

# *First round results from the FINUDA experiment*

**HypHI 05**  
**International Workshop**  
**"Hypernuclei with Heavy Ion Beams"**  
20 - 21 June 2005, GSI, Darmstadt, Germany  
<http://www.gsi.de/forschung/ko/kp2/experiments/HYPERNuclei/hypHI05.htm>

**Topics**

- Hypernuclear spectroscopy with heavy ions beams
- Hypernuclear magnetic moments
- Neutron and proton rich hypernuclei
- Multi-strangeness
- Progress in hypernuclear physics

**Invited Speakers**

P. Achenbach (Mainz Univ.)  
Y. Akaishi (Nihon Univ.)  
S. Batsouli (ORNL)  
A. Feliciello (Turin)  
N. Herrmann (Heidelberg Univ.)  
E. Hiyama (Nara Women's Univ.)  
D. Lansky (Moscow State Univ.)  
H. Lenske (Giessen Univ.)  
J. Lukstins (JINR)  
T. Motoba (Osaka El.-Com. Univ.) \*  
H. Ota (RIKEN)  
J. Pochodzalla (Mainz Univ.)  
T. R. Saito (GSI)  
J. Schaffner-Bielich (Frankfurt Univ.)  
P. Senger (GSI)  
H. Tamura (Tohoku Univ.)  
I. Tanihata (Argonne) \*  
\* to be confirmed

**Organizing Committee**

A. Banu (Mainz/GSI)  
J. Geri (GSI)  
M. Kavatsyuk (Kiev/GSI)  
O. Kavatsyuk (Kiev/GSI)  
N. Saito (GSI)  
T. R. Saito (Chair, GSI)  
A. Sanchez-Lorente (Mainz/GSI)  
C. Sienti (GSI)  
W. Traubmann (GSI)

**Secretaries**

T. Litvinova (GSI)  
M. Nasonava (GSI)  
S. Raß (GSI)

e-mail: [t.saito@gsi.de](mailto:t.saito@gsi.de)  
Sponsored by 



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



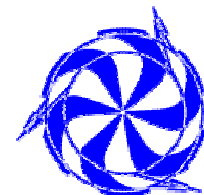
# Outline

- 1) the **FINUDA** experiment
  - the **physics** program
  - the **apparatus**
  
- 2) the **results**
  - hypernuclear **spectroscopy**
  - deeply-bound **kaonic state** ( $K$ - $pp$ )
  - **neutron-rich** hypernuclei
  - hypernucleus (rare) **decays**
  
- 3) **future** plans



# The FINUDA Collaboration

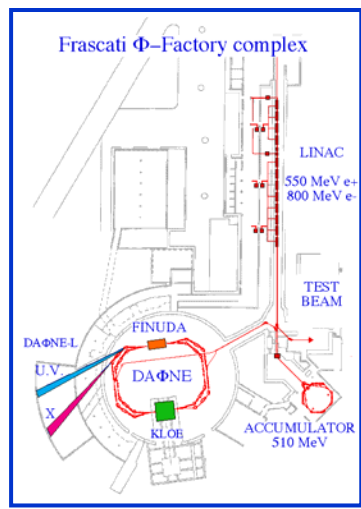
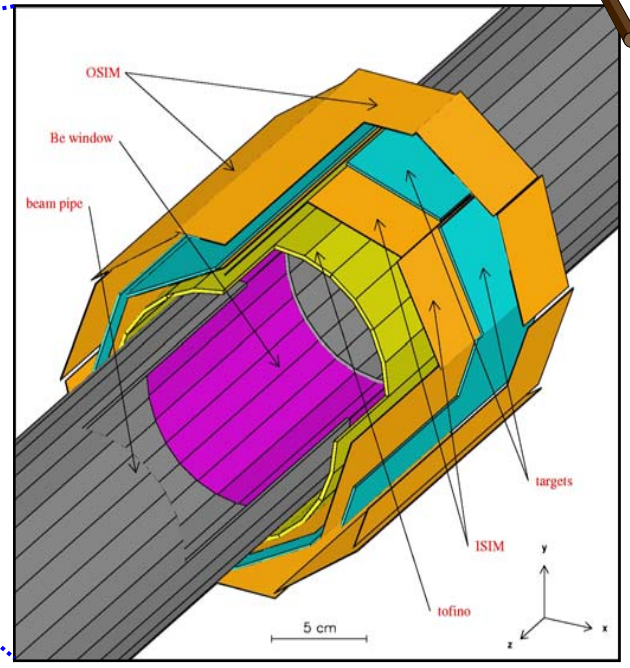
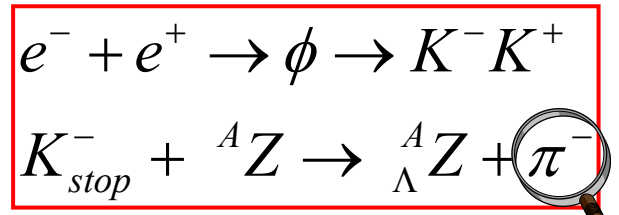
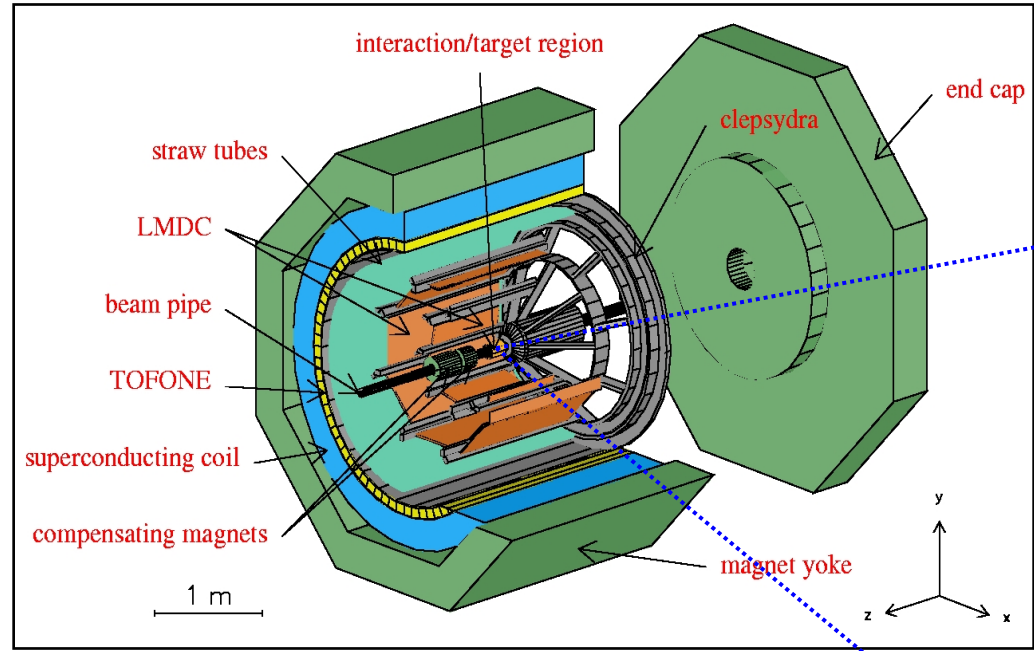
-  Bari University and I.N.F.N. Bari
-  Brescia University and I.N.F.N. Pavia
-  KEK
-  L.N.F. / I.N.F.N. Frascati
-  Pavia University and I.N.F.N. Pavia
-  RIKEN
-  Seoul National University
-  Teheran Shahid Beheshti University
-  Torino University and I.N.F.N. Torino
-  Torino Polytechnic and I.N.F.N.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



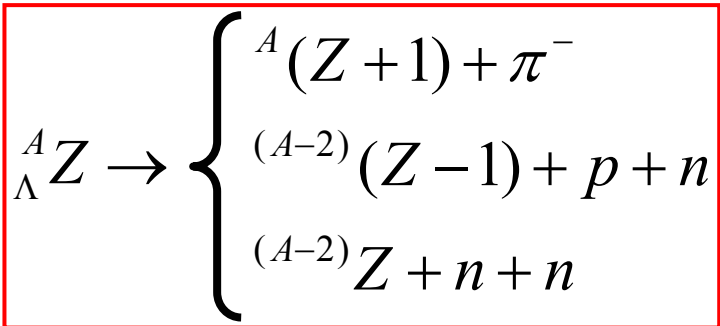


# FINUDA @ DAΦNE

A. Feliciello / International Workshop on Hypernuclei with Heavy Ion Beams – Darmstadt, Germany, June 20 – 21, 2005



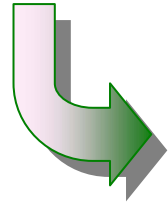
energy	510 MeV
luminosity	$5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
$\sigma_x$ (rms)	2.11 mm
$\sigma_y$ (rms)	0.021 mm
$\sigma_z$ (rms)	35 mm
bunch length	30 mm
crossing angle	12.5 mrad
frequency (max)	368.25 MHz
bunch/ring	up to 120
part./bunch	$8.9 \cdot 10^{10}$
current/ring	5.2 A (max)





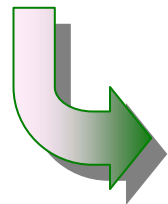
# FINUDA key features

- 👉 very thin nuclear targets ( $0.1 \div 0.3 \text{ g/cm}^2$ )



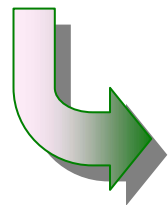
high resolution spectroscopy

- 👉 coincidence measurement with large acceptance



decay mode study

- 👉 irradiation of different targets in the same run

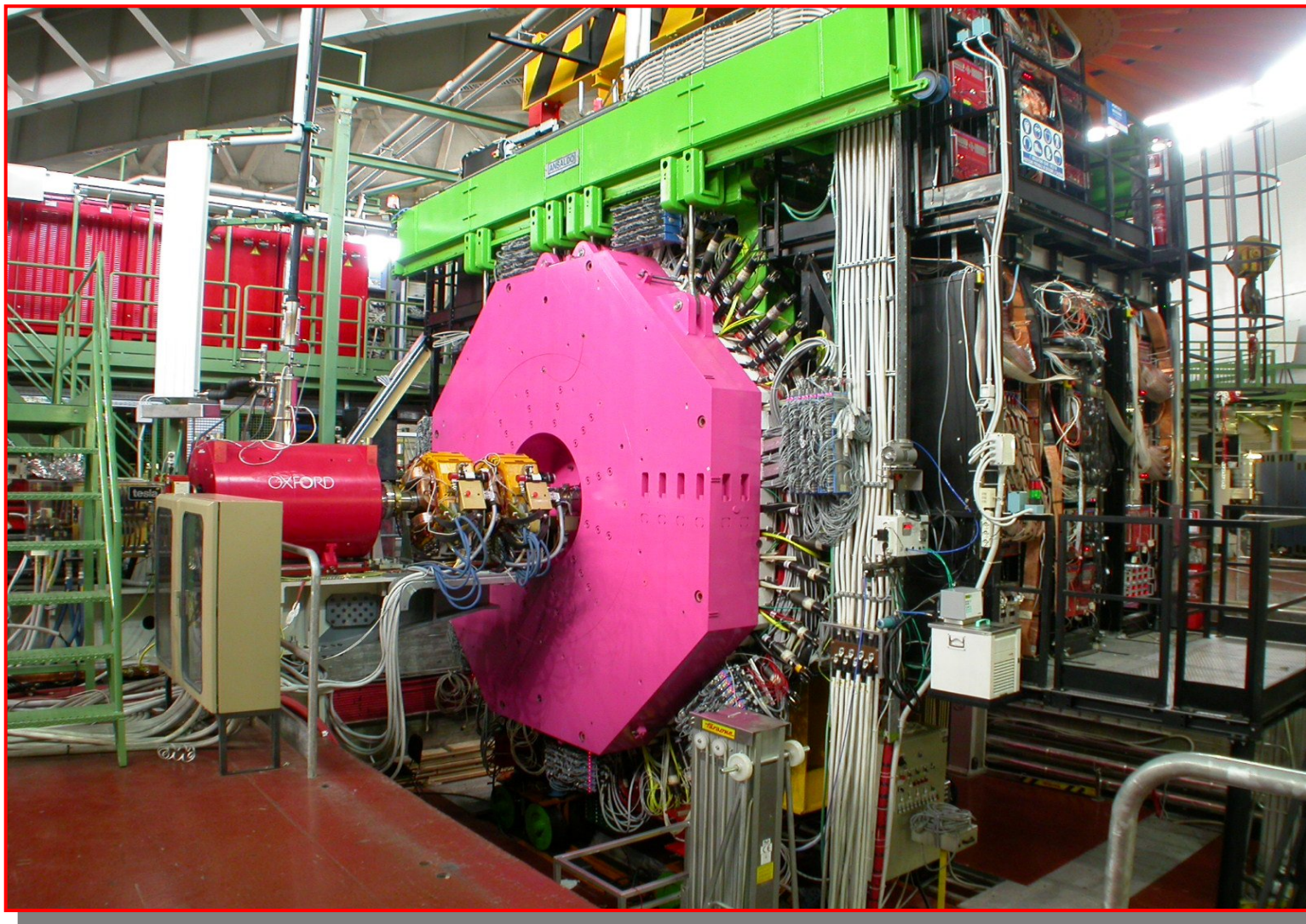


systematic error reduction



# FINUDA @ DAΦNE

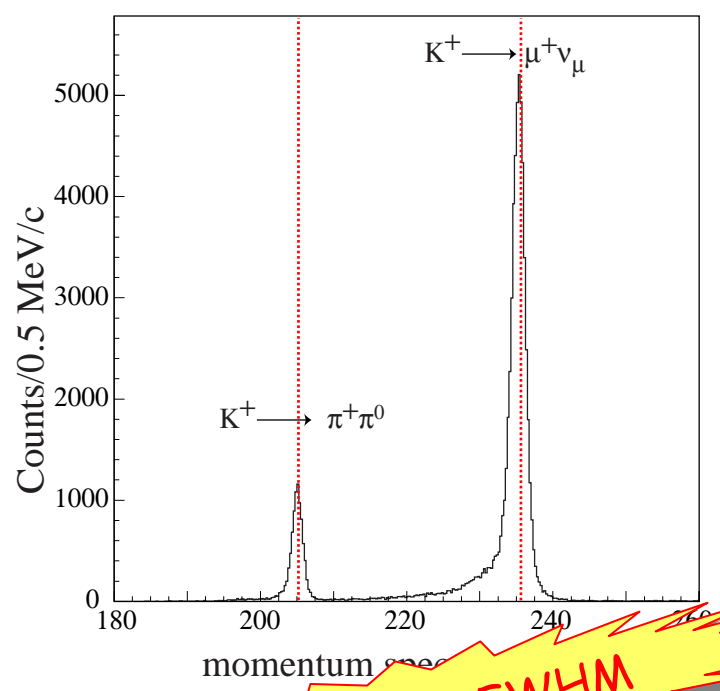
A. Feliciello / International Workshop on Hypernuclei with Heavy Ion Beams – Darmstadt, Germany, June 20 – 21, 2005





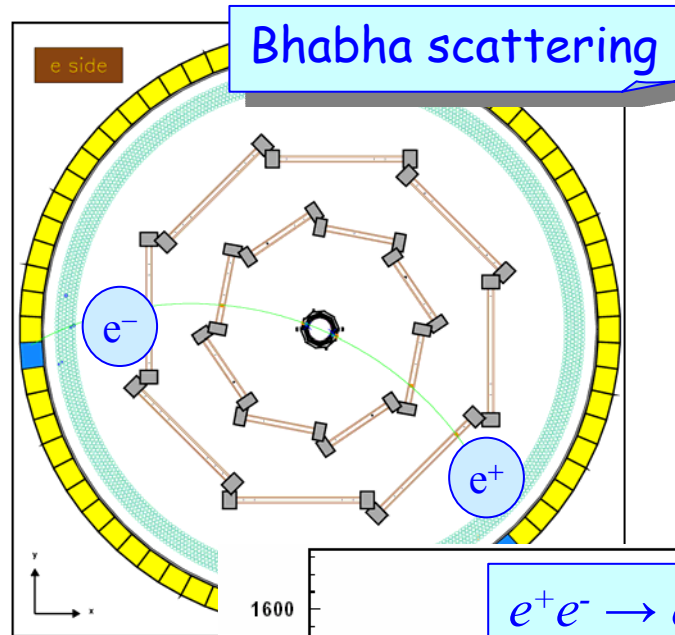
# Momentum and beam energy calibration

$K^+$  two body decays:  
**benchmark** for  
spectrometer calibration



$\Delta p/p \sim 0.6\% \text{ FWHM}$

$\Delta T_\pi = \Delta M_H \approx 1.25 \text{ MeV FWHM}$

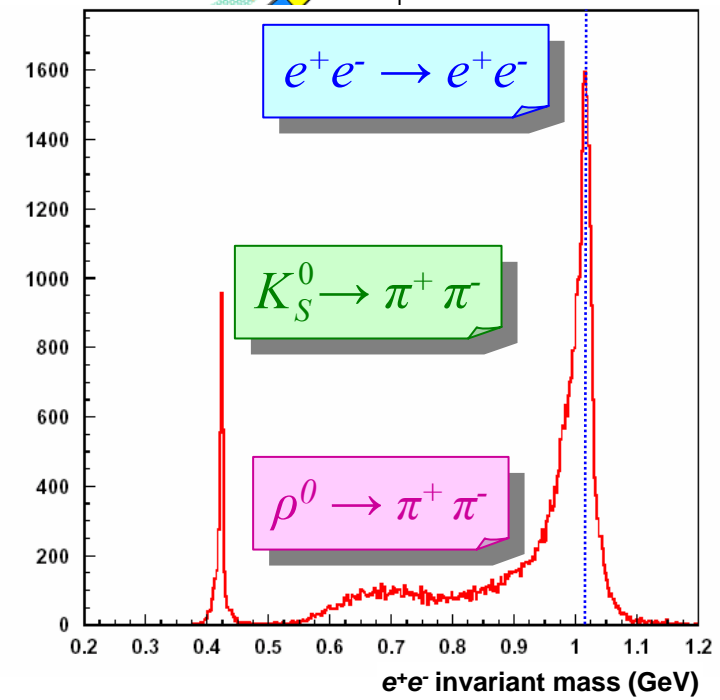


Bhabha scattering

$e^+e^- \rightarrow e^+e^-$

$K_S^0 \rightarrow \pi^+\pi^-$

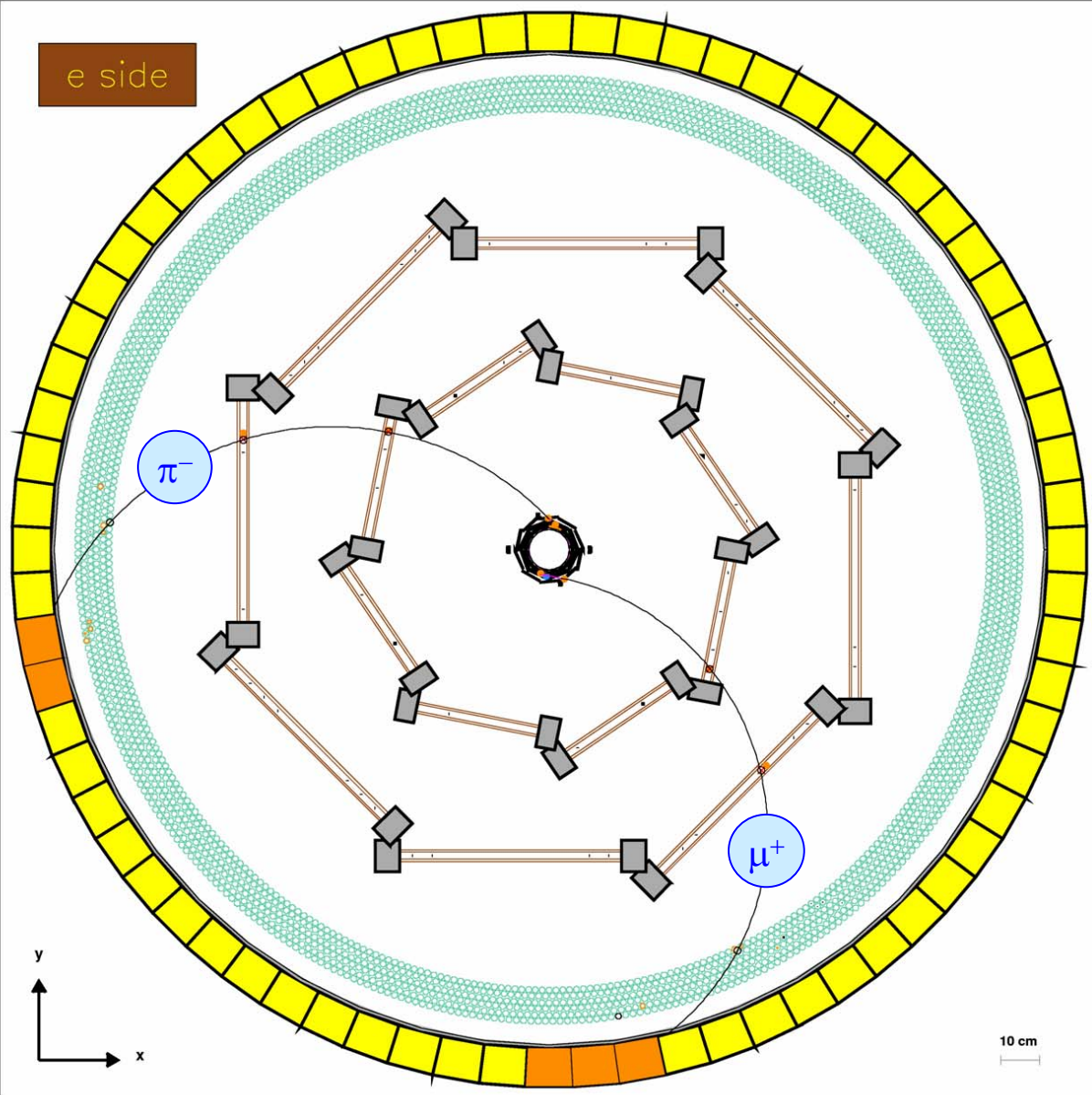
$\rho^0 \rightarrow \pi^+\pi^-$





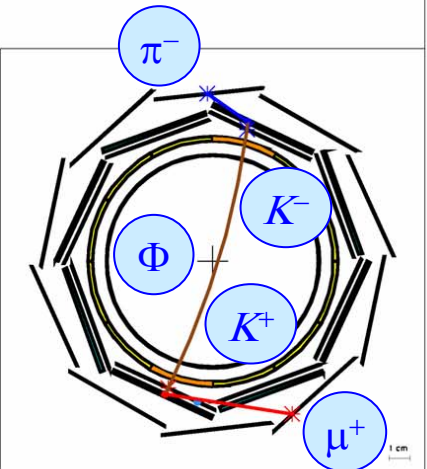
# The typical event

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FINUDA Experiment  
Run n.: 708  
Event n.: 4302  
Date: 09/12/03

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Rec. hits		
Pattern Recogn.		
Track Fitting		
Zoom		
Pick Info		
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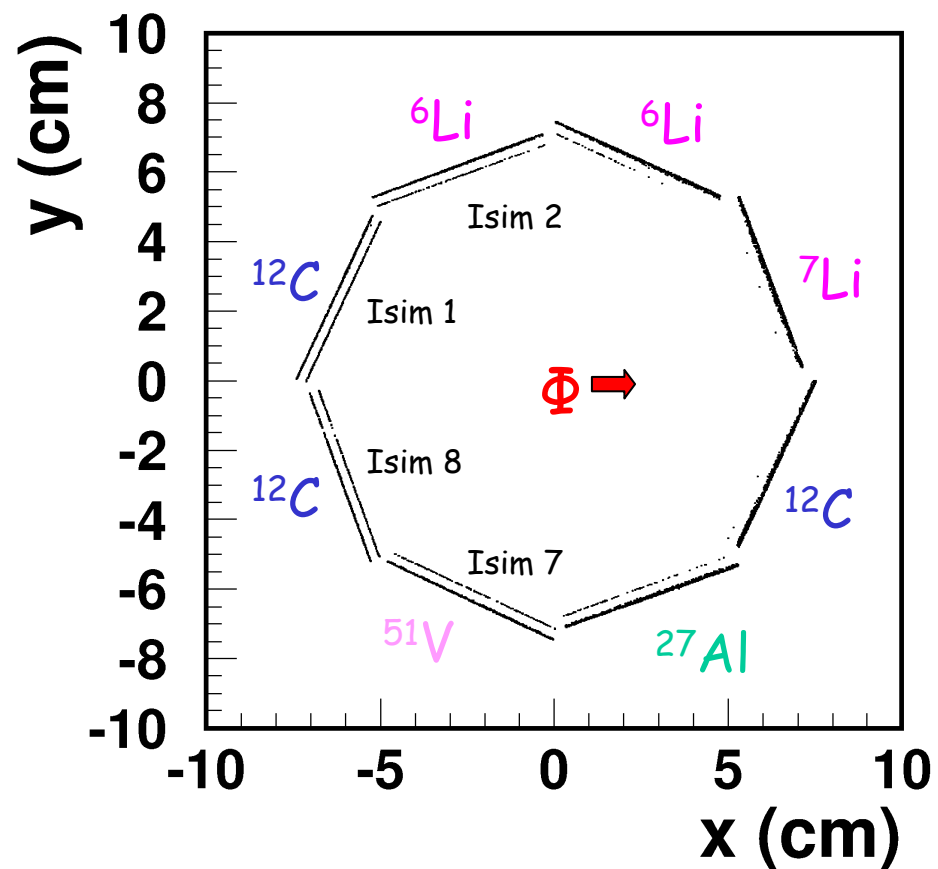
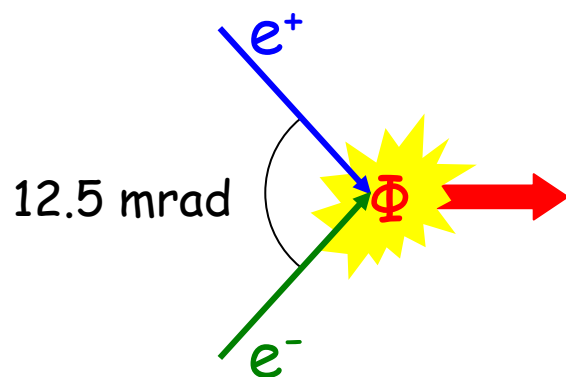
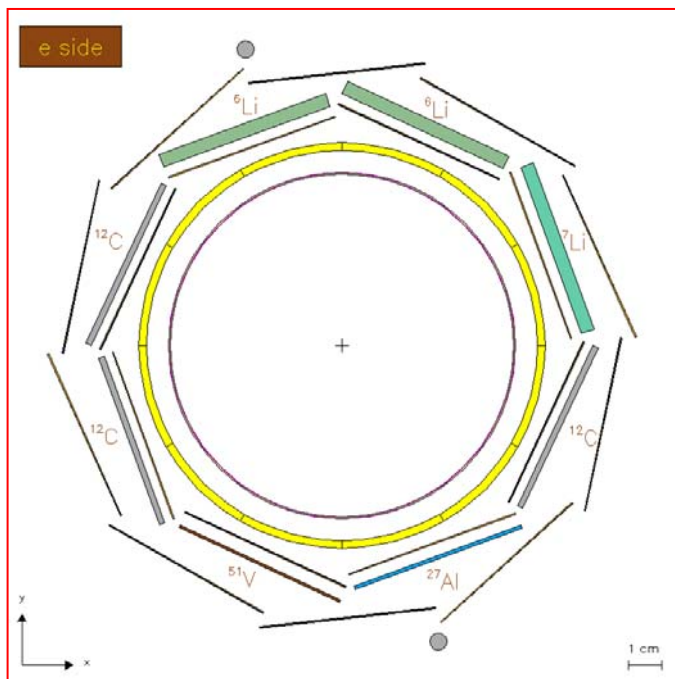






# Target envelope by $K$ - stopping points

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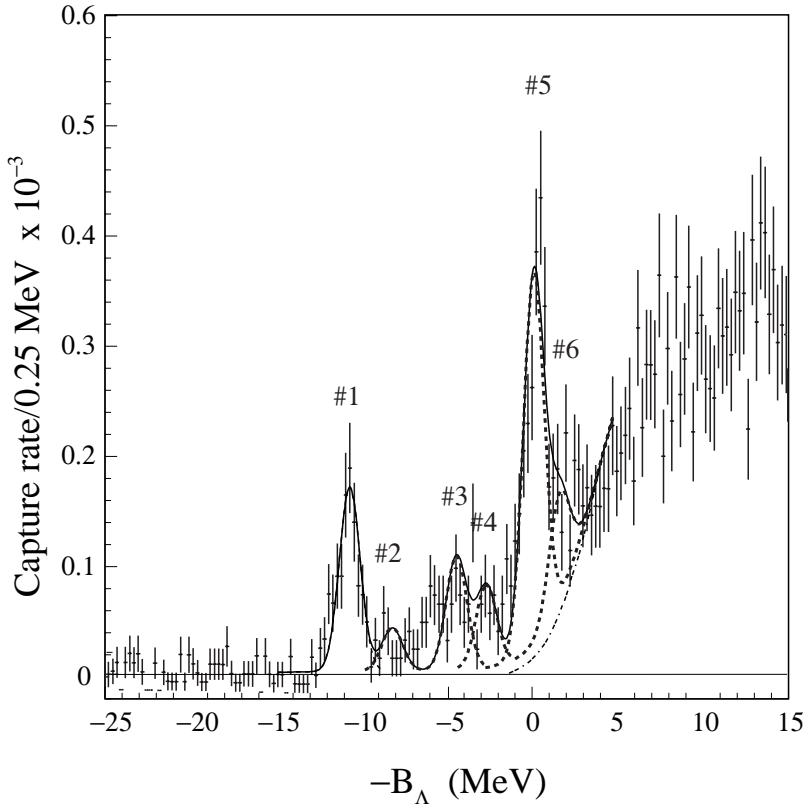


# FINUDA vs. KEK-E369

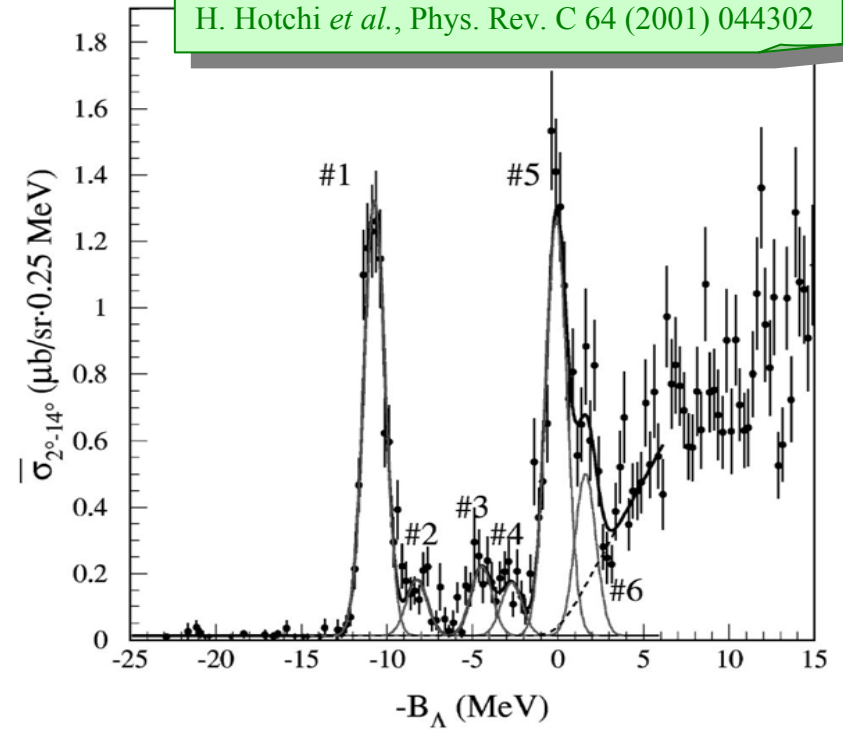
A. Feliciello / International Workshop on Hypernuclei with Heavy Ion Beams – Darmstadt, Germany, June 20 – 21, 2005



$\Delta E \sim 1.3 \text{ MeV FWHM}$



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



$\Delta E \sim 1.5 \text{ MeV FWHM}$



# FINUDA results on $^{12}\text{C}$

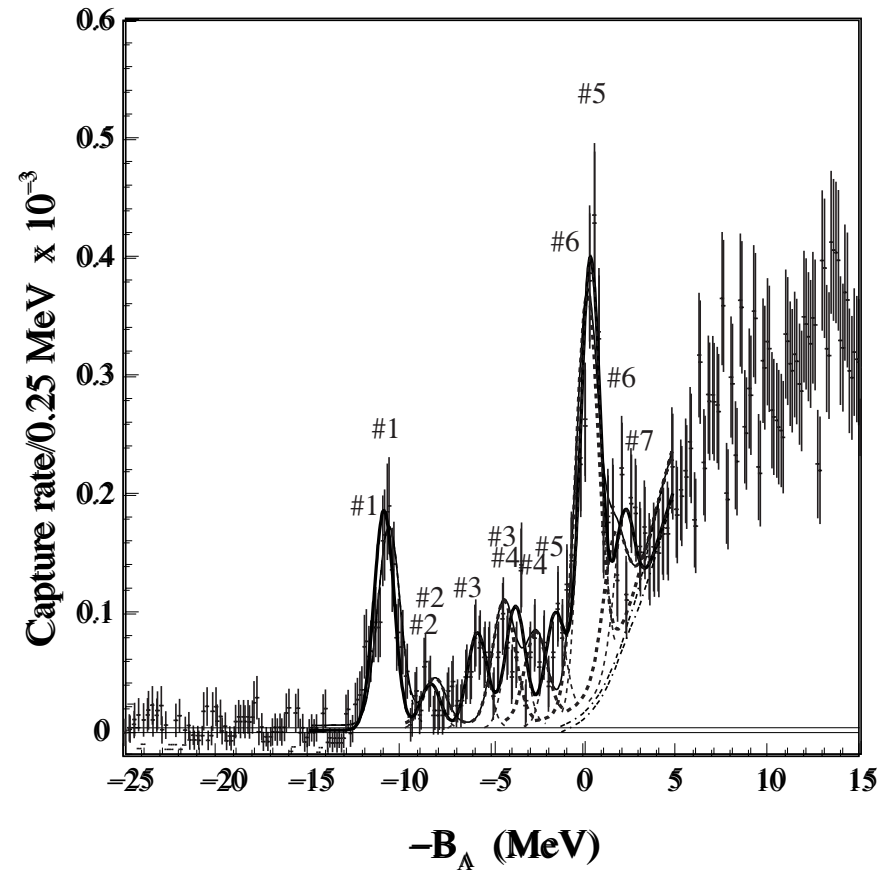
A. Feliciello / International Workshop on Hypernuclei with Heavy Ion Beams – Darmstadt, Germany, June 20 – 21, 2005

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	$0.23 \pm 0.05$
3	-4.46	$0.62 \pm 0.08$
4	-2.77	$0.45 \pm 0.07$
5	-0.10	$2.01 \pm 0.14$
6	1.61	$0.57 \pm 0.11$

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

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

$\Delta E \sim 1.3$  MeV FWHM



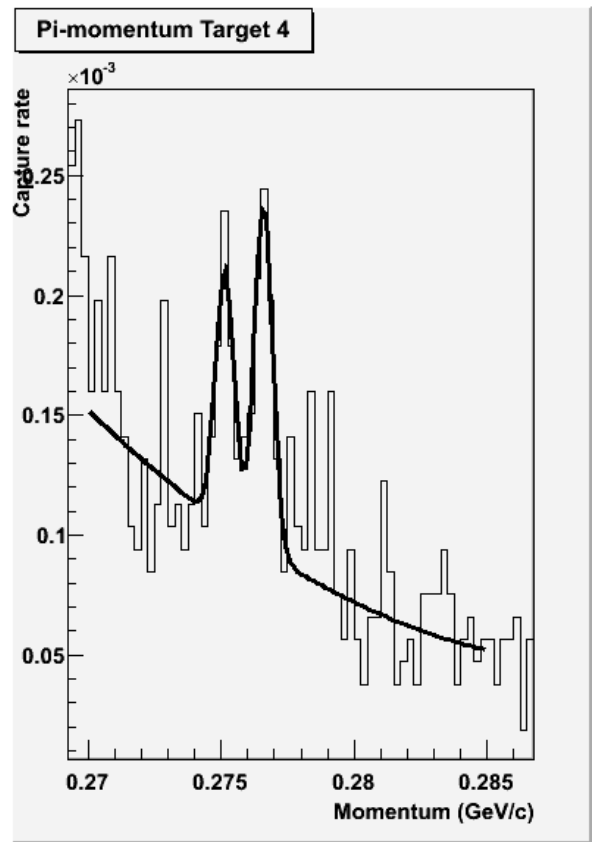
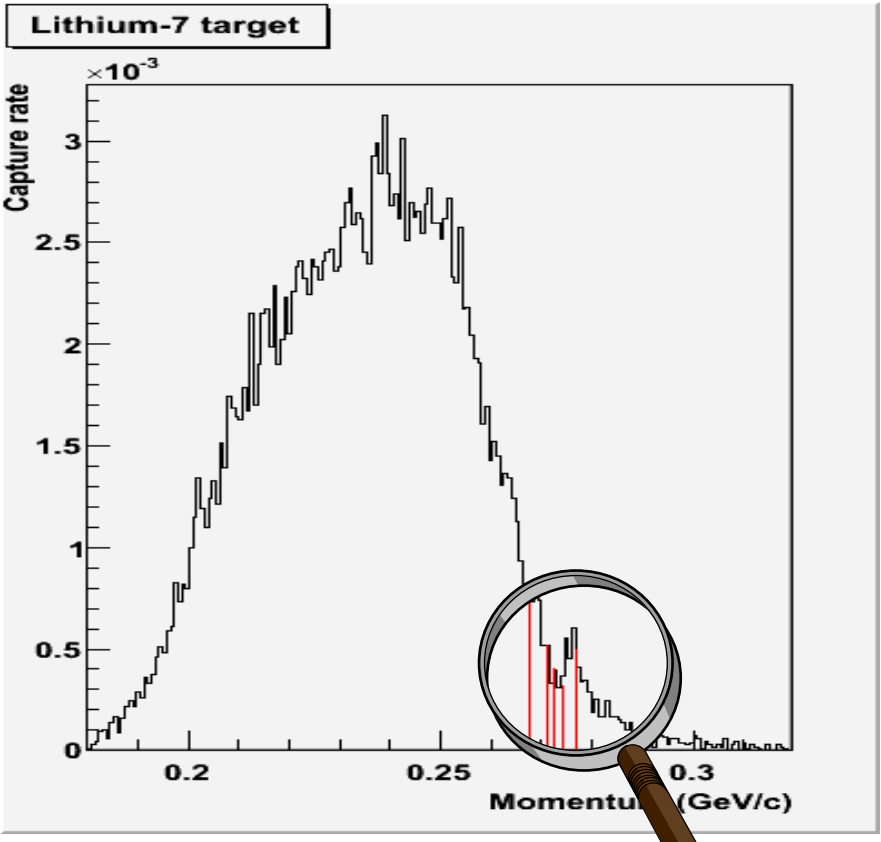


# FINUDA results on ${}^7\text{Li}$



$\Delta E \sim 1.9 \text{ MeV FWHM}$

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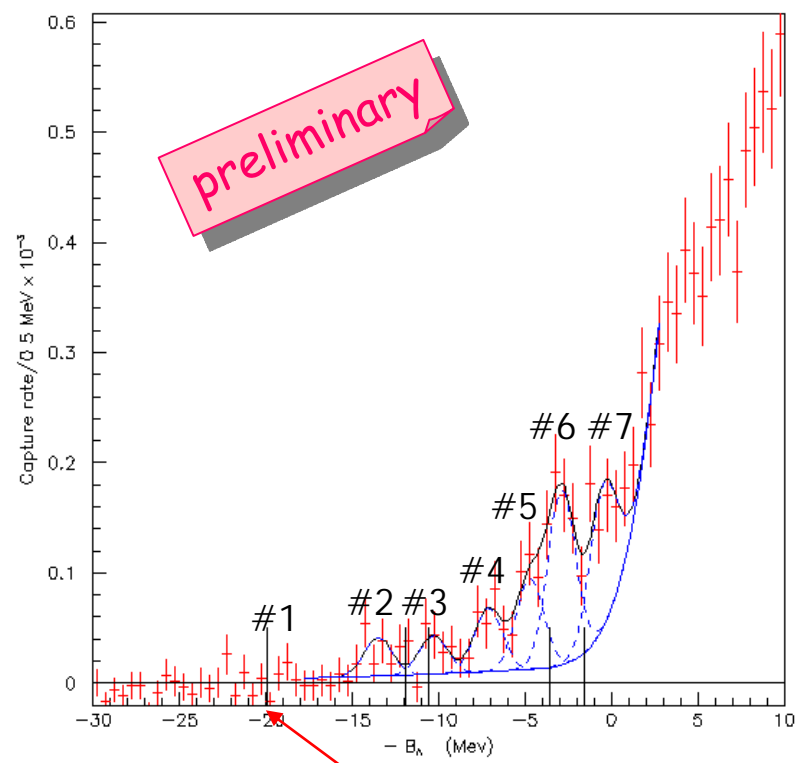


# FINUDA results on $^{51}\text{V}$

A. Feliciello / International Workshop on Hypernuclei with Heavy Ion Beams – Darmstadt, Germany, June 20 – 21, 2005

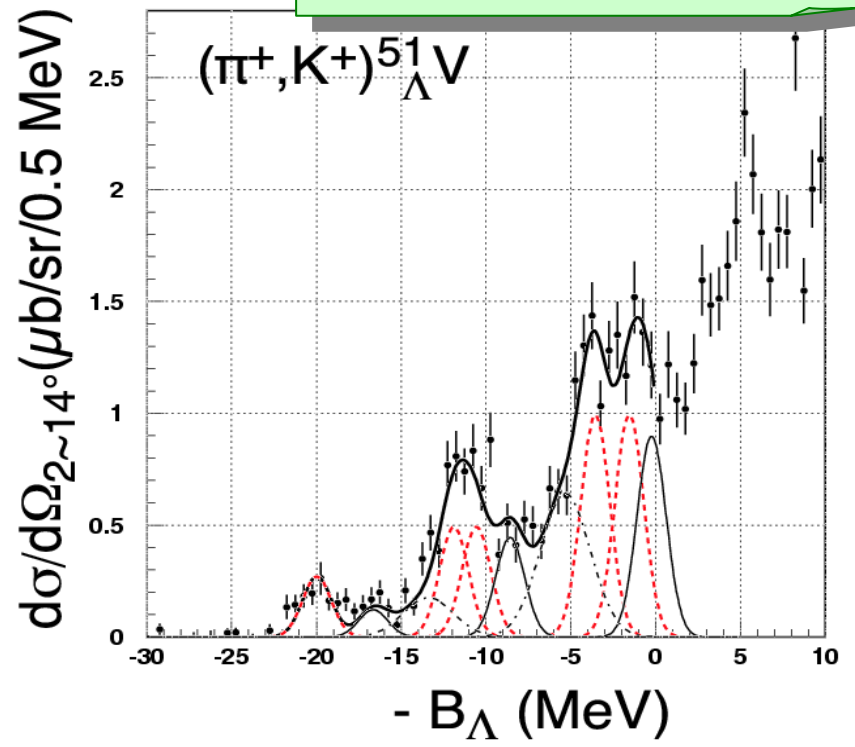
$$^{51}\text{V}(K_{\text{stop}}^-, \pi^-)^{51}_{\Lambda}\text{V}$$

$\Delta E \sim 1.9 \text{ MeV FWHM}$



ground state missing?

T. Nagaie, Nucl. Phys. A 691 (2001) 76c



$$^{51}\text{V}(\pi^+, K^+)^{51}_{\Lambda}\text{V}$$

$\Delta E \sim 1.9 \text{ MeV FWHM}$



# Kaonic nuclei: theoretical predictions

## hadron's properties inside nuclear medium:

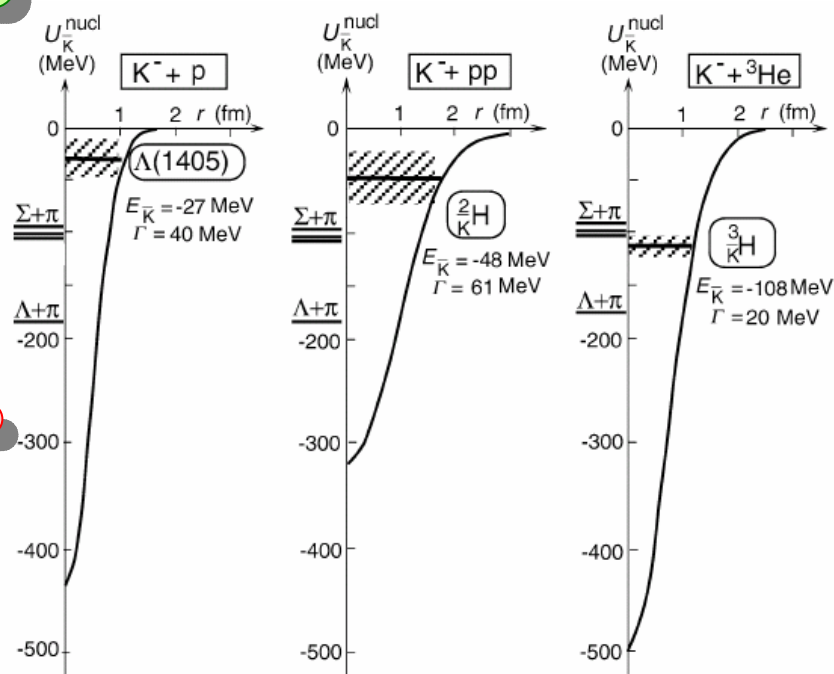
- mass and interaction change
- (partial) chiral symmetry restoration

## strangeness sector:

- strangeness condensation
- neutron stars
- K-N potential
- $\Lambda(1405)$

- A. Cieplý *et al.*, Nucl. Phys. A 696 (2001) 173
- N. Kaiser *et al.*, Nucl. Phys. A 594 (1995) 325
- T. Waas *et al.*, Phys. Lett. B 365 (1996) 12
- T. Waas *et al.*, Phys. Lett. B 379 (1996) 34
- A. Ramos *et al.*, Nucl. Phys. A 671 (2000) 481
- A. Baca *et al.*, Nucl. Phys. A 673 (2000) 335

- E. Friedmann *et al.*, Phys. Rev. C 60 (1999) 024314
- E. Friedman *et al.*, Nucl. Phys. A 579 (1994) 518
- Y. Akaishi *et al.*, Phys. Rev. C 65 (2002) 044005
- Y. Akaishi *et al.*, Phys. Lett. B 535 (2002) 70

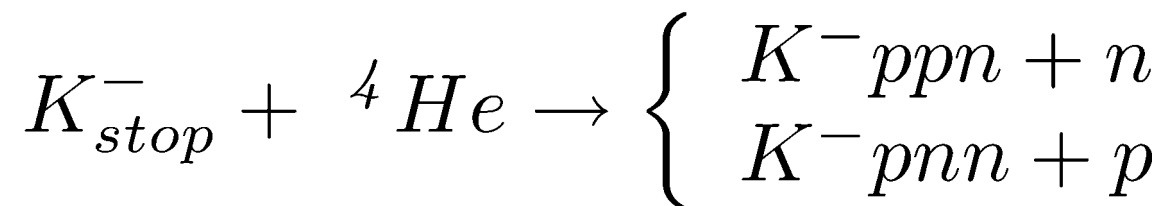




# Kaonic nuclei search with $\Lambda$ tagging

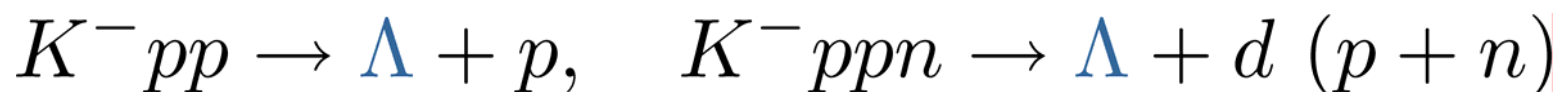
23

- ❖ **missing-mass** spectroscopy:



☞ a kaonic nucleus emits a hyperon in its decay

- ❖ **invariant-mass** spectroscopy:

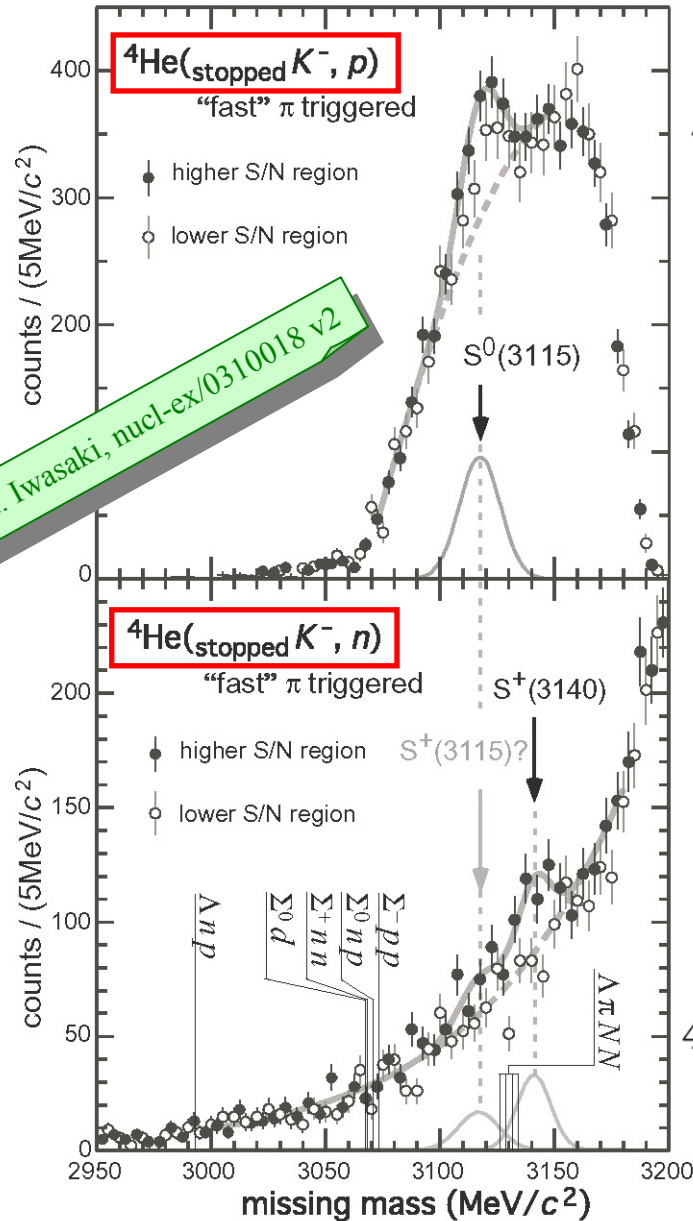




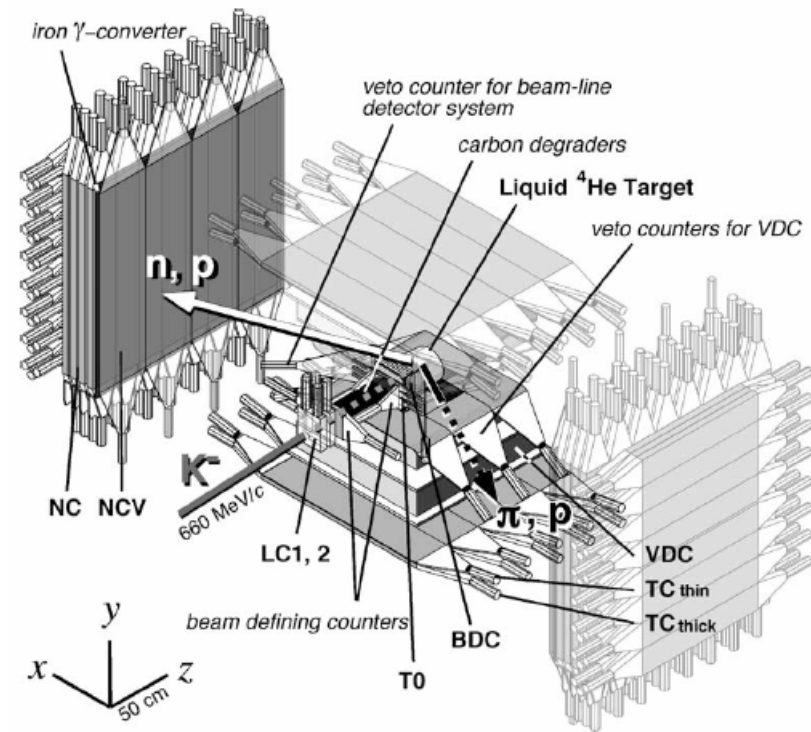
# E471 evidence for strange tribaryons

A. Feliciello / International Workshop on Hypernuclei with Heavy Ion Beams – Darmstadt, Germany, June 20 – 21, 2005

M. Iwasaki, nucl-ex/0310018 v2



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



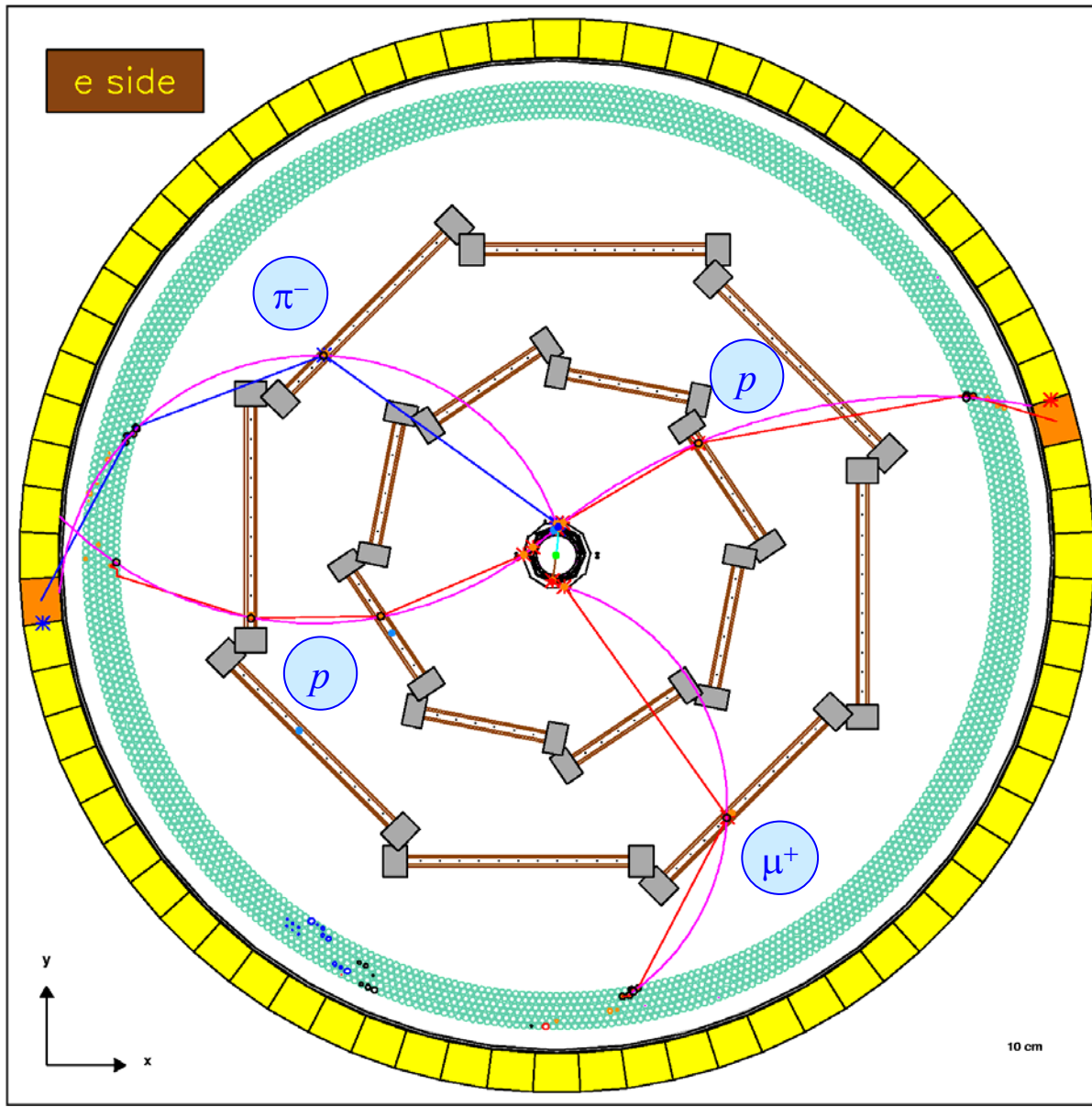
$${}^4\text{He}(K_{\text{stop}}^-, n) S^+(3140) \equiv K^- ppn$$





# "K<sup>-</sup>pp" → Λp → ppπ candidate event

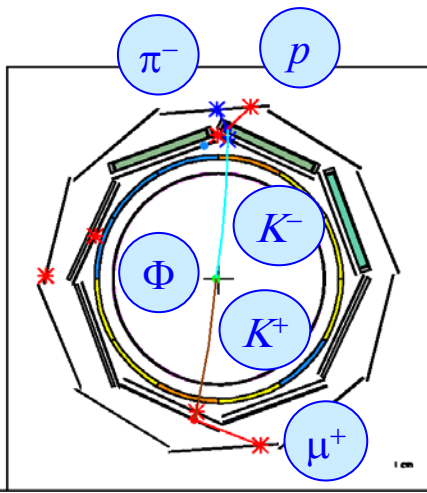
A. Feliciello / International Workshop on Hypernuclei with Heavy Ion Beams – Darmstadt, Germany, June 20 – 21, 2005



e side

FINUDA Experiment  
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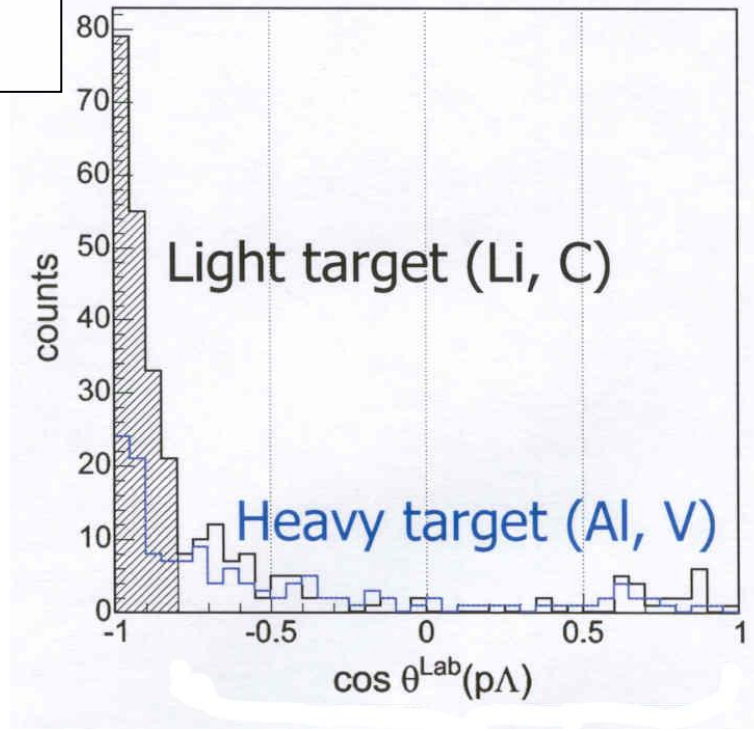
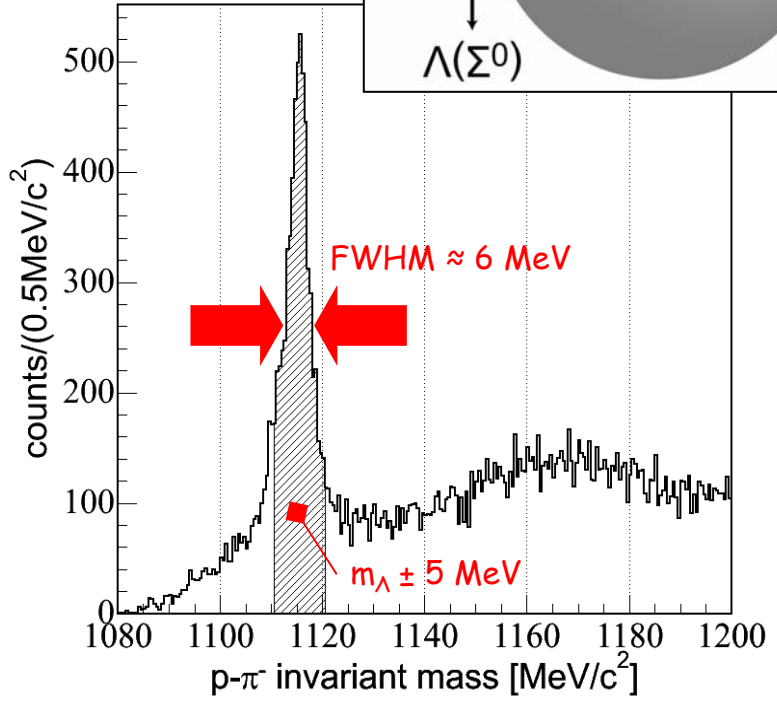
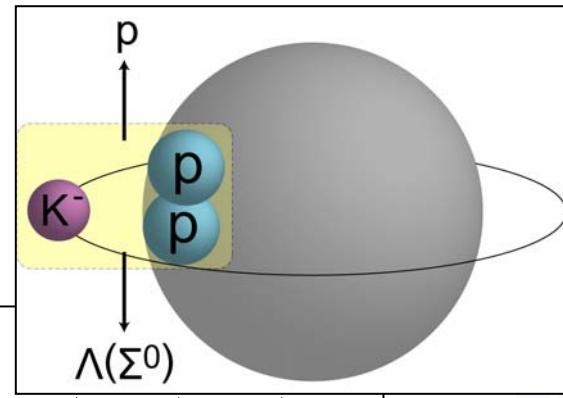
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- Track Fitting
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- Pick Info
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# $\Lambda$ momentum distribution and back-to-back correlations

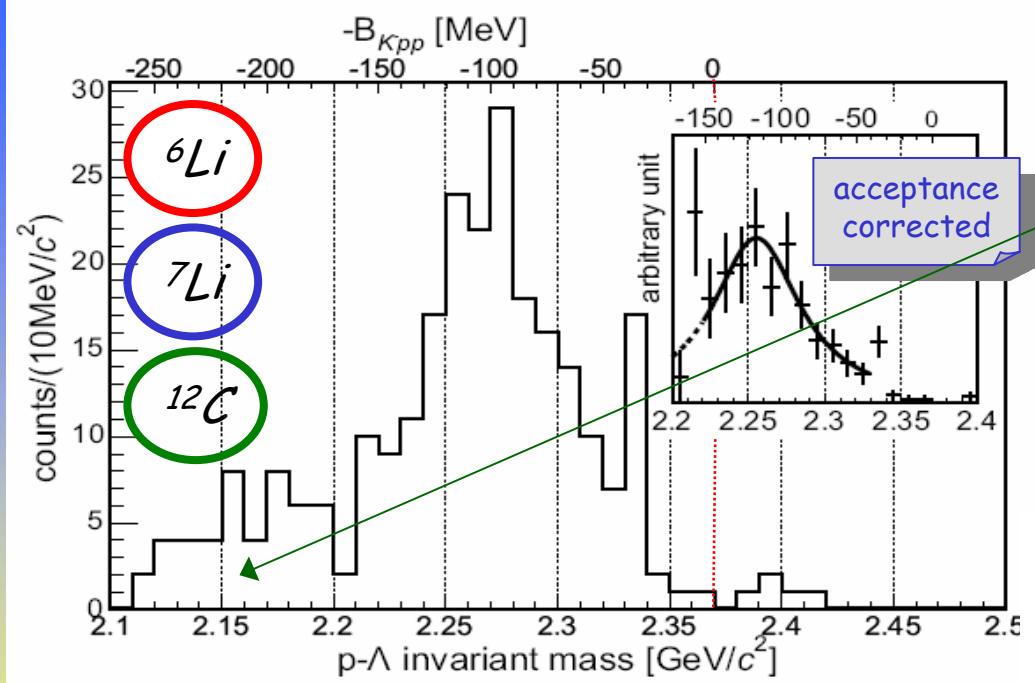
A. Feliciello / International Workshop on Hypernuclei with Heavy Ion Beams – Darmstadt, Germany, June 20 – 21, 2005





# K-pp deeply-bound state

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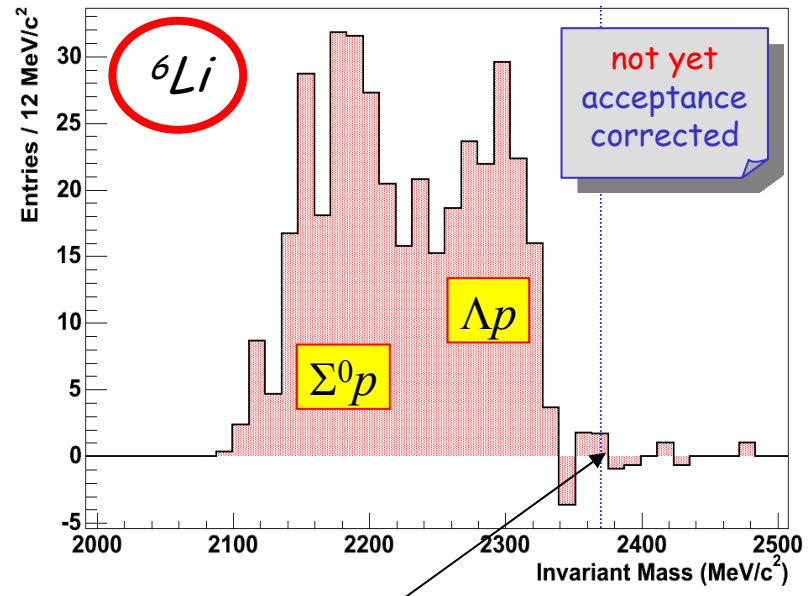


contribution from  $\Sigma^0 + p$  decay are seen in low mass region

improved P.R.

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

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



$$m_p + m_p + m_{K^-}$$

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

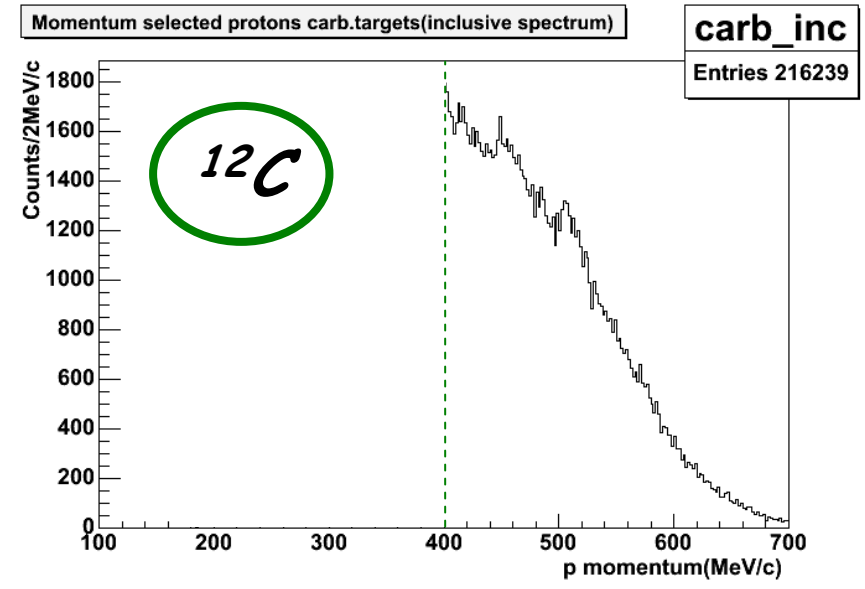
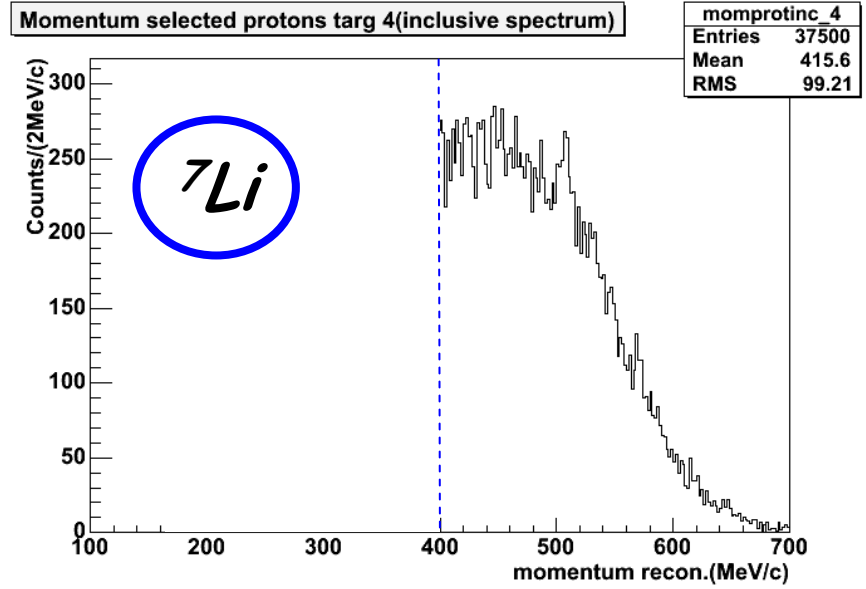
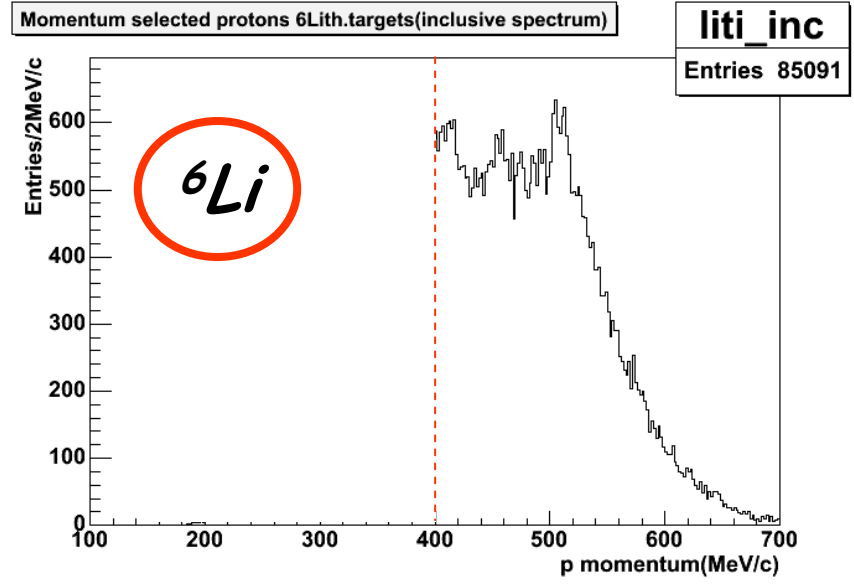
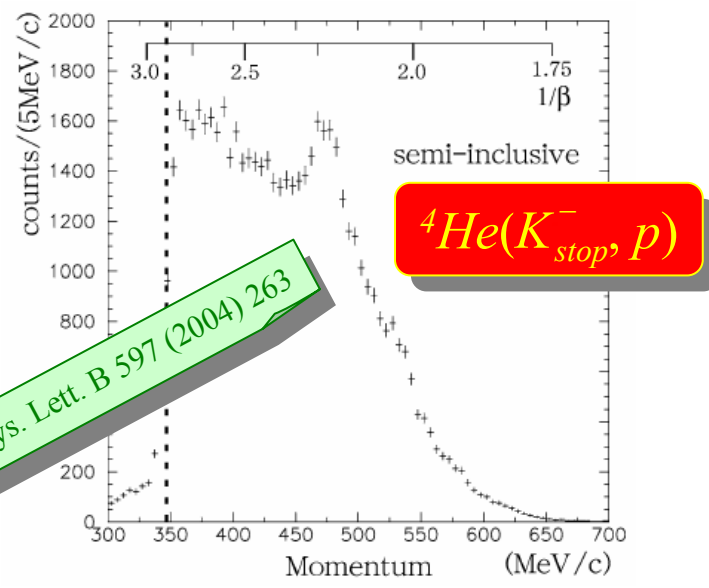




# FINUDA vs. KEK-E471

A. Feliciello / International Workshop on Hypernuclei with Heavy Ion Beams – Darmstadt, Germany, June 20 – 21, 2005

T. Suzuki, Phys. Lett. B 597 (2004) 263

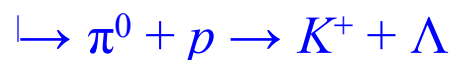
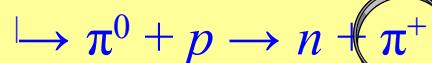




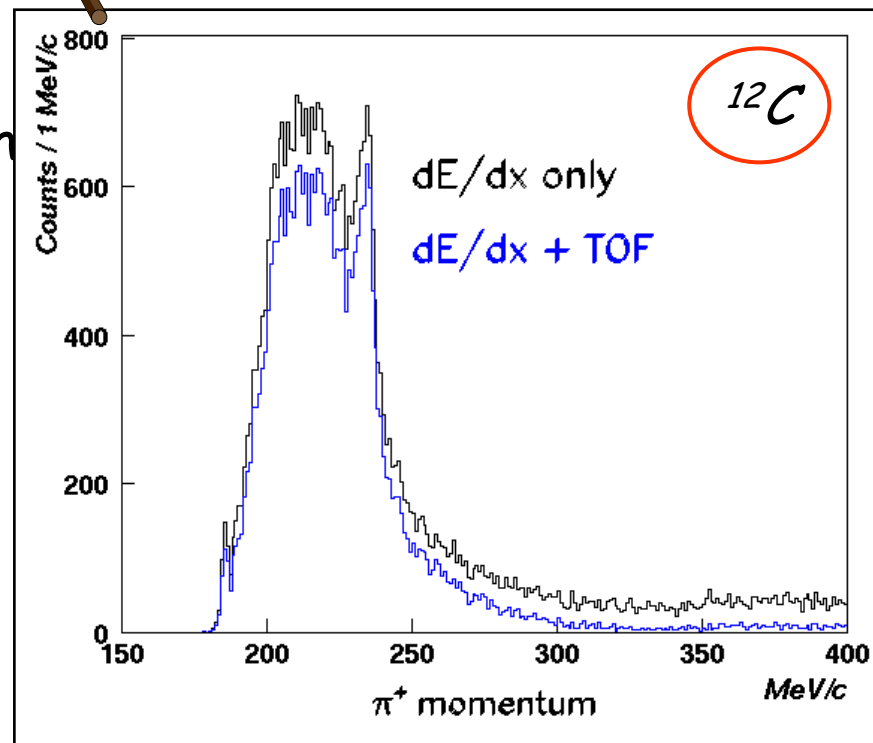
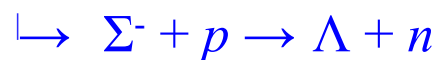
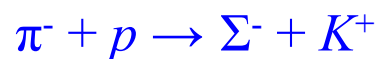
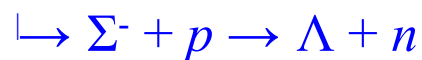
# neutron-rich hypernuclei

## 2 production mechanisms:

- 1) strangeness + double charge exchange



- 2) Strangeness exchange with

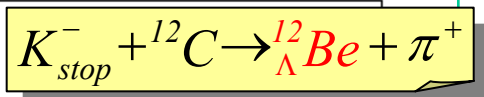
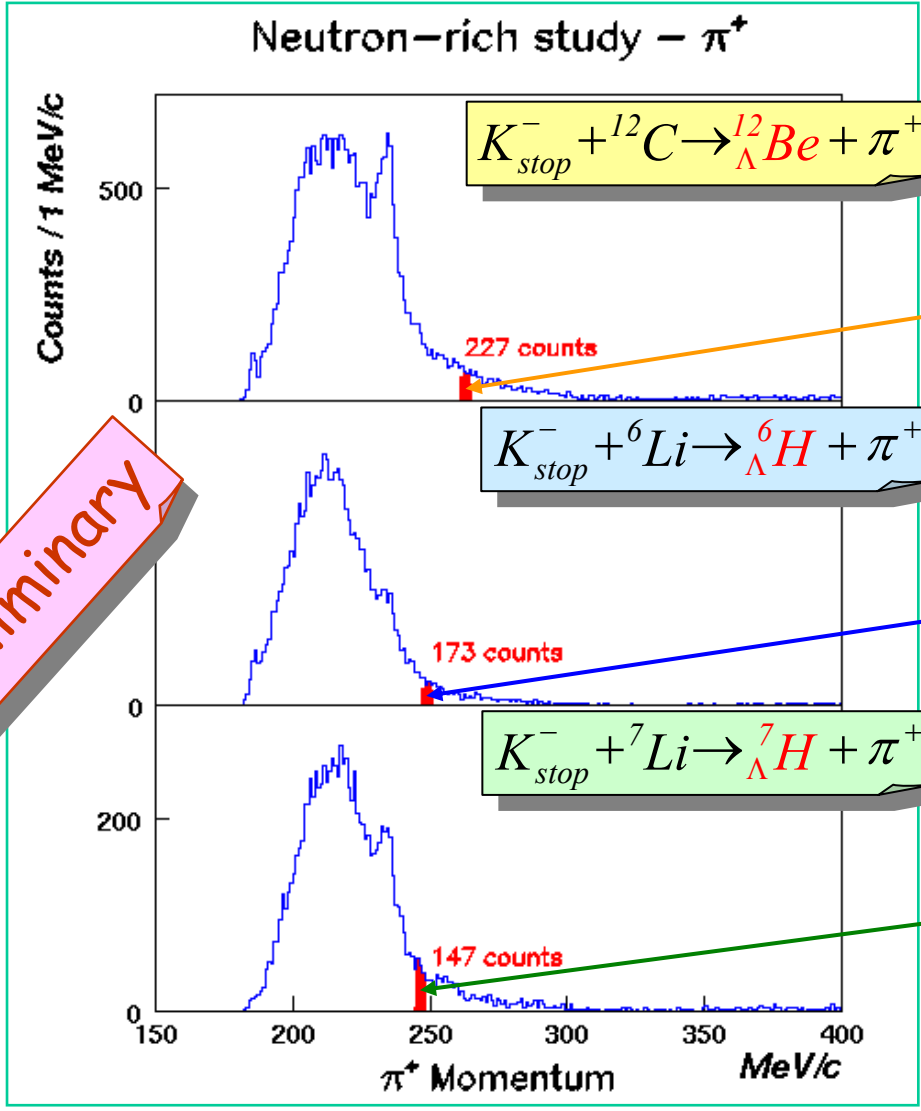




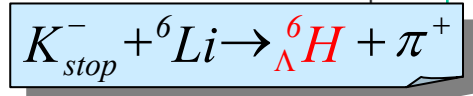
# neutron-rich hypernuclei

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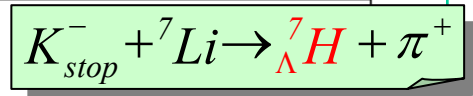
preliminary



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



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



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



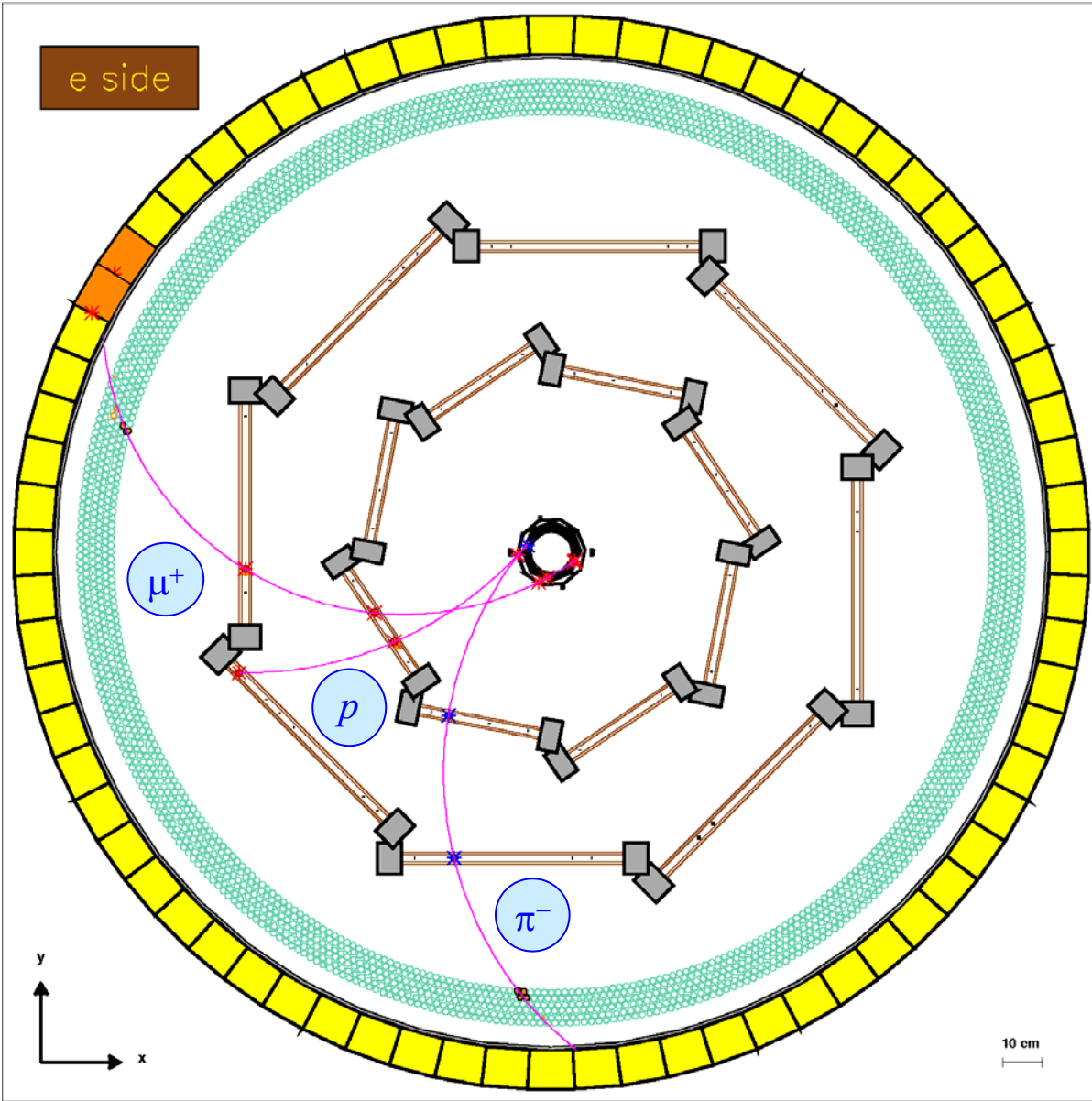
# neutron-rich hypernuclei

P <sub>NRH</sub> upper limit (× 10 <sup>-5</sup> )	90% C.L.		2 σ C.L.		3 σ C.L.		
	dE/dx PID	dE/dx + TOF PID	dE/dx PID	dE/dx + TOF PID	dE/dx PID	dE/dx + TOF PID	
<u>present</u> momentum resolution (9‰)	2.6	2.1	3.2	2.6	4.9	4.0	<sup>12</sup> <sub>Λ</sub> Be
	3.5	2.9	4.3	3.6	6.6	5.6	<sup>6</sup> <sub>Λ</sub> H
	4.9	4.3	6.1	5.3	9.4	8.3	<sup>7</sup> <sub>Λ</sub> H
<u>nominal</u> momentum resolution (3.5‰)	1.6	1.3	2.0	1.6	3.1	2.5	<sup>12</sup> <sub>Λ</sub> Be
	2.1	1.8	2.6	2.2	4.1	3.5	<sup>6</sup> <sub>Λ</sub> H
	3.3	2.8	4.1	3.5	6.5	5.6	<sup>7</sup> <sub>Λ</sub> H



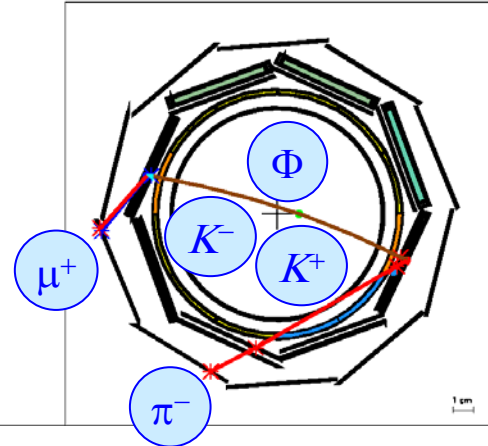
# A non mesonic weak decay

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FINUDA Experiment  
Run n.: 1588  
Event n.: 6765  
Date: 05/02/04

<input type="checkbox"/>	FRONT view	<input type="checkbox"/>
Raw data		
Rec. hits		
Pattern Recogn.		
Track Fitting		
Zoom		
Pick Info		
<ERASE>		<QUIT>

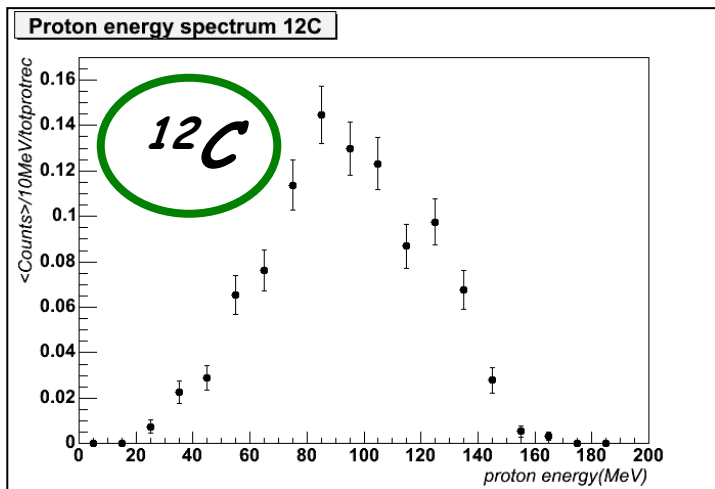




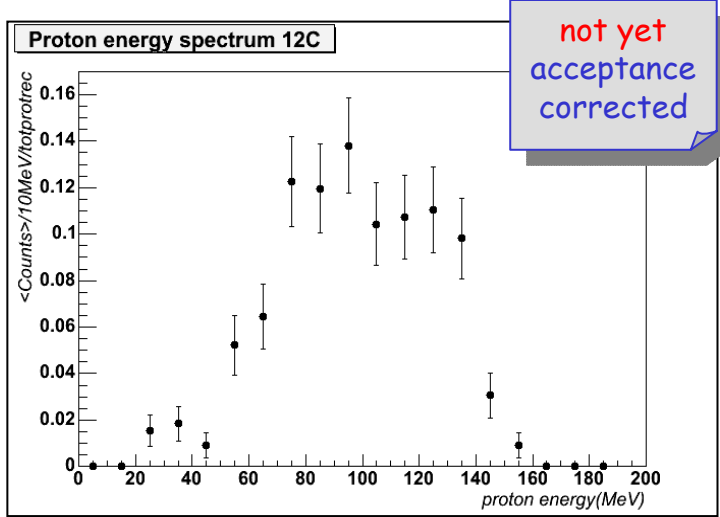


# proton spectrum from $^{12}\text{C}$ n.m. decay

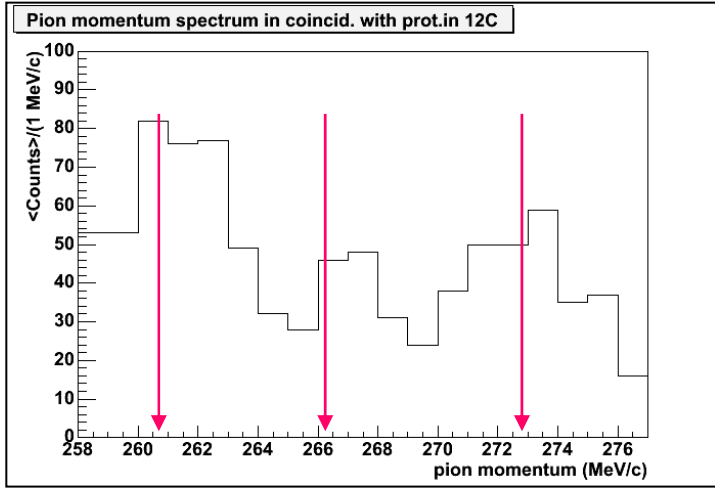
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inclusive spectrum bound region



ground state region



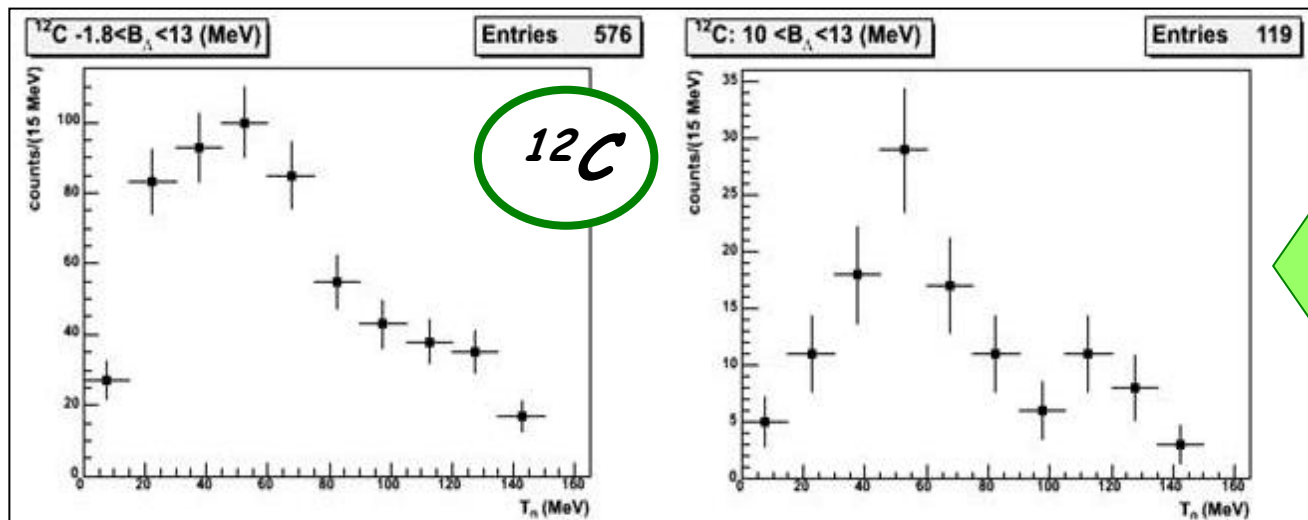
ground state region coincidence pions



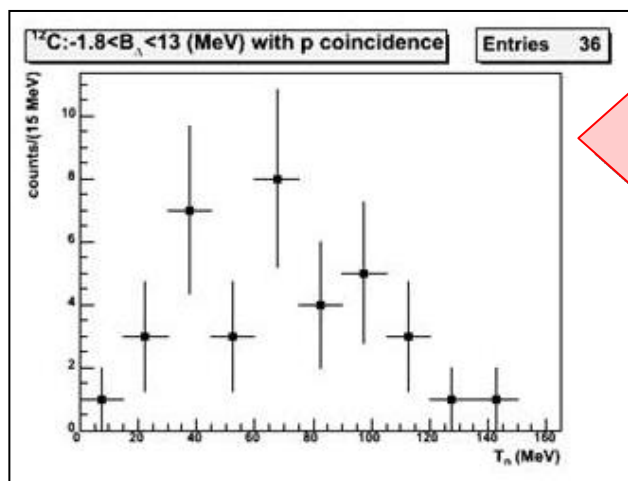


# neutron spectrum from $^{12}\text{C}$ n.m. decay

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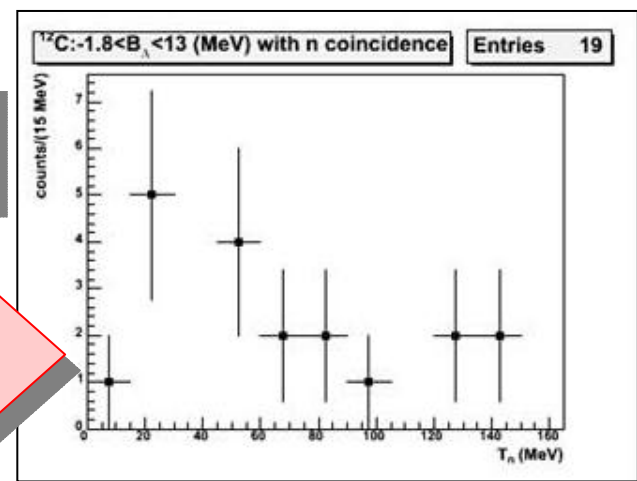


inclusive spectrum  
bound region  
g.s. region



bound region  
in coincidence with  $p$

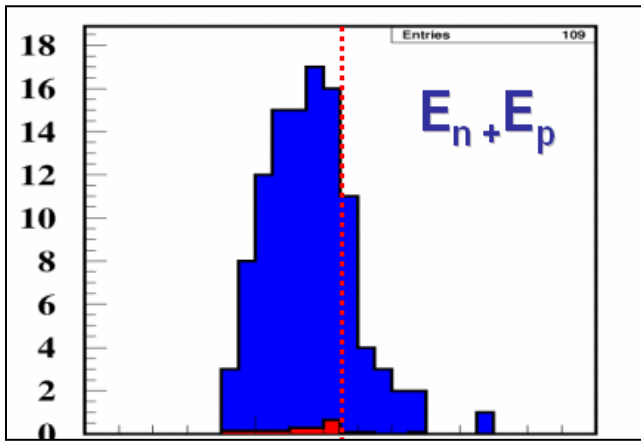
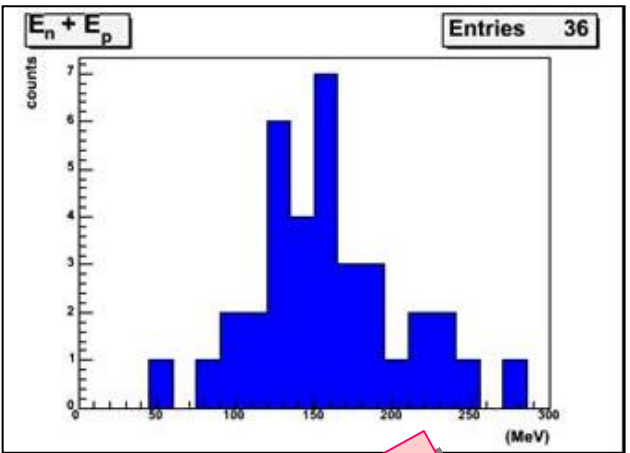
bound region  
in coincidence with  $n$





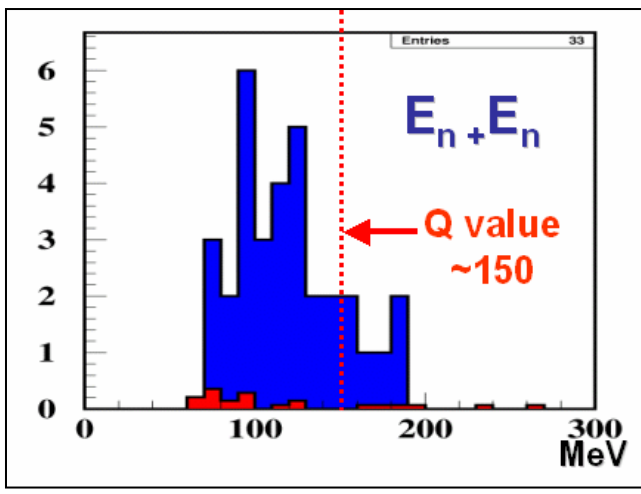
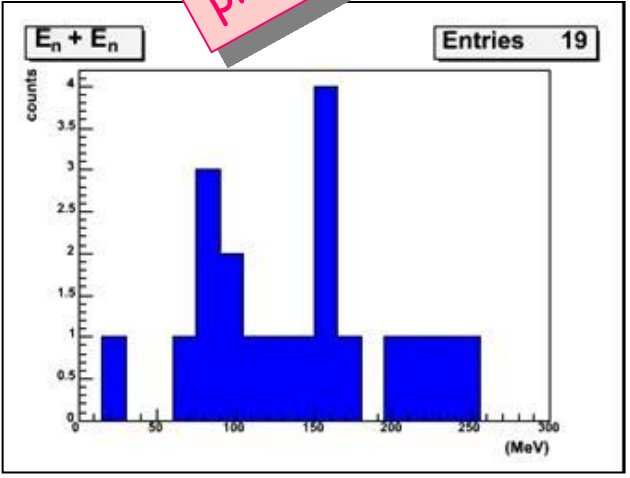
# Total energy spectra from $^{12}\text{C}$ n.m. decay

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KEK E462/E508

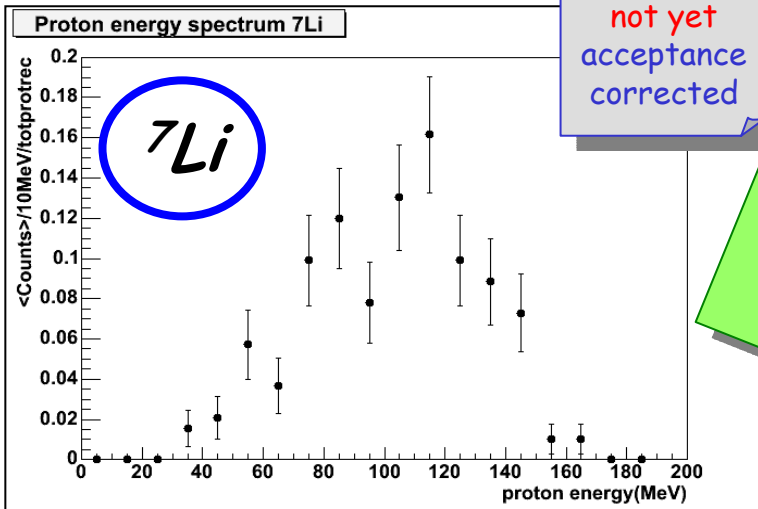
preliminary





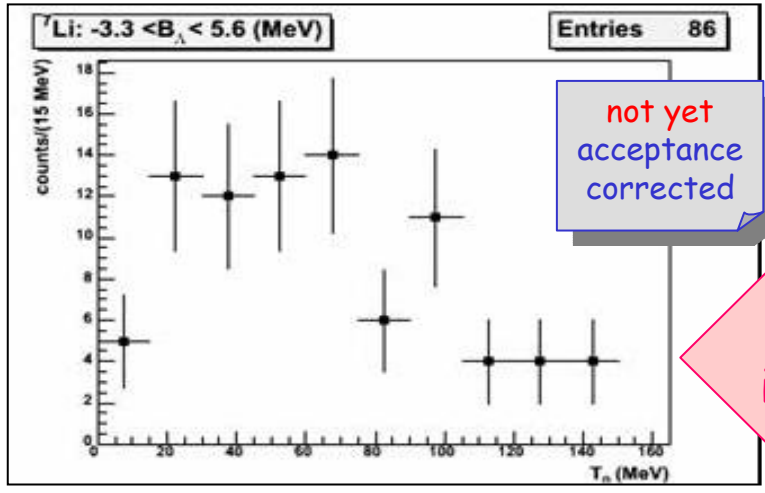
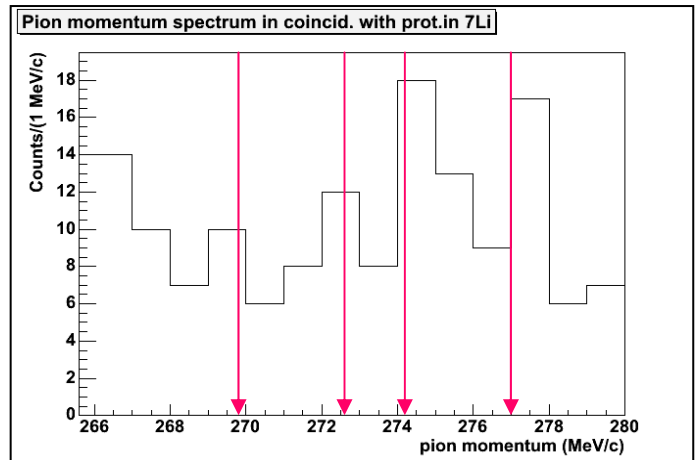
# *p & n spectra from ${}^7\text{Li}$ n.m. decay*

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protons inclusive spectrum

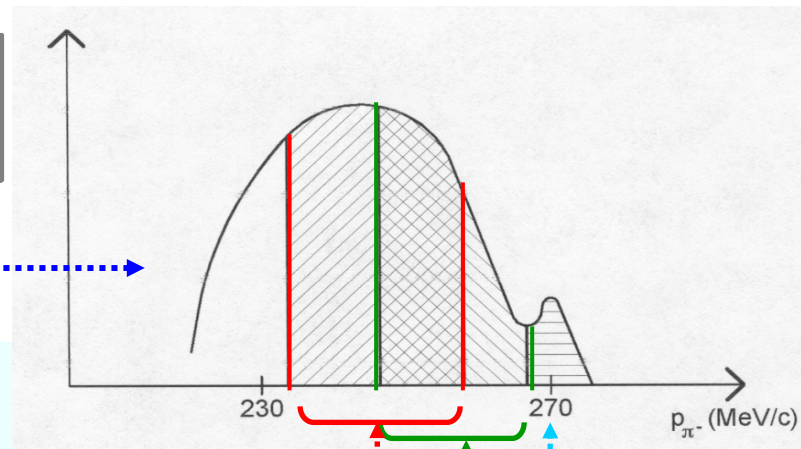
pion spectrum in coincidence with  $p$



neutrons inclusive spectrum

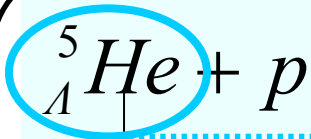
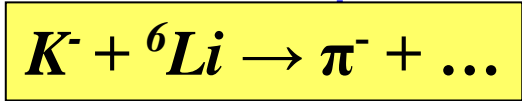


# ${}^4_{\Lambda}He$ (rare) decay

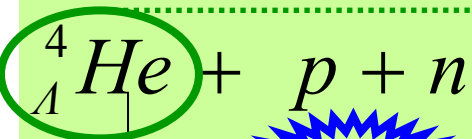


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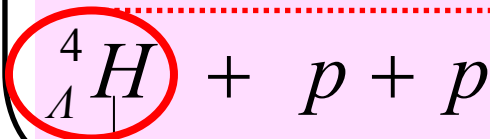
Spectroscopized



- $\tau$
- $\Gamma_p$  (in coinc.) about  $10/pb^{-1}$
- $\Gamma_n$  (in coinc.) a few/ $pb^{-1}$
- $\Gamma_{\pi^-}$  about  $10^2/pb^{-1}$



- $d + d$  spectr. ( $\sim 0.3/pb^{-1}$  if B.R.  $\sim 10^{-3}$ )
- $p + {}^3H$  spectr. ( $0.2/pb^{-1}$  if B.R.  $\sim 10^{-3}$ )
- $\pi^+ + n + {}^3H$  many events ( $\sim 10^2/pb^{-1}$ )  
how distinguishable?

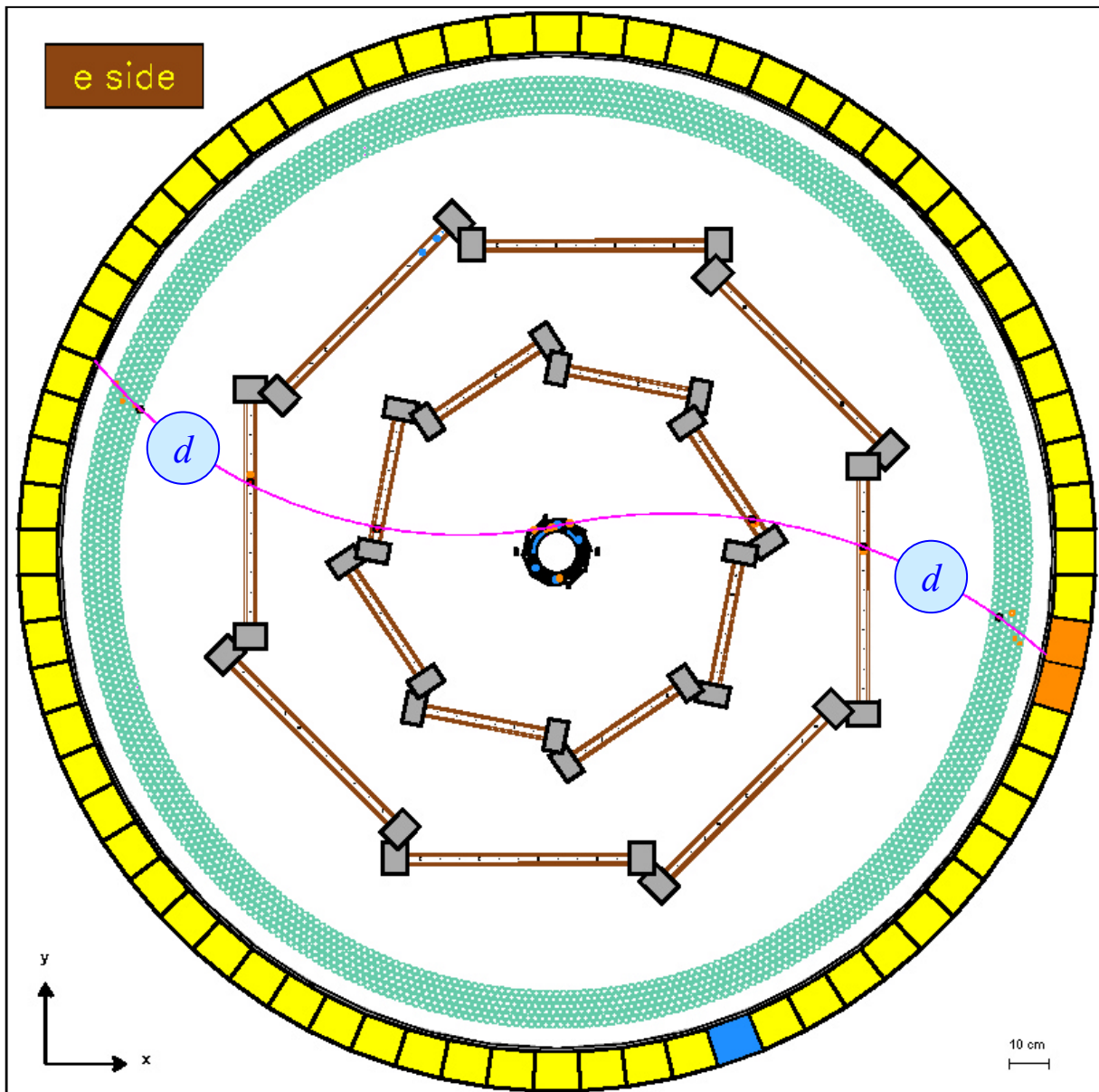


${}^4He + \pi^-$  spectr. ( $10^2/pb^{-1}$ ) calibration



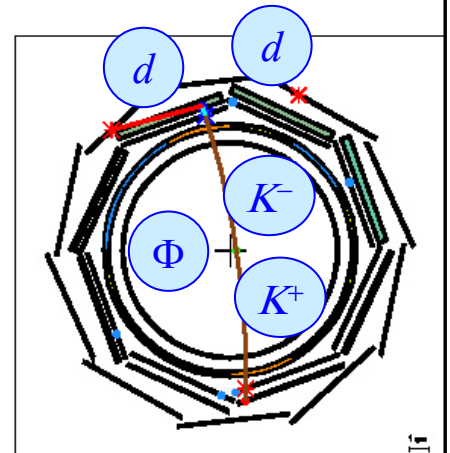
# ${}^4\text{He} \rightarrow d + d$ (rare) decay

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FINUDA Experiment  
Run n.: 1611  
Event n.: 5674  
Date: 06/02/04

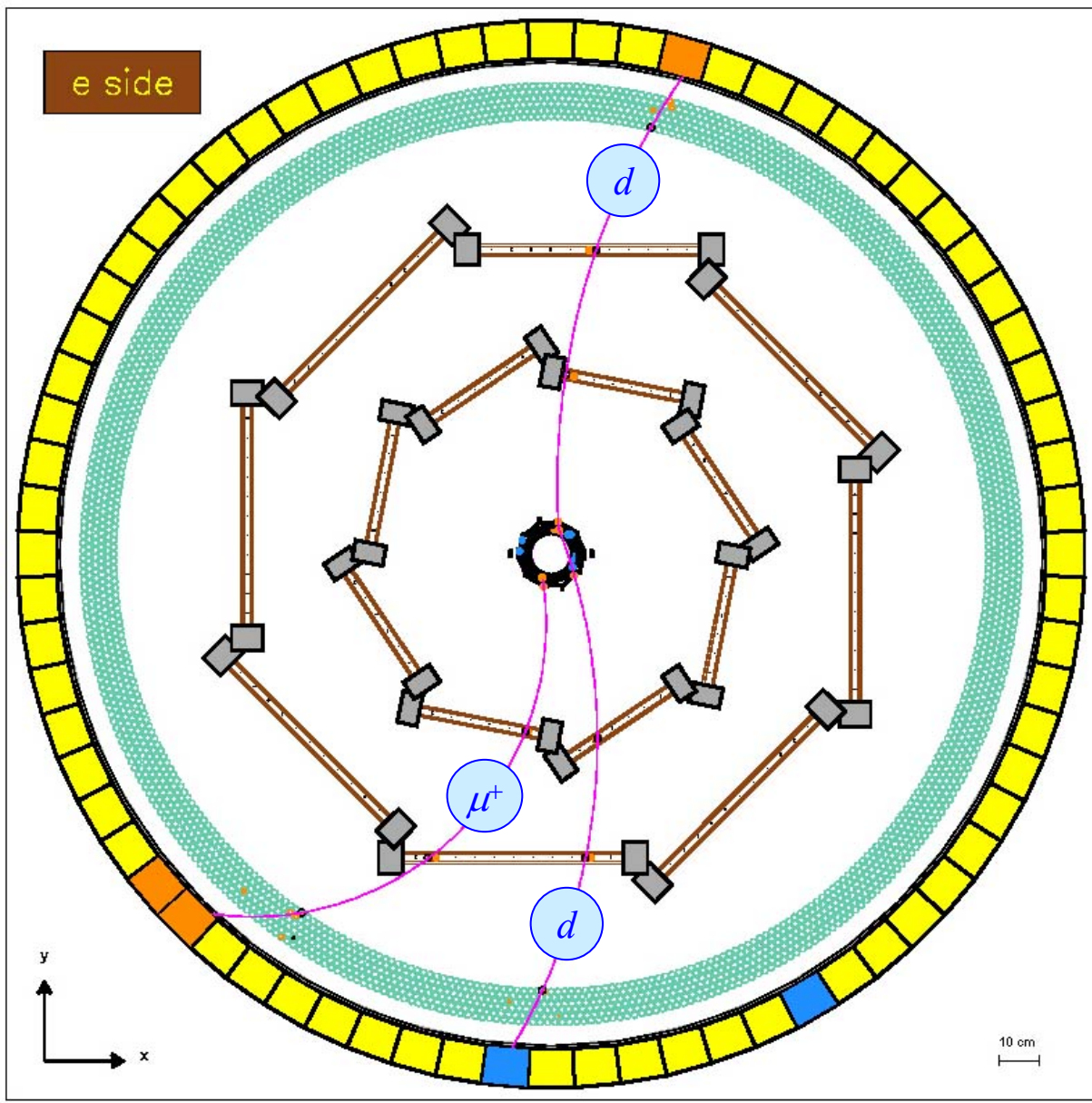
- FRONT view
- Raw data
- Rec. hits
- Pattern Recogn.
- Track Fitting
- Zoom
- Pick Info
- <ERASE> <QUIT>





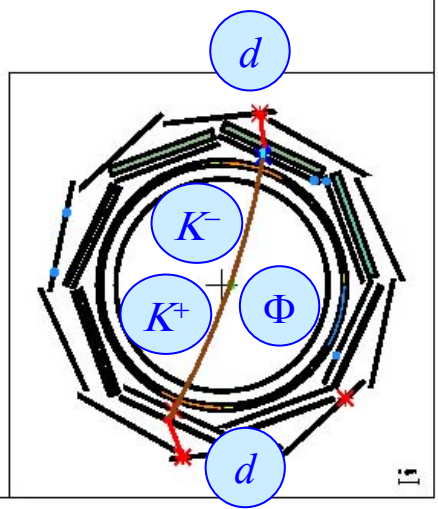
# ${}^4\text{He} \rightarrow d + d$ (rare) decay

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FINUDA Experiment  
Run n.: 1559  
Event n.: 577  
Date: 04/02/04

- FRONT view
- Raw data
- Rec. hits
- Pattern Recogn.
- Track Fitting
- Zoom
- Pick Info
- <ERASE> <QUIT>





# Summary

- 👍 first data taking period successfully carried out ( $30 \times 10^6$  events on tape)
- 👍 preliminary and partial results on spectroscopy are competitive with world published data
- 👍 observation of  $K$ - $pp$  deeply-bound states
- 👍 experimental upper limit for the  $NRH$  production:
  - ✓ better than published one for  ${}^1_{12}\text{Be}$
  - ✓ measured for the first time for  ${}^1_6\text{H}$  and  ${}^1_7\text{H}$
- 👍 first observation of  ${}^1_4\text{He}$  non mesonic (rare) decay





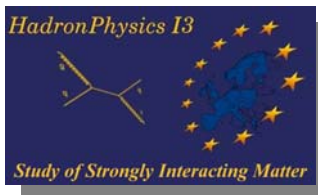
# Short term plans

- 1 Next data-taking period scheduled in 2006  
( $\sim 1 \text{ fb}^{-1}$   $\rightarrow$  present statistics  $\times 5$ )
  - ❖ effort focused on light-medium targets ( ${}^6\text{Li}$ ,  ${}^7\text{Li}$ ,  ${}^9\text{Be}$ ,  ${}^{16}\text{O}$ )
- ⚠ Increase by a factor 4 of the DAQ rate
- ⚠ Replacement of the internal TOF detector
- ⚠ Improvement of the reconstruction program
  - 👉 geometrical alignment
  - 👉 detector calibration
  - 👉 pattern recognition strategy
  - 👉 selection criteria
- 1 Further data-taking period (hopefully) in 2007/2008



# Long term plans

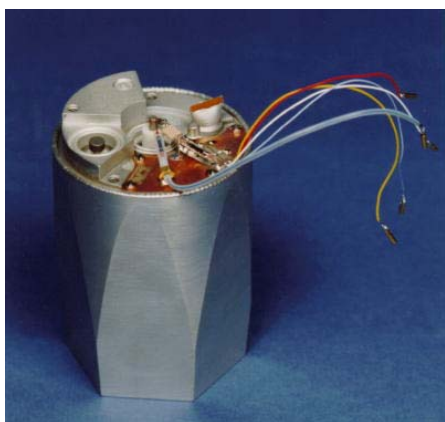
JRA6



FINUDA2  
@ DAΦNE2

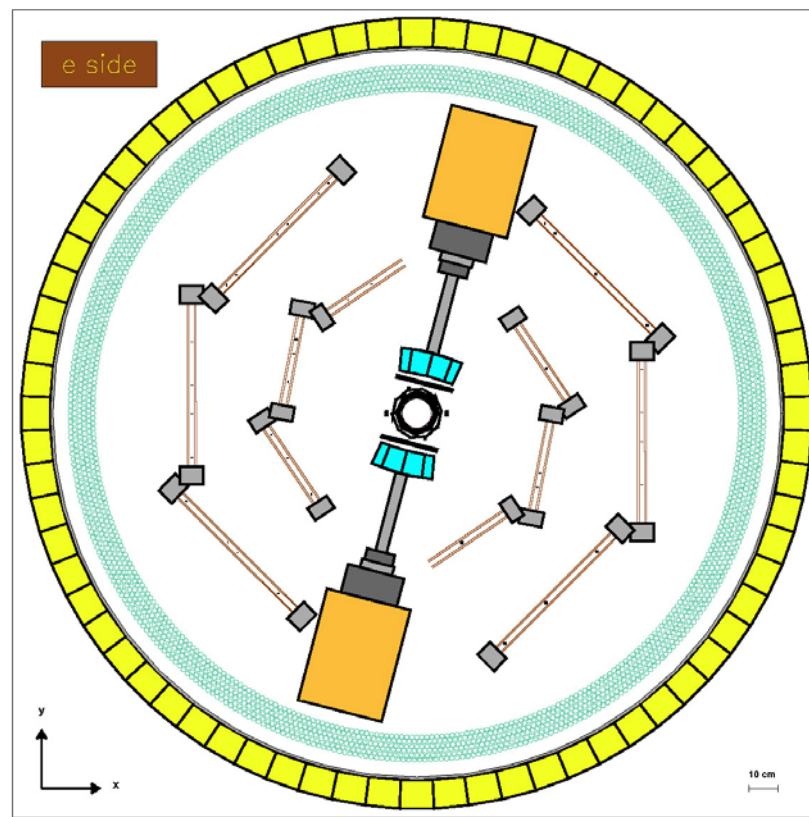
$\mathcal{L} \approx 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

The EUROBALL crystals



Geometrical acceptance  
reduced to 72%

The FINUDA spectrometer



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# Long term plans

## panda @ gsi

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