J-PARCにおけるΣ陽子散乱実験の結果

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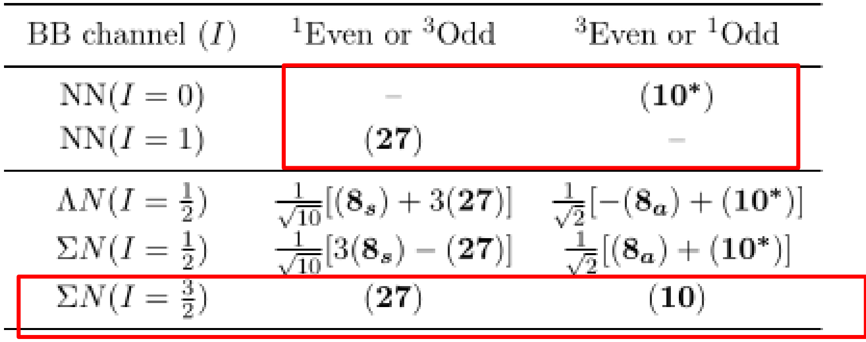
Kyoto University, JAEA

Baryon-Baryon interaction

- Hyperon-nucleon (YN) interaction
  - A extension of NN interaction
  - Mass of s quark is similar to u,d quarks
    - can be treated under the SU(3)$_f$ symmetry
    - Existence of hyperon in neutron star (Hyperon puzzle)
- B-B interaction between the octet baryons (n,p, Λ, Σ, Ξ)

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{8}_s \oplus \mathbf{1} \oplus \mathbf{10}^* \oplus \mathbf{10} \oplus \mathbf{8}_a .$$

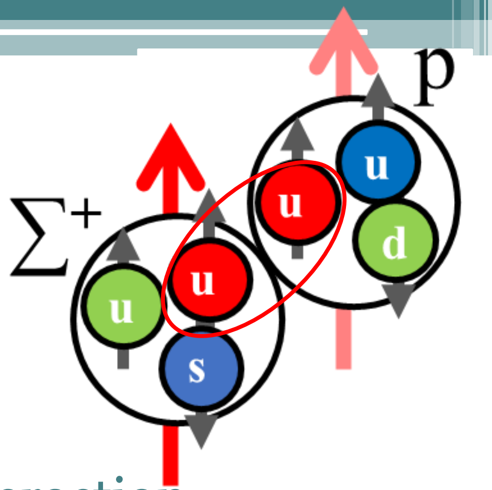
  - Some multiplets may have different futures from NN
    - Due to Quark-Pauli effect and color-magnetic interaction
    - 10, 8s-plets: strongly repulsive?
    - 1-plet: attractive core? (H-dybaryon?)
  - ΣN(I=3/2) is suitable to investigate 10-plet

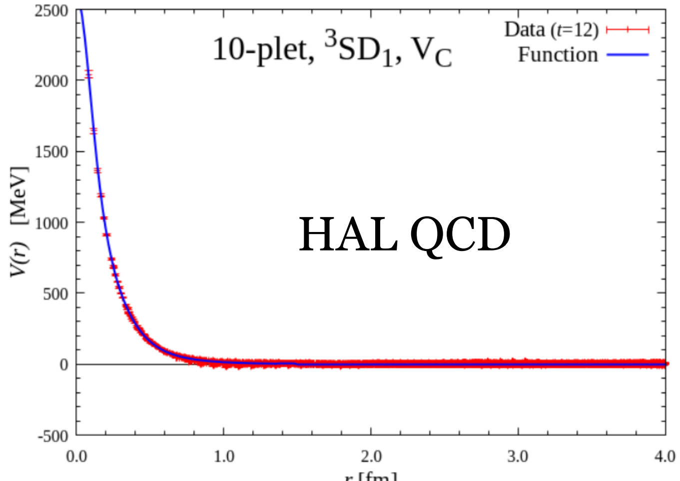


BB channel (I)	^{1}Even or ^{3}Odd	^{3}Even or ^{1}Odd
NN($I=0$)	–	$(\mathbf{10}^*)$
NN($I=1$)	$(\mathbf{27})$	–
$\Lambda N(I=\frac{1}{2})$	$\frac{1}{\sqrt{10}}[(\mathbf{8}_s)+3(\mathbf{27})]$	$\frac{1}{\sqrt{2}}[-(\mathbf{8}_a)+(\mathbf{10}^*)]$
$\Sigma N(I=\frac{1}{2})$	$\frac{1}{\sqrt{10}}[3(\mathbf{8}_s)-(\mathbf{27})]$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

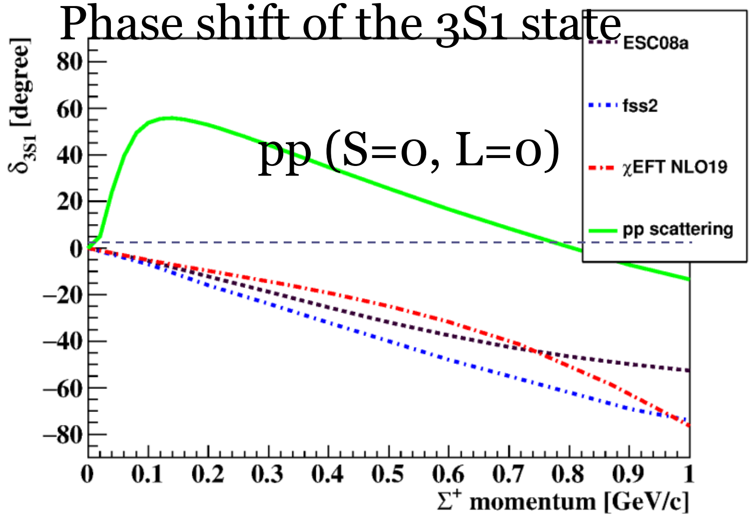
Σ^+p interaction

- Strong repulsive core is expected
  - Pauli exclusive principle in quark level
    - In **$^3S_1$ (S=1, L=0) state**, 2 u quarks
    - have same spin, color with a high probability
  - Some circumstantial evidences from Σ-nucleus interaction
    - Spin-isospin averaged potential is repulsive
    - Isospin dependence in A=4 system (I=1/2:bound I=3/2:unbound)
  - HAL QCD calculation
- However, the strength of "strong repulsion" was ambiguous.
  - It should be determined experimentally





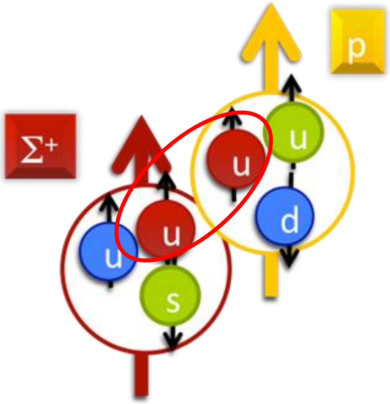
Phase shift of the 3S1 state



pp (S=0, L=0)

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
    - Determination of the strength of the repulsive force is also important.
  - 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
$NN(I=0)$	–	$(\mathbf{10}^*)$
$NN(I=1)$	$(\mathbf{27})$	–
$\Lambda N(I=\frac{1}{2})$	$\frac{1}{\sqrt{10}}[(\mathbf{8}_s)+3(\mathbf{27})]$	$\frac{1}{\sqrt{2}}[-(\mathbf{8}_a)+(\mathbf{10}^*)]$
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$\Sigma N(I=\frac{3}{2})$	$(\mathbf{27})$	$(\mathbf{10})$

- Purpose of experiments
  - Measurement of dσ/dΩ with high statistics
    - Σ-p elastic, Σ-p →Λn inelastic scattering (Σ- data)
    - **Σ+p elastic scattering (Σ+ data)**
  - Data taking had been finished on June 2020.

Difficulties of Σp scattering experiment

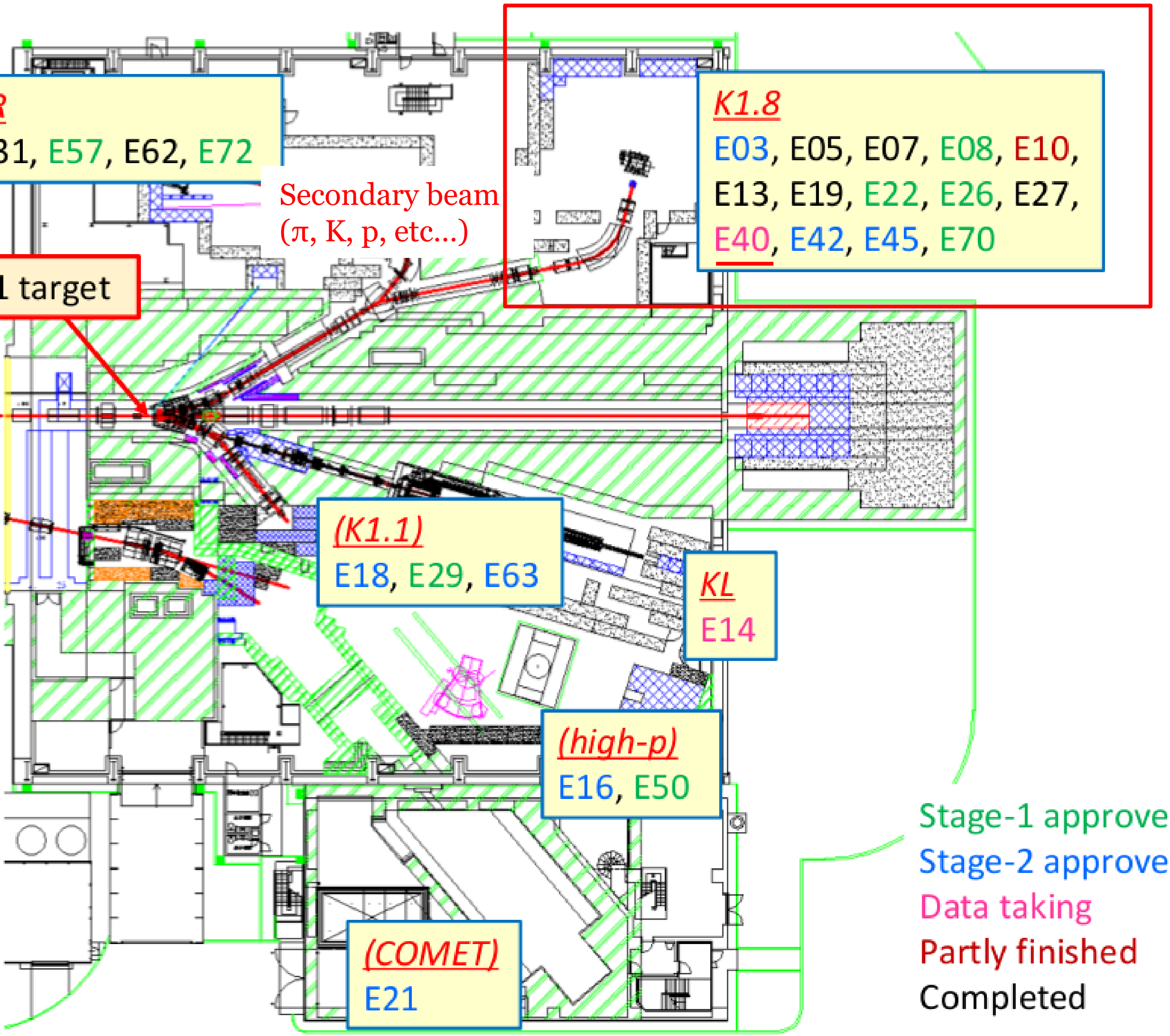
- Generally, hyperon-nucleon scattering experiment is difficult.
    - Short life time of hyperons : 10^{-10} s
        - Difficulty of producing plenty of hyperon beam
        - Difficulty of detection and identification of scattering hyperon
    - Previous Σp scattering experiments could identify only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

- Other experimental methods to extract ΣN interaction
    - Hypernuclei → only ${}^{4}_{\Sigma}$He is observed.
        - Large isospin dependence in A=4 system: attractive I=1/2 and repulsive I=3/2 state
        - Spin-isospin averaged potential was evaluated to be (V,W)=(30,-40) MeV
    - Femtoscopy by ALICE collaboration (for low relative momentum)
        - Results on Σ^0p interaction has been reported phys.lett.B 805 (2020) 135419
        - Now, statistical error is large. LHC Run3, 4 data is awaited.

→Scattering experiment is difficult, but it is necesarry.

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

K1.8 beamline @hadron hall



Here!

K1.8BR
E15, E31, E57, E62, E72

Secondary beam
(π, K, p, etc...)

K1.8
E03, E05, E07, E08, E10,
E13, E19, E22, E26, E27,
E40, E42, E45, E70

T1 target

primary proton beam

(K1.1)
E18, E29, E63

KL
E14

(high-p)
E16, E50

(COMET)
E21

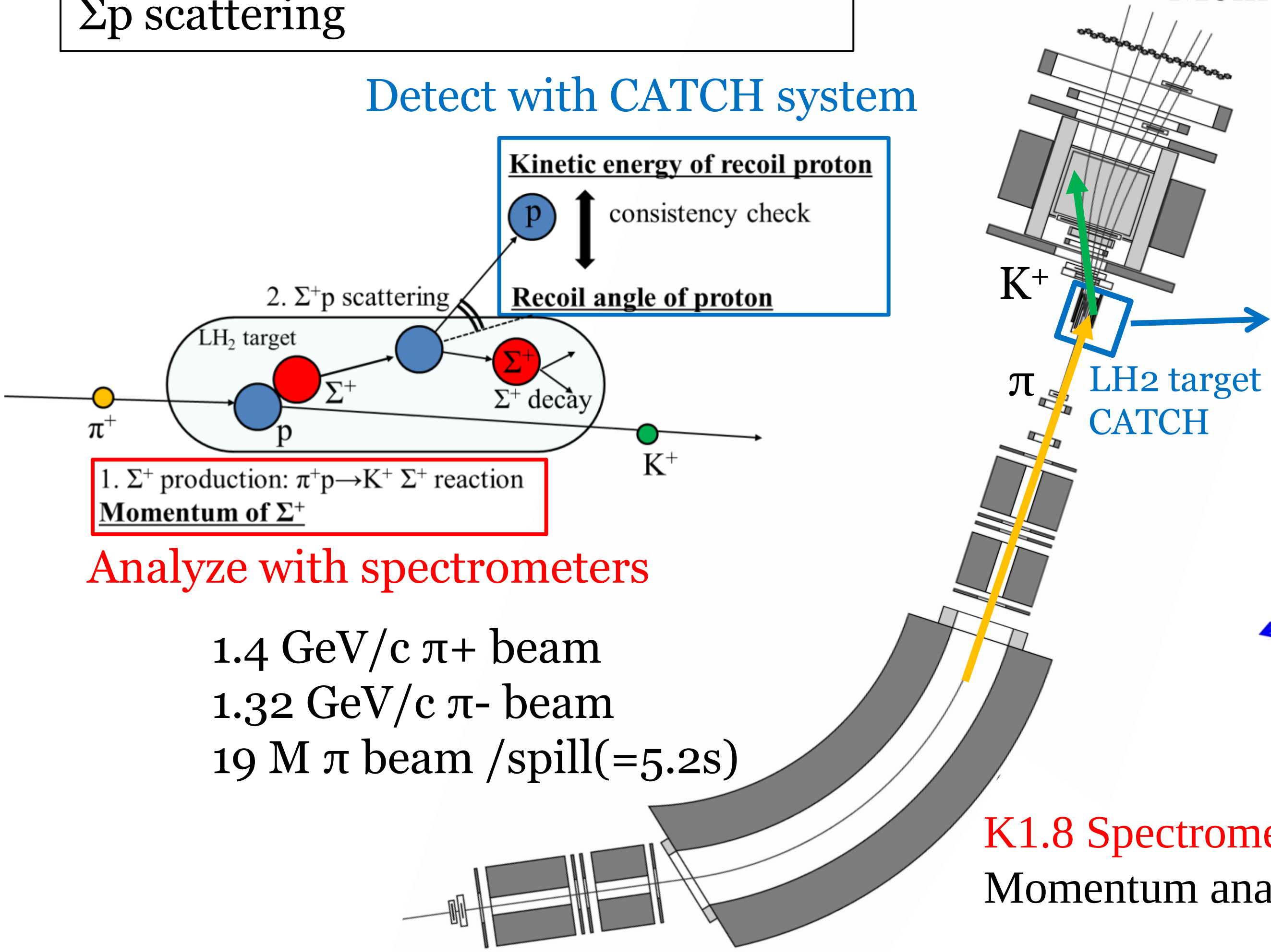
Stage-1 approved
Stage-2 approved
Data taking
Partly finished
Completed

Experimental setup

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

KURAMA Spectrometer
Identification of K^+
Momentum analysis

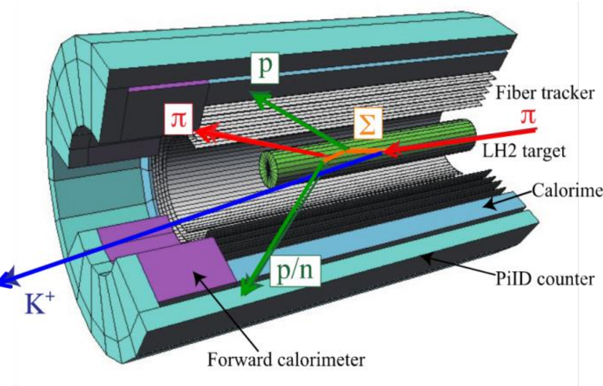
Detect with CATCH system



Analyze with spectrometers

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

CATCH system
- ・particle direction
- ・measuring energy of proton

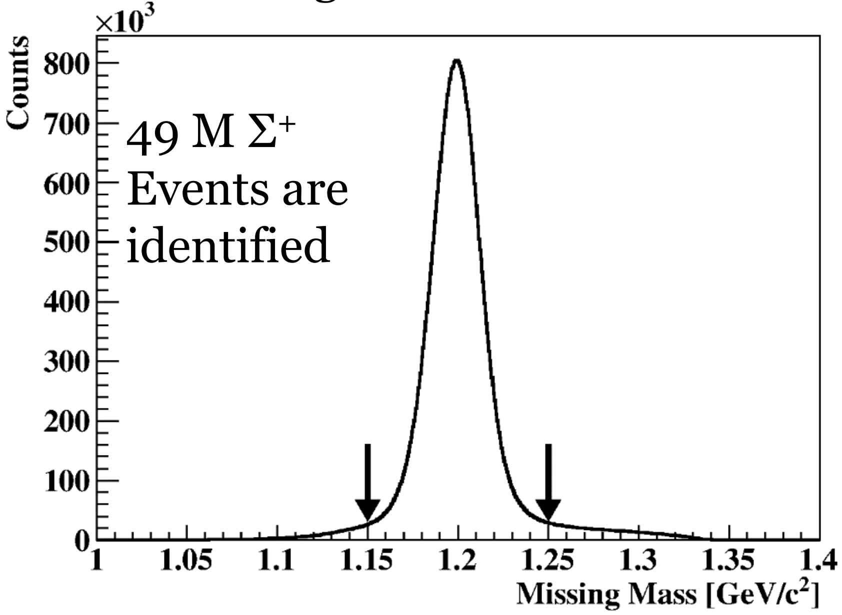


K1.8 Spectrometer
Momentum analysis of π beam

Analysis:Σ⁺ production

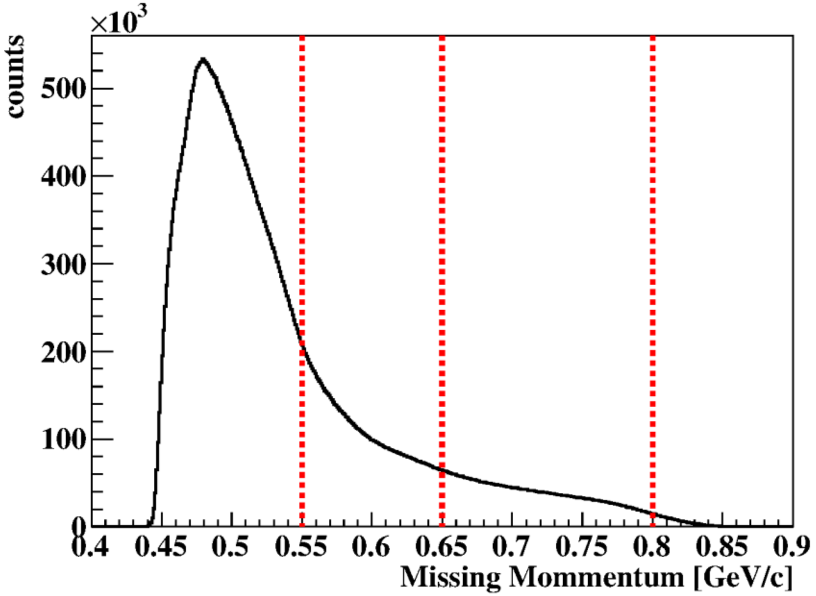
- Σ⁺ identification
  - Missing mass of $\pi^+ p \rightarrow K^+ X$ reaction
- Momentum of Σ⁺
  - Missing momentum of π^+, K^+
  - Σ+p scattering analysis was performed for three separated momentum region
    - Low (0.44-0.55 GeV/c), Middle (0.55-0.65 GeV/c), High (0.65-0.80 GeV/c)

Missing mass distribution



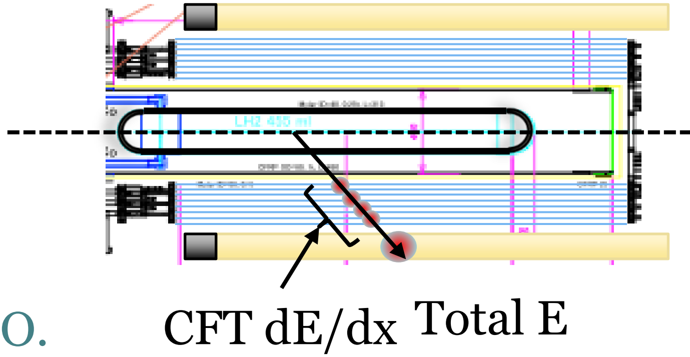
49 M Σ⁺ Events are identified

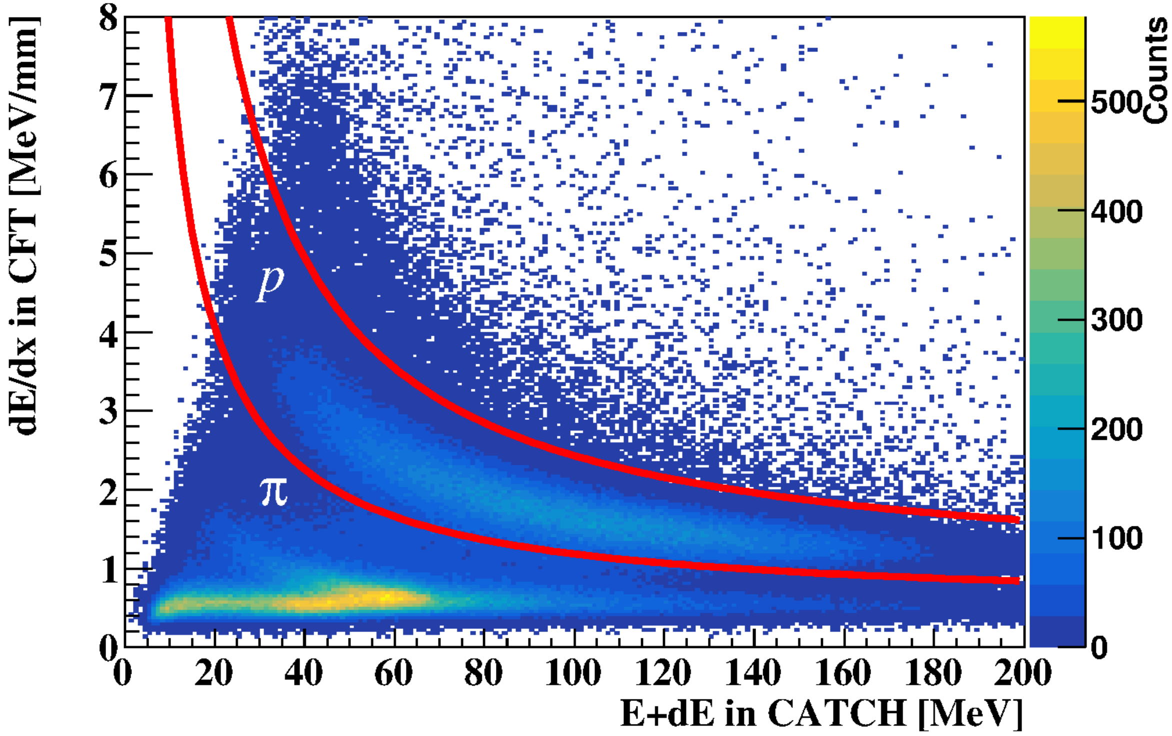
Σ+ momentum distribution



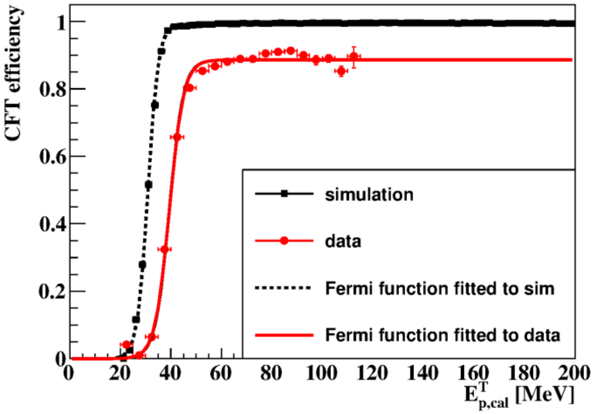
Analysis: CATCH part

- 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.



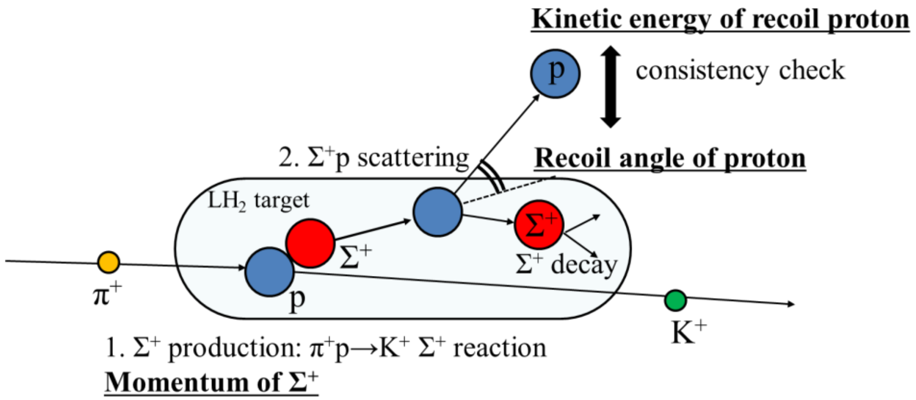


CFT tracking efficiency as a function of Ep @54°



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



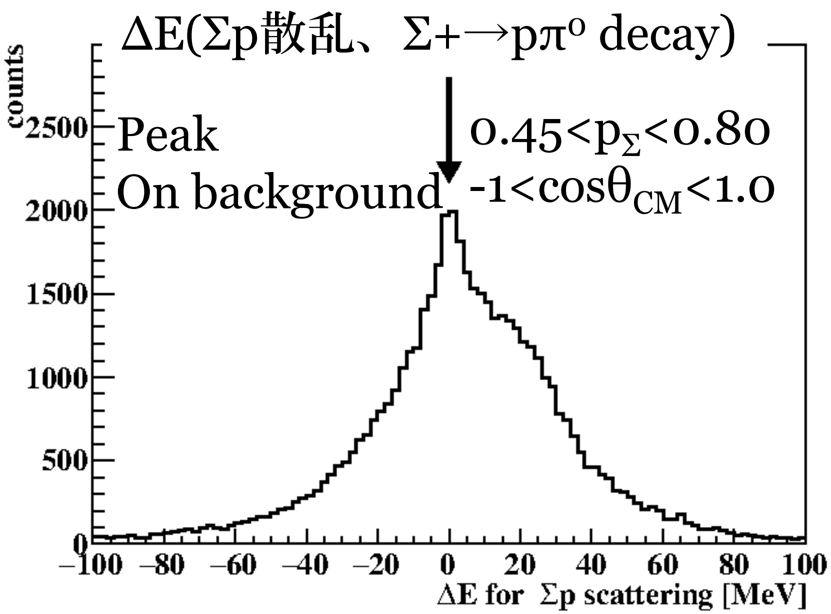
Checking a kinematical consistency for recoil proton

・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.

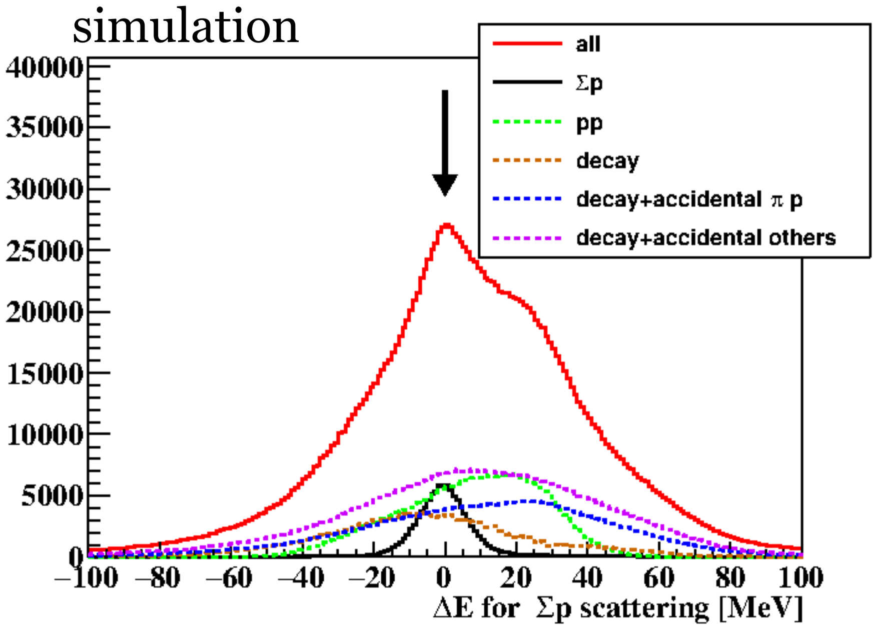


Peak On background

$0.45<p_{\Sigma}<0.80$

$-1<\cos\theta_{CM}<1.0$

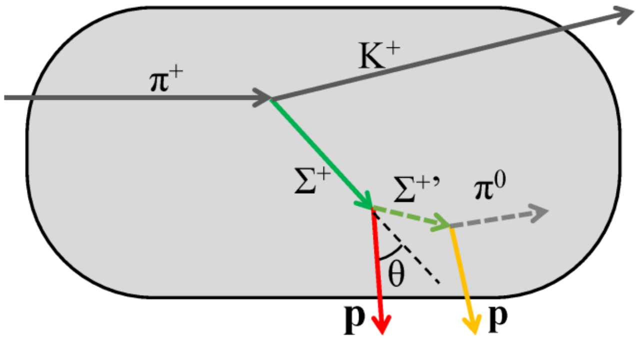
simulation



Background reduction

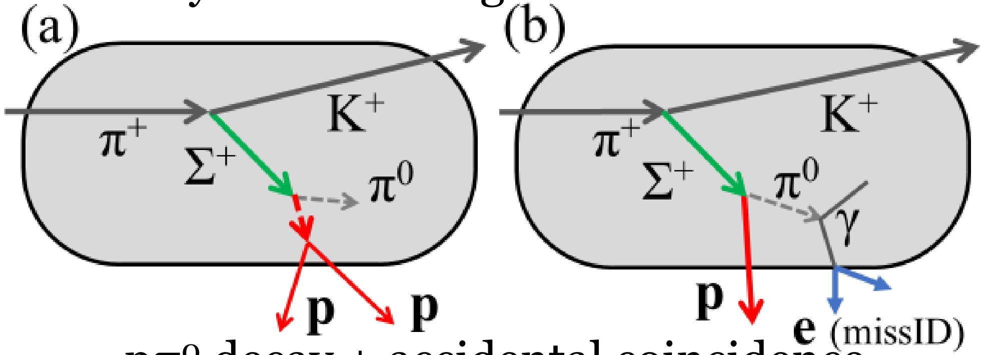
- Background reactions are also generate in a Monte Carlo simulation and distribution in $\Delta E(\Sigma^+ p)$ histogram is estimated.

signal

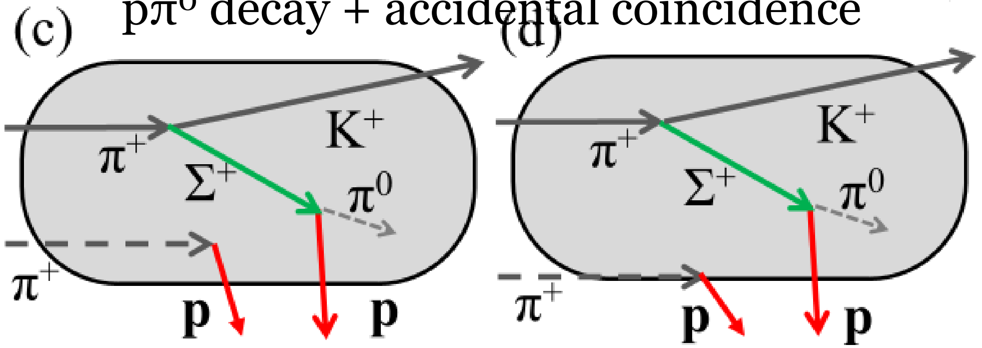


backgrounds

Secondary PP scattering



pπ⁰ decay + accidental coincidence



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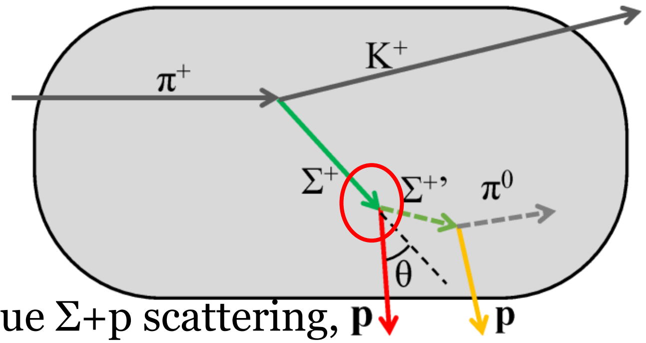
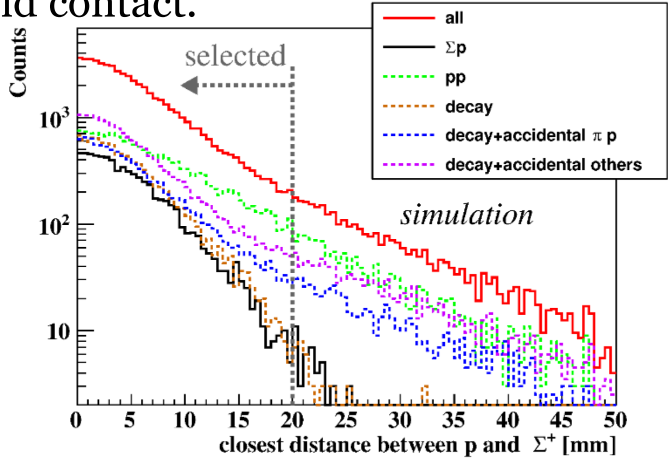
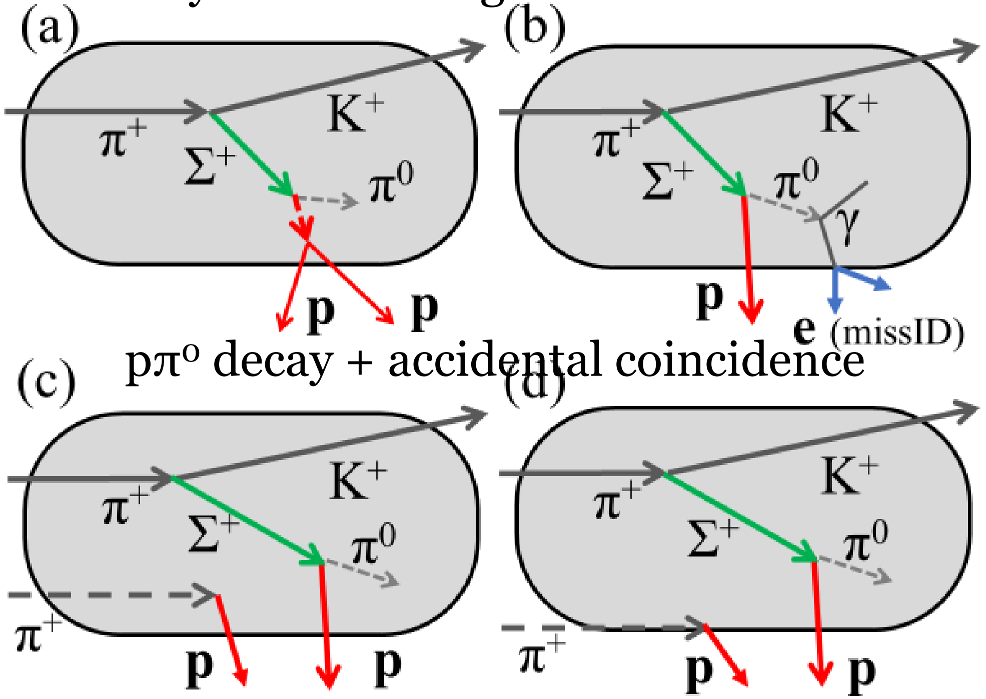


In true Σ+p scattering, p
Tracks of Σ+ and recoil proton should contact.



backgrounds

Secondary PP scattering



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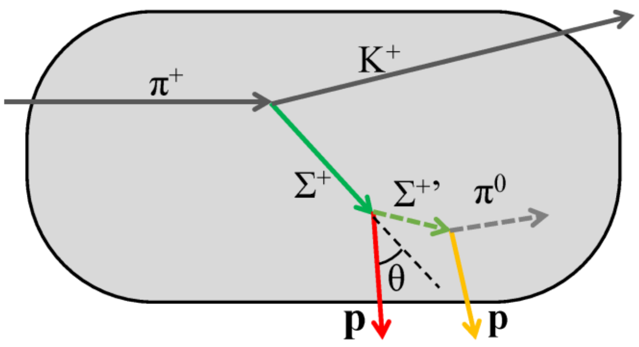
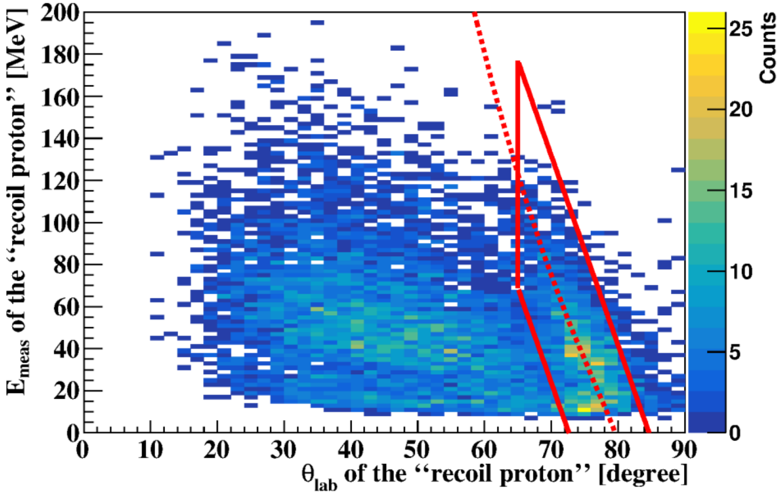
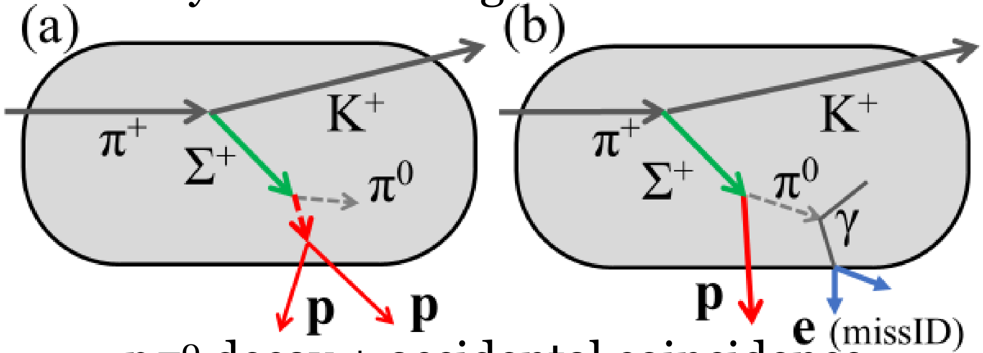


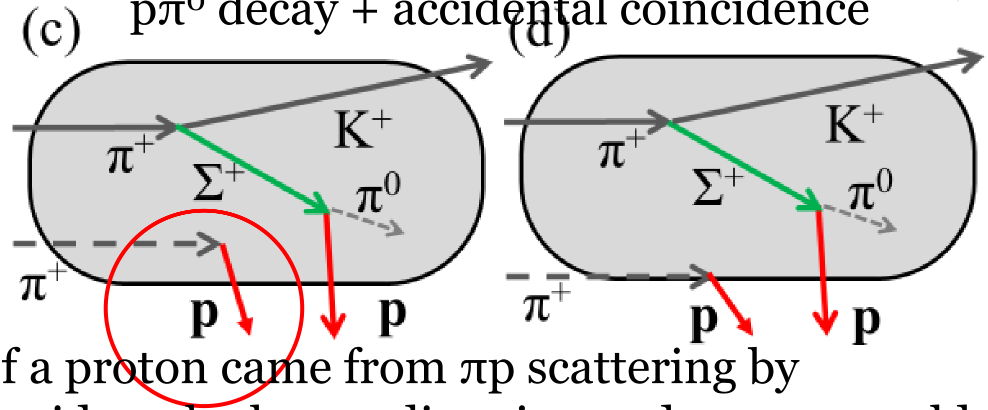


backgrounds

Secondary PP scattering



pπ⁰ decay + accidental coincidence



If a proton came from πp scattering by accidental π beam, direction and energy would be correlate following πp scattering kinematics.

Kinematical identification of Σ+p scattering events

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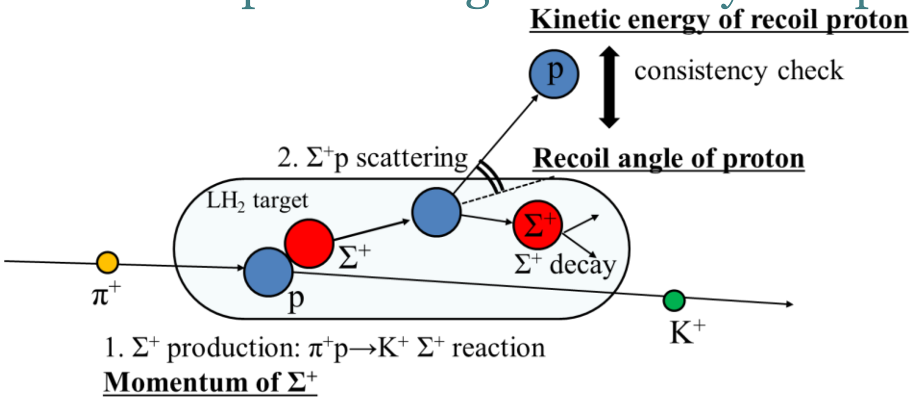

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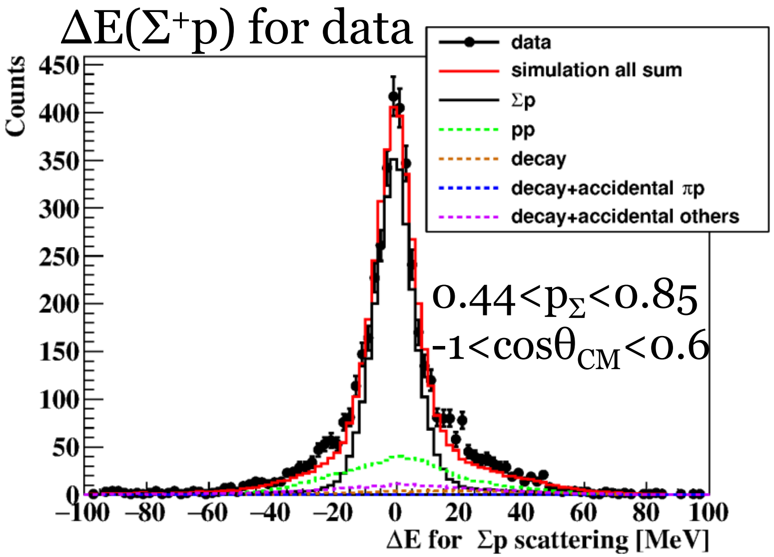
- For Σ^+p scattering events, ΔE distributes around 0.

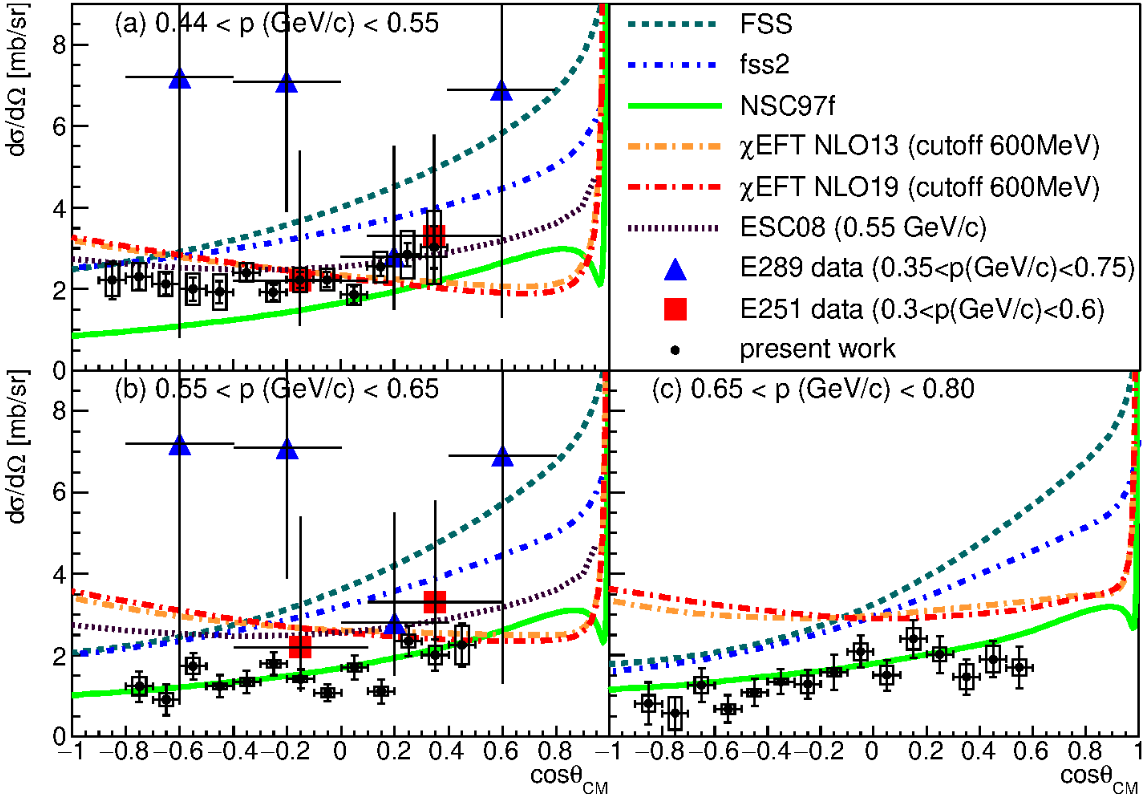


In total, approximately 2400 Σ^+p scattering events were identified !

80 times more than past KEK experiments

Differential cross sections

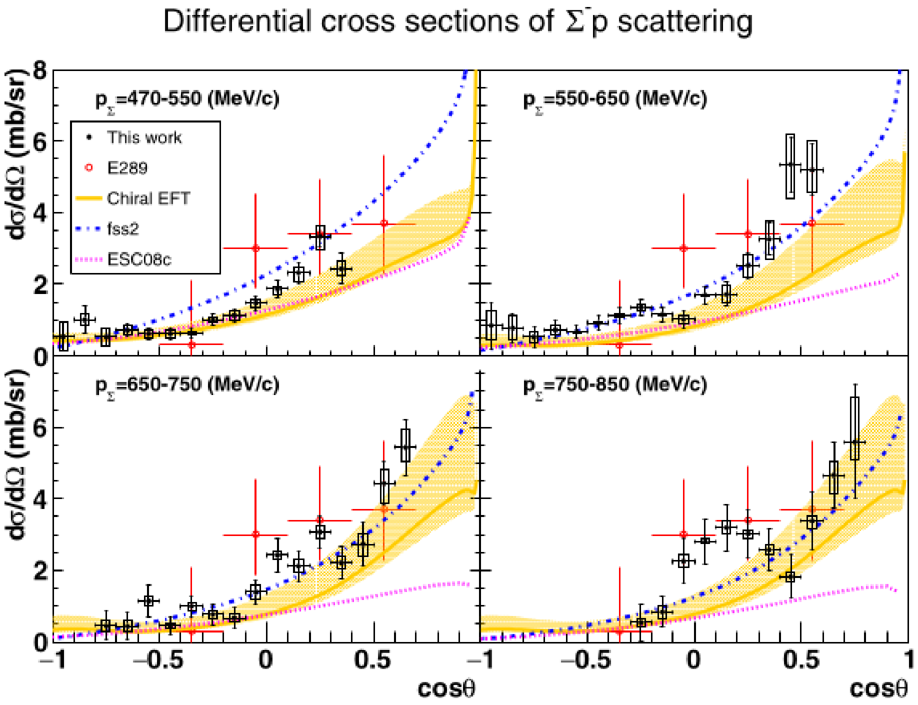
- Differential cross sections were derived from ～2400 Σ^+p scattering events.
  - ▫ The data quality has beem significantly improved!
    - Main sources of systematic error: background estimation, efficiency for low momentum proton.
  - ▫ FSS and fss2 are obviously larger. On the other hand, ESC08, NSC97f are consistent to some extent.
    - Note:NSC97f suggests the attractive ${}^3S_1$ interaction, which does not agree with the current common understanding of ΣN interaction.



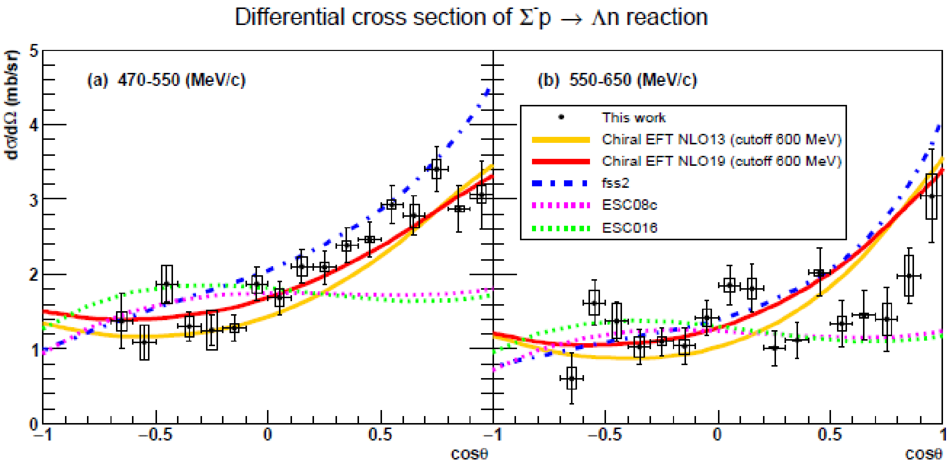
Results from Σ^{-} data

- We have already reported the differential cross sections of the $\Sigma^{-}p$ elastic scattering and $\Sigma^{-}p \rightarrow \Lambda n$ inelastic scattering.

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



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

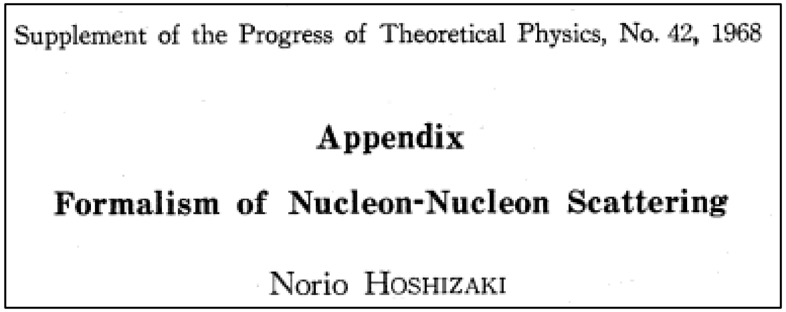


fss2 and χEFT well reproduced ∑- data. Anyway, together with Σ+p data, our data will be essential input to establish realistic BB interaction models.

Phase shift analysis for Σ^+p

- 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.

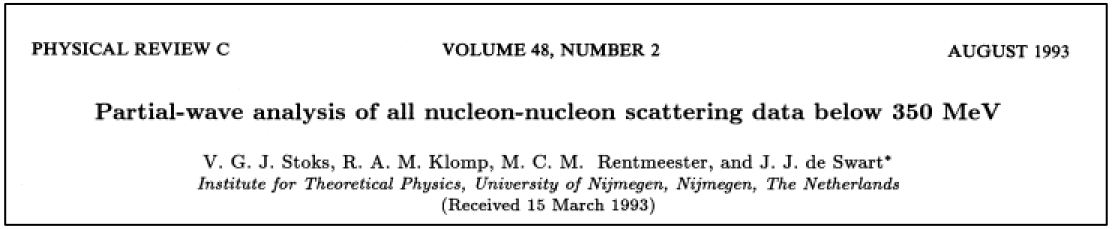


Supplement of the Progress of Theoretical Physics, No. 42, 1968

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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Institute for Theoretical Physics, University of Nijmegen, Nijmegen, The Netherlands
(Received 15 March 1993)

$$\psi^s_m(\mathbf{r}) \sim e^{ikz}\xi^s_m + \frac{e^{ikr}}{r}\sum_{s',m'} \xi^{s'}_{m'} M^{s's}_{m'm}(\theta,\phi)\,, \qquad (16)$$

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

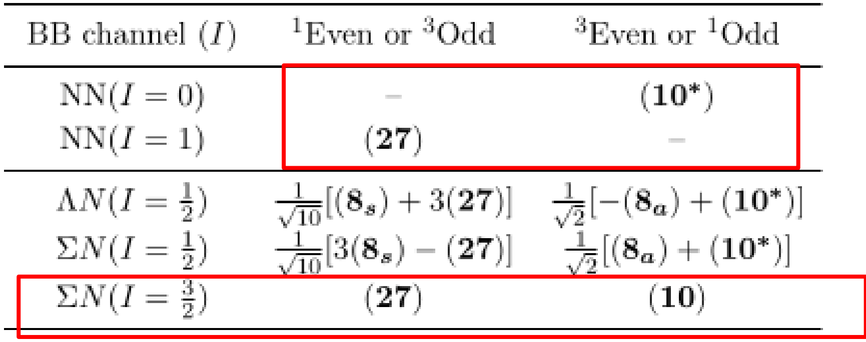
$$h_{{}^{2S+1}L_J} = \begin{cases} \frac{1}{2ik}(\cos(2\bar{\epsilon}_1)\exp(2i\bar{\delta}_{{}^{2S+1}L_J}) - 1) & ({}^3S_1 \text{ and } {}^3D_1 \text{ case}) \\ \frac{1}{2ik}(\exp(2i\bar{\delta}_{{}^{2S+1}L_J}) - 1) & (\text{else}) \end{cases} \tag{5.10}$$

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

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.

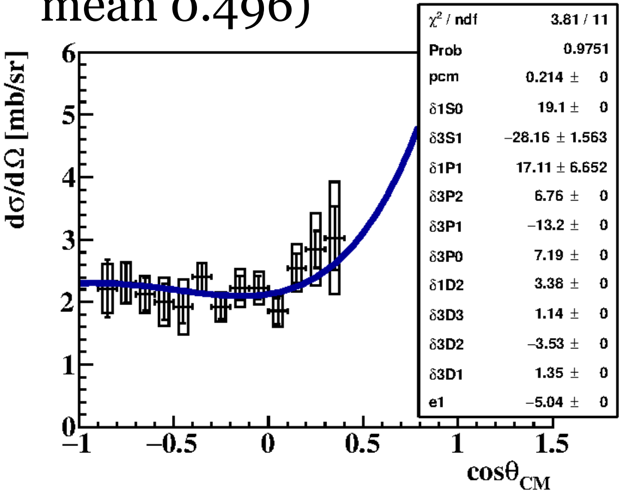


BB channel (I)	^{1}Even or ^{3}Odd	^{3}Even or ^{1}Odd
$NN(I=0)$	–	$(\mathbf{10}^*)$
$NN(I=1)$	$(\mathbf{27})$	–
$\Lambda N(I=\frac{1}{2})$	$\frac{1}{\sqrt{10}}[(\mathbf{8}_s)+3(\mathbf{27})]$	$\frac{1}{\sqrt{2}}[-(\mathbf{8}_a)+(\mathbf{10}^*)]$
$\Sigma N(I=\frac{1}{2})$	$\frac{1}{\sqrt{10}}[3(\mathbf{8}_s)-(\mathbf{27})]$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

Fitting results

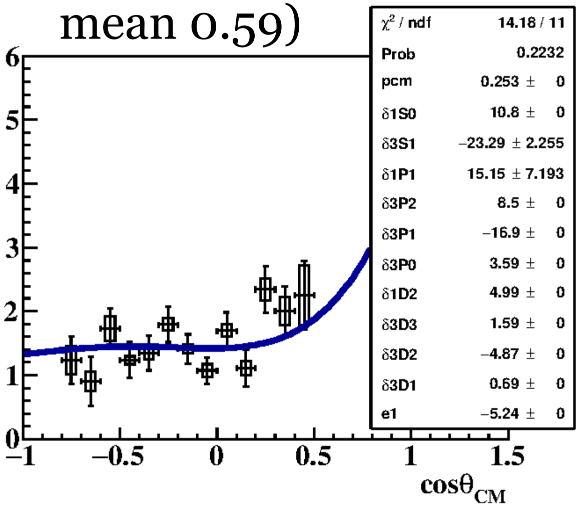
- Fixed phase shifts are taken from ESC16
- $\delta_{3S1}<0$ case
- χ^2/ndf is approximately 1.

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



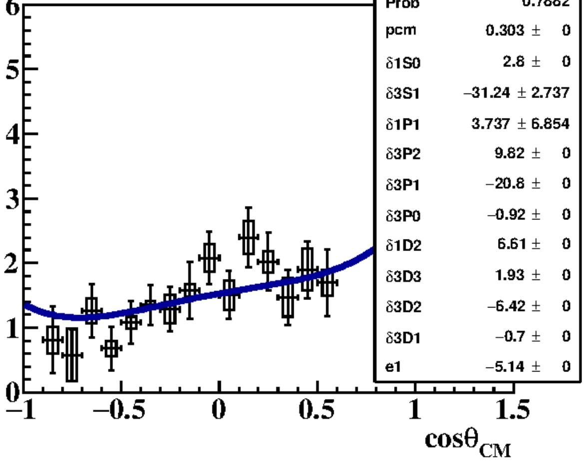
χ^2 / ndf	3.81 / 11
Prob	0.9751
pcm	0.214 ± 0
δ1S0	19.1 ± 0
δ3S1	−28.16 ± 1.563
δ1P1	17.11 ± 6.652
δ3P2	6.76 ± 0
δ3P1	−13.2 ± 0
δ3P0	7.19 ± 0
δ1D2	3.38 ± 0
δ3D3	1.14 ± 0
δ3D2	−3.53 ± 0
δ3D1	1.35 ± 0
e1	−5.04 ± 0

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



χ^2 / ndf	14.18 / 11
Prob	0.2232
pcm	0.253 ± 0
δ1S0	10.8 ± 0
δ3S1	−23.29 ± 2.255
δ1P1	15.15 ± 7.193
δ3P2	8.5 ± 0
δ3P1	−16.9 ± 0
δ3P0	3.59 ± 0
δ1D2	4.99 ± 0
δ3D3	1.59 ± 0
δ3D2	−4.87 ± 0
δ3D1	0.69 ± 0
e1	−5.24 ± 0

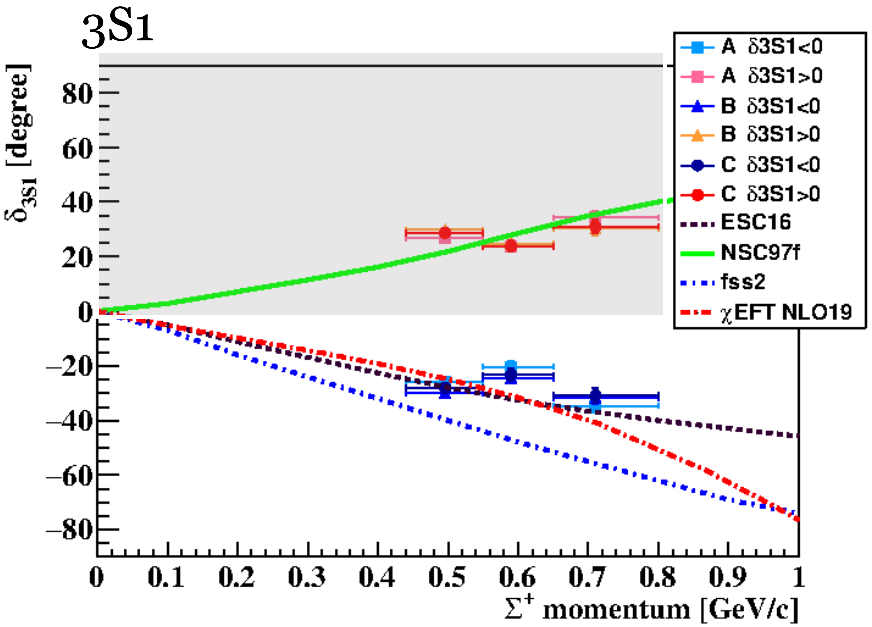
high momentum
(0.65<pΣ<0.80 GeV/c
mean 0.71)

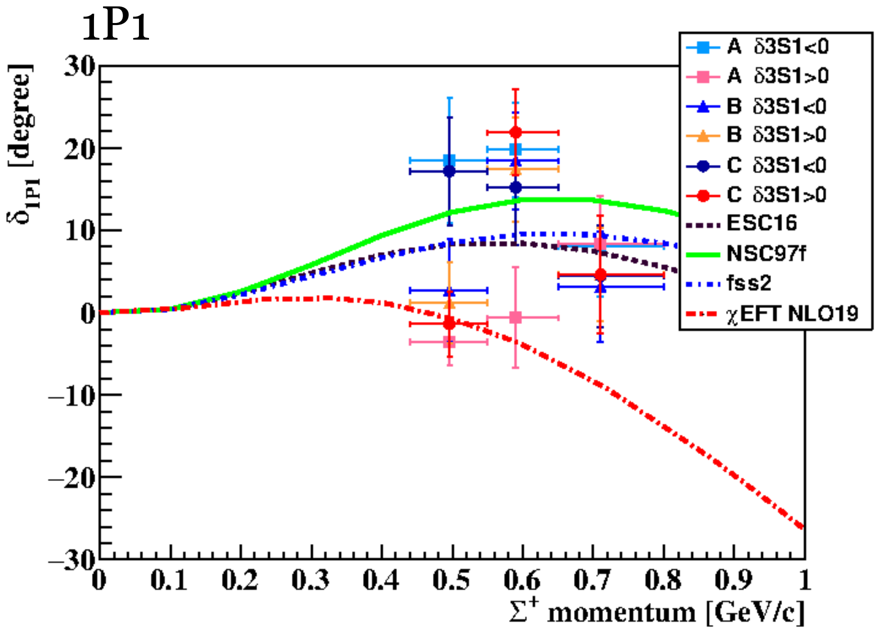


χ^2 / ndf	8.796 / 13
Prob	0.7882
pcm	0.303 ± 0
δ1S0	2.8 ± 0
δ3S1	−31.24 ± 2.737
δ1P1	3.737 ± 6.854
δ3P2	9.82 ± 0
δ3P1	−20.8 ± 0
δ3P0	−0.92 ± 0
δ1D2	6.61 ± 0
δ3D3	1.93 ± 0
δ3D2	−6.42 ± 0
δ3D1	−0.7 ± 0
e1	−5.14 ± 0

Obtained phase shifts

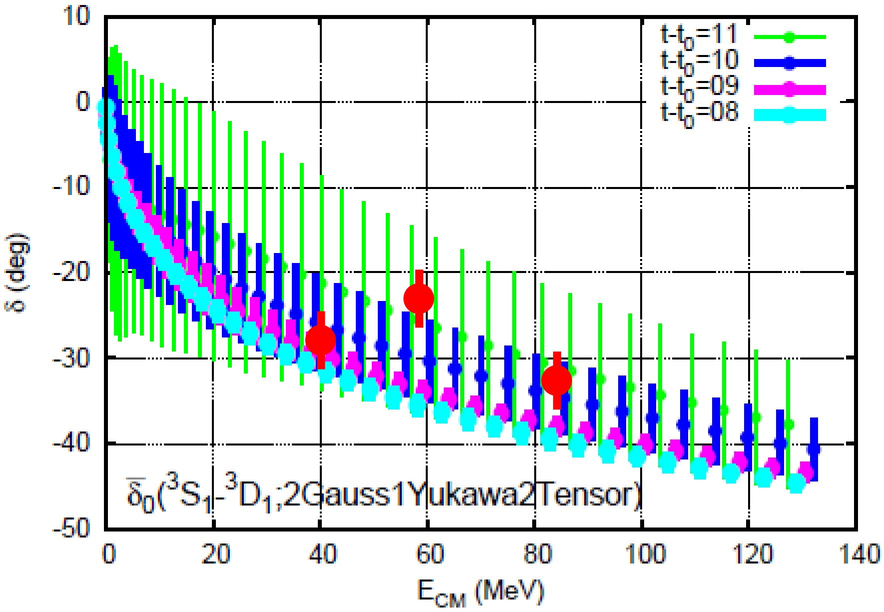
- $^{3}S_{1}$:almost consistent with ESC16 ($\delta<0$) or NSC97f ($\delta>0$).
  - $|\delta|$: 28.3±1.5±2.1 (low), 23.4±2.0±3.0 (mid), 32.5 ±2.5±2.5 (high)
    - Fitting error and effect of the different sets of the fixed parameters
  - The interaction in this channel is moderately repulsive.
- $^{1}P_{1}$:ambiguous.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


3S1


1P1

Comparison with HAL QCD

- $\delta{}^3S_1$ can be compared with HAL QCD!
- Our results are consistent with HAL QCD calculation with larger t-t0.



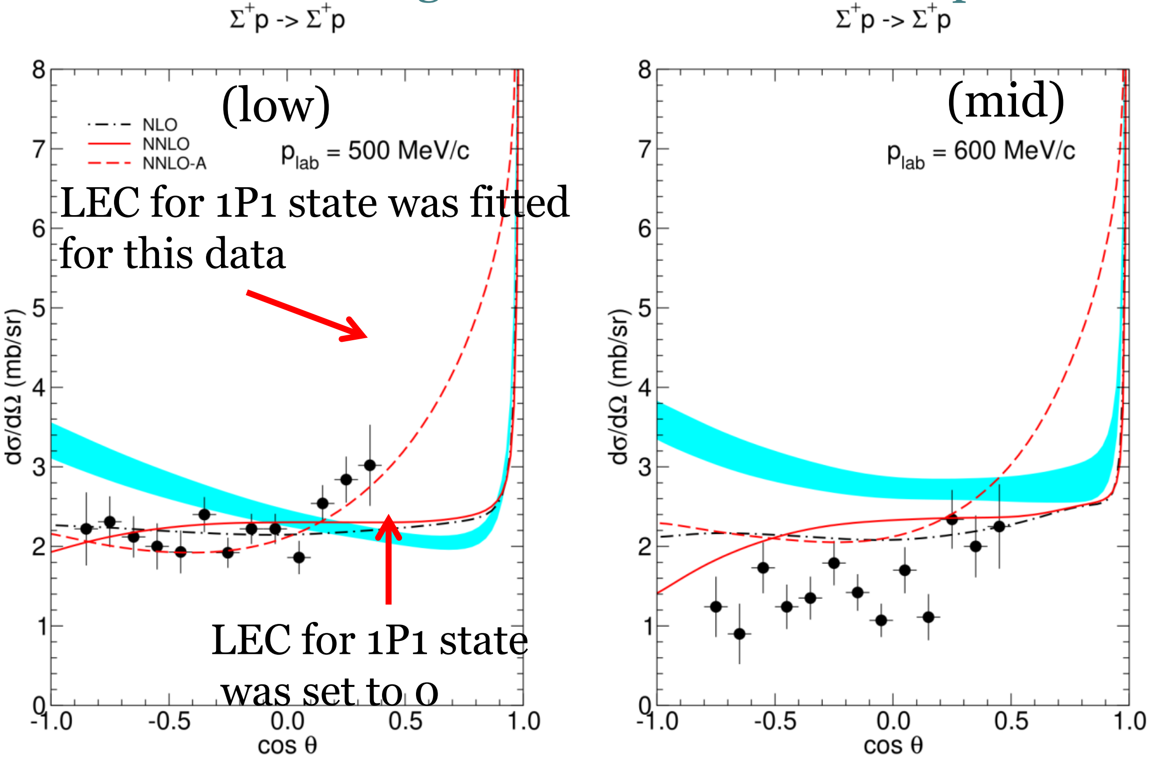
H. Nemura AIP Conf. Proc. 2130, 040005(2019)

xEFT N^2LO

- Recently, the χEFT N^2LO calculation for ΛN-ΣN interaction is presented.
  - J. Haidenbauer, HYP 2022 presentation
  - J. Haidenbauer, EPJ Web Conf., 271 (2022) 05001
- In χEFT N^2LO, Our data were used to determine LECs in P-wave
  - LECs in S-wave were determined by low-energy Σp scattering data.
  - From NLO to N^2LO, there are no new additional LECs in the two body sector.

Comparison with xEFT N^2LO

- Σ^+p scattering
  - χEFT N^2LO well agrees with our data in the low momentum region. However, small differential cross sections in the middle momentum region were not reproduced.
  - In our data, δ3S1 in the middle momentum region were smaller than in other momentum region. Influence of the Λπp threshold (pΣ=0.62 GeV/c)?



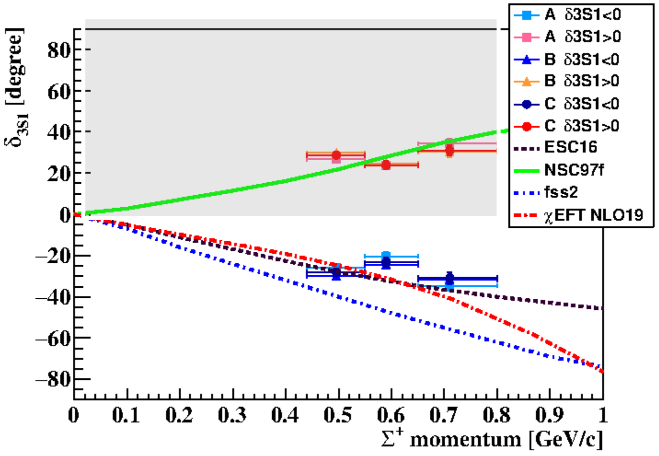
(low)

LEC for 1P1 state was fitted for this data

LEC for 1P1 state was set to 0

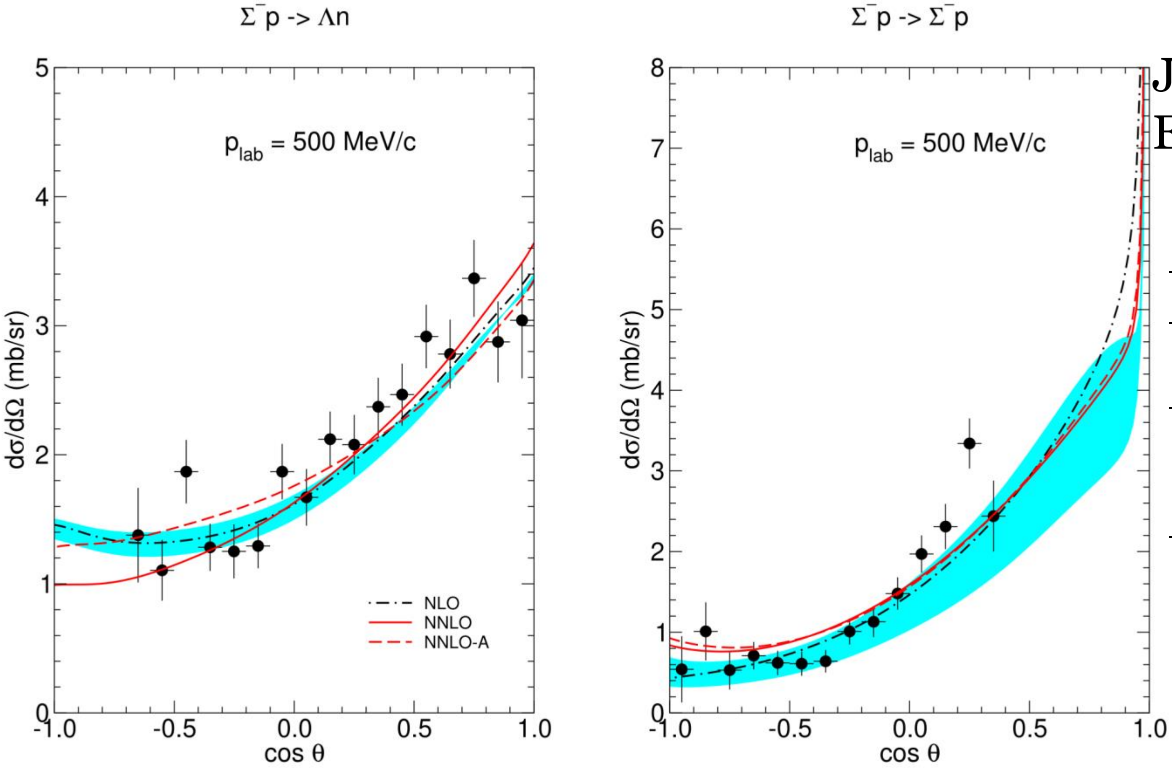
(mid)

J. Haidenbauer,
EPJ Web Conf., 271 (2022) 05001

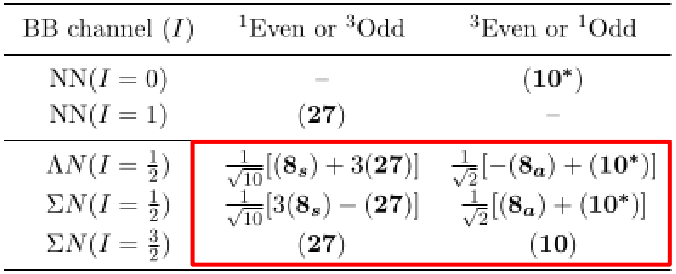


Comparison with χEFT N^{2}LO

- Σ^-p elastic, Σ^-p→Λn scattering
  - χEFT N²LO well agrees with our data, as the χEFT NLO.
  - To determine the P-wave LECs uniquely, data for additional channel (Λp elastic, Σ-p→Σ⁰n,) or observables are needed.
    - J-PARC E86 experiment (Λp scattering @K1.1 beam line)



J. Haidenbauer,
EPJ Web Conf., 271 (2022) 05001



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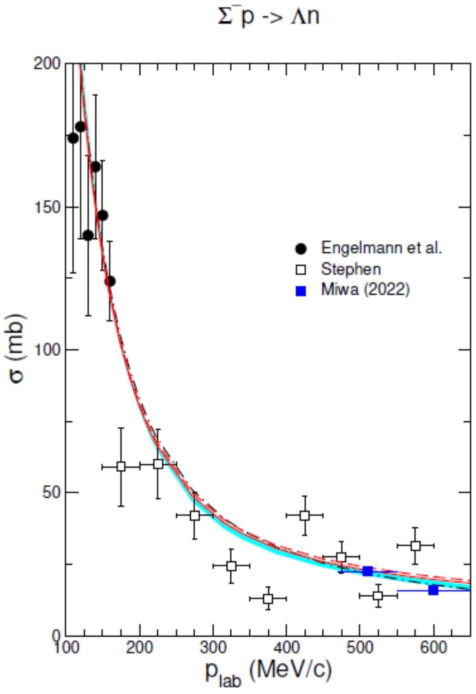
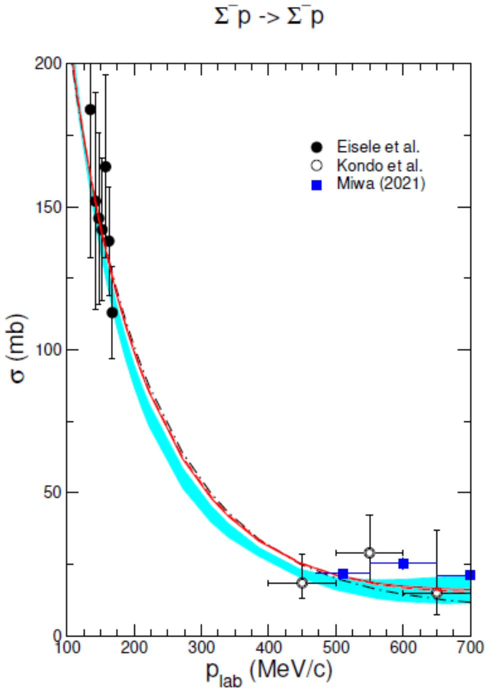
$\Sigma N(I=\frac{3}{2})$	$(\mathbf{27})$	$(\mathbf{10})$

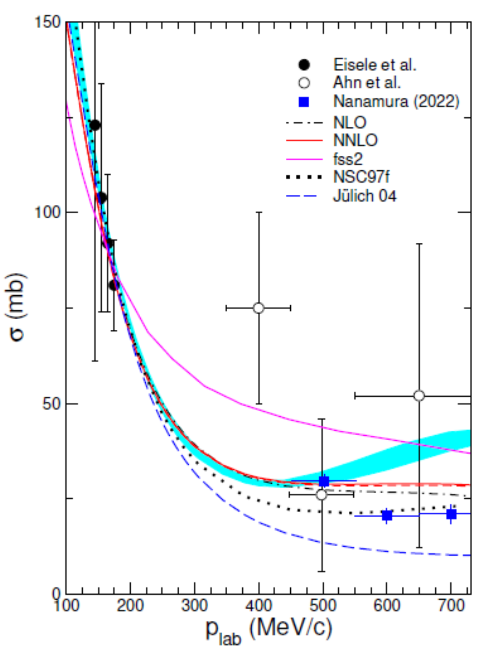
Comparison with xEFT N^2LO

- Total cross section
  - χEFT N^2LO well agrees with our data for pΣ～0.5 GeV/c.
  - In this plot, total cross sections from experiment were calculated as $2\times\sigma_{-0.5<\cos\theta<0.5}$. I think angular dependence (mainly come from contribution of P waves) should be considered for good comparison.

J. Haidenbauer,
HYP2022 presentation





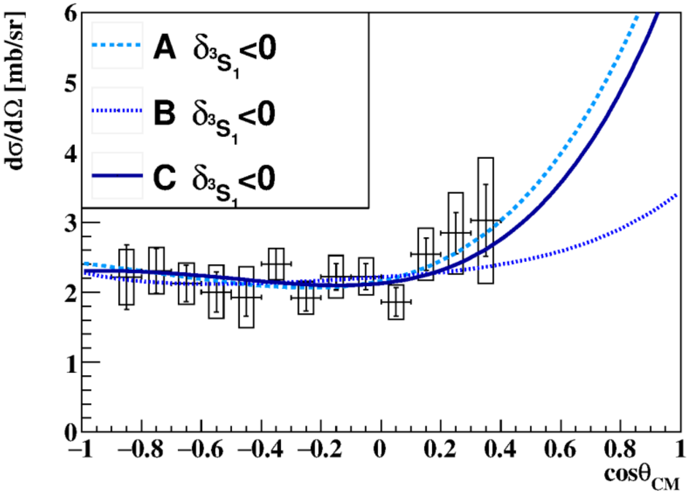


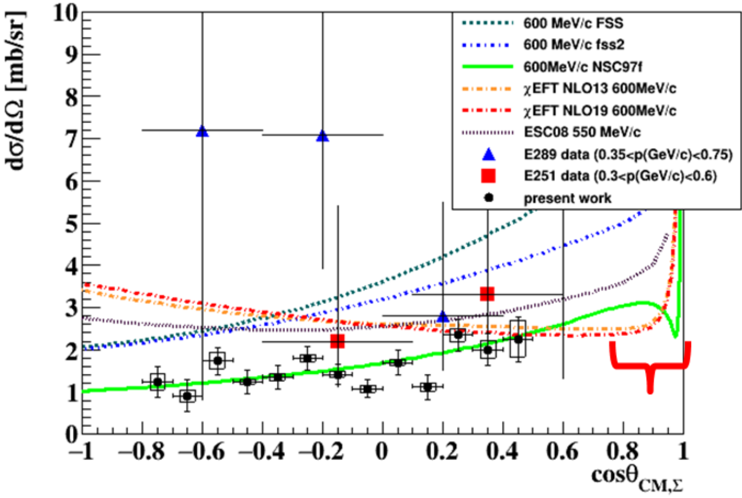
Future Σ^+p scattering experiments?

- Higher momentum?
  - To understand the short-range force and behavior of quark-Pauli effect, data for higher momentum is desired.
    - In present data, the distance of two particles were 0.5-0.8 fm.
  - As long as contributions of D- and higher waves are small (or well estimated), our phase shift analysis method will work. The phase shifts of the $^3S_1$ and $^1P_1$ could be determined only from $d\sigma/d\Omega$.
    - Most of theoretical models for BB interaction are constructed using below 1GeV/c data… Will they be reliable?
  - Different spectrometer setup for (π^+,K^+) reaction?
    - E40: 1.41 GeV/c π^+ and $3° < \theta_K < 25°$, more backward angle?
  - Experiment @π20 beam line will be possible?
    - LOI for Λp scattering (R. Honda et al., J-PARC LoI 2020-8)
- Additional observable?
  - If $^3D_1$ and ε1 can be determined with a aid of observables, our understanding of $^3S_1$-$^3D_1$ state will be deepened.
  - Analyzing power can be derived even from E40 data. I will study phase shift analysis using analyzing power together with $d\sigma/d\Omega$

Future Σ^+p scattering experiments?

- Wider angular acceptance?
  - More forward angle
    - cosθcm<0.8, 20<Ep [MeV] <30
    - Important to resolve a ambiguity of δ^1P_1
    - Recoil proton can be measured by major modification of CATCH?
      - (e.g. SSD tracker instead of CFT)
  - Ultra-forward angle
    - cosθCM～0.95, Ep <5 MeV
    - By checking Coulomb interference, the sign of δ3S1 will be determined.
    - Recoil proton would stop in LH2 target.
    - Low-density active target is needed.
      - TPC with H2 gas?





Summary

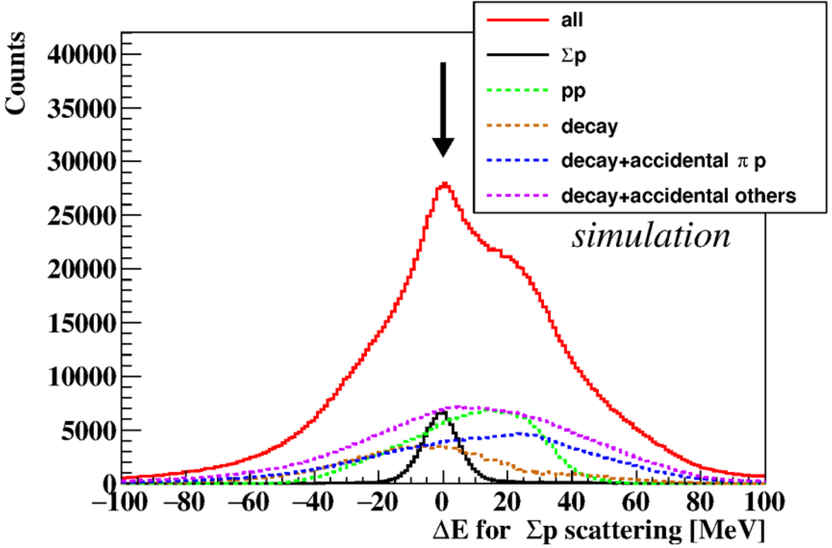
- Hyperon-nucleon scattering experiment gives us very important information for B-B interaction, especially quark Pauli effect.
- J-PARC E40 Experiment
    - High-statistics Σp scattering experiment
        - ∑+p elastic scattering, Σ-p elastic scattering, Σ-p→Λn inelastic scattering
    - Data taking was finished by June 2020.
- dσ/dΩ were derived by about 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 Σ^+p interaction was investigated.
    - The absolute value (and the strength of interaction) of the $^3S_1$ is much smaller than fss2 and FSS expected.
- Recent χEFT N^2LO calculation using our data was introduced.

Back up

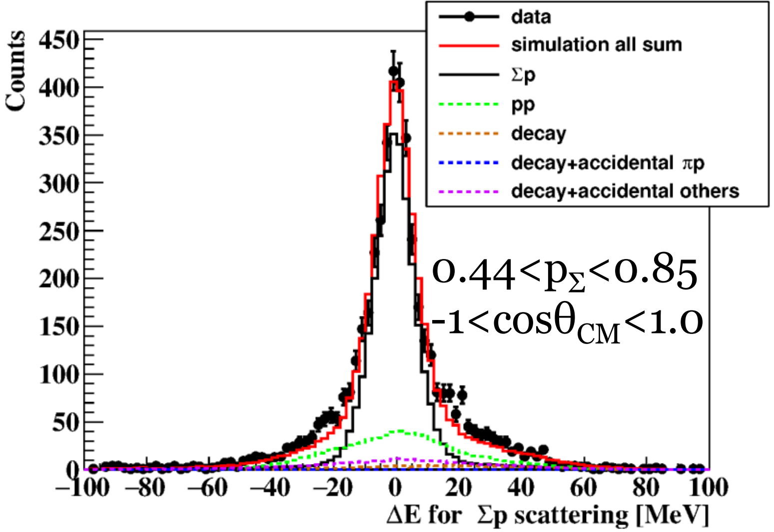
Cut conditions to select Σ+

- There are many backgrounds w/o cuts.
- Spatial consistency cut
  - At scattering and decay point
  - Vertex cut, closest distances cut
- Kinematical consistency cut
  - Missing mass cut for decay proton
  - pp scattering consistency
  - πp elastic scattering cut

$\Delta E(\Sigma^+ p)$ for simulation before cuts



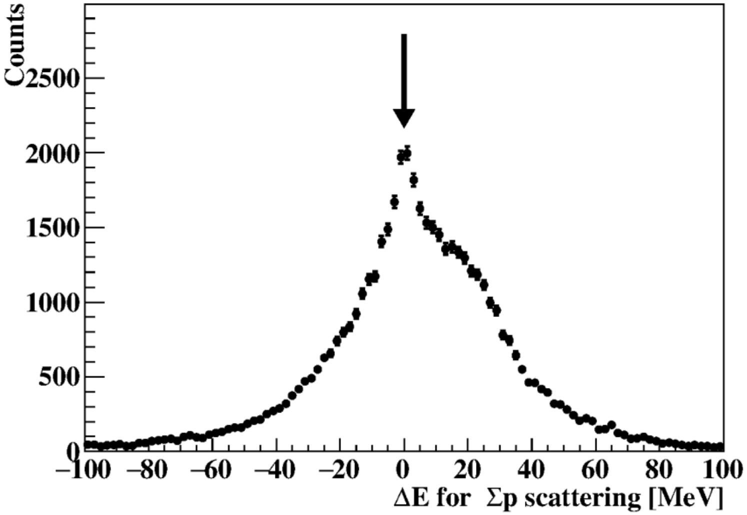
$\Delta E(\Sigma^+ p)$ for data after cuts



$0.44 < p_\Sigma < 0.85$

$-1 < \cos\theta_{CM} < 1.0$

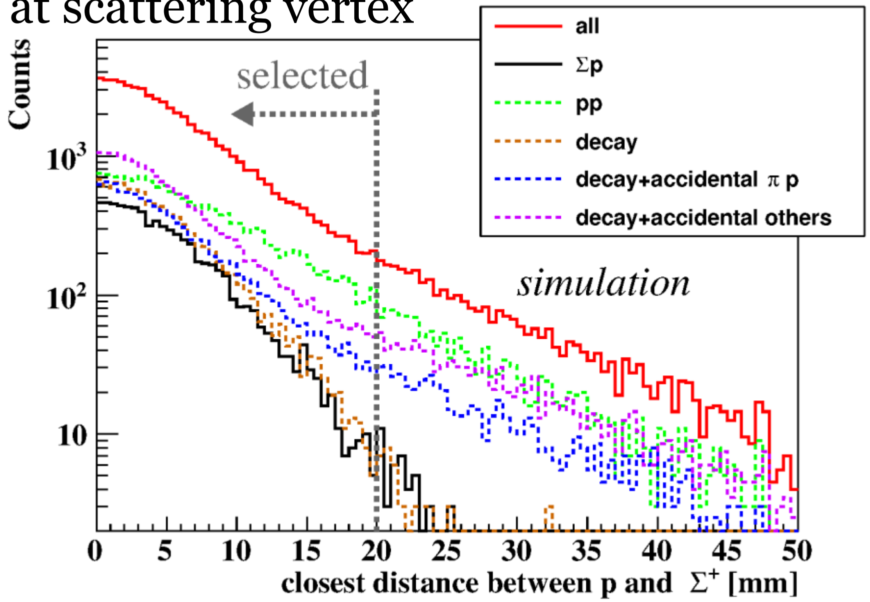
$\Delta E(\Sigma^+ p)$ for data before cuts



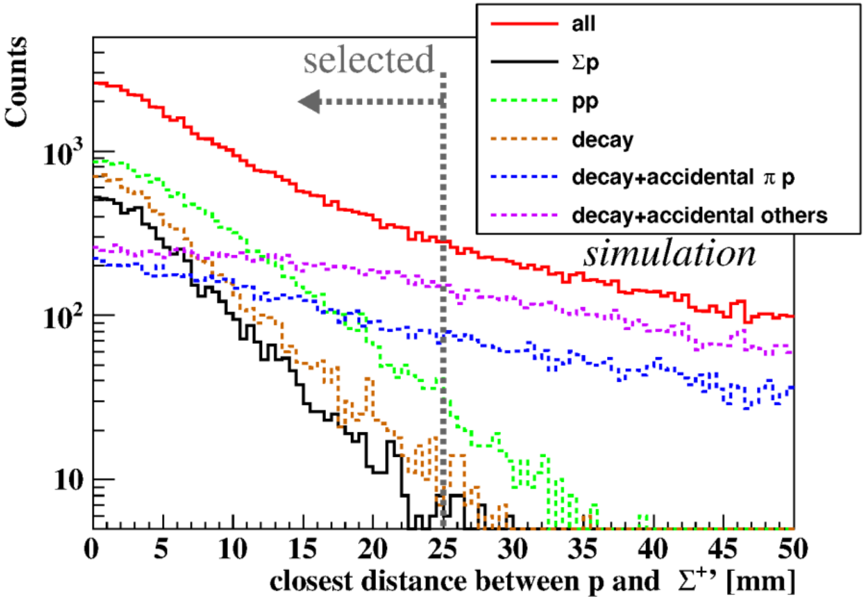
Cut conditions to select Σ+

- Spatial consistency cut
  - At scattering and decay point
  - Effective to cut backgrounds derived from accidental coincidences
- Vertex cut
  - Scattering vertex should be in the LH2 target, decay vertex after the scattering should not be far from the target.
- Closest distances cut

Simulated closest distance at scattering vertex



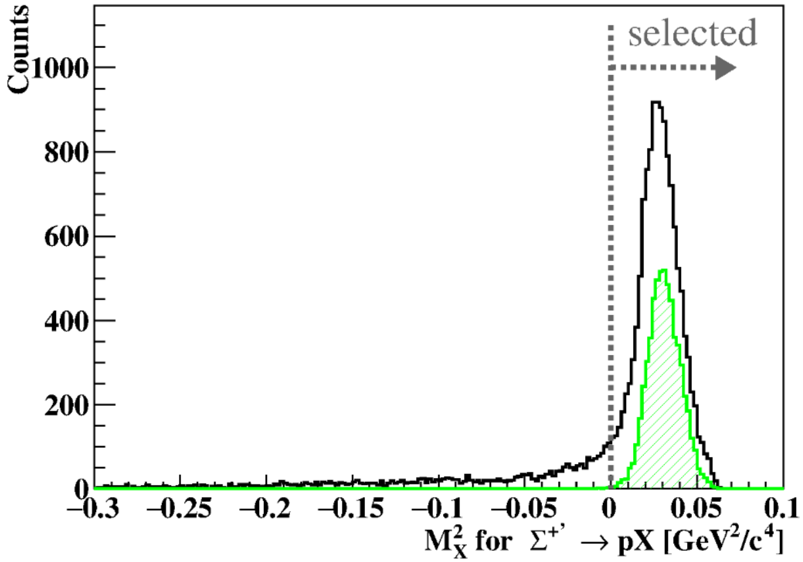
Simulated closest distance at decay vertex after scattering



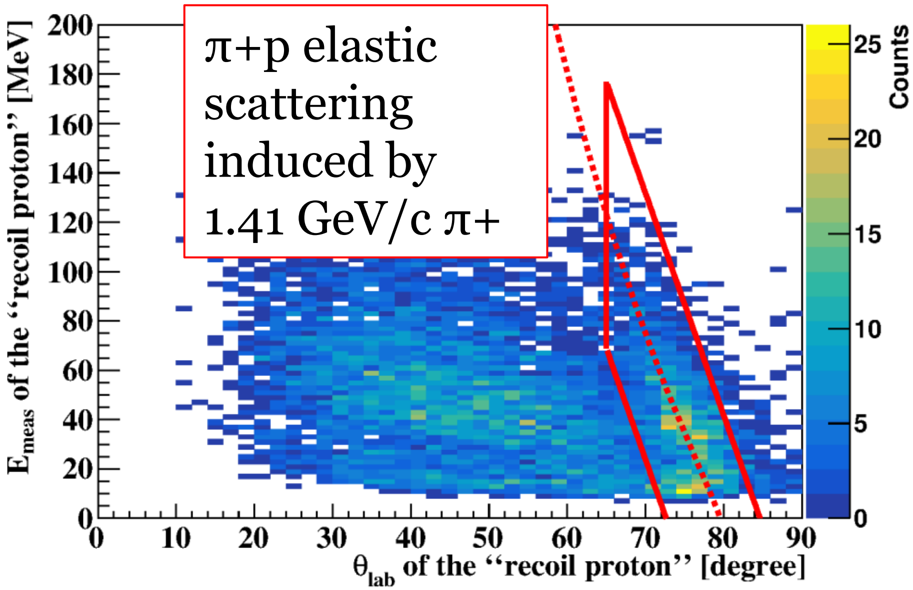
Cut conditions to select Σ+

- Kinematical cuts
- Missing mass cut for decay proton
  - π^0 missing reaction, Σ^+p scattering followed by $\Sigma^{+\prime}\to p\pi^0$ decay and secondary pp scattering events is selected.
- Elastic πp scattering cut
  - Proton from accidental π+p scattering induced by accidental 1.41 GeV/c π+ beam was rejected.

Missing mass for
$\Sigma^{+\prime}\to p\pi^0$ decay after scattering

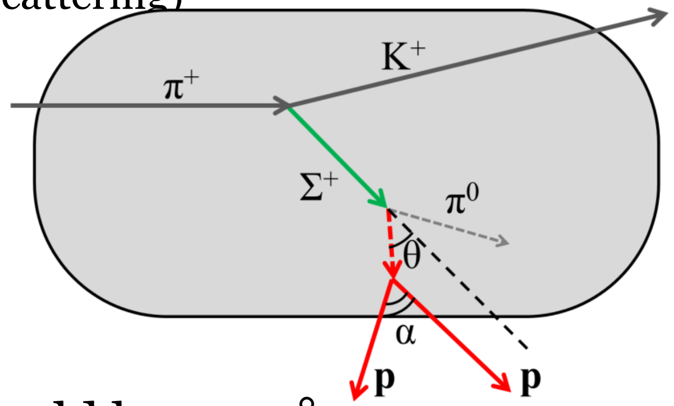


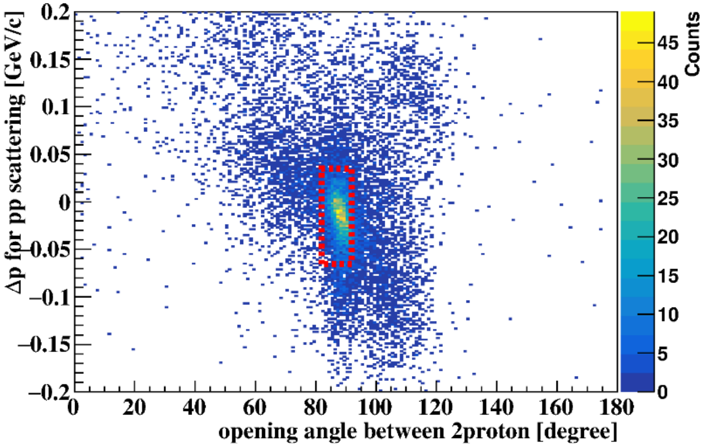
Correlation between θlab and E of proton


π+p elastic scattering induced by 1.41 GeV/c π+

Cut conditions to select Σ+

- Kinematical cuts
- Kinematical consistency cut for secondary pp scattering
  - The momentum of decay proton (incident proton for pp scattering)
  - Can be reconstructed by two ways:
    - Sum of the momenta of two detected proton
      - $\mathbf{p}_{\mathbf{sum}}$=p1+p2
    - Calculation from Σ+ momentum and direction of $\mathbf{p}_{\mathbf{sum}}$
      - $\mathbf{p}_{\mathbf{calc}}$
  - Consistency $\Delta p = p_{sum} - p_{calc}$
  - In pp scattering, opening angle of 2 proton should be ~90°
  - Secondary pp scattering events
  - Concentrates on around
  - (Δp, α)=(0, 90°).

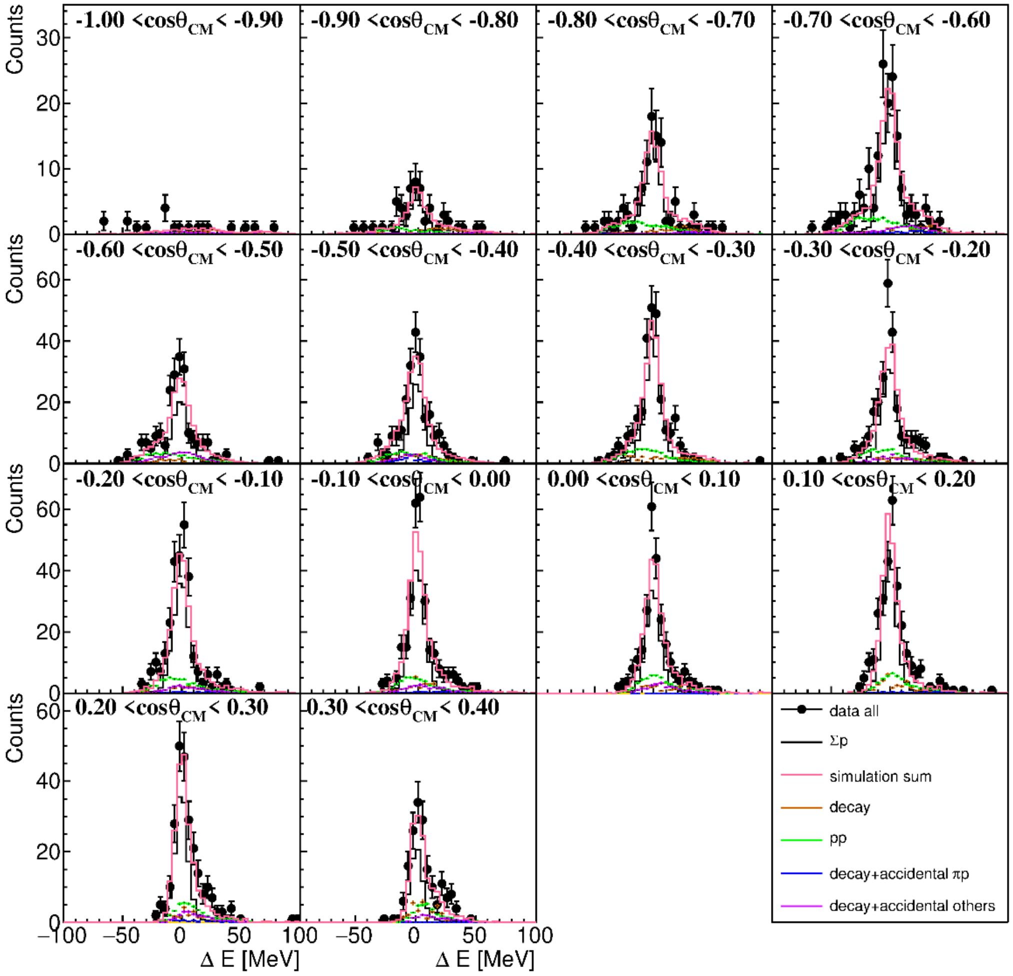




Background estimation

- ΔE spectra were fitted by the sum of the simulated distribution of considered reactions.
- Parameter: scale factor of each reaction
- Fitting was performed for each scattering angle and momentum independently.
- Uncertainty from binning of ΔE spectra and various constraints on parameters are considered.

Low-mommentum



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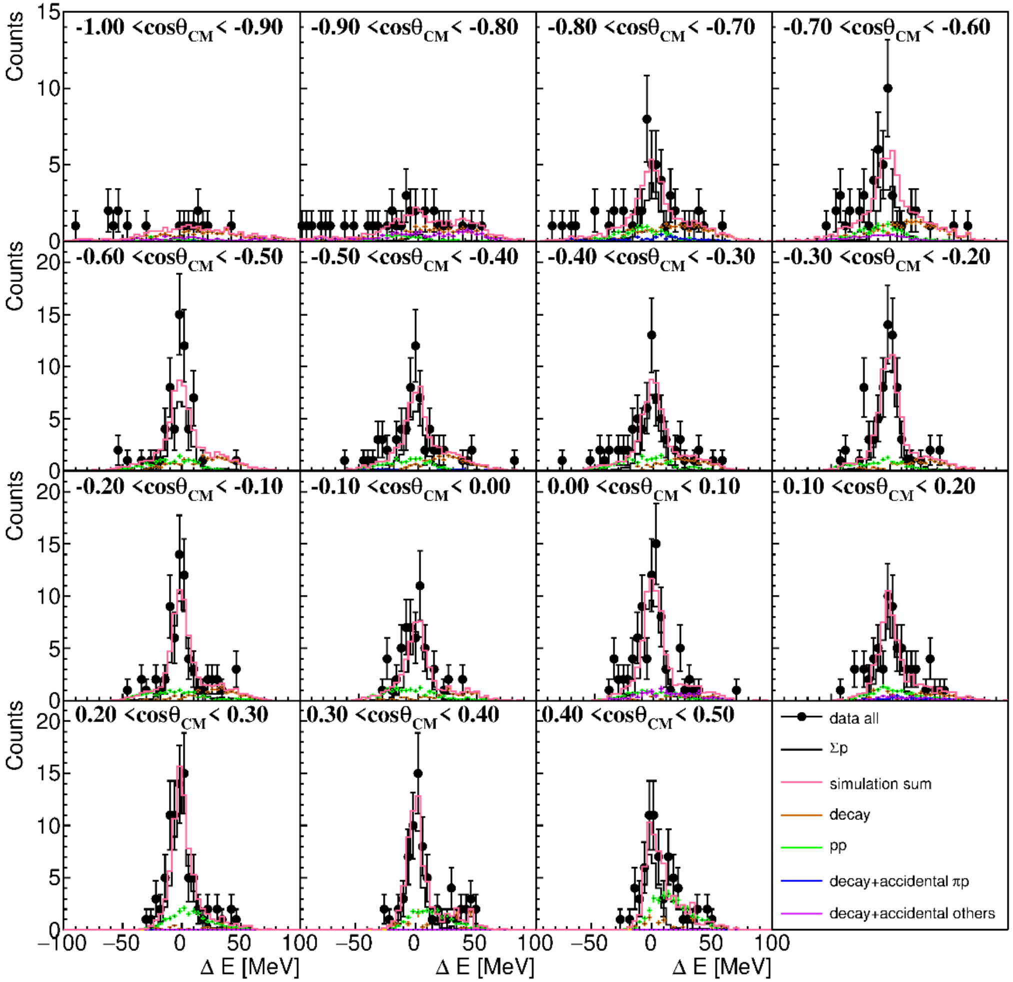
middle mommentum



Background estimation

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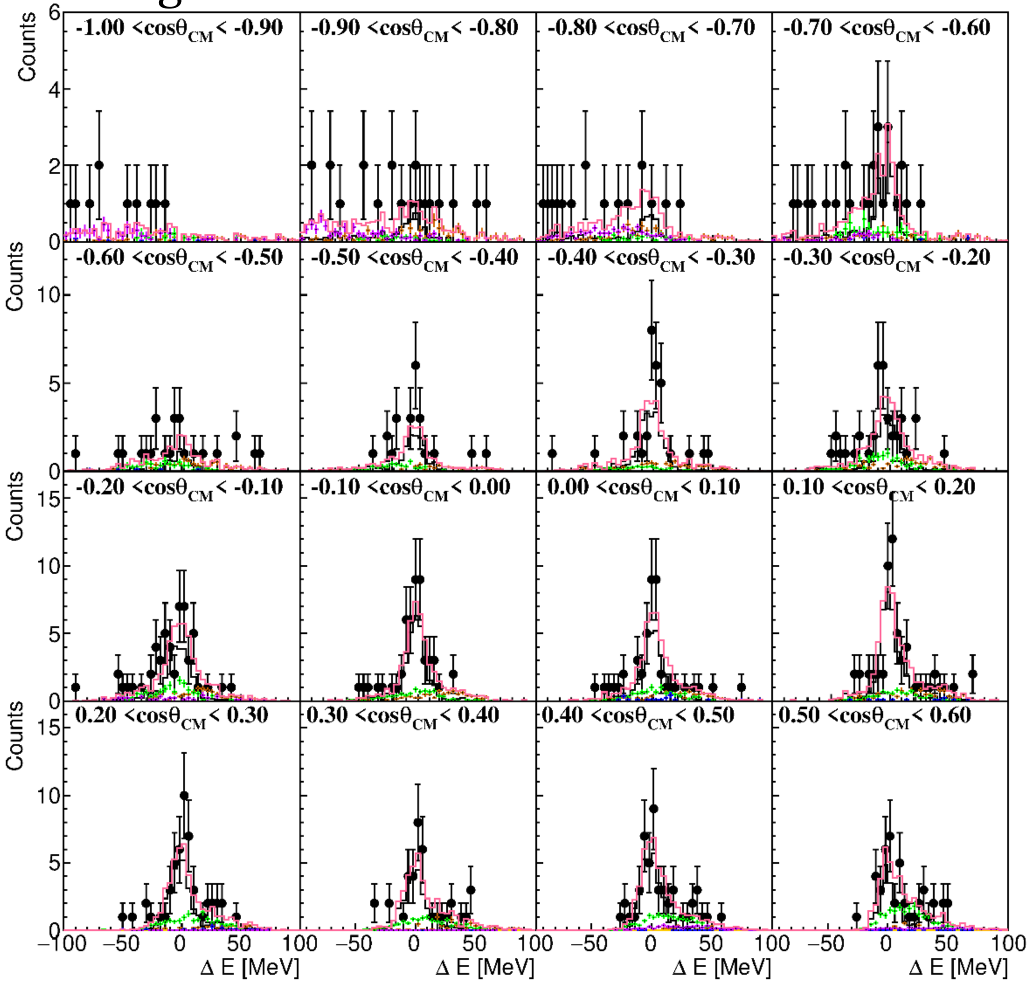
- Parameter: scale factor of
- each reaction

- Fitting was performed for ea
- scattering angle and mom
- independently.

- Uncertainty from binning of
- spectra and various const
- on parameters are consid

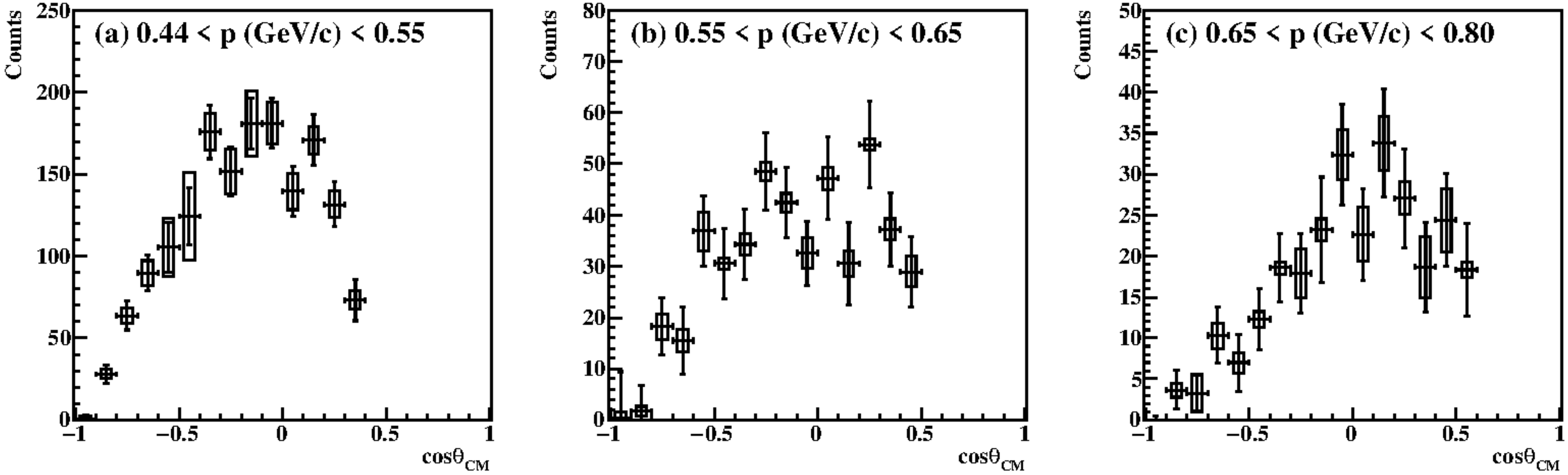
high momentum



The derivation of the differential cross sections

$$\frac{d\sigma}{d\Omega}(p, \cos\theta_{\mathrm{CM}}) = \frac{N(p, \cos\theta_{\mathrm{CM}})}{\varepsilon(p, \cos\theta_{\mathrm{CM}})\rho \cdot N_A \cdot L_{\mathrm{tot}}(p) \cdot \Delta\Omega}$$

- **N:the event number of ∑p scattering**
- ε:(averaged)efficiency evaluated by simulation
- L_{tot}: Total flight length of ∑+ in LH_2 target



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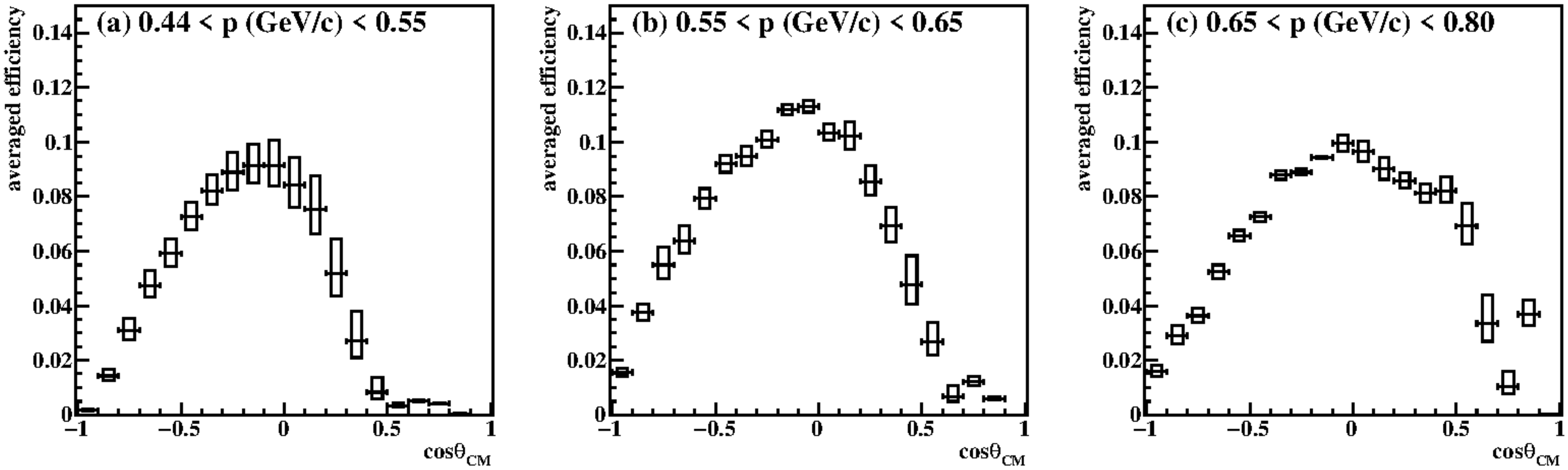
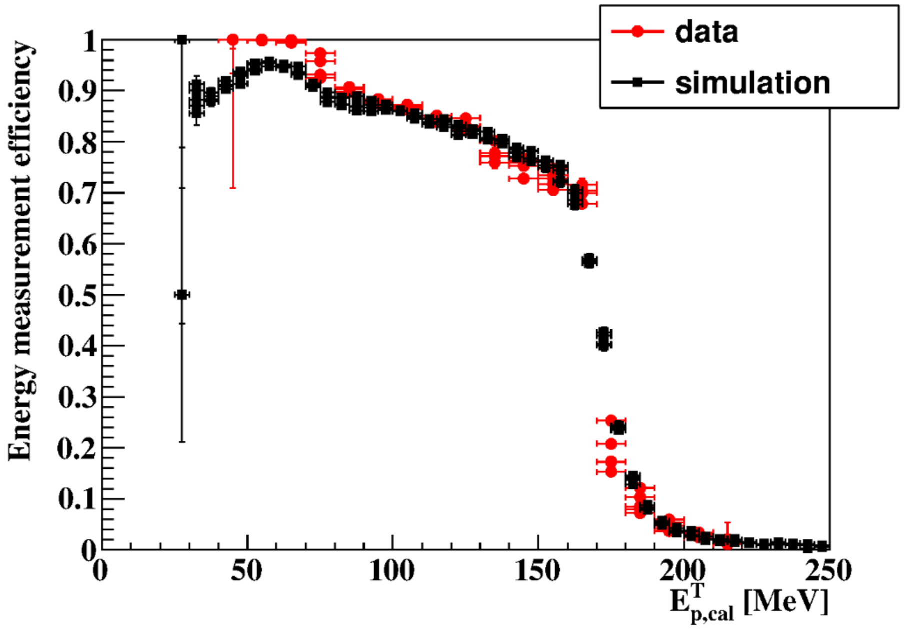


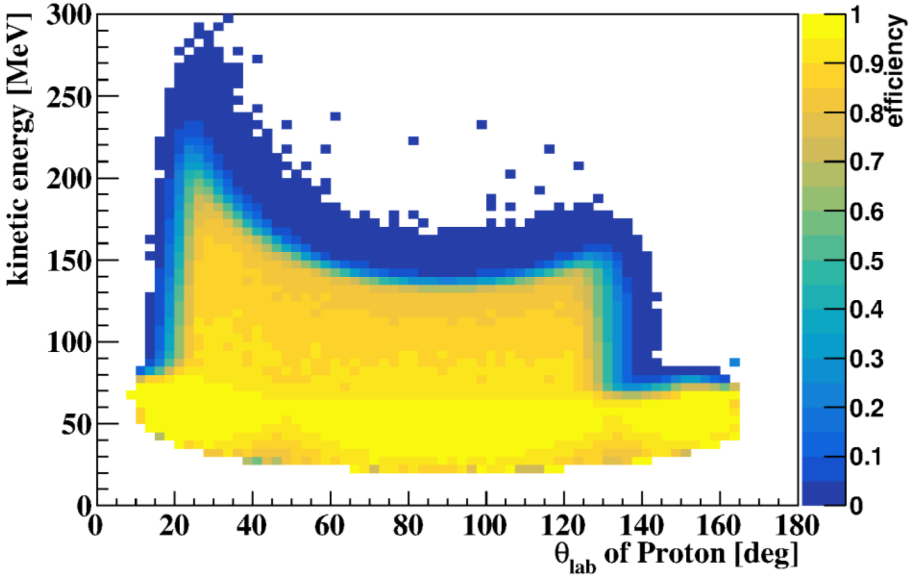
CATCH efficiency

- Proton detection efficiency of CATCH consists of
  - Energy measurement efficiency
  - CFT tracking efficiency
- They depends on (E_p, θ_p, z_{source})
- CATCH efficiency was evaluated from simulation and pp scattering data.
  - In simulation, proton with arbitrary (E_p, θ_p, z_{source}) can be generated.
  - In pp scattering data, (E_p, θ_p) is restricted by the kinematics of pp scattering.

CATCH efficiency

- Energy measurement efficiency
  - Simulated efficiency well agree with the data.
  - Simulated efficiency is used.



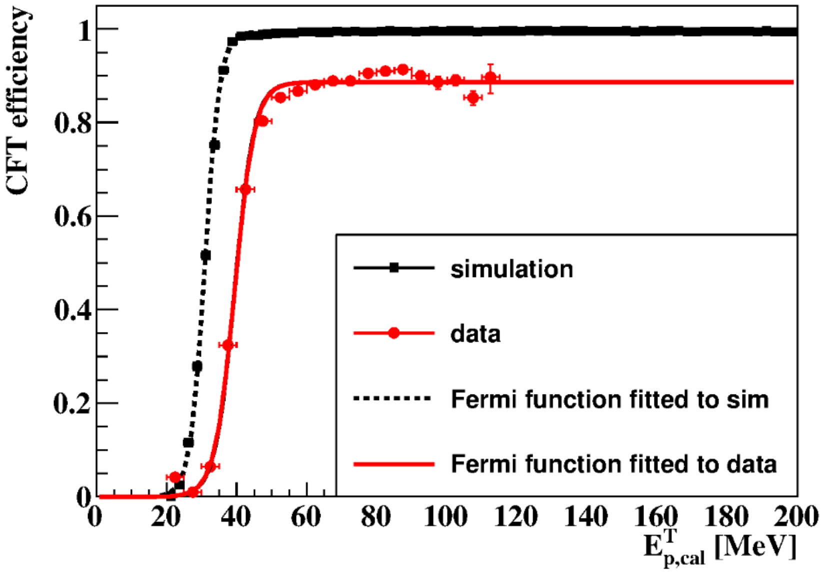


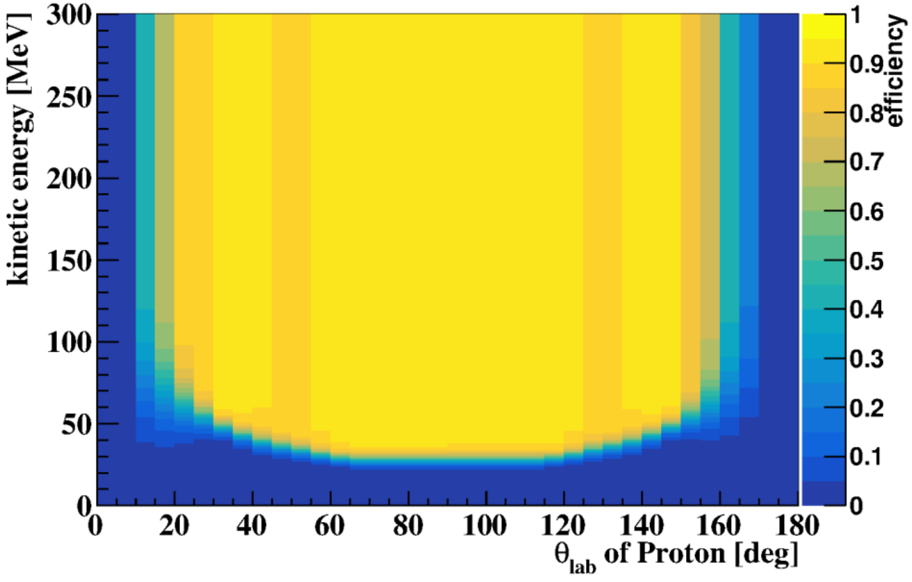
CATCH efficiency

- Data-based efficiency is less than simulation-based efficiency
  - Because of zig-zag structure of CATCH spiral layer
    - Difficult to reproduce in the Geant4
- CFT tracking efficiency is formulated as Fermi function and parameters are determined from pp scattering data.

$$\varepsilon_{\mathrm{CFT}}(\theta, E, z) = \frac{\varepsilon_{\mathrm{max}}(\theta, z)}{1 + \exp\left(\frac{E - E_{\mathrm{half}}(\theta)}{d(\theta)}\right)},$$

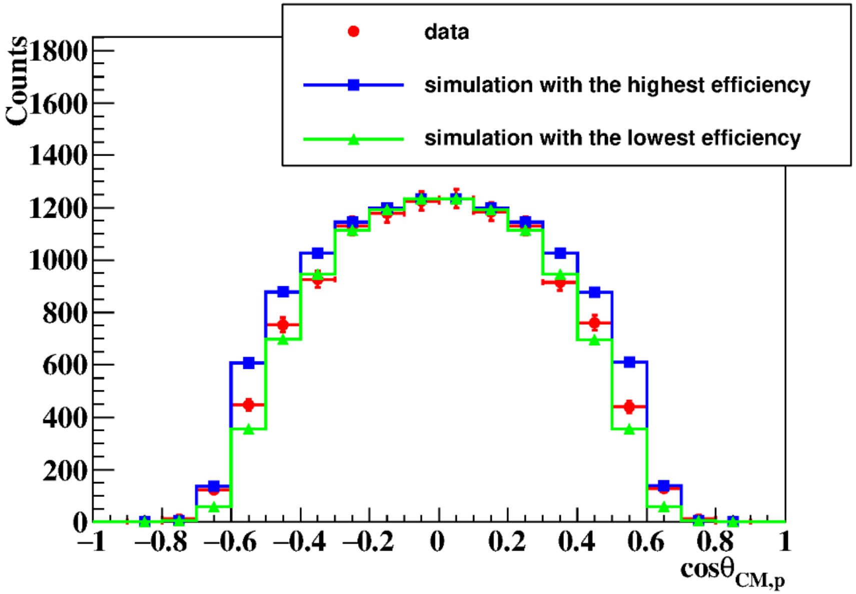
- Note; Because CFT tracking requires at least 6 layers hit in the fiber tracker, CATCH cannot analyze (detect) low energy protons.





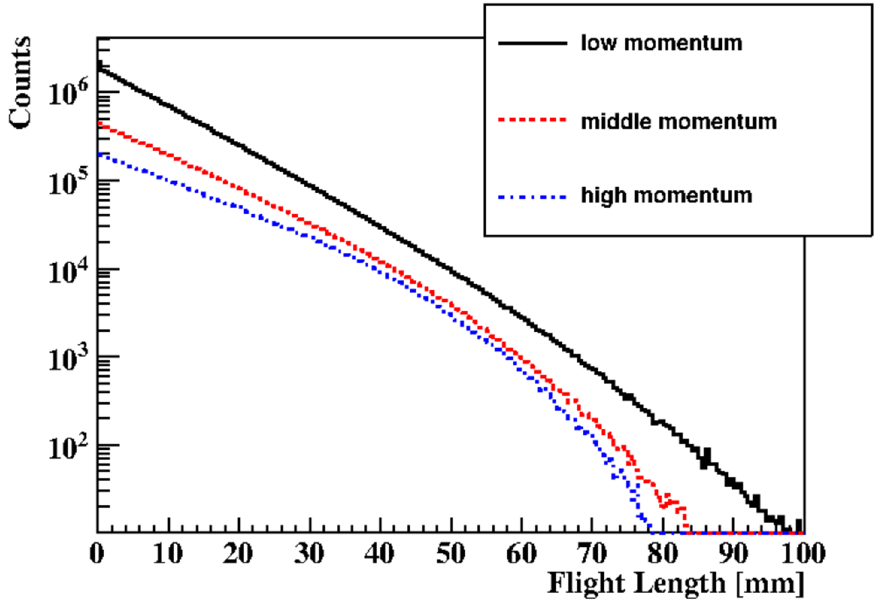
CATCH efficiency

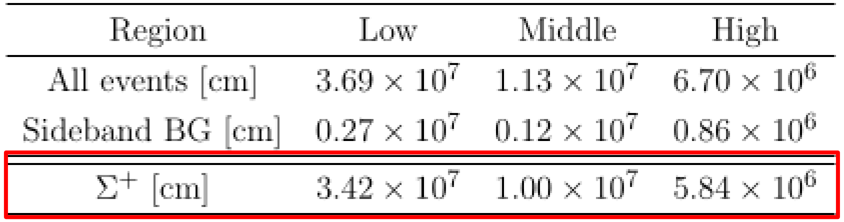
- To evaluate uncertainty of CFT tracking efficiency for low energy protons, two possible highest and lowest CFT efficiencies were considered.
  - Except for low energy protons, dσ/dΩ for pp scattering using proton beam in calibration data are well derived.
- The angular dependence of secondary pp scattering events is sandwiched by two efficiency-corrected simulations.



Total flight length of Σ

- Total flight length of Σ^+ particles in the LH2 target was estimated by a Monte Carlo simulation.
  - Σ^+ with analyzed momentum was generated at analyzed vertex in the LH2 target
  - Flight length were summed up until Σ decayed or exited LH2 target.





Region	Low	Middle	High
All events [cm]	3.69×10^7	1.13×10^7	6.70×10^6
Sideband BG [cm]	0.27×10^7	0.12×10^7	0.86×10^6
Σ^+ [cm]	3.42×10^7	1.00×10^7	5.84×10^6