Recent results of the FINUDA experiment

Francesca De Mori

The FINUDA physics program

- ✓ Λ Hypernuclei spectroscopy with the (K^-_{stop}, π^-) reaction on several different nuclei *(at the same time!)*
  - ✓ Tool to test
    - ✓ Theoretical models of ΛN (YN) potentials
    - ✓ Single particle nuclear models
    - ✓ Existence of bound states with strangeness
- ✓ Hypernuclear weak decays
  - ✓ Study of baryon-baryon weak processes in nuclear matter:
    - ✓ $\Lambda \rightarrow \pi N$ vs $\Lambda N \rightarrow NN$ (4-baryon weak interaction)
- ✓ Other topics:
  - ✓ Search for neutron rich hypernuclei
  - ✓ Study of hypernuclei rare decay channels
  - ✓ Σ-hypernuclei spectroscopy (if they exist)
  - ✓ ***Existence of deeply bound kaonic states***

Deeply bound kaonic nuclei

(S=-1) bound $\bar{K}$-nucleus systems

Do they exist?

Crucially depends on shape of $\bar{K}$-nucleus potential

YES (very deep attractive optical potential) 150-200 MeV

Akaishi-Yamazaki [PLB535(2002)70; PRC 65 (2002) 044005]
Kaiser et.al, [NPA594 (1995) 325]

NO (shallow optical potential) 50-75 MeV→small B & large Γ

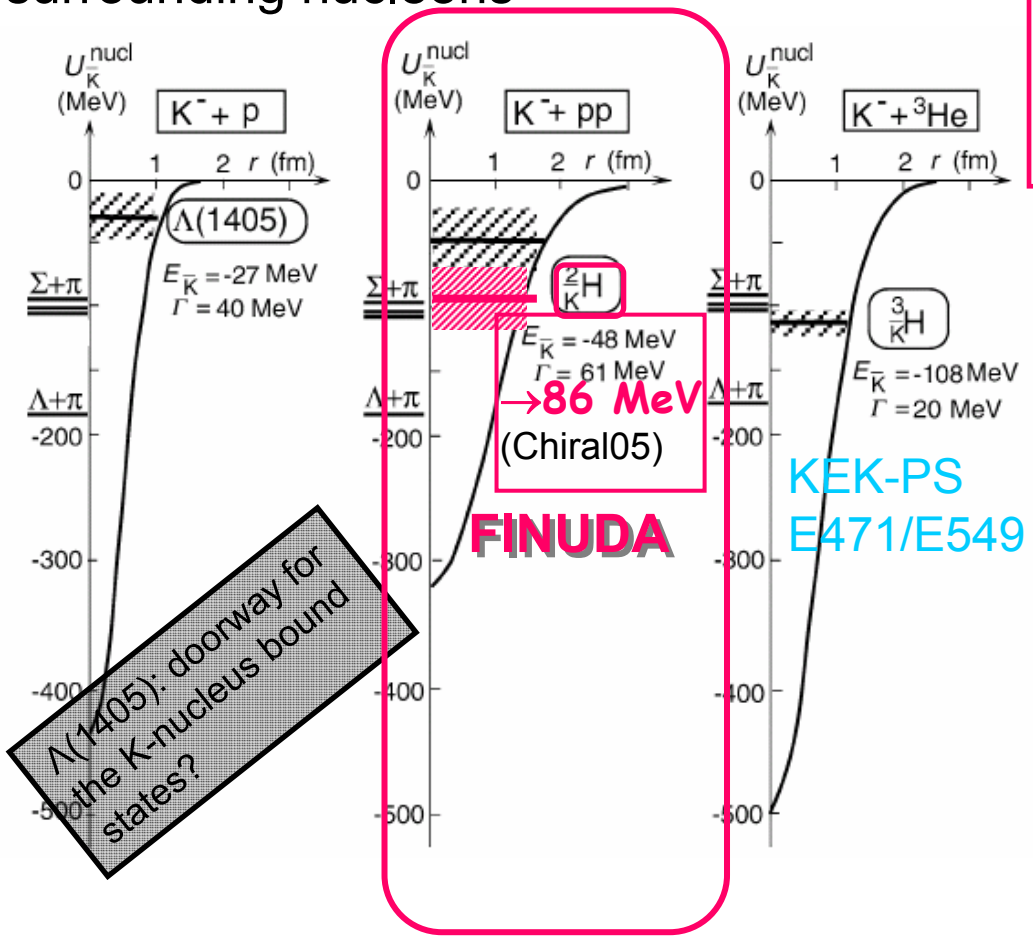
Schaffner-Bielich et.al [N.P. A669 (2000)],
Ramos et.al [N.P. A671 (2000) 481],
Cieply et.al [N.P. A696 (2001) 173]

If found, they would provide fundamental data about:

K-N potential, Λ(1405), nuclear compressibility, chiral symmetry restoration, **effective kaon mass inside nuclear matter** (strangeness condensation, neutron stars…), …

$\bar{K}$-nucleus bound states: theoretical expectations

The $\bar{K}N^{(I=0)}$ strong interaction stabilizes the nuclear matter attracting the surrounding nucleons



Simpler system (*strange dibaryon*): **K^-pp ($^{2}_{K}H$)** the presence of the $\bar{K}$ attracts the two unbound protons to form a bound state with B=86 MeV and Γ= 61 MeV .

The binding energy increases with the increase of the number of I=0 pairs, and the decrease of I=1 ones

If the state is located below the Σπ threshold, the I=0 single nucleon absorption channel is energetically closed

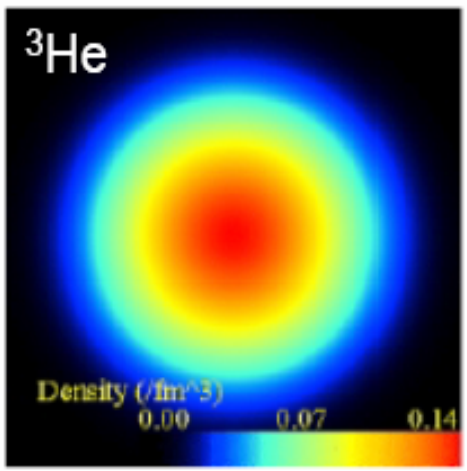
The predicted binding is far deeper than in any other hadron-nucleus bound system(B.E.~20% kaon rest mass)

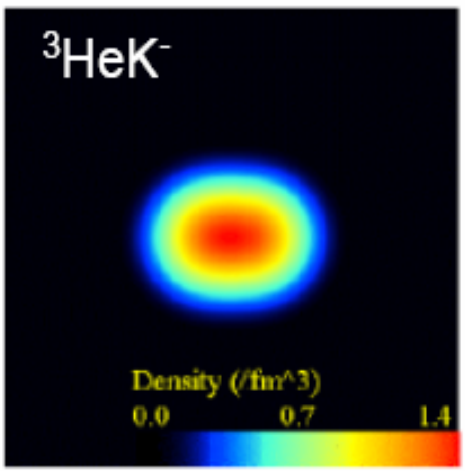
[Y.A. Phys. Lett. B 535, 70 (2002)]

$\bar{K}$-nucleus bound states features: theoretical expectations

- Doté et al. use an Antisymmetryzed Molecular Dynamics model to predict kaon bound system masses (PLB590(2004),51)
  - Prediction of the shrinking effect due to $\bar{K}N$ interaction
    - The bound states in the table lie below the $\Sigma\pi$ threshold
      ➡ narrow states, experimentally identifiable
  - **High nuclear density and low temperature systems**

$\rho_0 = 0.14\ fm^{-3}$ $\rho_0 = 1.39\ fm^{-3}$





System	Binding energy	Central density (fm^{-3})
ppn	10 MeV	ρ_0
ppnK	120 MeV	$10\rho_0$
ppnKK	220 MeV	$20\rho_0$

Search methods for deeply bound $\bar{K}$-states

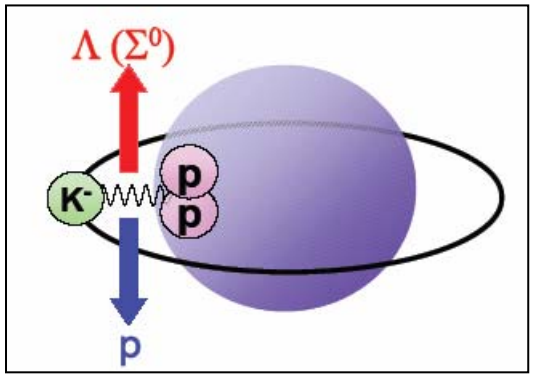
- **Invariant mass spectroscopy**
  - Based on the kaonic nuclear states feature of decaying into hyperons
    - $(K^-pp) \rightarrow \Lambda + p$
    - $(K^-ppn) \rightarrow \Lambda + d$
    - Typically:
      - $p_{\Lambda,p} \sim 500$ MeV/c
      - $p_{\pi} < 200$ MeV/c
      - $p_{decay\ p} \sim 500$ MeV/c

  – Necessary to fully reconstruct all the particles emitted in the decay!

  – The decay occurs at rest: angular correlation between the emitted particles required!

- **Missing mass spectroscopy**
  - Measurement of the momentum of the monochromatic recoiling particle in a A(K,N)X reaction

FINUDA @ DAΦNE
FOPI @ GSI

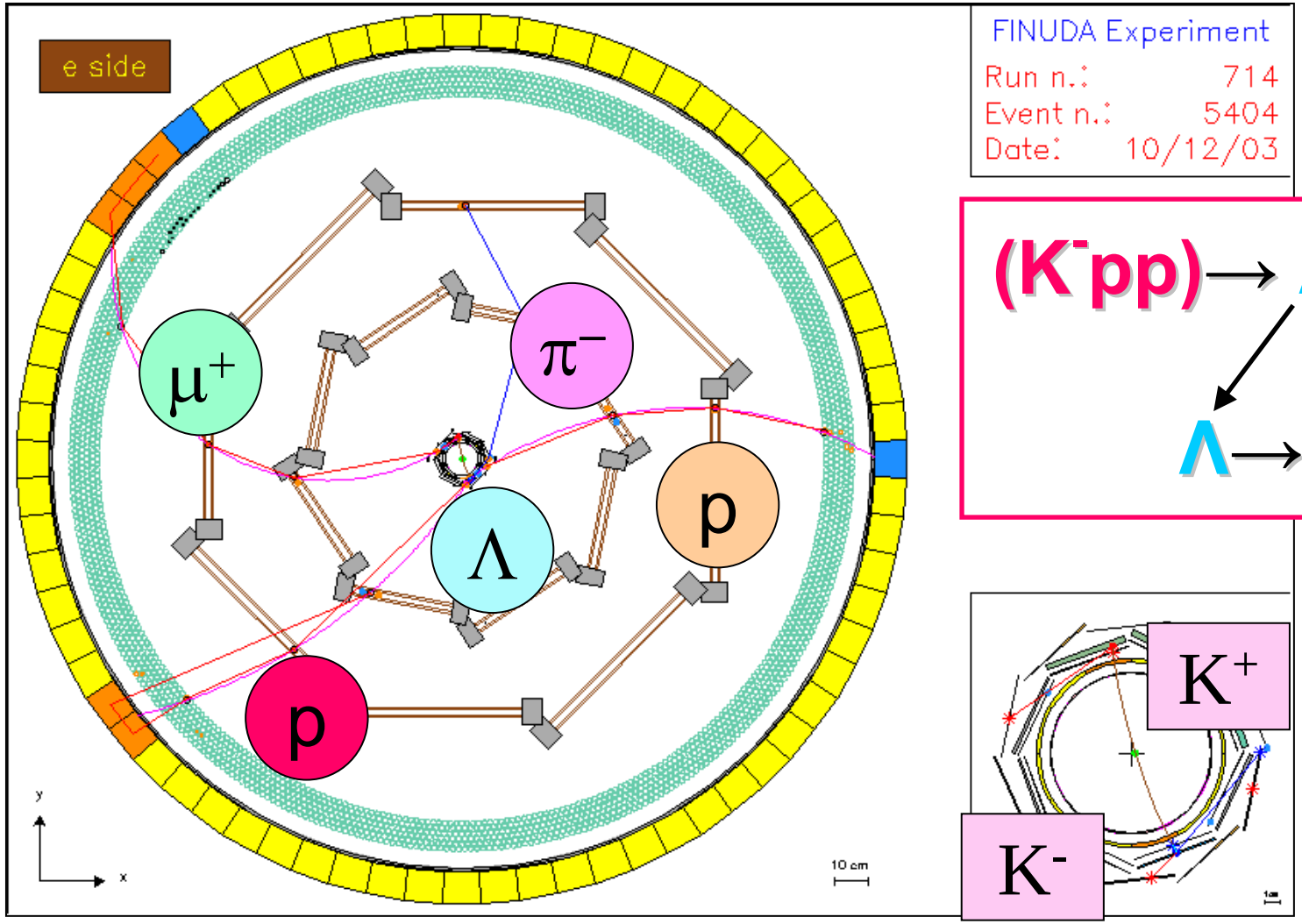


•With stopped K^-:
- •KEK-PS E471, E549
- •FINUDA @ DAΦNE

•With in flight K^-:
- •BNL-AGS E930
- •KEK-PS E548

Search of kaonic states (with two nucleons) in FINUDA with the invariant mass method

Evidences of the strange dibaryon in FINUDA with the invariant mass method

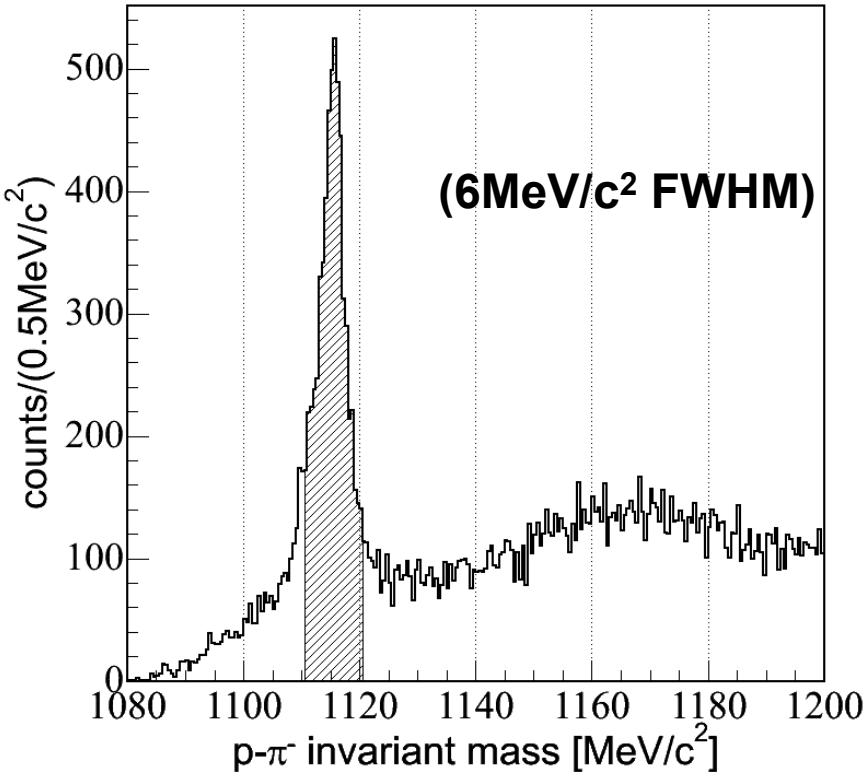


$$(K^- pp) \rightarrow \Lambda + p$$

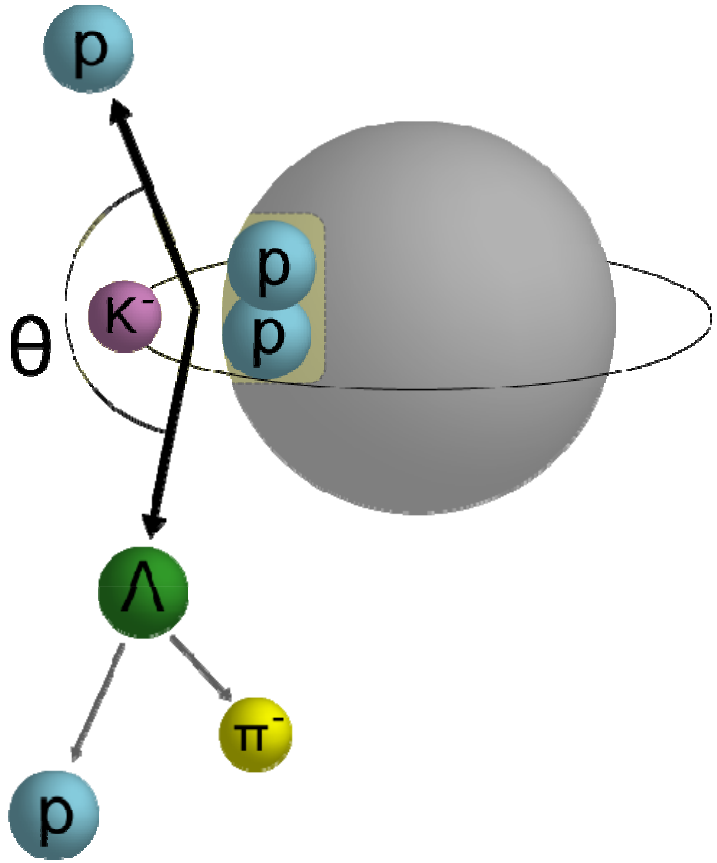
$$\Lambda \rightarrow p + \pi^-$$

K^-pp identification (1): direct observation of a Λ

Invariant mass spectrum for a proton and a negative pion system (PID with vertex detector)



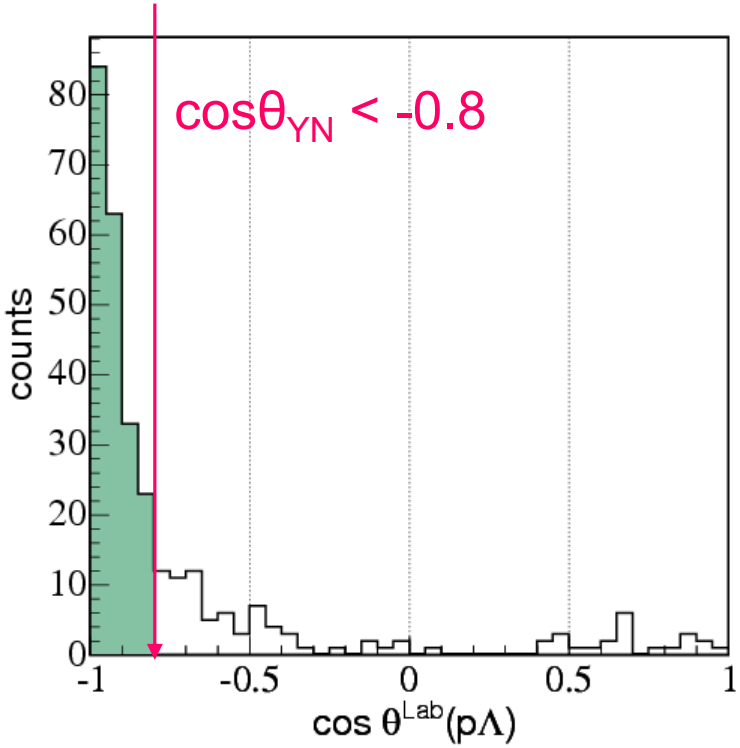
for all proton-pion pair

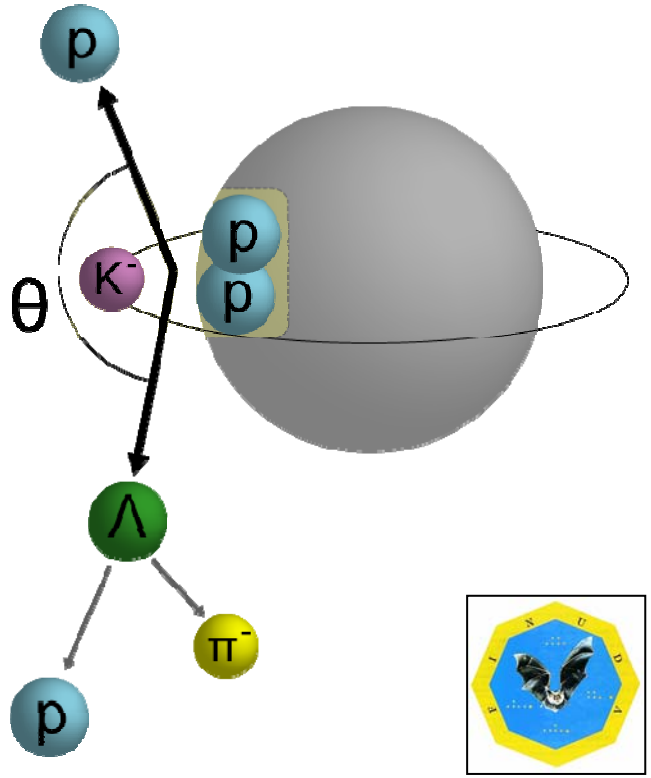


the acceptance of the apparatus cuts the Λ's with momentum less than 300 MeV/c, due to the momentum threshold for π^-

K^-pp identification (2): back-to-back p-Λ pair

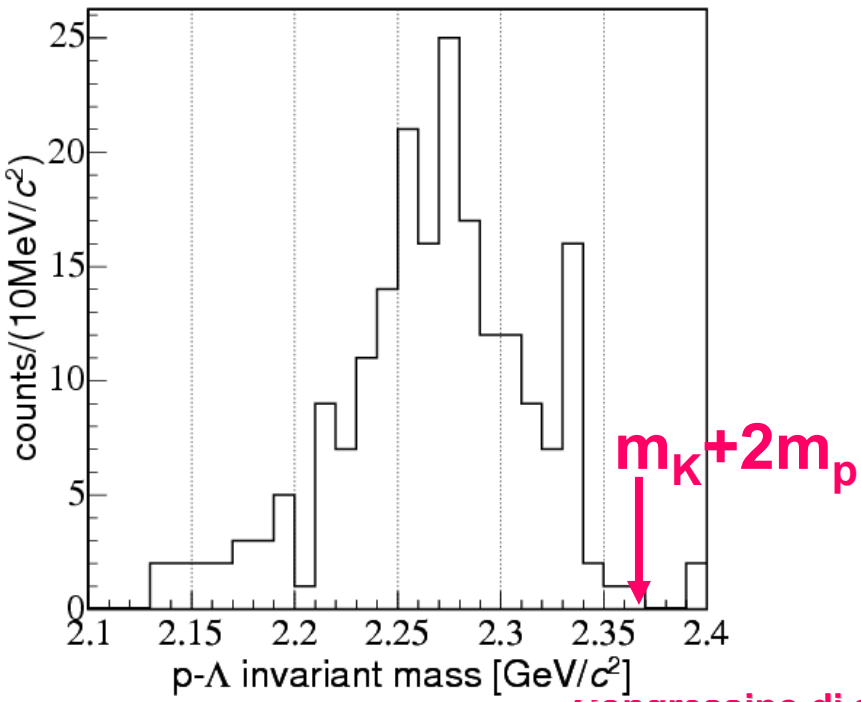
- When a kaon interacts with two nucleons and an hyperon-nucleon pair (Λp, Σ^0p, Σ^+n) is produced, they are expected to be emitted in opposite directions, ignoring a f.s.i. inside the nucleus.
- About the 5% of events in FINUDA have a (Λp) coincidence
- Event selection: $\cos\theta_{YN} < -0.8$

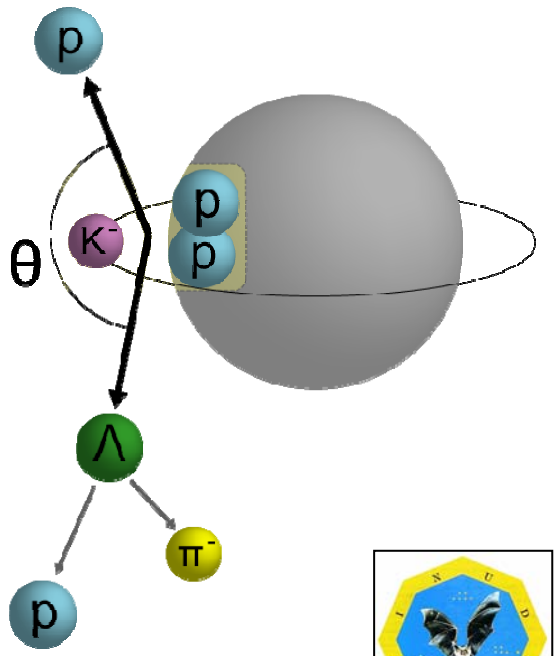




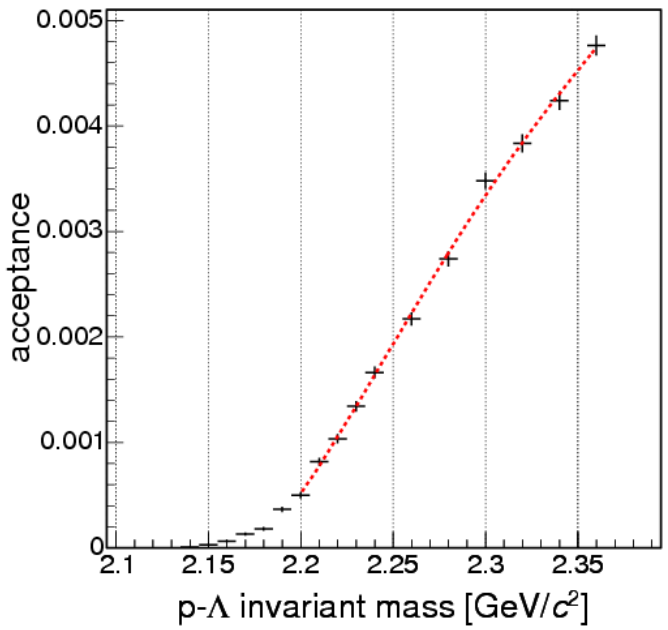
Invariant mass of the (Λp) system: light targets

- Two nucleon absorption: the mass of the system should be close to $m_K+2m_p \approx 2370$ MeV (minus the separation energy of the two protons < 20 MeV, & kinetic energy of the system)
- Significant mass decrease of the (K^-pp) system!
  - Consistency of the hypothesis of a bound state !!!!!



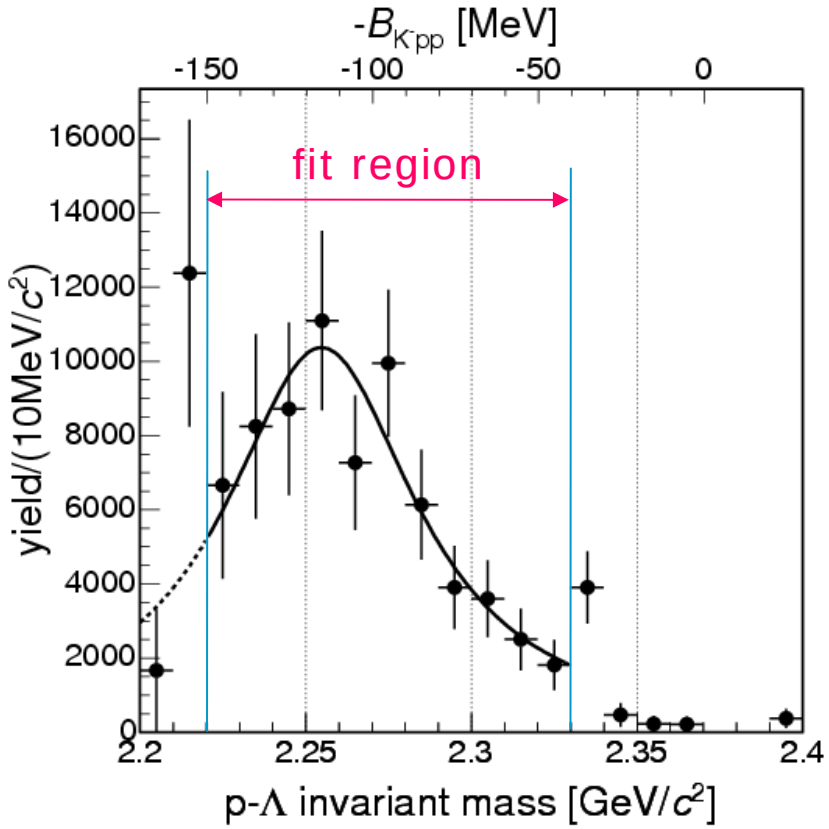


Acceptance correction and result



FINUDA Coll., PRL 94(2005)212303

6 light nuclear targets used: ^{6}Li,^{7}Li,^{12}C



The two nucleon absorption

$$K^- pp \rightarrow \Sigma^0 + p$$

And then the Σ^0 decay,may contribute in the low-mass region (<2.22GeV/c^2).

M = (2255 ± 9) MeV
Yield ≈ 10 $^{-3}$ stopped K$^-$

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

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

Congressino di sezione,

Theoretical calculation of K^-pp state

- Yamazaki and Akaishi
  [Phys. Lett. B 535 (2002) 70]
  B= 48MeV, Γ=61MeV
- Akaishi, Dote and Yamazaki
  [Phys. Lett. B 613 (2005) 140]
  B= 86MeV, Γ=58MeV
  - Relativistic effect
  - Enhanced KN interaction
- Ivanov et al. [nucl-th/0512037]
  B= 115MeV, $\Gamma^{non\text{-}pionic}$=28MeV ($\Gamma^{pionic}$=0MeV)

Invariant-mass spectroscopy for other channels:

$$(2\text{-}1)\ K^- pn \rightarrow \Lambda + n$$

$$(2\text{-}2)\ K^- pn \rightarrow \Sigma^- + p$$

preliminary

Search for K^-pn bound states

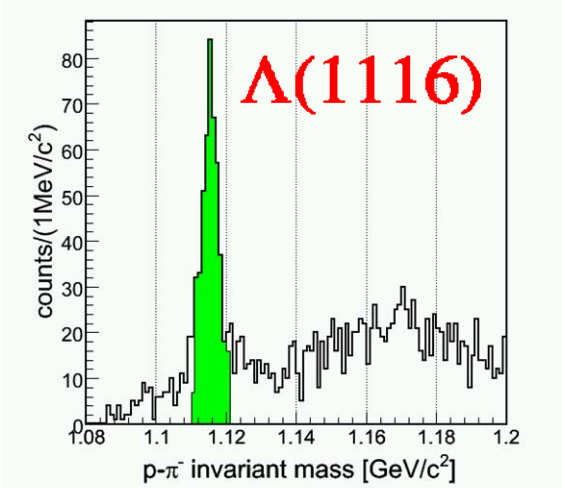
- Invariant-mass spectroscopy for

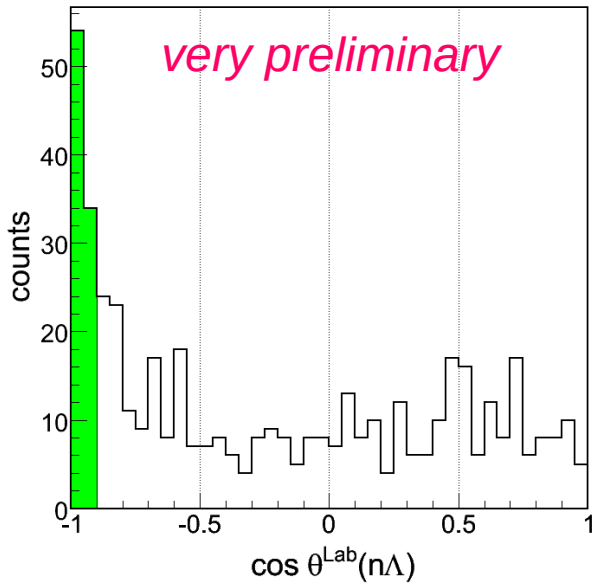
$$K^- pn \rightarrow \Lambda + n \, , \; \Sigma^- + p$$

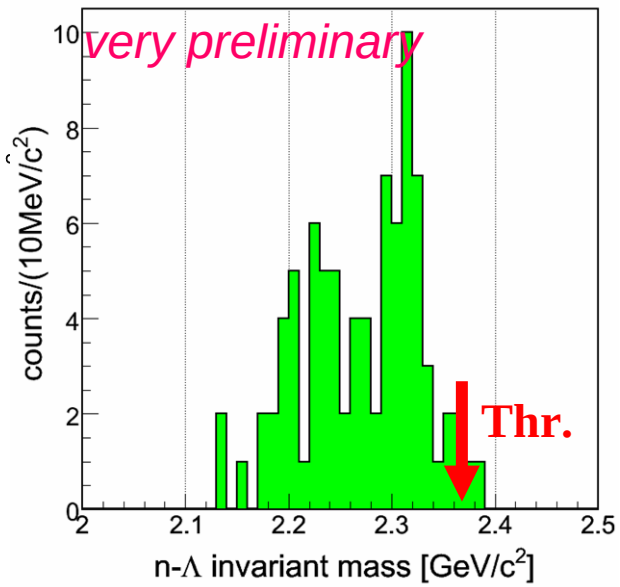
  – including a neutron in the final state
  – Two kinds of "K^-pn" states are expected.
    - Isobaric analog state of K^-pp (pn: T=1)
    - K^-d (pn: T=0) (much less bound)
    - Isospin dependence of *KN* interaction
  – Λ tagging and back-to-back Λn selection
  – Σ^- tagging and back-to-back Σ^-p selection

Λ / Σ^- selection and back-to-back correlation

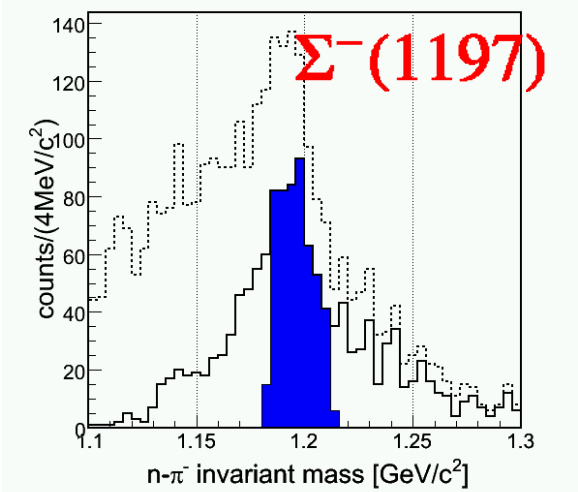
$K^- pn \rightarrow \Lambda + n$

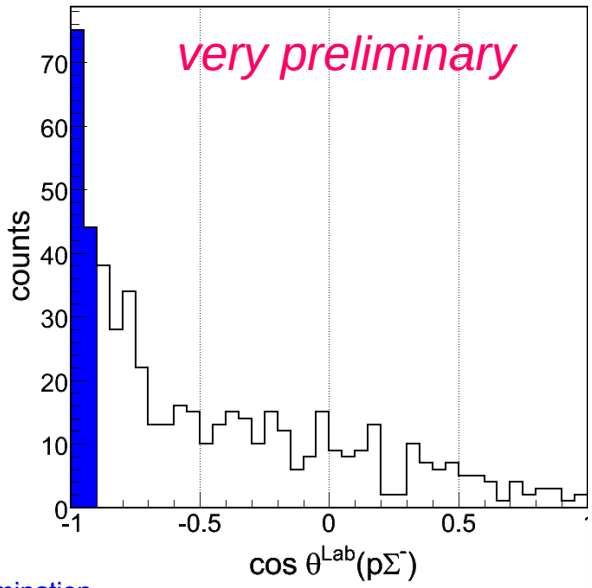


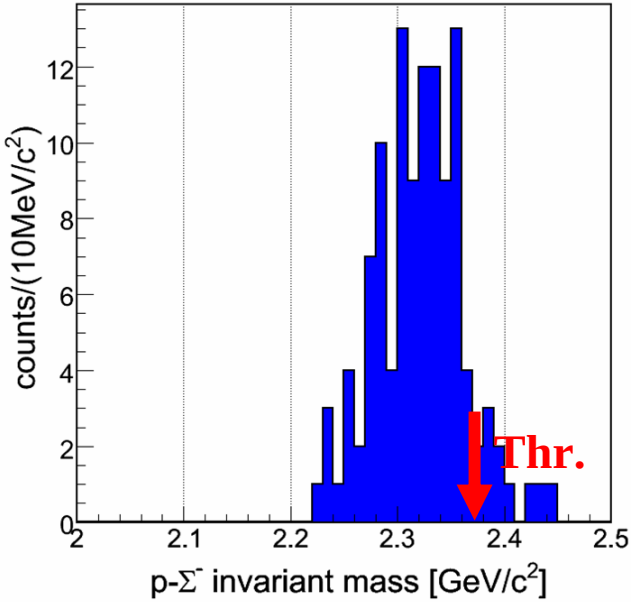




$K^- pn \rightarrow \Sigma^- + p$







..... no cuts

—— p_π>200MeV/c to reduce Λ decay contamination

Few comments on K^-pn analysis

- Not enough statistics (~100 each) to say something sure. Waiting for the new data taken in '06-'07.
- Theoretically, a loosely-bound K^-pn bound state is predicted by Yamazaki and Akaishi (PLB535(2002)70).
- The branching ratio of Λ+n to Σ^-+p will be obtained.

Search of the strange tribaryon S^0 with FINUDA

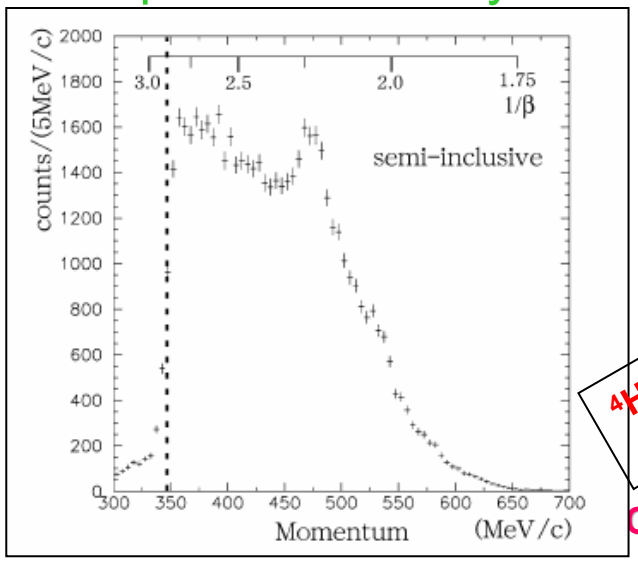
KEK-E471 experimental indications of the strange tribaryons

KEK-PS E471 ***miss. mass method***

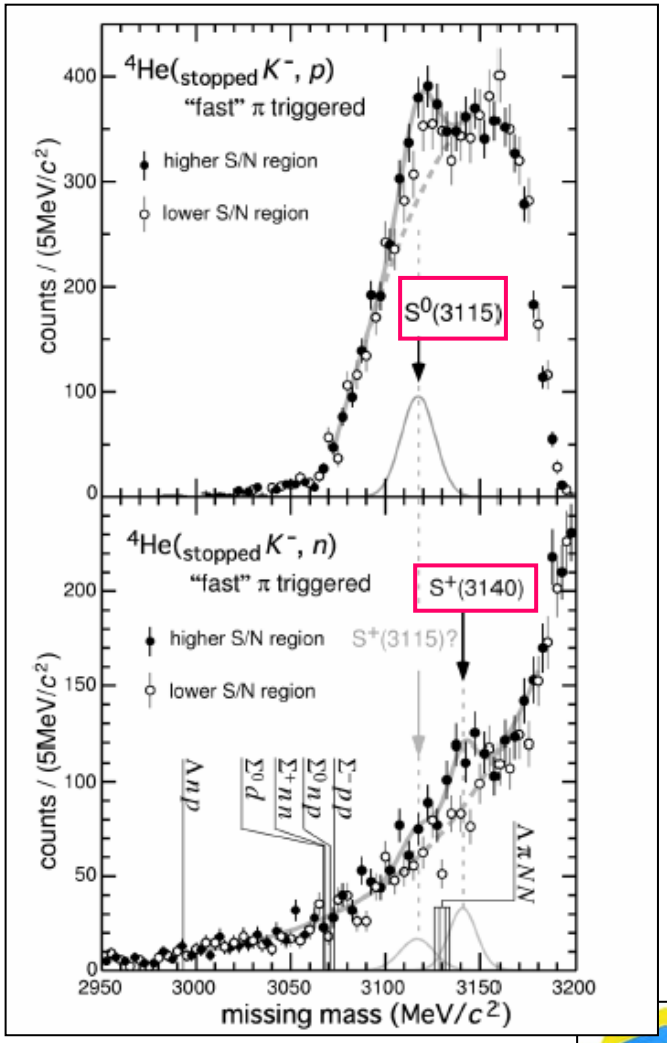
K^-pnn state: signal observed in the semi-inclusive p momentum spectrum, in coincidence with a fast π^-

S^0(3115), T = +1, S=-1
M = 3117.7 $^{+3.8}_{-2.0}$ (sys) ± 0.9(stat) MeV/c²
(B ≈ -193 MeV)
Γ< 21.6 MeV/c² (95% C.L.)

ΣNN preferred decay channel



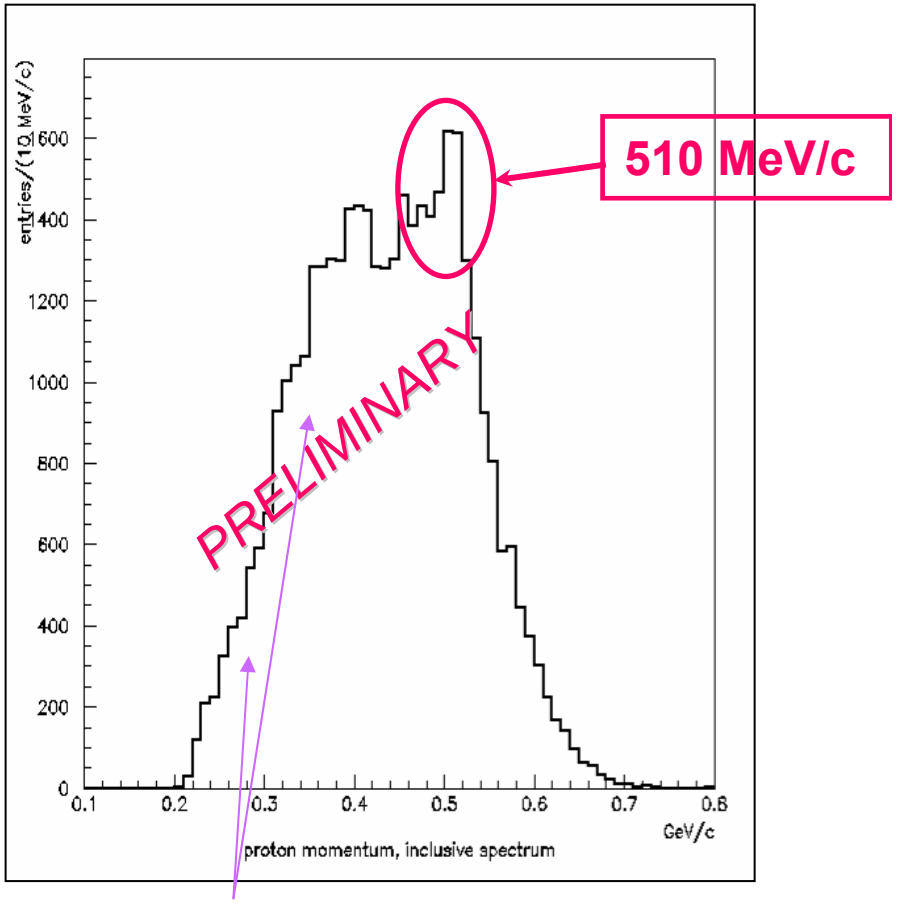
^{4}He target, energy loss uncorrected



Missing-mass spectroscopy @ FINUDA

- It is well known that in many reaction ^{6}Li behaves like a real deuteron bound to a real α–particle in relative s-wave
  - Behaviour observed in
    - $(\pi^+, 2p)$ reactions in flight
    - $(\pi^-, 2n)$ reactions at rest

- Looking for a signal due to the three-nucleon $\bar{K}$-bound state ($S^0(3115)$) as seen by KEK-PS E471 on a "quasi-^{4}He" substructure of ^{6}Li
  - $K^-_{stop} + {}^4He \rightarrow (K^- pnn) + p$
  - The proton momentum spectrum should exhibit a peak at about 500 MeV/c



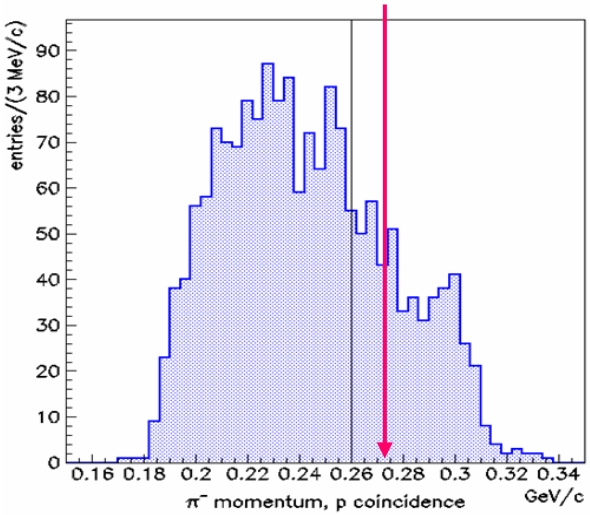
Contributions from hyperfragment non-mesonic decays

Sizeable signal at about 500 MeV/c in the inclusive proton momentum spectrum not acceptance corrected

^{6}Li target, energy loss *corrected*

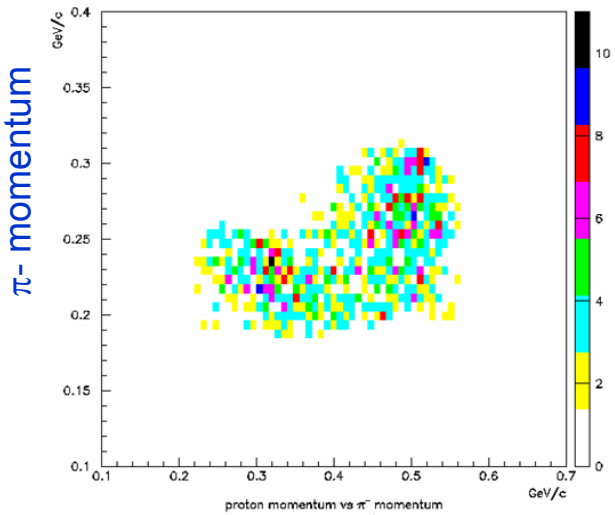
Tribaryon (K^-pnn) search with the missing mass technique in FINUDA (2)

- **Study of semi-inclusive proton/pion spectra on ^{6}Li (not acceptance corrected) : strong correlation of the 500 MeV/c protons with high momentum π^-**



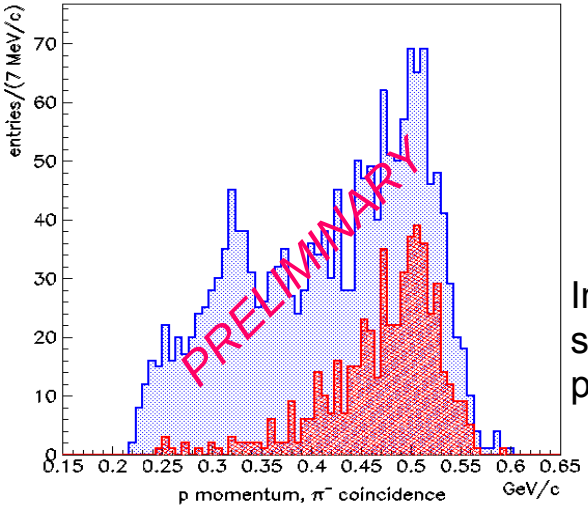
π momentum

Selected with fast pions (p > 275 MeV/c)
Clear peak structure!



p momentum

These high momentum pions could be originated by the decay of the $S^0(3115)$ into Σ^-d(and subsequent Σ^- decay), but...



p momentum

Indications for the presence of a secondary vertex from which the pion emerges, different from the K^- one

$K^-_{stop} + {}^4He \rightarrow (K^-pnn) + p$

$K^-pnn \rightarrow \Sigma^-d$

$\Sigma^- \rightarrow n\,\pi^-$

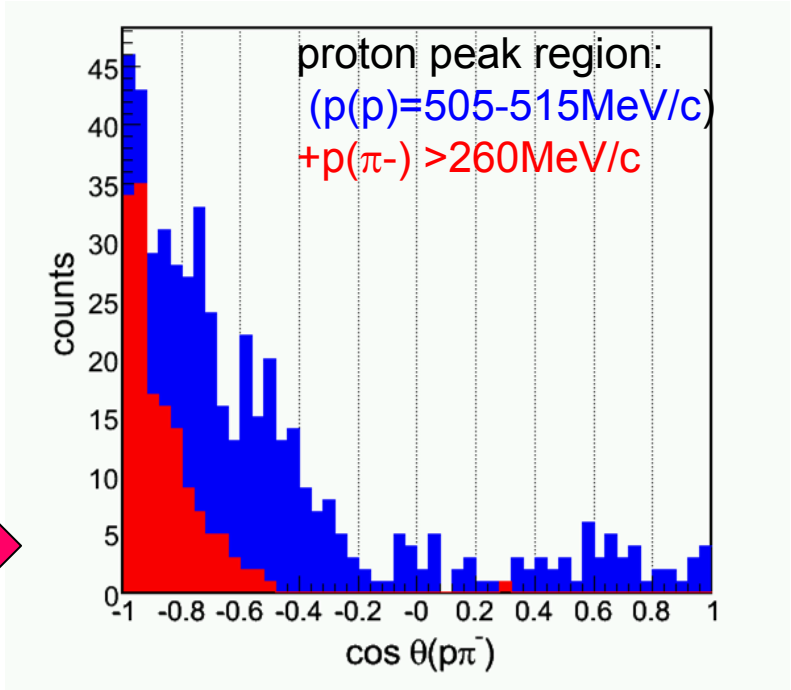
Tribaryon (K^-pnn) search with the missing mass technique in FINUDA (3)

If we observe a proton from S^0 formation and a pion from its decay:

$$K^-_{stop} + {}^4He \rightarrow S^0\,(3115) + p$$
$$S^0\,(3115) \rightarrow \Sigma^- NN$$

we expect no strong angular correlation between proton and pion

INSTEAD: BACKWARD CORRELATION OBSERVED BETWEEN PROTON AND PION!



This does NOT look like a signal from S^0 .

Interpretation of the peak

- **Kaon absorption by quasi-deuteron** (^{6}Li: α+d)

$$K^- + \text{“}d\text{”} \rightarrow p + \Sigma^-$$

  - Fast pion in opposite direction of the proton.
  - Large branching ratio
- **Rare decay of $^4_\Lambda$He into p+t**
  - Fast pion from $^6_\Lambda$Li* formation? / Triton not observed(ΔE/Δx on μ-strip detectors)
  - Proton momentum: 505 MeV/c
  - Small decay branching rate.
- **Formation and decay of kaonic nuclei** (*K^-ppnnn* from ^{6}Li or *K^-pnn* from α-cluster)
  - Fast pion could be from Σ^- (slower Σ^- than that from K^-+d).
  - No strong angular correlation between p and π^- expected.

Kaon absorption by quasi-deuteron is most probable.

Summary and Conclusions

- FINUDA at DAΦNE is a unique facility for the study of the K^-A interaction

- Possibility of studying the existence of predicted deeply bound kaonic states from a twofold point of view
  - Invariant mass method (new, due to the full event reconstruction in the apparatus, with high resolution)
    - *Clear indications* for the existence of deeply bound kaonic systems, directly observed for the first time!
    - *Waiting for next data taking to increase statistics for the kaonic systems studied*:
      - $K^-pn \rightarrow \Lambda n$, $K^-pn \rightarrow \Sigma^- p$
      - $K^-ppn \rightarrow \Lambda d$
  - Missing mass method (classical, but less precise)

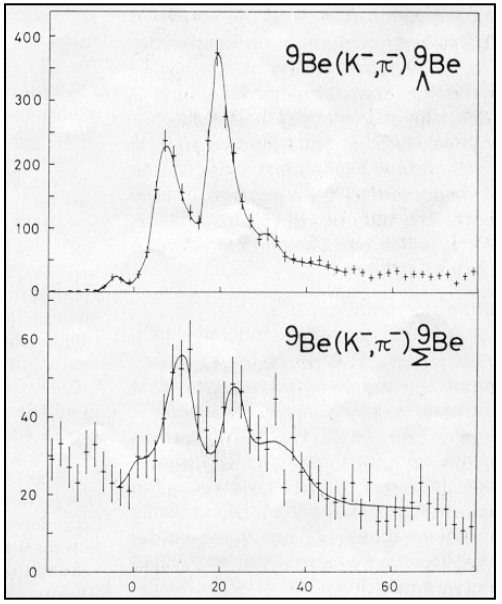
Formazione stati legati K-nucleo

- K^- fermati nella targhetta formano atomi kaonici, dopo la diseccitazione il kaone annichila sul nucleo

- <u>Modalità di assorbimento del kaone:</u> $K^- + A$
  - Produzione quasi libera di iperoni **$K^- N \rightarrow Y\pi$ (≈80%)**
  - Assorbimento su 2 nucleoni **$K^- NN \rightarrow YN$ (≈20%)**
    con **$Y = \Lambda$ o Σ**
  - Formazione di **ipernuclei**
  - Formazione di **stati legati K-nucleo**

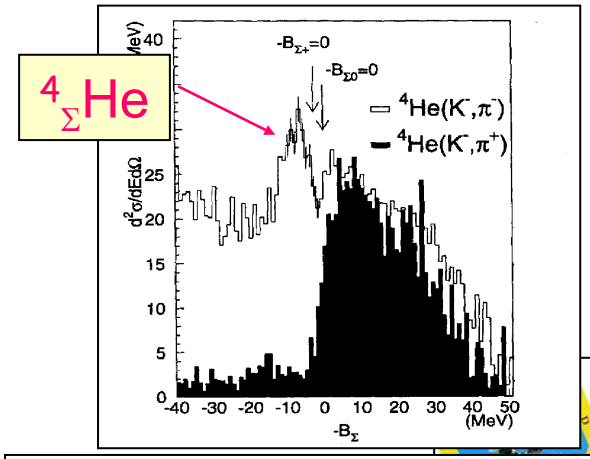
Ricerca di stati legati e ipernuclei Σ

- Ci si aspetta che gli ipernuclei Σ *non* esistano
  - La conversione $\Sigma N \rightarrow \Lambda n$ rilascia 80 MeV e la Λ ha una notevole probabilità di uscire dal nucleo
  - Per giustificare l'esistenza degli ipernuclei bisognerebbe ipotizzare una soppressione del processo di conversione $\Sigma N \rightarrow \Lambda n$



- Alcune osservazioni sperimentali di stati $^{9}_{\Sigma}Be$, $^{12}_{\Sigma}C$, $^{12}_{\Sigma}Be$, $^{12}_{\Sigma}C$, non confermate in esperimenti ad alta statistica

- Unica osservazione confermata: $^{4}_{\Sigma}He$ ($\Sigma \equiv \Sigma^0, \Sigma^+$)
  - Si può considerare un'eccezione, per la sua particolare struttura



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

Potenzialità di FINUDA per

$K^-_{stop} + A \rightarrow {}_{\Sigma}B + \pi^{\pm}_{prompt}$

$\Sigma + N \rightarrow \Lambda + N$

FINUDA e' in grado di osservare una reazione di questo tipo:

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

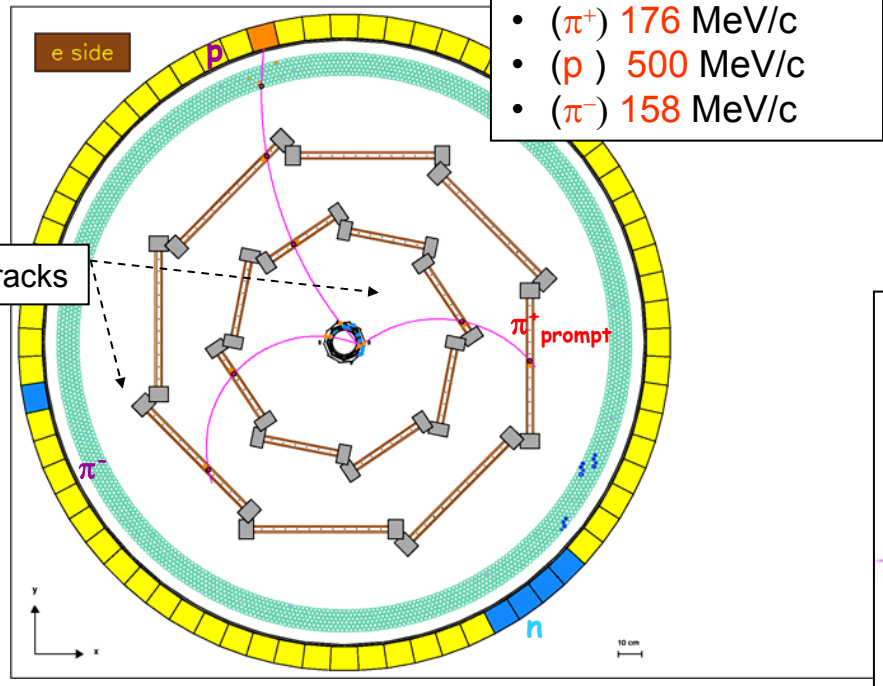
${}^{12}_{\Sigma}Be \rightarrow {}^{10}Be + \Lambda + n$

devono essere osservati:

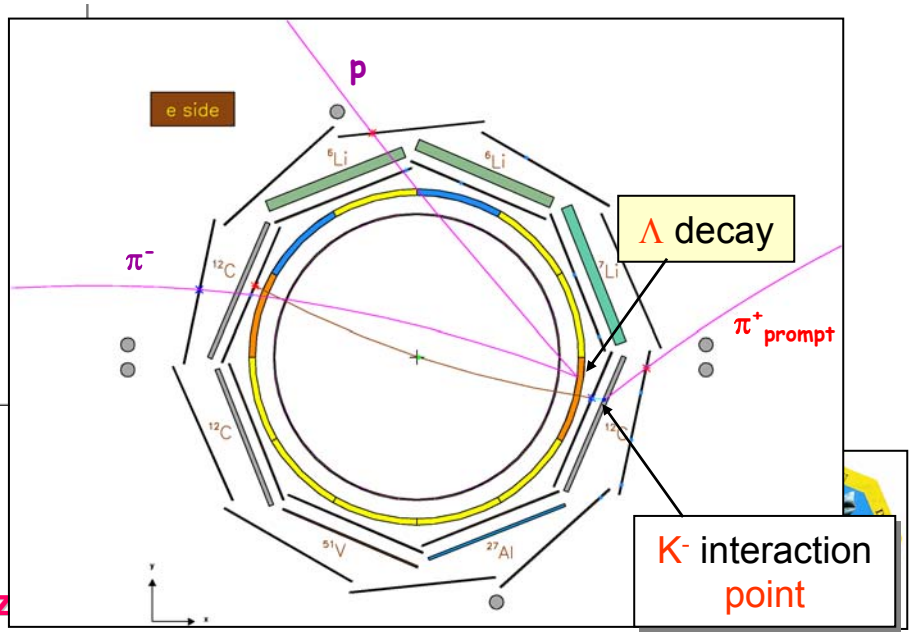
π^+_{prompt} (short, 150-180 MeV/c)

e π^-, p, n

Momenta at K^- vertex
- (π^+) 176 MeV/c
- (p) 500 MeV/c
- (π^-) 158 MeV/c



$M_{inv}(p,\pi^-) = 1114$ MeV/c^2



Congressino di sezione, 27/02/06