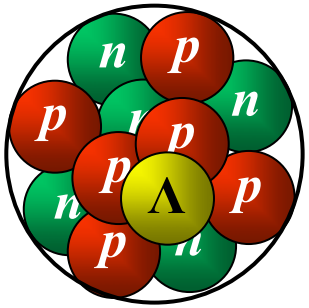
Experimental hypernuclear physics



7th European Research Conference

Electromagnetic Interactions with Nucleons and Nuclei (EINN 2007)

12-15 September 2007

Milos Conference Center - George Eliopoulos
Milos Island, Greece

Parallel Workshops:
September 10-11, 2007 Milos, Greece
Coordinator: Paul Hoyer

Electromagnetic studies of nuclear systems
Conveners: Kees de Jager, Bernd Krusche

Hadron Physics on the Lattice
Conveners: Constantia Alexandrou, Chris Michael

TOPICS
- Electromagnetic form factors
- Hard exclusive reactions
- Spin structure
- Hadrons in the nuclear medium
- Parity violation
- Future facilities

INFORMATION
Institute of Accelerating Systems and Applications (IASA)
P.O.Box 17214, Athens, 10 024 – Greece
Tel: +30 210 7257533, Fax: +30 210 7295069
E-mail:EINN07@iasa.gr, http://www.iasa.gr/EINN_2007

Background: Compputer animation with motifs from "The Wall-Paintings of Thera", Prof. Christos Doumas.
Wallpaintings: "Lilies", "Sea Daffodils" and "Mistress of Animals and Saffron Gatherer".

ORGANIZERS

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Michel Garcon, *Vice Chair*

Workshops:
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Alessandro Feliciello

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

Outline

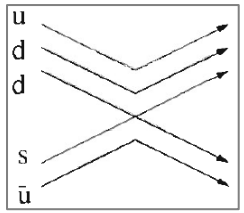
- strangeness nuclear physics:
  - interest
  - discovery potential
- experimental results
  - high resolution spectroscopy
  - decay modes
  - neutron-rich hypernuclei
  - deeply bound $\bar{K}$-nucleus states
- future prospects:
  - facilities
  - experiments

Single Λ-hypernucleus production

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

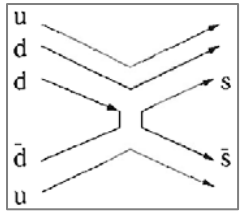
1) strangeness exchange (both in flight and at rest):

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



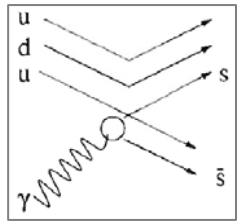
2) associated strangeness production:

$$\pi^+ + {}^A Z \rightarrow {}^A_\Lambda Z + K^+$$



3) "electro-production":

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



quality vs. quantity

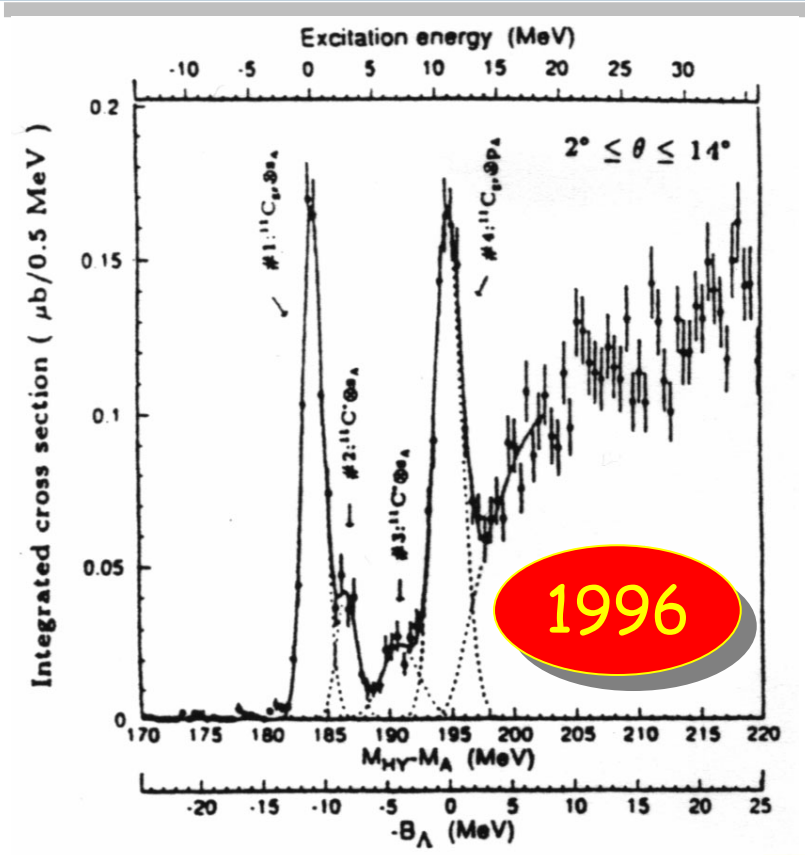
energy resolution

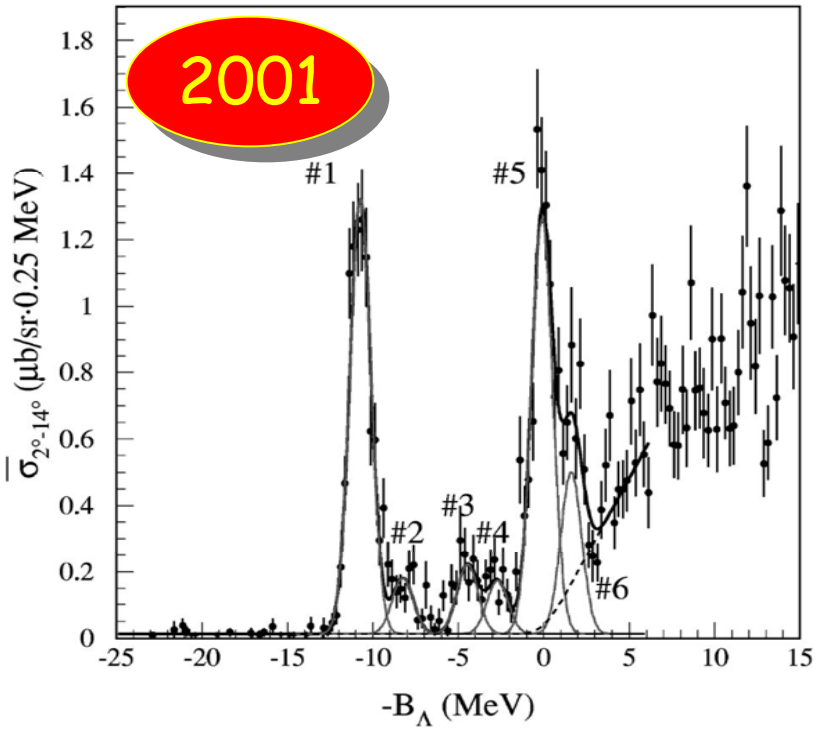
☺ spectrometer performance

interaction rate

☹ low cross section
☺ beam intensities
😐 apparatus acceptance (~100 msr)
☹ target thickness (g/cm^2)

Experimental technique improvement





ΔE ~ 1.9 MeV FWHM

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

ΔE ~ 1.5 MeV FWHM

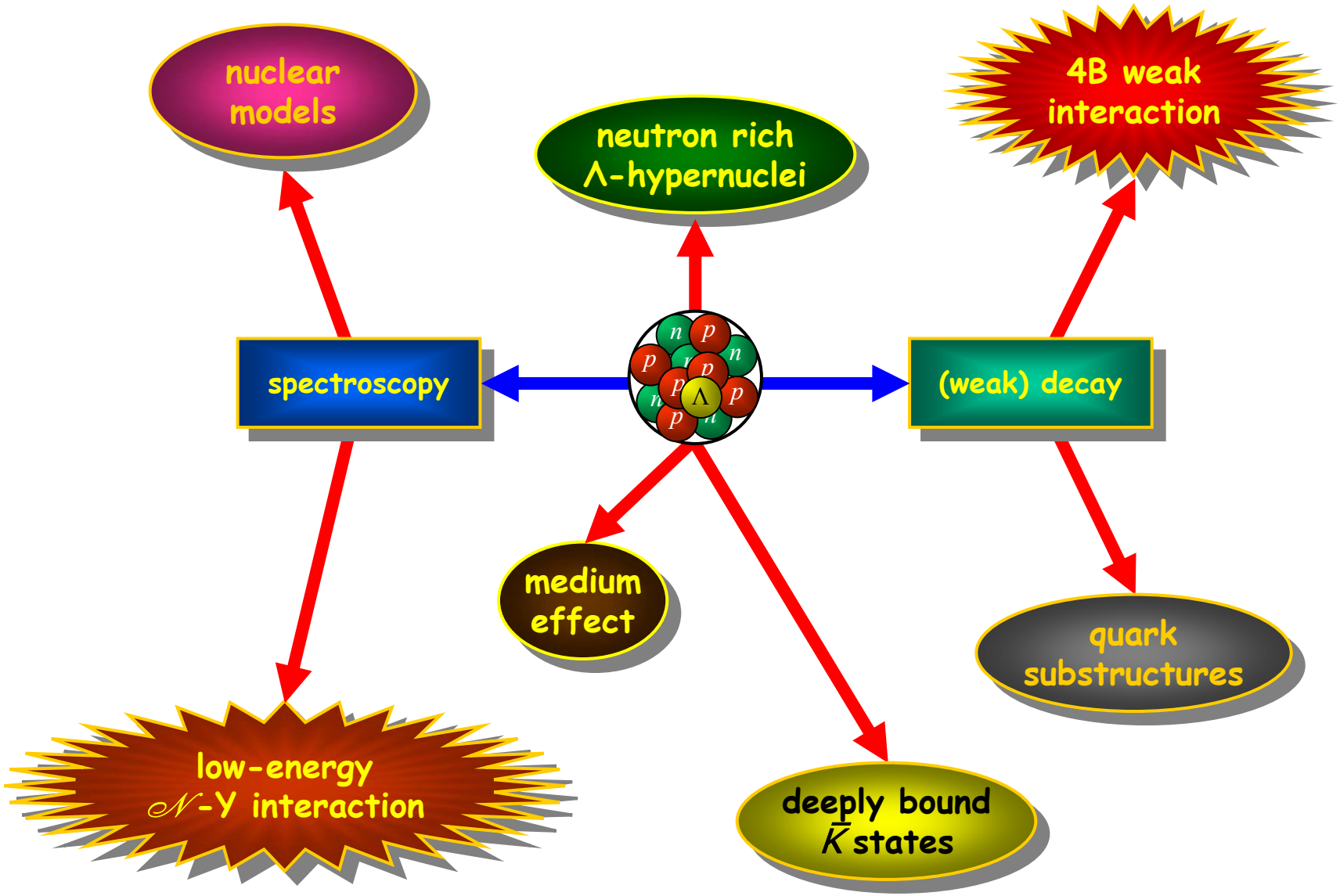
^{12}C target: 0.9 g/cm^2

T. Hasegawa *et al.*, Phys. Rev. C 53 (1996) 1210

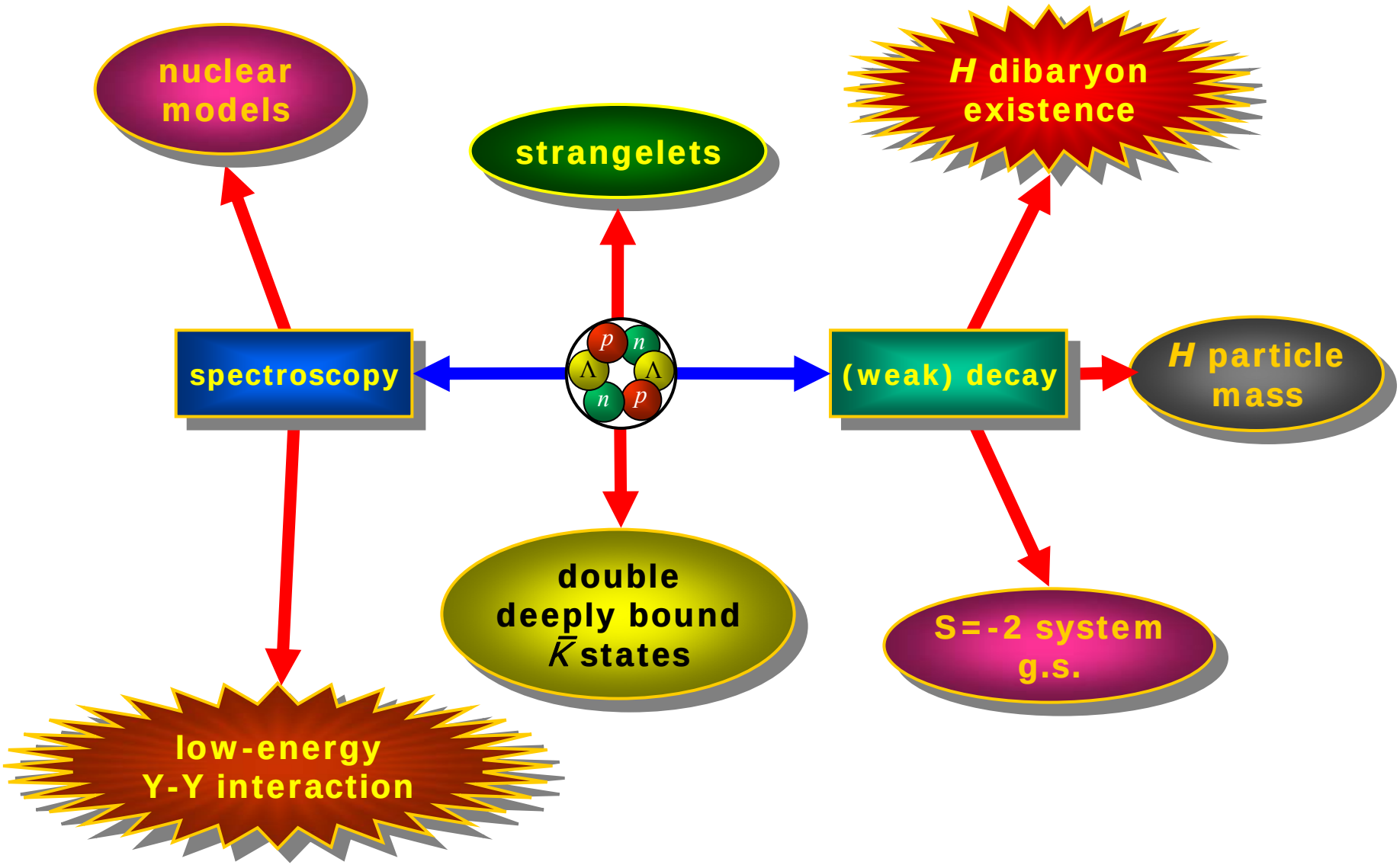
H. Hotchi *et al.*, Phys. Rev. C 64 (2001) 044302

5 years

Physics output (S = -1)



Physics output (S=-2)

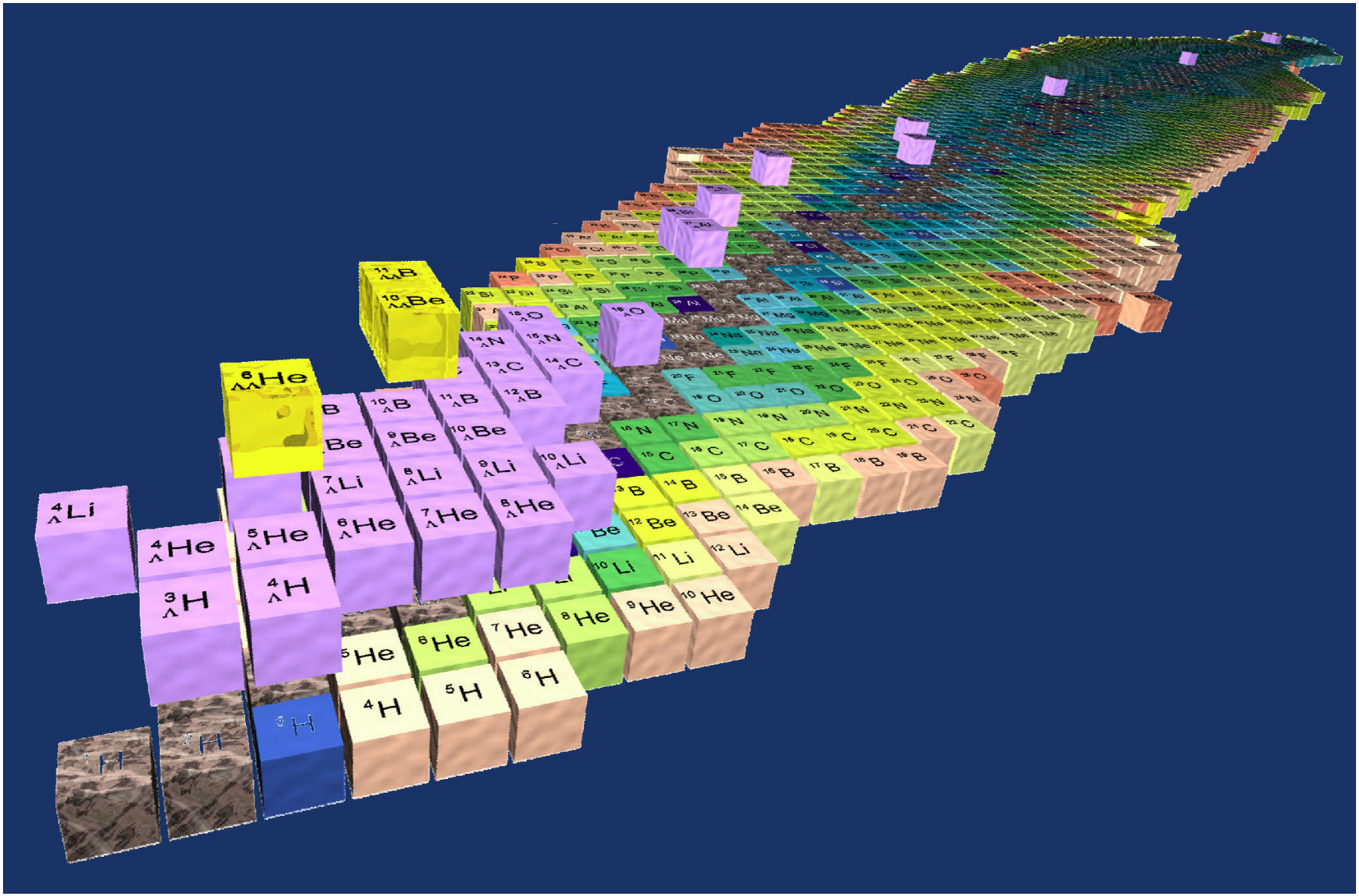


S=-2 systems

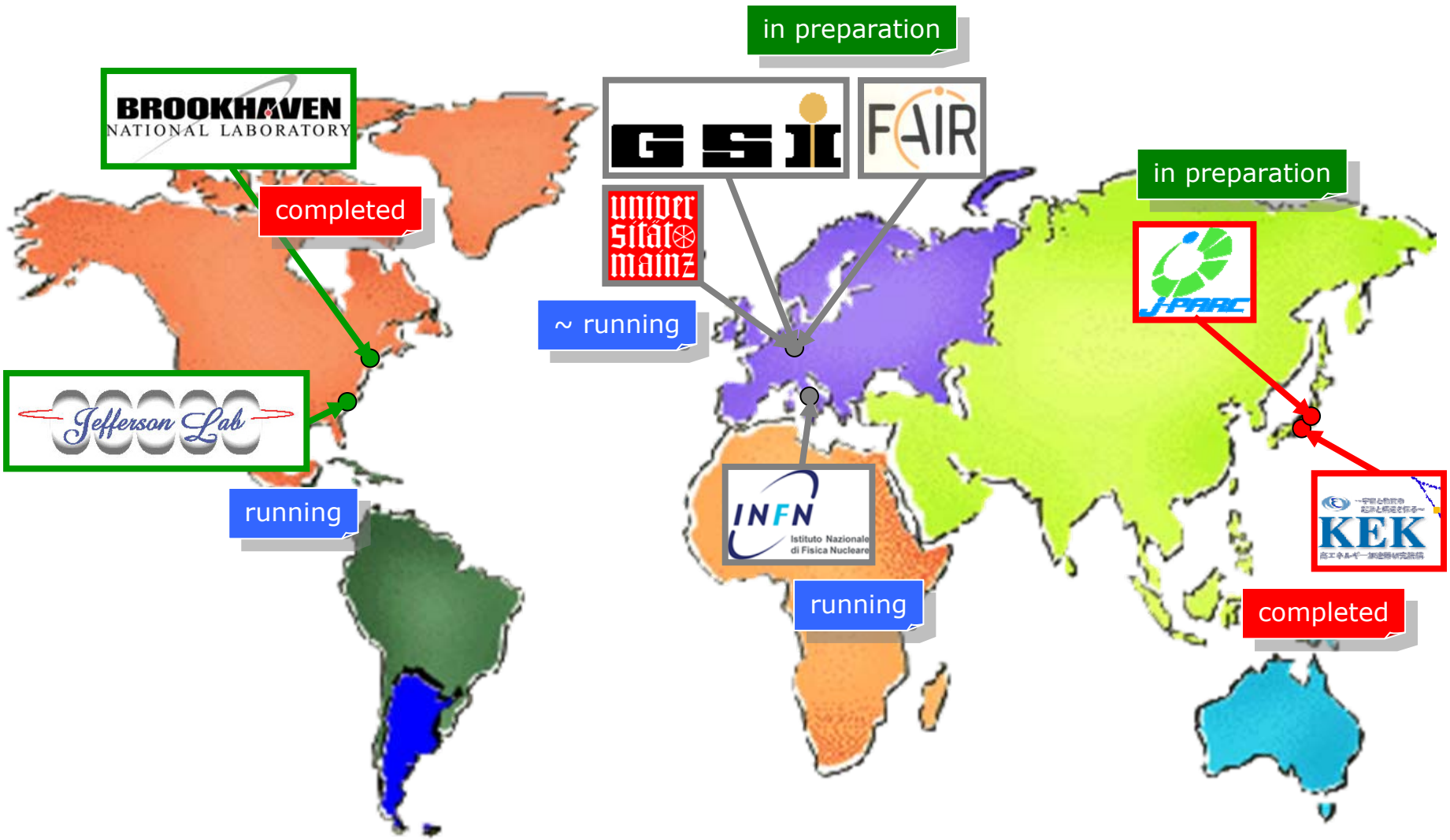
S = -2 systems study is not just a simple extension of what has been done for S = -1 system

- new physics items:
  - a detailed and consistent understanding of the quark aspect of the baryon-baryon forces in the SU(3) space will not be possible as long as experimental information on the *YY* channel is not available
  - search for *H* particle
  - existence of S = -2 (deeply) bound $\bar{K}$ states
- experimental challenges:
  - (abundant) production of ΛΛ-hypernuclei is very difficult
  - identification of produced hyperfragments is problematic
  - γ-ray measurement in coincidence

Hypernuclei's chart

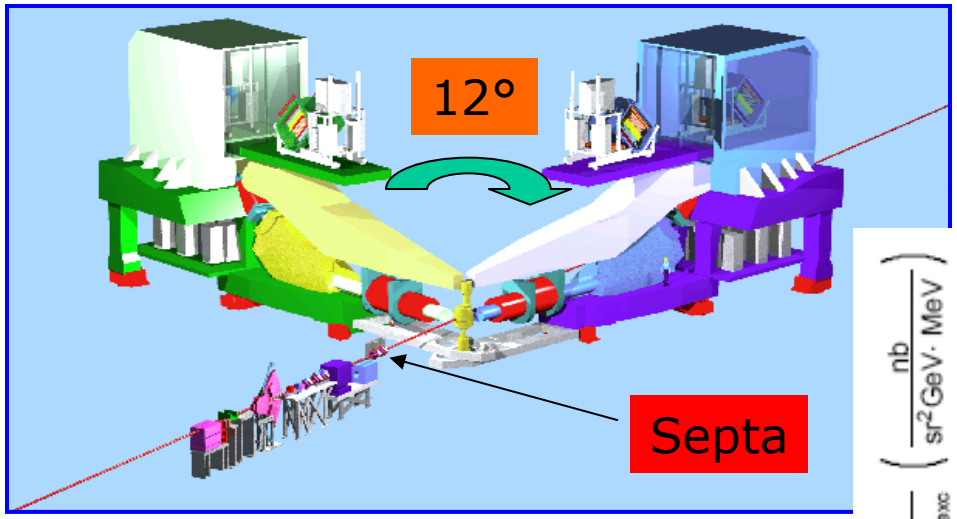


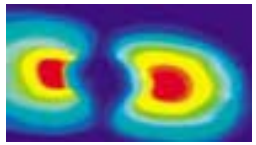
Hypernuclei's chart 2



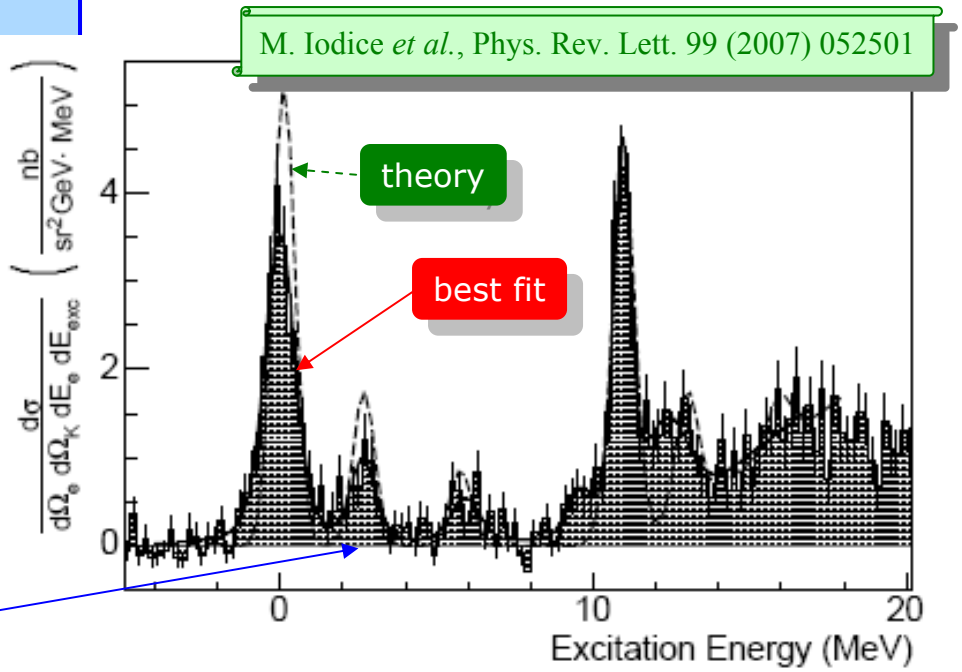
E94-107 results on $^{12}B_{\Lambda}$

Hall A





- I_{e^-}: 100 μA
- ^{12}C target: 100 mg/cm^2



nearly no background!

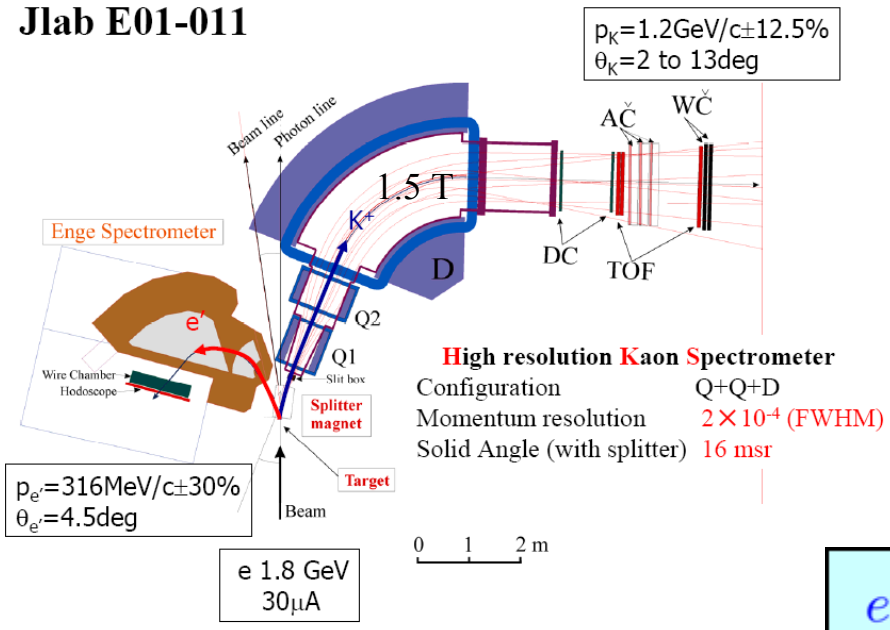
$$e^- + {}^{A}Z \rightarrow e^{-\prime} + K^+ + {}^{A}_{\Lambda}(Z-1)$$

ΔE ~ 0.67 MeV FWHM

E01-011 results

Hall C

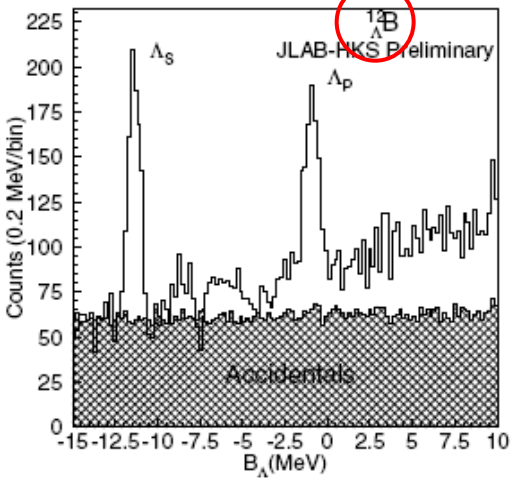
Jlab E01-011



High resolution Kaon Spectrometer

Configuration	Q+Q+D
Momentum resolution	2×10^{-4} (FWHM)
Solid Angle (with splitter)	16 msr

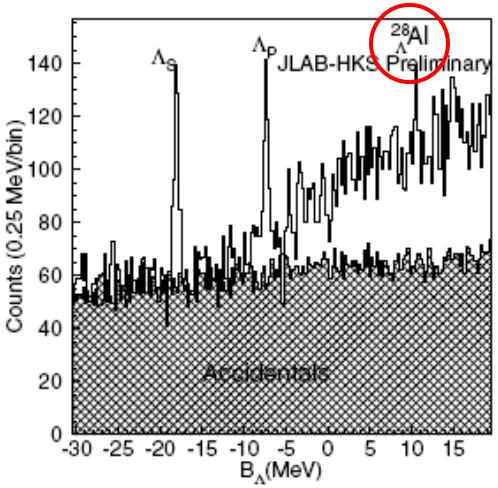
L. Tang *et al.*, Nucl. Phys. A 790 (2007) 679c

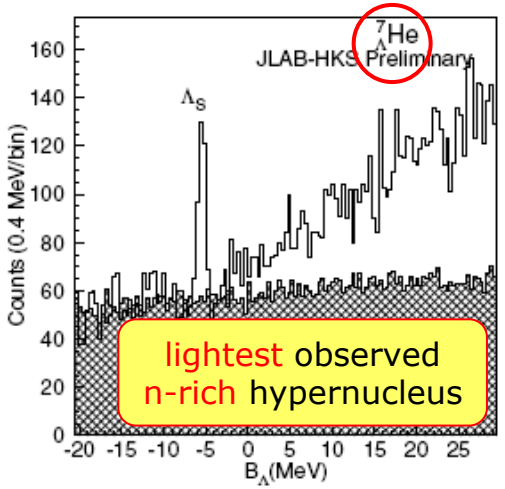


$$e^- + {}^{A}Z \rightarrow e^{-\prime} + K^+ + {}^{A}_{\Lambda}(Z-1)$$

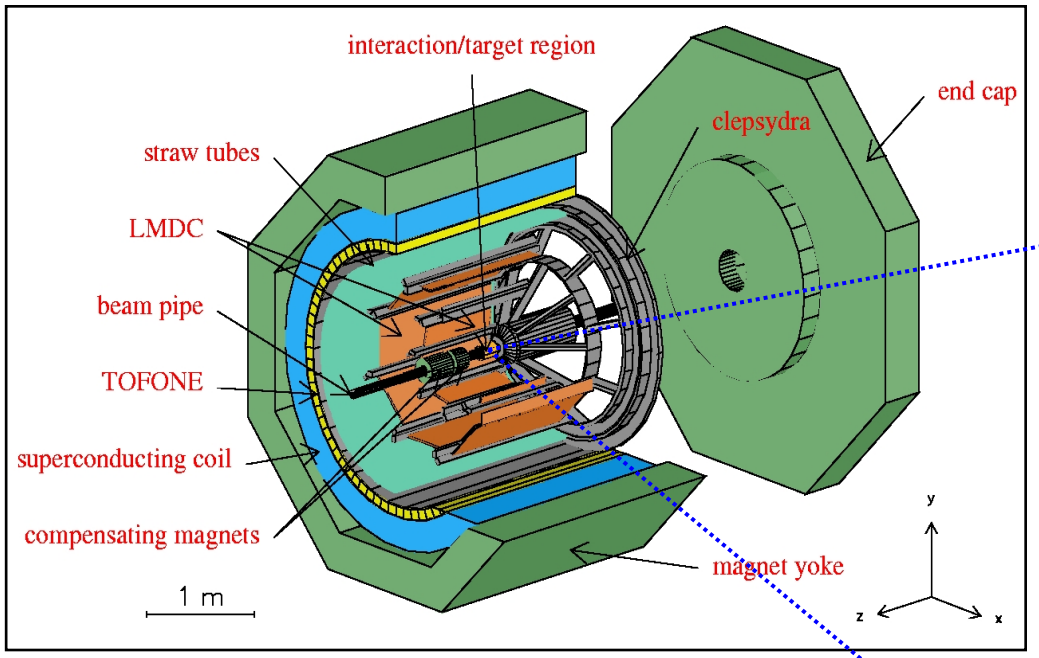
- I_{e^-}: 13 - 30 μA
- ΔΩ: ~16 msr
- targets: 100 mg/cm²

ΔE ~ 0.75 MeV FWHM



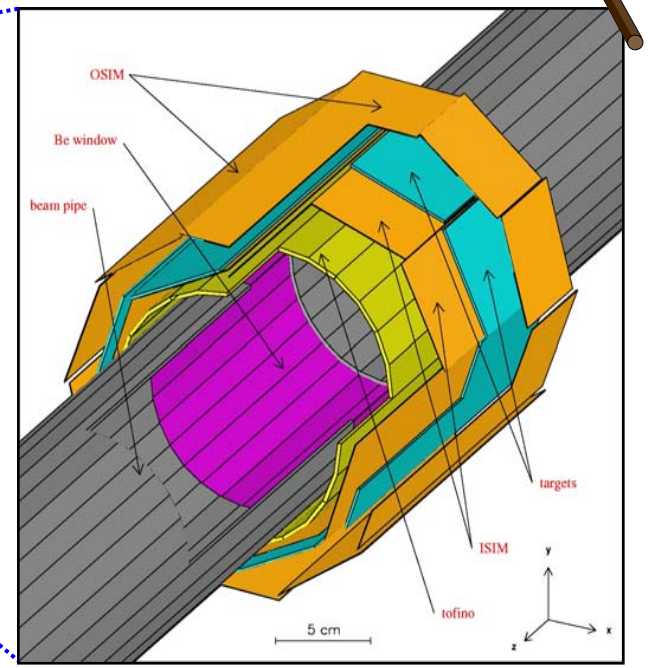


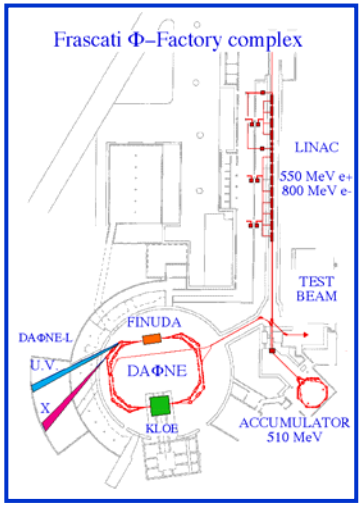
FINUDA @ DAΦNE



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

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

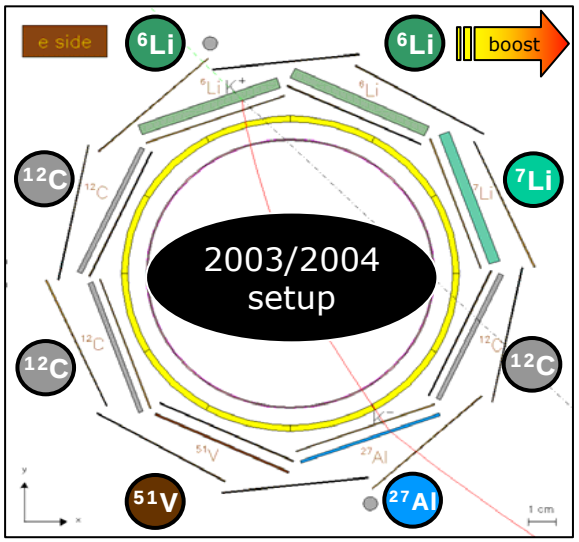




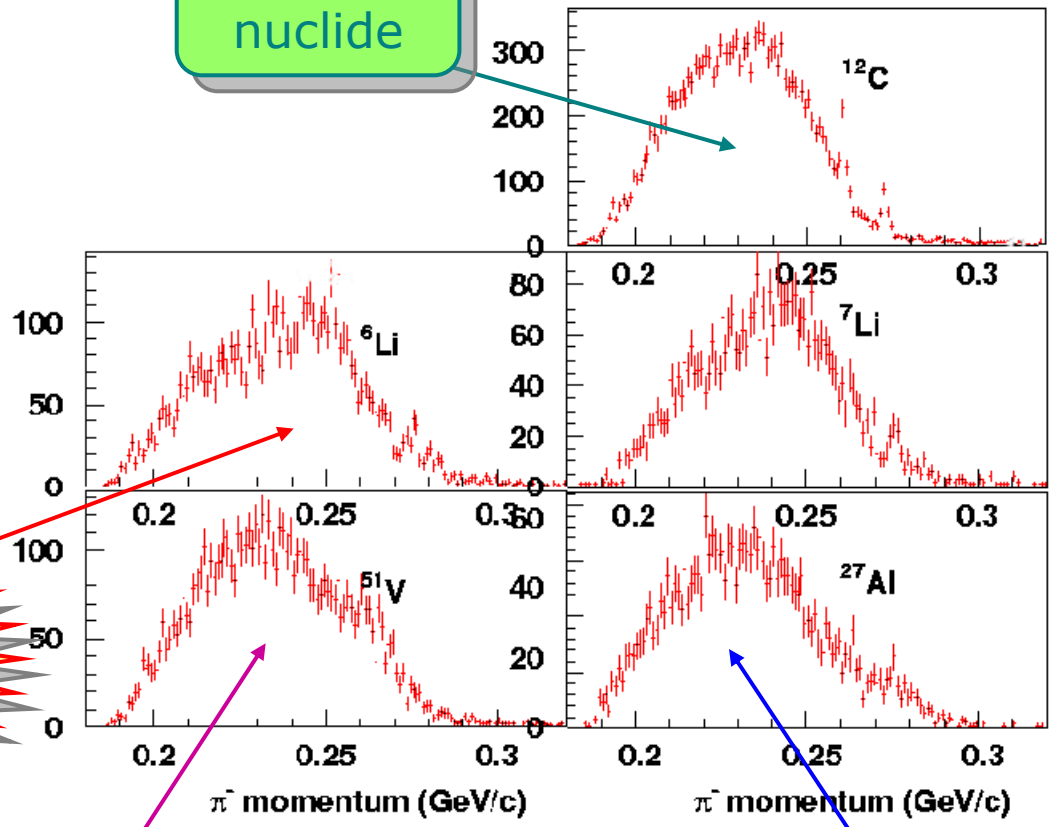
energy	510 MeV
luminosity	5 10^{32} cm^{-2} s^{-1}
σ_x (rms)	2.11 mm
σ_y (rms)	0.021 mm
σ_z (rms)	35 mm
bunch length	30 mm
crossing angle	12.5 mrad
frequency (max)	368.25 MHz
bunch/ring	up to 120
part./bunch	8.9 10^{10}
current/ring	5.2 A (max)

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

FINUDA 1st round



reference nuclide



doorway for light systems
(${}^{4}_{\Lambda}H$, ${}^{4}_{\Lambda}He$, ${}^{5}_{\Lambda}He$)

medium-A systems
(~ terra incognita)

never studied before

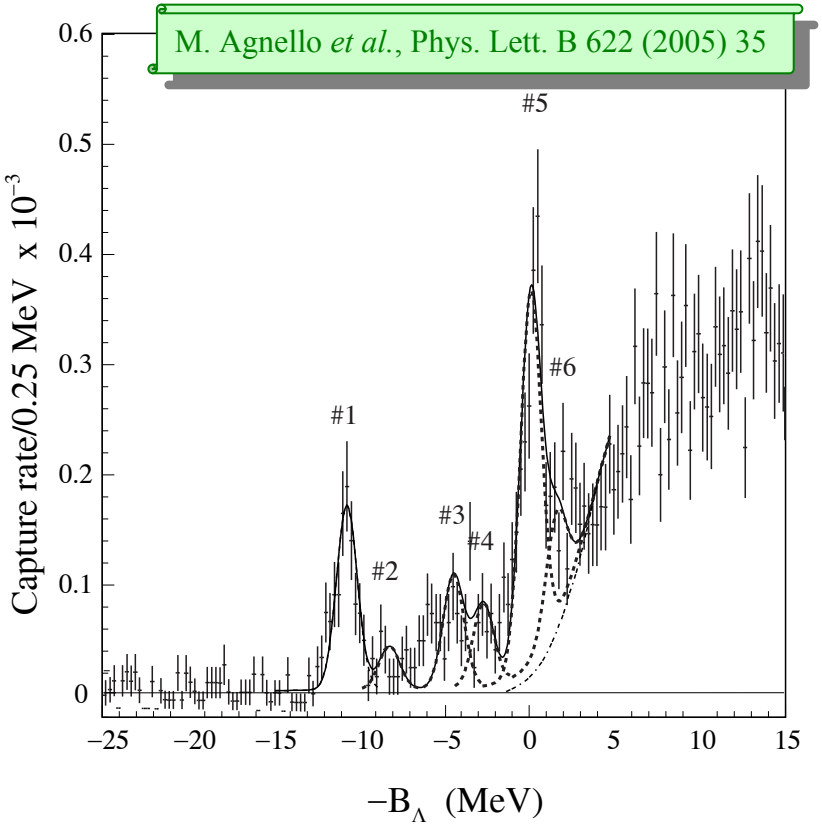
FINUDA vs. KEK-E369

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

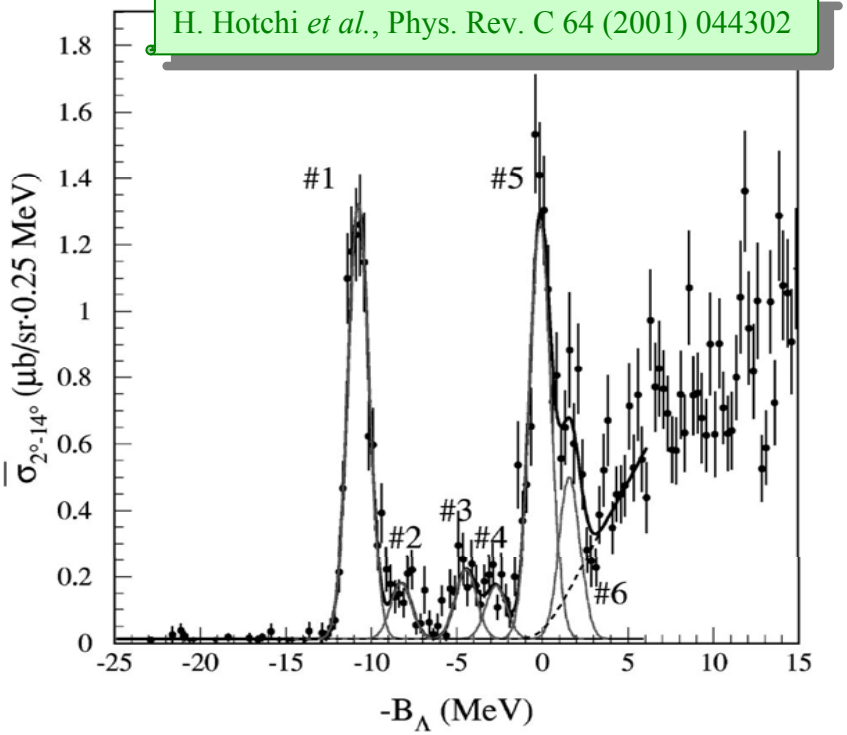
ΔE ~ 1.3 MeV FWHM

- ΔΩ: > 2π sr
- ^{12}C target: 0.2 g/cm^2

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

- ΔΩ: ~100 msr
- ^{12}C target: 0.9 g/cm^2

FINUDA results on ^{12}C

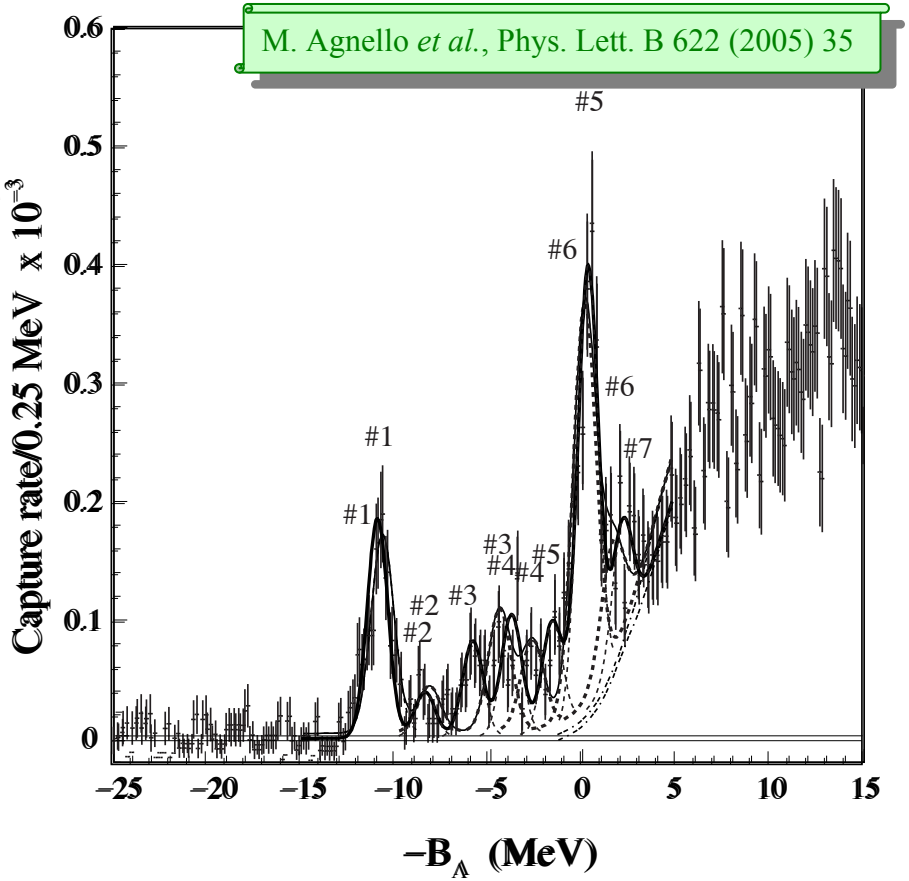
Peak number	$-B_\Lambda$ (MeV) (Fixed at E369 values)	Capture rate/(stopped K^-)$[\times 10^{-3}]$
1	−10.76	$1.01 \pm 0.11_{stat} \pm 0.10_{syst}$
2	−8.25	0.23 ± 0.05
3	−4.46	0.62 ± 0.08
4	−2.76	0.45 ± 0.07
5	−0.10	2.01 ± 0.14
6	1.61	0.57 ± 0.11

Peak number	$-B_\Lambda$ (MeV)	Capture rate/(stopped K^-)$[\times 10^{-3}]$
1	-10.94 ± 0.06	$1.01 \pm 0.11_{stat} \pm 0.10_{syst}$
2	-8.4 ± 0.2	0.21 ± 0.05
3	-5.9 ± 0.1	0.44 ± 0.07
4	-3.8 ± 0.1	0.56 ± 0.08
5	-1.6 ± 0.2	0.50 ± 0.08
6	0.27 ± 0.06	2.01 ± 0.17
7	2.1 ± 0.2	0.58 ± 0.18

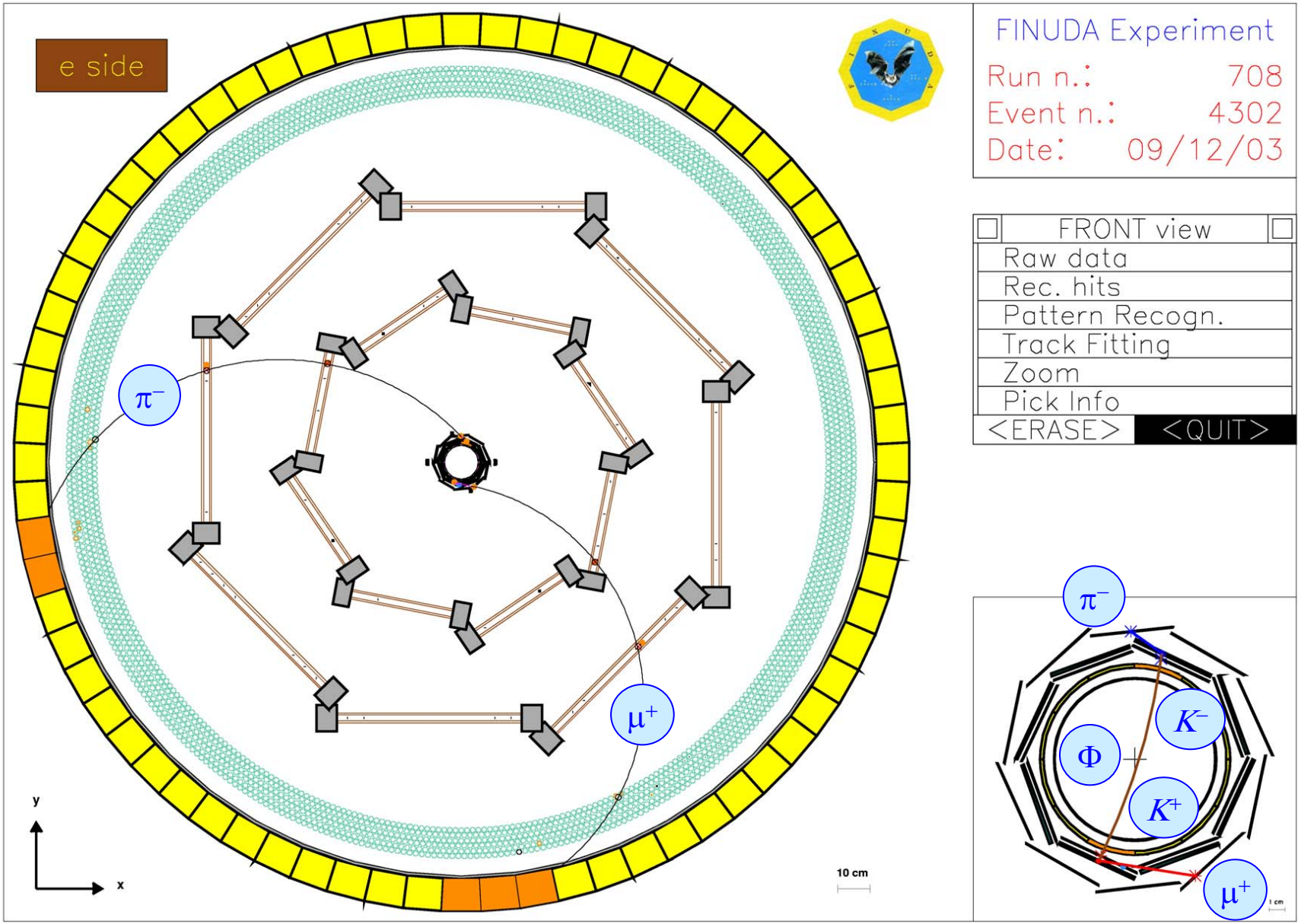
$^{12}C(K^-_{stop},\pi^-)^{12}_{\Lambda}C$

ΔE ~ 1.3 MeV FWHM

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



The typical event

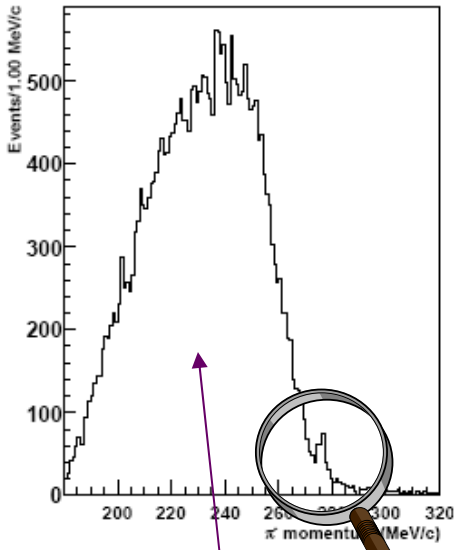


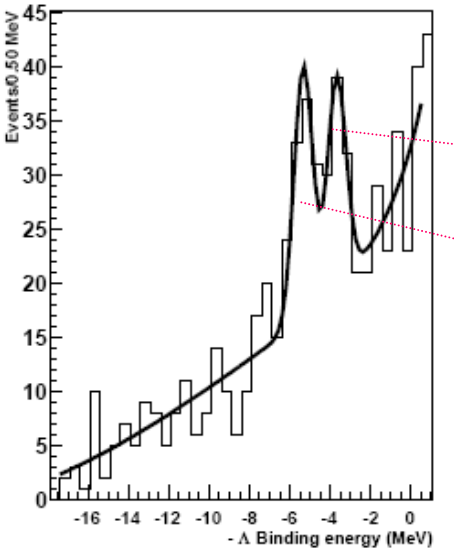
FINUDA results on ^{7}Li

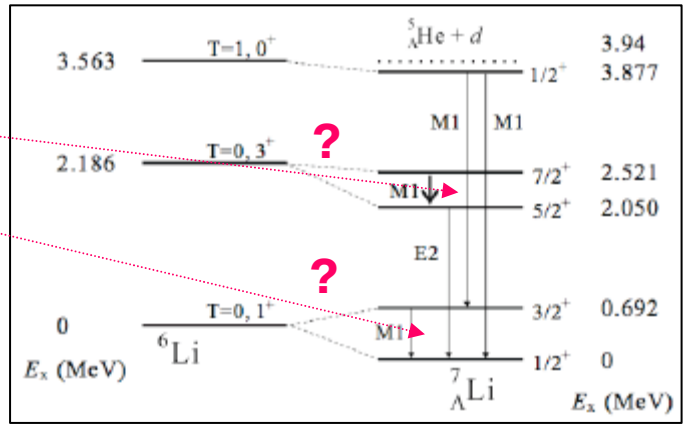
$^7Li(K^-_{stop},\pi^-)^7_\Lambda Li$

ΔE ~ 1.1 MeV FWHM

M. Ukai *et al.*, Phys. Rev. C 73 (2006) 012501







$B^{g.s.}_\Lambda = 5.58 \pm 0.03$ MeV

M. Jurić *et al.*, Nucl. Phys. Rev. B 52 (1973) 1

background process giving π^- following K^- absorption on ^{7}Li

$K^- (\mathcal{NN}) \rightarrow \Sigma^- \mathcal{N}$
$\Sigma^- \rightarrow n\pi^-$

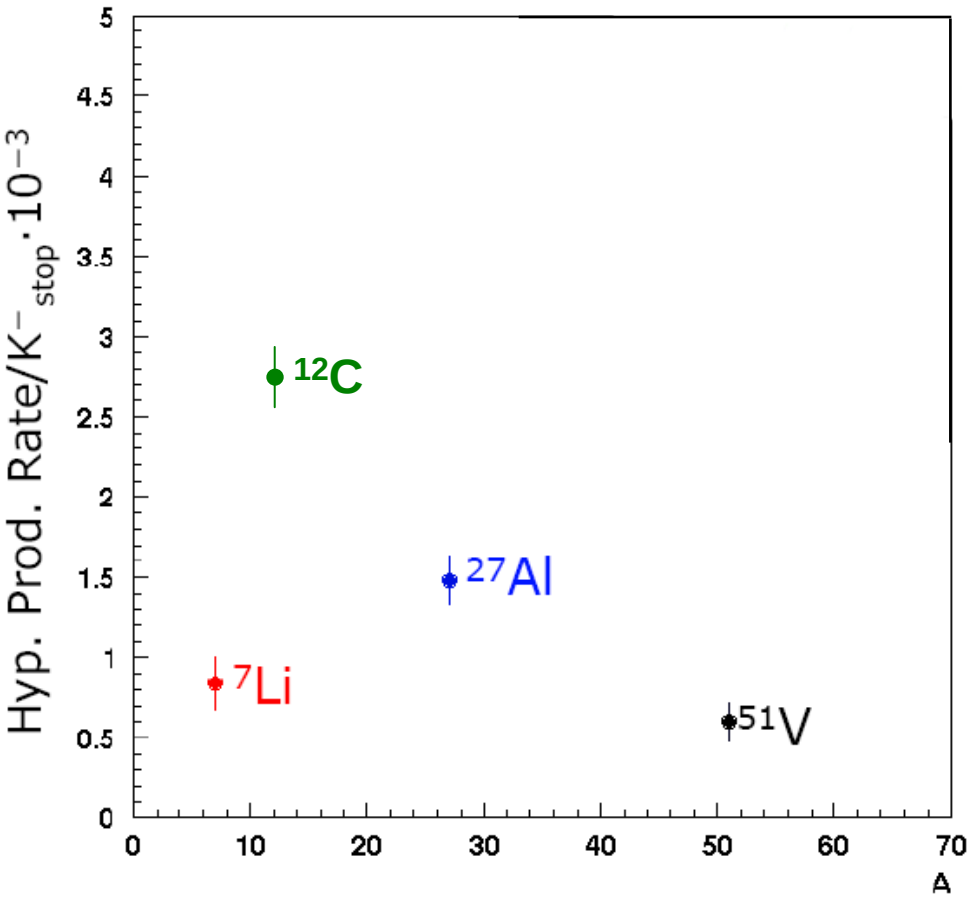
$K^- n \rightarrow \Lambda\pi^-$

$K^- \rightarrow \mu^-\nu_\mu$ in flight

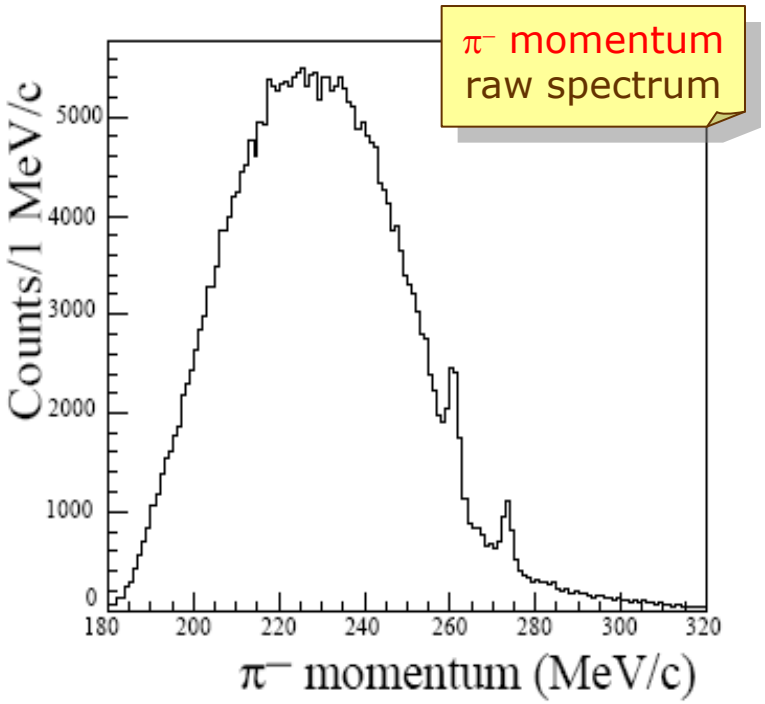
	$-B_\Lambda \pm stat. \pm syst.$ (MeV)	Yield (events)	Production rate (per K^- stop)
1	$-5.33 \pm 0.13 \pm 0.18$	52 ± 11	$0.47 \pm 0.12 \pm 0.11$‰
2	$-3.68 \pm 0.15 \pm 0.18$	44 ± 10	$0.39 \pm 0.11 \pm 0.11$‰

spin-flip amplitude ≈ 0 ⇒ ❶ ≡ 1/2⁺, ❷ ≡ 5/2⁺

Hypernuclear capture rates



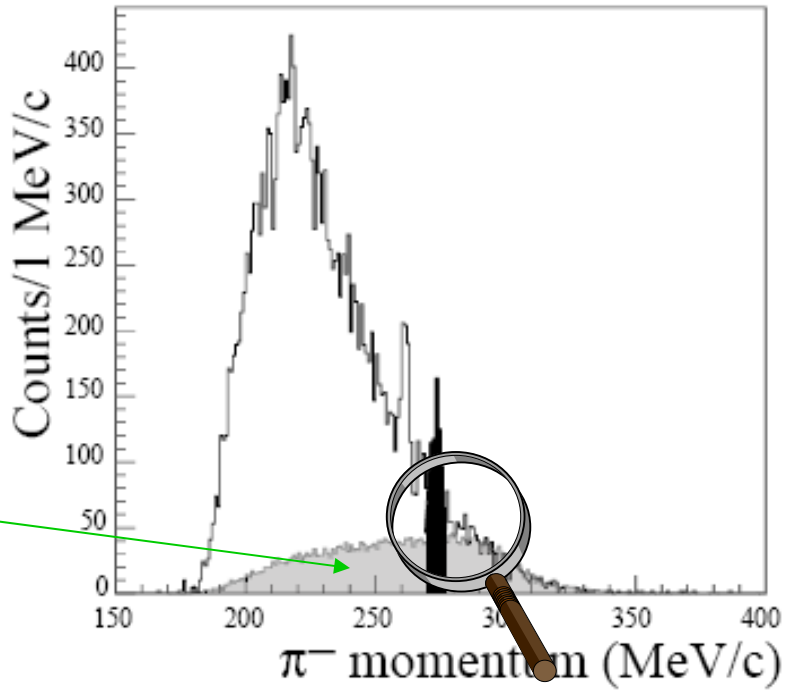
$^{12}C_{\Lambda}$ non-mesonic decay



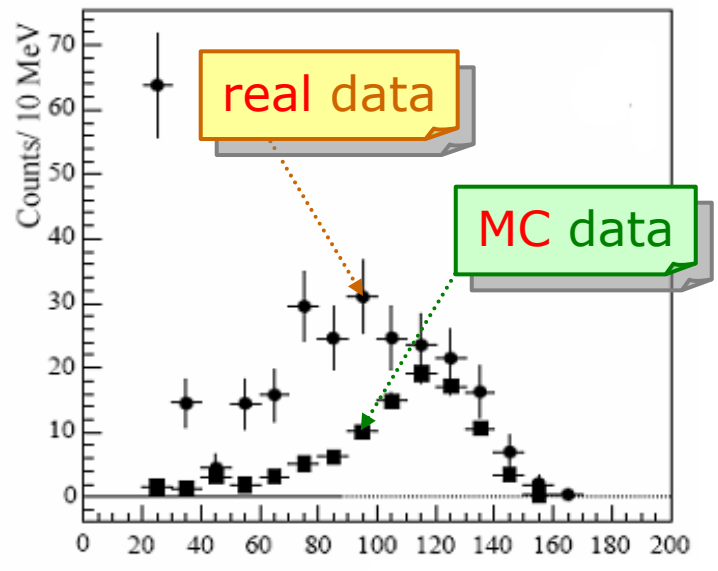
p detected
in coincidence

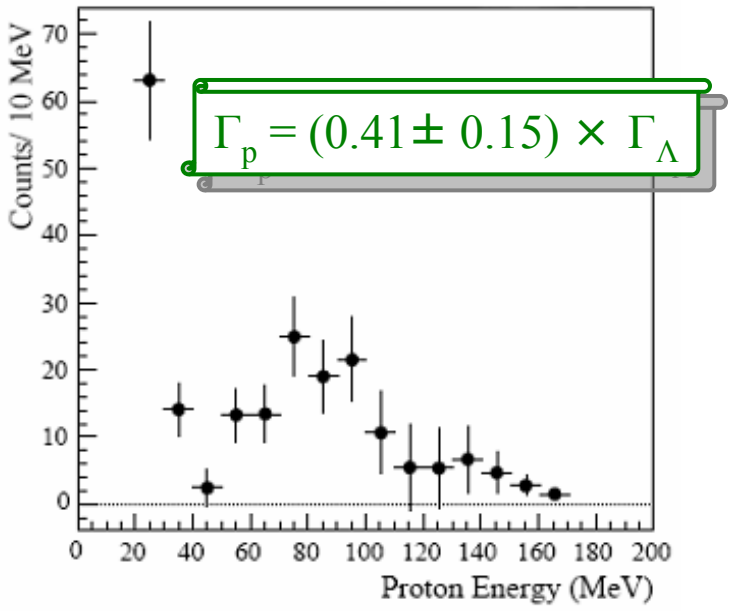
main background:

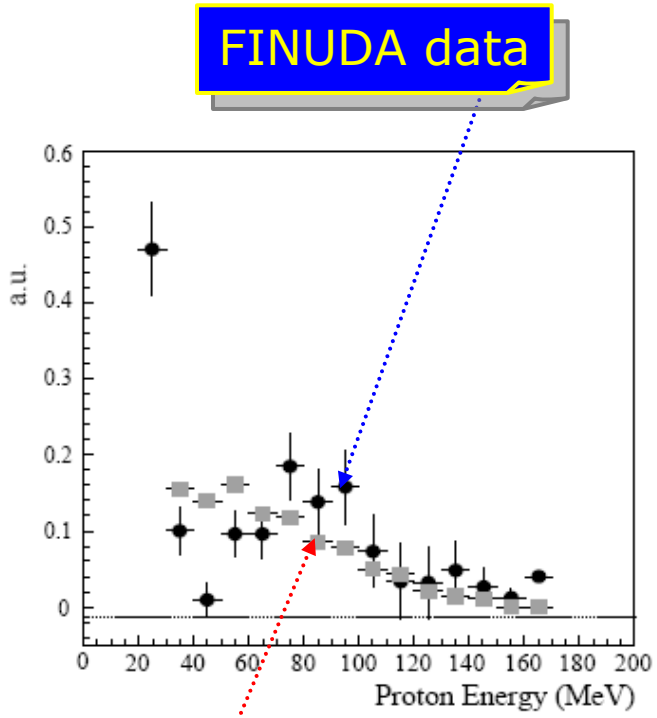
$K^- (np) \rightarrow \Sigma^- p$
$\Sigma^- \rightarrow n\pi^-$



$^{12}C_{\Lambda}$ non-mesonic decay







SKS data

S. Okada et al., Phys. Lett. B 597 (2004) 249

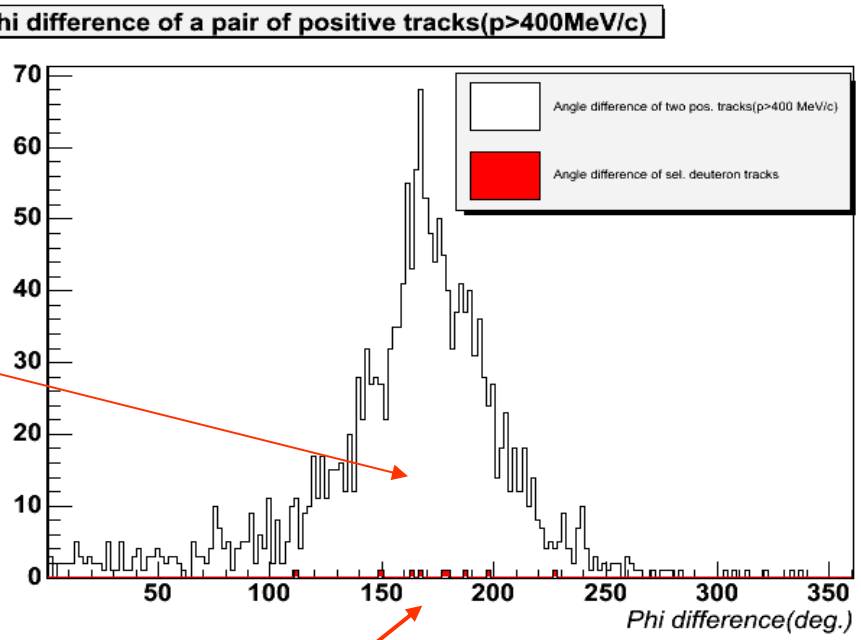
$^4He_\Lambda \rightarrow d + d$ (rare) decay

events with two positive tracks
from ^{6}Li targets
with momentum > 400 MeV/c

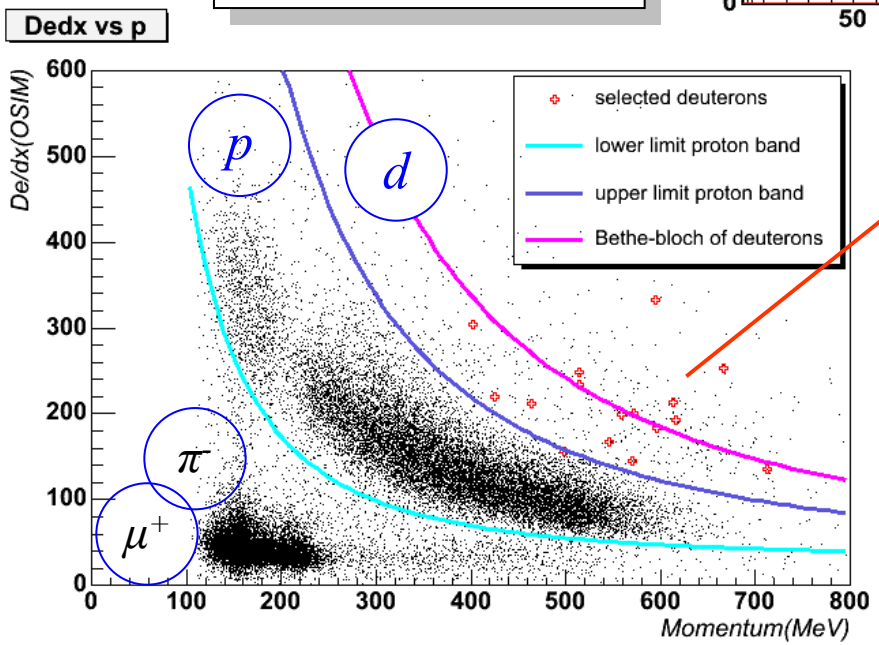
interesting events
to be recognized

$$^4_\Lambda He \rightarrow d + d$$

$$^4_\Lambda He \rightarrow d + p + n$$



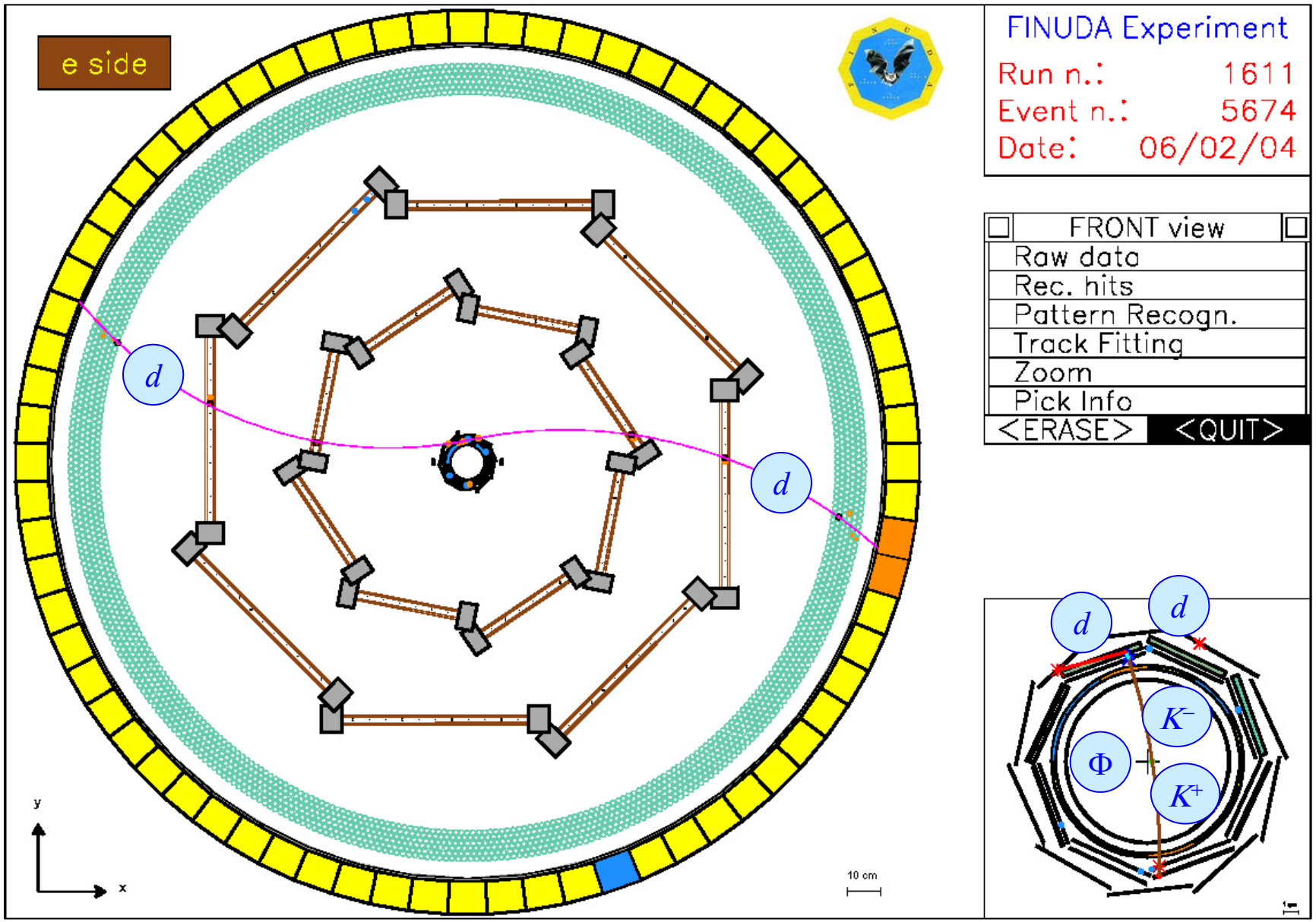
azimuthal angle difference



candidates $^4_\Lambda He \rightarrow d + d$

accurate backtracking and
kinematic analysis needed

$^4He_\Lambda \rightarrow d + d$ (rare) decay



neutron-rich hypernuclei

2 production mechanisms:

1) strangeness + double charge exchange

two step processes!

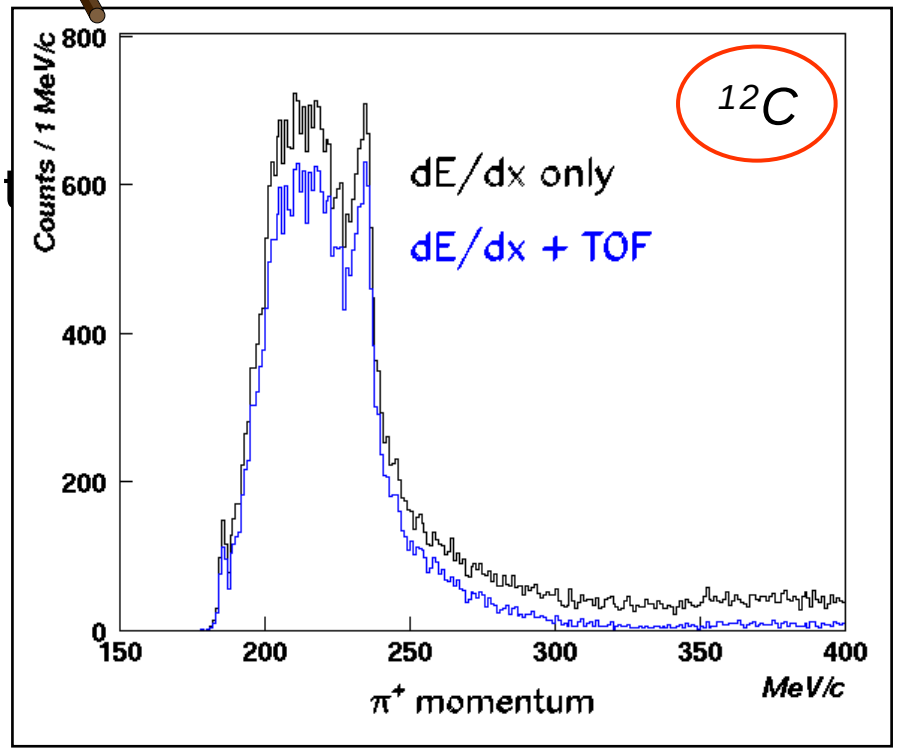
$$K^- + p \rightarrow \Lambda + \pi^0$$
$$\hookrightarrow \pi^0 + p \rightarrow n + \pi^+$$

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

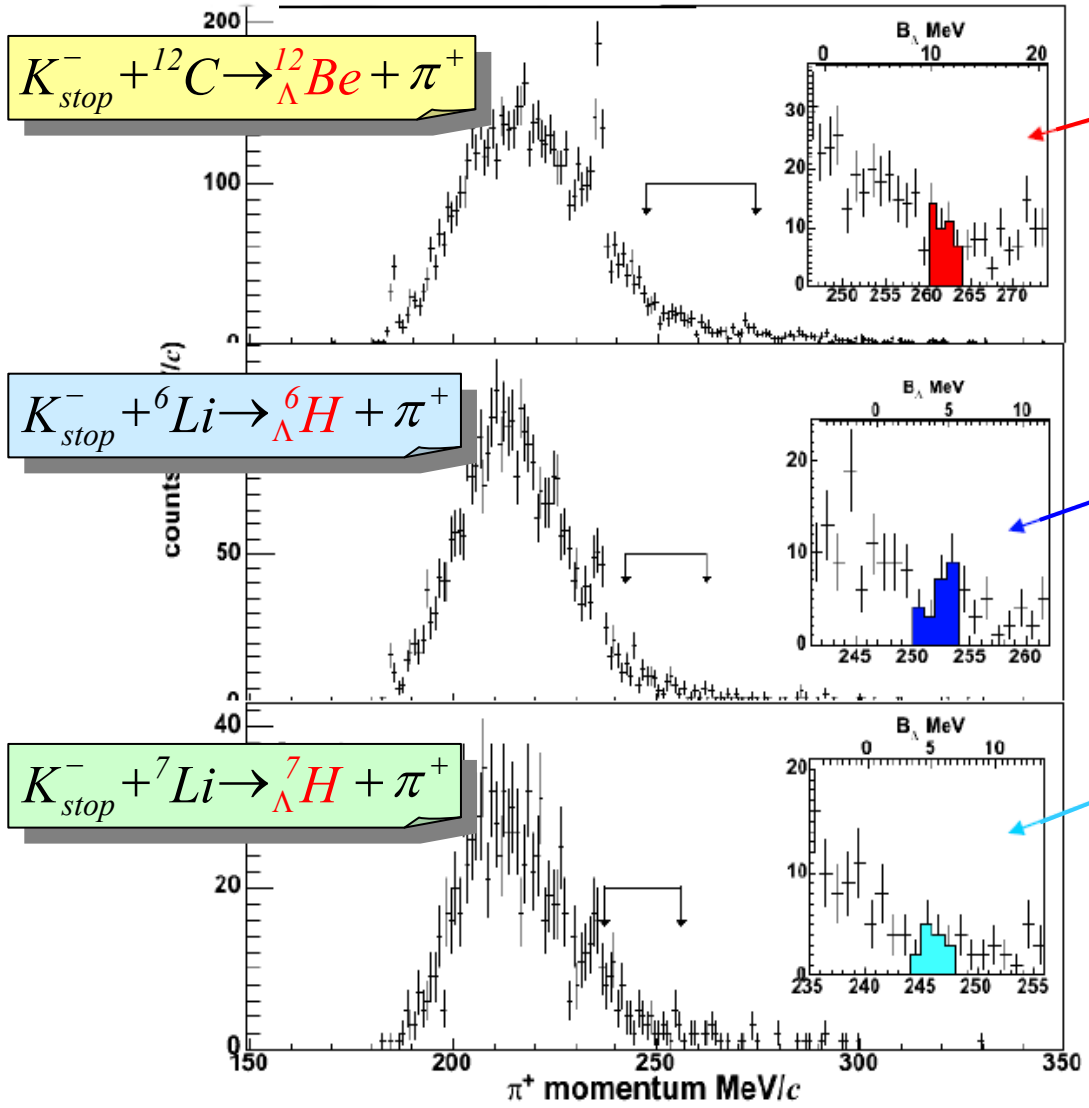
2) strangeness exchange wit
coupling

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

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



FINUDA results on NRH



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

$p_{\pi^+} = 262.9 \text{ MeV}/c \pm 2\sigma_{p_{\pi^+}}$

$< (2.0 \pm 0.4_{stat}\, ^{+0.3}_{-0.1}\, _{syst}) \times 10^{-5}$

$< 6.1 \times 10^{-5}$

M. Kubota *et al.*, Nucl. Phys. A 602 (1996) 327

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

$p_{\pi^+} = 249.1 \text{ MeV}/c \pm 2\sigma_{p_{\pi^+}}$

$< (2.5 \pm 0.4_{stat}\, ^{+0.4}_{-0.1}\, _{syst}) \times 10^{-5}$

$K^-_{stop} + {}^{7}Li \rightarrow {}^{7}_{\Lambda}H + \pi^+$

$p_{\pi^+} = 246.4 \text{ MeV}/c \pm 2\sigma_{p_{\pi^+}}$

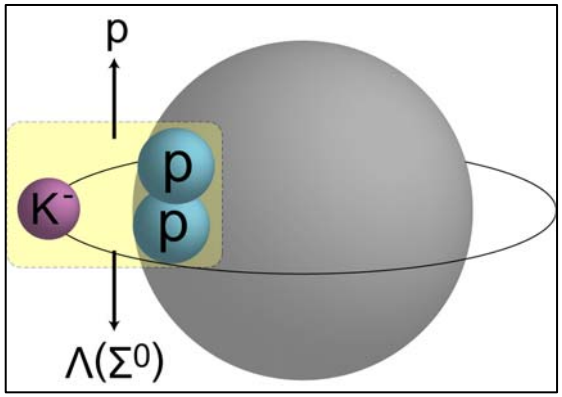
$< (4.5 \pm 0.9_{stat}\, ^{+0.4}_{-0.1}\, _{syst}) \times 10^{-5}$

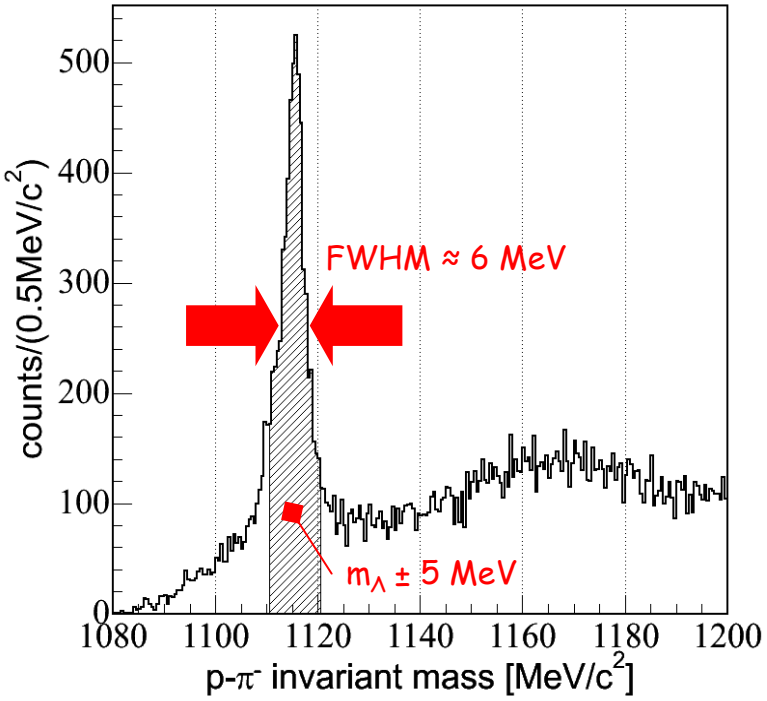
M. Agnello *et al.*, Phys. Lett. B 640 (2006) 145

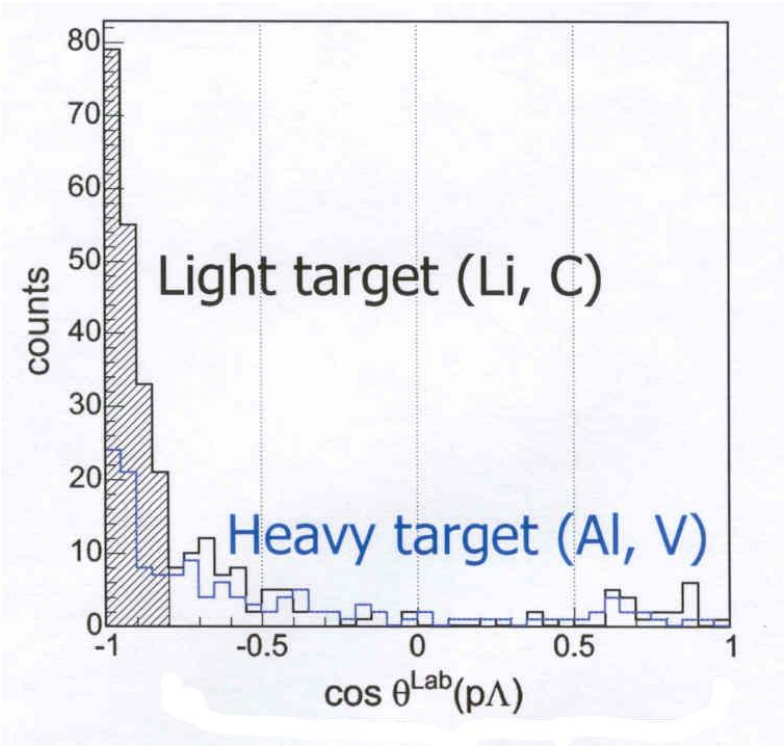
FINUDA search for B=2 kaon-nuclear states

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

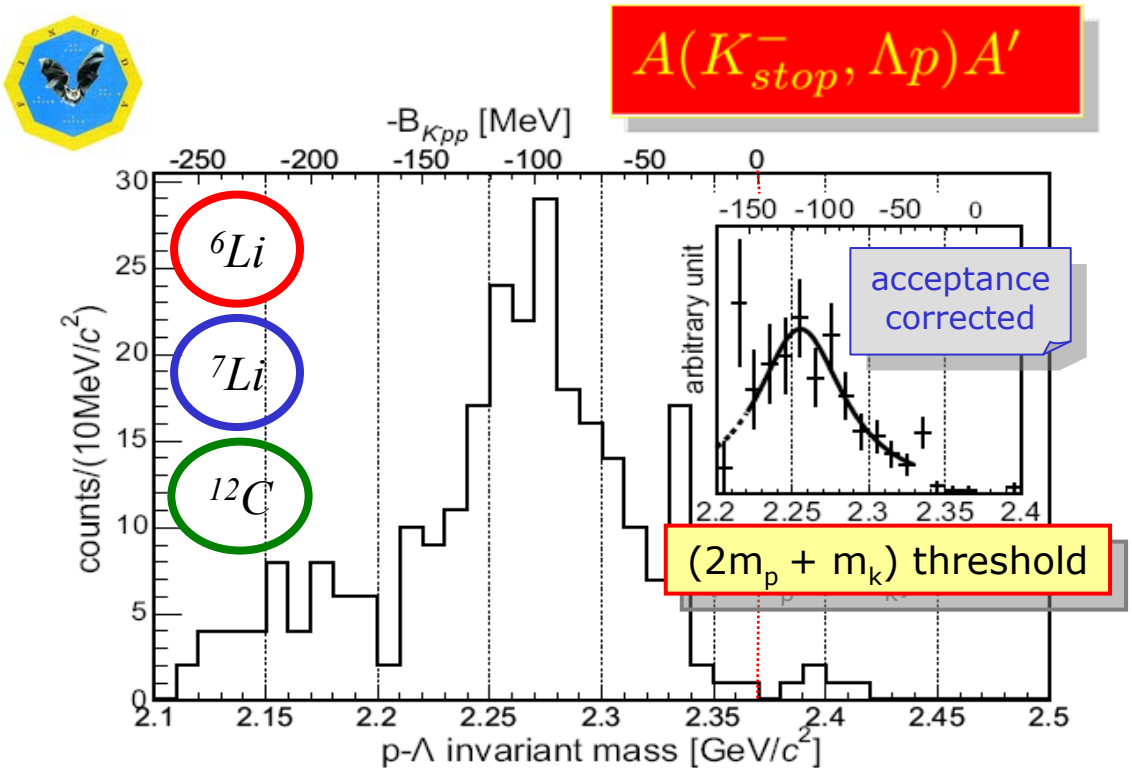
$$K^- pp \rightarrow [K^- pp] \rightarrow \Lambda p$$

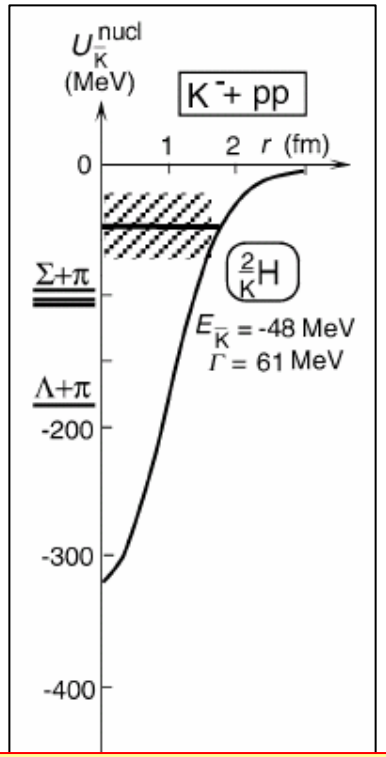






FINUDA search for B=2 kaon-nuclear states





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

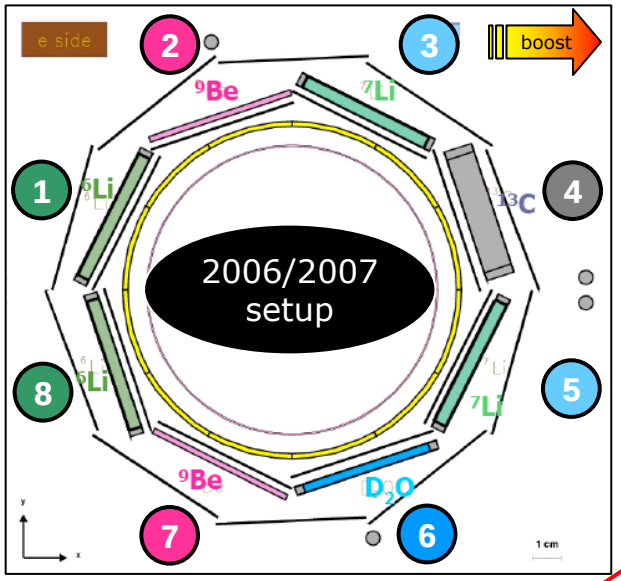
$$\Gamma = 67\,^{+14}_{-11}\,^{+2}_{-3}\ \mathrm{MeV}$$

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

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

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

FINUDA 2nd round



very preliminary

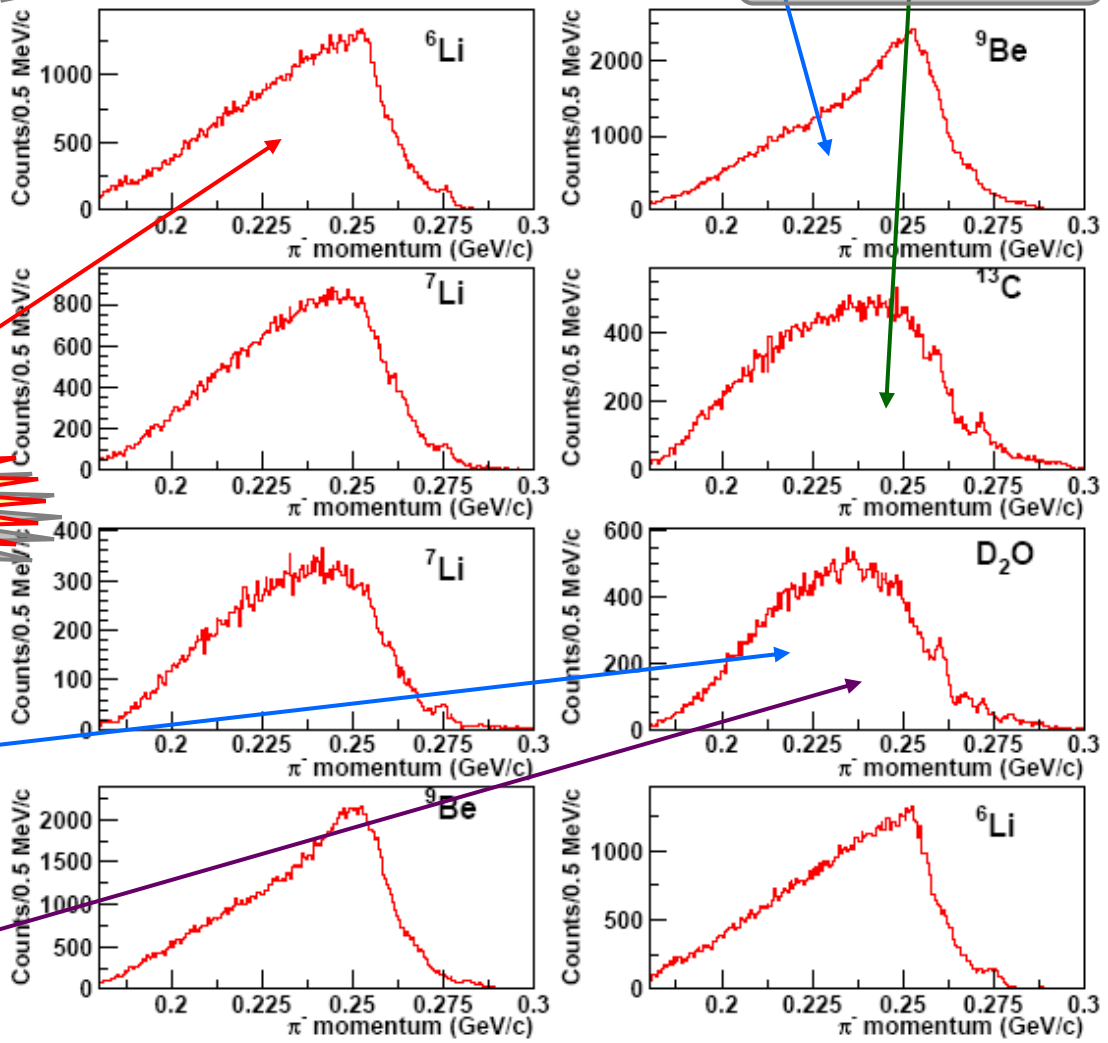
spectroscopy

spectroscopy

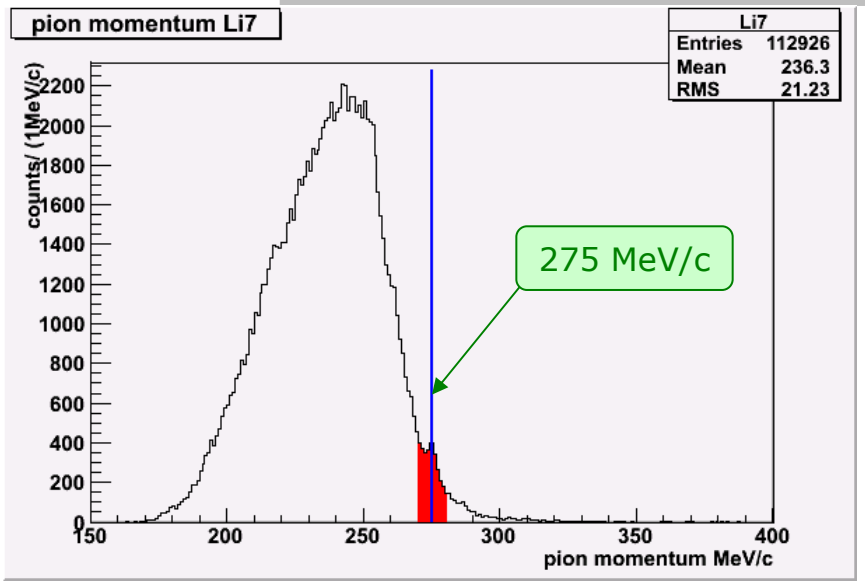
best suited for
$\bar{K}$ nuclear states

O_2
target

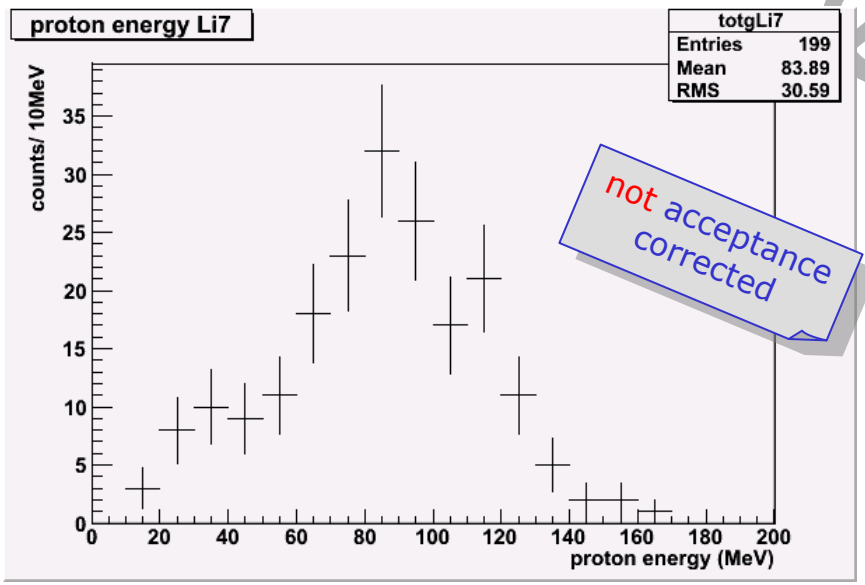
K^+ charge exchange
reaction on D_2

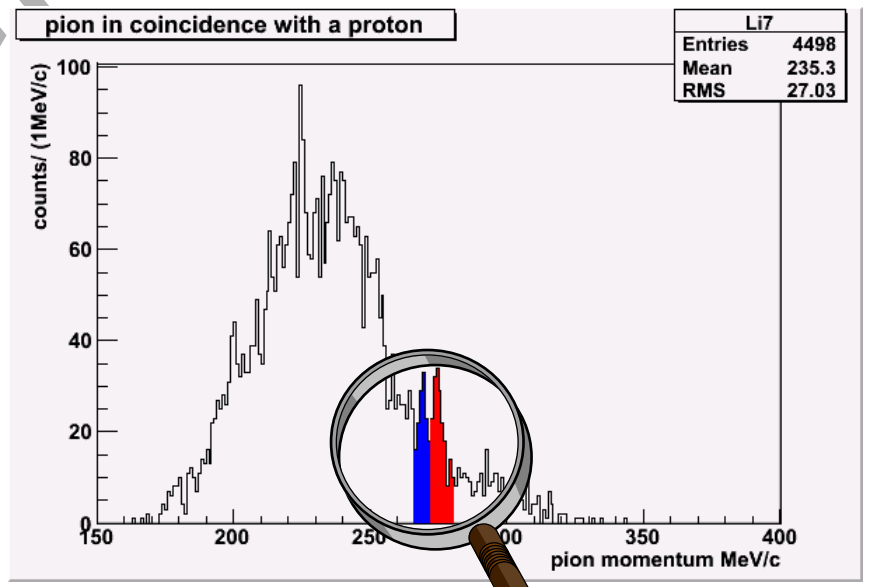


Last FINUDA results on ^{7}Li

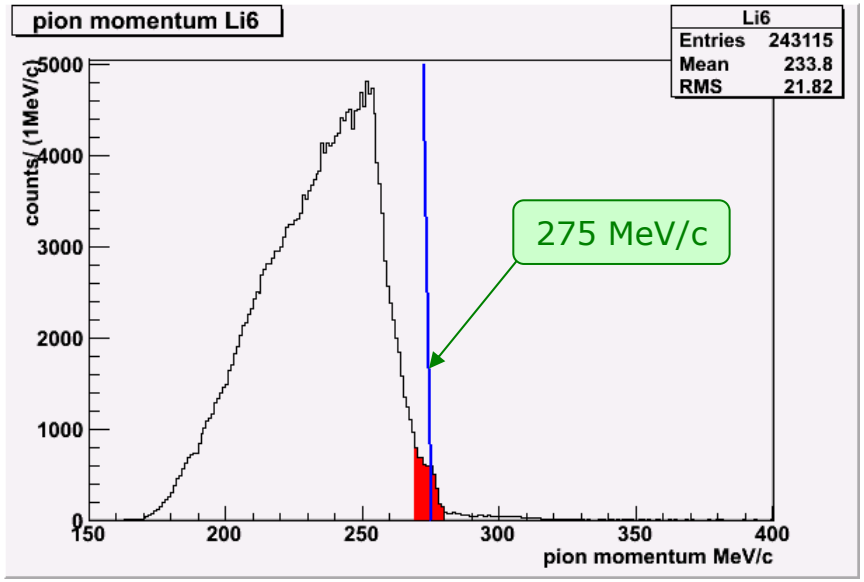


p detected in coincidence

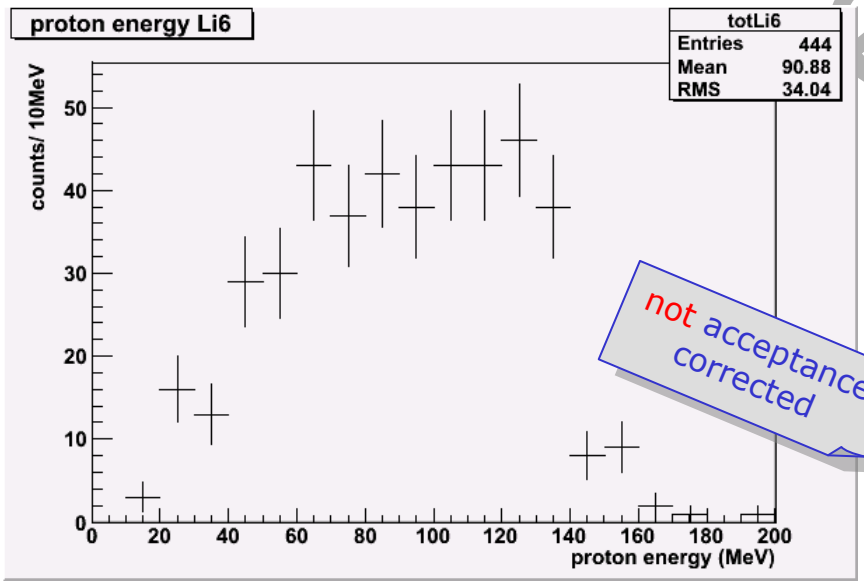


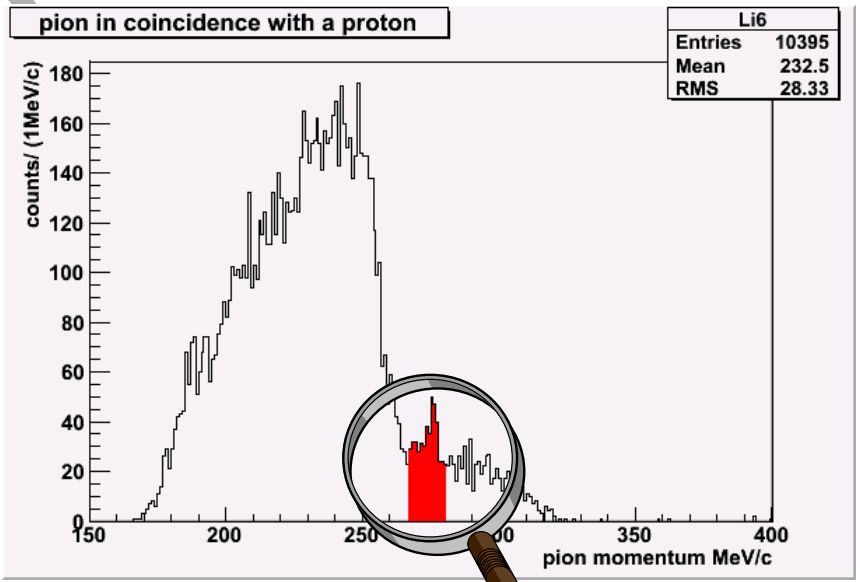


Last FINUDA results on ^{6}Li



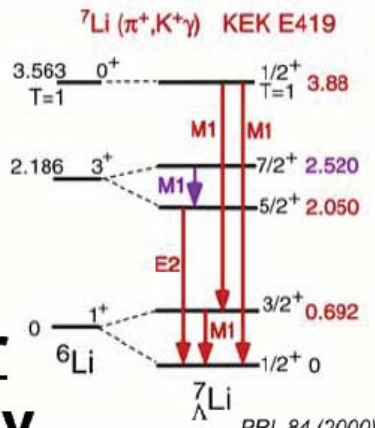
p detected
in coincidence



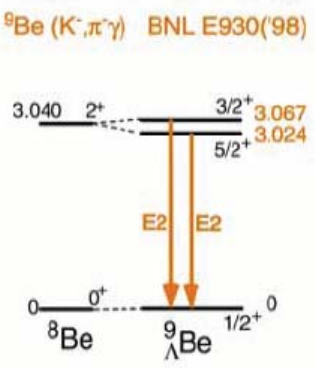


The role of γ–ray spectroscopy

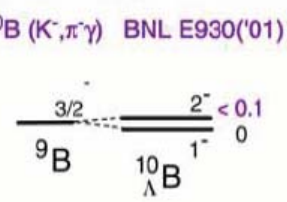
Status of hypernuclear γ spectroscopy



PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501

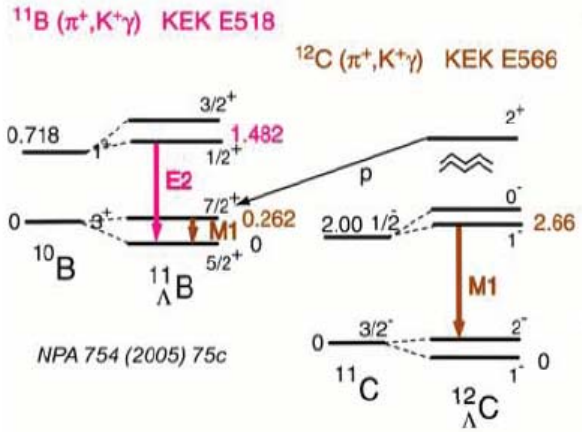


PRL 86 (2002) 082501
NPA 754 (2005) 58c

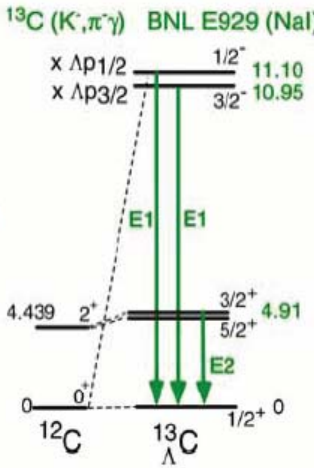


NPA 754 (2005) 58c

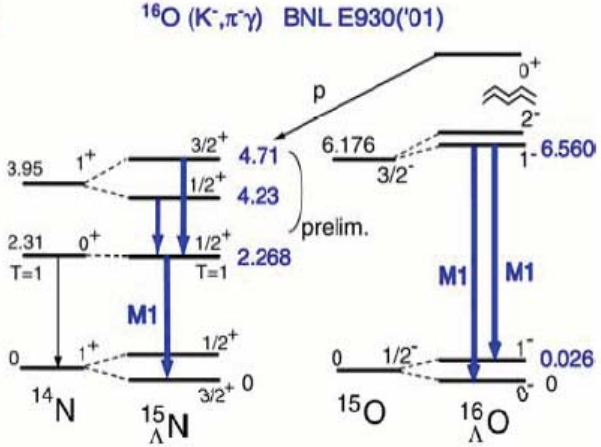
=> "Table of Hyper-Isotopes"



NPA 754 (2005) 75c



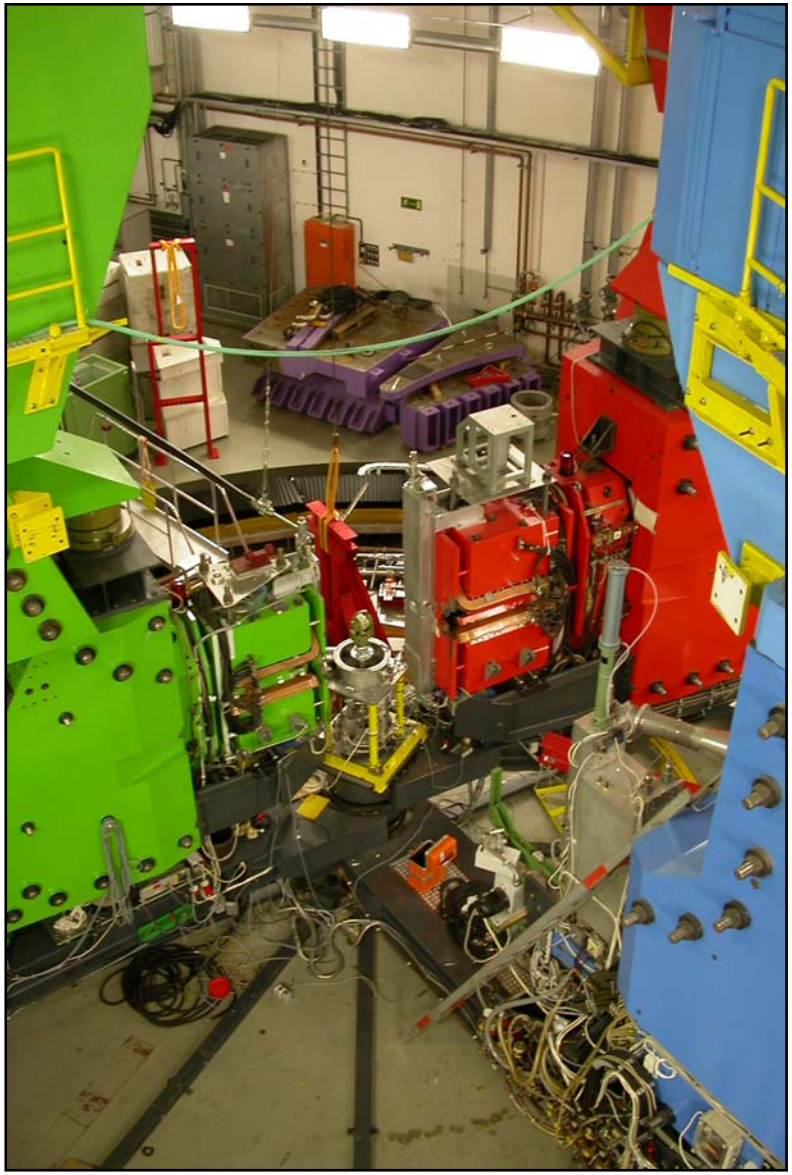
PRL 86 (2001) 4255
PRC 65 (2002) 034607



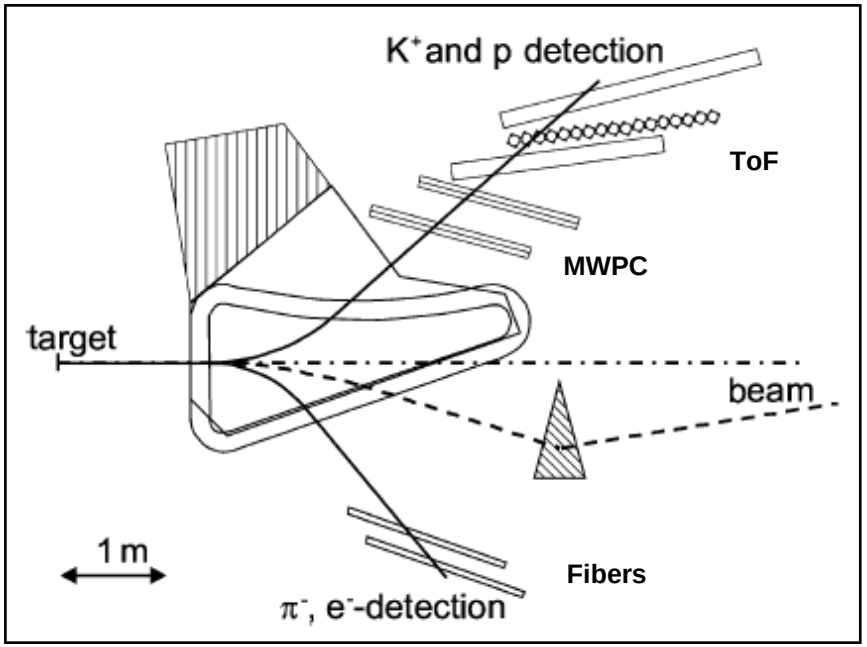
PRL 93 (2004) 232501

H. Tamura

A look to the future

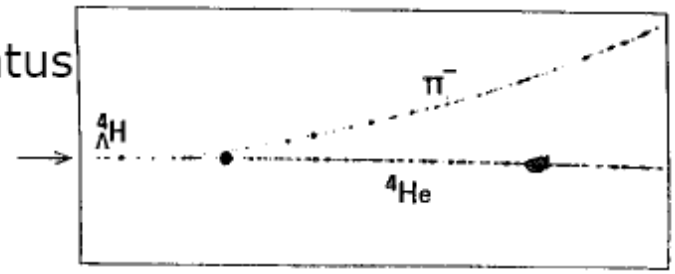


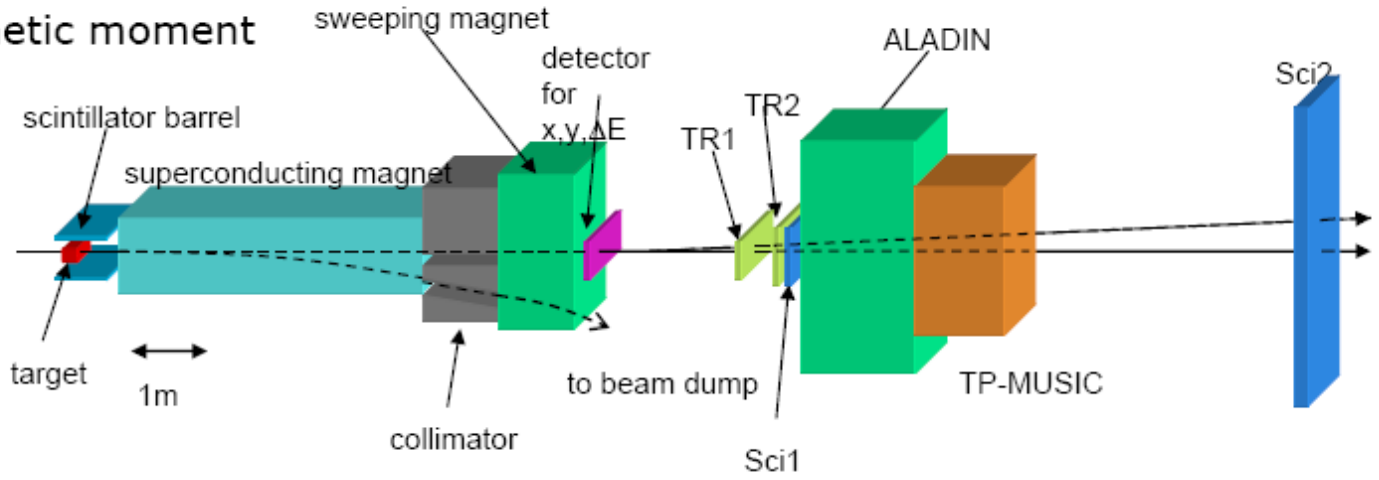
$$e^- + {}^A Z \rightarrow e^{-'} + K^+ + {}^A_\Lambda (Z-1)$$



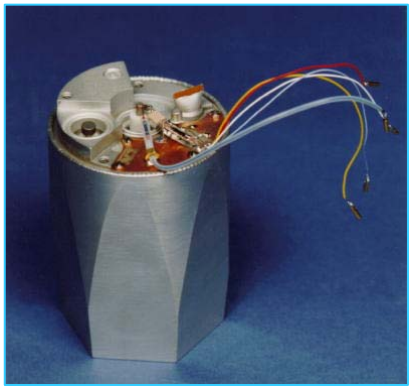
A look to the future

- Hypernuclear Spectroscopy with Stable Heavy-Ion beams and RI-beams at GSI
  - spokesperson: T. Saito
  - GSI PAC in February 2005
  - GSI scientific council in May 2005
- Phase 0: SIS beam and existing apparatus
  ⇒ verification of 1989 Dubna data
- Phase 1: SIS+FRS
  ⇒ proton rich hypernuclei
- Phase 2: FAIR+R3B@NUSTAR
  ⇒ neutron-rich hypernculei
- Phase 3: FAIR+Hypernuclei Separator
  ⇒ magnetic moment

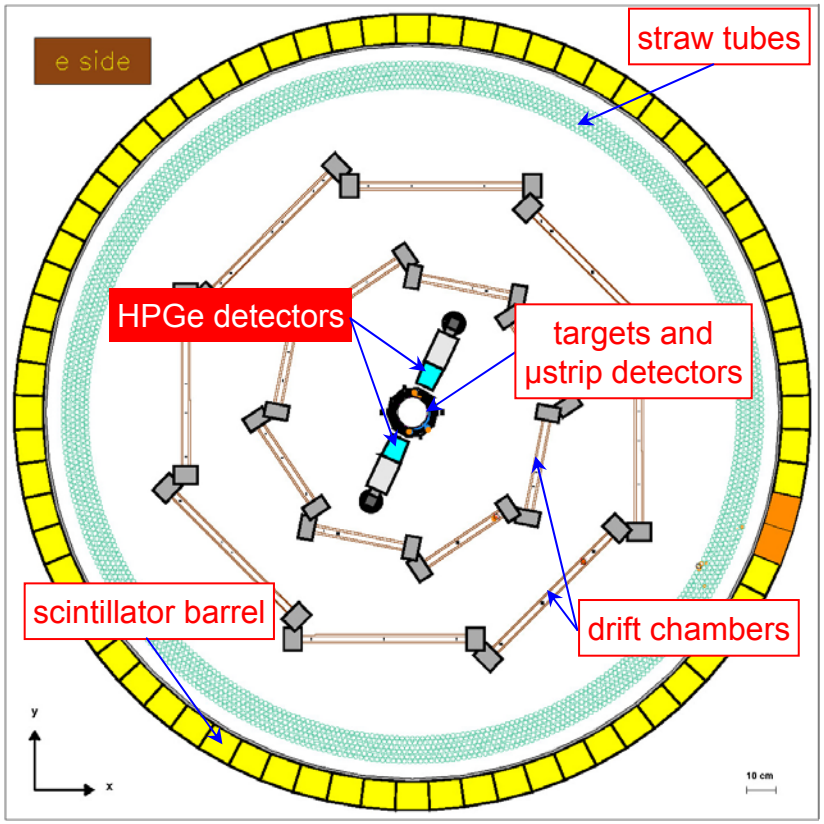


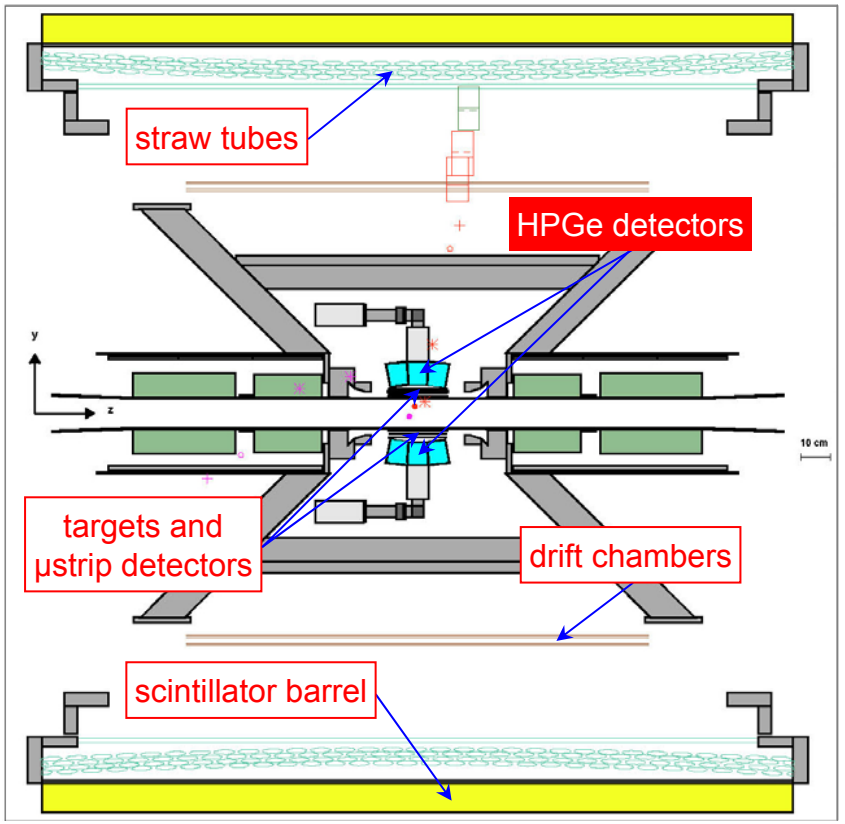


A look to the future

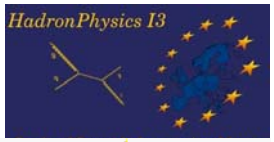


Geometrical acceptance reduced to 82%



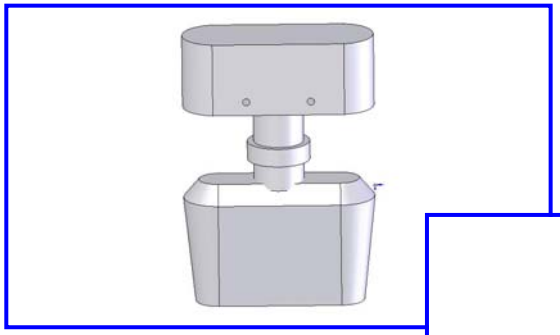


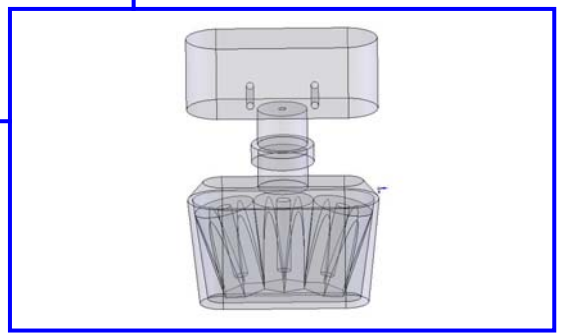
The hyper-triple cluster concept design



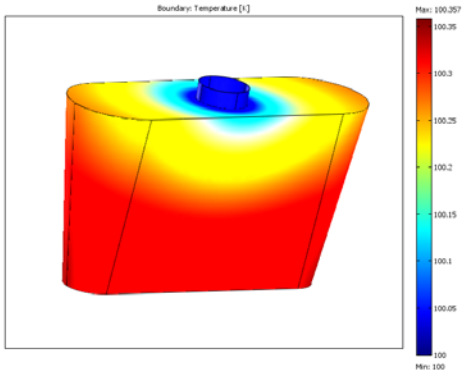
X – COOLER II, AMETEC, ORTEC

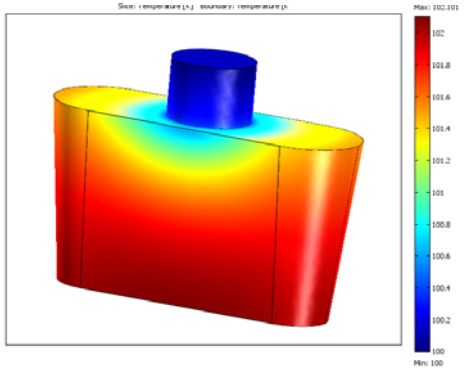
mechanical design





thermal studies

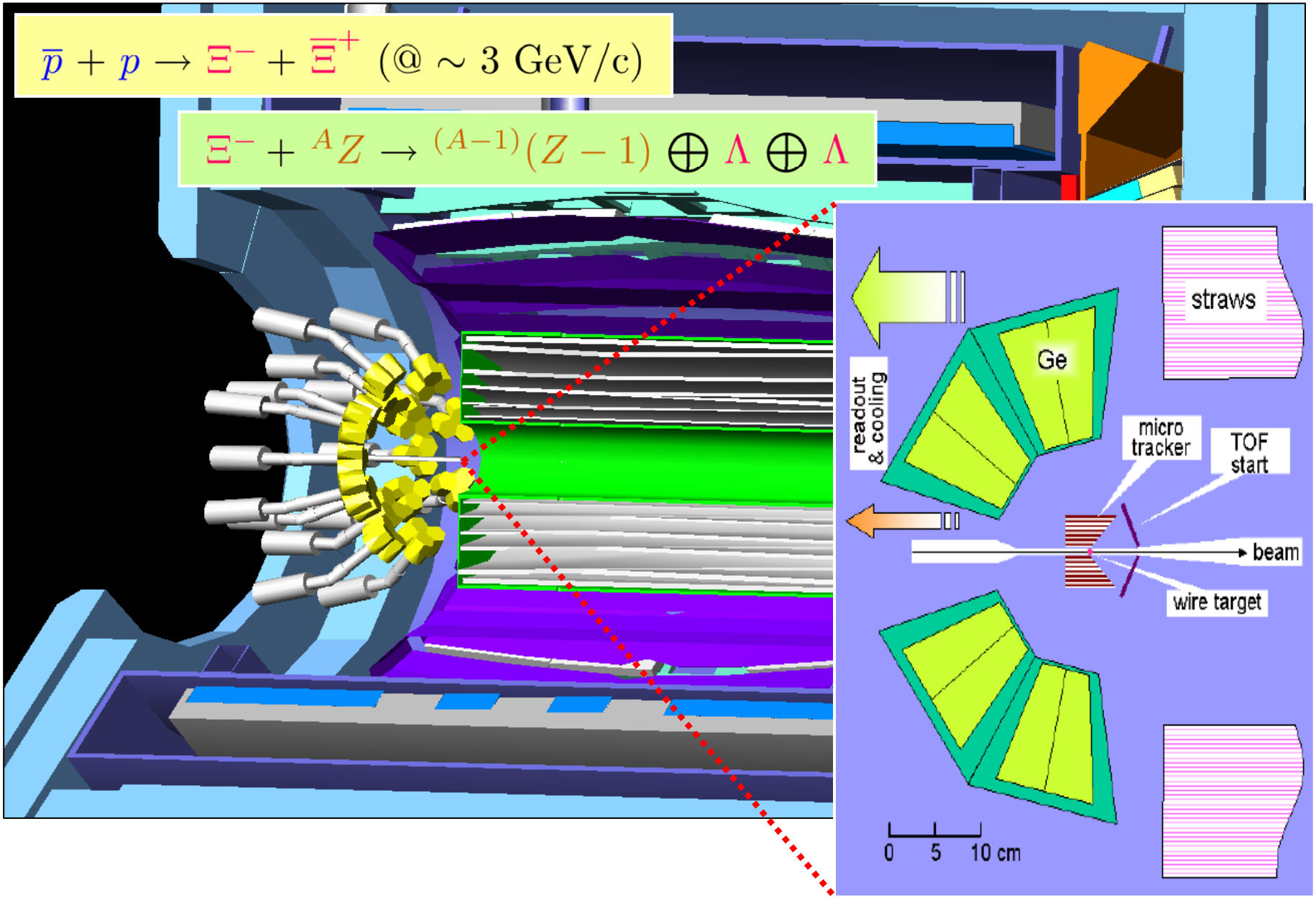




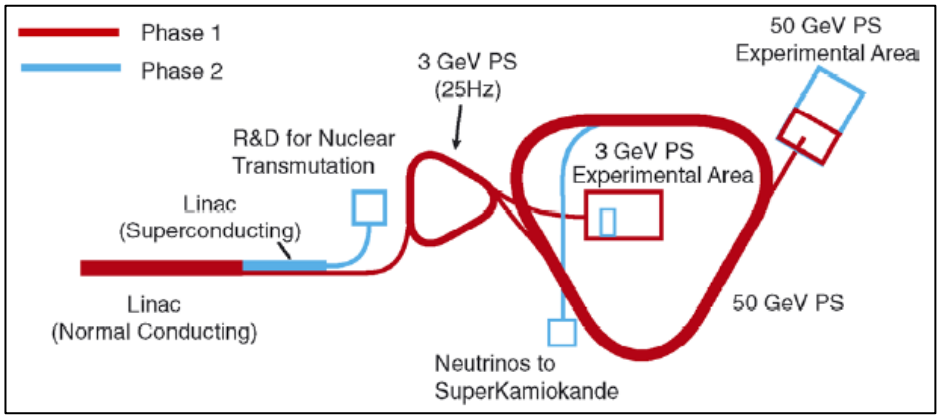
A look to the future

$$\overline{p} + p \rightarrow \Xi^- + \overline{\Xi}^+ \quad (@ \sim 3\ \mathrm{GeV/c})$$

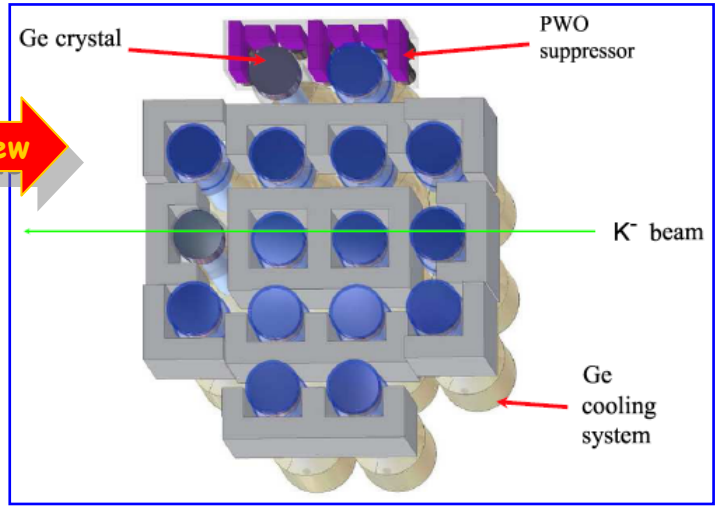
$$\Xi^- + {}^{A}Z \rightarrow {}^{(A-1)}(Z-1) \oplus \Lambda \oplus \Lambda$$

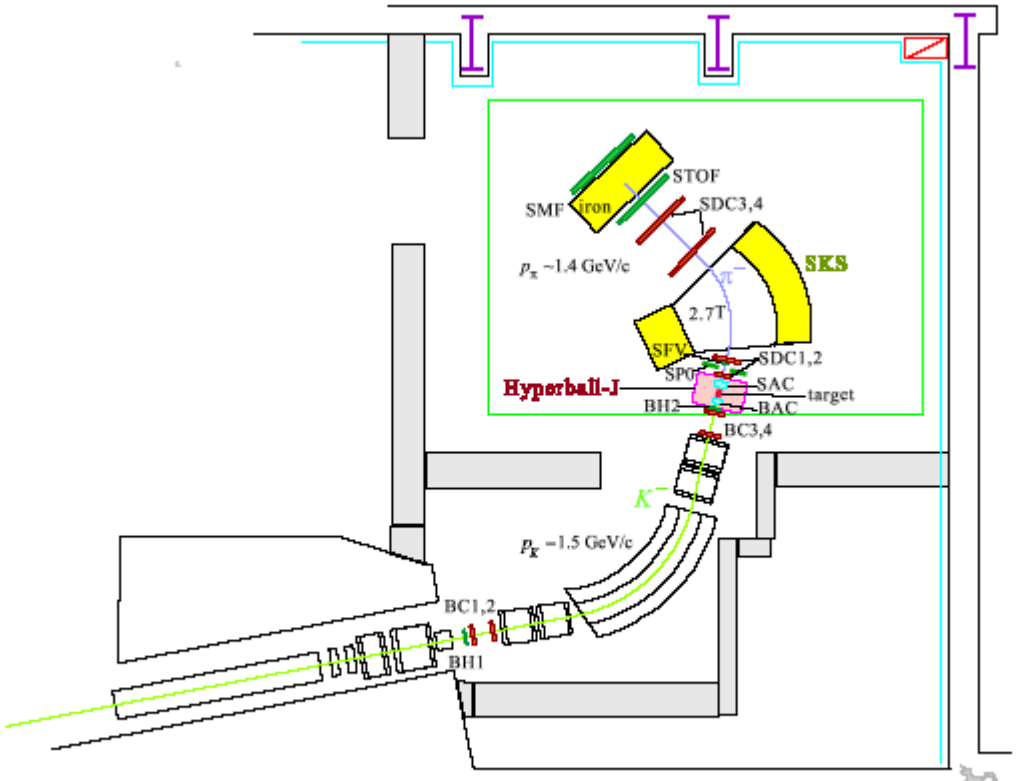


A look to the future

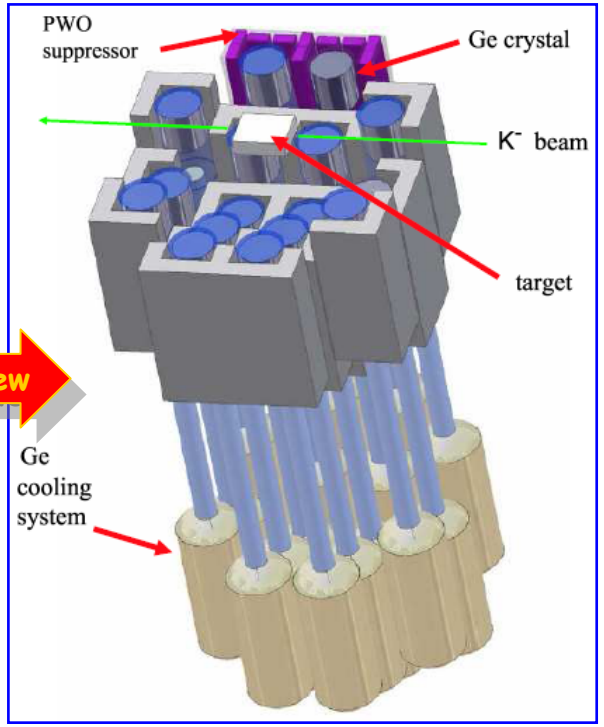


top view





side view



Summary

- ☑ The fifty-year-old field of strangeness nuclear physics is still alive and has a great discovery potential
  - number of exp. physicist involved is growing
  - significant theoretical effort, well tuned on exp. data
  - dedicated beams and apparatus
  - main item in several future physics program at new facilities