Study of the Hyperon Nucleon Interaction with CLAS

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(CLAS collaboration)

Outline

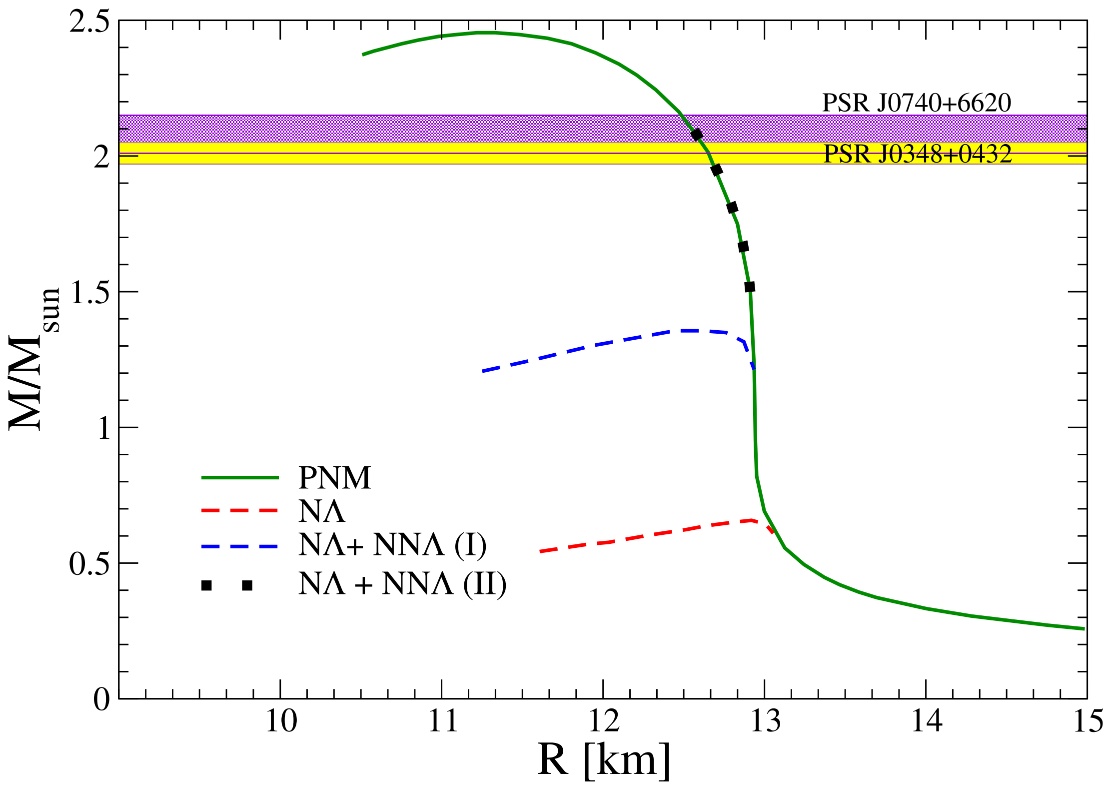
- Motivation
- Thomas Jefferson Laboratory
  - The CEBAF Large Acceptance Spectrometer
- The Hyperon-Nucleon Interaction via exclusive photoproduction reactions
  - Recent Results on Λp
  - Upcoming Results on $\Sigma^{-}p$ and Λd
  - Polarisation observables
- Summary and Outlook

Why study the Hyperon Nucleon Interaction?

- The understanding of both nucleon-nucleon and Hyperon-nucleon potential is necessary in order to have a comprehensive picture of the strong interaction
  - Understand composition of neutron stars
  - Understand hypernuclear structure and hyperon matter
  - Extend NN to a more unified picture of the baryon-baryon interaction

The Hyperon Puzzle

- Hyperons are expected to appear in the core of NS at ρ ~ 2 – 3 ρ_0
- Hyperons soften the EoS → Reduction on maximum NS mass
- Observation of NS with $M_G > 2M_s$ is incompatible with such soft EoS → Hyperon Puzzle



Hyperon Puzzle: Possible solutions

YY and YN forces

YNN and YYN three body forces

D. Lonardoni, Phys. Rev. Lett. 114, 092301 (2015)
J. Haidenbauer et al., Eur. Phys. J. A 53, 121 (2017)
I. Vidana, Proc. R. Soc. A 474, 20180145 (2018)

The Hyperon Puzzle

YN interaction is poorly constrained

- Total of <1300 observed Λp → Λ p: Difficulties associated with performing high-precision scattering experiments with hyperon beams
  - Large uncertainties in the scattering lengths

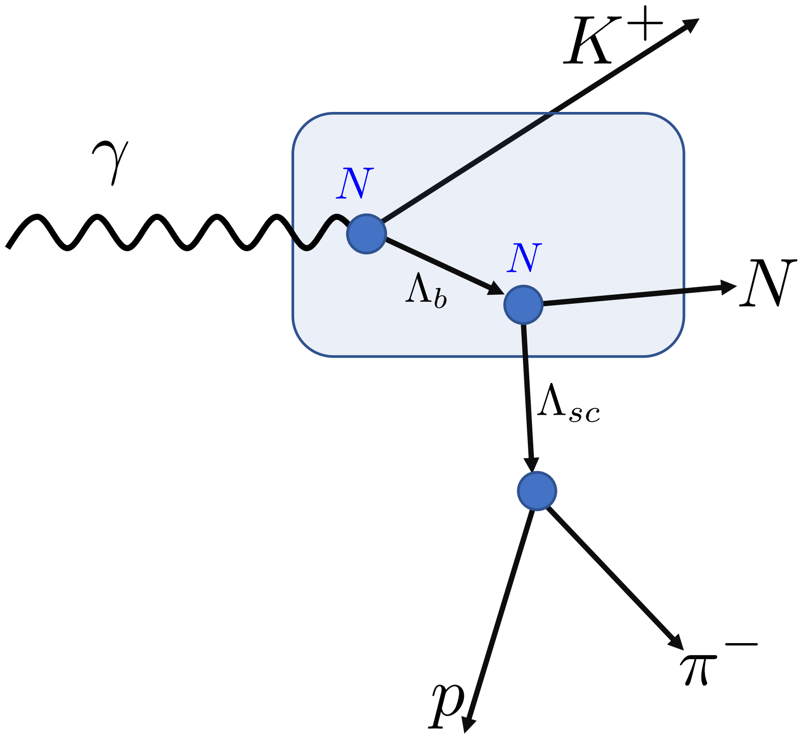
$$a(^1S_0) = -0.7 - -2.6 \text{ fm}$$

$$a(^3S_1) = -1.7 - -2.15 \text{ fm}$$

Experimental data are needed to place constraints on the interaction

- Complementary approaches
  - Hypernuclear studies
  - **Final state interactions and two step processes**

Exclusive photoproduction reactions



$\tau_\Lambda = 2.6 \times 10^{-10}\ s$
$c\tau_\Lambda = 7.89\ cm$

$BR(p\pi^-) = 63.9\%$

- Two-step process where Hyperon rescatters with secondary nucleon
- Kaon identification allows tagging of hyperon beam
- 4π detector allows full reconstruction of the event
- Hydrogen and deuterium targets

Cross sections
- Λp
- Σ^-p
- Λd

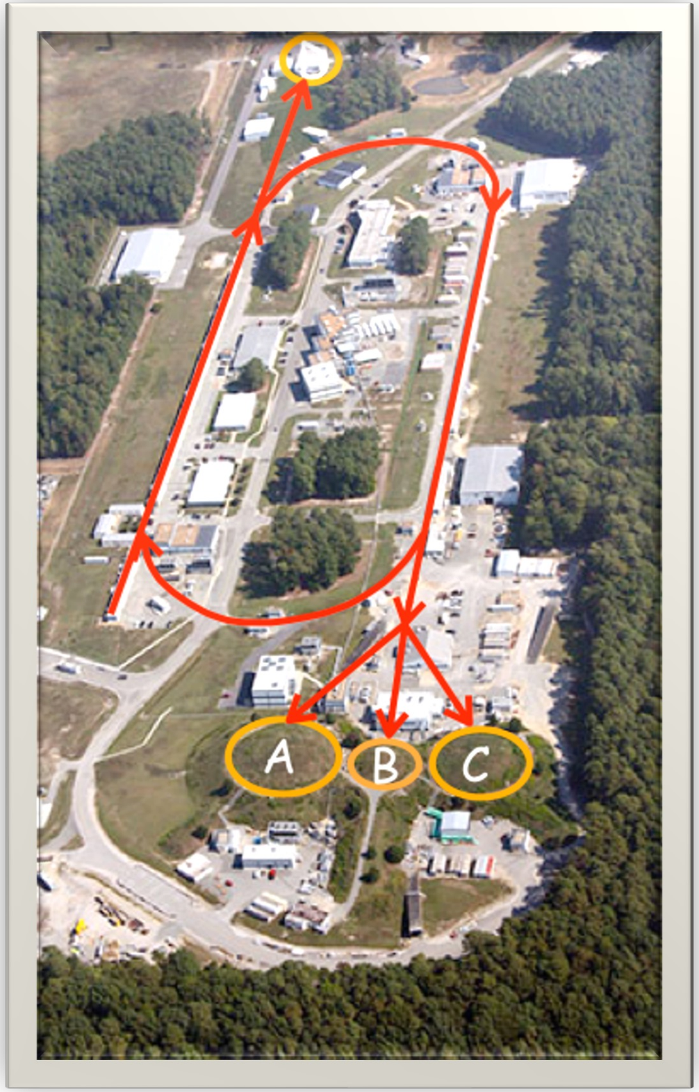
Polarization observables
- Λn
- Σ^-p
- Λd
- Λp

Cross section approach benchmarked using pp scattering

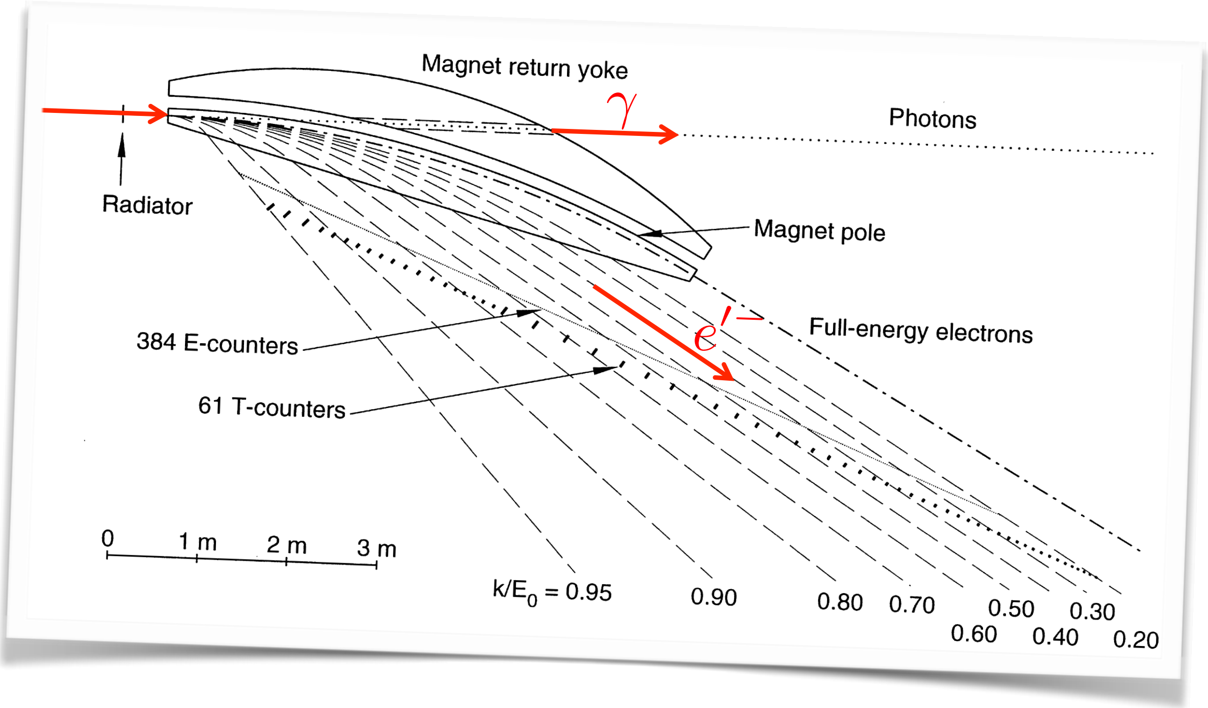
Thomas Jefferson Laboratory

6-GeV era: 1995-2012

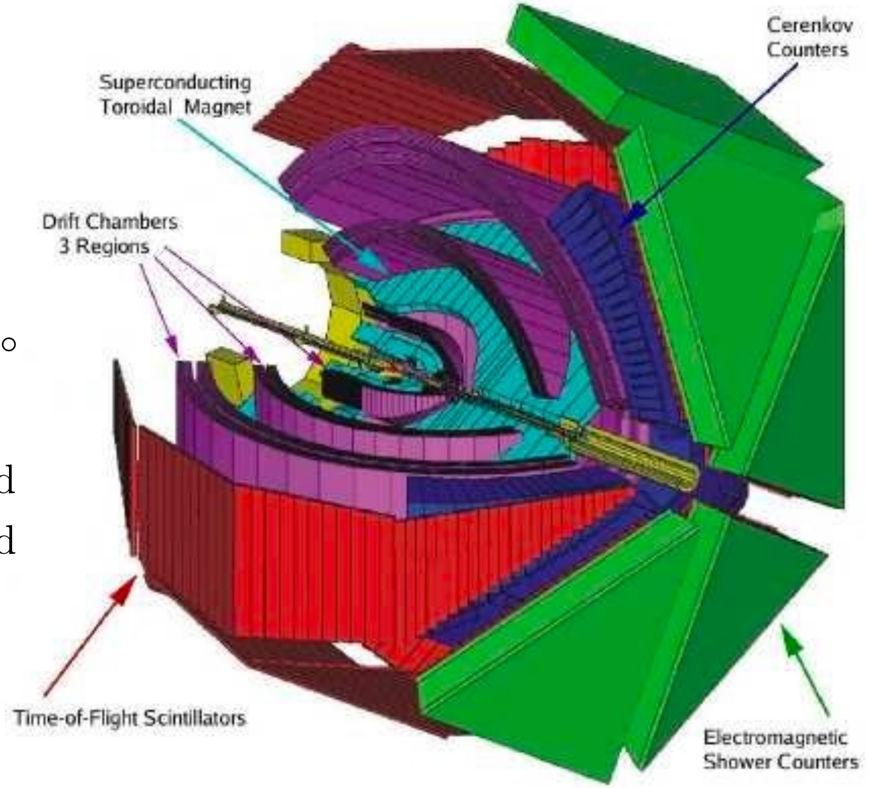
- C.W. electron beam: 2-ns wide bunch period, 0.2-ps bunch length
- Polarized Source: Pe ~ 86%
- Beam energies up to E_0 = 6 GeV
- Beam Current up to 200 μA



Hall-B: The CLAS detector and Tagger facility

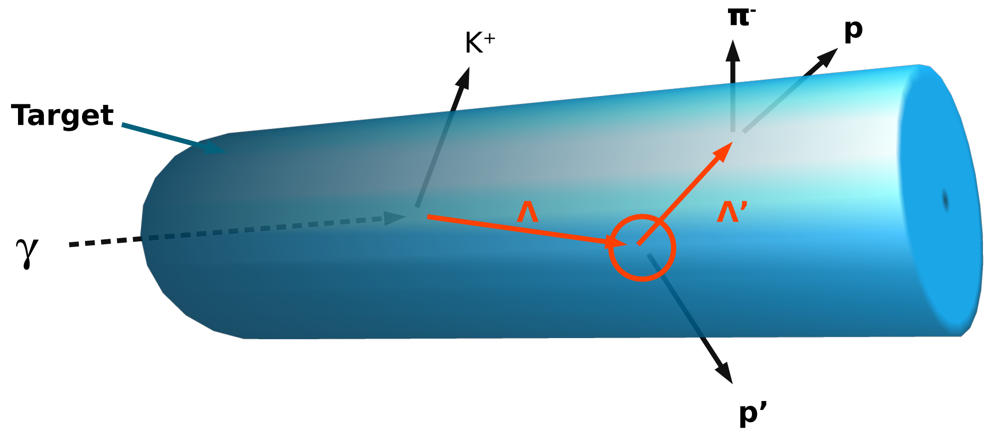


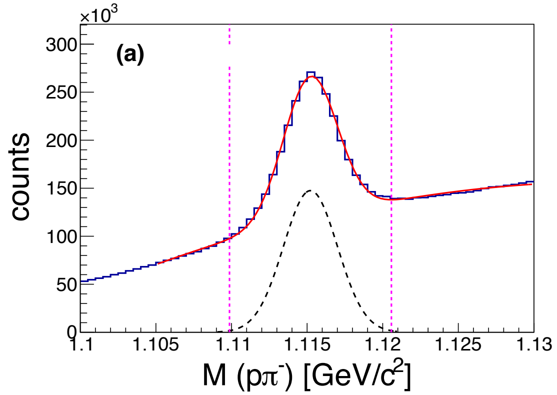
$$8^\circ < \theta < 140^\circ$$
$$\phi \sim 1.7\pi$$
$$\sigma_\theta \sim 1\ \mathrm{mrad}$$
$$\sigma_\phi \sim 4\ \mathrm{mrad}$$
$$\sigma_p/p \sim 1\%$$

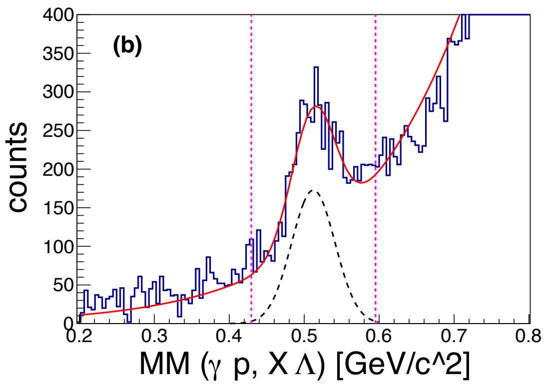


Improved Λp Elastic Scattering Cross Sections

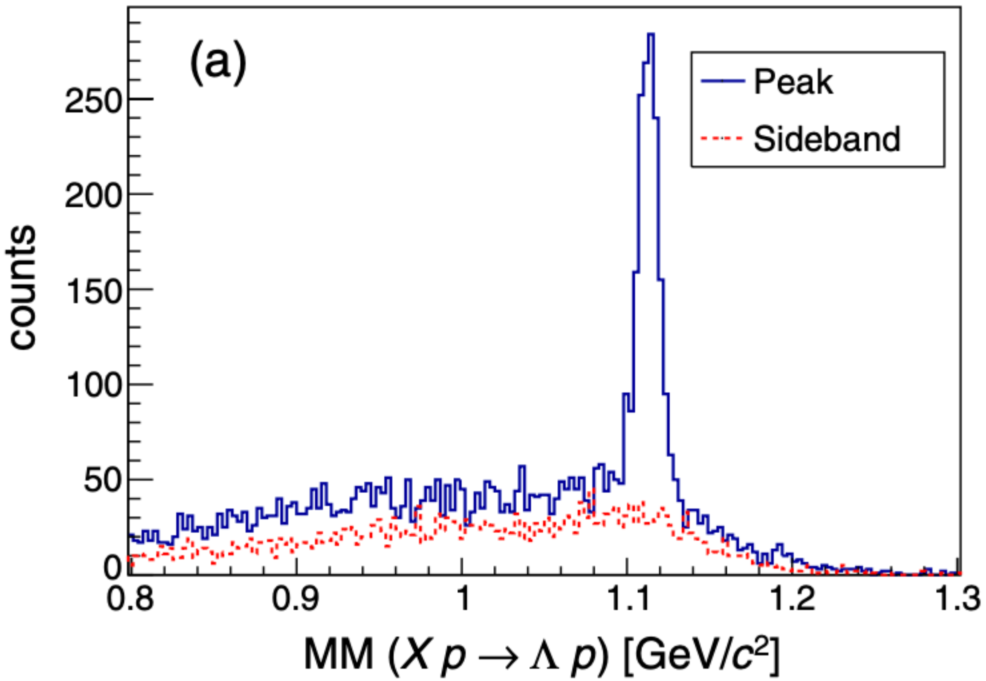
https://doi.org/10.1103/PhysRevLett.127.272303







Joey Rowley, Ken Hicks - OU



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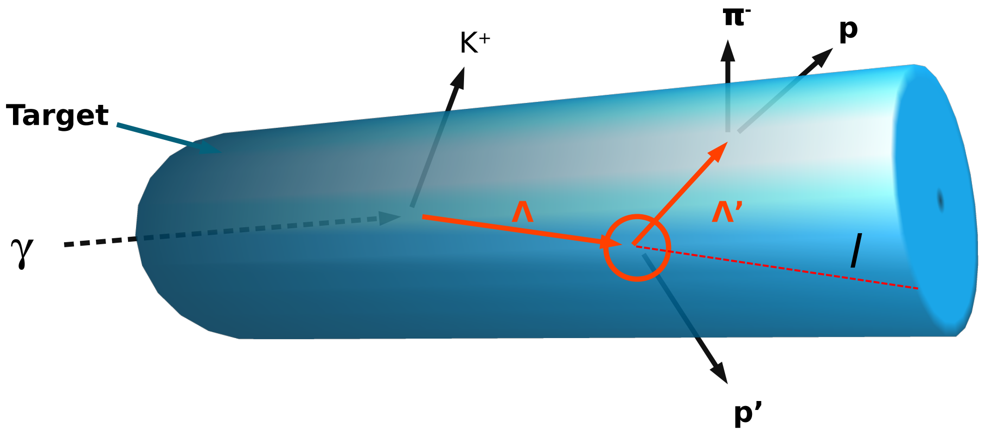


$$\sigma(p_\Lambda) = \frac{Y(p_\Lambda)}{A(p_\Lambda) \times \mathcal{L}(p_\Lambda) \times \Gamma}$$

$$\mathcal{L}(p_\Lambda) = \frac{N_A \times \rho_T \times l}{M} N_\Lambda(p_\Lambda)$$

$$\frac{N_\Lambda}{\mathcal{L}_\gamma} = \frac{d\sigma}{d\Omega}(2\pi)[\Delta\cos(\theta)] \qquad P(x) = \exp\left[-\frac{M}{p}\frac{x - x_0}{\tau}\right]$$

Cross section determination challenging

- Detector acceptance
- Detector efficiency
- **Hyperon beam luminosity**

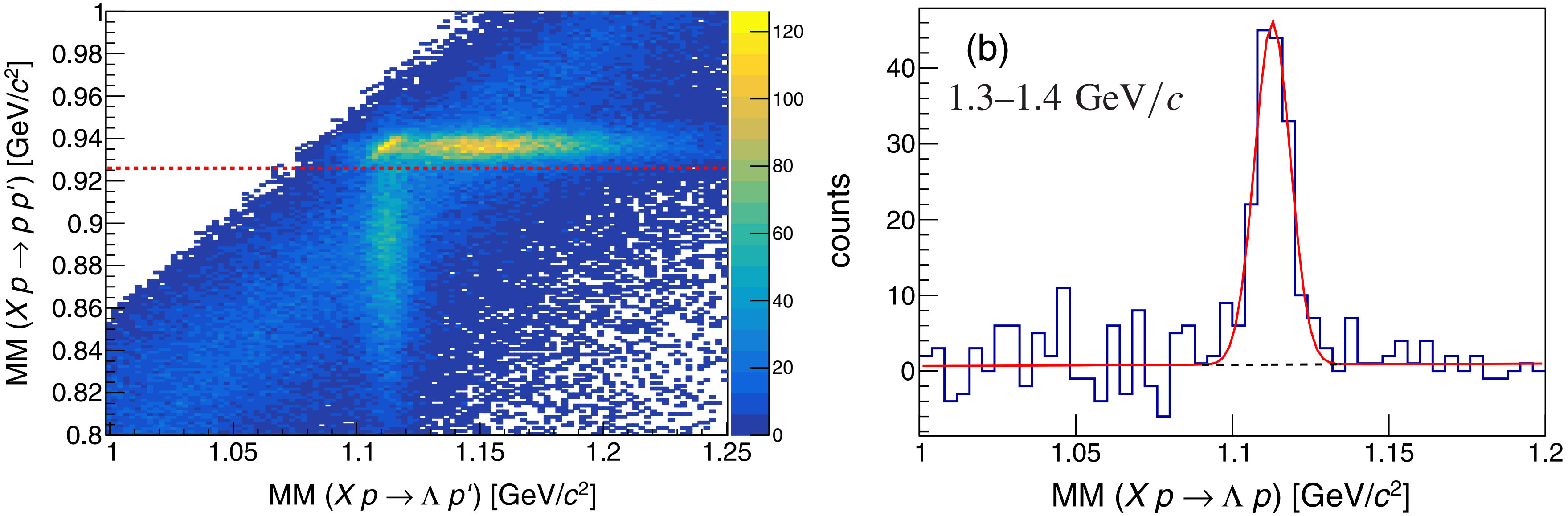
Order of magnitude higher statistics

L: Path length determined from realistic simulations, accounting for beam size and kinematic dependence of the photoproduction cross section, as well as the decay length of hyperons

Improved Λp Elastic Scattering Cross Sections

https://doi.org/10.1103/PhysRevLett.127.272303

- Background contribution
  - $\gamma p \rightarrow p\,\pi^+\pi^-$
  - $\gamma p \rightarrow K^+\Sigma^0\ (\Lambda\gamma)$
  - $p(\Lambda)p \rightarrow pp$



Improved Λp Elastic Scattering Cross Sections

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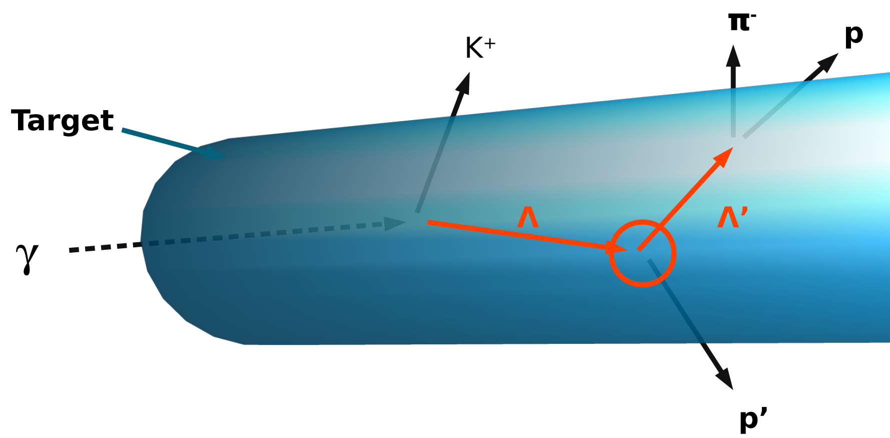
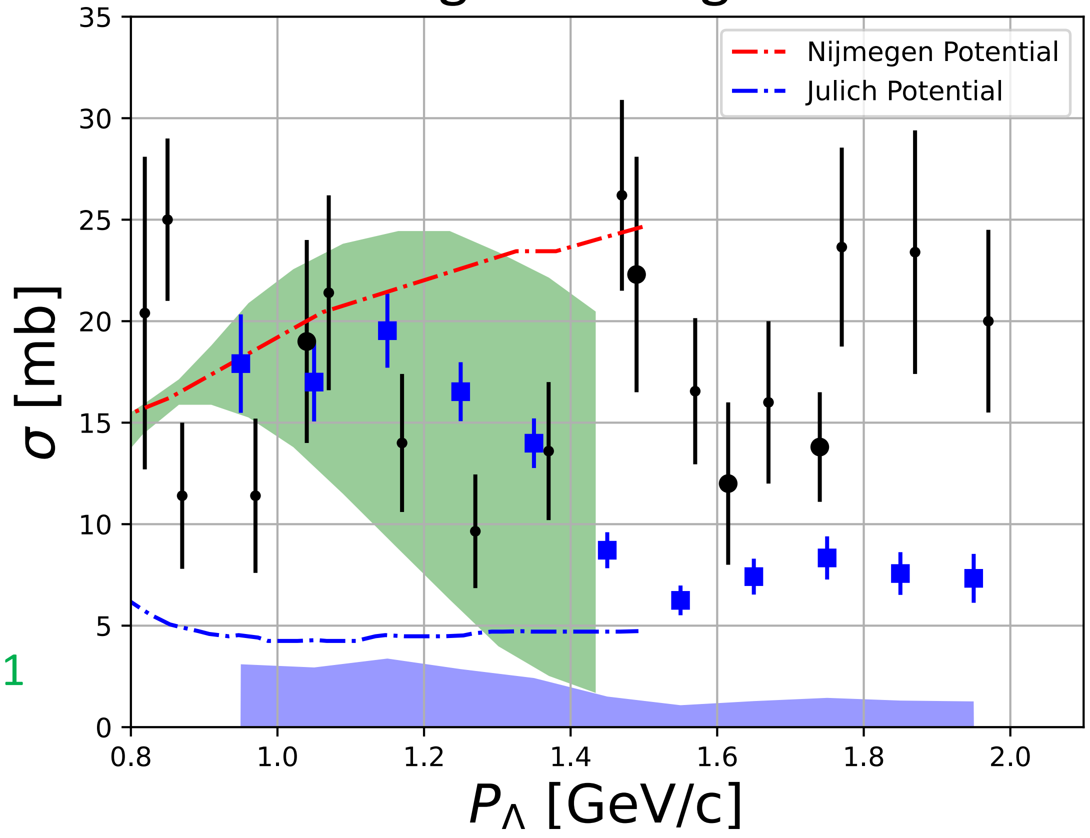


Order of magnitude higher statistics

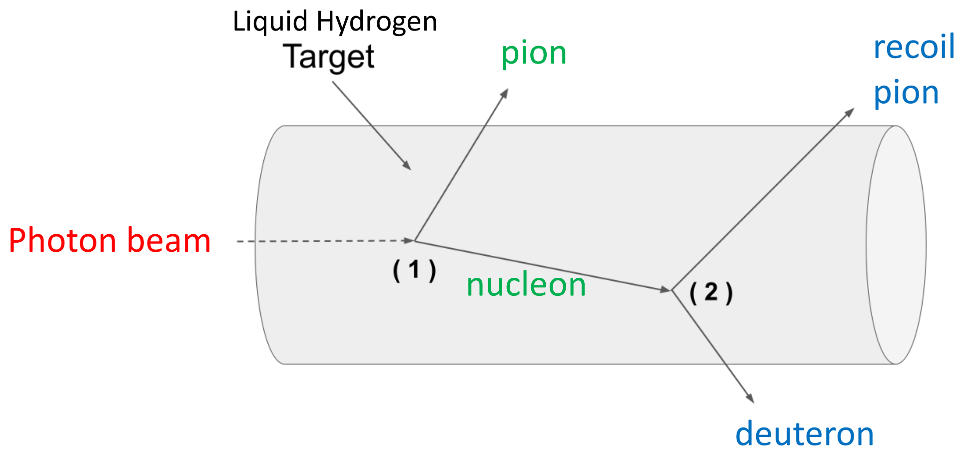


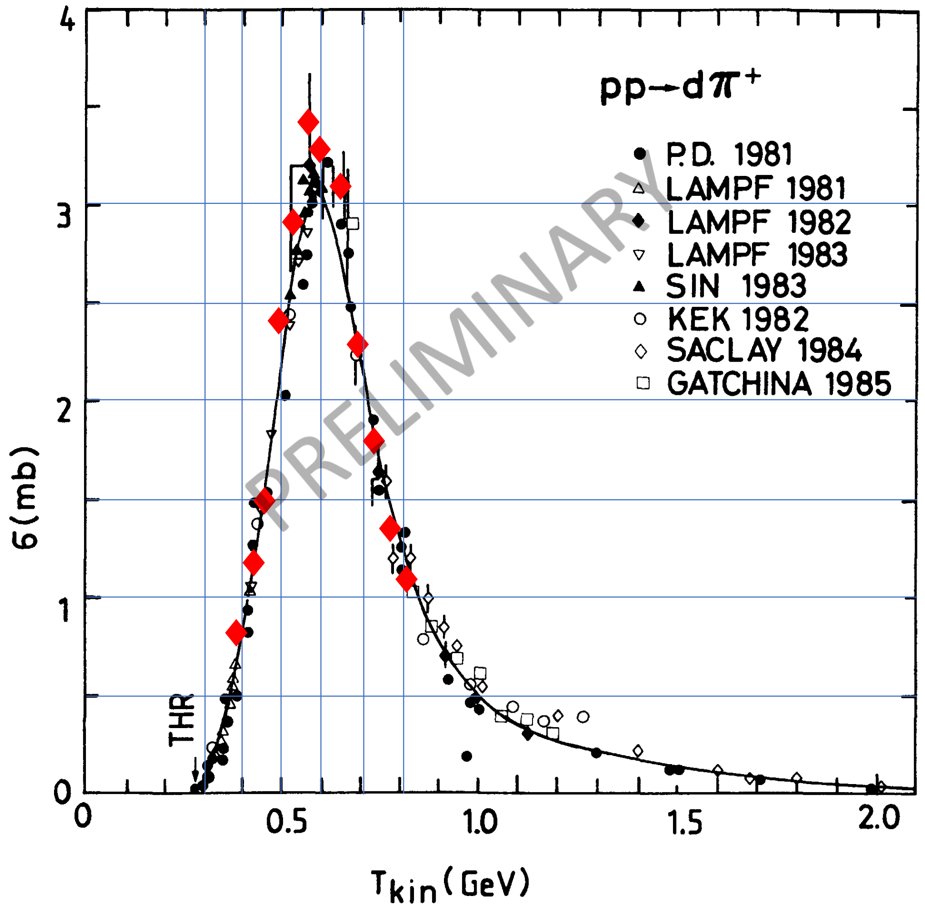
Calculation at next to leading order from chiral effective field theory (Haidenbauer *Eur. Phys. J. A* **56,** 91 (2020))

J. Haidenbauer and U.-G. Meißner, Phys. Rev. C 72, 044005 (2005)

T. A. Rijken, V. G. J. Stoks, and Y. Yamamoto, Phys. Rev. C 59, 21 (1999).

Approach confirmation via pp scattering

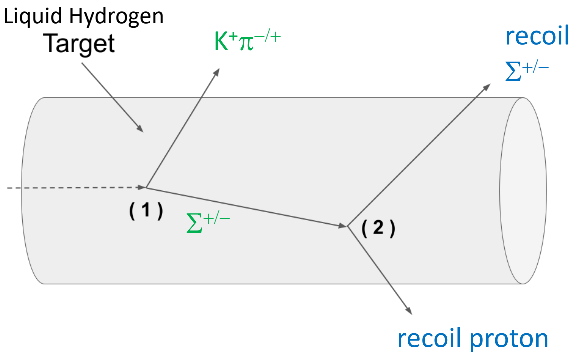


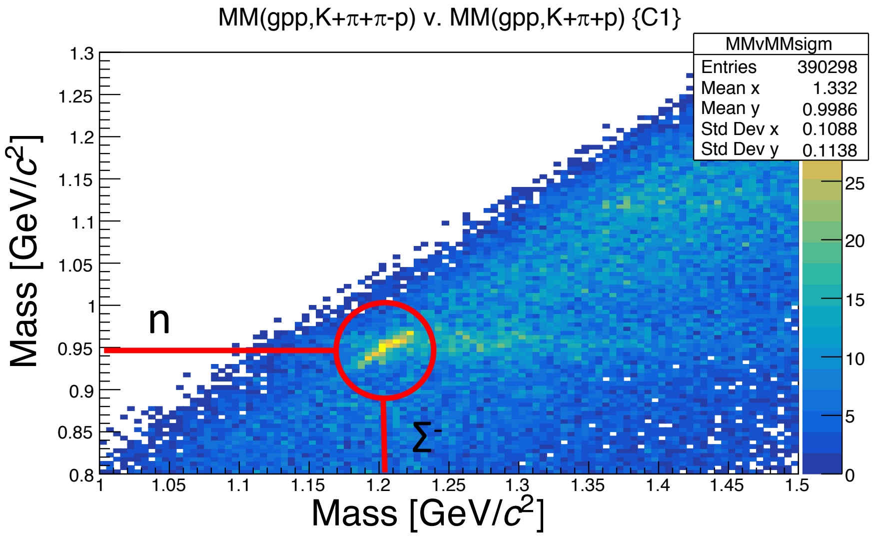


Statistical uncertainties -> size of marker
Systematic uncertainties of the order of 10%
Additional points at higher energies -- TBD

Σp Elastic Scattering Cross Sections

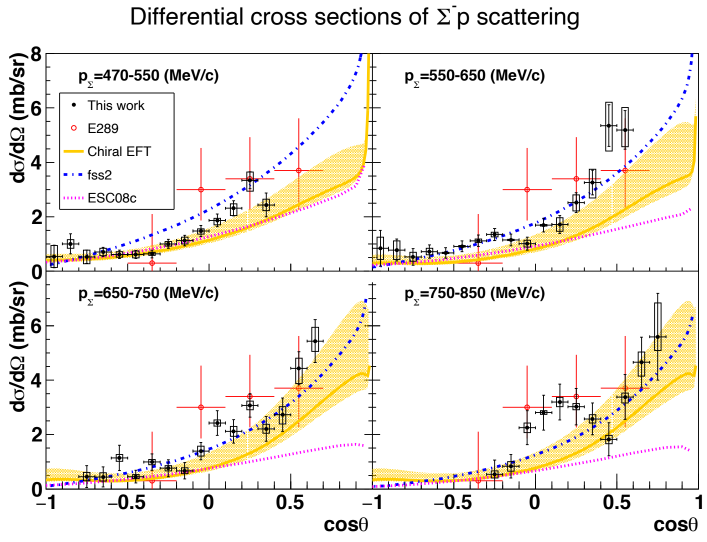
Approach identical to Λp channel

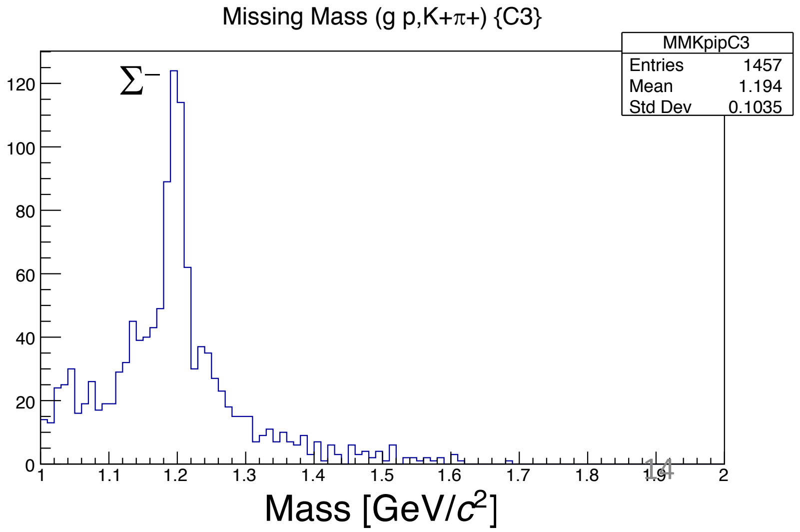




Recent results from JPARC Phys. Rev. C **104**, 045204

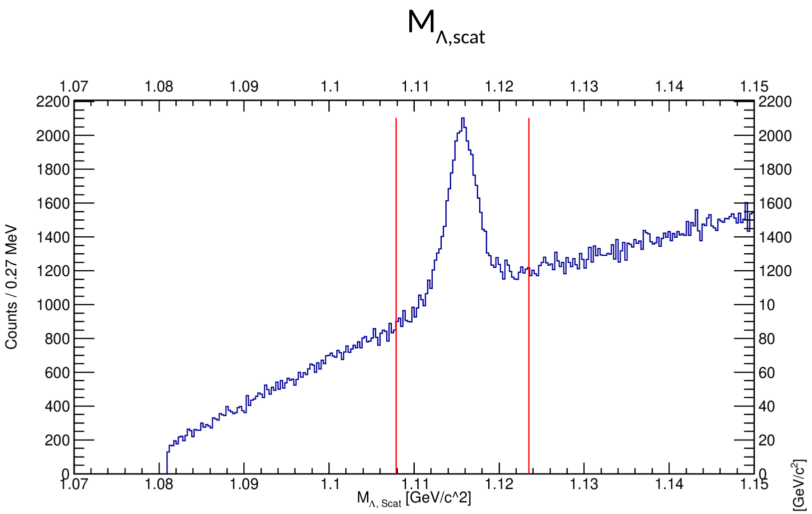
Extend momentum range

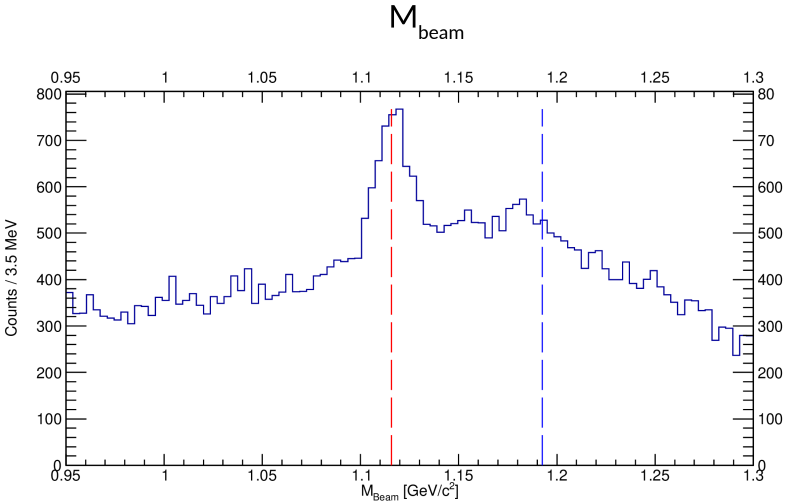


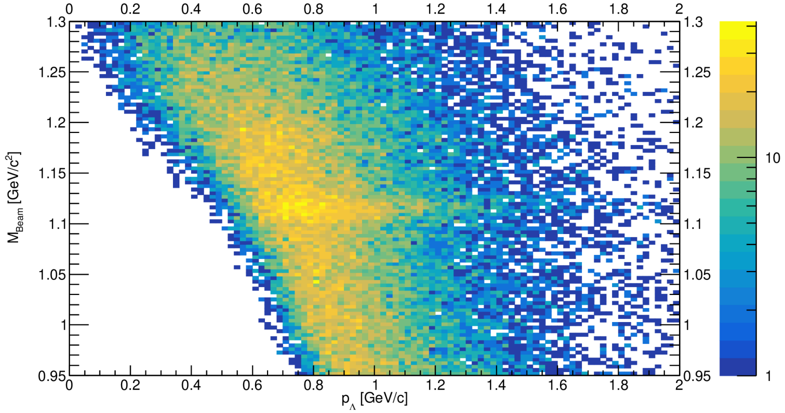


ΛNN Elastic Scattering Cross Section via Λd

- Cross section determination:
  - p_Λ >0.7 GeV/c
  - cos(θ) between -0.6 and 0.9
- > 4000 events



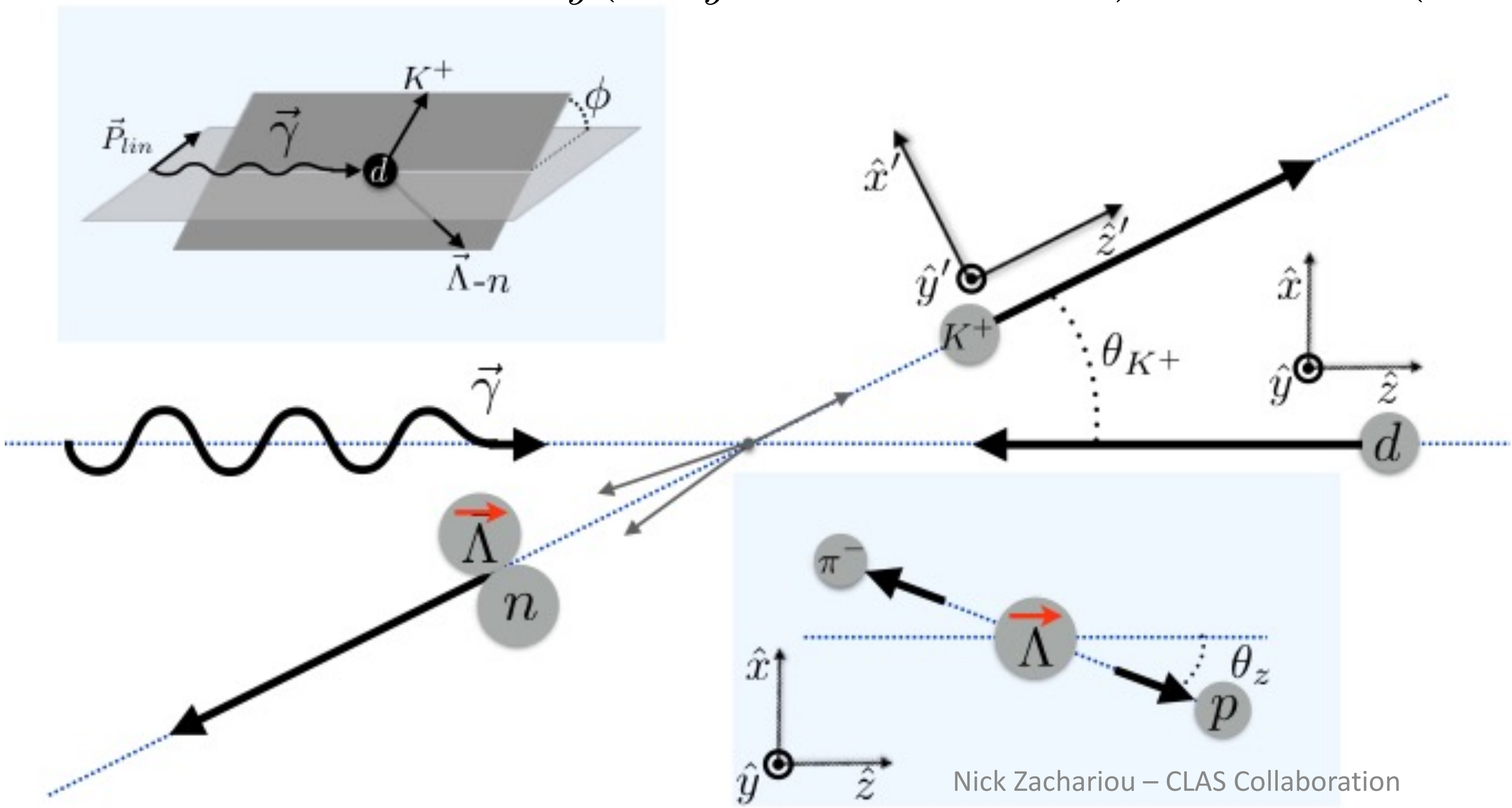




Brandon Tsumeo, Yordanka Ilieva - USC

Polarisation observables in Hyperon Photoproduction

$$\frac{d\sigma}{d\Omega} = \sigma_0\{1 - P_{lin}\Sigma\cos 2\phi + \alpha\cos\theta_x(-P_{lin}O_x\sin 2\phi - P_{circ}C_x)$$
$$- \alpha\cos\theta_y(-P_y + P_{lin}T\cos 2\phi) - \alpha\cos\theta_z(P_{lin}O_z\sin 2\phi + P_{circ}C_z)\}$$



Beam Polarisation

Linearly polarized

Circularly polarized

Λ Recoil Polarisation

Self-analysing power

α=0.75

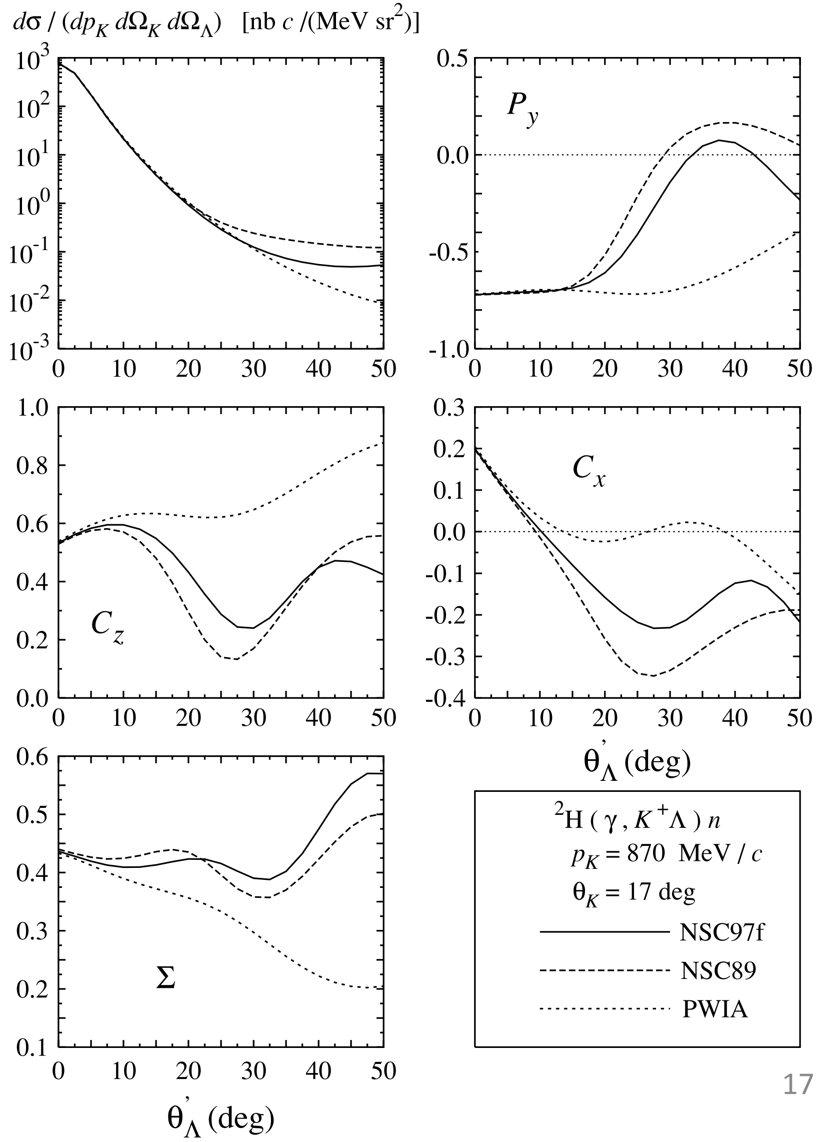
Polarisation Observables Λn

- Existing *YN* models allow the calculation of single and double polarization observables

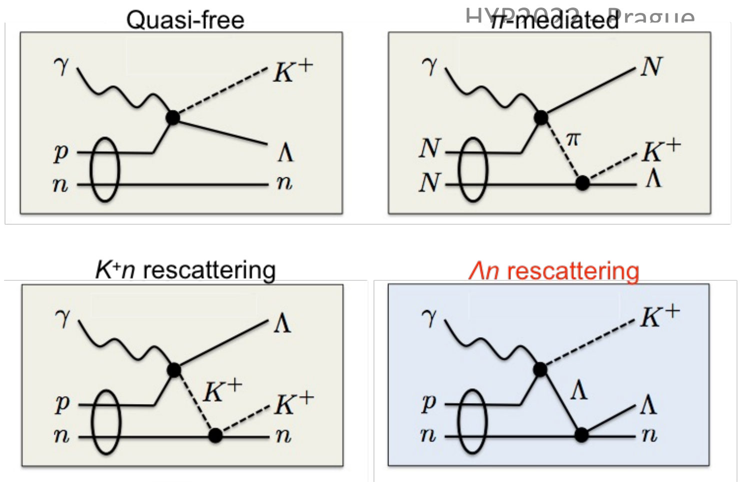
- Two *YN* potentials (NSC97F and NSC89) give the correct hypetrition binding energy

- NSC97F and NSC89 lead to very different predictions of polarisation observables at some kinematics

K. Miyagawa et al., Phys. Rev. C 74, 034002 (2006)

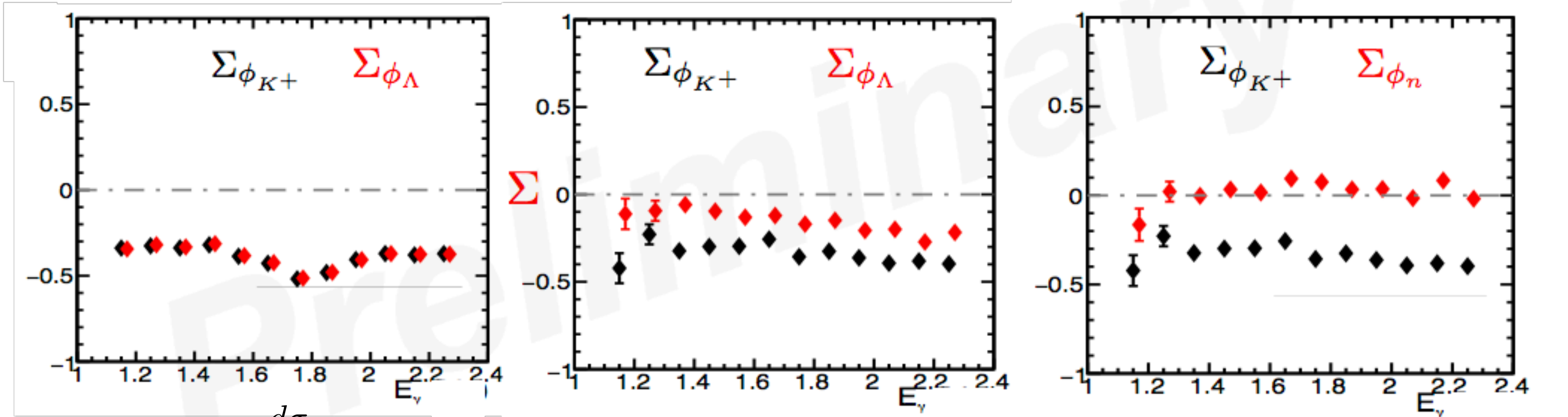


Polarisation Observables Λn



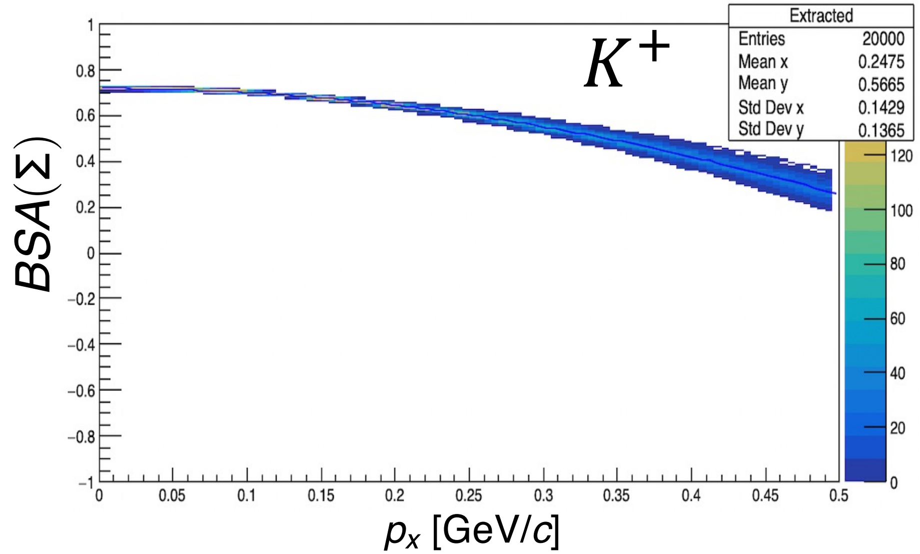
QuasiFree data

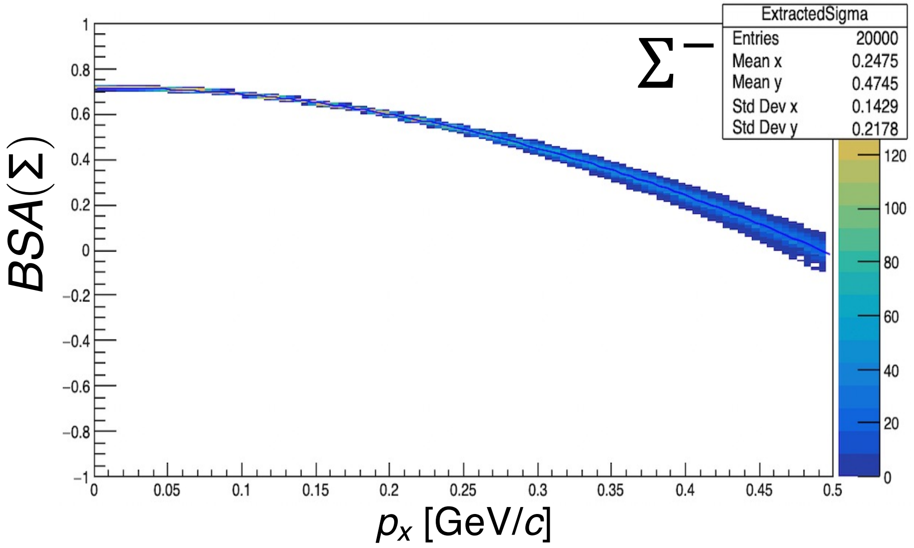
FSI data

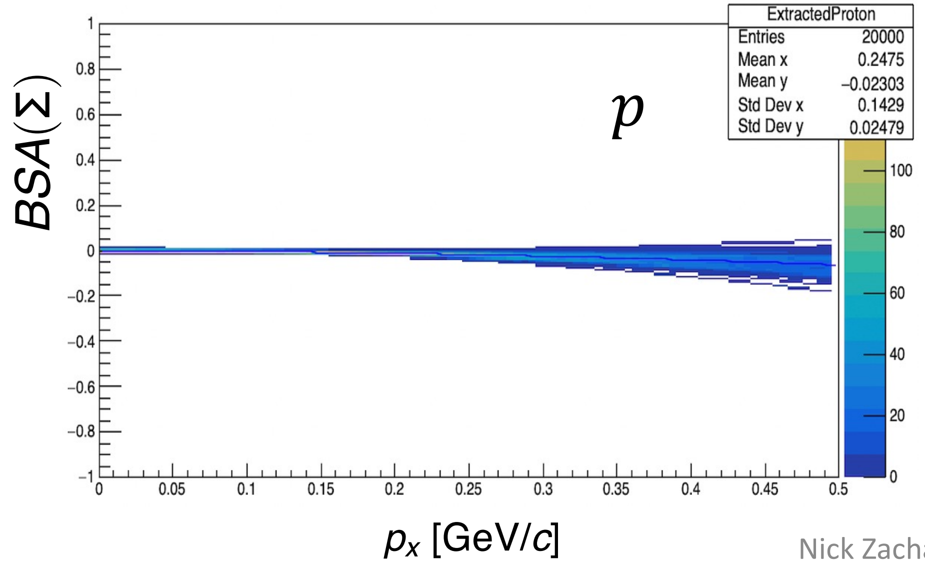


$$\frac{d\sigma}{d\Omega} = \sigma_0\{1 - P_{lin}\Sigma\cos 2\phi + \alpha\cos\theta_x(-P_{lin}O_x\sin 2\phi - P_{circ}C_x)$$
$$- \alpha\cos\theta_y(-P_y + P_{lin}T\cos 2\phi) - \alpha\cos\theta_z(P_{lin}O_z\sin 2\phi + P_{circ}C_z)\}$$

Polarisation Observables Σp

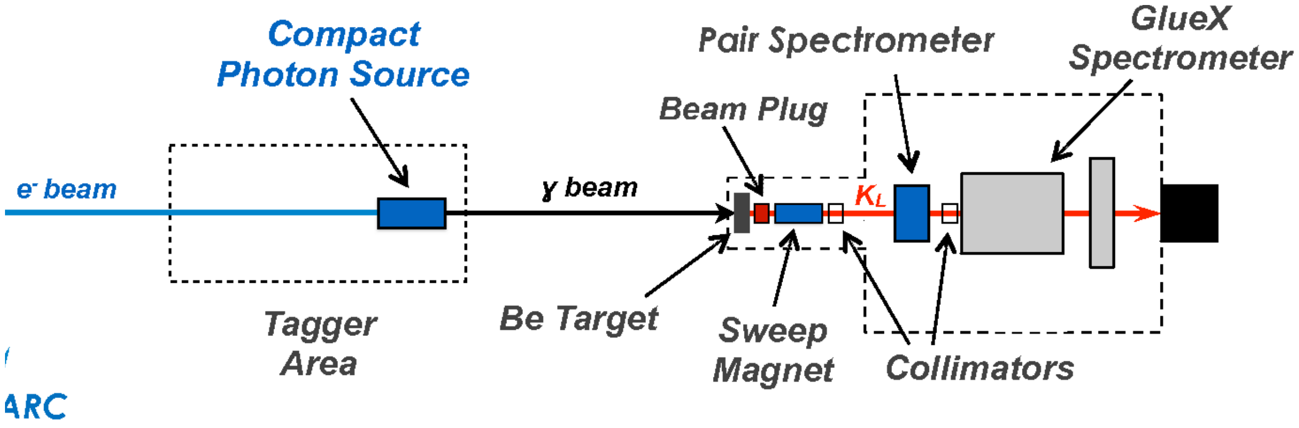


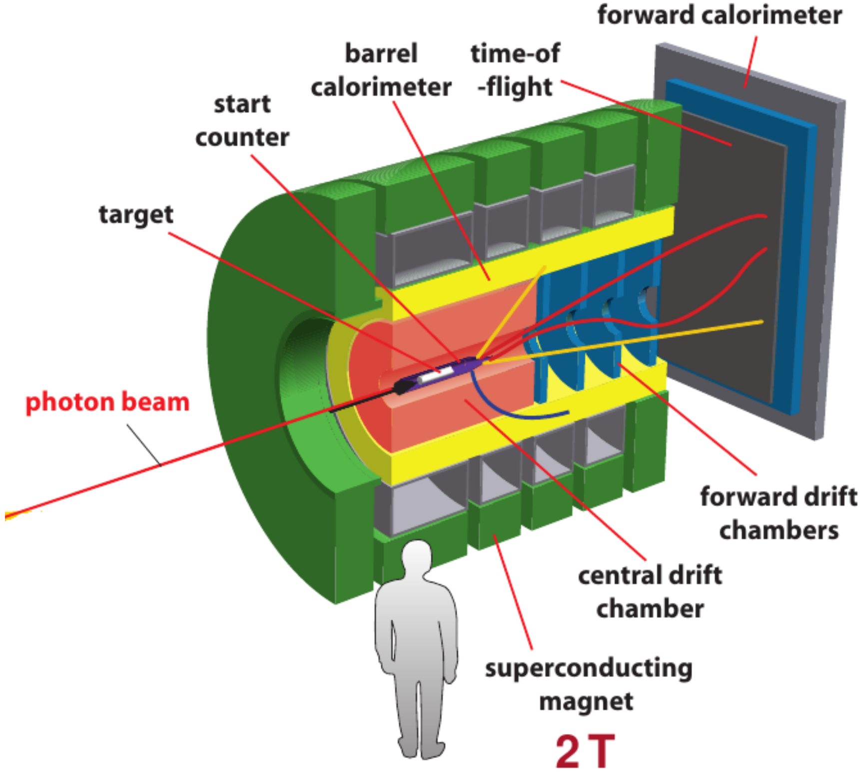




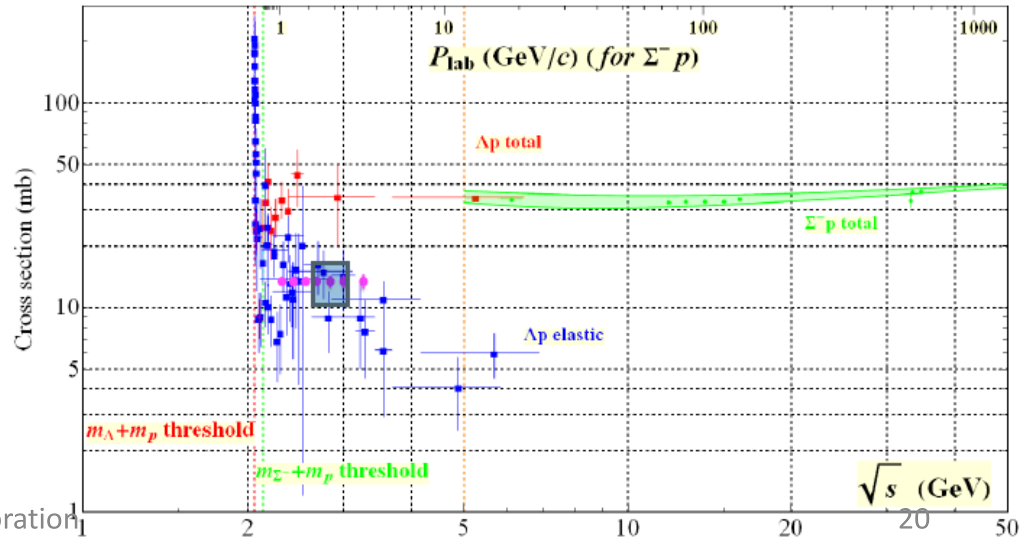
- Results extrapolated to zero missing-momentum agree with QF study
- Large dilutions at higher missing momenta due to FSI
- Relative dilutions can be attributed to the various FSI contributions
- Different reaction mechanisms cause unique combinations of
- $\Sigma_K(p_x)$, $\Sigma_\Lambda(p_x)$, and $\Sigma_p(p_x)$

Coming up!!!





- K-Long facility approved – Online 2025
- Compact photon source – 6 order mag. higher luminosity
- 3 orders of mag. higher cross section for hyperon production
- Access to Cascade-N interaction



Summary and outlook

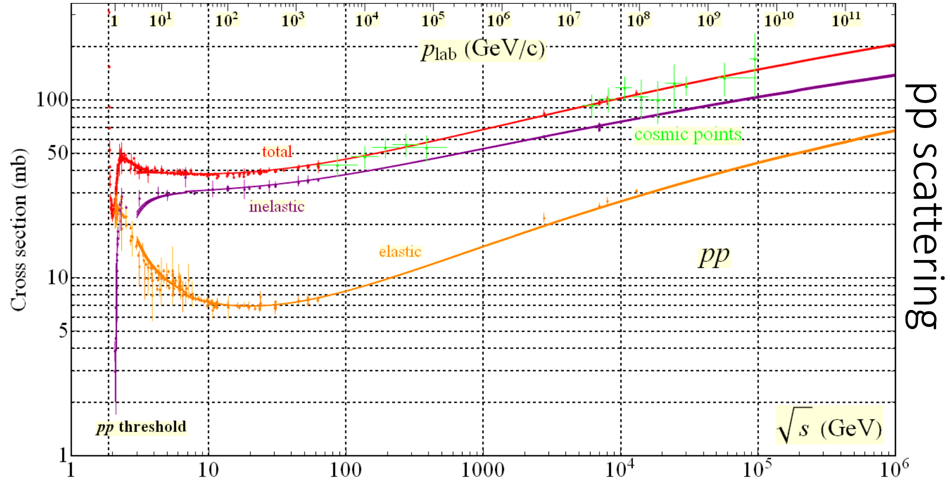
- Exclusive hyperon photoproduction provides us with tools to study the Hyperon-Nucleon interaction
- Access to both cross section and polarization observables
- First results on Λp elastic scattering published last year
- Ongoing efforts to establish Σp cross section
- Ongoing efforts to establish Λd cross section → access three body forces
- Polarisation observables provide additional constraints
- KLF facility to open door for doubly strange hyperon interactions with nucleons.
- Exciting results in the pipeline!!!

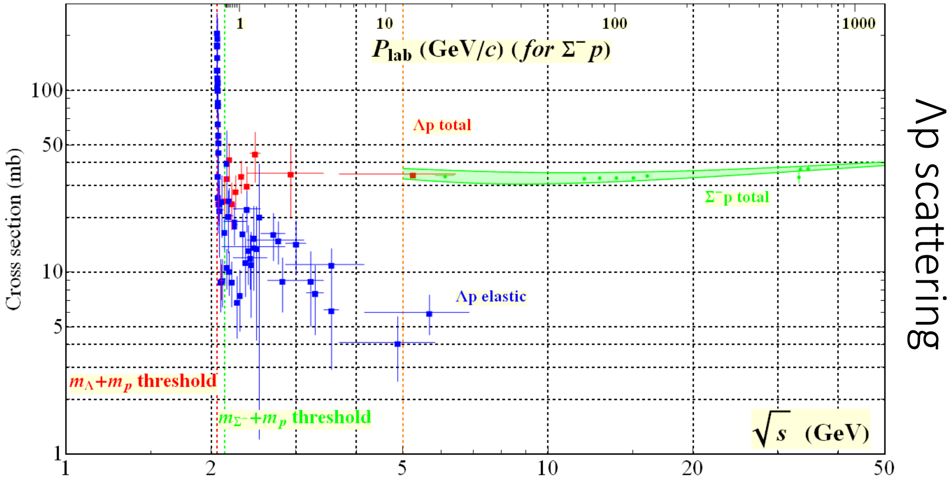
Thank you

What is available?

Best way to obtain information is through YN→YN





Plots from PDG 2018

Total of <1300 observed Λp → Λ p

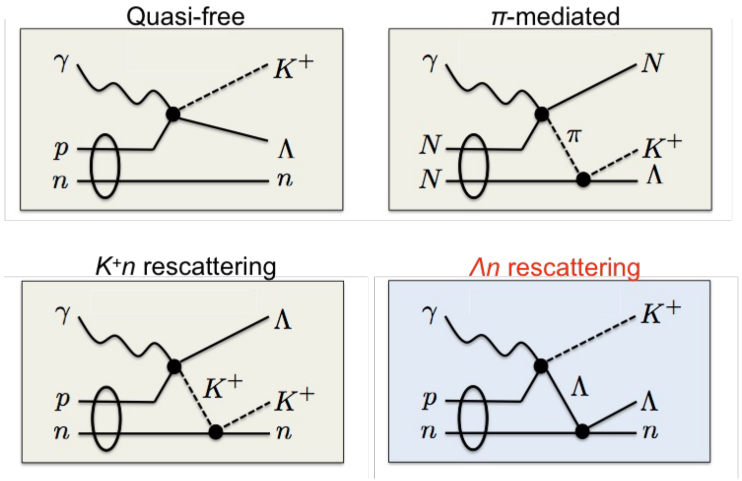
Λ source	Detector	p_Λ	$N_{\Lambda p \to \Lambda p}$
$\pi^- p \to \Lambda K^0$	LH_2 BC	0.5–1.0	4
$\pi^- p \to \Lambda K^0$	LH_2 BC	0.4–1.0	14
$K^- N \to \Lambda \pi$	Propane BC	0.3–1.5	26
$K^- N \to \Lambda \pi$	Freon BC	0.5–1.2	86
$K^- A \to \Lambda X$	Heavy Liquid BC	0.15–0.4	11
$K^- p \to \Lambda X$	LH_2 BC	0.12–0.4	75
$nA \to \Lambda X$	Propane BC	0.9–4.7	12
$K^- p \to \Lambda X$	LH_2 BC	1.0–5.0	68
$K^- p \to \Lambda X$	LH_2 BC	0.1–0.3	378
$K^- p \to \Lambda X$	LH_2 BC	0.1–0.3	224
$K^-\mathrm{Pt} \to \Lambda X$	LH_2 BC	0.3–1.5	175
$p\mathrm{Pt} \to \Lambda X$	LH_2 BC	1.0–17.0	109
$p\mathrm{Cu} \to \Lambda X$	LH_2 BC	0.5–24.0	71

Difficulties performing high-precision scattering experiments with short-lived beams

Complimentary approaches: Hypernuclear studies have uncertainties associated with medium modification as well as many-body effects

Polarisation Observables

Different reaction mechanisms cause unique combinations of
$\Sigma_K(p_x)$, $\Sigma_\Lambda(p_x)$, and $\Sigma_n(p_x)$



- $\frac{\Sigma_{det}}{\Sigma_{QF}} = F\left(\frac{N_{FSI}}{N_T}\right)$ determined from generated data
- Kinematic footprint of each mechanism into lookup tables
- Extract $\frac{\Sigma_{det}}{\Sigma_{QF}}(p_x)$ from data and determine $\left(\frac{N_{FSI}}{N_T}\right)$ from comparison with lookup tables

ML techniques that provides us with kinematic dependence of FSI-to-total ratios of each mechanism

Polarisation observable provides us with means to study YN reducing model dependent constraints