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.

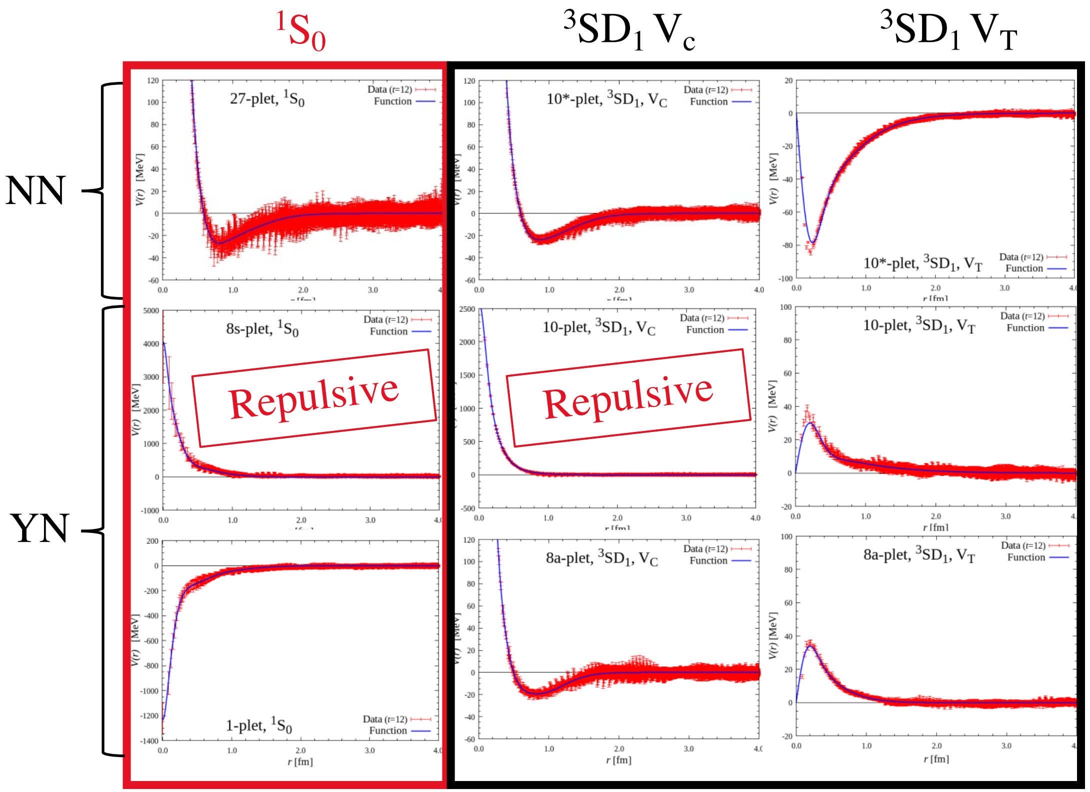
D2 Tamao SAKAO

2022/12/16 (Fri) 15:00 – 15:20

YN interaction

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

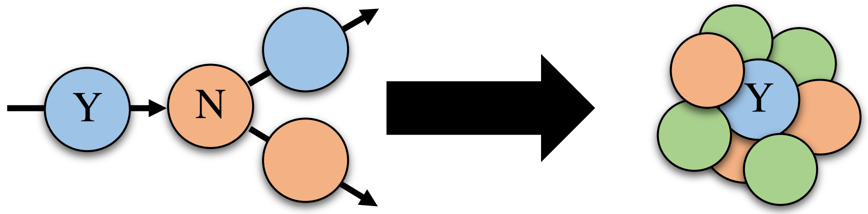
T. Inoue, AIP Conf. Proc. 2130, 020002 (2019)



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

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

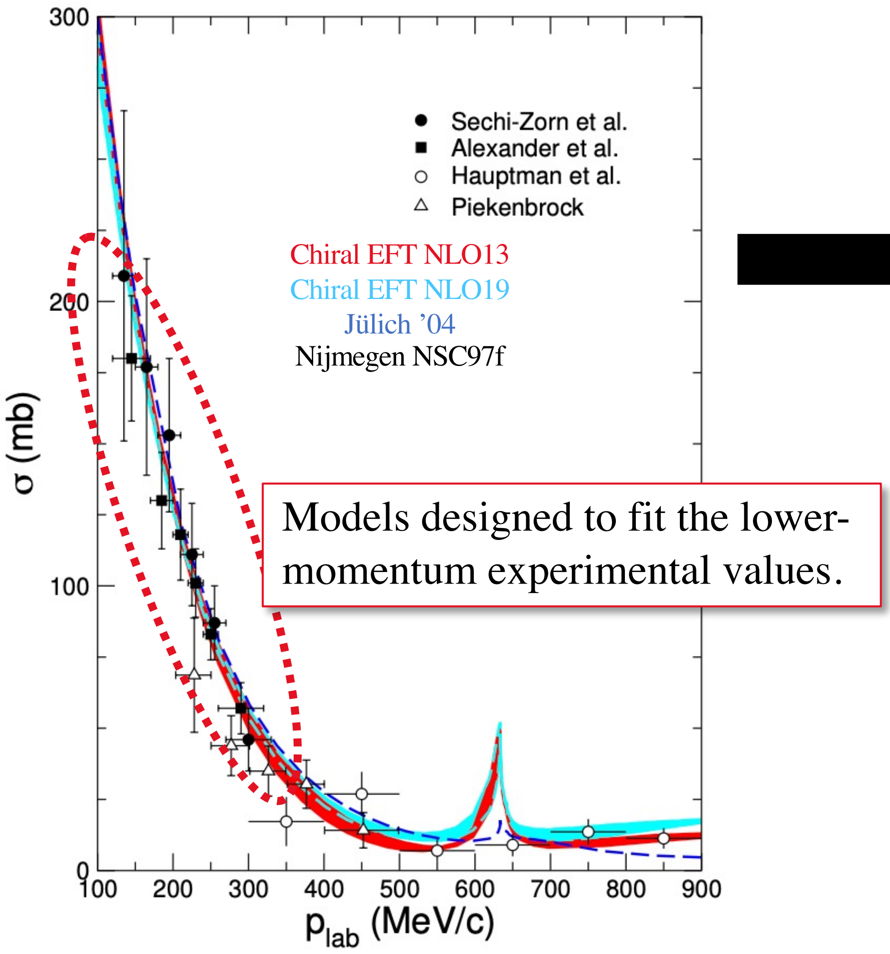


YN scattering   Hypernucleus

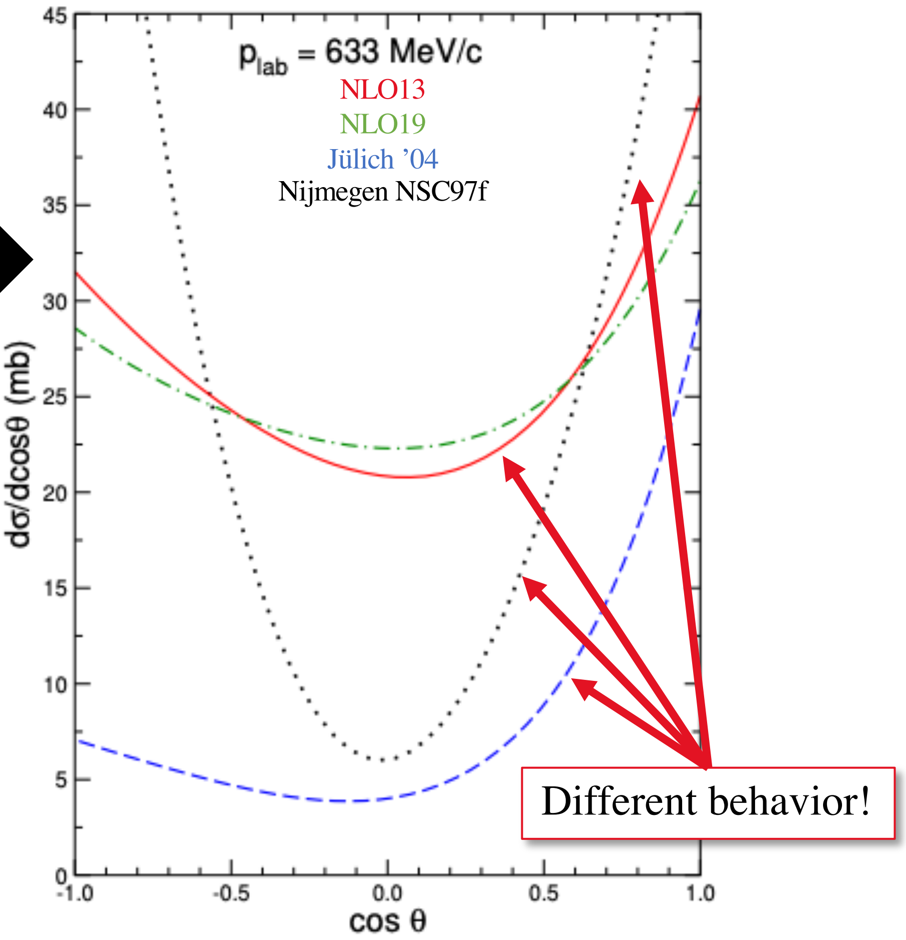
Λp channel is the 1st key to studying B_8B_8 int.

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

Total cross sections of
Λp -> Λp



Differential cross section of
Λp -> Λp

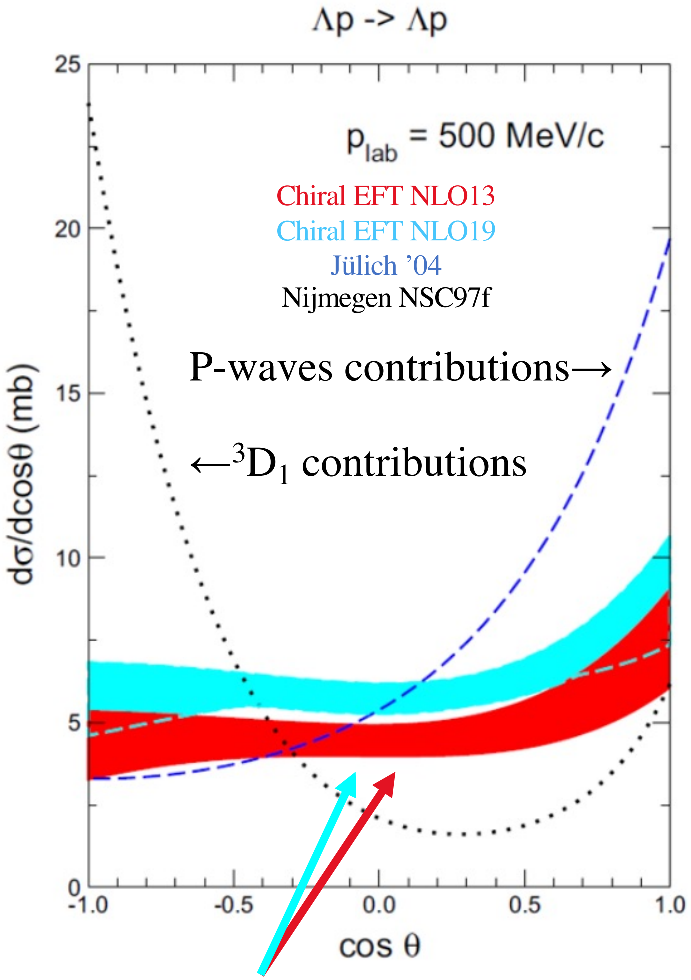


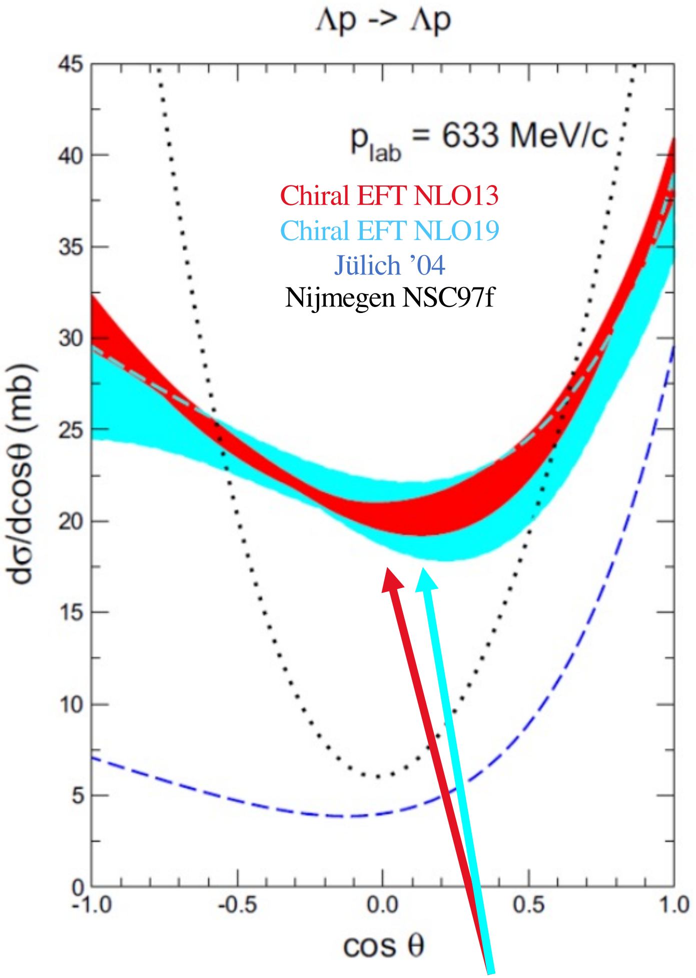
Broad momentum range of Λp data is necessary

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

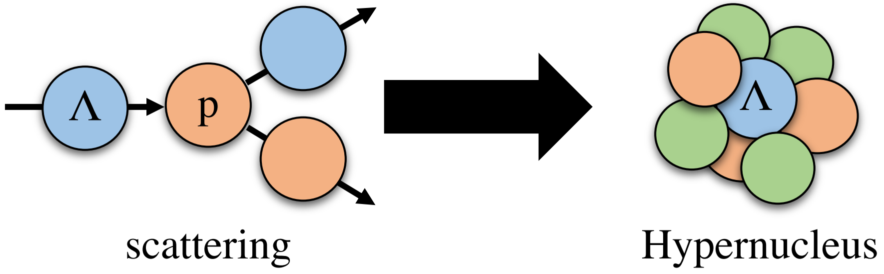
sizable angular dependence

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.

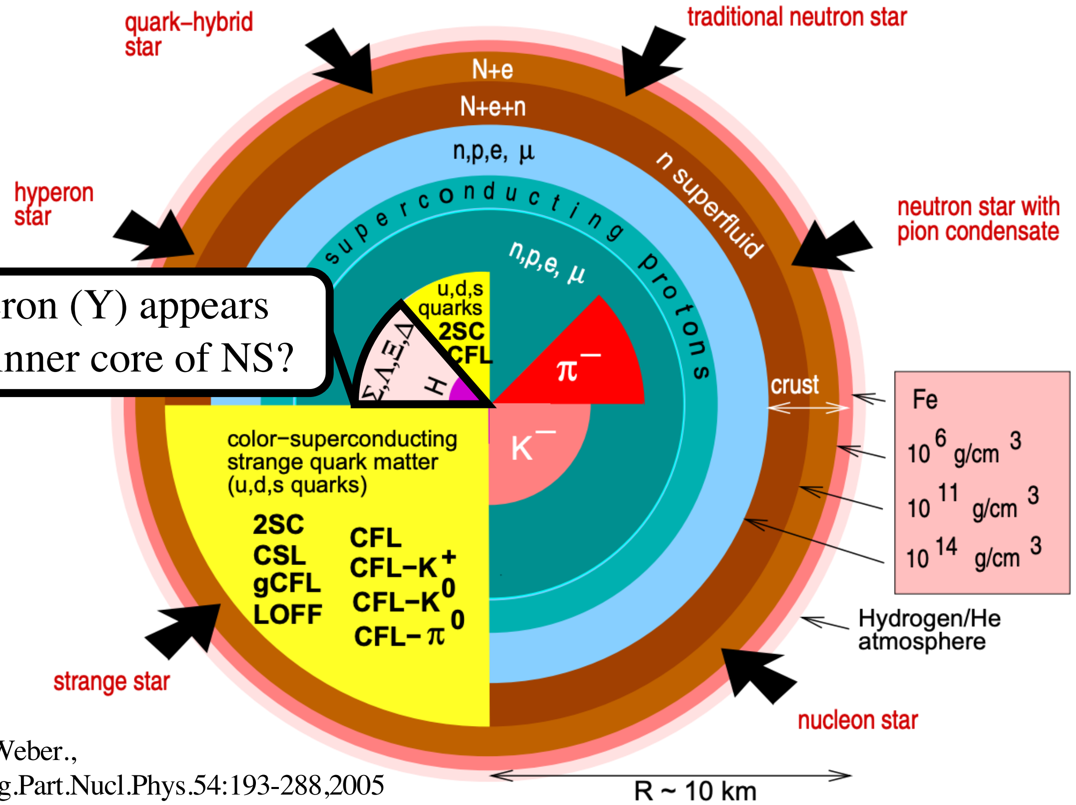


Hyperon puzzle of neutron star

Hyperon Mixing in NS?

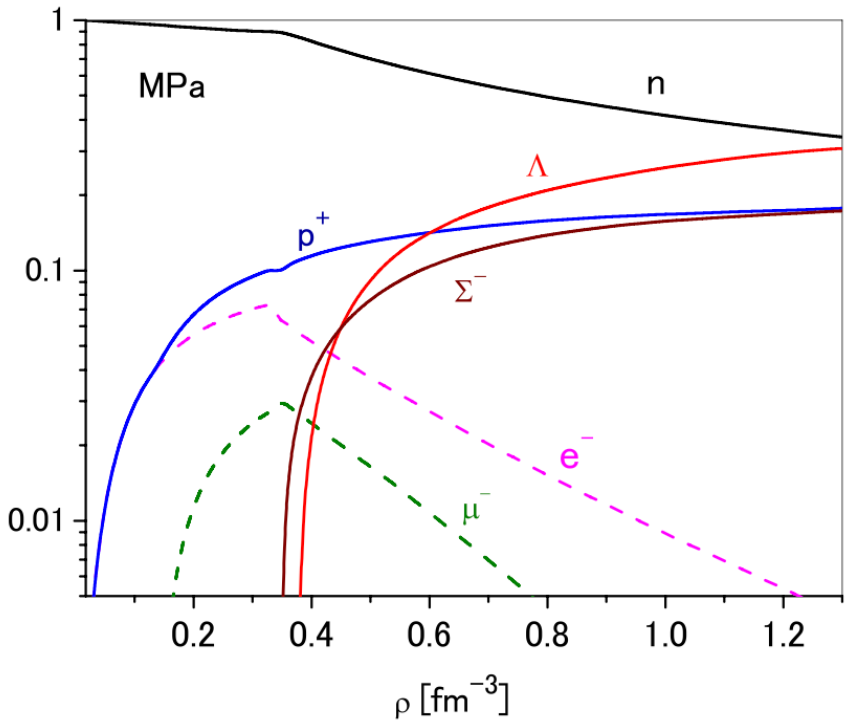
- Λ appears when $\mu_n - \mu\Lambda > m_\Lambda c^2 - m_n c^2$ (~176 MeV)?

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



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

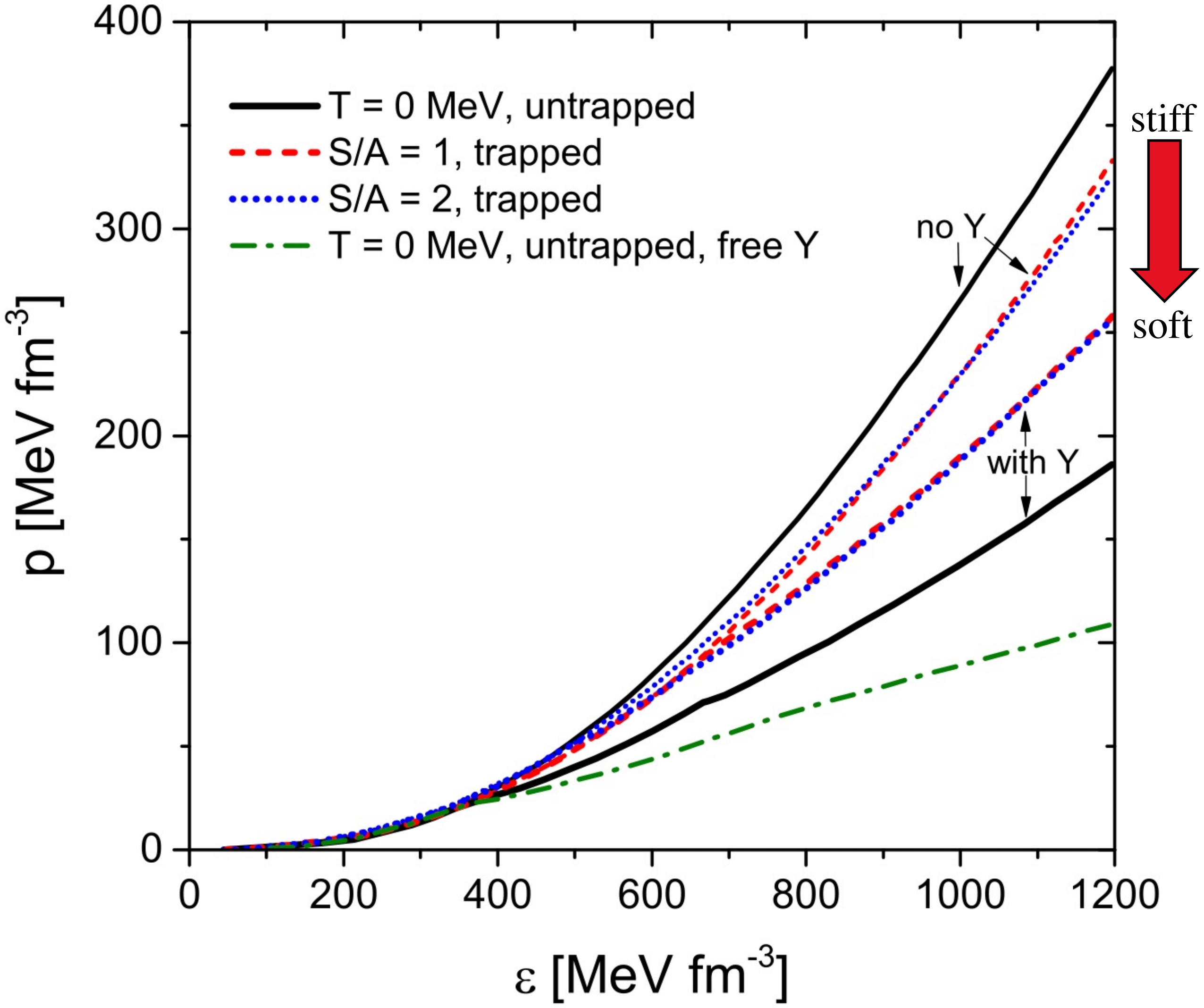
Composition of hyperonic neutron-star matter in the case of MPa(ESC+3BF)



Hyperon puzzle of neutron star

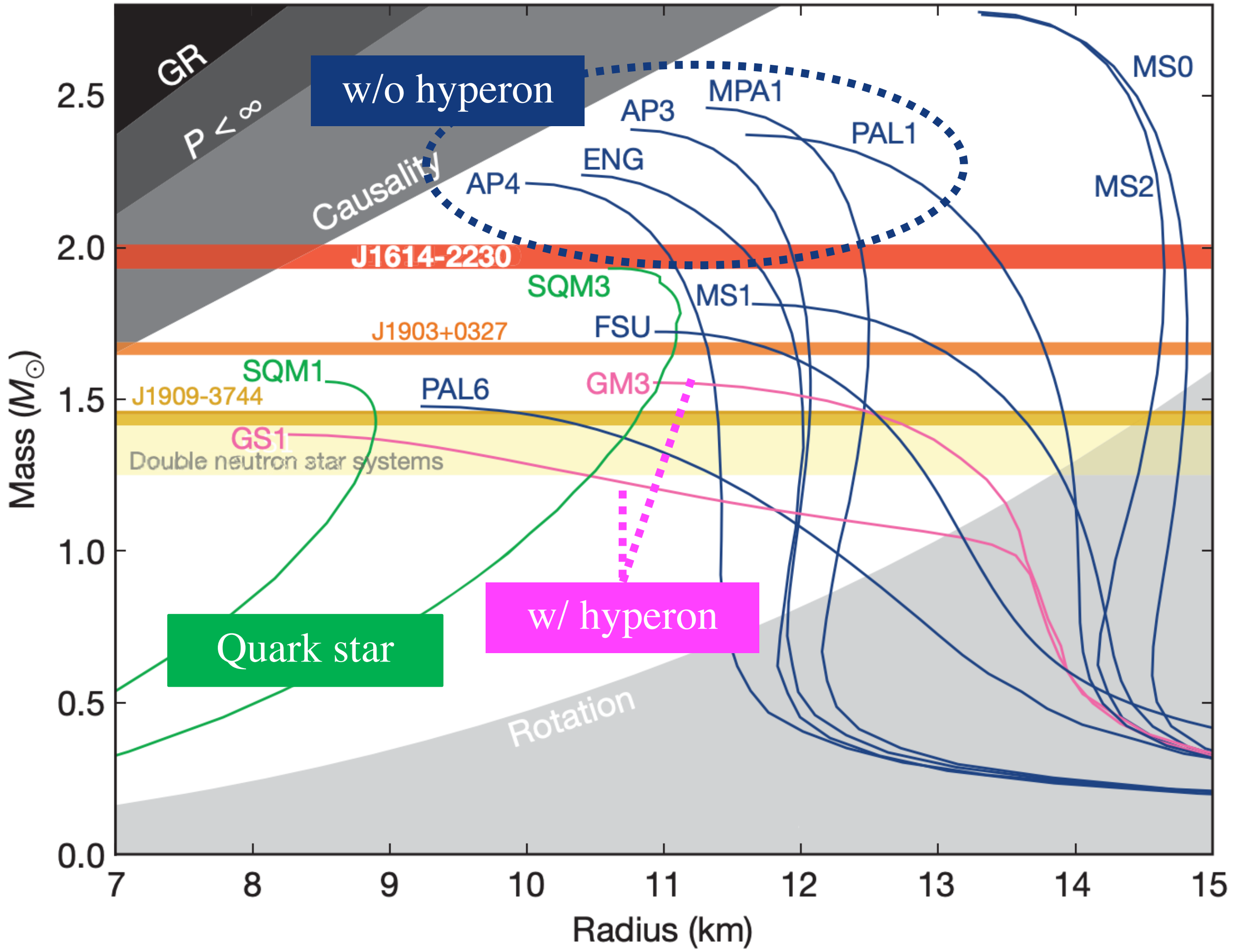
G.F. Burgio *et al*., arXiv:2105.03747v1, 2021

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.

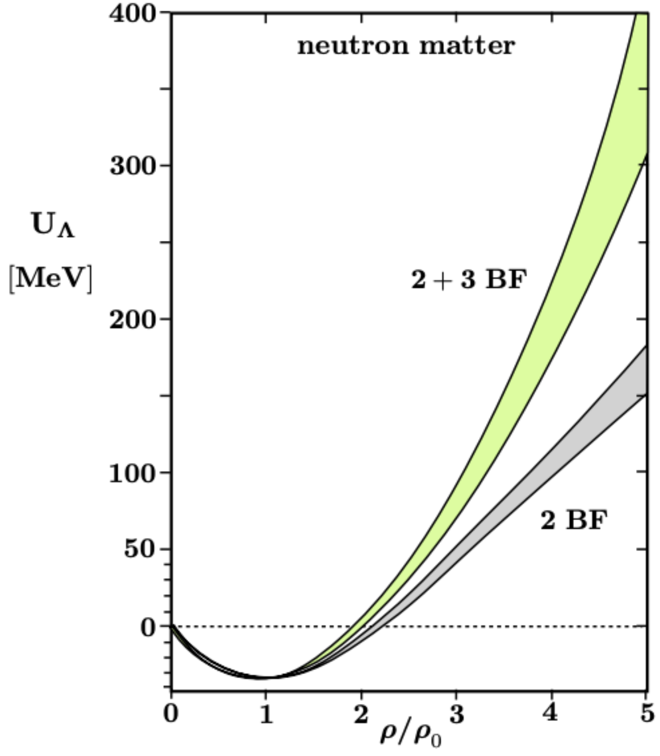


Some additional repulsion mechanism is necessary.

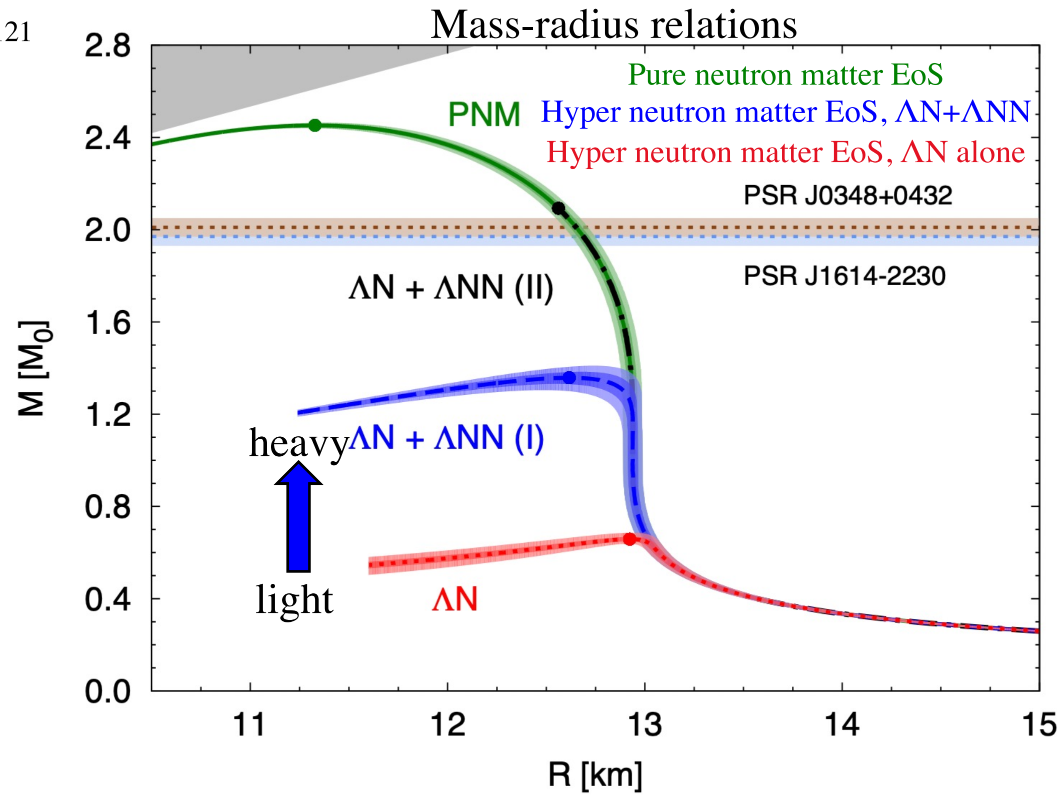
Both ΛN & ΛNN observations are necessary

- 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

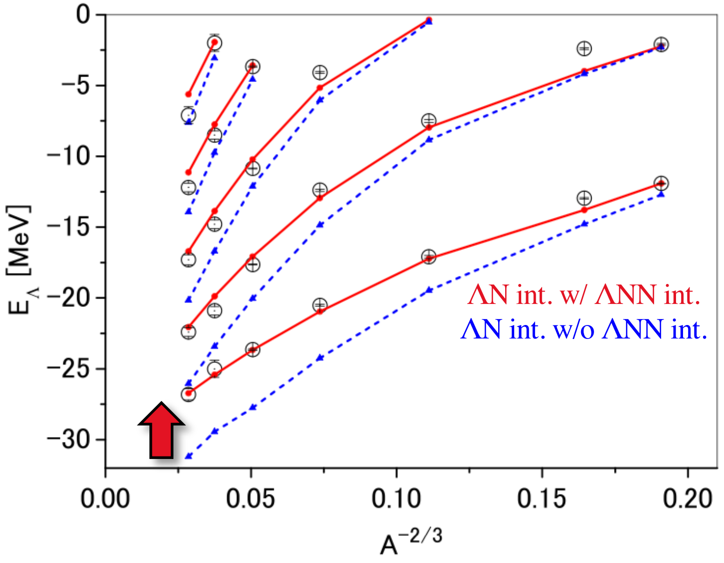


Diego Lonardoni *et al*., arXiv:1407.4448v2, 2015



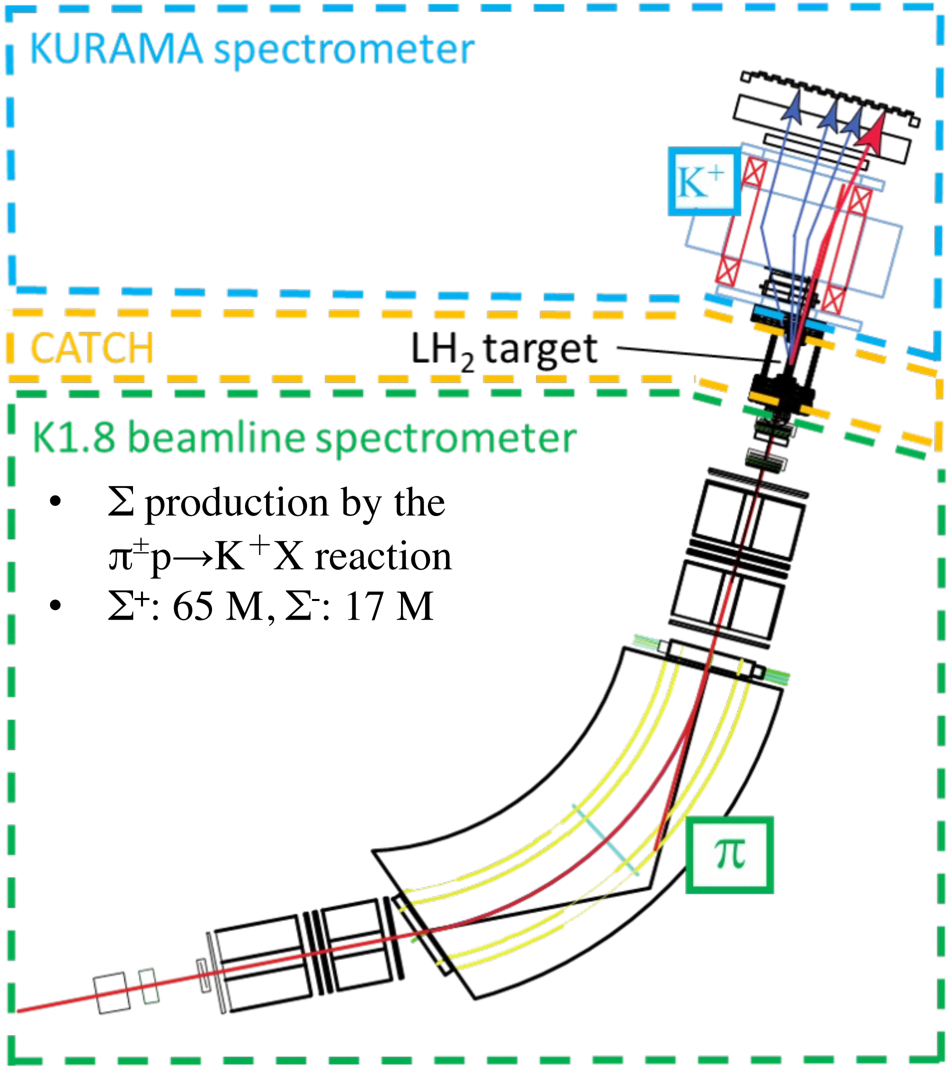
M. M. Nagels et al., PHYSICAL REVIEW C 99, 044003 (2019)
*Experimental data: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. **57**, 564 (2006)

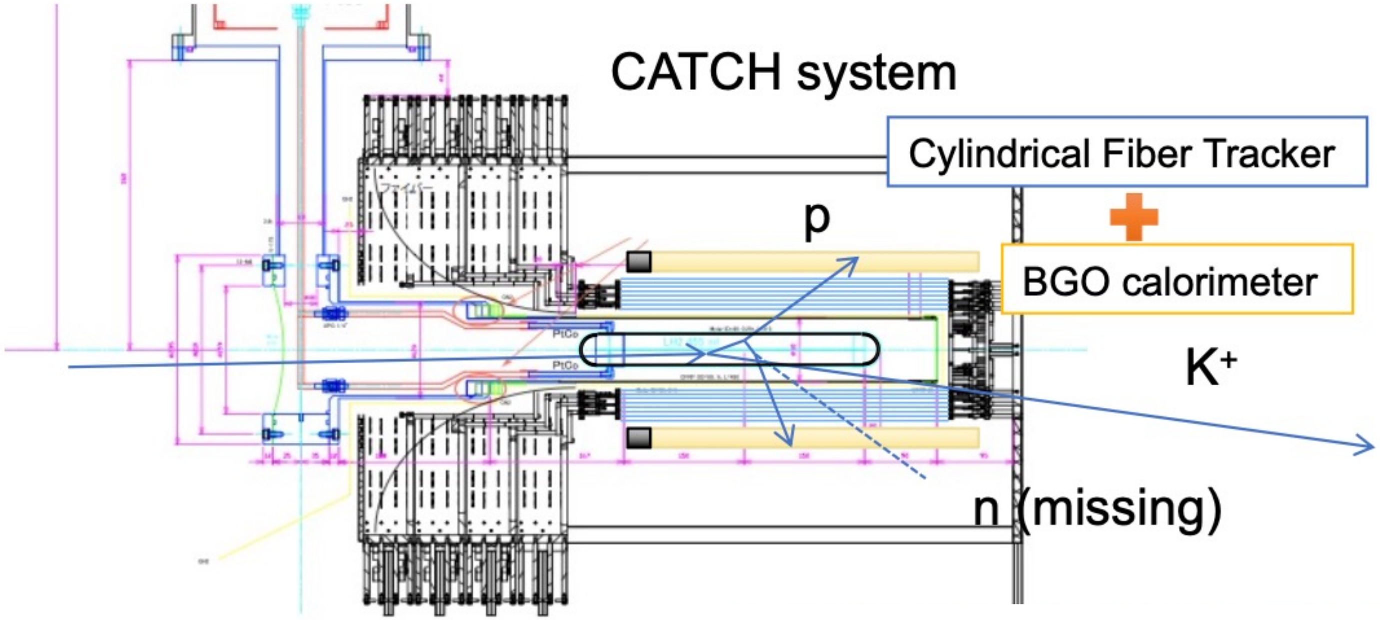
Energy spectra of $^{13}{}_\Lambda$C, $^{28}{}_\Lambda$Si, $^{51}{}_\Lambda$V, $^{89}{}_\Lambda$Y, $^{139}{}_\Lambda$La, and $^{208}{}_\Lambda$Pb (by ESC16 & ESC16$^+$)

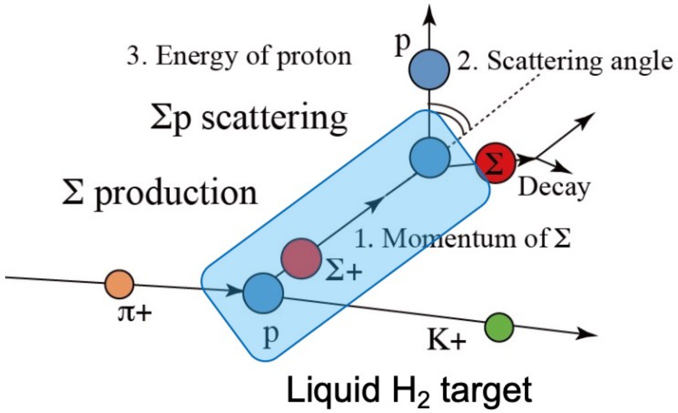


Study of the Λp scattering in J-PARC E40 ($\rightarrow$ E86)

J-PARC E40 (Σp scattering)







My research

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

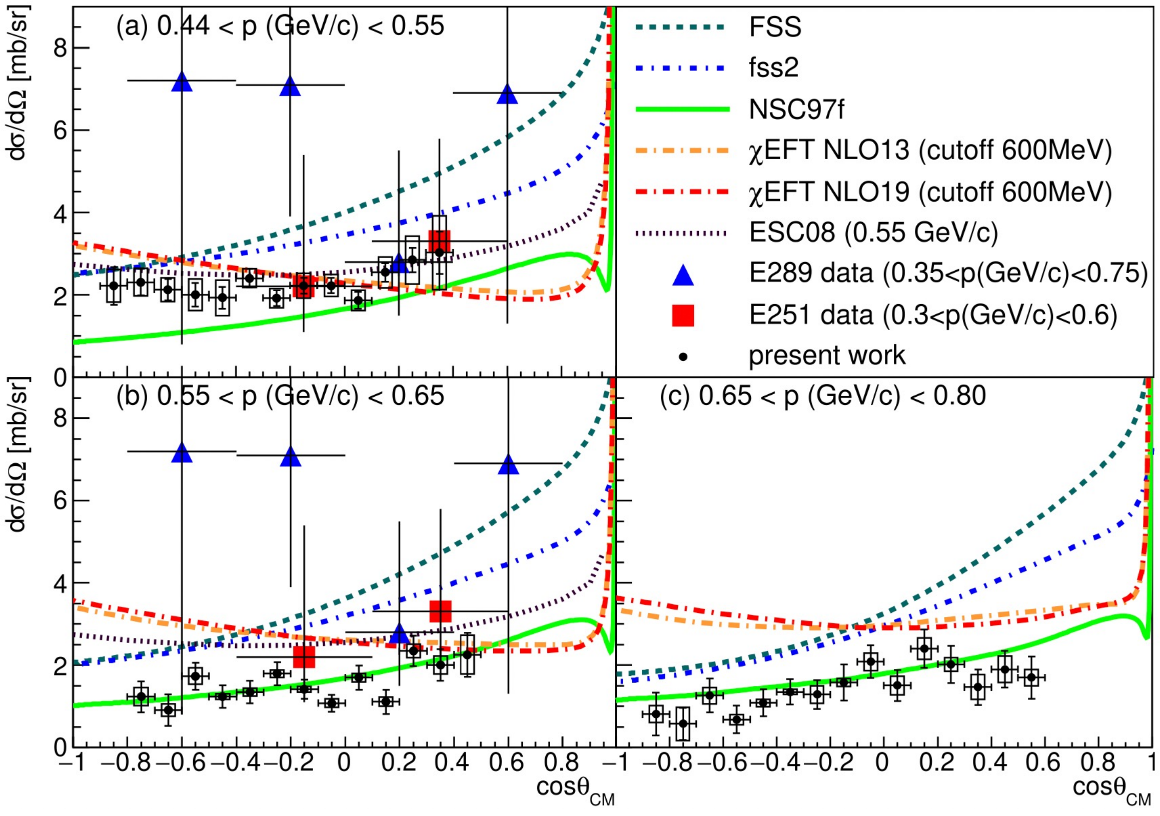
Experimental values of Σp $d\sigma/d\Omega$ in E40

The first systematic $d\sigma/d\Omega$ data of the Σp channel

- Quark model (fss2) & chiral EFT: Consistent
- Nijmegen (ESC) models: Inconsistent @the forward angle region

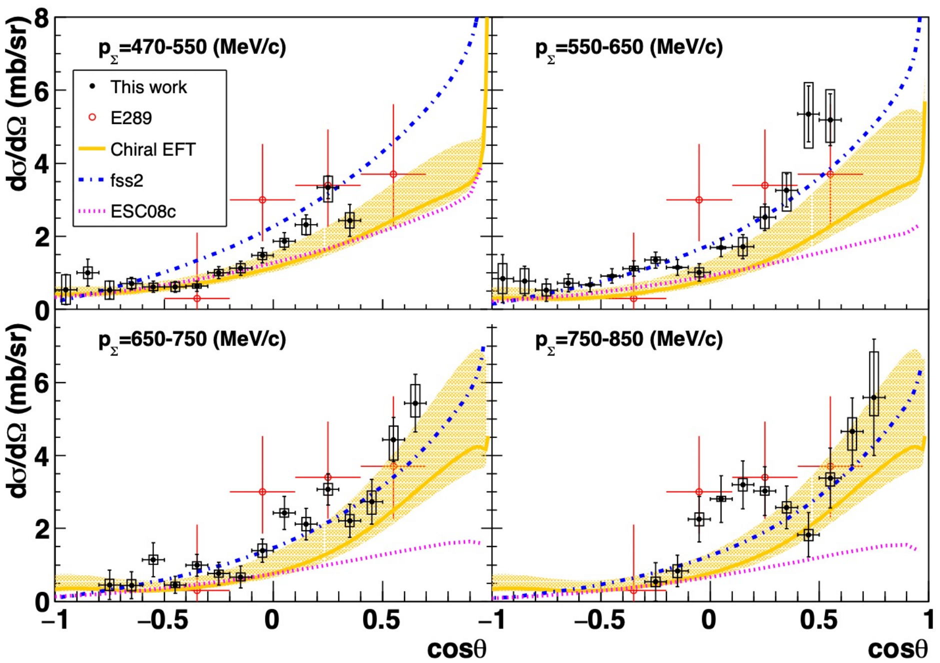
T. Nanamura et al. PTEP **2022**, 093D01 (2022)

Derived differential cross sections of the $\Sigma^+ p$ scattering for the three momentum regions



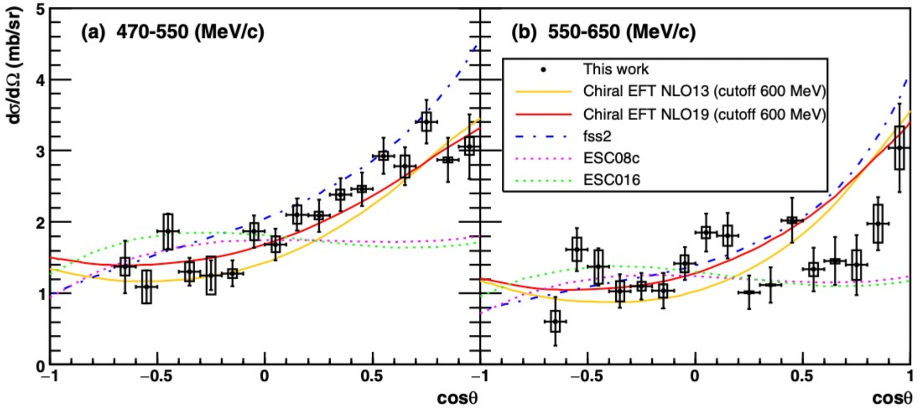
K. Miwa et al., arXiv:2104.13608

Differential cross sections of $\Sigma^- p$ scattering



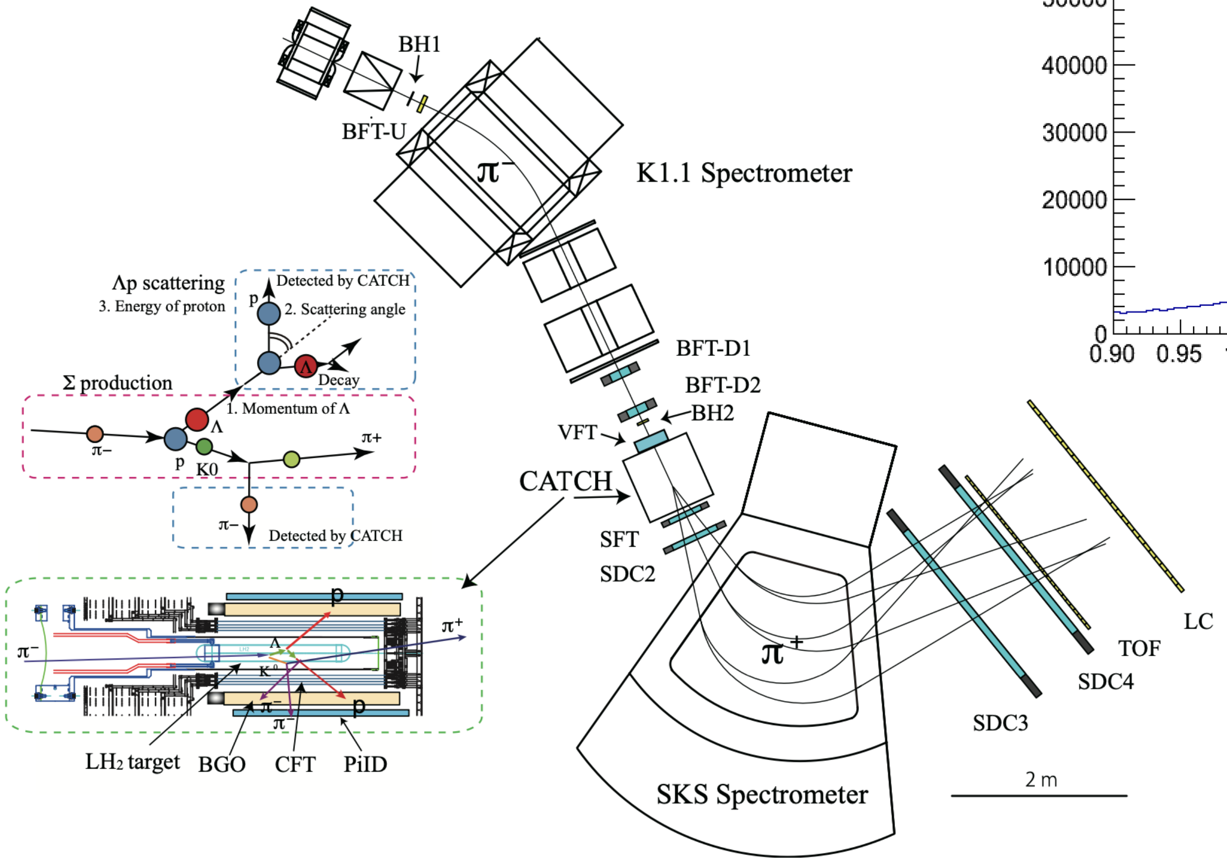
K. Miwa et al., Phys. Rev. Lett. 128, 072501 (2022)

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

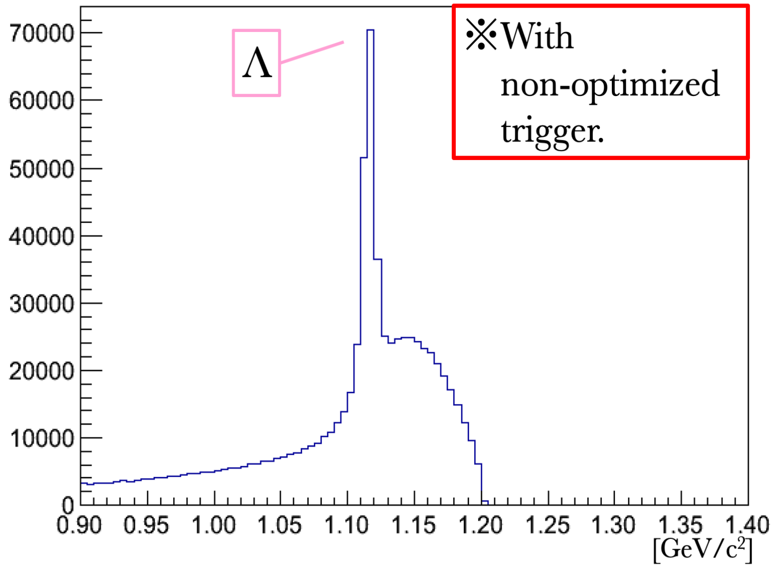


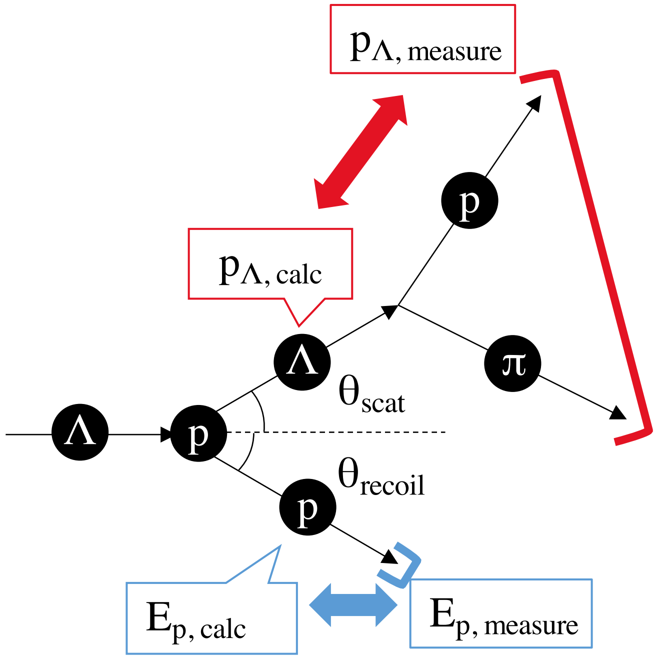
J-PARC E86 (new Λp scattering)

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



Simulated MM($\pi^- p \to K^0 X$)





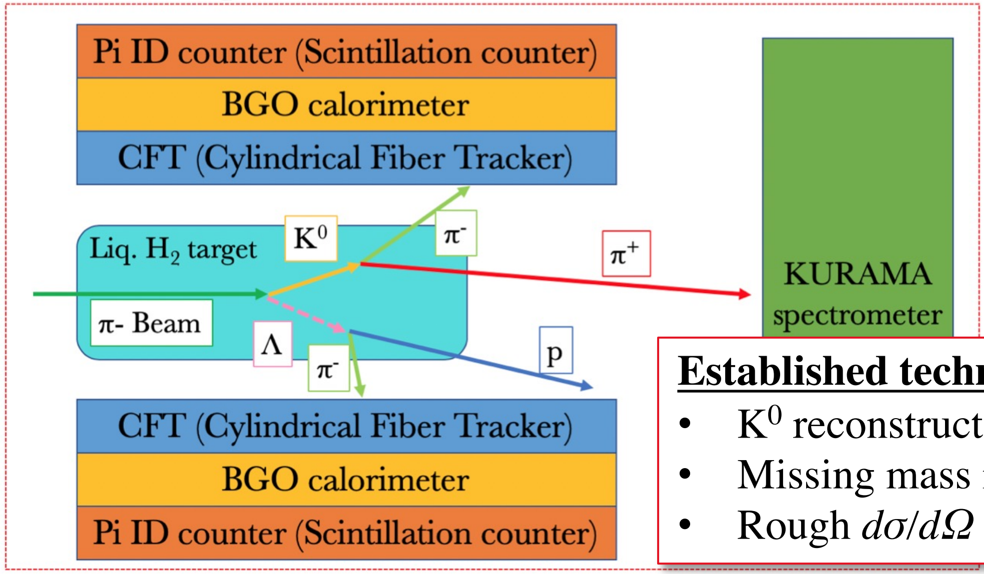
K^0 ID improvement
- CATCH upgrade
- ASIC upgrade
- BH, BFT, and SFT R&D
- SKS momentum resolution: ~0.1% (KURAMA: ~1%)

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

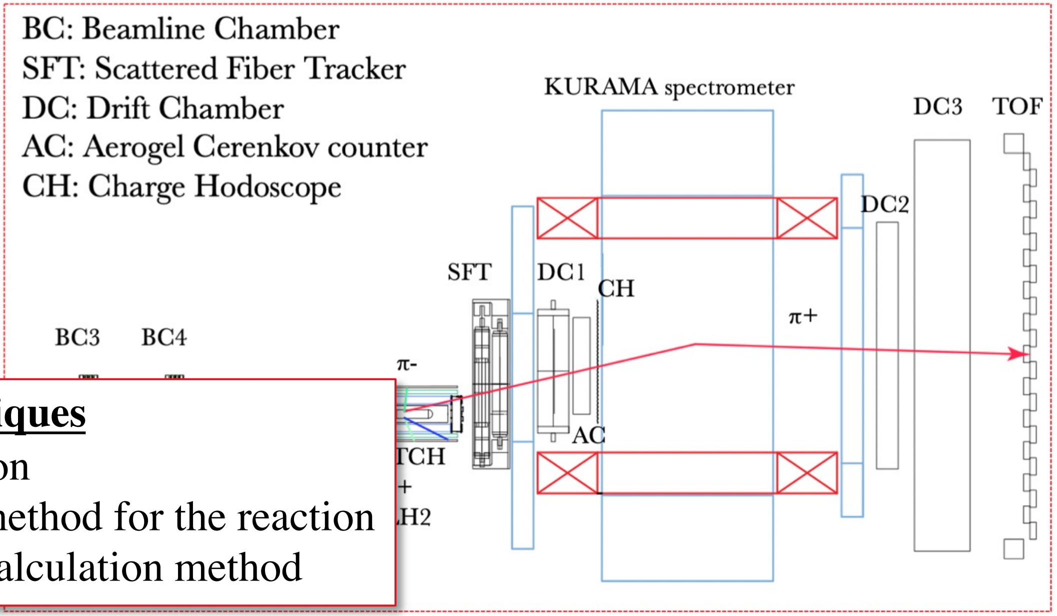
Feasibility study of E86 using E40 data

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.

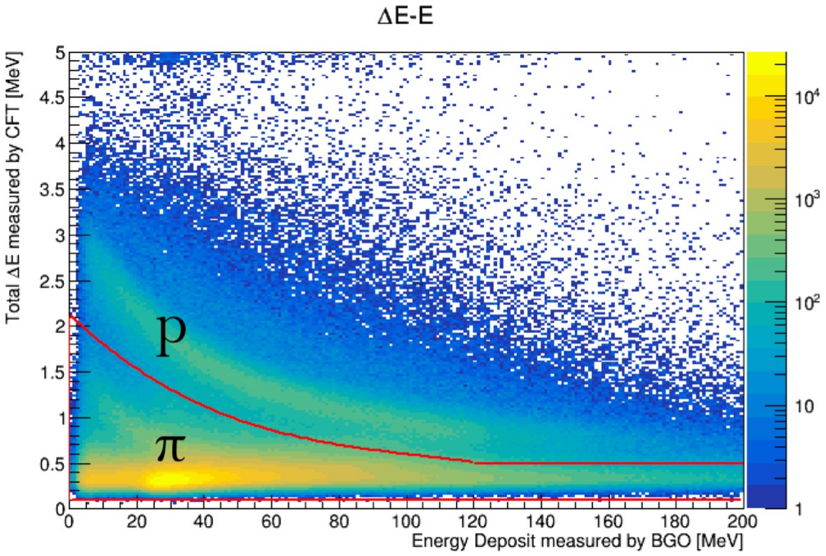


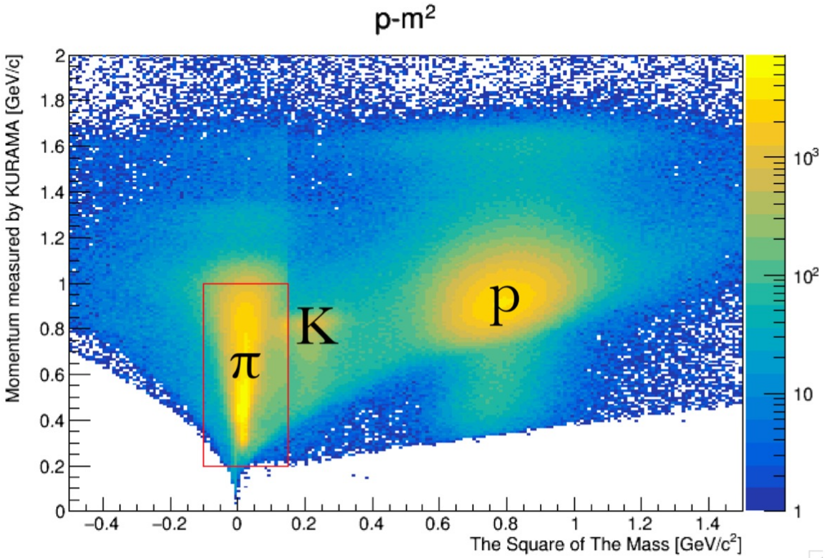
(2) J-PARC E40 detector setup.



Established techniques

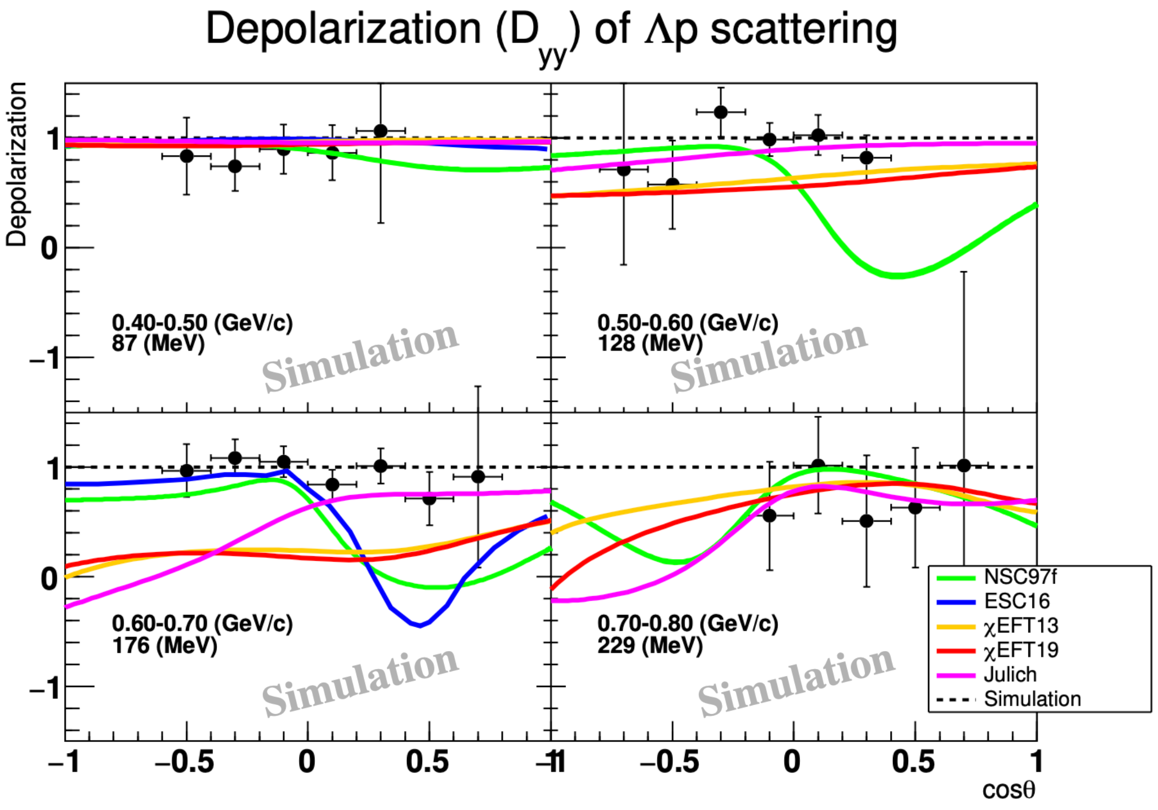
- K^0 reconstruction
- Missing mass method for the reaction
- Rough $d\sigma/d\Omega$ calculation method

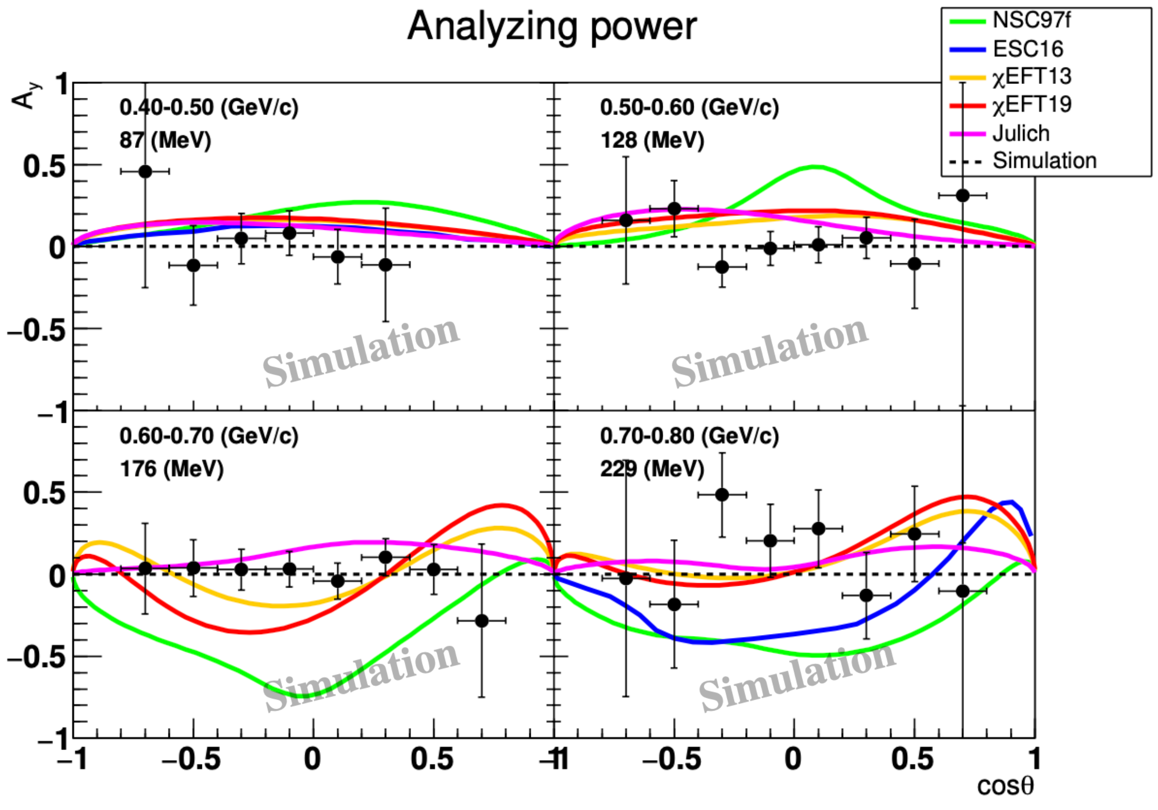




Λp spin observables will also be measured in E86

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 Spin-spin

Λp spin observables will also be measured in E86

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

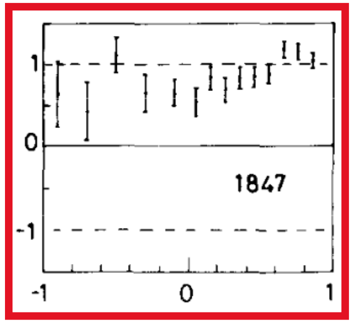
$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{1}{2}\left(\left(\frac{d\sigma}{d\Omega}\right)_L + \left(\frac{d\sigma}{d\Omega}\right)_R\right),$$

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

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

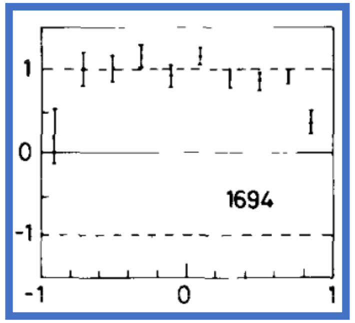
R.D. Baker et. al., B141 (1978) 29-47

Past experimental data of P_Λ for the E_{CM}



E40 range

E_{CM} = 1841 MeV

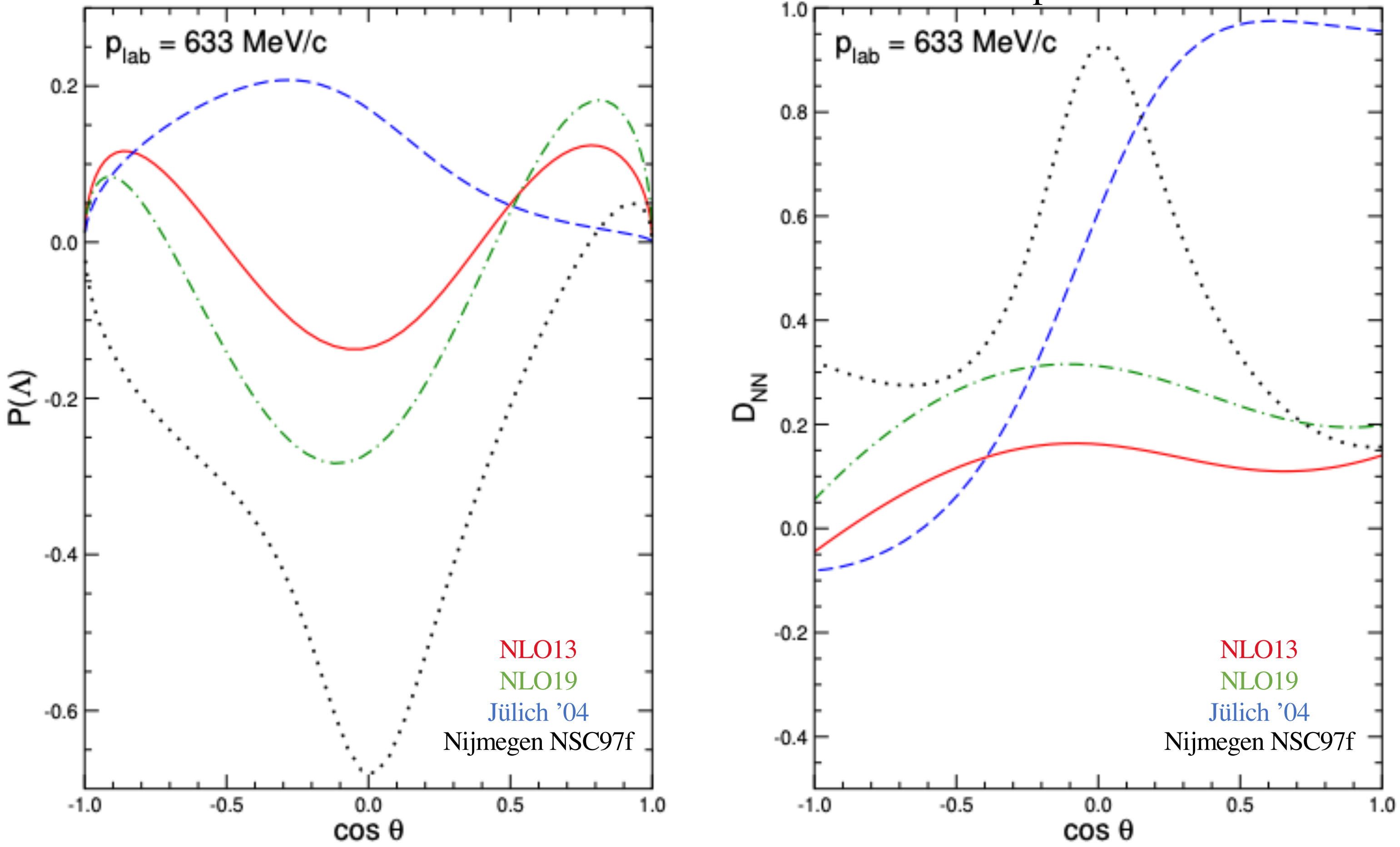


E86 range

E_{CM} = 1699 MeV

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

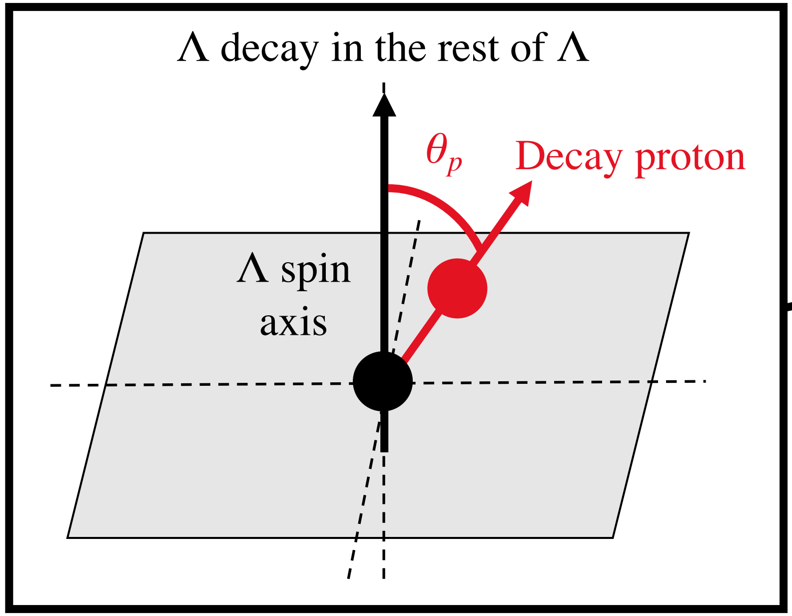
Polarization　　Depolarization



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

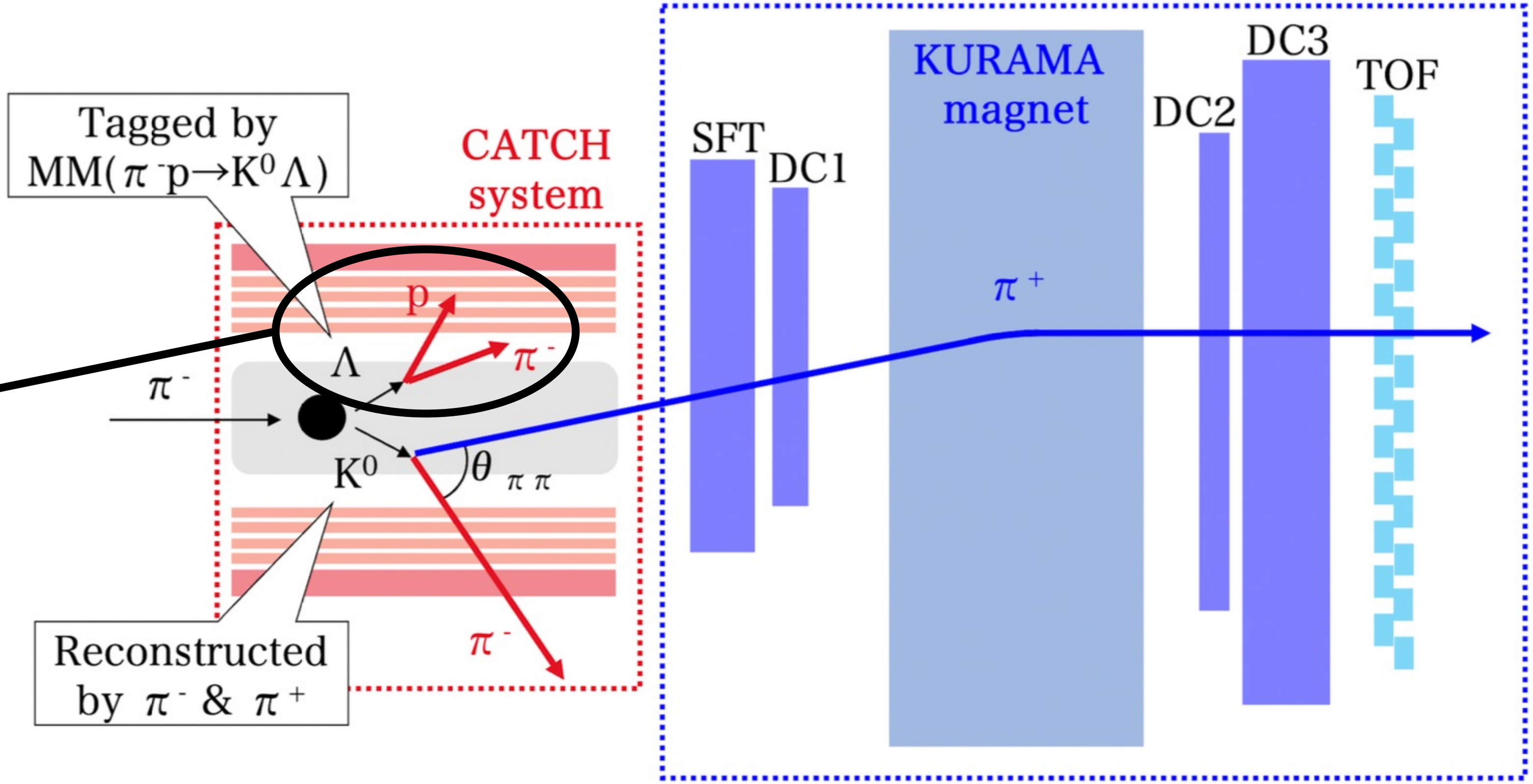
How to measure Λ beam polarization (P_Λ)

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

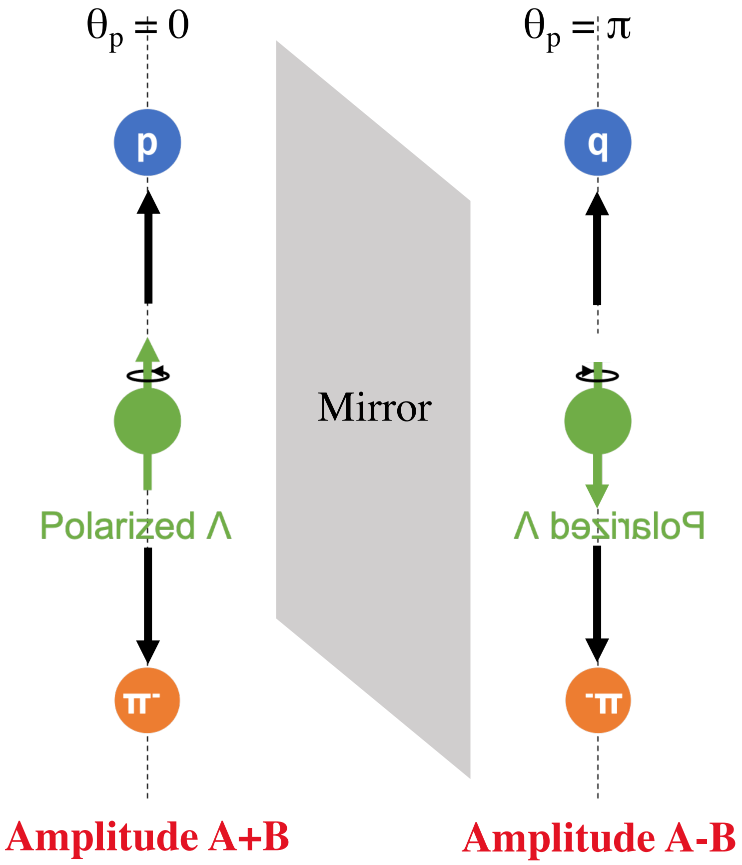


How to measure Λ beam polarization (P_Λ)

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

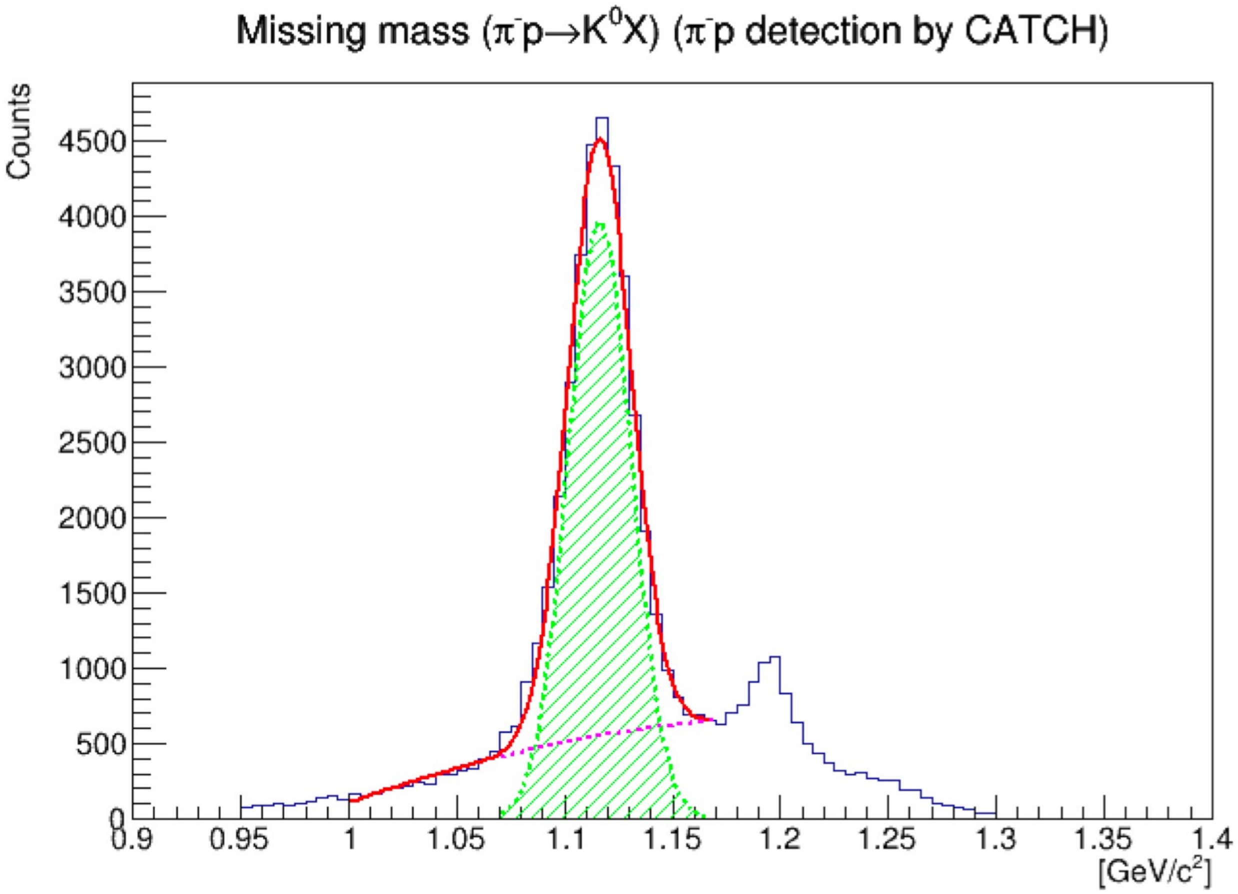
$S_{1/2}$: A

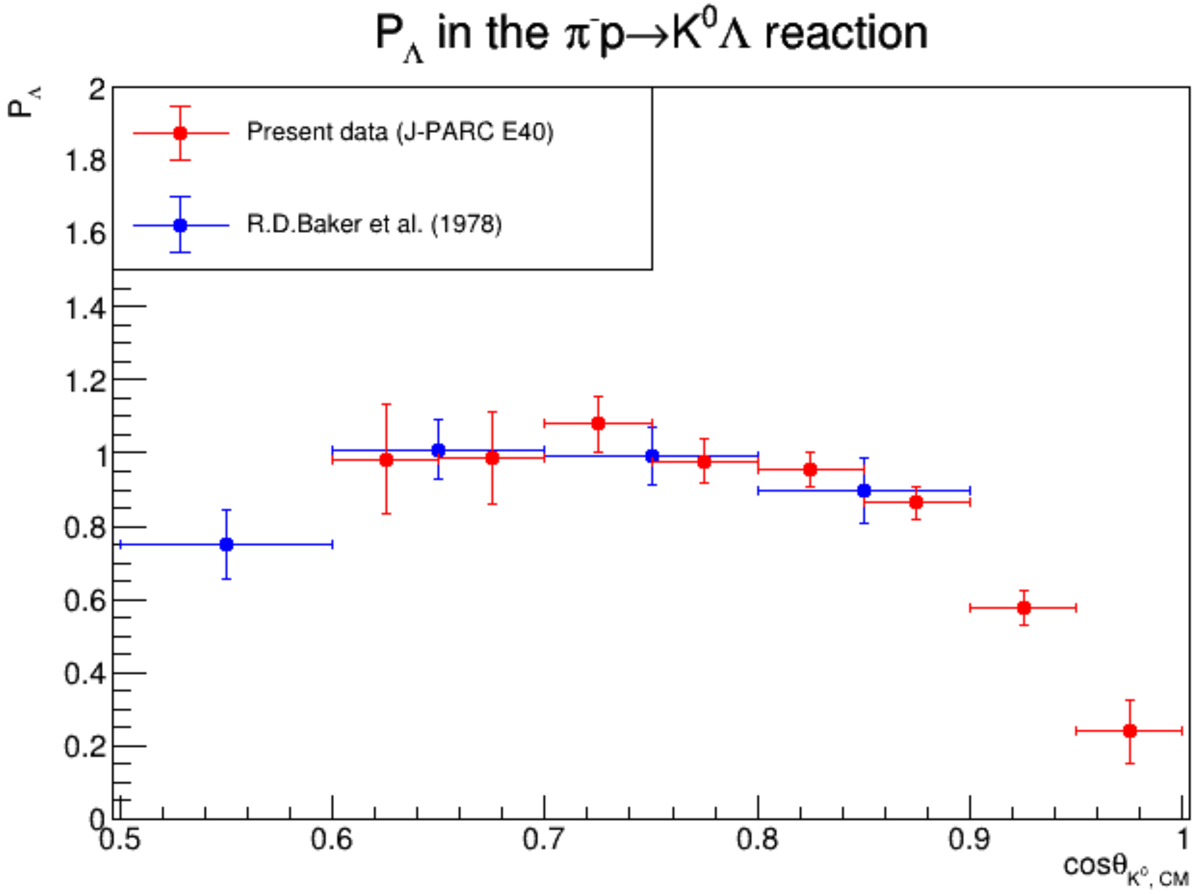
$P_{1/2}$: B

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

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.

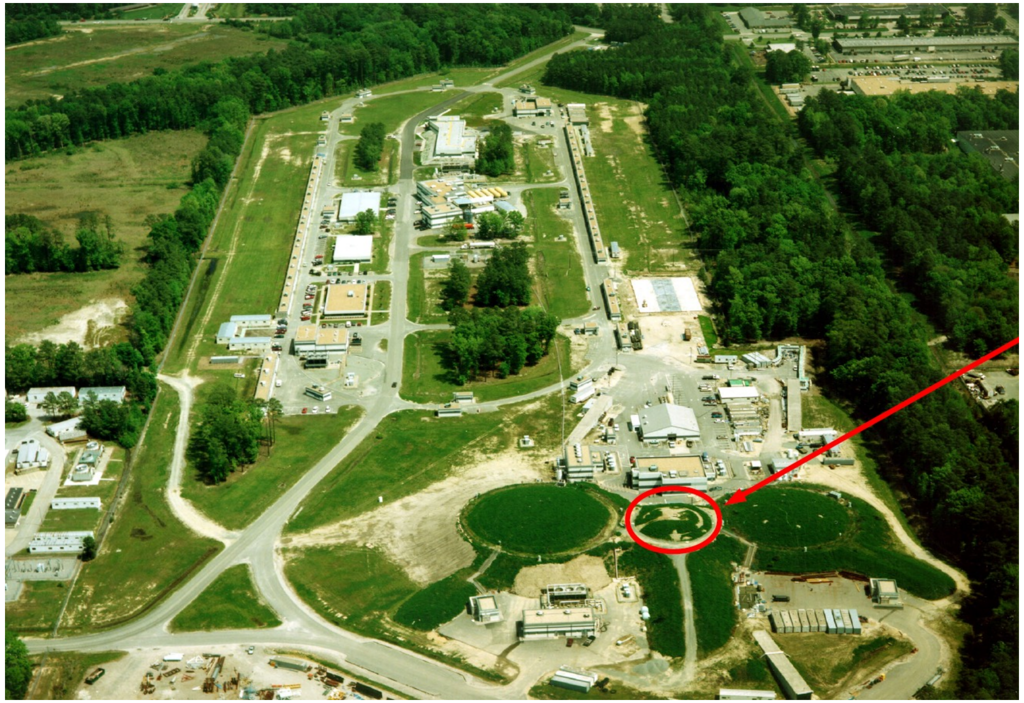
Table 1: Numerical values of parameters obtained by the fitting for the missing mass of the $\pi^- p \to K^0 X$ reaction with an Equation (**??**).

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

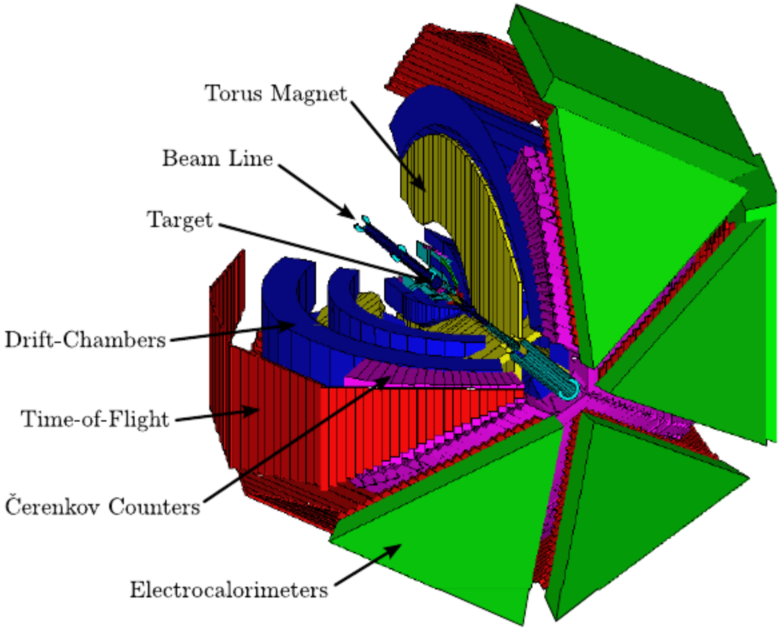
- Better accuracy than past.
- Λ beam is ~100 % polarized in the $\cos\theta_{K0,\,CM}$ range of 0.6 – 0.9.

Study of the Λd scattering in Jefferson-Laboraty CLAS g10

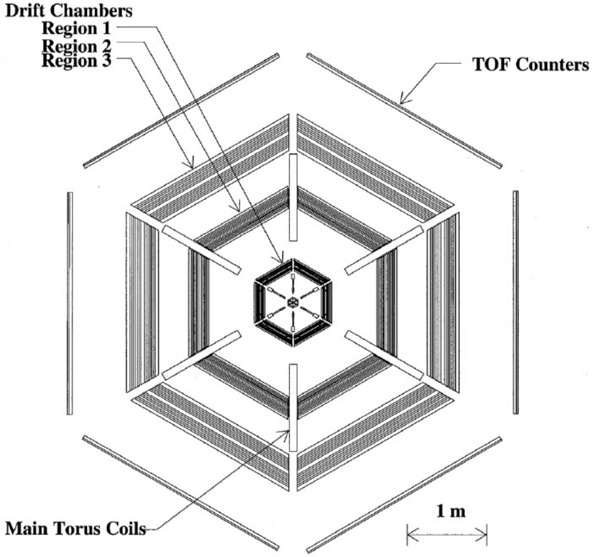
CEBAF Large Acceptance Spectrometer (CLAS)



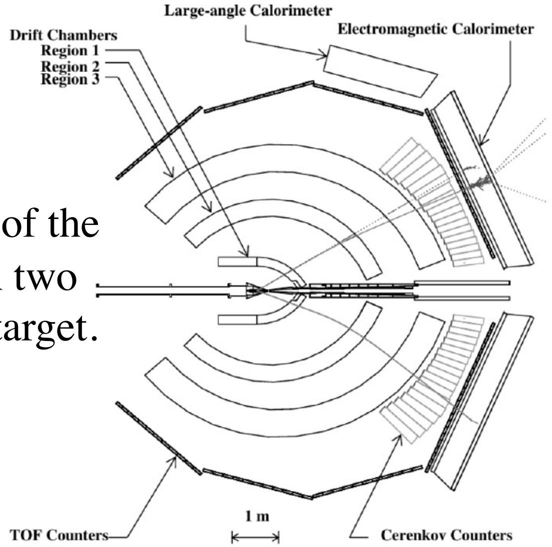
CLAS detector located in Hall B of Jefferson Lab with subsytems labeled.



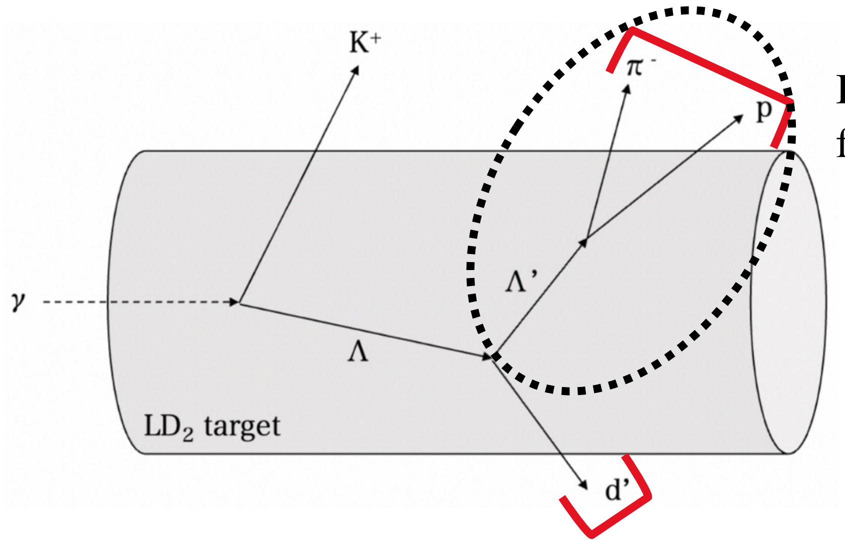
Front view of the CLAS detector seen from the beamline.



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

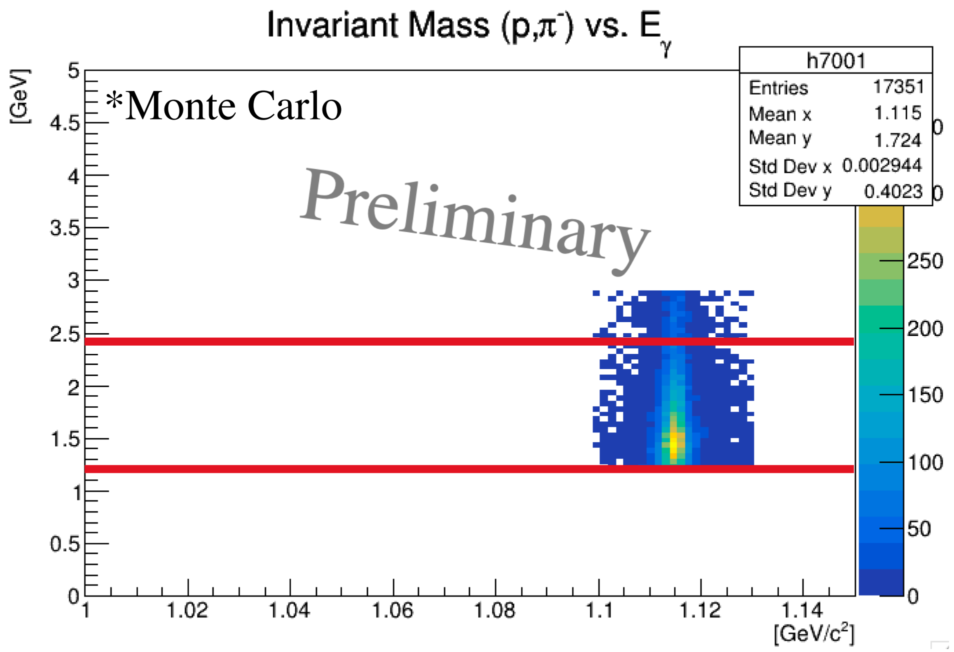


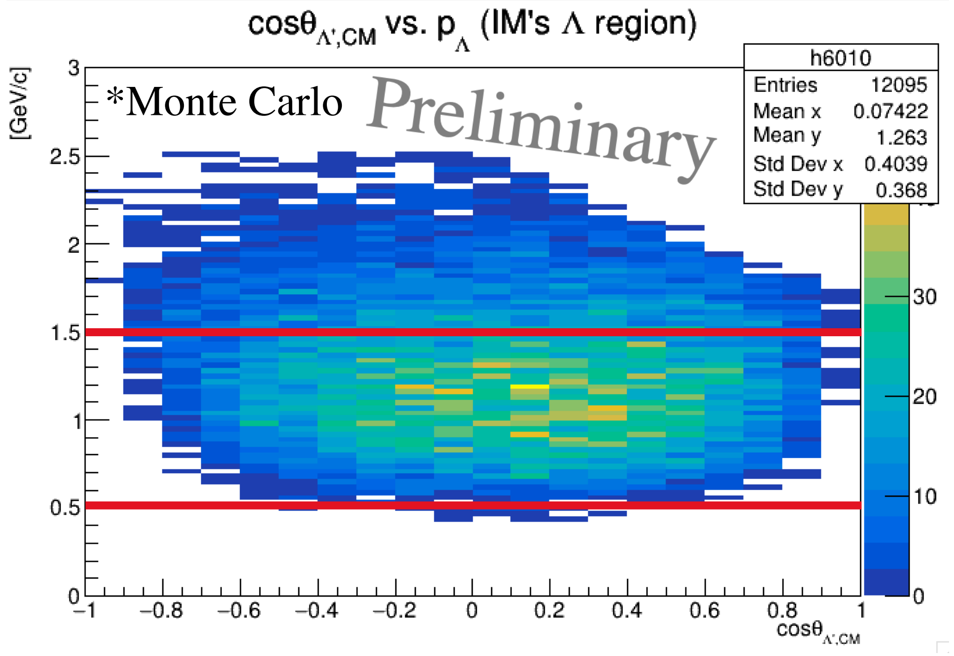
Toward Λd scattering measurement



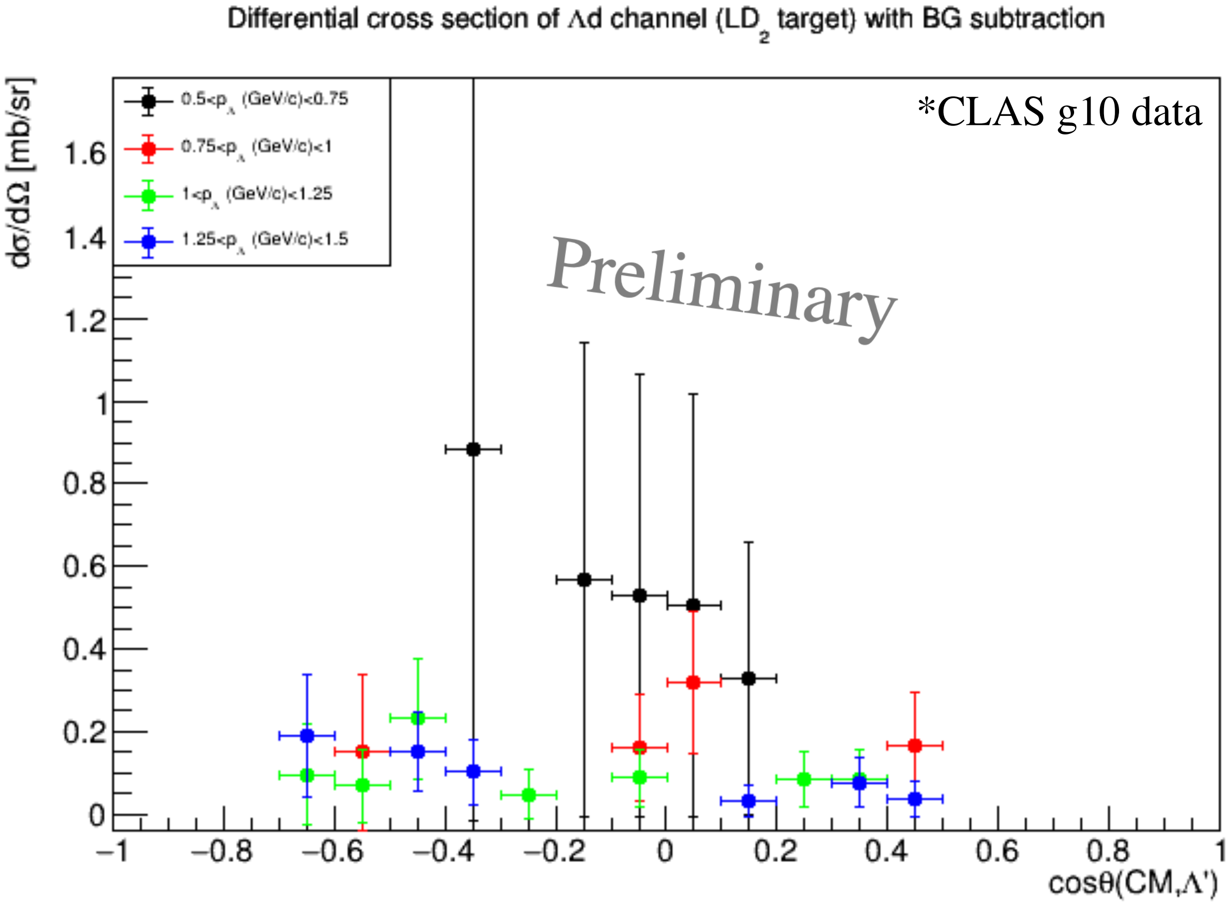
Invariant mass method
for the $\Lambda \rightarrow \pi^- p$ decay

- CLAS detects final state particles.
- E_γ range: 1.2 – 2.4 GeV
- p_Λ range: 0.5 – 1.5 GeV/c



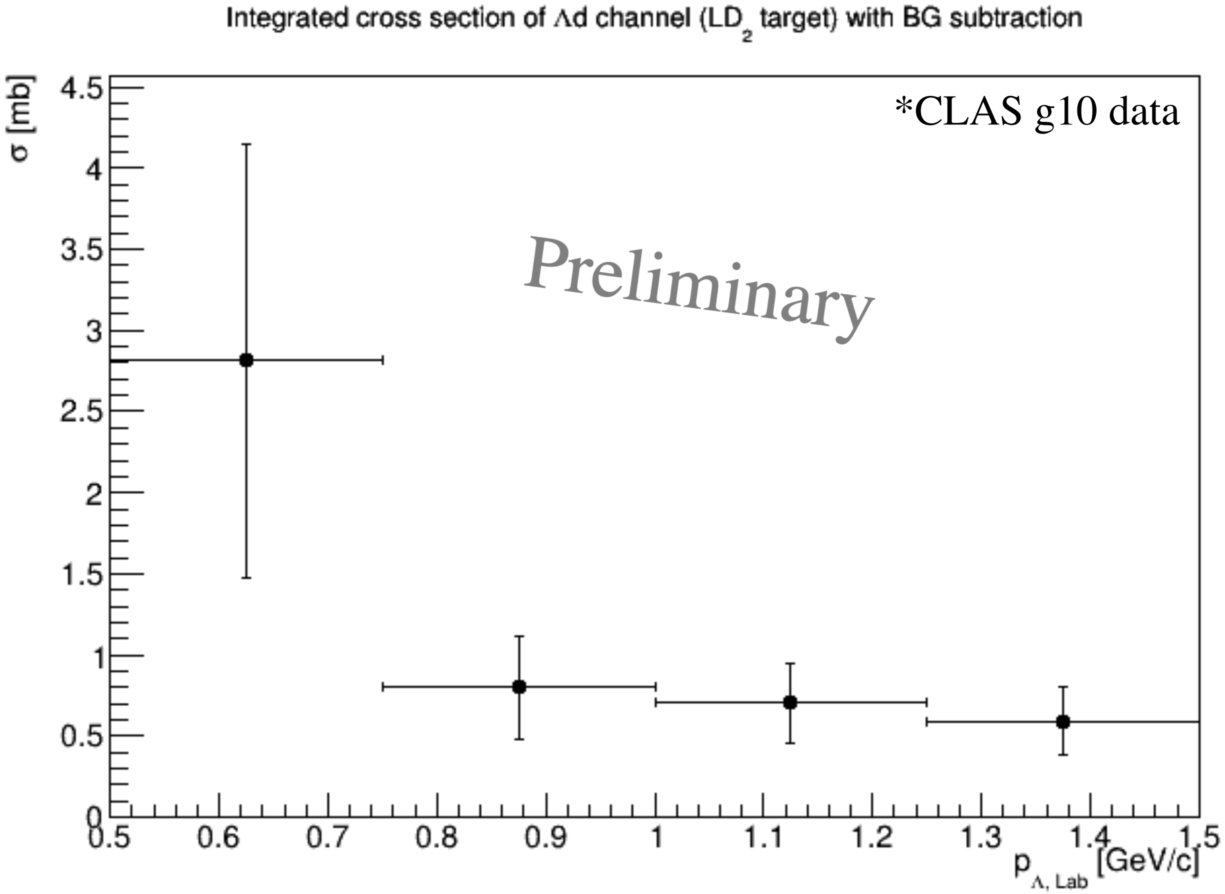


Estimated $d\sigma/d\Omega$ & σ_{int} of the Λd scattering



$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda d\ w/\ BG\ subt} = \frac{N_{\Lambda d,\ per-bin}}{E \cdot \tau \cdot L \cdot \Delta\Omega}$$

E: efficiency, τ: branching ratio of the Λ decay, L: luminosity,
$N_{\Lambda d,\text{ per-bin}}$: Λd yield every $\cos\theta_{CM,\Lambda'}$ bin



$$\sigma_{int,\ \Lambda d\ w/\ BG\ subt} = \sum_i \left(\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda d\ w/\ BG\ subt} \cdot \Delta\Omega \right)_i$$