Analysis report on kaon-bound systems and request for run '05

FINUDA-JAPAN group
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Contents

- Improved pattern recognition routine
- Present status of deeply-bound kaonic state search
  - Missing-mass spectroscopy
  - Invariant-mass spectroscopy (K^-pp)
  - Other results (experiment and theory)
- Request for run '05

Kaonic nuclei search with Λ tagging

Missing-mass spectroscopy

- Example:

$$^{6}\mathrm{Li} + K^{-} \to \left\{ \begin{array}{l} K^{-}pppnn + \boxed{n} \\ K^{-}ppnnn + \boxed{p}_{\text{monoenergetic}} \end{array} \right.$$

- A kaonic nucleus emits a hyperon in its decay.

Invariant-mass spectroscopy

- Example:

$$K^{-}pp \to \Lambda + p \quad , \quad K^{-}ppn \to \Lambda + d(p+n)$$

of tracks to analyze in kaon bound state search

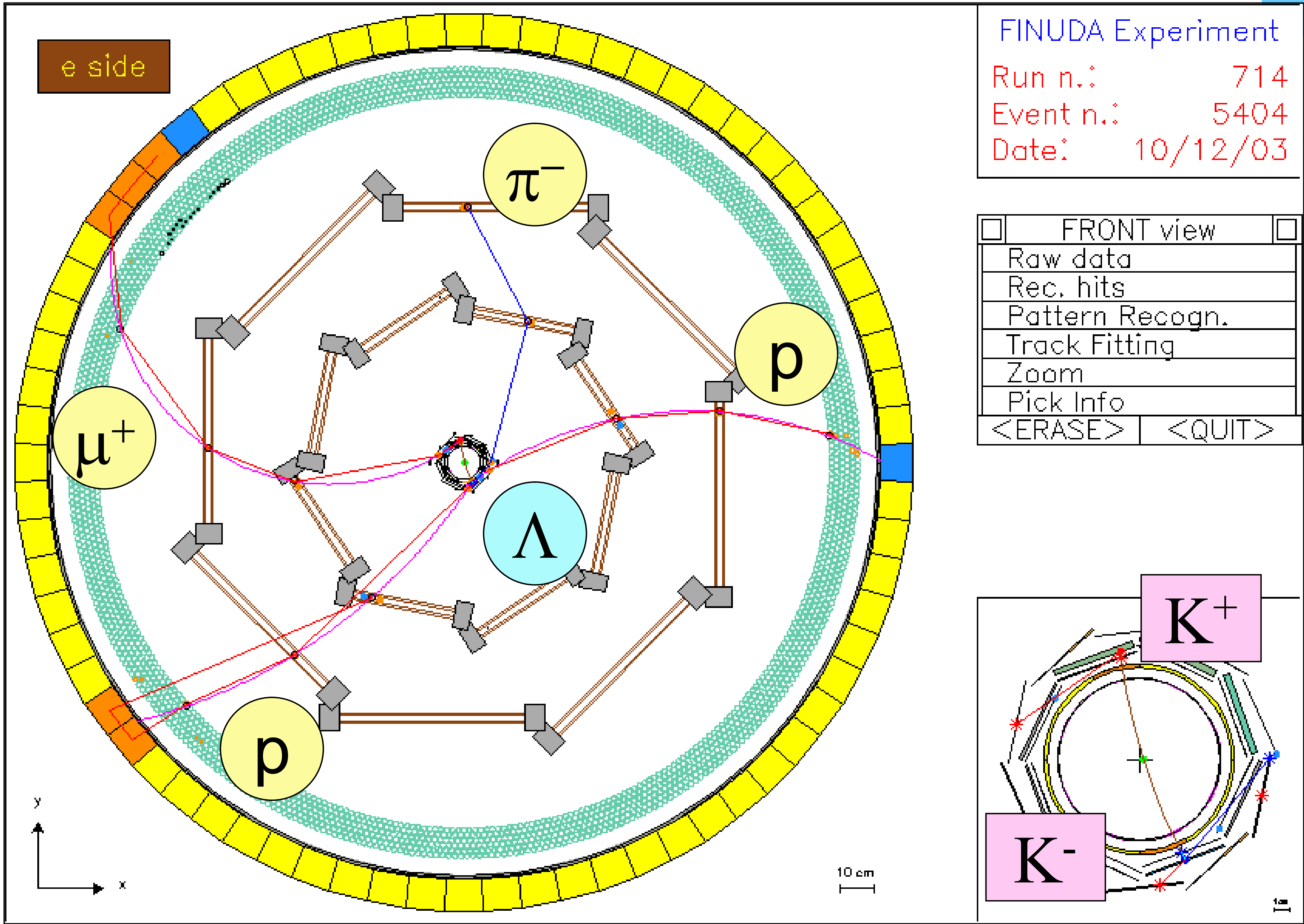
- The analysis of searching for kaon bound state requires three- (or four-) particle coincidence:

$$\boxed{\Lambda \text{ and p (and } \mu^+ \text{ from } K^+ \text{ decay)}}$$

- Typically,

$$\begin{cases} p_\Lambda \sim 500\,\mathrm{MeV}/c \\ \qquad \begin{cases} p_{\text{decay p}} \sim 500\,\mathrm{MeV}/c \\ p_{\text{decay }\pi^-} < 200\,\mathrm{MeV}/c \quad \text{(short track)} \end{cases} \\ p_{\mathrm{p}} \sim 500\,\mathrm{MeV}/c \end{cases}$$

Typical Event (K$^-$pp and μ^+ from K$^+$)



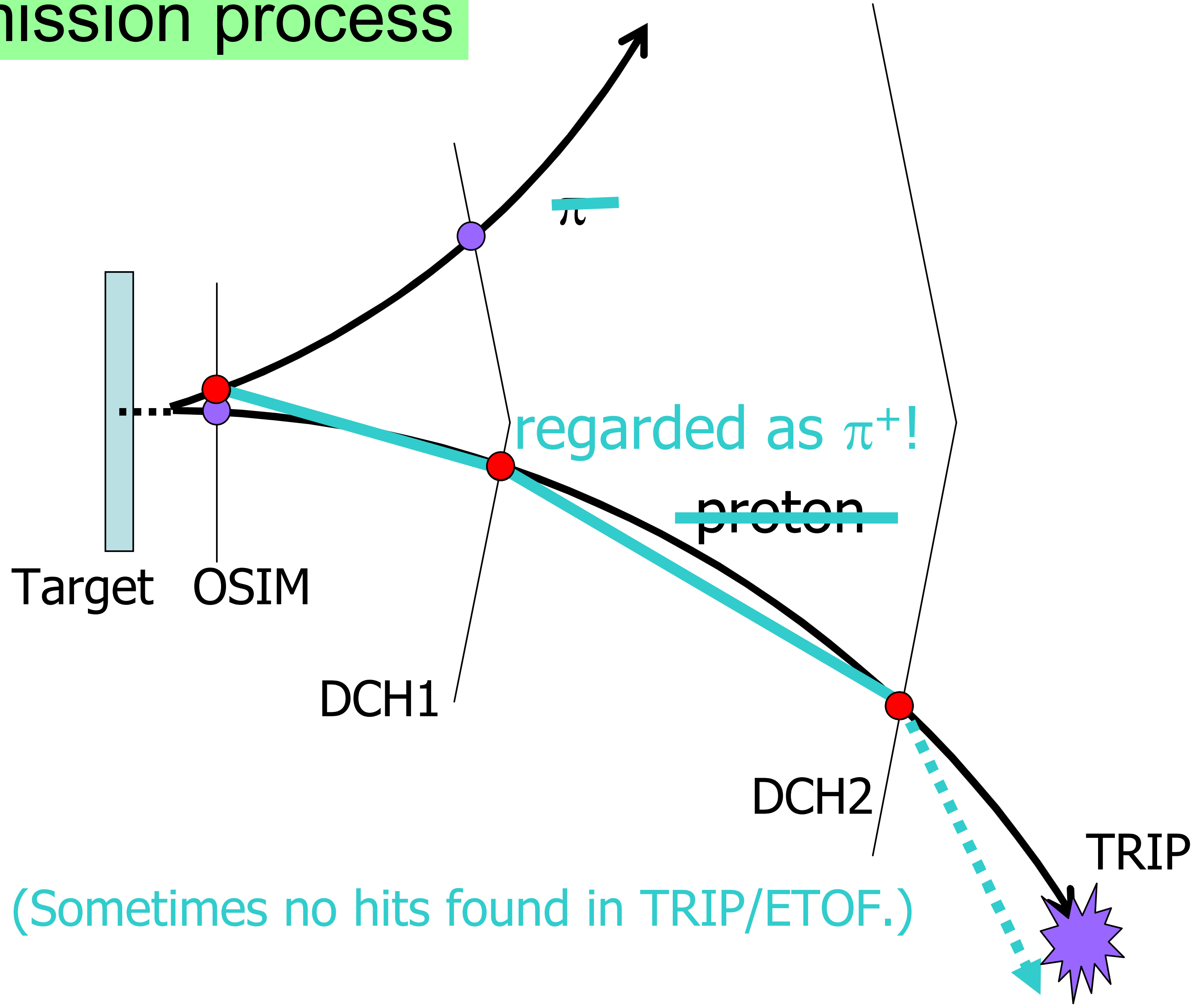
Comparison with other analyses

- kaon bound state : 2 long + 1 short
- hypernuclear spectroscopy : 1 long
- hypernuclear weak decay : 2 long or 1 long + 1 short
- ${}^{4}_{\Lambda}He$ rare decay : 2 long
- neutron-rich hypernucleus : 1 long
- Σ-hypernucleus : 1 long + 2 short

Pattern recognition has to be done very carefully.

Wrong recognition –example–

Λ emission process



Present pattern recognition (version 5.11)

1. short track : OSIM-DCH1-DCH2
2. long track : OSIM-DCH1-DCH2→TRIP→ETOF

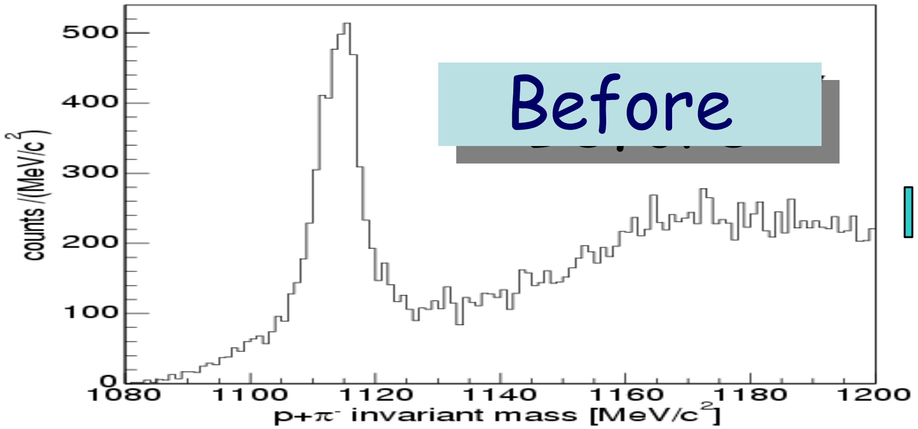
(extrapolation of short track)

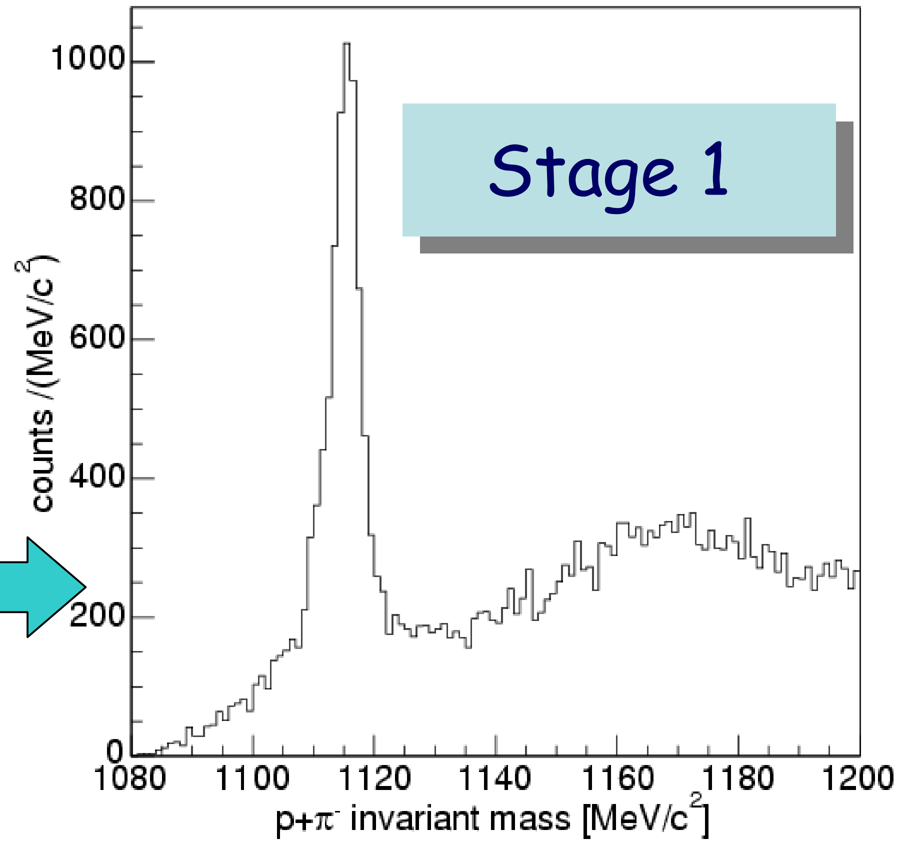
Problems:

- Wrong recognition sometimes occurs, particularly in Λ detection (previous page).
- dE/dx of OSIM is not used for P.R.

Solution (Stage 1)

1. long track : OSIM←DCH1-DCH2-TRIP→ETOF
2. short track : OSIM-DCH1-DCH2





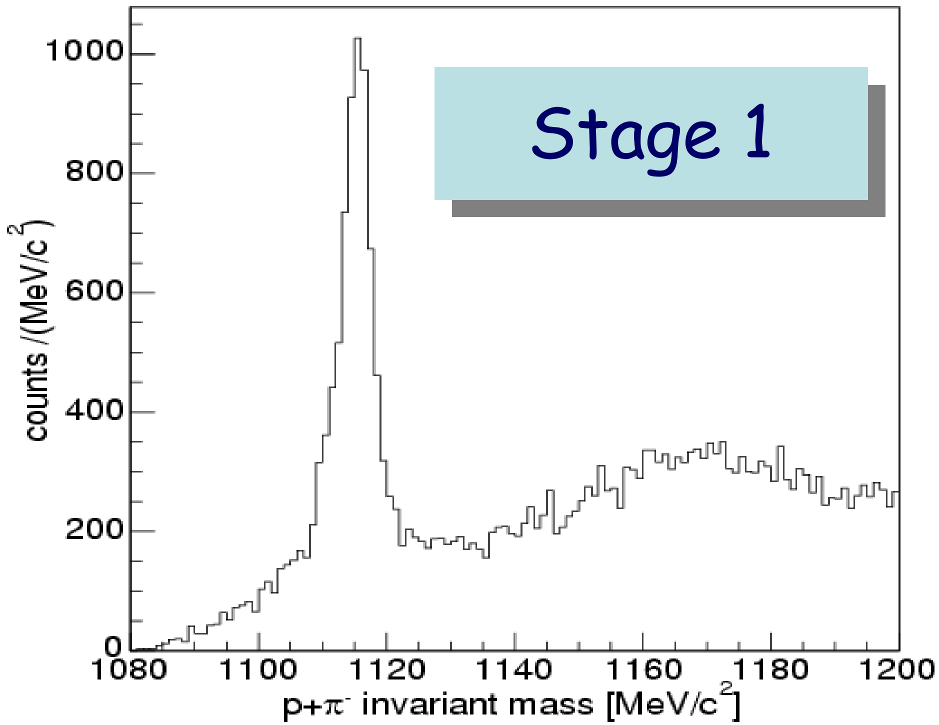
Solution (Stage 2)

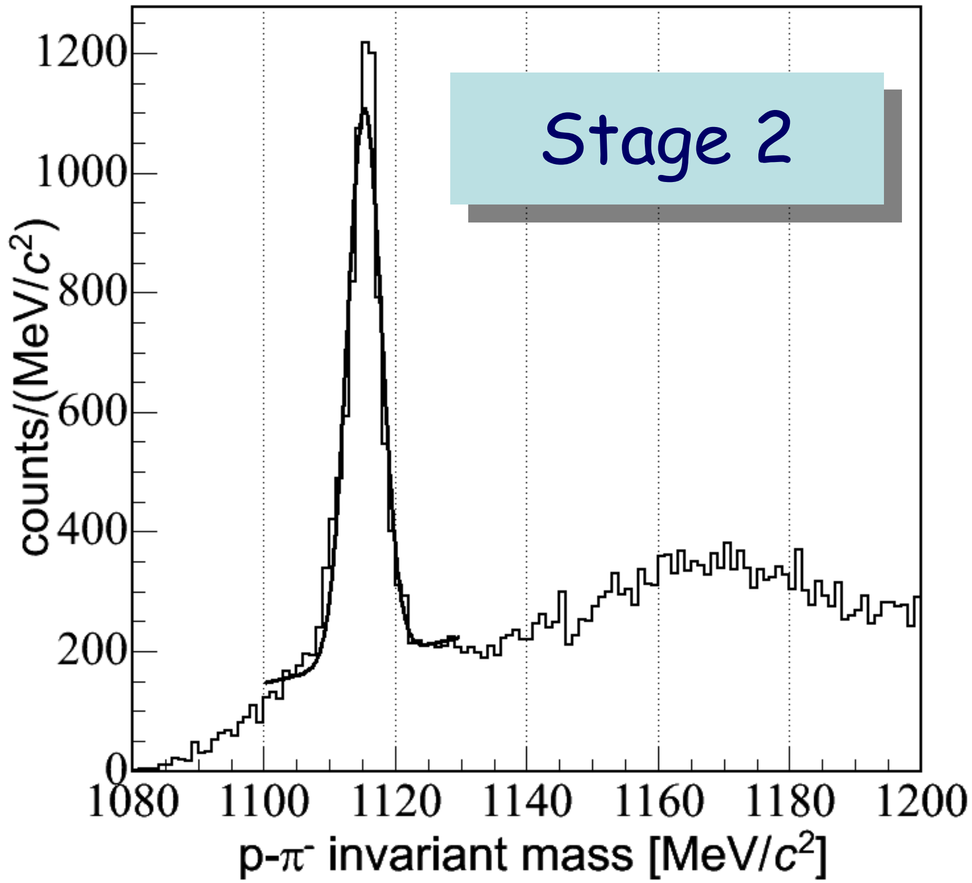
- A p-like hit should not be connected a negative tracks. (There's no $\bar{p}$ but π^-.)

1. long track (–) : OSIM←DCH1-DCH2-TRIP→ETOF
   Check consistency of dE/dx (π, not p)
   estimate the charge/momentum
2. long track (+) : DCH1-DCH2-TRIP→ETOF
3. short track (–) : OSIM-DCH1-DCH2
   estimate the charge/momentum
4. short track (+) : OSIM-DCH1-DCH2
5. long track (+) : OSIM←DCH1-DCH2-TRIP→ETOF

Result (Λ mass spectra)

- Problem on Λ detection is almost solved.





Kaonic nuclei search with Λ tagging

Missing-mass spectroscopy

KEK-PS E471/E549 (stopped K)
BNL-AGS E930/KEK-PS E548
(in-flight K)
FINUDA@DAΦNE
(stopped K)

- Example:

$$^{6}\mathrm{Li} + K^- \rightarrow \begin{cases} K^- ppppnn + \boxed{n} \\ K^- pppnnn + \boxed{p} \end{cases}$$

monoenergetic

- A kaonic nucleus emits a hyperon in its decay.

Invariant-mass spectroscopy

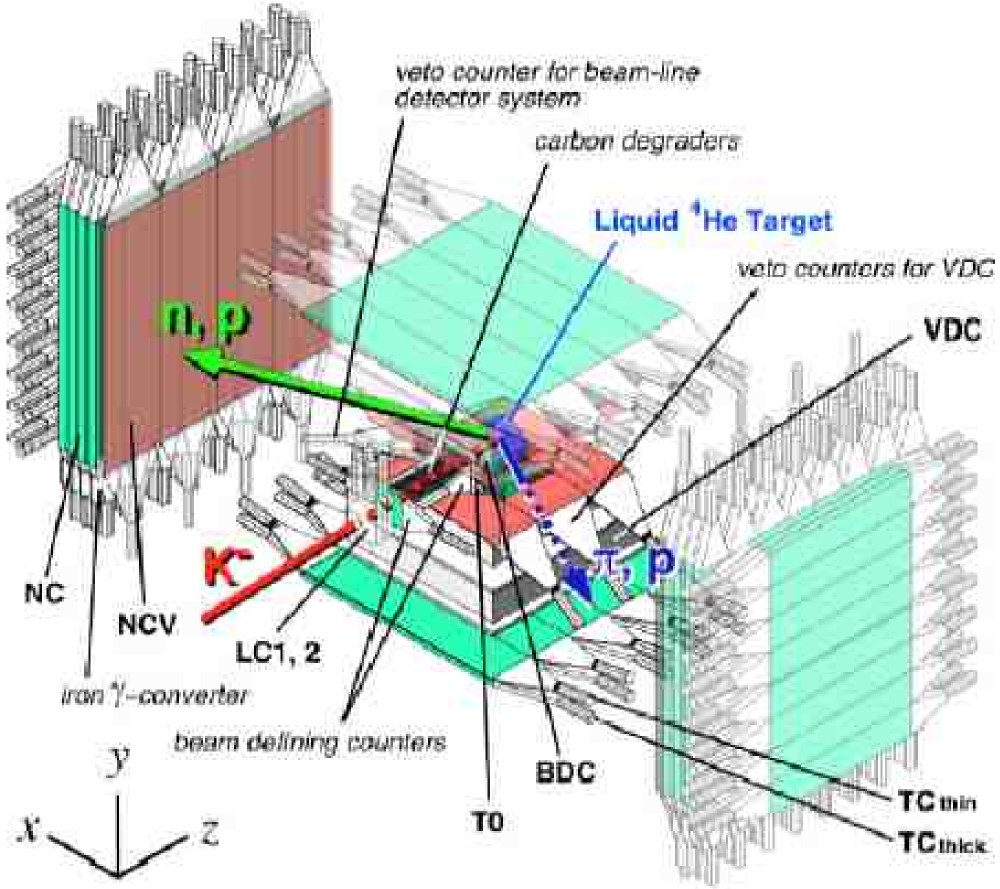
FINUDA@DAΦNE

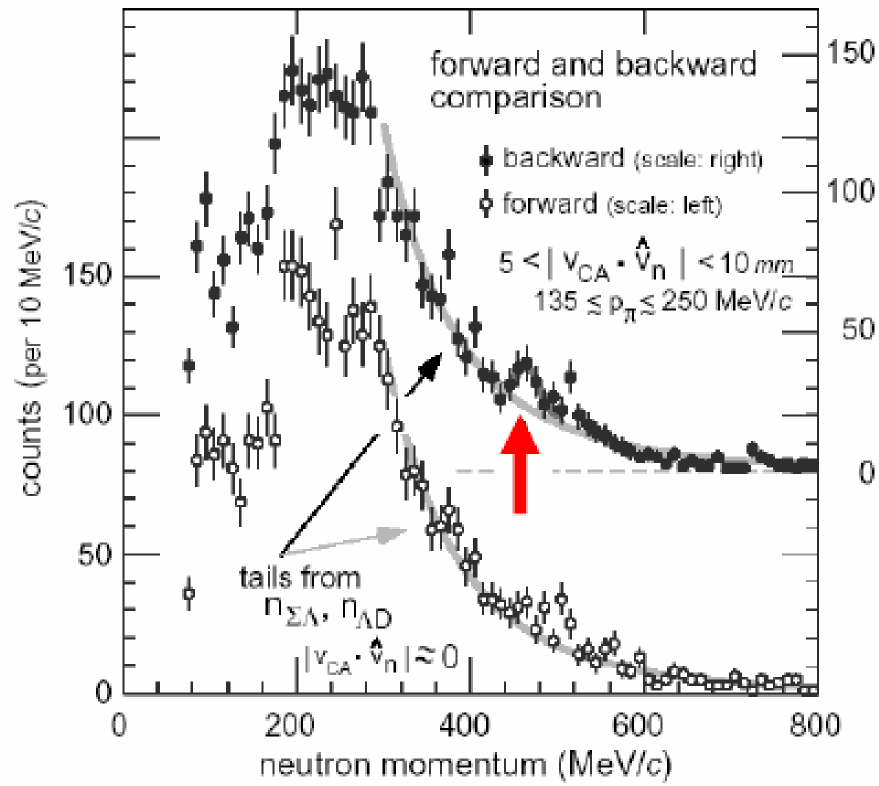
- Example:

$$K^- pp \rightarrow \Lambda + p \quad , \quad K^- ppn \rightarrow \Lambda + d(p+n)$$

KEK-PS E471 [missing-mass spectroscopy with stopped K-]

- ^{4}He (stopped K^{-}, n) $K^{-}ppn$





B = 173 ± 4 MeV
Γ < 25 MeV

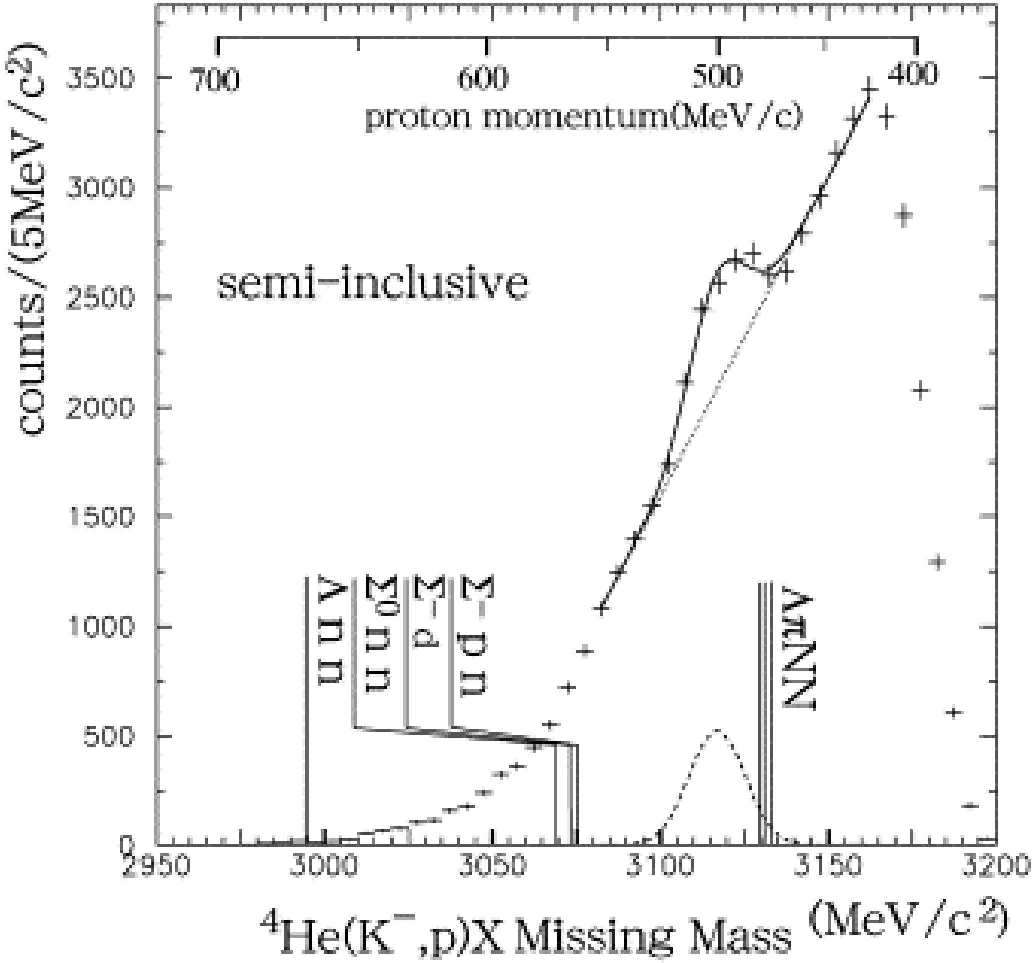
nucl-ex/0310018

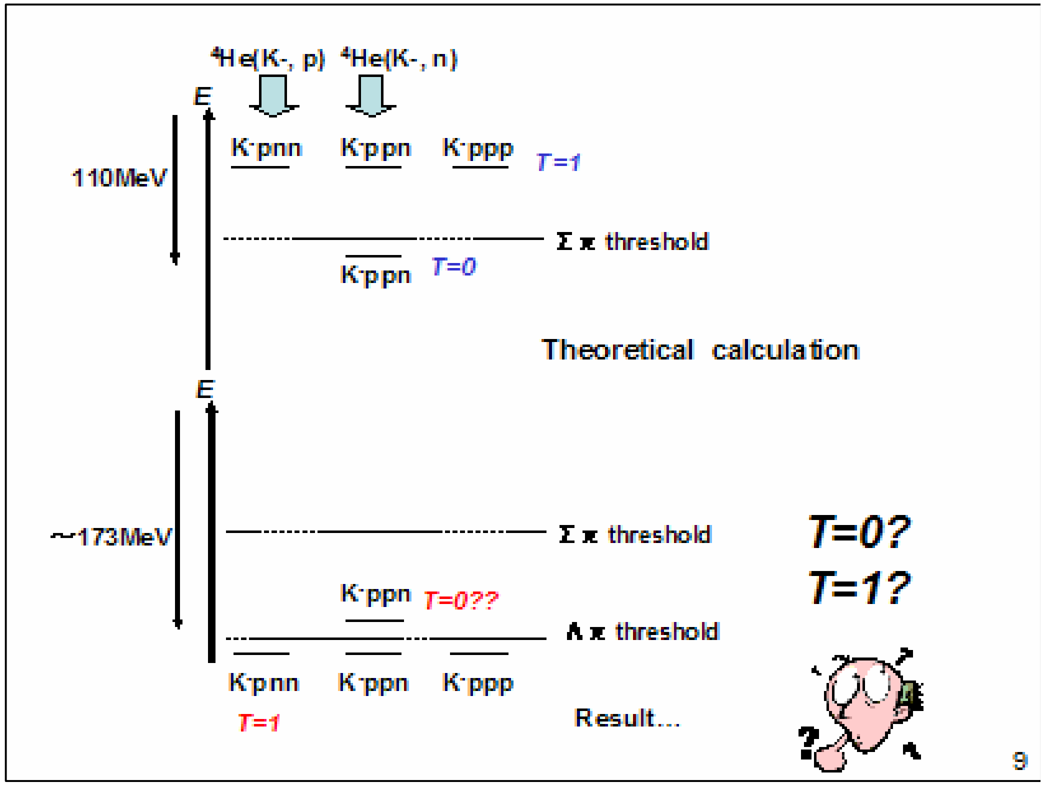
KEK-PS E471 [missing-mass spectroscopy with stopped K$^-$]

- ^{4}He (stopped K$^-$, p) S^0(3115) [K$^-$pnn?]

"Discovery of strange tribaryon"

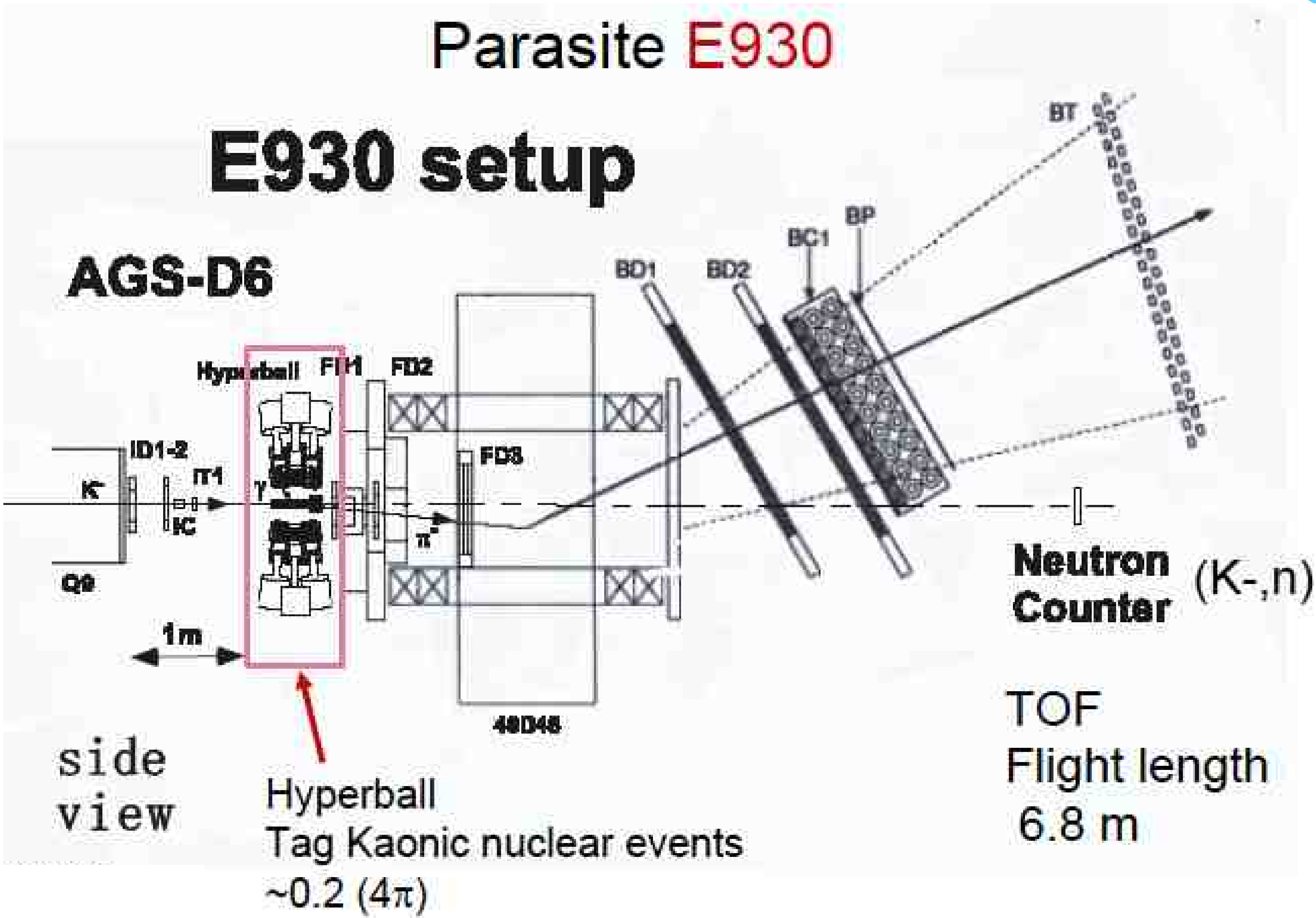
B = 193 $^{+4.4}_{-1.5}$ MeV
Γ < 21 MeV



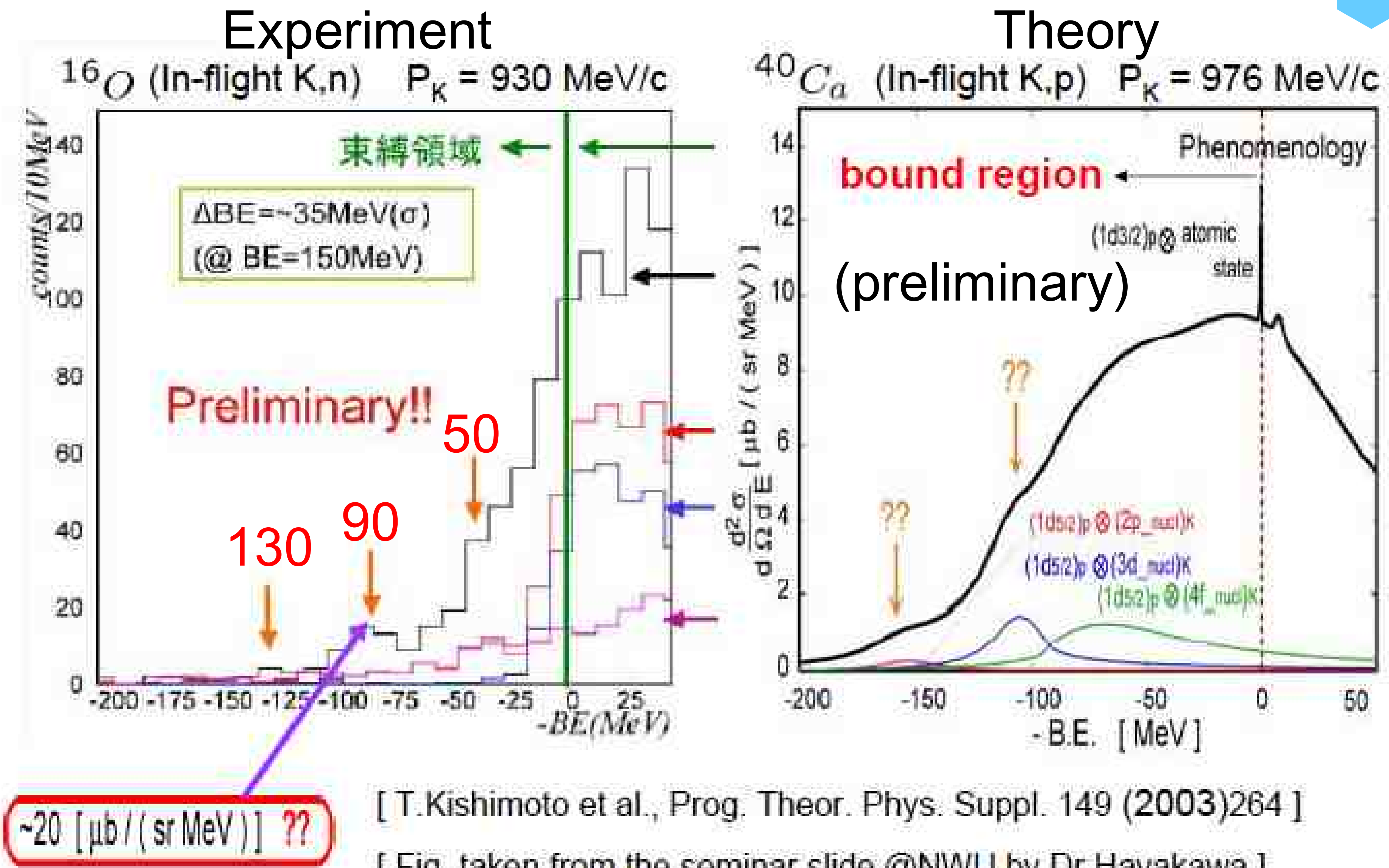


Phys. Lett. B 597 (2004) 263

BNL-AGS E930 [missing-mass spectroscopy with in-flight K^-]



BNL-AGS E930 [missing-mass spectroscopy with in-flight K$^-$]



[T.Kishimoto et al., Prog. Theor. Phys. Suppl. 149 (2003)264]

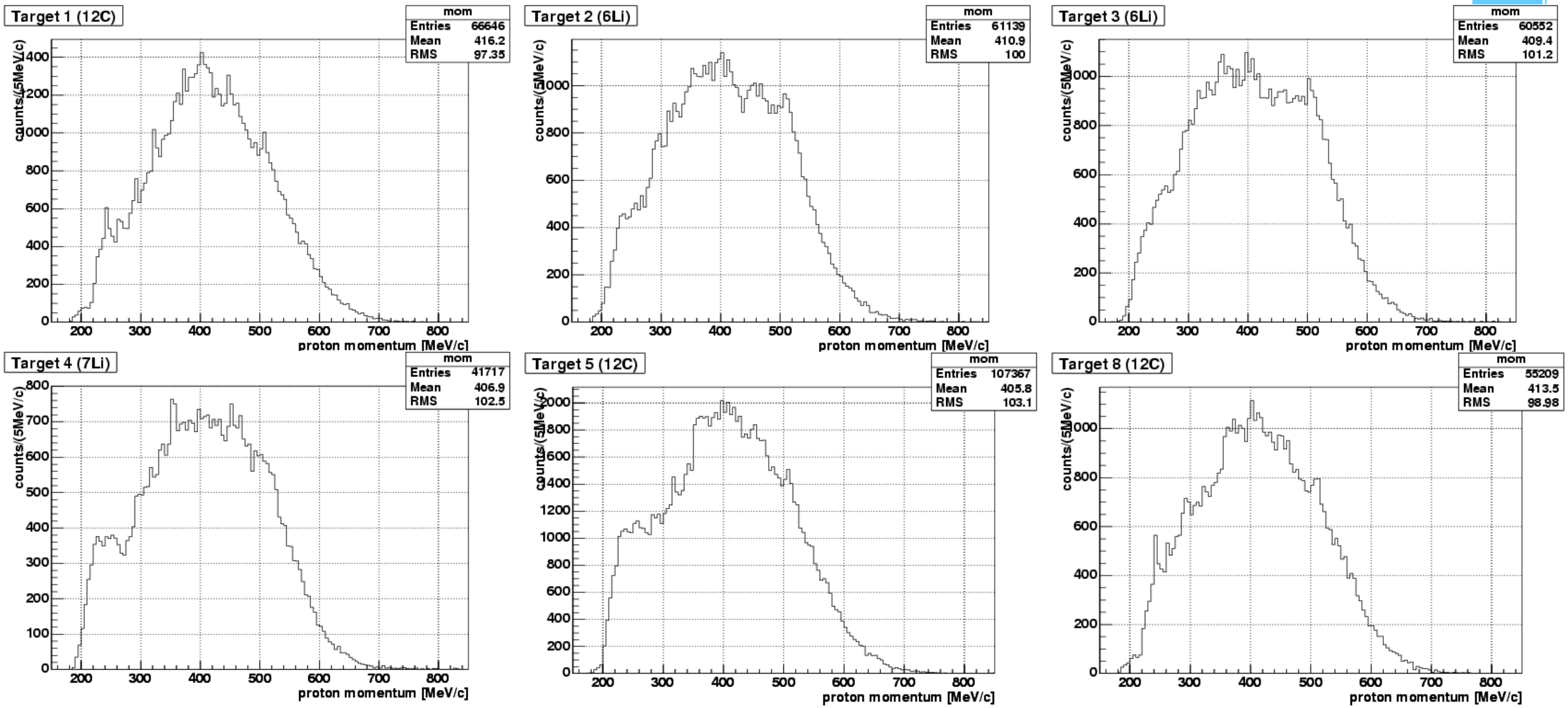
[Fig. taken from the seminar slide @NWU by Dr.Hayakawa]

(J. Yamagata, H. Nagahiro, S. Hirenzaki; private communication)

Back to FINUDA experiment…

- The key of kaon bound state search is to “tag” a hyperon from its decay directly or indirectly.
- FINUDA spectrometer gives us a unique opportunity to detect Λ-decay directly ($\Lambda \rightarrow p+\pi^-$).
- Not only missing-mass spectroscopy, but also invariant-mass spectroscopy is available.

Inclusive proton spectra

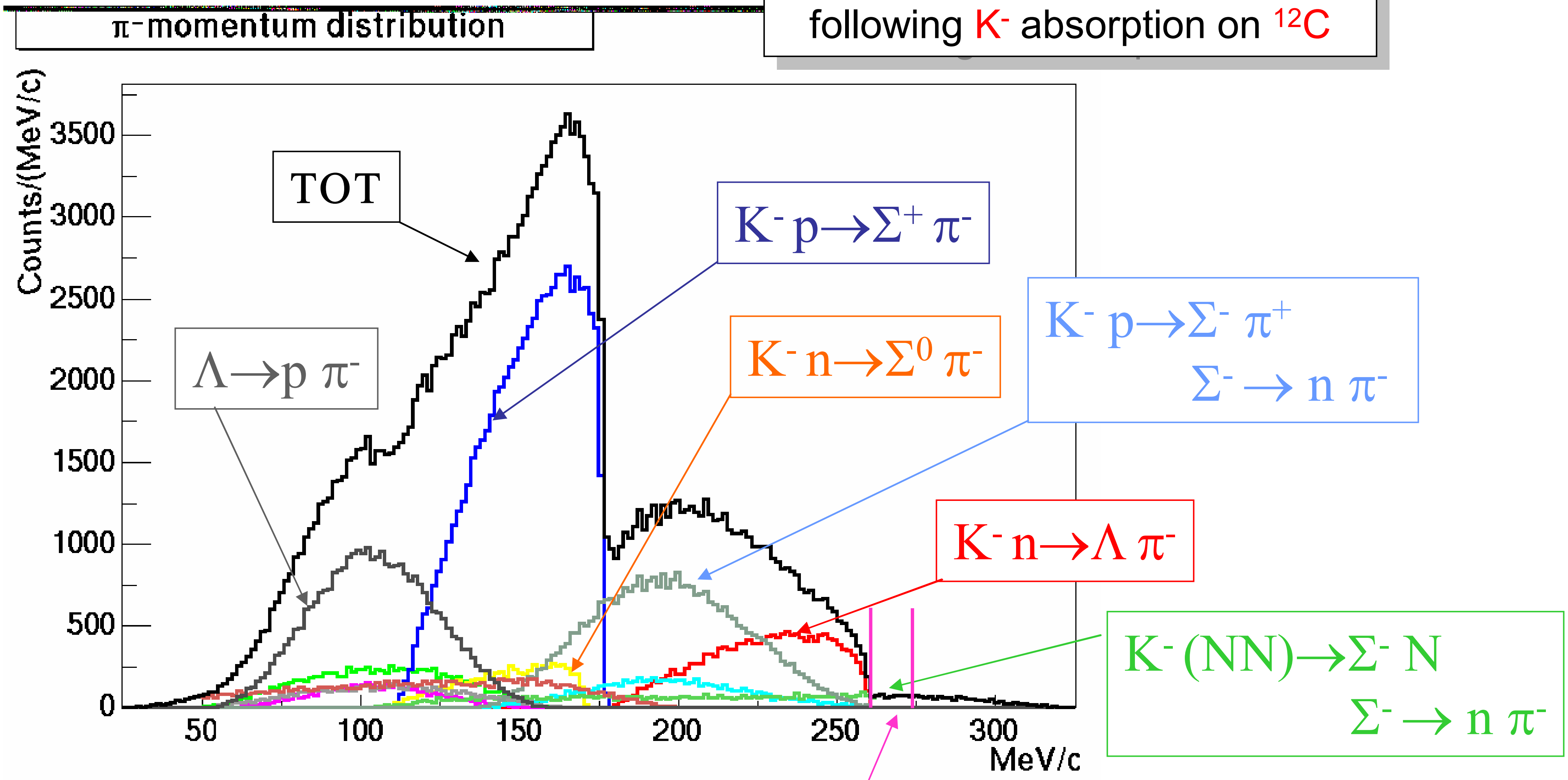


< 400 MeV/c : Quasi-free hyperon production

> 400 MeV/c : non-mesonic absorption process

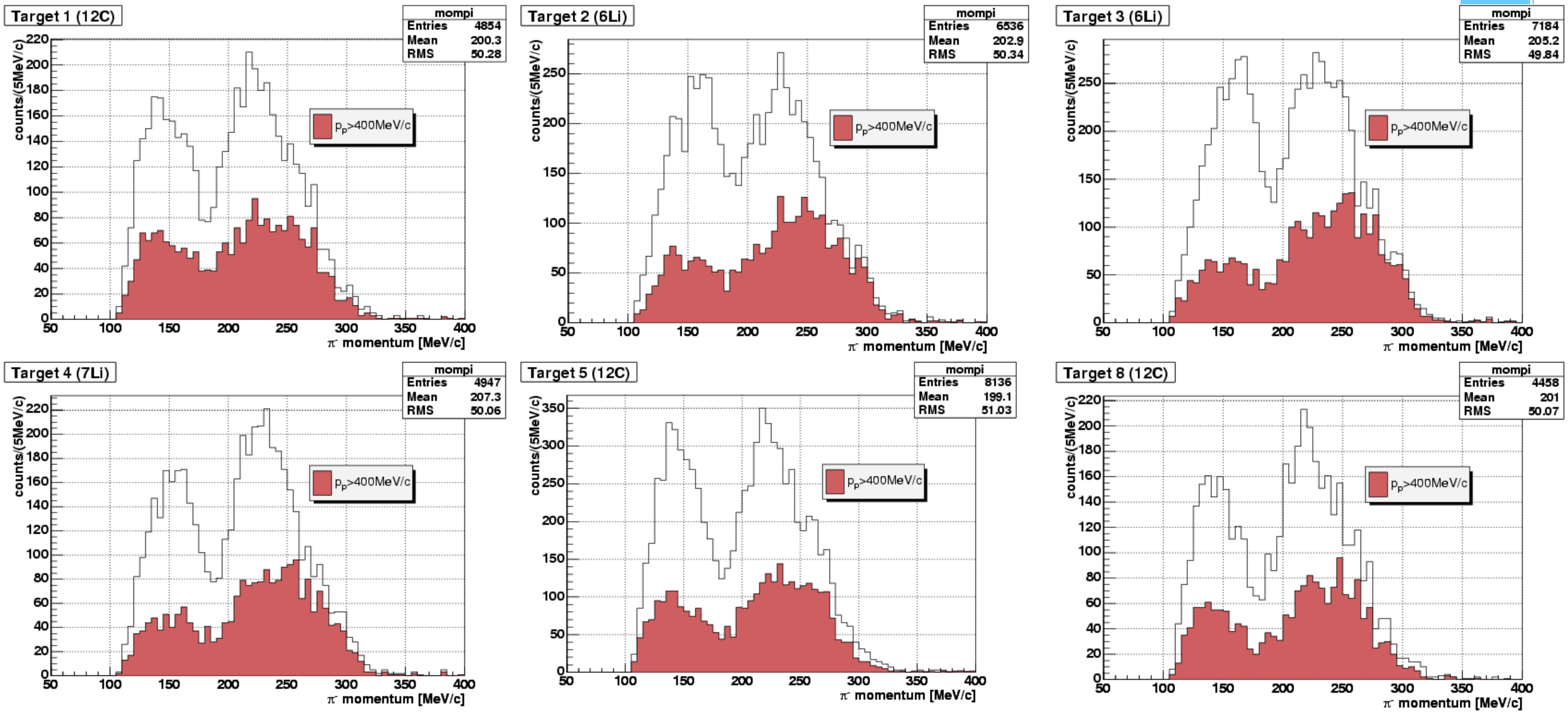
Negative pion spectrum (simulation)

Background processes giving π^- following K^- absorption on ^{12}C



Backgroud processes simulated in the FINUDA Monte Carlo

Pion spectra (proton and pion coincidence)

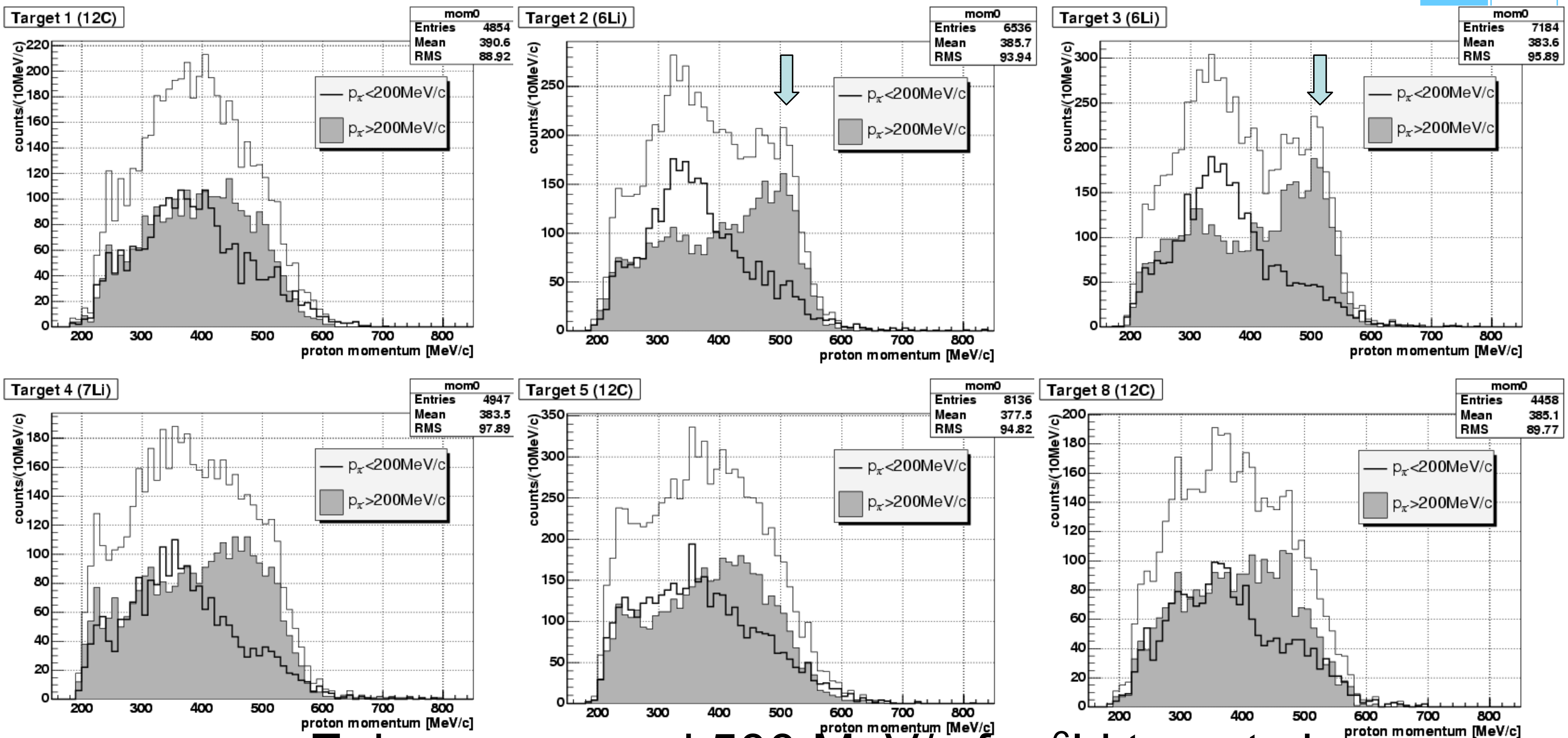


Very roughly speaking,

< 200 MeV/c : Λ decay and Σ production

> 200 MeV/c : Σ decay and Λ production

Proton spectra (proton and pion coincidence)

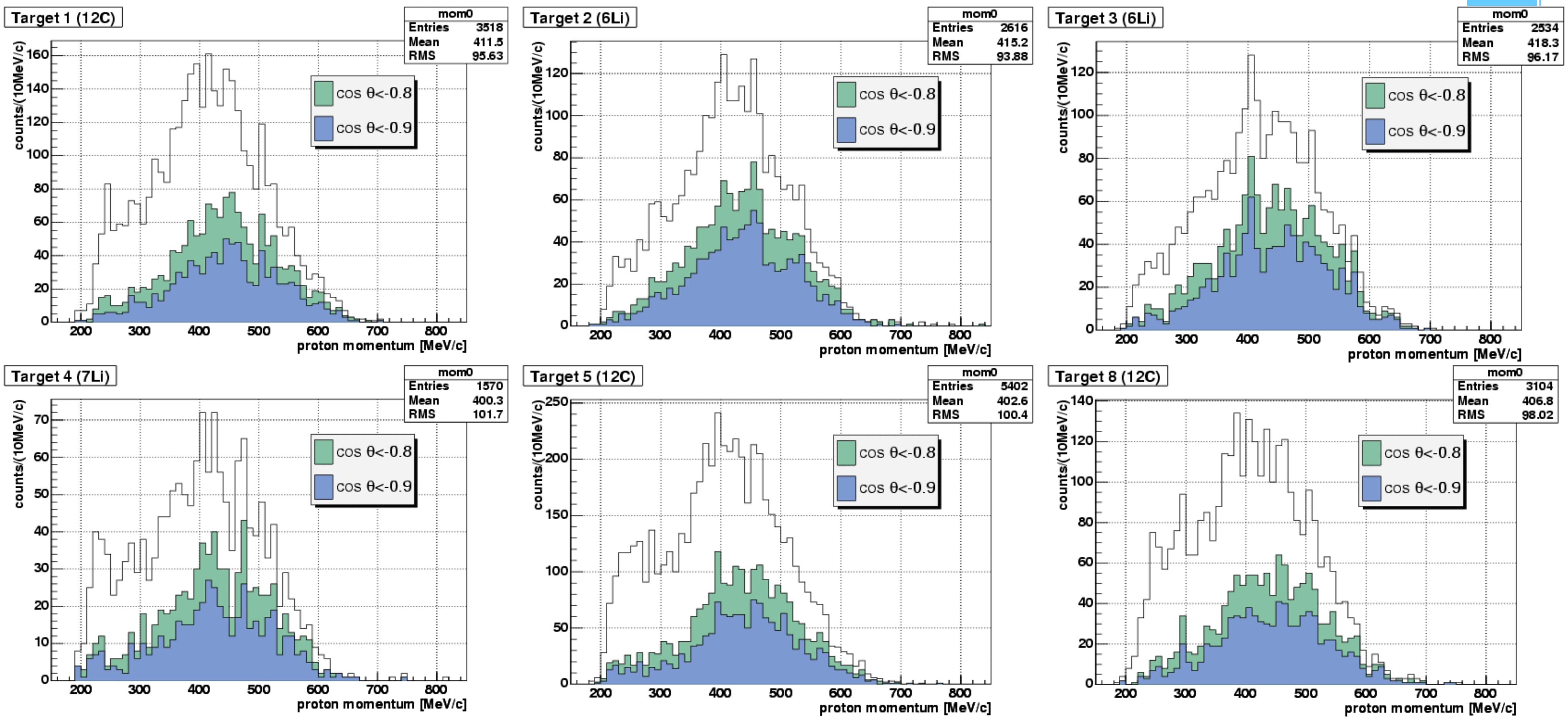


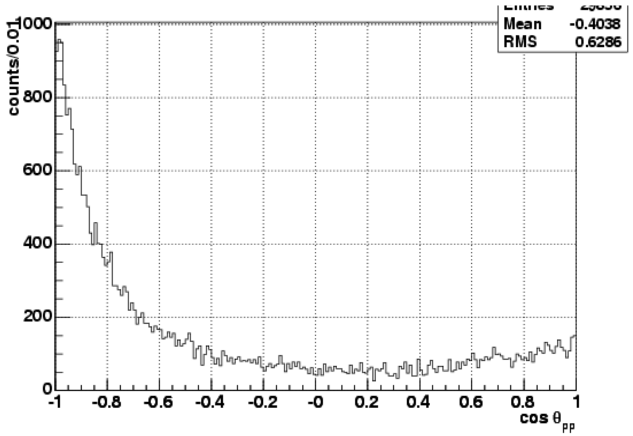
Enhance around 500 MeV/c for ^{6}Li targets is possibly due to quasi-deuteron reaction:

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

emits a fast pion

Proton spectra (two-proton coincidence)



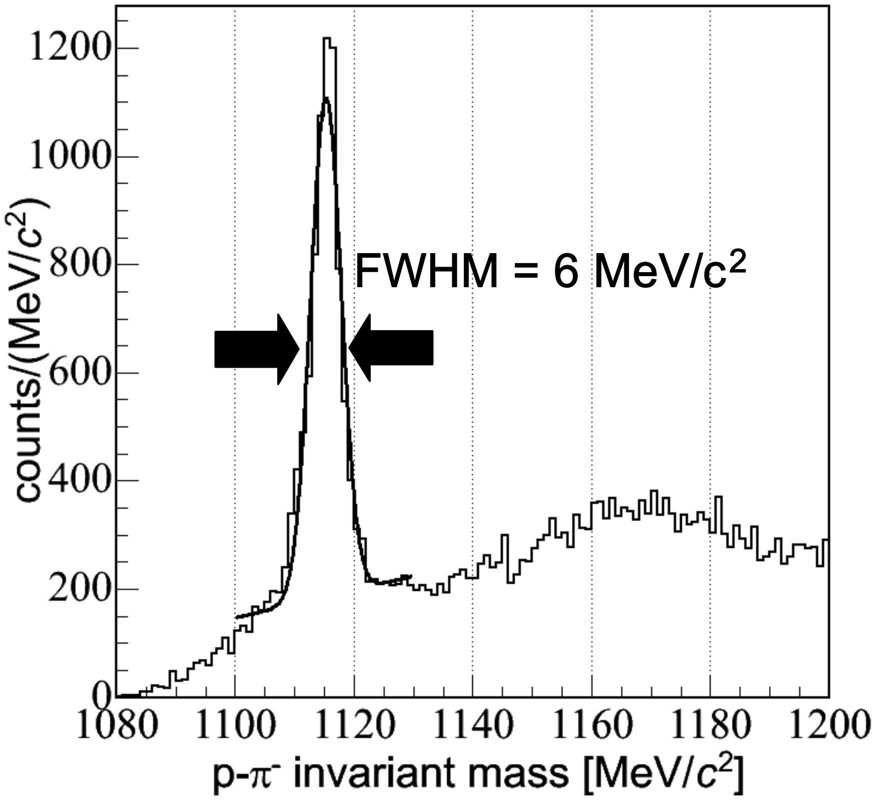


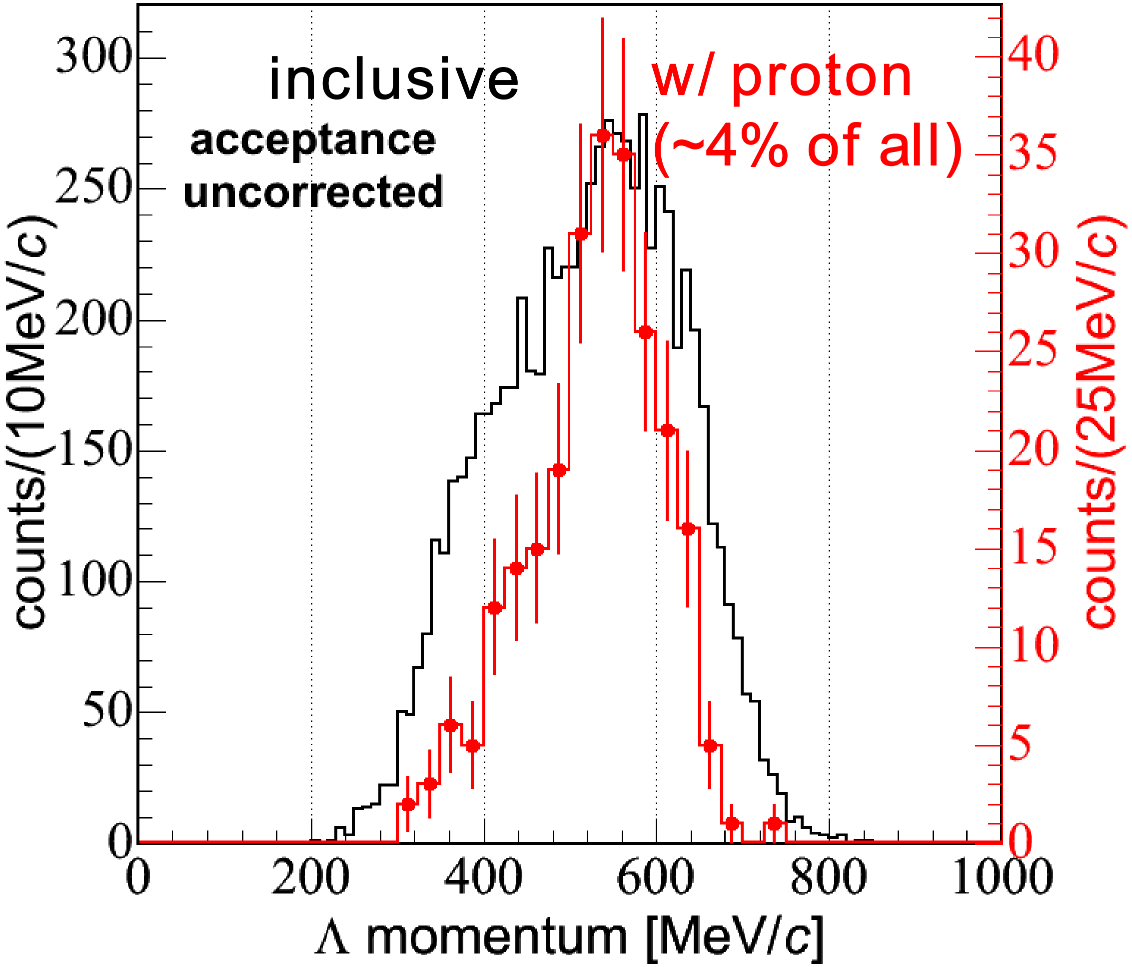
Back-to-back correlation between two protons

$$\boxed{K^- pp \rightarrow \Lambda(\Sigma^0) + p}$$

Λ momentum distribution

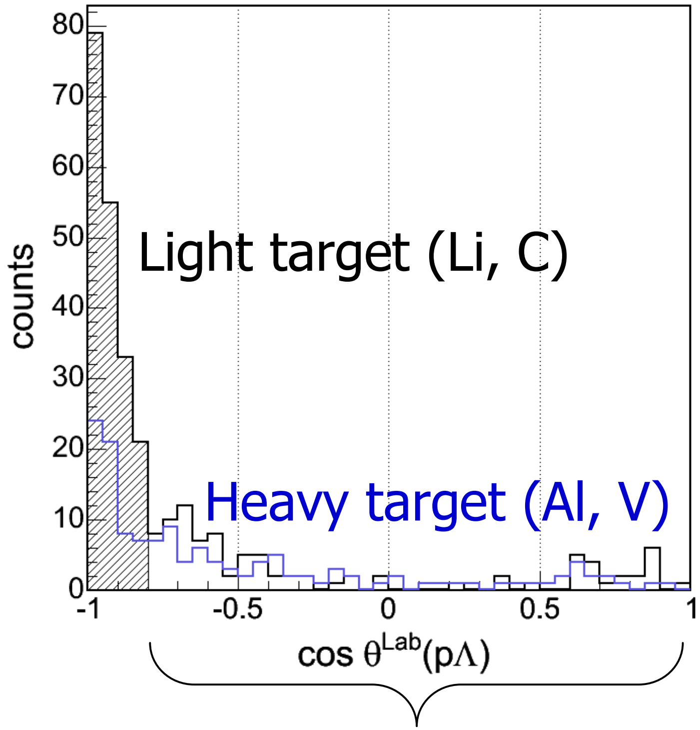
- Λ mass gate (±5 MeV/c^2) for Λ identification
- Momentum acceptance $\gtrsim$ 300MeV/c

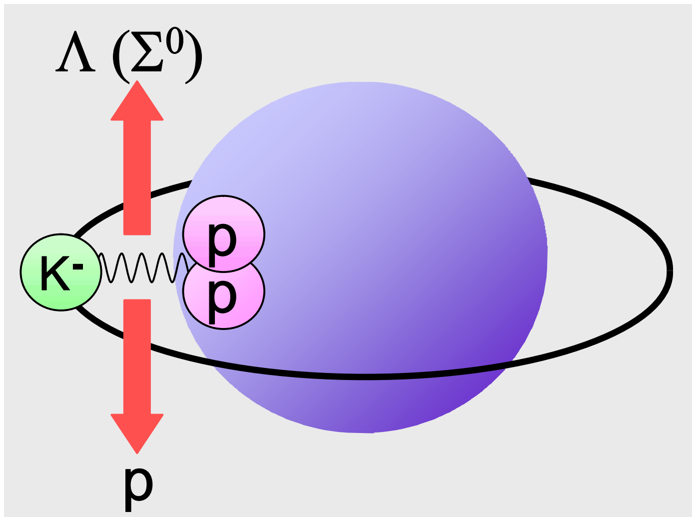




Back-to-back correlation of p-Λ

- Back-to-back correlation are seen for every target.
- Very significant for light (Li, C) targets.





Contribution from kaonic nuclei formation
via proton-emitting Auger process? ex. $^{6}\mathrm{Li} + K^{-} \rightarrow K^{-}ppnnn + p$

$$\hookrightarrow \Lambda + \cdots$$

Origin of back-to-back p-Λ

Two-nucleon absorption

$$K^- + \text{“}pp\text{”} \to \mathbf{Y^*N} \to p + \Lambda$$

$$\to p + \Lambda + \gamma(\Sigma^0)$$

Via kaon-bound state (K⁻pp)

$$K^- + \text{“}pp\text{”} \to \mathbf{X} \to p + \Lambda$$

$$\to p + \Lambda + \gamma(\Sigma^0)$$

Origin of back-to-back p-Λ

Two-nucleon absorption

$$K^- + \text{“}pp\text{”} \rightarrow \mathbf{Y^*N} \rightarrow p + \Lambda$$

$$\rightarrow p + \Lambda + \gamma(\Sigma^0)$$

- $(\Lambda N):(\Sigma^0 N)=(9.4\pm2.6)\%:(2.3\pm1.0)\%$ for ^{4}He

  [*Katz et al.*]
- B.R. of Σ^0N decay was estimated as the average of those of Σ^+N and Σ^-N.

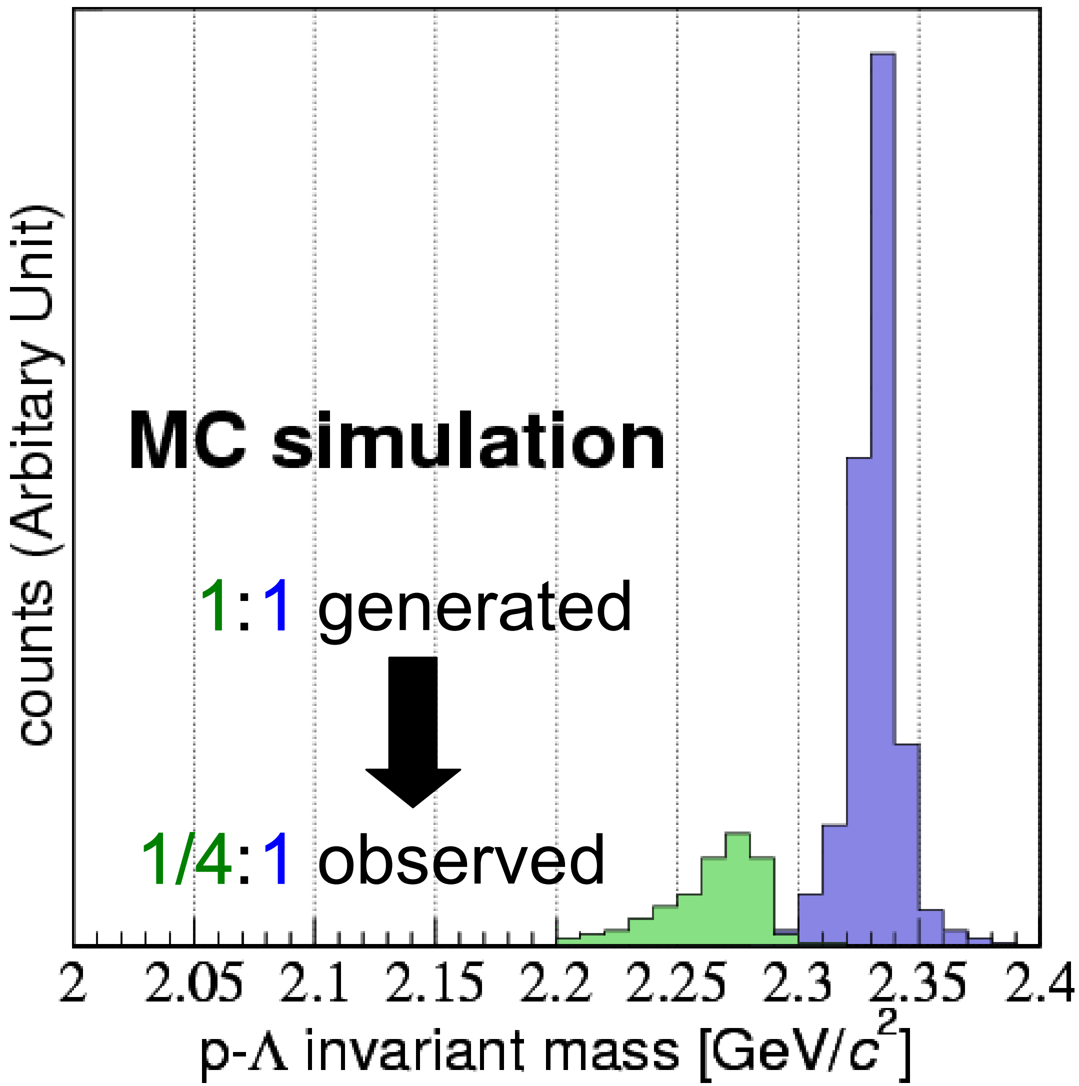
Two-nucleon absorption

p+Λ decay

- Almost same as the $K^- + 2p$ mass (2.37 GeV/c^2)
- Reduced because of
  - the separation energy
  - The Fermi energy

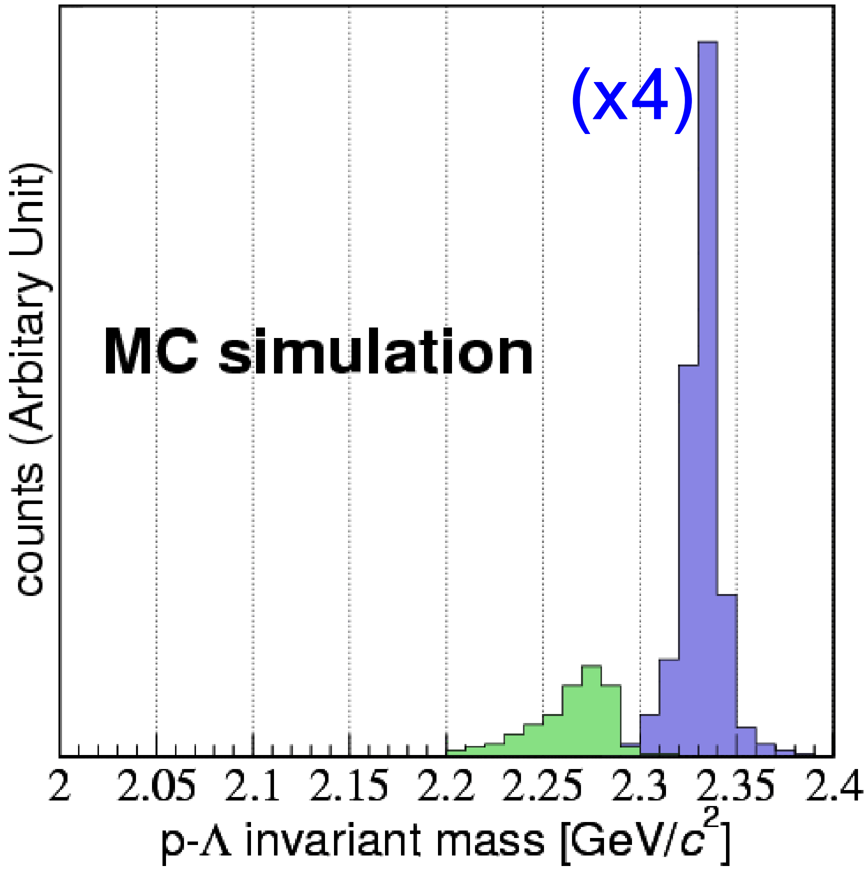
p+Σ^0 decay

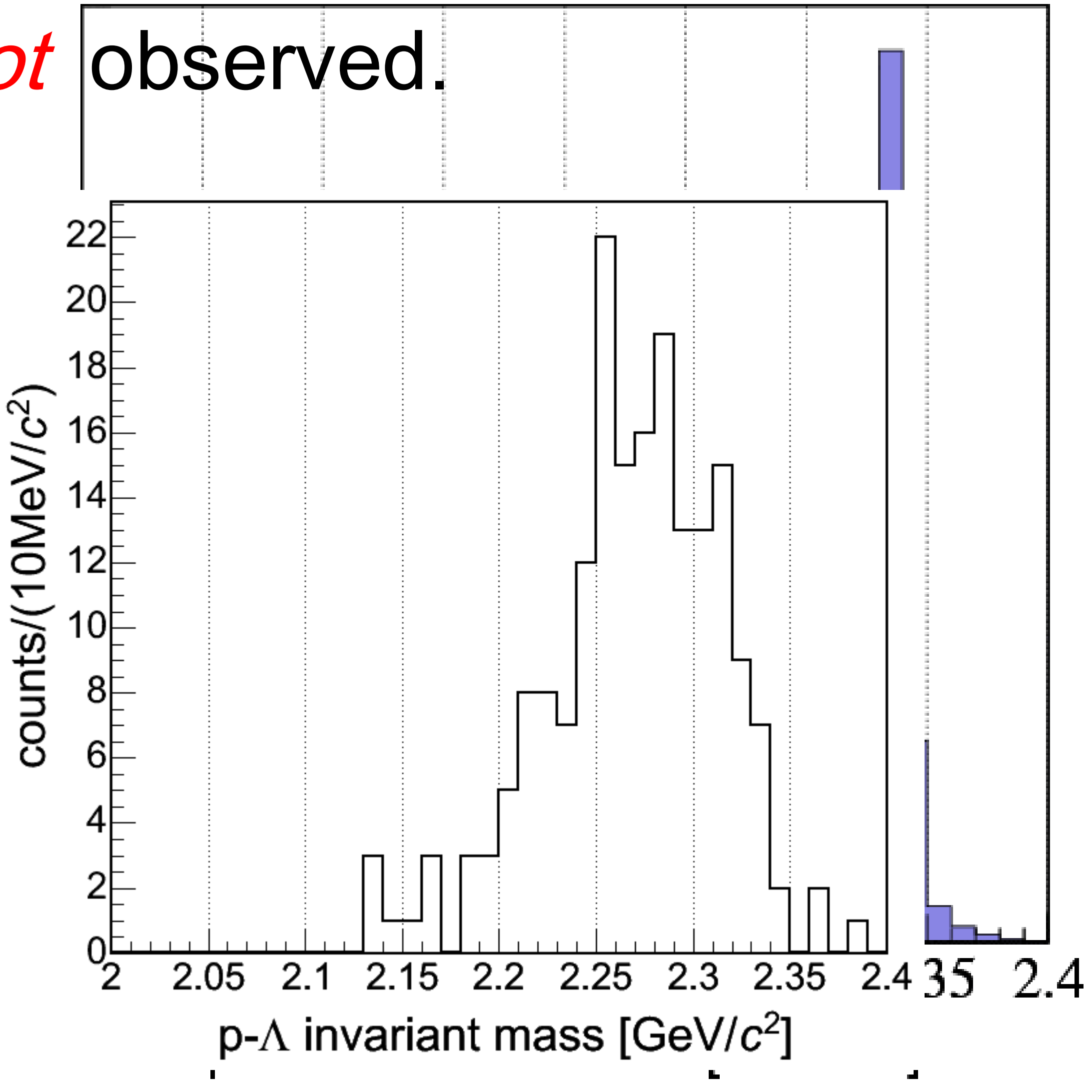
- Shifted due to missing γ energy, which is broadened from that in Σ^0 CMS (74MeV).



p-Λ invariant mass spectrum

- Assuming the Katz's B.R. (~4:1), the blue peak would be dominant.
- However, this peak is *not* observed.





Origin of back-to-back p-Λ

Two-nucleon absorption

$$K^- + \text{“}pp\text{”} \rightarrow \mathbf{Y^*N} \rightarrow p + \Lambda$$

$$\rightarrow p + \Lambda + \gamma(\Sigma^0)$$

Via kaon-bound state (K⁻pp)

$$K^- + \text{“}pp\text{”} \rightarrow \mathbf{X} \rightarrow p + \Lambda$$

$$\rightarrow p + \Lambda + \gamma(\Sigma^0)$$

Origin of back-to-back p-Λ

- We performed a Monte Carlo simulation with the actual acceptance considered.
- Input parameters :
  - Binding energy (B)
  - Width (Γ)

  Lorentzian function

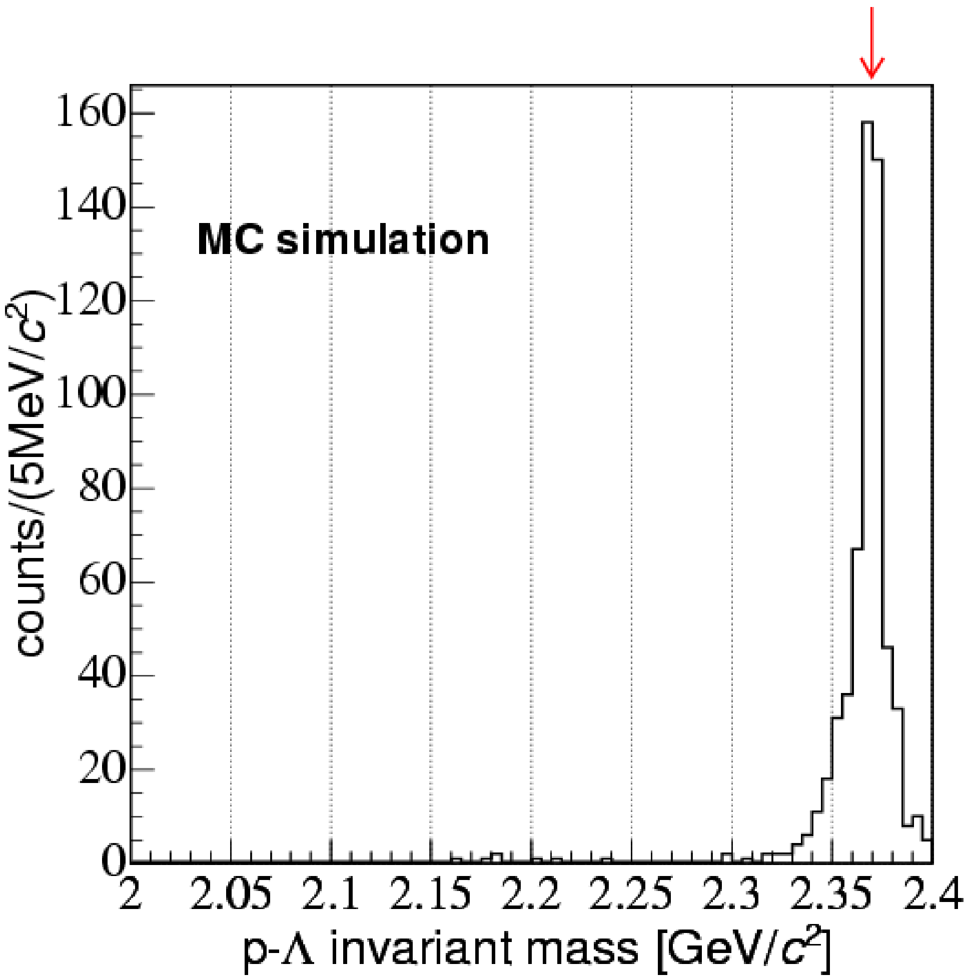
Via kaon-bound state (K⁻pp)

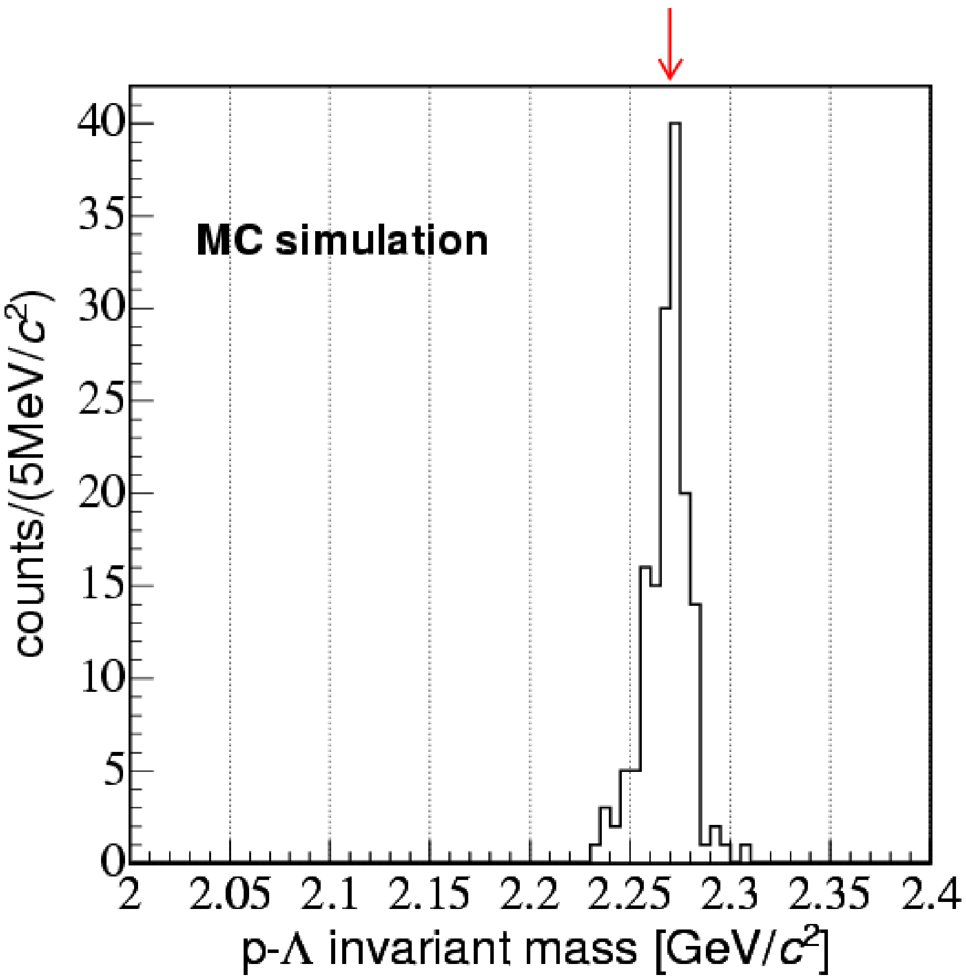
$$K^- + \text{“}pp\text{”} \rightarrow \mathbf{X} \rightarrow p + \Lambda$$

$$\rightarrow p + \Lambda + \gamma(\Sigma^0)$$

Results of Monte Carlo simulations

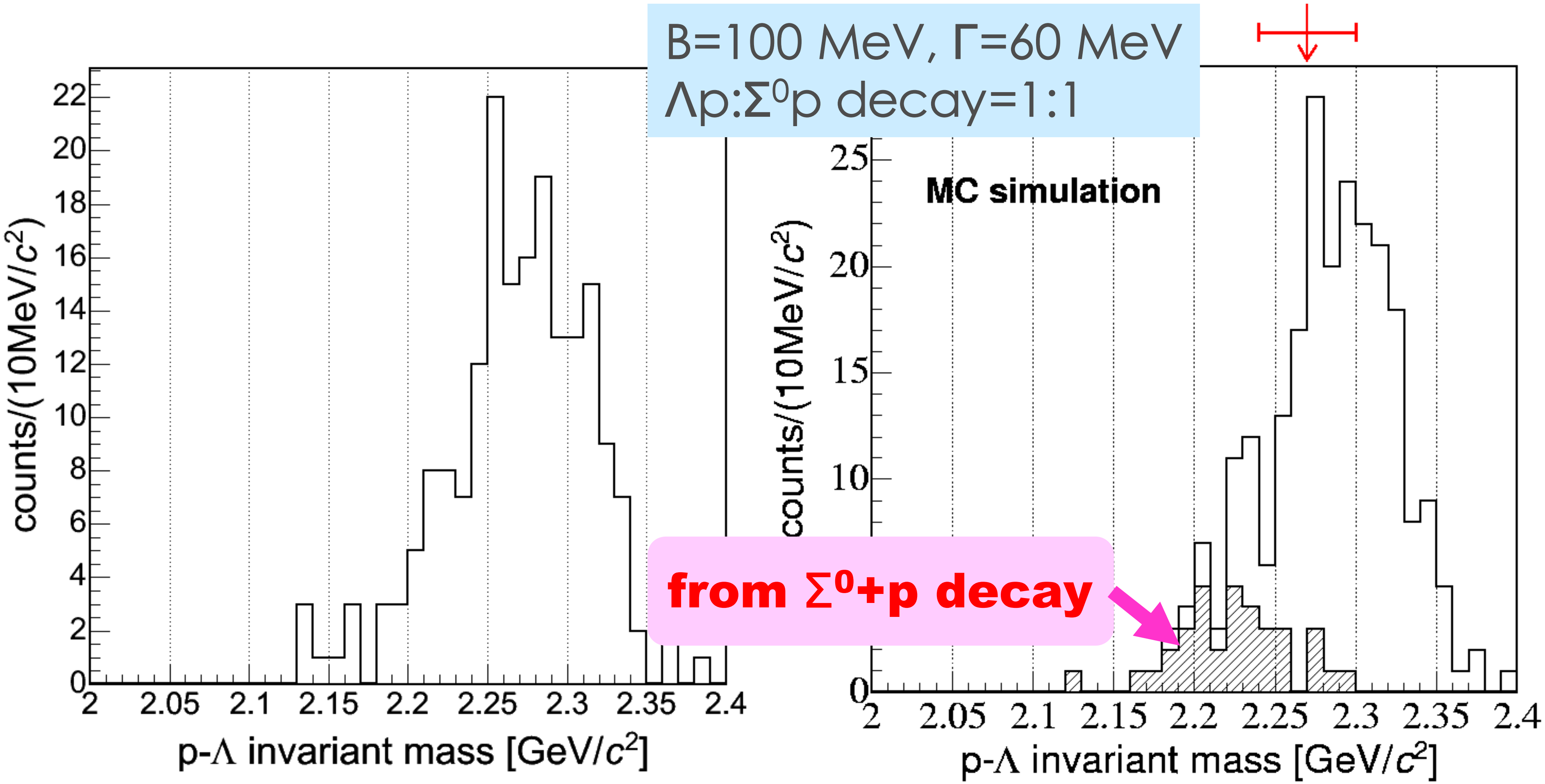
- The resolutions are estimated to be less than 10MeV (in FWHM).





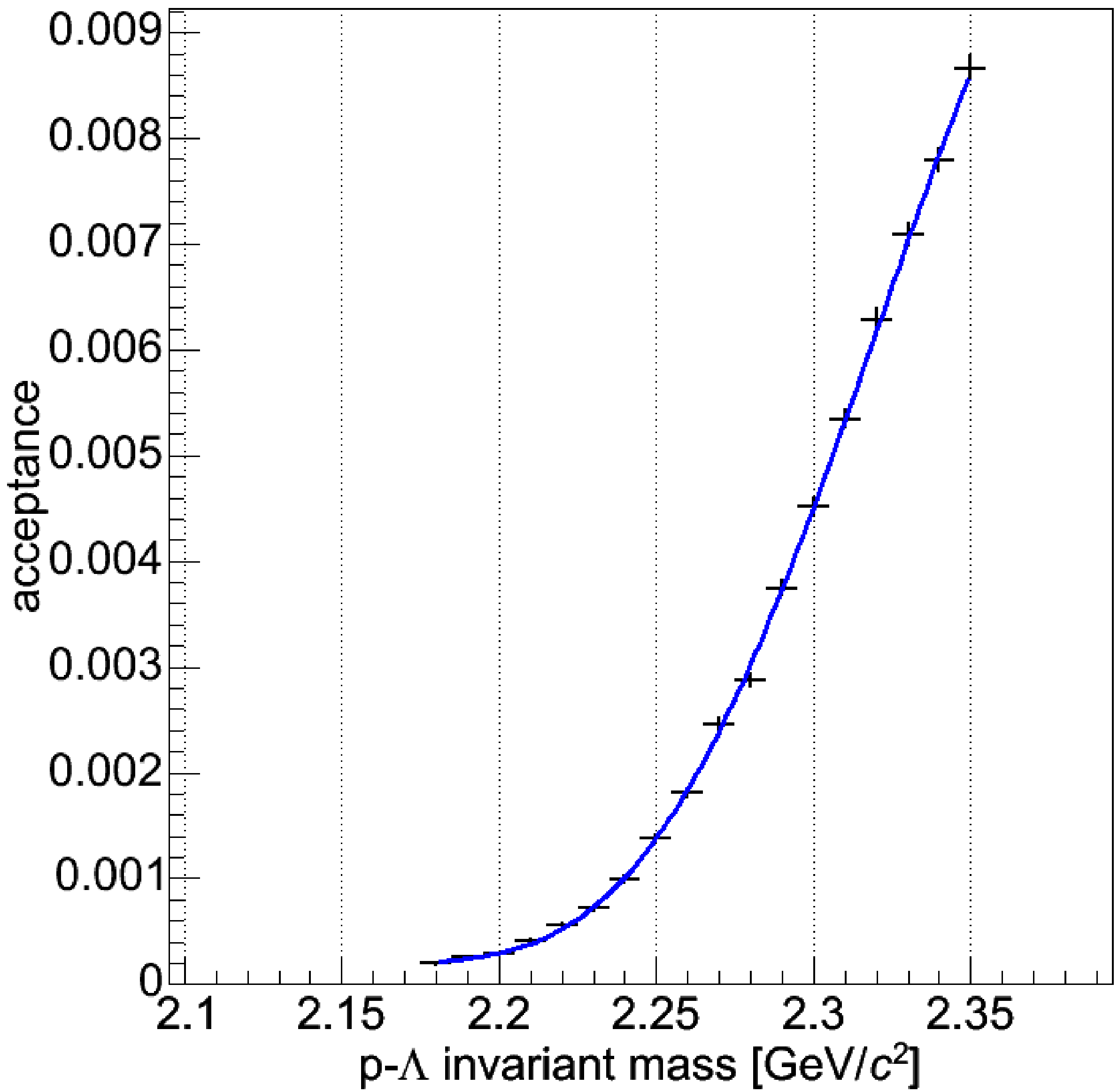
Results of Monte Carlo simulations

- The MC simulation indicates $K^{-}pp$ has a large binding energy and a wide width.



Acceptance function

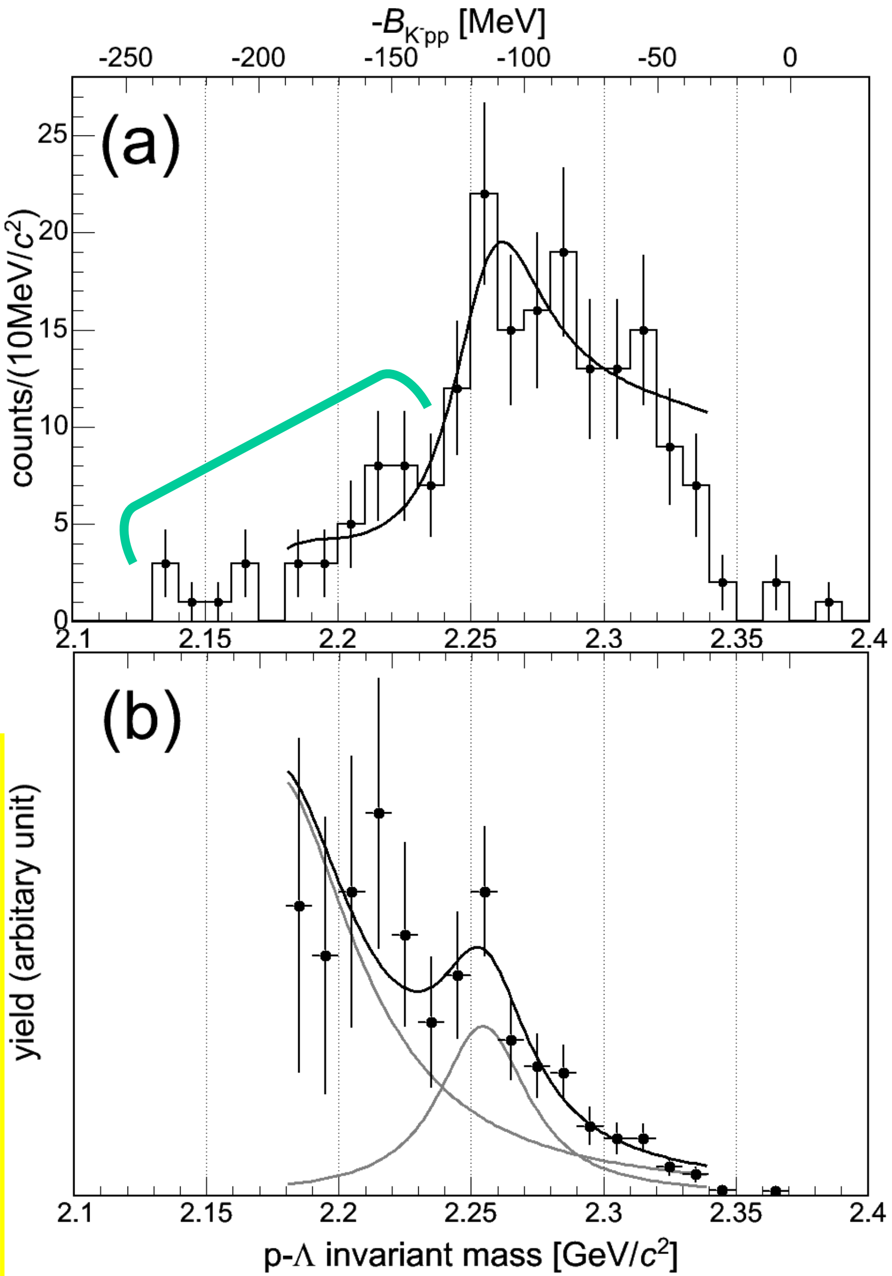
- Fitted by a 4th degree polynomial.



Before / after acceptance correction (fit 1)

Contribution from Σ^0+p decay are seen in low mass region

No other background exists !



$$B = 116^{+11}_{-6}\ \mathrm{MeV}$$

$$\Gamma = 39^{+20}_{-19}\ \mathrm{MeV}$$

Very preliminary !!

(systematic error to be added)

Before / after acceptance correction (fit 2)

Contribution from Σ^0+p decay are seen in low mass region

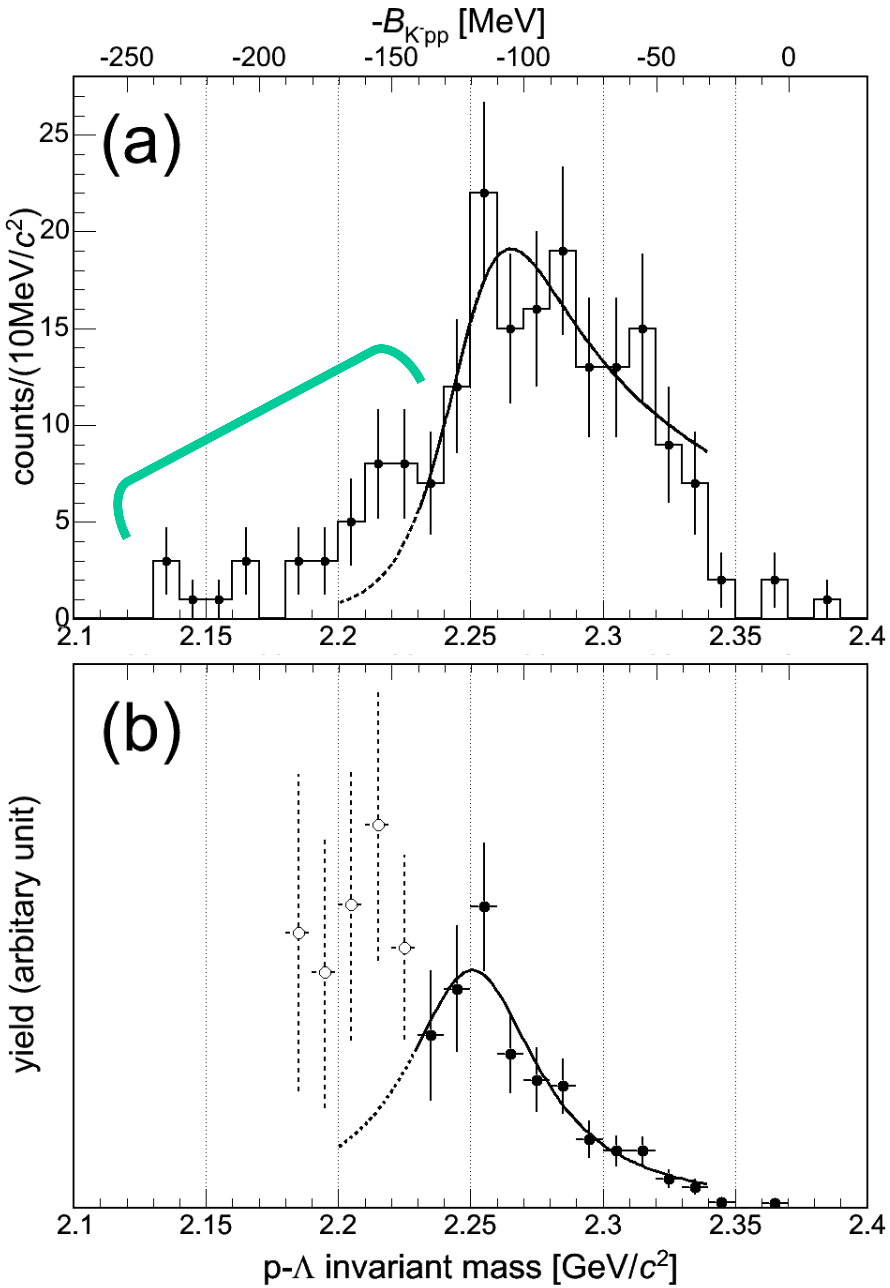
No other background exists !

$$B = 120^{+7}_{-5}\ \mathrm{MeV}$$

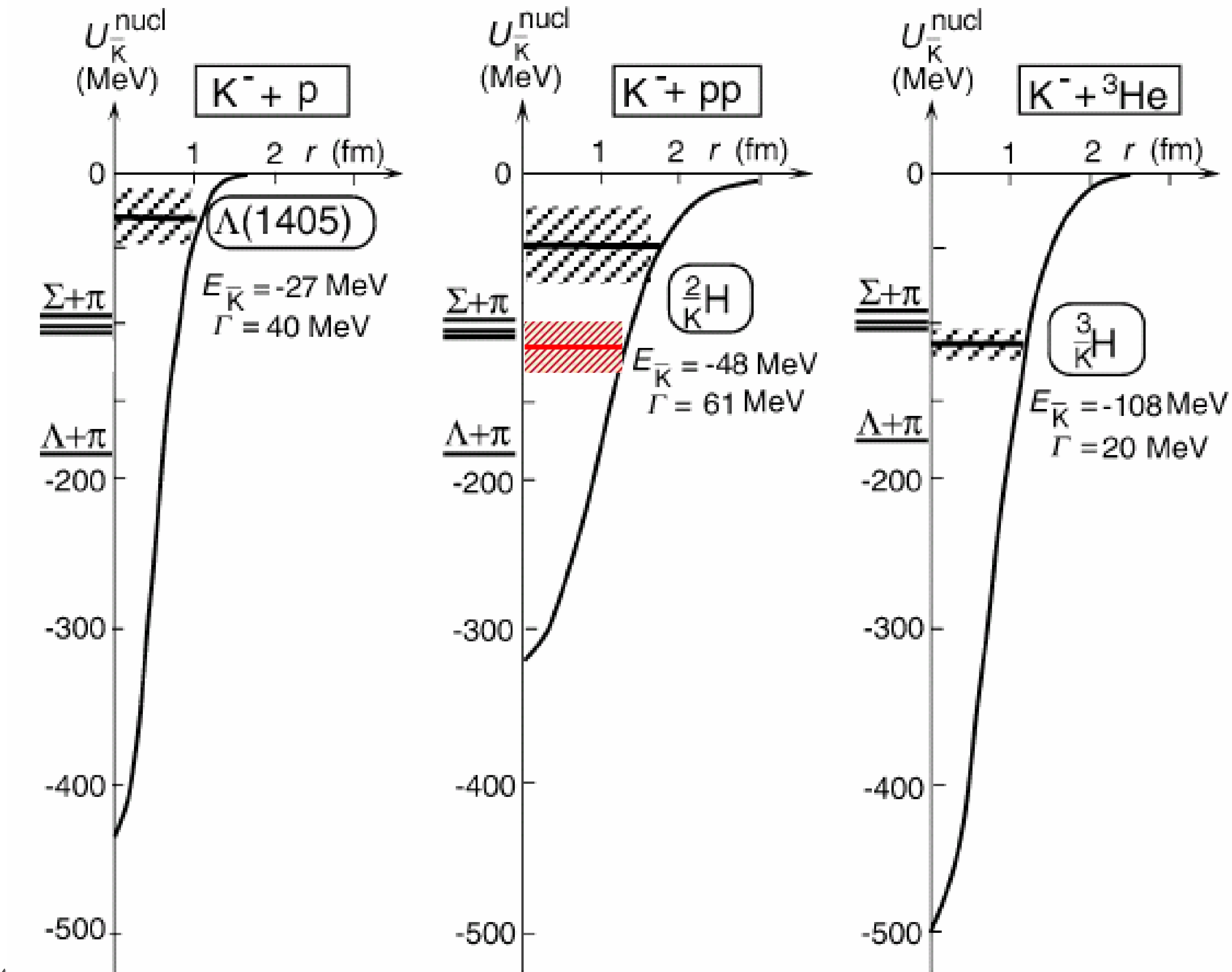
$$\Gamma = 58^{+10}_{-8}\ \mathrm{MeV}$$

Very preliminary !!

(systematic error to be added)



Theoretical calculations



Comment on production rate

- N(K-pp→Λp) ~ 2×10^6
- How many is the "effective" number of stopped kaons inside the light 6 targets ?
- Assuming it's 1×10^8, the b.r. is ~0.5%.

- Katz's result indicates:
  B.R.($K^-pp\rightarrow\Sigma^+n$ per stopped K^-) ~ 1.0±0.4%
  B.R.($K^-pp\rightarrow\Sigma^0p$ per stopped K^-) ~ 0.5±0.2%

Summary

- Two-body decay of K^-pp is seen, and mass and width are obtained (almost finalized result).
- Direct observation of kaon bound state (without any background) for the first time !!
- "It is vitally important to experimentally examine the simplest case of ppK^-, which can provide a gateway toward more complicated and more exotic systems." (Y. Akaishi)

Paper preparation (to be submitted to PRL)

Evidence for a kaon-bound state K^-pp produced in K^- absorption reactions at rest

M. Agnello,[1,2] G. Beer,[3] L. Benussi,[4] M. Bertani,[4] S. Bianco,[4] E. Botta,[5,2] T. Bressani,[5,2] L. Busso,[6,2] D. Calvo,[2] P. Camerini,[7,8] P. Cerello,[2] B. Dalena,[9,10] F. De Mori,[5,2] G. D'Erasmo,[9,10] D. Di Santo,[9,10] F. L. Fabbri,[4] D. Faso,[6,2] A. Feliciello,[2] A. Filippi,[2] V. Filippini,[11] E. M. Fiore,[9,10] H. Fujioka,[12] P. Gianotti,[4] N. Grion,[8] A. Krasnoperov,[13] V. Lucherini,[4] S. Marcello,[5,2] T. Maruta,[12] N. Mirfakhrai,[14] O. Morra,[15] T. Nagae,[16] A. Olin,[17] H. Outa,[18] E. Pace,[4] M. Palomba,[9,10] A. Pantaleo,[10] A. Panzarasa,[11] V. Paticchio,[10] S. Piano,[7,8] F. Pompili,[4] R. Rui,[7,8] G. Simonetti,[9,10] H. So,[19] S. Tomassini,[4] A. Toyoda,[16] R. Wheadon,[2] and A. Zenoni[20,11]
(FINUDA collabolation)

We have searched for a deeply-bound kaonic state by using the FINUDA spectrometer installed at the e^+e^- collider DAΦNE. Almost monochromatic K^-'s produced through the decay of ϕ mesons are used to observe K^- absorption reactions stopped on very thin nuclear targets. Taking this unique advantage, we have succeeded to detect a kaon-bound state K^-pp through its two-body decay into a Λ hyperon and a proton. The binding energy and the width are determined from the invariant mass distribution as 116^{+11}_{-6} MeV and 39^{+20}_{-19} MeV, respectively.

- The estimation of systematic error is under way. (maybe finished by the middle of November)
- We'd like to publish this result as soon as possible, *not after run '05*, because other two experiments will begin data taking in spring 2005.

Topics to study with the data taking '05

proton and Λ coincidence

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

- higher statistics

isospin dependence

neutron and Λ coincidence

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

- neutron detection with new TOFINO and TOFONE (in order to obtain a better resolution)
- K^-pn bound or not ?
  - If bound, the invariant mass has a very large width.
  - If unbound, two peaks (from two-nucleon absorption) appear in the invariant mass spectrum.
- The present analysis indicates the yield of K^-pn is one order larger than that of K^-pp. (Difference between inclusive and proton-coincided spectra of Λ momenta.)

Topics to study with the data taking '05

proton and Λ coincidence
neutron and Λ coincidence

heavier kaonic-fragment search

- Can K⁻ppp, K⁻ppn (or heavier) be produced ?
- invariant-mass spectroscopy of

$$K^- ppp \rightarrow \Lambda + p + p$$
$$K^- ppn \rightarrow \Lambda + d(p+n)$$

~30 candidates collected already

formation via Auger process

$$^6\mathrm{Li} + K^- \rightarrow K^- pppnn + n$$
$$^7\mathrm{Li} + K^- \rightarrow K^- pppnnn + n$$
$$(^6\mathrm{Li} + K^- \rightarrow K^- ppnnn + p)$$

decay-hyperon tagging

Run request

1. Target

We prefer to select light targets.

① 8 x ^{7}Li

② 6 x ^{7}Li and 2 x ^{6}Li

③ 4 x ^{7}Li and 4 x ^{6}Li

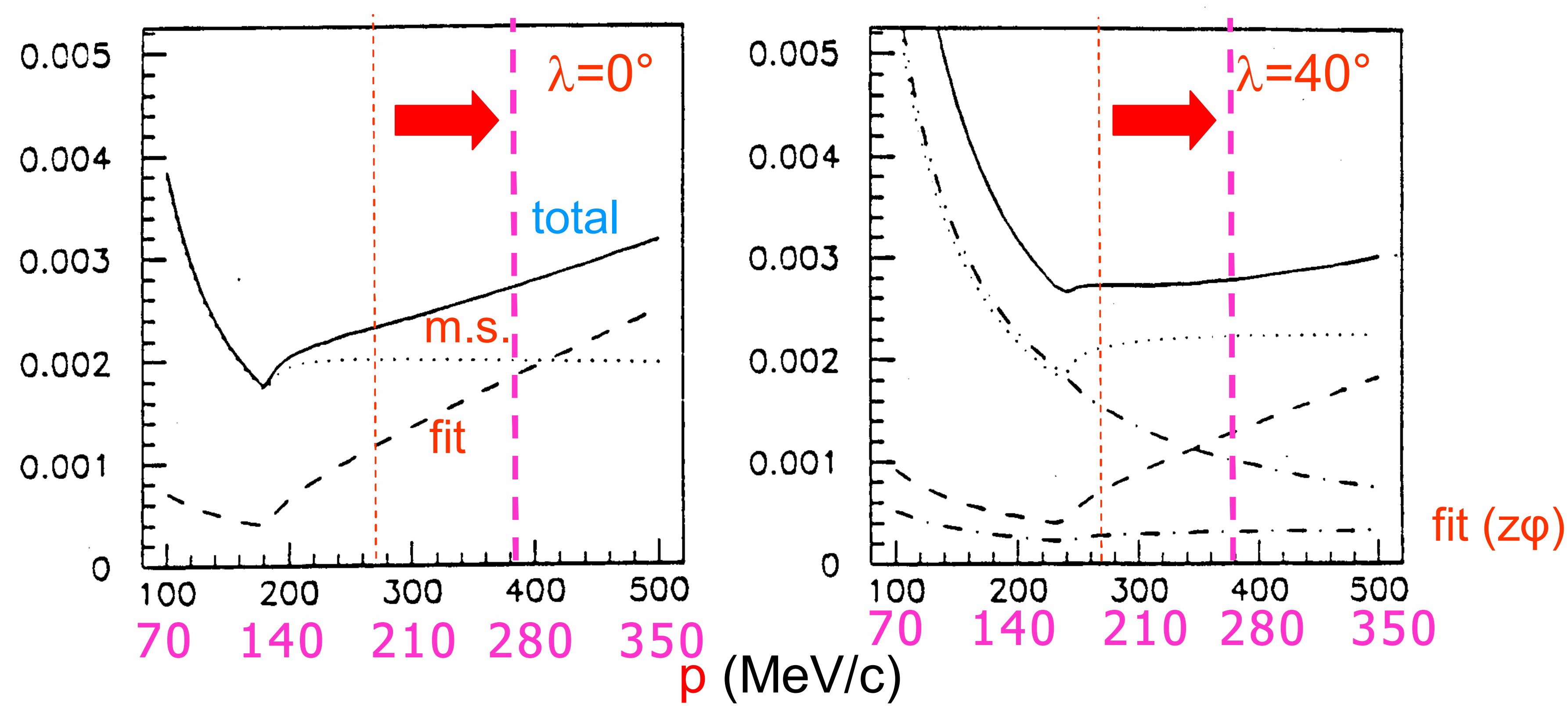
2. Magnetic field 1.0 T → 0.7 T

to enlarge the momentum acceptance

Number of Λ and K^{-}pp observed will increase greatly.

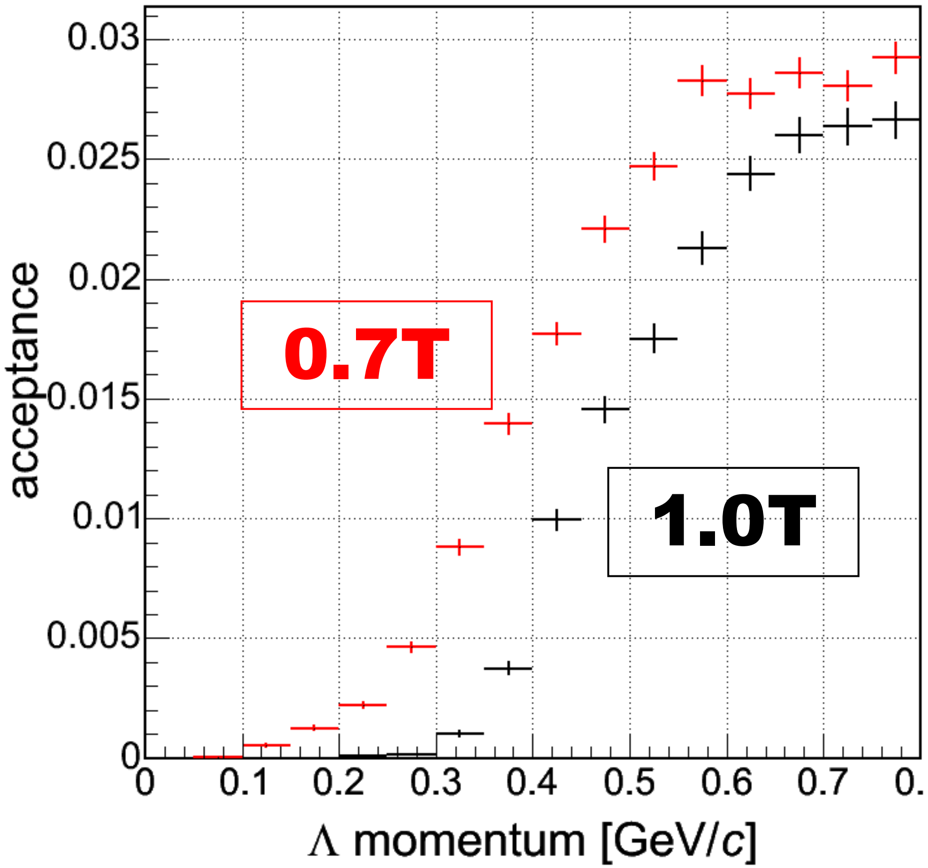
Δ p/p (FWHM) in 0.7T

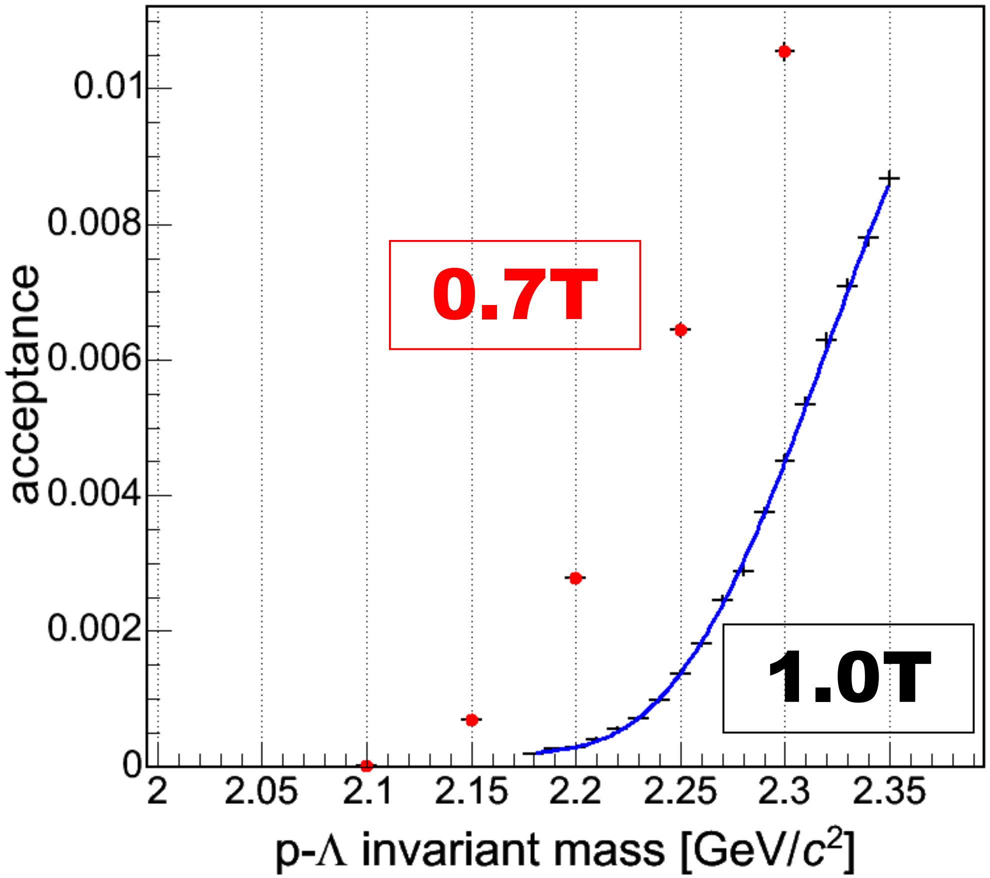
- Almost same as that in 1.0T.
- No problem for our analysis.



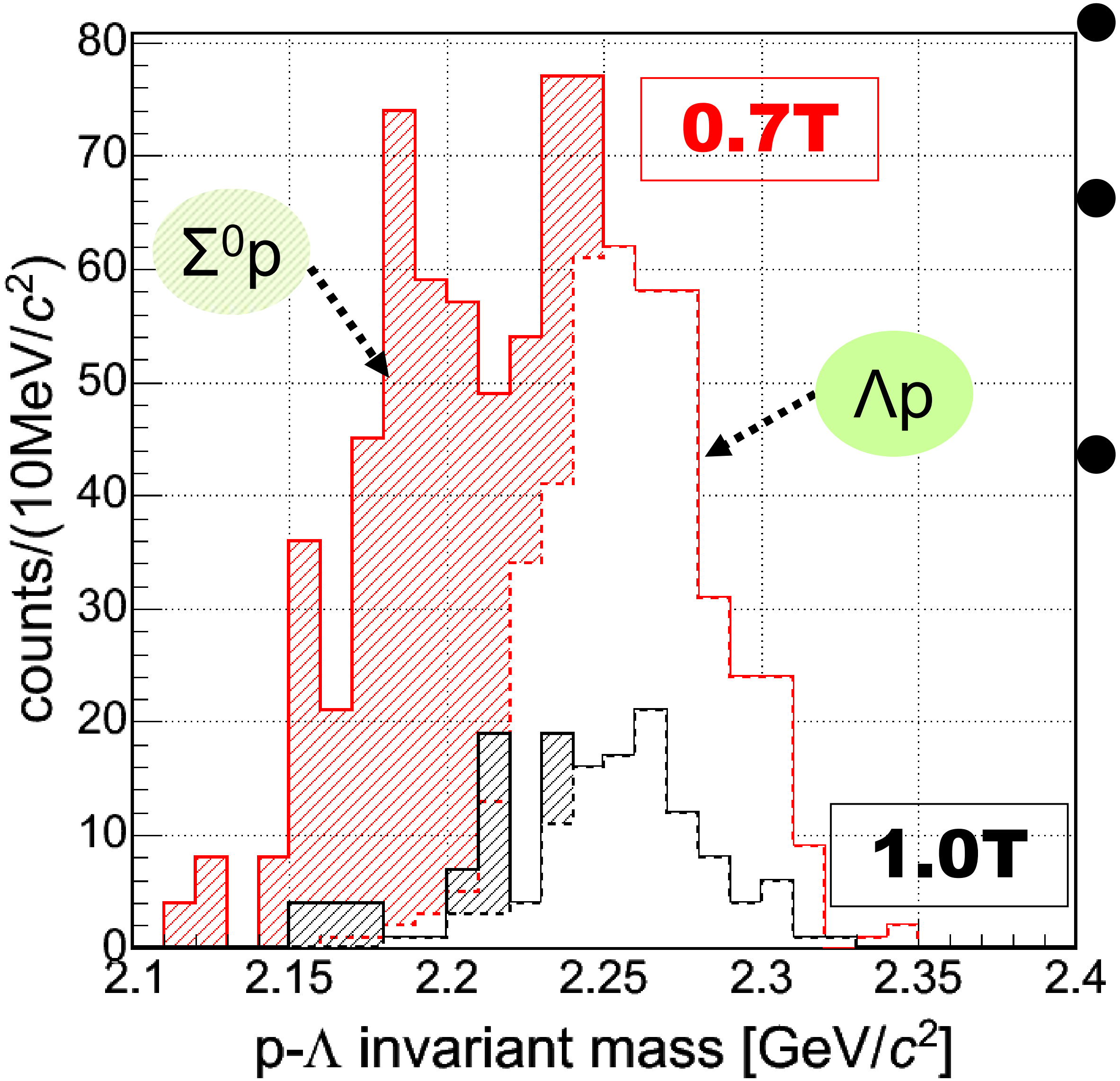
Comparison between B=1.0T and 0.7T

- Increased acceptance for low momentum Λ widens the observable region of $K^{-}pp$.





Change in invariant mass spectra



- Distortion of peak structure will be improved.
- Σ^0p decay component will be observed clearly in 0.7T.
- The total events will be increased more than 3 times (depending on B, Γ, and decay b.r.).

B=120 MeV
Γ=40 MeV
Kpp→Λp : Σp = 1:4