Results of analysis of Σ+p scattering events in J-PARC E40 experiment: differential cross sections and phase shifts of $^3S_1$ and $^1P_1$ states

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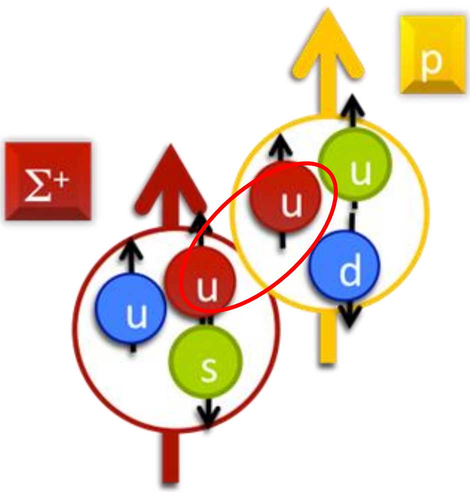
Contents of this presentation are based on arXiv: 2203.08393

J-PARC E40 experiment
Measurement of dσ/dΩ 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



I=3/2, ^{3}Even and ^{1}Odd:
10-plet of $SU(3)_f$ B-B interaction
$^3S_1$:Almost Pauli forbidden
→strong repulsive force?

BB channel (I)	^{1}Even or ^{3}Odd	^{3}Even or ^{1}Odd
$NN(I=0)$	−	$(\mathbf{10}^*)$
$NN(I=1)$	$(\mathbf{27})$	−
$\Lambda N(I=\frac{1}{2})$	$\frac{1}{\sqrt{10}}[(\mathbf{8}_s)+3(\mathbf{27})]$	$\frac{1}{\sqrt{2}}[-(\mathbf{8}_a)+(\mathbf{10}^*)]$
$\Sigma N(I=\frac{1}{2})$	$\frac{1}{\sqrt{10}}[3(\mathbf{8}_s)-(\mathbf{27})]$	$\frac{1}{\sqrt{2}}[(\mathbf{8}_a)+(\mathbf{10}^*)]$
$\Sigma N(I=\frac{3}{2})$	$(\mathbf{27})$	$(\mathbf{10})$

Σ^+p channel is the best channel to investigate 10-plet!

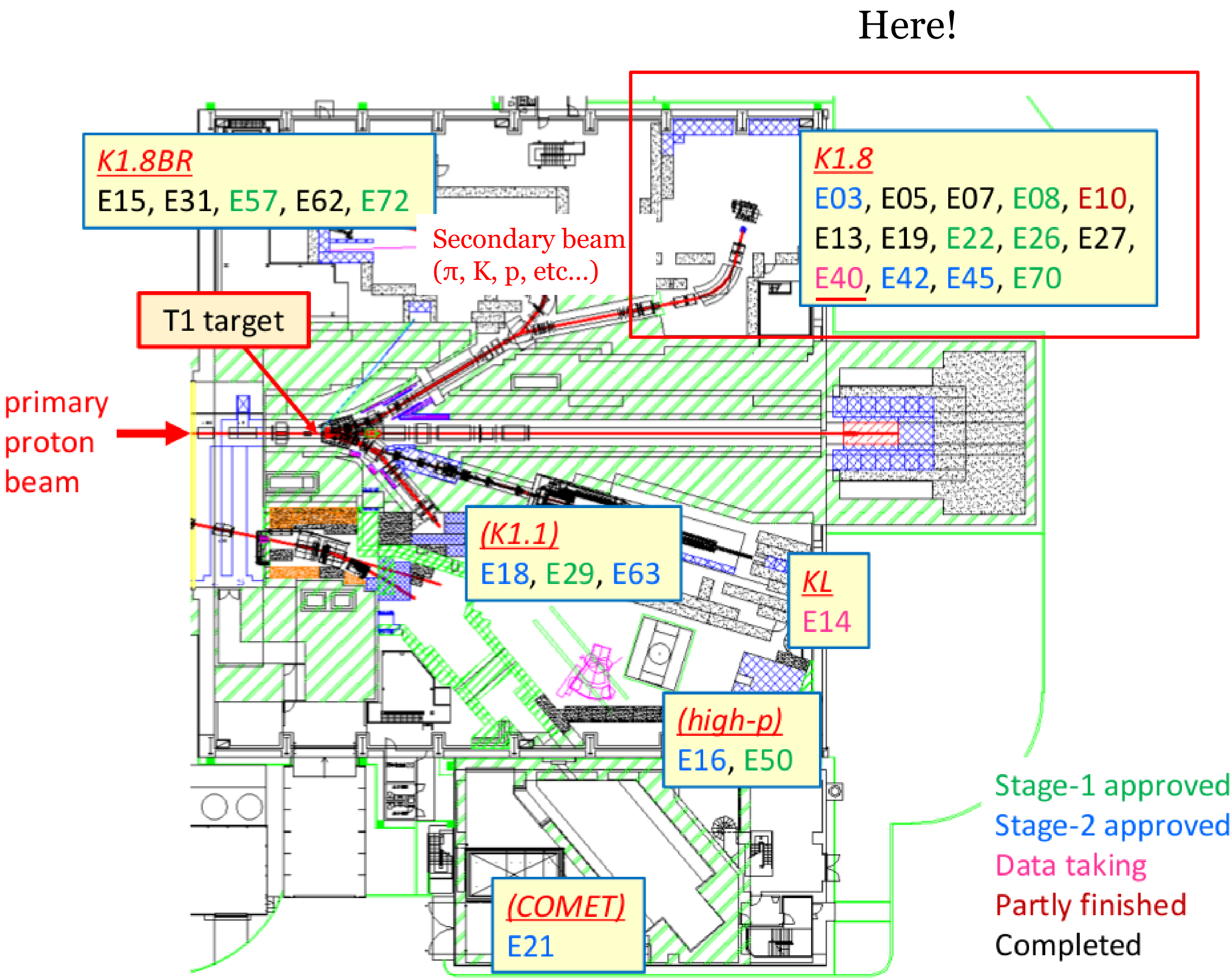
- Purposes of experiments
  - Measurement of dσ/dΩ with high statistics
    - Σ-p elastic K. Miwa PRC (2021), Σ-p →Λn inelastic scattering K. Miwa PRL (2022) (Σ- data)
    - **Σ+p elastic scattering (Σ+ data)**
  - Establishment of method to measure $\pi^-p\rightarrow K^0\Lambda$ reaction →T. Sakao (Thu-III a)
- Data taking was finished June 2020.

Difficulties of Σp scattering experiment

- Generally, hyperon-nucleon scattering experiment is difficult.
  - Short life time of hyperons : 10^{-10} s
    - Difficulty of producing plenty of hyperon beam
    - Difficulty of detection and identification of scattering hyperon
  - Previous Σp scattering experiments could identify only a few tens of events.

- How do we overcome these difficulties?
  - High rate π beam and large acceptance spectrometer
    - Producing and tagging large amount of incident Σ
  - LH2 target and Surrounding detector system
    - Reconstructing reactions from two body kinematics
    - Detecting the recoil proton with large acceptance

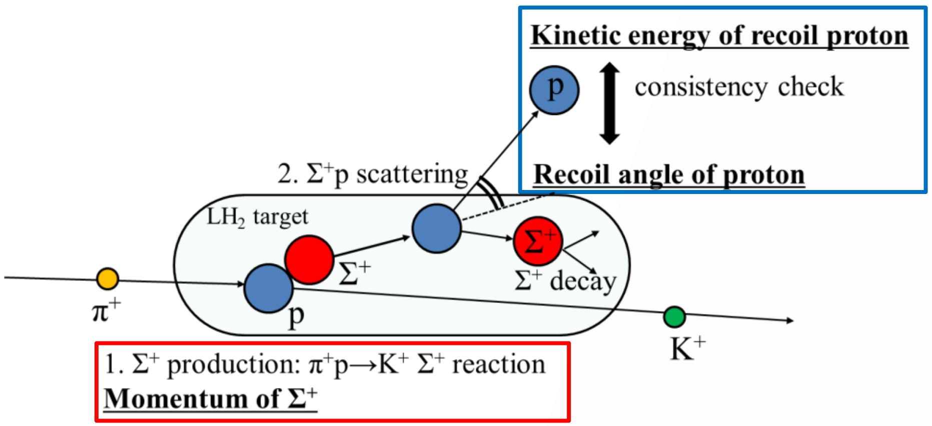
K1.8 beamline @hadron hall



Experimental setup

Two successive two body reactions:
Σ production ($\pi^+ p \rightarrow K^+ \Sigma^+$ reaction)
Σp scattering

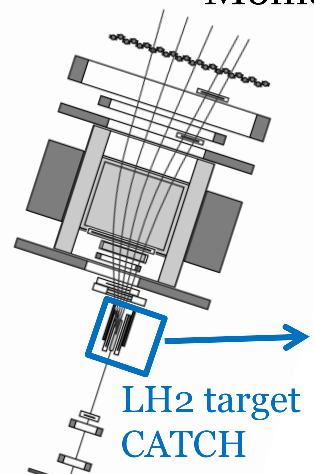
Detect with CATCH system



Analyze with spectrometers

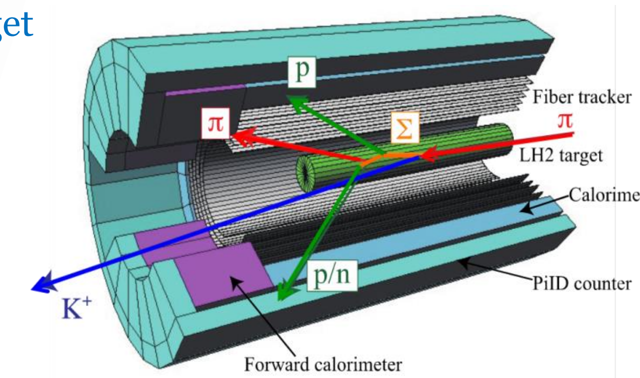
1.4 GeV/c π+ beam
19 M π beam /spill(=5.2s)

KURAMA Spectrometer
Identification of K^+
Momentum analysis



LH2 target
CATCH

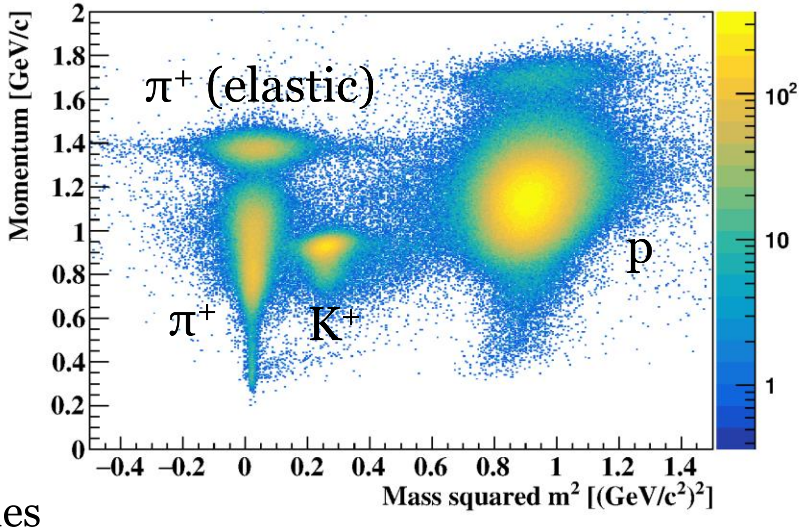
CATCH system
・particle direction
・measuring energy of proton



K1.8 Spectrometer
Momentum analysis of
π^+ beam

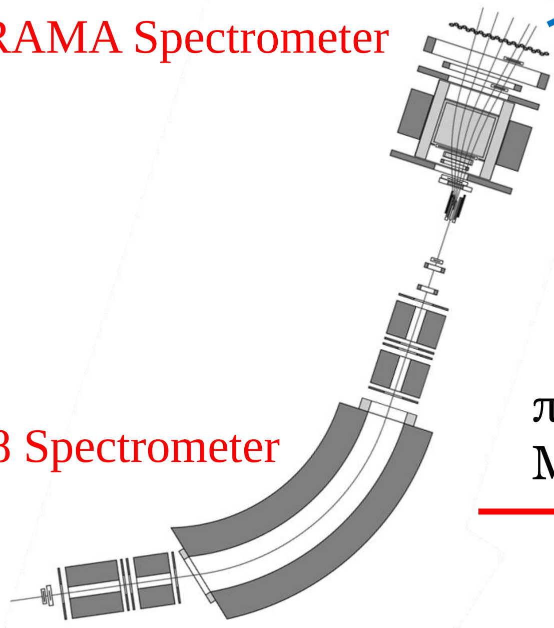
Analysis:Σ⁺ production

- Scattering particles
  - Momentum, path length
  - Runge-Kutta method
- π+beam
  - Momentum reconstruction
  - 3rd-order Transfer matrix



KURAMA Spectrometer

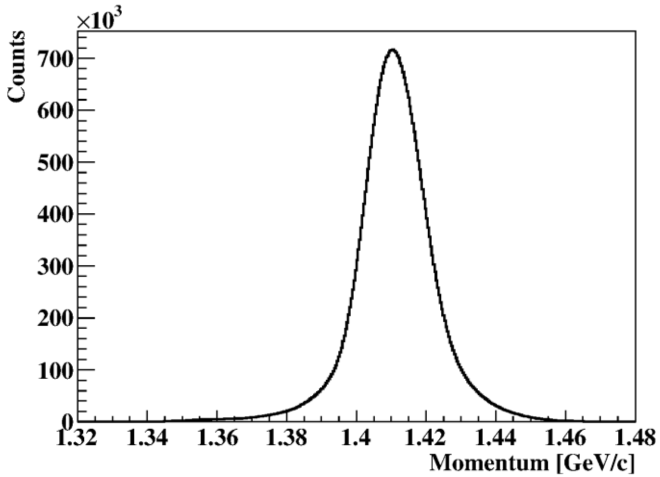
Scattering particles
Momentum
ToF and path→β



K1.8 Spectrometer

π beam
Momentum

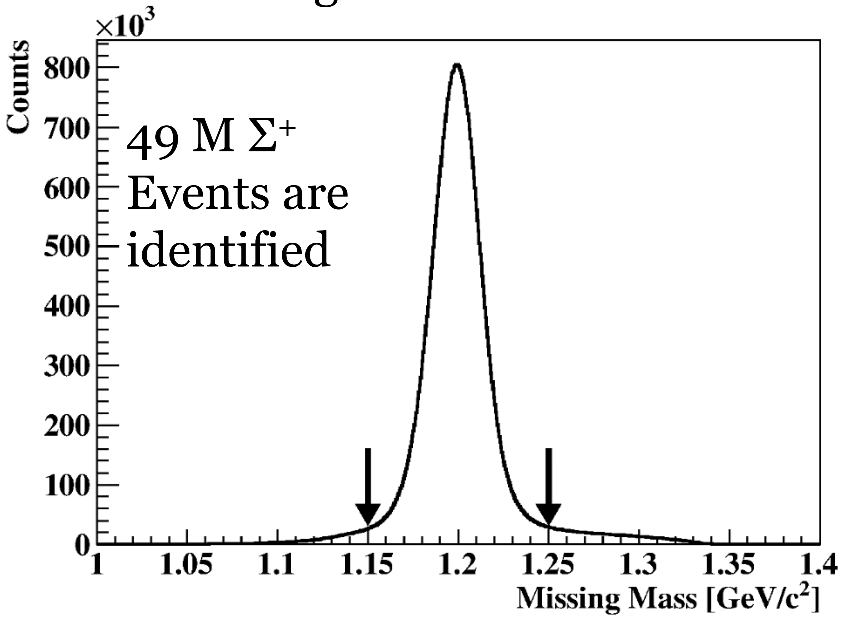
π momentum



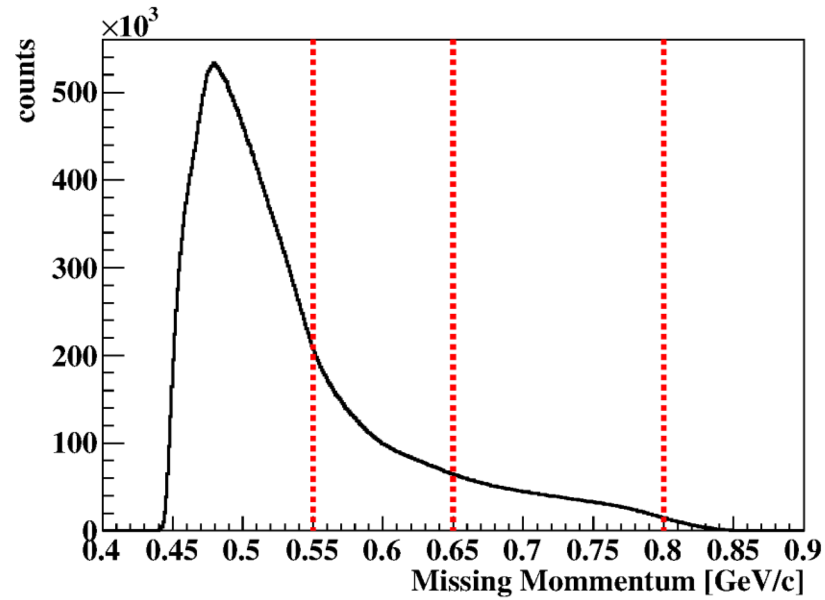
Analysis: Σ^+ production

- Σ^+ identification
  - Missing mass of $\pi^+ p \rightarrow K^+ X$ reaction
- Momentum of Σ^+
  - Missing momentum of π^+, K^+
  - Σ+p scattering analysis was performed for three separated momentum region
    - Low (0.44-0.55 GeV/c), Middle (0.55-0.65 GeV/c), High (0.65-0.80 GeV/c)

Missing mass distribution

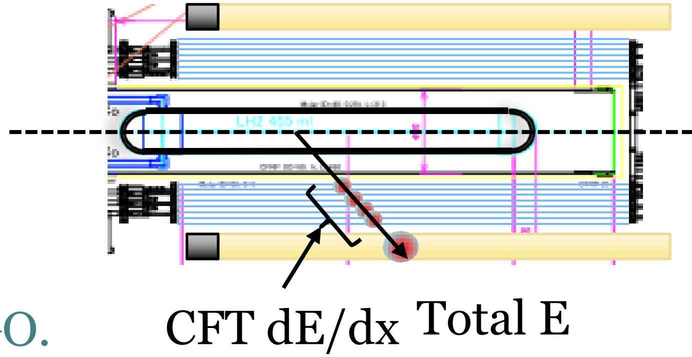


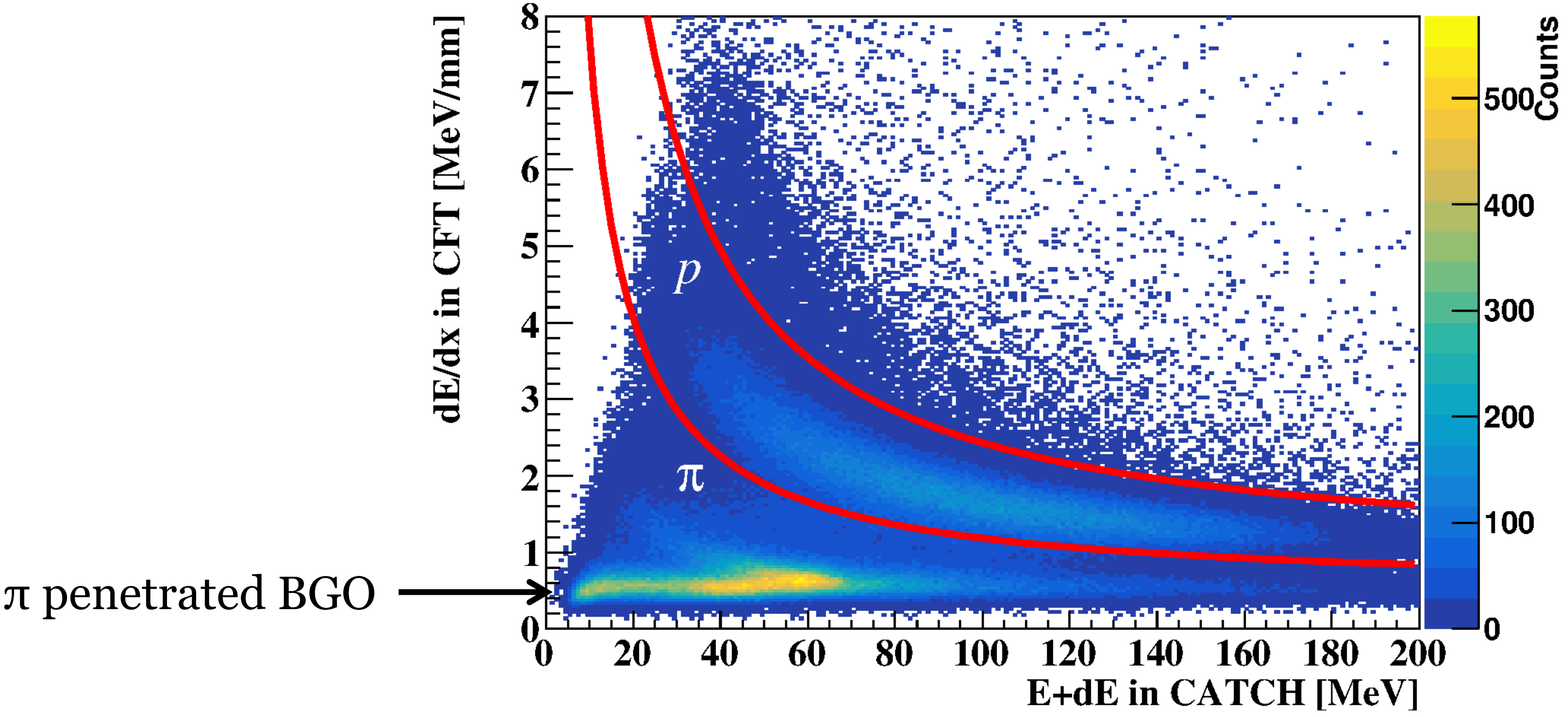
Σ+ momentum distribution



Analysis: CATCH part

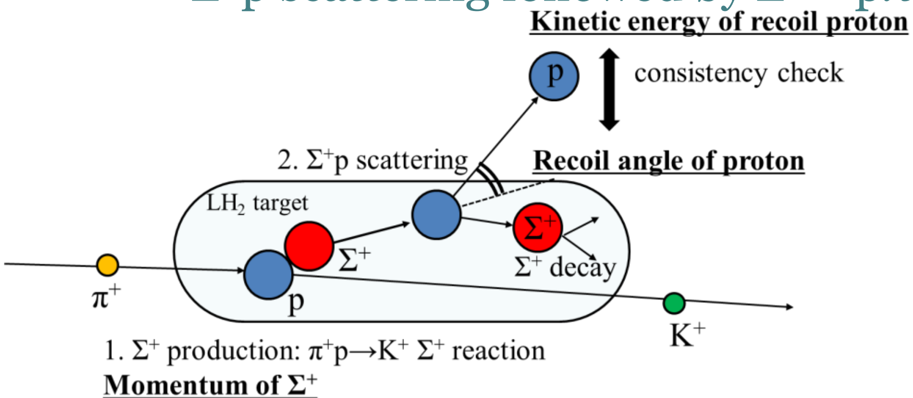
- Tracking by CFT
  - Particle trajectories are reconstructed.
- Particle identification
  - Using energy loss correlation between CFT & BGO
  - Protons are well distinguished.
  - Kinetic energy of protons are fully measured by BGO.





Kinematical identification of Σ+p scattering events

- Hereafter, we concentrate on events with 2 protons in final state.
  - Σ^+p scattering followed by $\Sigma^+ \to p\pi^0$ decay



Checking a kinematical consistency for recoil proton

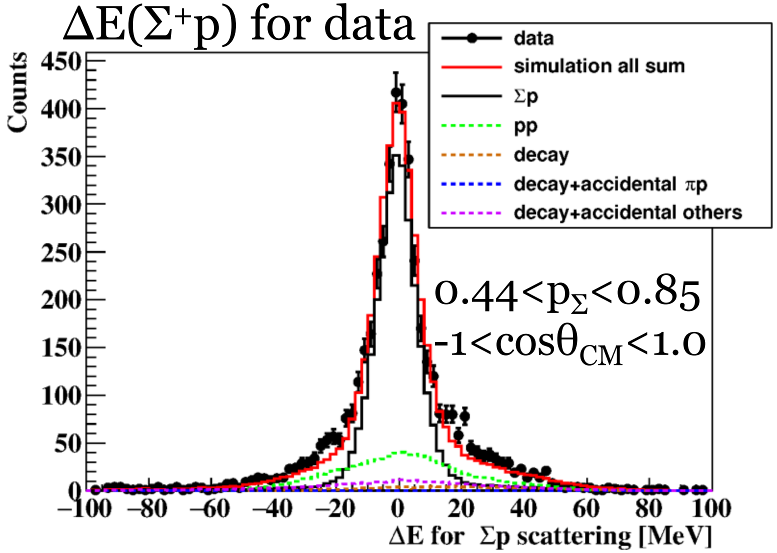
・E_{meas} : measured kinetic energy with CATCH

・E_{calc} : calculated kinetic energy from incident Σ^+ momentum and recoil angle

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

- For Σ^+p scattering events, ΔE distributes around 0.
  - A proton which minimize |ΔE| value was chosen as the recoil proton from two detected protons.

$\Delta E(\Sigma^+p)$ for data

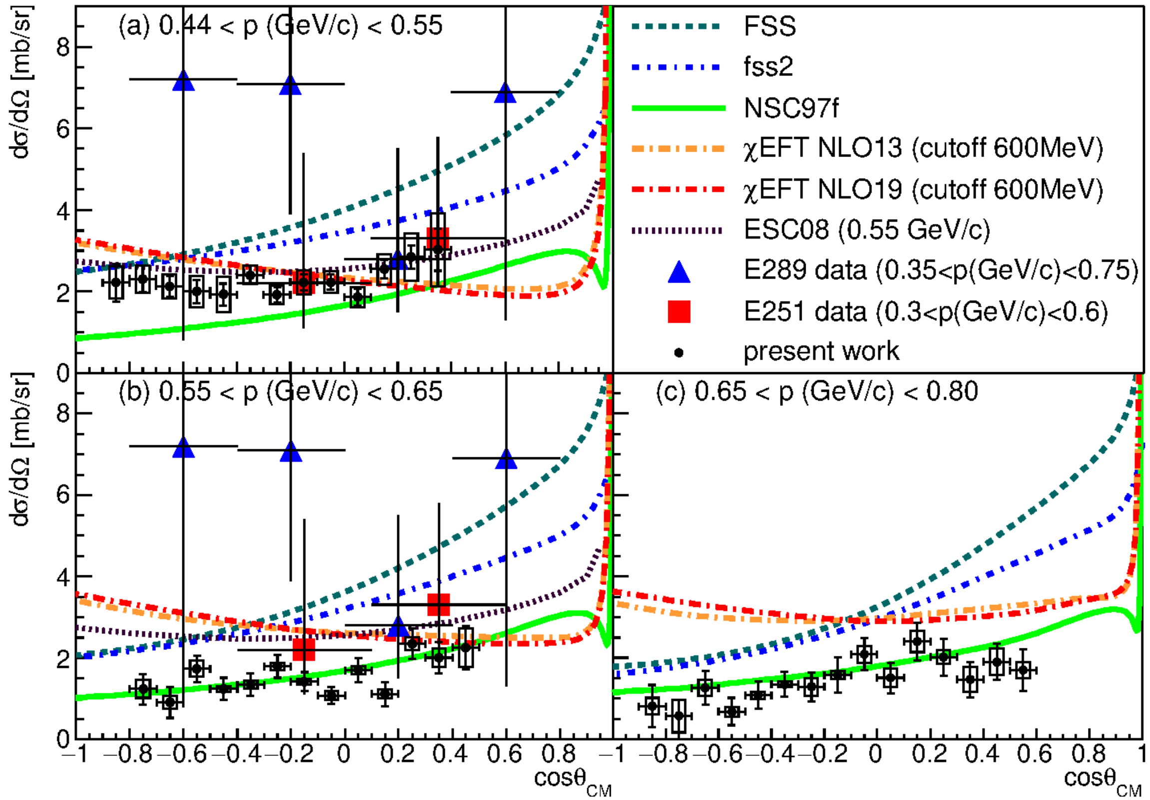


Cut conditions to select Σ+p scattering events were applied.
vertex position, distance between tracks
kinematical consistencies for decay proton, other reactions

In total, approximately 2400 Σ^+p scattering events were identified !
80 times more than past KEK experiments

Differential cross sections

- Differential cross sections were derived from ～2400 $\Sigma^{+}p$ scattering events.
  - The data quality has beem significantly improved!
    - Main sources of systematic error: background estimation, efficiency for low momentum proton.
  - FSS and fss2 are obviously larger. On the other hand, ESC08, NSC97f are consistent to some extent.
    - Note:NSC97f suggests the attractive $^{3}S_{1}$ interaction, which does not agree with the current common understanding of ΣN interaction.



Phase shift analysis

- Extracting the contribution of the $^3S_1$ is important to study the repulsive nature of Σ^+p system due to the quark Pauli effect.

- Referring to formalism of NN scattering, the differential cross section was calculated as a function of phase shifts and we tried to fit data.

Supplement of the Progress of Theoretical Physics, No. 42, 1968

Appendix

Formalism of Nucleon-Nucleon Scattering

Norio HOSHIZAKI

PHYSICAL REVIEW C VOLUME 48, NUMBER 2 AUGUST 1993

Partial-wave analysis of all nucleon-nucleon scattering data below 350 MeV

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(Received 15 March 1993)

$$\psi_m^s(\mathbf{r}) \sim e^{ikz}\xi_m^s + \frac{e^{ikr}}{r}\sum_{s',m'}\xi_{m'}^{s'} M_{m'm}^{s's}(\theta,\phi) \ , \qquad (16)$$

Phase shift analysis

- We considered contribution by D wave(L<=2), and Coulomb effects were merely ignored.(bar phase shifts were regarded as nuclear bar phase shifts)

$$I_0 = \frac{1}{4}|M^{0,0}_{0,0}|^2 + \frac{1}{2}|M^{1,1}_{1,1}|^2 + \frac{1}{4}|M^{1,1}_{0,0}|^2 + \frac{1}{2}|M^{1,1}_{0,1}|^2 + \frac{1}{2}|M^{1,1}_{1,0}|^2 + \frac{1}{2}|M^{1,1}_{1,-1}|^2 \tag{5.3}$$

$$M^{0,0}_{0,0} = h_{^1S_0} + 3h_{^1P_1}\cos\theta + 5h_{^1D_2} \times \left(\frac{3\cos^2\theta - 1}{2}\right), \tag{5.4}$$

$$\begin{aligned} M^{1,1}_{1,1} = {} & (h_{^3S_1} - \frac{\sqrt{2}}{2}h^{^3S_1-^3D_1}) + \left(\frac{3}{2}h_{^3P_2} + \frac{3}{2}h_{^3P_1}\right)\cos\theta \\ & + \left(2h_{^3D_3} + \frac{5}{2}h_{^3D_2} + \frac{1}{2}h_{^3D_1} - \frac{\sqrt{2}}{2}h^{^3S_1-^3D_1}\right) \times \frac{3\cos^2\theta - 1}{2}, \end{aligned} \tag{5.5}$$

$$\begin{aligned} M^{1,1}_{0,0} = {} & (h_{^3S_1} + \sqrt{2}h^{^3S_1-^3D_1}) + (2h_{^3P_2} + h_{^3P_0})\cos\theta \\ & + (3h_{^3D_3} + 2h_{^3D_1} + \sqrt{2}h^{^3S_1-^3D_1}) \times \frac{3\cos^2\theta - 1}{2}, \end{aligned} \tag{5.6}$$

$$\begin{aligned} M^{1,1}_{0,1} = {} & \left(-\frac{3}{2\sqrt{2}}h_{^3P_2} + \frac{3}{2\sqrt{2}}h_{^3P_1}\right) \times (-\sin\theta) \\ & + \left(-\frac{4}{3\sqrt{2}}h_{^3D_3} + \frac{5}{6\sqrt{2}}h_{^3D_2} + \frac{1}{2\sqrt{2}}h_{^3D_1} - \frac{1}{\sqrt{2}}h^{^3S_1-^3D_1}\right) \times (-3\cos\theta\sin\theta), \end{aligned} \tag{5.7}$$

$$M^{1,1}_{1,0} = \left(\frac{1}{\sqrt{2}}h_{^3P_2} - \frac{1}{\sqrt{2}}h_{^3P_0}\right) \times (-\sin\theta) + \left(\frac{1}{\sqrt{2}}h_{^3D_3} - \frac{1}{\sqrt{2}}h_{^3D_1} - \frac{1}{\sqrt{2}}h^{^3S_1-^3D_1}\right) \times (-3\cos\theta\sin\theta), \tag{5.8}$$

$$M^{1,1}_{1,-1} = \left(\frac{1}{6}h_{^3D_3} - \frac{5}{12}h_{^3D_2} + \frac{1}{4}h_{^3D_1} - \frac{1}{2\sqrt{2}}h^{^3S_1-^3D_1}\right) \times (3\sin^2\theta), \tag{5.9}$$

where partial wave amplitude h were defined as

$$h_{^{2S+1}L_J} = \begin{cases} \frac{1}{2ik}(\cos(2\bar{\epsilon}_1)\exp(2i\bar{\delta}_{^{2S+1}L_J}) - 1) & (^3S_1 \text{ and } ^3D_1 \text{ case}) \\ \frac{1}{2ik}(\exp(2i\bar{\delta}_{^{2S+1}L_J}) - 1) & (\text{else}) \end{cases} \tag{5.10}$$

$$h^{^3S_1-^3D_1} = \frac{1}{2k}\sin(2\bar{\epsilon}_1)\exp(i\bar{\delta}_{^3S_1} + i\bar{\delta}_{^3D_1}). \tag{5.11}$$

Phase shift analysis

- The function $I_0(\theta, p, \boldsymbol{\delta}[27](p), \boldsymbol{\delta}[10](p))$ has 11 phase shift parameters.
  - $\boldsymbol{\delta}[27]=\{\delta_{1S0},\delta_{3P2},\delta_{3P1},\delta_{3P0}, \delta_{1D2}\}$, $\boldsymbol{\delta}[10]=\{\delta_{3S1}, \delta_{1P1}, \delta_{3D3},\delta_{3D2},\delta_{3D1},\varepsilon_1\}$
- $\boldsymbol{\delta}[27]$ are well constrained from NN data and are regarded as constants taken from
  - pp scattering based on complete SU(3)f symmetry.
    - Less realistic, but independent from baryon-baryon interaction model.
  - NSC97f or ESC16 in order to approximately consider the effect of the flavor symmetry breaking and the difference of meson exchange potential.
- $\boldsymbol{\delta}[10]$ are to be investigated, but 6 parameters are still too much to perform meaningful fitting.
  - only δ_{3S1} and δ_{1P1} were treated as free parameters.
  - Rest 4 parameters ($\delta_{3D3},\delta_{3D2},\delta_{3D1}$, and ε_1) are fixed at 0 or NSC97f and ESC16.

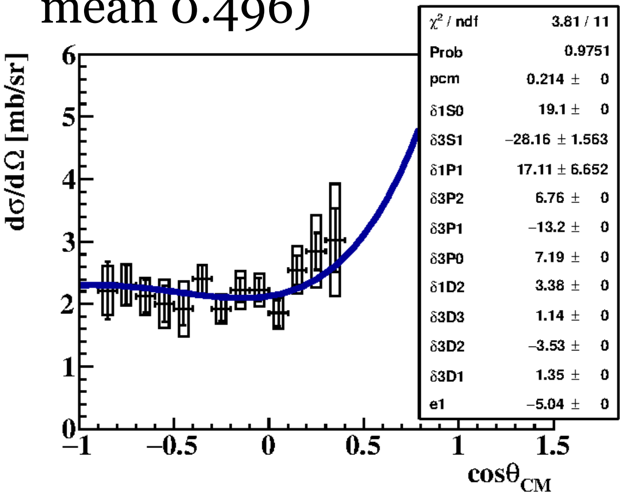
Note : the sign of δ_{3S1} cannot be determined.
Positive and negative cases are examined.

BB channel (I)	^{1}Even or ^{3}Odd	^{3}Even or ^{1}Odd
$NN(I=0)$	–	$(\mathbf{10}^*)$
$NN(I=1)$	$(\mathbf{27})$	–
$\Lambda N(I=\frac{1}{2})$	$\frac{1}{\sqrt{10}}[(\mathbf{8}_s)+3(\mathbf{27})]$	$\frac{1}{\sqrt{2}}[-(\mathbf{8}_a)+(\mathbf{10}^*)]$
$\Sigma N(I=\frac{1}{2})$	$\frac{1}{\sqrt{10}}[3(\mathbf{8}_s)-(\mathbf{27})]$	$\frac{1}{\sqrt{2}}[(\mathbf{8}_a)+(\mathbf{10}^*)]$
$\Sigma N(I=\frac{3}{2})$	$(\mathbf{27})$	$(\mathbf{10})$

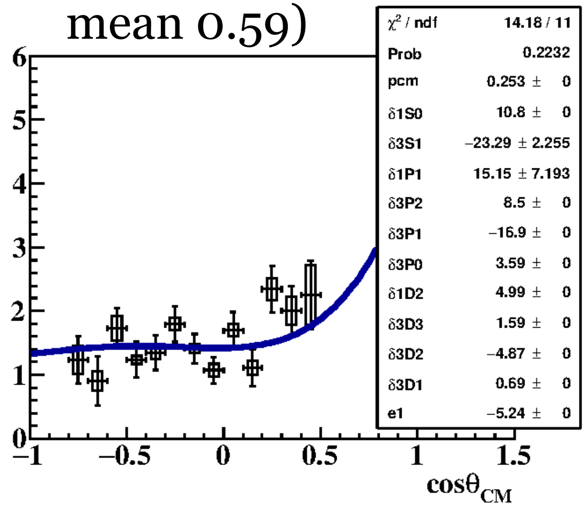
Fitting results

- Fixed phase shifts are taken from ESC16
- δ_{3S1}<0 case
- χ^2/ndf is approximately 1.

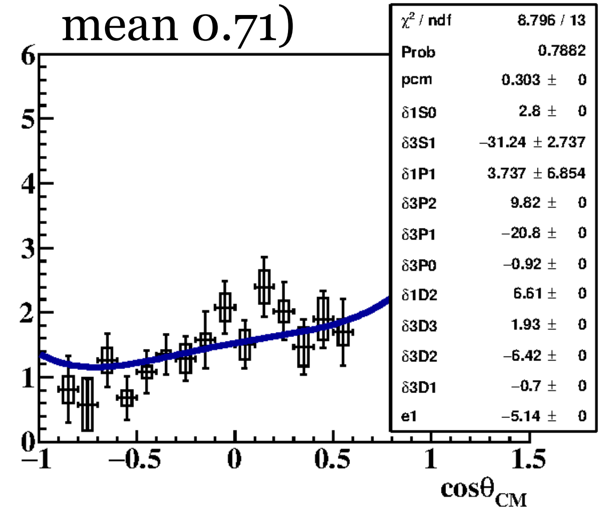
Low momentum
(0.44<pΣ<0.55 GeV/c
mean 0.496)



middle momentum
(0.55<pΣ<0.65 GeV/c
mean 0.59)



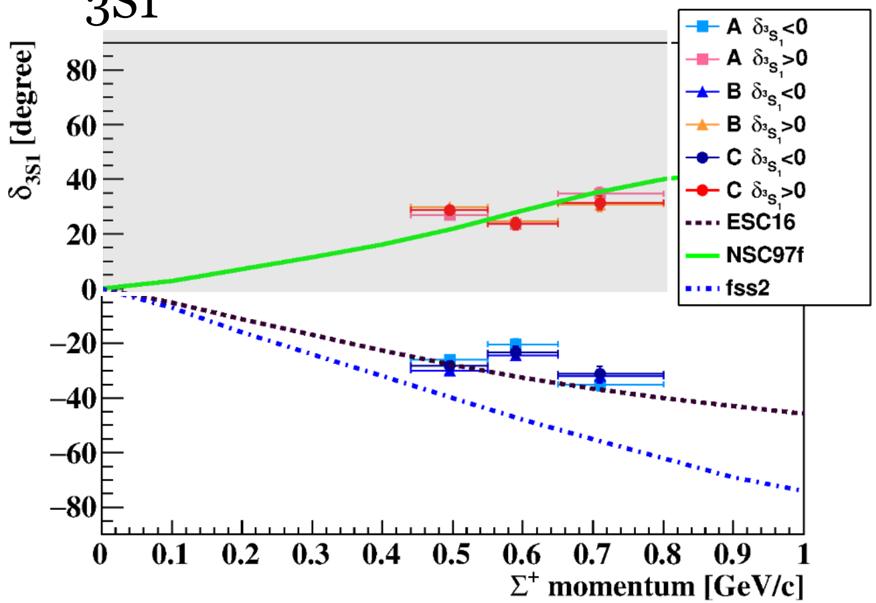
high momentum
(0.65<pΣ<0.80 GeV/c
mean 0.71)



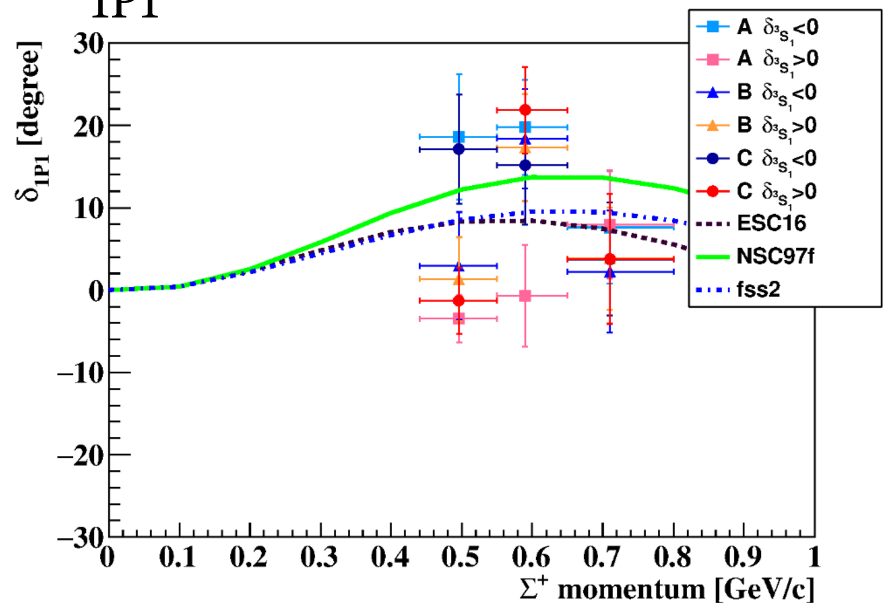
Obtained phase shifts

- $^3S_1$:almost consistent with ESC16 (δ<0) or NSC97f (δ>0).
  - |δ|: 28.3±1.5±2.1 (low), 23.4±2.0±3.0 (mid), 32.5 ±2.5±2.5 (high)
    - Fitting error and effect of the different sets of the fixed parameters
  - The interaction in this channel is moderately repulsive.
- $^1P_1$:ambiguous.
  - They may support the prediction of the fss2, ESC16, NSC97f in which the interaction of 1P1 channel is weakly attractive.

3S1



1P1



Summary

- Hyperon-nucleon scattering experiment gives us very important information for B-B interaction, especially quark Pauli effect.
- J-PARC E40 Experiment
  - High-statistics Σp scattering experiment
    - $\Sigma^+ p$ elastic scattering, $\Sigma^- p$ elastic scattering, $\Sigma^- p \to \Lambda n$ inelastic scattering
  - Data taking was finished by June 2020.
- $d\sigma/d\Omega$ were derived from approximately 2,400 Σ^+ p scattering events.
  - We successfully performed difficult YN scattering experiment!
- By not only comparison with the existing theoretical calculations but also derivation of the phase shifts of the ${}^3S_1$ and ${}^1P_1$ channels, the nature of $\Sigma^+ p$ interaction was investigated.
  - The differential cross sections and absolute value of the $\delta\,{}^3S_1$ were not as large as fss2 and FSS predicted and rather consistent with Nijmegen models.