Measurement of Hyperon-nucleon scatterings at J-PARC

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for the E40 collaboration

TOHOKU UNIVERSITY

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- Brief review of hyperon-proton scattering experiment
- Importance of hyperon-nucleon (YN) interaction study

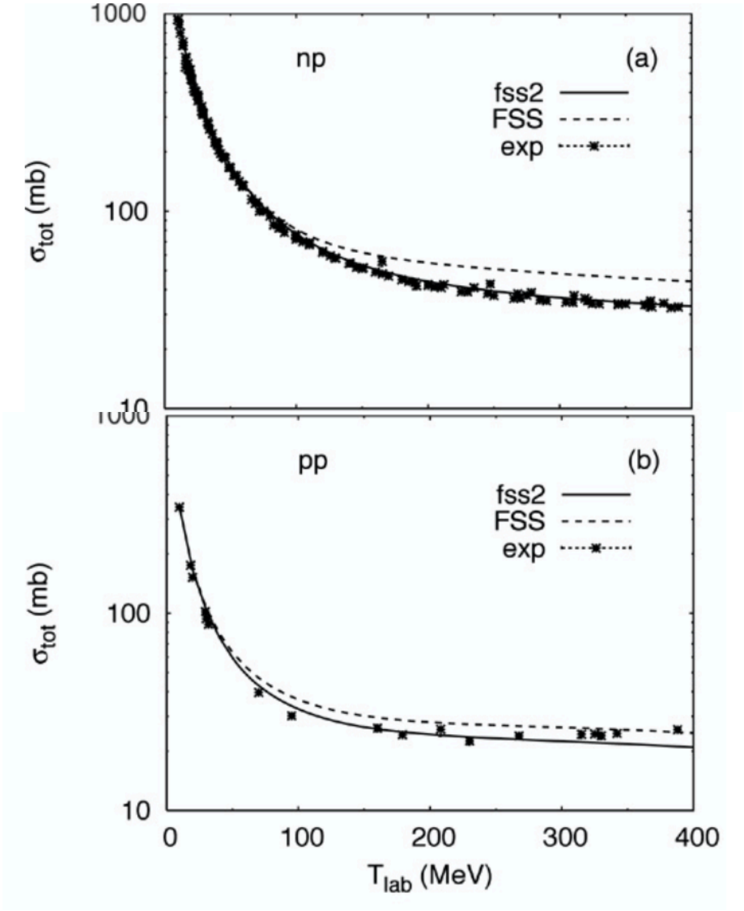
Σp scattering experiment at J-PARC

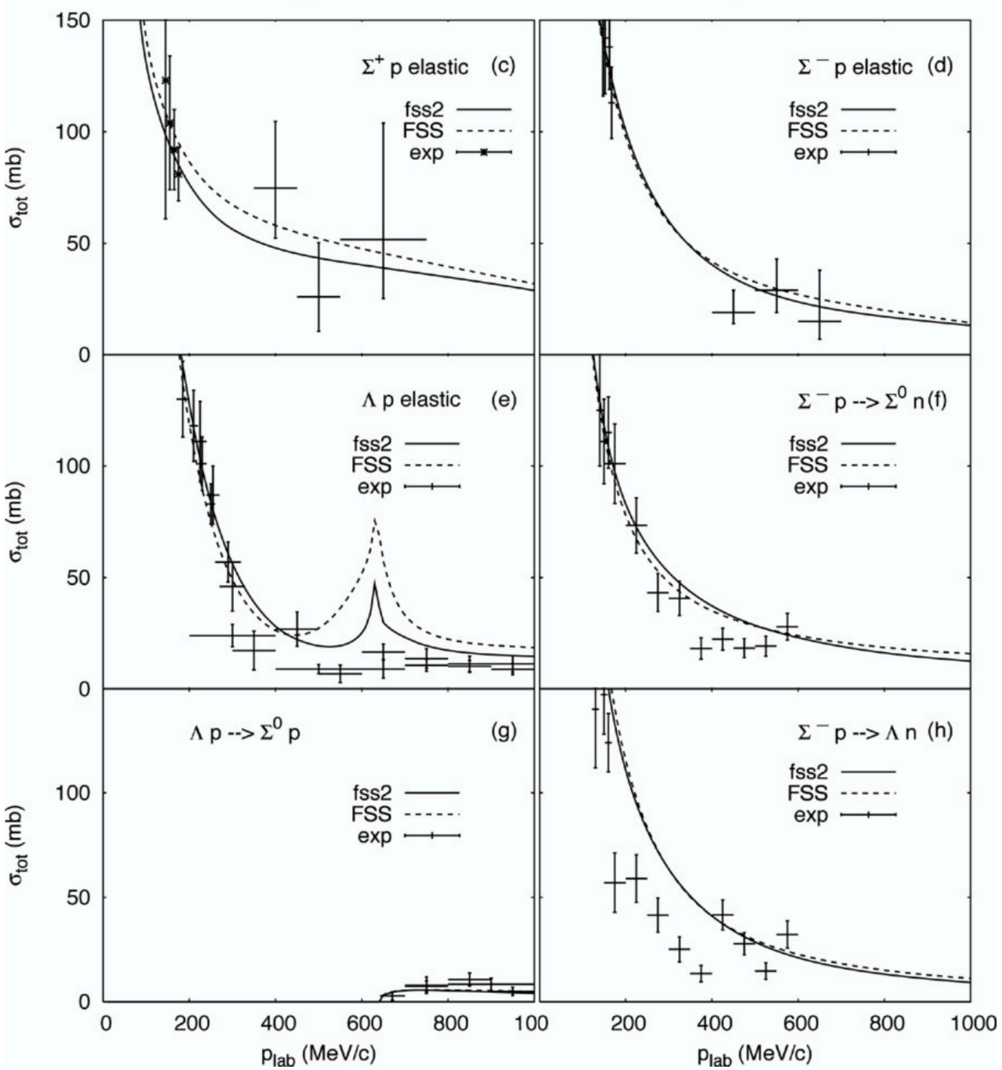
- Analysis status of scattering channels
- Prospects of spin observables

Future prospect on Λp scattering

NN AND YN SCATTERING DATA

Y. Fujiwara, Y. Suzuki, C. Nakamoto, Prog. Part. Nucl. Phys. 58 (2007) 439





Rich data of pp, np scattering.
→ Fundamental information to construct realistic model of nuclear force.

For YN case, data quality and quantity are insufficient.

DIFFICULTY OF YP SCATTERING (HYPERON BEAM)

Proton beam ($10^{12\sim13}$ particle / pulse)

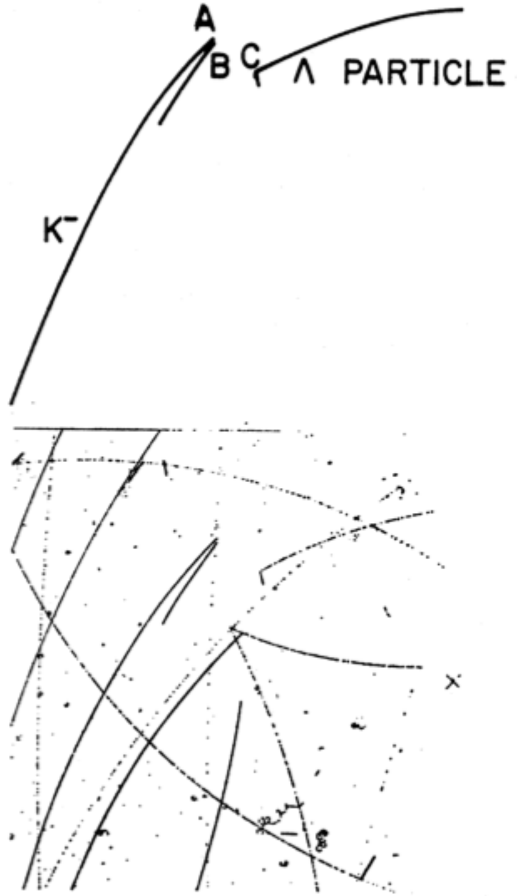
Secondary beam (π, K) (10^7 particle / pulse)

flight length : ~80 m

Third beam (Σ, Λ) (~100 particle / pulse) even in E40 experiment

flight length : ~1.2 cm

G. Alexander, et al. Phys. Rev. 173 (1968) 1452



In past experiment, imaging method was used to identify Yp scattering

STRATEGY OF HYPERNUCLEAR PHYSICS

Nuclear physics

Known nuclear force

Unknown nuclear structure

Hypernuclear physics

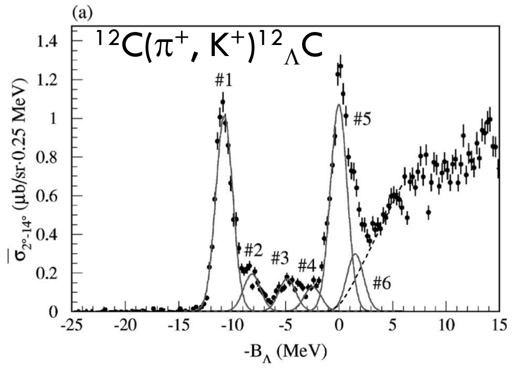
Unknown YN interaction

Hyperon proton scattering

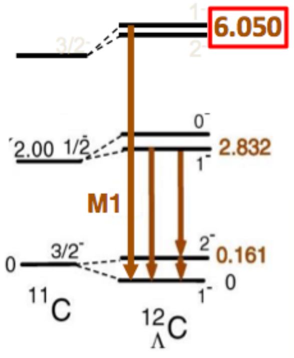
Lattice QCD

Theoretical framework extended to $SU_F(3)$ symmetry

Expect from hypernuclear structure



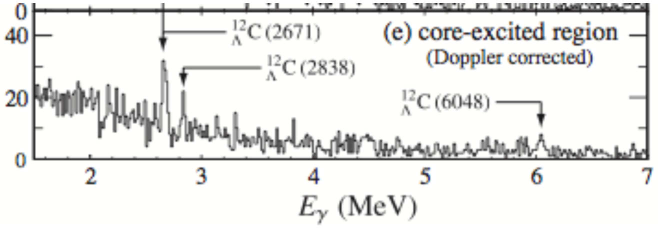
PRC 64 044302 (2001)

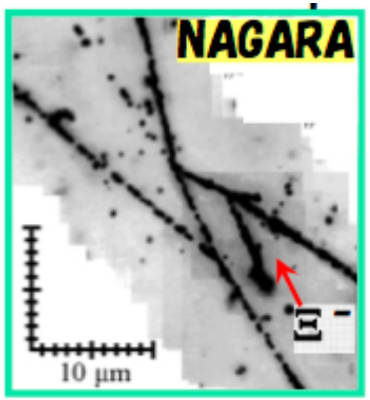


EPJ A33 (2007) 243

***PTEP* (2015) 081D01**

γ-ray spectroscopy





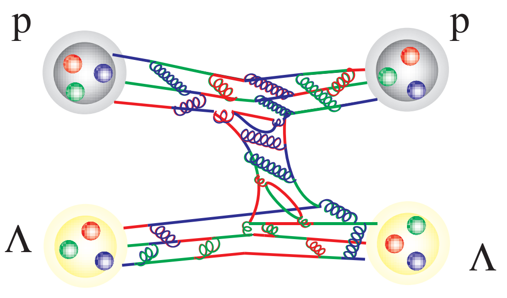
PRL 87 212502 (2001)

NEUTRON STAR AND YN INTERACTION

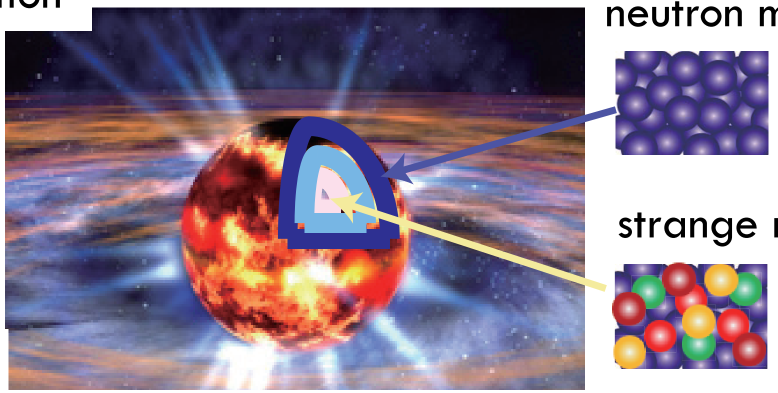
Two-body YN scattering is essential to understand the internal structure of neutron star.

- Interaction at short range
- Basic information to derive 3 body force from hypernuclear structure

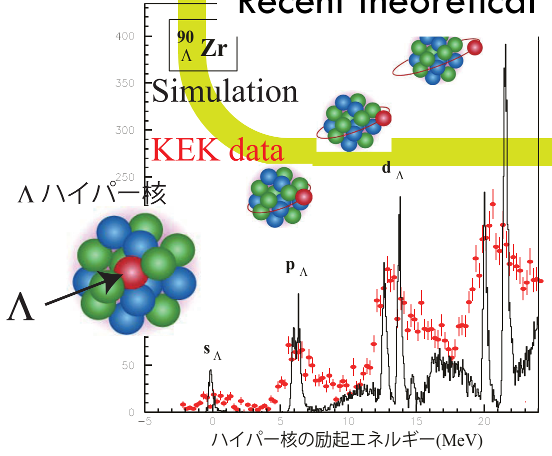
Hypernuclear physics based on Realistic YN interaction



YN scattering experiment
Lattice QCD
Recent theoretical framework

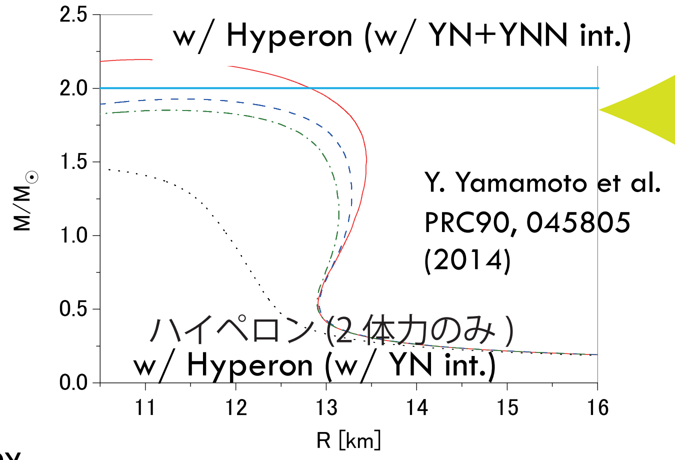


日本物理学会誌より
木内健太、関口雄一郎

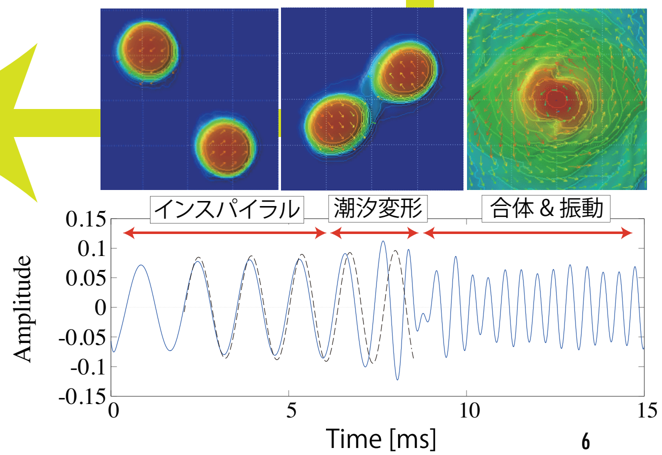


Ultra high-resolution Λ hypernuclear spectroscopy

EOS of neutron star



Gravitational wave from neutron star merger

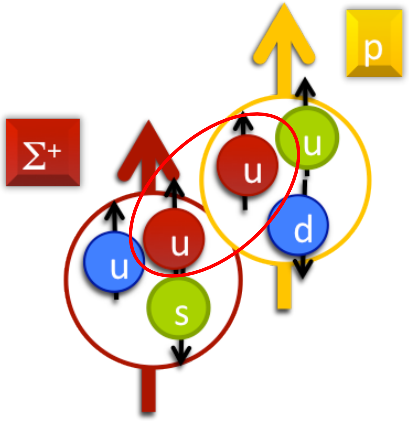


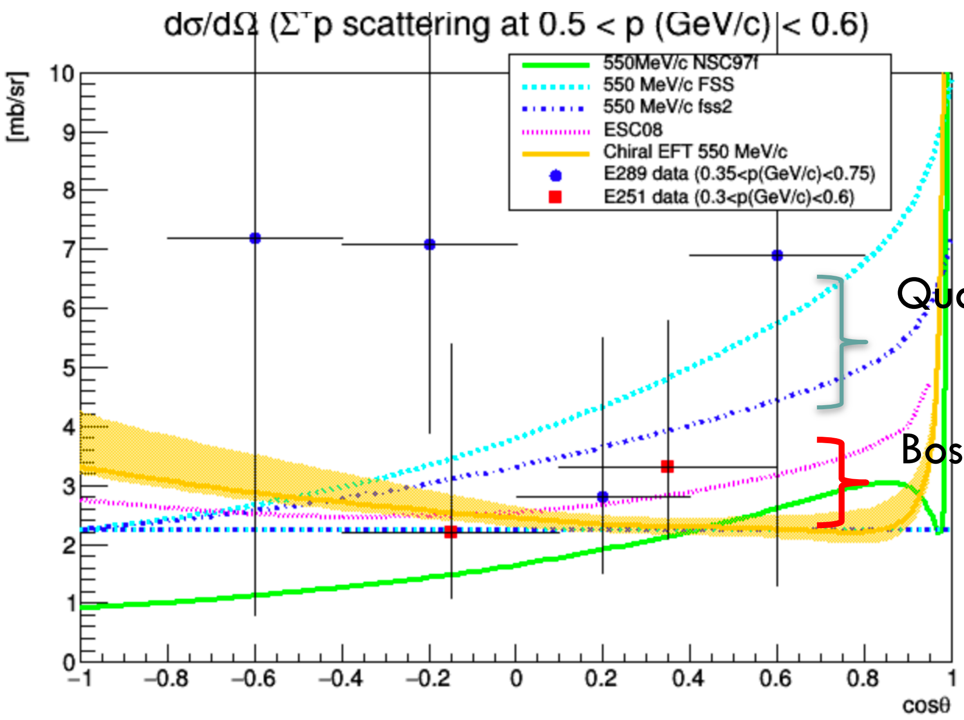
YN INTERACTION IN S=−1 SECTOR

	^1E or ^3O	^3E or ^1O
NN (I=0)	------	(27)
NN (I=1)	(10*)	-----
ΛN (I=1/2)	$1/\sqrt{10}[(8_s) + 3(27)]$	$1/\sqrt{2}[-(8_a) + (10^*)]$
ΣN(I=1/2)	$1/\sqrt{10}[3(8_s) - (27)]$	$1/\sqrt{2}[(8_a) + (10^*)]$
ΣN(I=3/2)	(27)	(10)

Pauli effect in quark level

Large repulsive core is expected in quark based model (Lattice QCD)

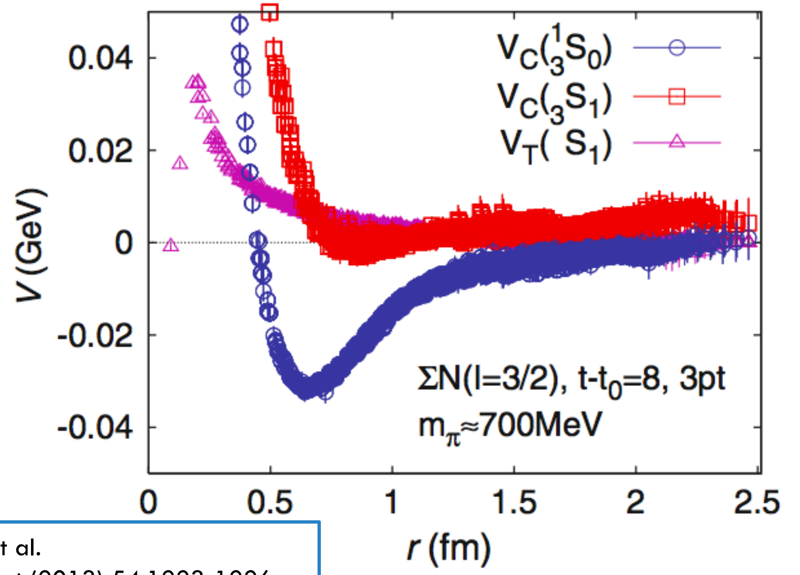




Quark based model : Large dσ/dΩ

Boson exchange model : Moderate dσ/dΩ

Σ^+p potential by Lattice QCD



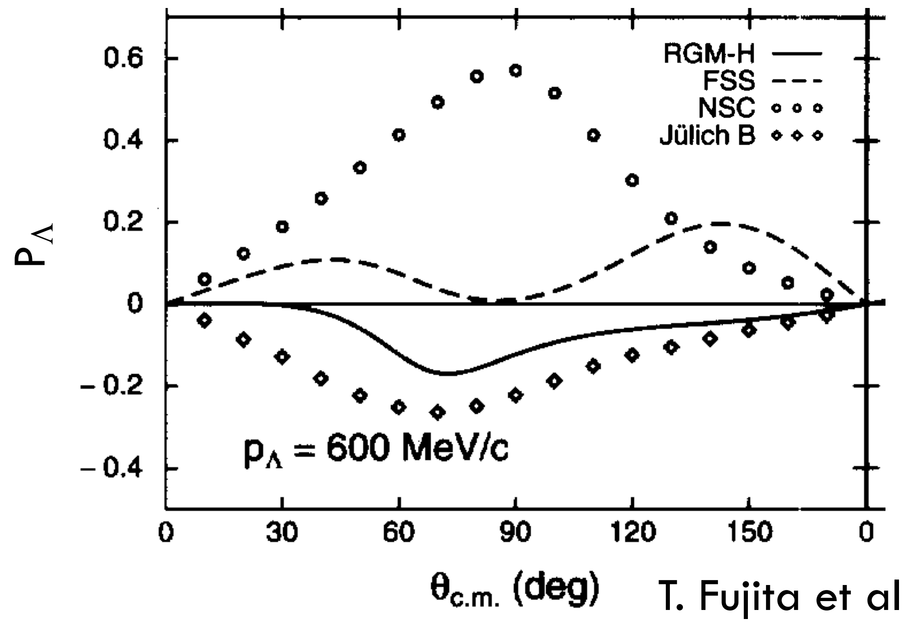
H. Nemura et al.
Few-Body Syst (2013) 54:1223-1226

YN INTERACTION IN S=−1 SECTOR

	^1E or ^3O	^3E or ^1O
NN (I=0)	Forbidden by isospin symmetry	(27)
NN (I=1)	(10*)	-----
ΛN (I=1/2)	$1/\sqrt{10}[(8_s) + 3(27)]$	$1/\sqrt{2}[-(8_a) + (10^*)]$
ΣN(I=1/2)	$1/\sqrt{10}[3(8_s) - (27)]$	$1/\sqrt{2}[(8_a) + (10^*)]$
ΣN(I=3/2)	(27)	(10)

$LS^{(-)}$ OK

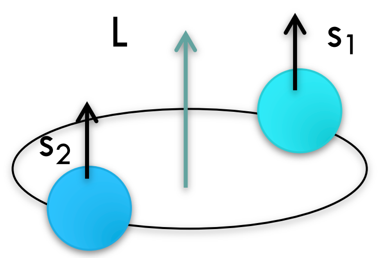
Polarization of Λ in Λp elastic scattering



T. Fujita et al., PTP 100 (1998) 931

New type of LS force appears in YN sector

Anti-symmetric $LS^{(-)}$ force : $V_{ALS} L \cdot (s_1 - s_2)$



Spin singlet $\xleftrightarrow{LS^{(-)}}$ Spin triplet

- Quark based model
  - Large ALS originated from coupling between (8s) and (8a) by one gluon exchange
- Boson exchange model
  - No large ALS contribution

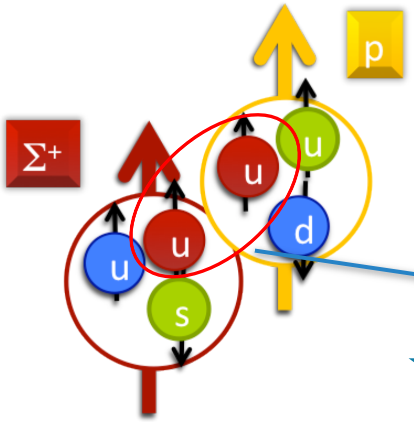
Difference theoretical prediction

- Polarization, Analyzing power
- Cross section

J-PARC E40 :
Measurement of $d\sigma/d\Omega$ of Σp scatterings

Physics motivations

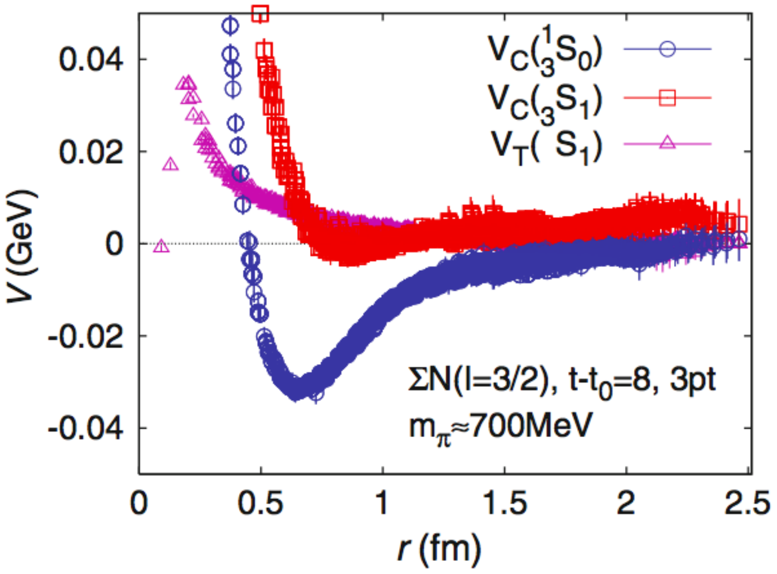
- Verification of repulsive force due to quark Pauli effect in the Σ^+p channel
- Systematic study of the ΣN interaction by separating isospin channel



Pauli effect in quark level

Large repulsive core is expected in Lattice QCD

Σ^+p potential by Lattice QCD



Large $d\sigma/d\Omega$ is predicted in Σ^+p channel

Measurement of $d\sigma/d\Omega$

Aim to detect 10,000 events

- Σ^+p elastic scattering
- Σ^-p elastic scattering
- $\Sigma^-p \rightarrow \Lambda n$ inelastic scattering

H. Nemura et al.
Few-Body Syst (2013) 54:1223-1226

Collaborators

Tohoku Univ. : T. Aramaki, N. Chiga, N. Fujioka, M. Fujita, R. Honda, M. Ikeda, Y. Ishikawa, H. Kanauchi, S. Kajikawa, T. Kitaoka, T. Koike, K. Matsuda, Y. Matsumoto, K. Miwa, S. Ozawa, T. Rogers, T. Sakao, T. Shiozaki, H. Tamura, J. Yoshida H. Umetsu, S. Wada

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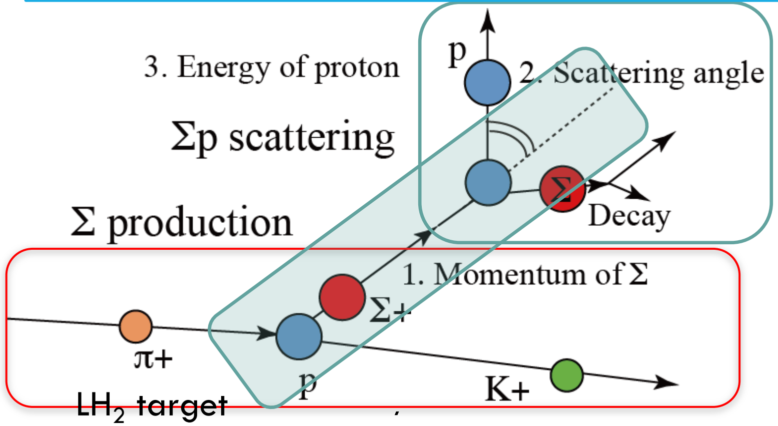
OMEGA Ecole Polytechnique-CNRS/IN2P3 : S. Callier, C.d.L. Taille, L. Raux

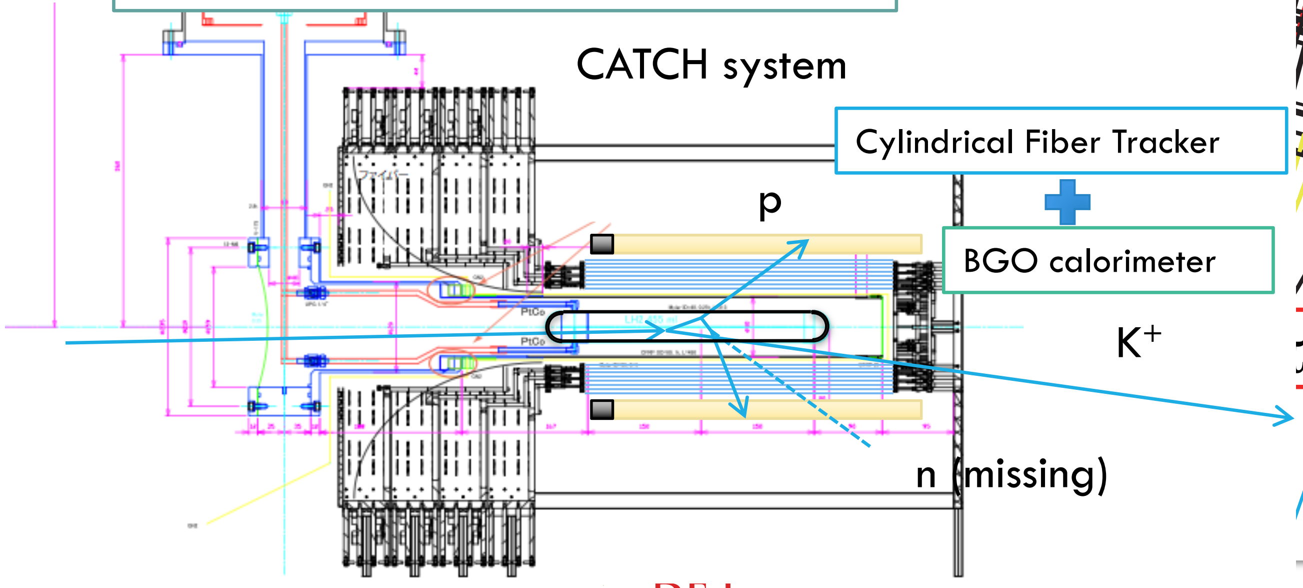
Joint Institute for Nuclear Research : P. Evtoukhovitch, Z. Tsamalaidze

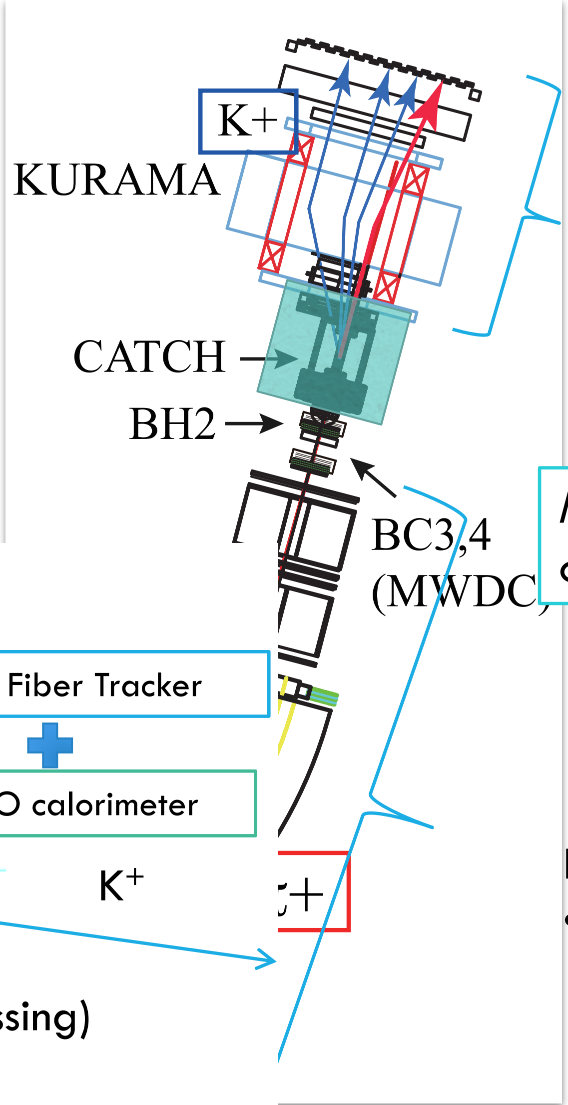
E40 EXPERIMENTAL SETUP

Two successive two-body reactions



Detection of Σp scattering event by CATCH detector





KURAMA spectrometer

- Identification of K^+
- Momentum analysis

Momentum reconstruction of Σ beam

Beamline spectrometer

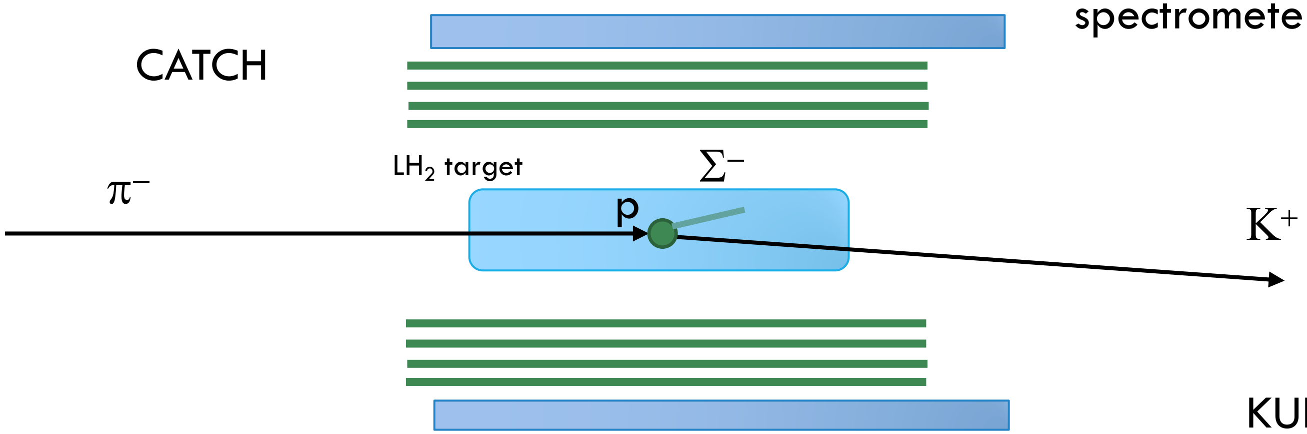
- Momentum analysis of π beam

J-PARC K1.8 beamline

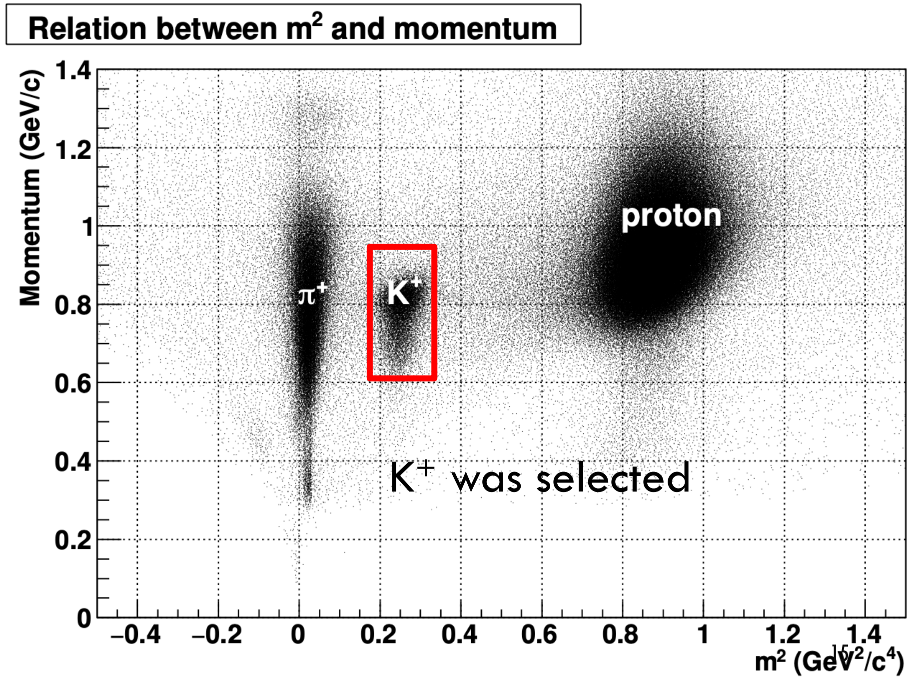
DATA ANALYSIS

Σ beam identification

Σ beam in LH_2 target is tagged by the magnetic spectrometers

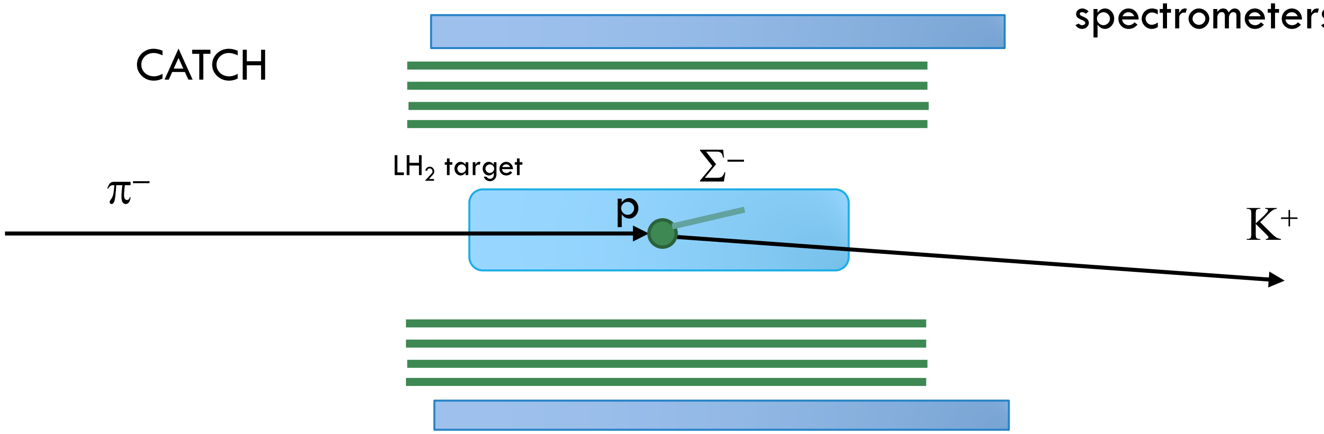


KURAMA spectrometer analysis

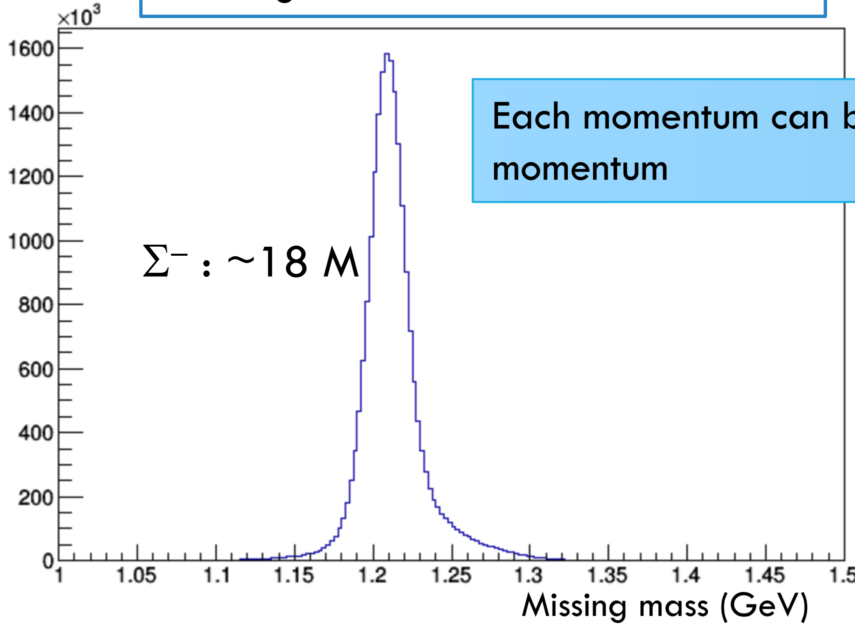


Σ beam identification

Σ beam in LH_2 target is tagged by the magnetic spectrometers

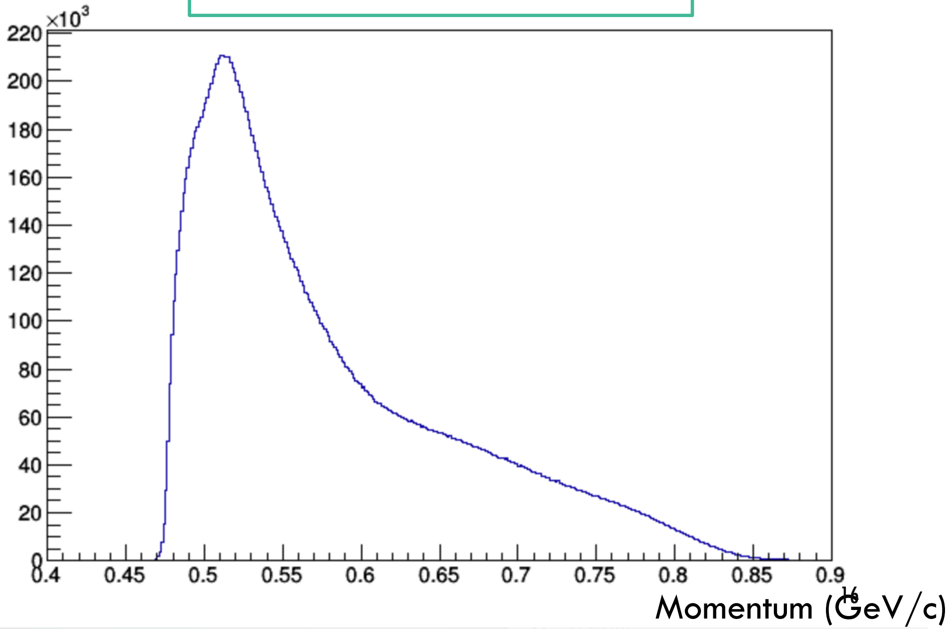


Missing mass from π^- and K^+

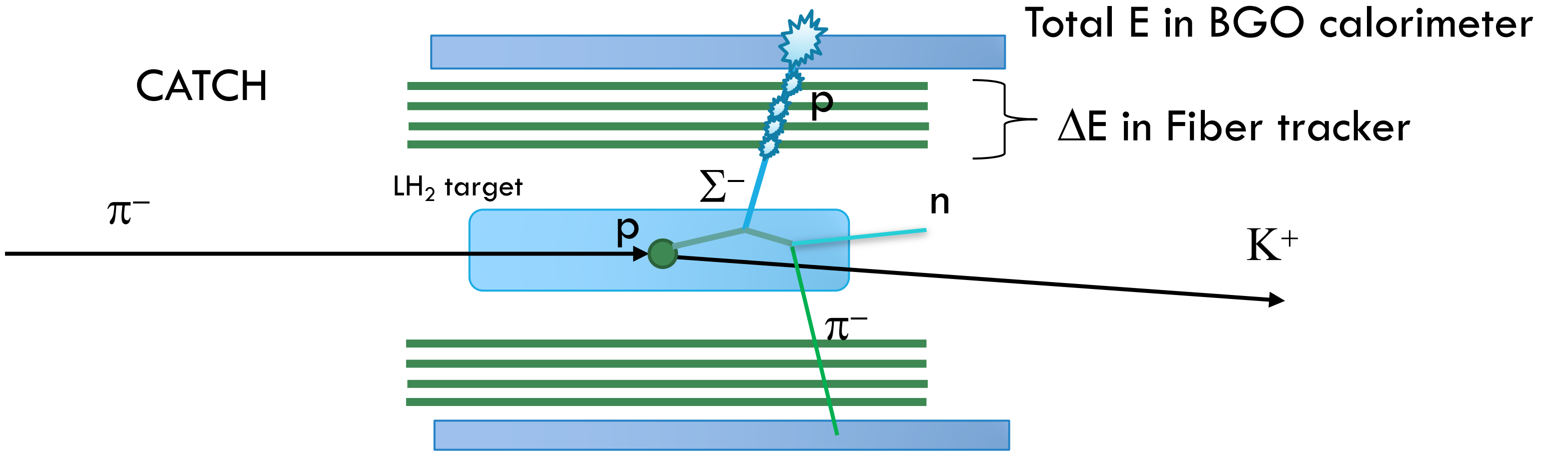


Each momentum can be reconstructed from missing momentum

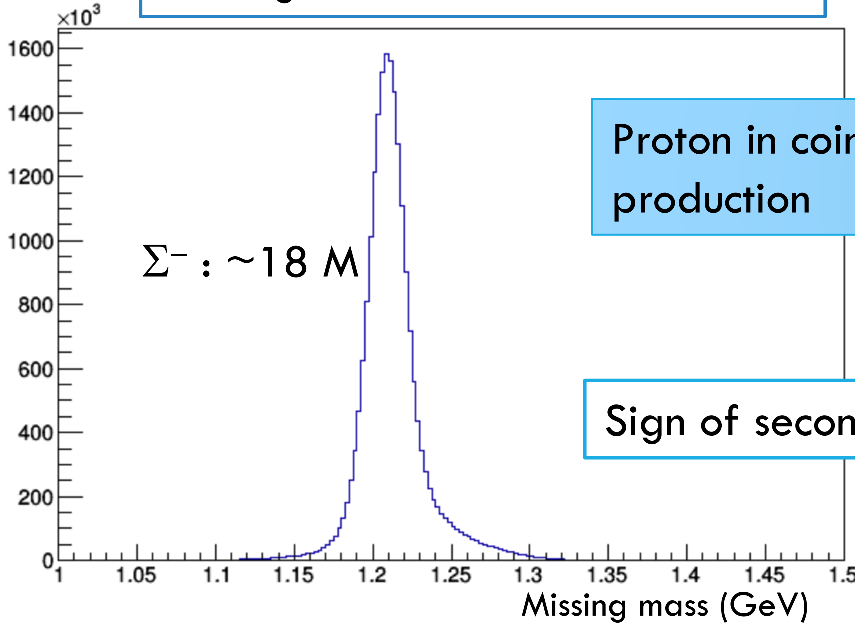
Σ^- beam momentum



Recoil proton identification



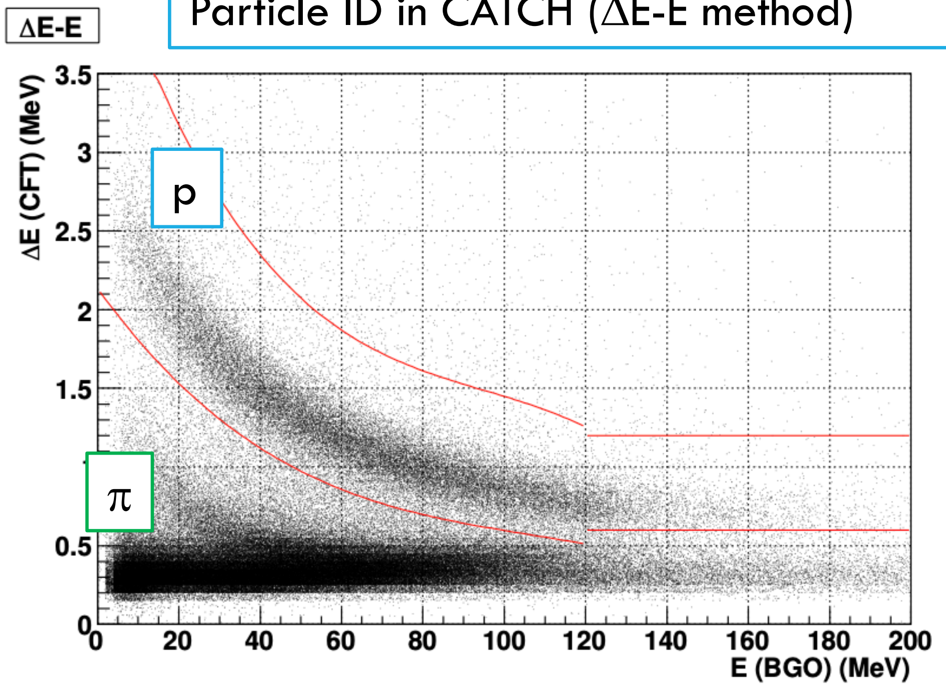
Missing mass from π⁻ and K⁺



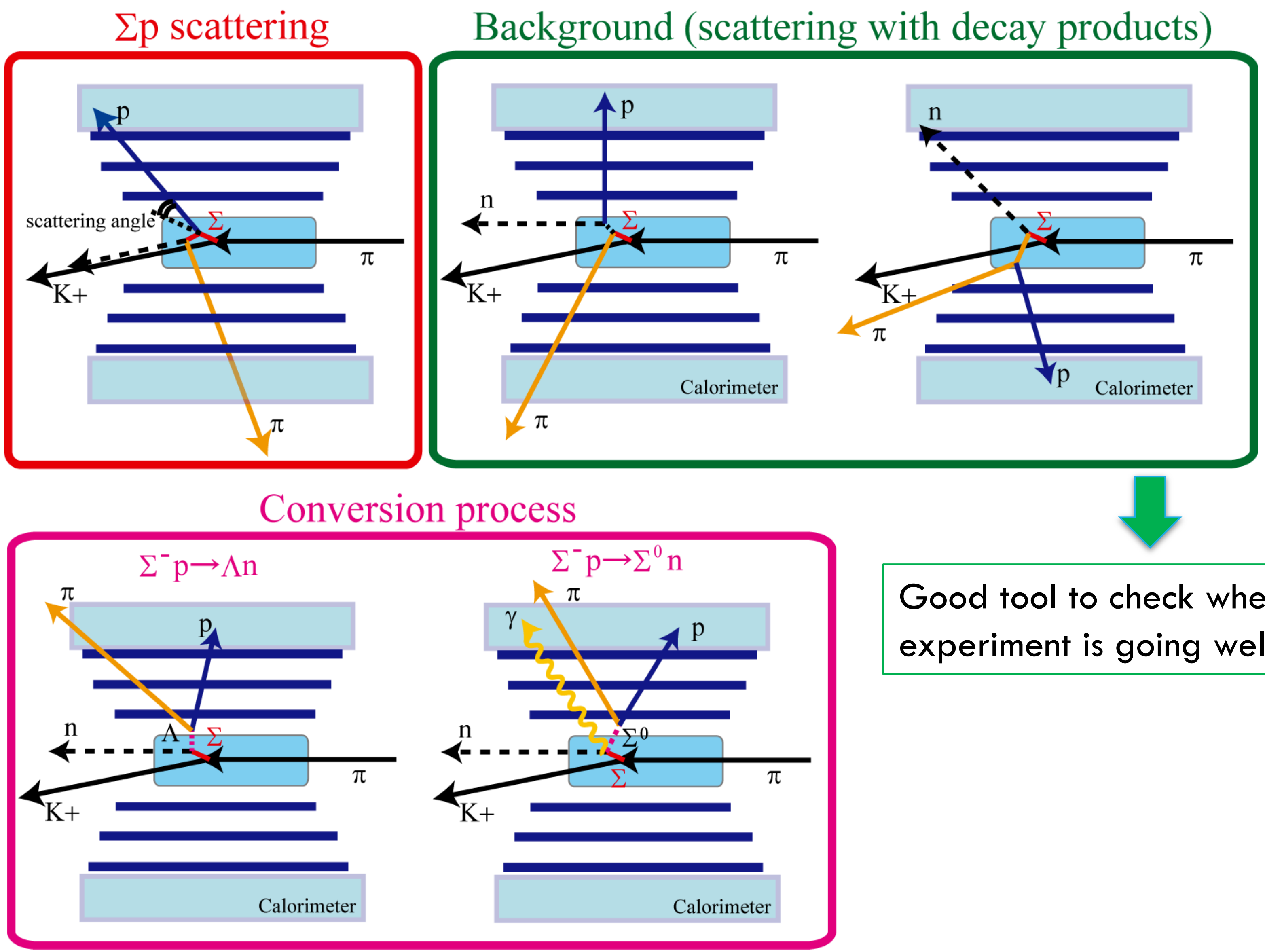
Proton in coincidence with Σ⁻ production

Sign of secondary reactions

Particle ID in CATCH (ΔE-E method)

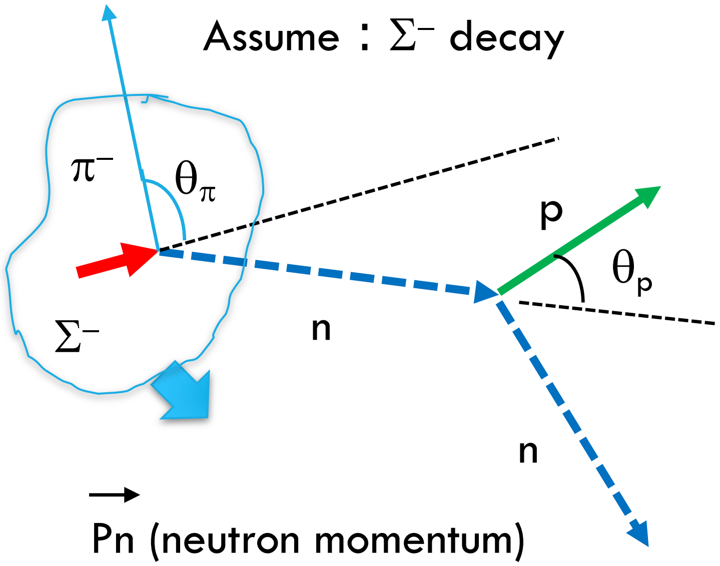


Proton event in Σ^- production



Good tool to check whether our experiment is going well or not.

Identification of np scattering from Σ^- decay



Assume np scattering kinematics

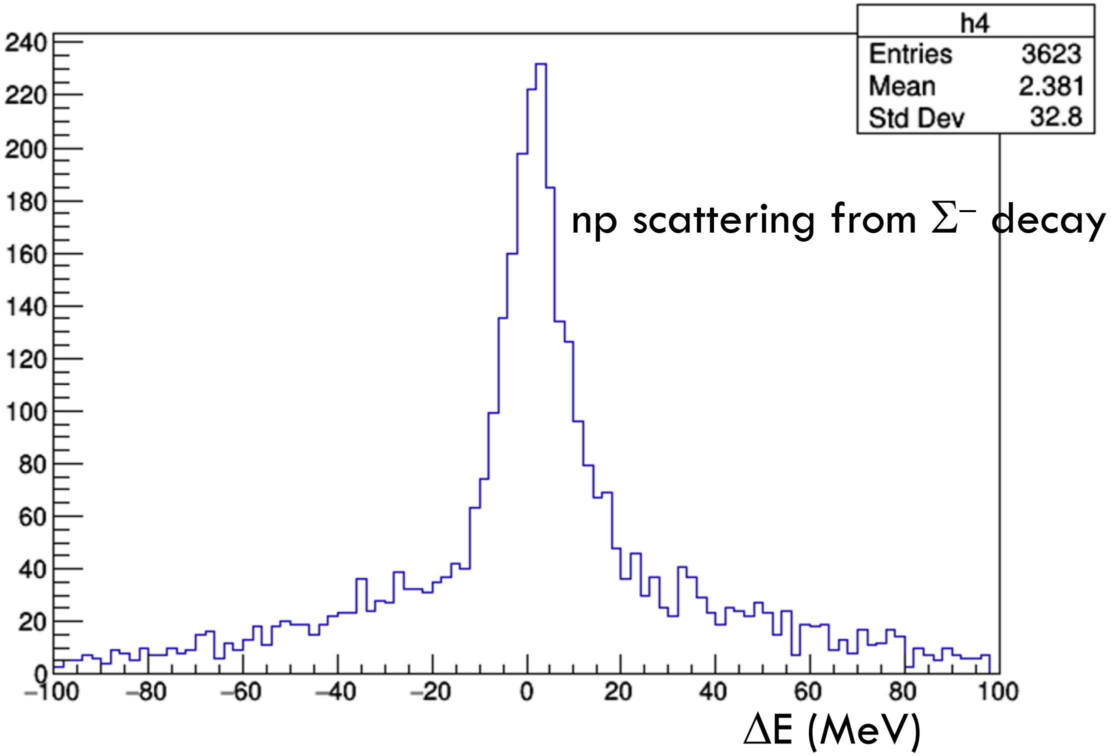
Ecalc (θp)

compare

$\Delta E(np) = E_{calc} - E_{measure}$

Emeasure

ΔE (np) distribution

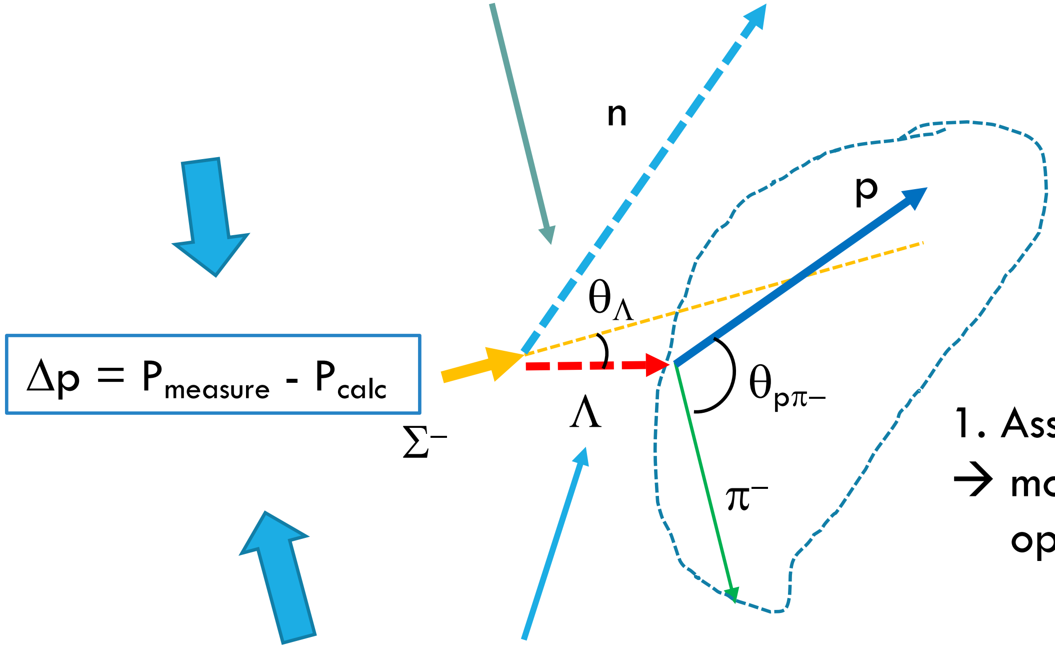


Identification with two successive reaction was possible

- Σ^- production
- Rescattering of Σ^- decay product

Identification of $\Sigma^{-}p \rightarrow \Lambda n$ conversion

3. From Scattering angle of Λ, momentum of scattered Λ can be calculated. (P_{calc})

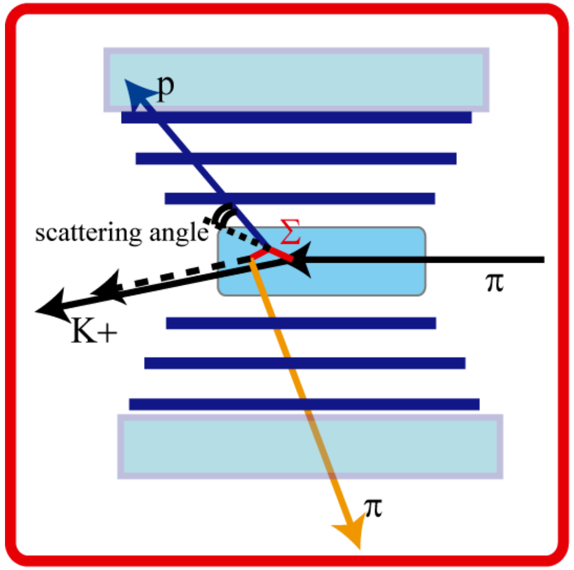


1. Assume π^{-} is emitted from Λ decay.
→ mom. of $\pi-$ can be calculated from opening angle ($\theta_{p\pi-}$).

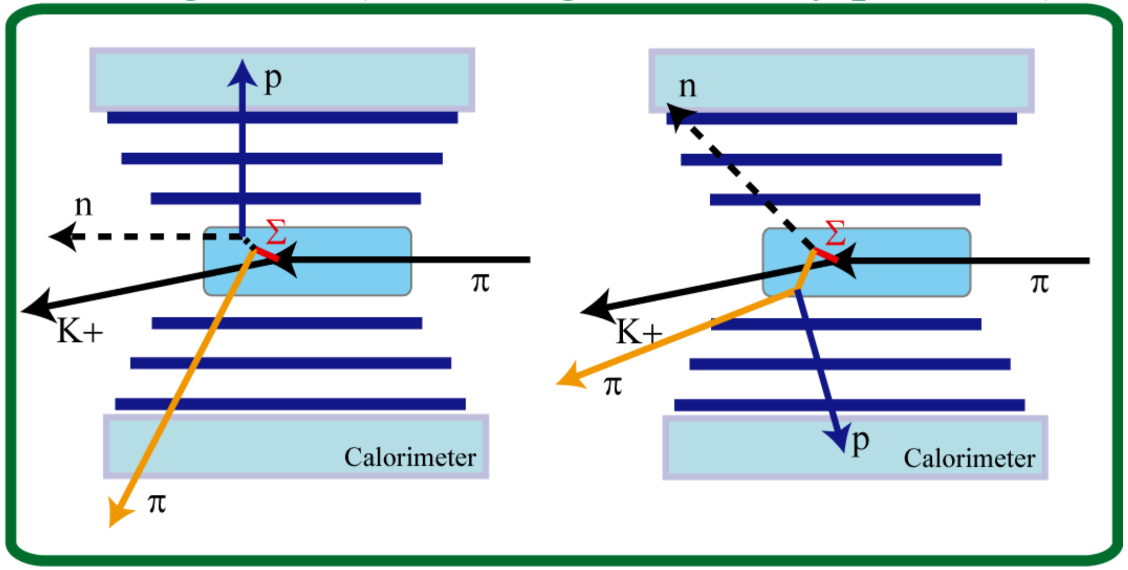
2. Mom. of Λ can be reconstructed. ($P_{measure}$)

Proton event in Σ^- production

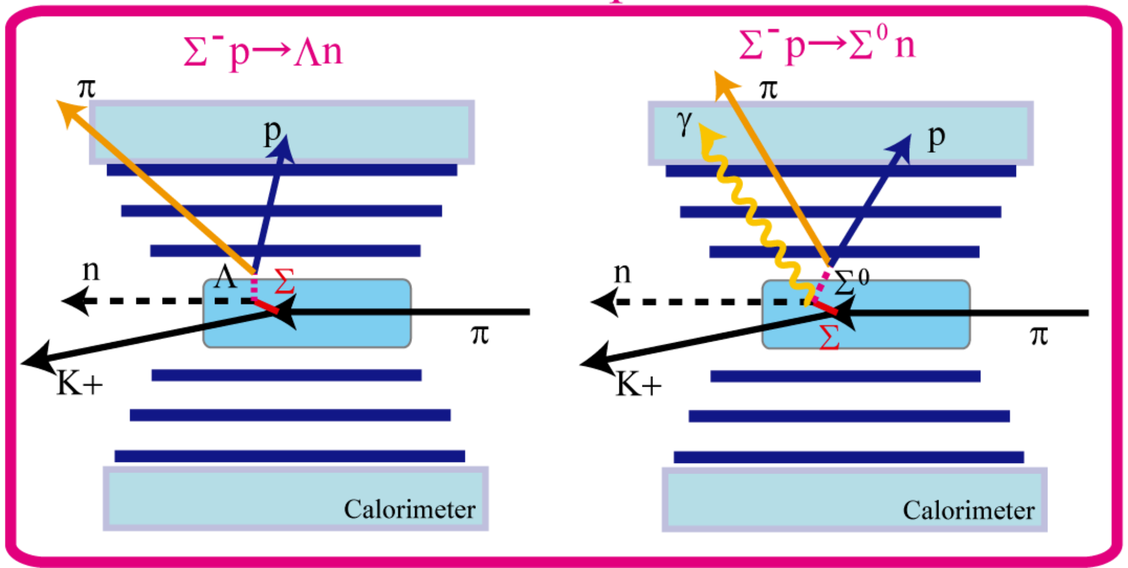
Σp scattering



Background (scattering with decay products)

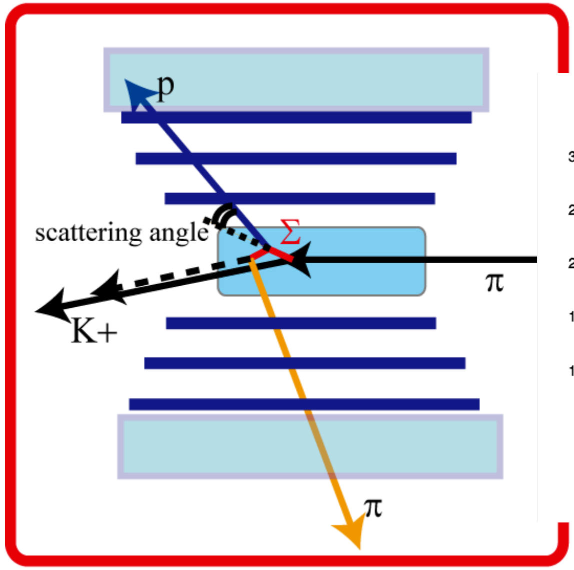


Conversion process

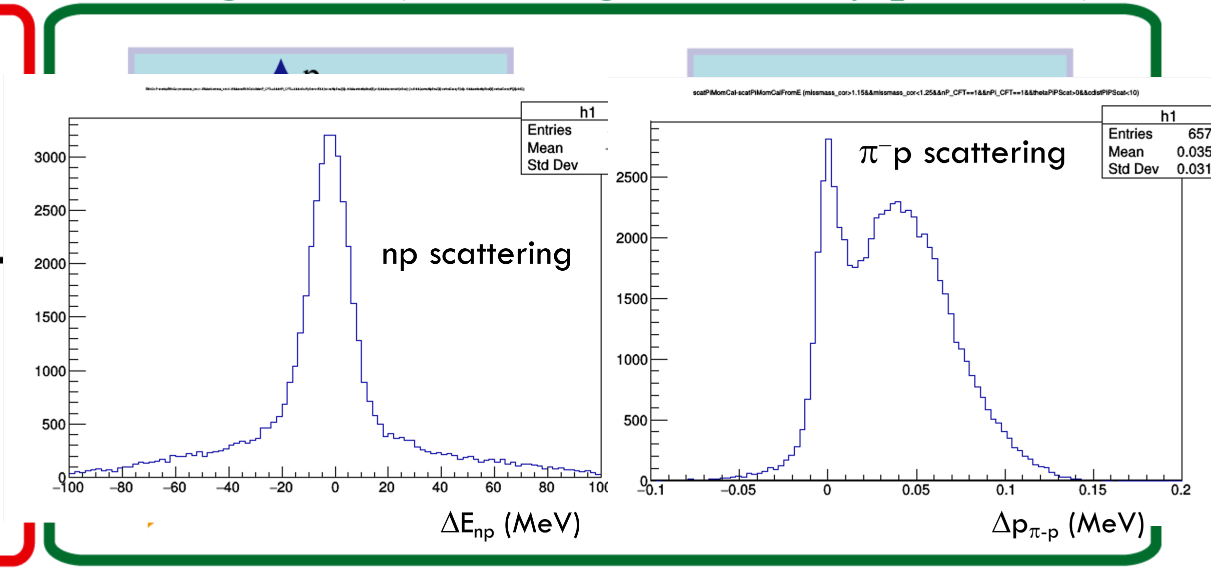


Proton event in Σ^- production

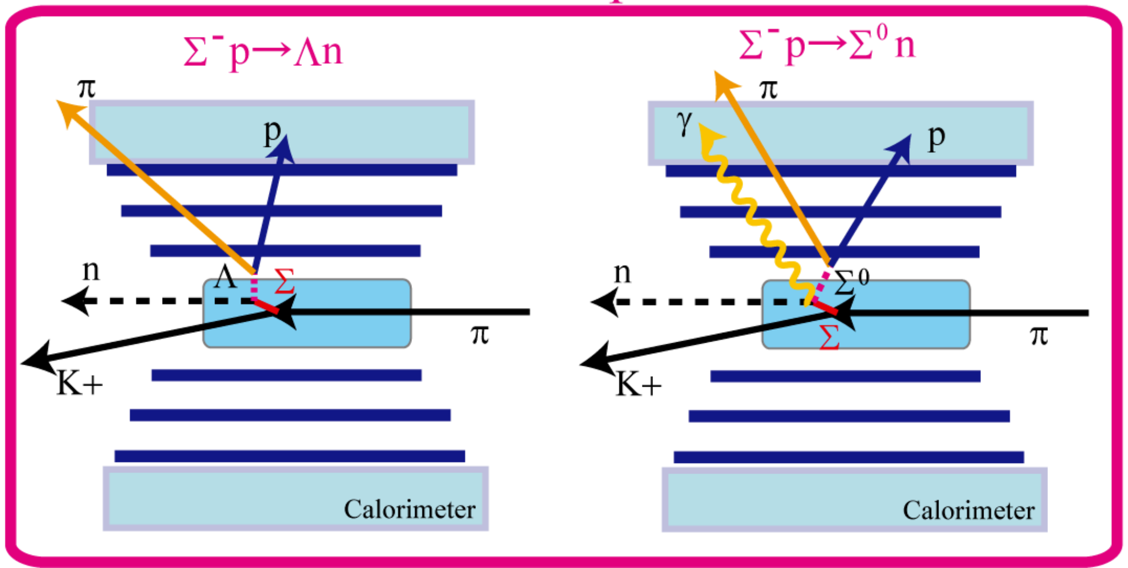
Σp scattering



Background (scattering with decay products)

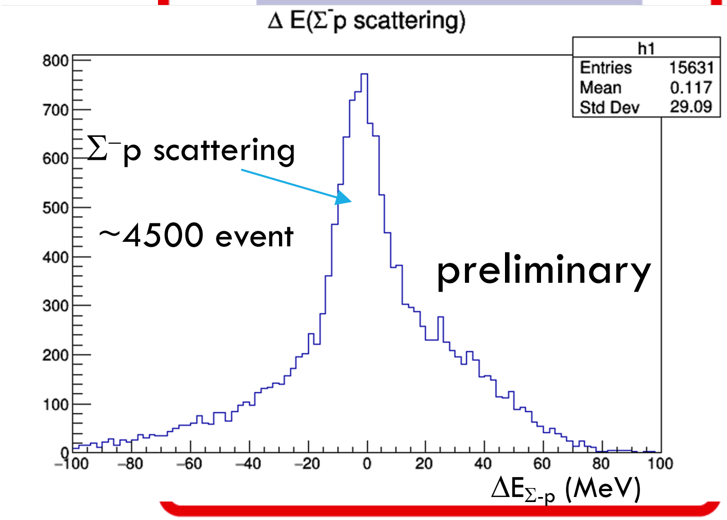


Conversion process

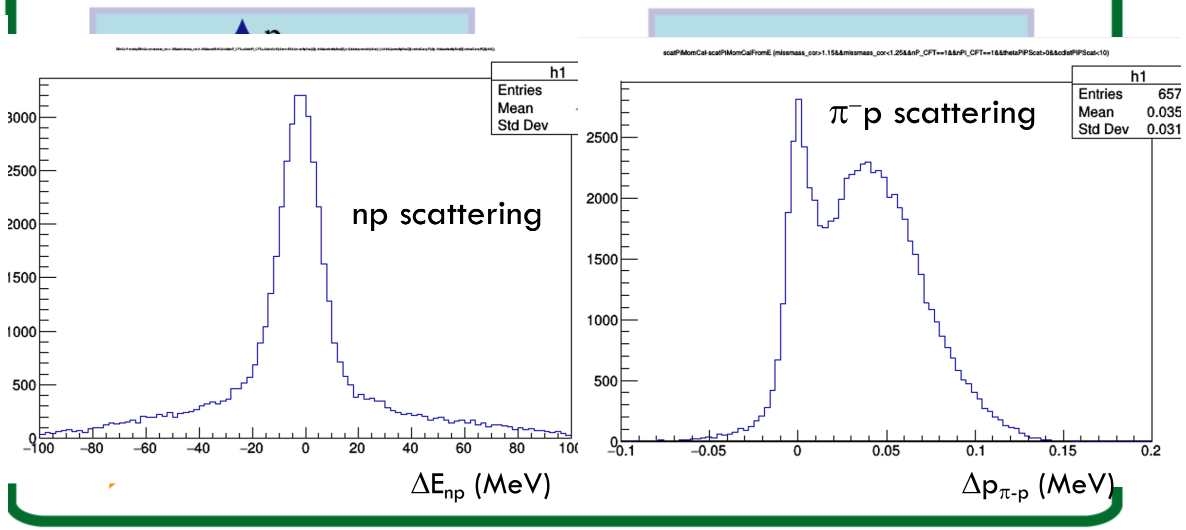


Proton event in Σ^- production

Σp scattering

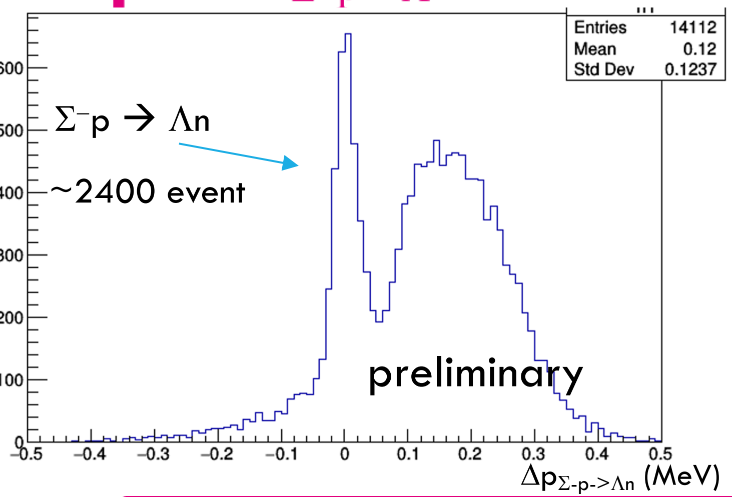


Background (scattering with decay products)

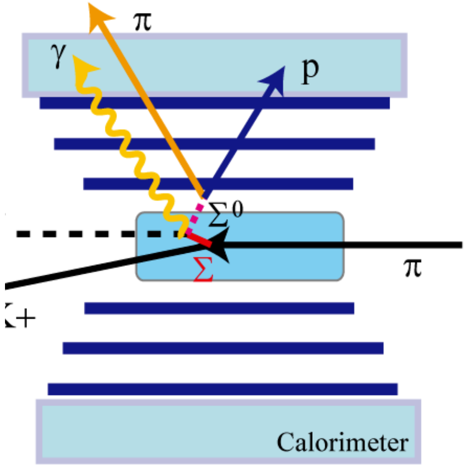


Conversion process

$\Sigma^- p \rightarrow \Lambda n$



$\Sigma^- p \rightarrow \Sigma^0 n$



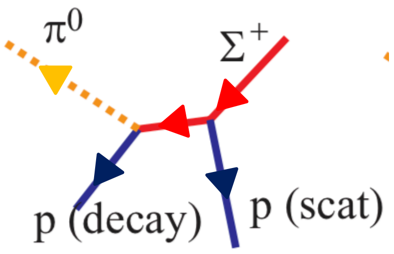
np scattering is good tool to check our systematics to measure $d\sigma/d\Omega$

We derive $d\sigma/d\Omega$ for np scattering

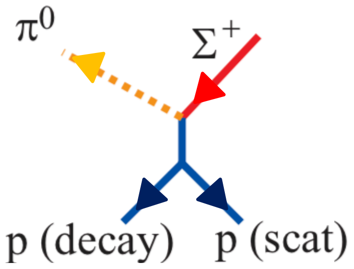
Σ^+p analysis

Analysis by T. Nanamura (Kyoto Univ.)

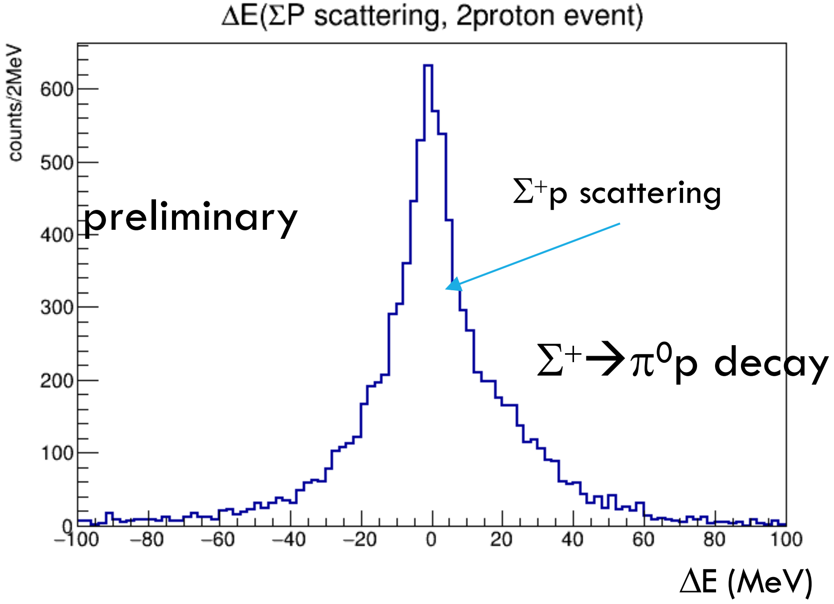
Σ^+p scattering

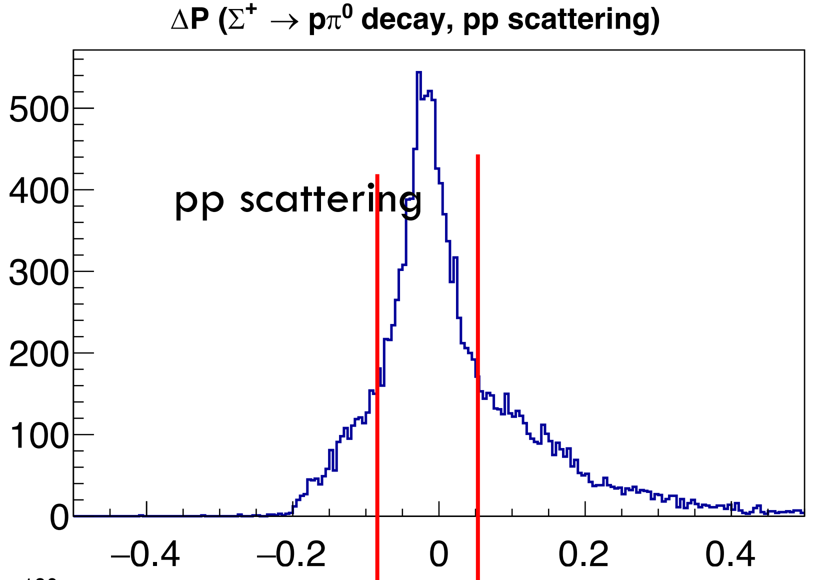


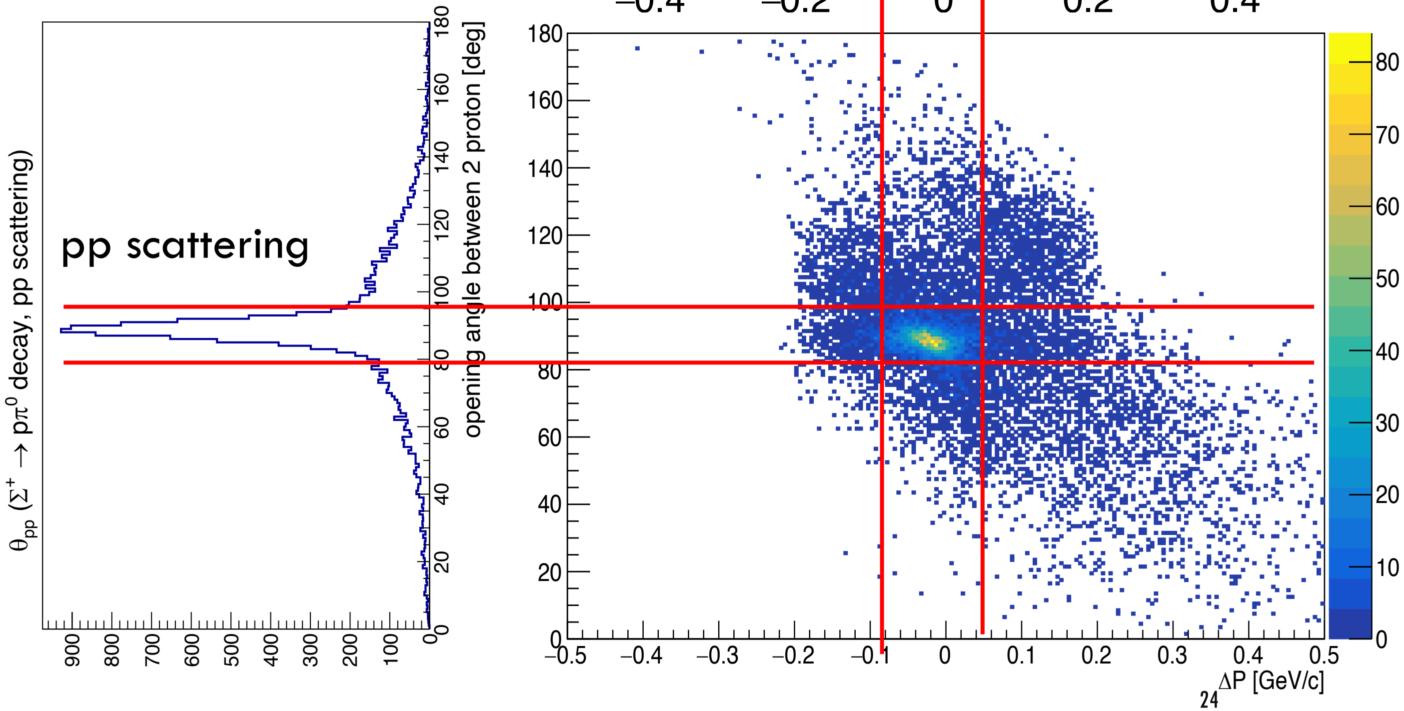
pp scattering from Σ^+ decay



Σ^+p scattering event ~4500







Summary of E40 scattering channel

pp scattering (CATCH detector calibration) with proton beam

- p momentum 0.5, 0.55, 0.6, 0.65, 0.75, 0.85 GeV/c

np scattering from $\Sigma^- \rightarrow n\pi^-$ decay

- $0.3 < p_n$ (GeV/c) < 0.6

$\Sigma^- p$ elastic scattering

- $0.45 < p_{\Sigma-}$ (GeV/c) < 0.8
- ~4,500 events

$\Sigma^- p \rightarrow \Lambda n$ scattering

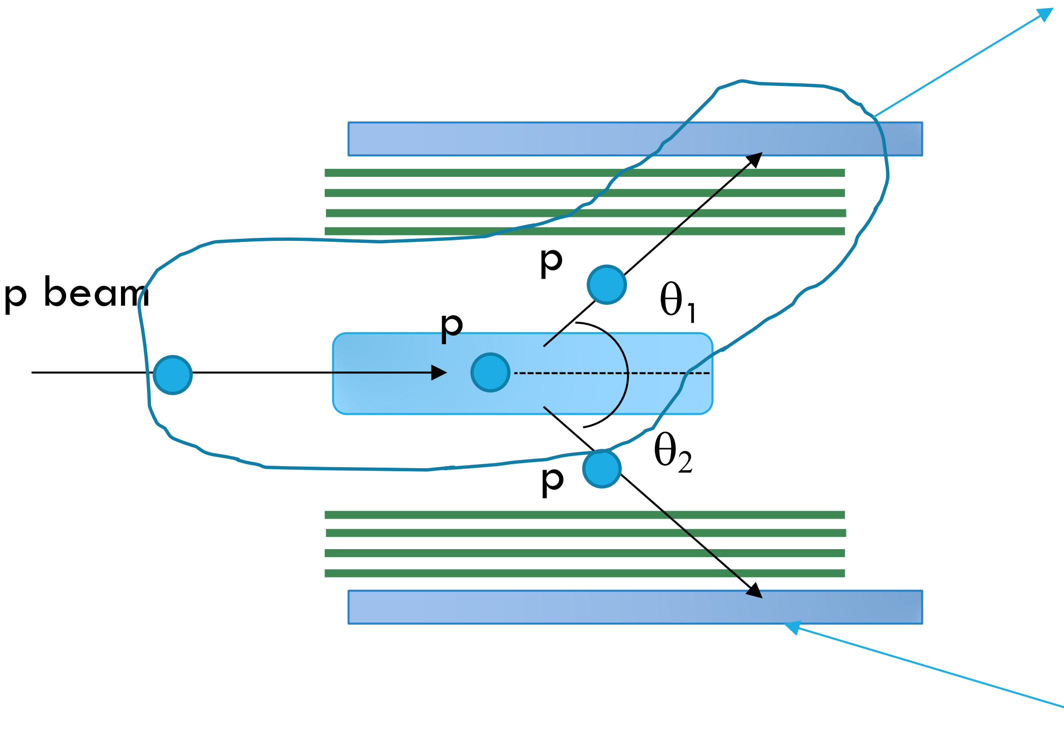
- $0.45 < p_{\Sigma-}$ (GeV/c) < 0.8
- ~2,500 events

$\Sigma^+ p$ elastic scattering

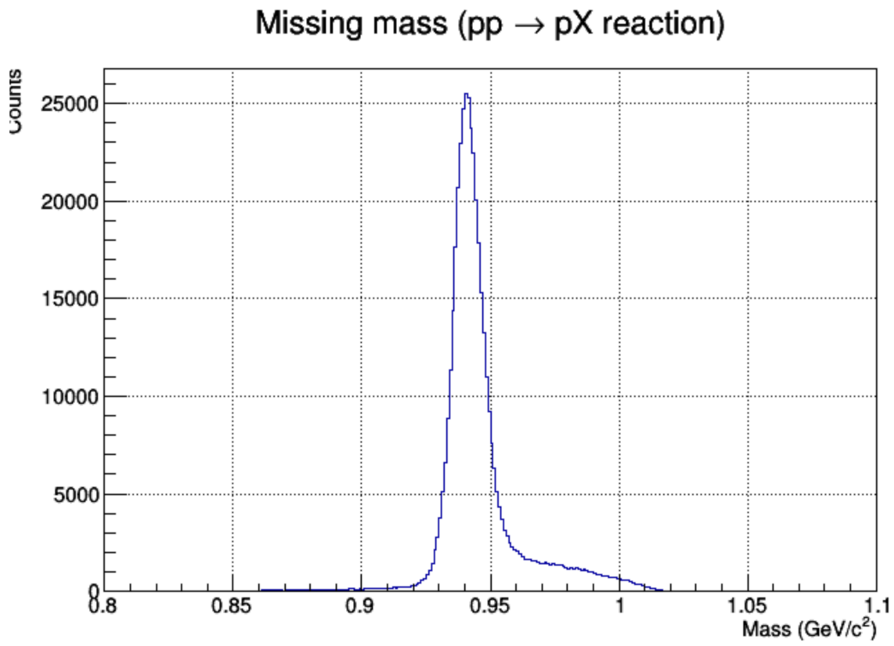
- $0.4 < p_{\Sigma+}$ (GeV/c) < 0.8
- ~4,500 events ($\Sigma^+ \rightarrow p\pi^0$ decay mode)
- ~3,500 events ($\Sigma^+ \rightarrow n\pi^+$ decay mode)

Efficiency for recoil proton in pp scattering

pp scattering
@ 0.45, 0.5, 0.55, 0.6, 0.65, 0.75, 0.85 GeV/c



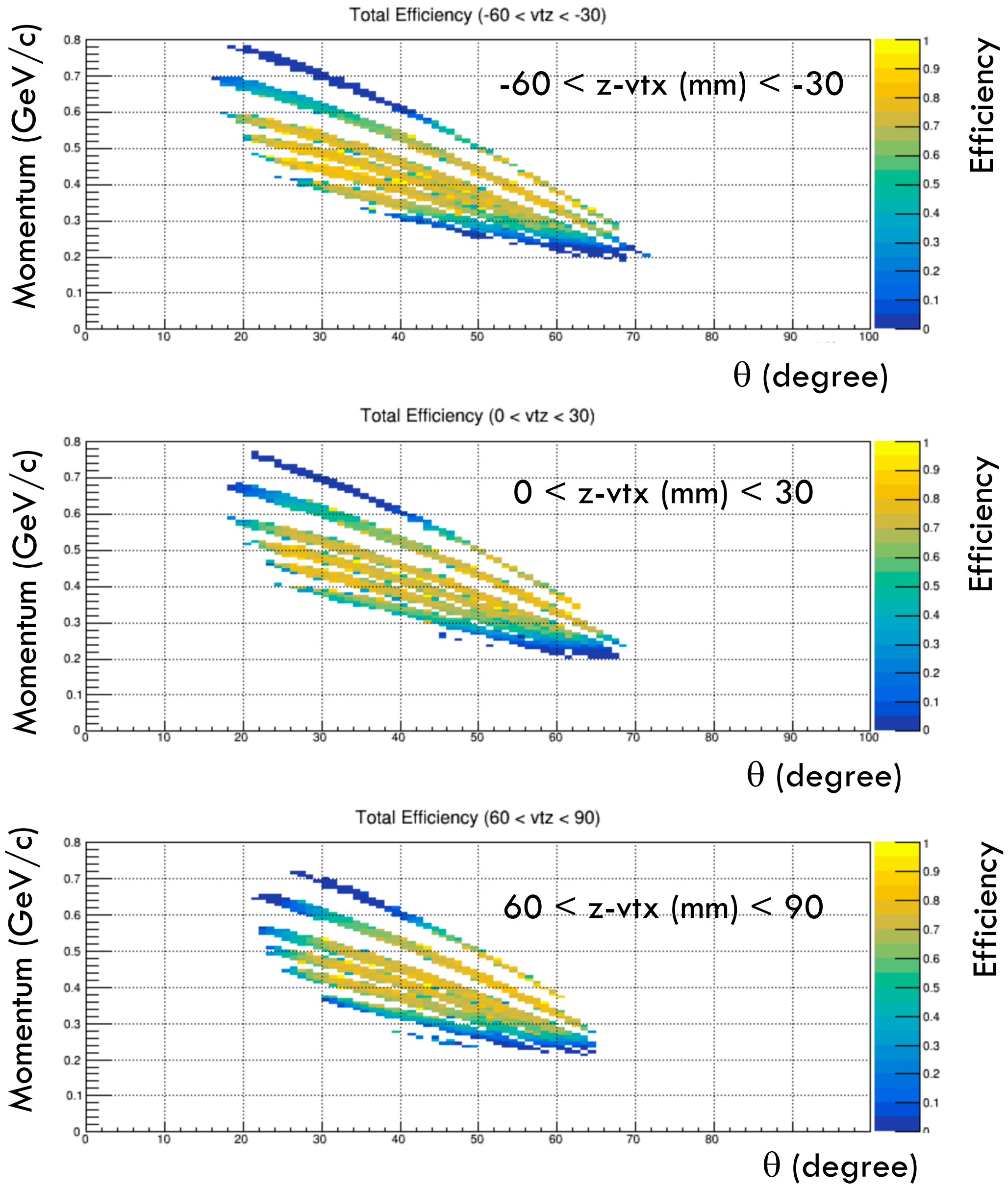
Identify pp scattering event from missing mass of pp→pX reaction



The other proton's angle and momentum can be predicted from missing momentum

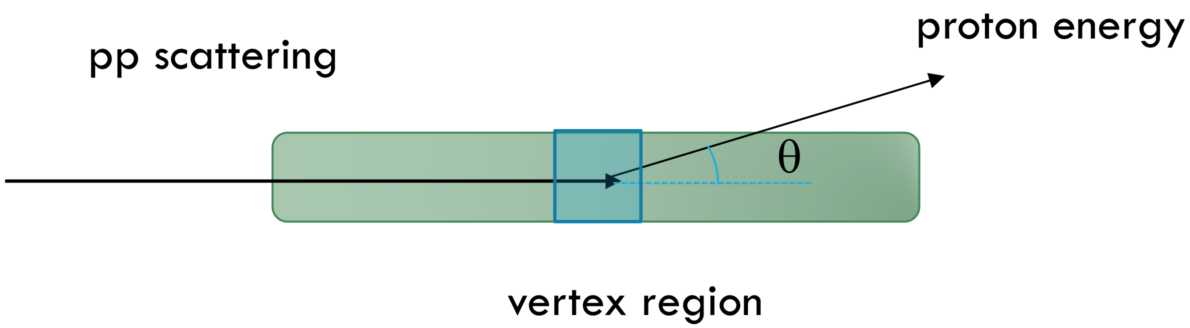
Check whether measured angle and energy are consistent or not.

CATCH Efficiency study



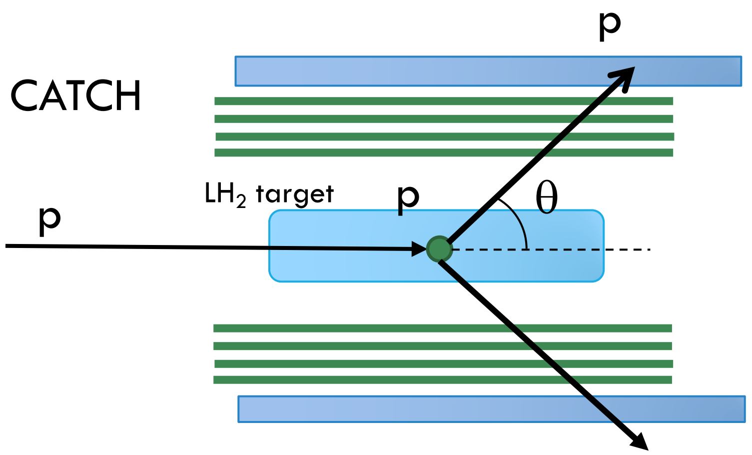
CATCH efficiency was measured as a function of

- Vertex position
- Angle
- Proton energy



We made an efficiency table of CATCH based on the pp scattering data and Geant4 simulation.

pp differential cross section with proton beams

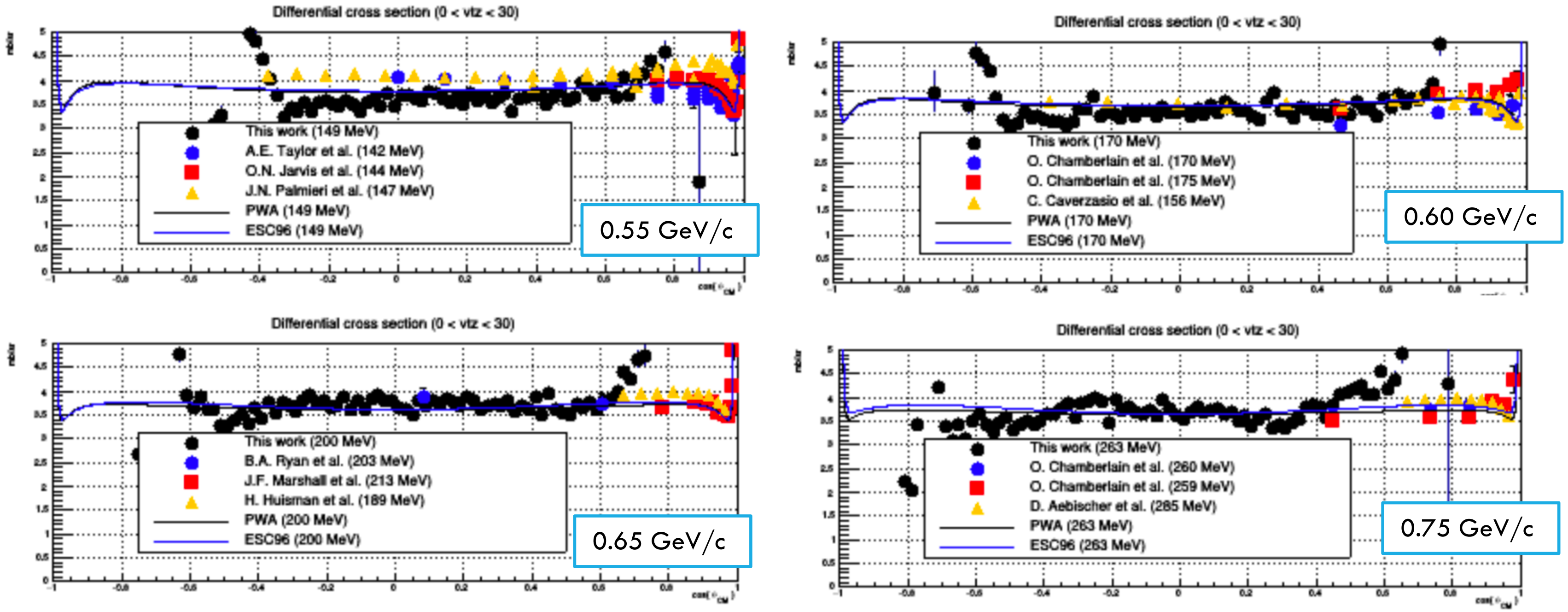


pp scattering data were used for

- CATCH detector calibration, efficiency study
- Consistency check for $d\sigma/d\Omega$ measurement

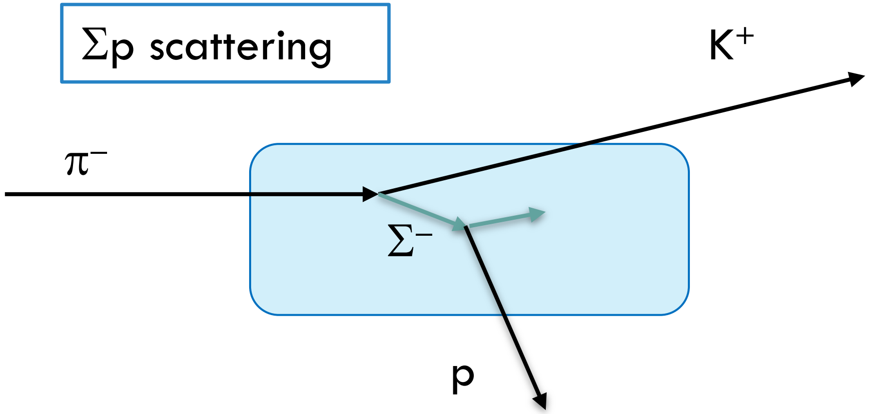
There are some inconsistencies at edge region of detector acceptance.
But the obtained $d\sigma/d\Omega$'s are reasonable.

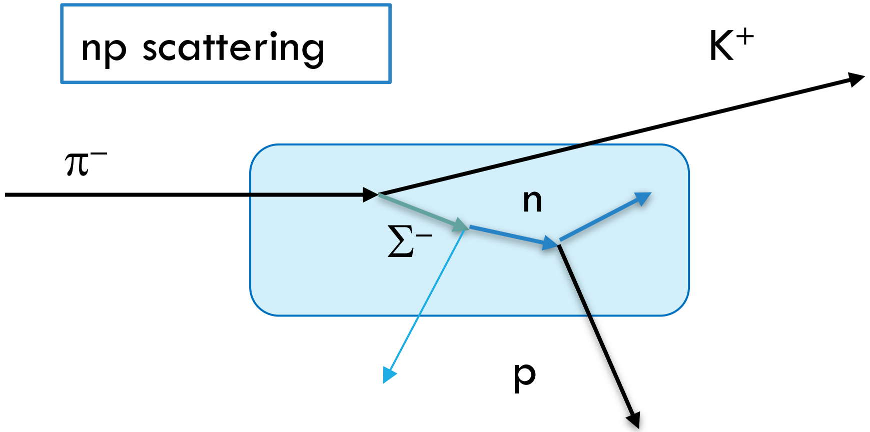
Preliminary



np scattering from Σ^- decay

Good practice to derive Σp scattering $d\sigma/d\Omega$





Beam does not pass though the whole size of target

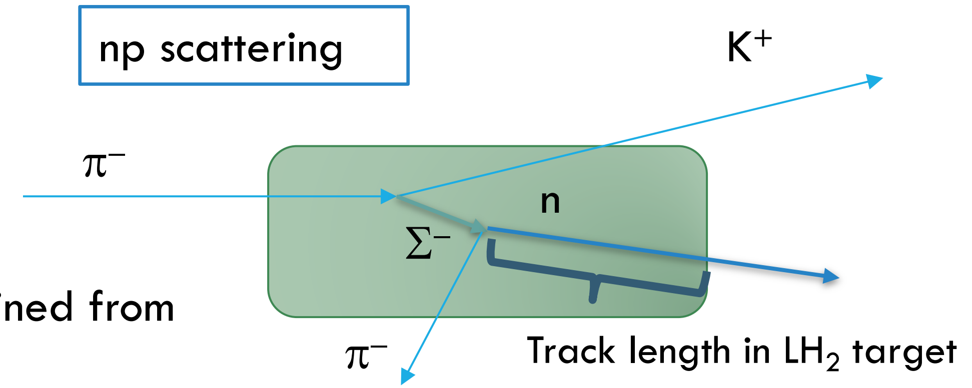
- Σ^- decay
- Various production point and direction

We have to estimate total track length in the LH_2 target from these information

- production vertex
- Σ^- or neutron momentum

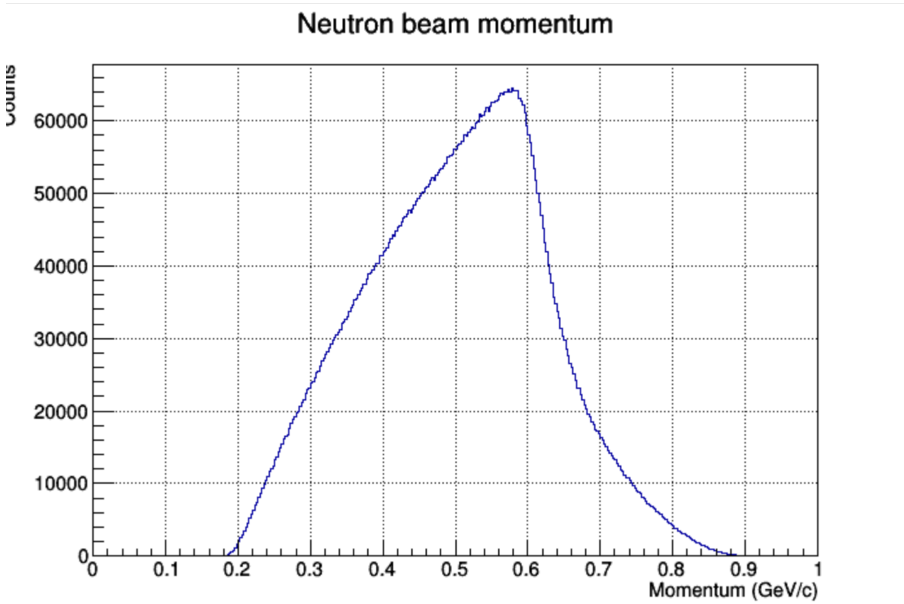
$$\frac{d\sigma}{d\Omega} = \frac{\sum_{i_{vtz}} \frac{N_{scat}(i_{vtz}, \cos\theta)}{eff(i_{vtz}, \cos\theta)}}{density_{tgt} \times TotalTrackLength \times d\Omega}$$

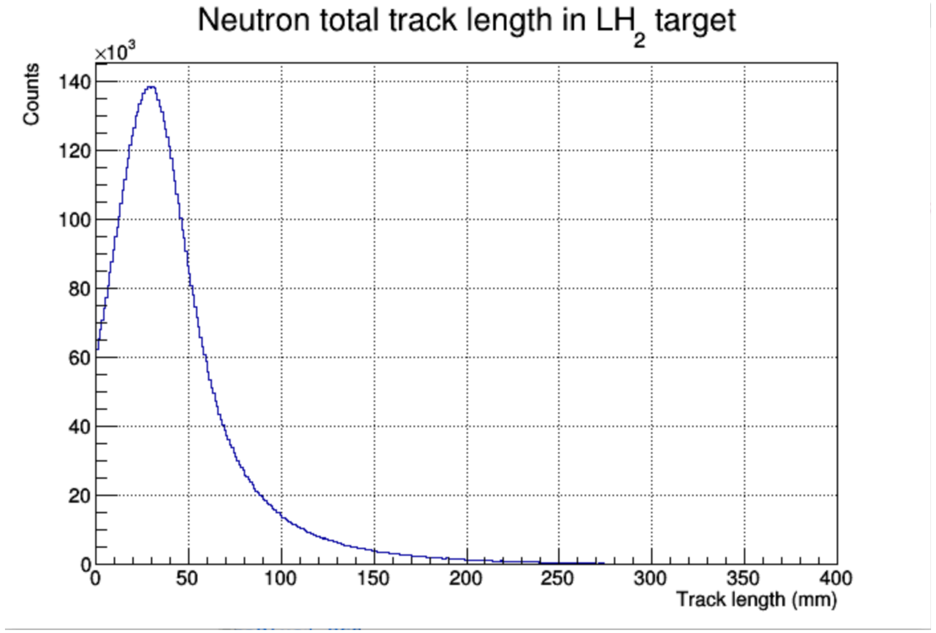
Neutron beam from Σ^- decay



Neutron momentum is obtained from $P_{\Sigma-}$ and $P_{\pi-}$

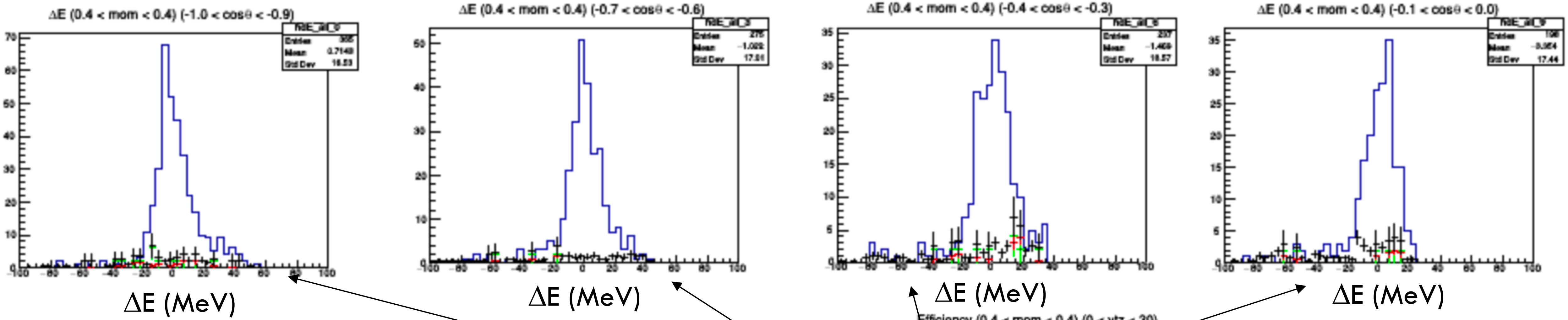
Track length in LH2 target was obtained from decay position and neutron direction





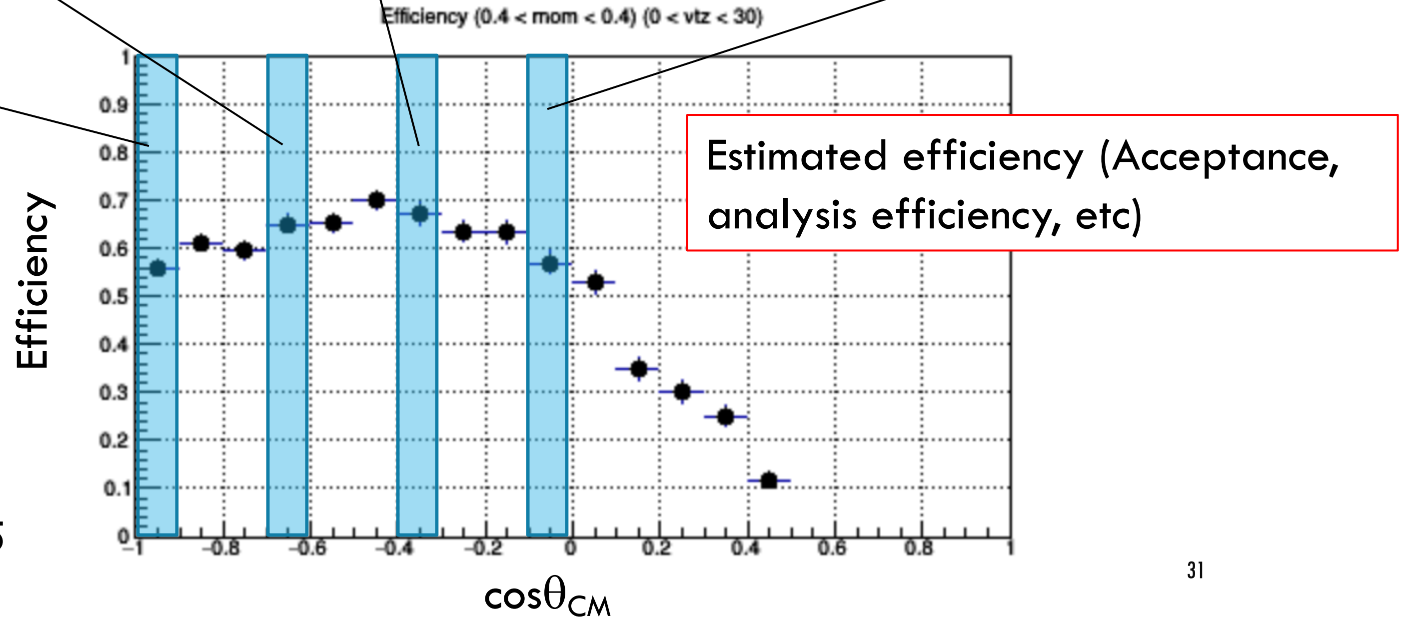
np scattering identification from Σ^- decay

Kinematical consistency check for each scattering angle → N_{scat} was derived

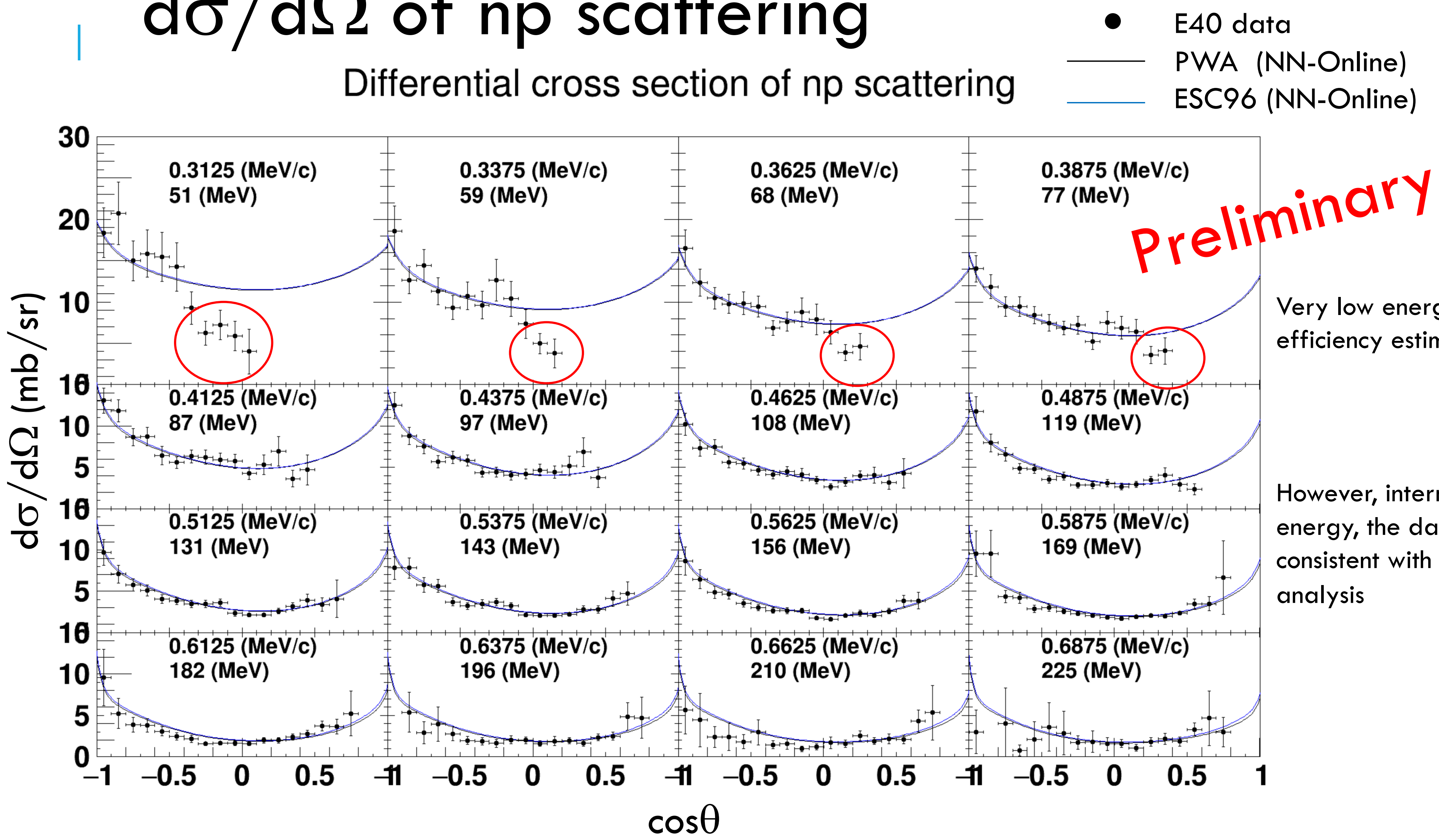


$$\frac{d\sigma}{d\Omega} = \frac{\sum_{i_{vtz}} \frac{N_{scat}(i_{vtz}, \cos\theta)}{eff(i_{vtz}, \cos\theta)}}{density_{tgt} \times TotalTrackLength \times d\Omega}$$

0.4 <p (GeV/c) < 0.425



dσ/dΩ of np scattering



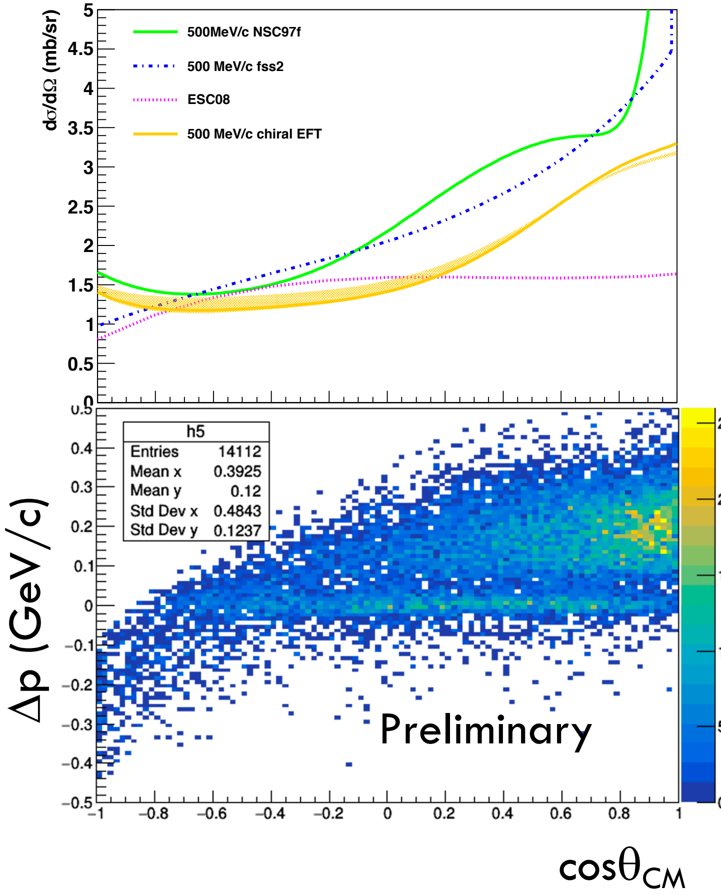
Very low energy region: efficiency estimation is difficult

However, intermediate beam energy, the data are almost consistent with partial wave analysis

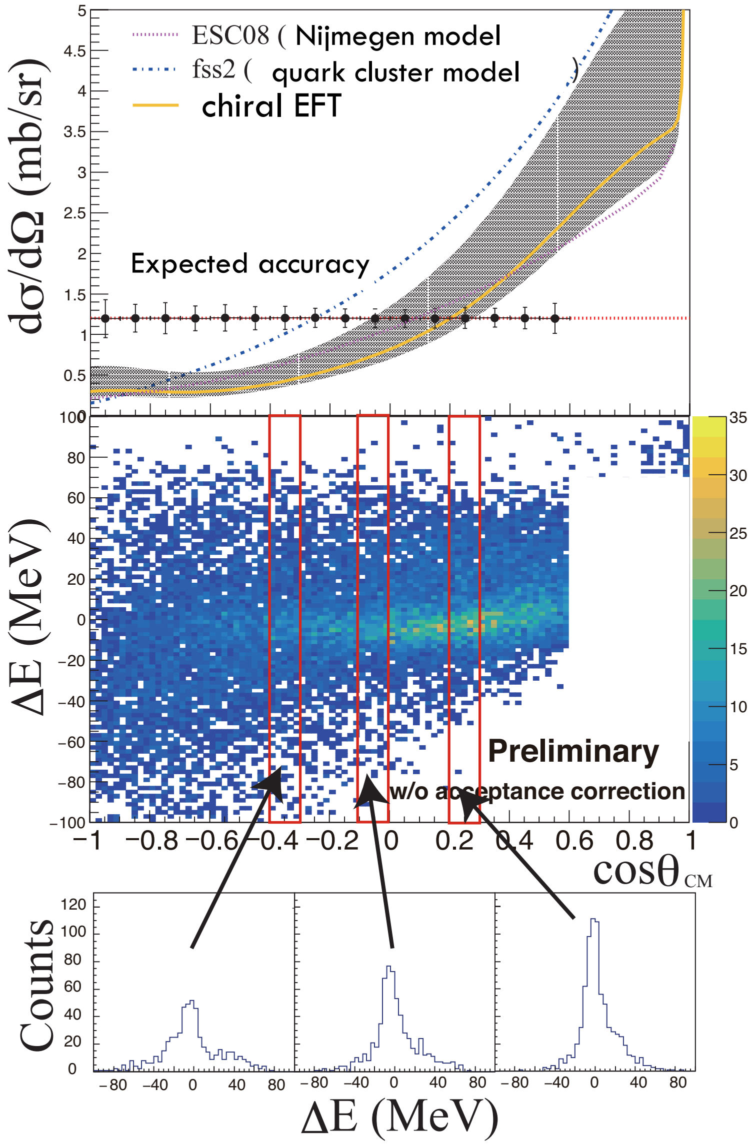
Σp channels

Data are w/o acceptance correction

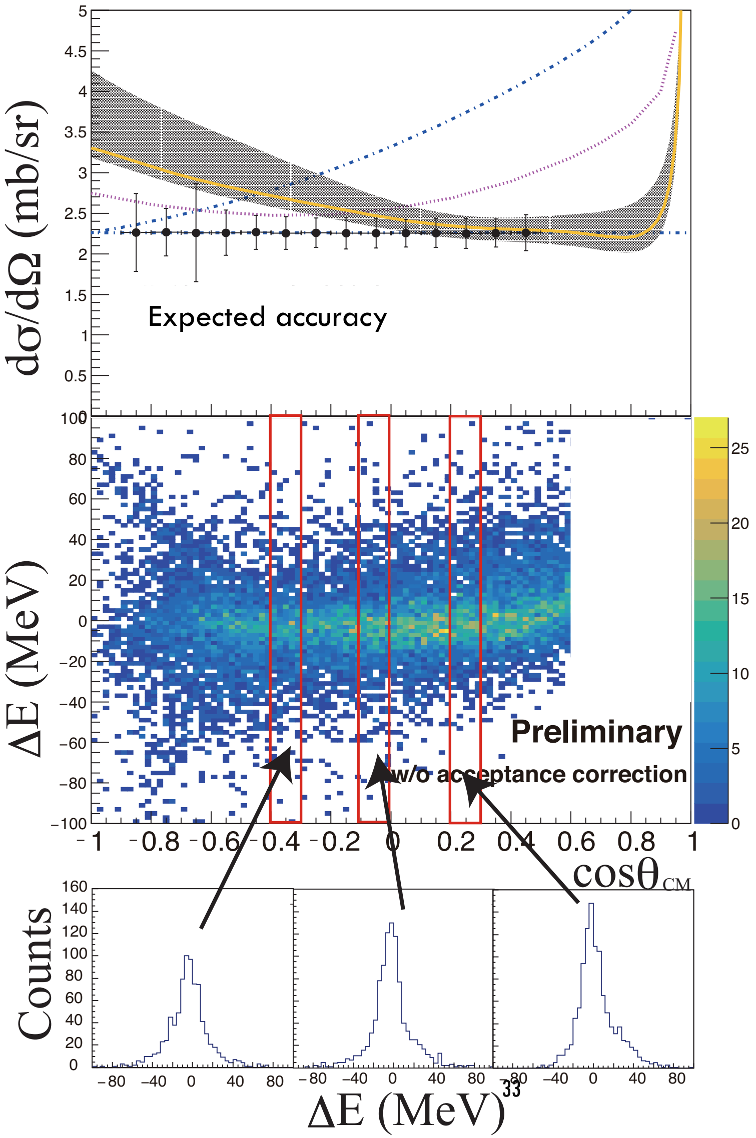
$\Sigma^{-}p \rightarrow \Lambda n$ scattering



Σ-p elastic scattering (0.55<p(GeV/c)<0.65)



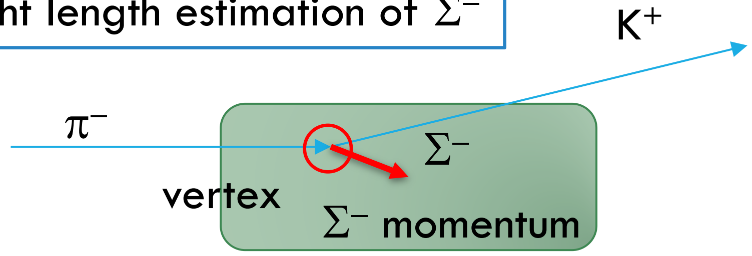
Σ+p elastic scattering (0.5<p(GeV/c)<0.6)



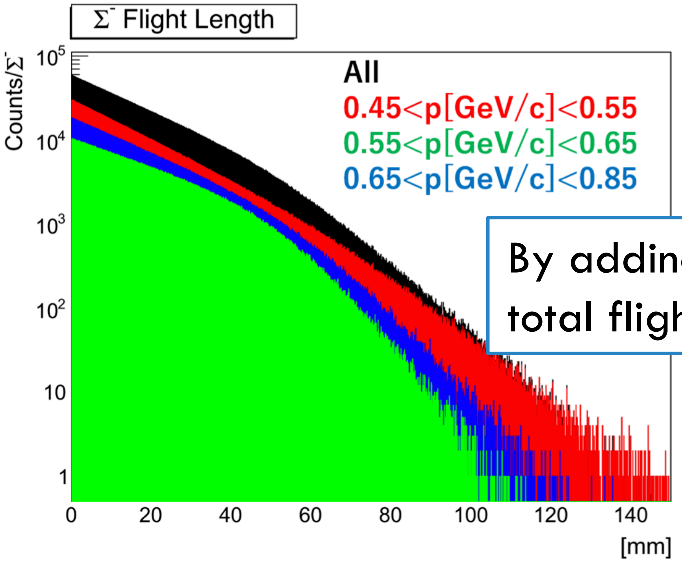
Analysis is on going to derive dσ/dΩ with acceptance and efficiency tables

Analysis of $\Sigma^{-}p \rightarrow \Lambda n$ channel

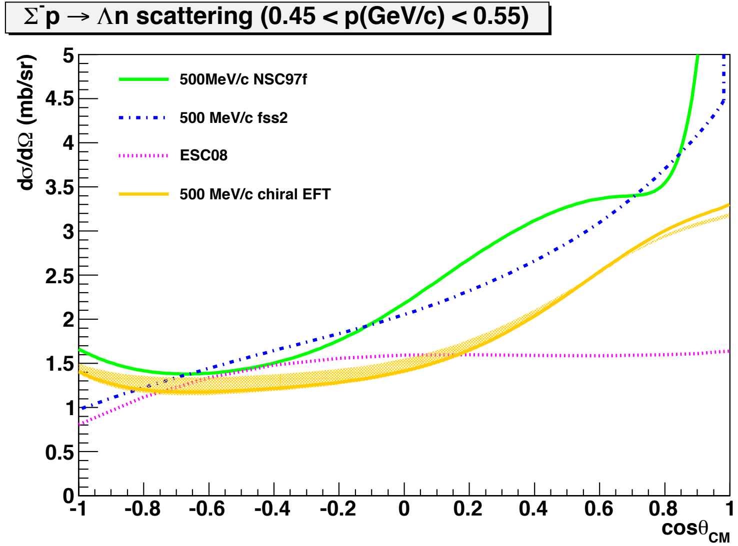
Flight length estimation of Σ^{-}

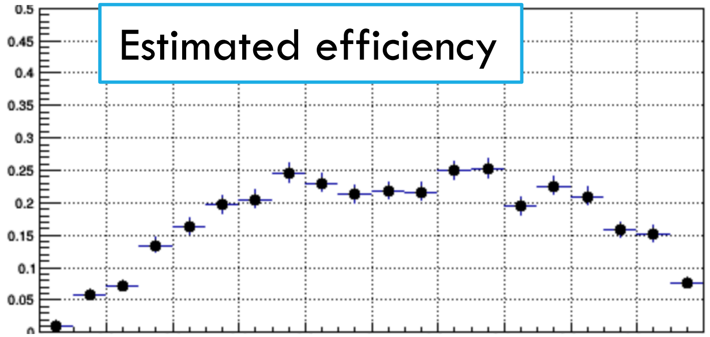


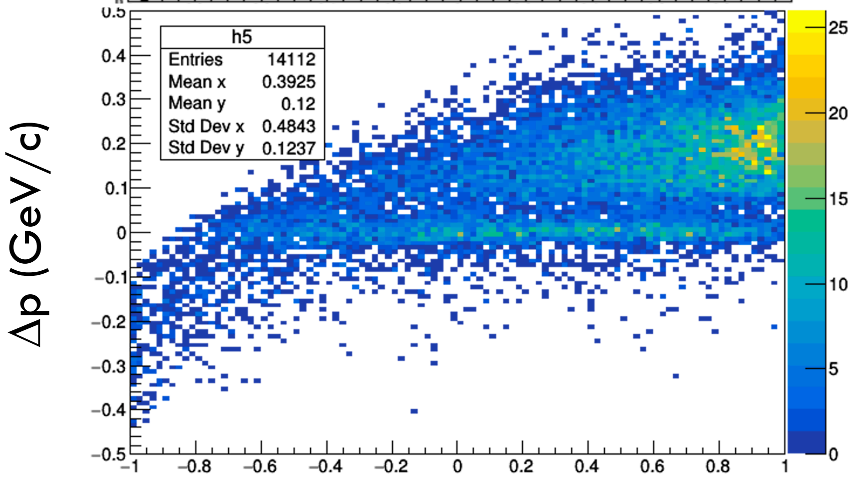
Based on the vertex position and momentum estimated from spectrometer analysis, Σ^{-} flight length was estimated from a Monte Carlo simulation.



By adding flight length in each event, total flight length can be obtained.

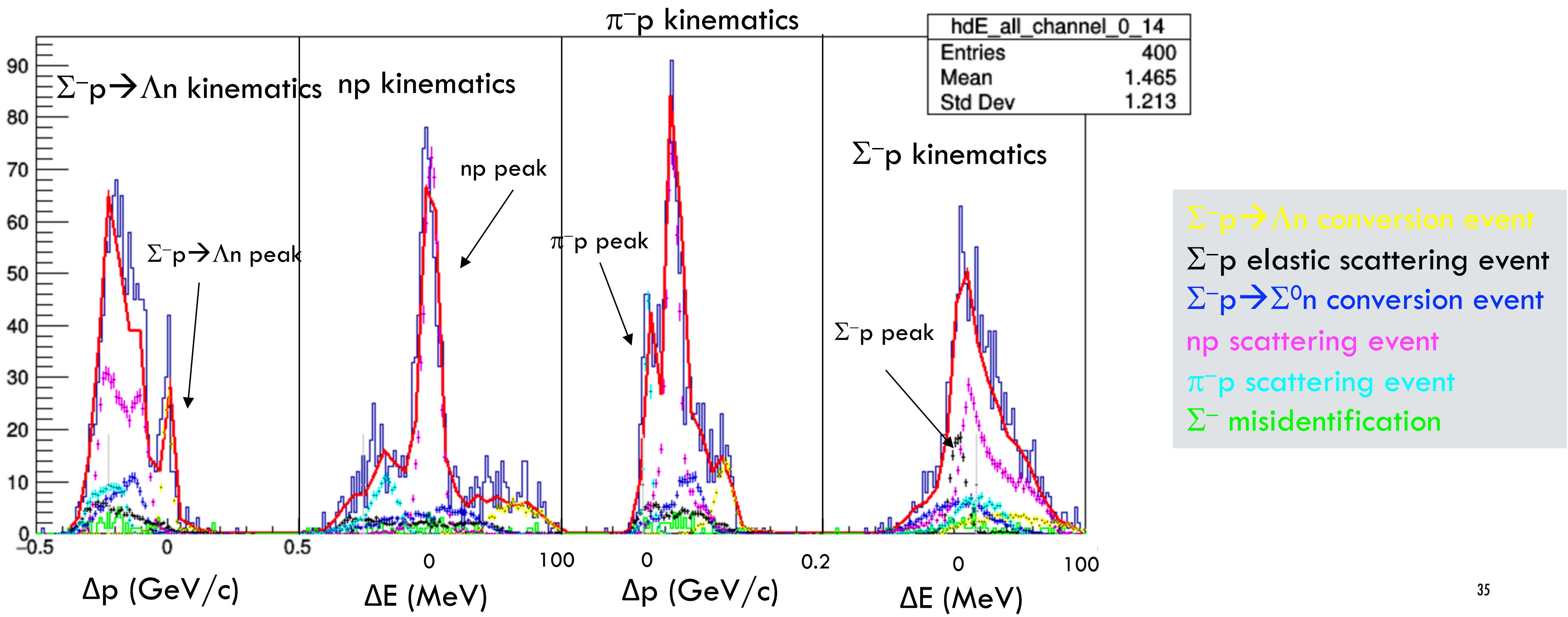




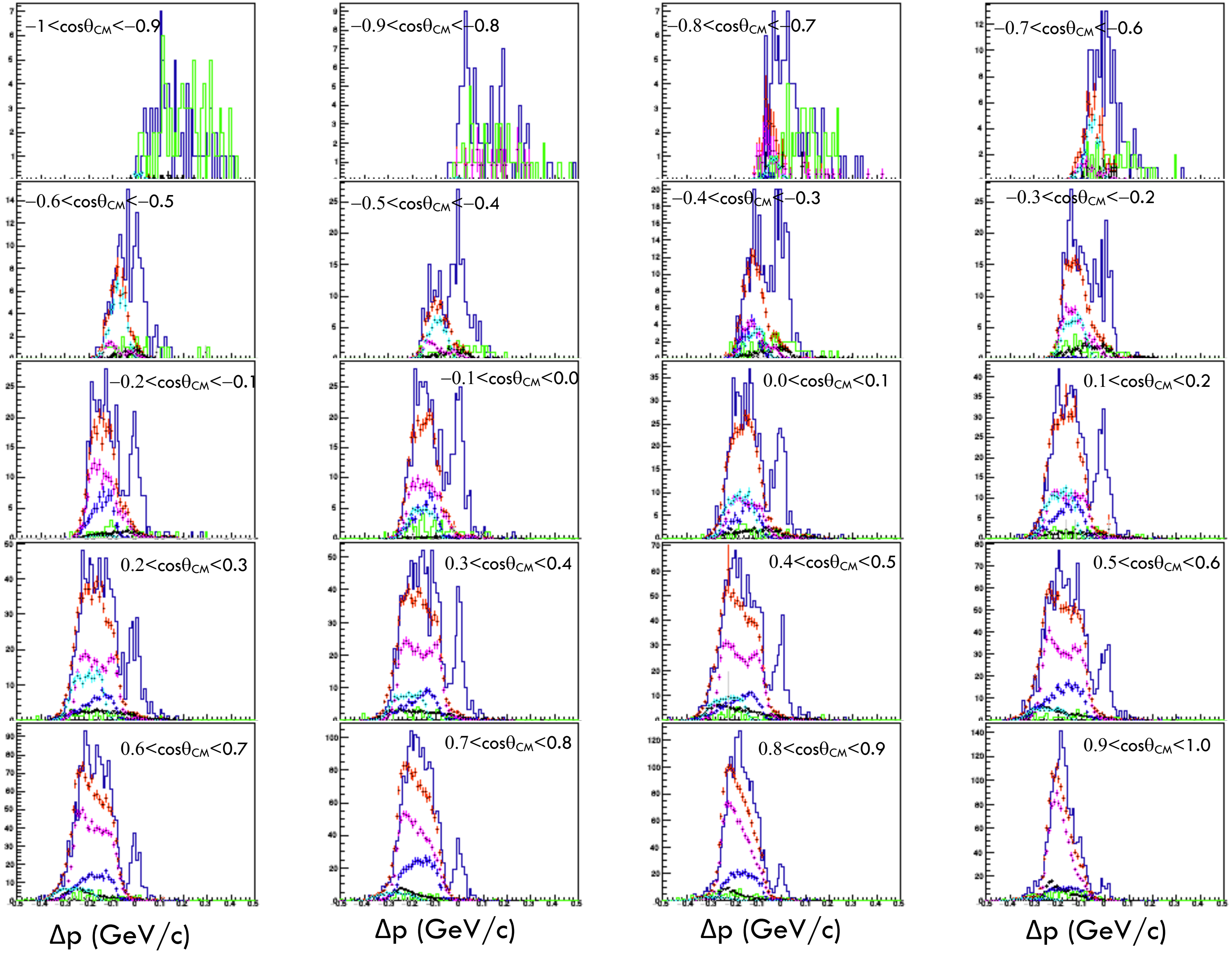


Analysis of $\Sigma^- p \rightarrow \Lambda n$ channel (BG estimation)

The $\Sigma^- p \rightarrow \Lambda n$ channel is separated from other background events.
We are trying to understand the background contribution as much as possible.
We fit the four kinematical spectra simultaneously with sum of each contribution.



Analysis of $\Sigma^- p \rightarrow \Lambda n$ channel (BG estimation)



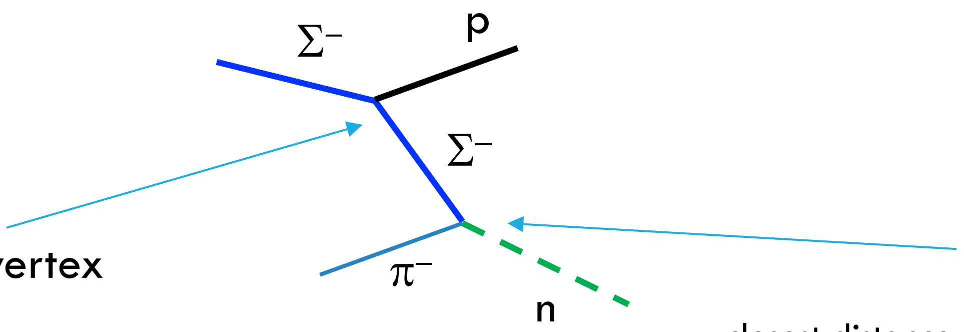
There are still discrepancy in background estimation.
But uncertainty of the background contamination in the Λn peak is not large.

We can maybe release $d\sigma/d\Omega$ spectra soon for $\Sigma^- p \rightarrow \Lambda n$ channel.

Σ^-P ELASTIC SCATTERING

In order to identify S-p scattering, much tighter cuts are necessary.

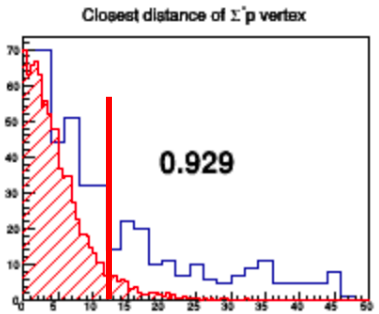
Scattering vertex



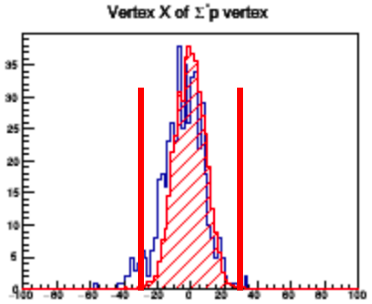
Decay vertex

Decay order

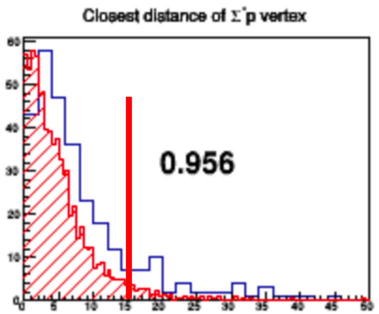
closest distance



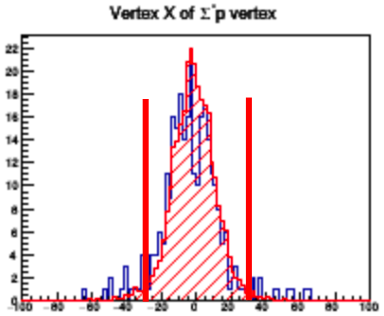
x(y) vertex position



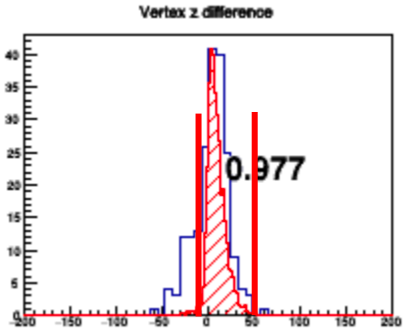
closest distance



x(y) vertex position



vtz(decay)-vtz(scat)



$0.45 < p(\mathrm{GeV}/c) < 0.55$, $-0.1 < \cos\theta < 0.1$

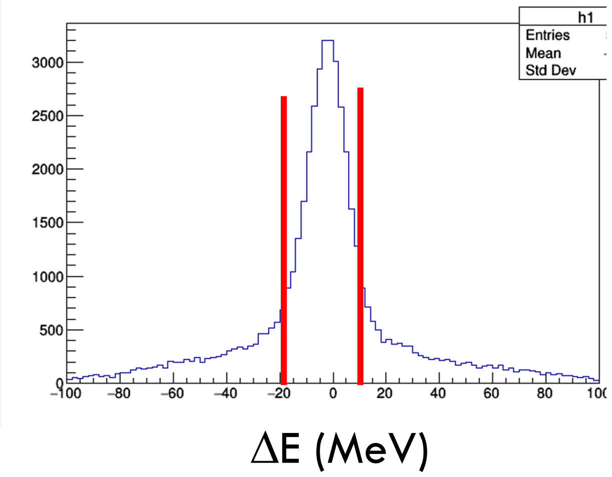
Red shaded：Simulation

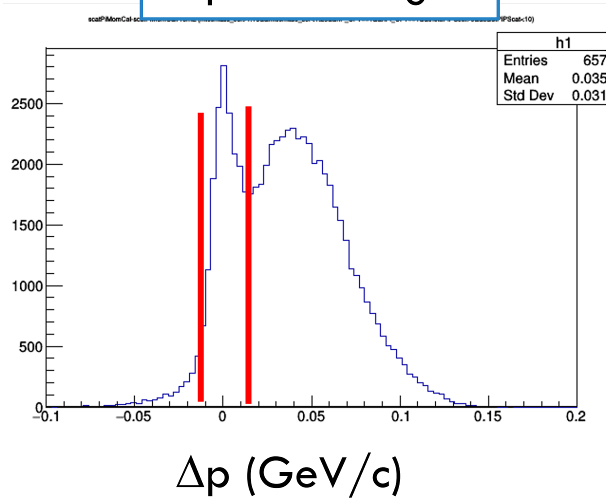
Open hist：data selected for $-20 < \Delta E_{\Sigma p} < 10$ region to enhance true Σ^-p scattering event

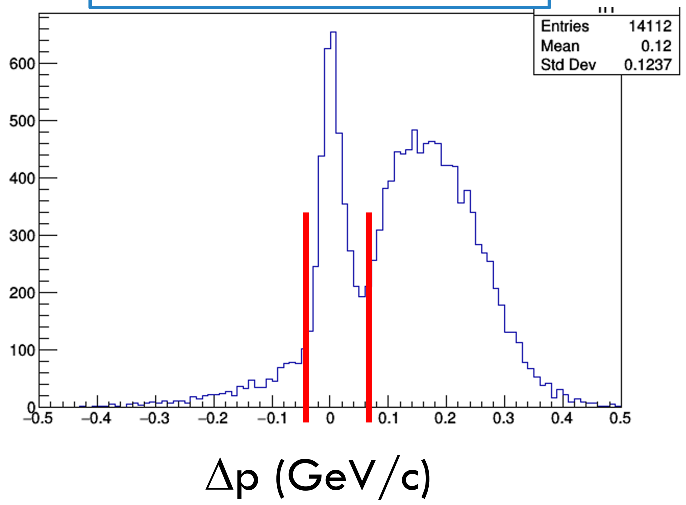
In order to estimate the efficiency, the simulation program was updated based on the measured vertex resolution (spectrometer), angular resolution (CFT) and energy resolution (BGO).

Σ^{-}P ELASTIC SCATTERING

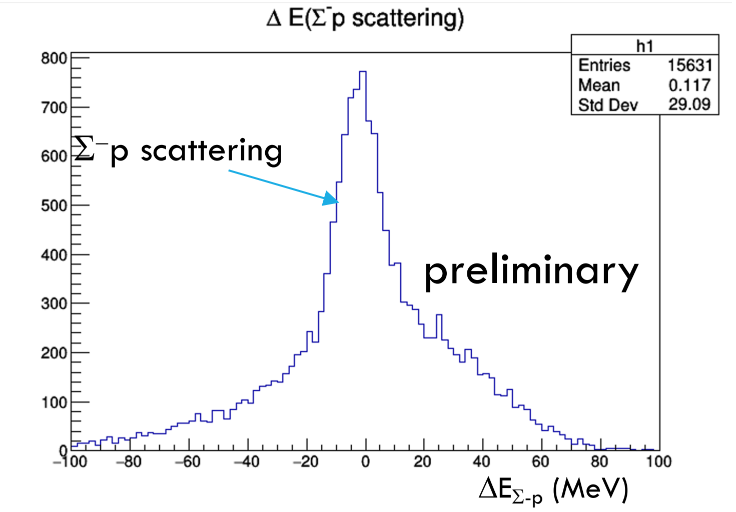
Subtraction of background reaction







In order to get better S/N ratio for identifying Σ^{-}p elastic scattering event, these background events were rejected.

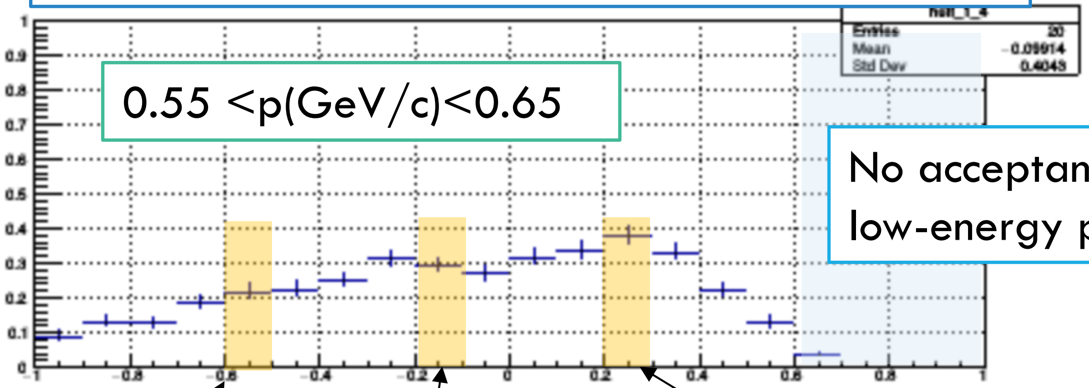


Σ^-P ELASTIC SCATTERING

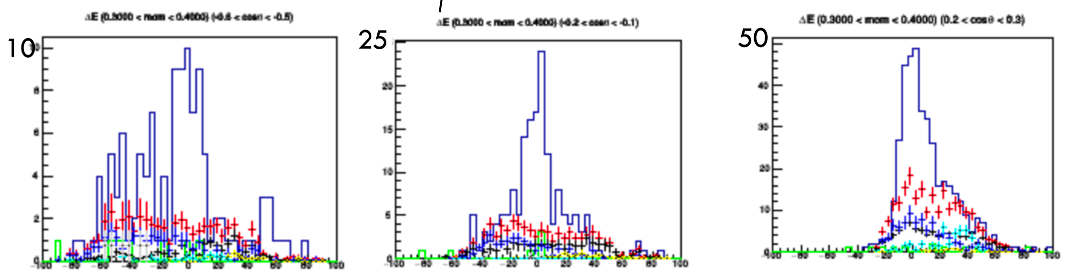
Efficiency for Σ^-p event for each scattering angle

0.55 <p(GeV/c)<0.65

No acceptance for low-energy proton

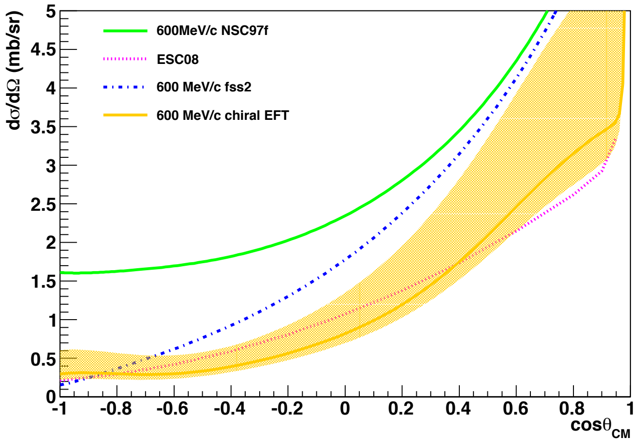


cos θ

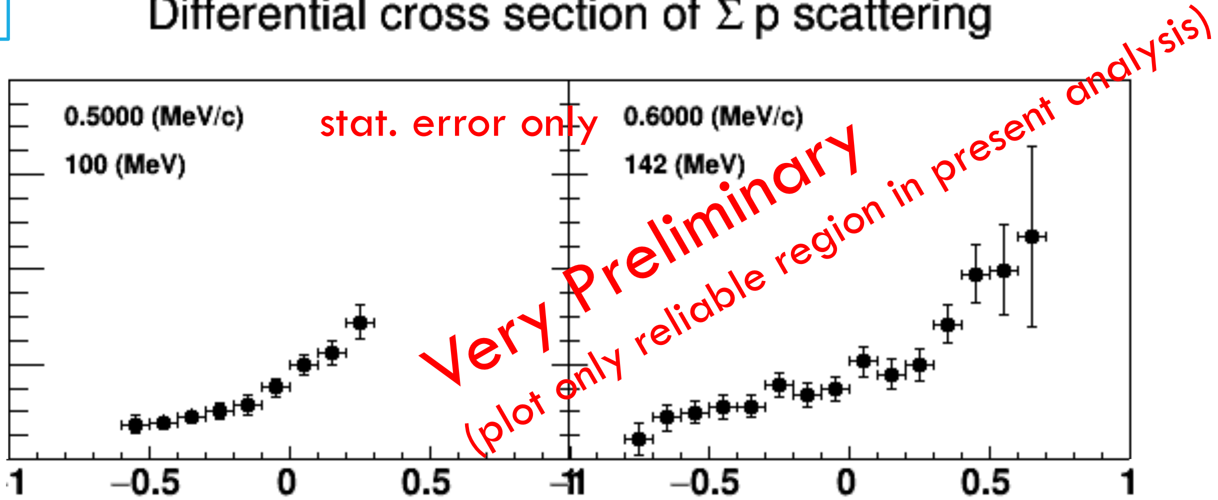


ΔE (MeV) ΔE (MeV) ΔE (MeV)

Σ^-p (0.55 < p (GeV/c) < 0.65)



Differential cross section of Σ^-p scattering

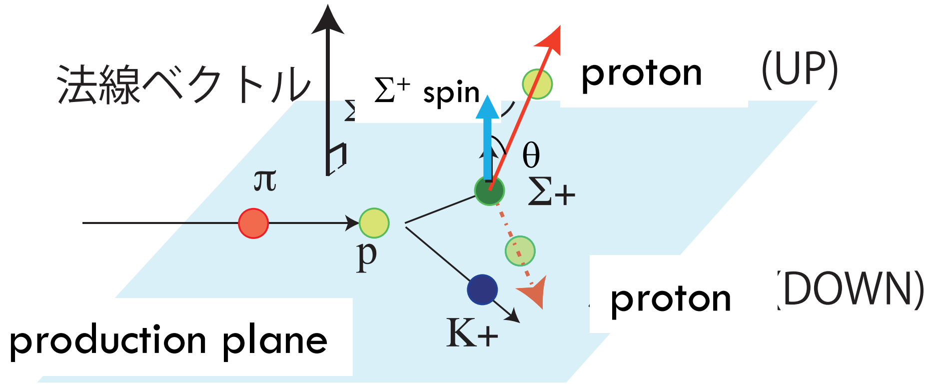


In Σ^-p scattering, forward peak structures were clearly identified.
The absolute value of $d\sigma/d\Omega$ will be released soon with more wider momentum range.

POLARIZATION OF HYPERON

Σ^+ polarization at production

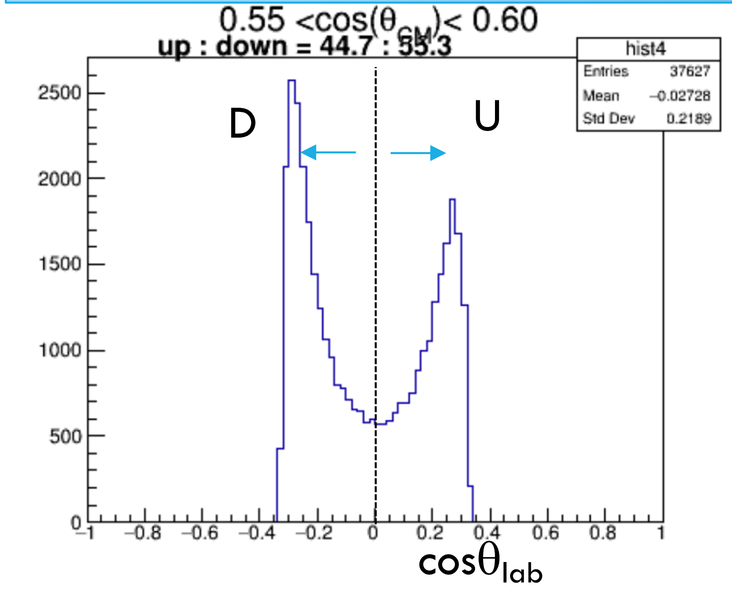
- Hyperon can be produced with some polarization for the production plane
- Spin direction of hyperon can be identified from angular dependence of decay product

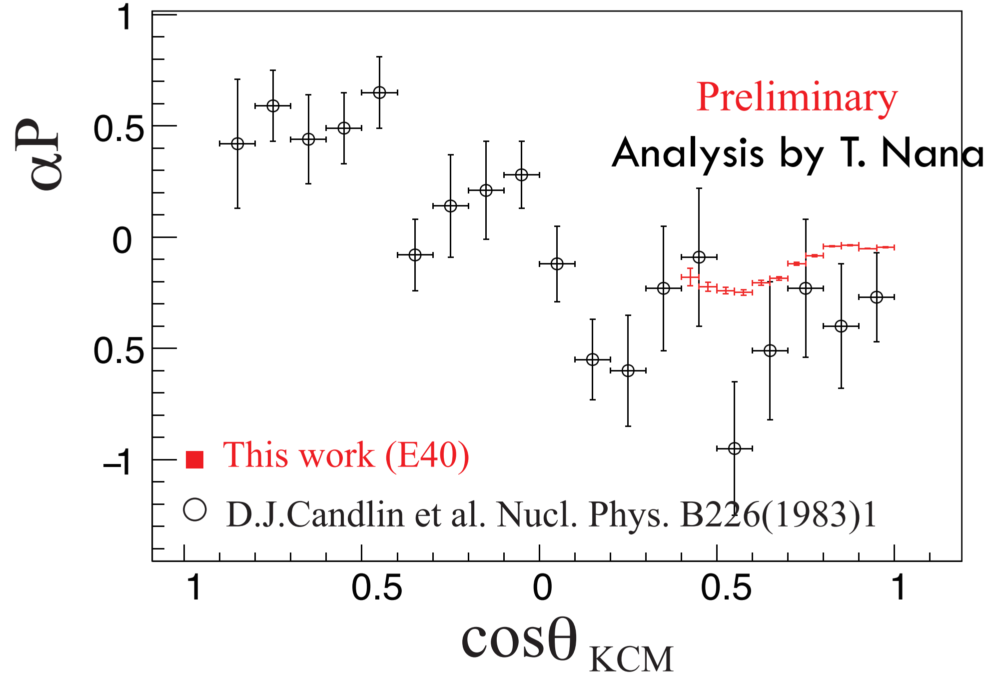


P : Polarization

α : Asymmetry parameter $0.98^{+0.017}_{-0.015}$ (Σ+)

U/D Asymmetry of p from Σ^+ decay





This method can be applied to Yp scattering to derive polarization in Yp scattering

Spin observables in E40

Progress of Theoretical Physics, Vol. 100, No. 5, November 1998

Scattering Observables of the NN and YN Interactions in the SU_6 Quark Model

Tadashi FUJITA, Yoshikazu FUJIWARA, Choki NAKAMOTO* and Yasuyuki SUZUKI**

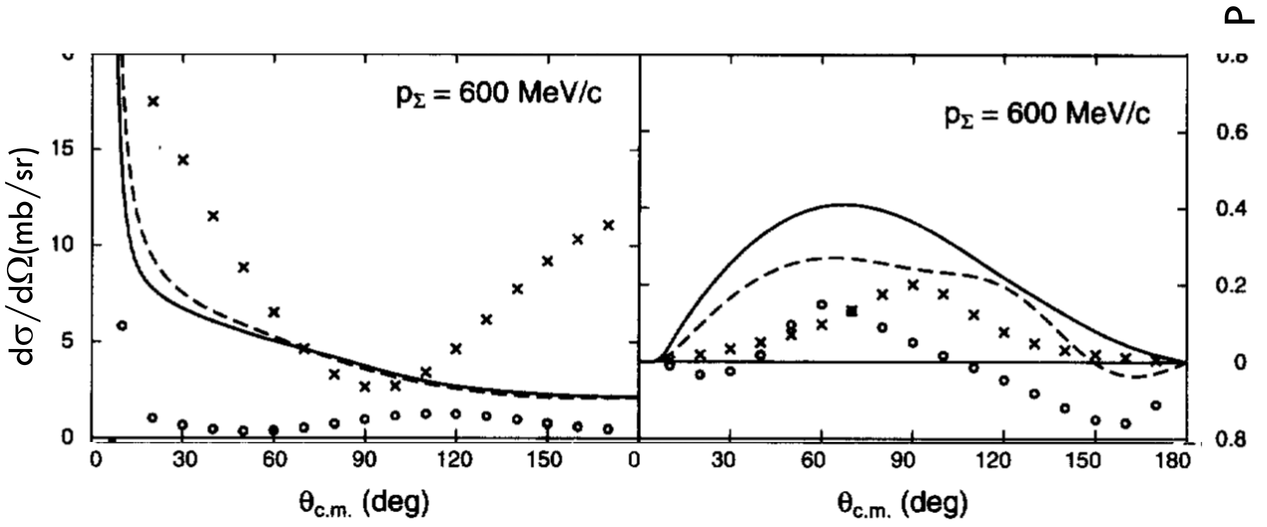
Department of Physics, Kyoto University, Kyoto 606-8502, Japan
**Suzuka National College of Technology, Suzuka 510-0294, Japan*
***Department of Physics, Niigata University, Niigata 950-2102, Japan*

Polarization in $\Sigma^+ p \rightarrow \Sigma^+ p$

- U/D asymmetry of proton from Σ^+ decay

Polarization in $\Sigma^- p \rightarrow \Lambda n$

- U/D asymmetry of proton from Λ decay



Theoretical calculation of spin observable in Yp scattering is not updated.
We want to collaborate (or ask) theorist for calculation of spin observable in Yp scattering.

Λp scattering with the $\pi^{-}p \rightarrow K^{0}\Lambda$ reaction

Possibility of Λp scattering

Λ identification by $\pi^- p \rightarrow K^0\Lambda$ reaction is one of milestones

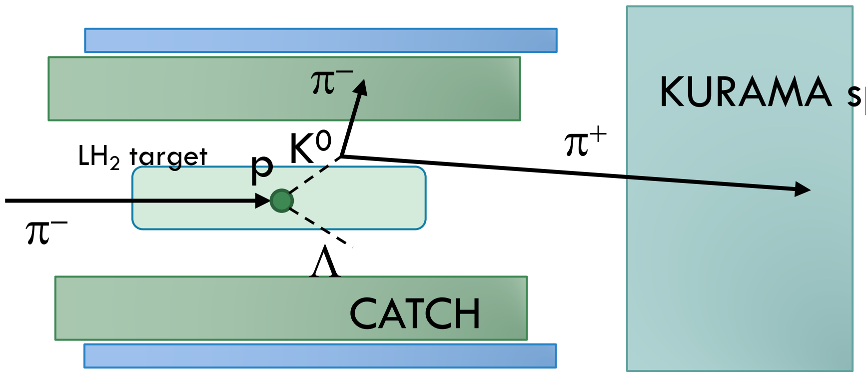
- Study of neutron-rich Λ hypernuclei
- Study of Λp scattering

New K^0 identify method

π^+ : magnetic spectrometer

π^- : CATCH

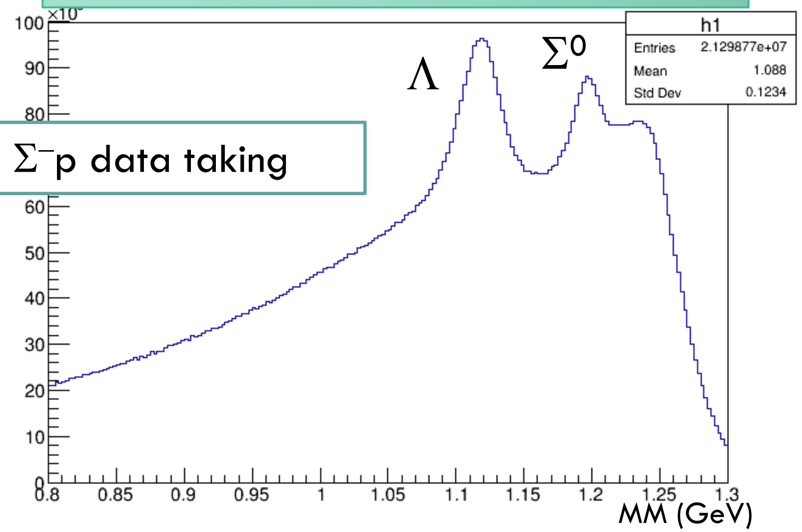
→ We can keep large acceptance for K^0



Byproduct of $\Sigma^- p$ data taking

We could establish Λ production method for proton target

Missing mass ($\pi^- p \rightarrow K^0 X$ reaction)



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π^+ : magnetic spectrometer
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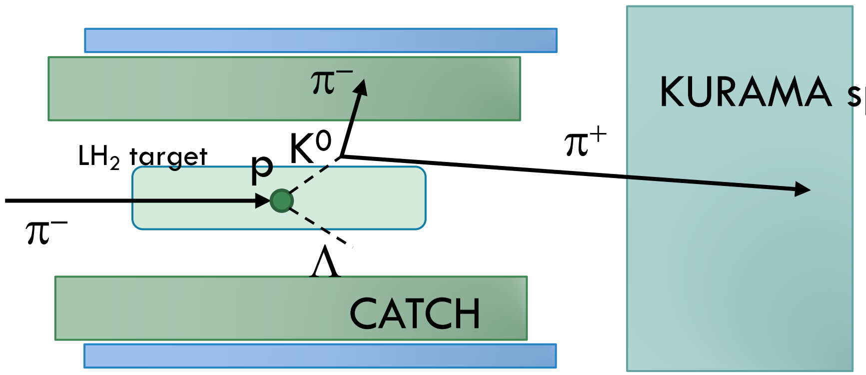

Missing mass ($\pi^{-}p \rightarrow K^{0}X$ reaction)

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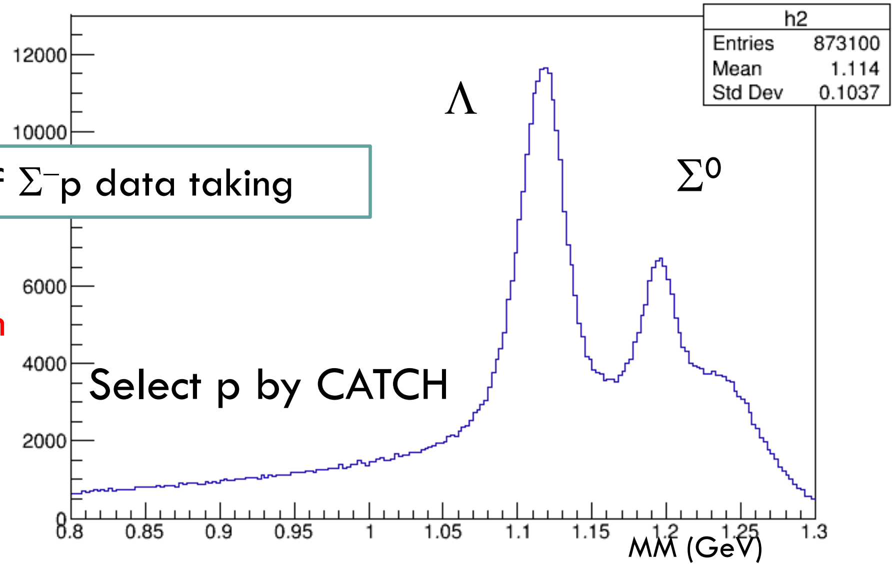
We could establish Λ production method for proton target



Accumulated Λ events ~200k $\rightarrow$ a several 10 Λp scattering might be collected

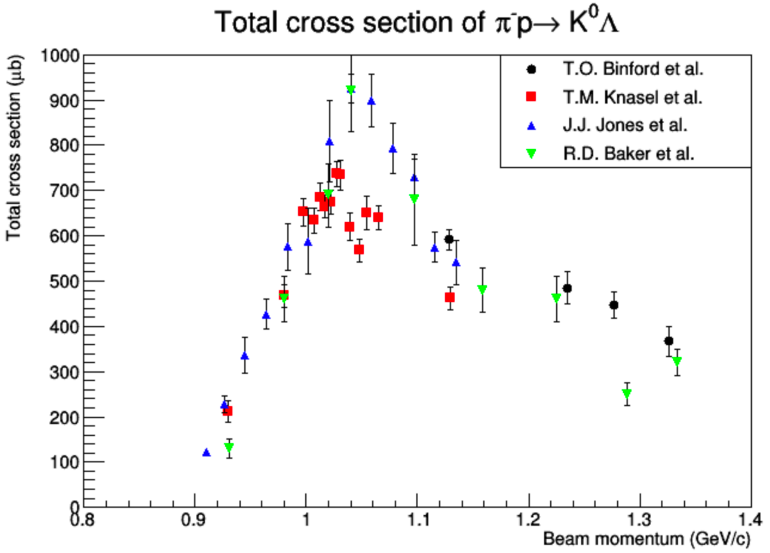
We will establish Λp scattering identification method by CATCH

FUTURE PROJECT : ΛP SCATTERING EXPERIMENT

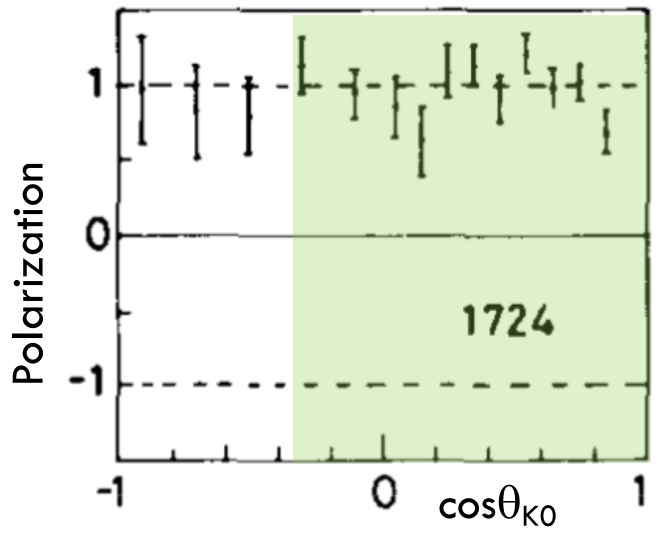
Planning to perform at (new) K1.1 beamline

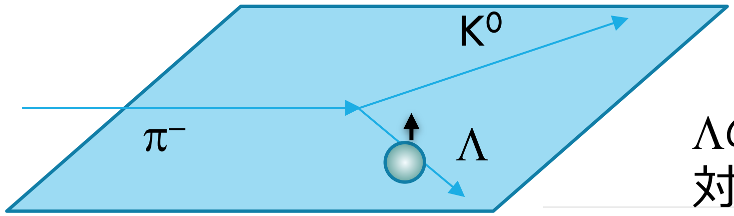
Λ production via $\pi^- p \rightarrow K^0 \Lambda$ at p_{π^-} = 1.05 GeV/c

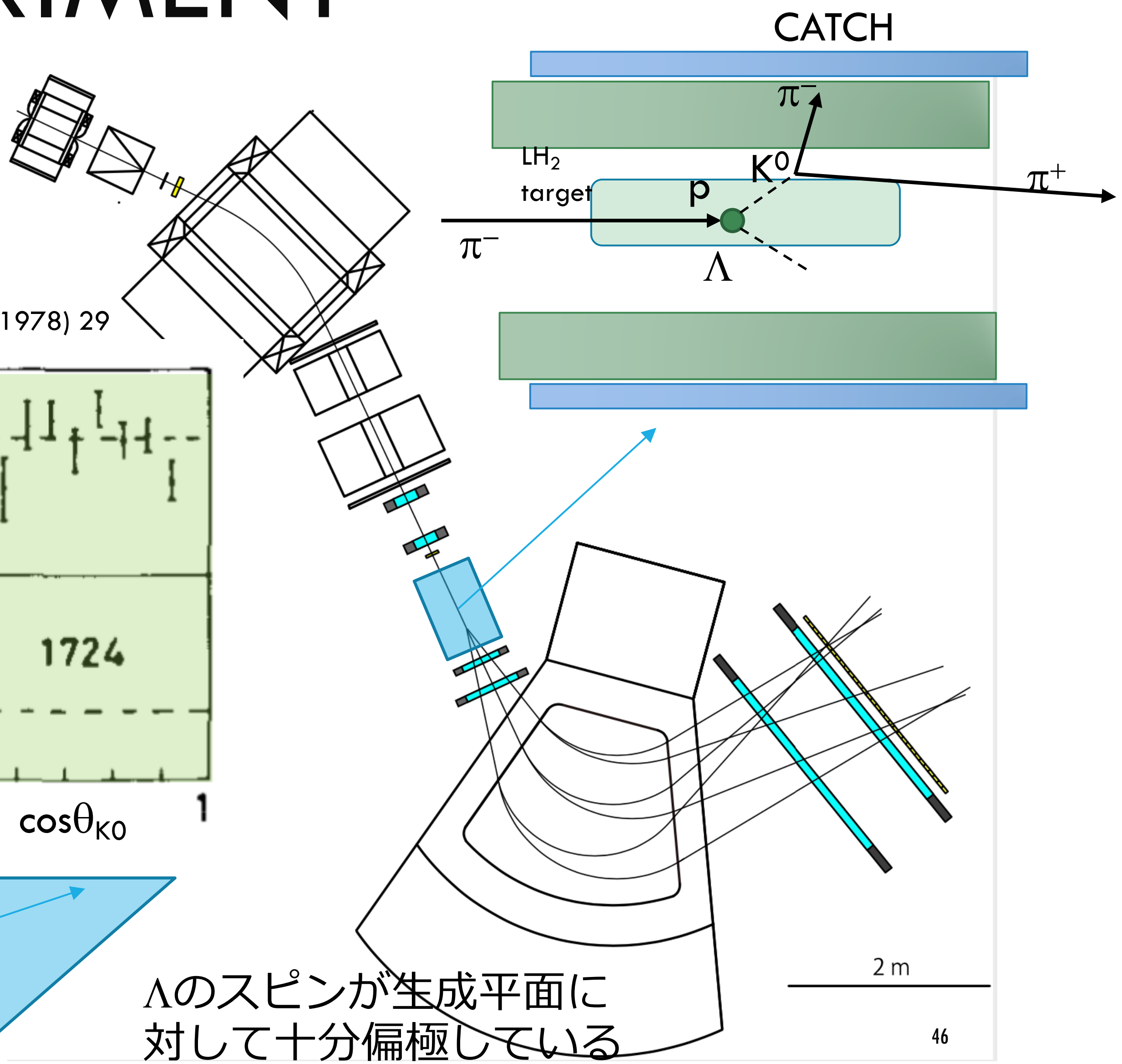
- High polarization of Λ beam



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







Λのスピンが生成平面に対して十分偏極している

Conventional representation of elastic scattering

From S. Ishikawa et al. PRC 69, 034001 (2004)

Scattering amplitude in $\vec{\frac{1}{2}} + \vec{\frac{1}{2}} \rightarrow \vec{\frac{1}{2}} + \vec{\frac{1}{2}}$ scattering : → 4 x 4 matrix

→ 6 components from the restriction of parity conservation and time-reversal invariance

spin-independent, spin-spin, symmetric LS (ΔS=0), anti-symmetric LS (ΔS=1), Tensor

T matrix

$$M = V_c + V_\sigma(s_a \cdot s_b) + V_{SLS}(s_a + s_b)\cdot L + V_{ALS}(s_a - s_b)\cdot L + V_T([s_a \otimes s_b]^{(2)} \cdot Y_2(\hat{r})),$$

Scalar amplitude

$$U_\alpha \equiv \langle k_f | V_c | k_i \rangle, \qquad U_\beta \equiv \langle k_f | V_\sigma | k_i \rangle,$$

→

$$U_0 = U_\alpha - \tfrac{3}{4} U_\beta, \qquad U_1 = \sqrt{3}\left(U_\alpha + \tfrac{1}{4} U_\beta\right),$$

Vector amplitude

$$S_\alpha \equiv \langle k_f | V_{ALS} L_1 | k_i \rangle, \qquad S_\beta \equiv \langle k_f | V_{SLS} L_1 | k_i \rangle,$$

→

$$S_1 = -S_2 = -S_\alpha, \qquad S_3 = \sqrt{2} S_\beta.$$

Tensor amplitude

The tensor amplitudes T_j ($j=1,2,3$) are calculated as

$$T_j = \tfrac{1}{2}\langle k_f | V_T Y_{2,j-1} | k_i \rangle, \qquad (18$$

↓

$$T_\alpha = \frac{1}{\sqrt{6}} T_1 + T_3,$$

$$T_\beta = \frac{1}{\sqrt{6}} T_1 - T_3,$$

We want to derive these scattering amplitudes separately.

Scattering observables

From S. Ishikawa et al.
PRC 69, 034001 (2004)

Differential cross section

$$\sigma(\theta) = \frac{1}{4}\mathrm{Tr}\left(\mathcal{M}\mathcal{M}^{\dagger}\right) = |U_\alpha|^2 + \frac{3}{16}|U_\beta|^2 + \frac{1}{2}(|S_{\mathrm{SLS}}|^2 + |S_{\mathrm{ALS}}|^2) + \frac{1}{4}|T_1|^2 + \frac{1}{2}(|T_2|^2 + |T_3|^2)$$

Analyzing power
(Polarization)

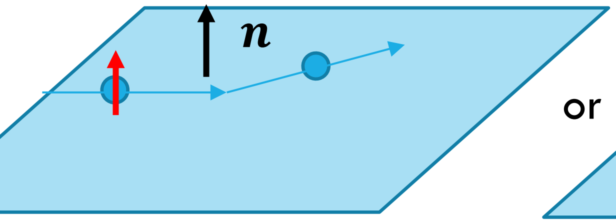
$$A_y(a) = -\frac{4\sqrt{2}}{N_R}\mathrm{Im}\left\{ U_\alpha^*(S_\alpha + S_\beta) + \frac{1}{4}U_\beta^*(-S_\alpha + S_\beta) - \frac{1}{2}T_\alpha^*(-S_\alpha + S_\beta)\right\},$$

Depolarization

$$D_y^y(a) = \frac{4}{N_R}\mathrm{Re}\left\{ \frac{1}{2\sqrt{3}}\left(U_0 + \frac{1}{\sqrt{3}}U_1\right)^* U_1 + \frac{1}{2}\left(U_0 - \frac{1}{\sqrt{3}}U_1\right)^* \times \left(\frac{1}{\sqrt{6}}T_1 + T_3\right) - S_1^* S_2 + \frac{1}{2}|S_3|^2 - \frac{1}{\sqrt{6}}T_1^*\left(\frac{1}{\sqrt{6}}T_1 - T_3\right) - \frac{1}{2}|T_2|^2 \right\},$$

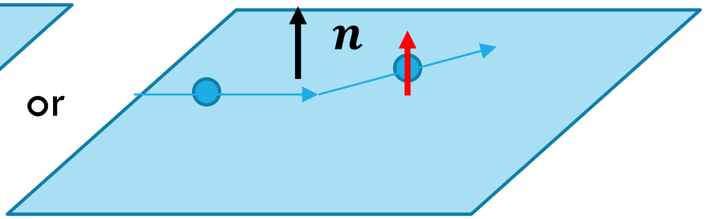
Analyzing power (Polarization)

Scattering with polarized Λ

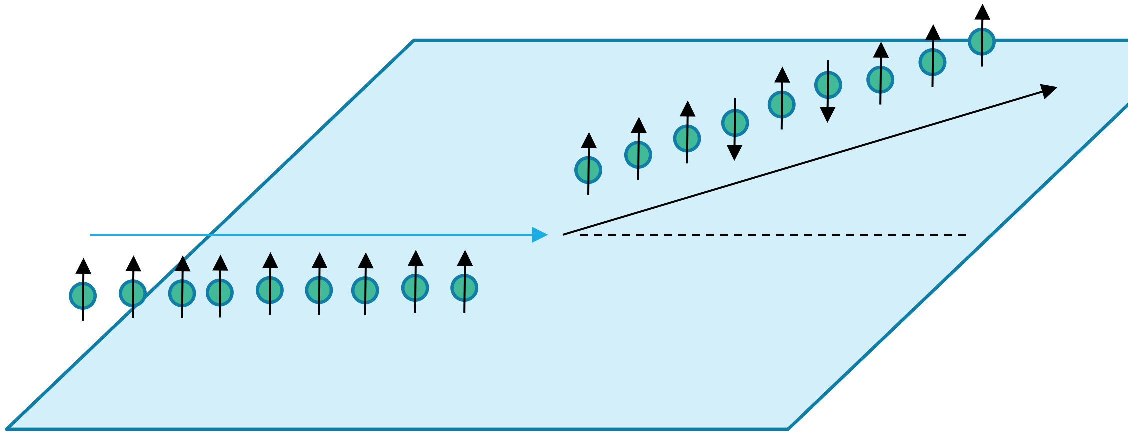


or

Measure polarization of scattered Λ with unpolarized Λ



Depolarization (D_y^y)



A lot of measurements of scattering observables enable us to investigate each matrix components

SUMMARY OF EXPERIMENTAL CONDITION

Beam time : ~1 month (w/ 20 M /spill π^- beam intensity)

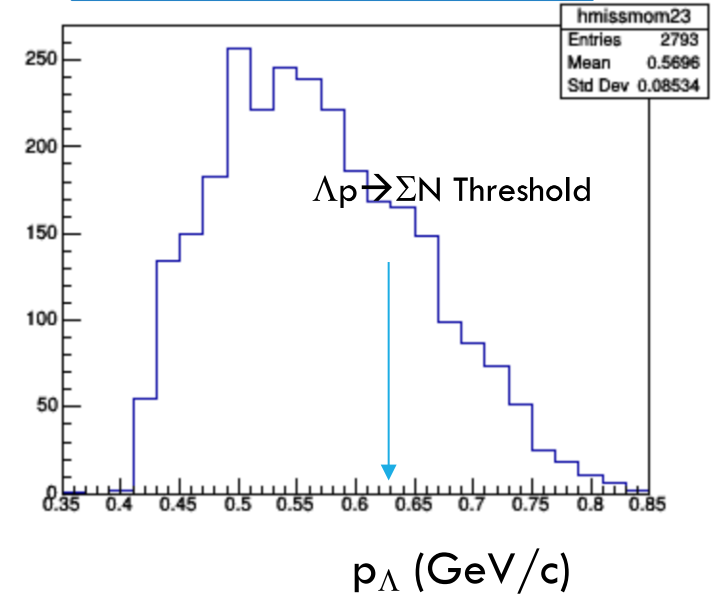
Λ beam

- Momentum range 0.4 ~ 0.8 GeV/c
- Λ beam yield : ~17 M (~0.55% of produced Λ can be tagged by SKS)
- ~100% polarization

Λp scattering

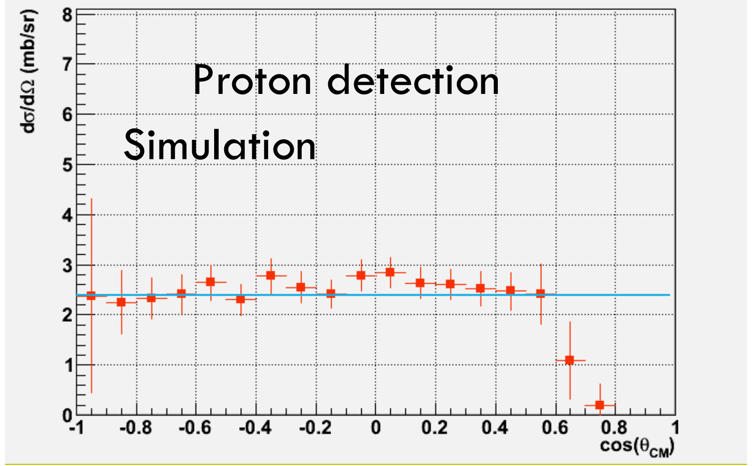
- Total cross section of 30 mb was assumed
- 10,000 Λp scattering events can be identified

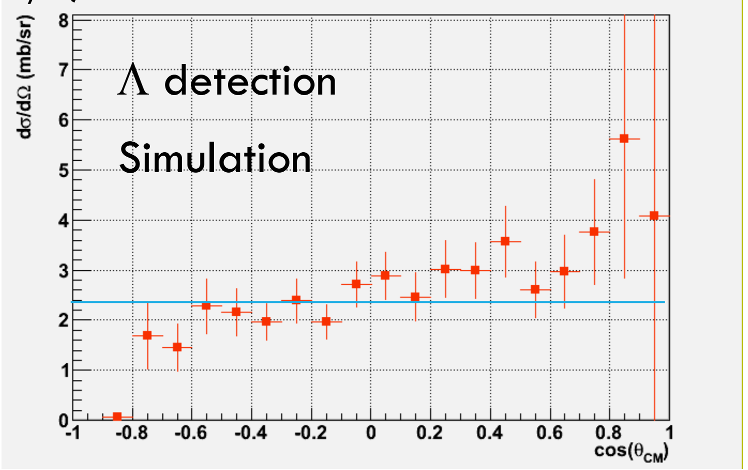
Tagged momentum distribution



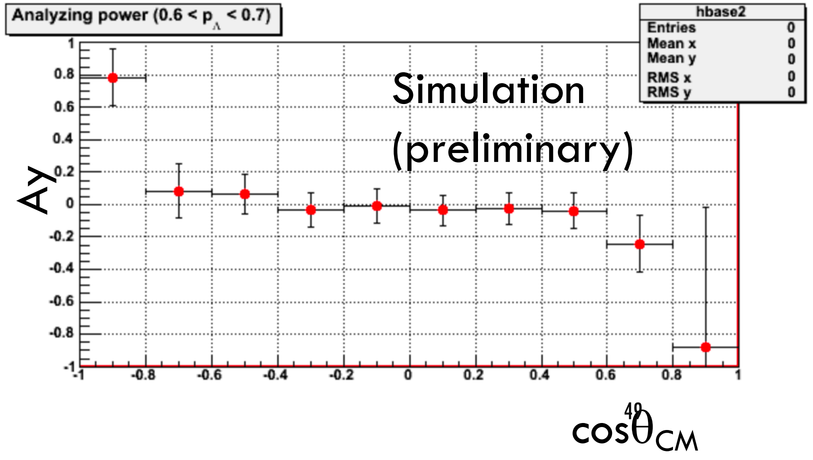
Differential cross section

0.5 < p (GeV/c) < 0.6





Analyzing power (Λ)

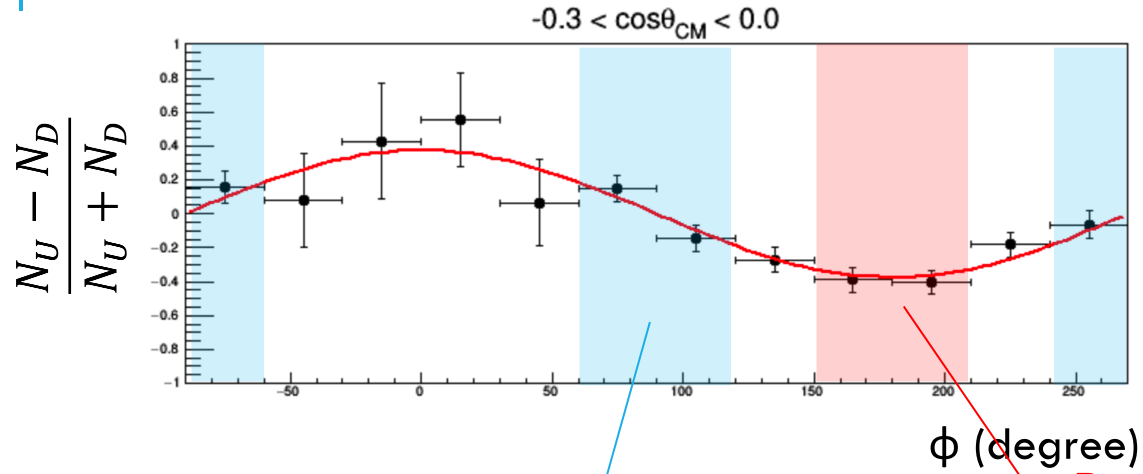


UP/DOWN ASYMMETRY FOR DEPOLARIZATION MEASUREMENT

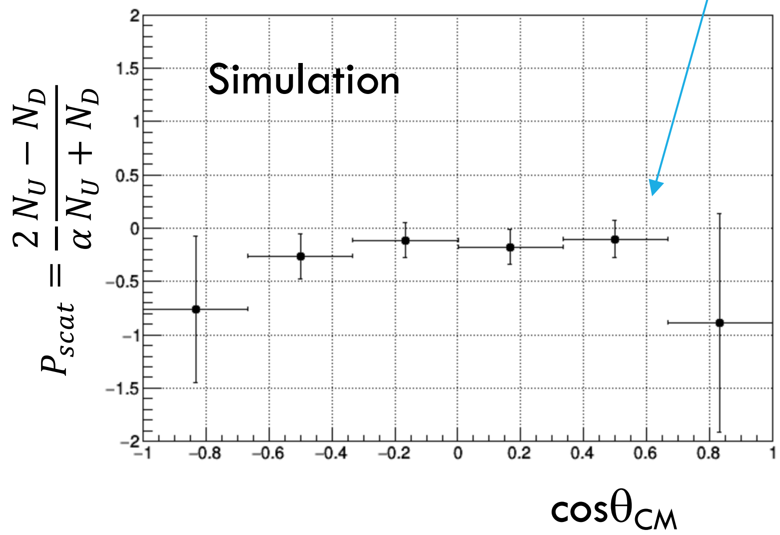
Polarization case ($P_{beam} = 1, P = 0, D_y^y = 1$)

$$P_{scat}(\phi = 180°) = \frac{P + D_y^y P_{beam}(\phi = 180°)}{1 + P P_{beam}(\phi = 180°)}$$

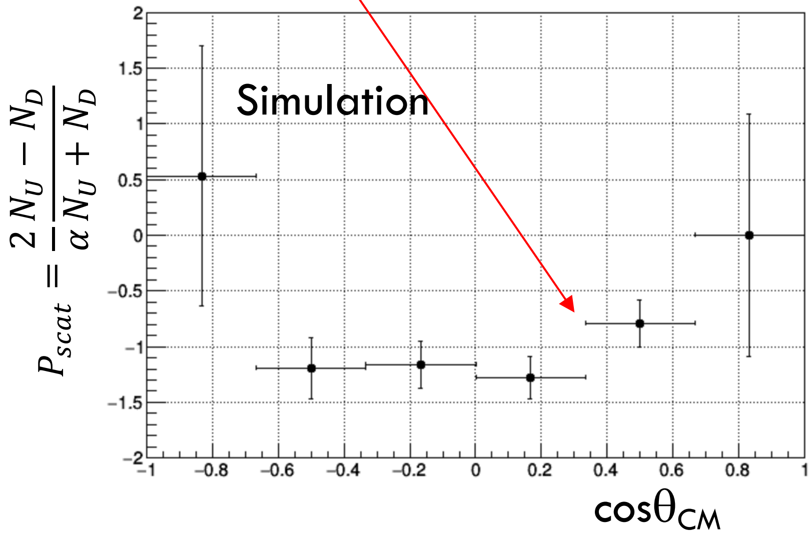
$P_{beam}(\phi = 180°) = -1$: should be measured



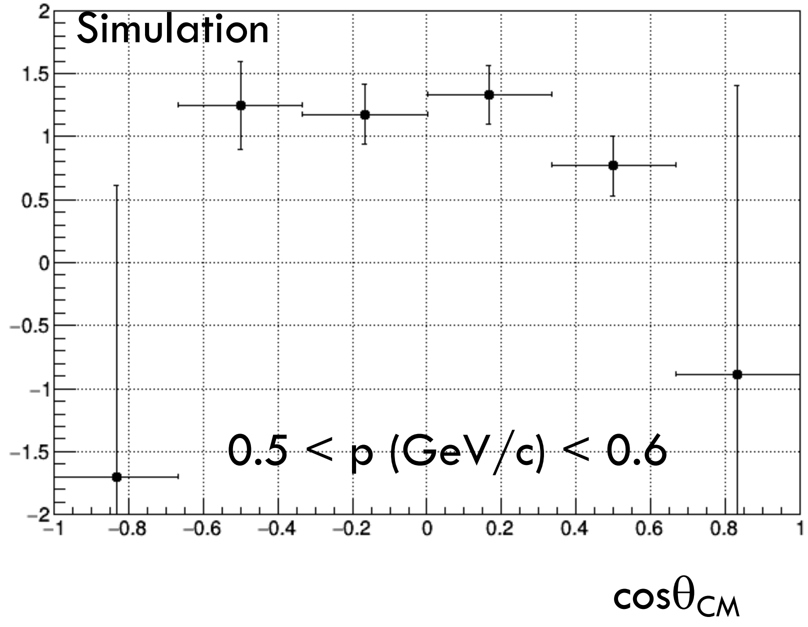
P : Polarization



P_{scat} ($\phi = 180°$)



D_y^y: Depolarization



SUMMARY

Hyperon-proton scattering experiment has become possible.

- Study of two-body YN interaction from scattering experiment is very important to understand two-body interaction without uncertainty from many-body system.

Σp scattering experiment at J-PARC

- ΣN interaction is a key to understand the origin of repulsive core in nuclear force.
- Σ^-p, Σ^-p→Λn, Σ^+p channels are clearly identified with much better statistics.
- Derived $d\sigma/d\Omega$ of pp and np scattering are consistent with partial wave analysis.
- Analysis is on going to derive differential cross section.
- Polarization in Σ^+p scattering might be obtained.

Prospect on Λp scattering

- Λ production by π^-p→$K^0\Lambda$ reaction was established.
- By using polarized Λ beam, we are planning a new experiment to measure $d\sigma/d\Omega$ and spin obserbables such as P_Λ and D_{yy}.

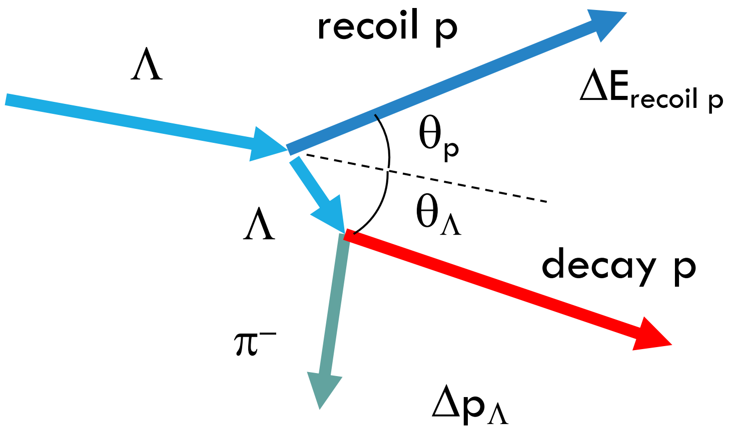
We want to keep close discussion with theorist to investigate YN interaction.

BACKUP

Λp scattering : Event category

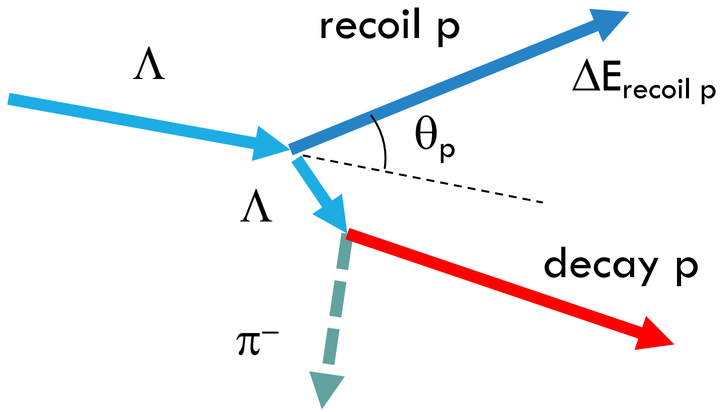
1. All particles can be detected

Kinematical check by both $\Delta E_{recoil\ p'}$ and Δp_{Λ}



2. two protons can be detected

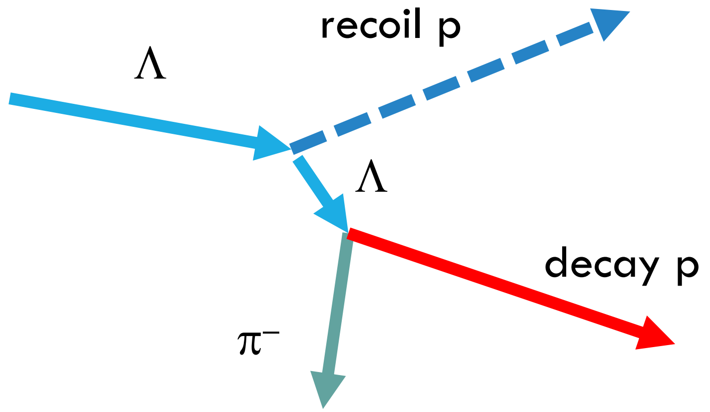
Kinematical check by $\Delta E_{recoil\ p'}$

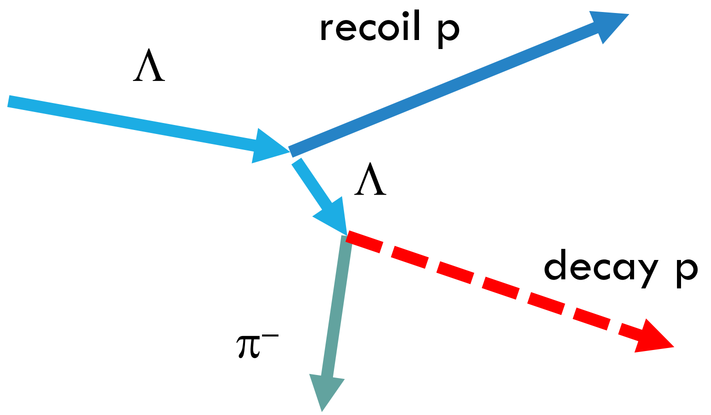


π^- can be identified by MissingMass($\Lambda_{scat} \rightarrow pX$)

3. 1 proton and 1 $\pi-$ can be obtained

Kinematical check by Δp_{Λ} or $\Delta E_{recoil\ p'}$

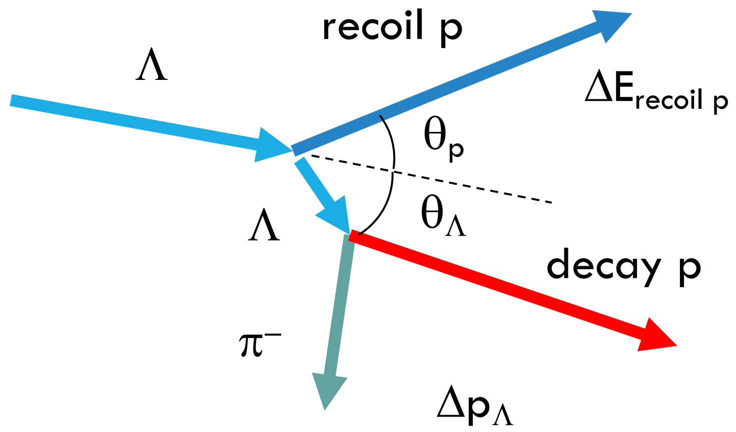




Λp scattering event might be identified even in the bad S/N ratio in missing mass spectrum

Start the Λp scattering analysis from case 1

Λp scattering identification



Kinematical consistency from recoil proton

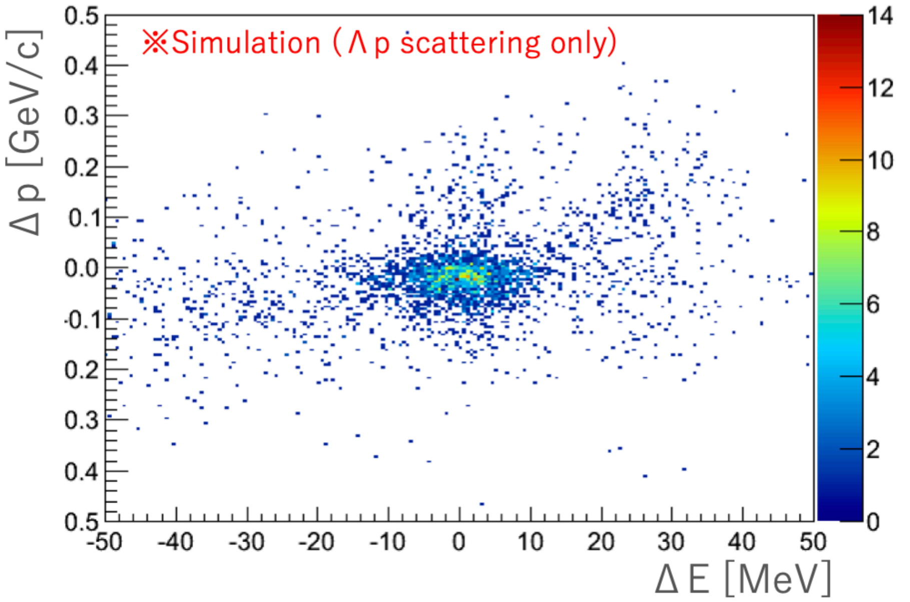
$\Delta E_{recoil\ p} = E_{measured} - E_{calc}(\theta_p)$

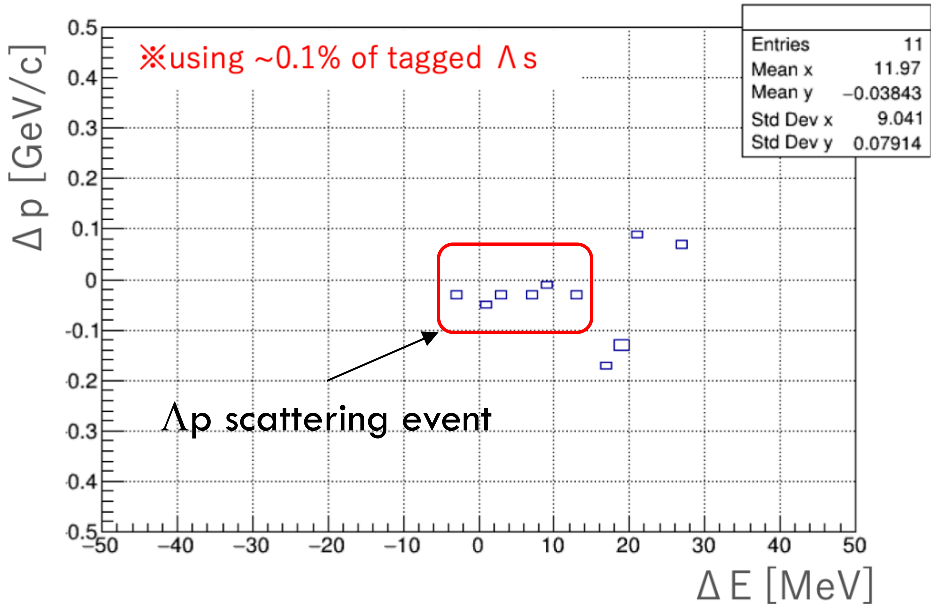
Kinematical consistency from scattered Λ

$\Delta p_\Lambda = p_{measured} - p_{calc}(\theta_\Lambda)$

Analysis by T. Sakao (Tohoku Univ.)

Correlation between Δp & ΔE

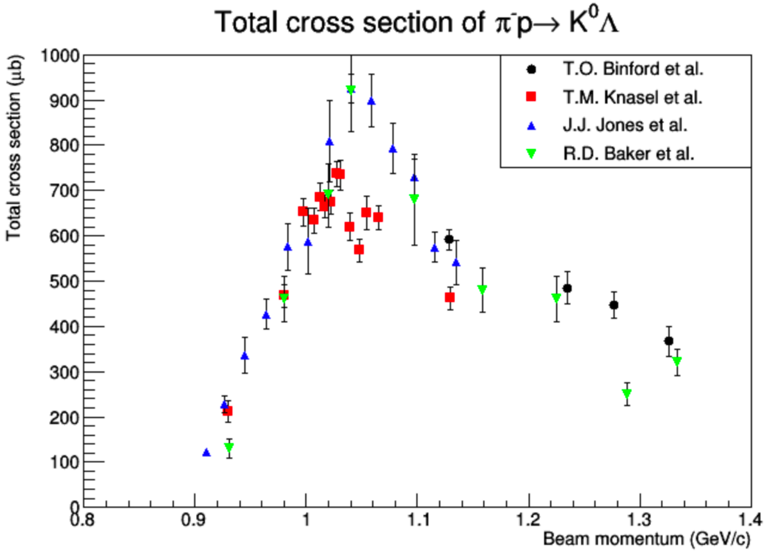




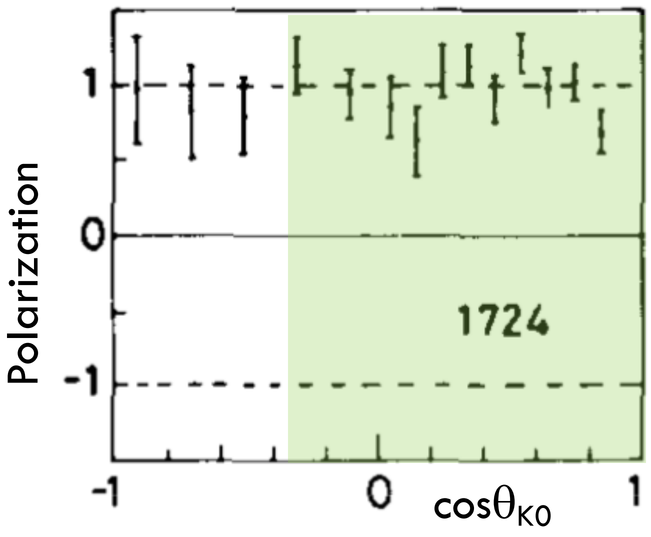
Future project : Λp scattering experiment

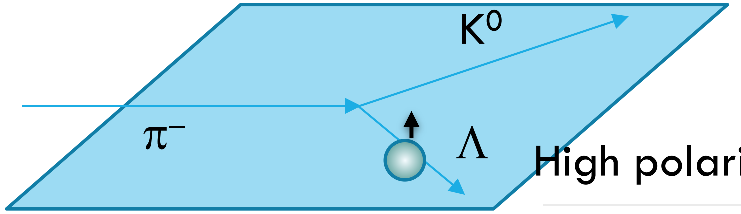
Planning to perform at (new) K1.1 beamline

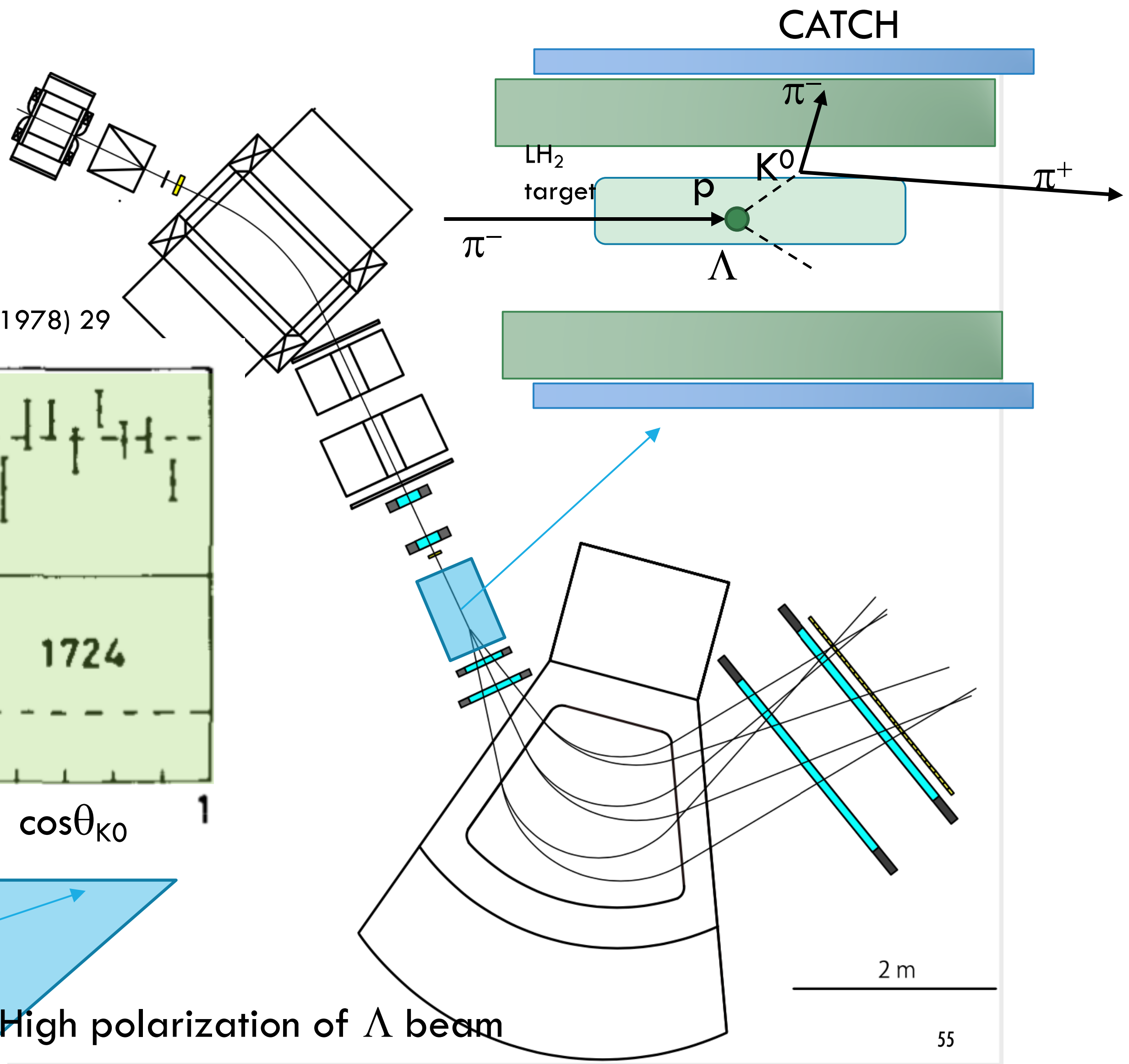
Λ production via $\pi^- p \rightarrow K^0 \Lambda$ at $p_{\pi-}$ = 1.05 GeV/c



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







High polarization of Λ beam

Conventional representation of elastic scattering

From S. Ishikawa et al.
PRC 69, 034001 (2004)

Scattering amplitude in $\frac{\vec{1}}{2}+\frac{\vec{1}}{2}\rightarrow\frac{\vec{1}}{2}+\frac{\vec{1}}{2}$ scattering : → 4 x 4 matrix

→ 6 components from the restriction of parity conservation and time-reversal invariance

spin-independent — spin-spin — symmetric LS (ΔS=0) — anti-symmetric LS (ΔS=1)

T matrix

$$\boldsymbol{M}=V_{\mathrm{c}}+V_{\sigma}(\boldsymbol{s}_a\cdot\boldsymbol{s}_b)+V_{\mathrm{SLS}}(\boldsymbol{s}_a+\boldsymbol{s}_b)\cdot\boldsymbol{L}+V_{\mathrm{ALS}}(\boldsymbol{s}_a-\boldsymbol{s}_b)\cdot\boldsymbol{L}+V_{\mathrm{T}}([\boldsymbol{s}_a\otimes\boldsymbol{s}_b]^{(2)}\cdot\boldsymbol{Y}_2(\hat{\boldsymbol{r}})),$$

Tensor

Scalar amplitude

$$U_\alpha\equiv\langle\boldsymbol{k}_{\mathrm{f}}|V_{\mathrm{c}}|\boldsymbol{k}_{\mathrm{i}}\rangle,$$

$$U_\beta\equiv\langle\boldsymbol{k}_{\mathrm{f}}|V_{\sigma}|\boldsymbol{k}_{\mathrm{i}}\rangle,$$

→

$$U_0=U_\alpha-\tfrac{3}{4}U_\beta,$$

$$U_1=\sqrt{3}\left(U_\alpha+\tfrac{1}{4}U_\beta\right),$$

Vector amplitude

$$S_\alpha\equiv\langle\boldsymbol{k}_{\mathrm{f}}|V_{\mathrm{ALS}}L_1|\boldsymbol{k}_{\mathrm{i}}\rangle,$$

$$S_\beta\equiv\langle\boldsymbol{k}_{\mathrm{f}}|V_{\mathrm{SLS}}L_1|\boldsymbol{k}_{\mathrm{i}}\rangle,$$

→

$$S_1=-S_2=-S_\alpha,$$

$$S_3=\sqrt{2}S_\beta.$$

Tensor amplitude

The tensor amplitudes T_j $(j=1,2,3)$ are calculated as

$$T_j=\tfrac{1}{2}\langle\boldsymbol{k}_{\mathrm{f}}|V_{\mathrm{T}}Y_{2,j-1}|\boldsymbol{k}_{\mathrm{i}}\rangle, \quad (18$$

↓

$$T_\alpha=\frac{1}{\sqrt{6}}T_1+T_3,$$

$$T_\beta=\frac{1}{\sqrt{6}}T_1-T_3,$$

We want to derive these scattering amplitudes separately.

Scattering observables

From S. Ishikawa et al.
PRC 69, 034001 (2004)

Differential cross section

$$\sigma(\theta) = \frac{1}{4}\mathrm{Tr}\left(\mathcal{M}\mathcal{M}^{\dagger}\right) = |U_\alpha|^2 + \frac{3}{16}|U_\beta|^2 + \frac{1}{2}(|S_{\mathrm{SLS}}|^2 + |S_{\mathrm{ALS}}|^2) + \frac{1}{4}|T_1|^2 + \frac{1}{2}(|T_2|^2 + |T_3|^2)$$

Analyzing power (Polarization)

$$A_y(a) = -\frac{4\sqrt{2}}{N_R}\mathrm{Im}\left\{ U_\alpha^*(S_\alpha + S_\beta) + \frac{1}{4}U_\beta^*(-S_\alpha + S_\beta) \quad -\frac{1}{2}T_\alpha^*(-S_\alpha + S_\beta)\right\},$$

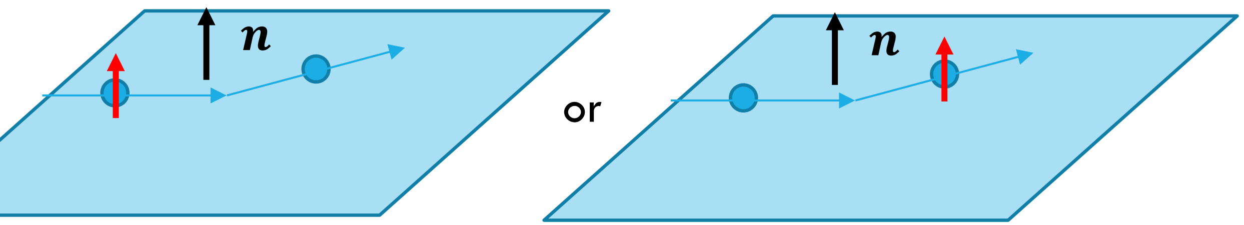
Depolarization

$$D_y^y(a) = \frac{4}{N_R}\mathrm{Re}\left\{ \frac{1}{2\sqrt{3}}\left(U_0 + \frac{1}{\sqrt{3}}U_1\right)^* U_1 + \frac{1}{2}\left(U_0 - \frac{1}{\sqrt{3}}U_1\right)^* \times \left(\frac{1}{\sqrt{6}}T_1 + T_3\right) - S_1^* S_2 + \frac{1}{2}|S_3|^2 - \frac{1}{\sqrt{6}}T_1^*\left(\frac{1}{\sqrt{6}}T_1 - T_3\right) - \frac{1}{2}|T_2|^2 \right\},$$

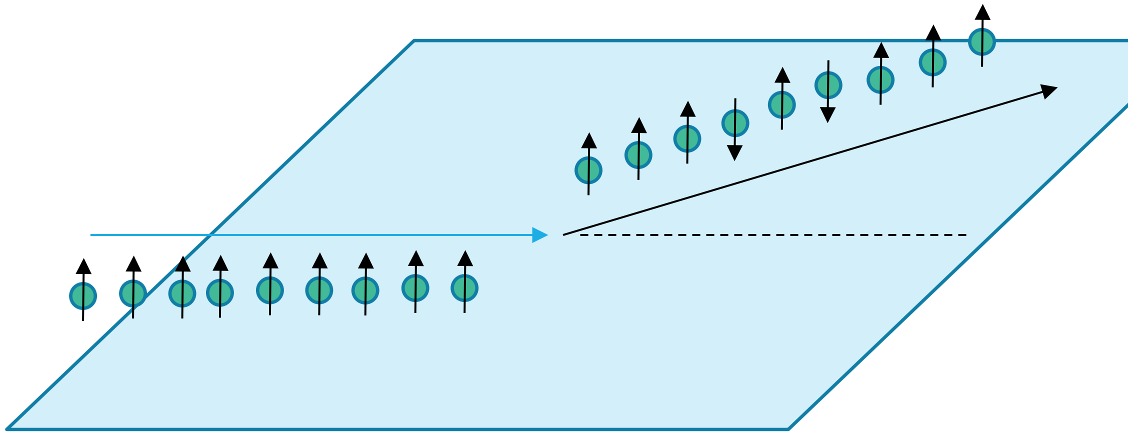
Analyzing power (Polarization)

Scattering with polarized Λ

Measure polarization of scattered Λ with unpolarized Λ



Depolarization (D_y^y)



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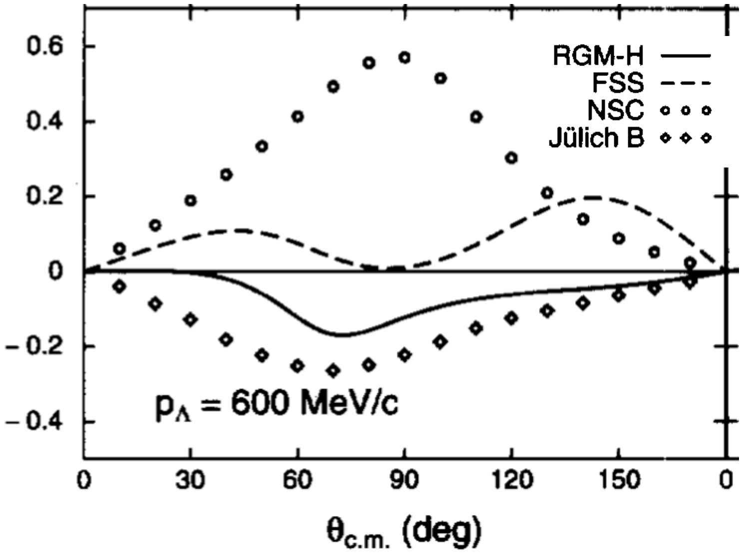
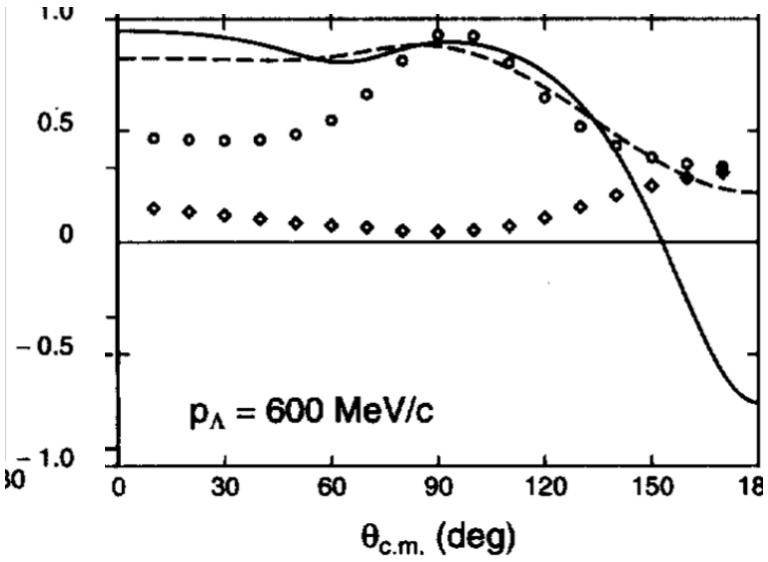
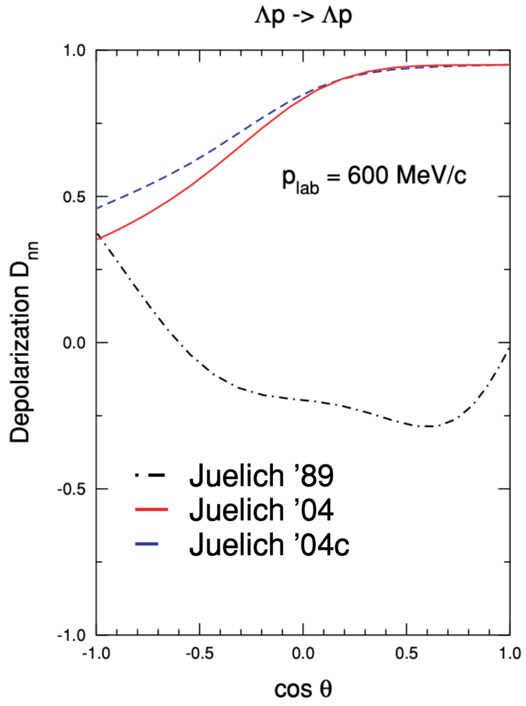
Polarization of Λ in Λp elastic scattering



Depolarization in Λp elastic scattering





T. Fujita et al., PTP 100 (1998) 931

J. Haidenbauer et al., Phys. Rev. C72, (2005), 044005

Summary of experimental condition

Beam time : ~1 month (w/ 20 M /spill π^- beam intensity)

Λ beam

- Momentum range 0.4 ~ 0.8 GeV/c
- Λ beam yield : ~17 M (~0.55% of produced Λ can be tagged by SKS)
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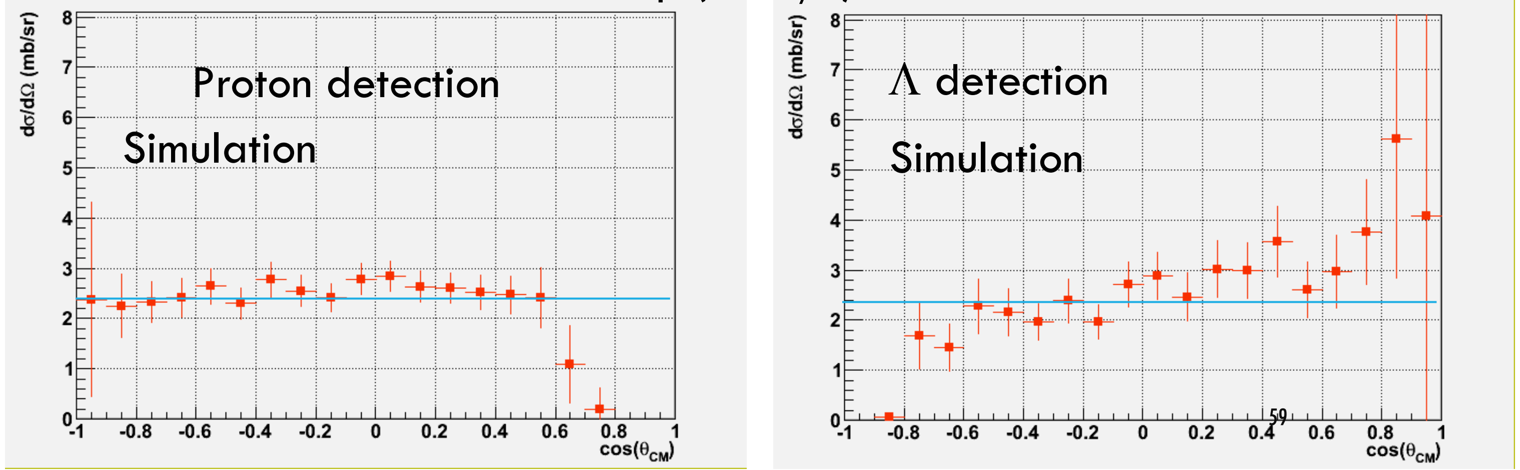
0.5 < p (GeV/c) < 0.6

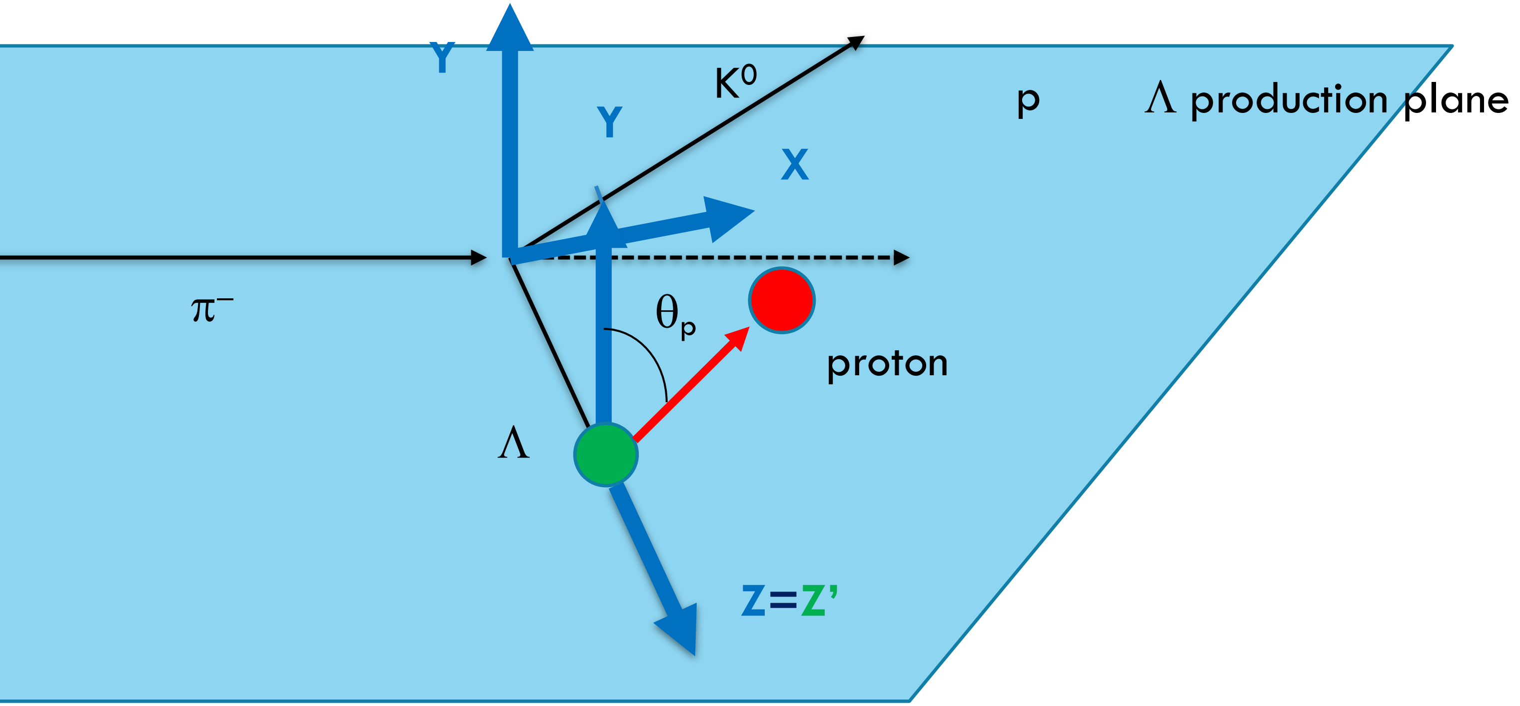


Definition of quantization axis

$\mathbf{Y} = \mathbf{P}_{\pi-} \times \mathbf{P}_{K0}$

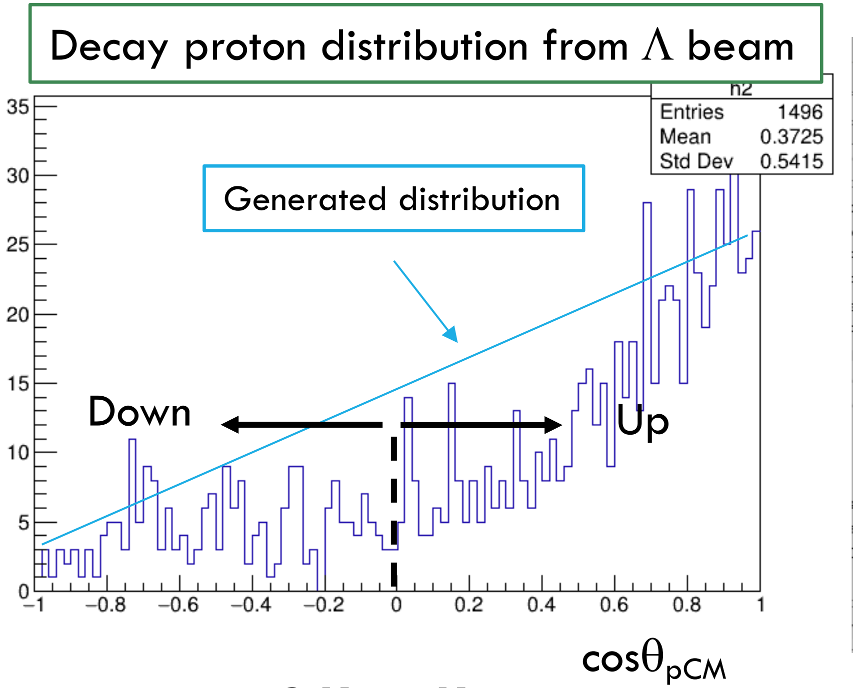
$\mathbf{X} = \mathbf{Y} \times \mathbf{P}_{\Lambda beam}$

$\mathbf{Z} = \mathbf{P}_{\Lambda beam}$



Λ beam polarization

$$\frac{1}{N_0}\frac{dN}{d\cos\theta_p} = \frac{1}{2}\left(1 + \alpha P_{beam}\cos\theta_p\right)$$



$$P_{beam} \sim \frac{2}{\alpha}\frac{N_U - N_D}{N_U + N_D}$$

$$\alpha = 0.750 \pm 0.009 \pm 0.004$$

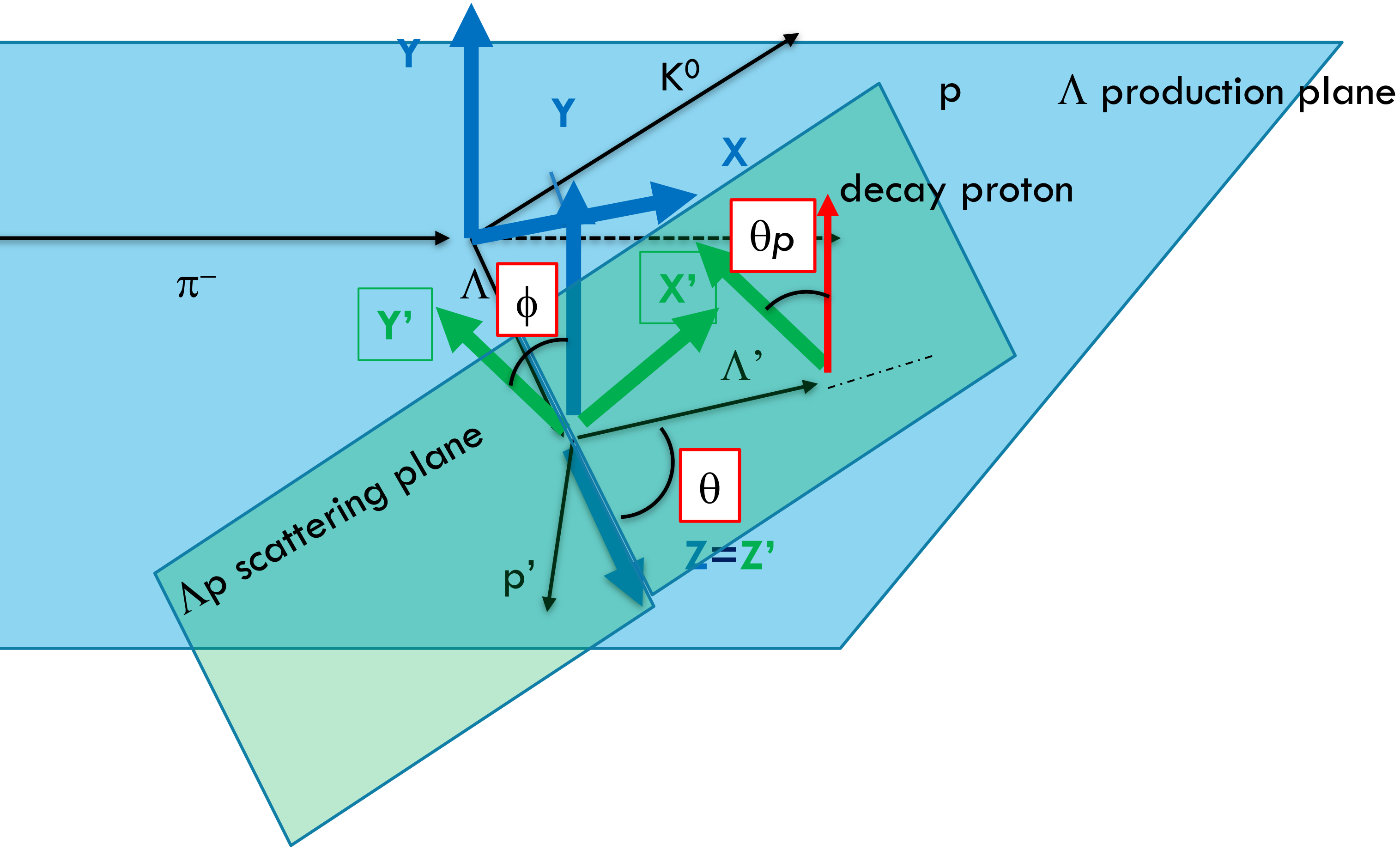
(BESⅢ M. Ablikim et al. arXiv:1808.08917)

Definition of quantization axis

Y = **P**$_{\pi-}$ x **P**$_{K0}$

X = **Y** x **P**$_{\Lambda beam}$

Z = **P**$_{\Lambda beam}$



Beam Λ polarization

$$P_{beam} = P(\phi = 0) \times \cos\phi$$

$\phi = 0, 180^{O}$ Maximum polarization

$\phi = 90, 270^{O}$ Unpolarized beam

Scattered Λ polarization

$$P_{scat} = \frac{2}{\alpha} \frac{N_U - N_D}{N_U + N_D}$$

$$\alpha = 0.750 \pm 0.009 \pm 0.004$$

(BESIII M. Ablikim et al. arXiv:1808.08917)

$$N_U : 0 < \theta_p(deg) < 90$$

$$N_D : 90 < \theta_p(deg) < 180$$

Up/Down asymmetry for depolarization

No beam polarization case

Spin polarization in the final state

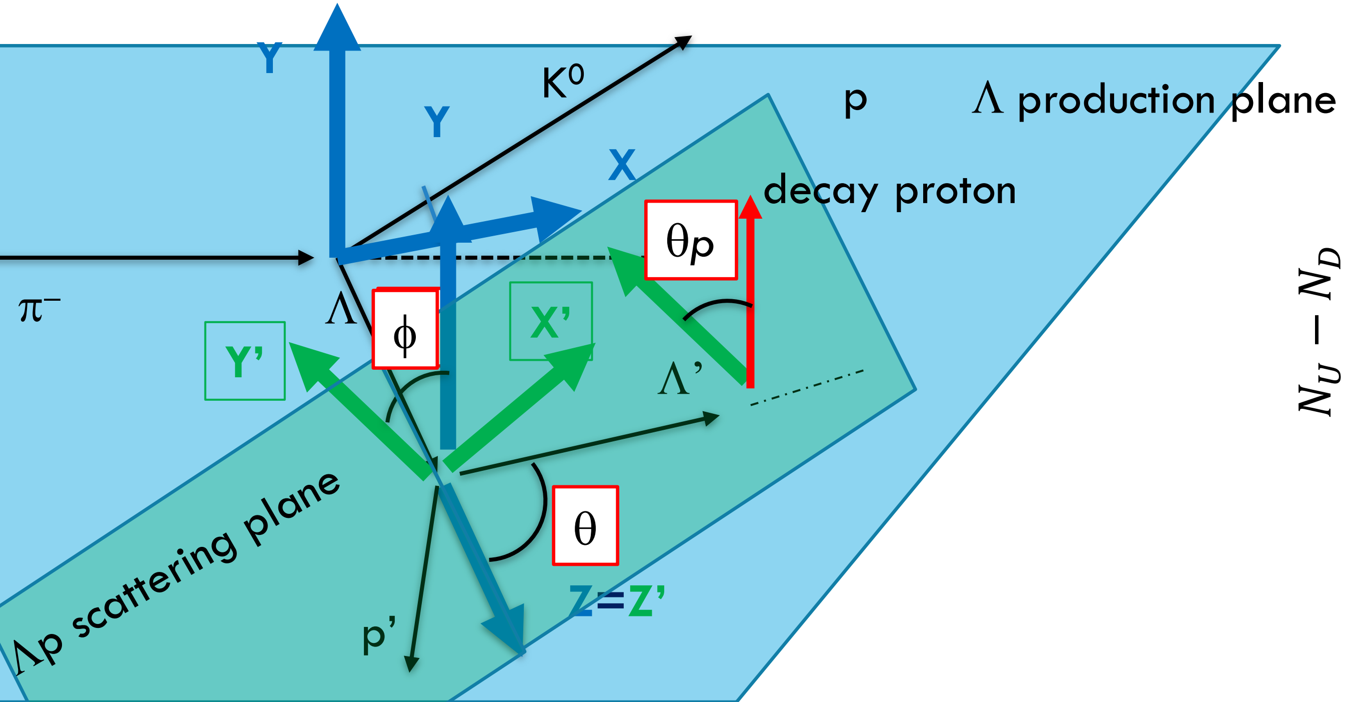
$$P_{scat} = \frac{2}{\alpha}\frac{N_U - N_D}{N_U + N_D} = \frac{P + D_y^y P_{beam}}{1 + PP_{beam}}$$

P_{beam} : Polarization of beam

$$P_{beam} = P(\phi = 0)\times \cos\phi$$

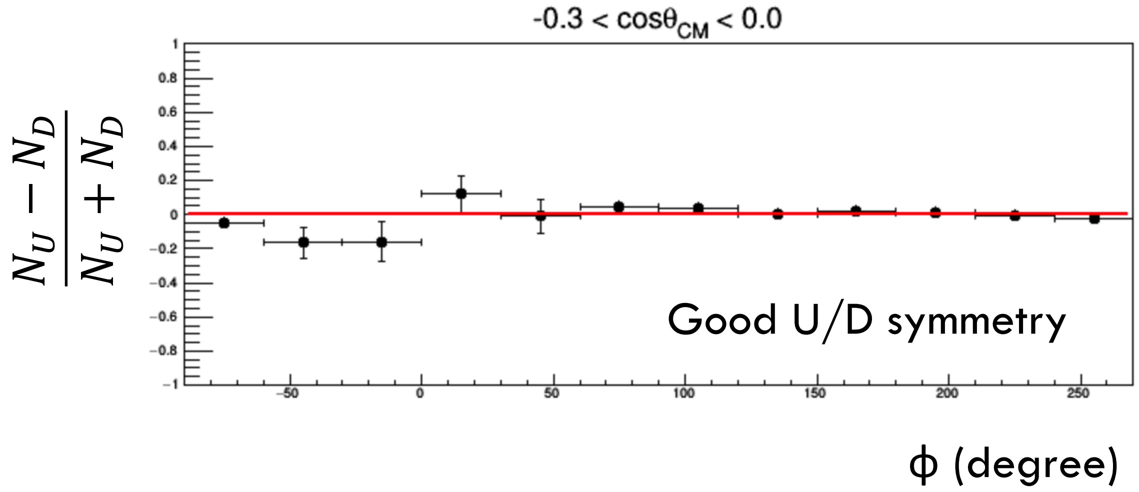
P : Induced polarization by the unpolarized beam

D_y^y : Depolarization



No polarization case ($P_{beam} = 0, P = 0$)

for symmetry study of detector



Up/Down asymmetry for depolarization

Polarized case

Spin polarization in the final state

$$P_{scat} = \frac{2}{\alpha}\frac{N_U - N_D}{N_U + N_D} = \frac{P + D_y^y P_{beam}}{1 + P P_{beam}}$$

P_{beam} : Polarization of beam

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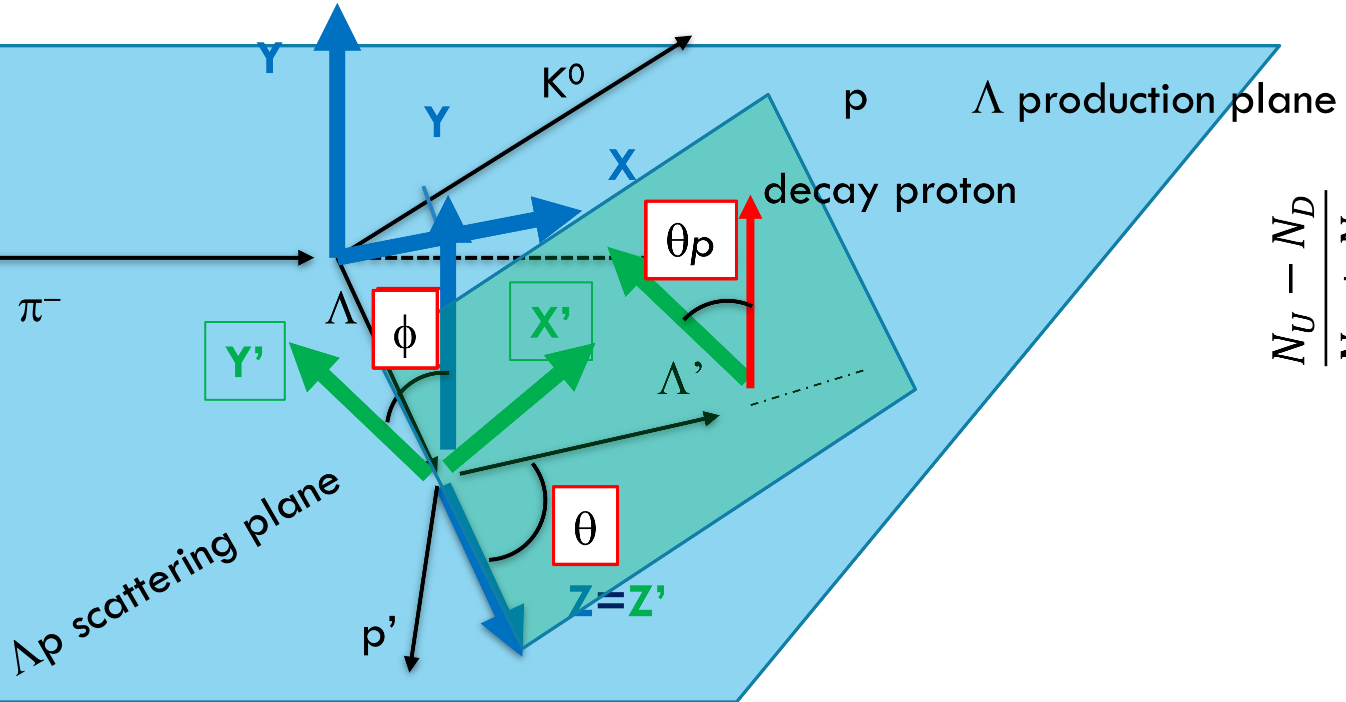
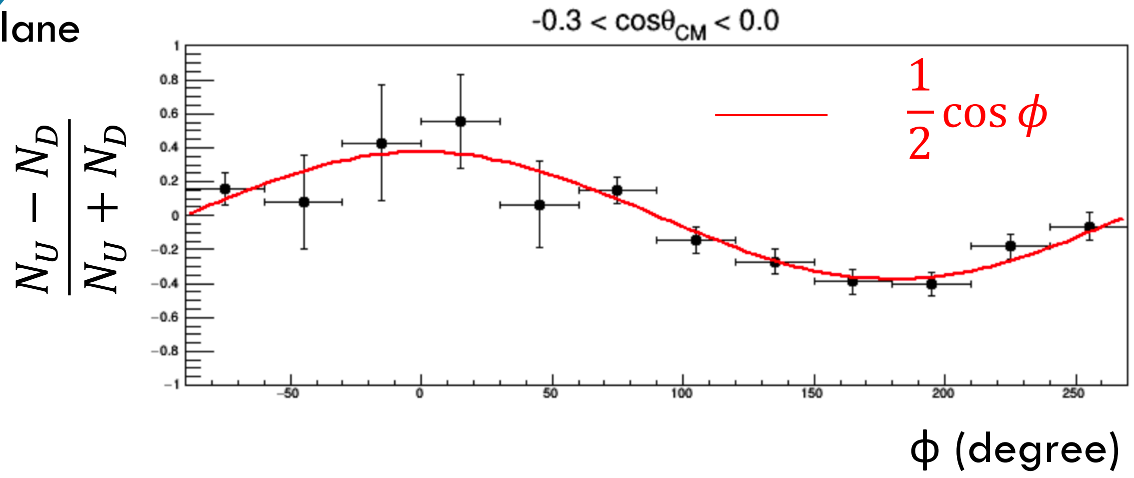


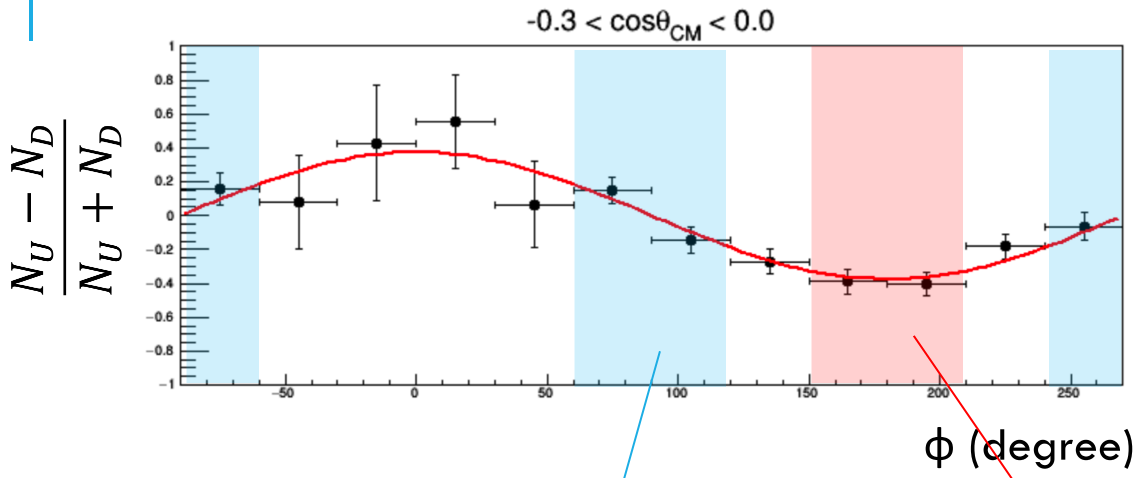
Polarization case ($P_{beam} = 1, P = 0, D_y^y = 1$)



ϕ dependence of U/D asymmetry can be observed

Up/Down asymmetry for depolarization measurement

Polarization case ($P_{beam} = 1, P = 0, D_y^y = 1$)



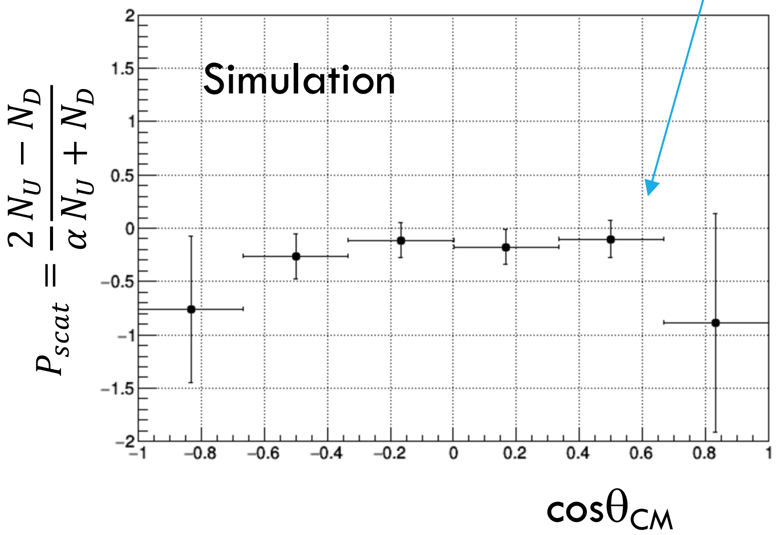
ϕ~90, 270 deg

$P_{beam} = 0 \rightarrow P_{scat} = P$, Polarization can be measured

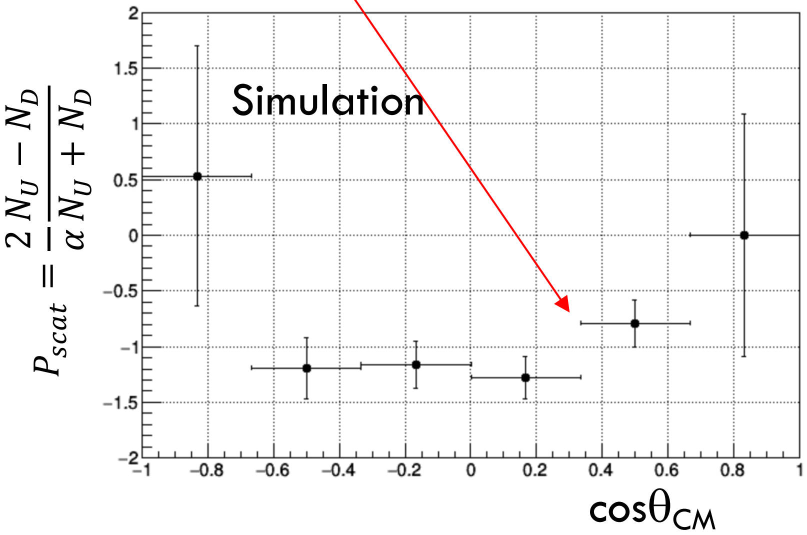
ϕ~180 deg

P_{beam} maximum → $P_{scat} = \frac{P + D_y^y P_{beam}}{1 + P P_{beam}}$, D_y^y can be measured

P : Polarization



P_{scat} (ϕ = 180°)



Up/Down asymmetry for depolarization measurement

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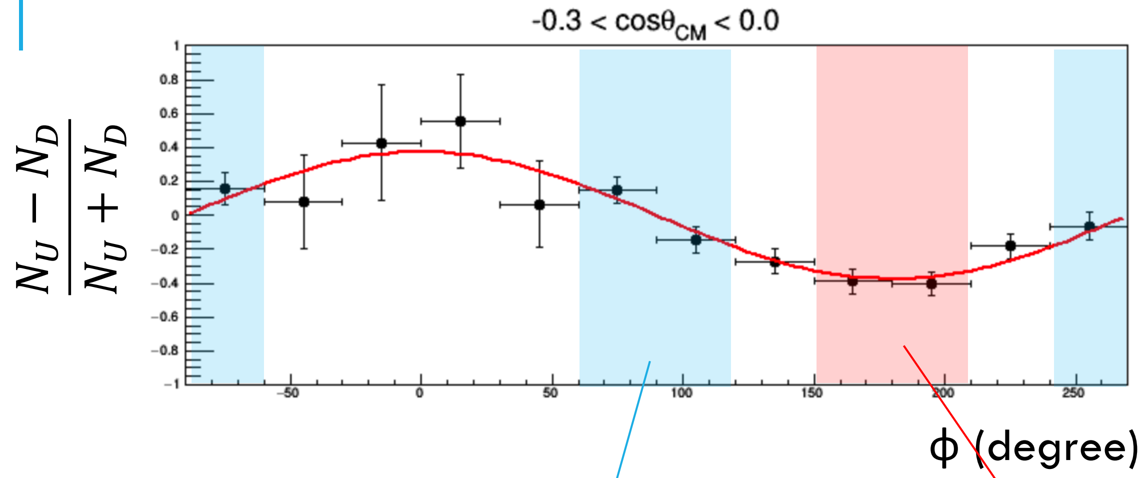
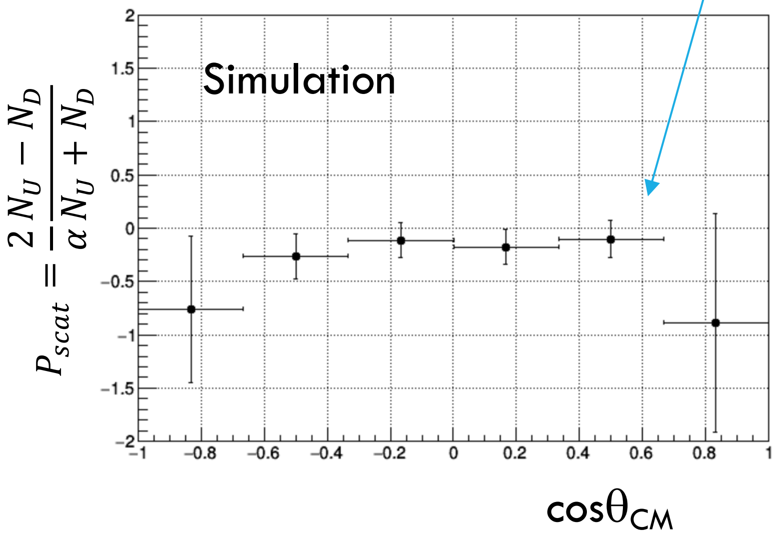


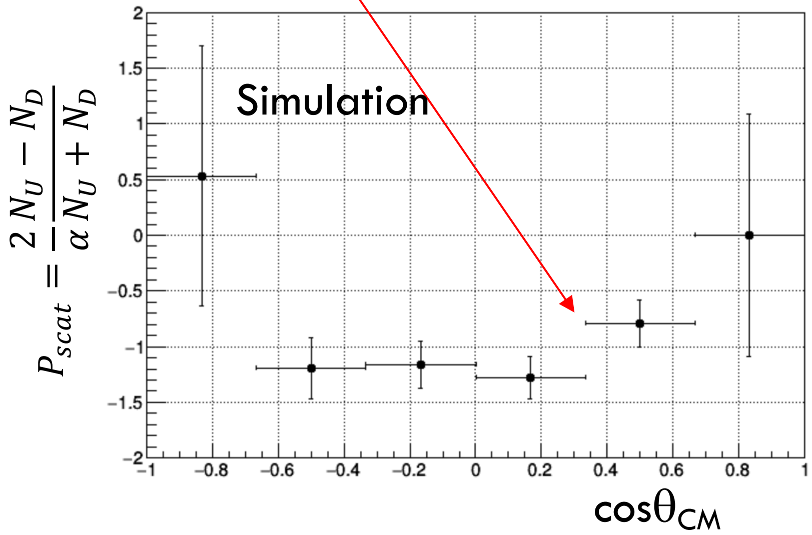
$$P_{scat}(\phi = 180°) = \frac{P + D_y^y P_{beam}(\phi = 180°)}{1 + P P_{beam}(\phi = 180°)}$$

$P_{beam}(\phi = 180°) = -1$: should be measured

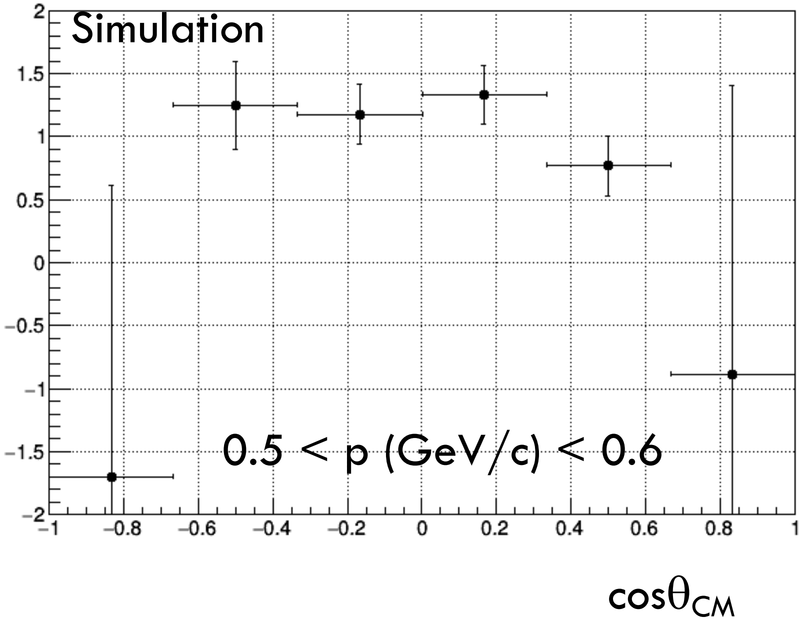
P : Polarization



P_{scat} ($\phi = 180°$)



D_y^y: Depolarization



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- Study of two-body YN interaction from scattering experiment is very important to understand two-body interaction without uncertainty from many-body system.

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- Σ^-p, Σ^-p→Λn, Σ^+p channels are clearly identified with much better statistics.
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Prospect on Λp scattering

- Λ production by π^-p→$K^0\Lambda$ reaction was established.
- By using polarized Λ beam, we are planning a new experiment to measure $d\sigma/d\Omega$ and spin obserbables such as P_Λ and D_{yy}.

We want to keep close discussion with theorist to investigate YN interaction.

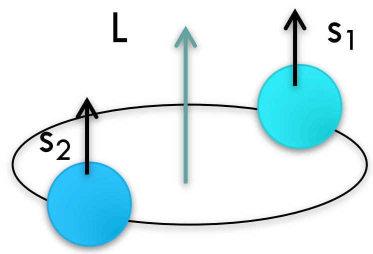
YN INTERACTION IN S=−1 SECTOR

	^{1}E or ^{3}O	^{3}E or ^{1}O
NN (I=0)	Forbidden by isospin symmetry	(27)
NN (I=1)	(10*)	-----
ΛN (I=1/2)	$1/\sqrt{10}[(8_s) + 3(27)]$	$1/\sqrt{2}[-(8_a) + (10^*)]$
ΣN(I=1/2)	$1/\sqrt{10}[3(8_s) - (27)]$	$1/\sqrt{2}[(8_a) + (10^*)]$
ΣN(I=3/2)	(27)	(10)

$LS^{(-)}$ OK

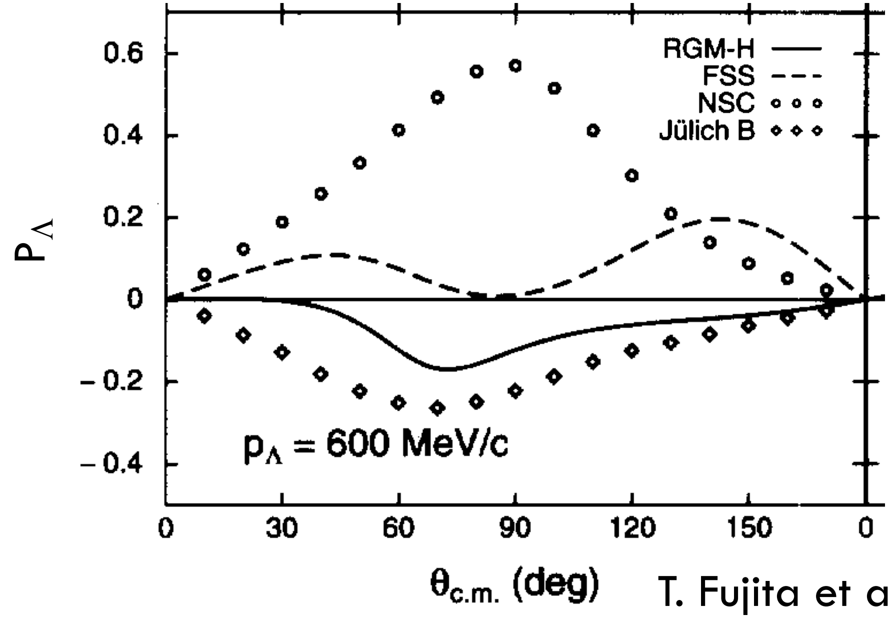
New type of LS force appears in YN sector

Anti-symmetric $LS^{(-)}$ force : $V_{ALS} L\bullet(s_1 - s_2)$



Spin singlet $\xleftrightarrow{LS^{(-)}}$ Spin triplet

Polarization of Λ in Λp elastic scattering



T. Fujita et al., PTP 100 (1998) 931

- Quark based model
  - Large ALS originated from coupling between (8s) and (8a) by one gluon exchange
- Boson exchange model
  - No large ALS contribution

Difference theoretical prediction

- Polarization, Analyzing power
- Cross section

Baryon-Baryon Interaction

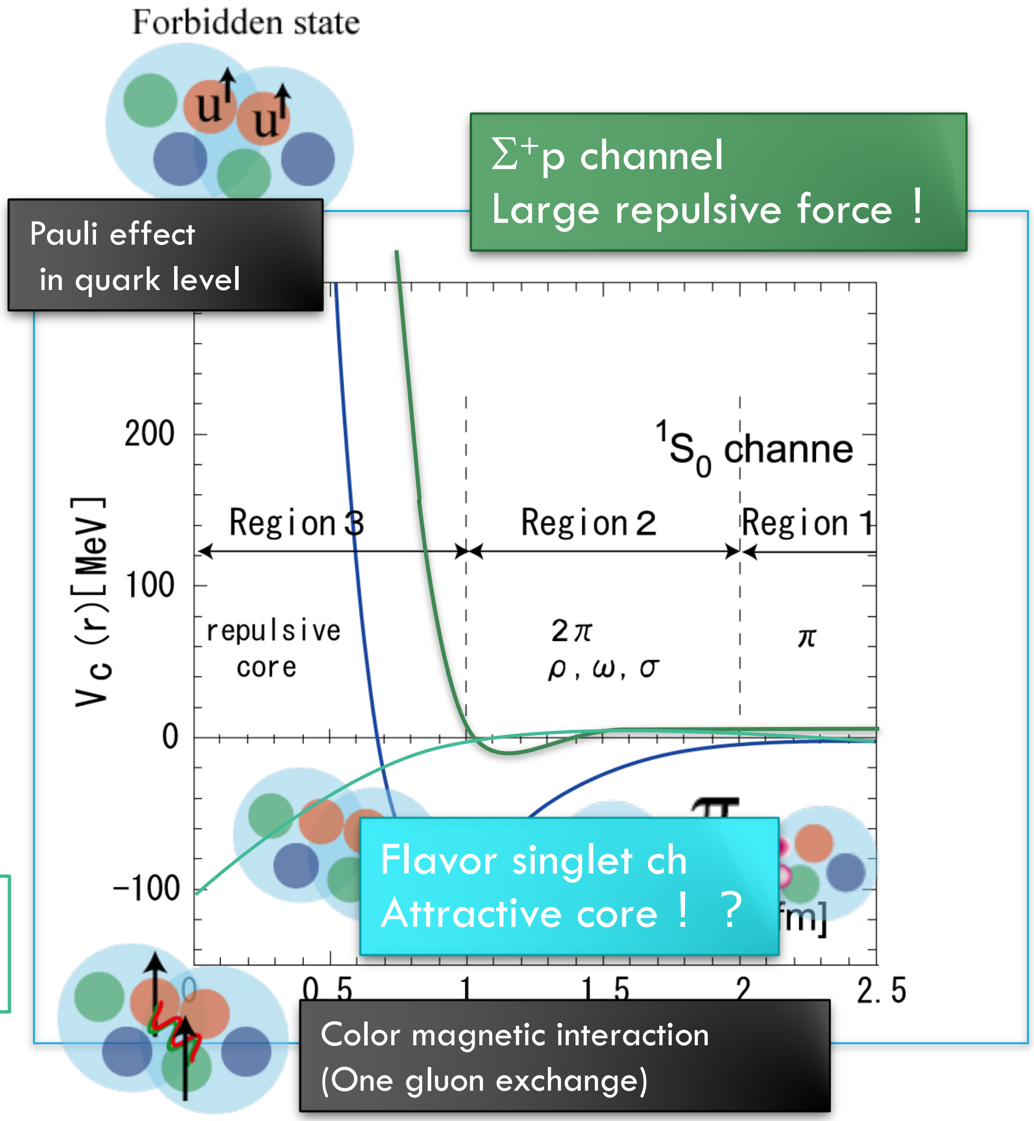
Investigation of BB interaction

- Basic information to describe the system with Hyperon
  - Hypernuclei
  - High density matter inside neutron star
- Origin of short-range core

Short range interaction by
Quark Cluster model

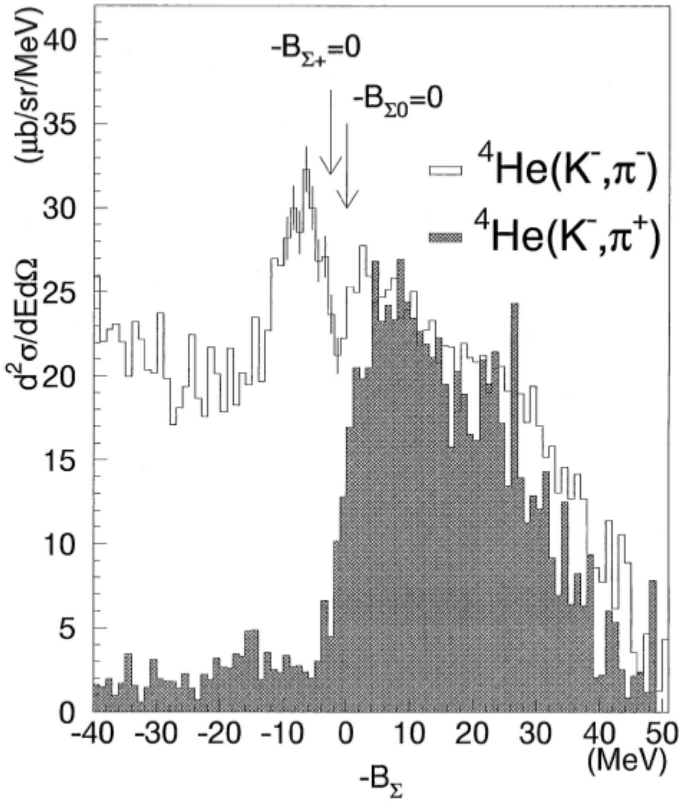
- Pauli effect in quark level
- Color magnetic interaction

YN, YY interactions show rich aspect especially in short range region



Σ hypernucleus and ΣN interaction

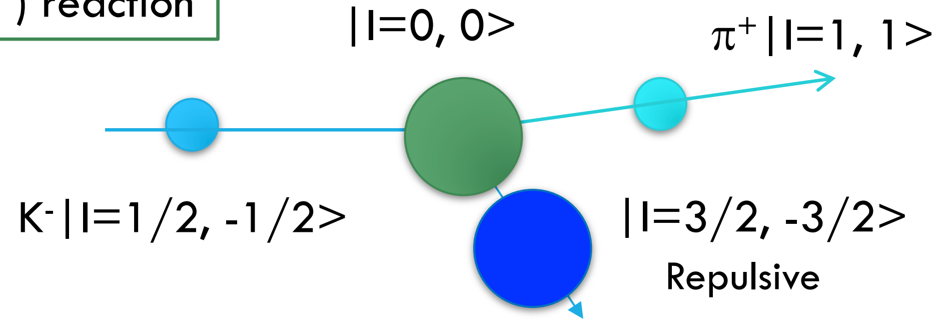
$^4_\Sigma$He : only observed bound Σ hypernucleus



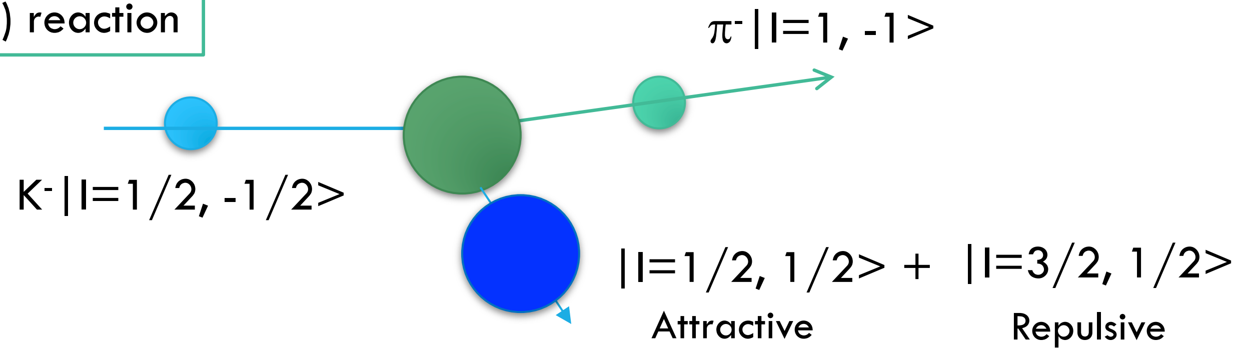
T. Nagae *et al.*, Phys. Rev. Lett. 80 (1998) 1605

	S=0	S=1
ΣN(I=1/2)	$1/\sqrt{10}[3(8_s) - (27)]$	$1/\sqrt{2}[(8_a) + (10^*)]$
ΣN(I=3/2)	(27)	(10)

^{4}He (K^-, π^+) reaction



^{4}He (K^-, π^-) reaction



Suggest large isopin-(spin) dependence of SN interaction

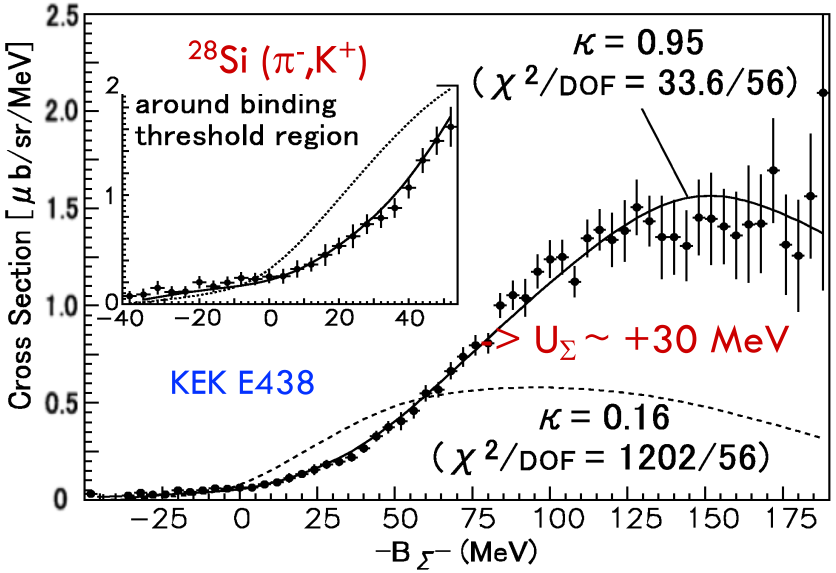
Σ hyperon in light and medium heavy nuclei

Σ-nucleus potential

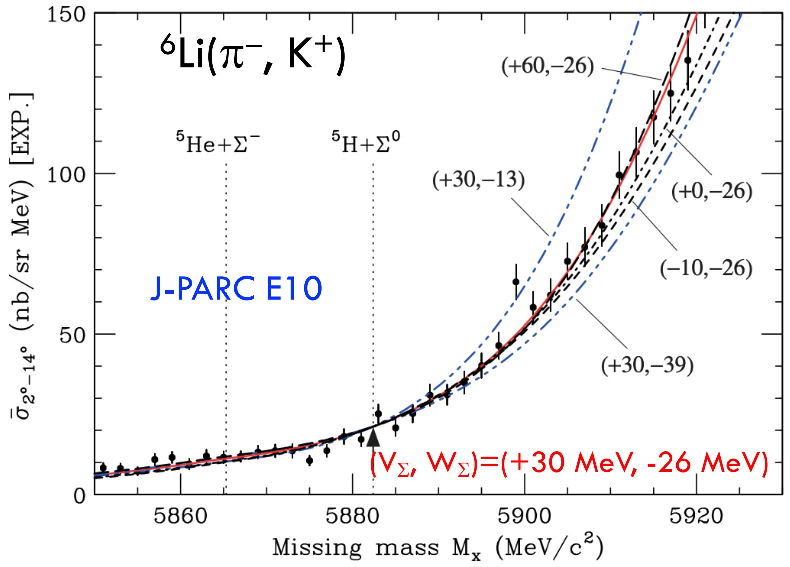
$$U_0^{\Sigma} + U_\tau^{\Sigma}(T_c t_\Sigma)/A_{core}$$

spin-isospin averaged potential   Lane's term : isospin dependent potential

Spin-isospin averaged potential can be studied from shape of quasi-free Σ^- production spectrum in medium heavy nuclei



P.K. Saho et al.;Phys.Rev.C70(2004)044613



T. Harada, R. Honda, Y. Hirabayashi,
Phys. Rev. C97 (2018) 024601

Σ feels repulsive potential in nuclei