The FINUDA experiment: recent results

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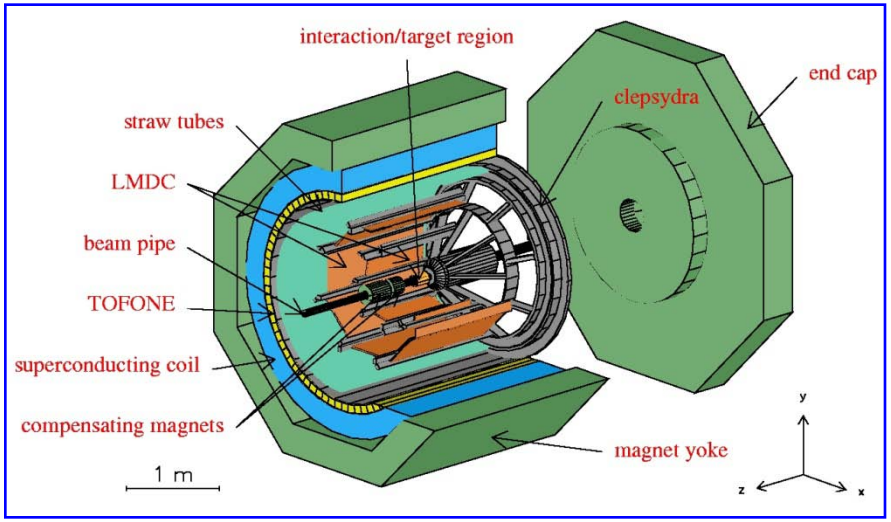
Outline

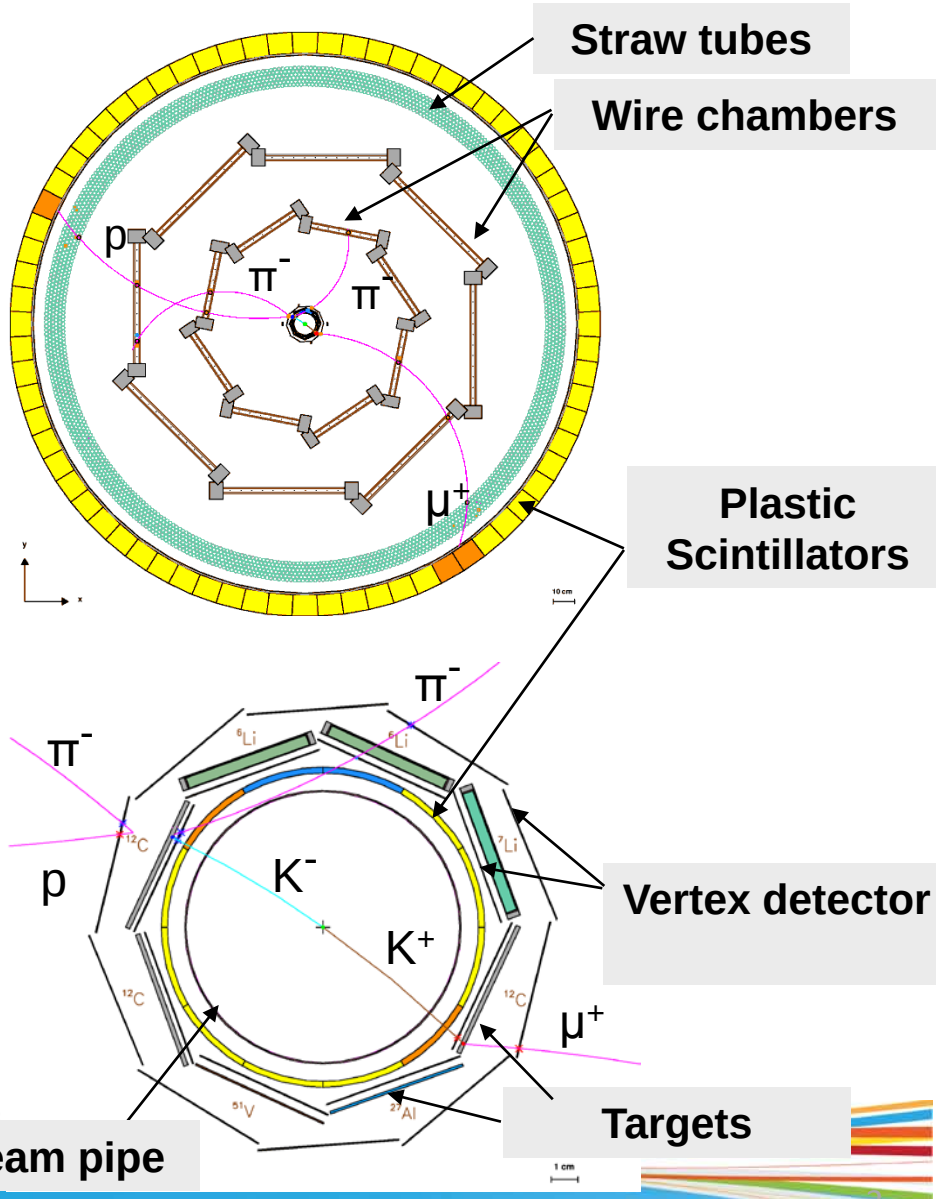
- Introduction
  - The FINUDA experiment at DAΦNE
  - Free hyperon production in K^- absorption in (pp) vs (pn) pairs in nuclei
    - Study of K^-(pp) absorption: (Λp) final state
    - Study of K^-(pn) absorption: (Σ^-p) final state *(preliminary)*

- Analysis method
  - data selection: hyperon + prompt particle final states identification
  - acceptance correction
  - spectra study and decomposition – global fits
    - Models, basic hypotheses and add-ons

- Results
- Conclusions

FINUDA @DAΦNE: K^-_{stop} on nuclei (A>4)





Two data takings in 2003-2004 (~190 pb^{-1}) and 2006-2007 (~960 pb^{-1})

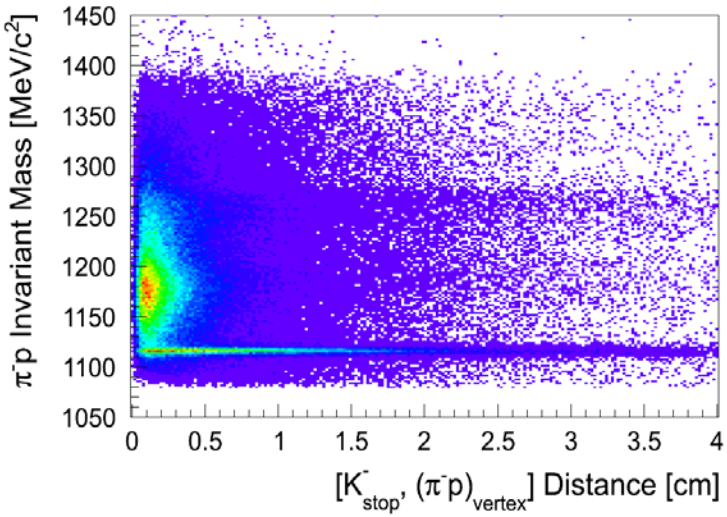
Simultaneous use of different targets

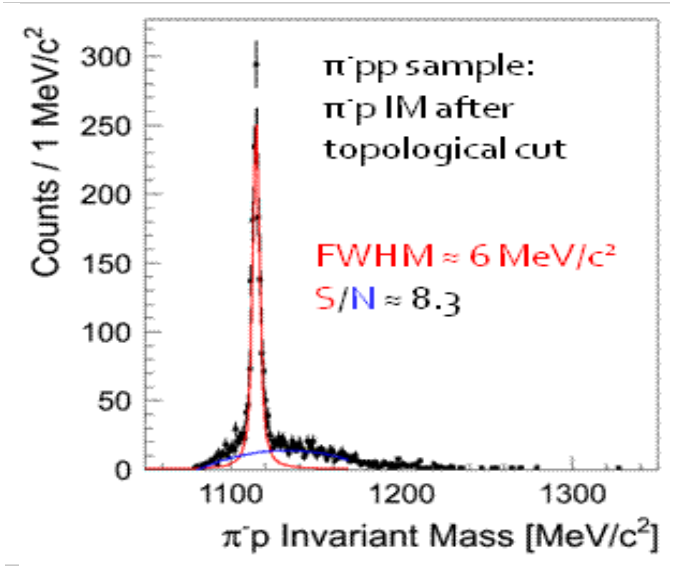
A = ^{6}Li, ^{7}Li, ^{9}Be, ^{12}C, ^{13}C, ^{16}O, ^{27}Al, ^{51}V

Free hyperons signals in (2N) absorptions

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

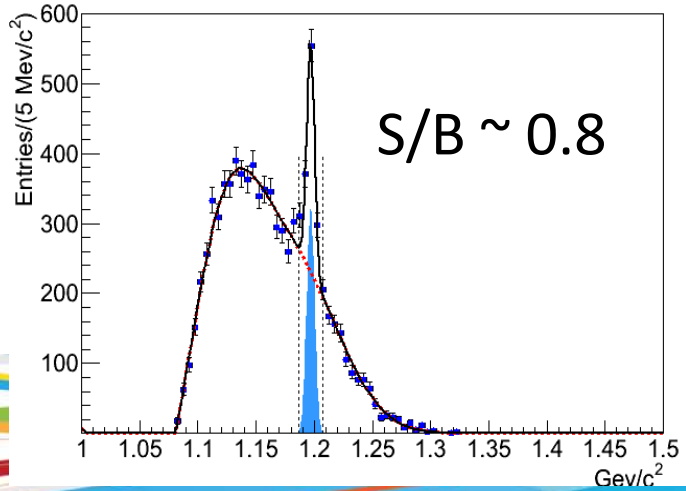
p as prompt particle (id purity: ~98%)

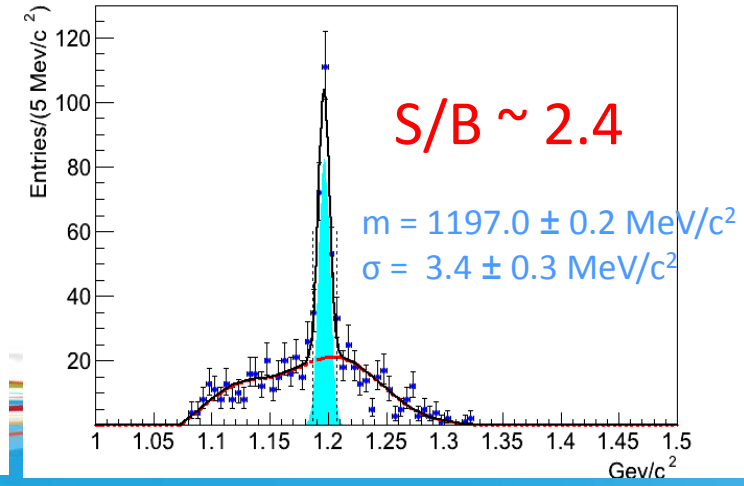




ppπ^-

- Low mom. thr.'s:
  - p_π > 70 MeV/c
  - p_p > 130 MeV/c
- Topological cuts
- S/N = 8.3





npπ^-

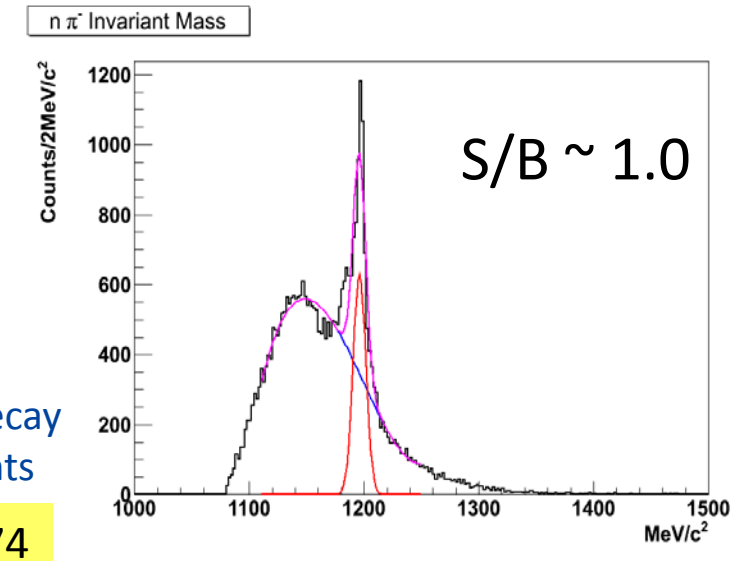
- reject events with unphysical missing mass
- track fitting
- vertex selection
- Λ rejection

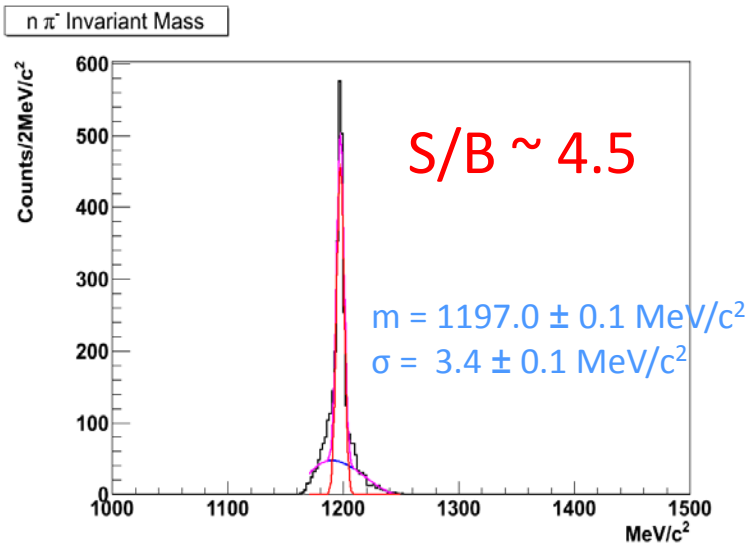
Σ^- signal identification quality

$n\pi^+\pi^-$

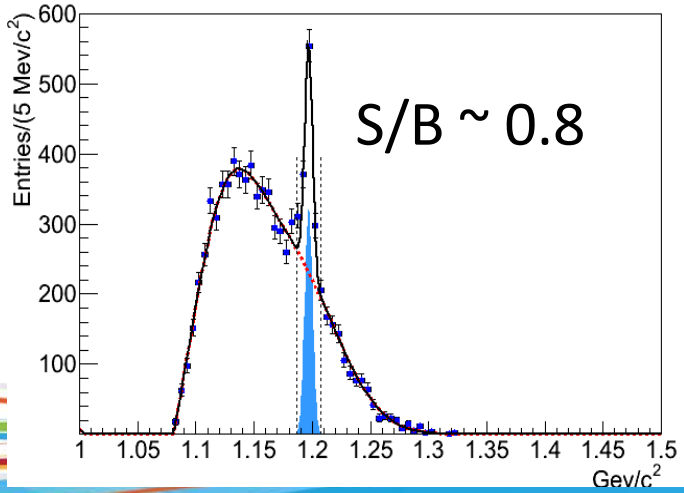
- reject events with unphysical missing mass
- track fitting
- vertex selection
- Σ^- decay angle
- $\pi^+\pi^-$ production/decay kinematic constraints

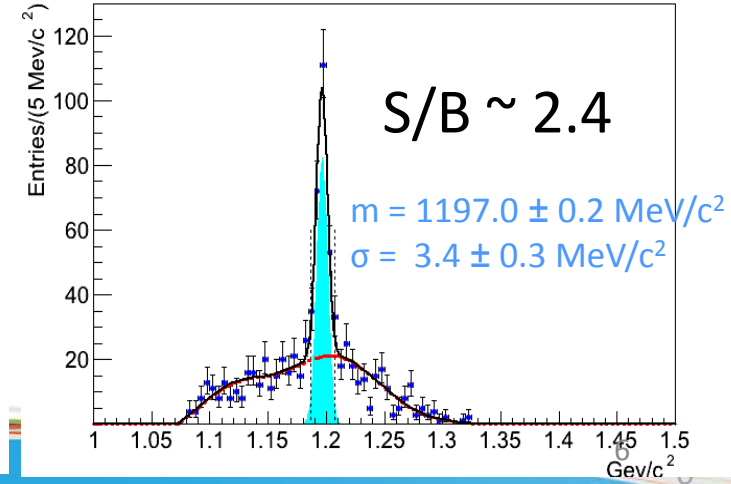
PLB704 (2011), 474





$np\pi^-$

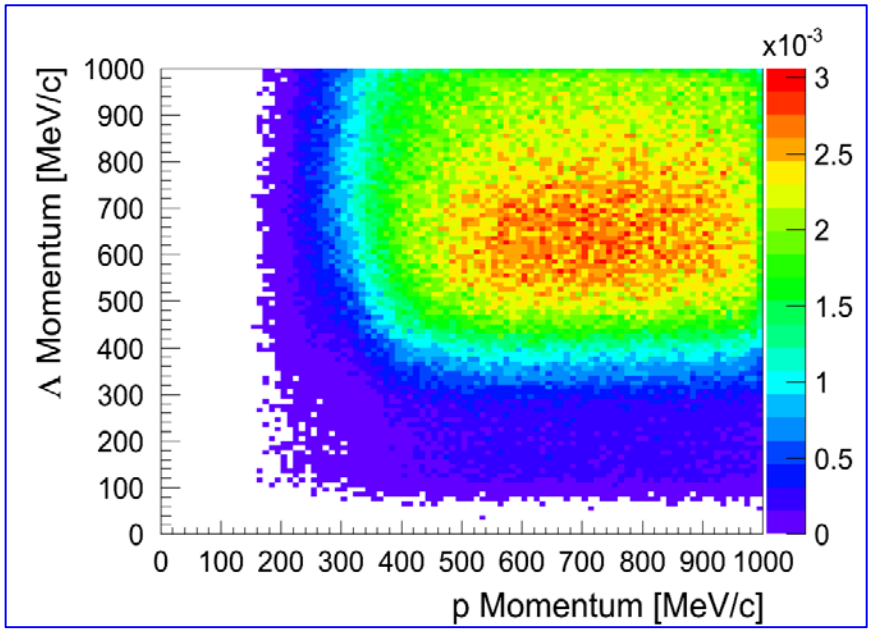


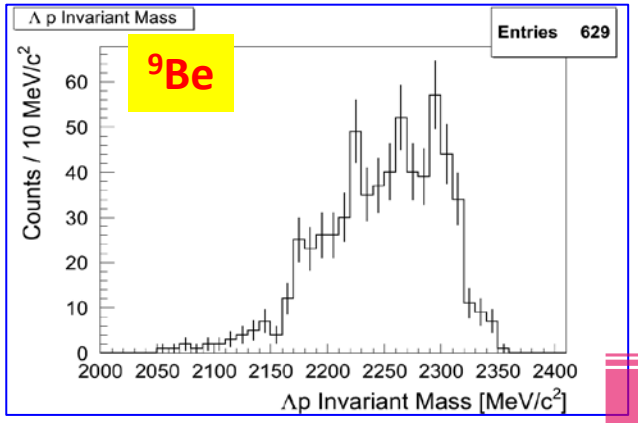


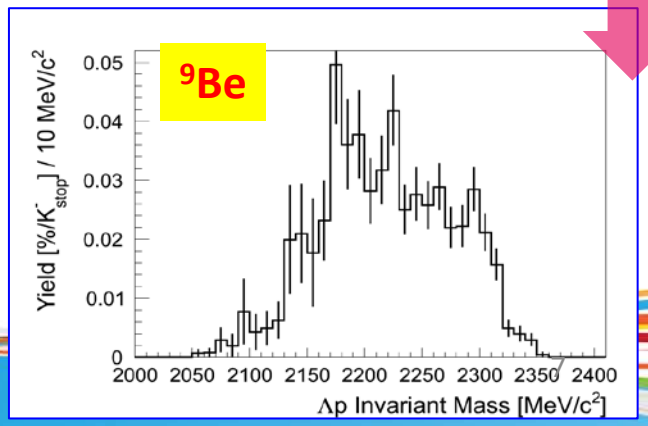
Acceptance corrections: effects

- Simulations of three particles with flat momenta in the relevant kinematic range of the reaction: O(10^9) events simulated
- Smooth but not flat multi-dim maps
- Event by event correction through a 9-dim matrix (per particle)
- Borders may be critical: cuts on particle momenta needed to minimize systematic errors

$pp\pi^-$



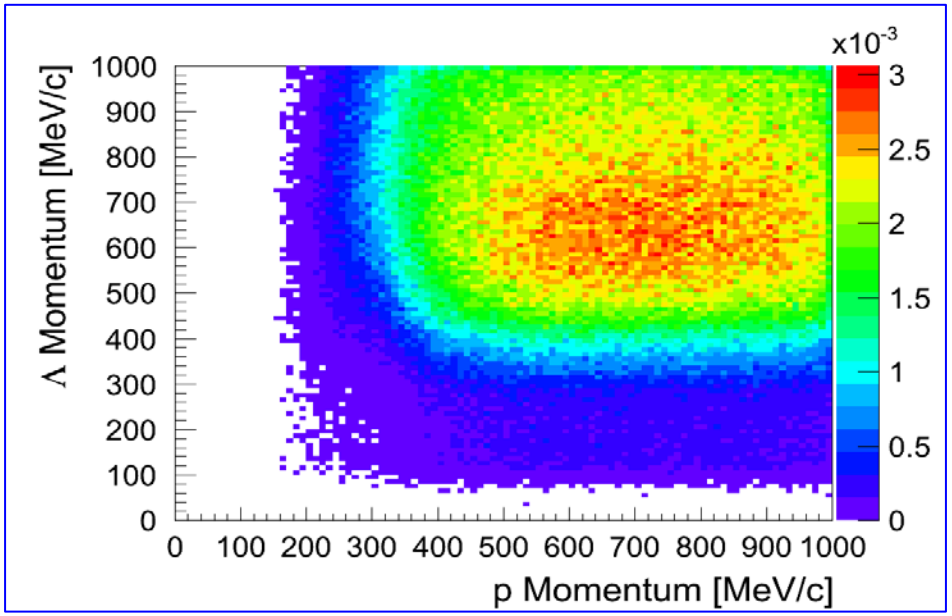




Applied acceptance cuts: p_p, p_Λ > 300 MeV/c

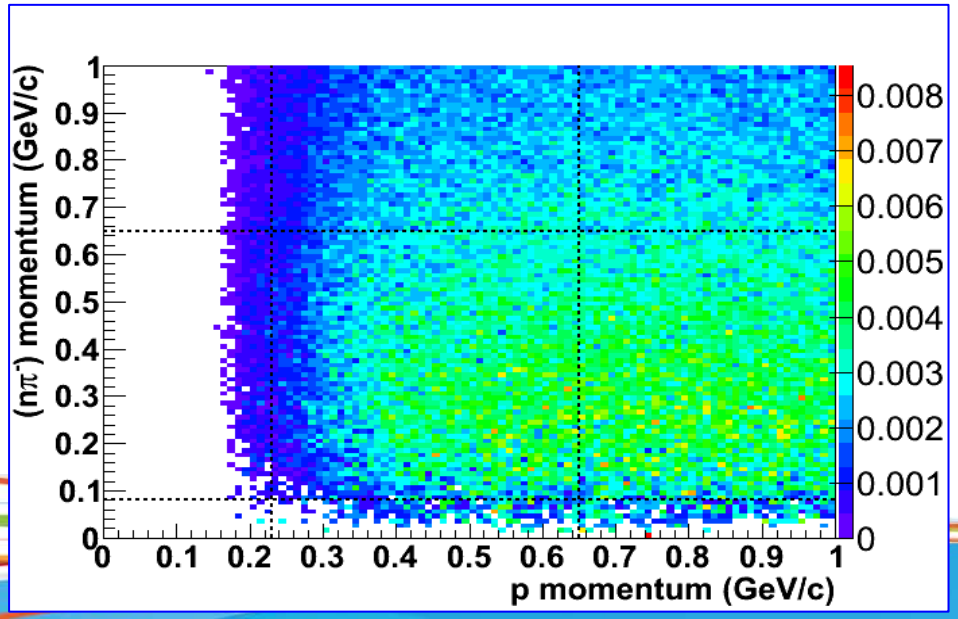
Acceptance corrections: comparison

$pp\pi^-$



- acceptance cuts:
  $p_p > 300$ MeV/c
  $p_{(pp\pi-)} > 300$ MeV/c

$np\pi^-$



- (almost) flat neutron geometrical acceptance
- smoother variation
- milder cuts are enough:
  $p_p > 200$ MeV/c
  $p_{(np\pi-)} > 80$ MeV/c

Spectral analysis approach

- Problem: how to determine the composition of spectra to understand physics and spot (possibly) new effects

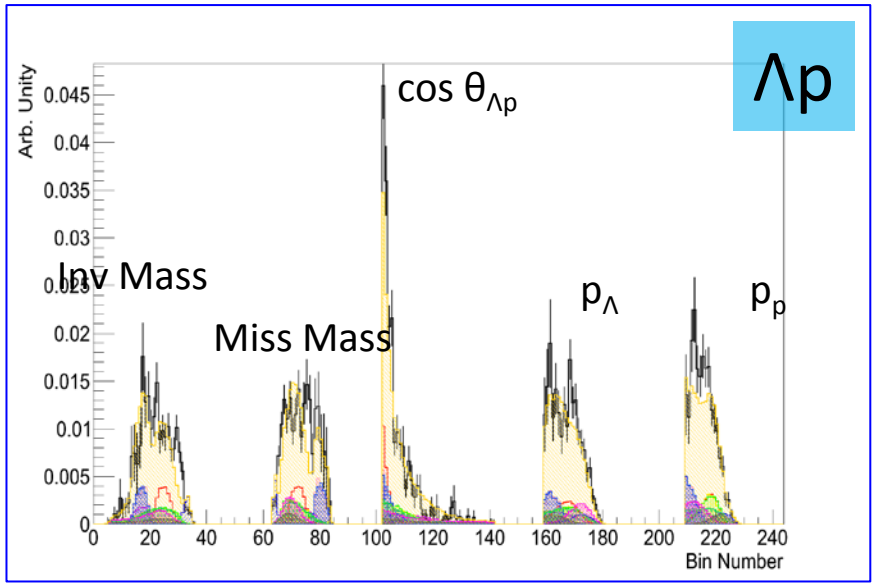
- Several experimental distributions to be considered at the same time to track the most of the data features
  - 2D distributions difficult to use (recoiling nuclear system, moderate statistics)

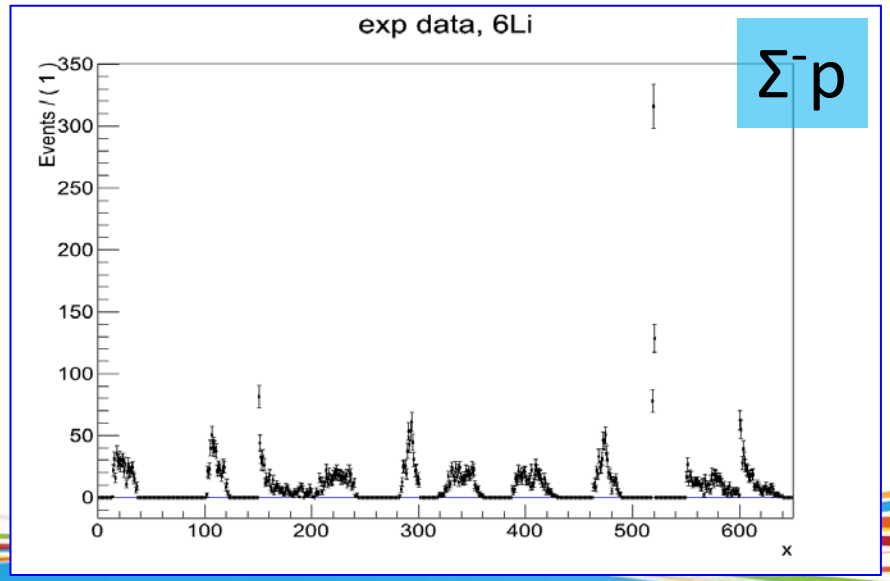
- Experimental data to be modeled by known QF reactions leading to the same final state and/or set of uncorrelated particles
  - Physical backgrounds
  - Accidental feedthroughs

- Approach: binned maximum likelihood fits of sets of experimental histograms based on Montecarlo simulations of quasi-free reactions

The multidimensional fit

- Several experimental distributions are required to be fitted at the same time by the sum of many QF reactions, TFractionFitter based on Poisson statistics
  - (Λp)
    - 5 experimental distributions
    - ≥10 QF reactions In the model
  - (Σ^-p)
    - 11 experimental distributions
    - ≥15 QF reactions In the model
- Output from the fit: fraction of each background reaction
- Iterative procedure with additional hypotheses until a satisfactory data description is achieved





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

(Λ p) FINAL STATE ANALYSIS

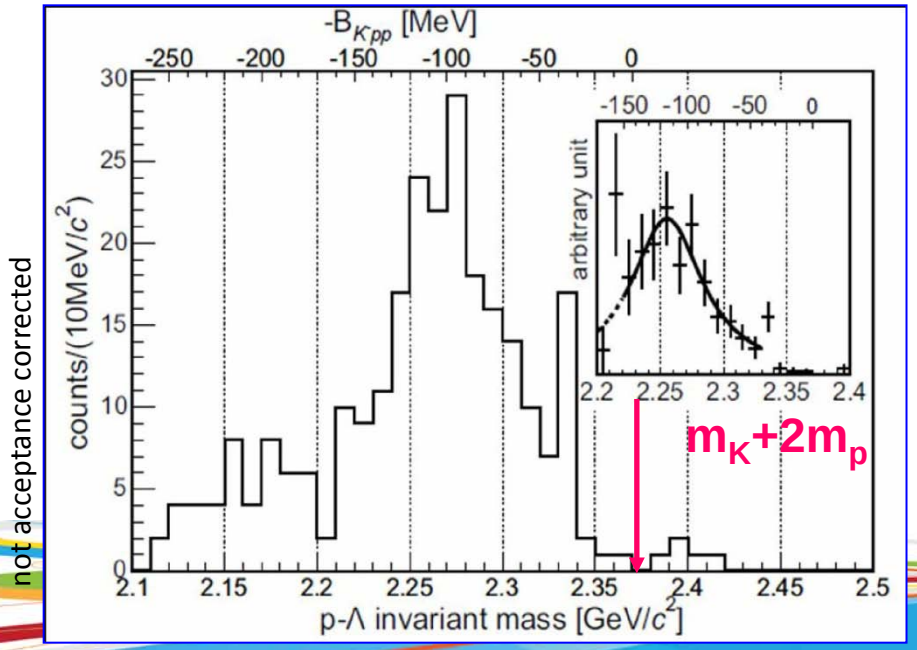
Old vs new data taking

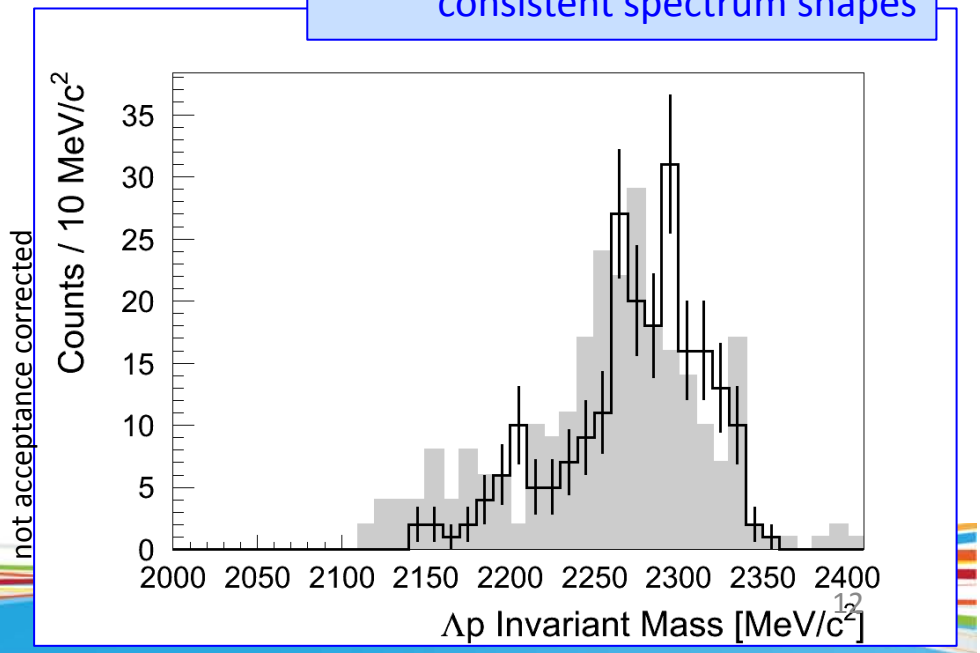
- 2003 data: all lighter targets together: $2x^6Li + 2x^7Li + 3x^{12}C$
- Different cuts applied on the data
- Different analysis approach
- Look for (K^-pp) bound state confirmation

FINUDA Coll., PRL 94(2005)212303

$B = 115^{+6}_{-5}$ (stat)$^{+3}_{-4}$ (sys) MeV
$\Gamma = 67^{+14}_{-11}$(stat)$^{+2}_{-3}$ (sys) MeV

2006-2007: $2x^9Be+2x^6Li+2x^7Li$
same normalization
no acceptance correctio
angular cut: $\cos\theta_{\Lambda p} < -0.8$
mom. cuts for Λ, p: > 300 MeV/c
consistent spectrum shapes

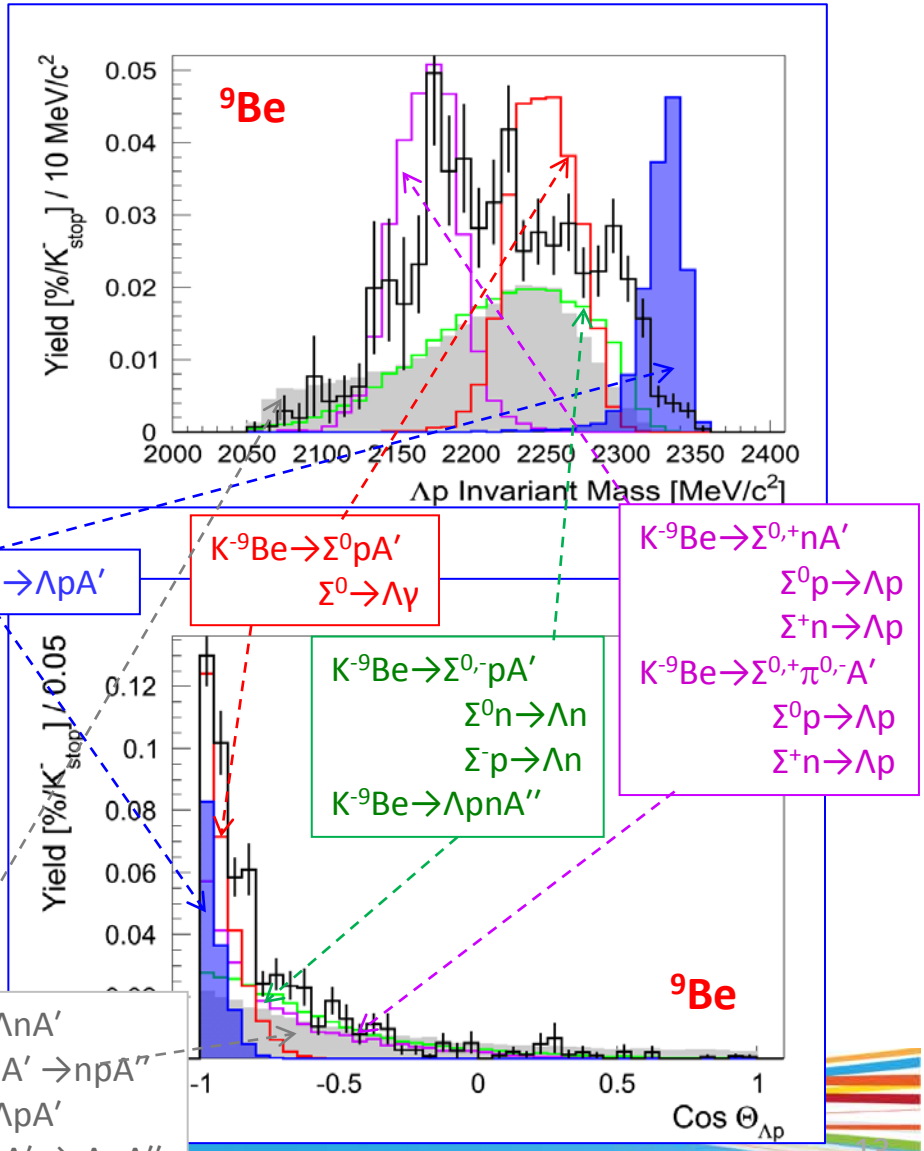




$K^-_{stop}A \rightarrow \Lambda pA'$ reaction: the models

- Several QF reactions are simulated (Fermi mom. for nucleons, nucleon pairs and recoiling A'), subject to reconstruction through FINUDA acceptance + analysis chain
- Start hypothesis: **A'** assumed **in its ground state**
- **grouped according to phase space coverage**
- **fits on acceptance corrected distributions**

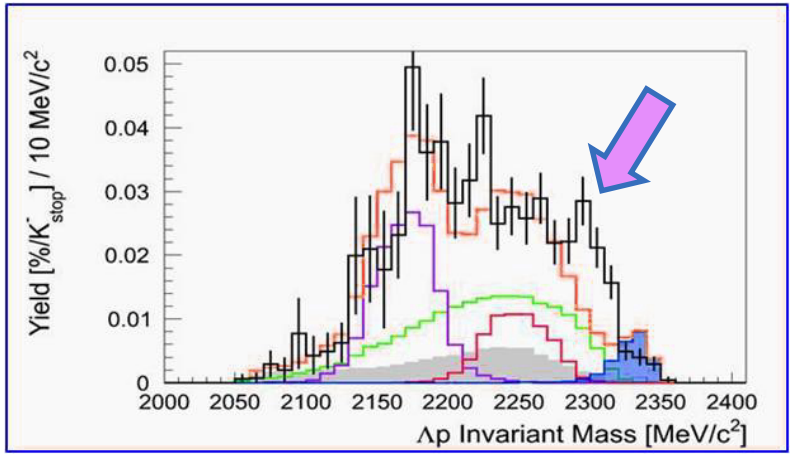
MC arbitrary normalizations

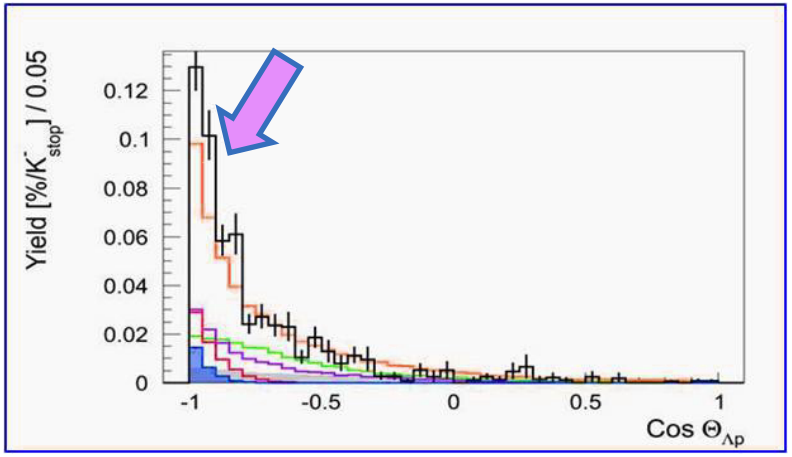


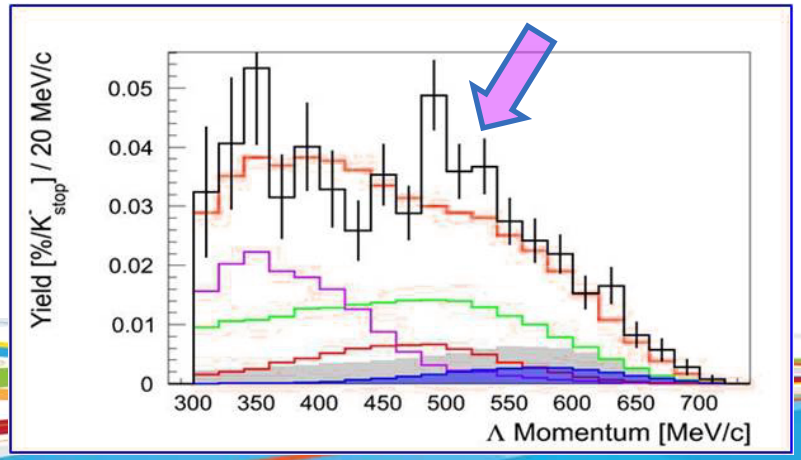
- K^- pp[A-pp]$_{g.s.}$ → **Λp A'**
- K^- pp[A-pp]$_{g.s.}$ → **Σ^0p A'**
- K^- pp[A-pp]$_{g.s.}$ → **Σ^+n A' + $\Sigma^+\Lambda$ C.R.**
- K^-n[A-n]$_{g.s.}$ → **$\Sigma^0\pi^0$ A' + ΣΛ C.R.**
- K^-p[A-p]$_{g.s.}$ → **$\Sigma^+\pi^-$ A' + ΣΛ C.R.**
- K^- pp[A-pp]$_{g.s.}$ → **Σ^0p A' + ΣΛ C.R.**
- K^- pn[A-pn]$_{g.s.}$ → **Σ^-p A' + ΣΛ C.R.**
- K^- ppn[A-ppn]$_{g.s.}$ → **Λpn A"**
- K^- pN[A-pn]$_{g.s.}$ → **ΛN A' + N FSI**
- K^- pp[A-pp]$_{g.s.}$ → **Λp A' + Λ FSI**

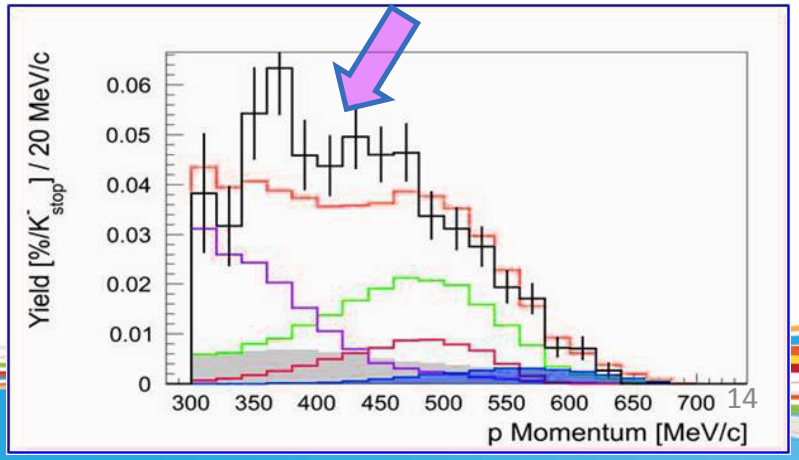
$^{9}Be(K^{-}_{stop},\Lambda p)X$ global fit results: base hypothesis

- The sum of **11 QF background reactions** (standard set) explains ~90% of the experimental spectra: $\chi^2_{NDF} = 3.2$ *- not satisfactory: additional reactions needed*
- The best fit cannot explain neither the (Λp) inv. mass excess at ~ 2300 MeV/c^2, nor the angular distribution for back-to-back angles







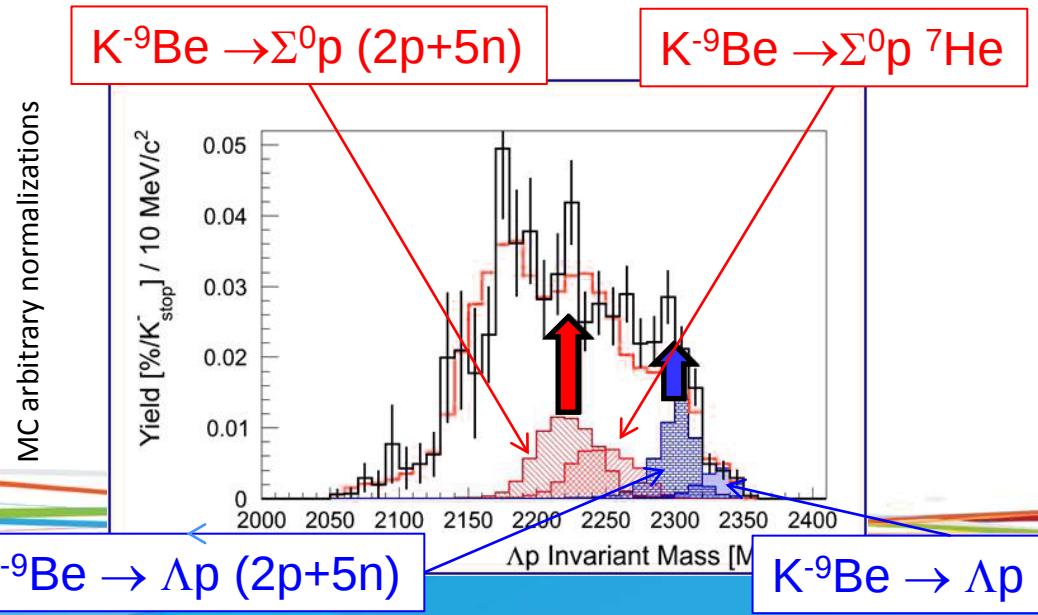


Add-on #1: excited/fragmented recoiling nucleus

- The kaon might be absorbed by a nucleon pair not on the nucleus surface, but inside the nucleus
  - The recoiling nucleus might be left in an excited state, and then fragment
    - The energy available for the (Yp) system could be lower
  - Sizeable energy difference in heavier nuclei (^{9}Be vs ^{6}Li)

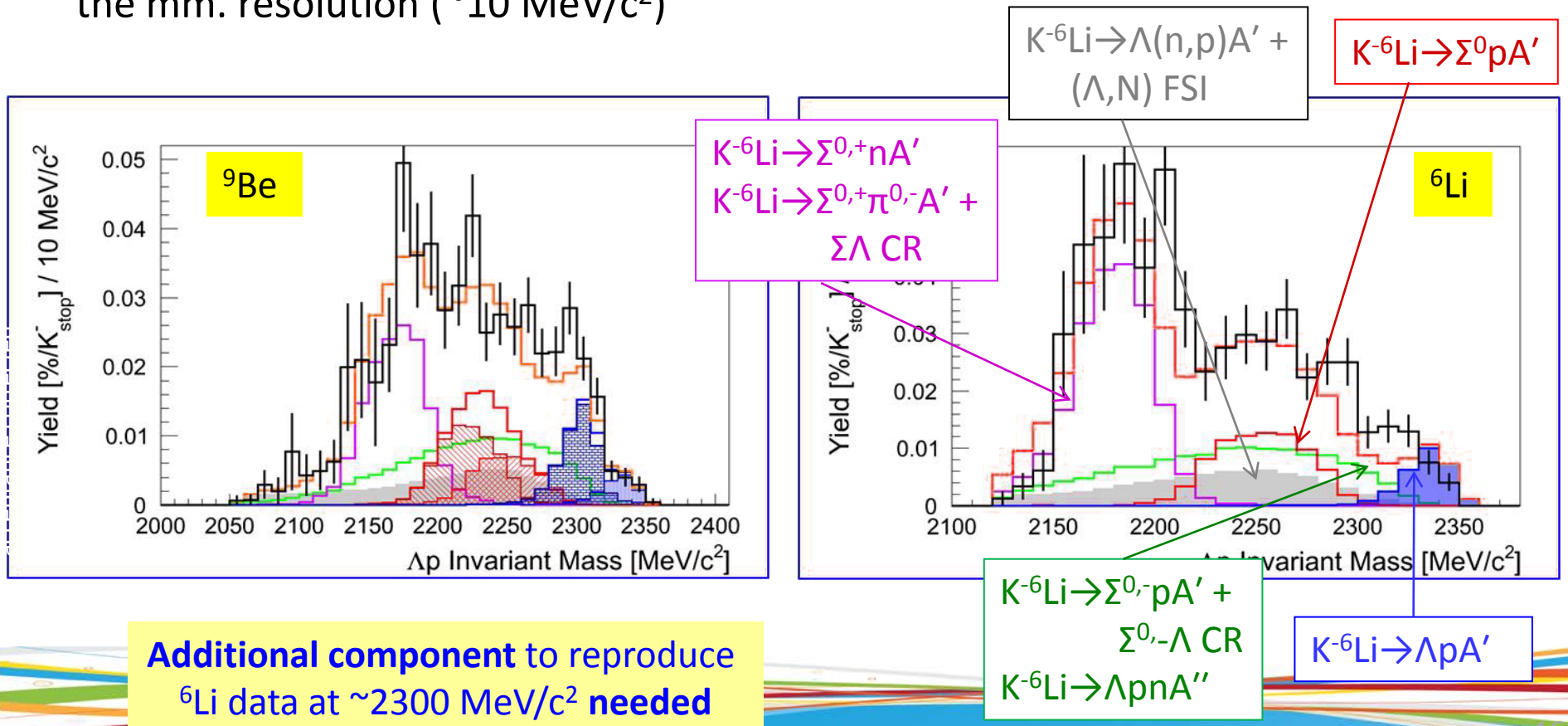
^{6}Li	A – [pp]	^{4}H	t + n	d + 2n	p + 3n
	Mass(MeV)	3751.37	3748.49	3754.76	3756.97

^{9}Be	A – [pp]	^{7}He	^{6}He + n	^{5}He + 2n	^{4}He + 3n	t+p+3n	d+p+4n	2p+5n
	Mass(MeV)	6545.54	6545.09	6546.96	6546.08	6565.89	6572.16	6574.37



Excited/fragmented recoiling nucleus: ^{9}Be vs ^{6}Li

- Sizeable improvement of ^{9}Be data description when different recoiling configurations are added
- Same for heavier targets (^{13}C, ^{16}O)
- Not critical for ^{6}Li since most of the excited/fragmented configurations are within the mm. resolution (~10 MeV/c^{2})

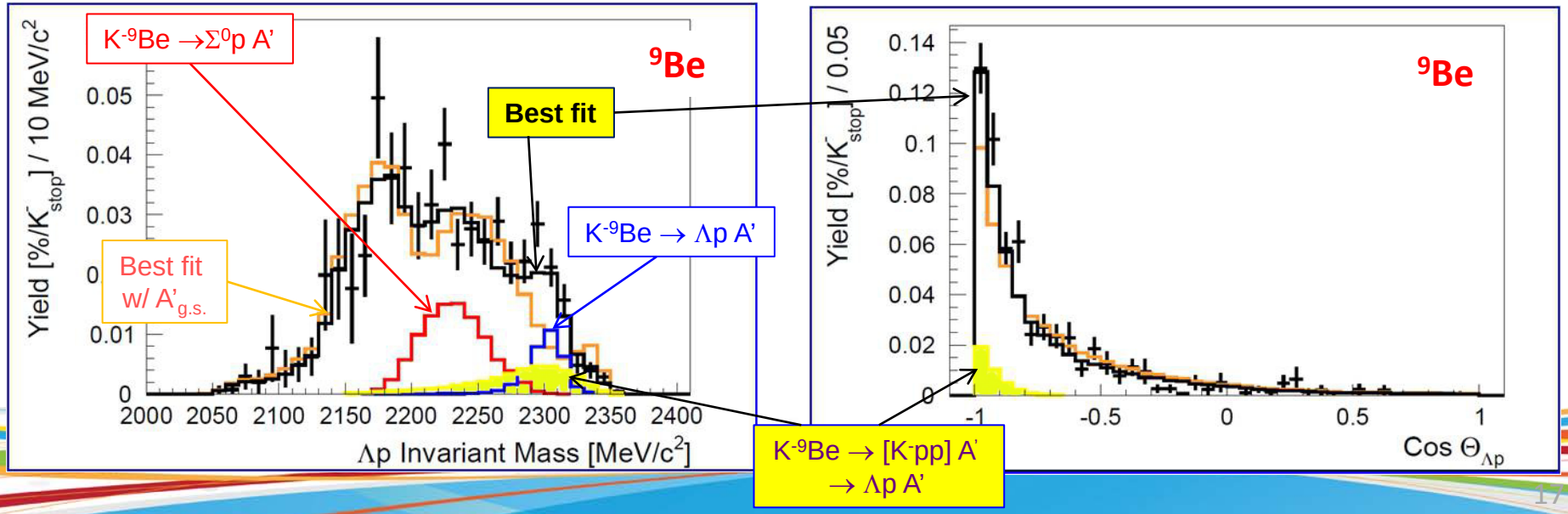


Additional component to reproduce ^{6}Li data at ~2300 MeV/c^{2} **needed**

Add-on #2: test of the [K⁻pp] resonant hypothesis

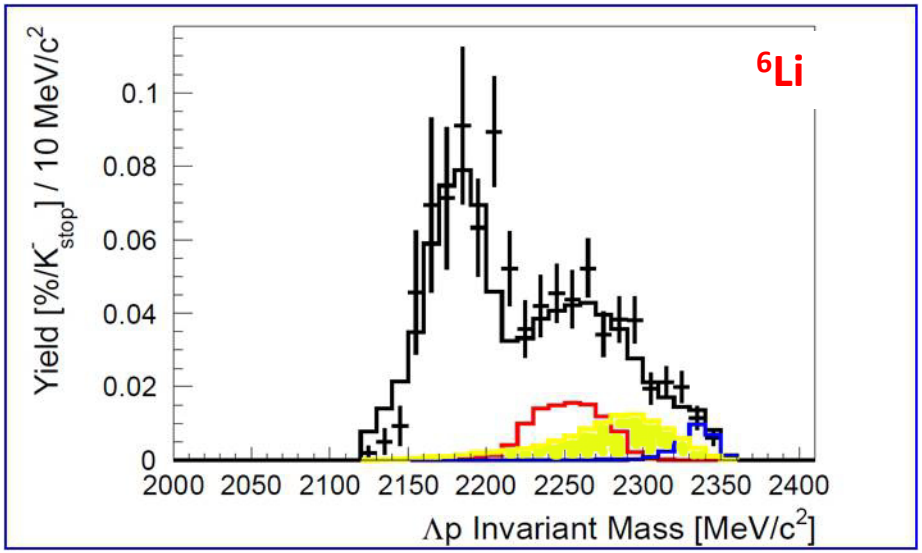
- Additional term: resonant contribution (Breit-Wigner) of an intermediate [K^-pp] system decaying at rest in Λp

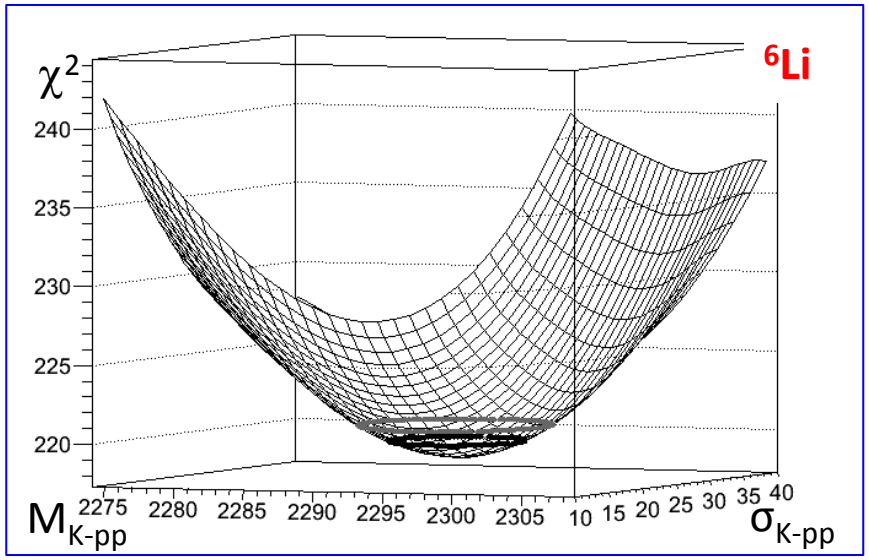
- Mass? Width?
  - Discrete scan along a 2D-grid (thorough simulation for each grid node)
  - Best fit solution: ($M_{\Lambda p}$, $\Gamma_{\Lambda p}$) pair delivering the minimum likelihood-χ^2
  - The additional component is decisive to solve many of the fits' problems and improve the overall description



Global fits in all targets

- [K^-pp] inclusion especially important for ^{6}Li
  - Best fit solution corresponding to χ^2 minimum, over the grid values





	$M_{\Lambda p}$ (MeV/c²)	$\Gamma_{\Lambda p}$ (MeV)	R(10^{-4}/K_{stop})	χ^2_ν	S
^{6}Li	2290±9	79±15	8.5±0.7±1.6	2.4	5.0
^{7}Li	2292±12	88±18	3.9±0.3±0.3	2.5	4.6
^{9}Be	2288±19	70±35	3.6±0.2±0.6	1.7	2.7
^{13}C	2292±12	71±41	9.7±1.1±0.3	2.2	2.5
^{16}O	2312±18	93±29	5.0±0.5±0.3	1.6	3.6

As compared to PRL results (light tgt mixture):

- larger width (but within errors)
- higher mass (~40 MeV/c²)

(Σ^- p) FINAL STATE ANALYSIS

Work in progress

Σ^-p spectra global fit – the model

Two classes of Quasi-Free reactions are being considered:

- reactions with (Σ^-p) pairs in the final state, recoiling against a nucleus in its *ground state*
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^-p\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma(1385)^-p\ {}^{A-2}(Z-1) \rightarrow \Sigma^-p\ \pi^0\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^-p\ \pi^0\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^-p\ \pi^+\ {}^{A-2}(Z-2)$ (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)
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Lambda n\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 n\ {}^{A-2}(Z-1) \rightarrow \Lambda n\gamma\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 n\ {}^{A-2}(Z-1) \rightarrow \Lambda np\ {}^{A-3}(Z-2)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 n\ {}^{A-2}(Z-1) \rightarrow \Lambda nn\ {}^{A-3}(Z-1)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^- n\ {}^{A-2}Z \rightarrow \Lambda nn\ {}^{A-2}Z$

  $\Sigma\ \Lambda$ conv. react.
  - Incoherent bck contributions (rescatterings, …)

Σ^-p spectra global fit – the model

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  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^-p\ {}^{A-2}(Z-1)$ + p rescattering
  - $K^-_{stop}\ {}^{A}Z \rightarrow \Sigma^-pn\ {}^{A-3}(Z-2)$ (on 3N or np pair in ^{3}H substructure)

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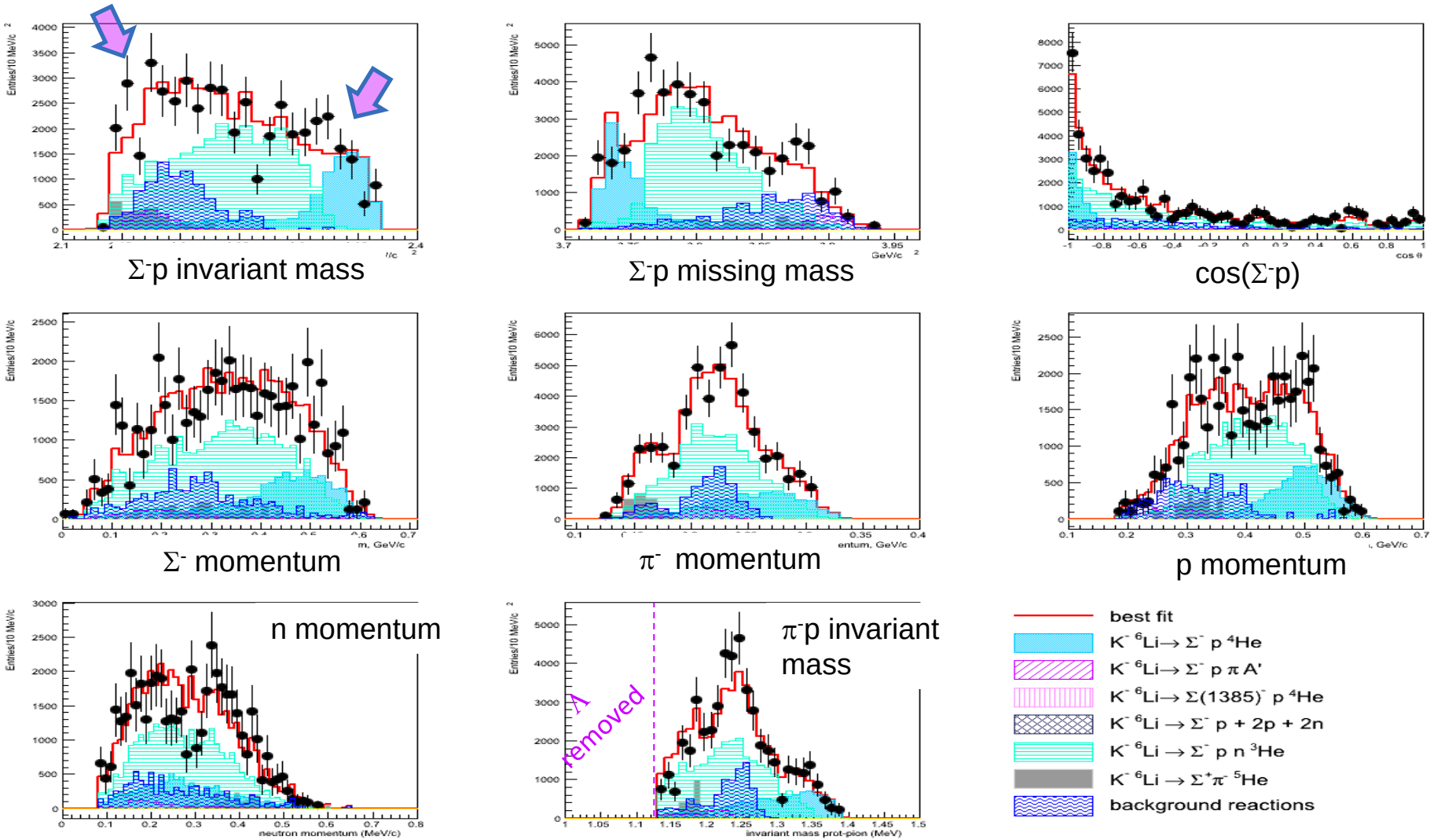
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0\pi^0\ {}^{A-1}(Z-1)$ (γ/n misidentif.)
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^+\pi^-\ n\ {}^{A-2}(Z-1)$ (2N absorption)
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Lambda n\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 n\ {}^{A-2}(Z-1) \rightarrow \Lambda n\gamma\ {}^{A-2}(Z-1)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 n\ {}^{A-2}(Z-1) \rightarrow \Lambda np\ {}^{A-3}(Z-2)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^0 n\ {}^{A-2}(Z-1) \rightarrow \Lambda nn\ {}^{A-3}(Z-1)$
  - $K^-_{stop}\ {}^{Z}A \rightarrow \Sigma^- n\ {}^{A-2}Z \rightarrow \Lambda nn\ {}^{A-2}Z$
  - Incoherent bck contributions (rescatterings, …)

$\Sigma\ \Lambda$ conv. react.

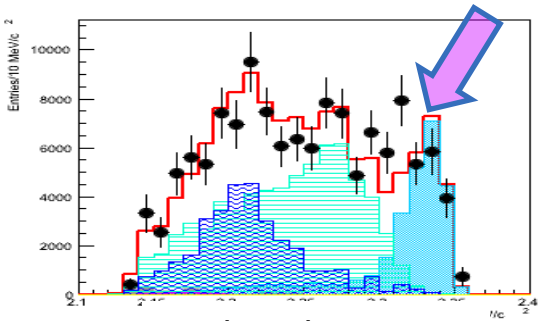
Contaminating reactions: $O(10^{-7}/K_{stop})$ only 1N absorption meaningful

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

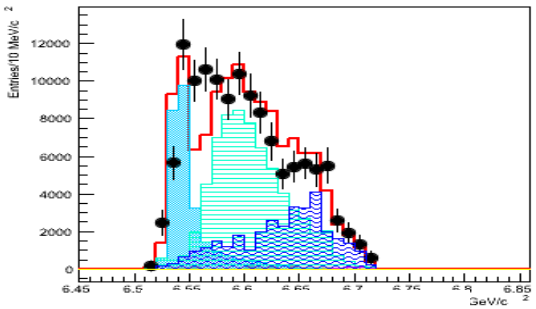


- 4 main reactions describe most of the spectra
- Not sensitive enough to separate $\Sigma^- p \pi^0$, $\Sigma(1385)^- p$ and $\Sigma^- p \pi^-$ contributions
- **Sizeable contribution from $\Sigma^- pn$ final state - Missing strength at 2150 and 2300 MeV/c^2**

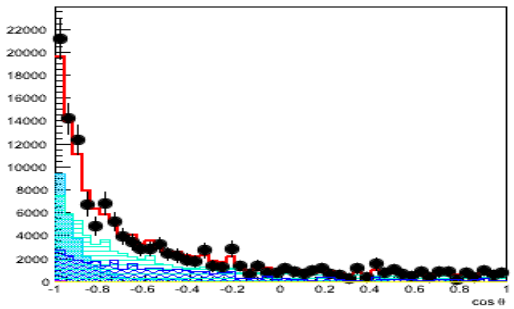
^{9}Be: fit with QF reactions, $A_{g.s.}$ $\chi_R^2 = 1.56$



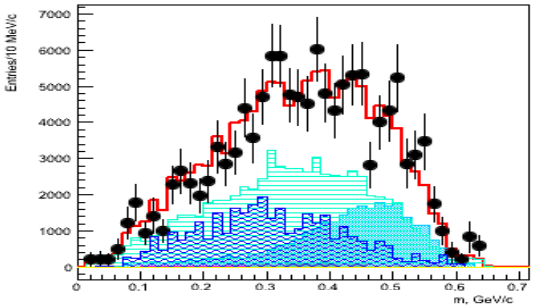
Σ^-p invariant mass



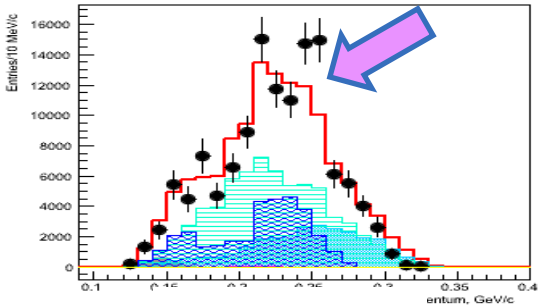
Σ^-p missing mass



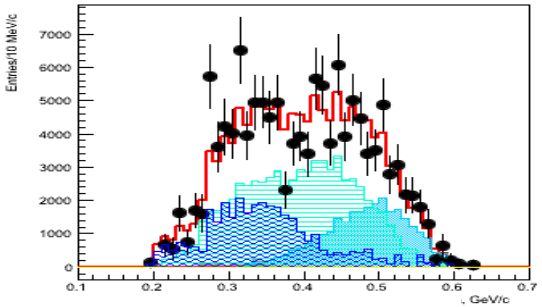
cos(Σ^-p)



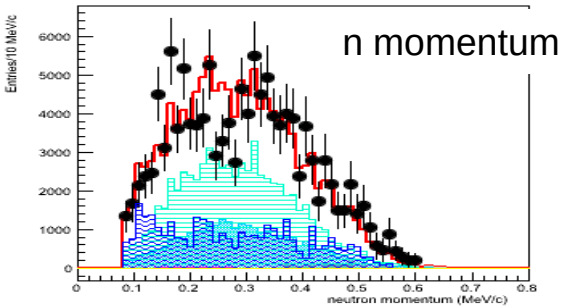
Σ^- momentum

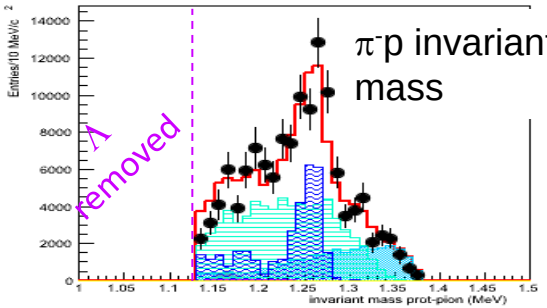


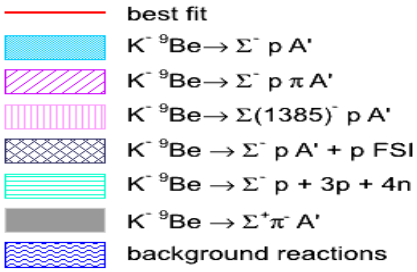
π^- momentum



p momentum





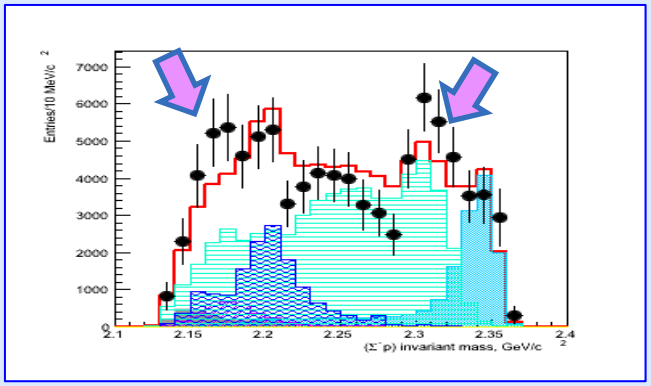


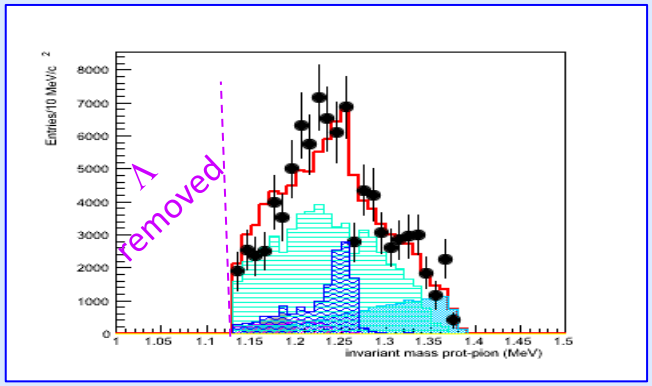
- 3 main reactions describe most of the spectra
- pion momentum fit not satisfactory
- **Sizeable contribution from Σ^-pn final state - Missing strength at 2300 MeV/c^2**

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

Σ^-p invariant mass

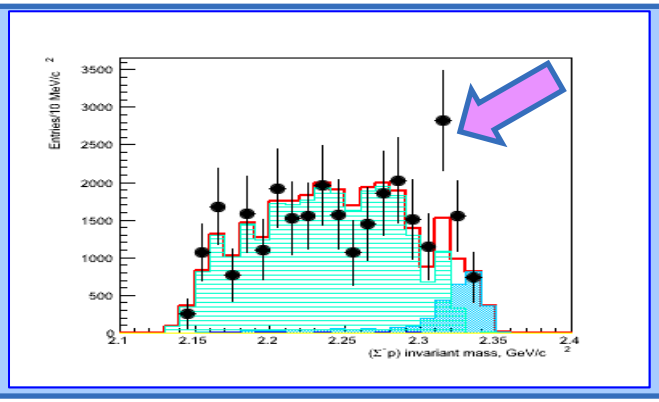
π^-p invariant mass

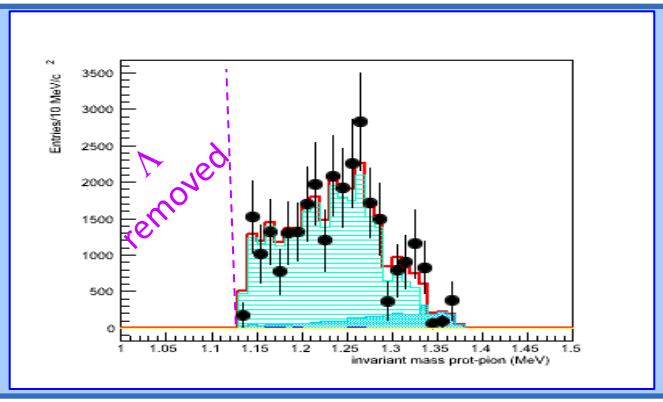




^{7}Li

- **4 main reactions** describe most of the spectra
- **Sizeable contribution from Σ^-pn final state - Missing strength at 2150 and 2300 MeV/c^2**
- $\chi_R^2 = 1.24$

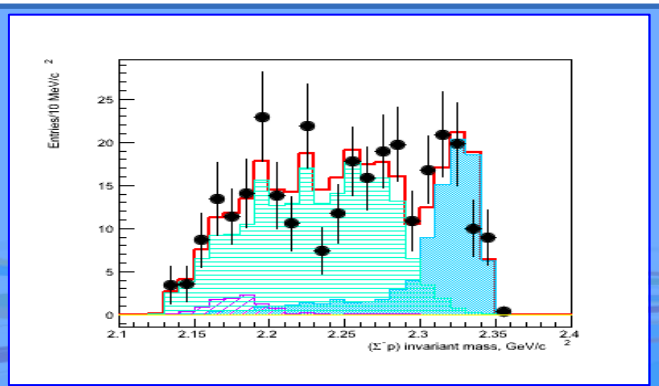


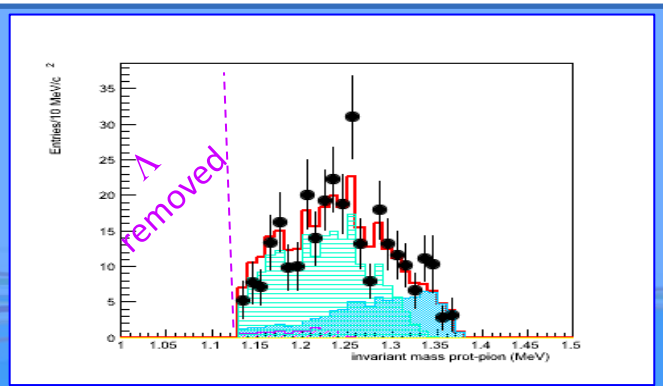


^{13}C

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

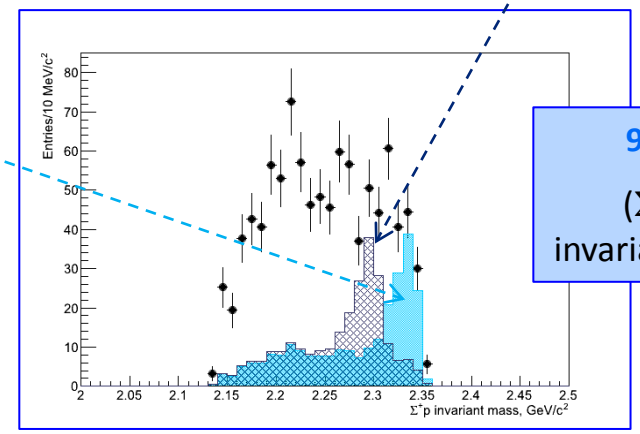
1st test: add components with a **maximally fragmented system** produced in Σ^-p QF

^{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

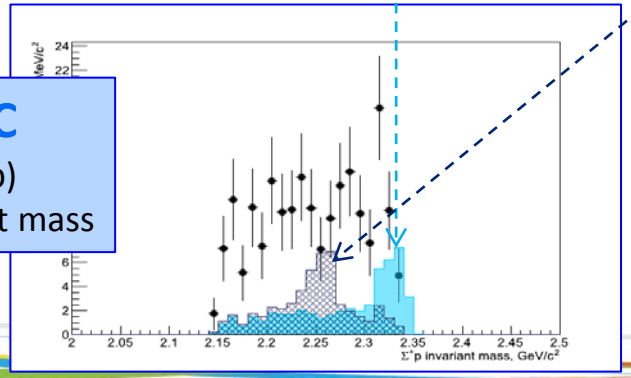
^{13}C	A – [np]	^{11}B	…	3p + 4n
	Mass(MeV/c^2)	10252.55		10328.75



^{9}Be (Σ^-p) invariant mass

Arbitrary normalizations

^{13}C (Σ^-p) invariant mass

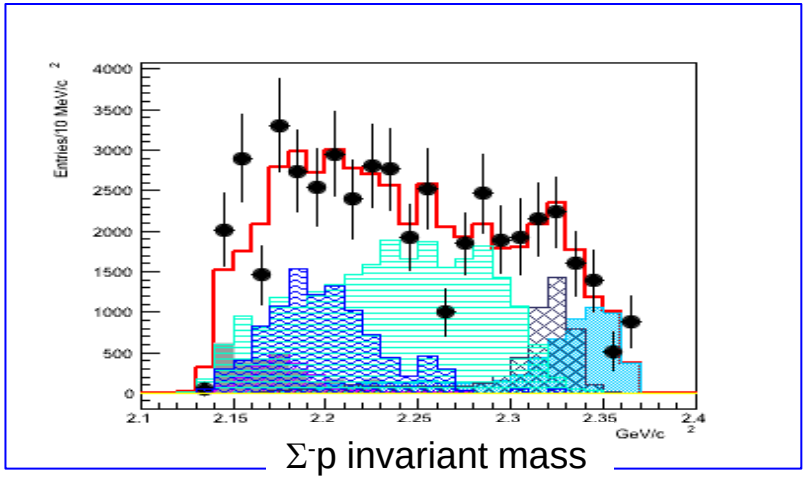


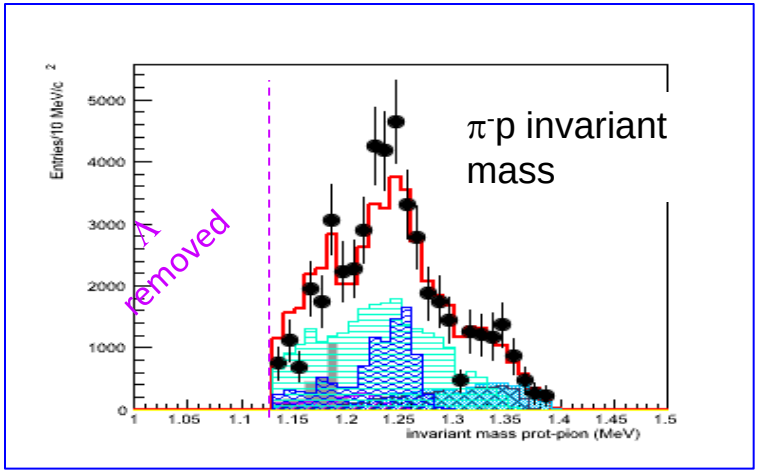
Arbitrary normalizations

^{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

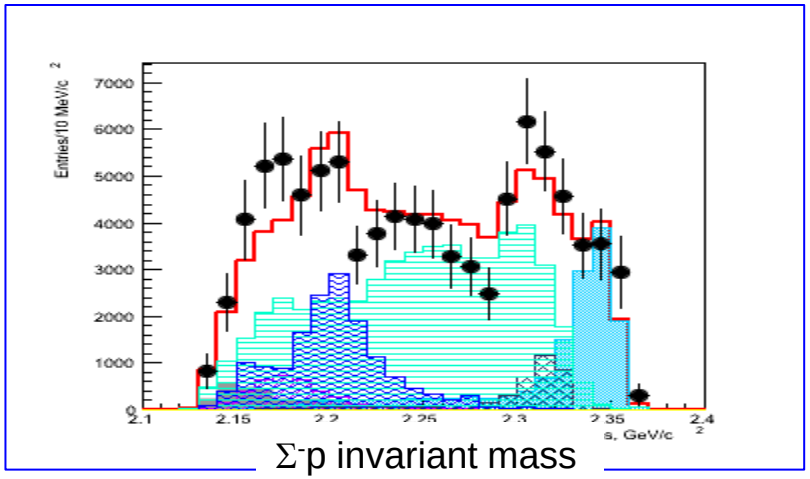
(meaningful contributions for lighter targets – heavier: too displaced)

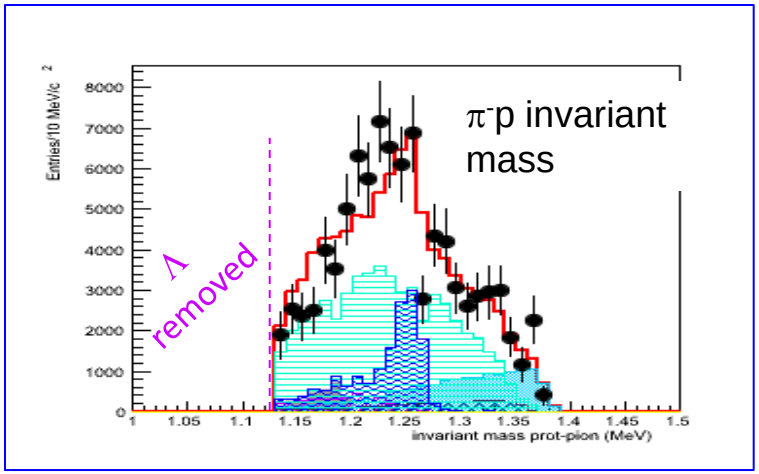




^{6}Li

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 (Σ^-p) mass region at 2320 MeV/c^2, still imperfect for (π^-p)

Summary

- New technique for the description of experimental spectra: global fit with a (large) set of absorption reactions and 2-step processes (conversion, rescattering), with the recoiling system in different configurations

- Original purpose: study of the existence of a [K^-pN] bound state:
  - **K^-[pp] → Λp**
    - Additional contribution needed at 5σ level to provide a good fit of the ^{6}Li data
    - Lower statistical significance for ^{9}Be
  - **K^-[pn] → Σ^-p**
    - No evidence from the data calling a resonant structure at the same mass
    - The significance of an additional resonance is less than 3σ
    - Rather, some sort of cusp-like needed close to **Λn** threshold
    - Preliminary results, further inquiries underway

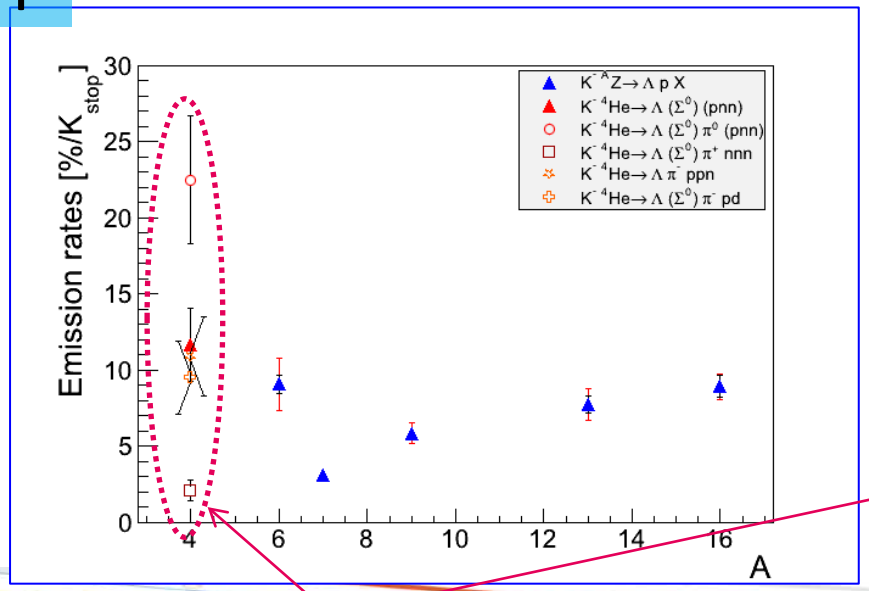
- Complementary observations/results which provide interesting additional hints on the absorption mechanism

BACKUP SLIDES

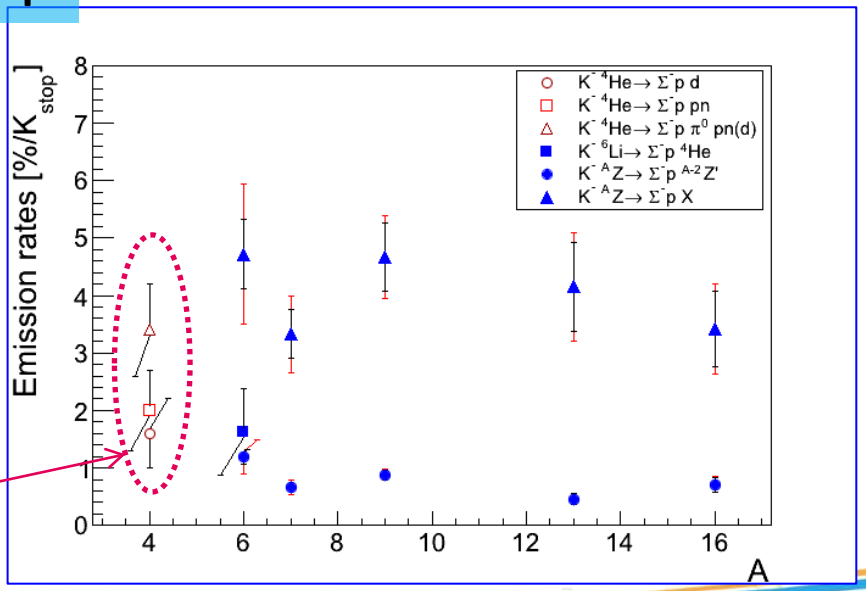
Emission rates evaluation

- Emission rates can be evaluated from the number of hyperons in their invariant mass spectrum (background corrected)
- Measured rates are in agreement with older (few) data
  - New measurements for A > 6

Λp



Σ⁻p

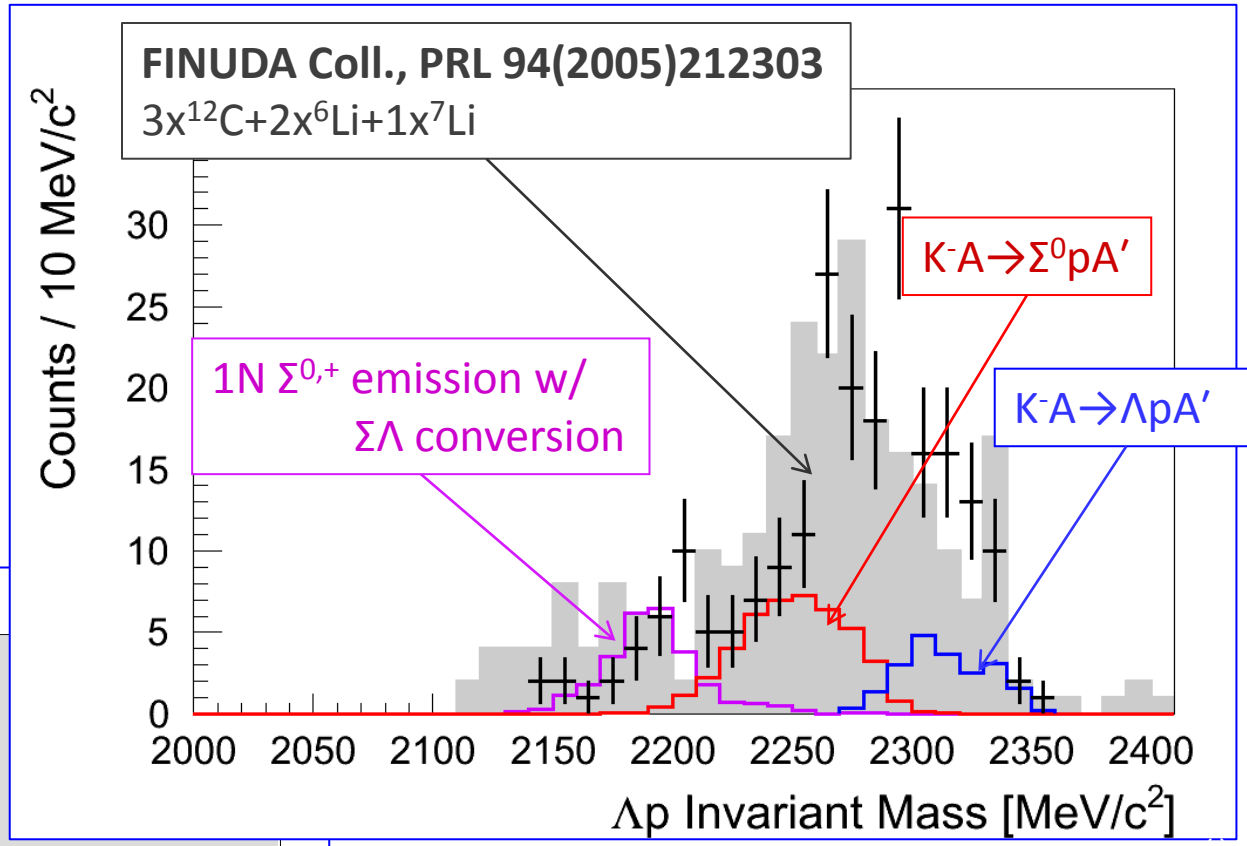


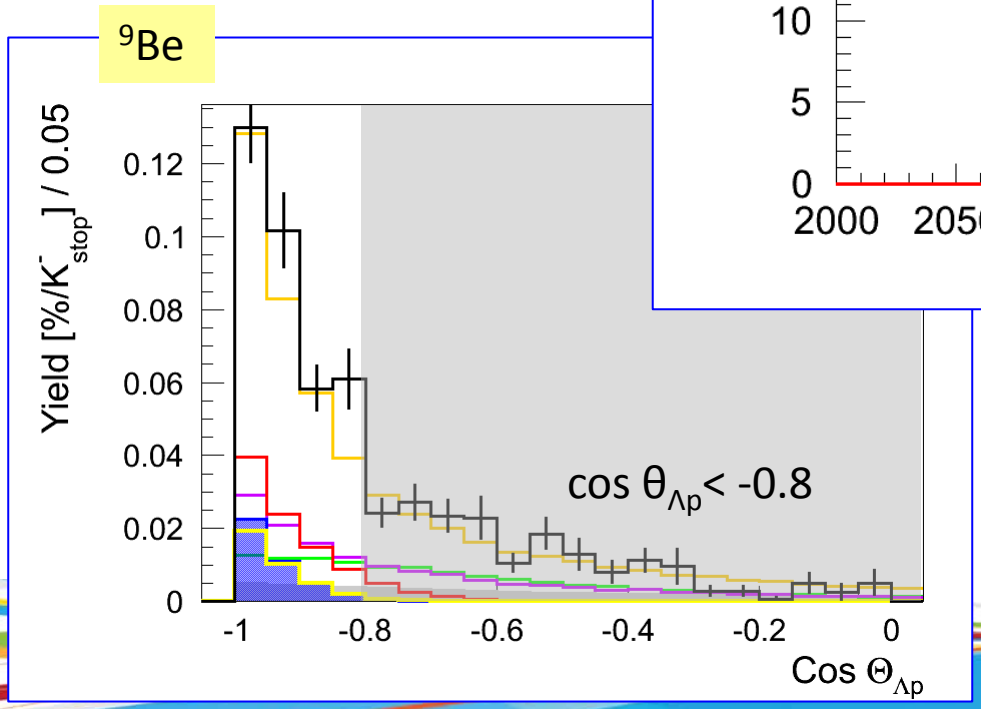
Red markers, ^{4}He data: Katz, PRD1 (1970), 1267

Comparison with the former result

- The applied angular cut does not affect Λp QF emission nor $\Sigma^0 p$

- A sizeable part of 1N and 2N reactions with Σ emission and $\Sigma\Lambda$ conversion, or reactions with FSI are antiselected





MC arbitrary normalizations

reshaping of the invariant mass projections