Strange Strong Force and Bound System 2022

J-PARCおよびJ-LabにおけるΛN・ΛNN系測定の現状と展望

― 断面積からスピン観測量まで―

Tohoku University.,
Graduate school of science., Nuclear physics experiment group.

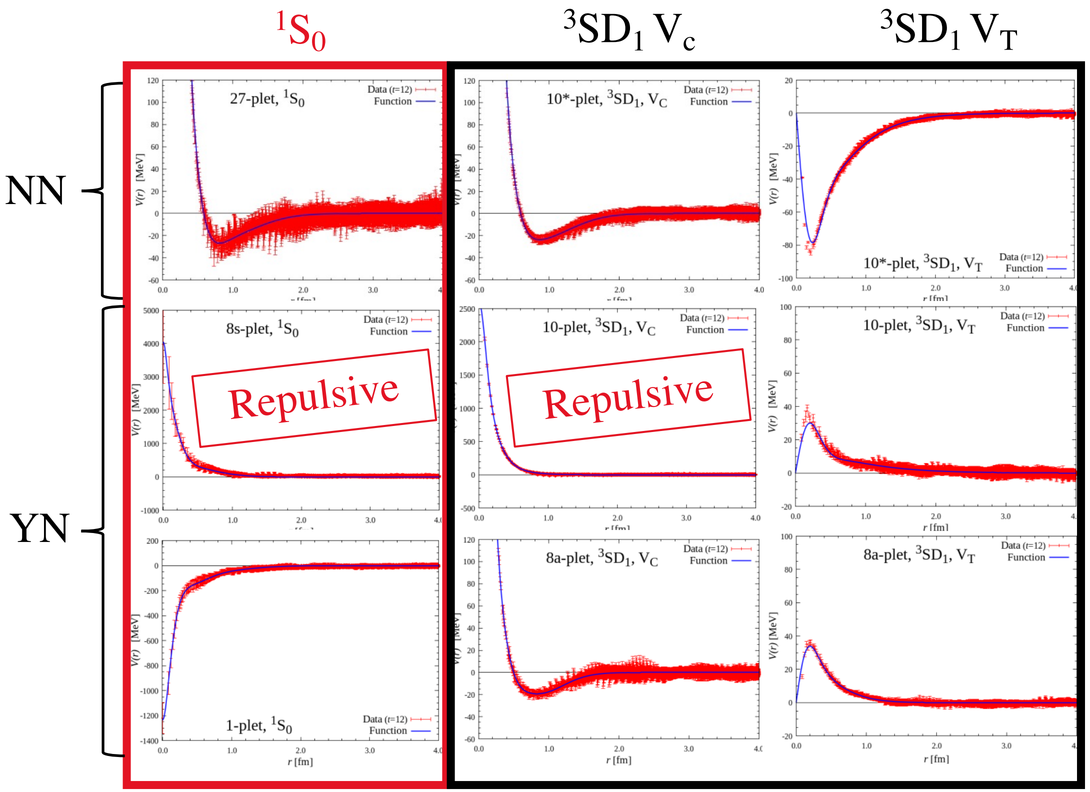
D2 Tamao SAKAO

2022/12/16 (Fri) 15:00 – 15:20

YN interaction

S-wave potentials of NN & YN (by Lattice QCD)

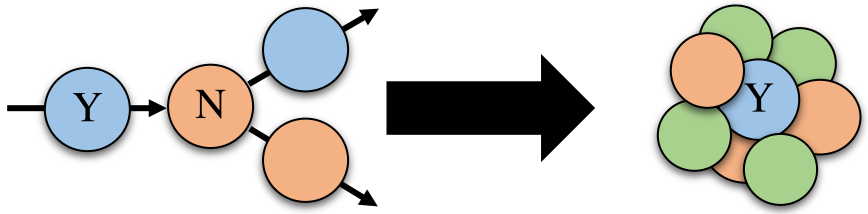
T. Inoue, AIP Conf. Proc. 2130, 020002 (2019)



S-wave B_8B_8 interactions of NN & YN

$B_8B_8(I)$	spin-singlet	spin-triplet	
$NN(I=0)$	—	$(\mathbf{10^*})$	Past NN scattering
$NN(I=1)$	$(\mathbf{27})$	—	
$\Sigma N(I=1/2)$	$\frac{1}{\sqrt{10}}[(3(\mathbf{8s}) - (\mathbf{27})]$	$\frac{1}{\sqrt{2}}[(\mathbf{8a}) + (\mathbf{10^*})]$	J-PARC E40 (Σp scattering)
$\Sigma N(I=3/2)$	$(\mathbf{27})$	$(\mathbf{10})$	
ΛN	$\frac{1}{\sqrt{10}}[(\mathbf{8s}) + 3(\mathbf{27})]$	$\frac{1}{\sqrt{2}}[-(\mathbf{8a}) + (\mathbf{10^*})]$	New exp.

- ΣN int. may be strongly repulsive.
- ΛN int. is a fundamental input for studying Λ hypernucleus.



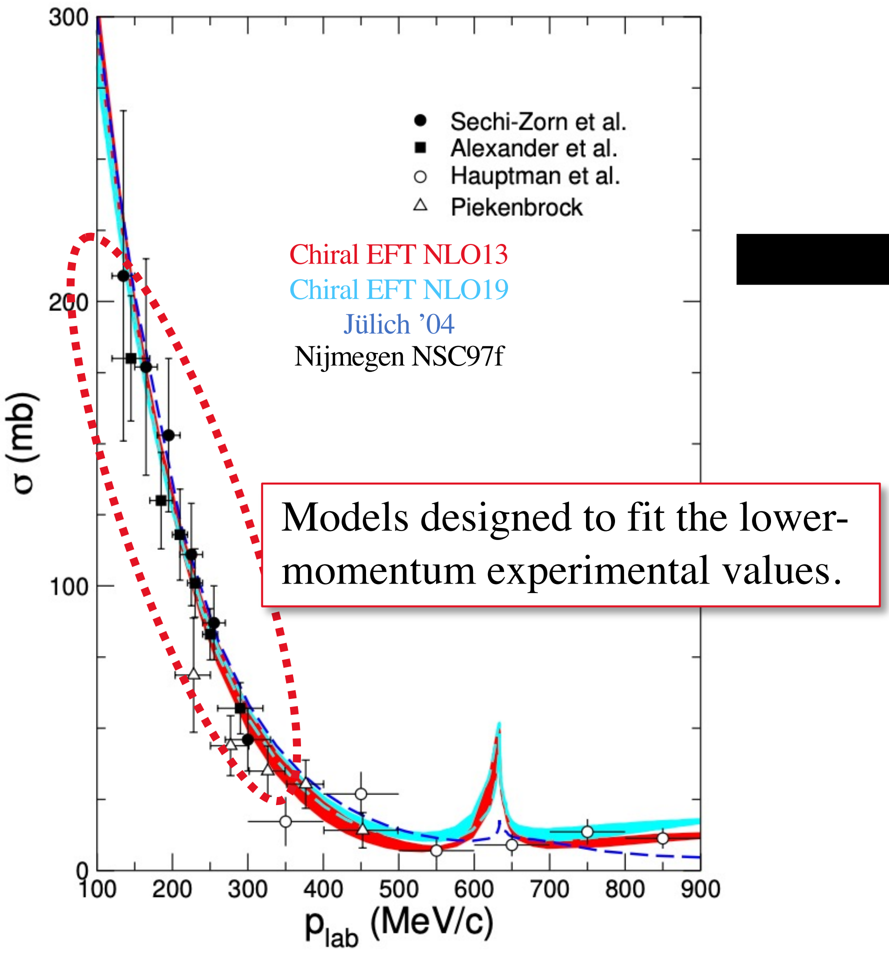
YN scattering

Hypernucleus

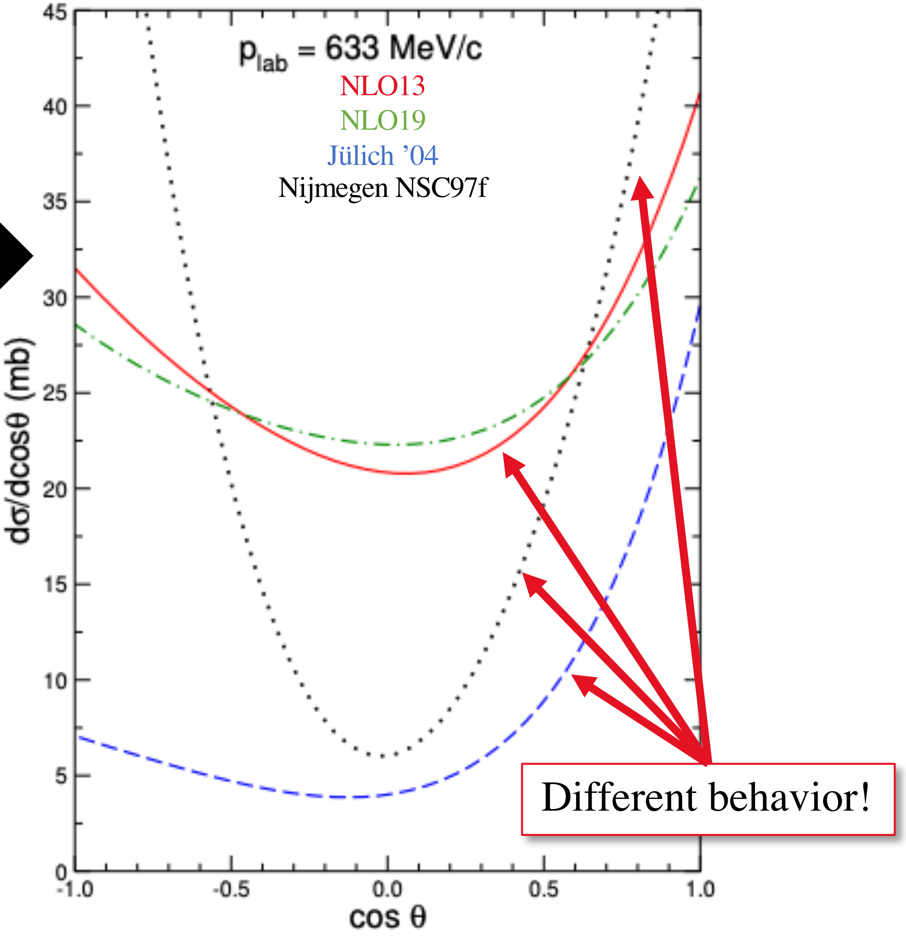
Λp channel is the 1st key to studying B_8B_8 int.

Haidenbauer, J., Meißner, UG. & Nogga, Eur. Phys. J. A 56, 91 (2020)

Total cross sections of
Λp -> Λp



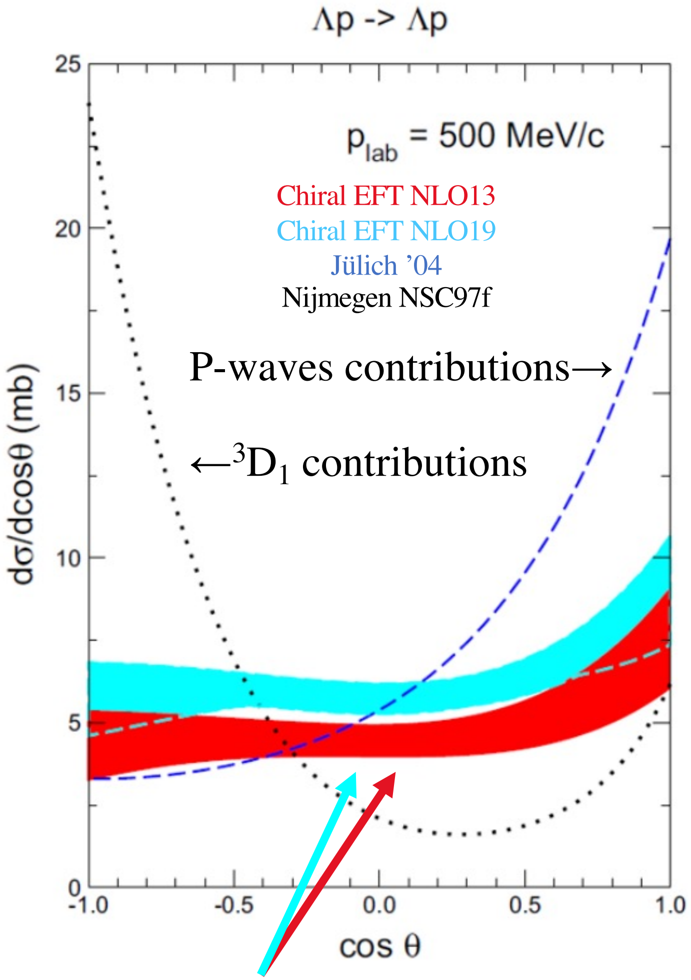
Differential cross section of
Λp -> Λp



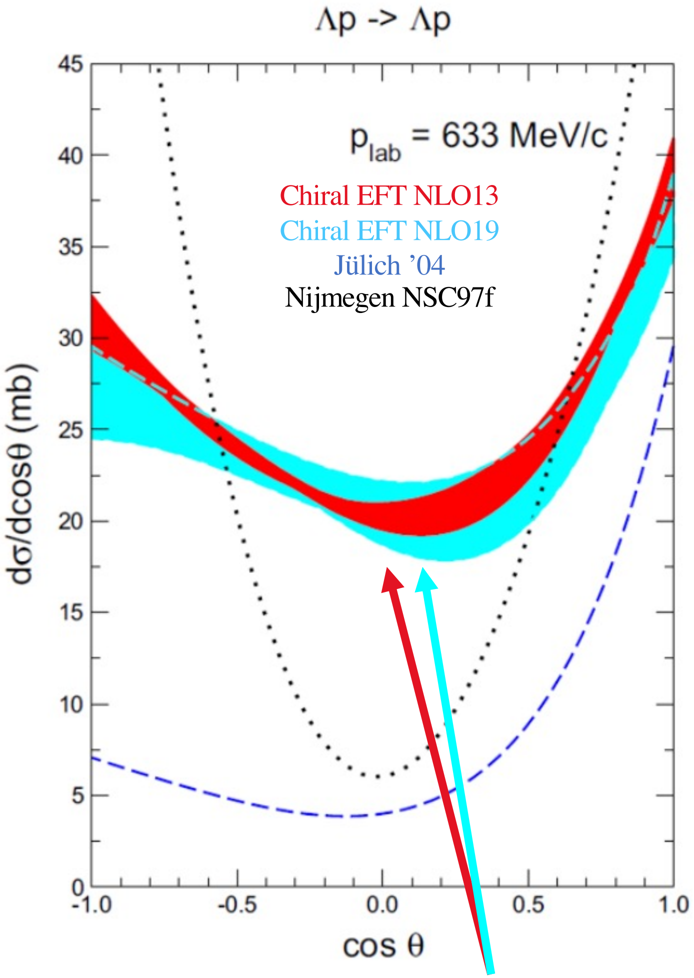
Broad momentum range of Λp data is necessary

J. Haidenbauer, U.-G. Meißner, A. Nogga, Eur. Phys. J. A, 56 (2020).

Differential cross-sections
at the Λ momentum of 500 and 633 MeV/c.



S-waves dominate



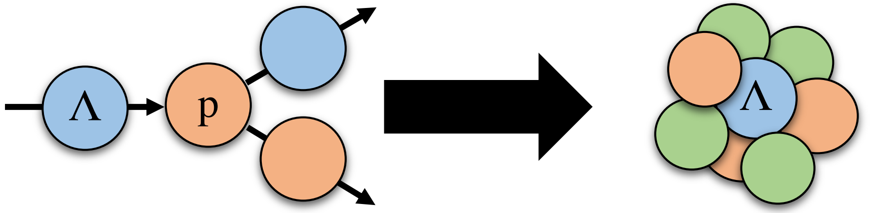
sizable angular dependence

P or higher waves of Λp int.

- B_Λ of light hypernucleus is insensitive to study P or higher partial waves.

What’s needed to study partial waves

- Precise Λp scattering data for the Λ momentum over 400 MeV/c.
- B_Λ and energy scheme data of light Λ hypernucleus.



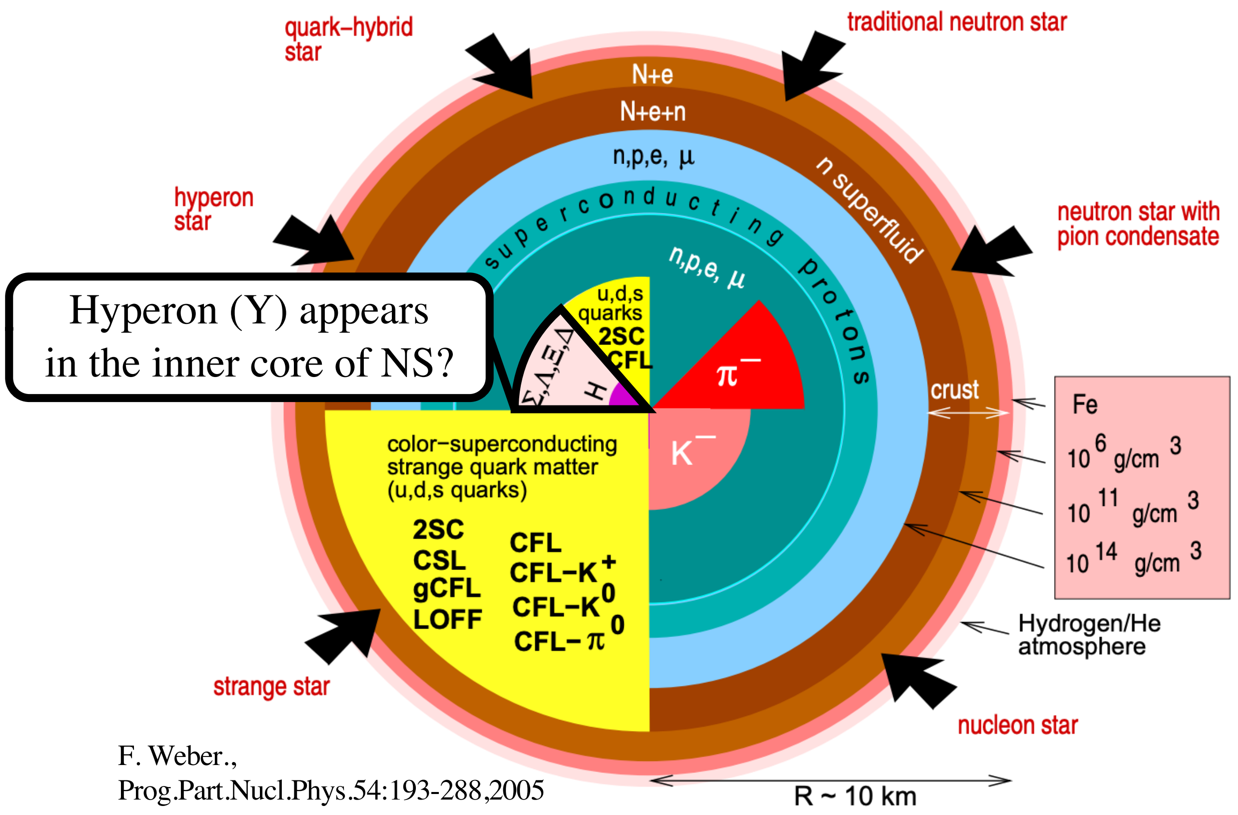
scattering Hypernucleus

Hyperon puzzle of neutron star

Hyperon Mixing in NS?

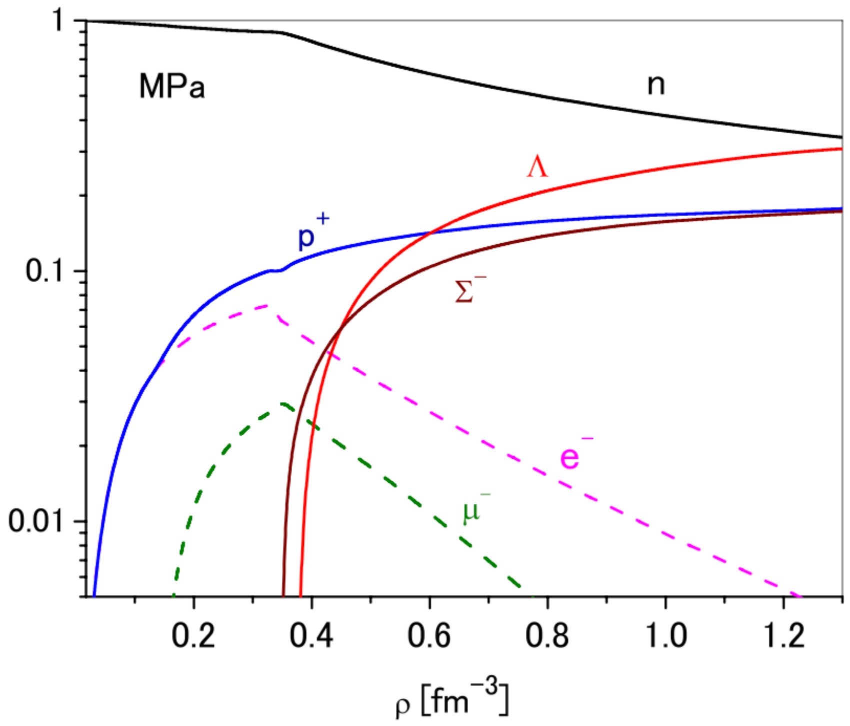
- Λ appears when μ_n – $\mu\Lambda > m_\Lambda c^2 - m_n c^2$ (~176 MeV)?

$$\mu_n = \varepsilon_F^n + m_n c^2 + U_n$$
$$\mu_\Lambda = (\varepsilon_F^\Lambda +)\, m_\Lambda c^2 + U_\Lambda$$



F. Weber., Prog.Part.Nucl.Phys.54:193-288,2005

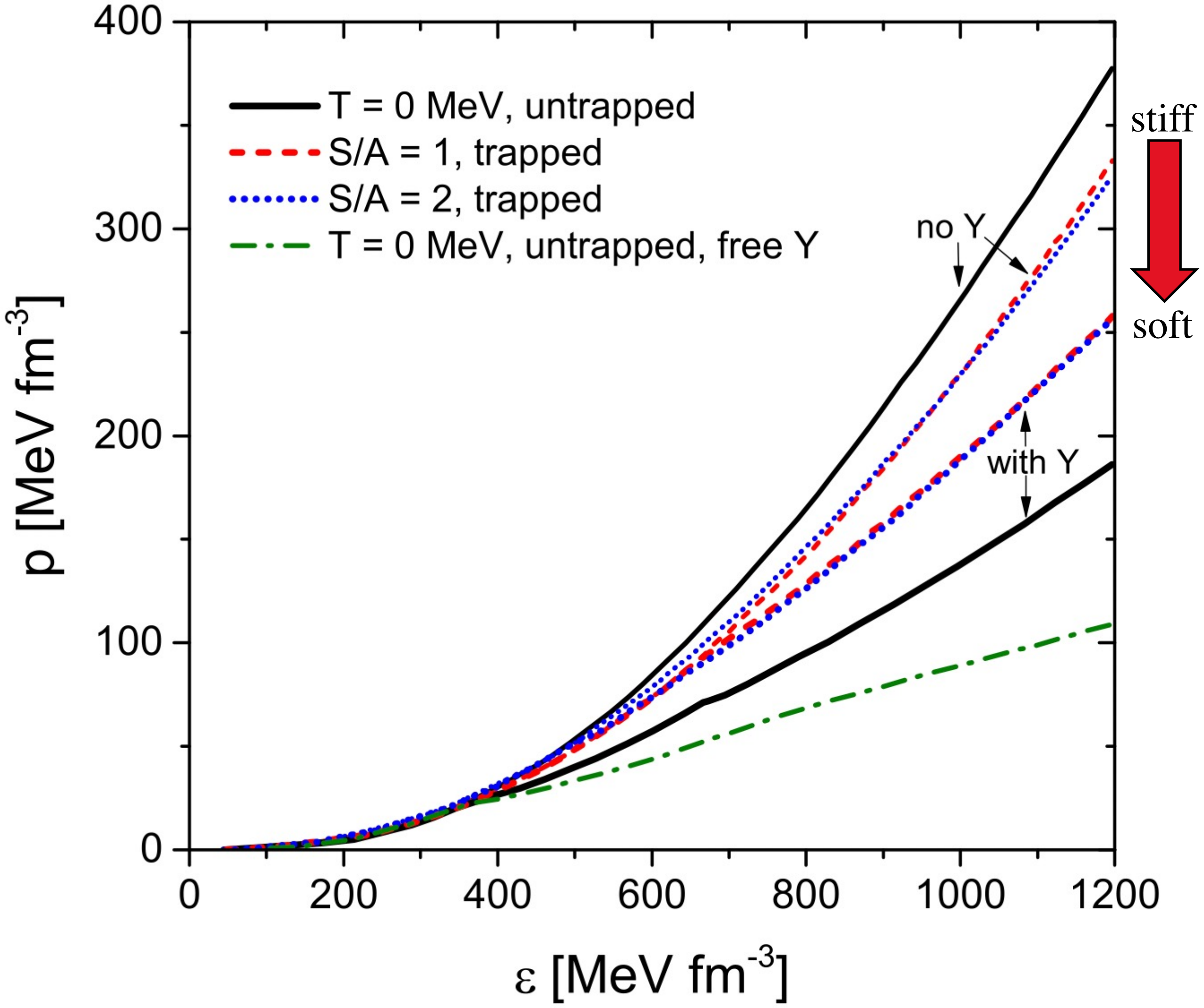
Composition of hyperonic neutron-star matter in the case of MPa(ESC+3BF)



Hyperon puzzle of neutron star

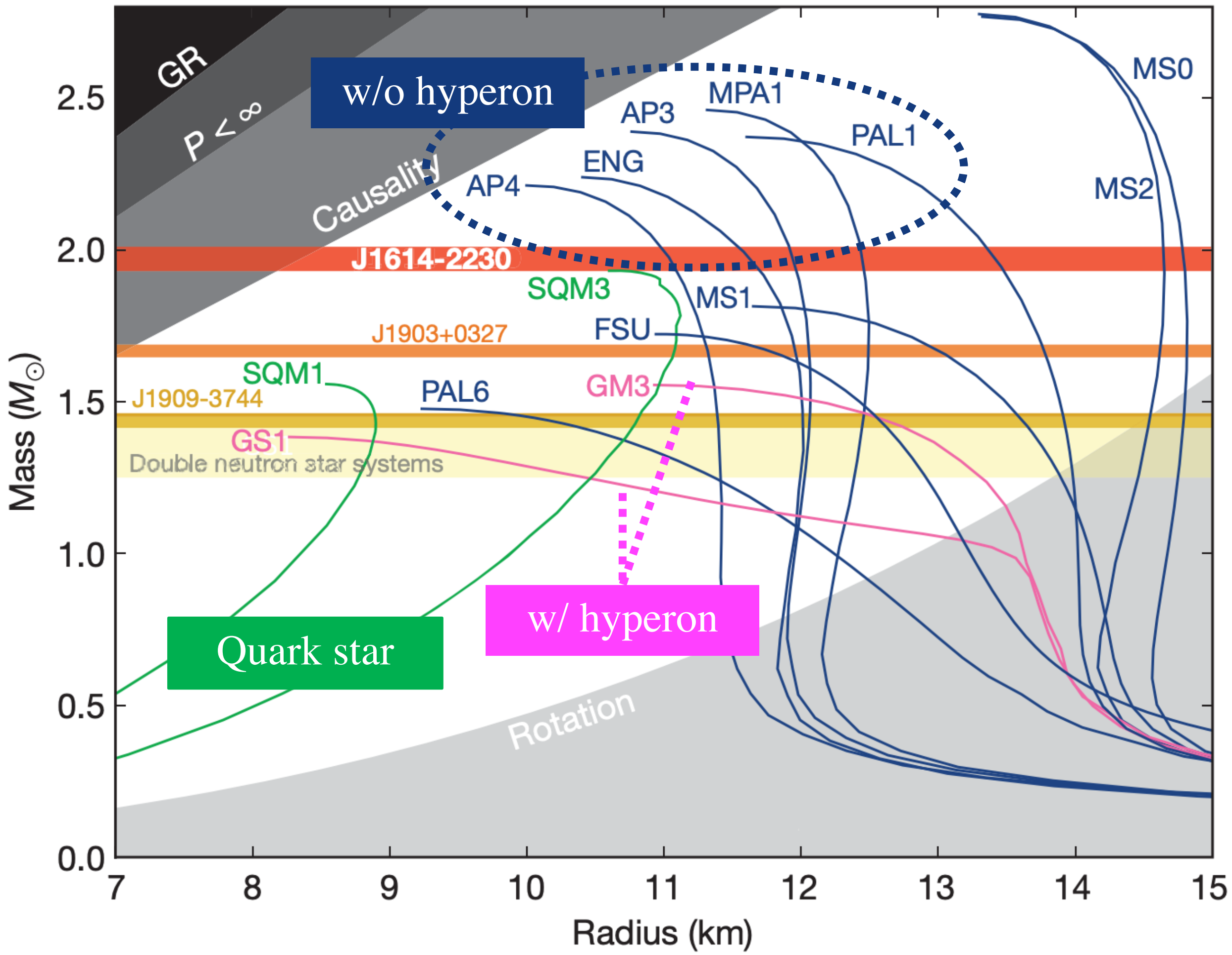
G.F. Burgio *et al*., arXiv:2105.03747v1, 2021

EoS for neutrino-free and neutrino-trapped matter for several fixed entropy values per particle S/A = 0, 1, 2 with and without hyperons.



P.B. Demorest et al., Nature. 467., 2010

Mass-radius trajectories for typical EOSs.

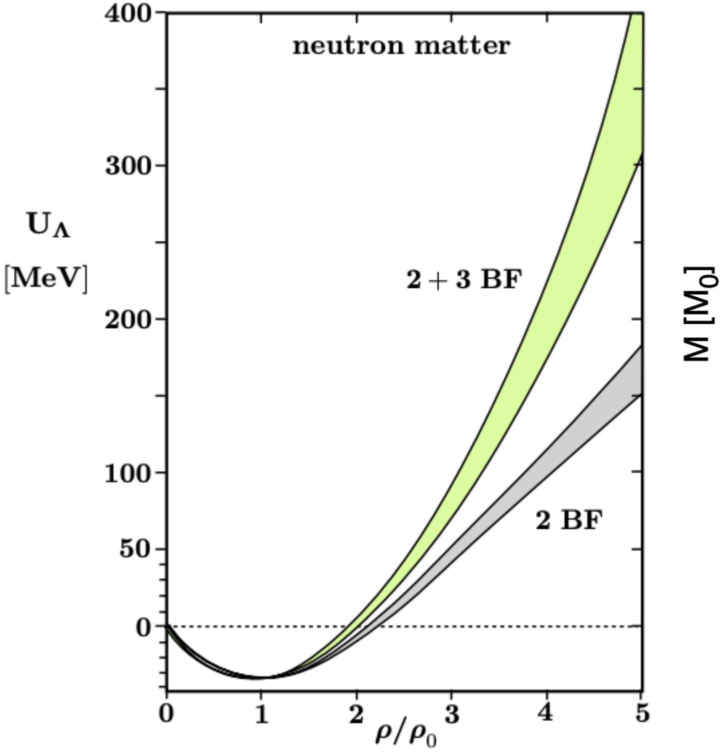


Some additional repulsion mechanism is necessary.

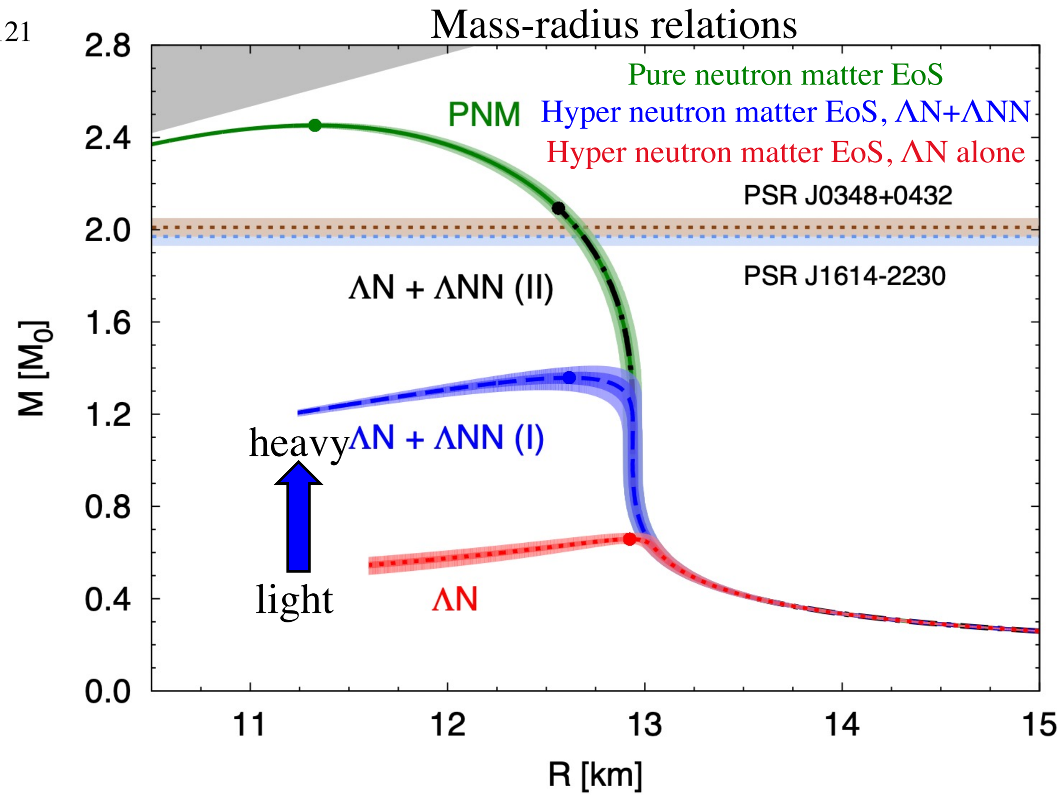
Both ΛN & ΛNN observations are necessary

- YN interaction has a short-range repulsive force.
- This hyperon repulsion may be seen for both YY and YN interactions.
- However, existing experiments do not show evidence of a repulsive YN interaction.
- The first order in the EoS calculation is the ΛN potential.
- We should measure the ΛN & ΛNN to restrict the theories.

J. Haidenbauer *et al*., Eur. Phys. J. A (2017) 53: 121

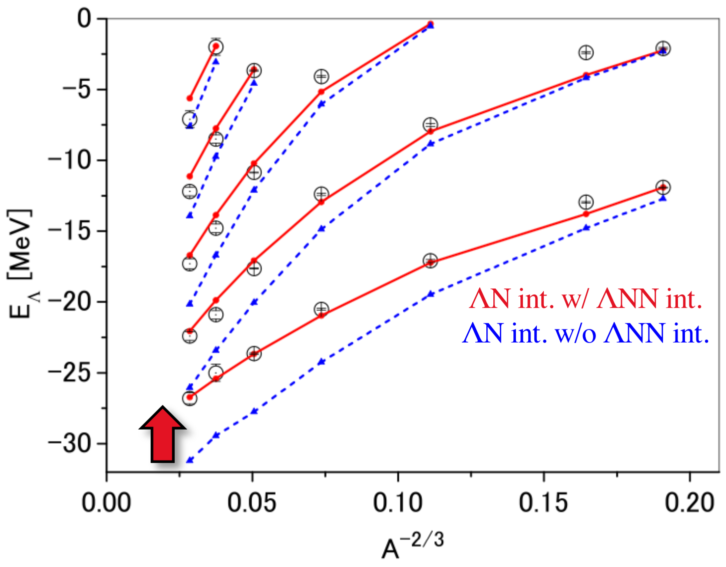


Diego Lonardoni *et al*., arXiv:1407.4448v2, 2015



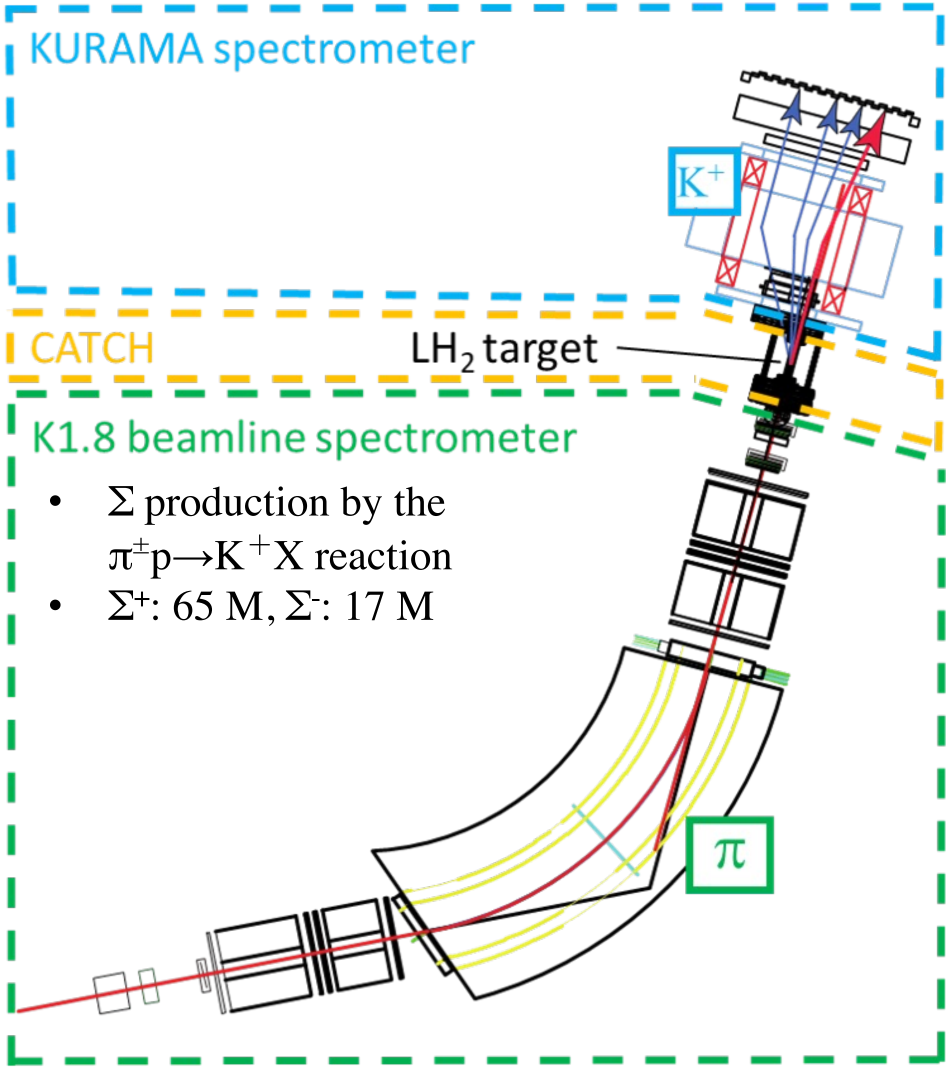
M. M. Nagels et al., PHYSICAL REVIEW C 99, 044003 (2019)
*Experimental data: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. **57**, 564 (2006)

Energy spectra of $^{13}{}_{\Lambda}$C, $^{28}{}_{\Lambda}$Si, $^{51}{}_{\Lambda}$V, $^{89}{}_{\Lambda}$Y, $^{139}{}_{\Lambda}$La, and $^{208}{}_{\Lambda}$Pb (by ESC16 & ESC16$^+$)

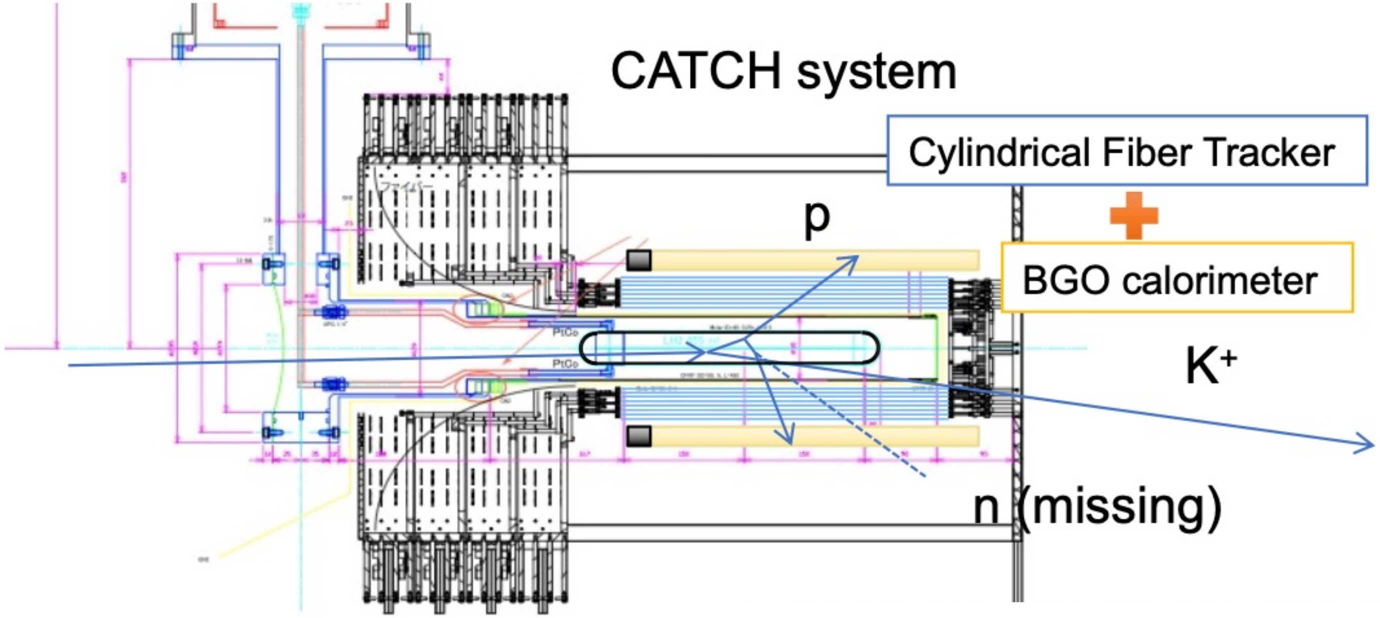


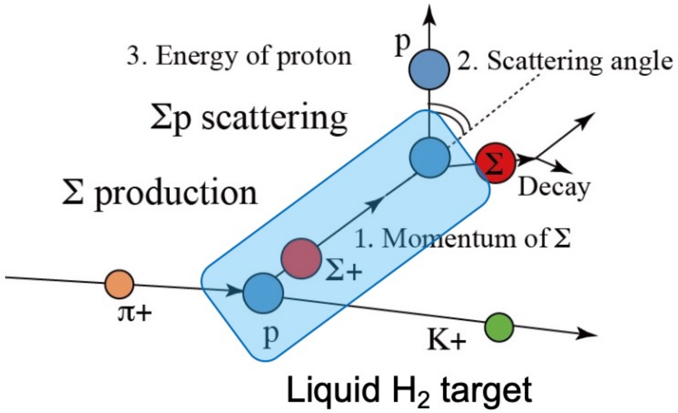
Study of the Λp scattering in J-PARC E40 ($\rightarrow$ E86)

J-PARC E40 (Σp scattering)



- Σ production by the $\pi^{\pm}p \rightarrow K^{+}X$ reaction
- Σ^{+}: 65 M, Σ^{-}: 17 M





My research

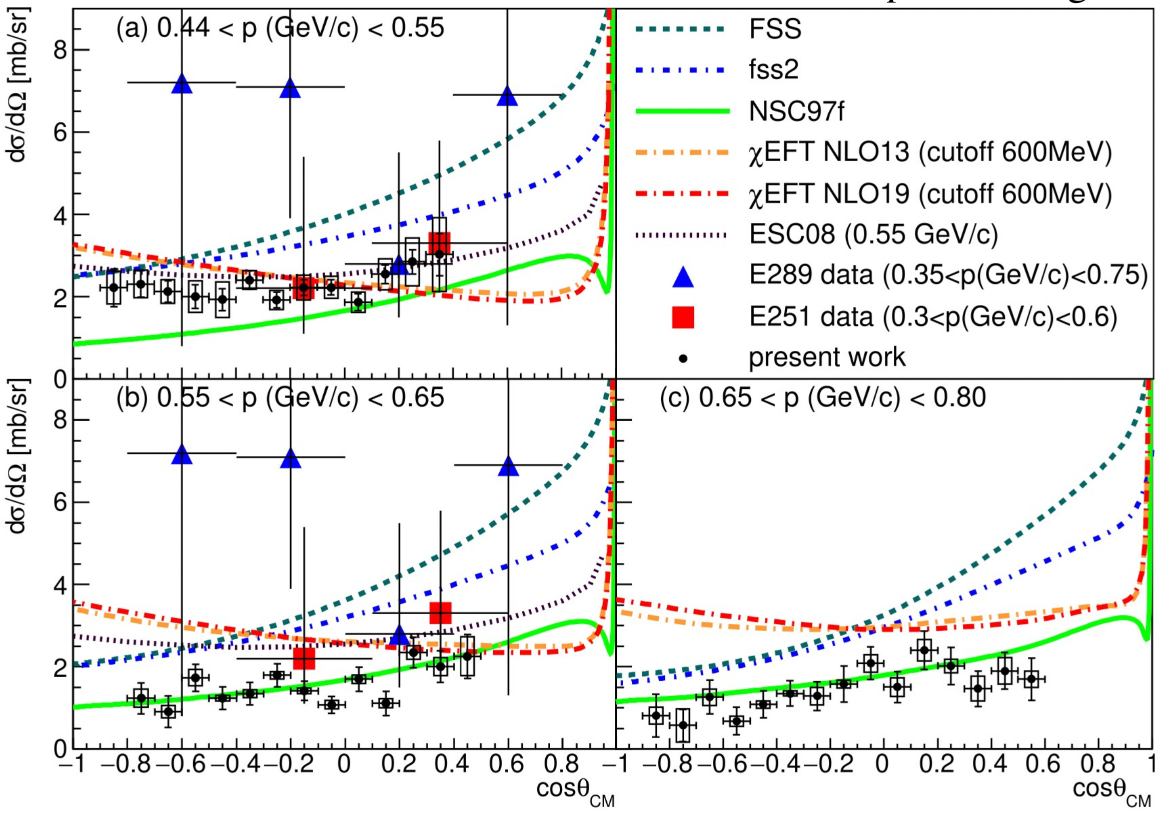
- Feasibility study of the next Λp scattering exp. using the $\pi^{-}p \rightarrow K^{0}\Lambda$ reaction data (= ~1 % of E40 Σ^{-} production data)

Experimental values of Σp $d\sigma/d\Omega$ in E40

- FSS (larger size parameter) indicating a repulsive interaction increases the differential cross section, but fss2 & FSS's repulsions are too large.
- NSC97f reproduces the data here,
  but it generally predicts Σ^+p interaction is attractive.
- ESC (Pomeron potential) is relatively closer to data.
- Precise YN scattering data should determine LECs for S & P waves of χEFT.

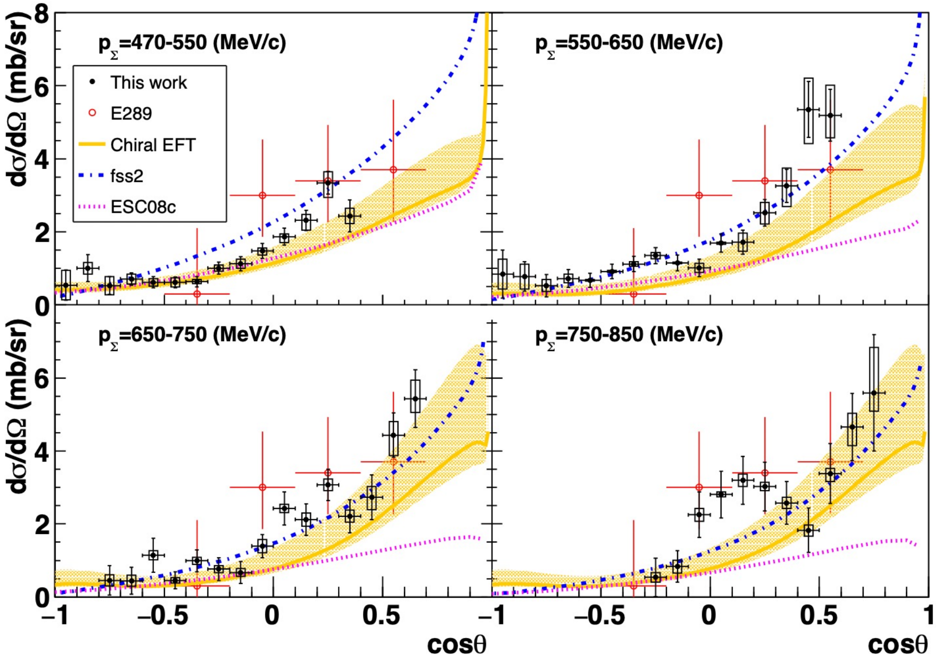
T. Nanamura et al. PTEP **2022**, 093D01 (2022)

Derived differential cross sections of the Σ^+p scattering



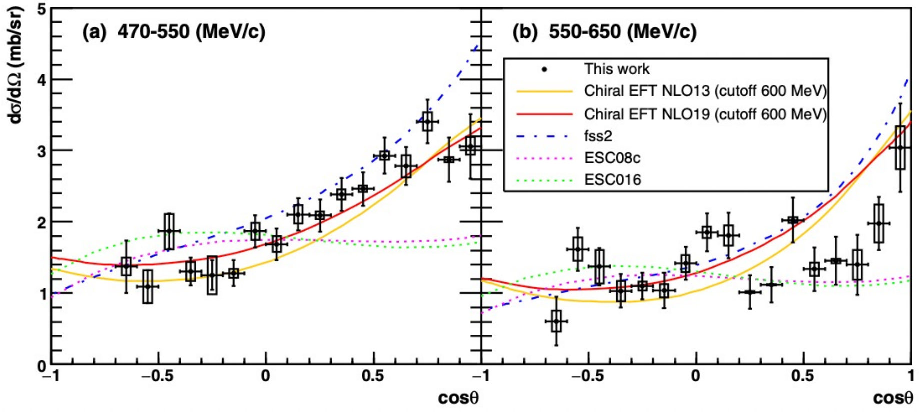
K. Miwa et al., arXiv:2104.13608

Differential cross sections of Σ^-p scattering



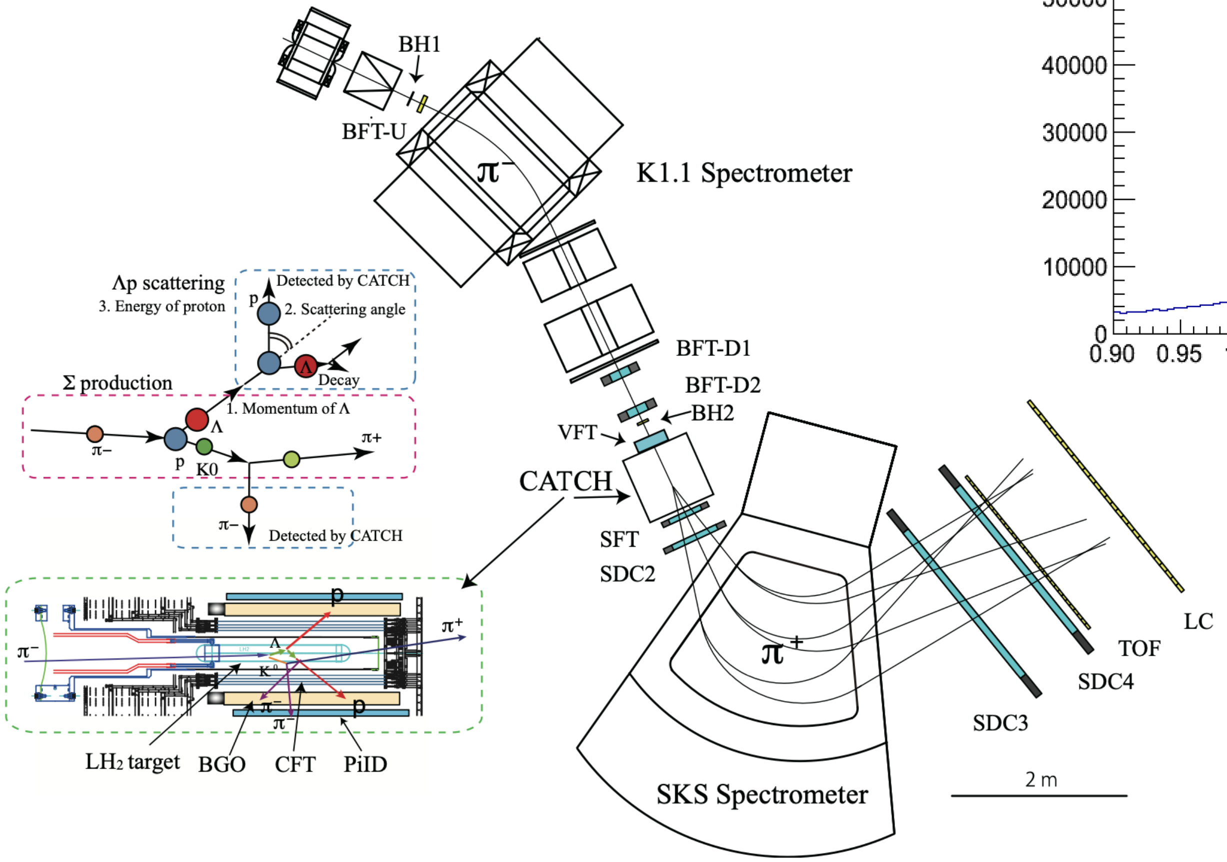
K. Miwa et al., Phys. Rev. Lett. 128, 072501 (2022)

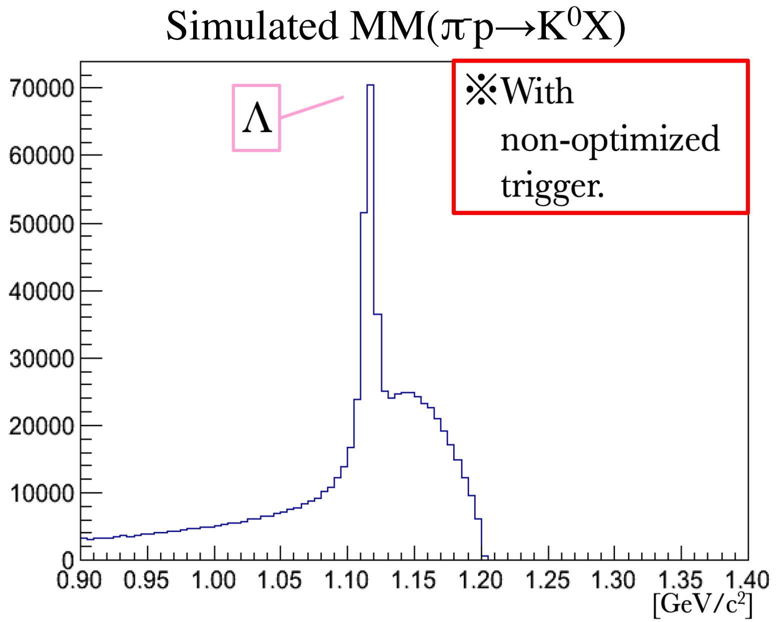
Differential cross section of $\Sigma^-p \to \Lambda n$ reaction

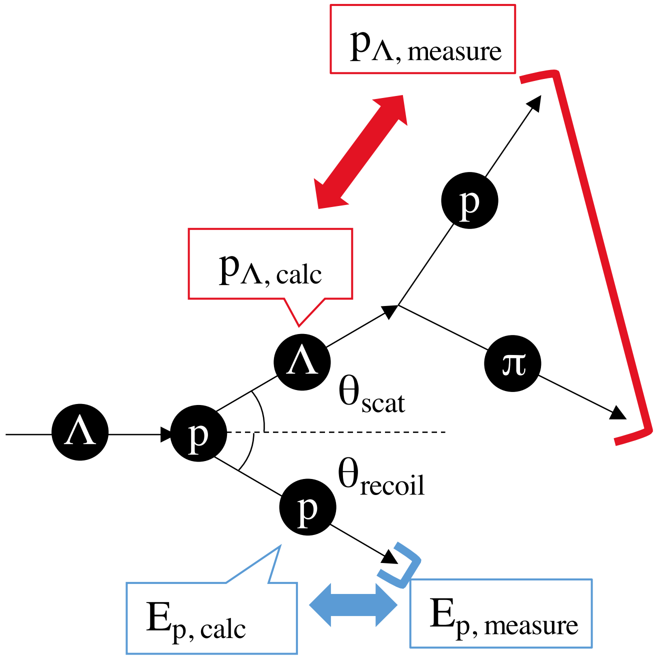


J-PARC E86 (new Λp scattering)

K. Miwa et al., Proposal for an experiment at the 50-GeV PS.







K⁰ ID improvement

- CATCH upgrade
- ASIC upgrade
- BH, BFT, and SFT R&D
- SKS momentum resolution: ~0.1% (KURAMA: ~1%)

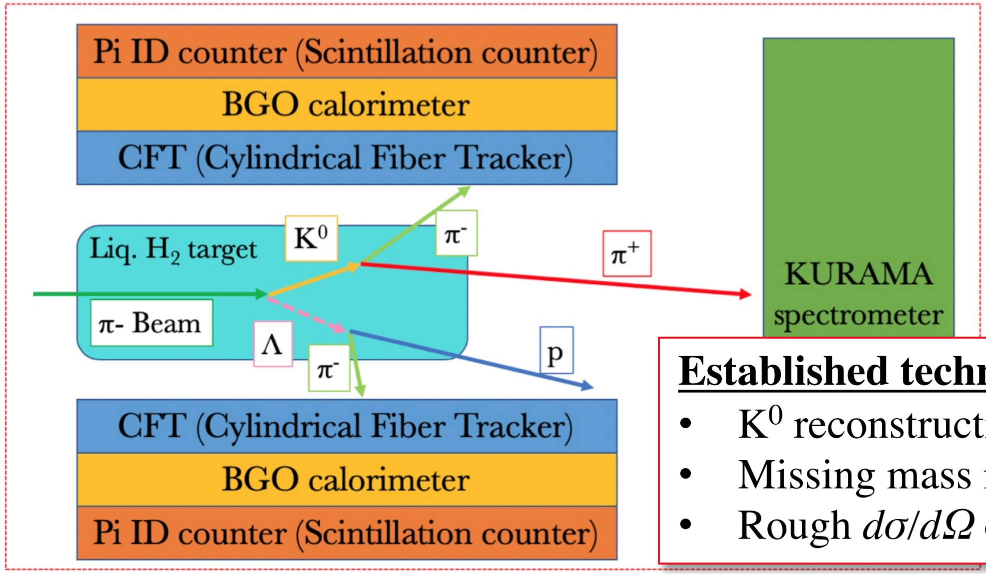
Estimated performance

- Tagged-Λ beam momentum range: 400 – 800 MeV/c
- Tagged-Λ beam (58 days): 100 M

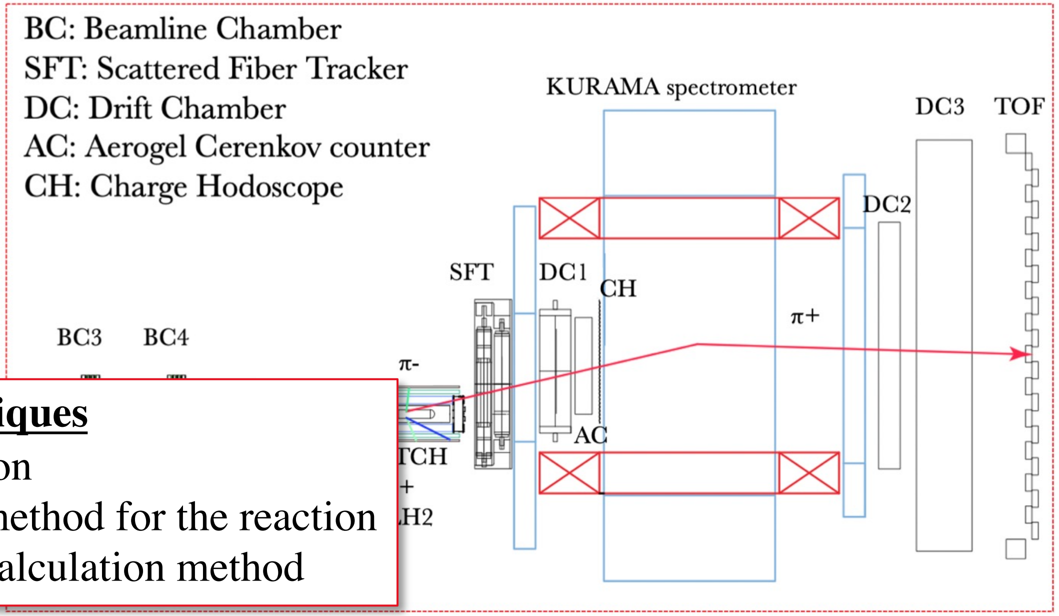
Feasibility study of E86 using E40 data

T. Sakao et al., *Proc. 3rd J-PARC Symposium (J-PARC2019)* JPS Conf. Proc. **33**, 011133 (2021)

(1) Conceptual drawing of the detection method for the $\pi^- p \rightarrow K^0 \Lambda$ reaction.

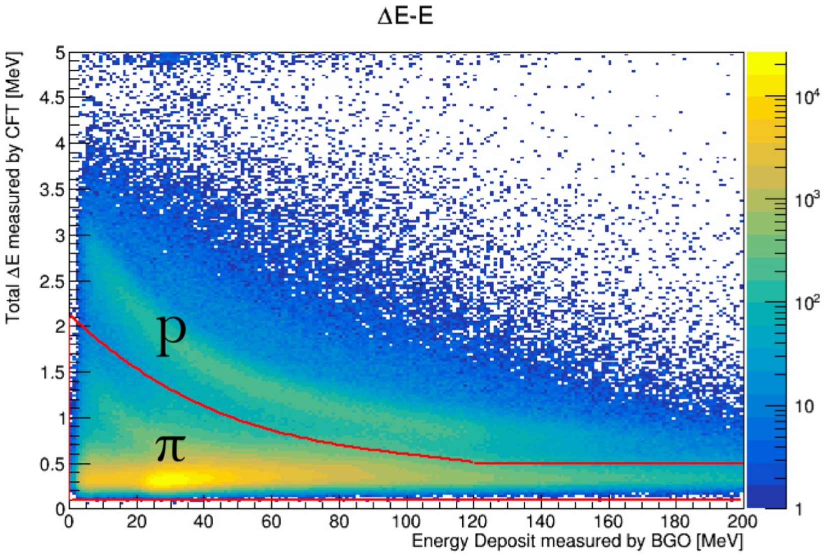


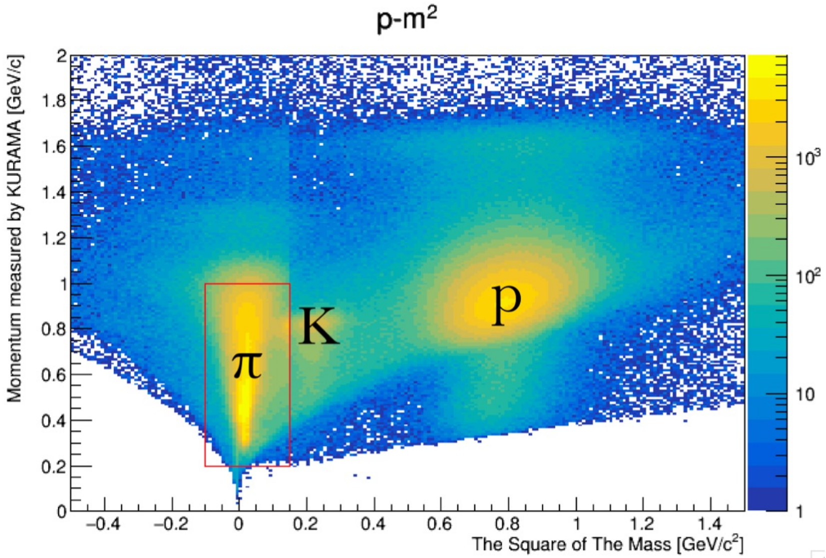
(2) J-PARC E40 detector setup.



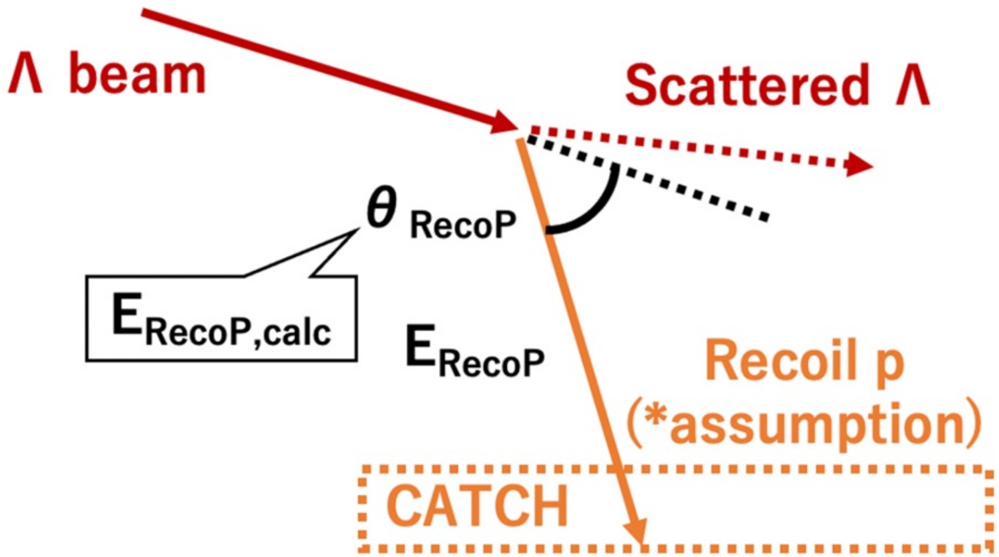
Established techniques

- K^0 reconstruction
- Missing mass method for the reaction
- Rough $d\sigma/d\Omega$ calculation method





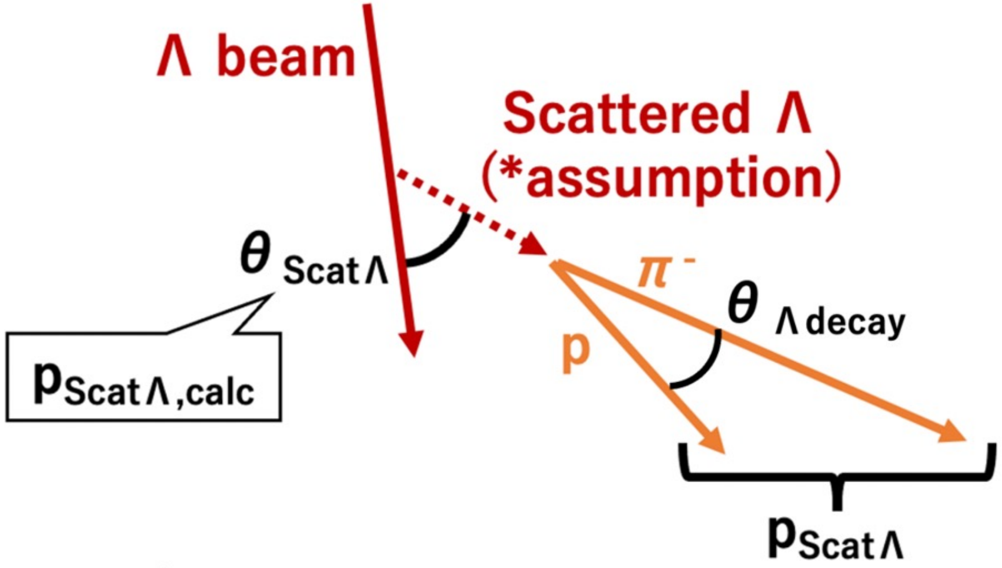
Double event optimization (ΔE & Δp methods)



$$p_{p',calc} = \frac{2m_p(E_{\Lambda beam} + m_p)p_{\Lambda beam}\cos^2\theta_{p'}}{(E_{\Lambda beam} + m_p)^2 - p^2_{\Lambda beam}\cos^2\theta_{p'}}$$

$$E_{p',calc} = \sqrt{m^2_{p'} + p_{p'}} - m_{p'}$$

$$\Delta E = E_{measure} - E_{calc}$$



$$p_{\Lambda',calc} = \frac{A p_{\Lambda beam}\cos\theta_{scat\Lambda} + (E_{\Lambda beam} + m_p)\sqrt{B}}{2((E_{\Lambda beam+m_p})^2 - p^2_{\Lambda beam}\cos\theta_{scat\Lambda})}$$

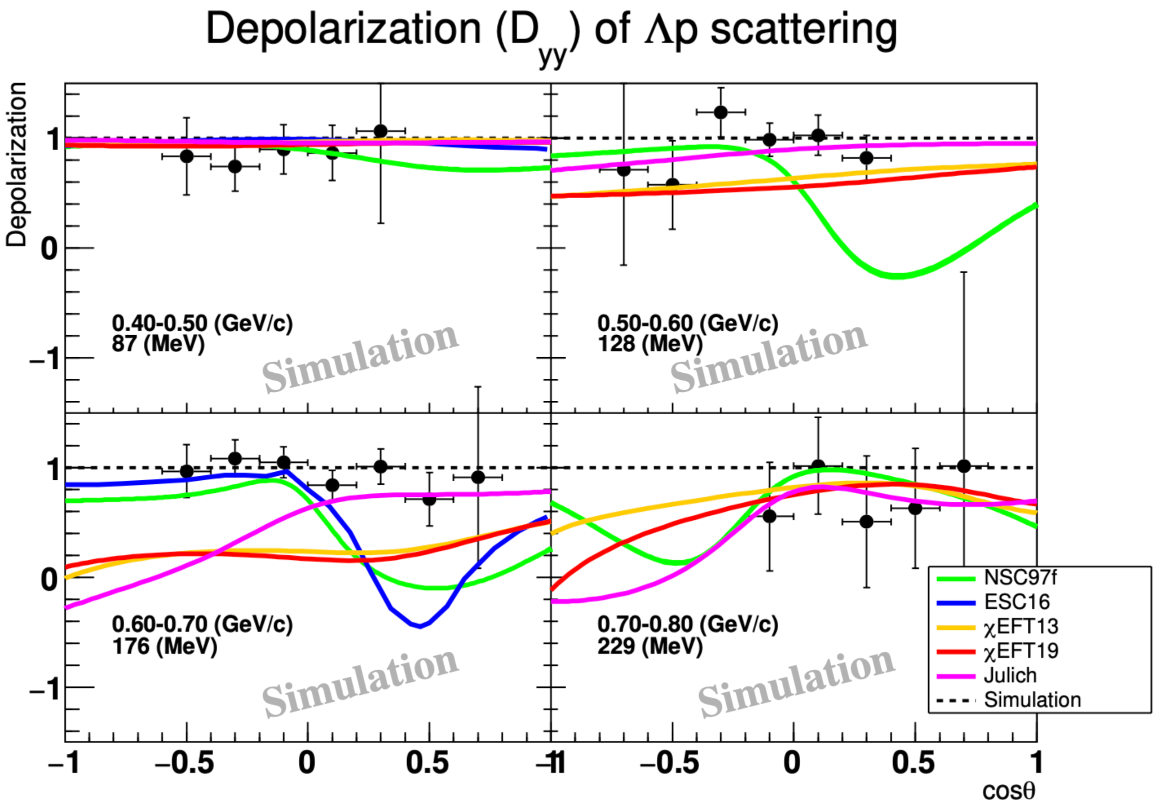
$$\Delta p = p_{measure} - p_{calc}$$

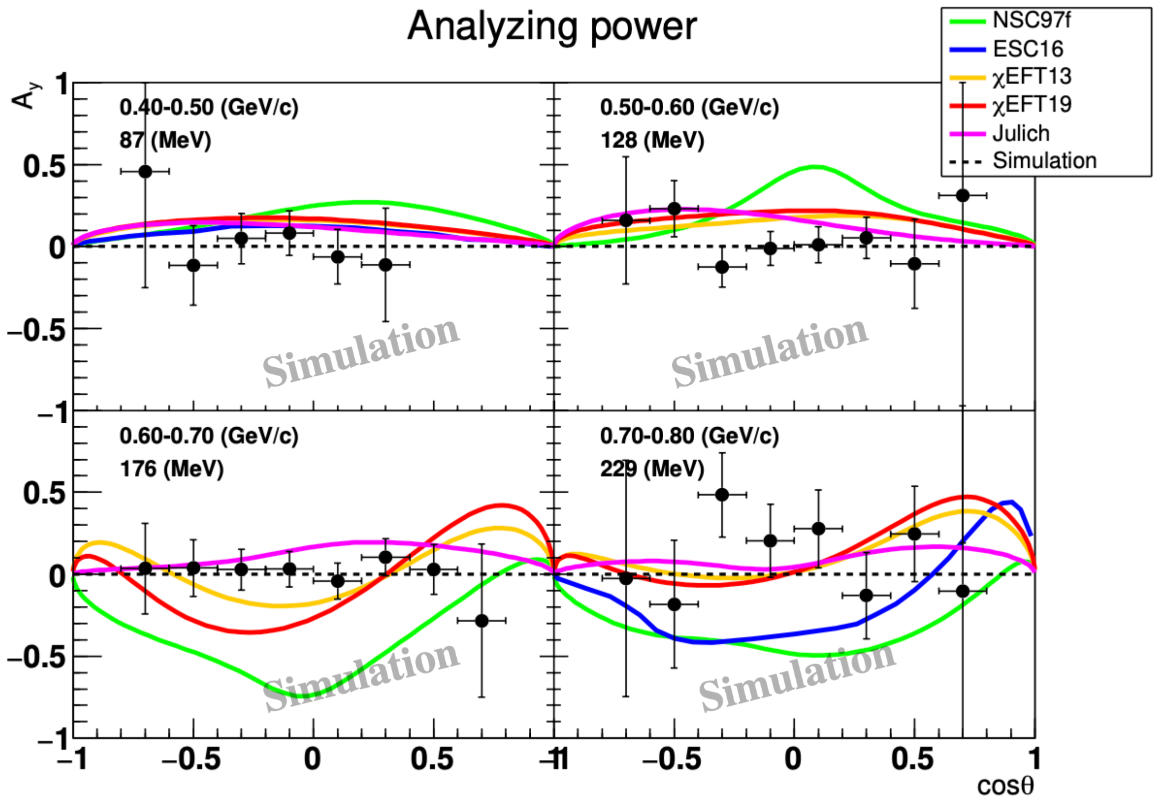
$$A = m^2_{\Lambda beam} + m^2_p + m^2_{scat\Lambda} - m_{p'} + 2E_{\Lambda beam}m_p$$

$$B = 4m^2_{scat\Lambda}(p^2_{\Lambda beam}\cos\theta_{scat\Lambda} - (E_{\Lambda beam} + m_p)^2) + A^2$$

Λp spin observables will also be measured in E86

K. Miwa *et al*., “Proposal for an experiment at the 50-GeV PS”





D_{yy} is expected to be closely related to the tensor force.

A_y is sensitive to the anti-symmetric LS force (ALS).

$$D^y_y = \frac{1}{\sigma(\theta)}\mathrm{Re}\left\{\frac{1}{2\sqrt{3}}\left(U_0+\frac{1}{\sqrt{3}}U_1\right)^* U_1 + \frac{1}{2}\left(U_0-\frac{1}{\sqrt{3}}U_1\right)^*\left(\frac{1}{\sqrt{6}}T_1+T_3\right) - S_1^* S_2 + \frac{1}{2}|S_3|^2 - \frac{1}{\sqrt{6}}T_1^*\left(\frac{1}{\sqrt{6}}T_1 - T_3\right) - \frac{1}{2}|T_2|^2\right\}.$$

$$A_y(Y) = -\frac{1}{\sqrt{2}\sigma(\theta)}\mathrm{Im}\left\{(U_\alpha + \frac{1}{4}U_\beta)^* S_{SLS} + (U_\alpha - \frac{1}{4}U_\beta)^* S_{ALS} - \frac{1}{2}T_\alpha^*(-S_{ALS}+S_{SLS})\right\}$$

Central (U_α) Spin-spin (U_β)

Λp spin observables will also be measured in E86

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 + A_y(\theta) P_\Lambda \cos\phi),$$

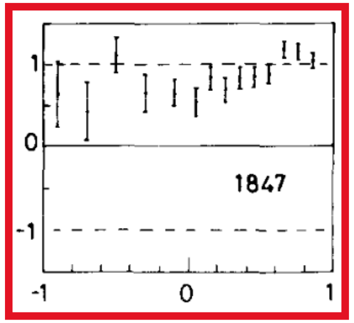
$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{1}{2}\left(\left(\frac{d\sigma}{d\Omega}\right)_L + \left(\frac{d\sigma}{d\Omega}\right)_R\right),$$

$$A_y(\theta) = \frac{\pi}{2P_\Lambda} \frac{\left(\frac{d\sigma}{d\Omega}\right)_L - \left(\frac{d\sigma}{d\Omega}\right)_R}{\left(\frac{d\sigma}{d\Omega}\right)_L + \left(\frac{d\sigma}{d\Omega}\right)_R},$$

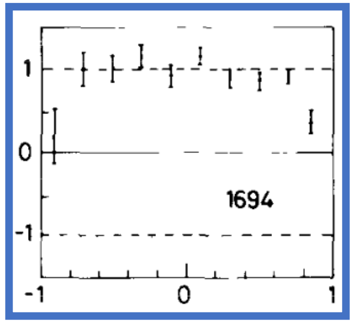
$$P_{scat} = \frac{P + D_y^y P_\Lambda \cos\phi}{1 + P P_\Lambda \cos\phi},$$

R.D. Baker et. al., B141 (1978) 29-47

Past experimental data of P_Λ for the E_{CM}

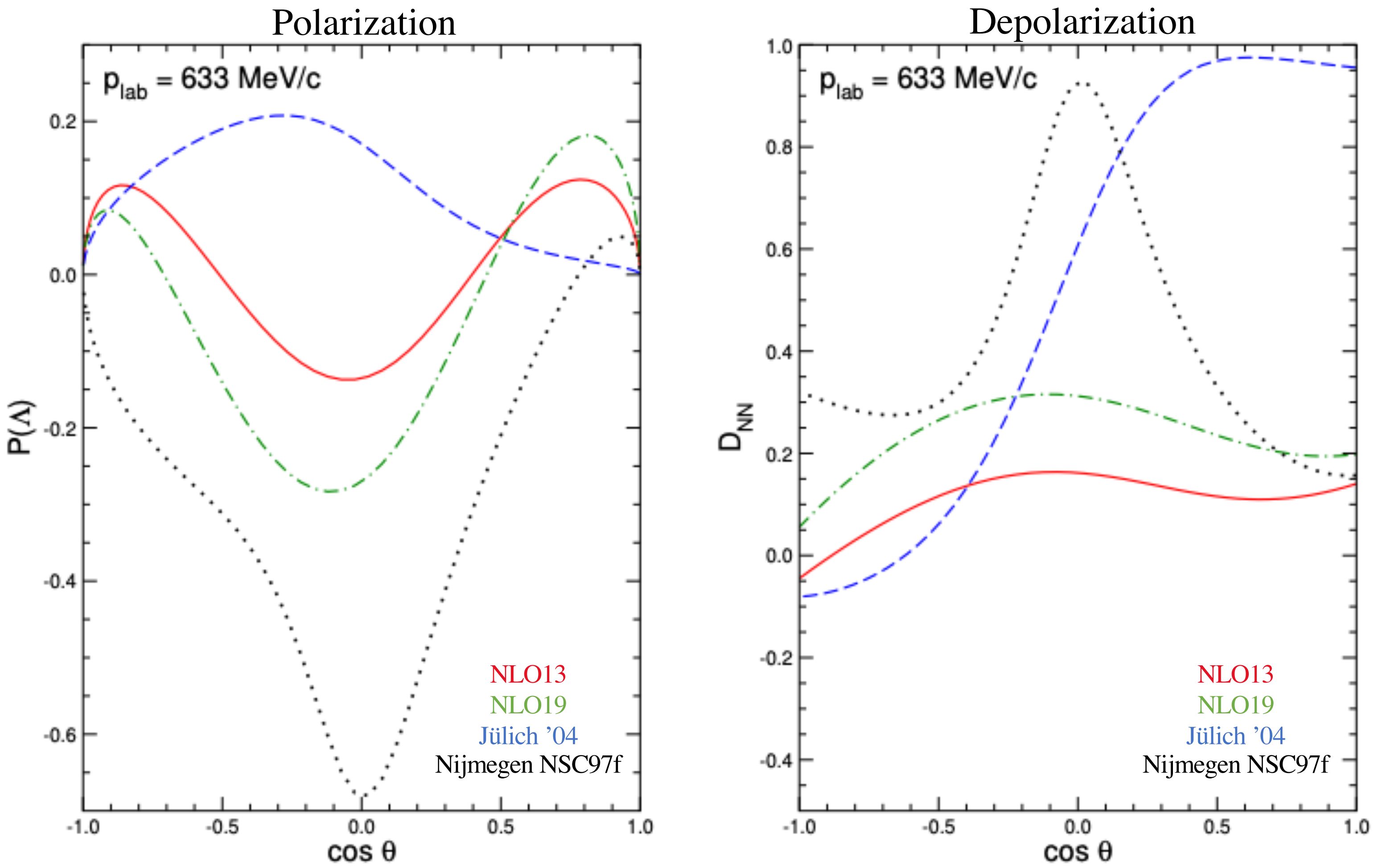


E40 range
E_{CM} = 1841 MeV



E86 range
E_{CM} = 1699 MeV

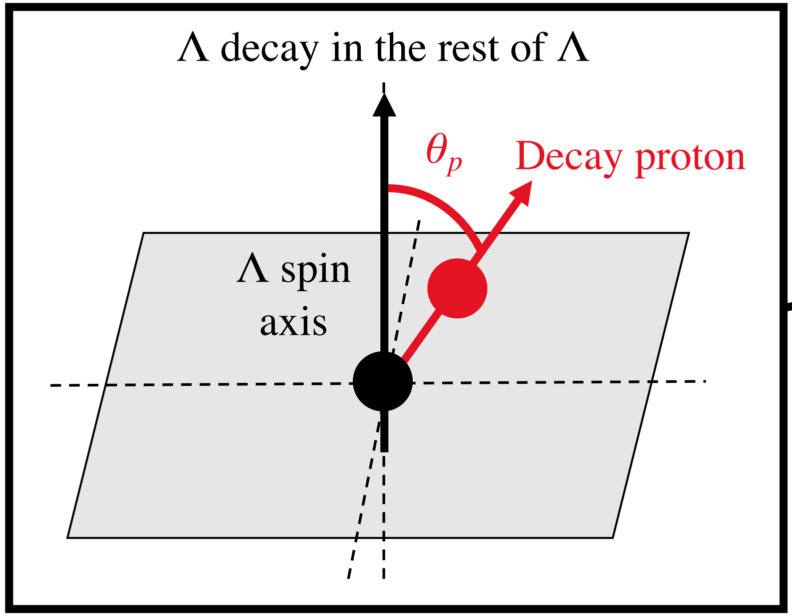
Johann Haidenbauer et al., arXiv:2105.00836v1 [nucl-th] 3 May 2021



We will approach models with abundant experimental data of Λp spin observables!

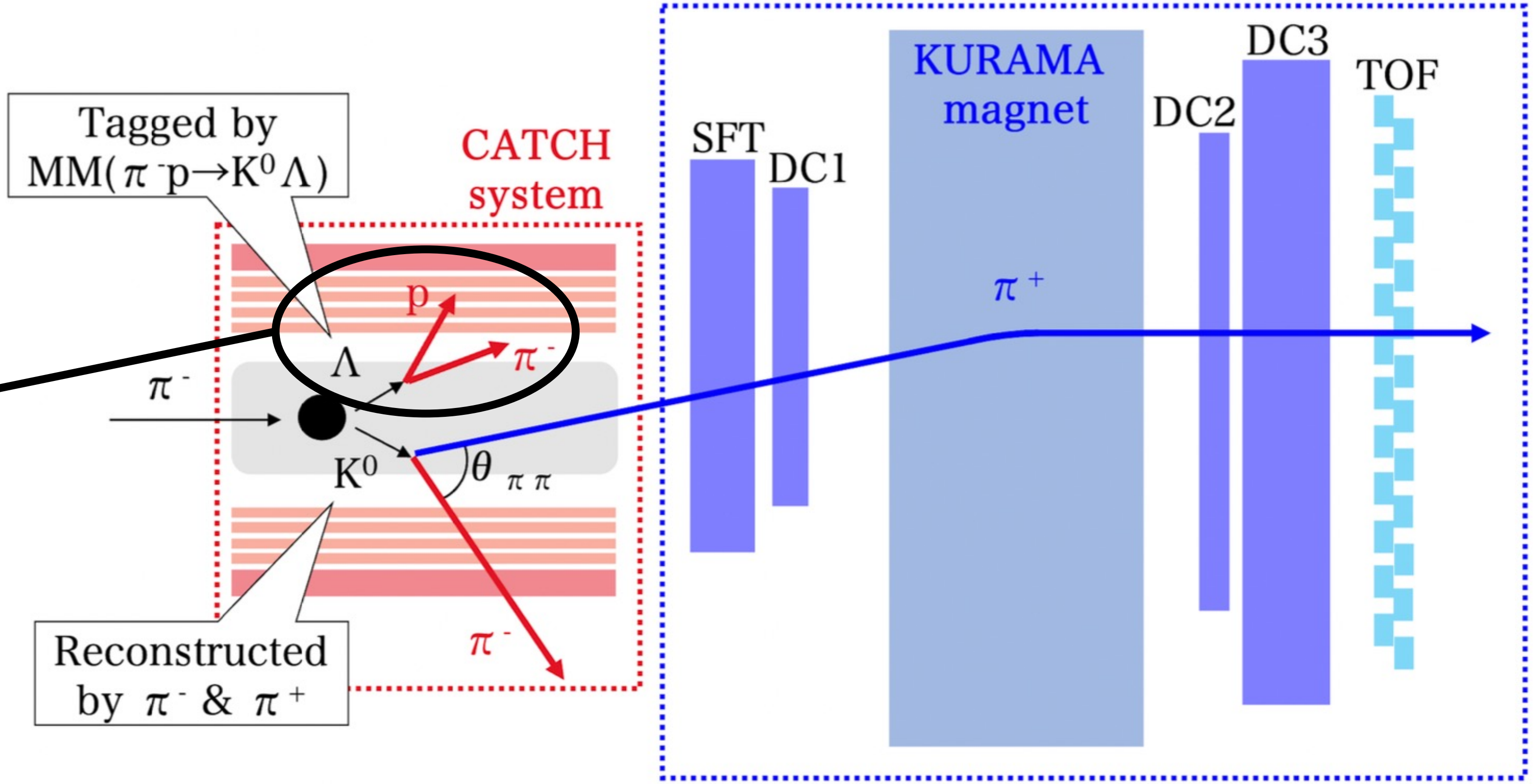
How to measure Λ beam polarization (P_Λ)

If measuring P_Λ in E40, you should analyze the Λ→π-p decay detected by CATCH.



T. Sakao *et al.*, HYP2022. **271**, 02008 (2022)

Detection of the Λ→π-p decay from tagged-Λ beam in E40

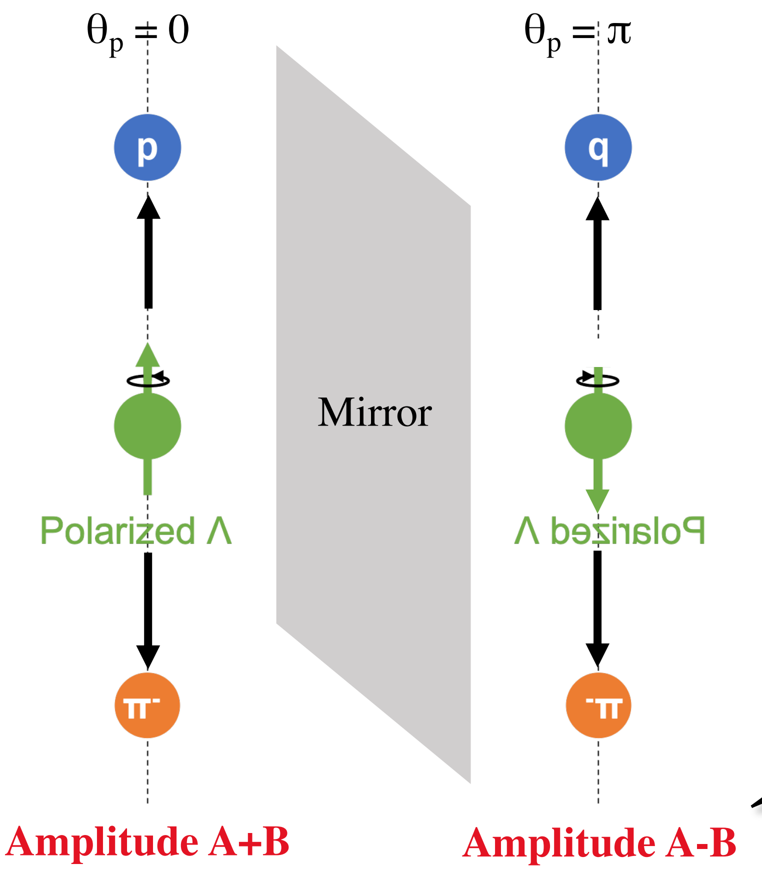


How to measure Λ beam polarization (P_Λ)

Points

- Due to Λ polarization (spin), the parity of the Λ→π-p decay violates.
- Due to that violation, the scattering angle distribution of the decay proton (θ_p) becomes asymmetric.
  (= Up/Down asymmetry)
- We can obtain P_Λ By measuring $\cos\theta_p$ and fitting it with the equation.

Λ decay (parity violation (P_p=+1, P_π=-1))



Amplitudes of the π-N system

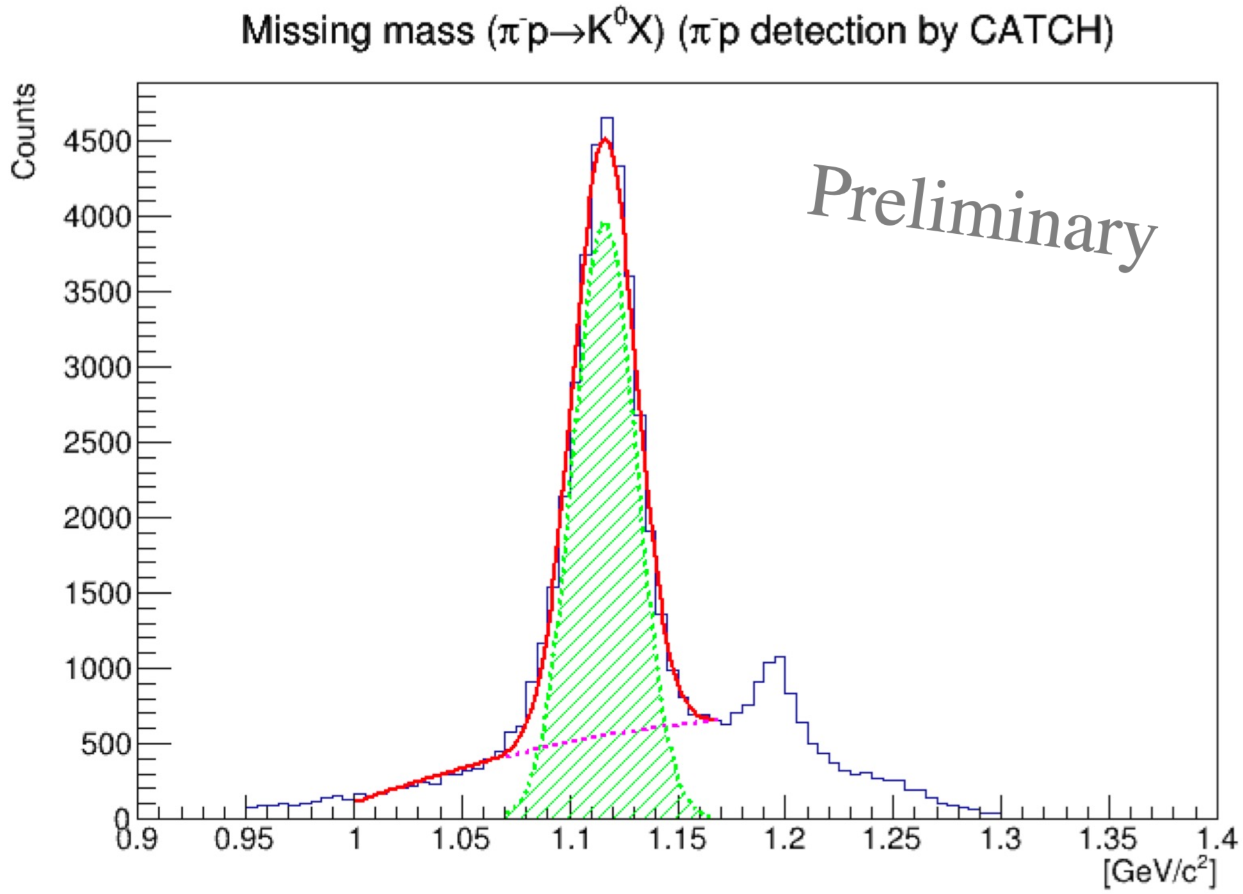
$S_{1/2}$: A

$P_{1/2}$: B

$$\frac{1+\alpha}{1-\alpha} = \frac{|A+B|^2}{|A-B|^2}$$

T. D. Lee and C. N. Yang
Phys. Rev. 108, 1645 – Published 15 December 1957

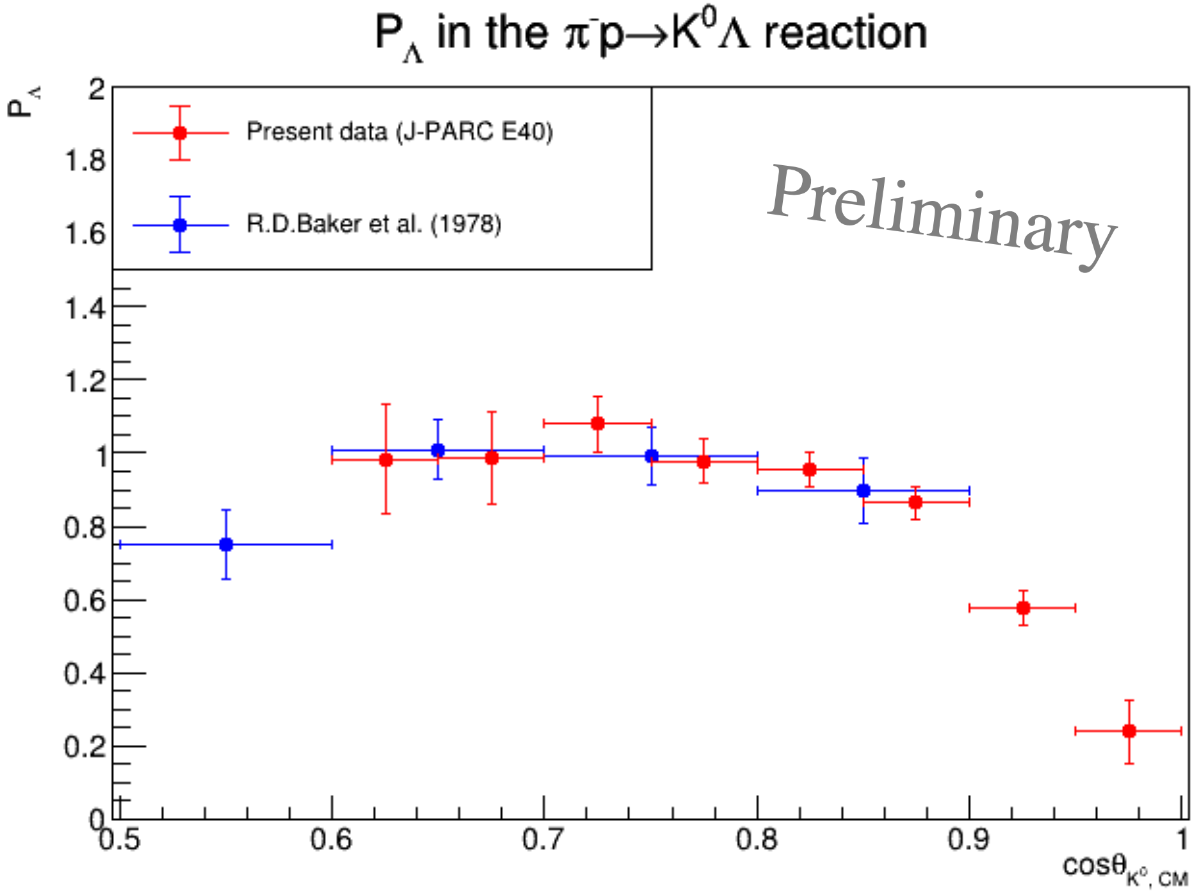
Λ beam polarization (P_Λ) measured in E40



Λ beam tagging method for P_Λ study was established.

Table 1: Numerical values of parameters obtained by the fitting for the missing mass of the $\pi^- p \to K^0 X$ reaction with an Equation (??).

All entries	Λ peak integral range	Λ entries	Background entries	S/N ratio
5.56×10^4	$1.07 - 1.16$ (GeV/c^2)	2.92×10^4	1.25×10^4	2.66

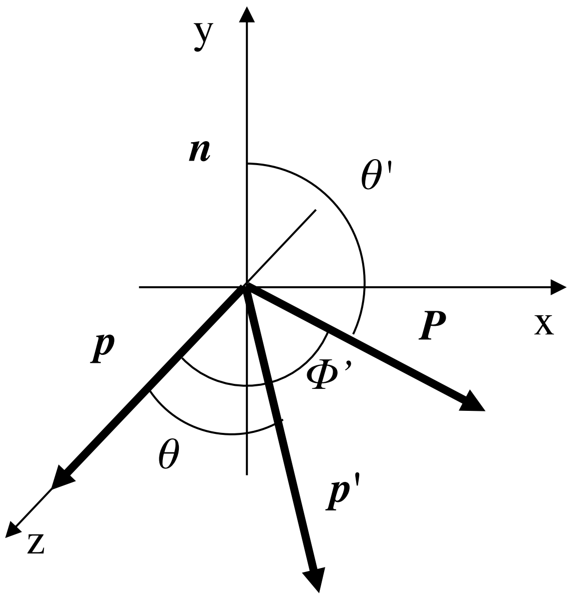


- Better accuracy than past.
- Λ beam is ~100 % polarized in the $\cos\theta_{\mathrm{K0,\,CM}}$ range of 0.6 – 0.9.

Scattering theory

T. Sasakawa, "Scattering theory", Shokabo, Tokyo (1991)

The scattering plane with polarization



p: incident beam vector
p': scattered particle vector
P: polarization vector

$f(\theta)$: scattering amplitude
$g(\theta)$: green function

Scattering matrix (spin matrix)

$$M = f(\theta) + \boldsymbol{\sigma} \cdot \boldsymbol{n}\, g(\theta)$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

σ_y is the spin-flip operator,

so the back term of $\boldsymbol{M}$ is called the "**spin-flip term**."

Scattering matrix (spin matrix)

$$M = f(\theta) + \boldsymbol{\sigma} \cdot \boldsymbol{n}\, g(\theta)$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

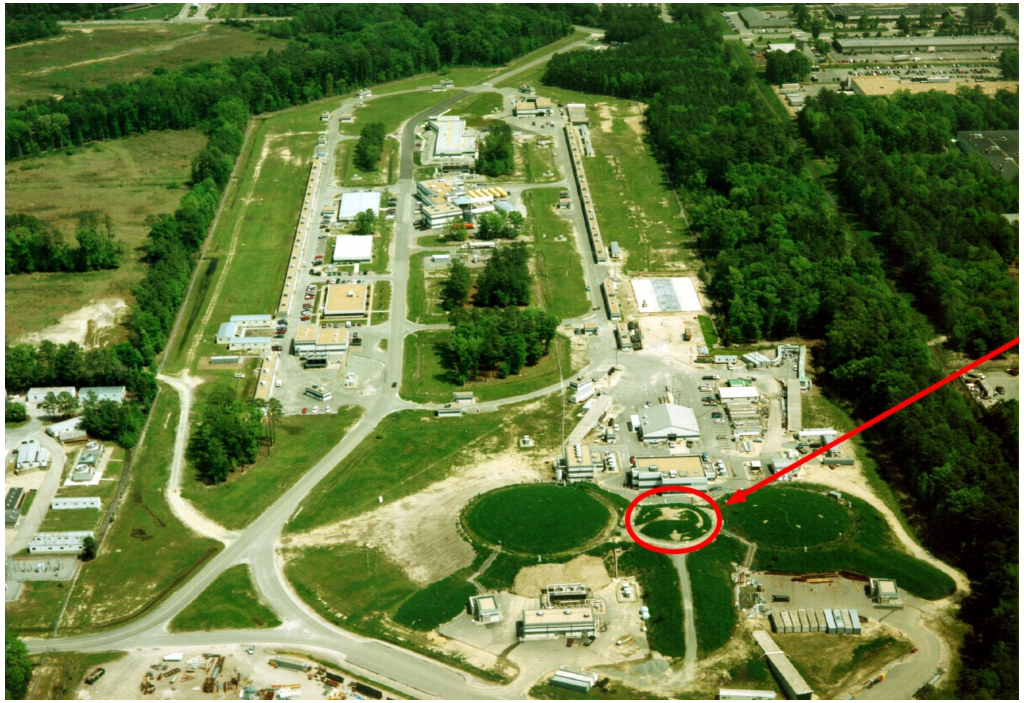
The polarization in the final state
(no polarization in the incident state)

$$\boldsymbol{P}_f = \frac{\mathrm{Tr}(\sigma \rho_f)}{\mathrm{Tr}(\rho_f)} = \frac{\mathrm{Tr}(M M^{+} \sigma)}{\mathrm{Tr}(M M^{+})} = \frac{\left(f^*(\theta) g(\theta) + g^*(\theta) f(\theta)\right)\boldsymbol{n}}{|f(\theta)|^2 + |g(\theta)|^2}$$

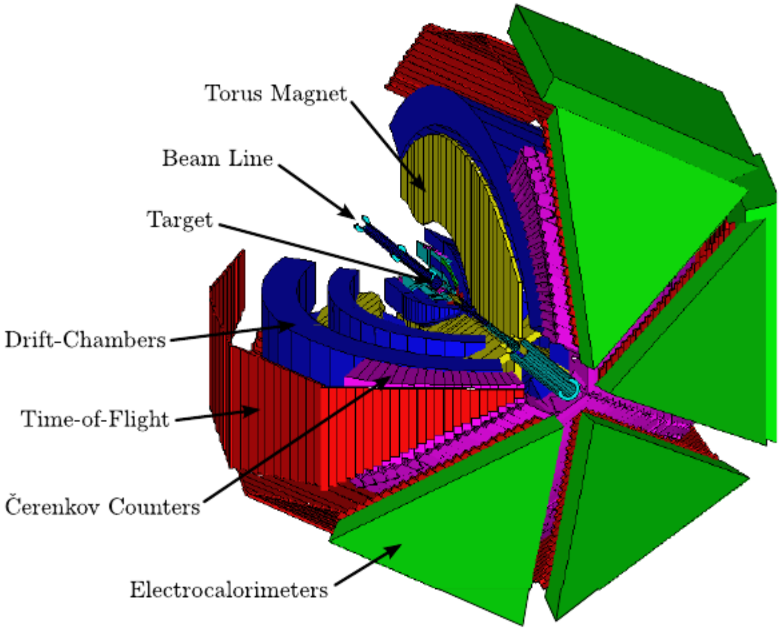
- In the $\pi^- p \rightarrow K^0 \Lambda$ reaction, if $\theta_{K0,\,CM} = 0$ or $180°$, the normal vector $\boldsymbol{n} = \boldsymbol{0}$. → P_Λ becomes 0.
- if $\theta_{K0,\,CM} = 90°$, P would correspond to $f(\theta)$?

Study of the Λd scattering in Jefferson-Laboraty CLAS g10

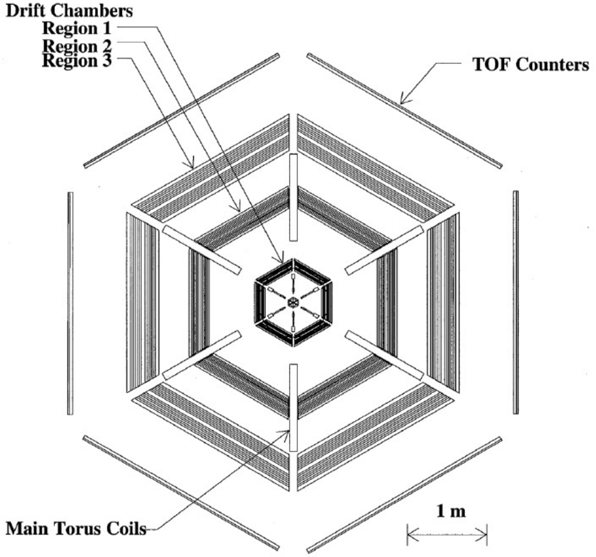
CEBAF Large Acceptance Spectrometer (CLAS)



CLAS detector located in Hall B of Jefferson Lab with subsytems labeled.



Front view of the CLAS detector seen from the beamline.



Cross sectional view of the CLAS detector with two tracks created at the target.