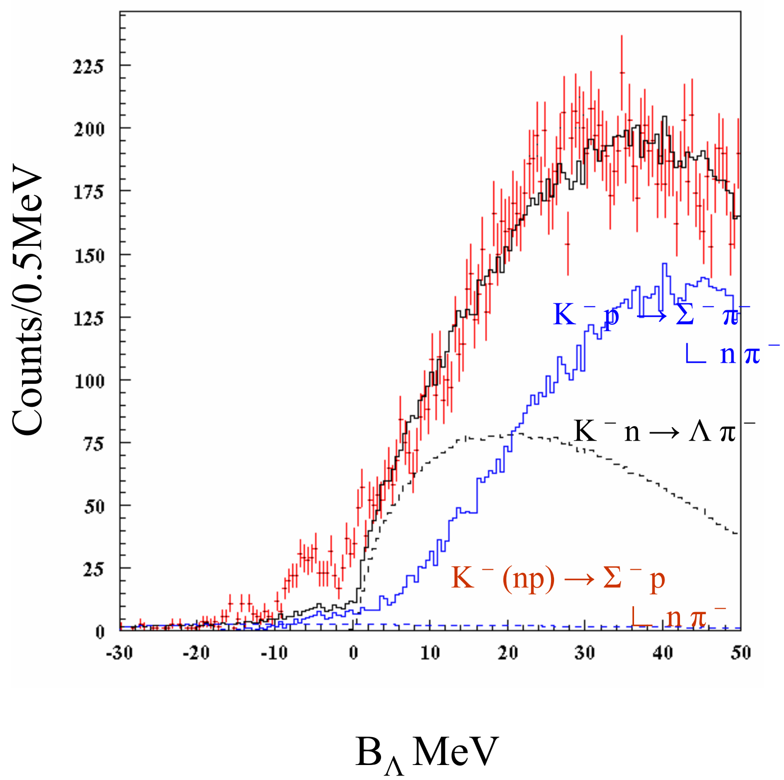


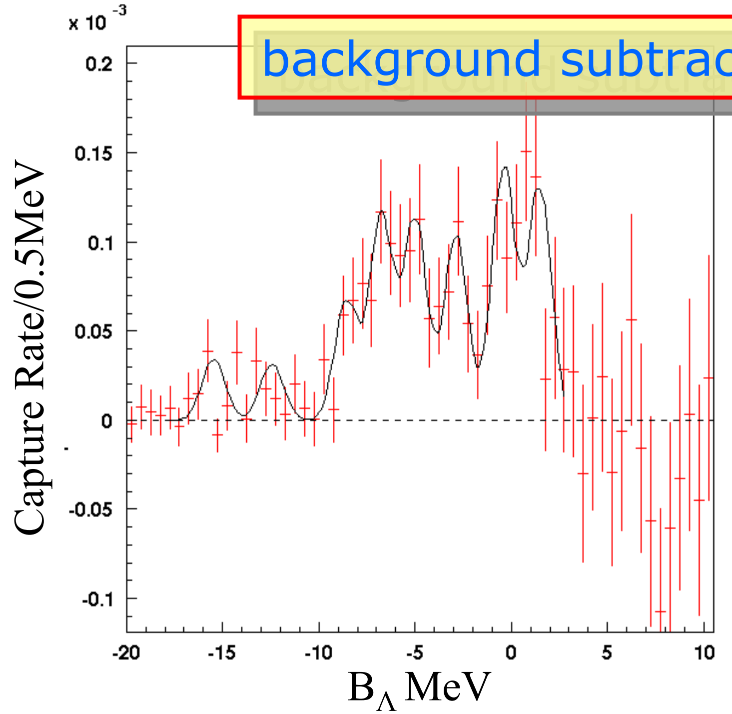
FINUDA spectrum with background reactions superimposed



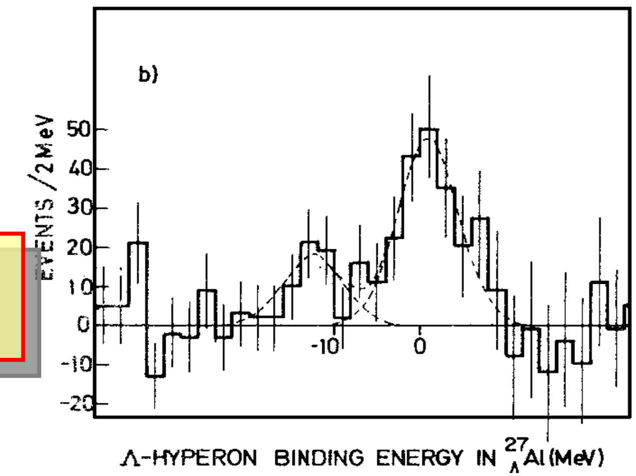
With respect to (π^+, K^+) reaction, (K^-, π^-) can access only excited states

Aluminum spectroscopy





background subtracted

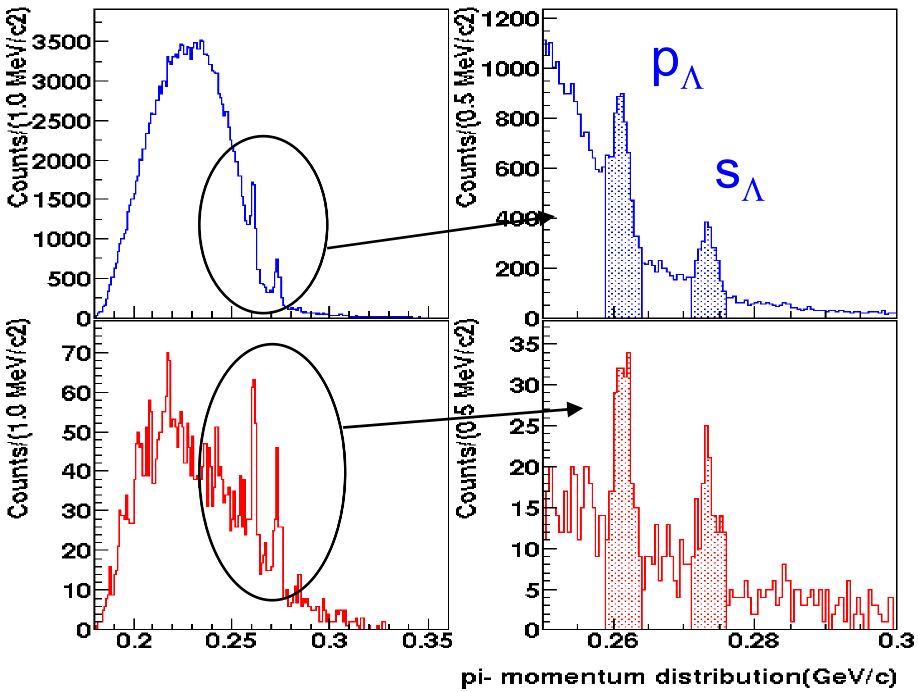


The only available data have poor resolution

$^{12}{}_{\Lambda}$C Non Mesonic Weak Decay

In medium-heavy hypernuclei mesonic decays ($\Lambda \rightarrow p\,\pi^-$; $\Lambda \rightarrow n\,\pi^o$) are suppressed due to Pauli blocking

non-mesonic weak interaction ($\Lambda\, p \rightarrow n\, p$; $\Lambda\, n \rightarrow n\, n$) are then more favored

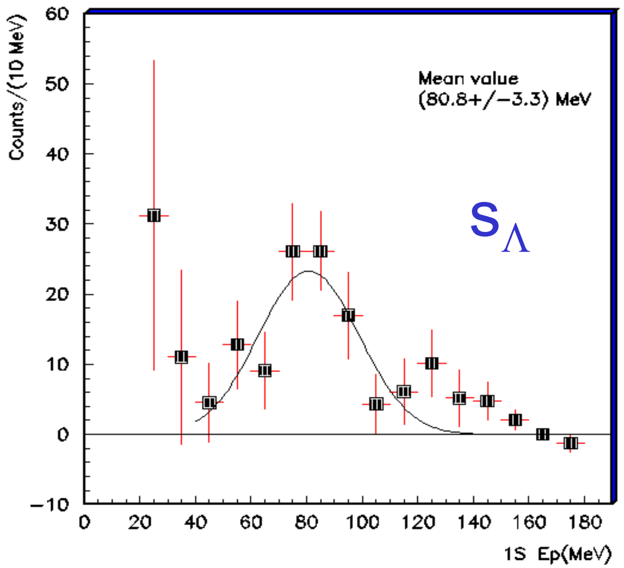


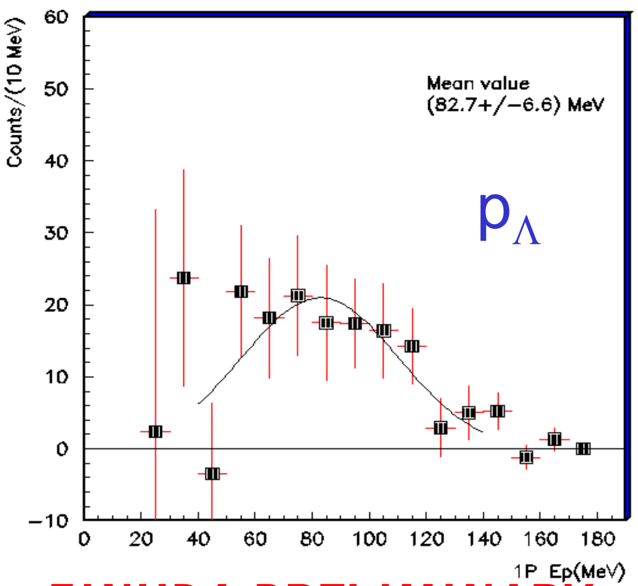
Pion momentum from $^{12}{}_{\Lambda}$C formation

Pion momentum from $^{12}{}_{\Lambda}$C formation **in coincidence with proton** from decay $^{12}{}_{\Lambda}$C :
s_{Λ} and p_{Λ} clearly show up with better S/N.

BRANCHING FRACTION in agreement with previous results
Γ_p ~ (0.38 ± 0.10) in 1s, (0.23 ±0.06) in 1p

Proton energy spectrum



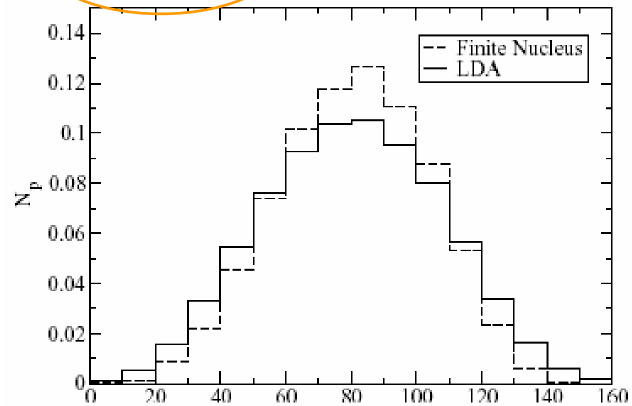


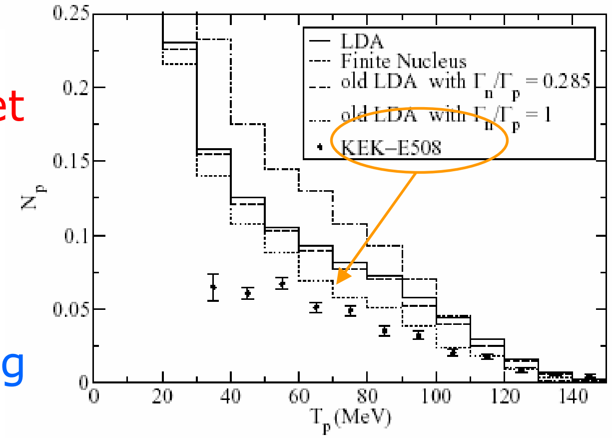
FINUDA PRELIMINARY

E.Bauer, Ramos et al., 2006:nucl-th/0602066:

Theoretical calculation of Ep without (top) and with (bottom) FSI effects. Data are from KEK-E508

Proton energy spectra in **coincidence with a π- from** hypernucleus formation in the s_Λ, p_Λ region.





Thanks to its thin target FINUDA has reduced the Ep low energy theshold. Spectrum shape at 20-40MeV is important for evaluating FSI contribution.

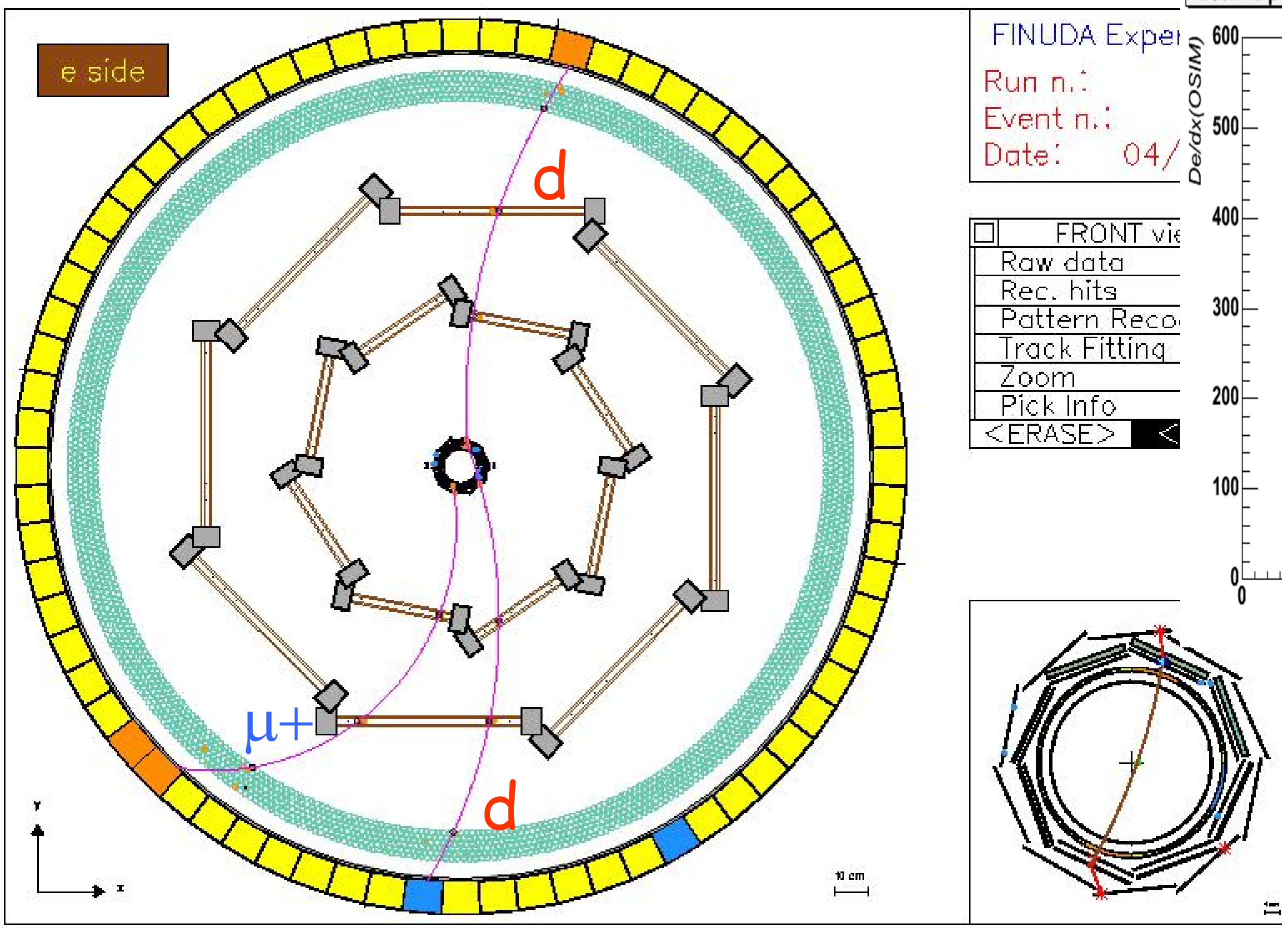
Hypernuclear rare decay

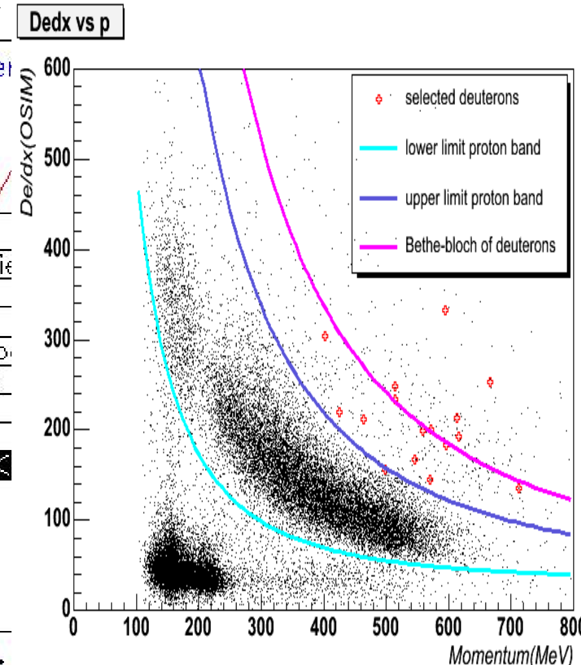
$$K^- + {}^6Li \rightarrow \pi^- + \begin{cases} {}^5_\Lambda He + p \\ {}^4_\Lambda He + p + n \\ {}^4_\Lambda H + p + p \end{cases}$$

Hyper-fragments production

$${}^4_\Lambda \mathrm{He} \rightarrow \begin{cases} d + d \\ p + t \\ d + p + n \end{cases}$$

p_d = 570 MeV/c
back to back topology





Neutron-rich hypernuclei

Hypernuclei with a large neutron excess have been theoretically predicted (L. Majling, *NPA 585 (1995) 211c*).

The Pauli principle does not apply to the Λ inside the nucleus + *extra* binding energy (Λ "*glue-like*" role) ⇒ a larger number of neutrons can be bound with respect to ordinary nuclei.

- **Hypernuclear physics**:

  ΛN interactions at low densities, the role of 3-body forces
- **Neutron drip-line**:

  response of neutron halo on embedding of Λ hyperon, hypernuclear species with unstable nuclear core

  T. Yu. Tretyakova and D. E. Lanskoy, Nucl. Phys. ***A 691****: 51c, 2001.*
- **Astrophysics**:

  Feedback with the astrophysics field: phenomena related to *high-density nuclear matter* in neutron stars.

  S. Balberg and A. Gal, Nucl. Phys. ***A 625****: 435, 1997.*

Neutron-rich hypernuclei

Two production mechanisms:

1) strangeness + double charge exchange

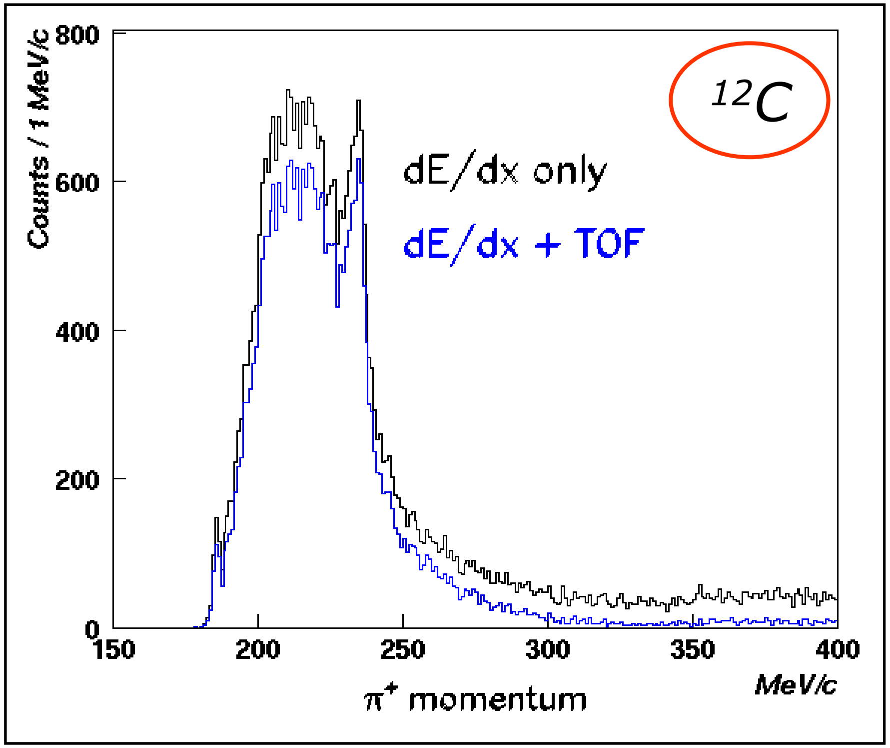
$$K^- + p \rightarrow \Lambda + \pi^0$$
$$\hookrightarrow \pi^0 + p \rightarrow n + \pi^+$$

$$\pi^- + p \rightarrow \pi^0 + n$$
$$\hookrightarrow \pi^0 + p \rightarrow K^+ + \Lambda$$

2) Strangeness exchange with Λ-Σ coupling

$$K^- + p \rightarrow \Sigma^- + \pi^+$$
$$\hookrightarrow \Sigma^- + p \rightarrow \Lambda + n$$

$$\pi^- + p \rightarrow \Sigma^- + K^+$$
$$\hookrightarrow \Sigma^- + p \rightarrow \Lambda + n$$



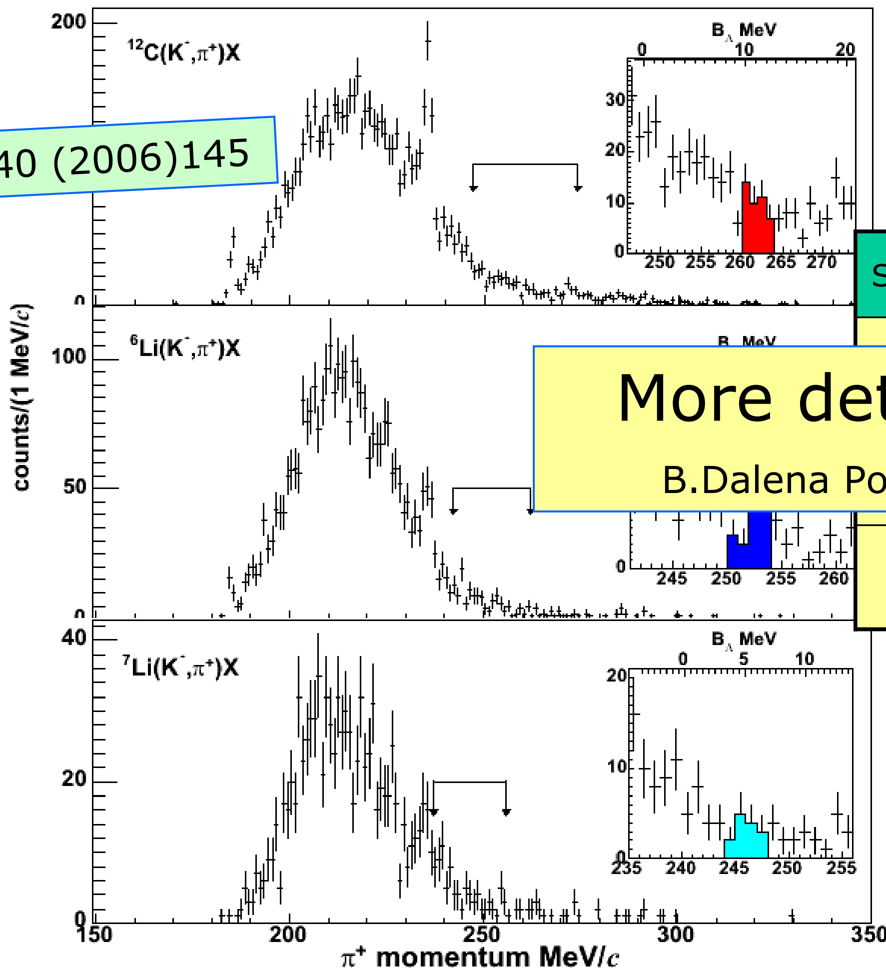
neutron-rich hypernuclei

$K^- + {}^6Li \rightarrow {}^6_\Lambda H + \pi^+$ (N/Z= 5) NEW

$K^- + {}^7Li \rightarrow {}^7_\Lambda H + \pi^+$ (N/Z= 6) NEW

$K^- + {}^{12}C \rightarrow {}^{12}_\Lambda Be + \pi^+$ (N/Z= 2)

PLB 640 (2006)145



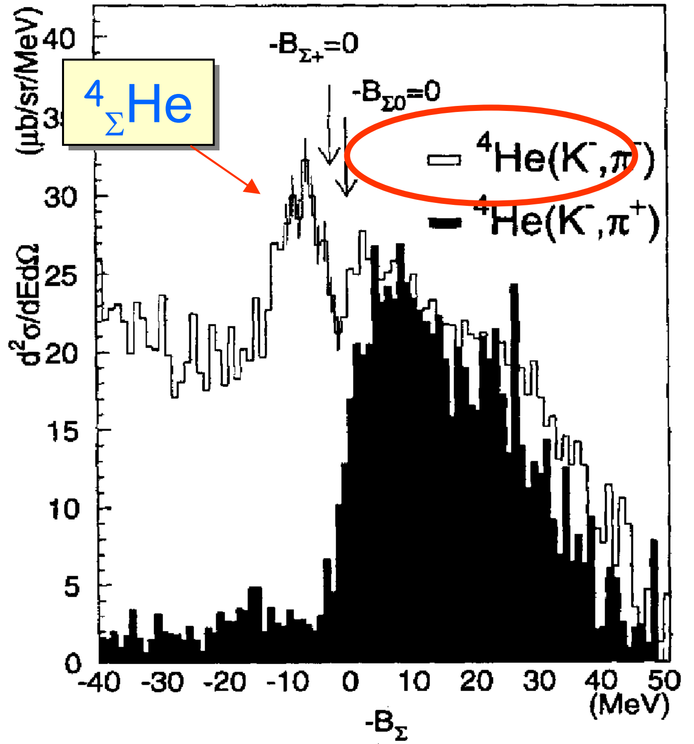
More details

B.Dalena Poster

System	FINUDA value 90% C.L.	From litterature
	$\pm 0.4_{stat}{}^{+0.4}_{-0.1}{}_{syst}) \cdot 10^{-5}/K^-_{stop}$	-
	$\pm 0.9_{stat}{}^{+0.4}_{-0.1}{}_{syst}) \cdot 10^{-5}/K^-_{stop}$	-
${}^{12}_\Lambda Be$	$(2.0 \pm 0.4_{stat}{}^{+0.3}_{-0.1}{}_{syst}) \cdot 10^{-5}/K^-_{stop}$	$6.1 \cdot 10^{-5}/K^-_{stop}$

Sigma hypernuclei

The strong ΣN→ ΛN conversion reaction in nuclear matter is broad as few tens of MeV.
To detect a Σ-bound state, the Σ width must be less than the separation between two adjacent Σ hypernuclear levels.



PL B 231(1989)355, PRL 80 (1998) 1605

FINUDA can detect the formation and decay of Σ-hypernuclei via $(K^-_{stop}, \Sigma\pi)$

$$K^-_{stop} + A \to {}_\Sigma B + \pi^\pm_{prompt}$$

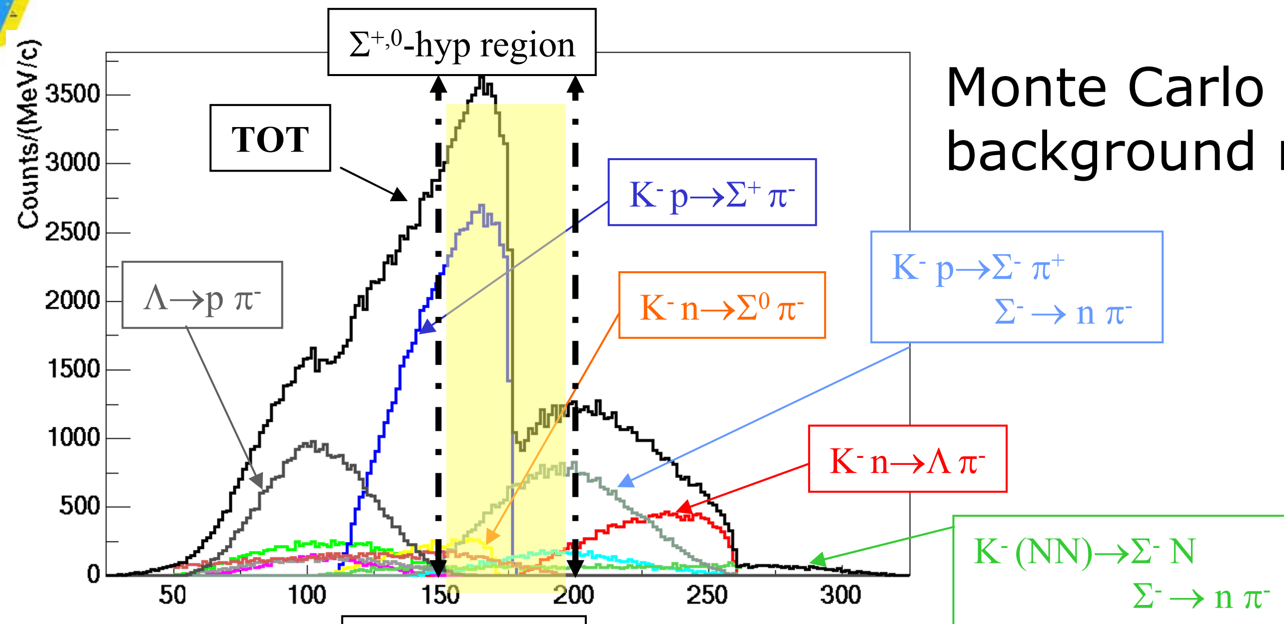
$$\Sigma + N \to \Lambda + N$$

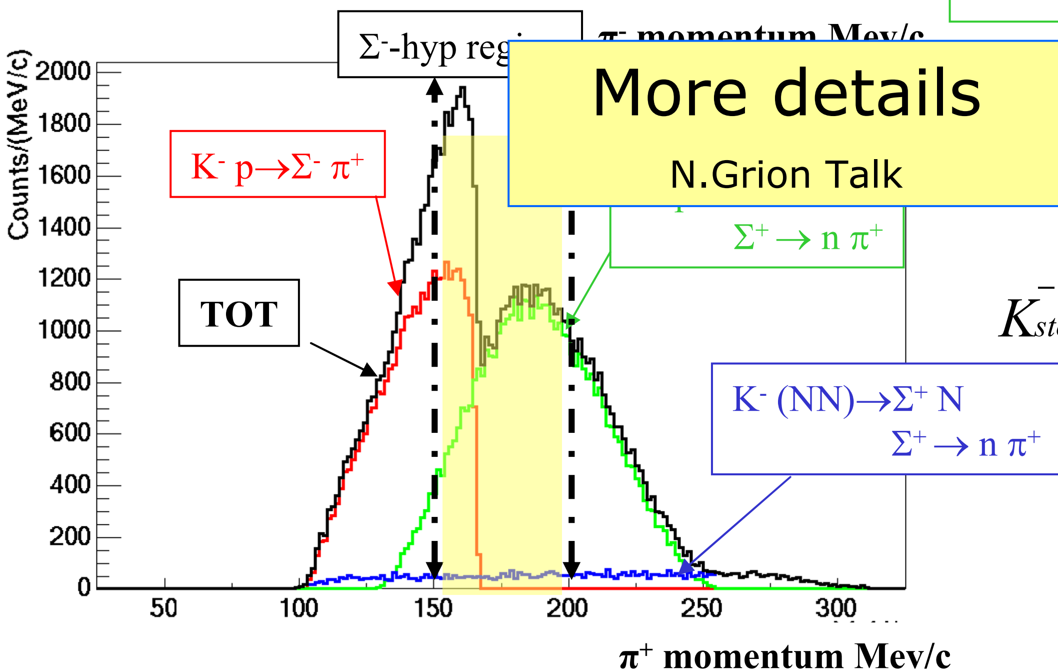
The momentum of the $\pi^\pm$ produced with the Σ is between 150 -200 MeV/c. To increase acceptance lower resolutions tracks are used

The Λ is reconstructed via its decay products

^{12}C Sigma hypernuclei

Monte Carlo simulations of background reactions for ^{12}C





More details

N.Grion Talk

$$K^-_{stop} + {}^{12}C \rightarrow \begin{cases} {}^{12}_{\Sigma^-}Be + \pi^+_{prompt} \\ \quad {}^{12}_{\Sigma^-}Be \rightarrow {}^{10}Be + \Lambda + n \\ {}^{12}_{\Sigma^+}C + \pi^-_{prompt} \\ \quad {}^{12}_{\Sigma^+}C \rightarrow {}^{10}B + \Lambda + p \\ {}^{12}_{\Sigma^0}C + \pi^-_{prompt} \\ \quad {}^{12}_{\Sigma^0}C \rightarrow {}^{10}C + \Lambda + n \\ \quad {}^{12}_{\Sigma^0}C \rightarrow {}^{10}B + \Lambda + p \end{cases}$$

Deeply Bound Kaonic States

- Akaishi-Yamazaki — deep potentials → large B.E.
  small widths
  ↘ a few nucleon aggregate

- Weise et al.
- Gal et al.
- Oset, Ramos et al.
- Wycech et al.
- Schäffner-Bielich et al.

} shallow potentials → moderate-large B.E.
large widths(>50 MeV),
↘ more visible on heavy systems

FINUDA results

A. Filippi Talk

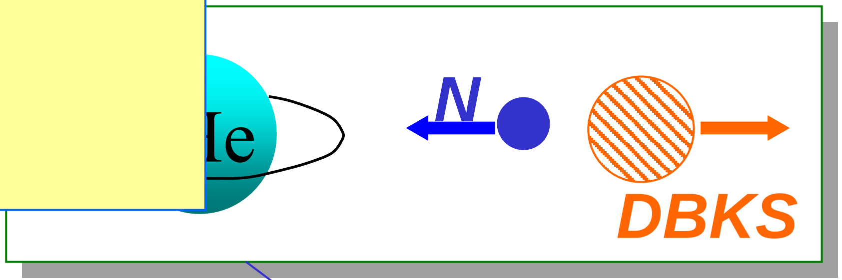
S. Piano Talk

Fujioka Poster

EXP. SITU

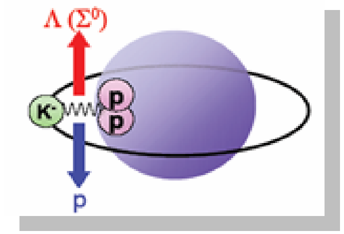
Scarce information → Missing mass; Invariant mass

Missing mass



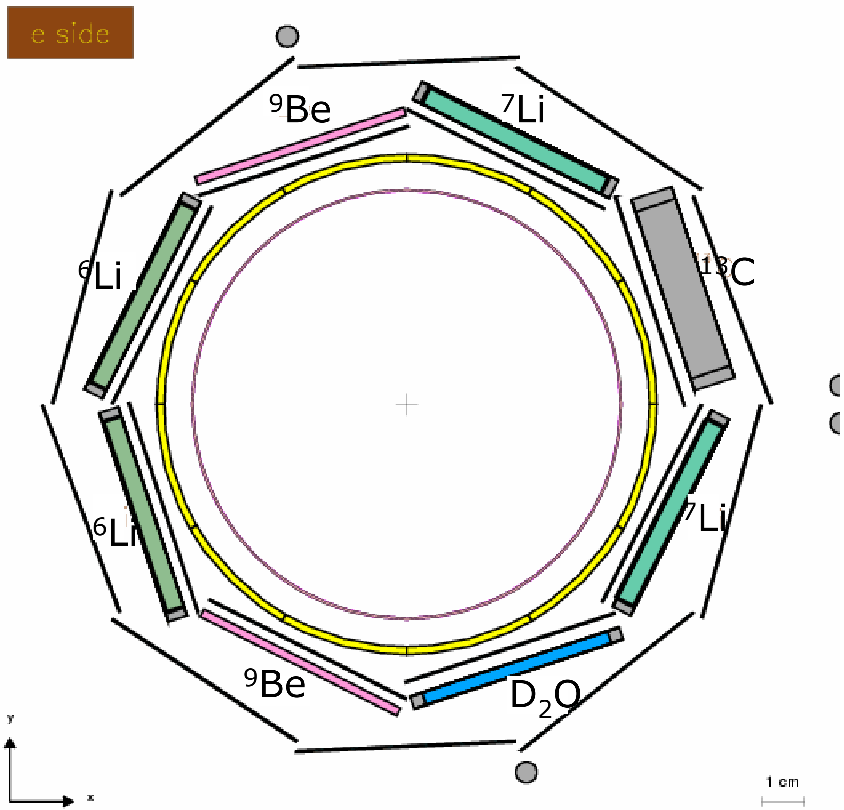
KEK, AGS, FINUDA

Invariant mass



FINUDA, FOPI

Targets' setup for next data-taking



- Choice: 2x ^{6}Li, 2x ^{7}Li, 1x D_2O, 2x ^{9}Be, 1x ^{13}C
- We focused on medium-light target to allow a wider spectrum of analyses
  - Hypernucelar spectroscopy
  - Hypernuclei decay modes
  - Bound kaonic states
  - Rare hypernuclear decay

Target's thickness evaluated taking into account the narrower (1.8 mm) TOFINO:
^{7}Li, ^{6}Li as in the previous run (+cover)
^{9}Be: 2 mm
D_2O: 3 mm + cover (e.g. 100 μm mylar)

NMWD: yield estimation for next data taking (1 fb^{-1})

Target	np (π coinc.)	nn (π coinc.)	nnp/nnn (π coinc.)
^{6}Li (2T)	1200	800	120/80
^{7}Li (2T)	1200	800	120/80
^{9}Be (2T)	800	600	80/60
^{13}C (1T)	300	200	no
^{16}O(1T)	300	200	no

- Such statistics are adequate to improve our analyses on
  - Neutron Rich Hypernuclei
  - Spectroscopy of p-shell Hypernuclei
  - Mesonic decays

Expected events for NRH

Hypernucleus	Target	B_{Λ} (MeV)	p_{π} (MeV/c)	Production rate / k^{-}_{stop}	Events	U.L. 90% C.L.
${}^{6}_{\Lambda}H$	${}^{6}Li$	4.1[1]	252	$< 2.5\times10^{-5}$ [3]	430	6.5×10^{-6}
${}^{7}_{\Lambda}H$	${}^{7}Li$	5.2[2]	245	$< 4.5\times10^{-5}$ [3]	460	6.9×10^{-6}
${}^{9}_{\Lambda}He$	${}^{9}Be$	8.5[2]	257	$< 2.3\times10^{-4}$ [4]	600	6.7×10^{-6}
${}^{13}_{\Lambda}Be$	${}^{13}C$	11.7[2]	259	(?)	100	1.1×10^{-5}
${}^{16}_{\Lambda}C$	${}^{16}O$	7.3(2^{+})[5]	264	$< 6.2\times10^{-5}$ (0^{+})[4]	200	8.2×10^{-6}
		13.6(0^{+})[2]	271	6×10^{-8} (2^{+})[5] 3×10^{-8} (0^{+})[5]	190	8.5×10^{-6}

[1] *Y. Akaishi et al., PRL 84 (2000) 3539*
[2] *L. Majling, NPA 585 (1995) 211c*
[3] *M. Agnello et al. PLB 640 (2006) 145*
[4] *NPA 602 (1996) 327*
[5] *T. Yu. Tretyakova and D.E. Lanskoy, Proc. Of Workshop "Recent progress in Strangeness nuclear physics ", H. Outa et al. eds., KEK (2003) 80.*

Summary

- Data analysis of first data taking period carried out successfully (30×10^6 events on tape)
- Results on spectroscopy are competitive with world published data
- Observation of K^--Nucleons bound states
- Upper limit for the *NRH* production:
  - ☺ better than published for ${}_{\Lambda}^{12}Be$
  - ☺ measured for the first time for ${}_{\Lambda}^{6}H$ and ${}_{\Lambda}^{7}H$
- Hints on NMWD possibilities and other rare decays

Future plans

- Next data-taking starting now (~ $1 fb^{-1} \rightarrow$ statistics x 5)
  focused on light-medium targets (^{6}Li, ^{7}Li, ^{9}Be, ^{16}O)

- New internal TOF system (KEK)
  to improve Trigger capabilities

- Increased 4 DAQ rate by a factor
  to stand higher DAFNE luminosity

- Improvement of the reconstruction program
  - ✓ geometrical alignment
  - ✓ detector calibration
  - ✓ pattern recognition strategy
  - ✓ selection criteria