Systematic measurements of the differential cross sections of Sigma-proton scatterings at J-PARC

Koji Miwa (Tohoku Univ./ KEK)

for the J-PARC E40, P86 Collaborations

The 20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023),
Genova, Italy, J**une 5th to 9th 2023**.,

Contents

- Introduction
- Σp scattering experiment (J-PARC E40)
  - Σ^-p channels (Differential cross sections)
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- Future project : Λp scattering with polarized Λ beam
- Summary

Realistic nuclear force : base for nuclear physics

Realistic Nucleon-Nucleon Potential (CD Bonn, AV18, Nijmegen I, II)

Updated based on a lot of scattering observables of NN scattering

Solid base for nuclear studies

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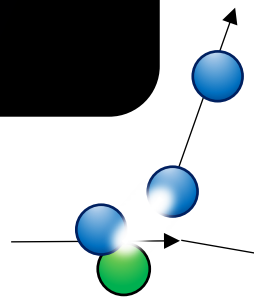
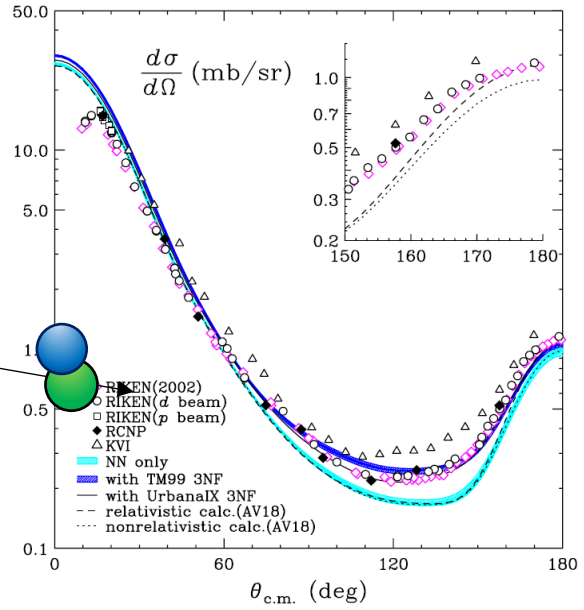


Nucleon-Deuteron scattering



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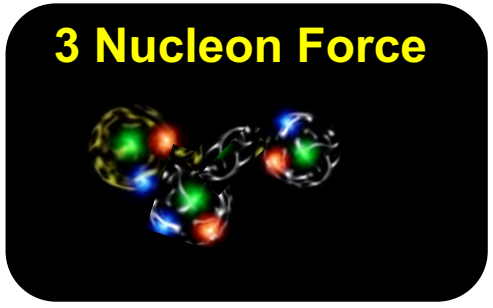

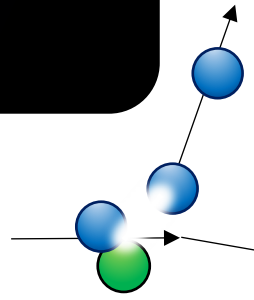

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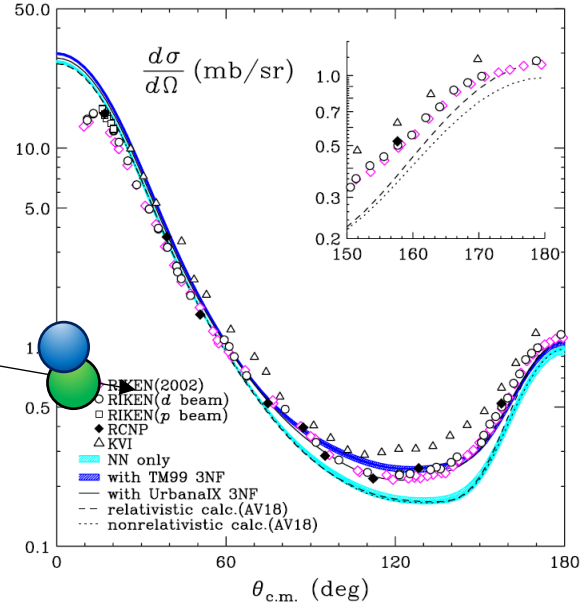

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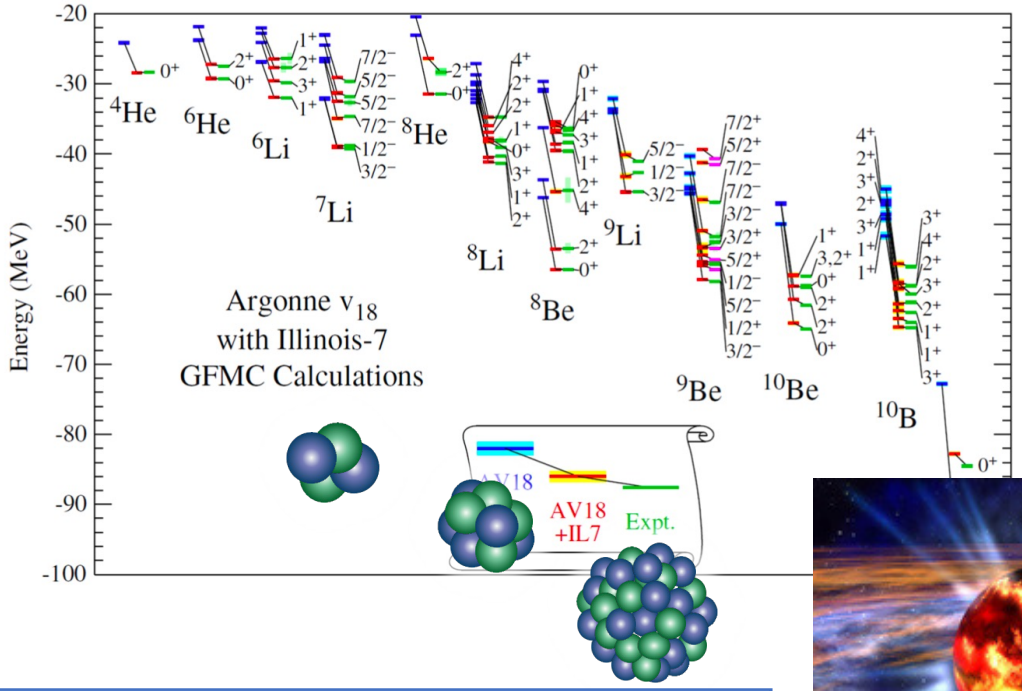
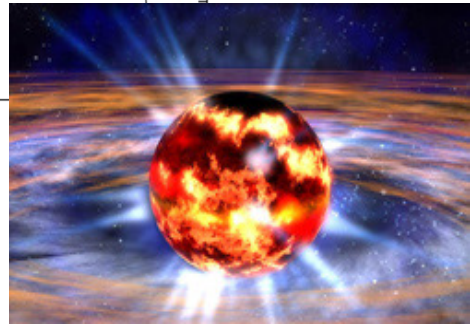
Nuclear binding energy

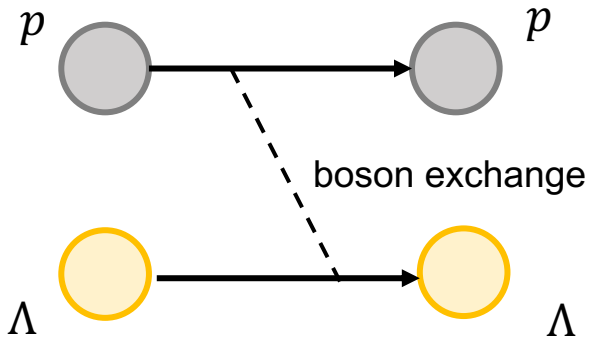


Equation of State of Nuclear Matter



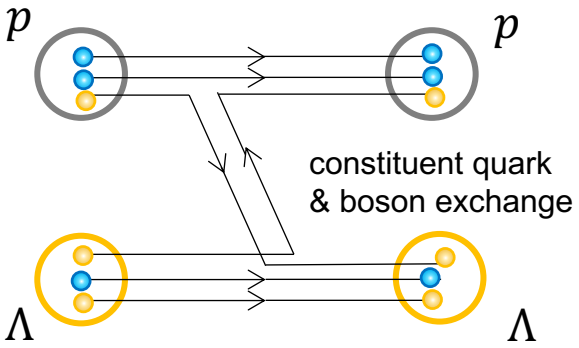
Baryon-Baryon Interaction

Boson exchange picture



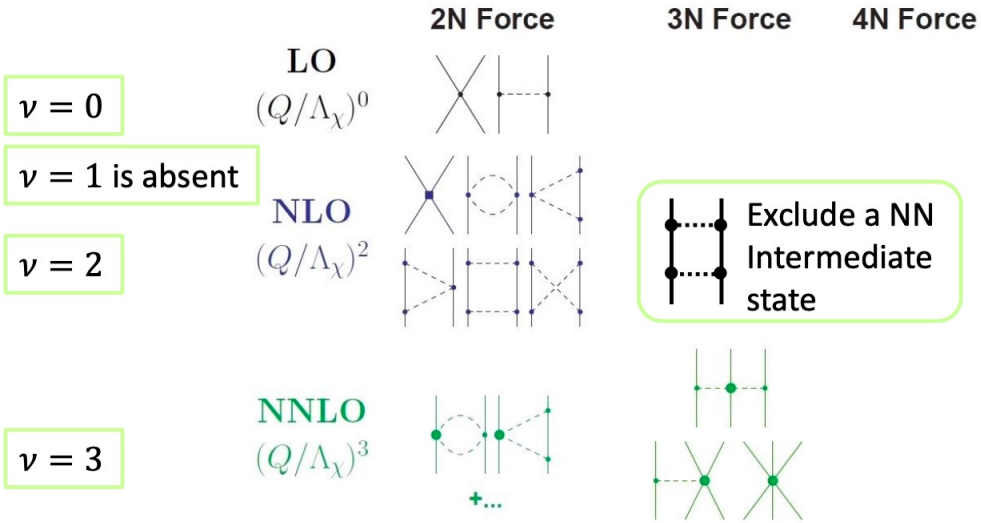
Nijmegen model

Quark based model with effective QCD



Quark Cluster model

Chiral EFT



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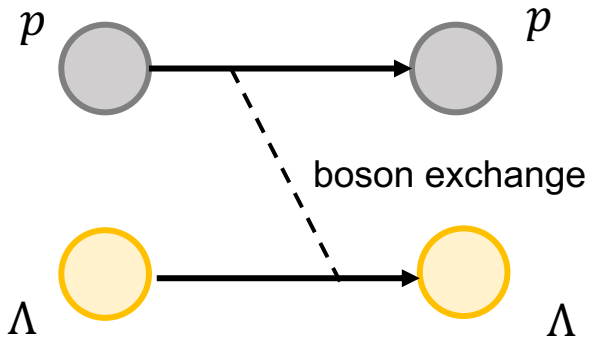

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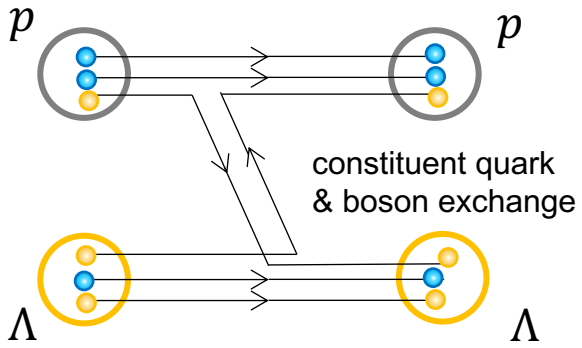

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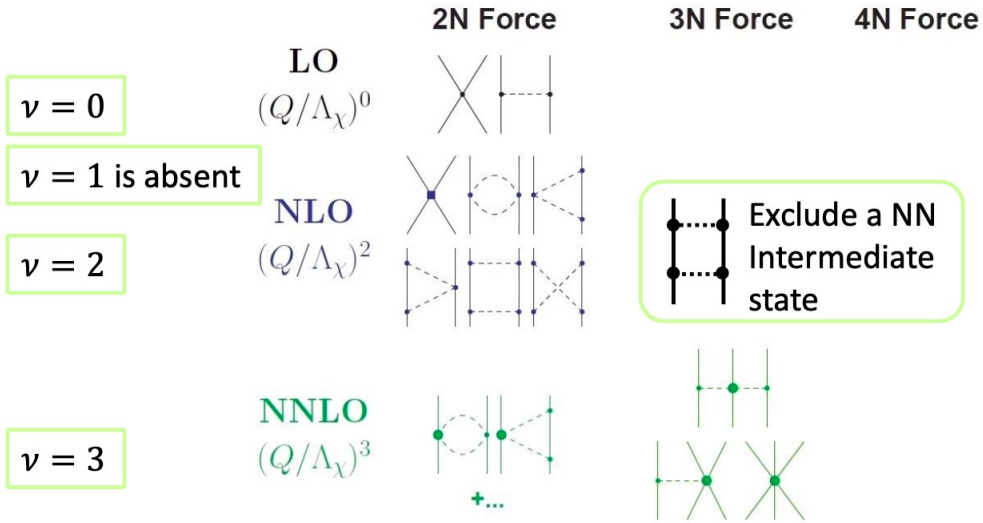

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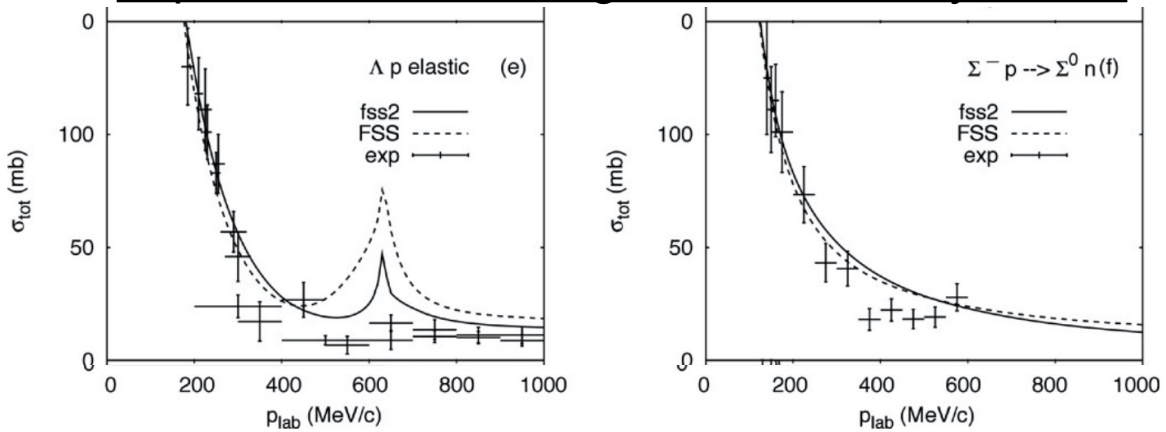
Experimental scattering data : extremely scarce



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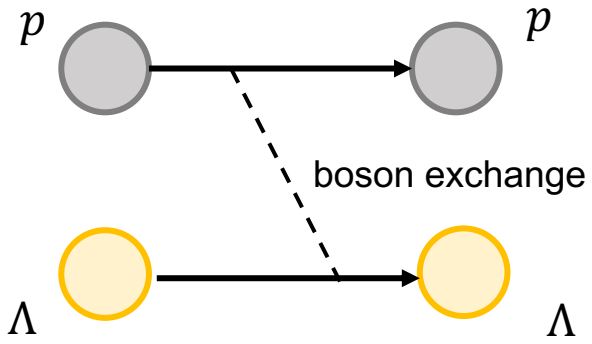

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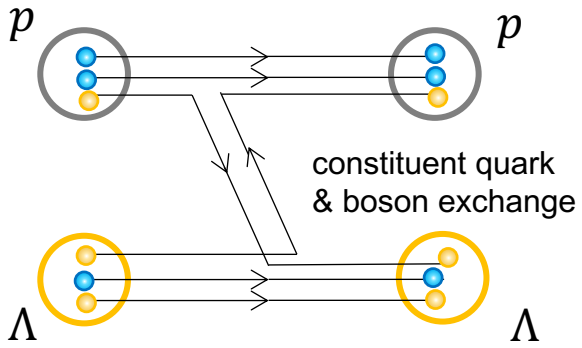

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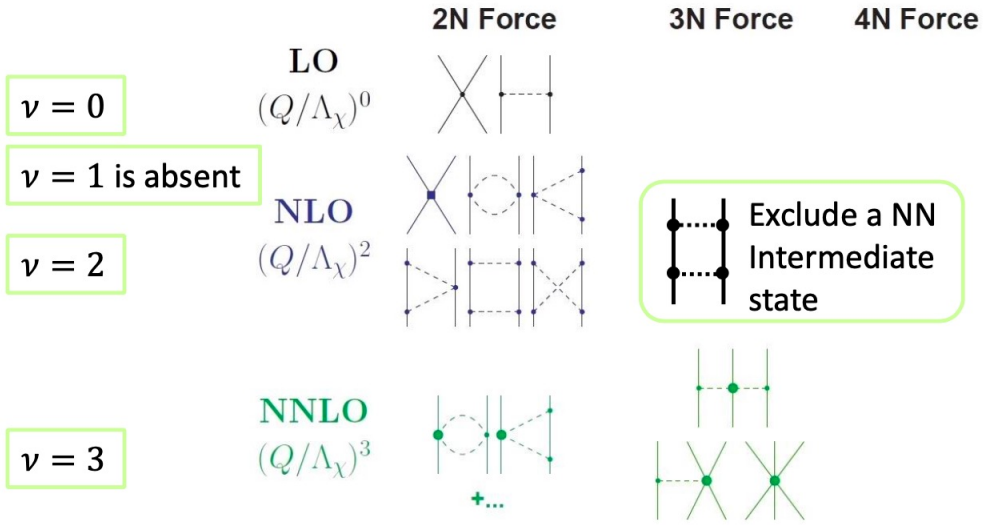

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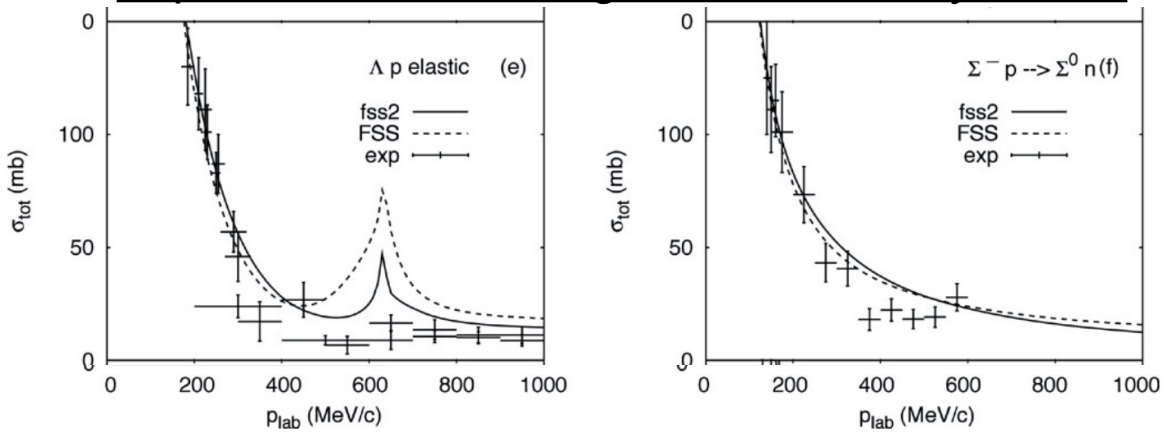

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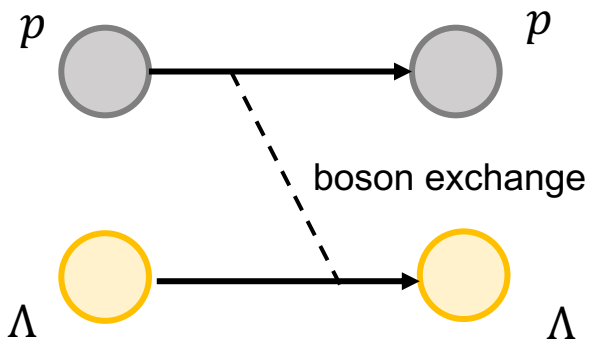

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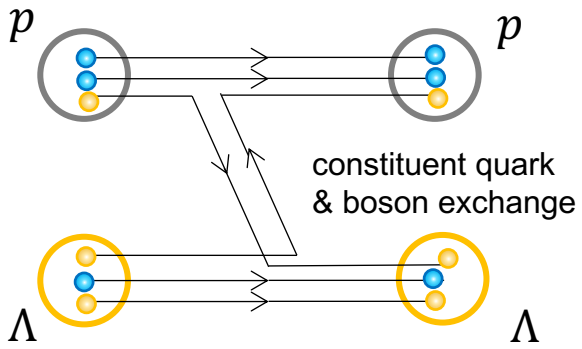

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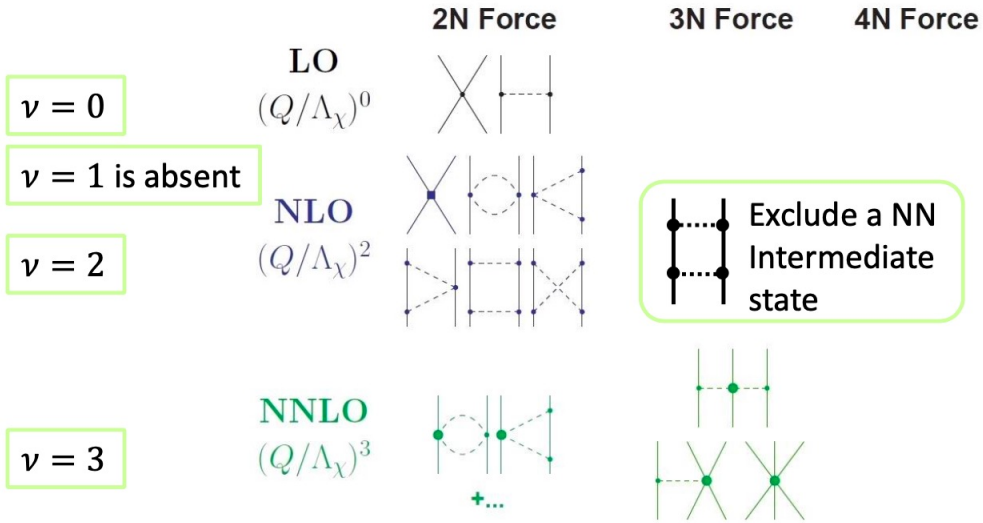

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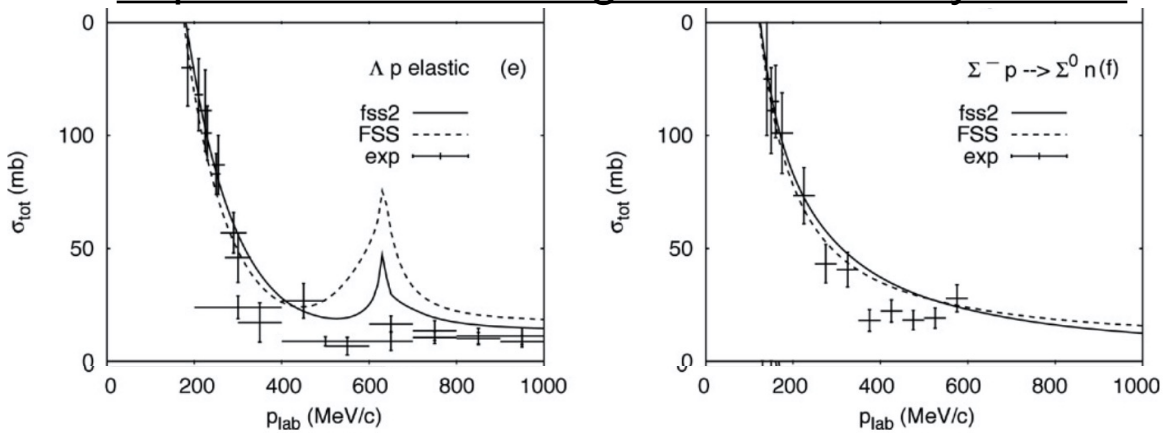
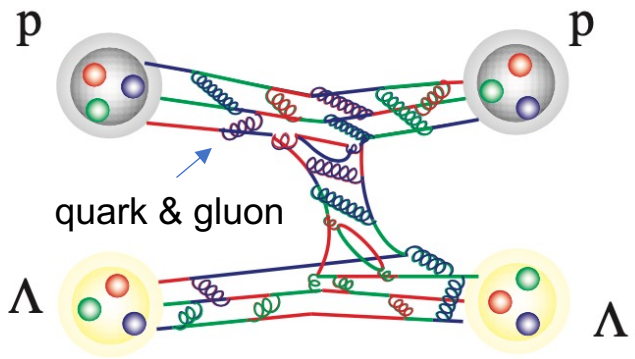


Test of theories

Quantum Chromo Dynamics (QCD)

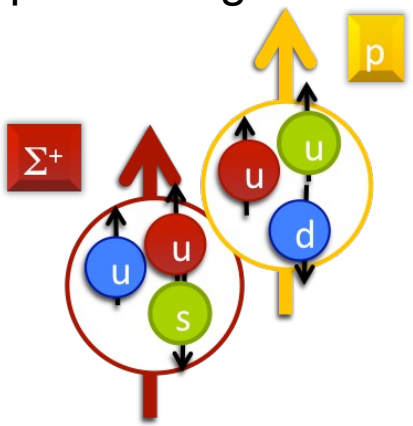


Lattice QCD

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

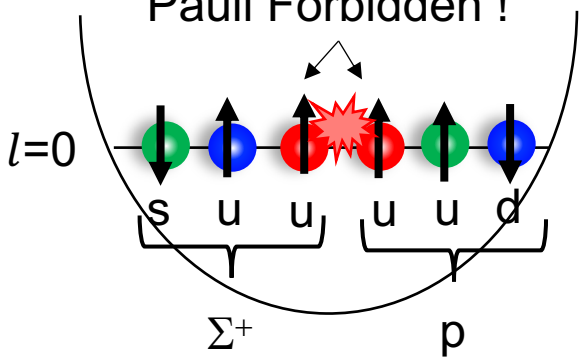
Verification of quark Pauli repulsion

$\Sigma^+ p$ scatterng



6 quarks can stay in s state in normal case

Pauli Forbidden !



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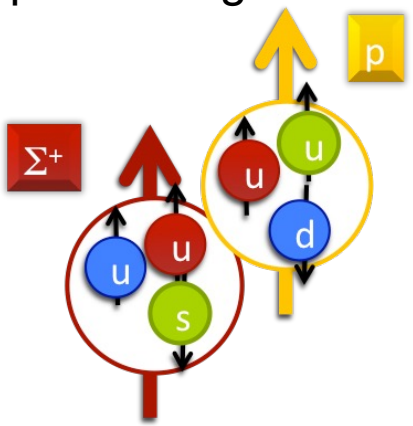

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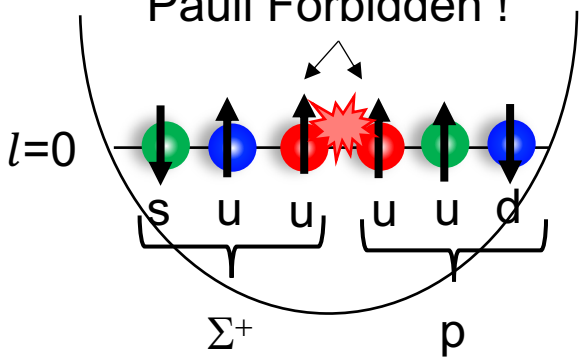

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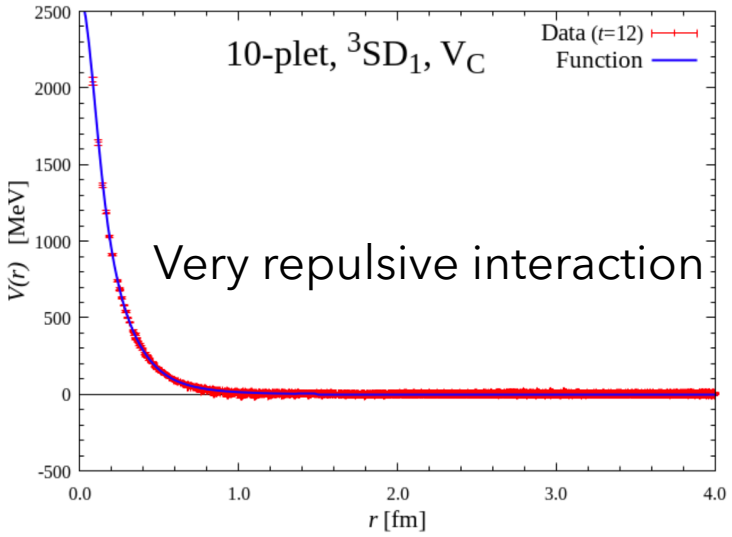
T. Inoue, AIP Conf. Proc. 2130, 020002 (2019)



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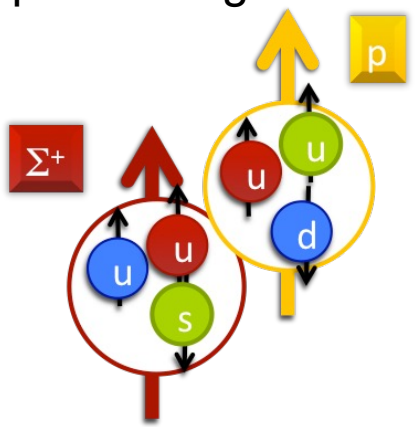

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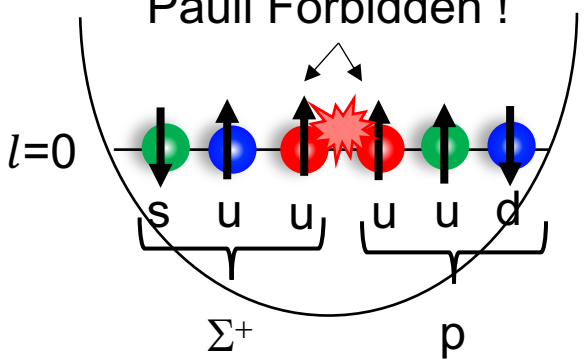

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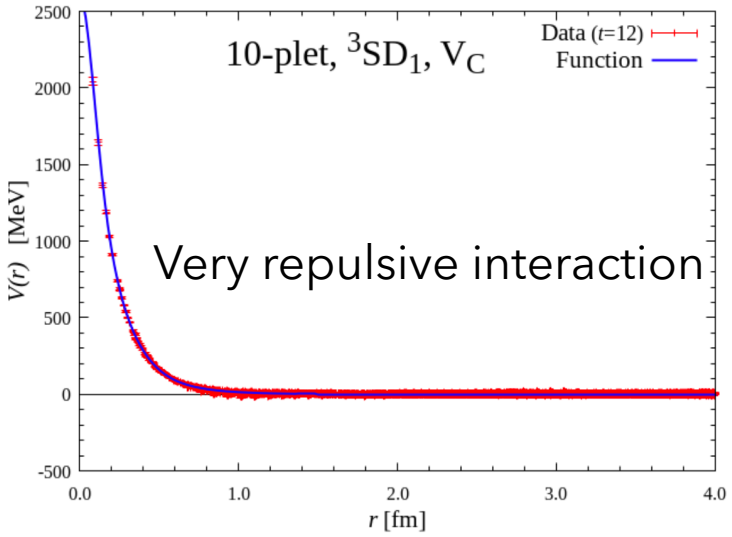

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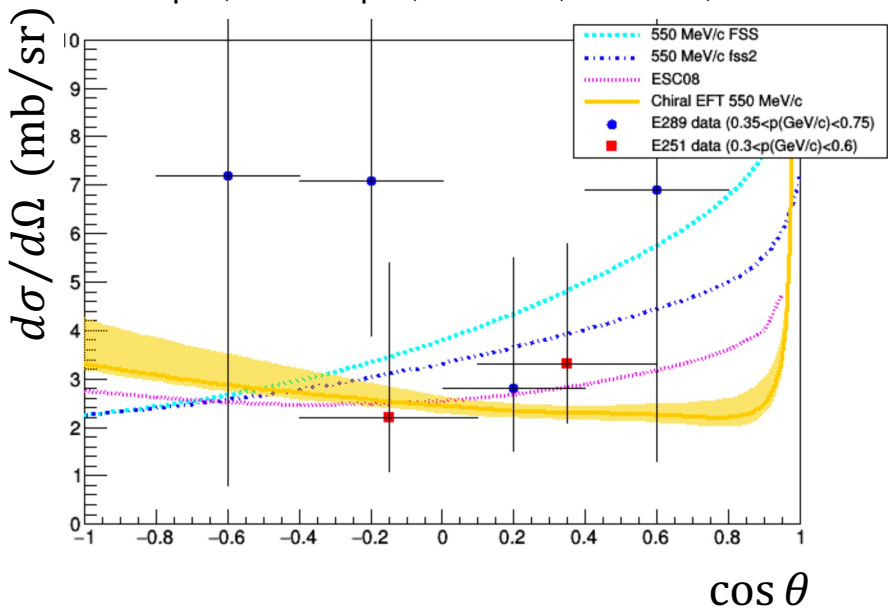
Σ⁺p (0.5 < p (GeV/c) < 0.6)



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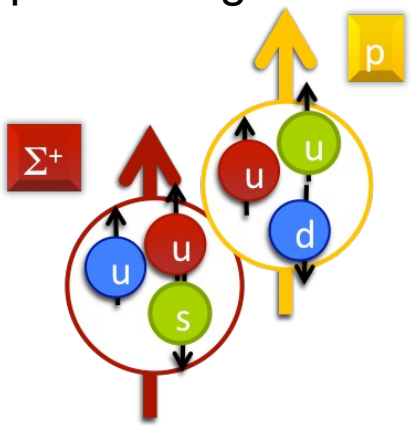

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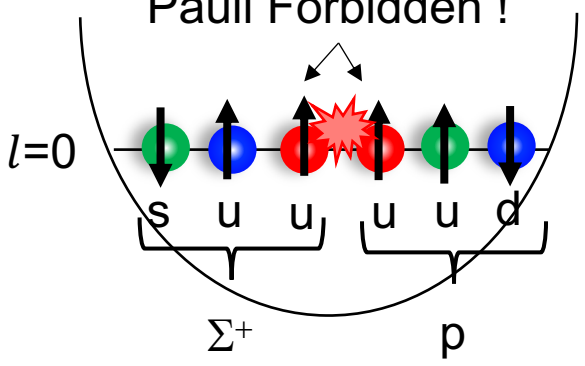

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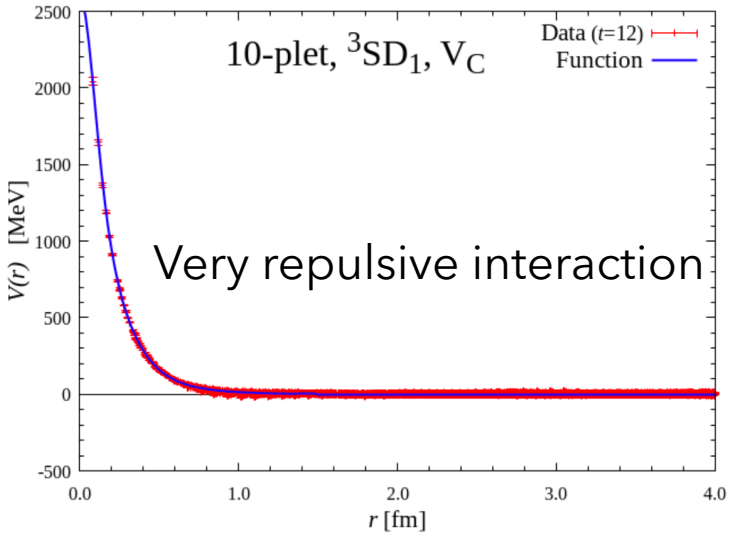

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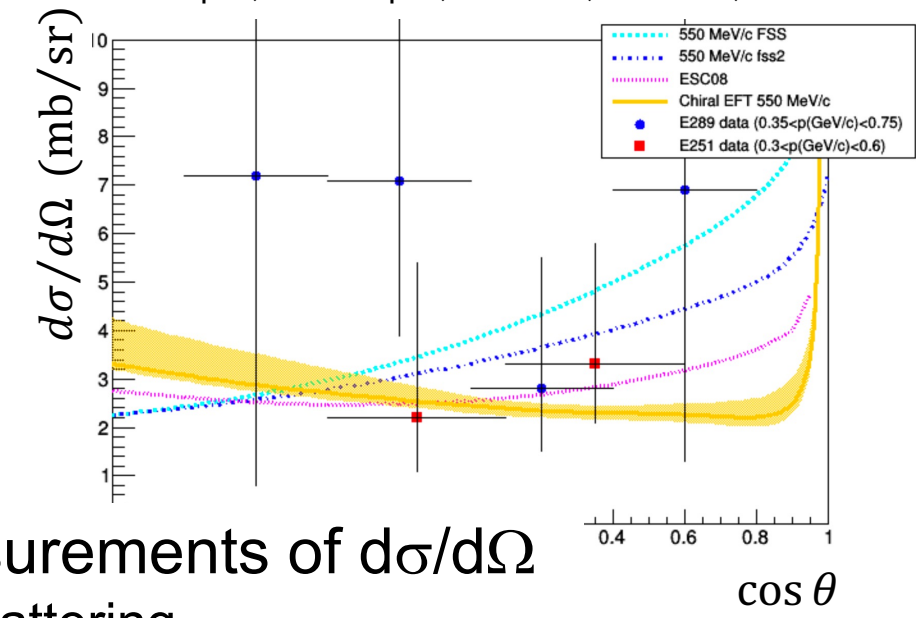

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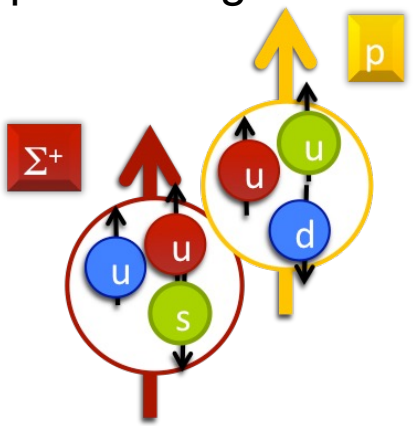

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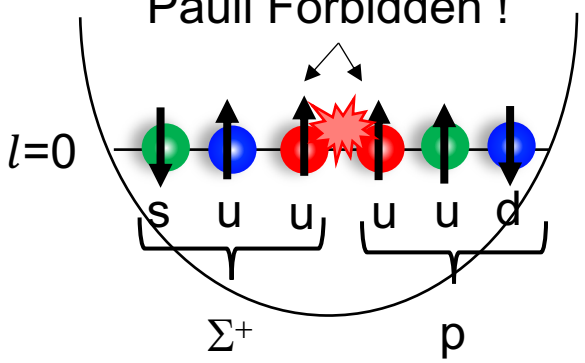

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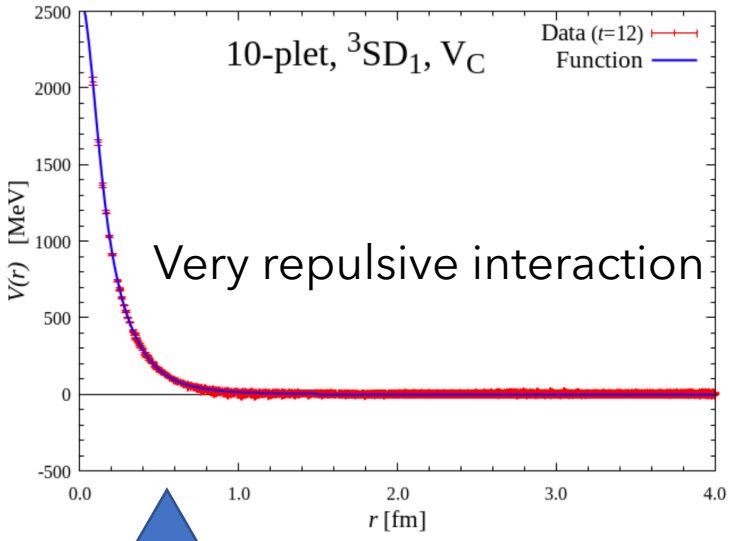

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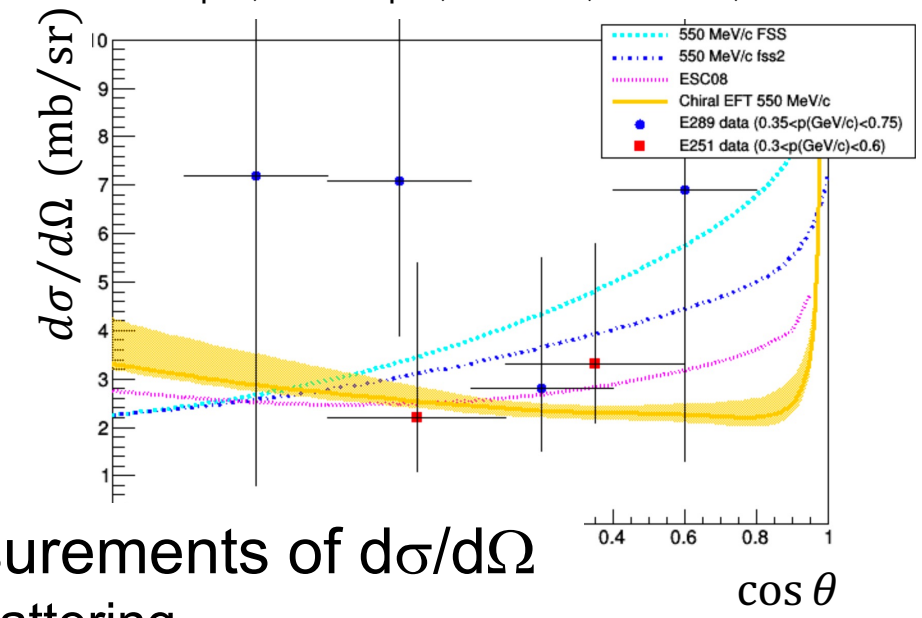

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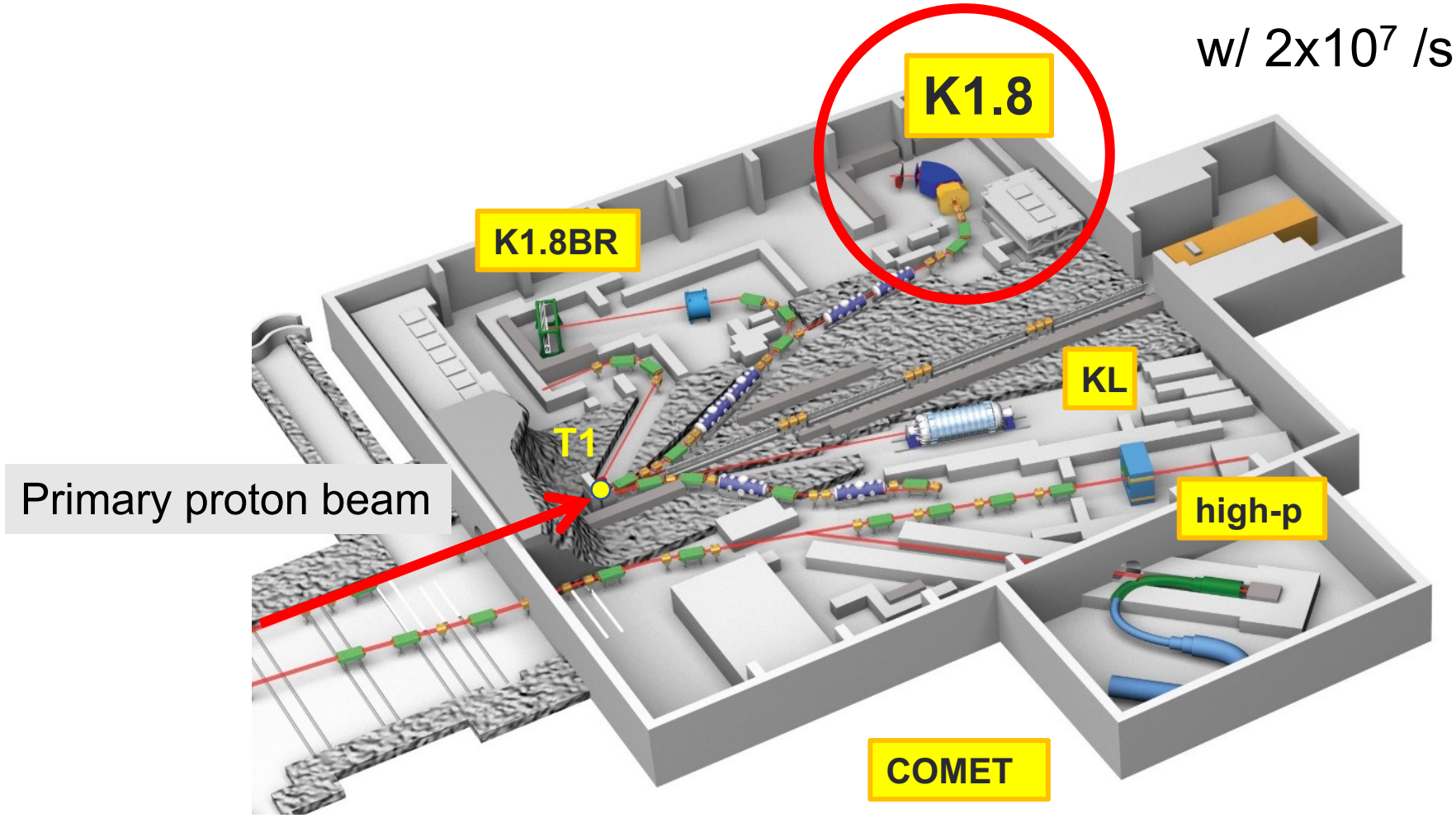
J-PARC Hadron Experimental Facility

High intensity secondary beams (K/π) are available
from high intensity proton beam

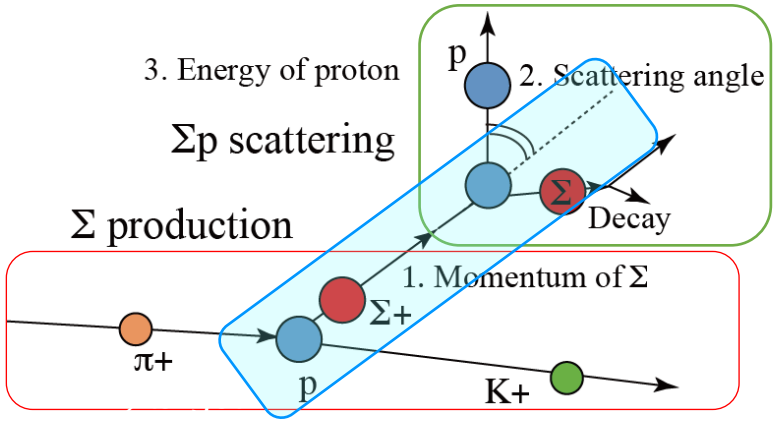
Σp scattering experiment :

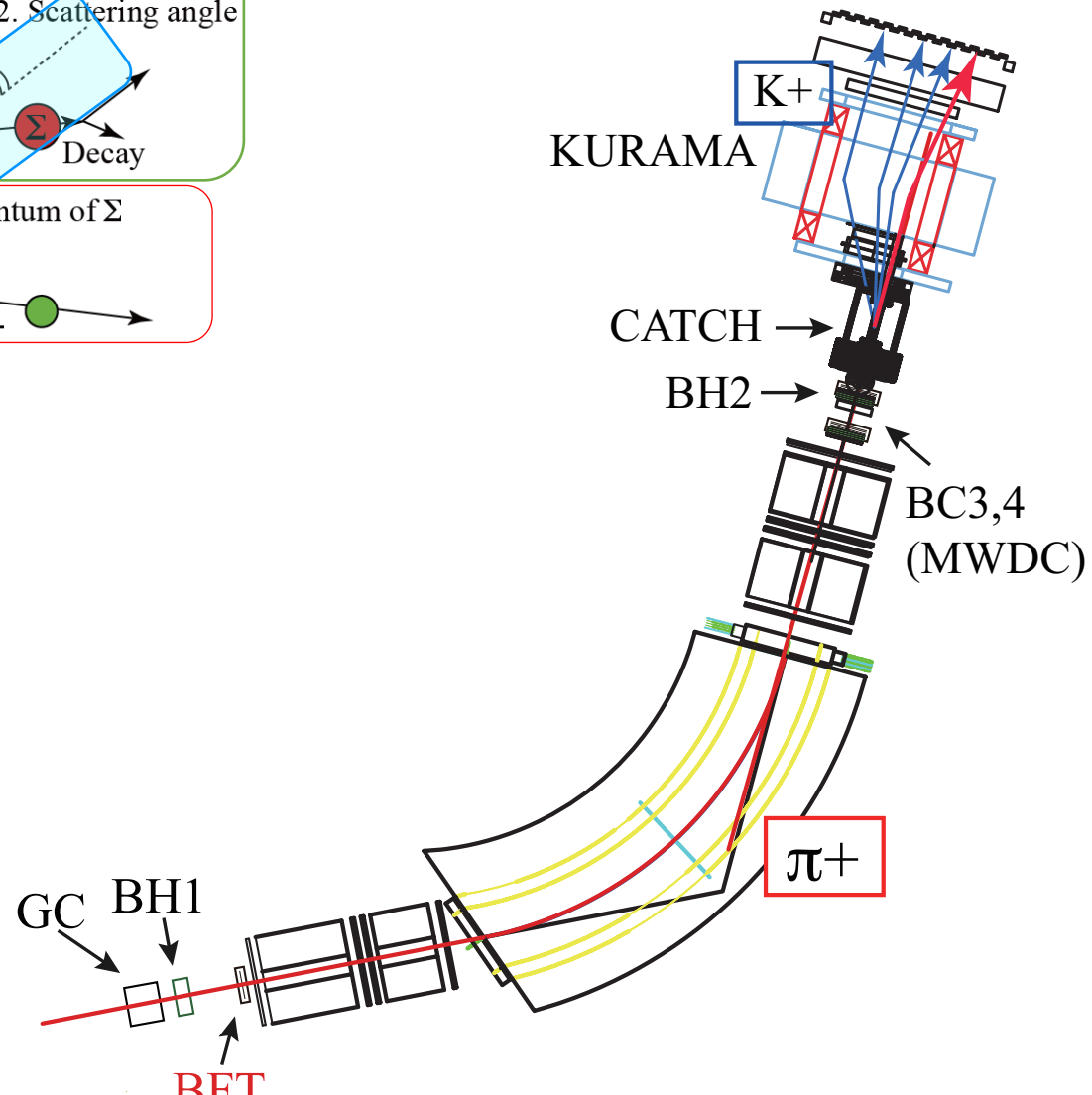
w/ 2×10^7 /spill π beams



J-PARC E40 experimental setup

Two successive two-body reactions





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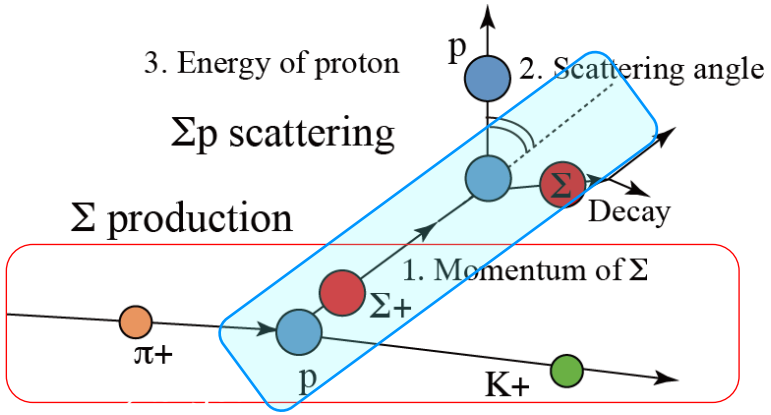

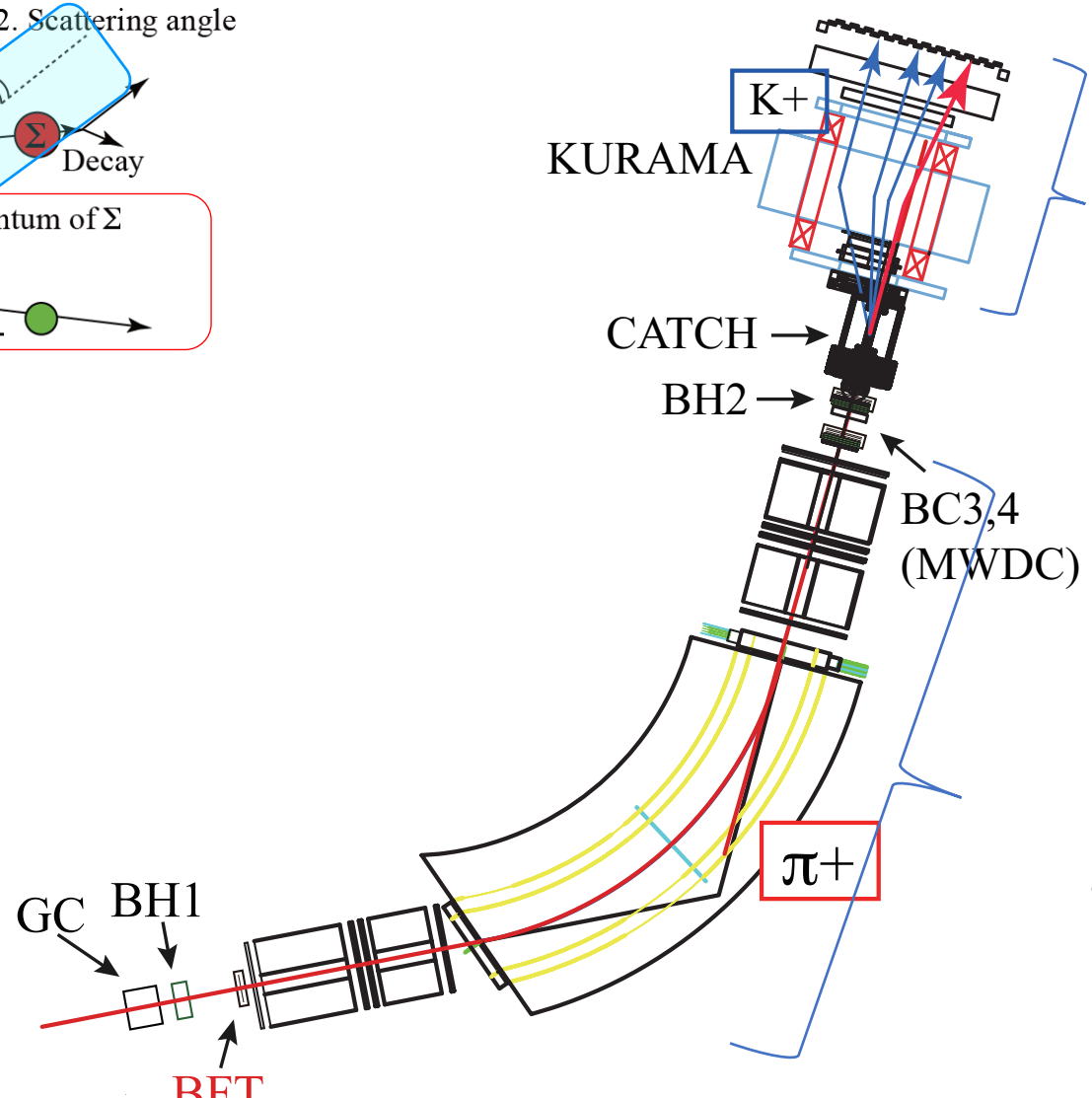

KURAMA spectrometer
- Identification of K^+
- Momentum analysis

Momentum tagging of Σ beam

Beam-line spectrometer
- Momentum analysis of π beam

J-PARC K1.8 beam line

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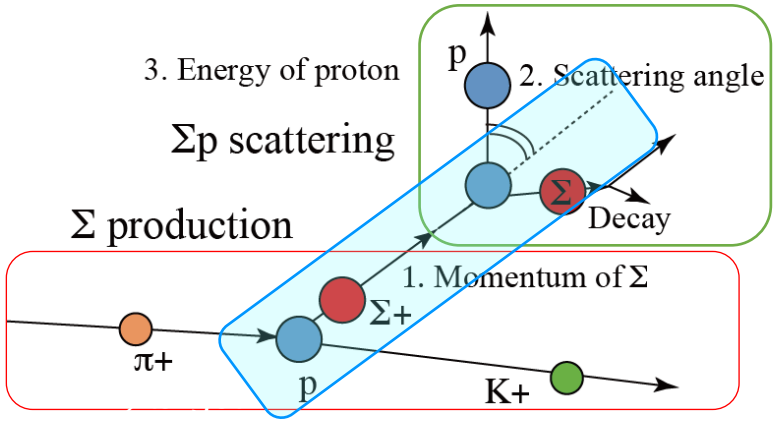
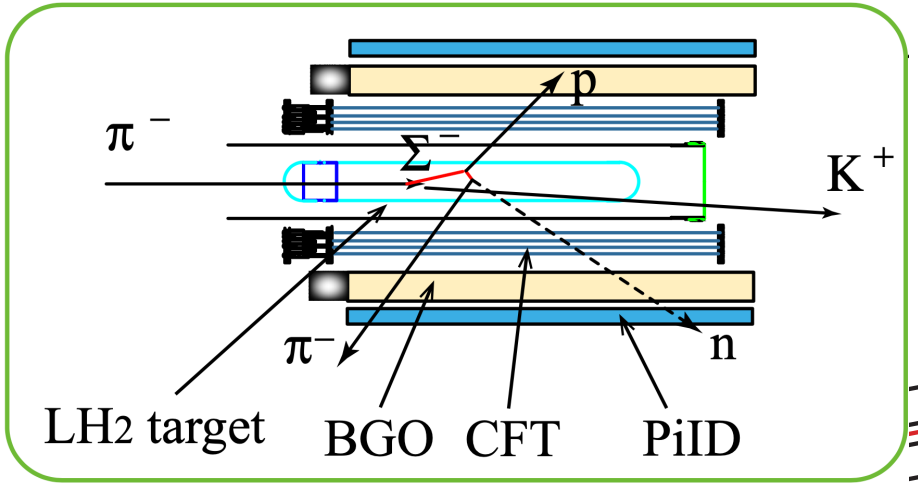
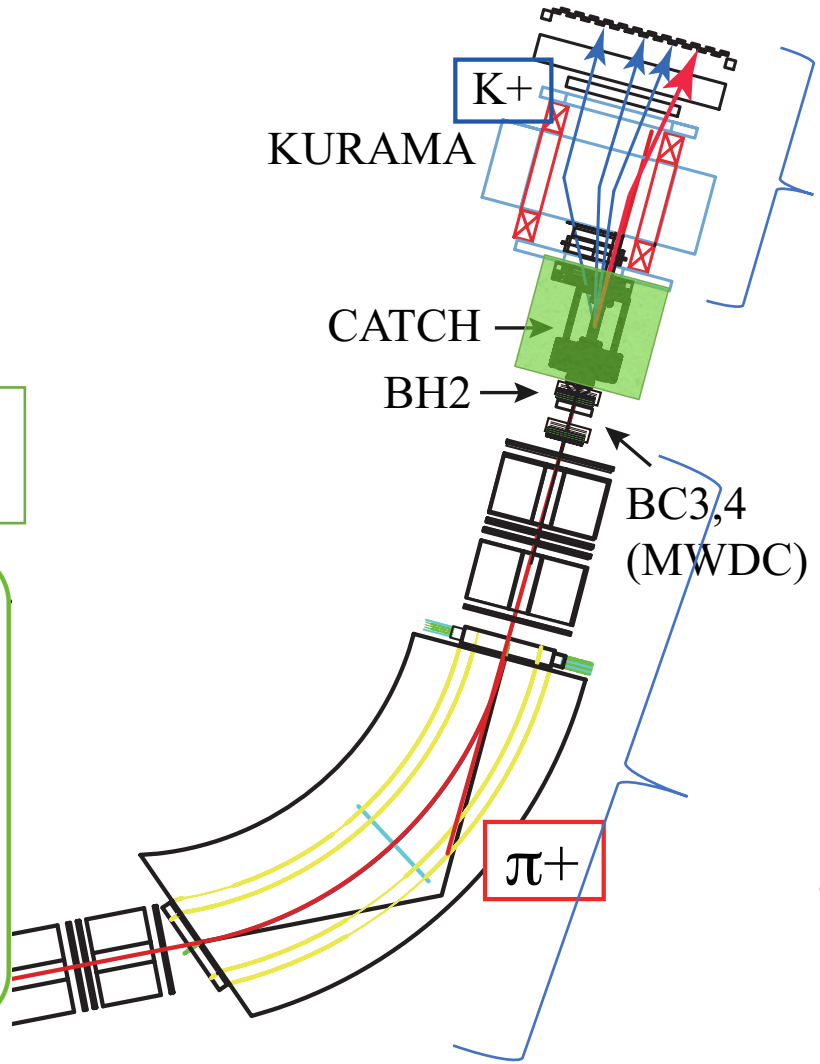


Detection of Σp scattering event by CATCH detector





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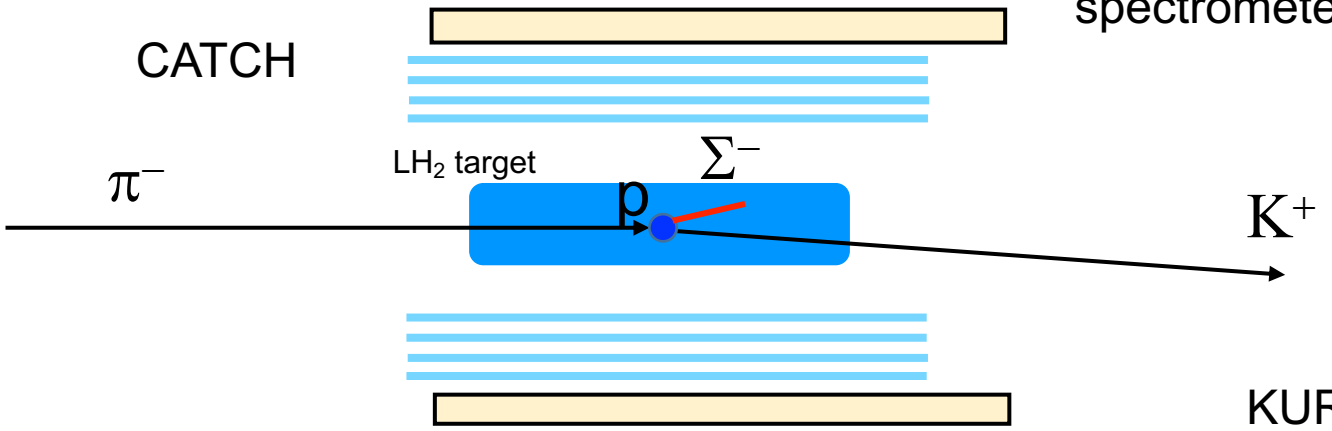
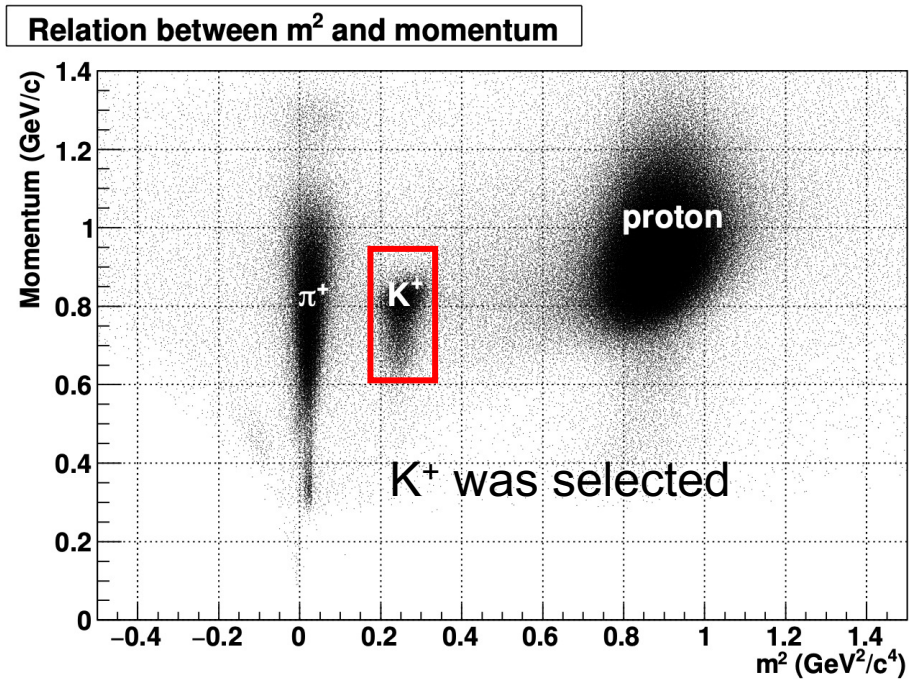


Σ beam in LH_2 target is tagged by the magnetic spectrometers

KURAMA spectrometer analysis



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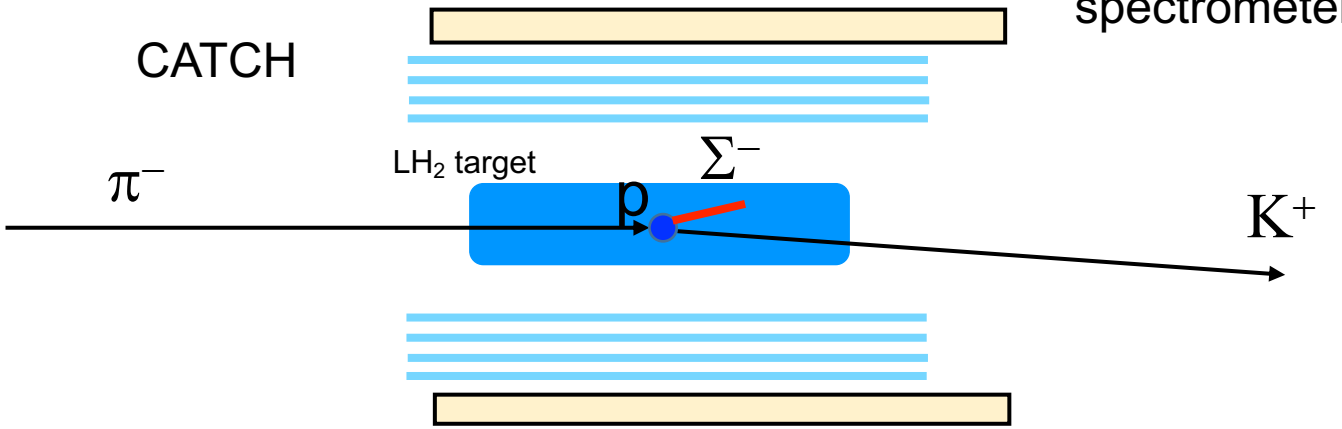
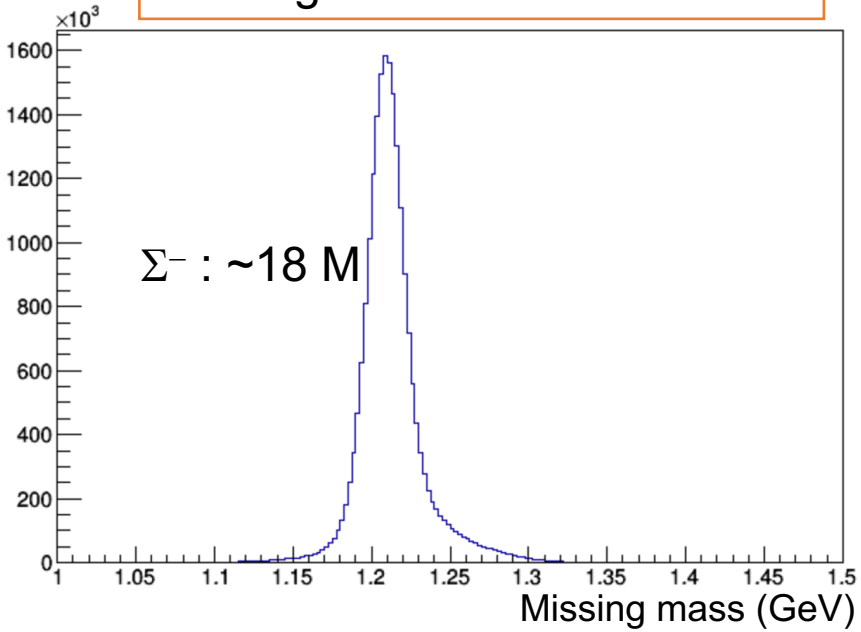


Missing mass from π^- and K^+



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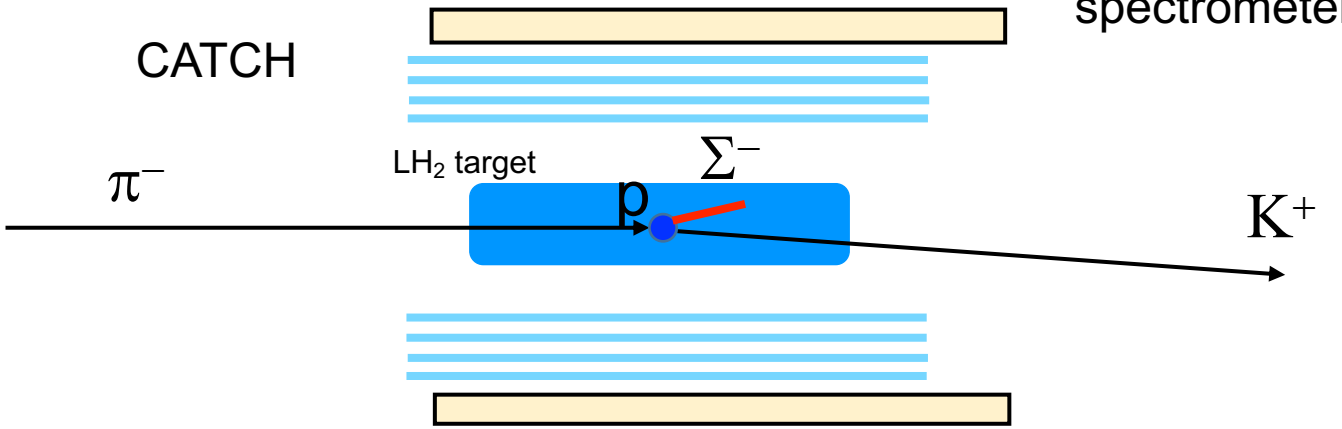

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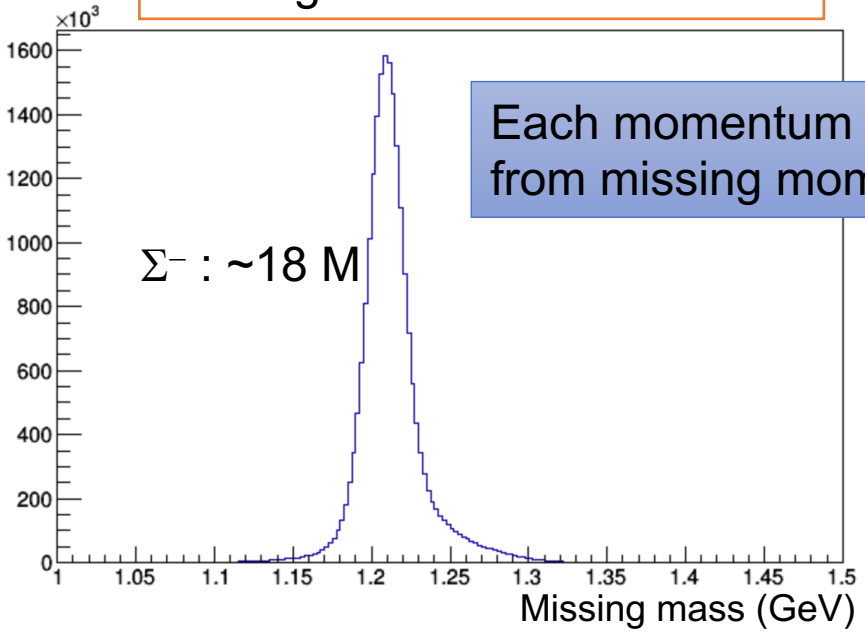
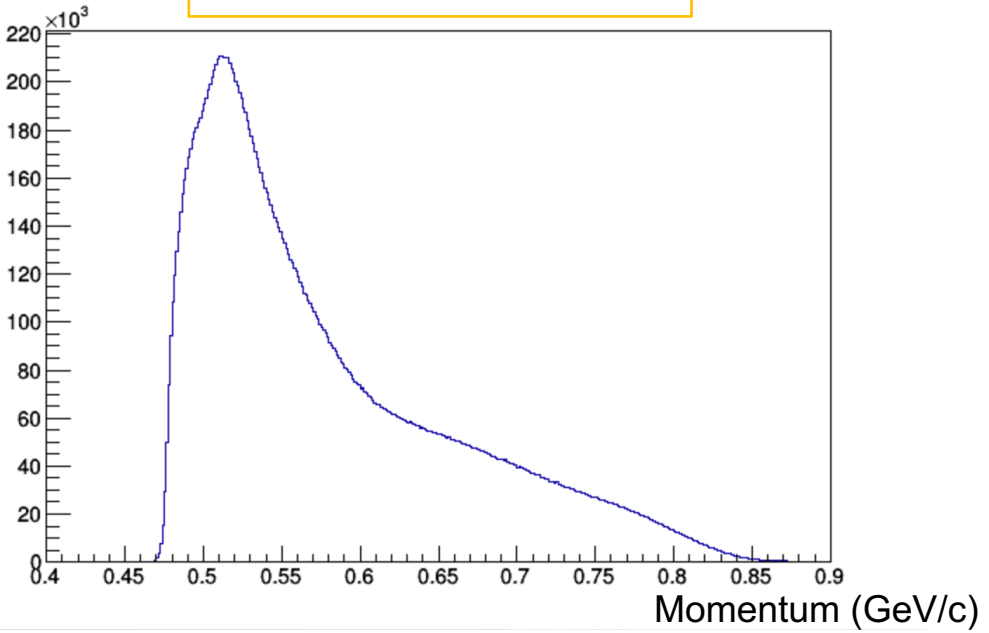


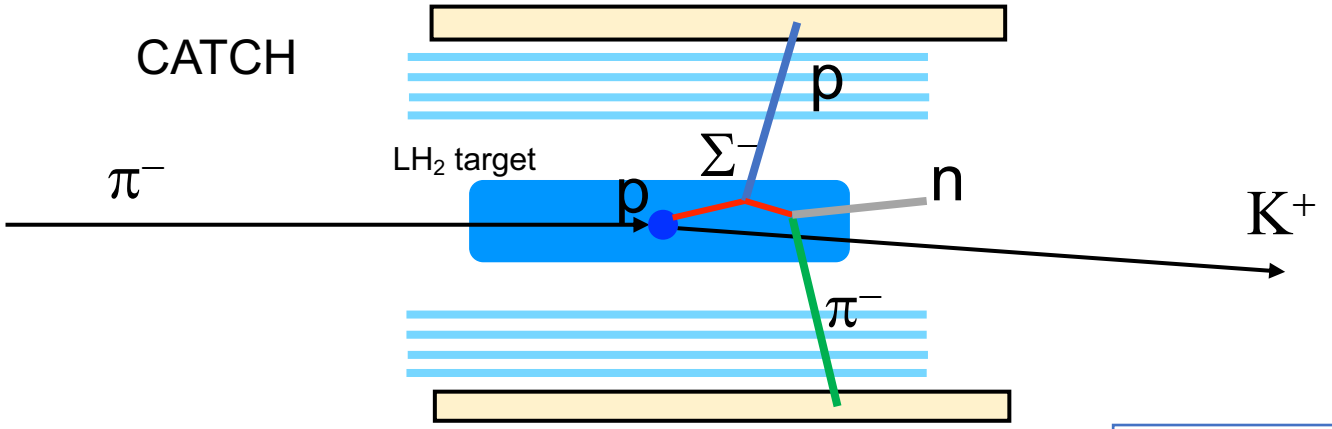
Σ^- : ~18 M

Each momentum can be reconstructed from missing momentum

Σ^- beam momentum



Recoil proton identification



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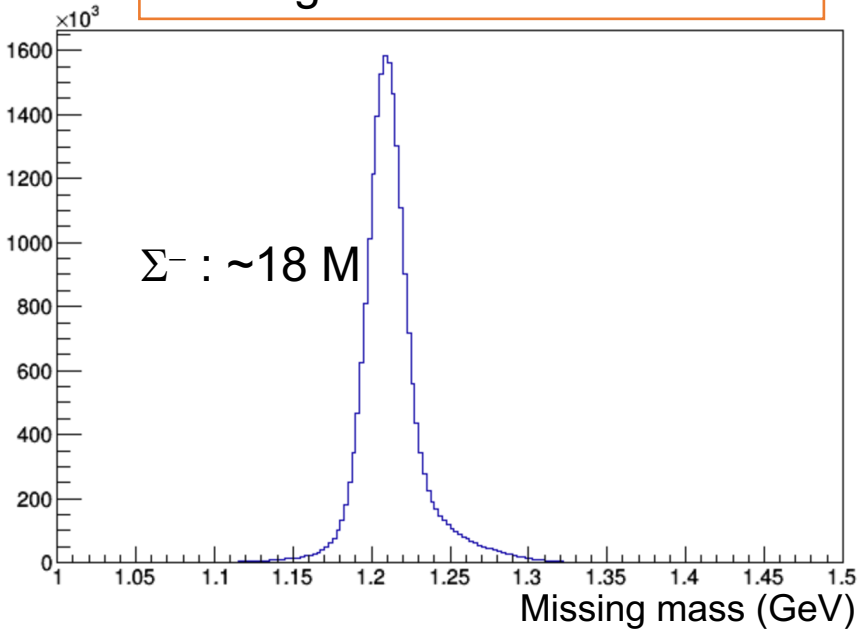
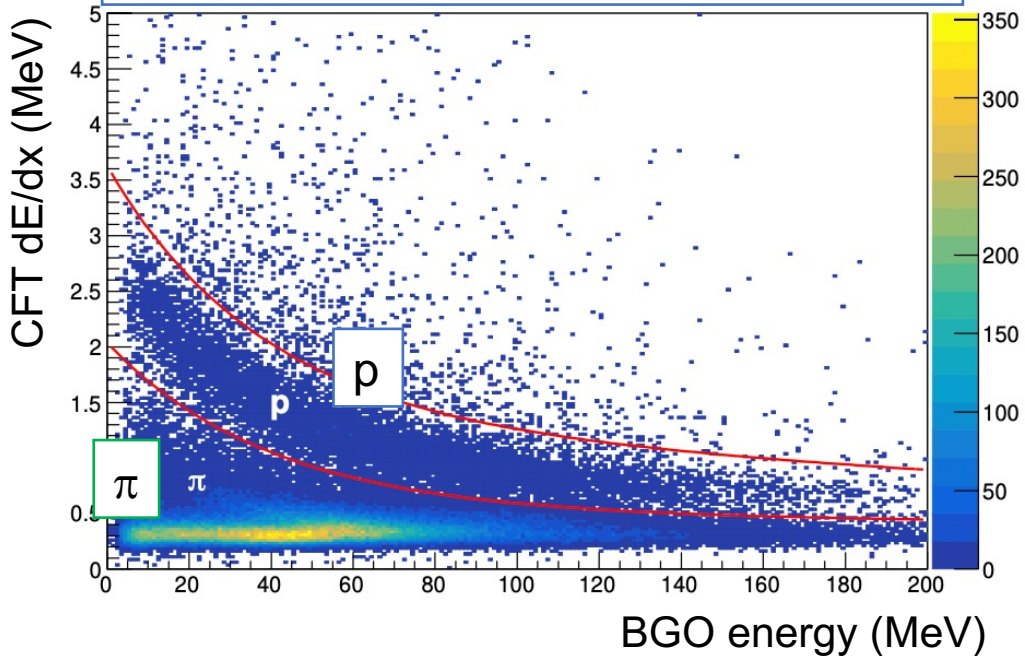


Particle ID in CATCH (ΔE-E method)



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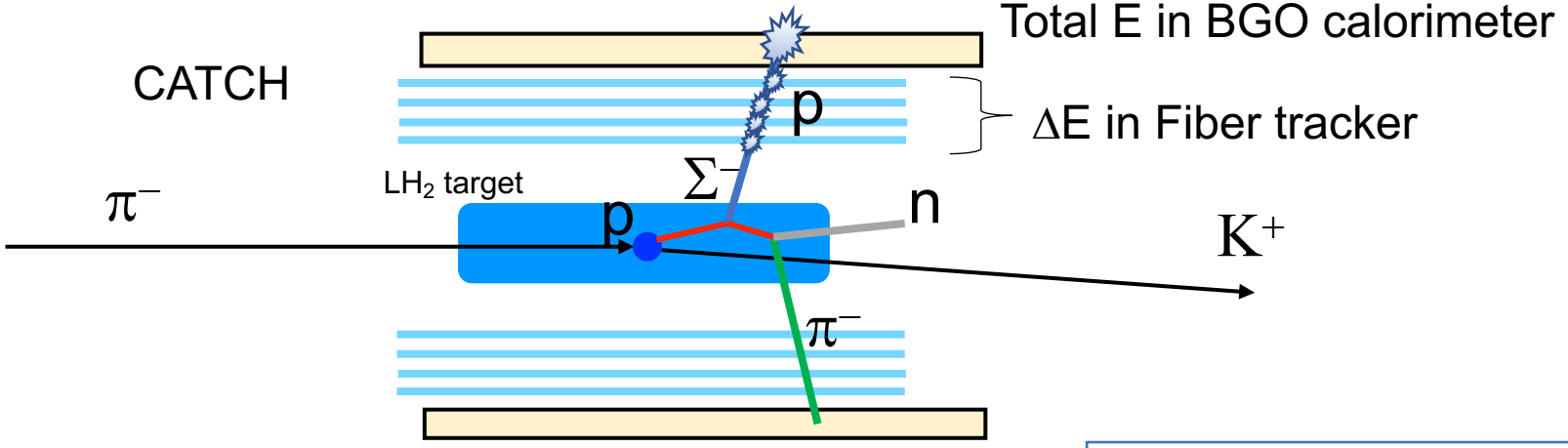

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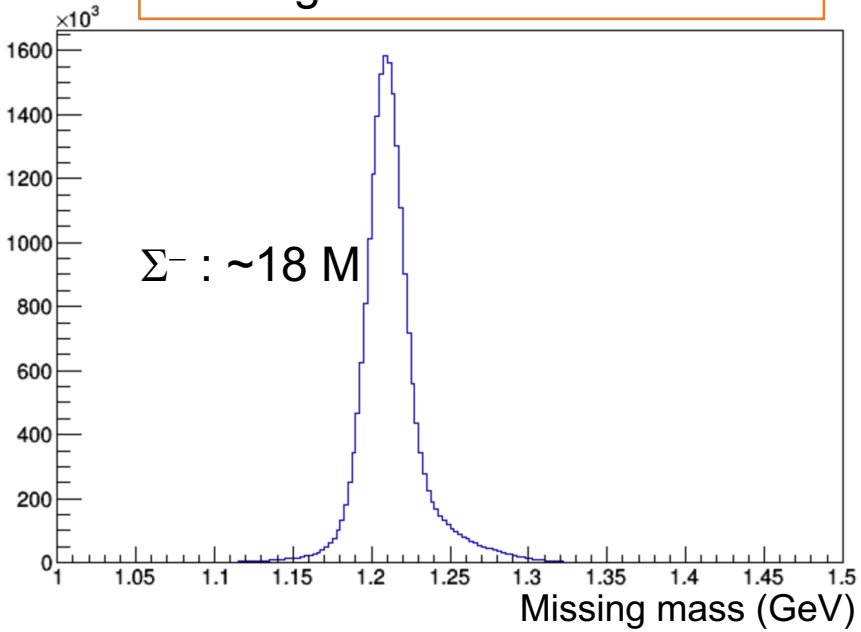

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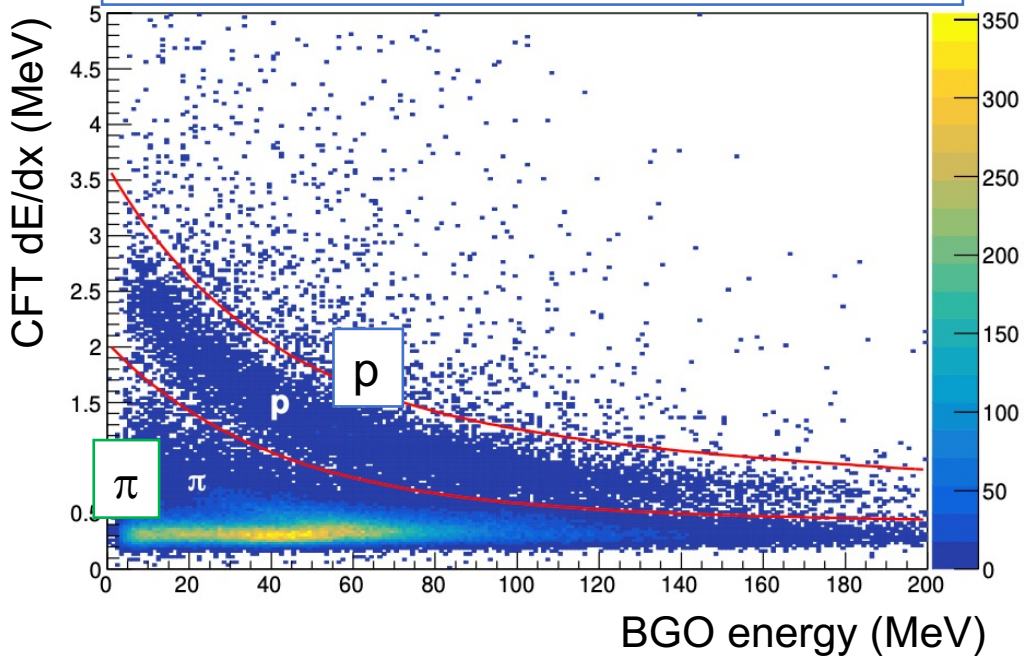

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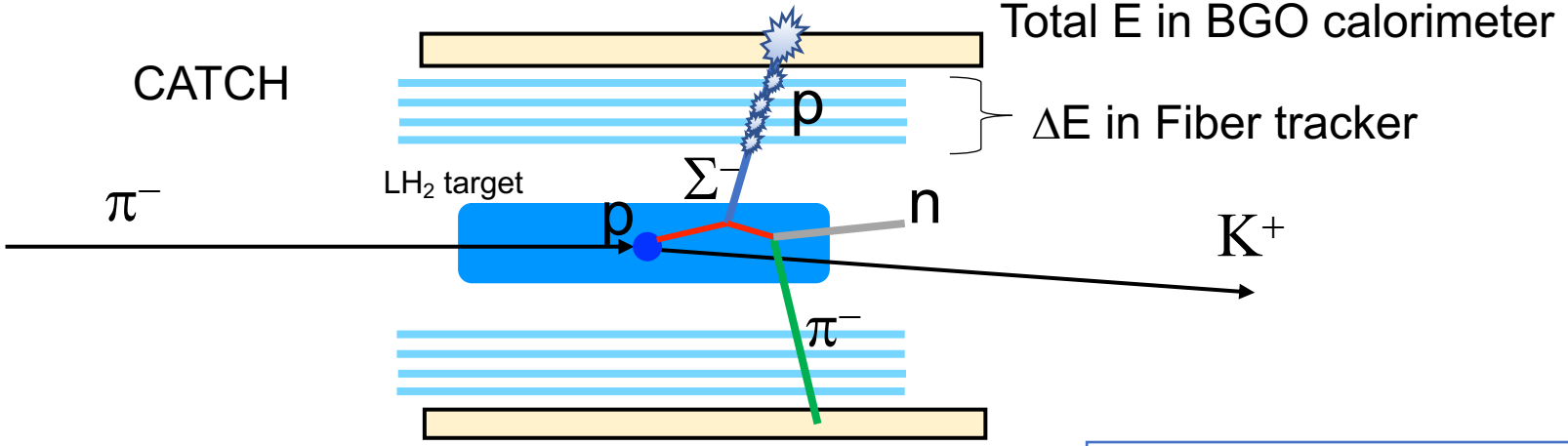

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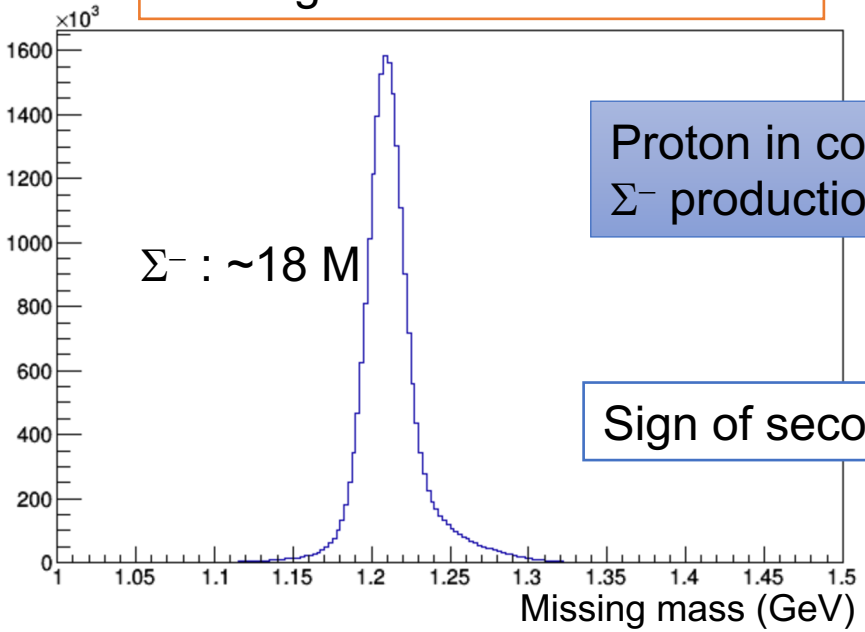
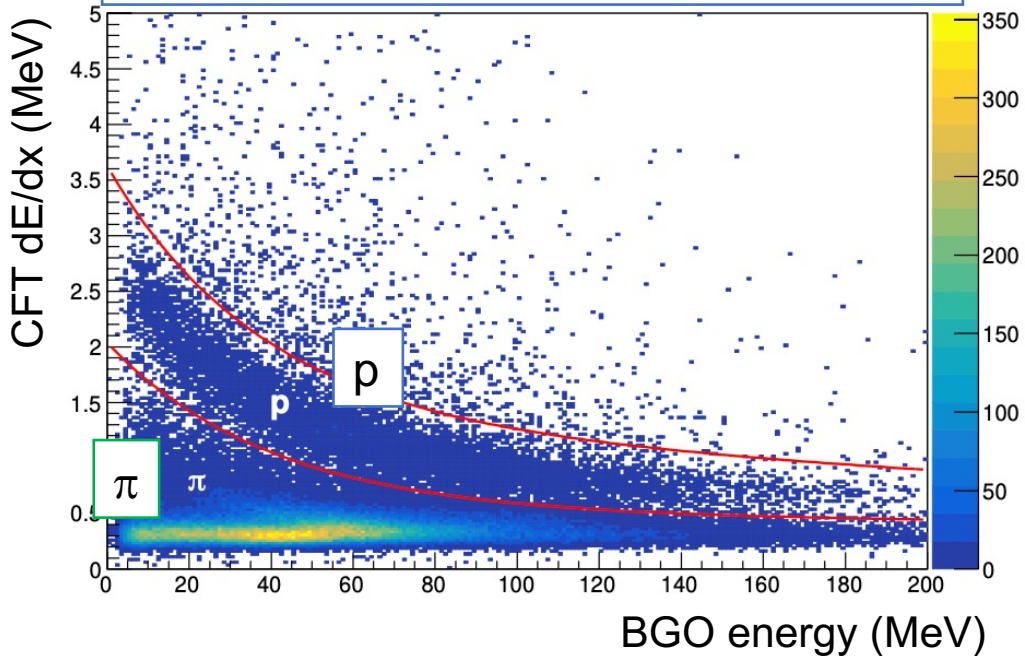


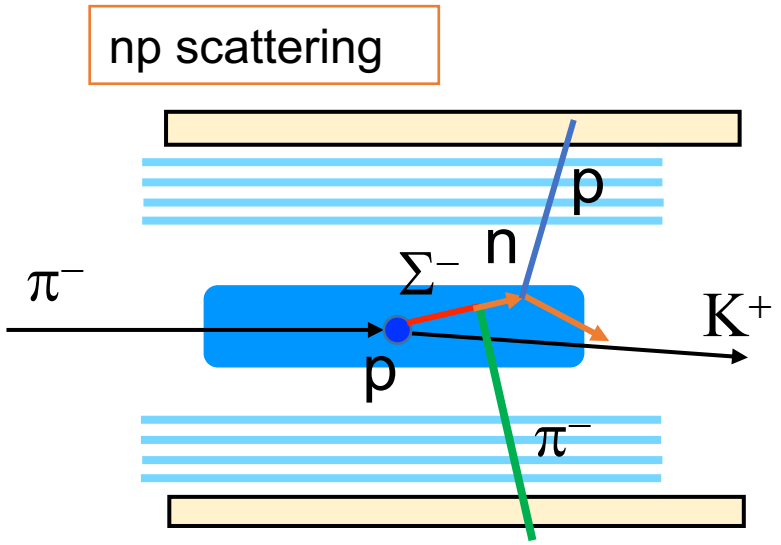
Proton in coincidence with Σ^- production

Sign of secondary reactions

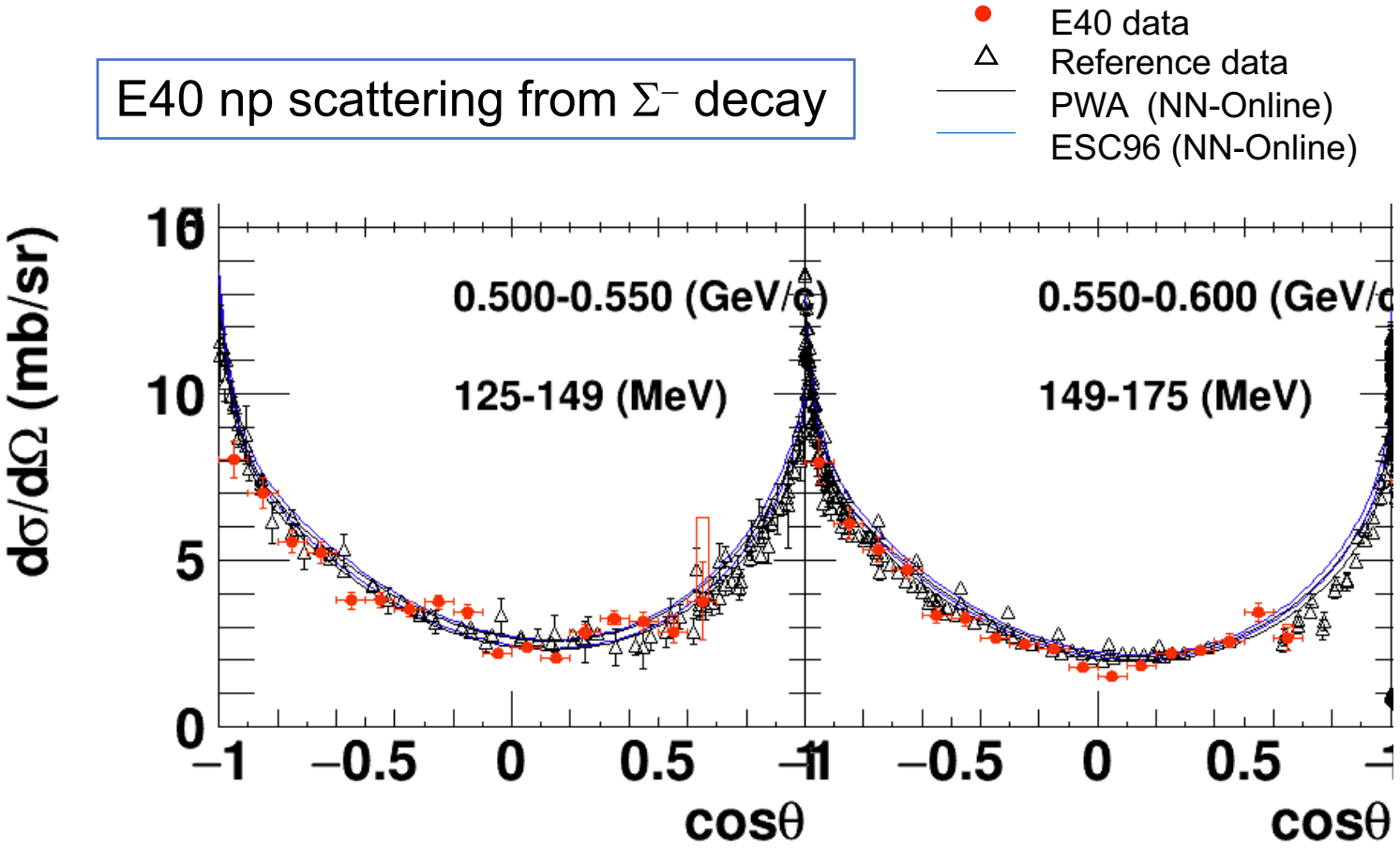
Particle ID in CATCH (ΔE-E method)



dσ/dΩ of np scattering from Σ^- decay

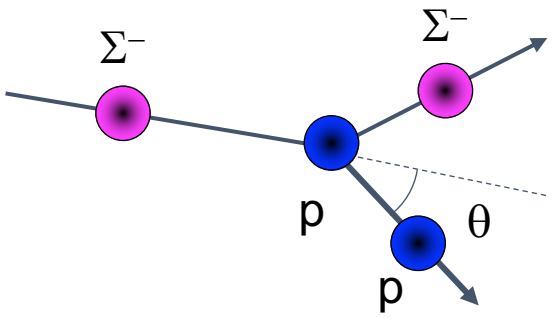


Good reaction to understand our systematics of the dσ/dΩ measuremer



The derived dσ/dΩ of np scattering are reasonable.

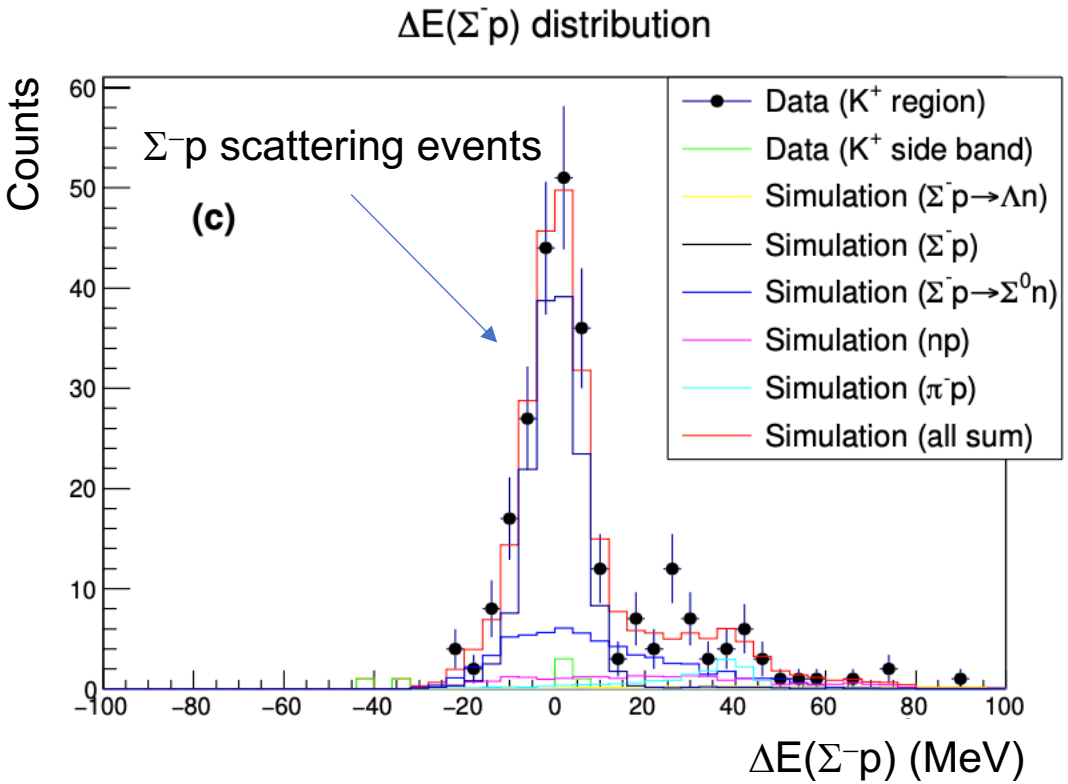
Kinematical identification of Σ^-p scatterings



Check kinetic energy difference between

- $E_{measured}$: measured energy
- E_{calc} : calculated energy from scattering angle
  based on Σ^-p elastic scattering kinematics

$\Delta E(\Sigma^-p) = E_{measured} - E_{calc}$



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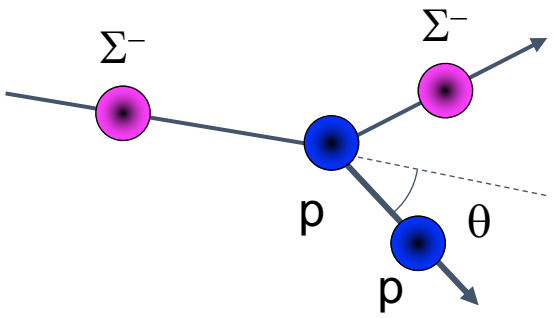

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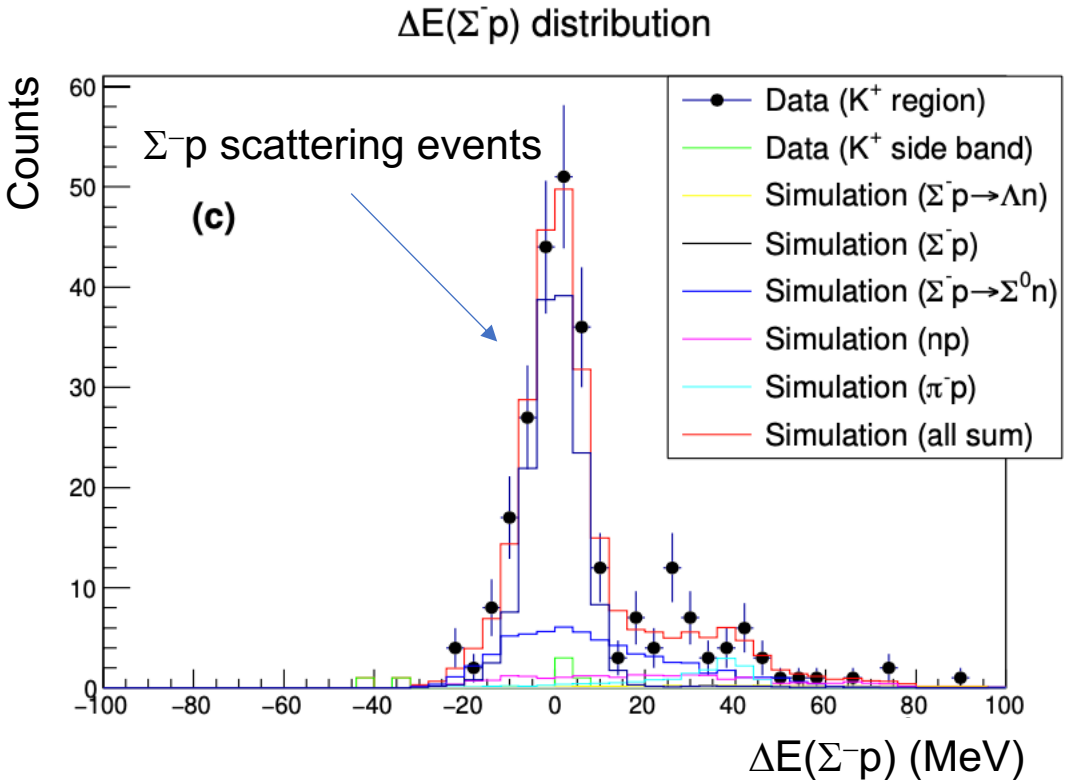
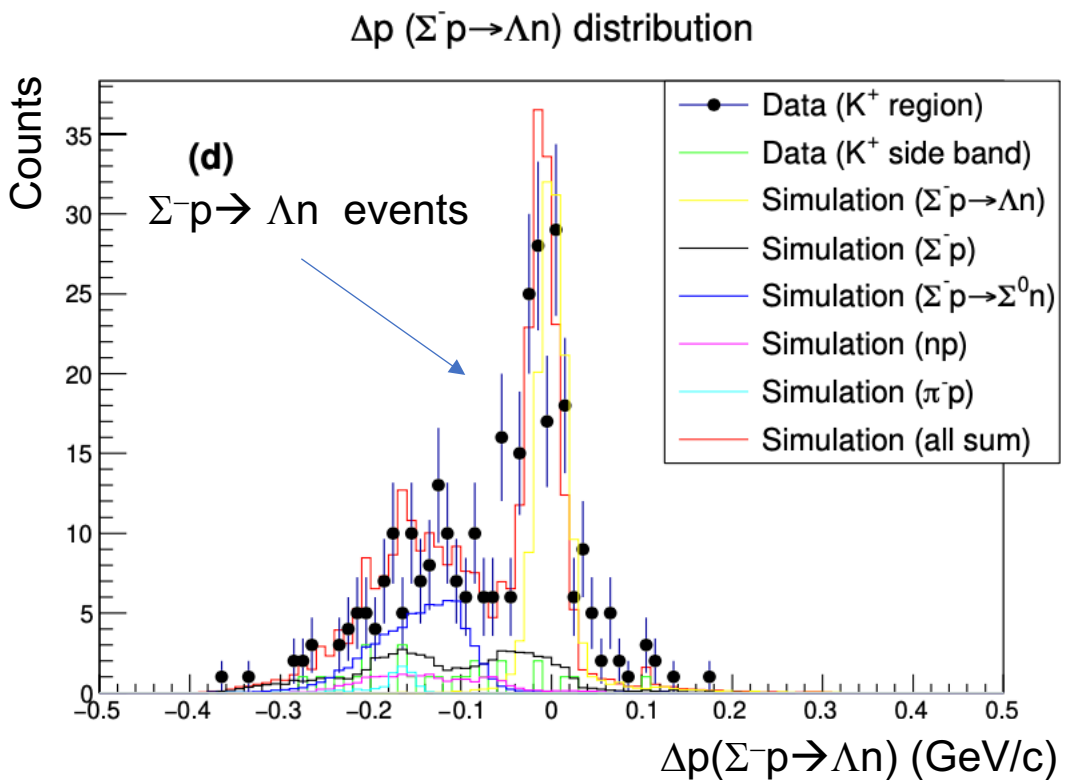
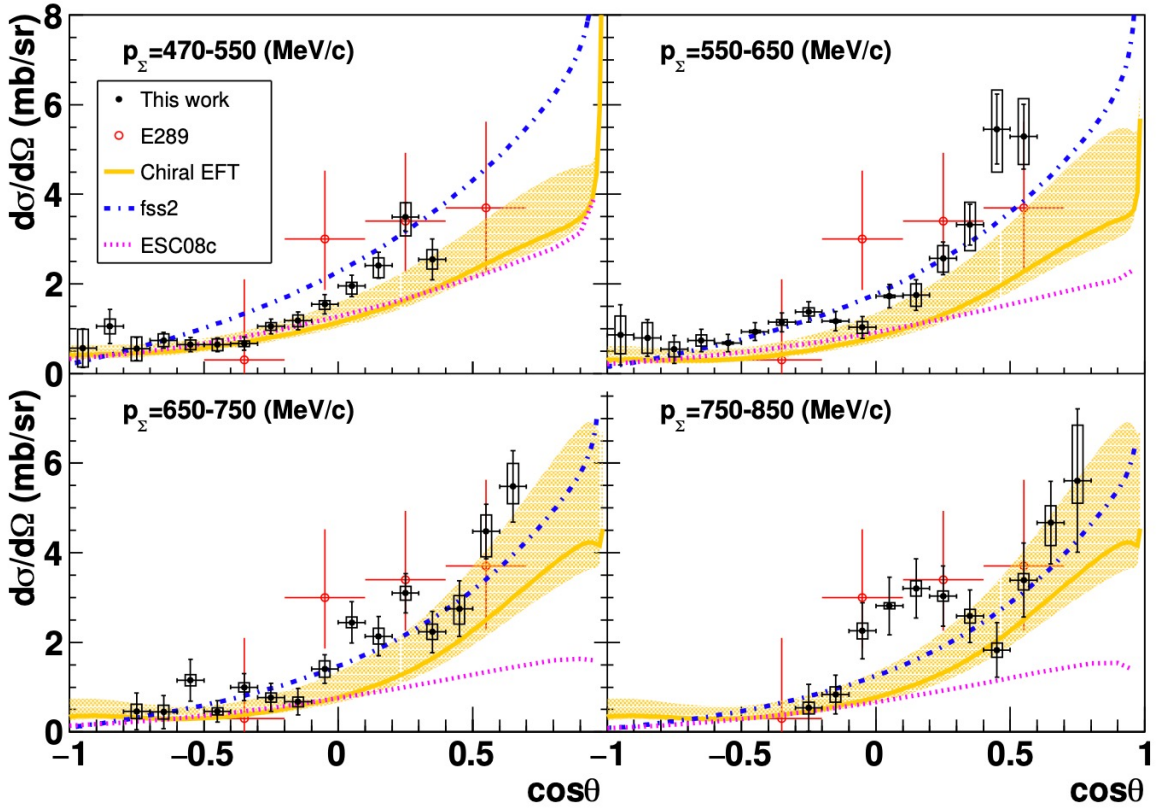




dσ/dΩ of the Σ⁻p channels

Σ⁻p elastic scattering

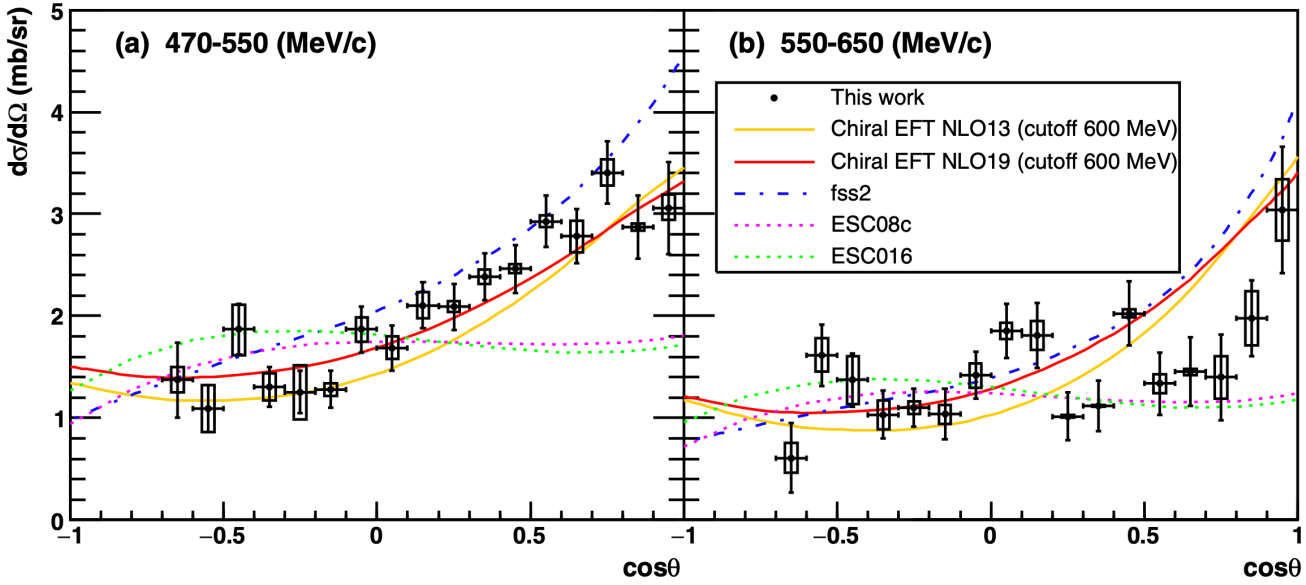
K. Miwa et al., PRC 104, 045204 (2021)



Clear forward peaking angular dependence

Σ⁻p→Λn inelastic scattering

K. Miwa et al., PRL 128, 072501 (2022)



Moderate forward peaking dependence

Comparison with theories

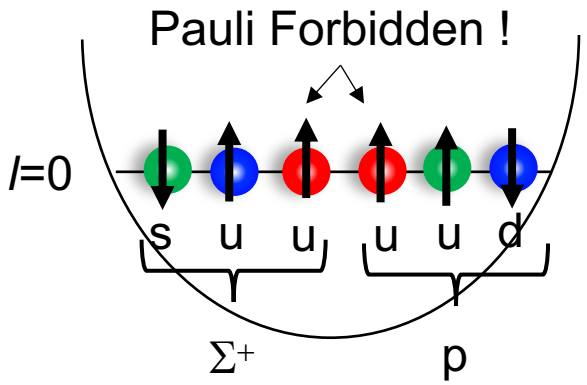
- fss2, Chiral EFT show a reasonable angular dependence.
- Nijmegen ESC models clearly underestimate the forward angle.

dσ/dΩ of Σ^+p elastic scattering

T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01

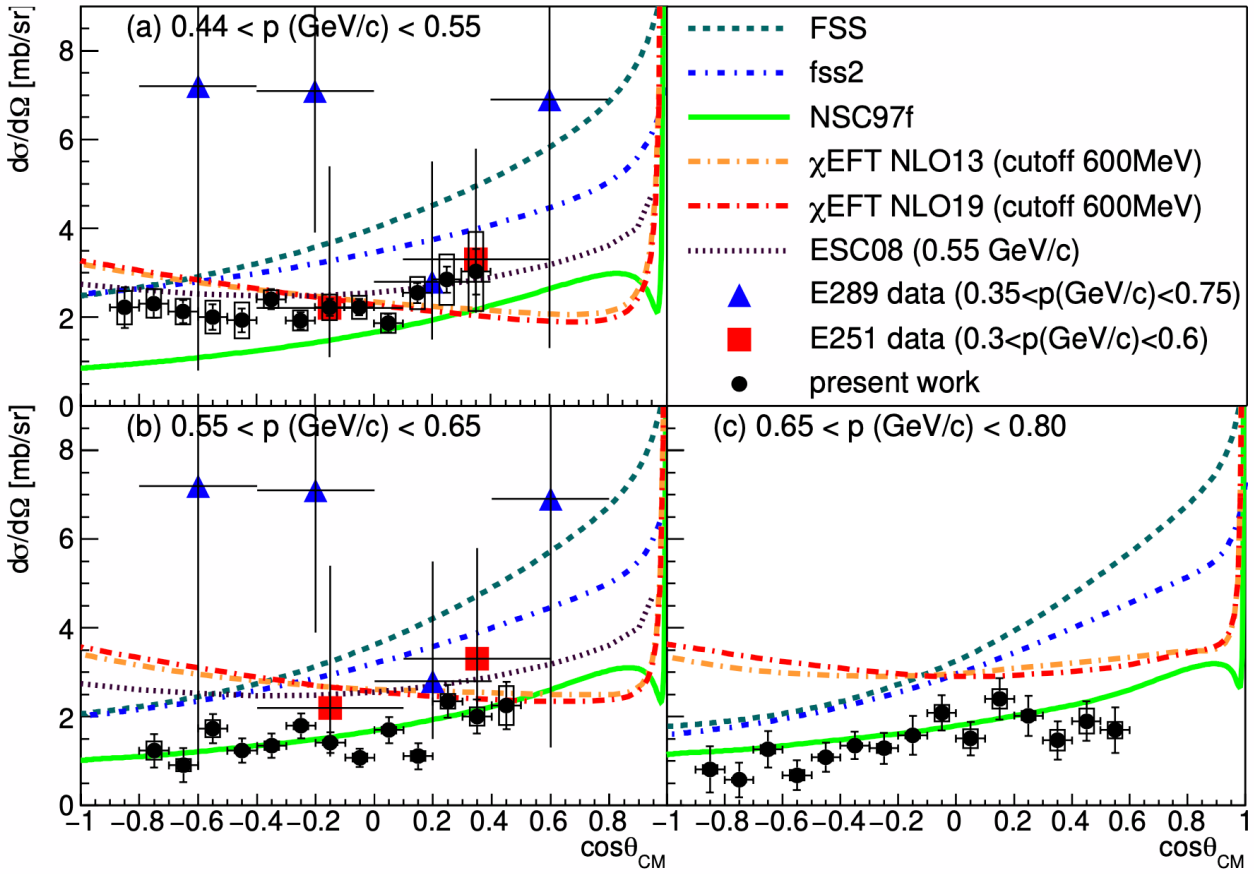
Σ^+p scatterng

6 quarks can stay in s state in normal case



The more repulsive potential in $^3S_1$

→ The larger dσ/dΩ (like fss2)



E40 data : much smaller than fss2 prediction and E289 results

Comparison with theories

- fss2, FSS (quark model) are too large compared to data
- Chiral EFT's momentum dependence does not match with data
- Nijmegen (ESC) models are rather consistent.

Phase shift analysis

T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01

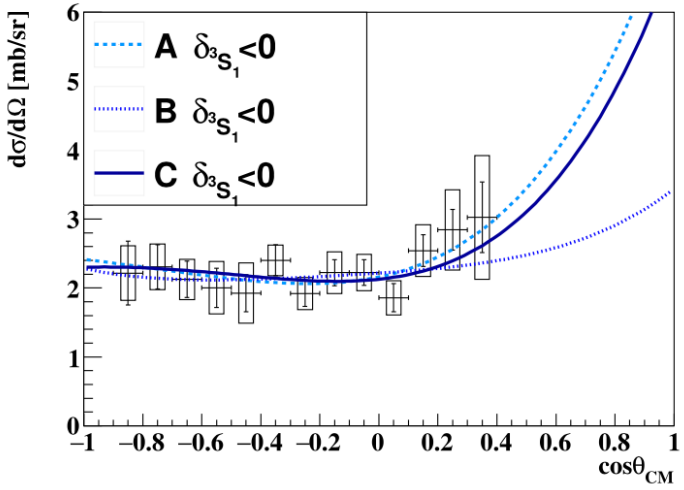
Phase shift analysis for Σ^+p $d\sigma/d\Omega$

- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
- Other phase shifts up to D wave :

  fixed on NSC97f, ESC16, pp scat

Fitting $d\sigma/d\Omega$ with sum of partial waves

0.44<p(GeV/c)<0.55



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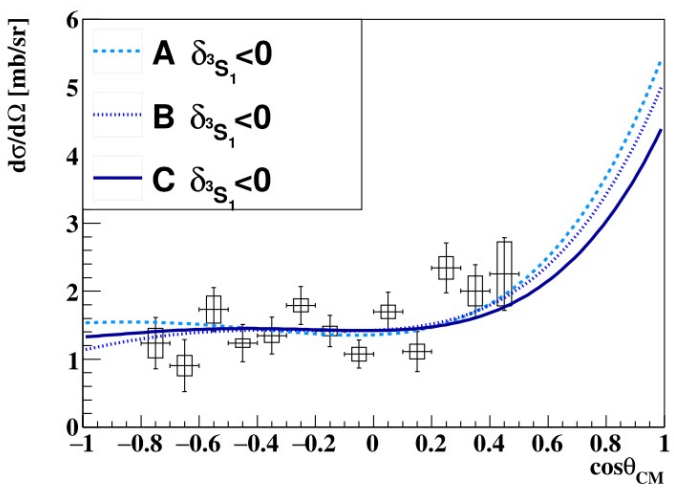

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T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01

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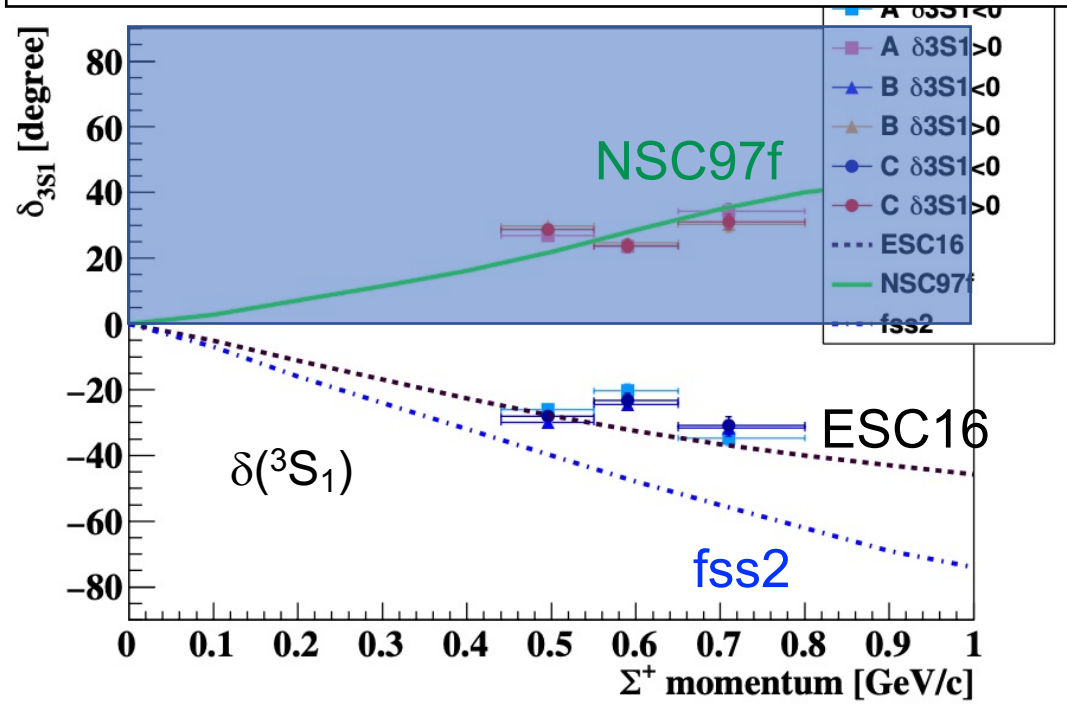
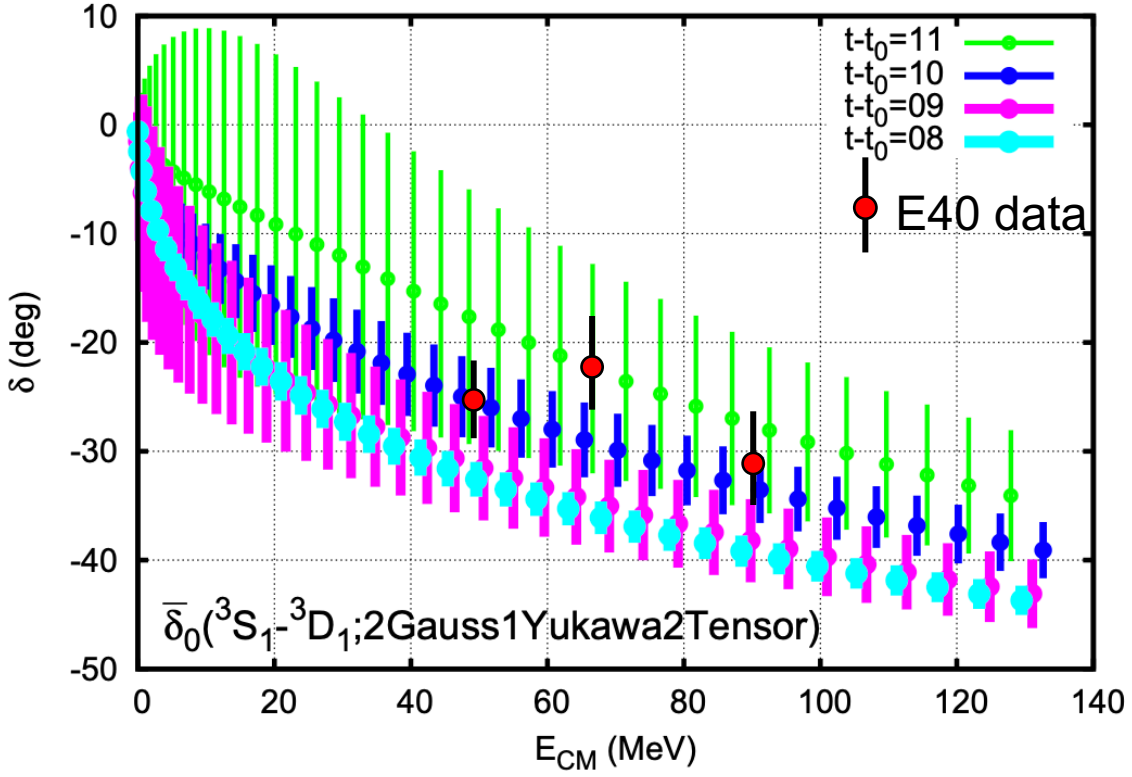
First experimental derivation of phase shift of $^3S_1$



Comparison with HAL QCD ΣN potential



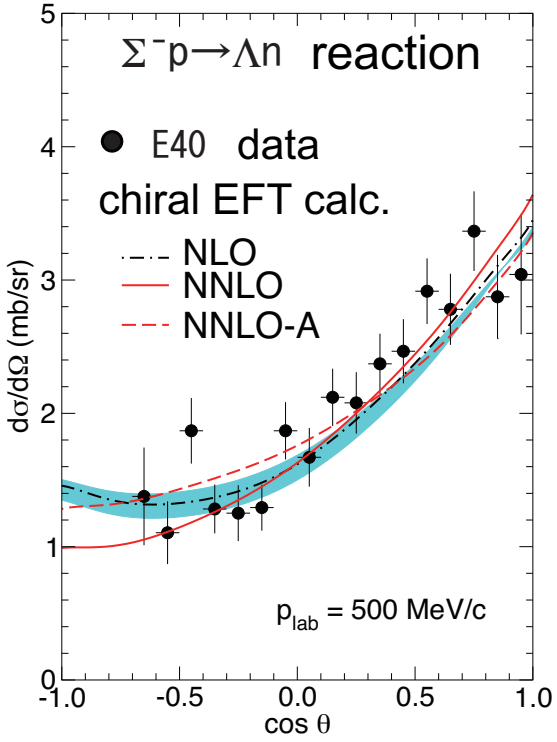
H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

Derived phase shift suggest that **the $^3S_1$ interaction is moderately repulsive**.

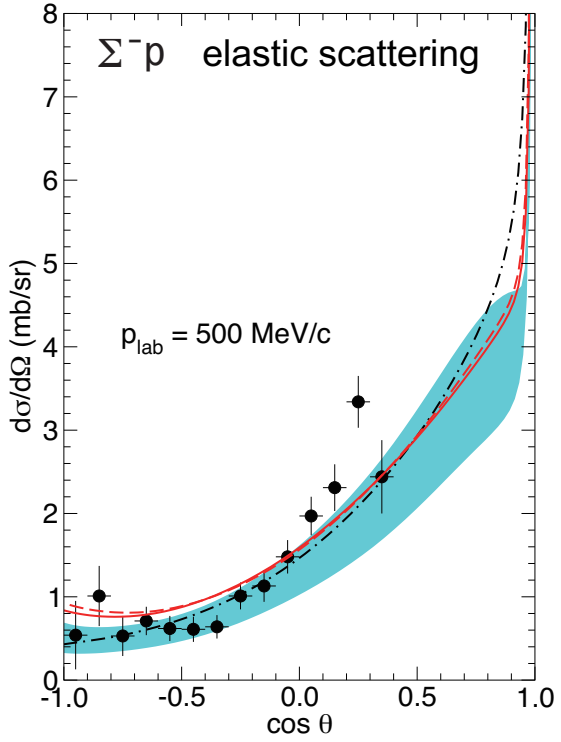
New Σp scattering data and progress of Chiral EFT

Development of Chiral EFT at NNLO have got started with E40 data

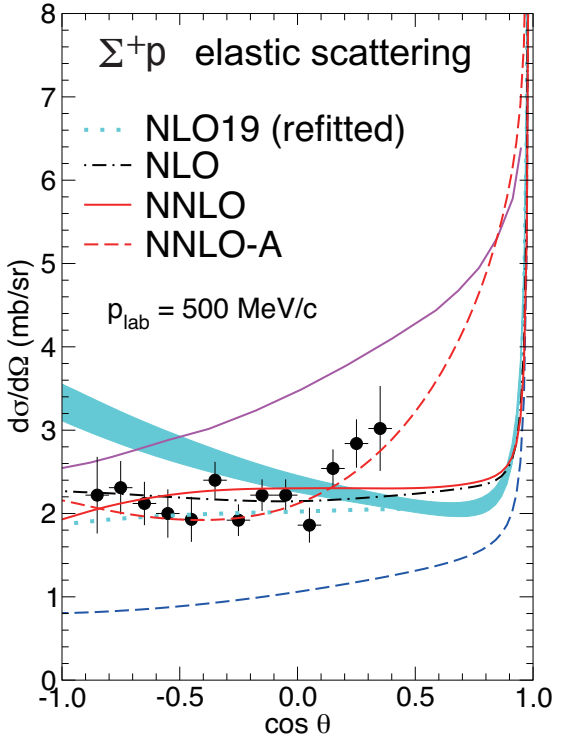
Difficulty at higher momentum



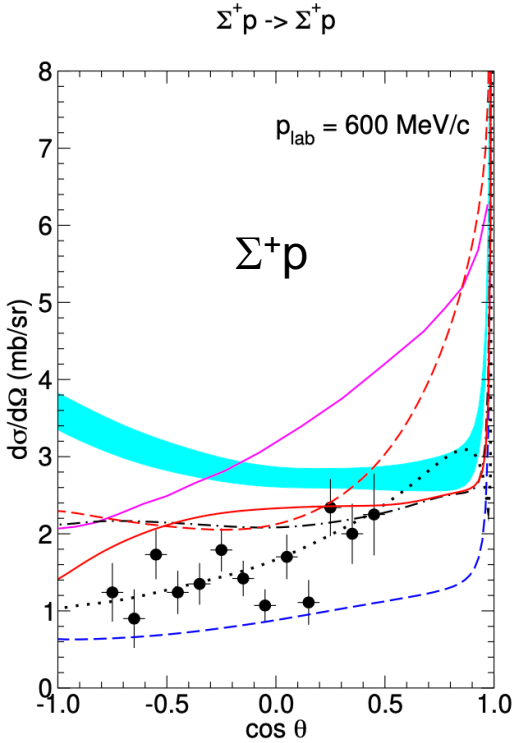
K. Miwa et al.,
PRL 128, 072501 (2022)



K. Miwa et al.,
PRC 104, 045204 (2021)



T. Nanamura et al., PTEP 2022 093D01



J. Haidenbauer et al.,
arXiv:2301.00722

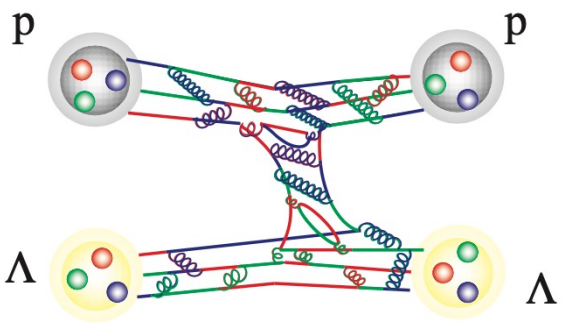
But, the interactions are not uniquely determined yet.
We need more data from additional channels (Λp, …) and additional differential observables (polarizations, …)

Future Λp scattering experiment w/ polarized Λ in the extension project.

Toward Λp scattering

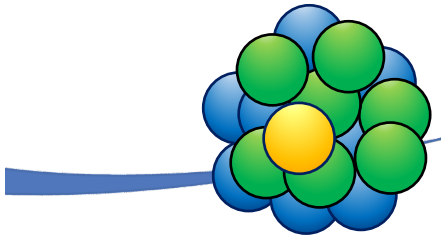
<u>Reliable ΛN two-body interaction :</u>

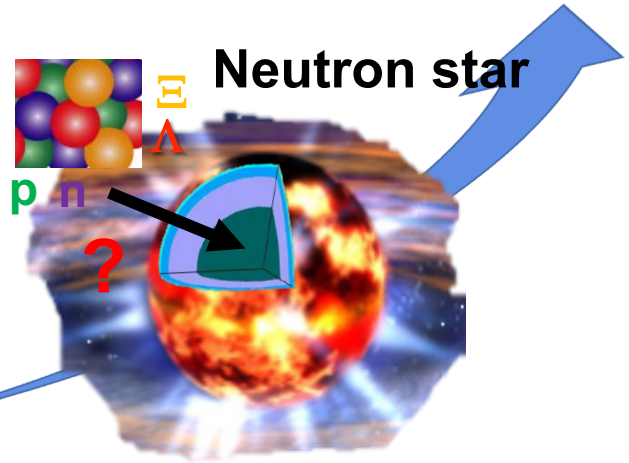
key to deepen Λ hypernuclear physics



Λ hypernuclei

key to reveal ΛNN int.





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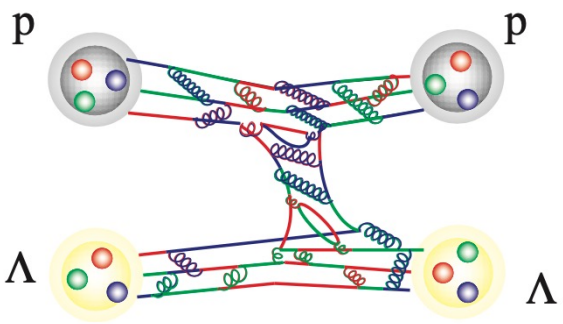

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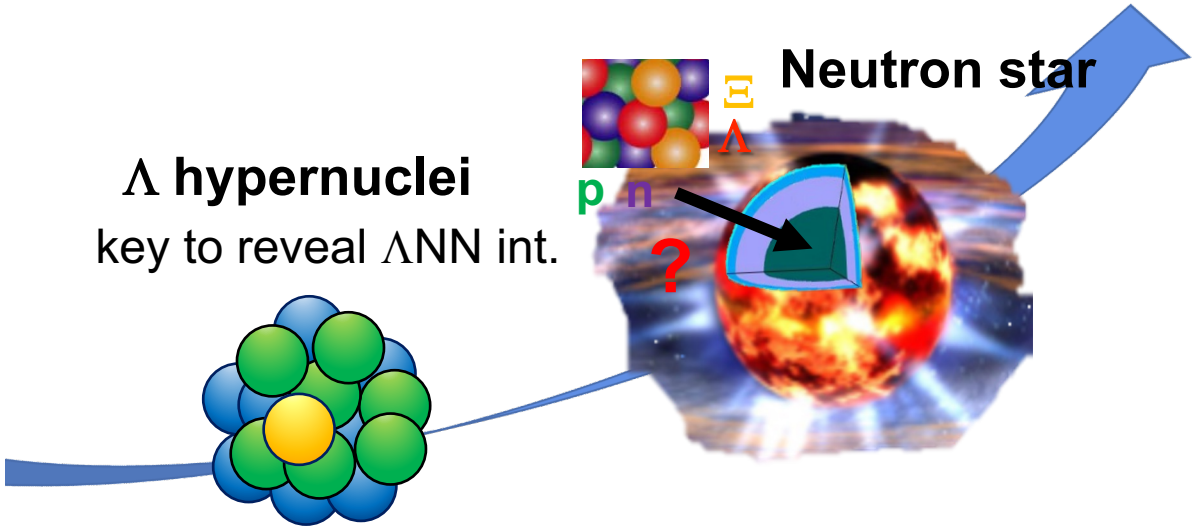
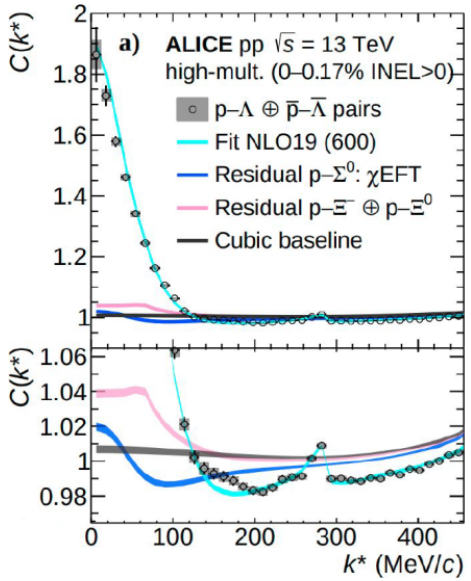
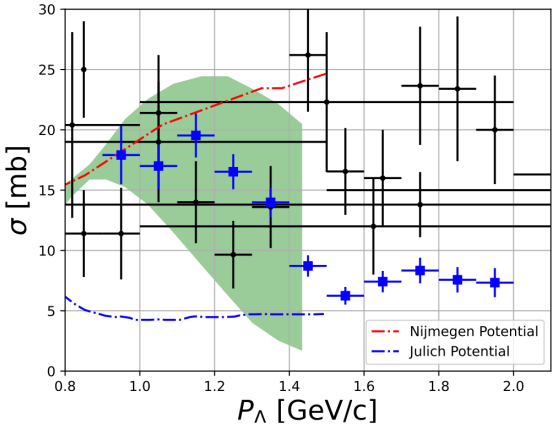


Femtoscopy from HIC



ALICE Collaboration, arXiv:2104.04427

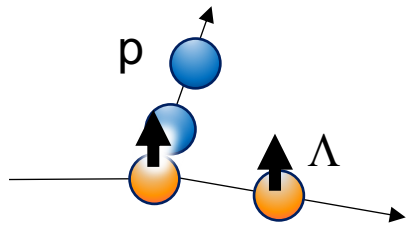
New cross section data
from Jlab CLAS



J. Rowley et al. (CLAS), Phys. Rev. Lett. 127 (2021) 272303

New project at J-PARC

Λp scattering w/ polarized Λ



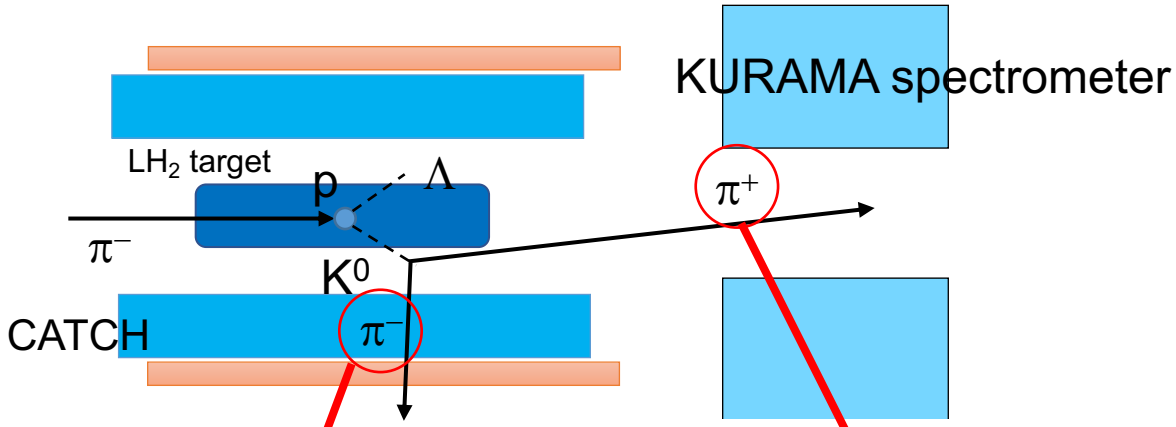
- Feasibility test w/ E40 data
- Expected results in new experiment

Feasibility study in E40 (Σp scattering)

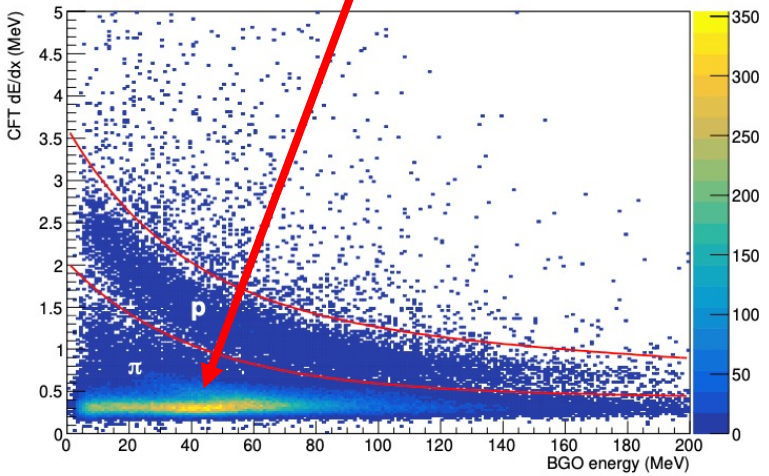
By using by-product data in E40, we already checked feasibility of Λp scattering

New K^0 identify method
π^+ : magnetic spectrometer
π^- : CATCH

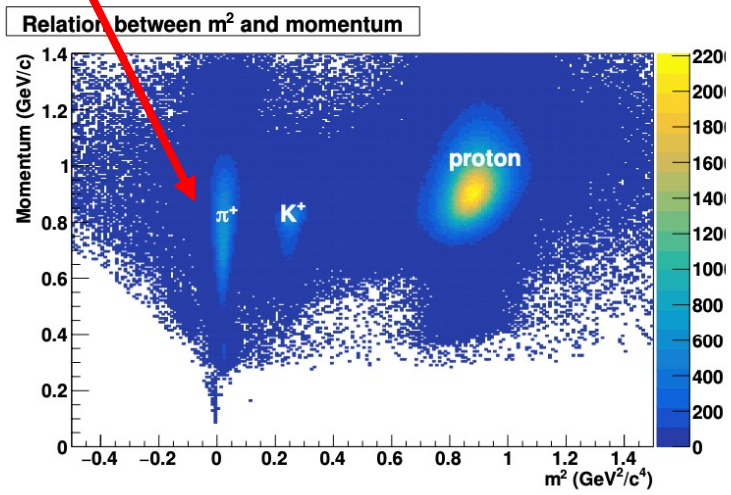
We can keep large acceptance for K^0



Particle ID in CATCH by ΔE-E method



Relation between m^2 and momentum



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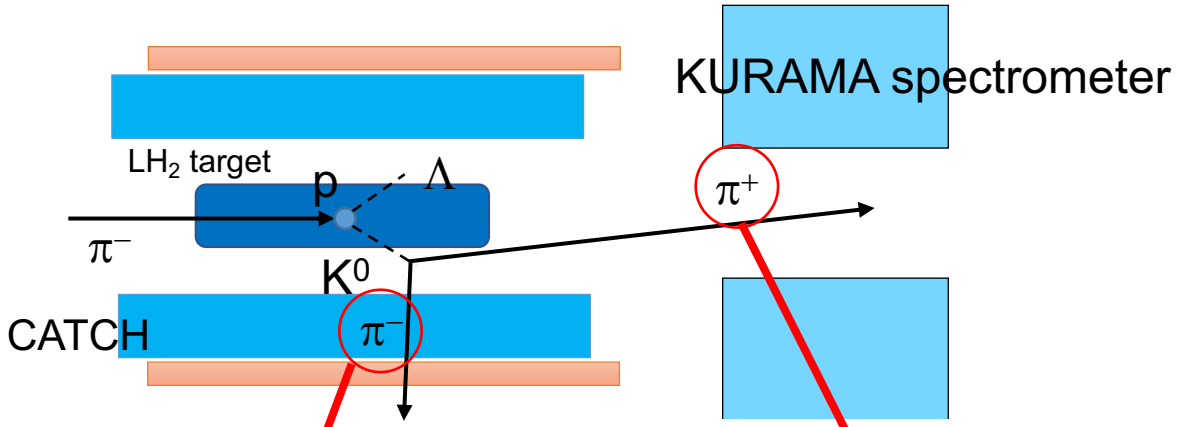
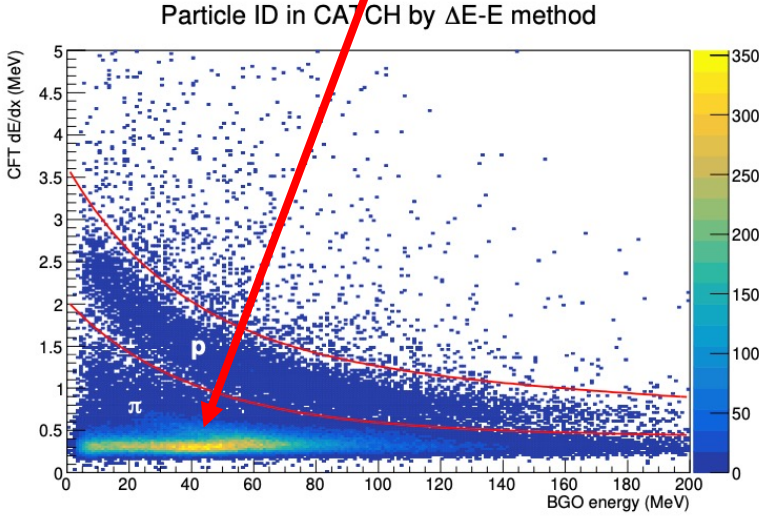
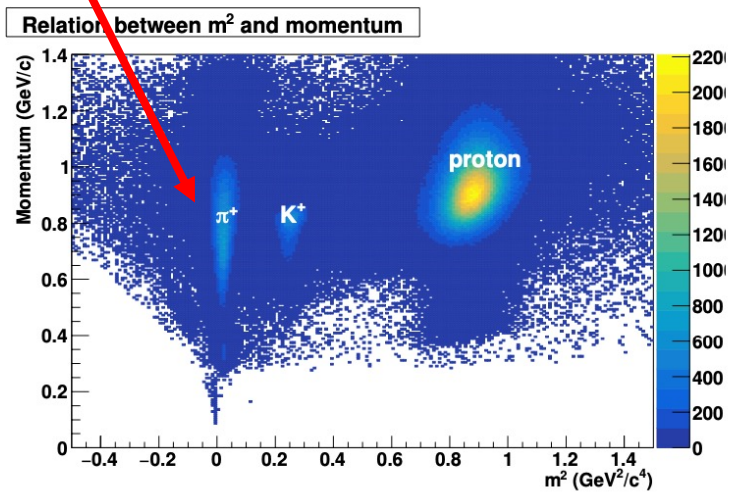
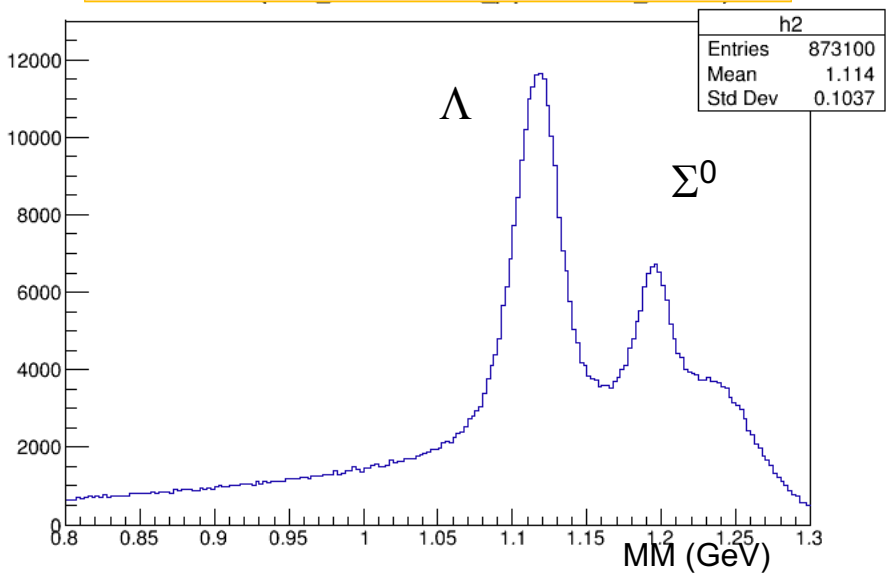






Missing mass ($\pi^- p \rightarrow K^0 X$ reaction)



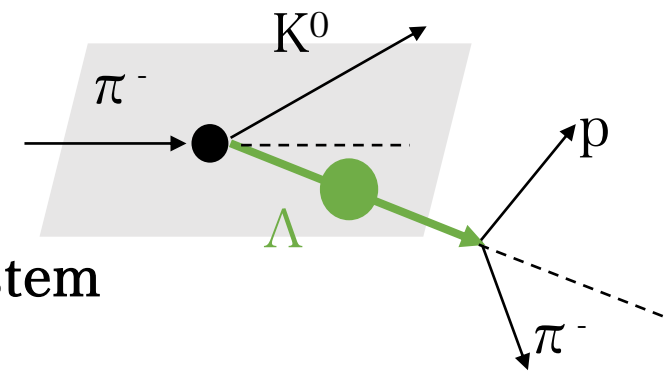
We could establish Λ production method for proton target !

Future upgrade is considered to measure π^- momentum to clean up the background

Λ polarization measurement

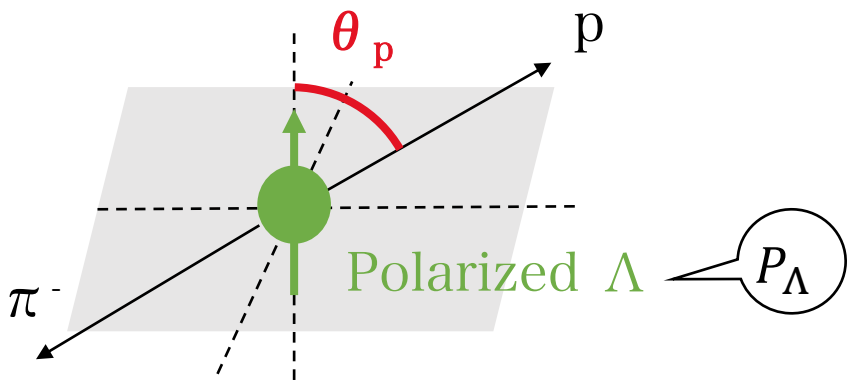
Λ spin can be polarized on Λ production plane in the $\pi^- p \rightarrow K^0 \Lambda$ reaction around p_π=1.0-1.4 GeV/c

Detect p from the $\Lambda \rightarrow \pi^- p$ decay.



*LAB system

Measure θ_p in the rest of Λ.

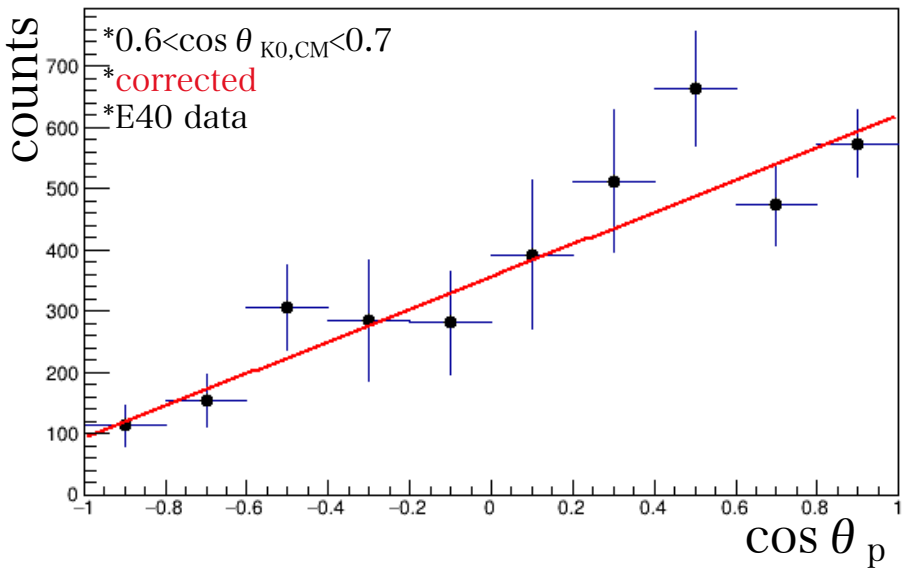


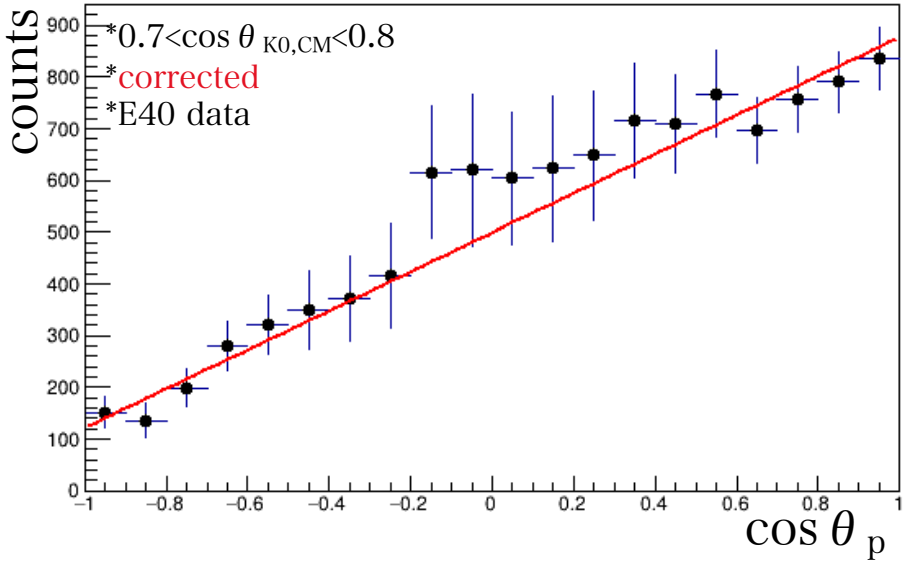
Λ polarization measurement in E40

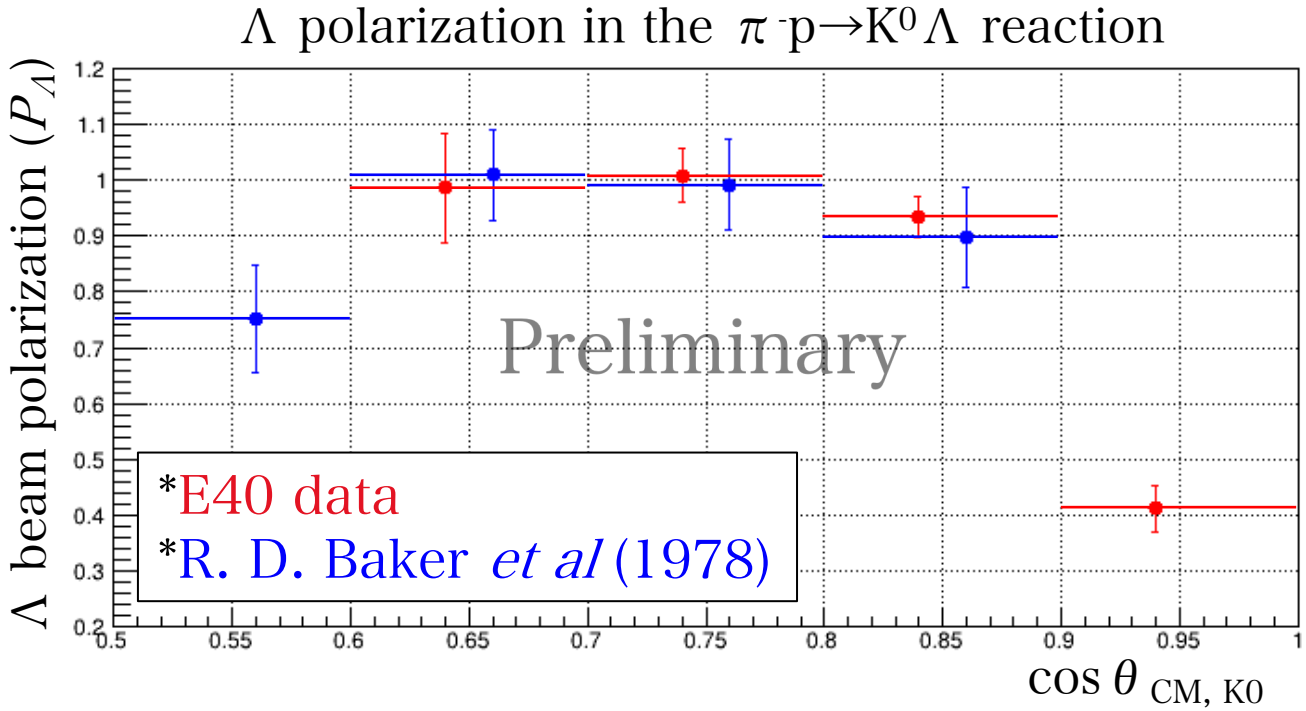
Angule measurement of decay proton

Analysis by T. Sakao (Tohoku)

Measured P_Λ in E40 Data & Prospect







Achievement

1. 1st step for establishing the P_Λ analysis was done.
2. High polarization of Λ beam was confirmed.

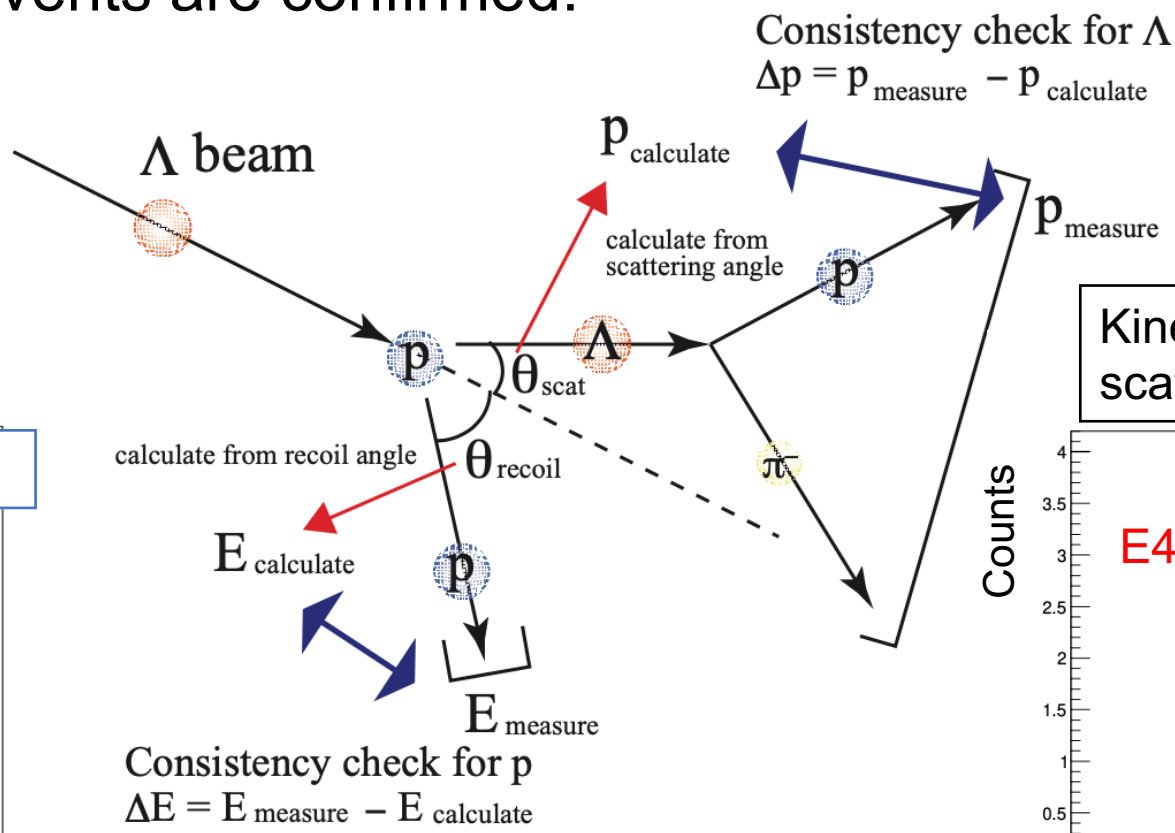
   (P_Λ = 1.009 ± 0.049 in 0.7<cos $\theta_{K0,CM}$<0.8 region)

3. The Λp spin observable measurement is possible in the future J-PARC experiment.

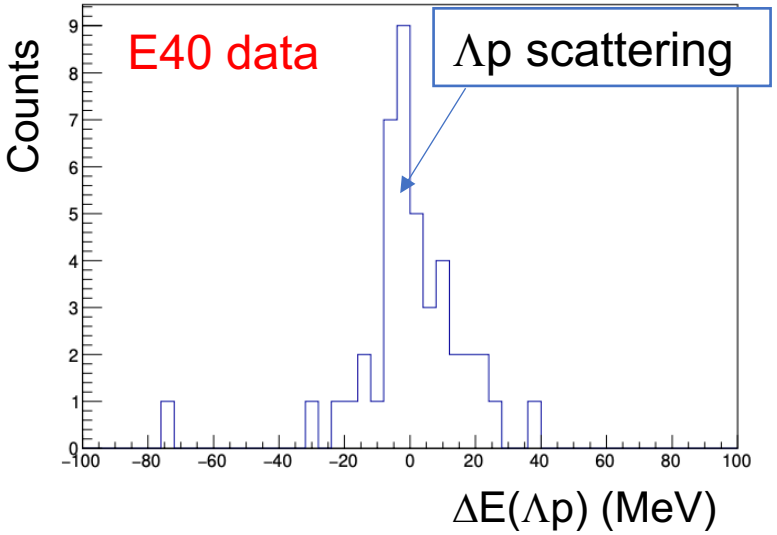
Λp scattering identification

From ~2.5x10^4 Λ beam

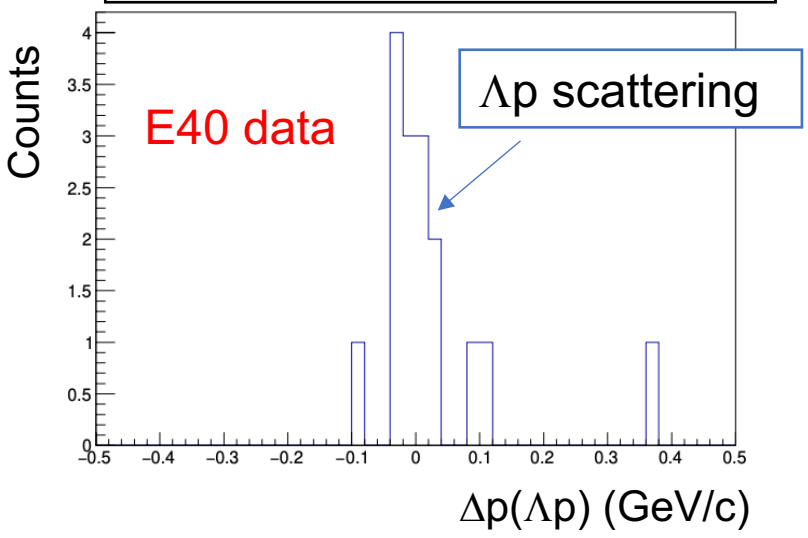
Λp scattering events are confirmed!



Kinematical consistency for recoil proton



Kinematical consistency for scattered Λ



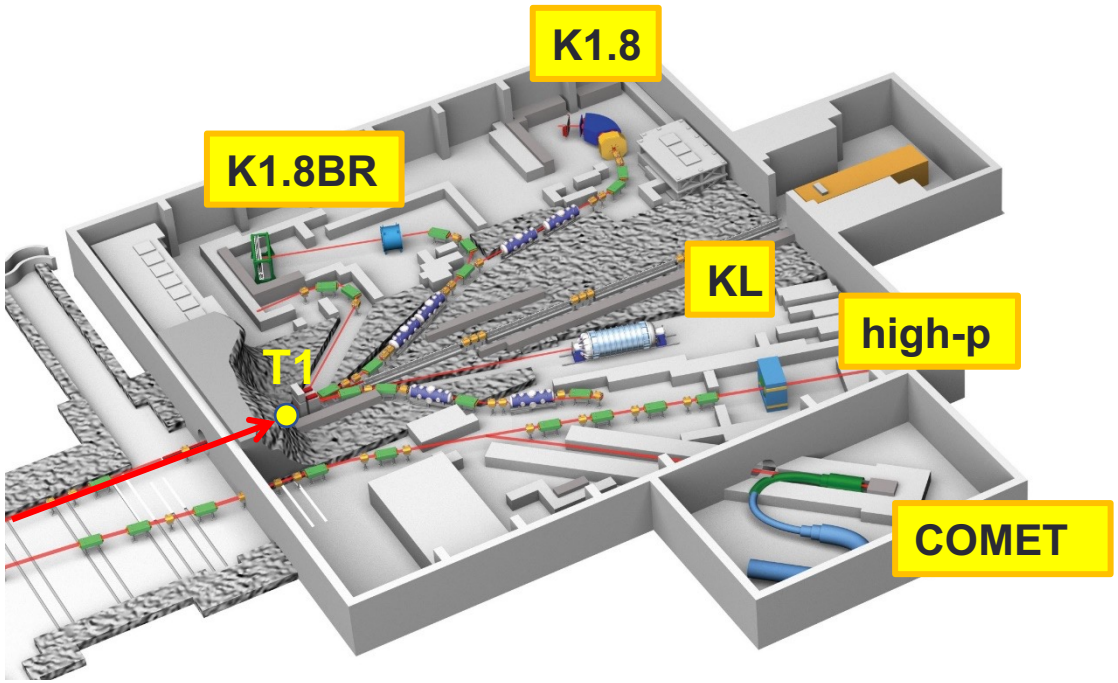
Hadron Experimental Facility Extension (HEF-EX) project

K1.8BR
(~1.0 GeV/c K^-)

K^{bar} N interaction

K1.8 (~1.8 GeV/c K^-)

BB interaction (focusing on S=-2)



high-p (30GeV primary proton beam)
π20 (20GeV/c secondary beam)

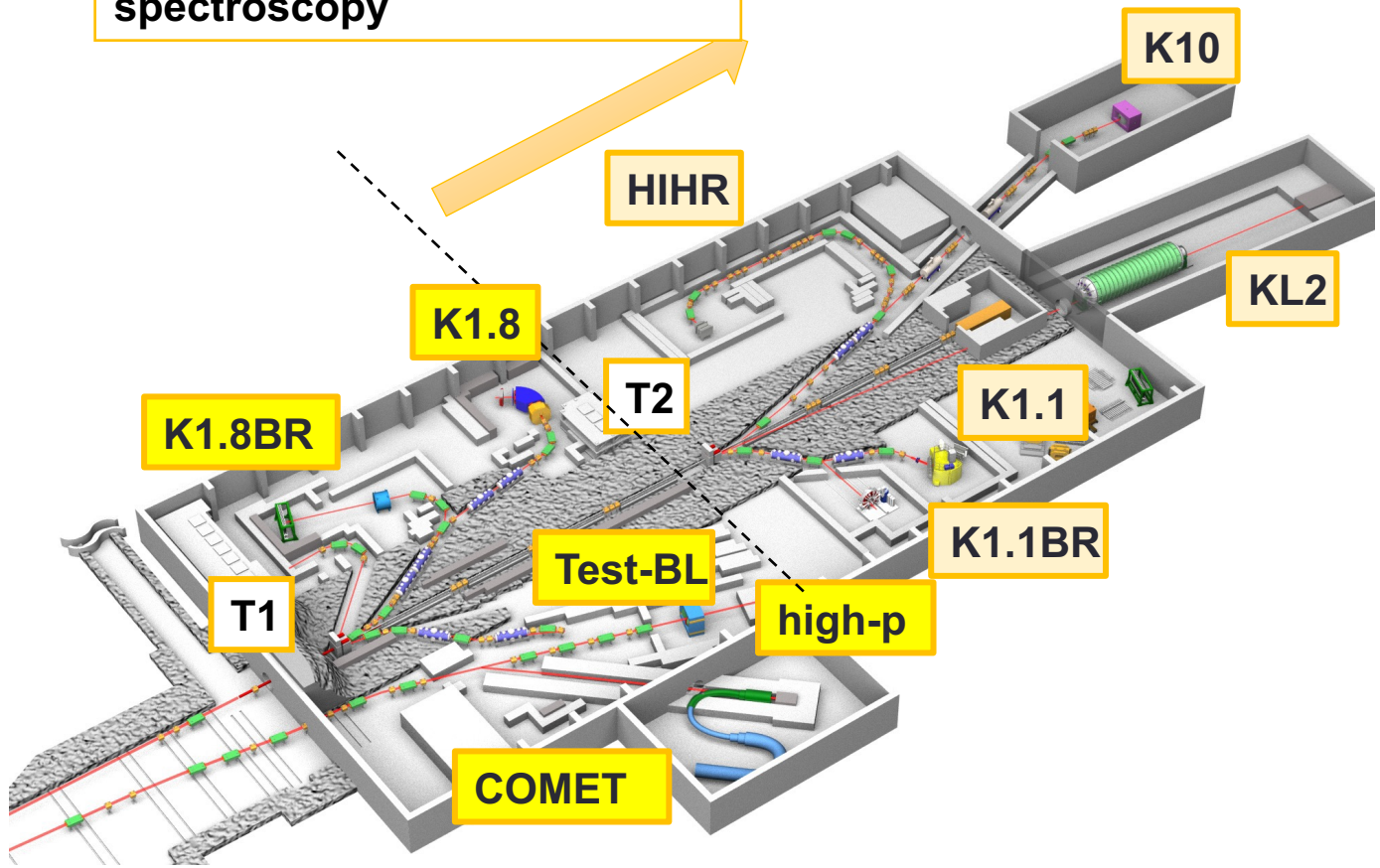
Hadron property in nuclear medium
Baryon spectroscopy

HIHR (~2 GeV/c π)

Ultra precise Λ hypernucler spectroscopy

K10 (~10 GeV/c K^-)

Ω baryon spectroscopy



K1.1BR (~0.8 GeV/c π/K)

Physics using a low energy Kaon

K1.1 (~1.2 GeV/c π/K)

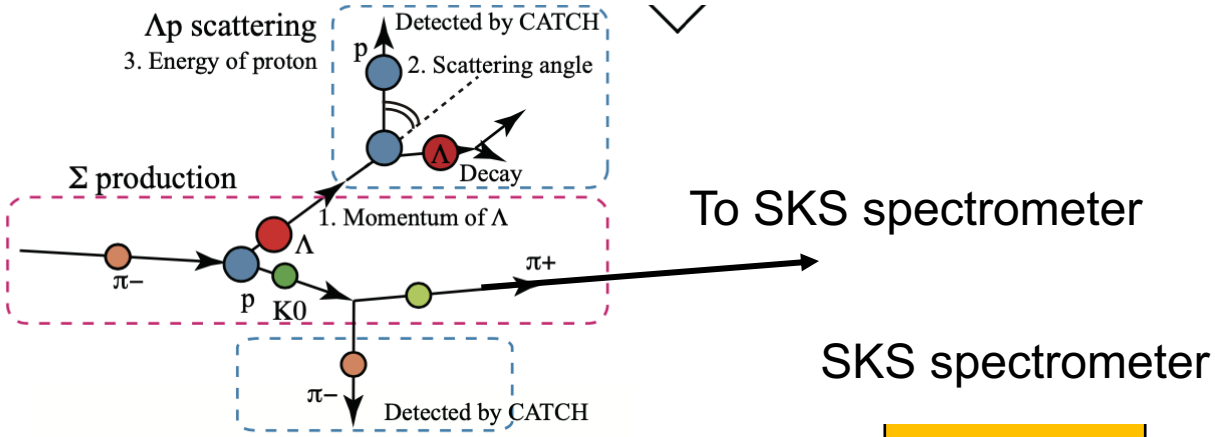
BB interaction (focusing on S=-1)

Perform physics not accessible in the present hadron hall
Perform physics programs in parallel with twice more beam lines

Λp scattering experiment with polarized Λ beam

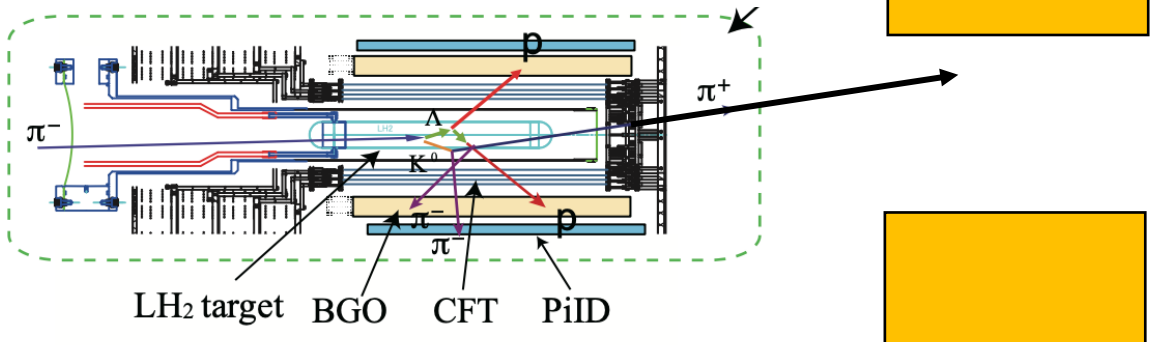
Λ beam identification

Tagged by $\pi^- p \rightarrow K^0 \Lambda$ reaction at p=1.05 GeV/c



To SKS spectrometer

SKS spectrometer

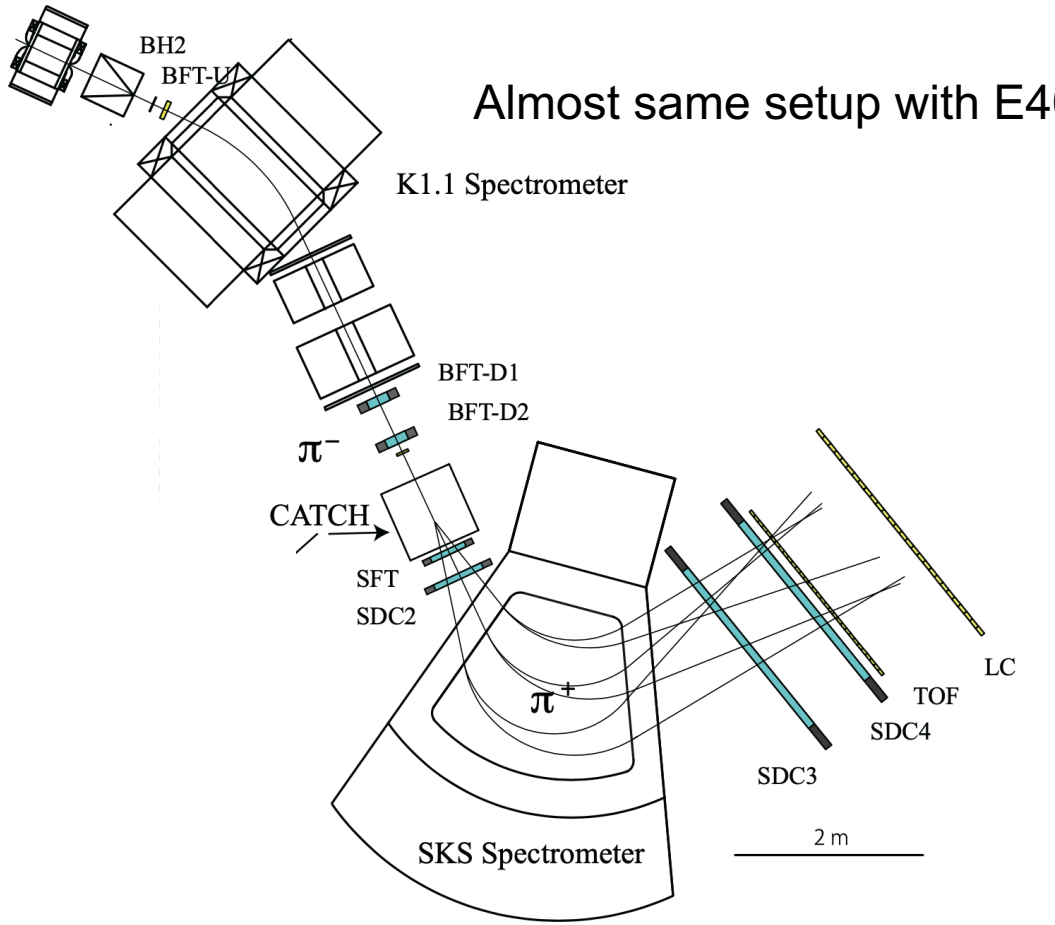


Λp scattering identification

Detected by CATCH

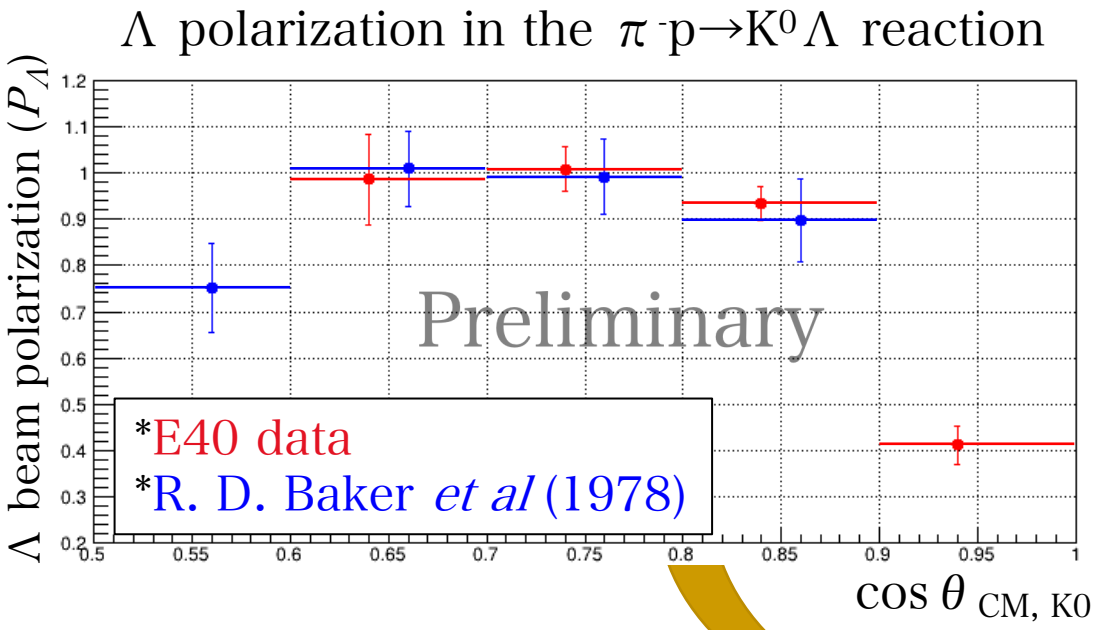
J-PARC P86 (J-PARC EX project)
at K1.1 beam line

Almost same setup with E40



Λp scattering experiment with polarized Λ beam

High spin polarization of Λ



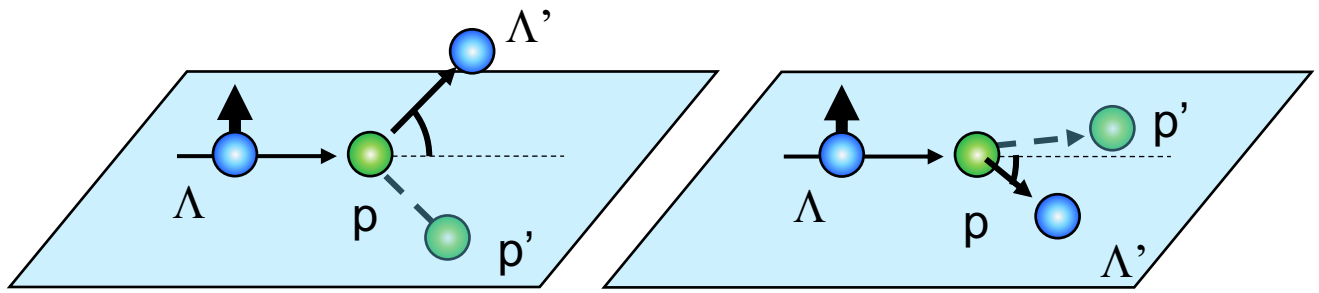
Realize spin observable measurement

Analyzing power

Left/Right asymmetry of Λp scattering

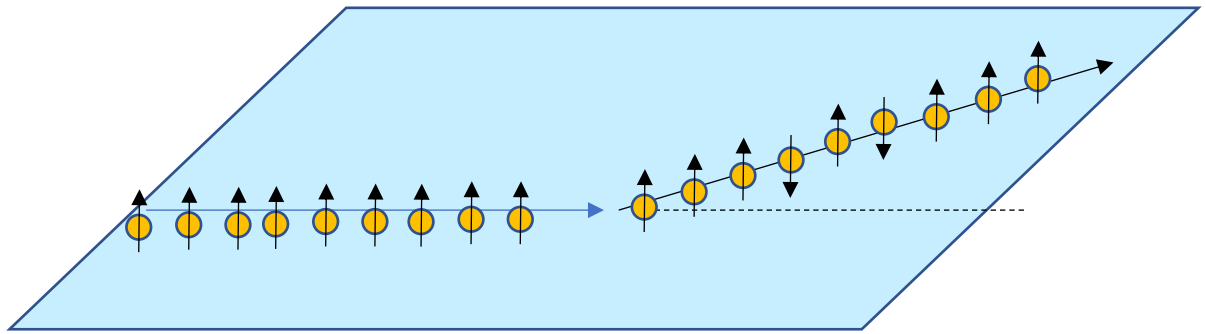
Left scattered event

Right scattered event



Depolarization (D_y^y)

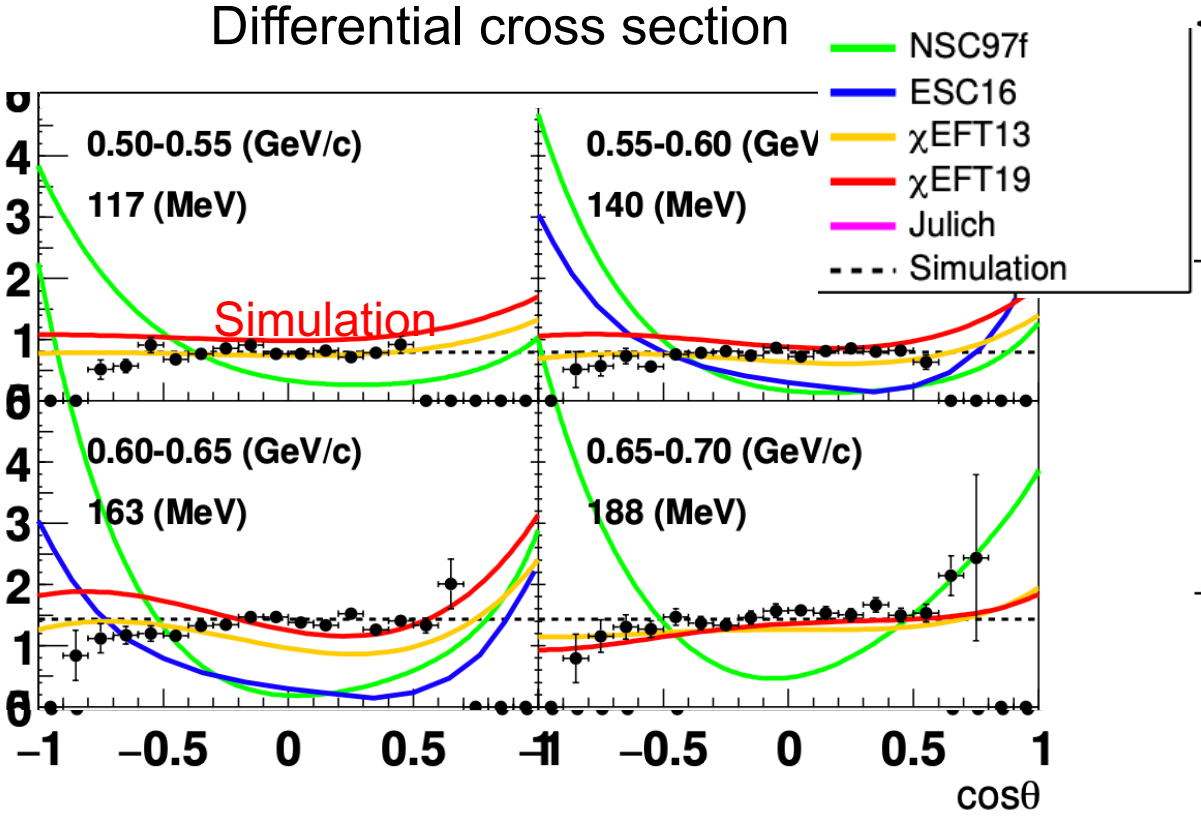
Change the spin polarization after the Λp scattering



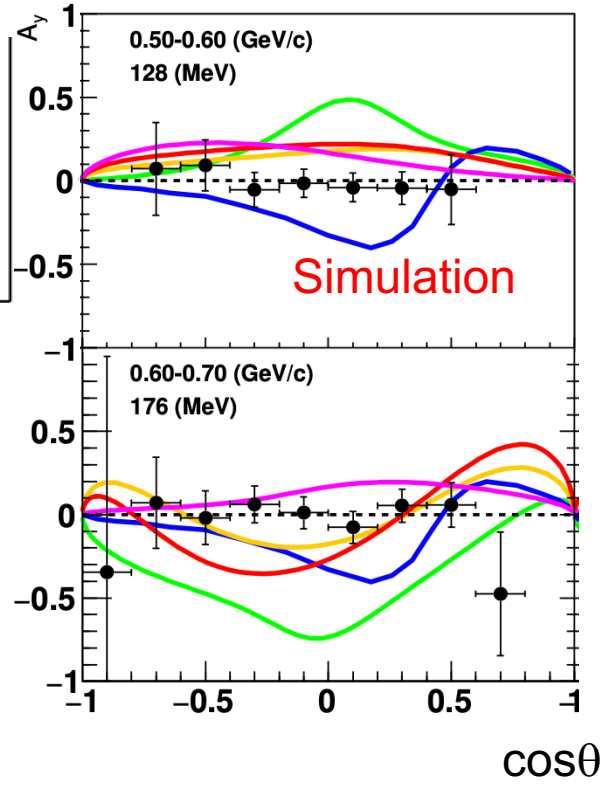
dσ/dΩ and Spin observables in Λp scattering

J-PARC P86 (J-PARC EX project) at K1.1 beam line

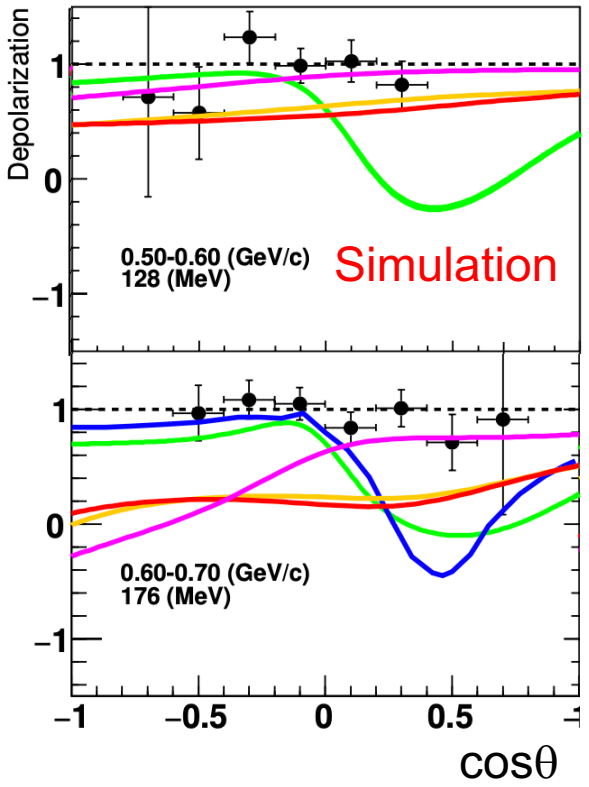
Differential cross section



Analyzing power



Depolarization (D_y^y)



No differential observables of Λp scattering SO FAR

Simulated results w/ 10^8 Λ

--> Large uncertainty in P-wave and higher-wave interaction.

Theoretical prediction shows quite different angular dependence in dσ/dΩ, A_y and D_y^y

These new scattering data become essential constraint to determine spin-dependent ΛN interaction

Summary

- BB interactions are important to understand
  - Generalized meson-exchange picture with (broken) $SU_F(3)$ symmetry
  - Role of quarks at the short range
  - Dynamics of nuclear system with hyperon (hypernuclei, neutron star) as its basic interaction
- YN scattering experiment gets possible!
- Systematic measurements of Σp scattering at J-PARC
  - $d\sigma/d\Omega$ for Σ^+p, Σ^-p, $\Sigma^-p \rightarrow \Lambda n$ scatterings with ~10% level accuracy for fine angular pitch ($d\cos\theta=0.1$)
  - Momentum dependence of Σ^+p $\delta(^3S_1)$ channel was derived (–20 ~ −30 degrees)
- Future project to measure $d\sigma/d\Omega$ and spin observables of Λp scattering w/ polarized Λ beam
  - These measurements are important to reinforce the current ΛN interaction for deepening hypernuclear physics.

We hope our data become important inputs to improve theoretical models

E40 Collaborators

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Osaka Univ. : K. Kobayashi, S. Hoshino, Y. Nakada, R. Nagatomi, M. Nakagawa, A. Sakaguchi

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Korea Univ. : J.K. Ahn, S.H. Kim, W.S. Jung, S.W. Choi, B.M. Kang

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

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

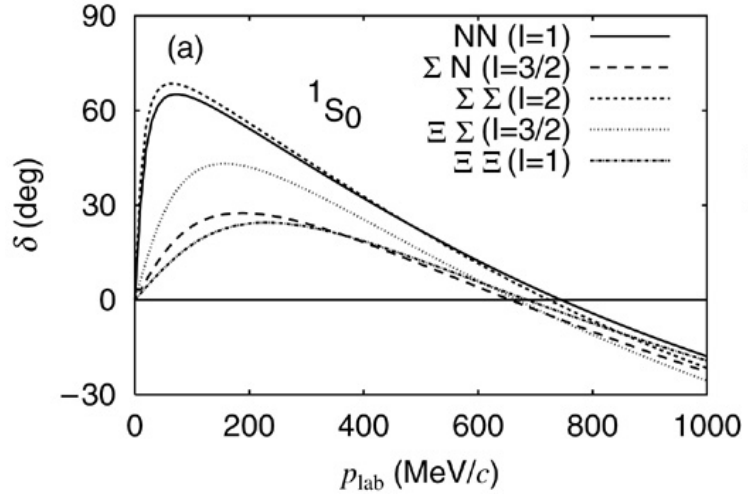
backup

Phase shift analysis

T. Nanamura et al., arXiv:2203.08393
Talk in June 30th

strangeness	BB channel (I)	^{1}Even or ^{3}Odd	^{3}Even or ^{1}Odd
0	$NN(I=0)$	–	$(\mathbf{10^*})$
	$NN(I=1)$	$(\mathbf{27})$	–
	$\Sigma N(I=\frac{3}{2})$	$(\mathbf{27})$	$(\mathbf{10})$

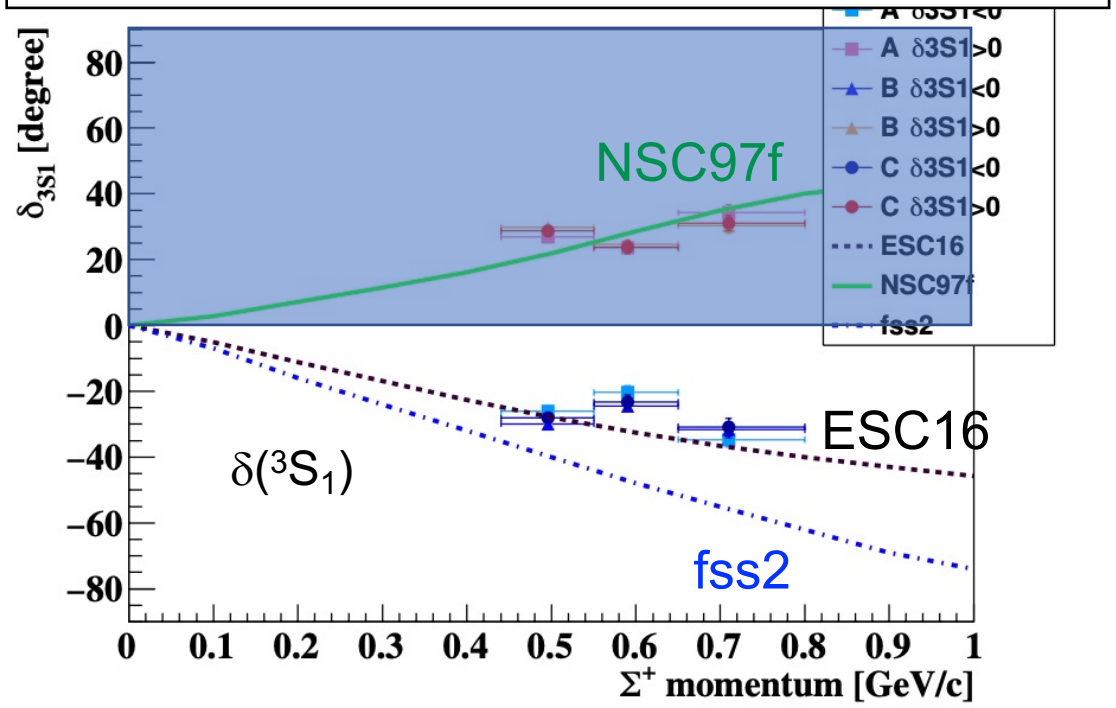
- Constrained from NN (I=1) channel
- Smaller uncertainty



Phase shift analysis for Σ^+p $d\sigma/d\Omega$

- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
- Other phase shifts up to D wave :
  fixed on NSC97f, ESC16, pp scat

First experimental derivation of phase shift of $^3S_1$

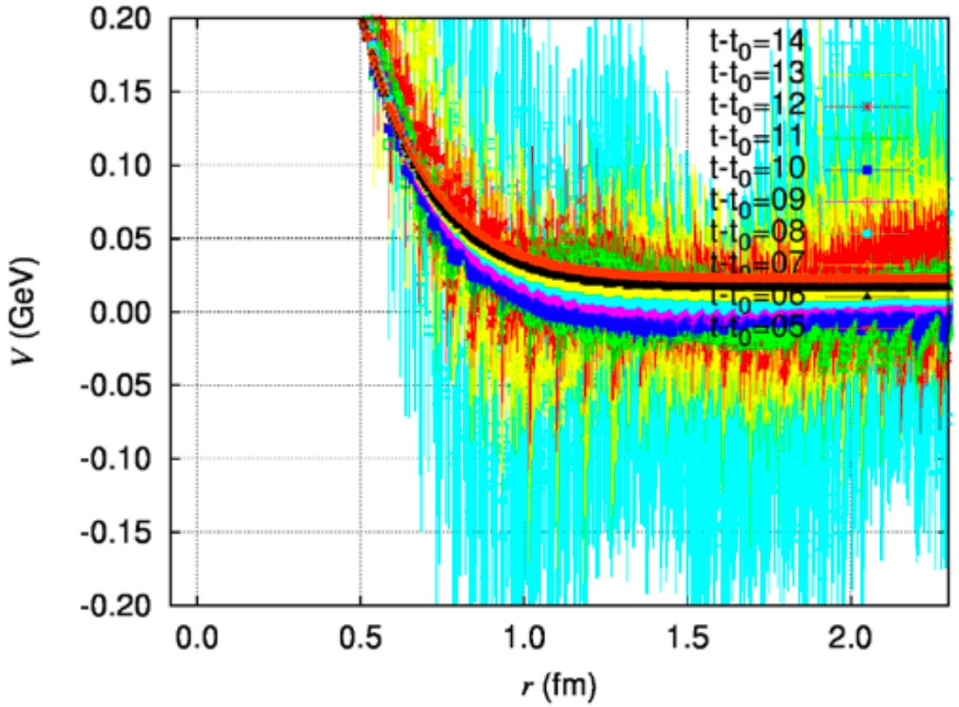


Derived phase shift suggest that **the $^3S_1$ interaction is moderately repulsive**.

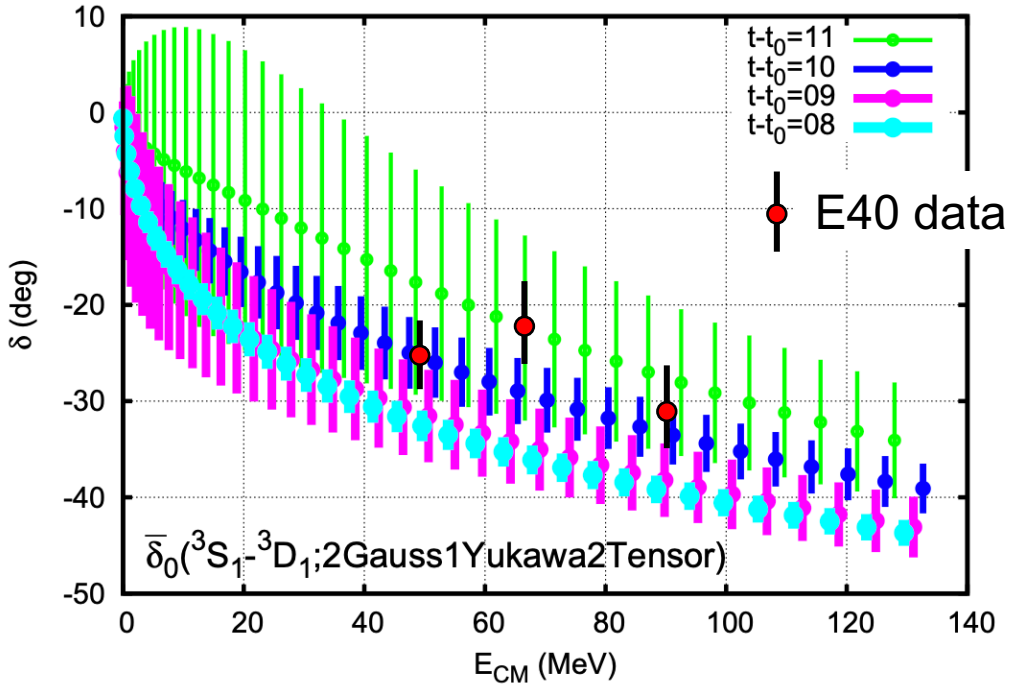
Comparison with HAL QCD

Our phase shift values are consistent with HAL QCD's prediction.

Potential of Σ^+p $^3S_1$ channel

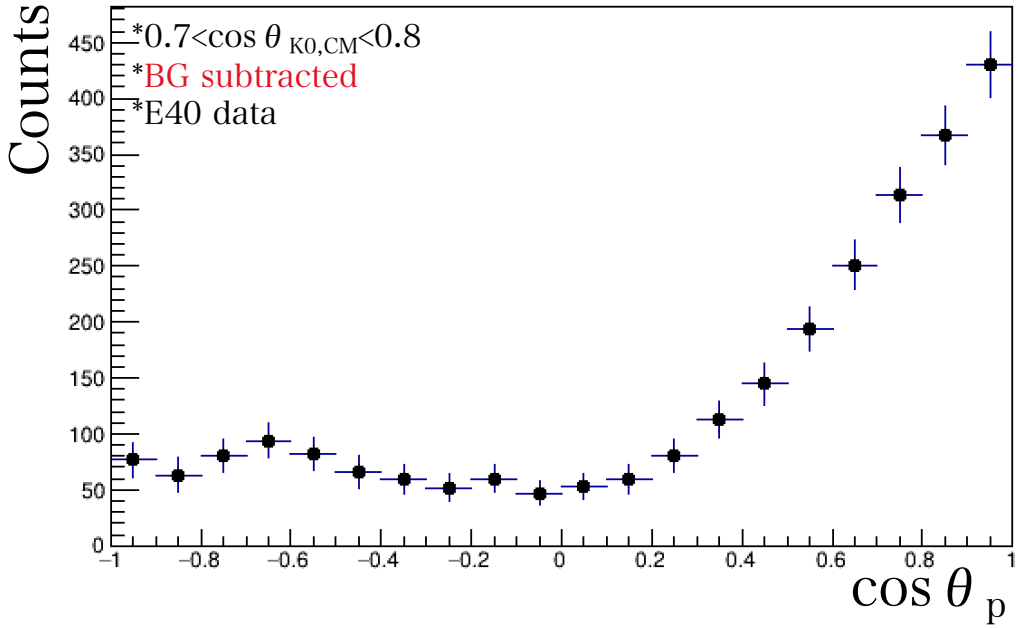


Phase shift of Σ^+p $^3S_1$ channel

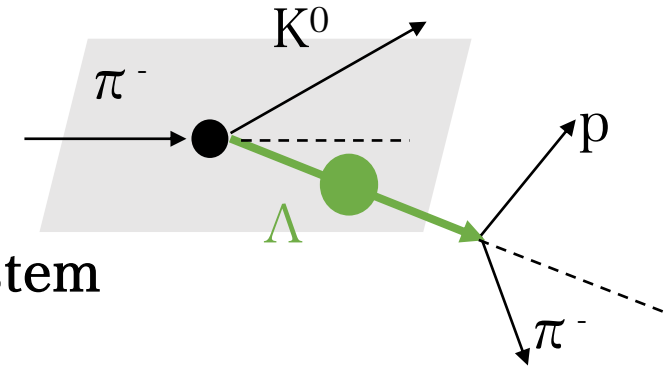


H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

Angular dependence of decay proton from Λ measured by CATCH

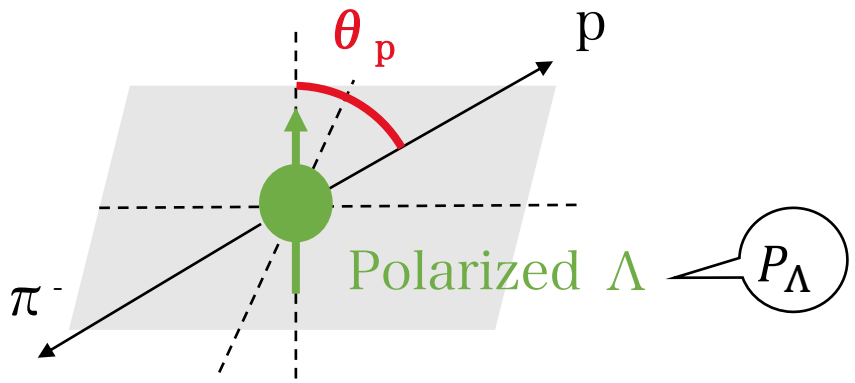


Detect p from the $\Lambda \rightarrow \pi^- p$ decay.

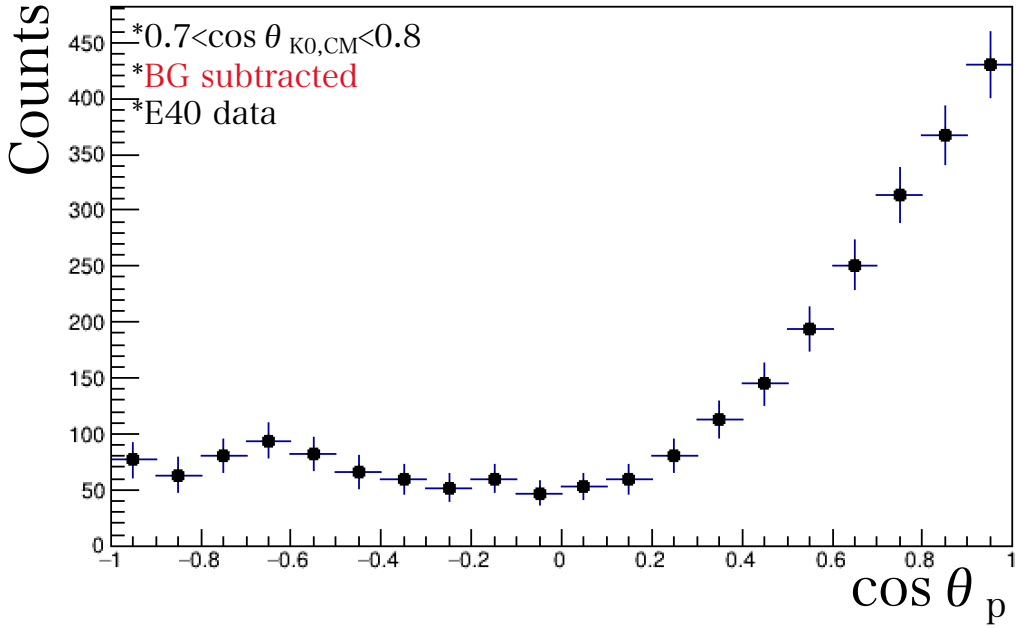


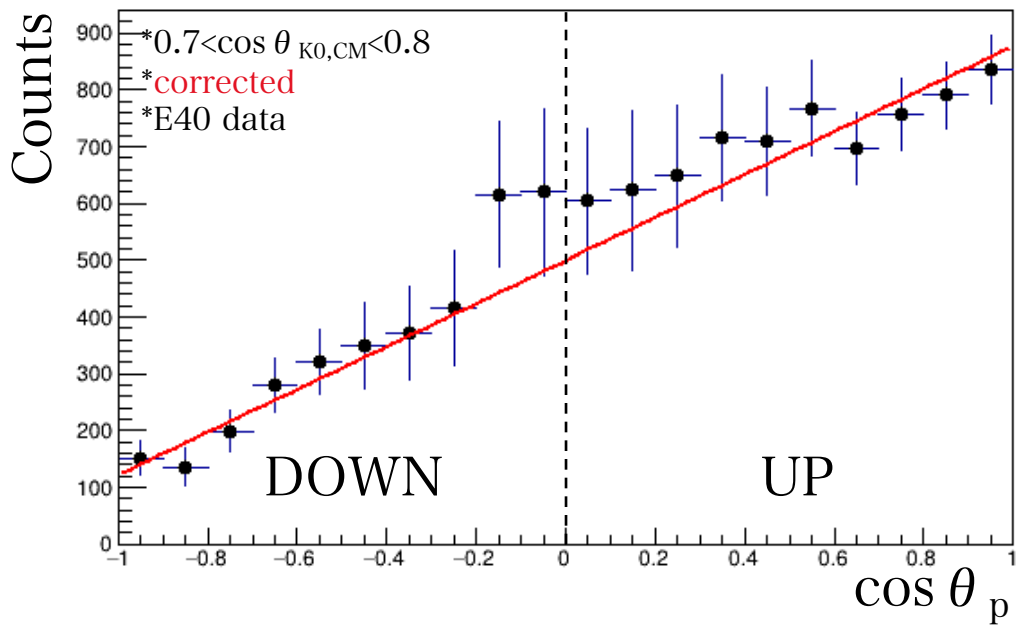
*LAB system

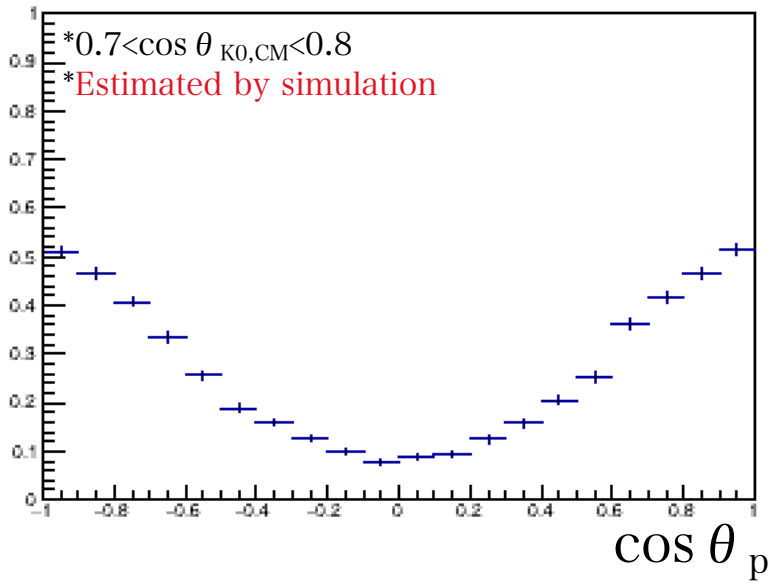
Measure θ_p in the rest of Λ.



Angular dependence of decay proton from Λ measured by CATCH

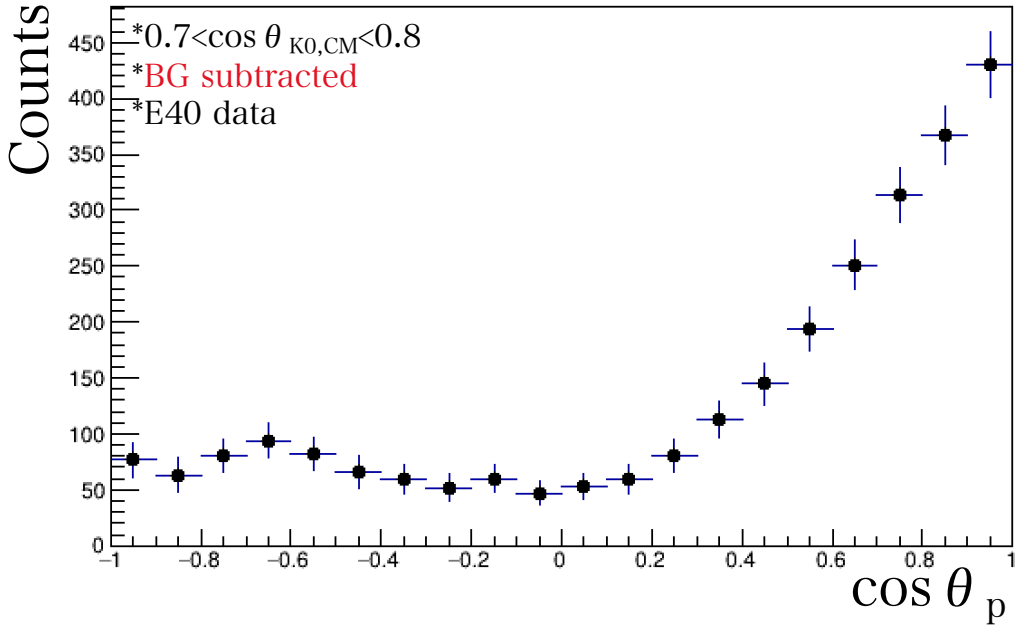


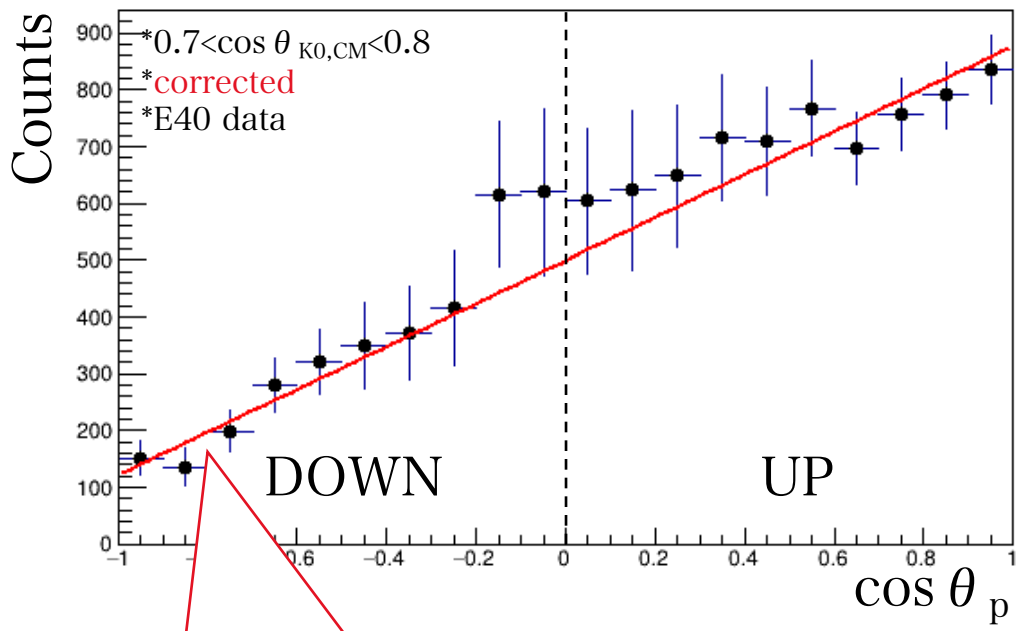


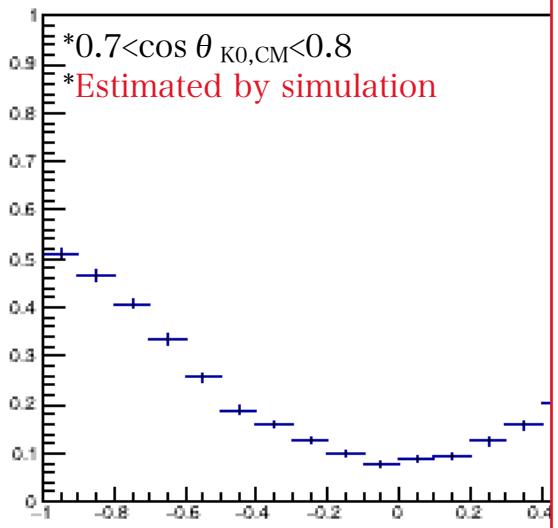


Efficiency correction

Angular dependence of decay proton from Λ measured by CATCH







P_Λ fitting function:

$$\frac{1}{N_0}\frac{dN}{d\cos\theta_p} = \frac{1}{2}(1 + \alpha \boldsymbol{P_\Lambda} \cos\theta_p)$$

α : asymmetry parameter

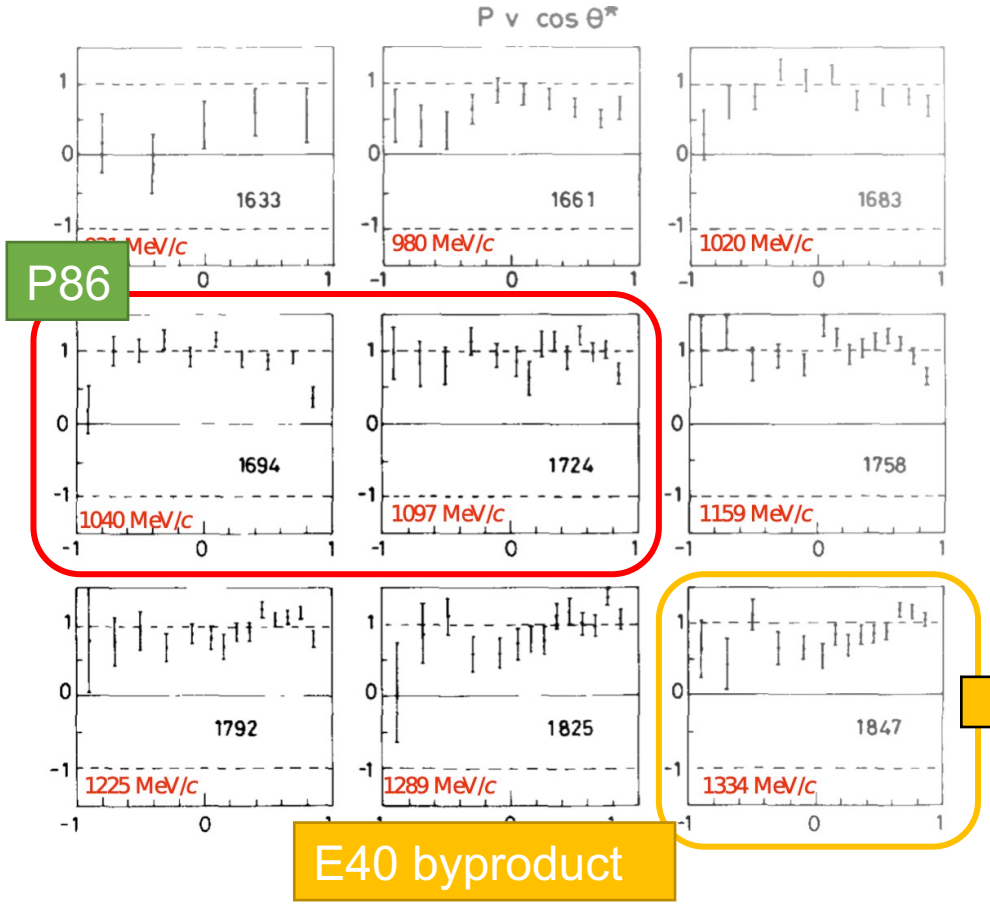
$(= 0.750 \pm 0.009 \pm 0.004$ [2]),

[2] M. Ablikim et al. (2019).

tion

Λ polarization measurement

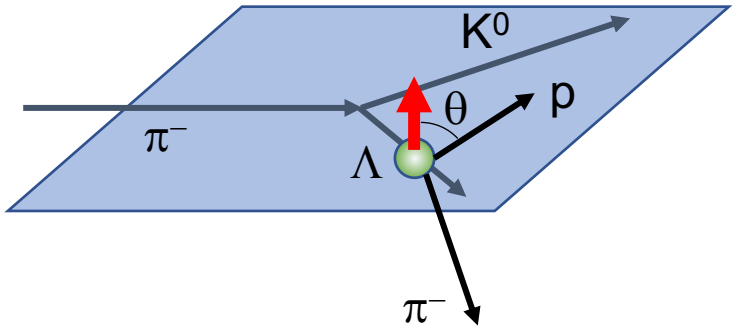
Past measurement by R.D. Baker et al.



~100% Λ polarization was confirmed

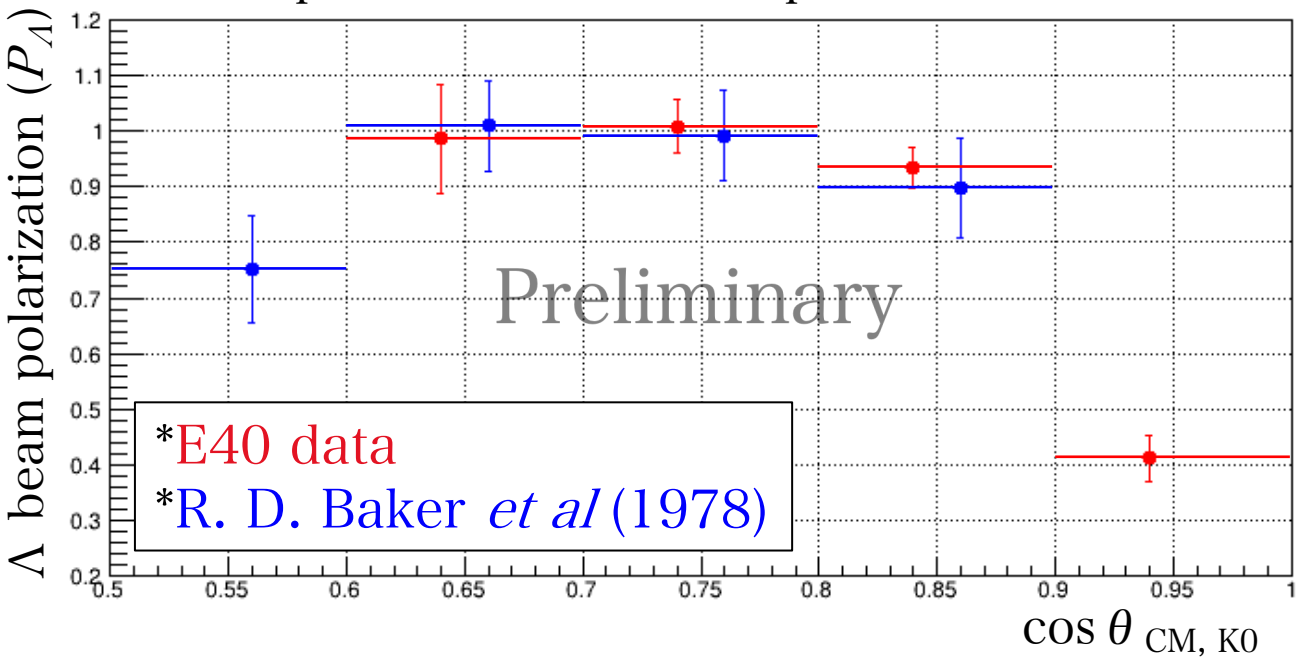
Λ polarization measurement in E40

Production plane was defined event by event



Analysis by T. Sakao (Tohoku)

Λ polarization in the $\pi^- p \to K^0 \Lambda$ reaction



Experimental progress on two-body YN interactions

Link between here are connected

2-body scattering data

Femtoscopy

Lattice QCD

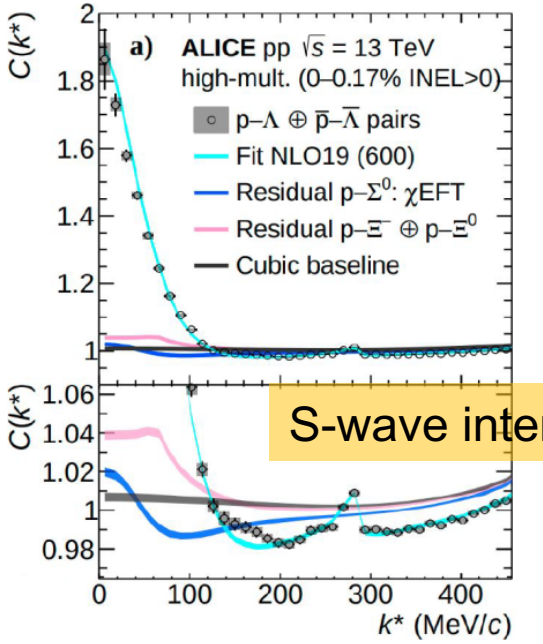
Base to improve to **realistic two-body BB interaction** is being constructed both theoretically and experimentally.

BB interaction model

- Meson exchange BB int. models
- Chiral EFT

Small relative-momentum region

ALICE Collaboration, arXiv:2104.04427



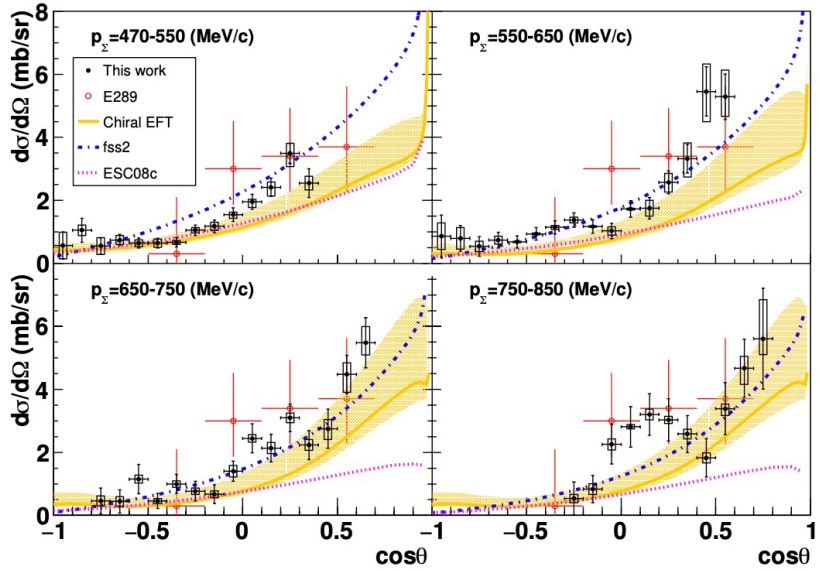
S-wave interaction

Femtoscopy from HIC

Intermediate energy region

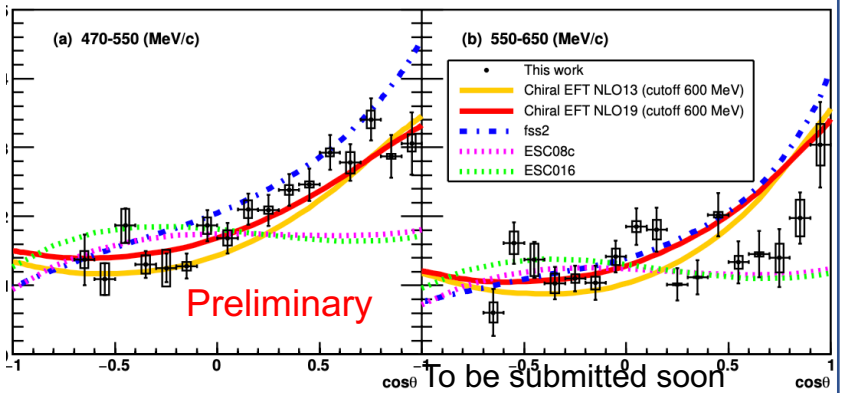
K. Miwa et al. arXiv:2104.13608

Differential cross sections of Σ^-p scattering



P- and higher wave interaction

Differential cross section of $\Sigma^-p \to \Lambda n$ reaction

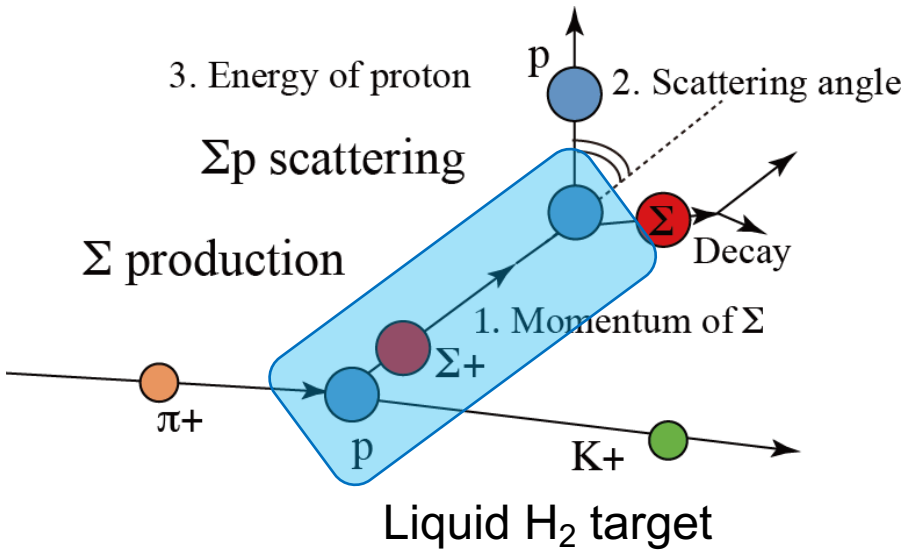


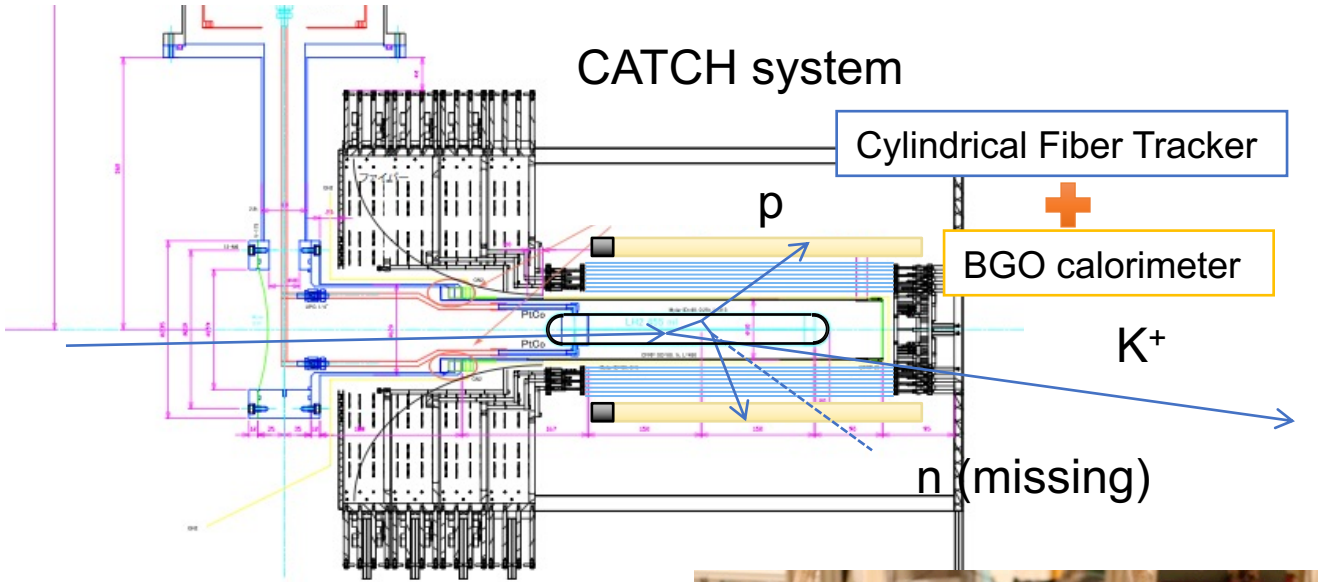
To be submitted soon

J-PARC E40 (K1.8 beam line)

Experimental method for YN scattering was established.

Hyperon-proton scattering experiment becomes possible at J-PARC





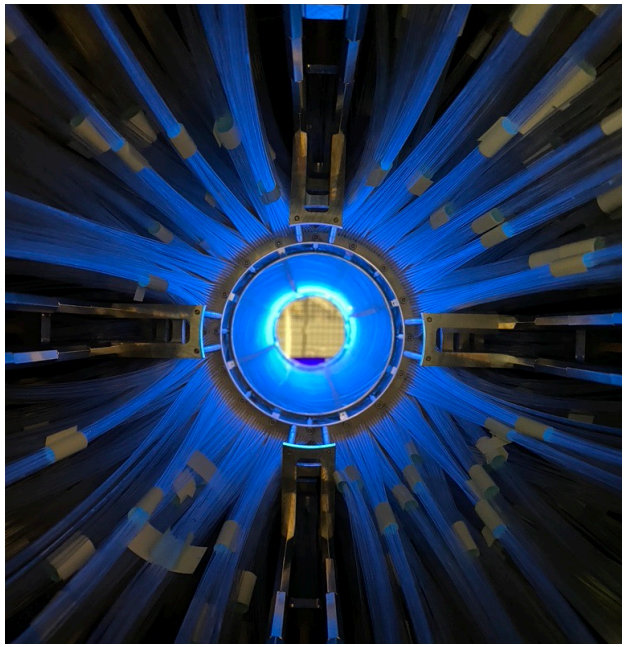
Many Σ hyperons are produced in LH_2 target

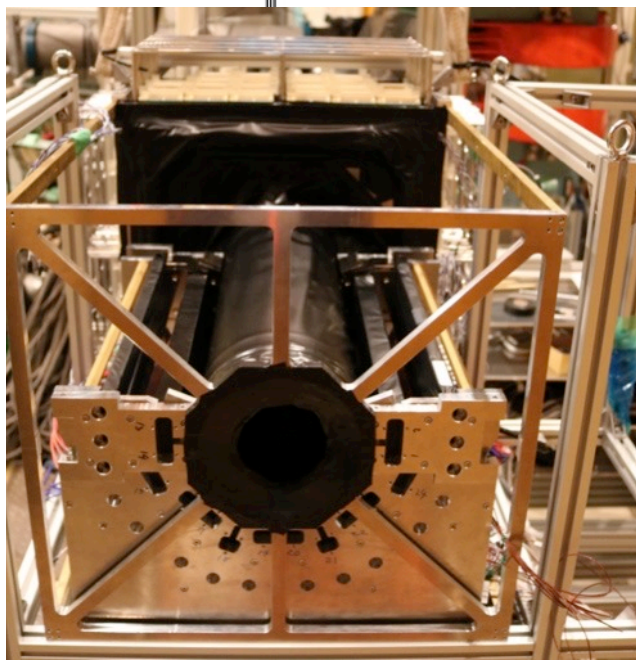
Σ are tagged by $\pi^{\pm}p \rightarrow K^{+}X$ reaction

- Σ^{-} beam : 17 M
- Σ^{+} beam : ~65 M

Secondary Σp scattering events are detected by surrounding detectors

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

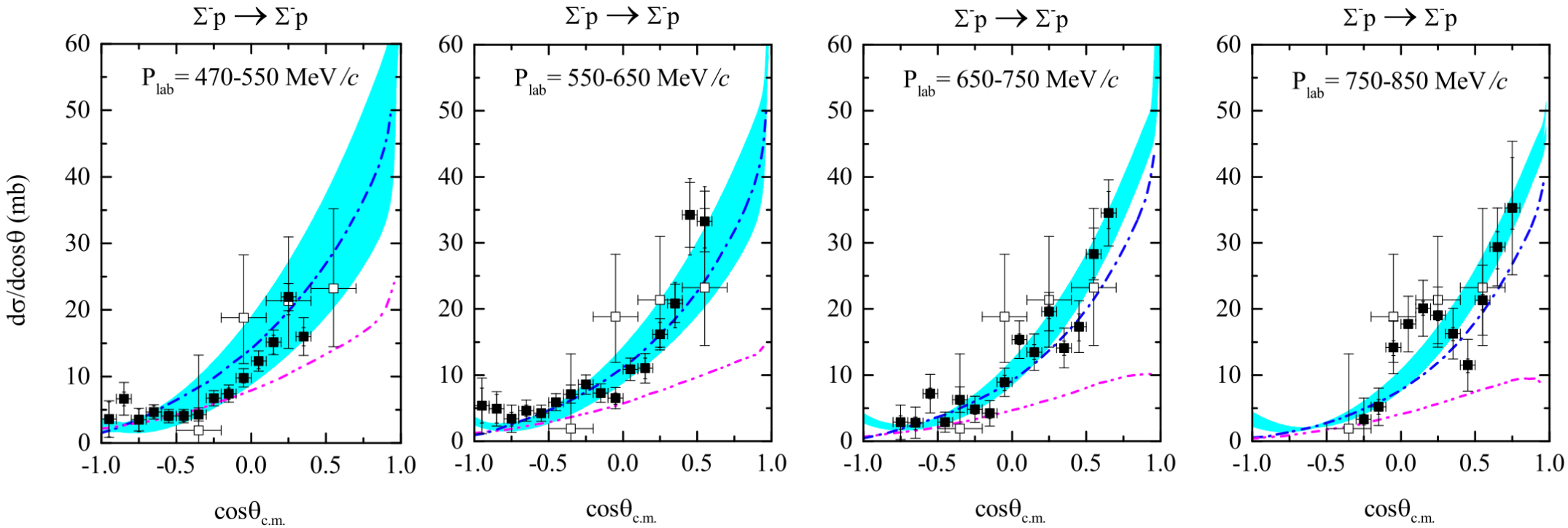




chiral EFT study in Chinese group

Leading order covariant chiral effective field theory

J. Song et al., arXiv:2107.04742

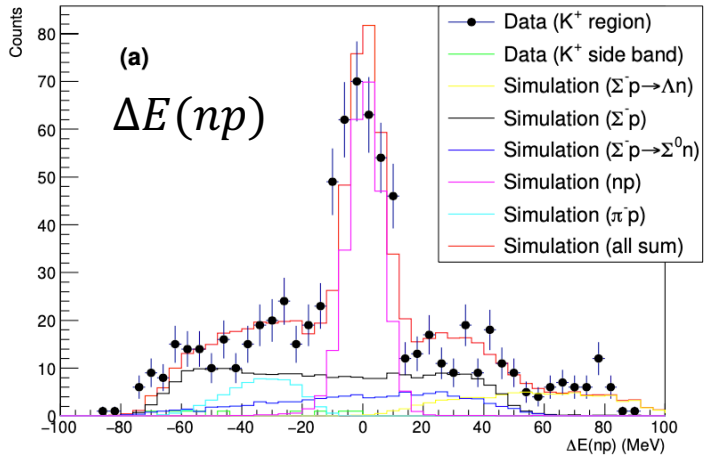


Close connection between BB int. theory and scattering experiment is necessary.

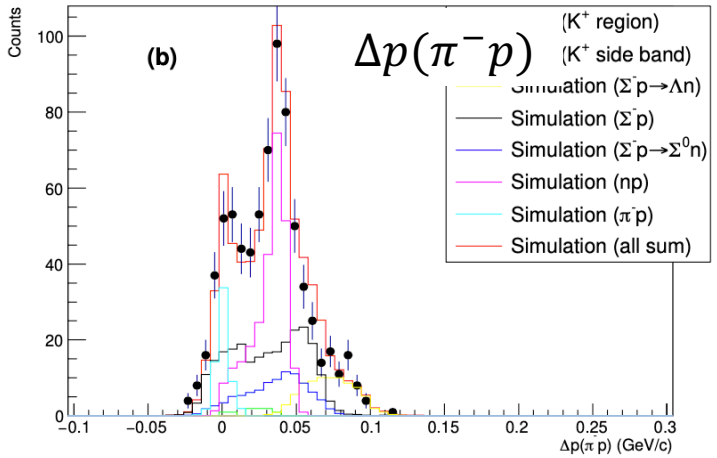
Signal and BG estimation for each reaction

We are trying to understand the background contribution as much as possible.

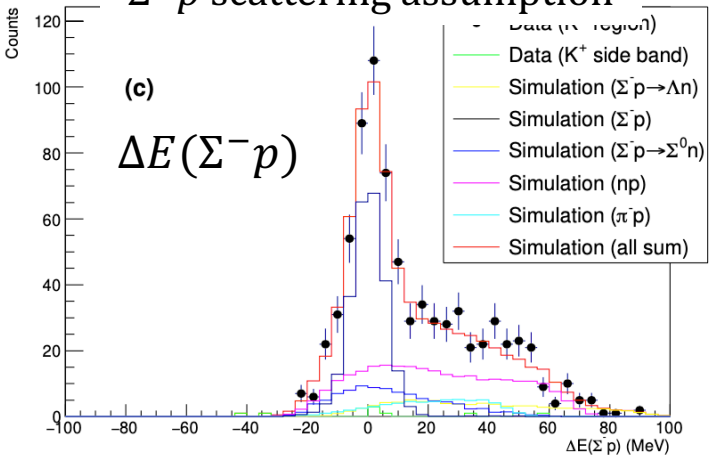
np scattering assumption



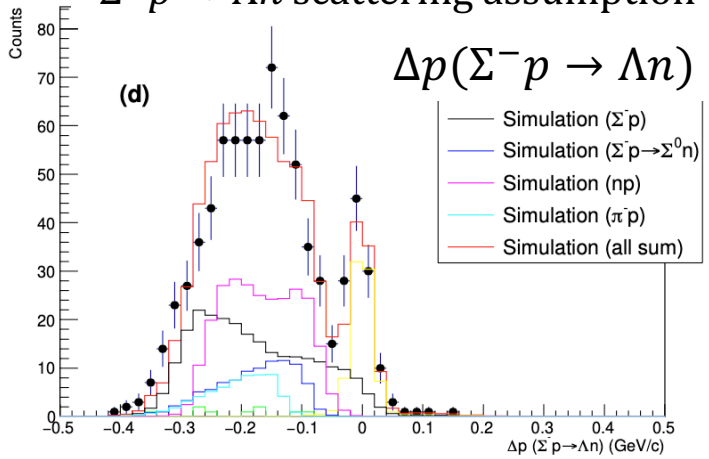
$\pi^- p$ scattering assumption



$\Sigma^- p$ scattering assumption



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



For, example,
np scattering events becomes

- peak for np scattering kinematics
- background for other scattering kinematics

<u>Considered reaction</u>

- np scattering
- π^-p scattering
- Σ^-p scattering
- Σ^-p→Λn scattering
- Σ^-p→Σ^0n scattering

We fit the four kinematical spectra simultaneously with sum of each contribution.
Left 4 reactions are well constrained by the peak number of each ΔE distribution.