Probe short-range YN interaction via scattering experiment

y.ma@riken.jp

Step. 10th, 2015

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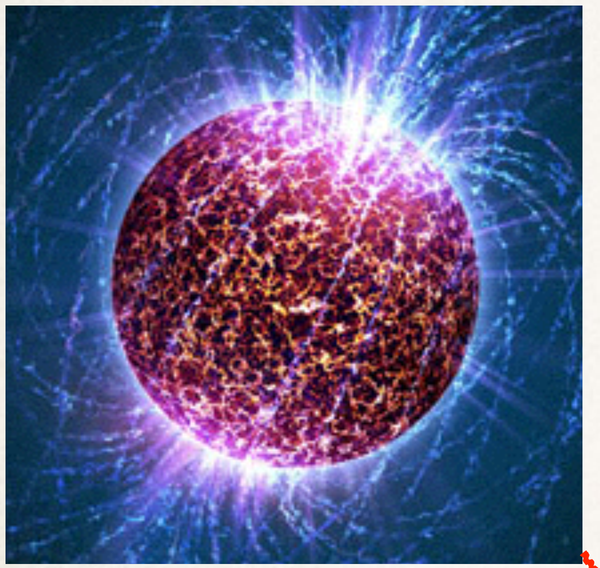
Outline

- Physics motivation
- Feasibility & experiment concept
- Results & discussion

Physics Motivation

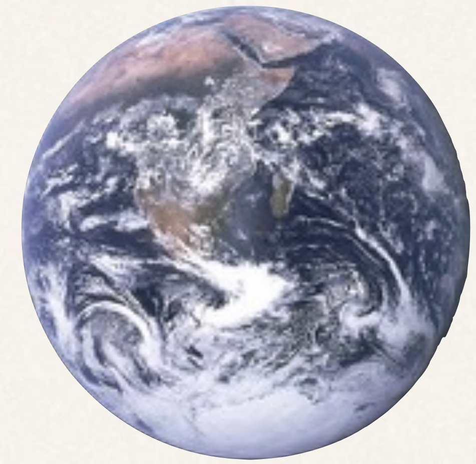
- Average ΛN potential is well ***known*** from Hypernucleus physics;
- Short range ΛN potential is still ***unknown***;
- Short range ΛN interaction is important for EOS of ***neutron star***

Physics motivation (personal understanding)



Major difference:

$\rho_{\text{neutron star}} \sim 3\times\rho_{\text{nuclear density}}$



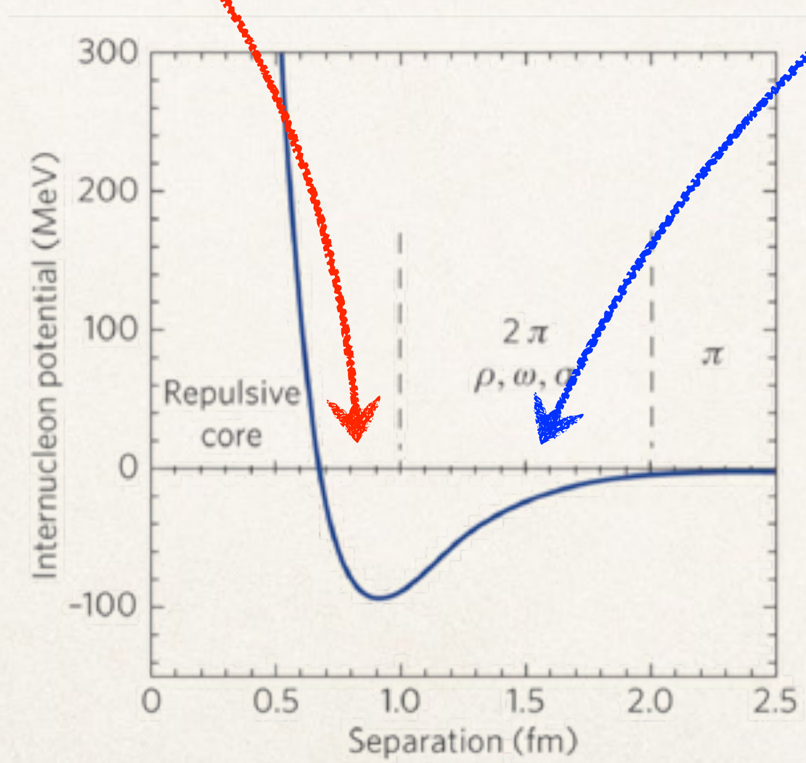


Illustration of bare BB potential

Different sensitive regions in baryon-baryon interaction:

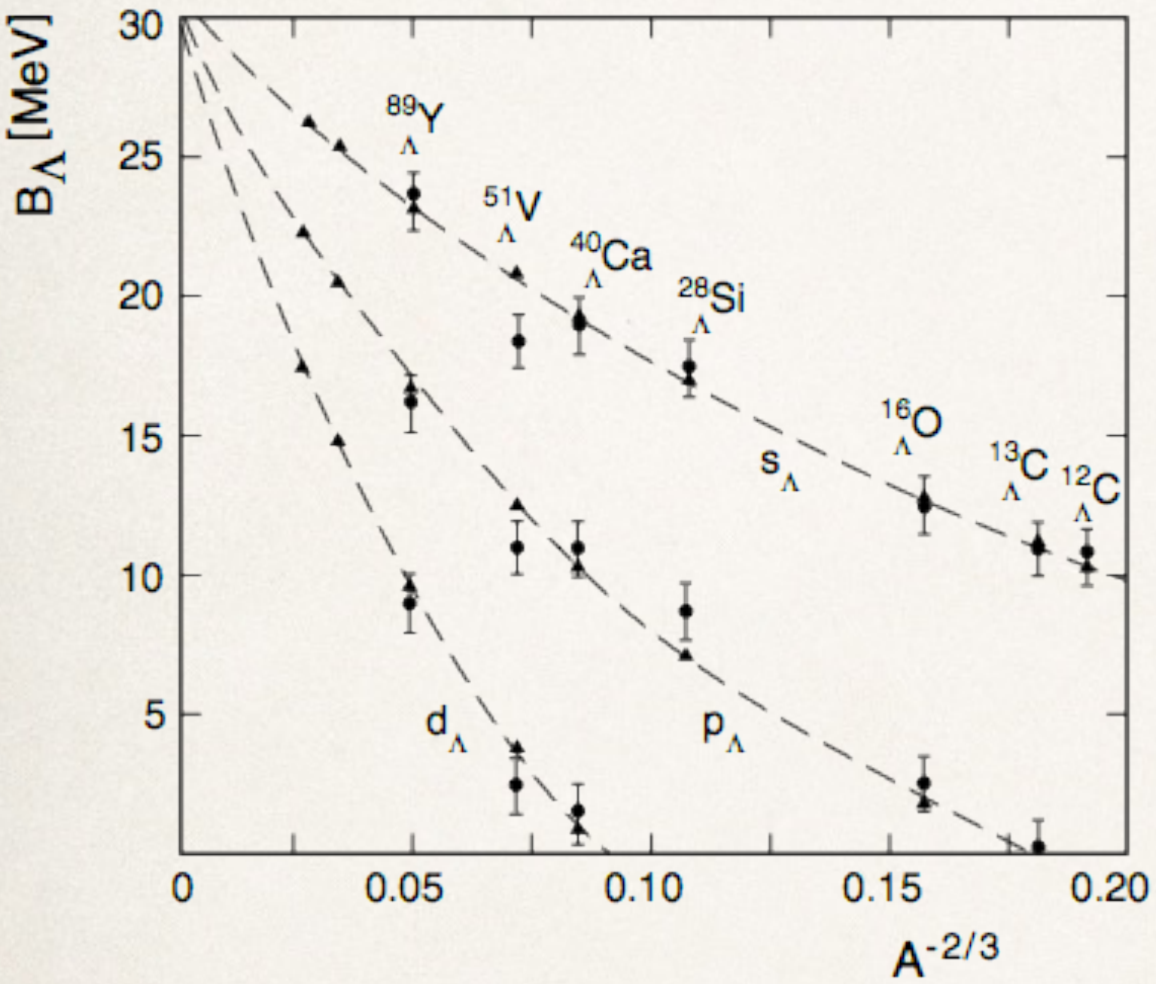
long-range interaction

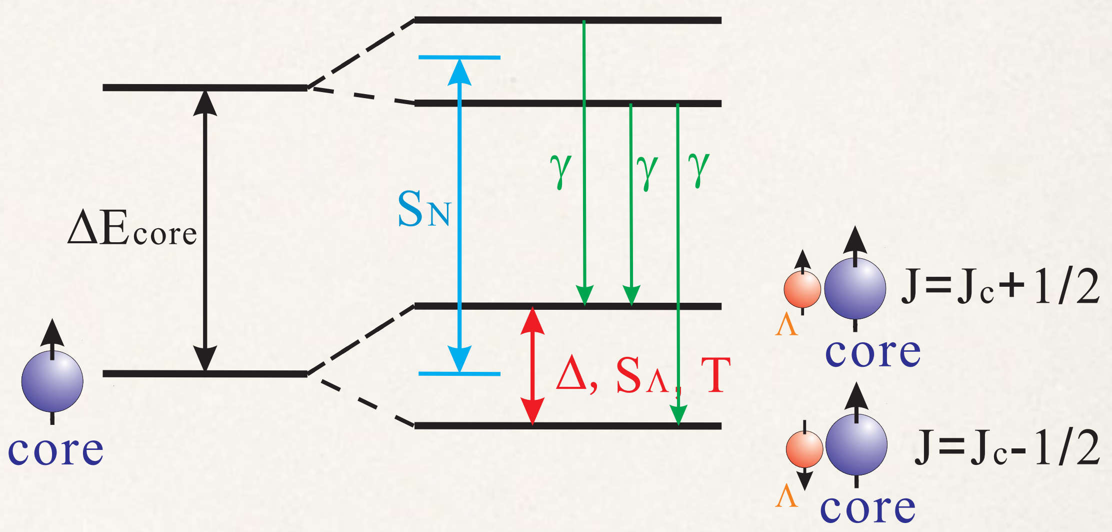
vs.

short-range interaction

Picture taken from wikipedia.org, NASA and Nature

ΛN interaction on the Earth (Lab.)





1. Λ hyperon binding energy (hypernuclear spectroscopy)
2. spin-dependent ΛN interaction

Sensitive to the depth of average ΛN potential in nuclear density.

Perhaps, not enough for Neutron Star matter.

Picture taken from Povh.

ΛN interaction in Neutron Star

Hyperon puzzle/crisis:
Recently observed 2-solar mass neutron star requires *YN interaction to be repulsive* or, *no hyperon represented*.

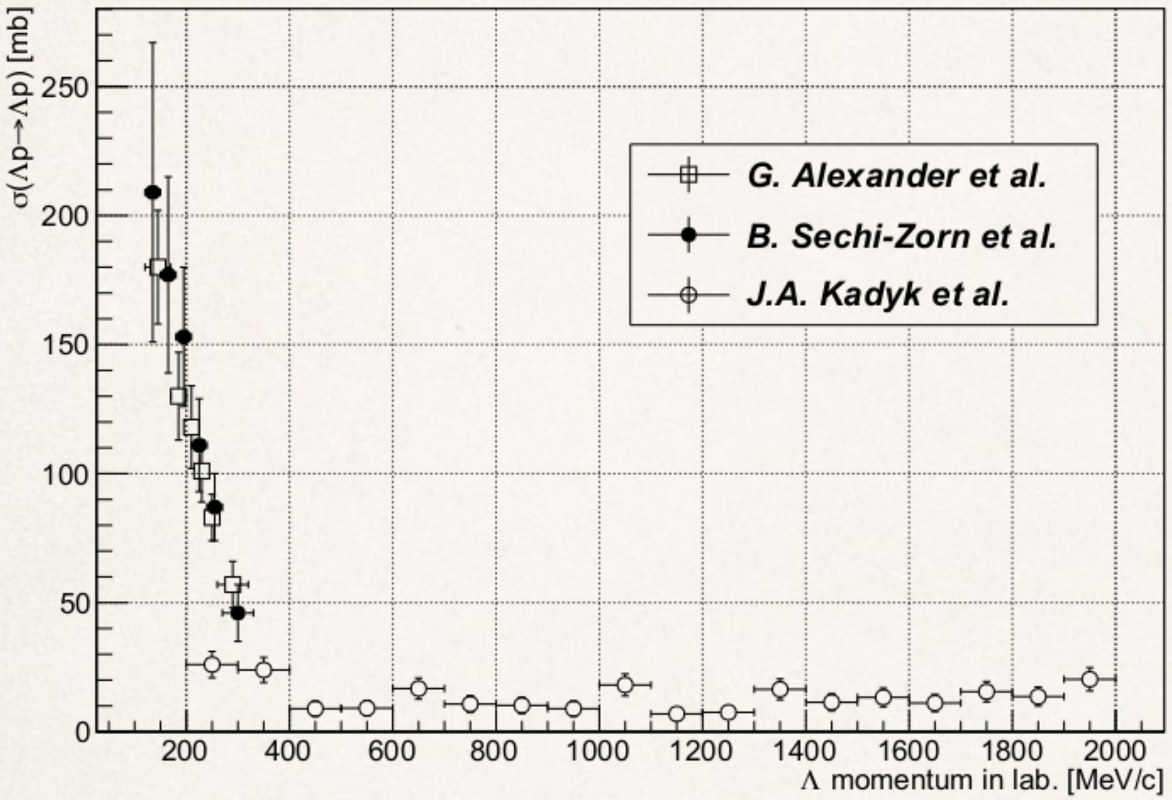
Theoretical trials:

1. Implementation of artificial vector meson;
2. 3-body YNN interaction contributes as repulsive force;
3. ***YN short range interaction?***

(Neutron star core density: a few times higher than nuclear density.)

How to approach *YN short-range interaction* experimentally?
High momentum YN elastic scattering?
$\Delta p \geq 200\text{MeV}/c \Longrightarrow$ short range probe

Λp elastic scattering data survey



$$k cot\delta_{s,t} = -1/a_{s,t} + 0.5 r_{s,t} k^2$$

$$\sigma = \frac{1}{4}\sigma_s + \frac{3}{4}\sigma_t$$

$$= \frac{\pi}{k^2 + (-1/a_s + 0.5 r_s k^2)^2} + \frac{3\pi}{k^2 + (-1/a_t + 0.5 r_t k^2)^2}$$

p_Λ range [GeV/c]	statistics	references
0.12~0.32	378 Λp	G. Alexander ***et al.*** Phys. Rev. 173, (1968) 1452
0.11~0.33	244 Λp	B. Sechi-Zorn, ***et al.*** Phys. Rev. 175, (1968) 1735
0.3~1.5	250 ΛpΣp	J. A. Kadyk ***et al.*** Nucl. Phys. B27, (1971) 13

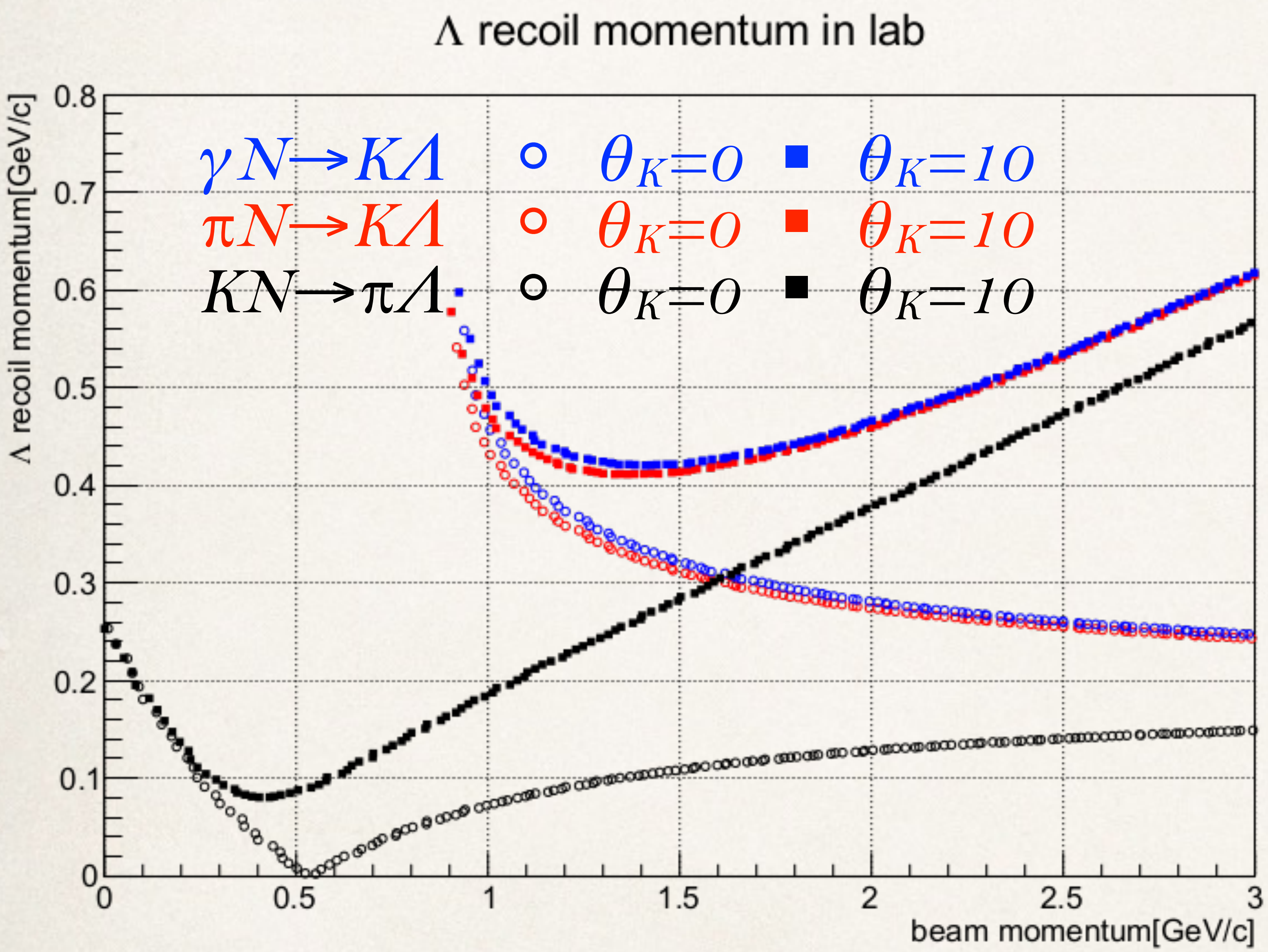
$$a_s \approx -1.8\mathrm{F}$$
$$a_t \approx -1.6\mathrm{F}$$
$$r_s \approx 2.8\mathrm{F}$$
$$r_t \approx 3.3\mathrm{F}$$

Plotted with lambda_p_elastic_data.C

Feasibility & experiment concept

- Λ production channel: $\pi^- + p \rightarrow K^0 + \Lambda$
- Data analysis procedure: lack of "good" trigger
- Statistics and precision: break down of errors

Production method

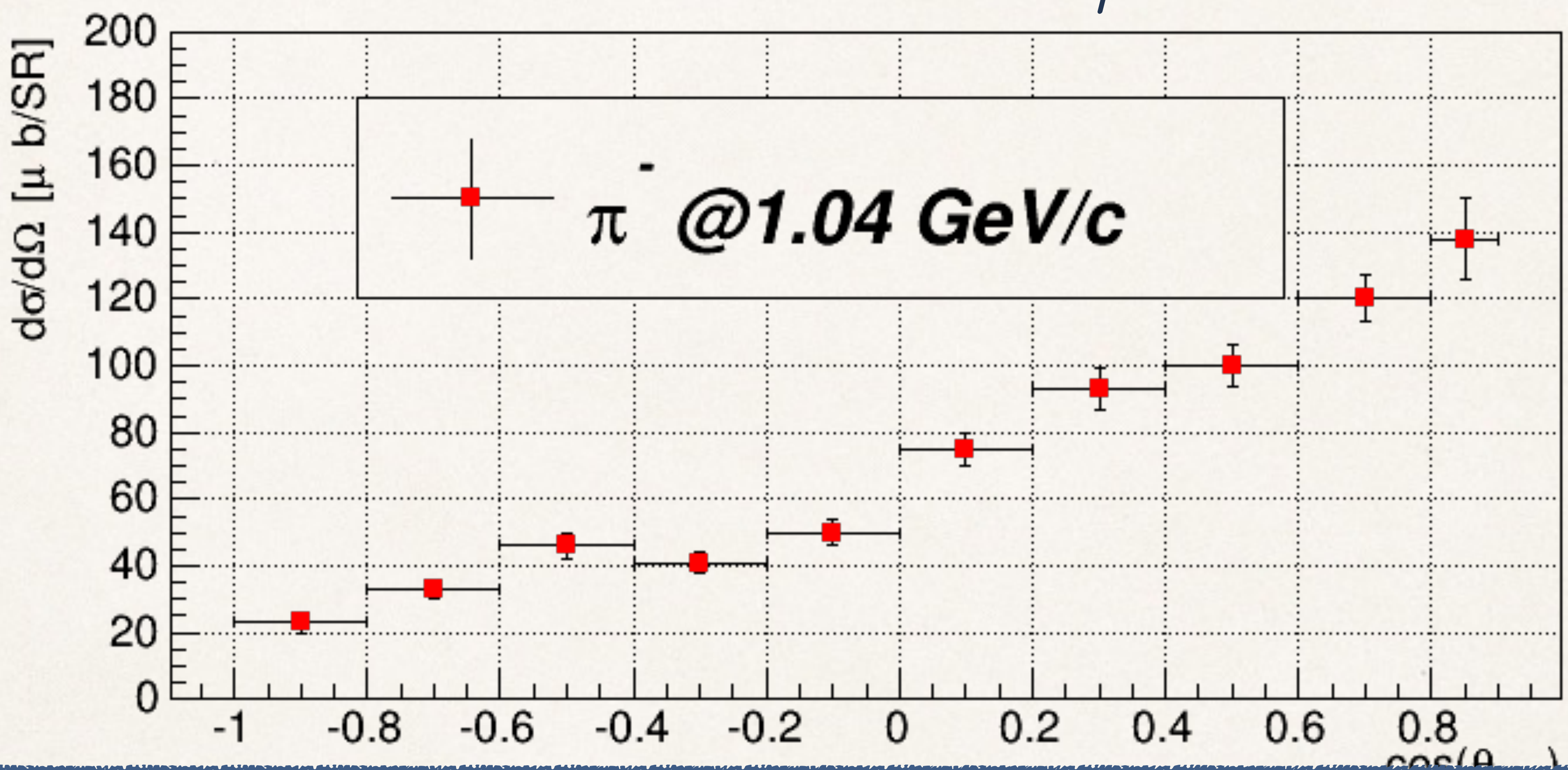


1. Λ production by γ/π near threshold favours large recoil momentum.
2. Thick target for Λp scattering makes ee' method formidable.
3. K+D channel suffers from Fermi motion.
4. pion production channel is our first choice.

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

Λ production cross section

$$\sigma = 903 \pm 90 \ \mu b$$



Kinematics in laboratory frame

p_Λ [GeV/c]	0.96	0.91	0.86	0.81	0.76	0.71	0.65	0.59	0.53	0.47
$Cos\Theta_\Lambda$	0.99	0.98	0.97	0.95	0.95	0.94	0.93	0.93	0.94	0.96
p_{K0} [GeV/c]	0.13	0.22	0.28	0.34	0.39	0.43	0.48	0.52	0.56	0.59
$Cos\Theta_{K0}$	0.63	0.63	0.68	0.74	0.79	0.83	0.87	0.91	0.95	0.97

R.D. Baker *et al.*, Nucl. Phys. B141 (1978) 29

Λ yield estimation

LH2 target

$\rho = 0.07 g/cm^3$

20 cm

5 cm

Beam intensity

$I_{\pi^-} = 2 \times 10^7 / 6s$

Beam time: one month

$3600 \times 24 \times 30 = 2.6 \times 10^6 s$

Λ production cross section

$\sigma = 903 \pm 90 \ \mu b$

Expected Λ yield in one month

$\Lambda = 6 \times 10^9$

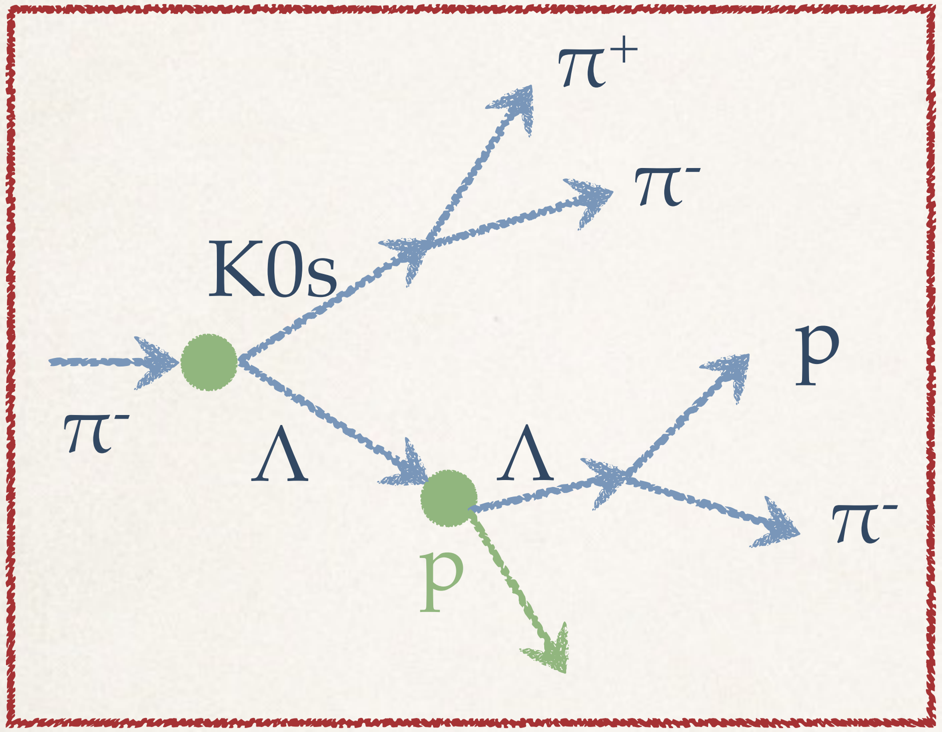
Λp scattering probability: ~0.1%

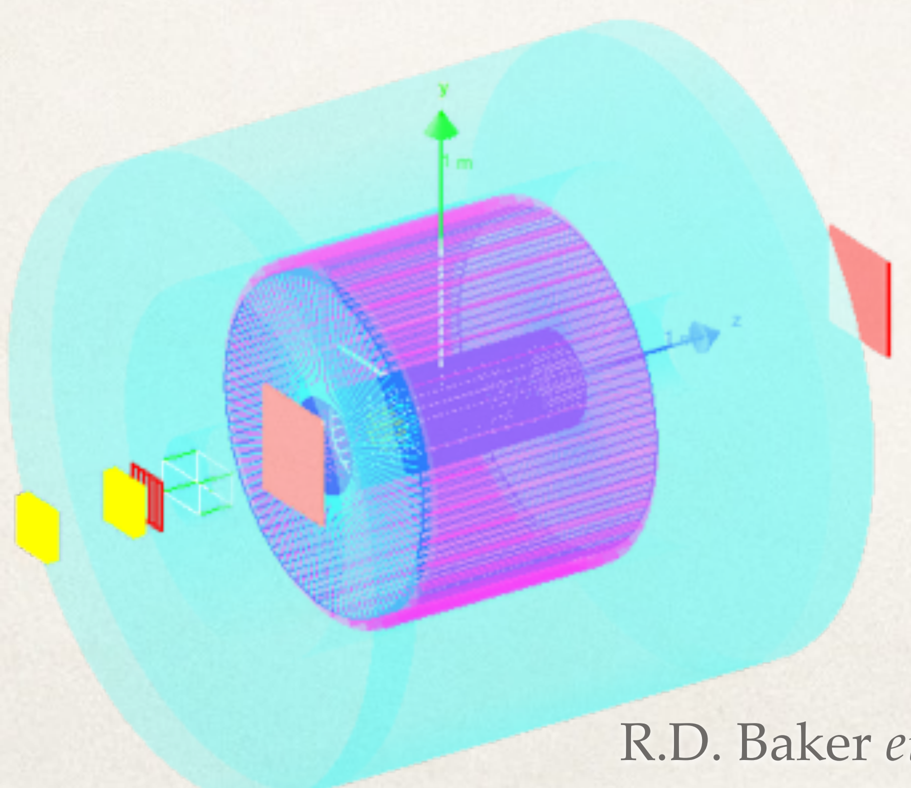
Detectable branching ratio: ~15%
(including absorption inside LH2 target)

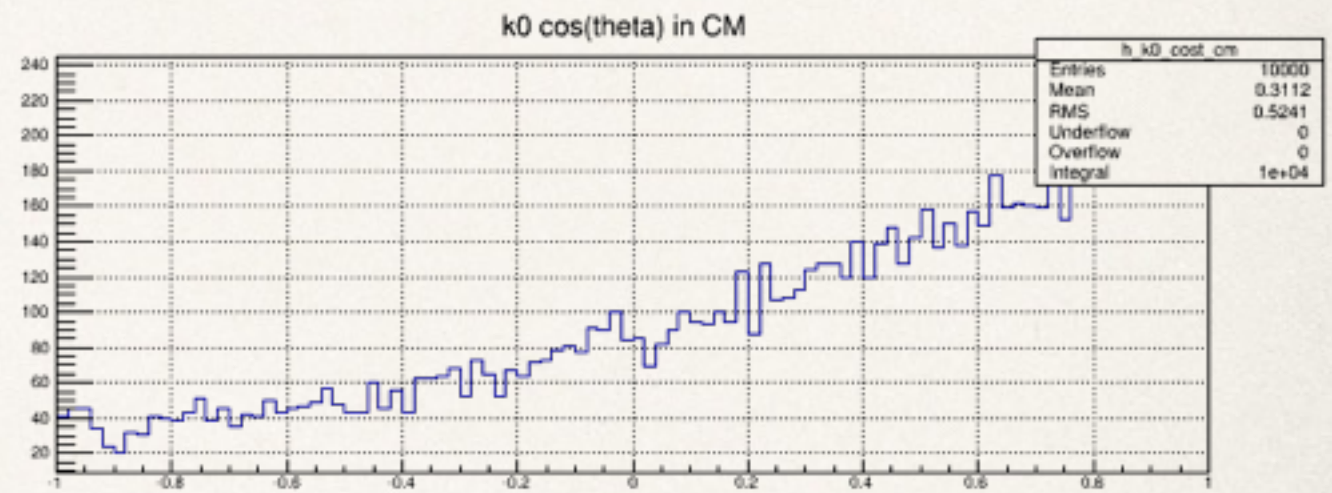
Total event number:
~10^6 in one month
final state: $2p \oplus 2\pi^- \oplus 1\pi^+$

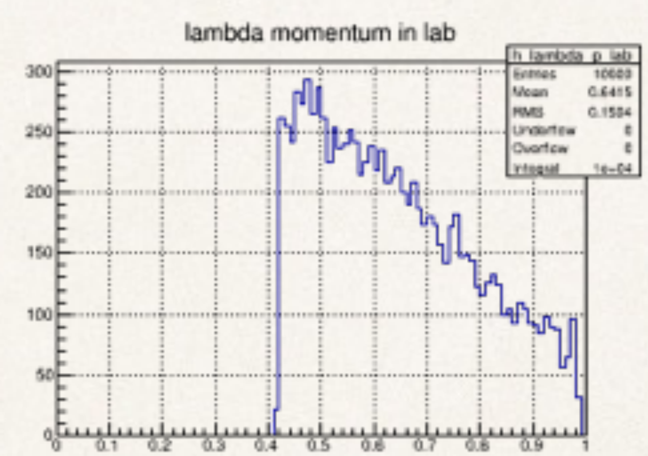
GEANT4: trigger rate is 4 kHz
when multiplicity == 5

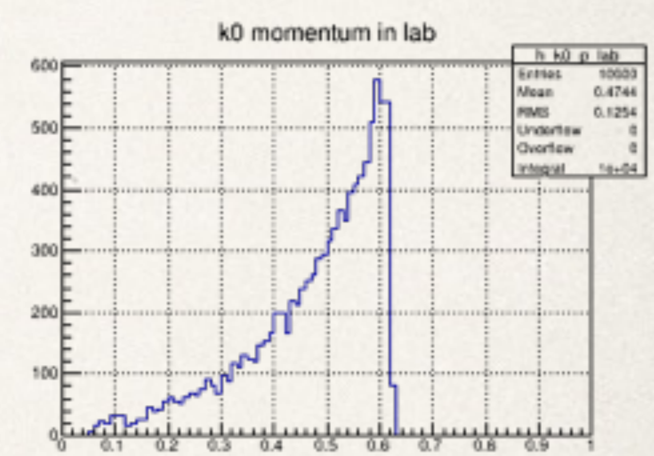
Simulation setup 1







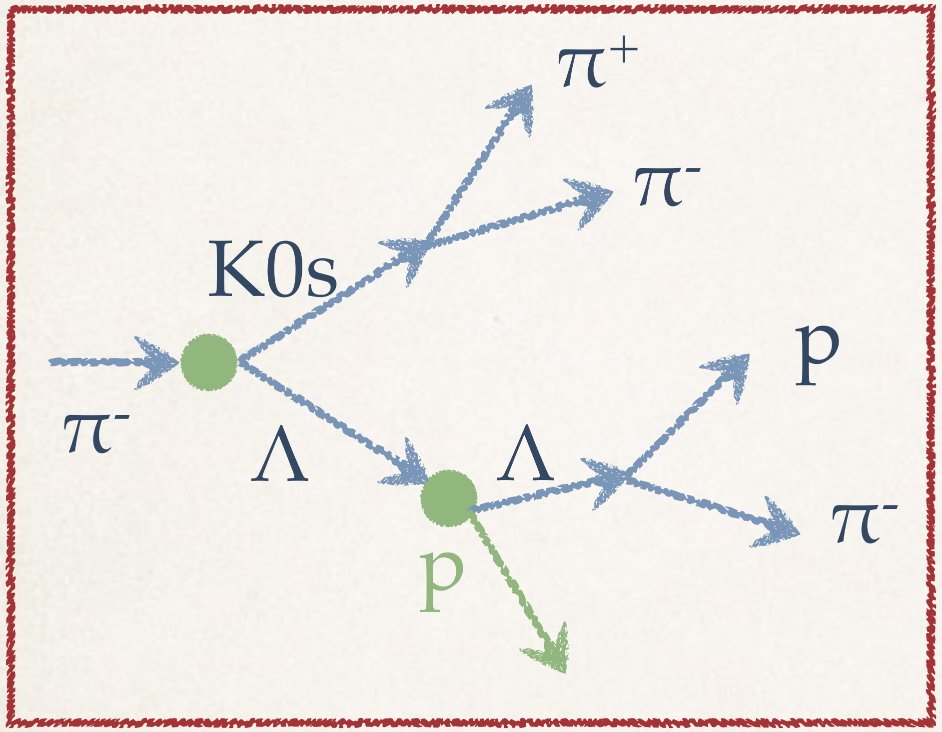


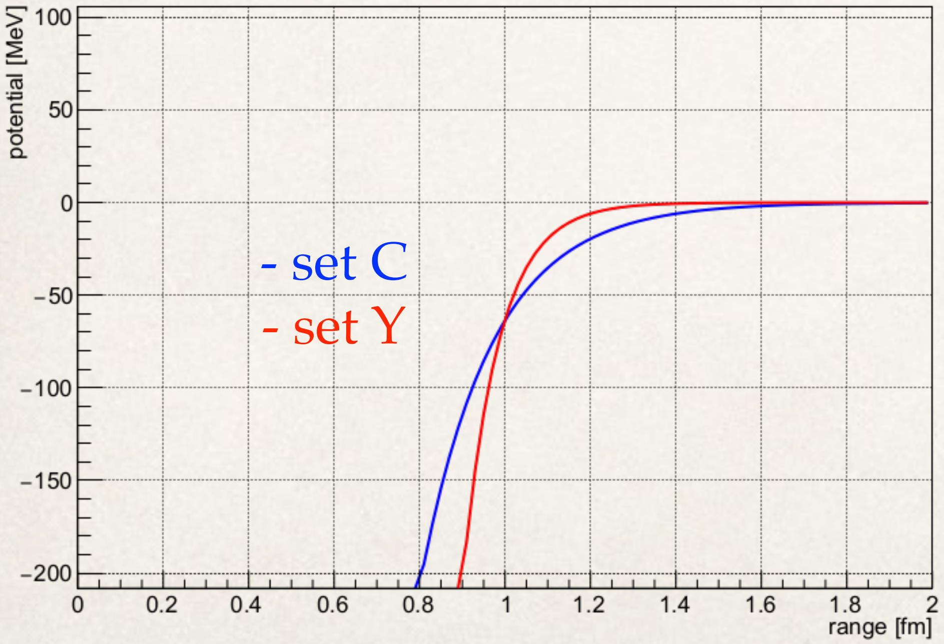


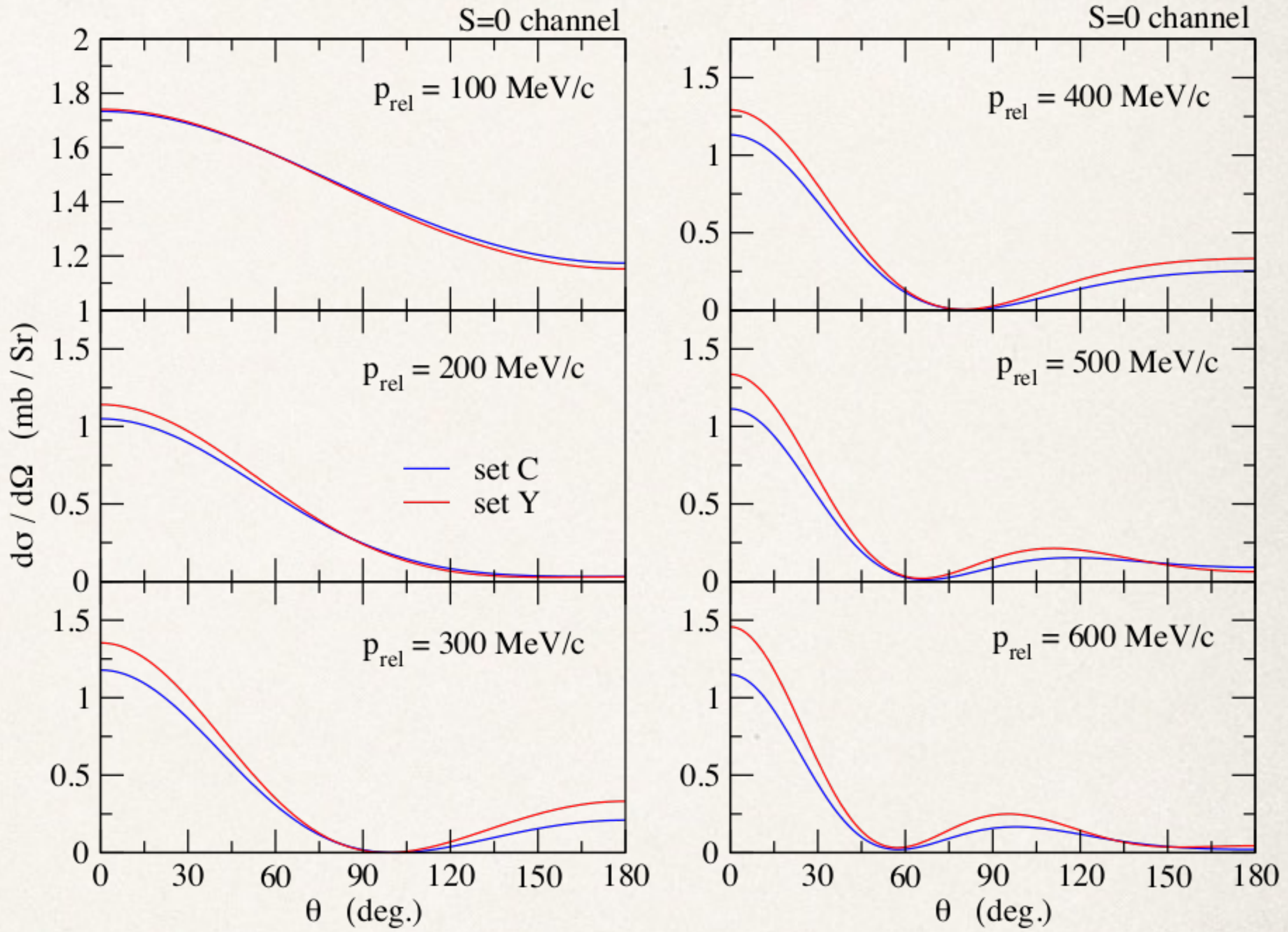
Λ production follows ref.

R.D. Baker *et al.*, Nucl. Phys. B141 (1978) 29

Simulation setup 2







Λp elastic scattering cross section calculated by Prof. Hagino with potential in ref.

A. Deloff, Phys. Rev. C20 (1979) 1528

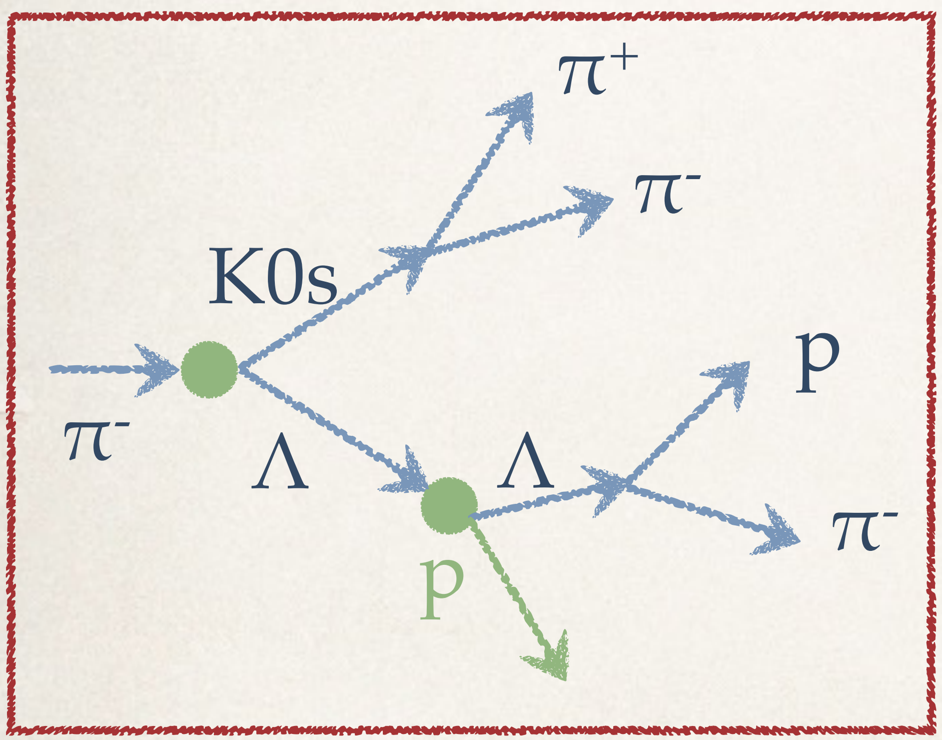
Challenge and strategy

$$\pi^- + p \to K^0 + \Lambda$$

No “good” trigger to guarantee the production of strangeness,

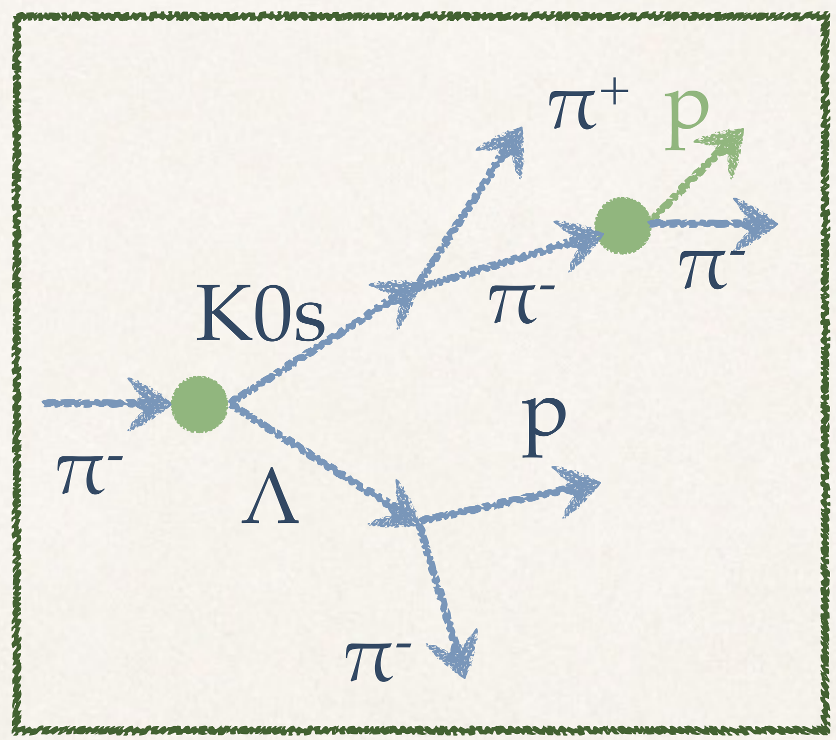
when requesting the final state = $2p \oplus 2\pi^- \oplus 1\pi^+$,

signal/background = 1/400



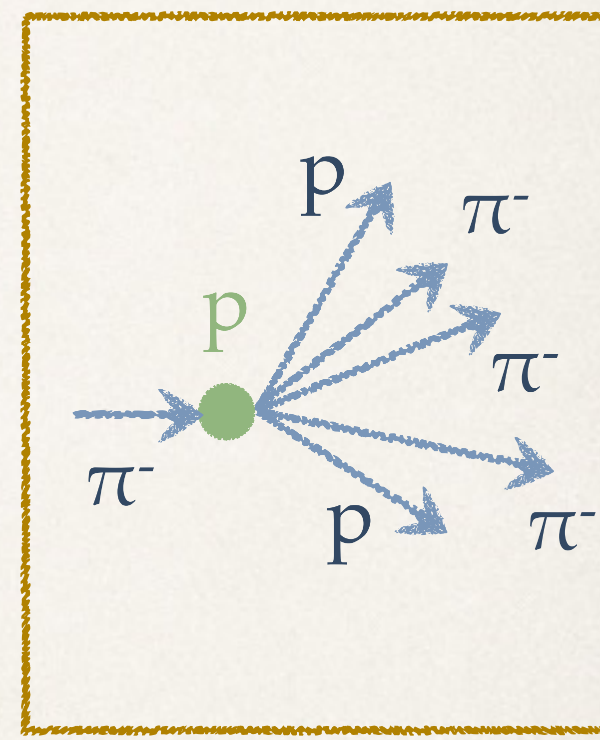
Signal event

Relative yield: 1



background event

Relative yield: 10



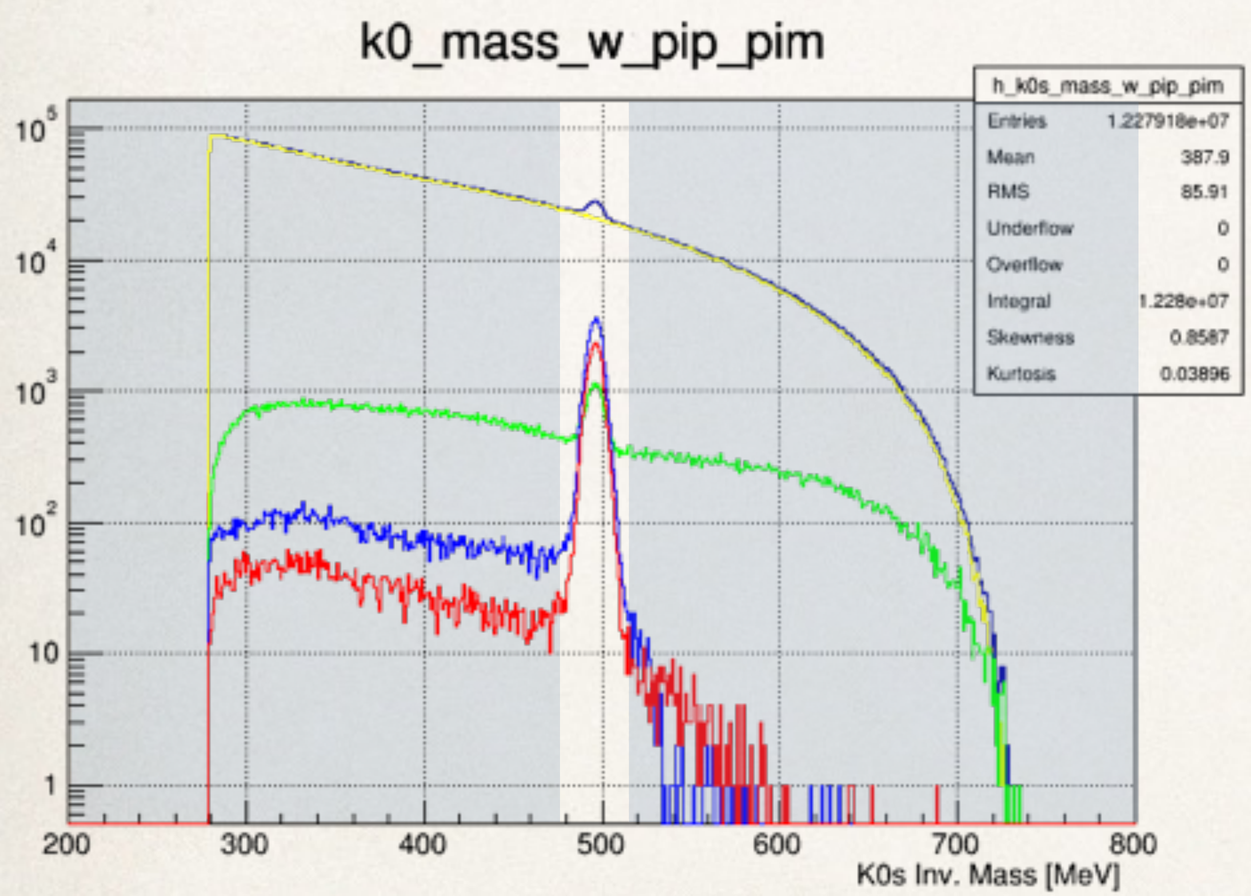
phase space
background event

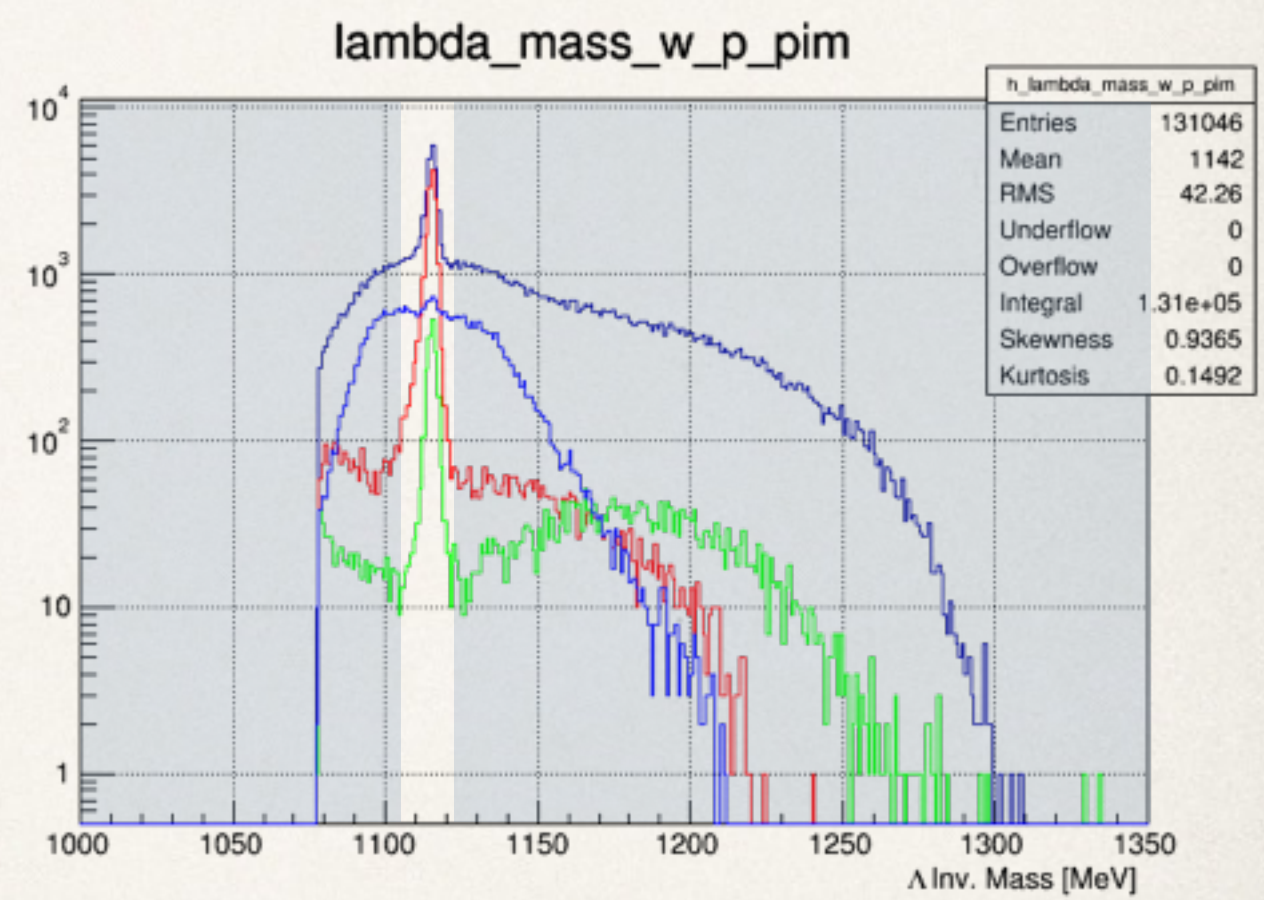
Relative yield: 400

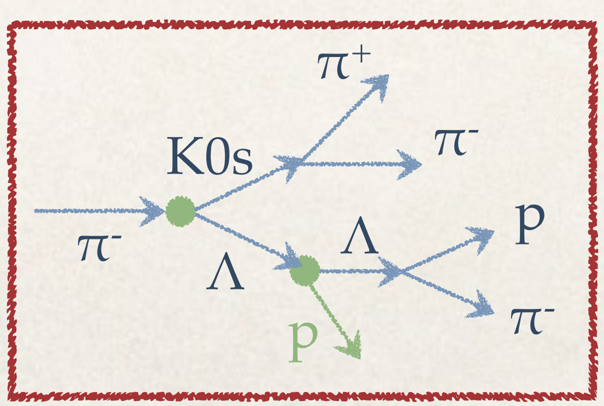
Event selection

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

Event selection by cutting on invariant mass, scattering angle, vertex…





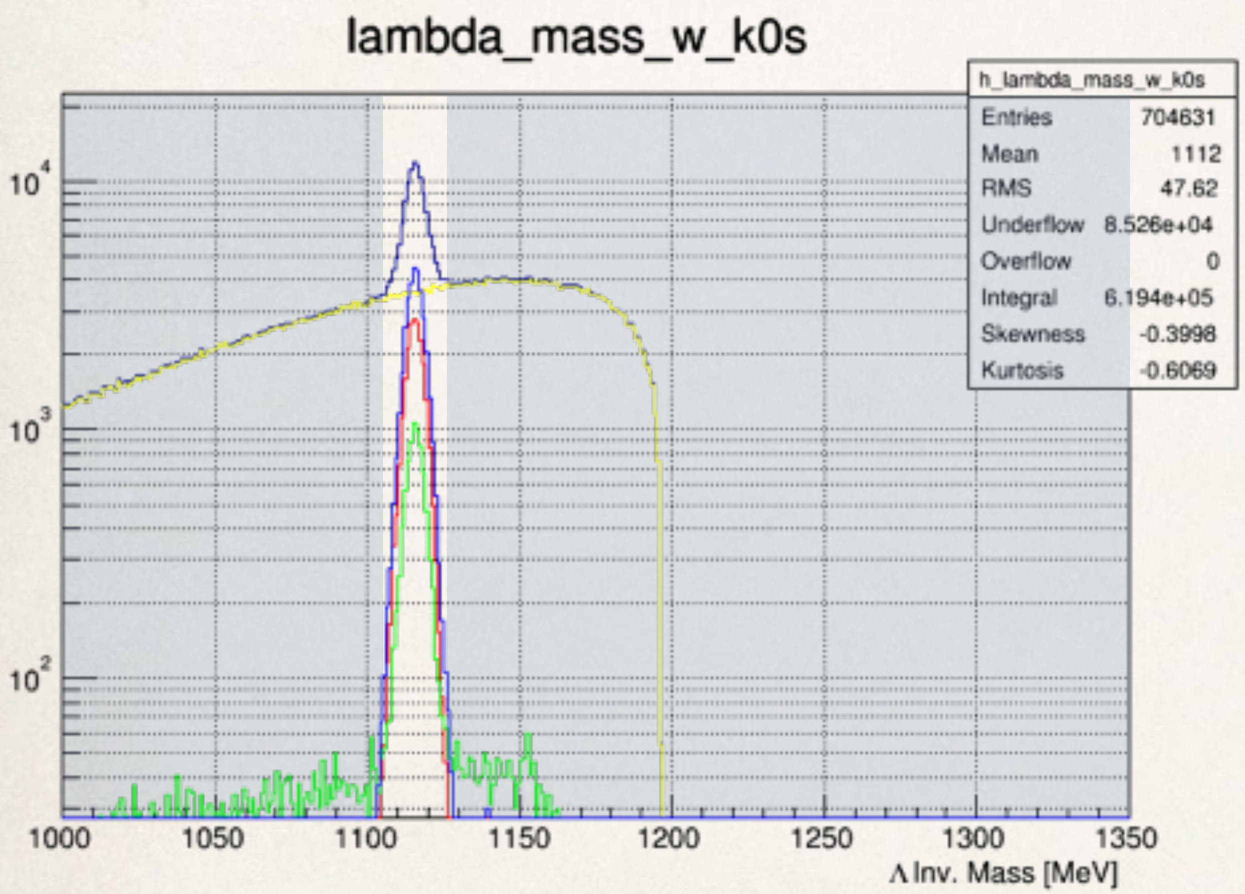


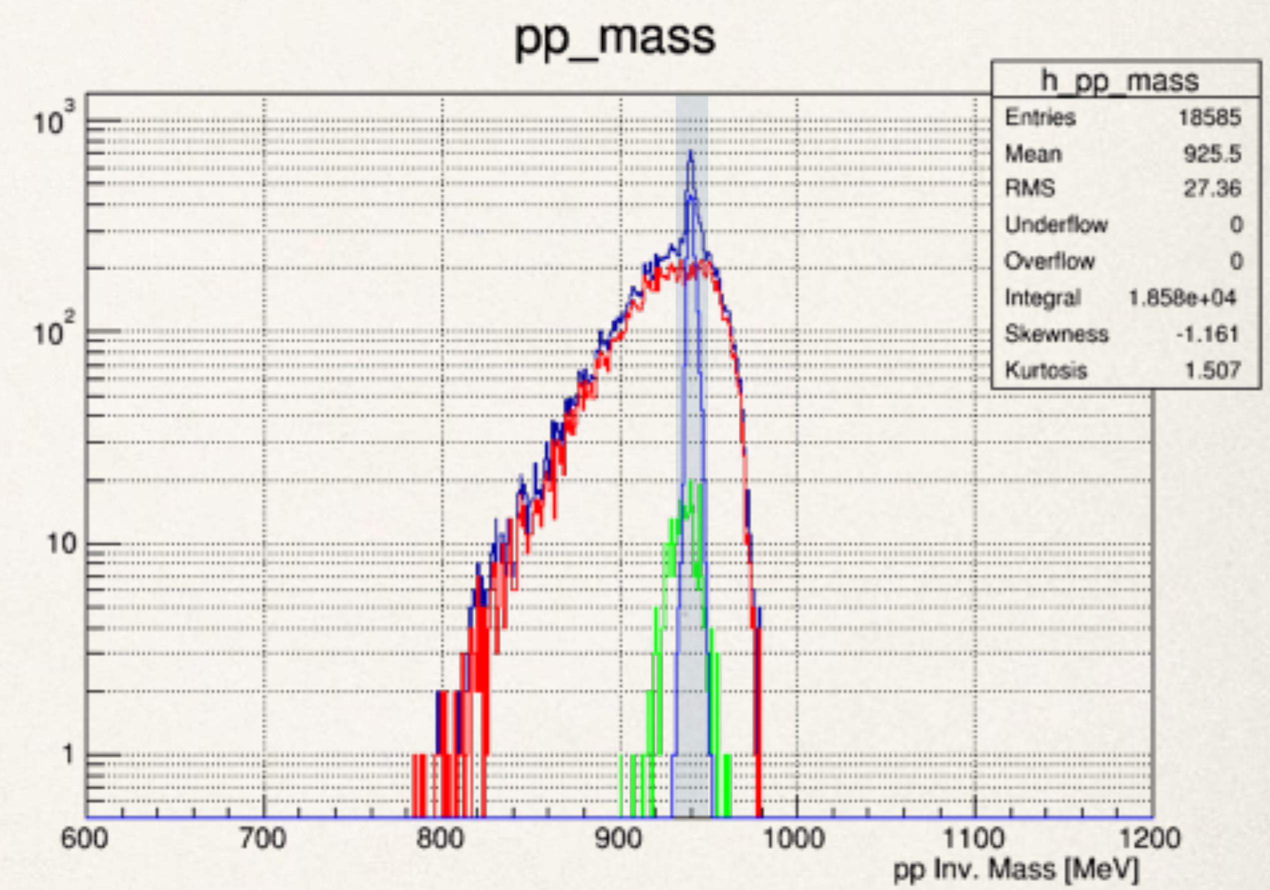
Phase space background events
Signal event
pion kick event
proton kick event

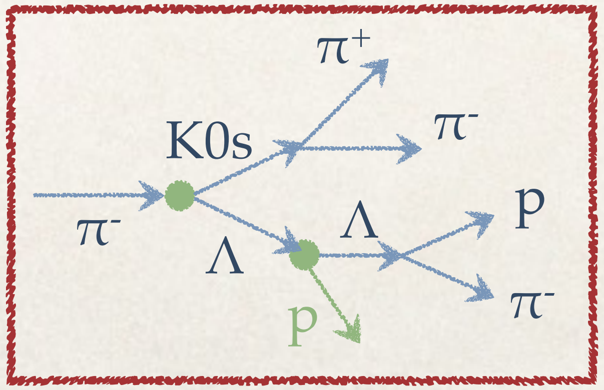
Event selection

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

Event selection by cutting on invariant mass, scattering angle, vertex…







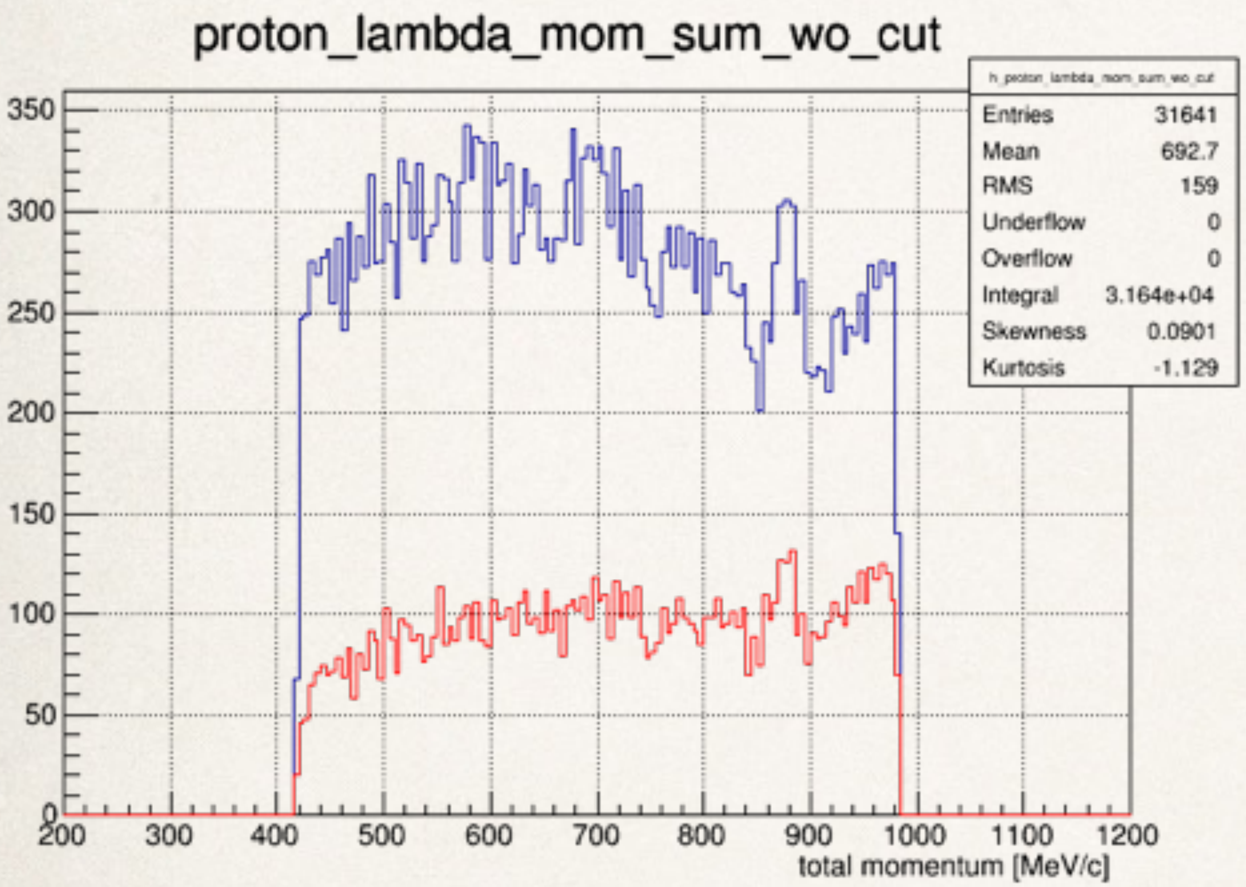
Phase space background events

Signal event

pion kick event

proton kick event

Analysis efficiency



before event selection

after event selection

- Analysis efficiency: ~30%;
- Background level: ~15%;
- Momentum resolution: 2%;
- ***Good momentum resolution is essential for event selection! Otherwise, very bad S/N ratio because of no strangeness trigger.***

Statistics & precision

$$\sigma = \frac{N}{L}$$

N: YP scattered events;
L: integrated luminosity

$$\frac{\delta\sigma}{\sigma} = \sqrt{\left(\frac{\delta N}{N}\right)^2 + \left(\frac{\delta L}{L}\right)^2}$$

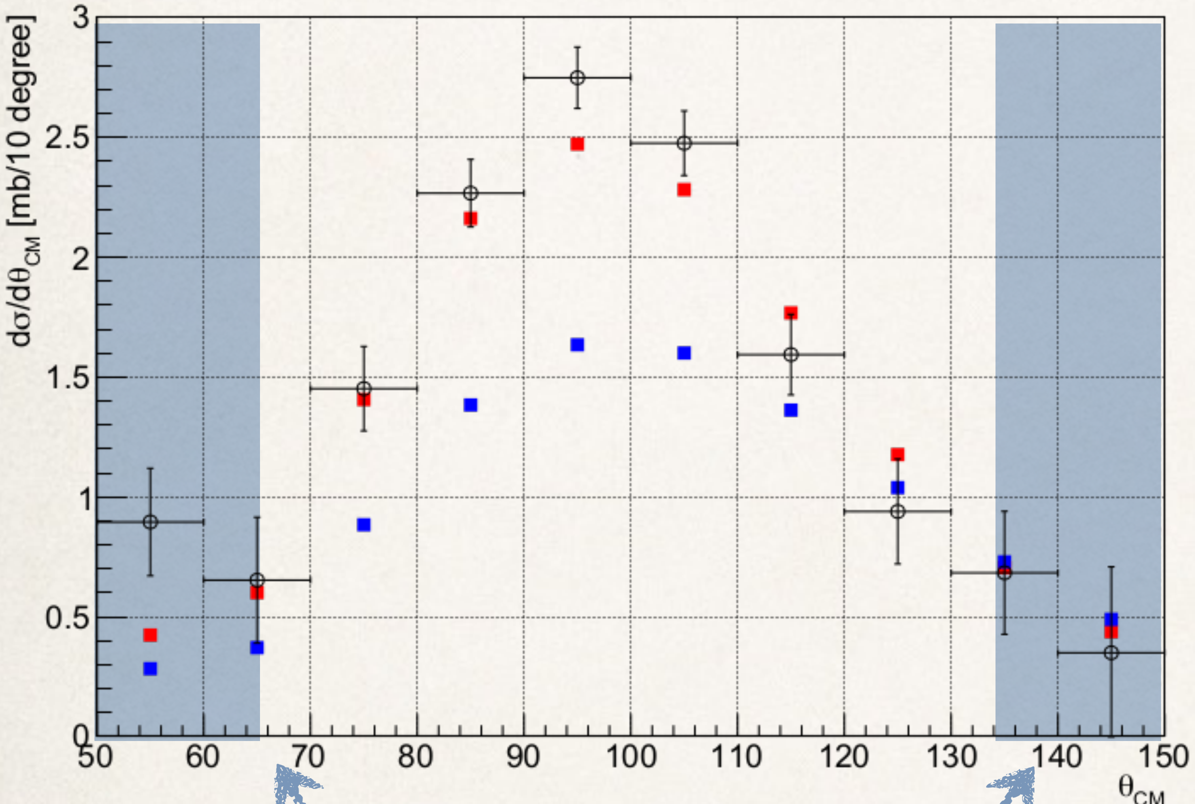
$N = 1\times10^6\times\varepsilon_{analysis}\times\text{Acceptance} = 3\times10^4$
$\Rightarrow \delta N/N \sim 15\%$

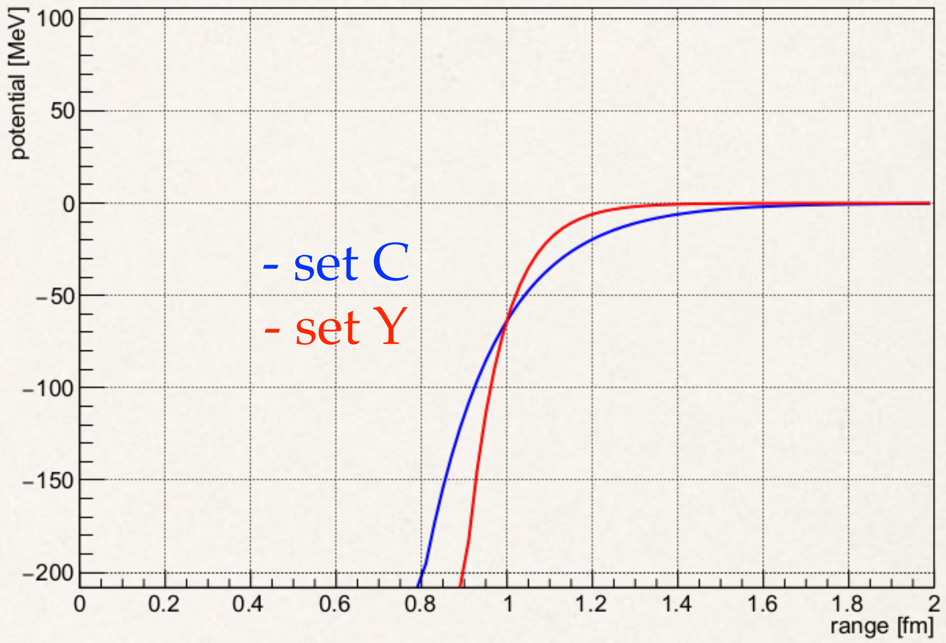
10% error in Λ production cross section
$\Rightarrow \delta L/L \sim 12\%$ (can be improved!)

$\delta\sigma/\sigma$=15%(statistics)$\oplus$12%(systematics)

Preliminary results

$850MeV/c<p_{\Lambda}<950MeV/c$





Acceptance

(Only statistical error is displayed.)

A set of measurement,
from 0.6GeV/c to 1GeV/c.

1. What can be derived from these data?
2. Can we say something about short-range YN interaction?
3. Is it helpful for Neutron Star puzzle/crisis?

Discussions

- Provided the difficulty of phase shift analysis, a direct comparison with phenomenological model is possible

- *A suggestion for theorists: how about devise a phenomenology potential with strong enough short-range repulsive core to sustain neutron star EOS (if possible) and compare it with high momentum YN scattering data (if available)?*

Acknowledgement (incomplete)

- Prof. M. Iwasaki, Prof. H. Noumi, Prof. E. Hiyama,
- Prof. K. Miwa, Prof. K. Hagino
- Dr. Y. Ikeda, Dr. S. Ohnishi, Prof. J. Hu
- Dr. M. Sato, Dr. F. Sakuma

Future plan

- More sophisticated event generator;
- Including $\Lambda + p \rightarrow \Sigma N$ channel;
- R&D for spectrometer with $\delta p/p \leq 2\%$;
- Tracking program(combinatorial background effect);
- photo-production & polarisation?(Prof. K. Miwa);
- $K^- + p \rightarrow \Lambda(\pi\pi)^0$?(Dr. M. Sato);
- Deuteron target? Effects of Fermi motion?
- proton primary beam production?

Questions

Derive some useful short-range interaction information?

Experimentally measured differential cross section

Bare interaction (potential)

Direct comparison with LQCD calculation?

Standard protocol

Phase shift analysis

Standard protocol

Bare interaction (potential)

Translation

EOS of Neutron Star

G-Matrix at $\rho_{\text{neutron star}}$?

ab-initial calculation?

Λp elastic scattering data survey

p_Λ range [GeV/c]	statistics	detector	references
0.12~0.32	378 Λp	81 cm hydrogen bubble chamber	G. Alexander ***et al.*** Phys. Rev. 173, (1968) 1452
0.11~0.33	244 Λp	81cm hydrogen bubble chamber	B. Sechi-Zorn, ***et al.*** Phys. Rev. 175, (1968) 1735
0.3~1.5	250 ΛpΣp	63.5 cm hydrogen bubble chamber	J. A. Kadyk ***et al.*** Nucl. Phys. B27, (1971) 13
1.0~17.0	108 Λp	203 cm hydrogen bubble chamber	K. J. Anderson ***et al.*** Phys. Rev. D 11, (1975) 473
1.0~10.0	992 ΛpΣπ	208 cm hydrogen bubble chamber	J. M Hauptman, ***et al.*** Nucl. Phys. B125, (1977) 29

How to derive potential from Λp data?

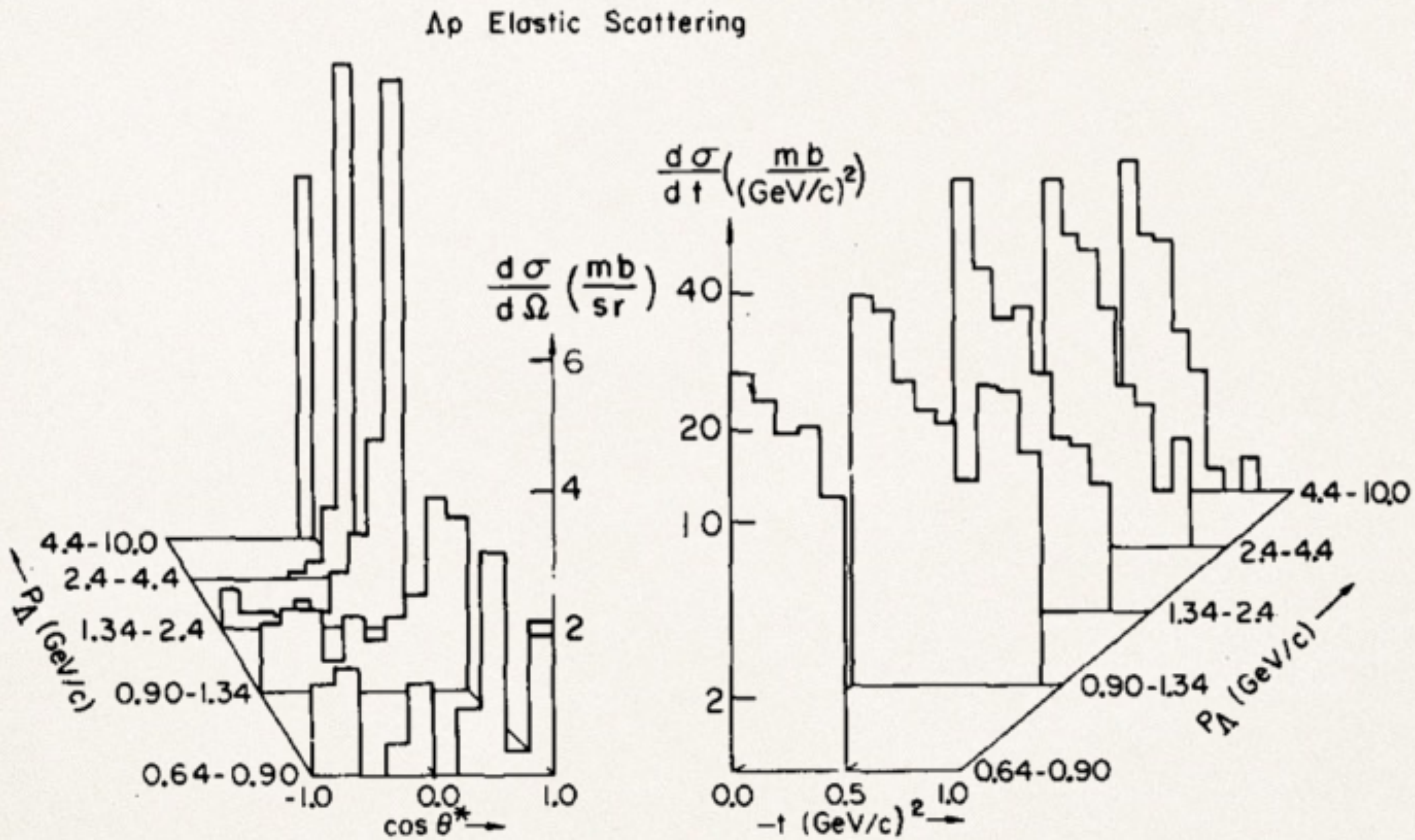


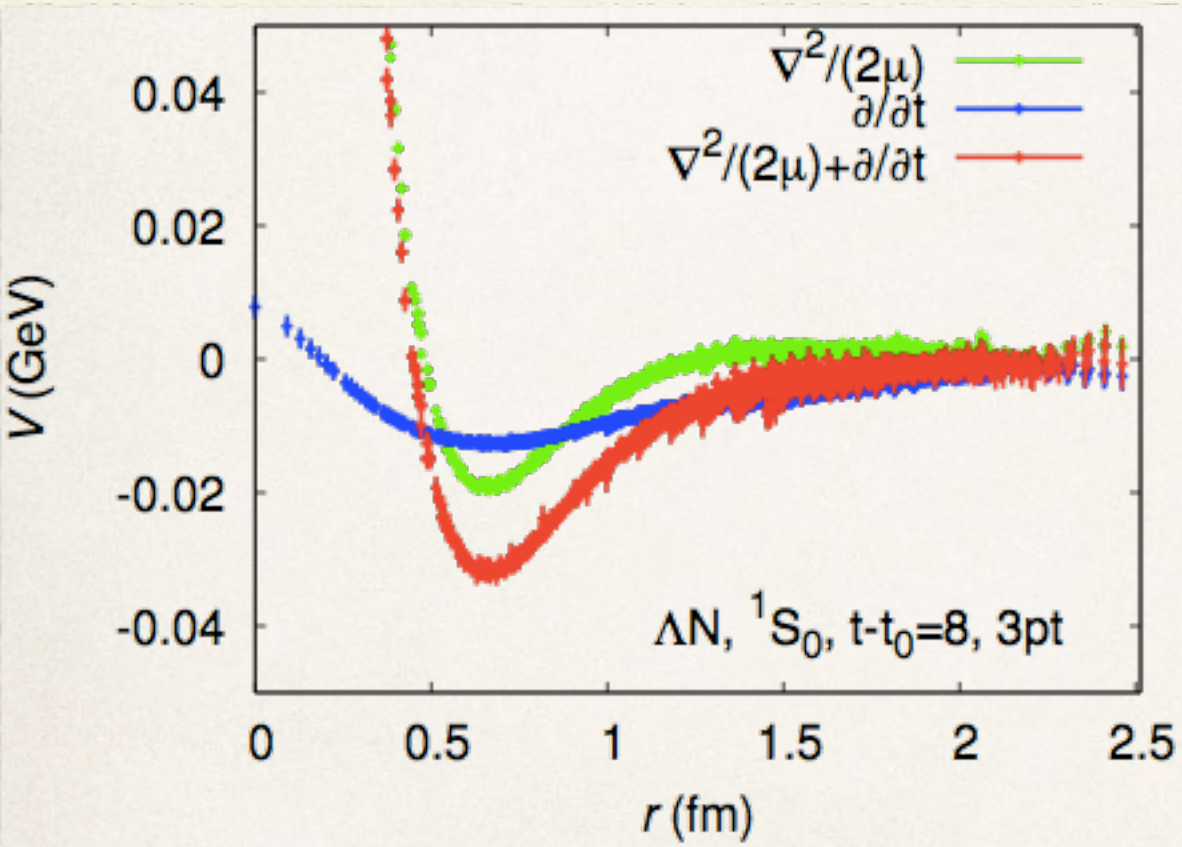
Fig. 3. (a) The Λp elastic differential cross section in mb/sr averaged over five regions in Λ lab momentum, (b) The Λp elastic differential cross section in mb/(GeV/c)^2 of momentum transfer squared averaged over the same five regions of lab momentum.

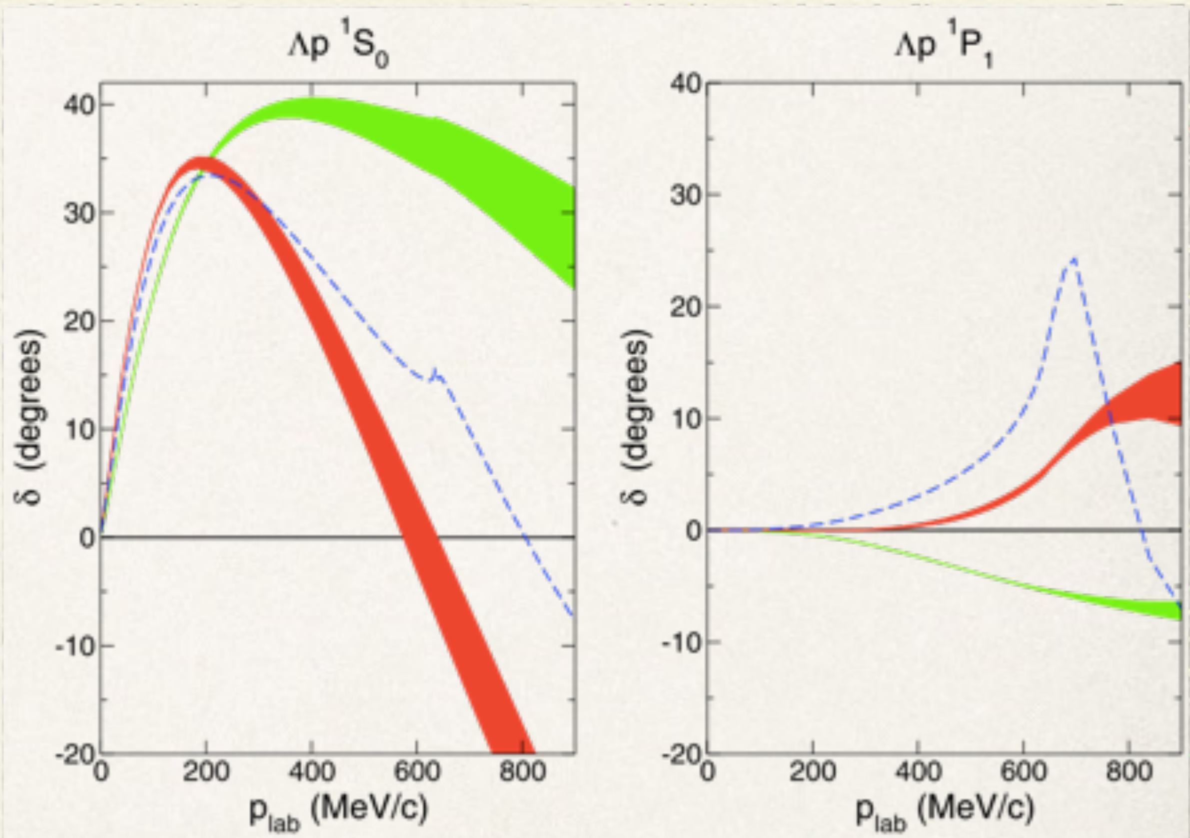
J. M Hauptman, *et al.* Nucl. Phys. B125, (1977) 29

ΛN interaction: short range part(unknown)

Lattice QCD calculation
for ΛN interaction.

Chiral model based calculation.

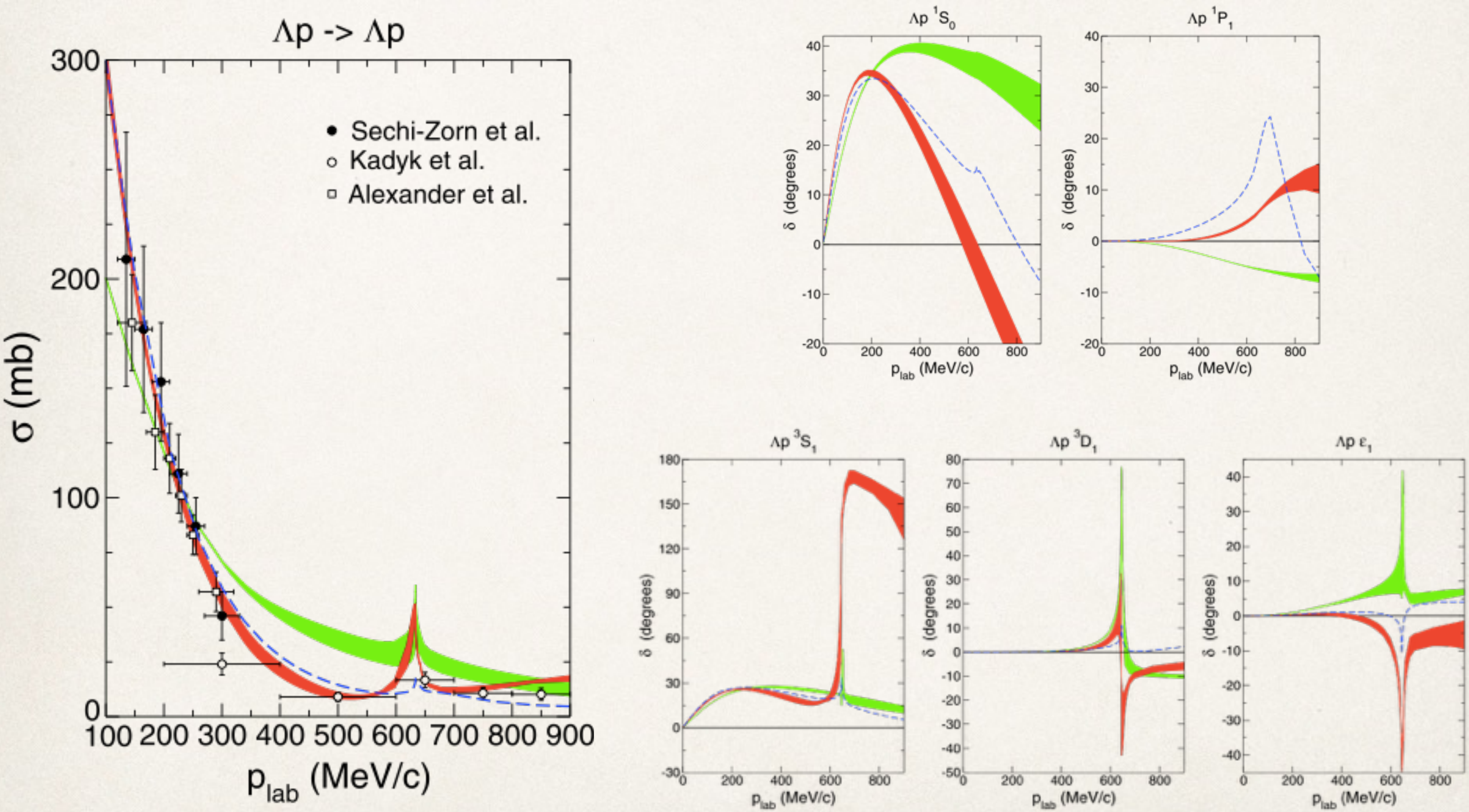




H. Nemura arXiv:1203.3320v1

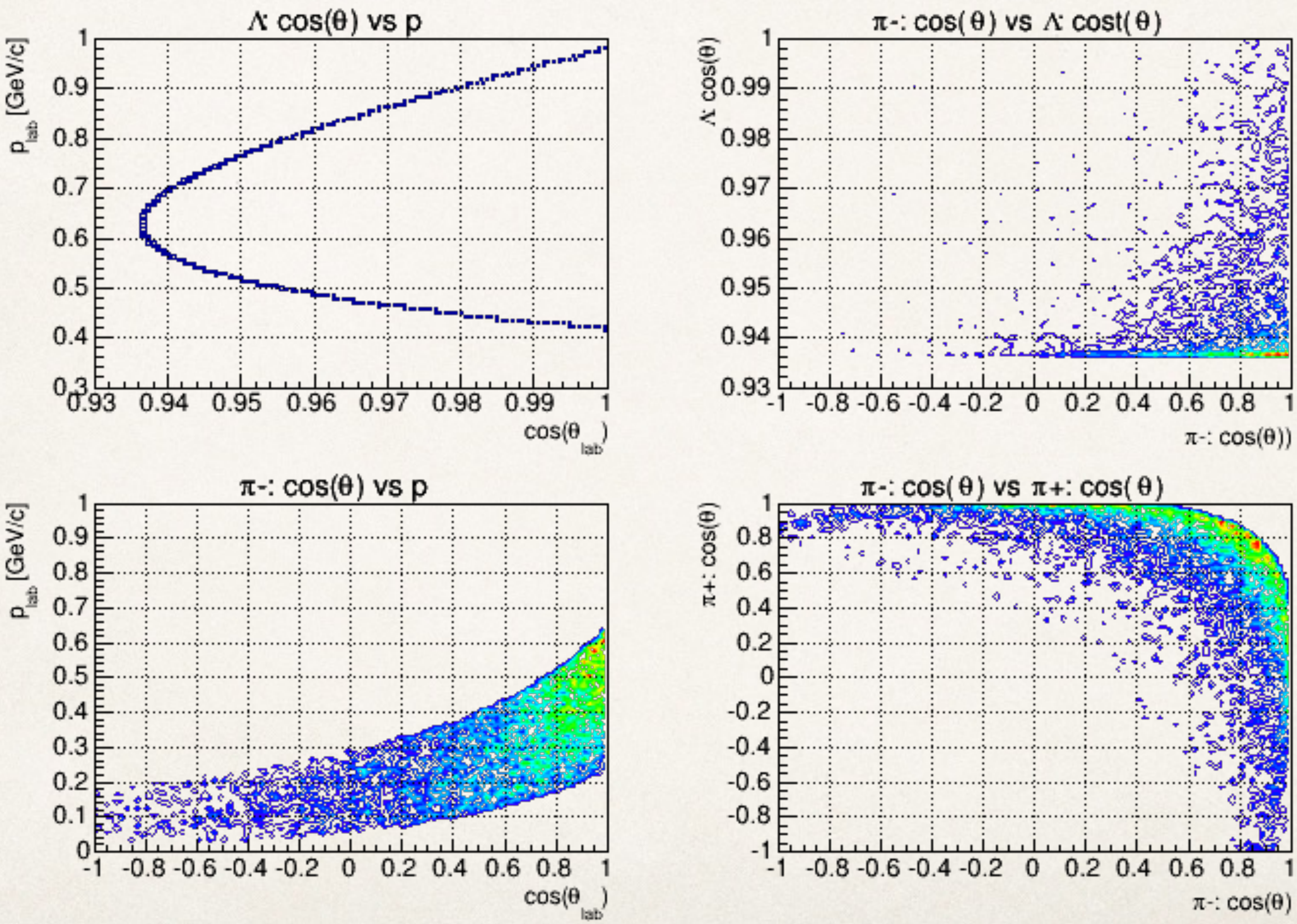
J. Haidenbauer et al. Nucl. Phys. A 915 (2013) 24

How to derive potential from Λp data?



J. Haidenbauer, ***et al.*** Nucl. Phys. A 915 (2013) 24

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



Detector concept & acceptance

Illustration of detector concept;

Acceptance: ~10%