Search for neutron rich Λ-hypernuclei with the FINUDA spectrometer

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on behalf of the FINUDA Collaboration

Outline

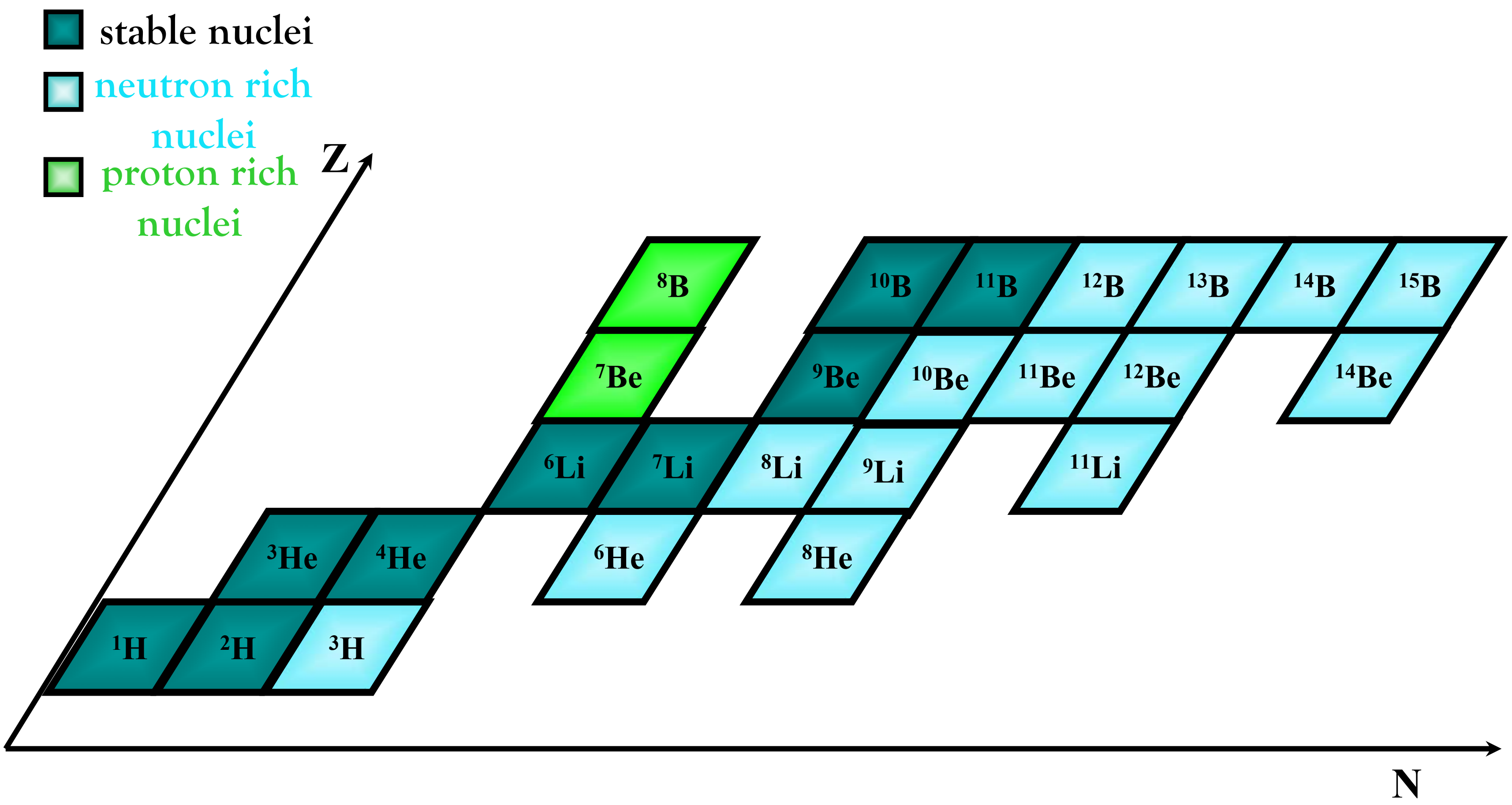
- The scientific case: Neutron Rich Λ-Hypernuclei
- Production of NRΛH with the FINUDA spectrometer
- Upper Limits of the NRΛH production rate

    results of the first FINUDA data taking

- Expected events for next FINUDA run 2006/2007
- Summary

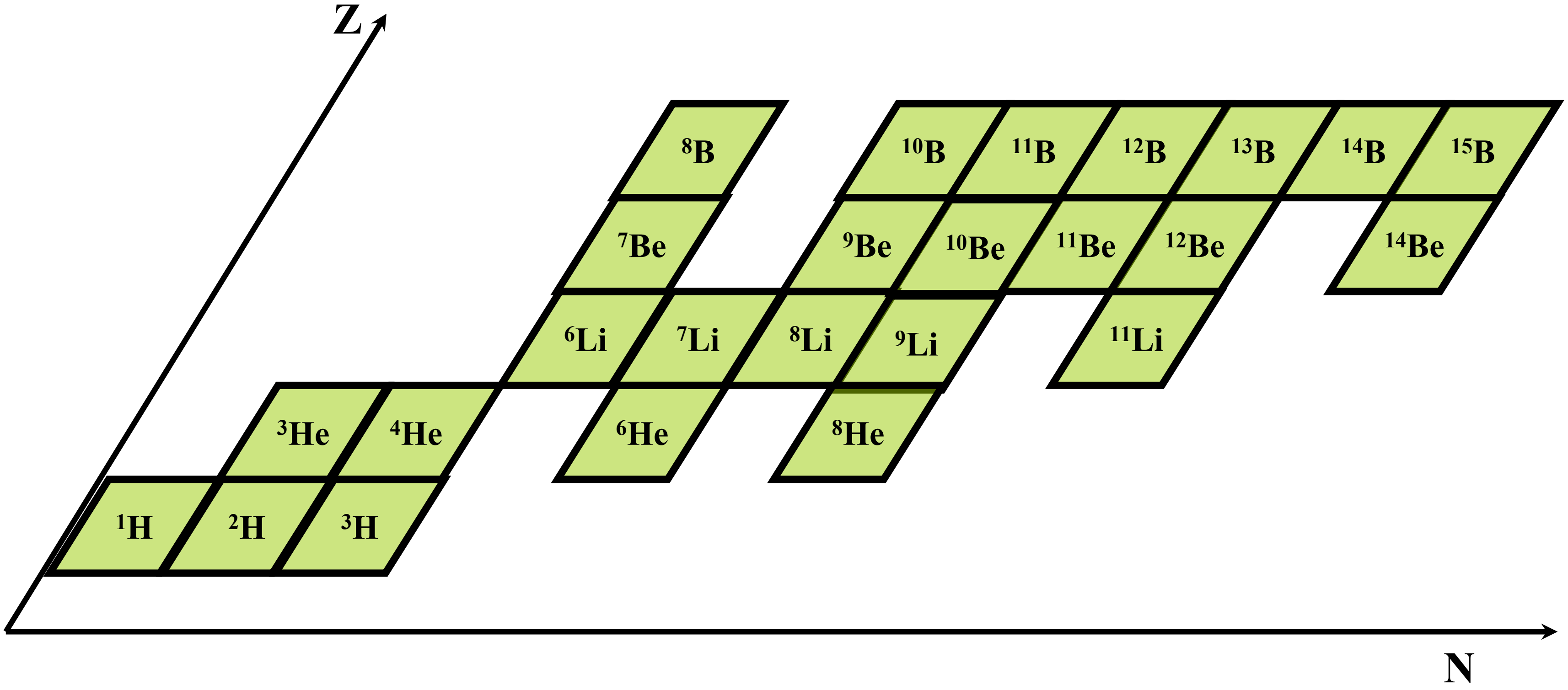
Neutron rich Λ-hypernuclei

Hypernuclei with a large neutron excess.



Neutron rich Λ-hypernuclei

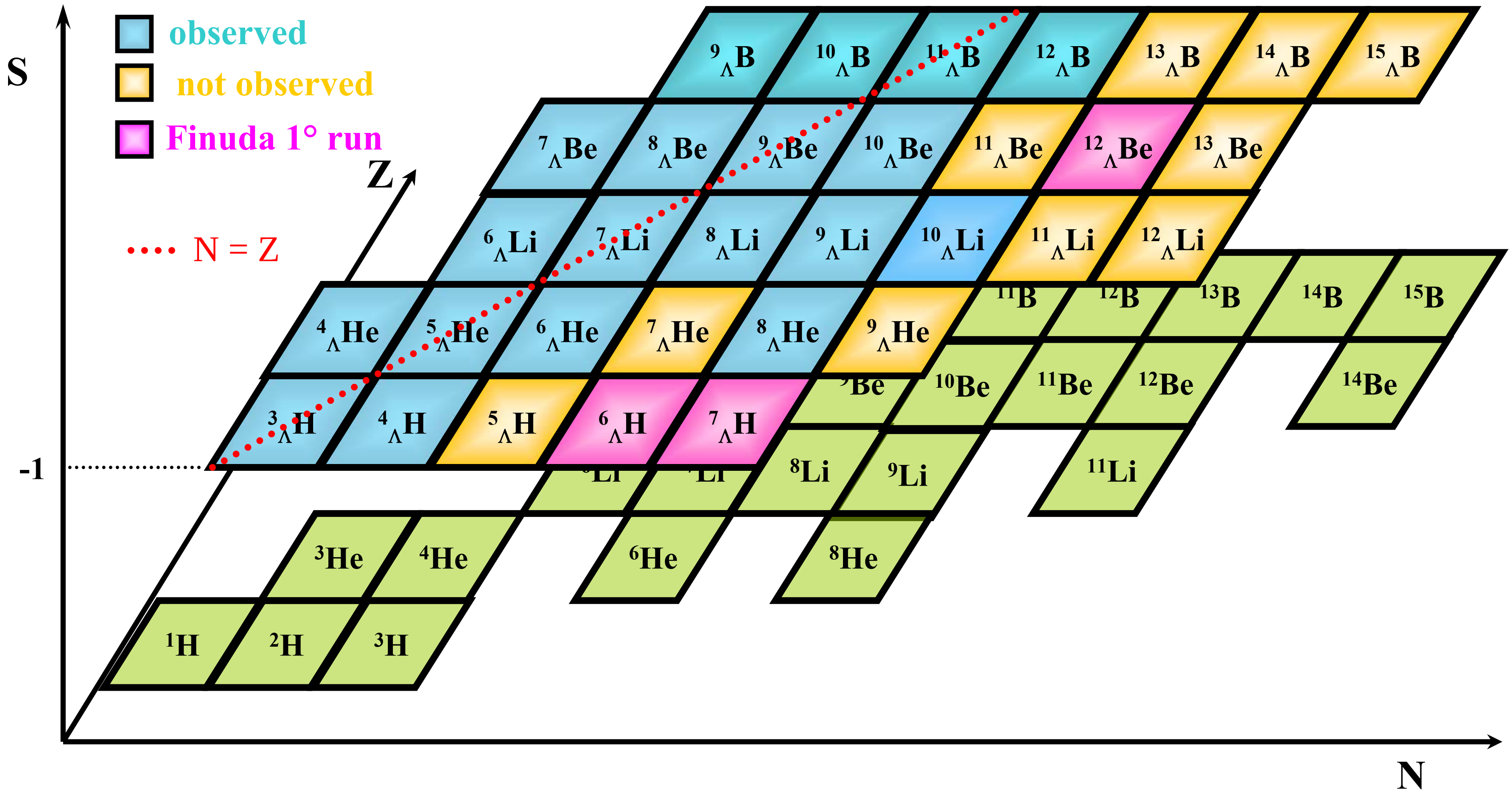
Hypernuclei with a large neutron excess.
Their existence has been theoretically predicted (L. Majling, *NP A 585 (1995) 211c*).



Neutron rich Λ-hypernuclei

Hypernuclei with a large neutron excess.

Their existence has been theoretically predicted (L. Majling, *NP A 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



Motivations

- **Hypernuclear physics:**

  ΛN interactions at low densities, the role of 3-body forces

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  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.*

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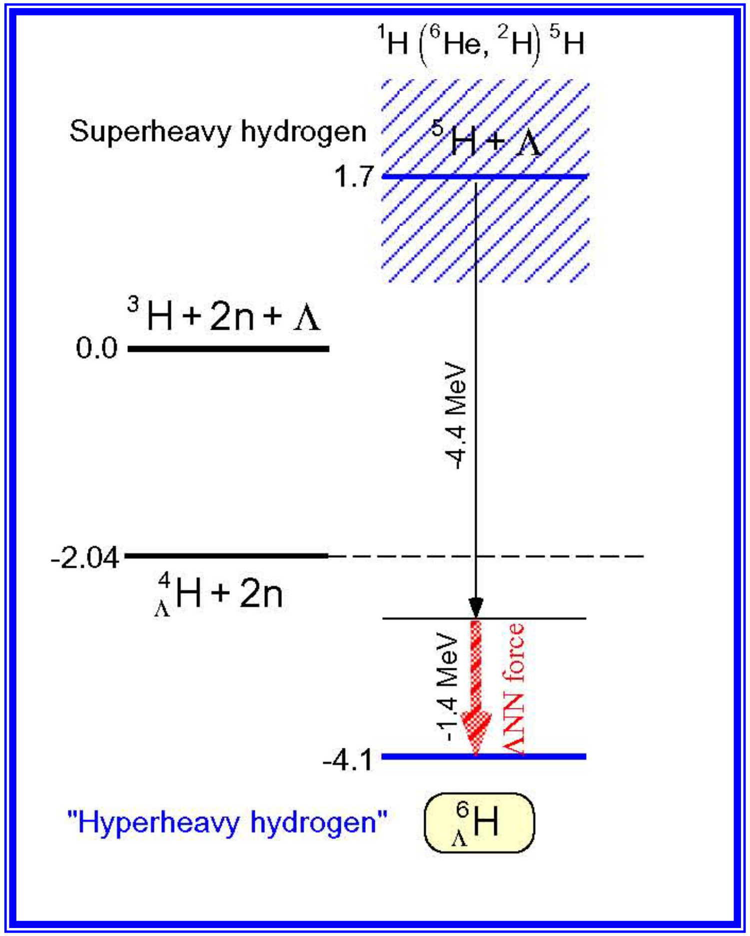
- **Astrophysics:**

  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.*



Y. Akaishi et al., Phys. Rev. Lett. 84: 3539,2000

Production of Neutron Rich Λ-hypernuclei

Brown	$K^- + p \to \pi^- + \Lambda$ $\pi^+ + n \to K^+ + \Lambda$
Orange	$K^- + p \to \pi^0 + \Lambda$ $\pi^- + p \to K^0 + \Lambda$ $e(\gamma) + p \to e' K^+ + \Lambda$
Yellow-green	$K^- + p \to \pi^0 + \Lambda$; $\pi^0 + p \to n + \pi^+$ $K^- + p \to \pi^+ + \Sigma^-$; $\Sigma^- p \leftrightarrow \Lambda n$ $\pi^- + p \to K^0 + \Lambda$; $K^0 + p \to n + K^+$ $\pi^- + p \to K^+ + \Sigma^-$; $\Sigma^- p \leftrightarrow \Lambda n$

(brown) (K^-, π^-), (π^+, K^+)

(orange) (K^-, π^0), (π^-, K^0), $(e, e' K^+)$

(yellow-green) (K^-, π^+), (π^-, K^+)

B_Λ : bound hypernuclei (Λ binding energy known)

(B_Λ) : must be bound (Λ binding energy calculated)

(?) : critically bound

— : known to be unbound

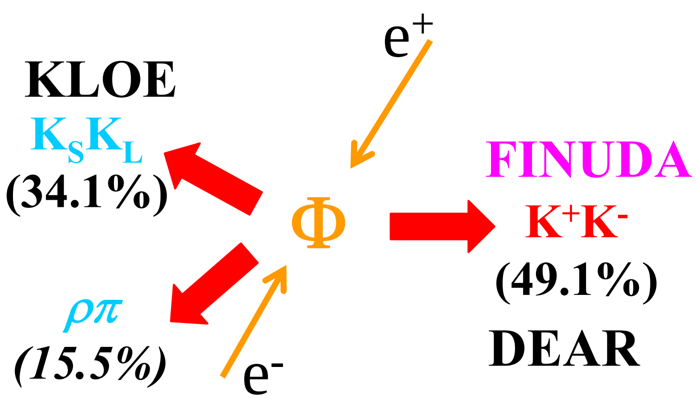
Z ↑, N →

		(?) $^{8}_{\Lambda}B$	8.29 $^{9}_{\Lambda}$B	8.89 $^{10}_{\Lambda}$B	10.24 $^{11}_{\Lambda}$B	11.37 $^{12}_{\Lambda}$B	(11.7) $^{13}_{\Lambda}B$	(12.2) $^{14}_{\Lambda}B$	(13.6) $^{15}_{\Lambda}B$	(?) $^{16}_{\Lambda}B$	(?) $^{17}_{\Lambda}B$	(?) $^{18}_{\Lambda}B$
	(?) $^{6}_{\Lambda}Be$	5.16 $^{7}_{\Lambda}$Be	6.84 $^{8}_{\Lambda}$Be	6.71 $^{9}_{\Lambda}$Be	9.11 $^{10}_{\Lambda}$Be	(10.2) $^{11}_{\Lambda}Be$	(11.4) $^{12}_{\Lambda}Be$	(11.7) $^{13}_{\Lambda}Be$	(?) $^{14}_{\Lambda}Be$	(?) $^{15}_{\Lambda}Be$	(?) $^{16}_{\Lambda}Be$	
		—	5.58 $^{7}_{\Lambda}$Li	6.80 $^{8}_{\Lambda}$Li	8.50 $^{9}_{\Lambda}$Li	(9.1) $^{10}_{\Lambda}Li$	(10.2) $^{11}_{\Lambda}Li$	(?) $^{12}_{\Lambda}Li$	(?) $^{13}_{\Lambda}Li$			
—	2.39 $^{4}_{\Lambda}$He	3.12 $^{5}_{\Lambda}$He	4.18 $^{6}_{\Lambda}$He	5.23 $^{7}_{\Lambda}$He	7.16 $^{8}_{\Lambda}$He	(8.5) $^{9}_{\Lambda}He$	(?) $^{10}_{\Lambda}He$	(?) $^{11}_{\Lambda}He$				
—	0.13 $^{3}_{\Lambda}$H	2.04 $^{4}_{\Lambda}$H	(3.1) $^{5}_{\Lambda}H$	(4.1) $^{6}_{\Lambda}H$	(5.2) $^{7}_{\Lambda}H$							
Λ												

Calculated Production Rate per K^-_{stop} of (yellow-green) is ~ 3 order of magnitude less than the measured one of (brown) (~ 10^{-3}) .

FINUDA
(FIsica NUcleare a DAΦNE)

DAΦNE: Double Annular e^+- e^-
Φ-factory for Nice Experiments:
Beam Energy 510 MeV
$L \sim 5 \cdot 10^{31} cm^{-2}s^{-1}$ - 250 Φ's s^{-1}



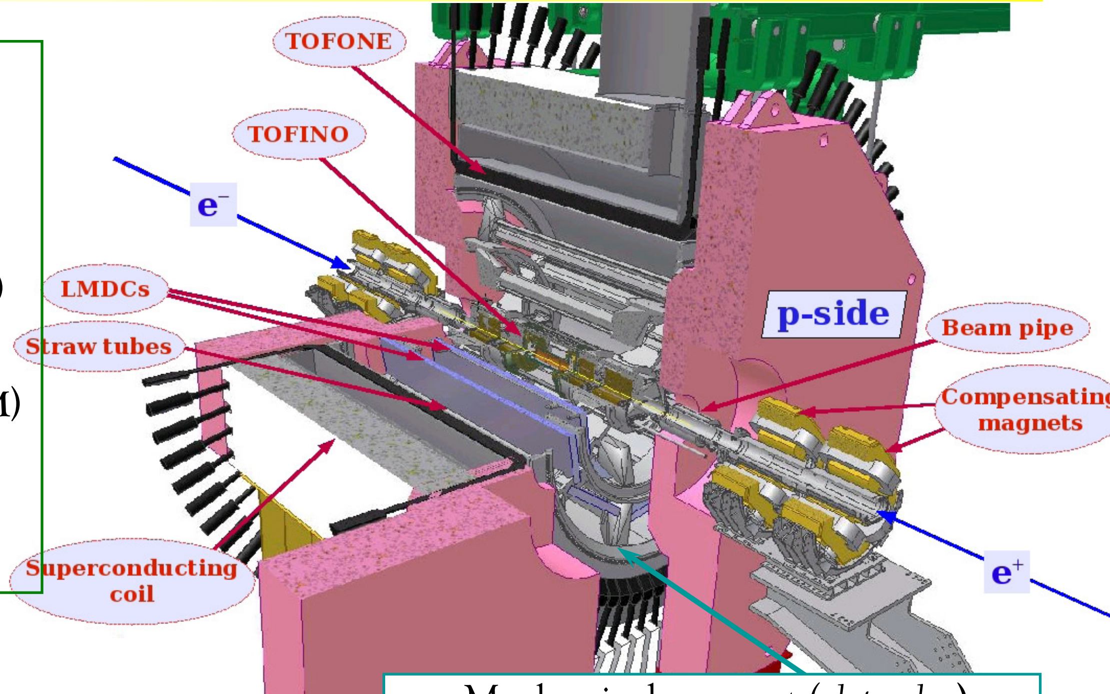
The decay of the Φ is an intense source of:

- couples of neutral and charged kaons
- collinear and tagged
- monochromatic and low energy (~16 MeV)

The FINUDA detector

<u>Detector capabilities</u>:

- ***Selective trigger*** **based on fast scintillation detectors (TOFINO, TOFONE)**
- ***Clean*** **K^- *vertex identification***
  (ISIM P.ID.+ *x,y,z* resolution + K^+ tagging)
- **p, K, p, d, … P.ID. (OSIM d*E*/d*x*)**
- ***High momentum resolution*** **(6‰ FWHM)**
  (tracker resolution + He bag + thin targets)
- ***Neutron detection*** **(TOFONE)**
- **Time-Of-Flight (TOFONE-TOFINO)**



Mechanical support (*clepsydra*)
For:

- *2424 Straw Tubes (longitudinal + stereo)*
- *16 Low-Mass Drift Chambers*
- *18 m-strip vertex detectors (ISIM/OSIM)*
- *Inner scintillator barrel – 12 slabs (TOFINO)*
- *8 Targets*

<u>Apparatus designed for a typical *collider experiment*:</u>

- **Cylindrical geometry**
- **large solid angle (> 2π sr)**
- **multi-tracking analysis**

Simultaneous study of formation and decay of strange hadronic systems by *full event reconstruction*

Neutron Rich production in FINUDA

ELEMENTARY

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

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

FINUDA data taking 2003-2004:

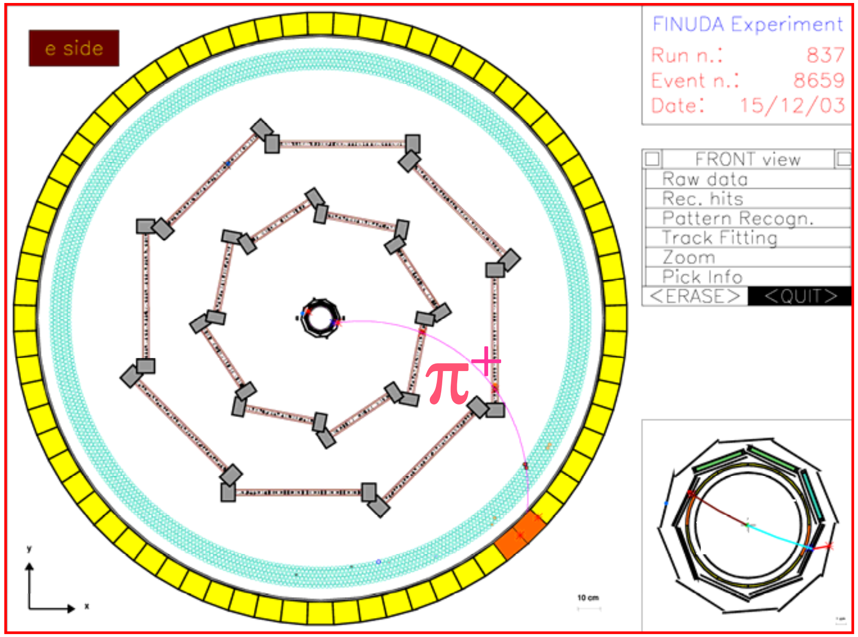
$K^-_{stop} + {}^{12}C \rightarrow {}^{12}_{\Lambda}Be + \pi^+$

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

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

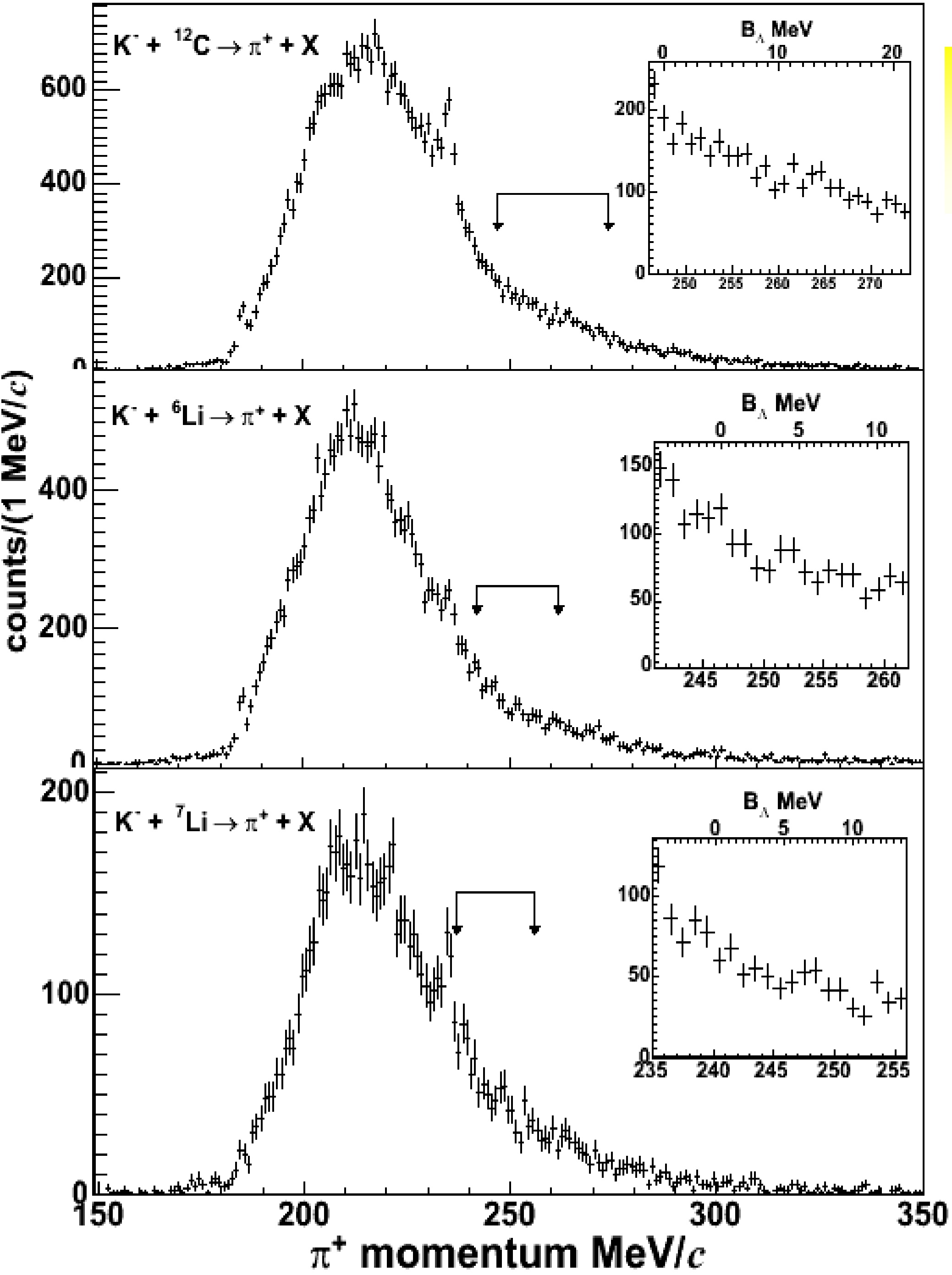
π^+ momentum is related to the Λ binding energy (B_Λ)

	B_Λ (MeV)	p_π (MeV/c)
${}^{12}_{\Lambda}Be$	11.4	262
${}^{6}_{\Lambda}H$	4.1	252
${}^{7}_{\Lambda}H$	5.2	246



Event selection:

- Reconstruction of a π^+ with a momentum value in the hypernucleus bound region
- P.ID. made using d*E*/dx from OSIM and TOF from TOFINO & TOFONE



Inclusive spectra

Background:

• $K^- + p \rightarrow \Sigma^+ + \pi^-$

$\Sigma^+ \rightarrow \pi^+ + n$

($130 < p_\pi < 250$ MeV/c)

• $K^- + pp \rightarrow \Sigma^+ + n$

$\Sigma^+ \rightarrow \pi^+ + n$

($100 < p_\pi < 320$ MeV/c)

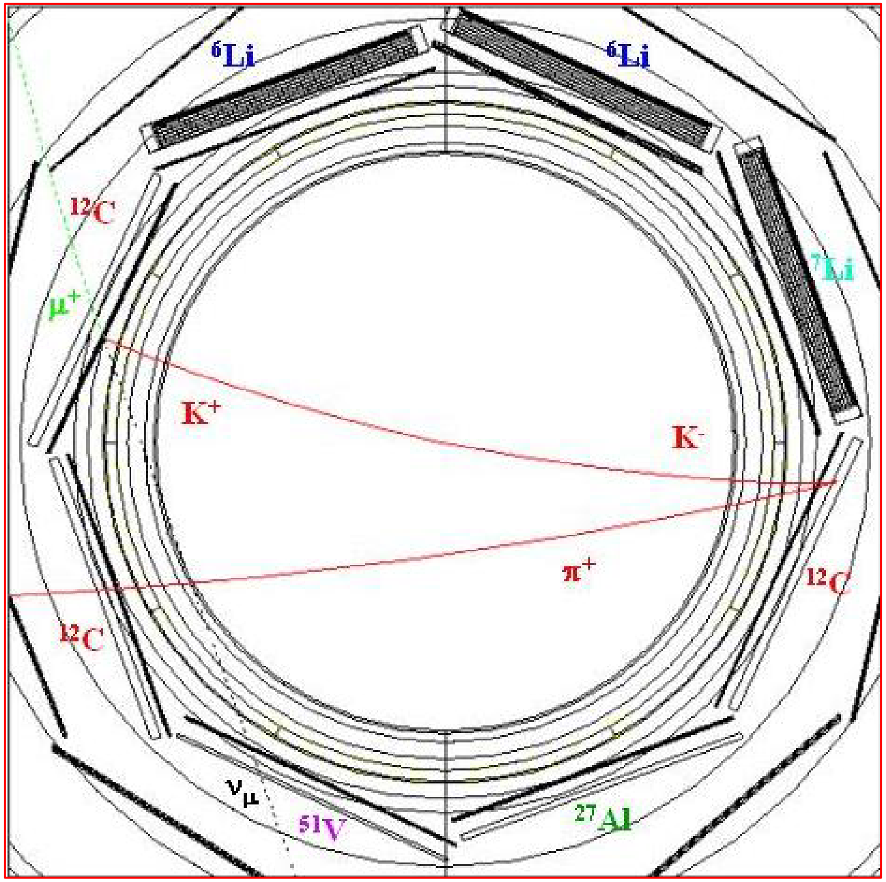
Contaminations:

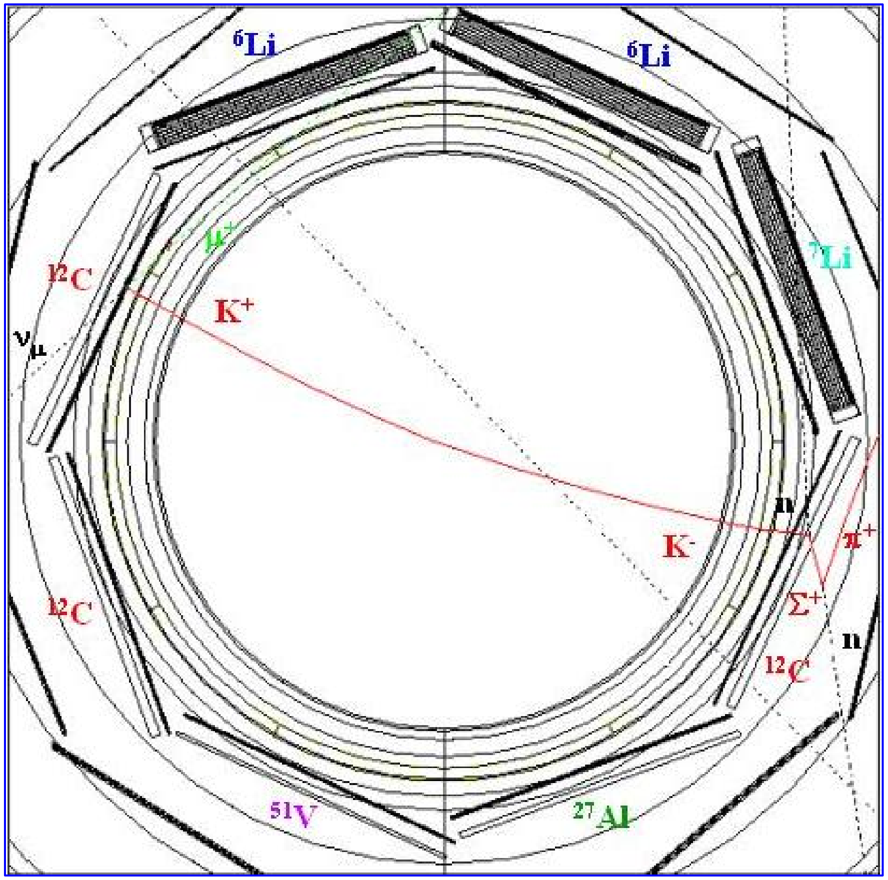
- μ^+ K^+ decay (peak@~235MeV/c)
- p Λ/Σ decay

Background reduction

Simulated NRΛH production event
(FINUDA vertex view)

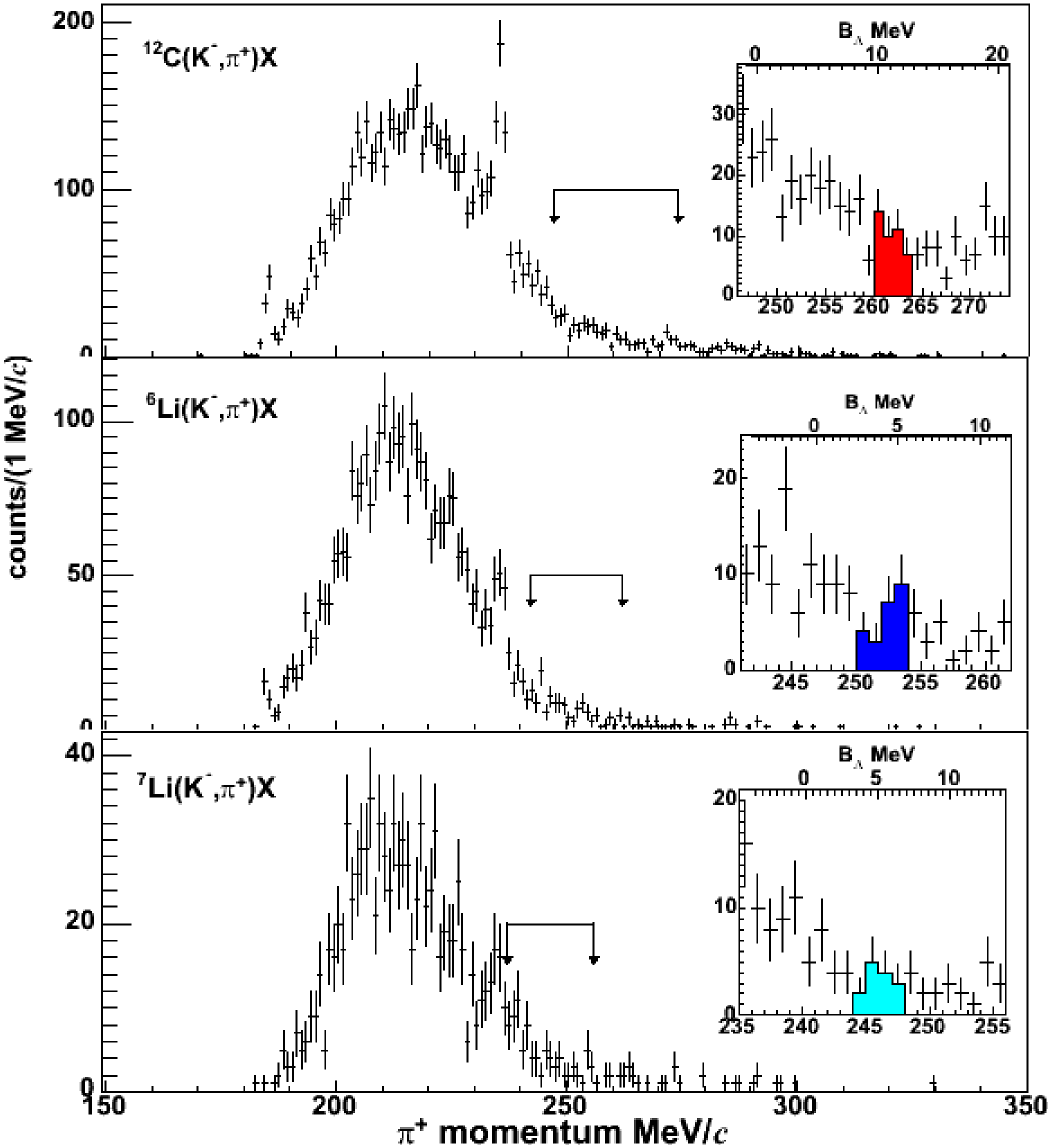
Simulated event of : $K^- + pp \rightarrow \Sigma^+ + n$
$\Sigma^+ \rightarrow \pi^+ + n$





The reconstructed distance between the origin point of π^+ and the K^- stopping point it is broader (up to 8mm) for a π^+ coming from Σ^+ decay than for the signal (peaked at less than 1mm).

Final spectra and U.L. evaluation



NRΛH	Rate / stopped K^- (90% C.L. Upper Limit)	
	FINUDA PLB 640 (2006) pp. 145-149 ($\times 10^{-5}$)	Previous best published value
$^{12}_{\Lambda}Be$	$2.0 \pm 0.4(stat)\ _{-0.1}^{+0.3}(sys)$	6.1×10^{-5}
$^{6}_{\Lambda}H$	$2.5 \pm 0.4(stat)_{-0.1}^{+0.4}(sys)$	NEW
$^{7}_{\Lambda}H$	$4.5 \pm 0.9(stat)_{-0.1}^{+0.4}(sys)$	NEW

Expected events for next run

HYPER-NUCLEUS	TARGET	B_Λ (MeV)	p_π (MeV/c)	PRODUCTION RATE / k^-_{stop}	EVS ROI	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] 6×10^{-8} (2^+)[5] 3×10^{-8} (0^+)[5]	200	8.2×10^{-6}
		13.6(0^+)[2]	271		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.*

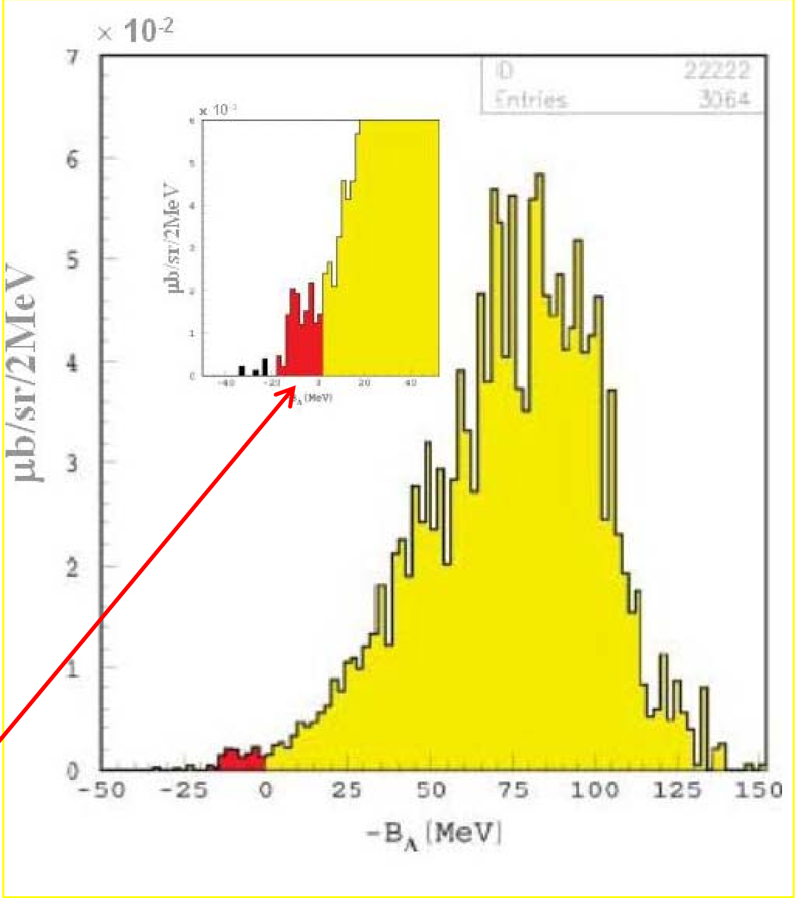
Summary

- The search of hypernuclei with large neutron excess is a field of interest in modern nuclear physics
- FINUDA spectrometer can study NRΛH states
- The first FINUDA data taking established the best published U.L. 90% C.L. value for $^{12}{}_{\Lambda}Be$ and for the first time determined the same values for $^{6}{}_{\Lambda}H$ and $^{7}{}_{\Lambda}H$.
- FINUDA run 2006/2007 will improve its published U.L. values of a factor 4. At the same time we will search for $^{9}{}_{\Lambda}He$, $^{13}{}_{\Lambda}Be$ and $^{16}{}_{\Lambda}C$.

Back-up slides

Neutron rich Λ-hypernuclei

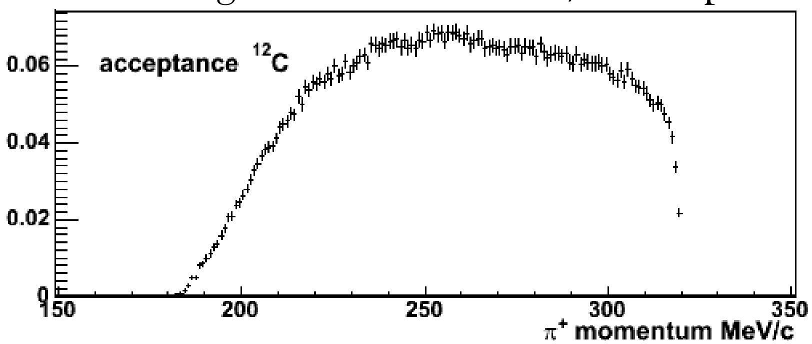
- 1953: Discovery of hypernuclei by M. Danysz e J. Pniewski (Philos. Mag. 44: 348, 1953)
- 1985: Evidence of production of ^{11}Li e ^{11}Be (Neutron Rich nuclei) $\Rightarrow$ Halo phenomena
- 1995: "*Λ* hypernuclei may be even better candidates to exhibit large values of N/Z and halo phenomena" L.Majling (Nucl. Phys. A 585: 211c,1995)
- 2005: "Production of the Neutron-Rich Hypernucleus $^{10}{}_{\Lambda}Li$ *in the* (π^-, K^+) *Double Charge-Exchange Reaction*" P.K. Saha et al. (Phys. Rev. Lett. 94: 052502, 2005)

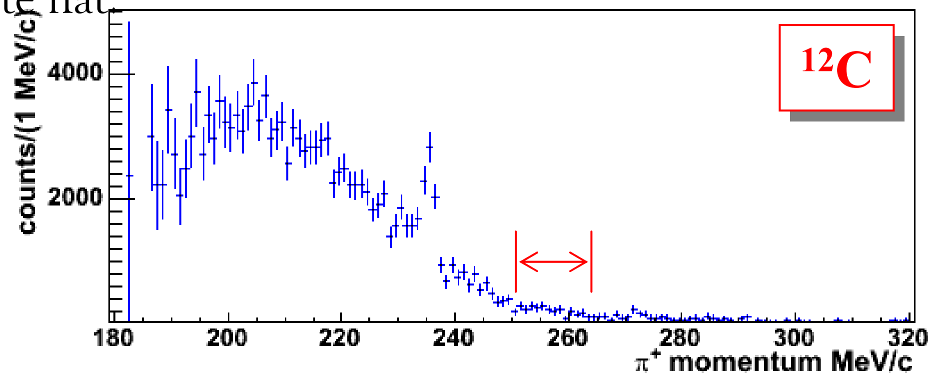


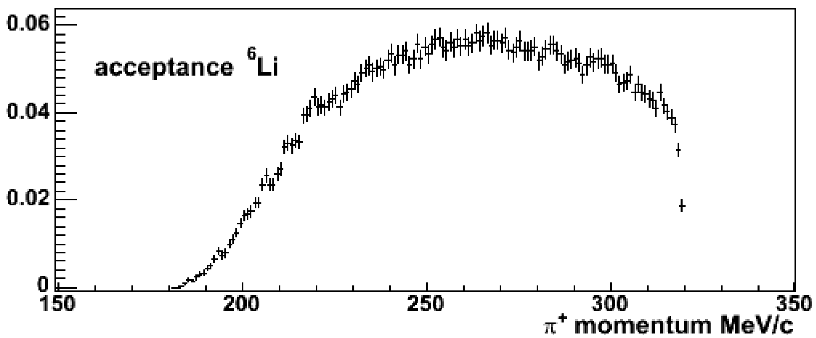
40 events of $^{10}{}_{\Lambda}Li$

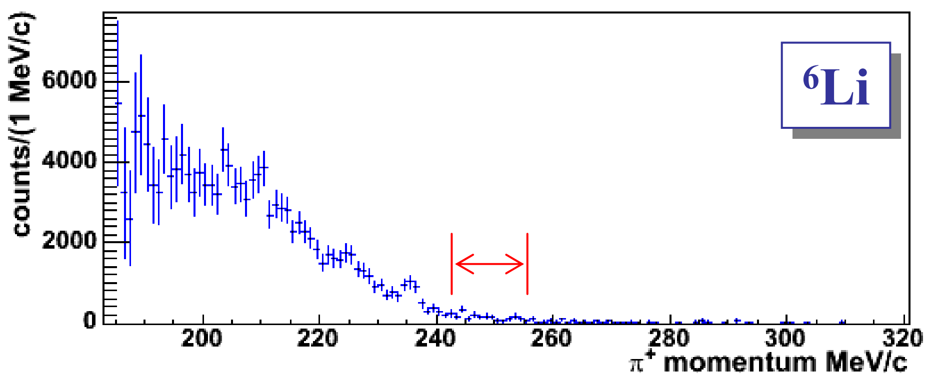
Acceptance

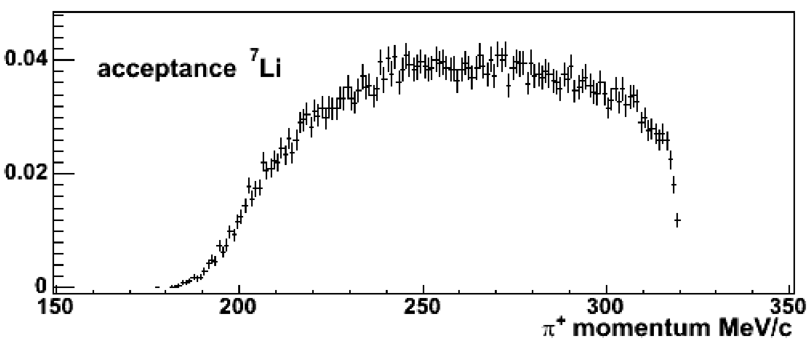
In the region 220-320 MeV/c acceptance is quite flat



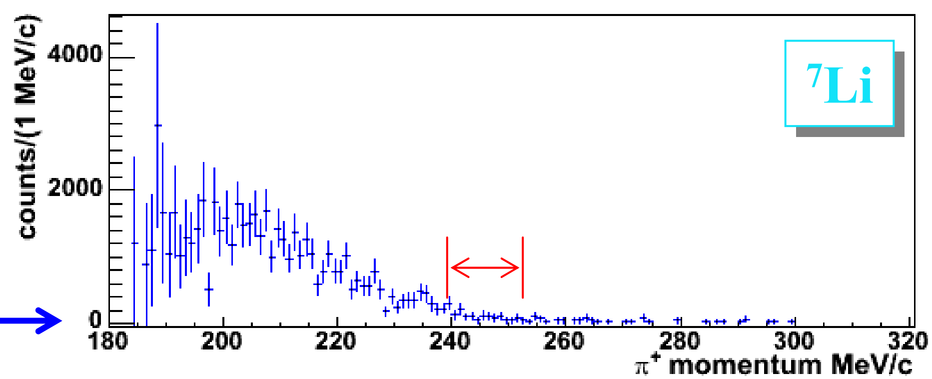




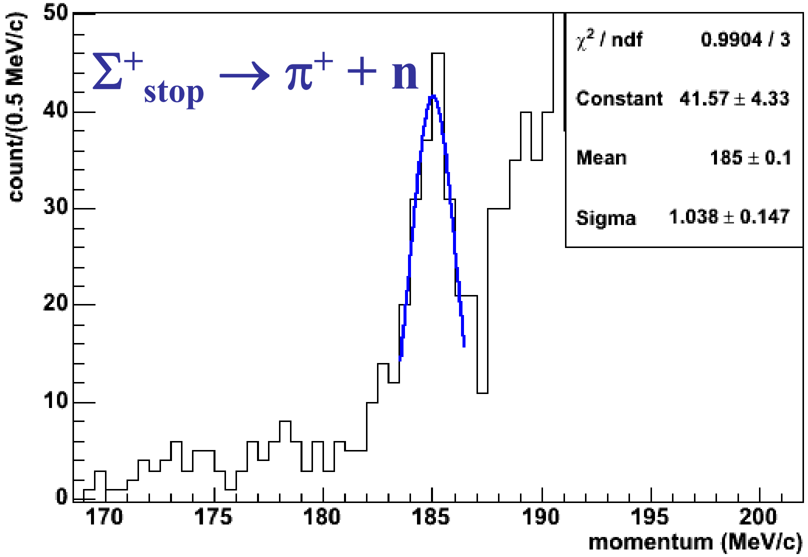


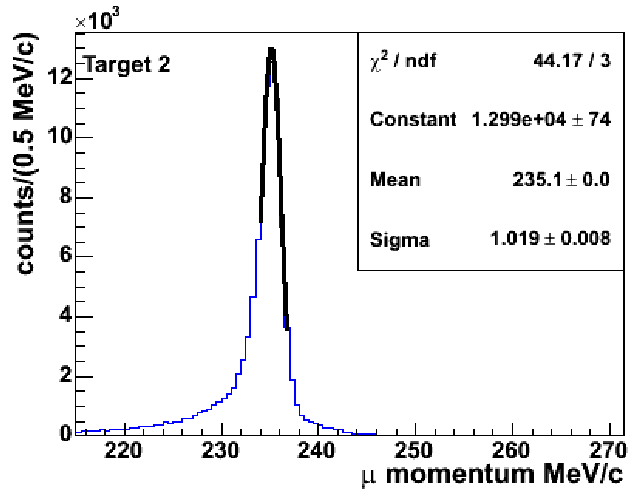


Final spectra acceptance corrected →

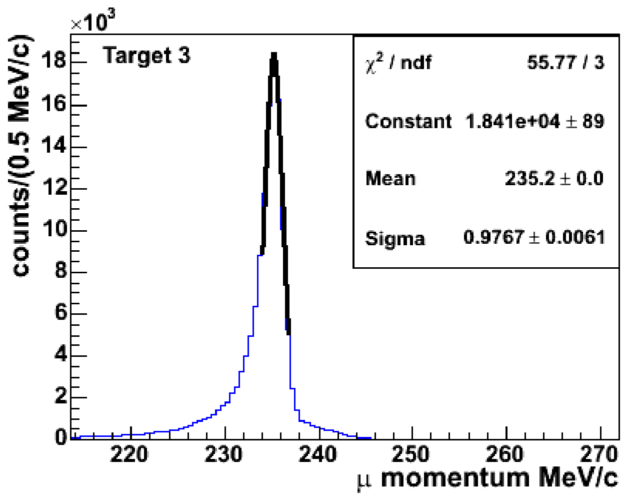


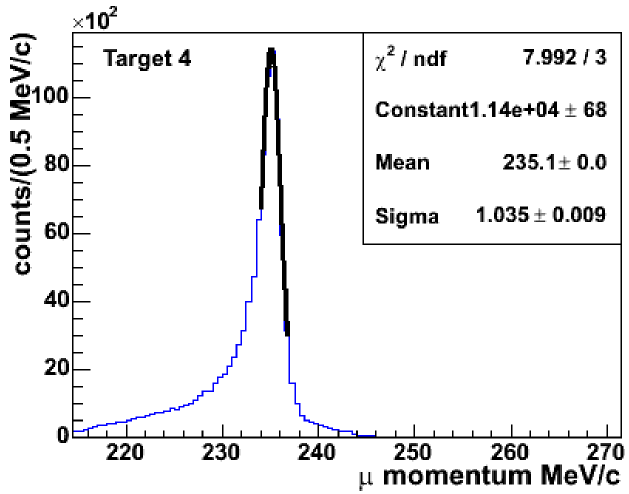
Momentum resolution in our track selection conditions





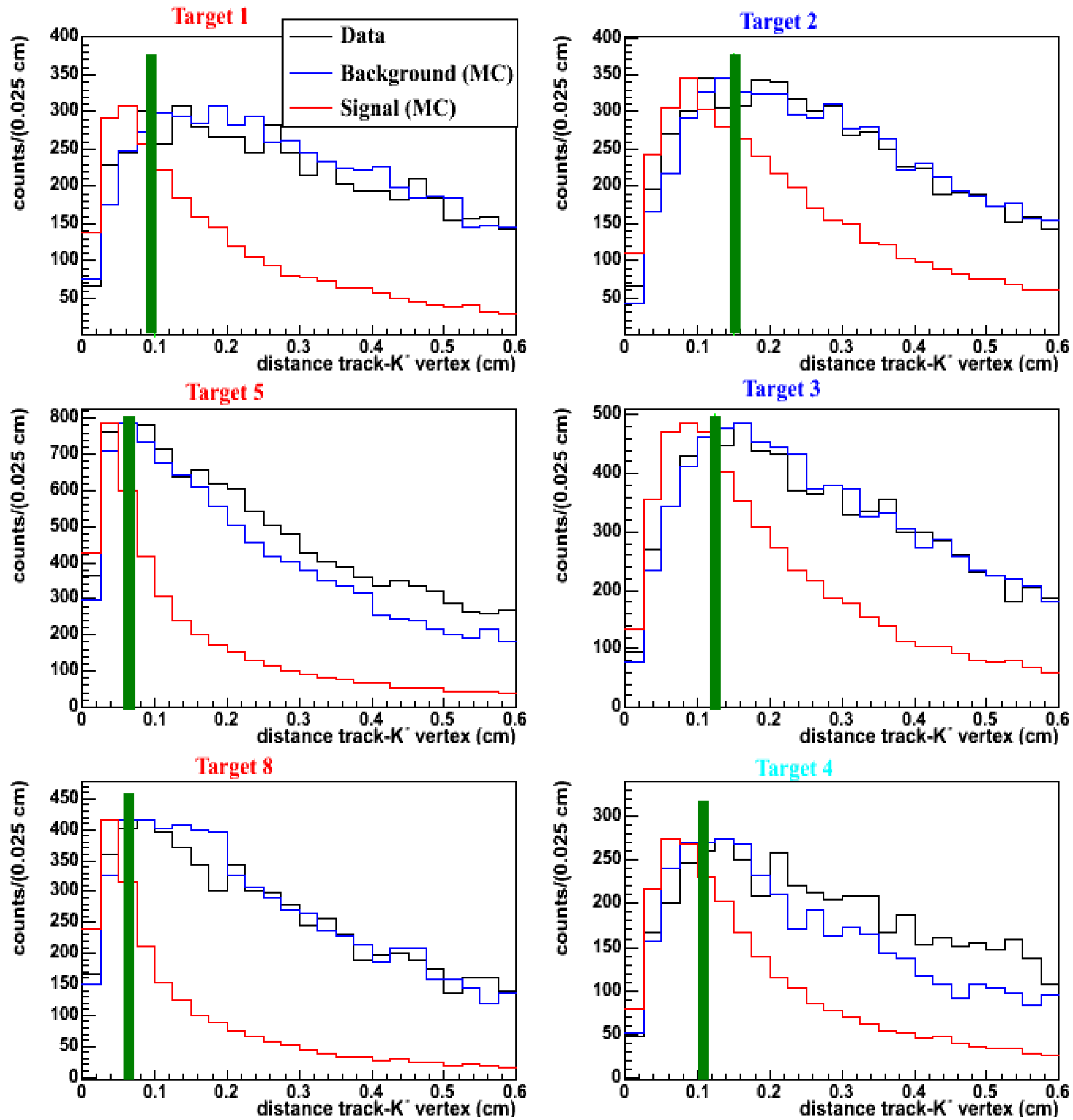
$\sigma_p \approx 0.9\%$ FWHM
@235 MeV/c
$\approx$ 1 MeV/c
[220-300 MeV/c]





Distance Selection

- The reconstructed distance between the origin point of π^+ and the K^- stopping point is peaked at less than 1 mm for a π^+ coming from the signal (**red line**).
- **Green** line select ~10% of background vs ~50% of signal ⇒ Noise to signal ratio improved of a factor ~ 5.



Rate /K^-_{stop} in the ROI

$$\mathbf{R}_{ROI} = \frac{\mathbf{N}_{\pi^+}}{\mathbf{N}_{\mu^+}} \cdot \frac{\mathbf{K}^+_{stop}}{\mathbf{K}^-_{stop}} \cdot \frac{\varepsilon_D(\mu^+)}{\varepsilon_D(\pi^+)} \cdot \frac{\varepsilon_G(\mu^+)}{\varepsilon_G(\pi^+)} \cdot \mathbf{BR}(\mathbf{K}_{\mu 2})$$

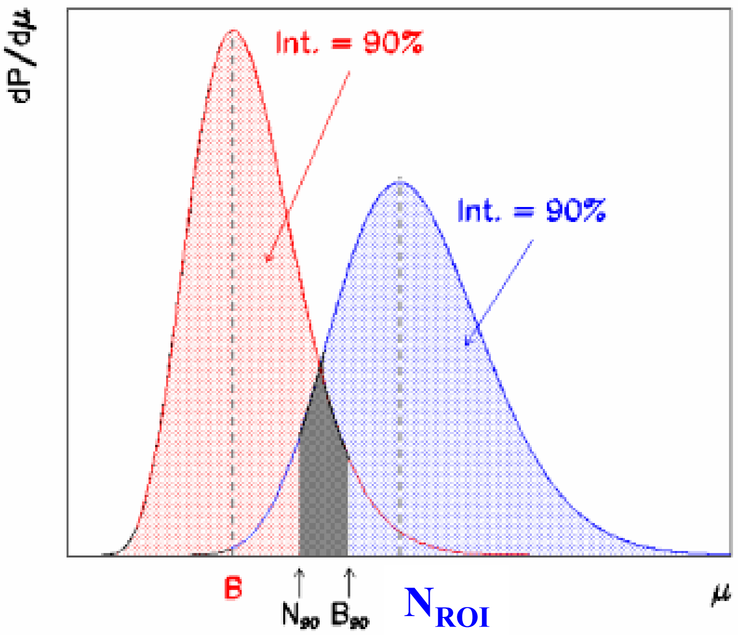
- N_π = number of π^+ in the region of interest.
- N_μ = number of μ^+.
- K^+_{stop}, K^-_{stop} = number of stopped kaons.
- $\varepsilon_D(\pi^+) \cong \varepsilon_D(\mu^+)$.
- $\varepsilon_G(\pi^+) = \alpha_G(\pi^+) \cdot \varepsilon_T(\pi^+)$, MC/RC.
- $\varepsilon_G(\mu^+) = \alpha_G(\mu^+) \cdot \varepsilon_T(\mu^+) \cdot \alpha_T(\mu^+)$, MC/RC.
- $BR(K_{\mu 2}) = 0.6343$.

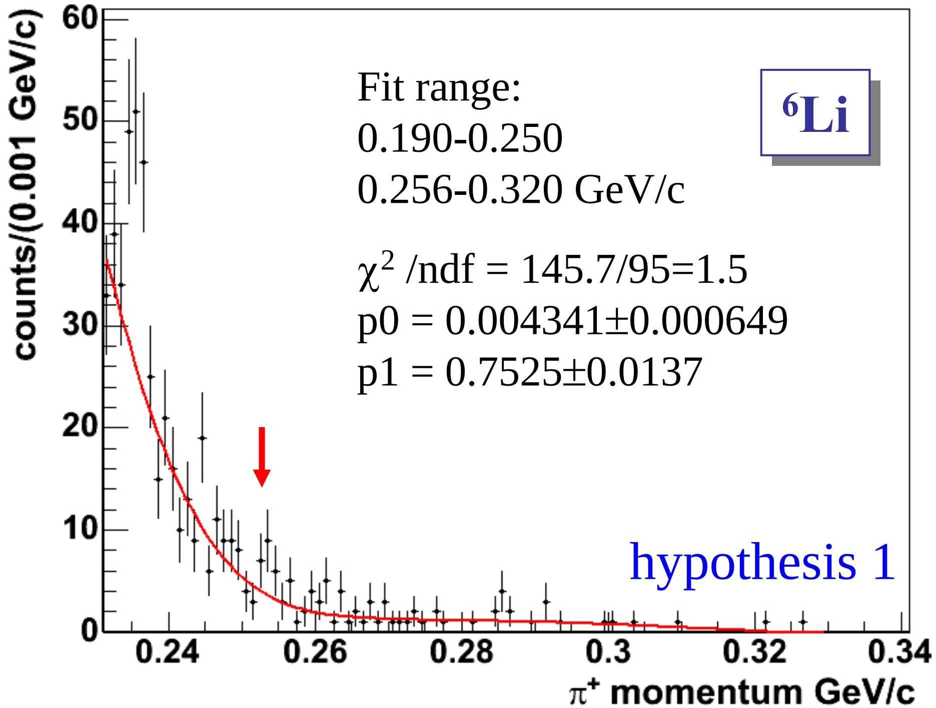
Upper Limit (U.L.)

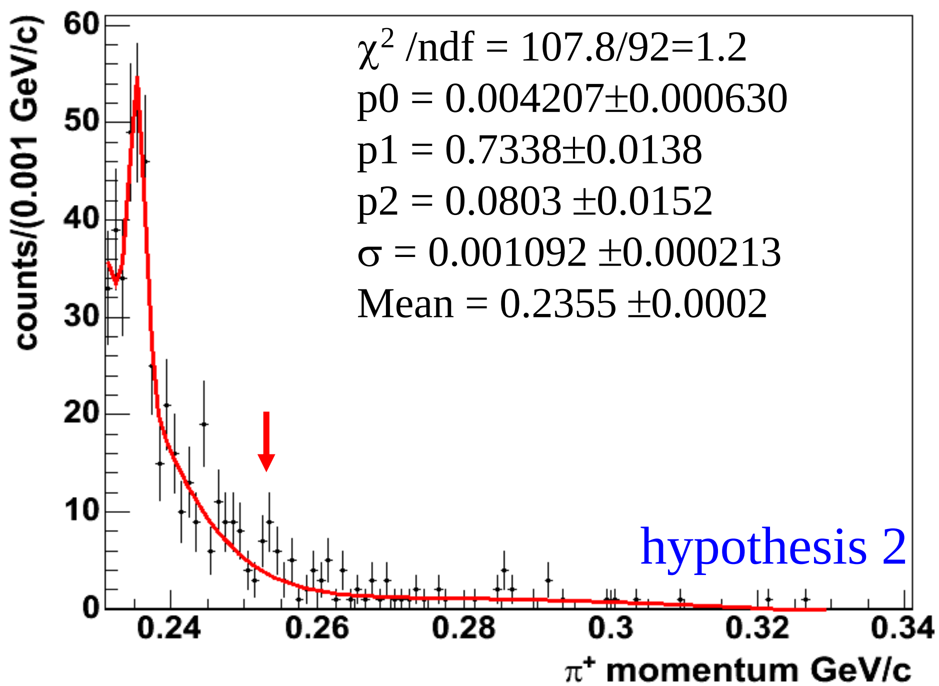
$$\text{U.L.} = x \cdot R_{ROI}$$

- ✓ S = signal, B = background : $N_{ROI} = S + B$.
- ✓ $x = \dfrac{S}{N_{ROI}}$ maximum fraction of N_{ROI} that may be ascribed to NRΛH at fixed C.L. (90%).
- ✓ $S = N_{ROI} - B$
- ✓ $\displaystyle\int_{N_{C.L.}}^{\infty} \frac{\mu^{N_{ROI}} e^{-\mu}}{N_{ROI}!} d\mu = C.L.$

$$\int_{0}^{B_{C.L.}} \frac{\mu^{B} e^{-\mu}}{B!} d\mu = C.L.; \quad B_{C.L.} \geq N_{C.L.}$$







Background estimation

1) Different background shapes give good χ^2 [1.2 – 1.5] (due to big error), but different value of B and S = N-B ⇒ Need to incorporate uncertainties in order to use Feldman & Cousins method.
2) Any evaluation of S = N-B gives values lower than the maximum not significant signal at 90% C.L.

hypothesis	N_{tot} ROI	S=N-B	R/K^-_{stop} (U.L.)
1	25	9.64	$1.8 \pm 0.9 \times 10^{-5}$
2	25	10.54	$2.0 \pm 0.9 \times 10^{-5}$
U.L.	25	11	$2.0 \pm 0.4 \times 10^{-5}$