Σ^- production in kaon absorptions by FINUDA

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Outline

- Introduction: hyperon production in single/two nucleon kaon absorptions
- Free Σ production in FINUDA: signal extraction in $\Sigma^{\pm}\pi^{\mp}$ vs $\Sigma^{-}p$ reactions
  - Data features
  - production rates

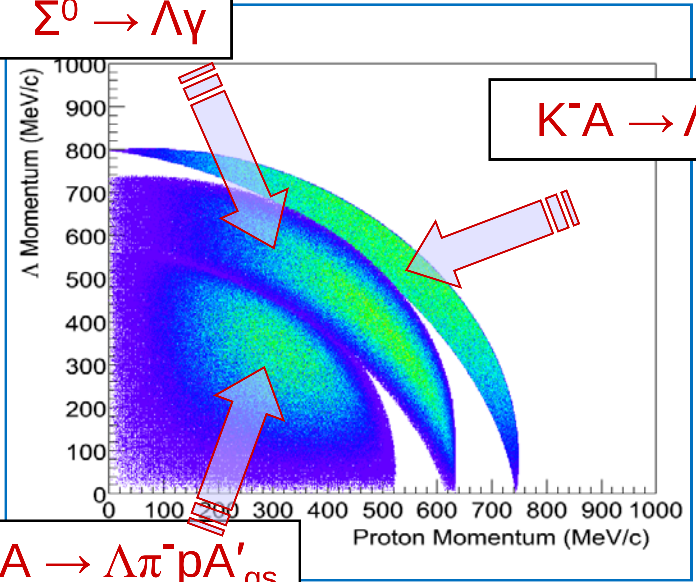
- $\Sigma^{-}p$: global fit to the data – ^{6}Li, ^{7}Li (^{9}Be, ^{13}C, ^{16}O)
  - Method: binned likelihood fits
  - Basic hypotheses (Quasi-Free dynamics)
    - Ingredients
    - Backgrounds and contaminations
    - Results and fits quality
  - Add-ons

- Conclusions

K^-_{stop} absorption by one vs many nucleons

$K^-A \rightarrow \Sigma^0 pA'_{gs}$
$\Sigma^0 \rightarrow \Lambda\gamma$

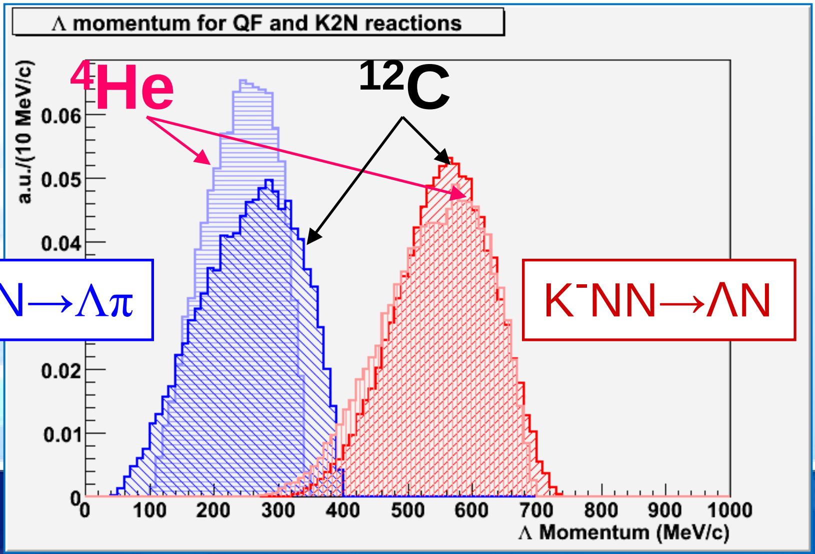
Phase space simulation: $K^-_{stop}{}^6Li$



$K^-A \rightarrow \Lambda pA'_{gs}$

$K^-A \rightarrow \Lambda\pi^- pA'_{gs}$

Expected signatures:
in pionless reactions
emission of **high momentum nucleons**
(or light nuclei) and
hyperons



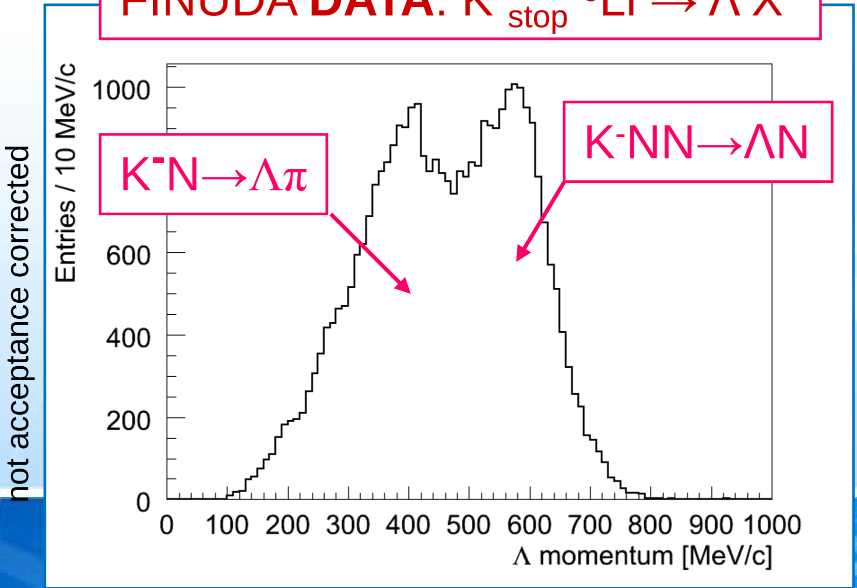
^{4}He

^{12}C

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

$K^-NN \rightarrow \Lambda N$

FINUDA **DATA**: $K^-_{stop}\ {}^6Li \rightarrow \Lambda X$



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

$K^-NN \rightarrow \Lambda N$

Σ^- signal extraction in FINUDA (^{6}Li target)

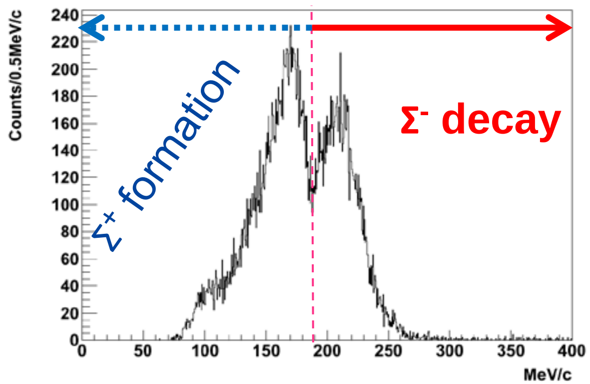
- One charged pion, one neutron
- The π^- from the Σ^- decay has the largest momentum
- Σ^+ can decay at rest, Σ^- are always absorbed by the hit nucleus
- Study of the **decay pion** & the **prompt** particle (raw spectra)

particle	Momentum resolution (σ)	Det+rec efficiency
proton	1%	75%
π^-	0.6%	73%
neutron	5%	3%

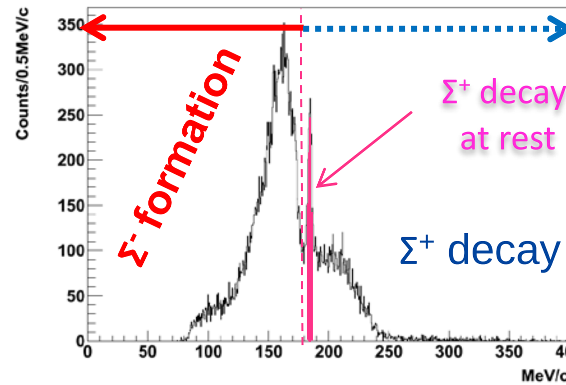
$n\pi^+\pi^-$

FINUDA Coll., PLB704 (2011), 474

π^- momentum

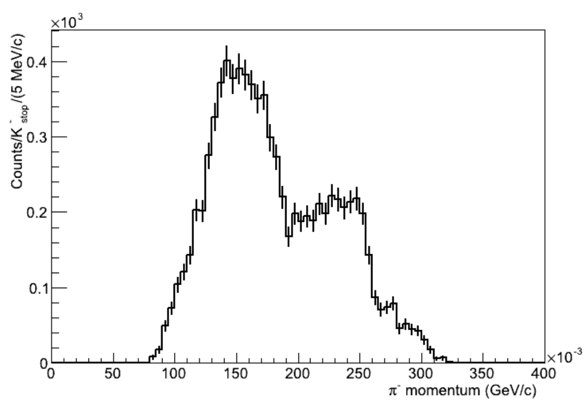


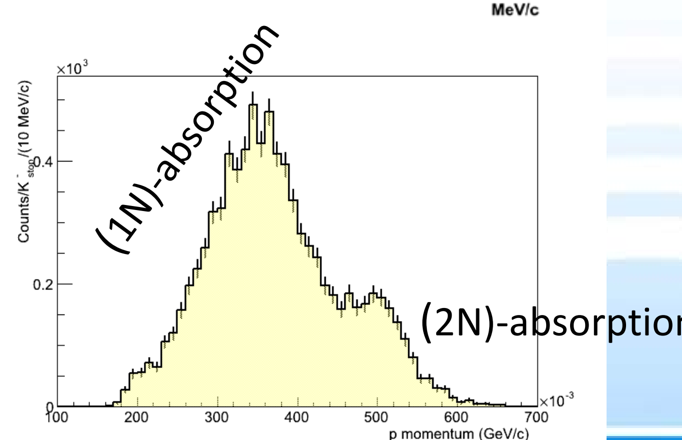
π^+ momentum



$np\pi^-$

Large background!





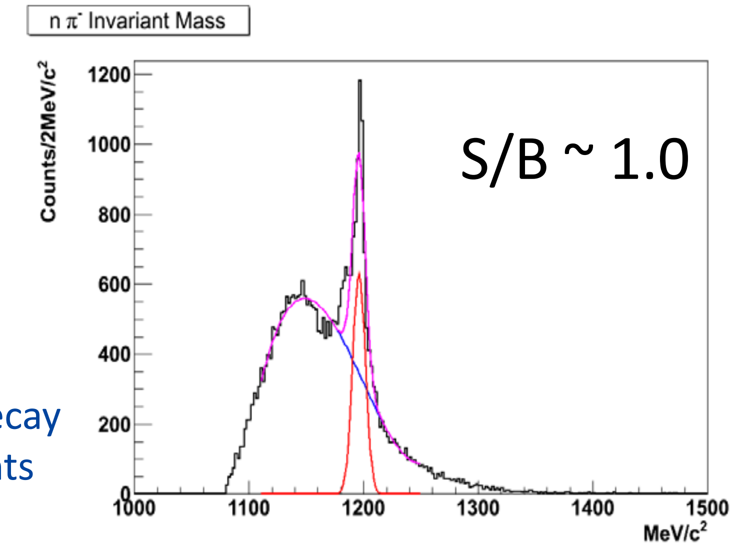
π^- momentum

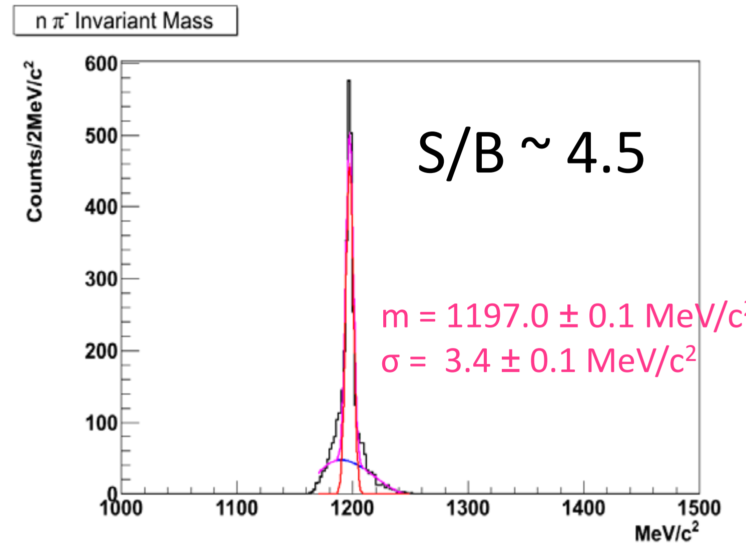
p momentum

Σ^- signal identification

$n\pi^+\pi^-$

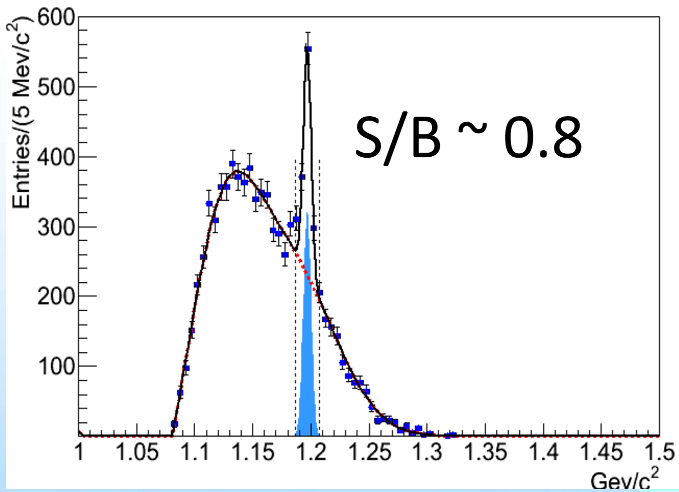
- reject events with unphysical missing mass
- track fitting
- vertex selection
- Σ^- decay angle
- $\pi^+\pi^-$ production/decay kinematic constraints

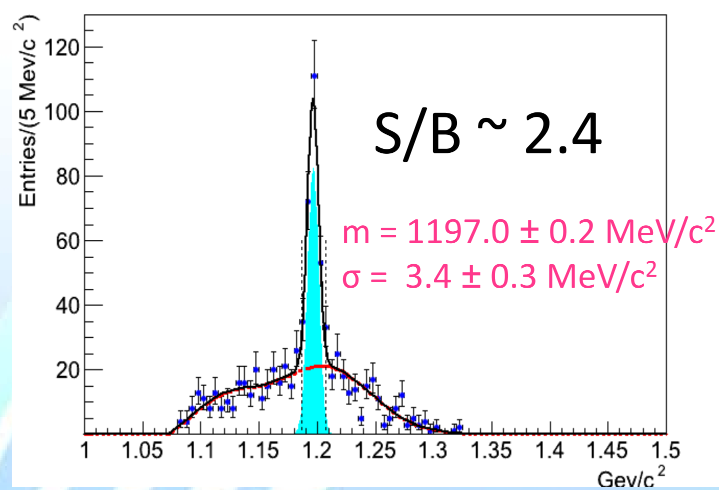




$np\pi^-$

- reject events with unphysical missing mass
- track fitting
- vertex selection
- Λ rejection

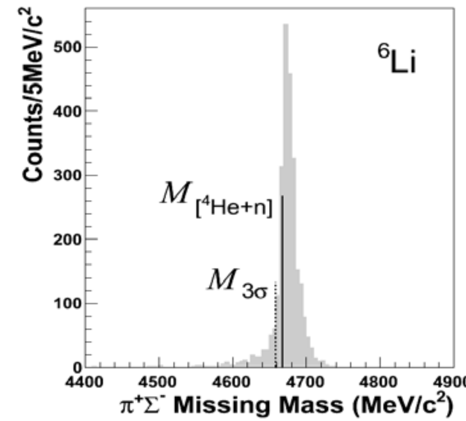




Missing mass studies ($K^{-}\,{}^{6}Li$ – (final state particles))

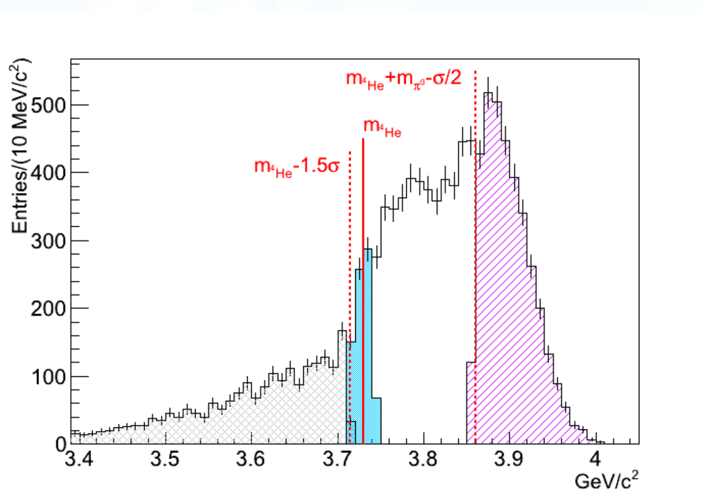
$n\pi^{+}\pi^{-}$

- pure QF $\Sigma^{-}\pi^{+}$ reaction: very little missing energy (~4%)
- exclusive measurement (no missing π, N)
- peak: ~3 MeV above physical threshold
- width: σ ~ 9 MeV

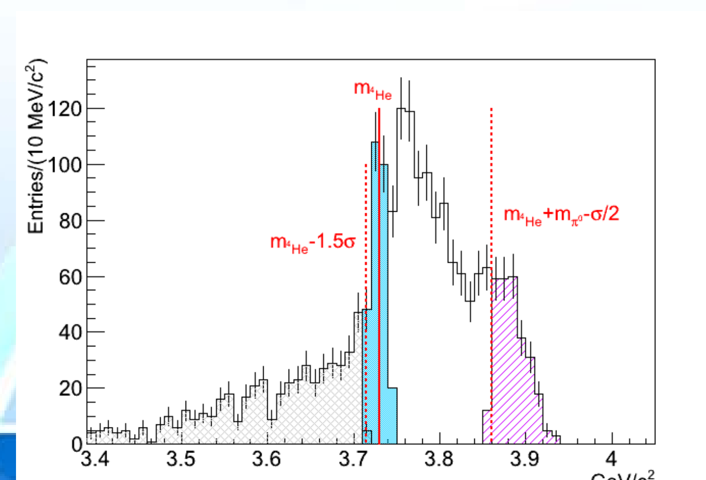


$np\pi^{-}$

- large amount of unphysical events: neutron rescattering, reconstruction errors, misidentifications (wrong n, n/γ, …)
- missing mass resolution: σ ~ 10 MeV
- inclusive $\Sigma^{-}p$ reaction (all physical data) vs exclusive QF $\Sigma^{-}p$ (“g.s. region”)
- QF reactions identifications: **$\Sigma^{-}p$**, **$\Sigma^{-}p\pi^{0}$**

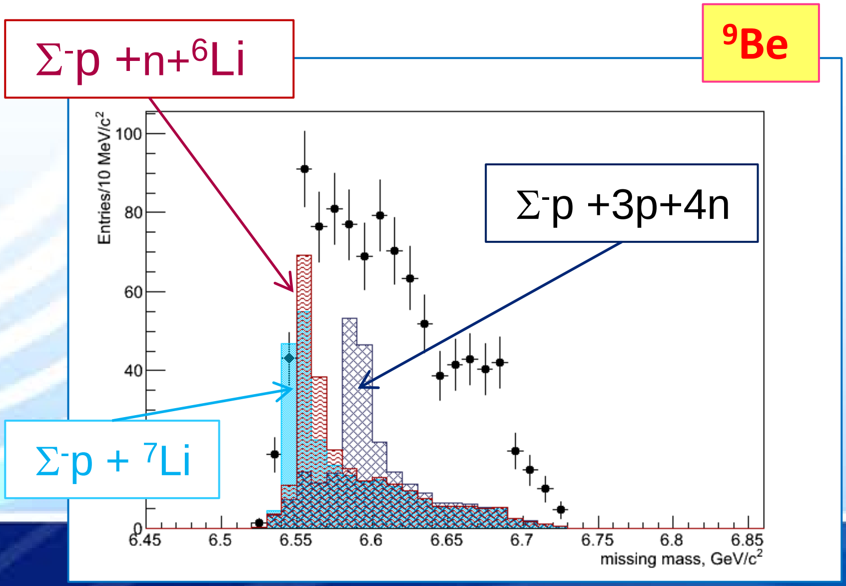


Σ^{-} selection in proper ($n\pi^{-}$) mass window

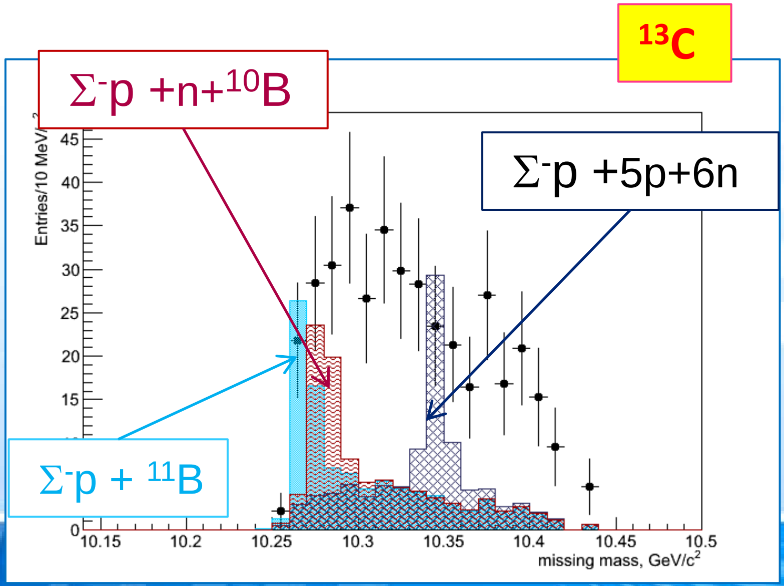


"Exclusive" QF $\Sigma^{-}p$ absorption

- $\Sigma^{-}p$ production recoiling against a nuclear system in its minimal mass configuration – occurs when the absorption is *exactly* on a (pn) pair
- Many nucleon absorptions can also occur leaving the recoiling system in a fragmented/excited configuration with larger mass/energy
- Important effect especially for heavy nuclei (energy difference > 40 MeV/c^2), but not negligible for lighter ones
- **Missing mass resolution: 9-12 MeV/c^2**
  - The width of the missing mass band chosen for the selection is optimized to exclude the overlap of the fartest configurations
  - Unavoidable overlap with closer energy configurations: included in the rate calculation
    - **"Ground state": minimal mass state within the experimental resolution (i.e., ~3σ)**



Arbitrary normalizations



Arbitrary normalizations

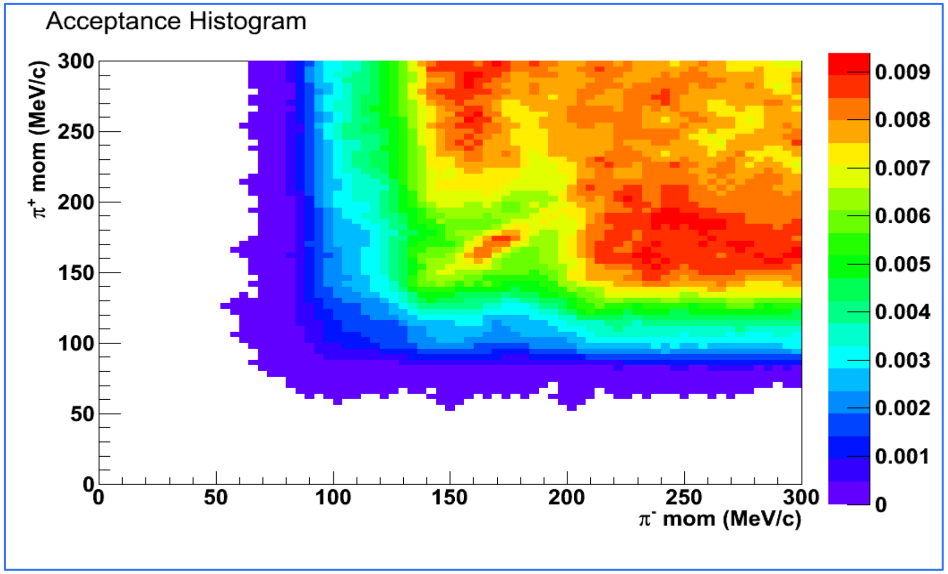
Acceptance corrections

- Simulations of three particles with flat momenta in the relevant kinematic range of the reaction
  - $O(10^9)$ events simulated

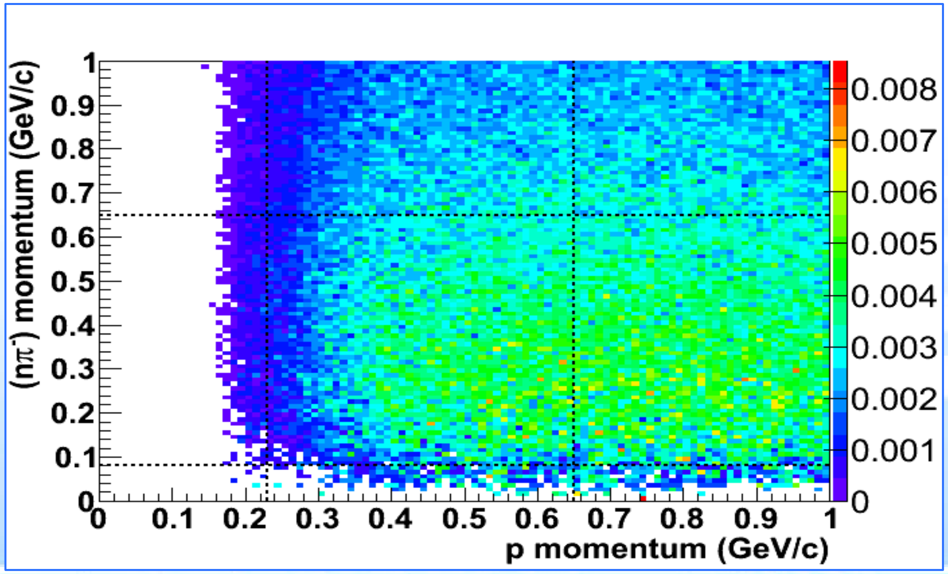
- Event-by-event correction: each event is assigned a weight according to its location in phase space (9 coordinates/particle)

- Critical correction at edges: large statistical+systematic error
  - Cuts to reduce the total uncertainty at the phase space borders

$n\pi^+\pi^-$

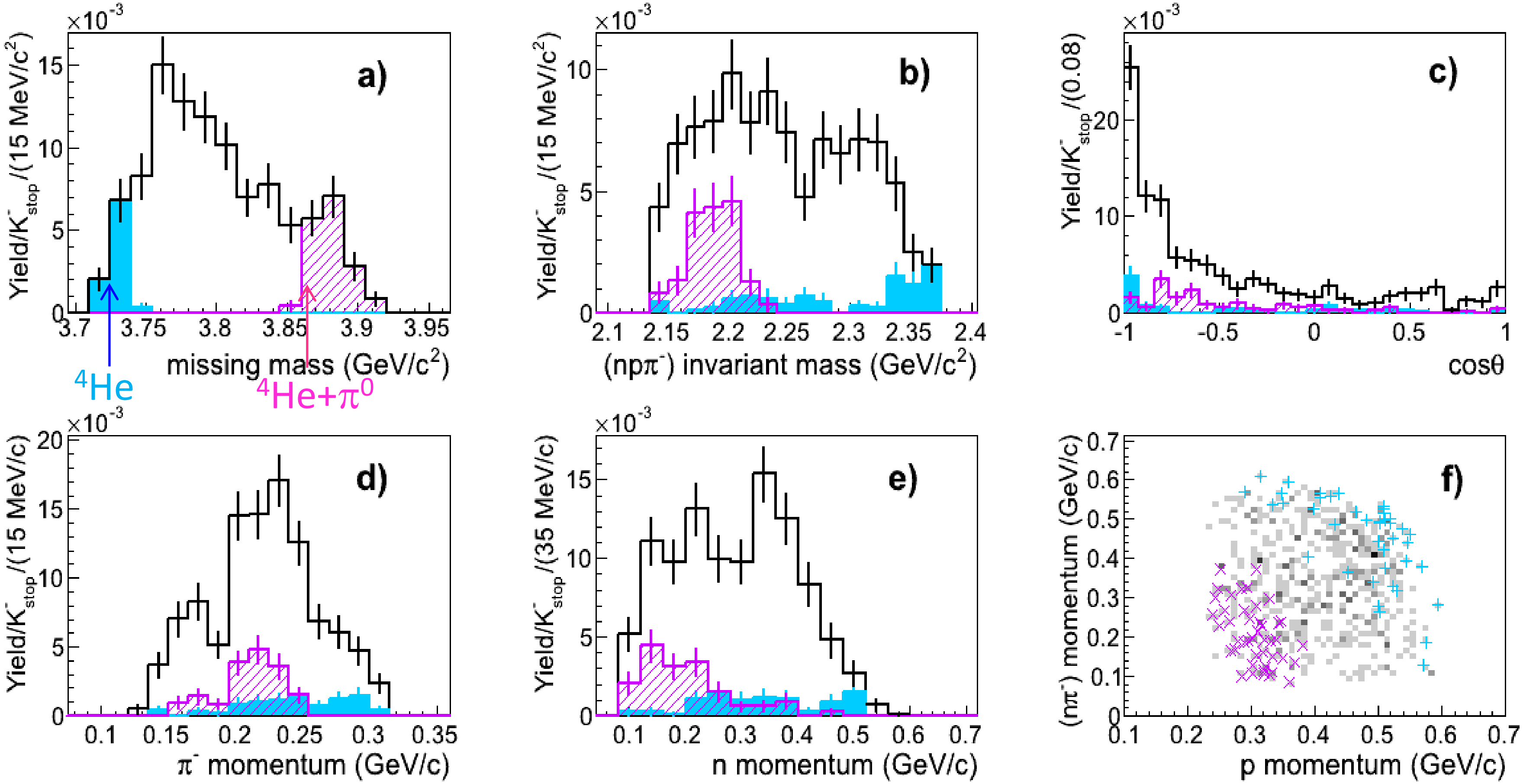


$np\pi^-$



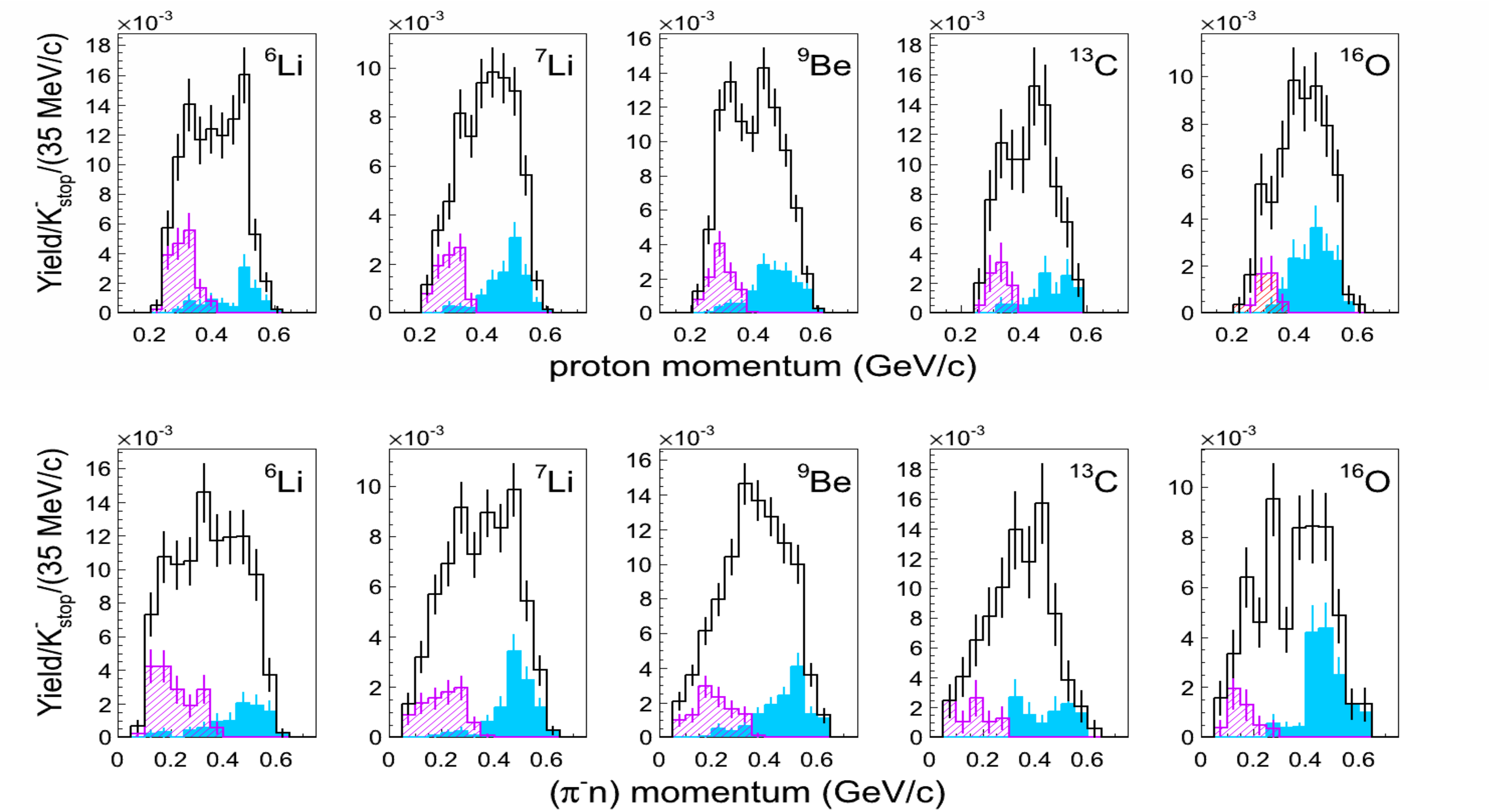
Σ⁻ p: acceptance corrected spectra, Σ⁻ region selection – ^{6}Li

Events selected in the **^{4}He missing mass band** distribute as expected by the QF Σ^-p reaction



Σ^- p: acceptance corrected spectra proton and Σ^- momenta in all targets

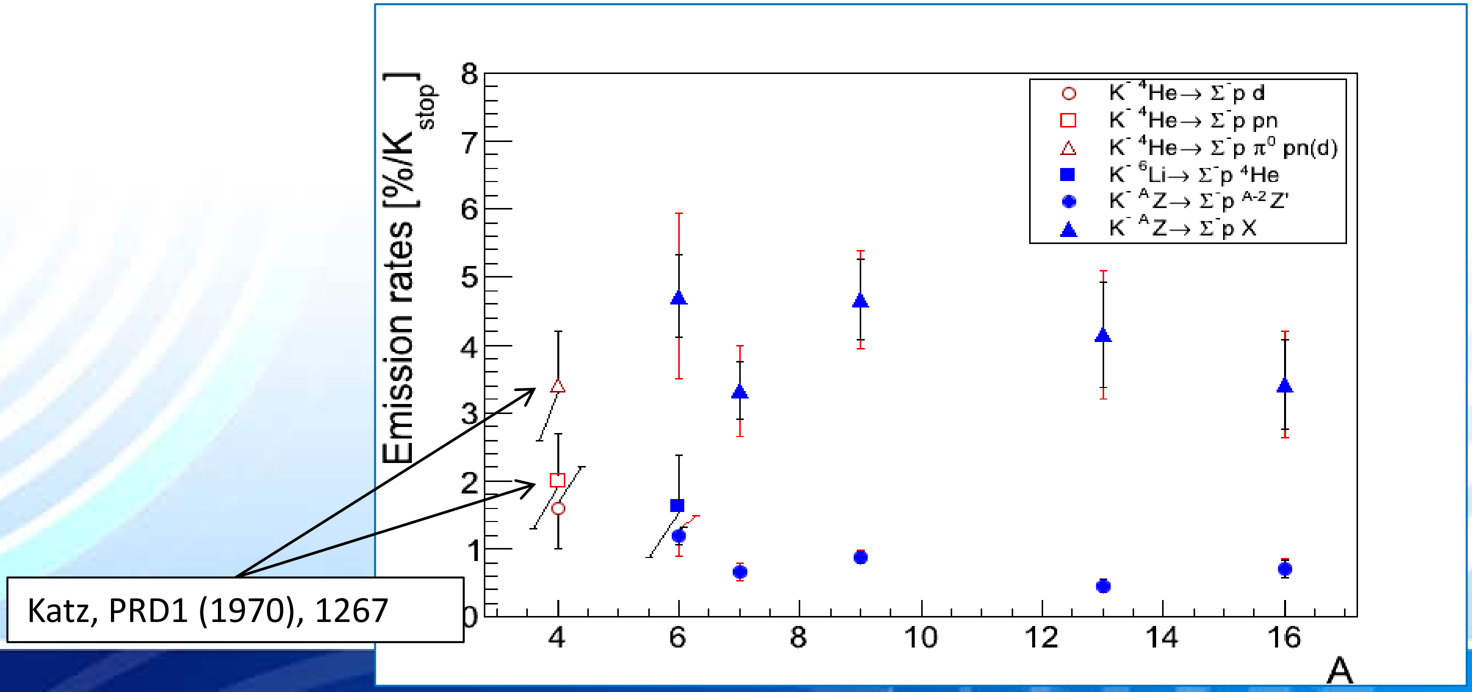
Similar trends for both p and ($n\pi^-$) momentum in all targets: **QF Σ^-p reaction almost at rest**



$\Sigma^- p$ emission rates in p-shell nuclei

- Emission rates: from the number of events in the Σ^- peak, background subtracted
  - both for the inclusive and the exclusive sample
    - Inclusive measurement: integrated over the full phase space volume
  - corrected for the fraction of Σ^-'s lost for nuclear capture (PLB 704 (2011), 474)
  - No correction for pion attenuation nor $\Sigma\Lambda$ conversion

- Measured rates are in agreement with older (few) data
  - New measurements for A > 6

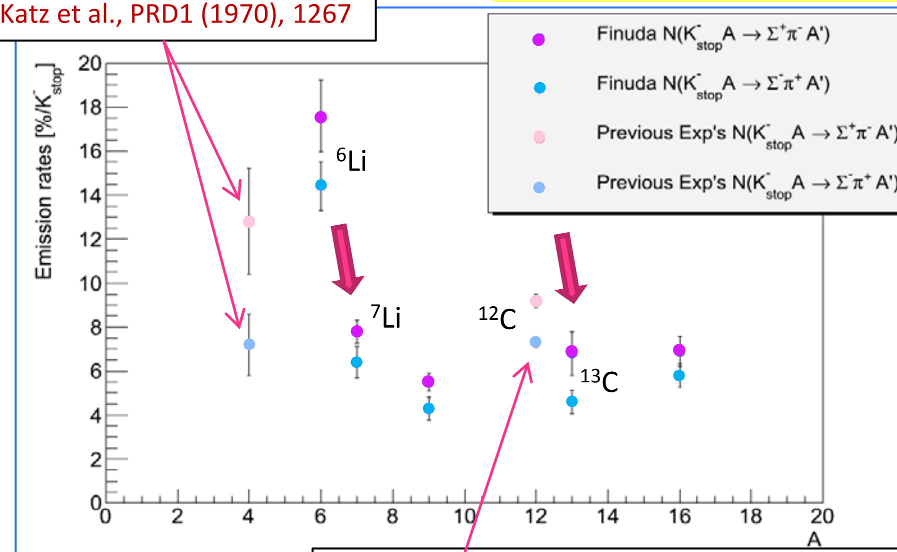


$\Sigma^{\pm}\pi^{\mp}$ vs $\Sigma^{-}p$ emission rates: comparison

PLB704 (2011), 474

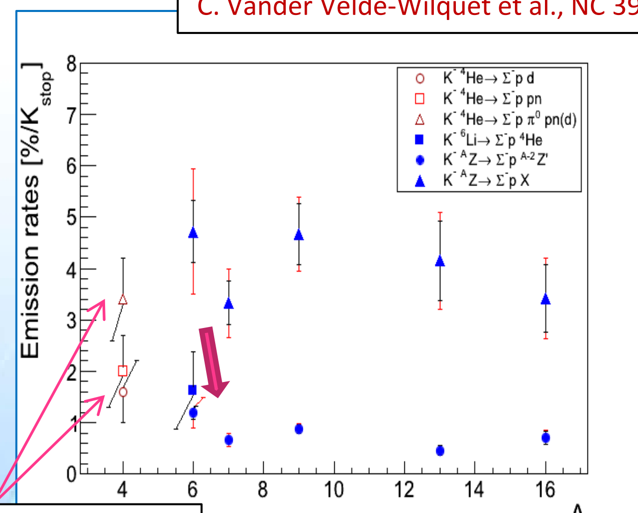
- $\Sigma^{\pm}\pi^{\mp}$ rates
  - Remarkable decrease between ^{6}Li-^{7}Li and ^{12}C-^{13}C pairs
  - less K^{-}A stop centers available for these final states
- $\Sigma^{-}p$ "exclusive" rates
  - Same behavior: ^{6}Li-^{7}Li
  - Reduced probability of 2N vs 1N absorptions

P. Katz et al., PRD1 (1970), 1267



C. Vander Velde-Wilquet et al., NPA241 (1975) 511
C. Vander Velde-Wilquet et al., NC 39A (1977) 538

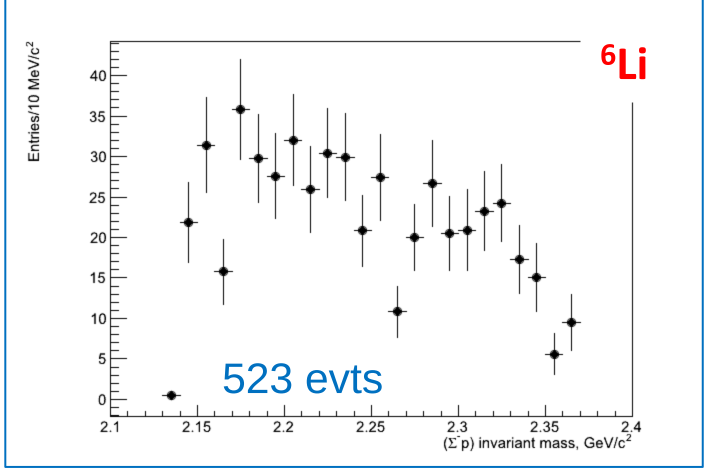
- Signature of nuclear shell structure: one more neutron in external shell
- Surface behavior of interactions: little dependence on A (except ^{6}Li – cluster structure)
- $\Sigma^{-}p$ inclusive reaction: about 1/3 of $\Sigma^{\pm}\pi^{\mp}$

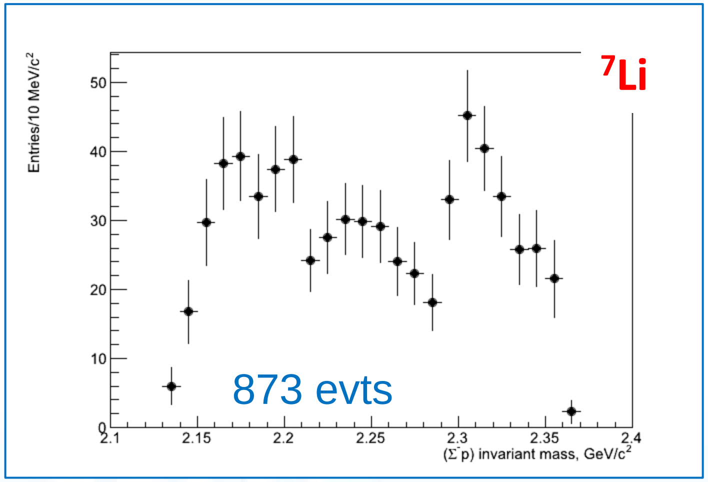


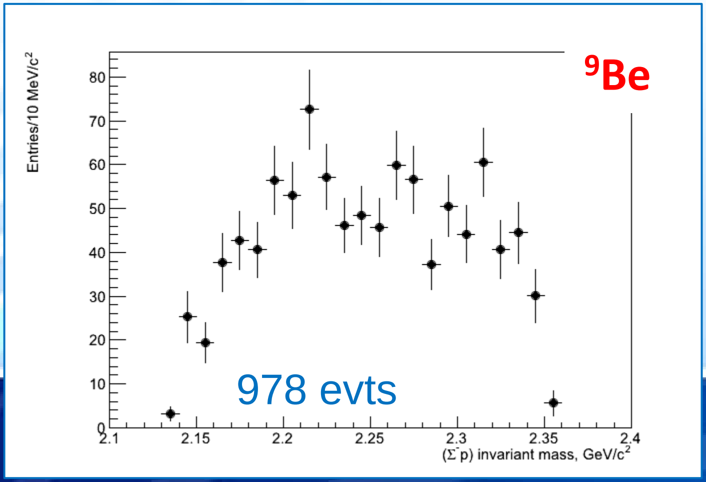
P. Katz et al, PRD1 (1970), 1267

Σ^-p: a closer look to the data

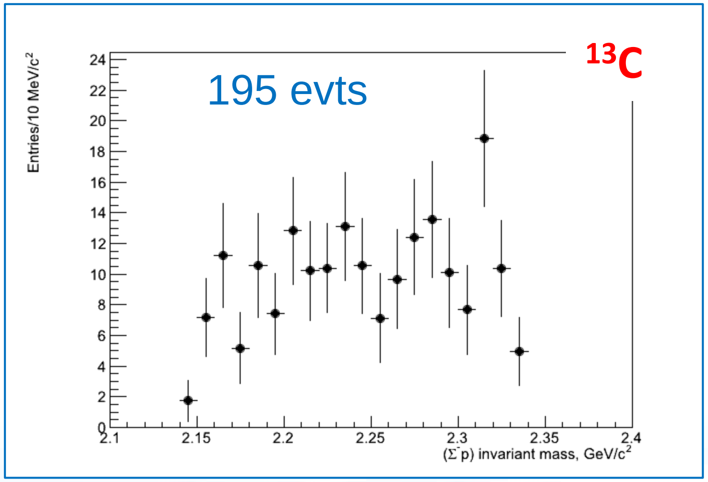
Acceptance corrected **invariant mass** spectra of the **$(n\pi^-)p$** system, selected in the $(n\pi^-)$ mass band of the Σ^- (background included)

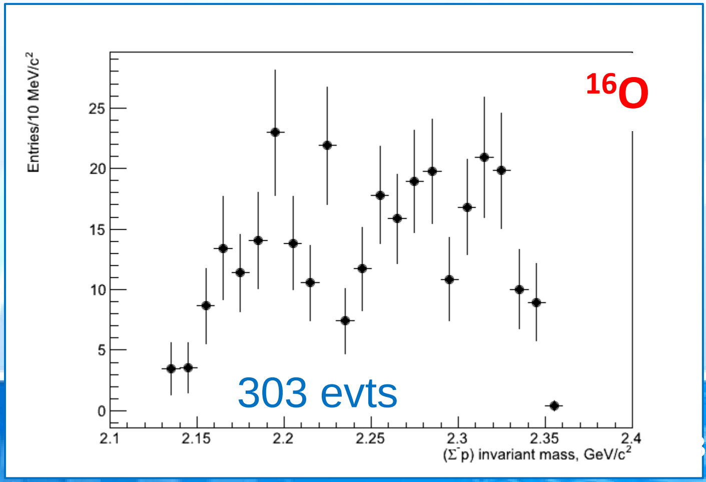






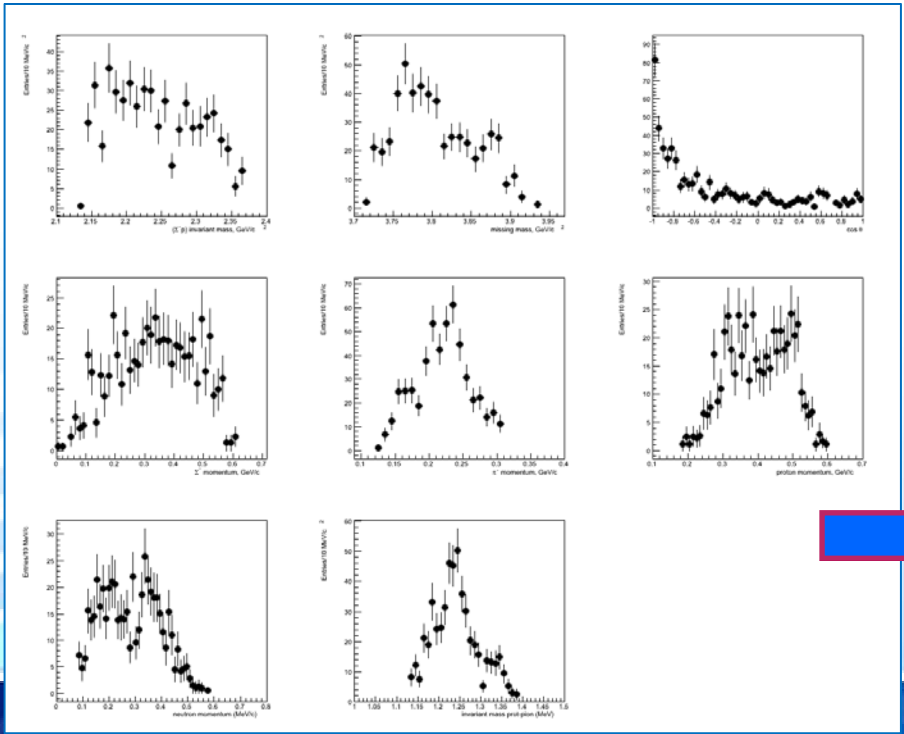
The distributions must be fitted taking into account several reactions and several other observables: **GLOBAL FIT**



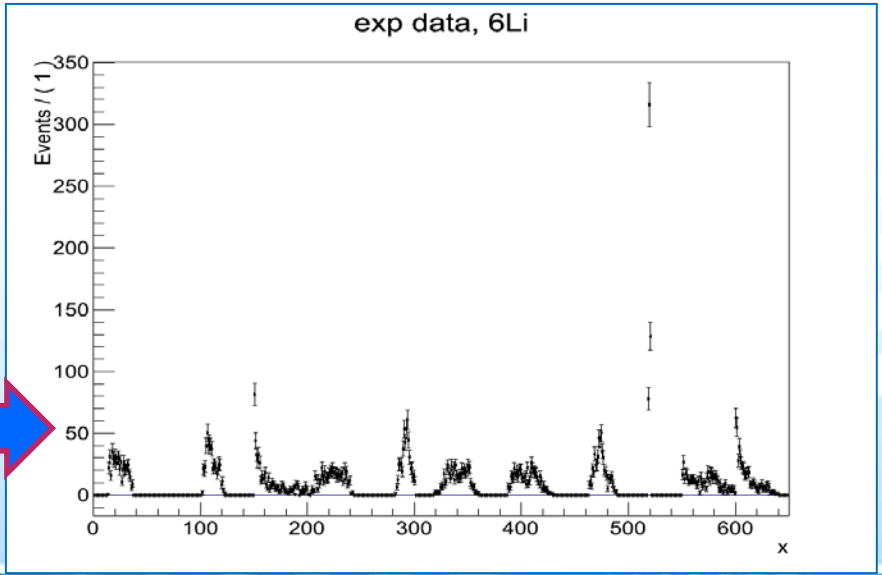


$\Sigma^{-}p$ spectra global fit – the method

- Binned maximum likelihood fit to 11 1D experimental distributions
  - Wide redundance (and correlations)
  - Independent kinematic features (momenta, angles, energy/mass spectra) taken into account in one shot
- To be fitted: one single histogram (11 histograms in a row)



Barlow, Beeston, Comp. Phys. Comm. 77 (1993), 219



Σ^{-}p spectra global fit – the method

- Fit ingredients: Monte Carlo histograms of several reactions producing Σ^{-} p or ($n\pi^{-}$p) in the final state, reconstructed through the same chain and acceptance corrected
  - Fitting several observables is crucial to take into account all the kinematic feature of each reaction
- Fit outputs:
  - fractions of each reaction
  - Goodness of fit estimators (give an indication on the quality of the hypothesis)
    - Histogram χ^2
    - Maximum (-minimum) (log) likelihood
- Minimization engine: MINUIT through TFractionFitter (or Roofit)

$\Sigma^- p$ spectra global fit – the model

Two classes of Quasi-Free reactions are being considered:

- reactions with $(\Sigma^- p)$ pairs in the final state, recoiling against a nucleus in its *ground state (or fragmented configuration)*
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^- p\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma(1385)^- p\ {}^{A-2}(Z-1) \rightarrow \Sigma^- p\ \pi^0\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^- p\ \pi^0\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^- p\ \pi^+\ {}^{A-2}(Z-2)$ (on pp pair)
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^- p\ {}^{A-2}(Z-1)$ + p rescattering
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^- pn\ {}^{A-3}(Z-2)$ (on 3N or np pair in ^{3}H substructure)

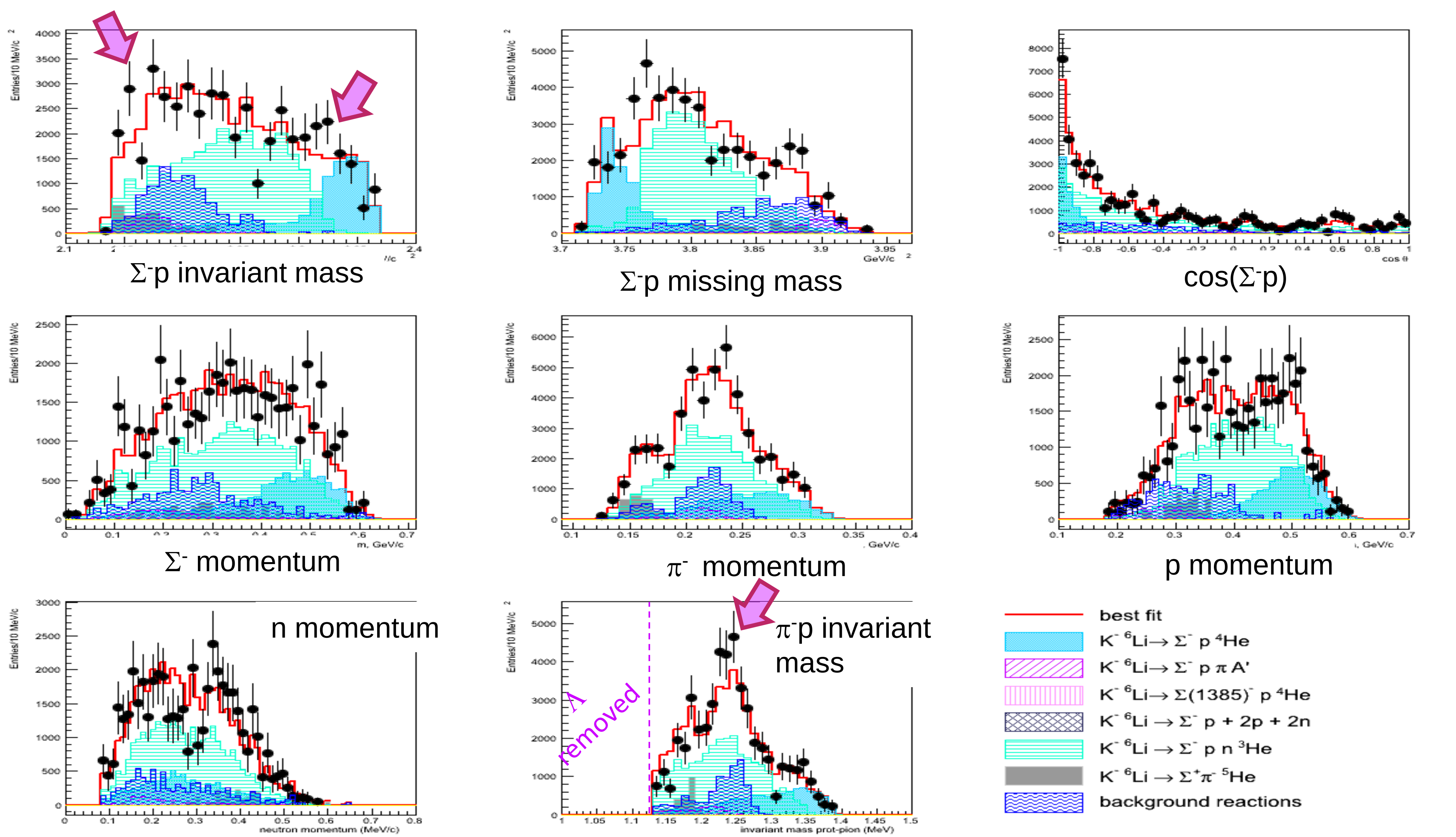
- reactions leading to $(n\pi^- p)$ in the final state, leaking through the selection criteria and entering the Σ^- mass window
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^+ \pi^-\ {}^{A-1}(Z-1)$ (π^+/p misidentif.)
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 \pi^0\ {}^{A-1}(Z-1)$ (γ/n misidentif.)
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^+ \pi^-\ n\ {}^{A-2}(Z-1)$ (2N absorption)
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Lambda n\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 n\ {}^{A-2}(Z-1) \rightarrow \Lambda n \gamma\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 n\ {}^{A-2}(Z-1) \rightarrow \Lambda n p\ {}^{A-3}(Z-2)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 n\ {}^{A-2}(Z-1) \rightarrow \Lambda n n\ {}^{A-3}(Z-1)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^- n\ {}^{A-2}Z \rightarrow \Lambda n n\ {}^{A-2}Z$

$\Sigma\ \Lambda$ conv. react.

Σ^{-}p spectra global fit – study of backgrounds

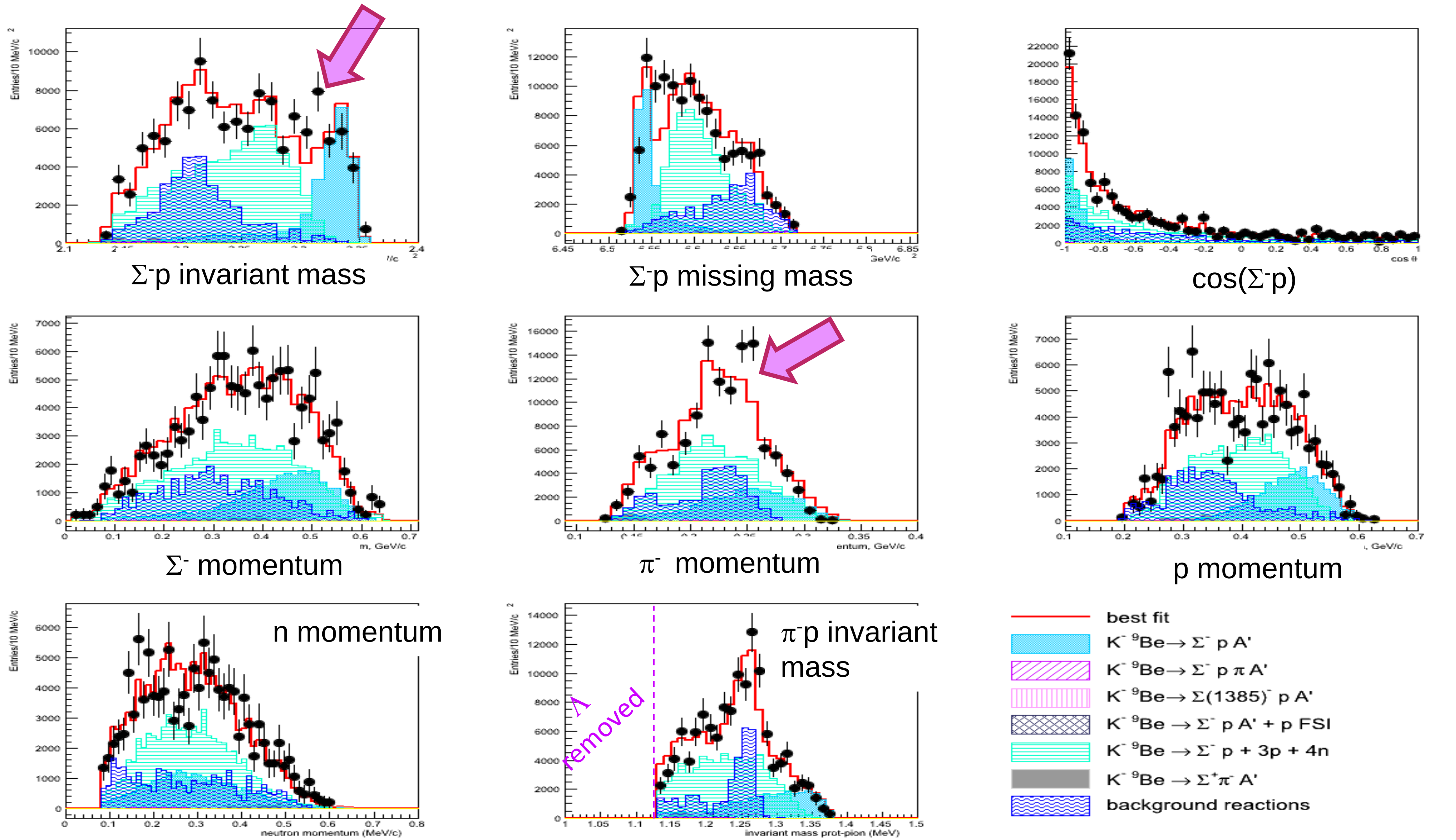
- Large systematic errors expected
  - Larger background contamination due to n/π^0/γ misidentification
    - Similar detection+reconstruction efficiency for all neutrals:
      - $\varepsilon_n = 3.5 \times 10^{-2}$
      - $\varepsilon_{\pi 0} = (2.16 \pm 0.01) \times 10^{-2}$
      - $\varepsilon_\gamma = (2.33 \pm 0.01) \times 10^{-2}$
  - Kinematic cuts reduce the contamination of each background reaction to the level of $10^{-7}/K^{-}_{stop}$
  - The only sizeable contribution from (npπ^-) background reactions given by one-nucleon absorption: $K^{-}_{stop}\ {}^{Z}A \rightarrow \Sigma^{+}\pi^{-}\ {}^{A-1}(Z-1)$
  - No inverse $\Lambda\Sigma$ conversion taken into account (suppressed)
  - Incoherent background component: mixture of QF reactions + conversion and/or rescattering not leading to Σ^{-}p in the final state

^{6}Li: fit with QF reactions only, $A_{g.s.}$ $\chi_R^2 = 1.42$



- 4 main reactions describe most of the spectra – incoherent background at 15-20% level
- Not sensitive enough to separate $\Sigma^- p \pi^0$, $\Sigma(1385)^- p$ and $\Sigma^- p \pi^-$ contributions
- **Sizeable contribution from $\Sigma^- pn$ final state – Imperfect fit at 2150 and 2300 MeV/c^2**

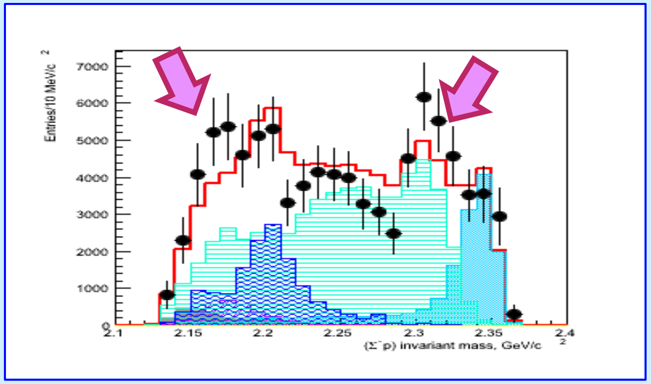
^{9}Be: fit with QF reactions, $A_{g.s.}$ $\chi_R^2 = 1.56$

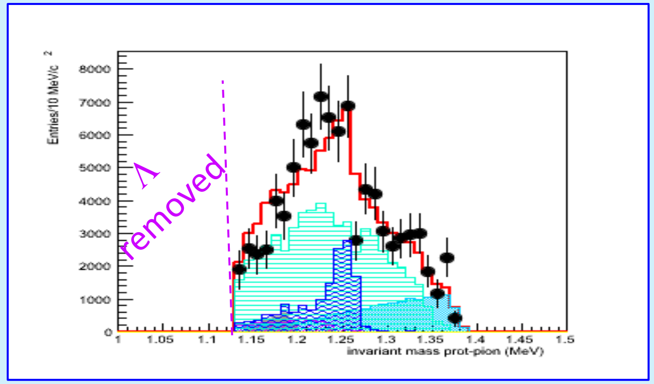


- 3 main reactions describe most of the spectra – incoherent background at 20% level
- pion momentum fit not satisfactory
- **Sizeable contribution from Σ^-pn final state - Missing strength at 2300 MeV/c^2**

^{7}Li, ^{13}C, ^{16}O: fit with QF reactions only, $A_{g.s.}$

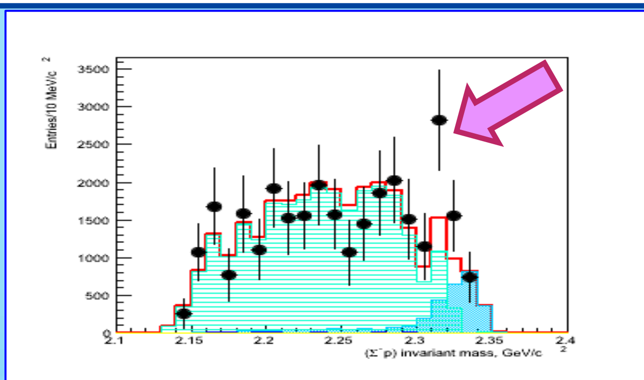
Σ^{-}p invariant mass | π^{-}p invariant mass

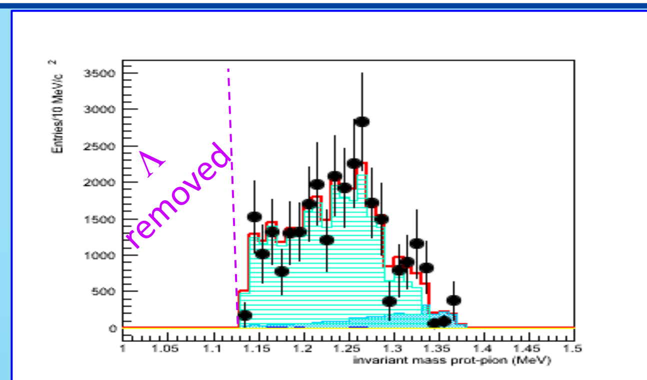




^{7}Li

- **4 main reactions** describe most of the spectra – incoherent background at 15-20% level
- **Sizeable contribution from Σ^{-}pn final state - Missing strength at 2150 and 2300 MeV/c^{2}**
- **$\chi_R^2 = 1.24$**

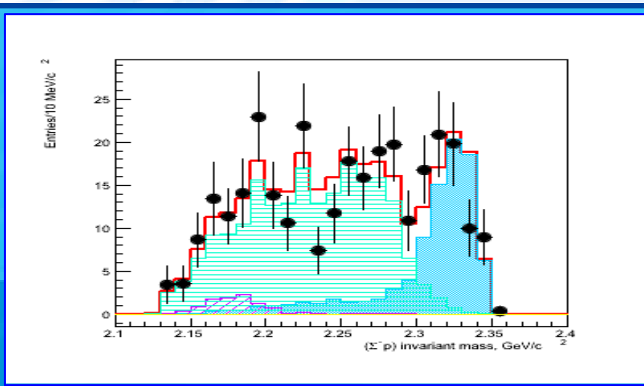


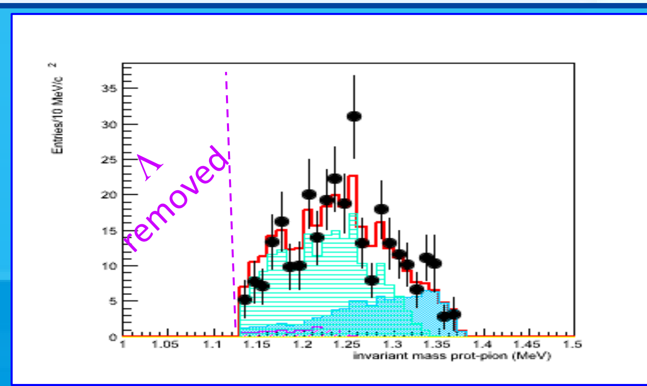


^{13}C

Low statistics

- **2 main reactions** describe most of the spectra
- **Sizeable contribution from Σ^{-}pn final state - Missing strength at ~2320 MeV/c^{2}**
- **$\chi_R^2 = 0.61$**





^{16}O

Low statistics

- **3 main reactions** describe most of the spectra
- **Sizeable contribution from Σ^{-}pn final state -**
- **$\chi_R^2 = 0.83$**

Add-on #1: QF reactions with recoiling fragmented nucleus

1st test: add components with a **maximally fragmented system** produced in $\Sigma^{-}p$ QF

^{6}Li

A – [np]	^{4}He	^{3}He + n	d + d	2p + 2n
Mass(MeV/c^2)	3727.38	3747.95	3751.23	3755.67

^{7}Li

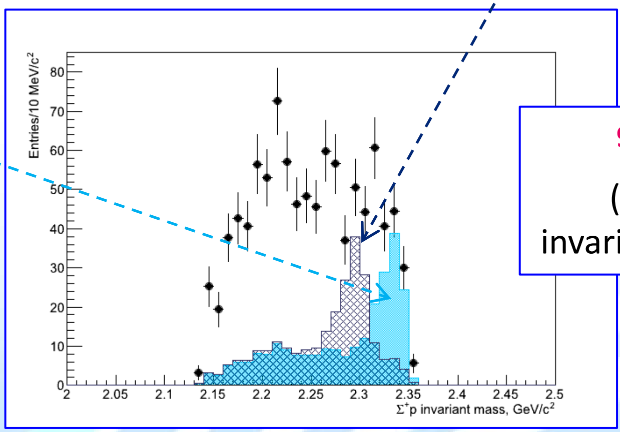
A – [np]	^{5}He	^{4}He + n	t+d	^{4}H + p	^{3}He + 2n	2p+3n
Mass(MeV/c^2)	4667.83	4666.95	4684.55	4689.64	4687.52	4695.24

^{9}Be

A – [np]	^{7}Li	^{6}Li + n	^{5}Li + 2n	^{4}Li + 3n	…	3d+n	3p+4n
Mass(MeV/c^2)	6533.83	6541.09	6546.75	6568.46	…	6566.40	6573.08

^{13}C

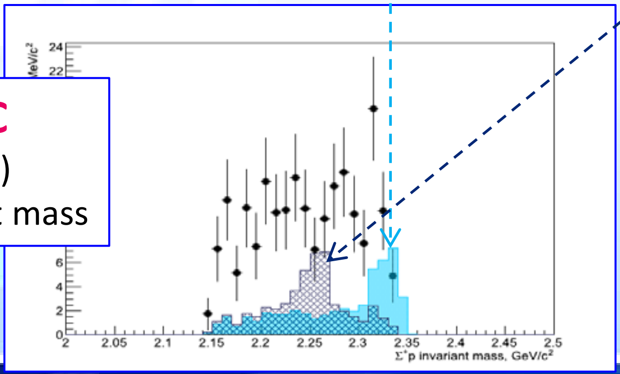
A – [np]	^{11}B	…	3p + 4n
Mass(MeV/c^2)	10252.55		10328.75



^{9}Be
($\Sigma^{-}p$)
invariant mass

Arbitrary normalizations

^{13}C
($\Sigma^{-}p$)
invariant mass



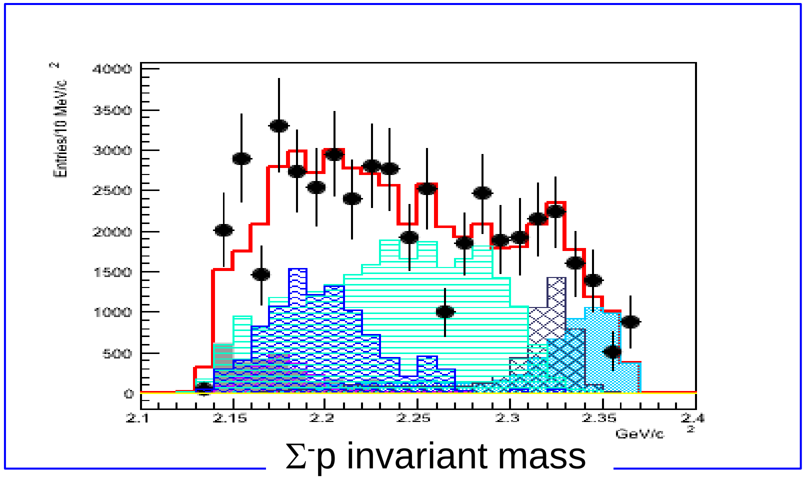
Arbitrary normalizations

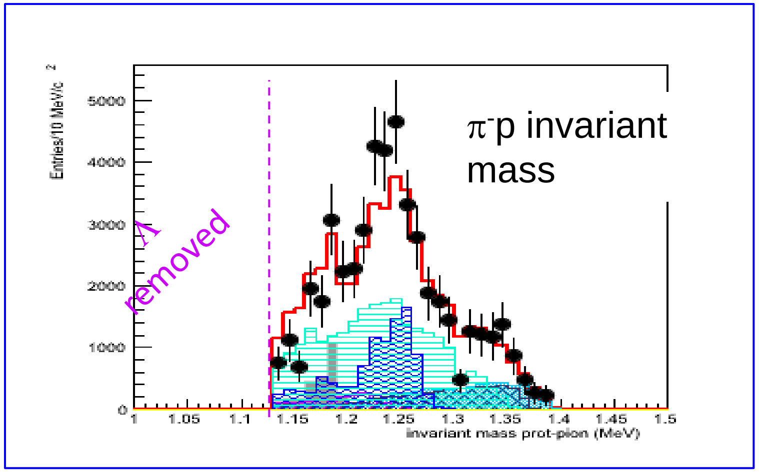
^{16}O

A – [np]	^{14}C	…	7p + 7n
Mass(MeV/c^2)	13040.87		13144.86

^{6}Li, ^{7}Li: fit with QF + recoiling fragmented configuration

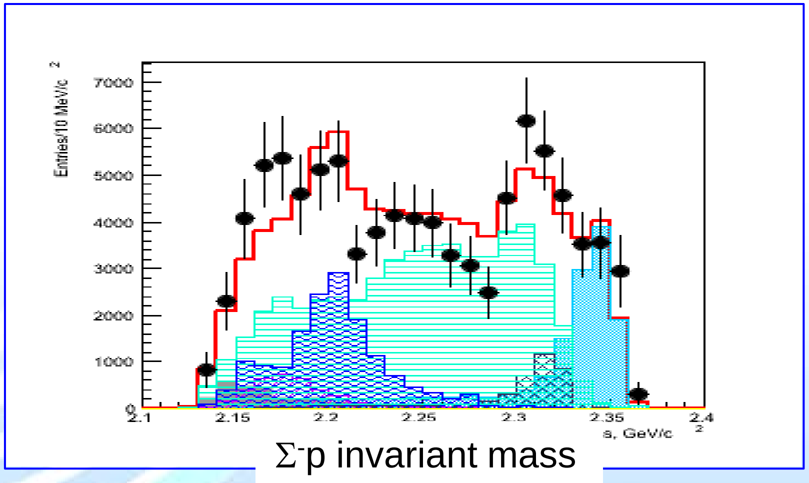
(meaningful contributions for lighter targets – heavier: too displaced)

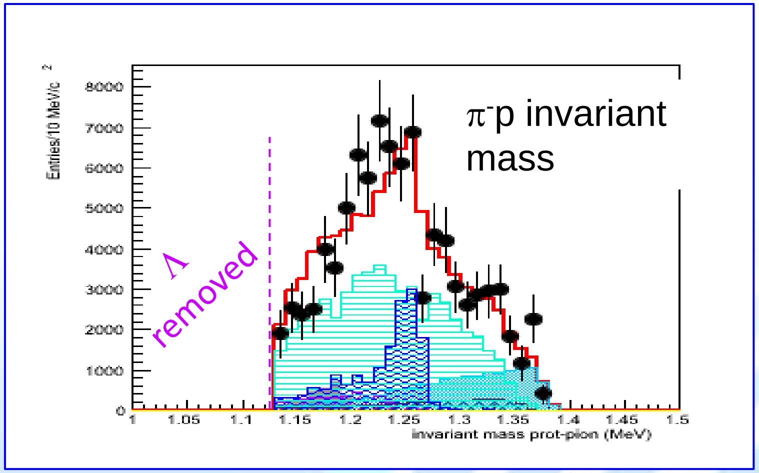




^{6}Li

χ^2_{NDF} = 1.39





^{7}Li

χ^2_{NDF} = 1.26

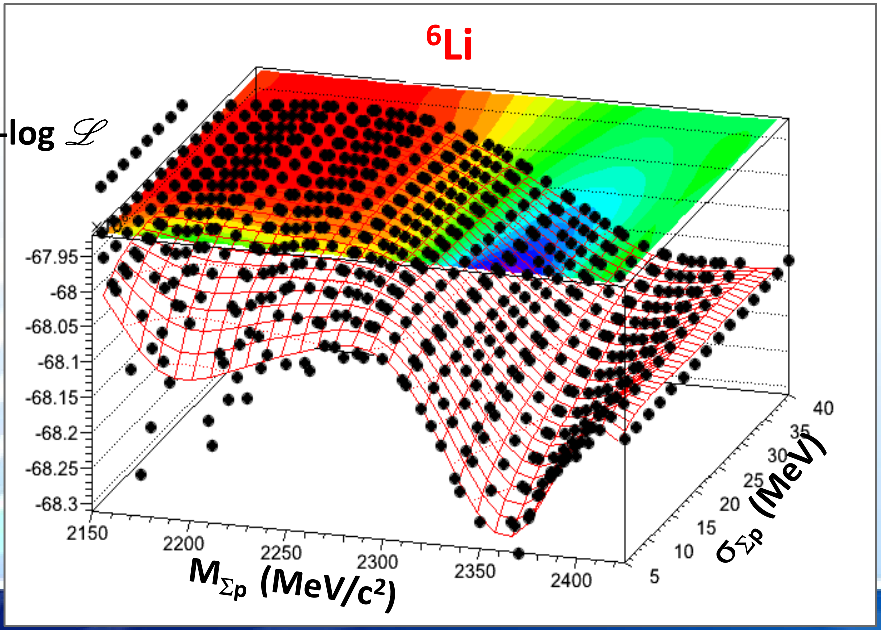
- ^{6}Li: QF reaction recoiling against a totally fragmented system ~10%, g.s.:13%
- ^{7}Li: QF reaction recoiling against a totally fragmented system ~5%, g.s.:15%
- Clear improvement of the ($\Sigma^{-}p$) mass region at 2320 MeV/c^2, still imperfect for ($\pi^{-}p$)

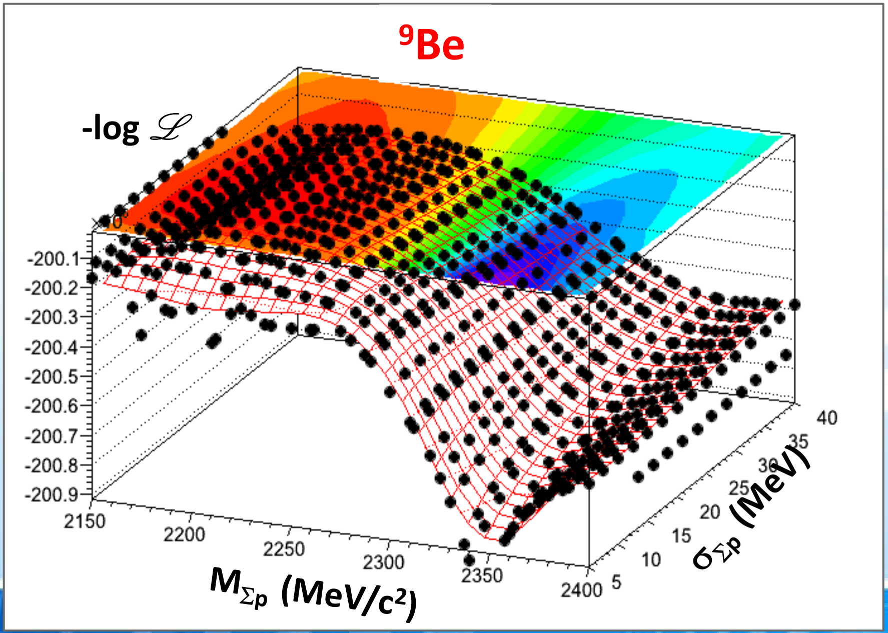
Add-on #2: extra component needed?

- Purpose: cusp effect at threshold? More exotic component?
- Additional hypothesis: a [K^-pn] resonant state decaying into Σ^-p
- Parameterized through a Breit-Wigner distribution, with mass $m_{\Sigma\text{-}p}$ and width $\Gamma_{\Sigma\text{-}p}$ as floating parameters
- Two approaches:
  - Best fit search over a discrete 2D grid over $m_{\Sigma\text{-}p}$ and width $\Gamma_{\Sigma\text{-}p}$
    - For each ($m_{\Sigma\text{-}p}$,$\Gamma_{\Sigma\text{-}p}$) hypothesis a dedicated simulation must be performed
    - Very time consuming
  - modeling of phase space (nπ^-p) events imposing proper kinematic constraints
    - (nπ^-) $\rightarrow \Sigma^-$
    - Back-to-back Σ^-p angle
    - Missing mass in the proper range
    - (Σ^- p) $\rightarrow$ Breit-Wigner with given mass and width, floating on a discrete grid
    - Fast localization of relative and absolute likelihood minima to have a rough indication of the region to be finer-tuned

Σ^-p fits with additional resonant amplitude

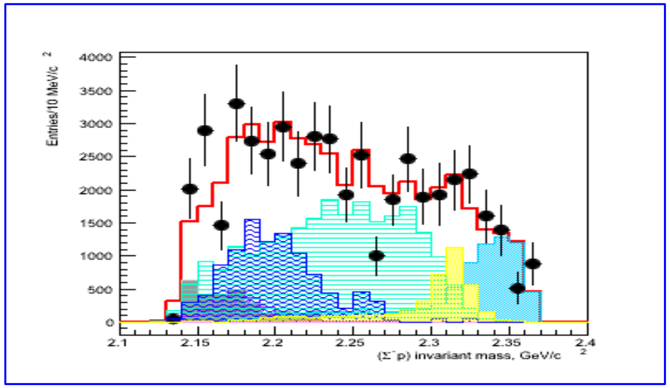
- Once the correct minimum region has been spotted, a complete simulation may be performed to look after the effective best fit solution
- General observations:
  - for all targets the fits are **poorly sensitive to the width** of the resonant signal: narrow widths are preferred, all of them within the experimental resolution
  - Two minima: one below 2200 MeV/c^2, the second (absolute) around 2350 MeV/c^2



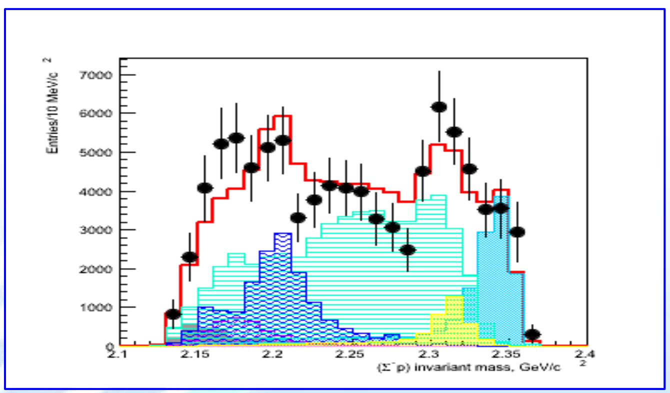


Fits with QF (g.s. recoil) + [K^-pn] resonant state

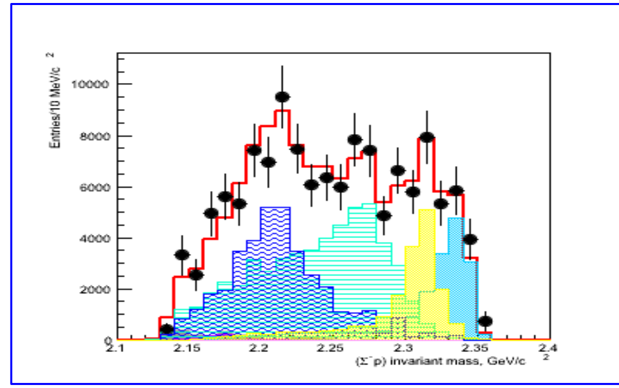
Rather marginal improvements
Statistical significance of $< 3\sigma$
Better for heavier targets



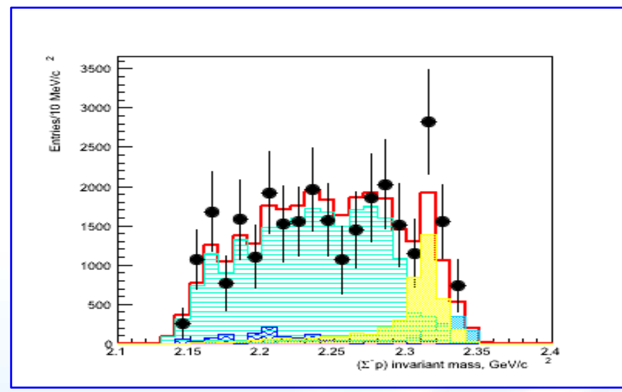
^{6}Li
$\chi^2 = 1.43$
Fraction: 8%



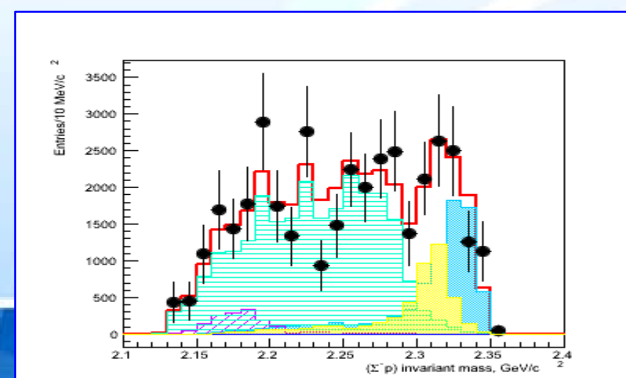
^{7}Li
$\chi^2 = 1.27$
Fraction: 5%



^{9}Be
$\chi^2 = 1.56$
Fract.: 14%



^{13}C
$\chi^2 = 0.72$
Fract.: 14%



^{16}O
$\chi^2 = 0.86$
Frac.: 12%

- Best fit (average):
  - $m_{\Sigma\text{-}p} = 2320 \pm 5_{st} \pm 10_{sys}$ MeV/c^2
  - $\Gamma_{\Sigma\text{-}p} = 12 \pm 11_{st} \pm 10_{sys}$ MeV/c^2

Summary and outlook

- Progress in the study of spectral composition in two-nucleon kaon absorptions on some p-shell nuclei: study of Σ^- emission
- **$K^-[pn] \rightarrow \Sigma^- p$ in several targets**
  - Capture rate evaluations (useful for background estimations)
  - Detailed study of QF contributions to experimental spectra: *global fits* with QF reactions
  - Imperfect fits: several tests for add-on's done and planned
    - Fragmentation/excited recoiling nucleus effect? YES, needed!
      - 3N absorption quite sizeable: try to include 4N (α) absorption
    - Resonance in the ($\Sigma^- p$) system? significance < 3σ (not promising)
    - Cusp effect at ΣN and/or $\Sigma N \pi$ threshold?
    - More complex $\Sigma/p/\pi$ rescatterings?
- New and interesting information on $K^-(np)$ absorption dynamics in nuclei