Strangeness in Neutron Stars

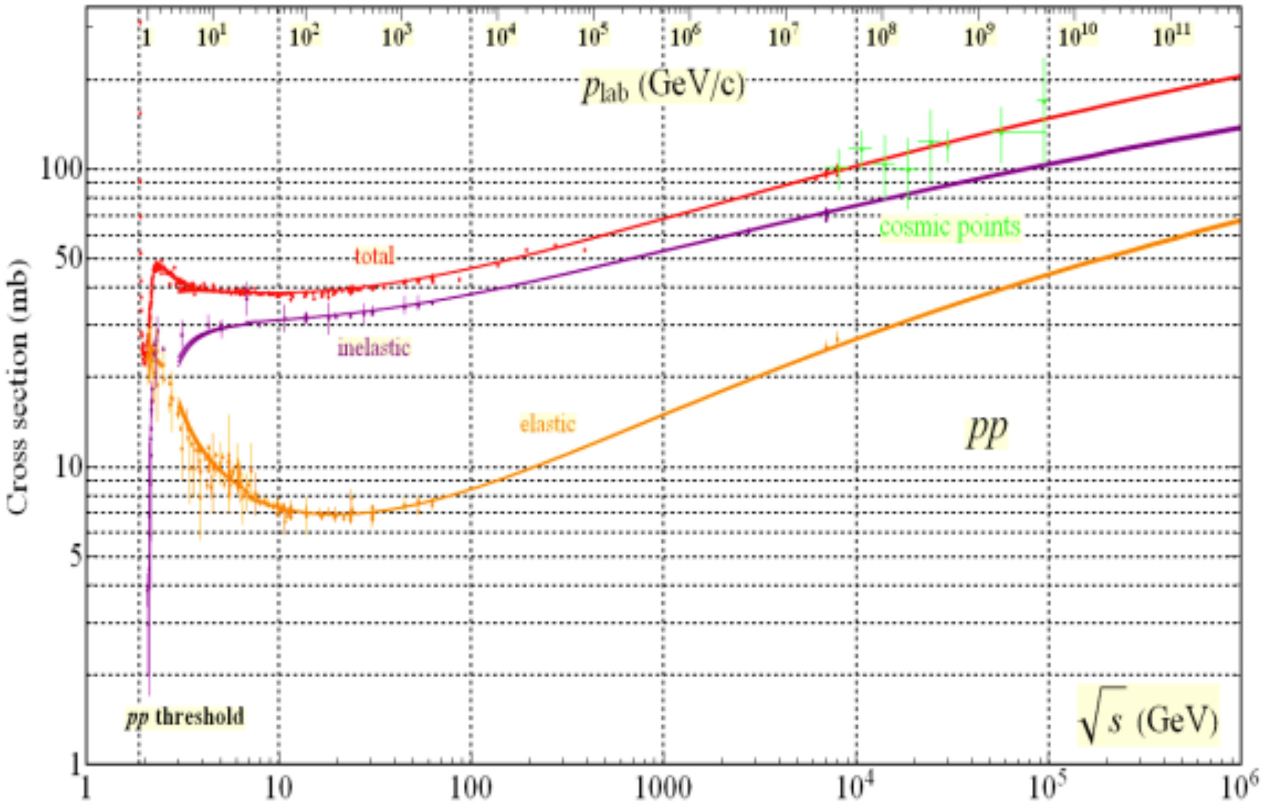
Constraining the Hyperon Nucleon Interaction

Nicholas Zachariou

(CLAS collaboration)

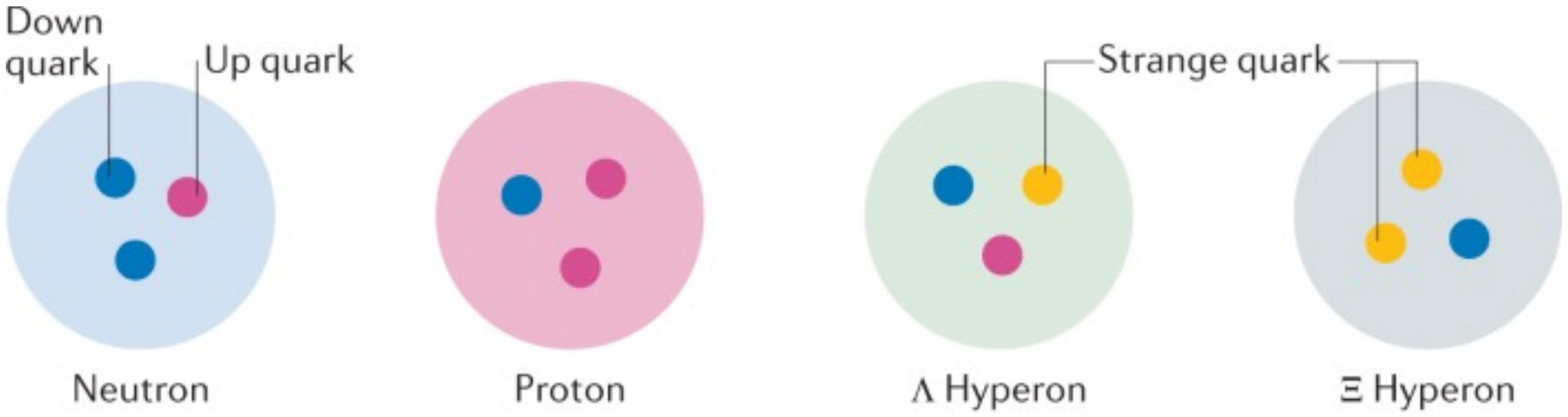
The Nucleon-Nucleon interaction

- Gain insights into the structure of atomic nuclei
- Understand the properties of nuclear matter
- Understand the strong interaction (QCD) and how quarks and gluons interact in nuclear matter
- ``Easy" to conduct experiments with nucleon beams/targets
- Plethora of experimental data
- Fundamental interactions well understood



The Baryon-Baryon interaction

What happens when we replace one of the quarks in the nucleon with a strange quark?

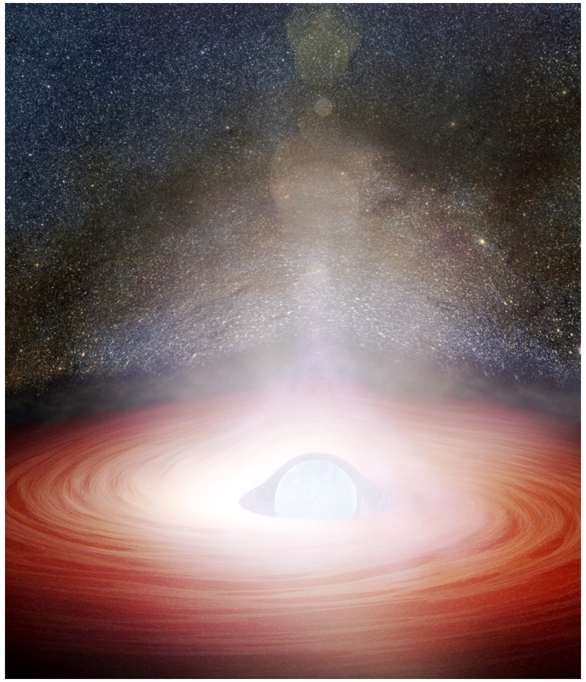


Different properties
Different fundamental interaction

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

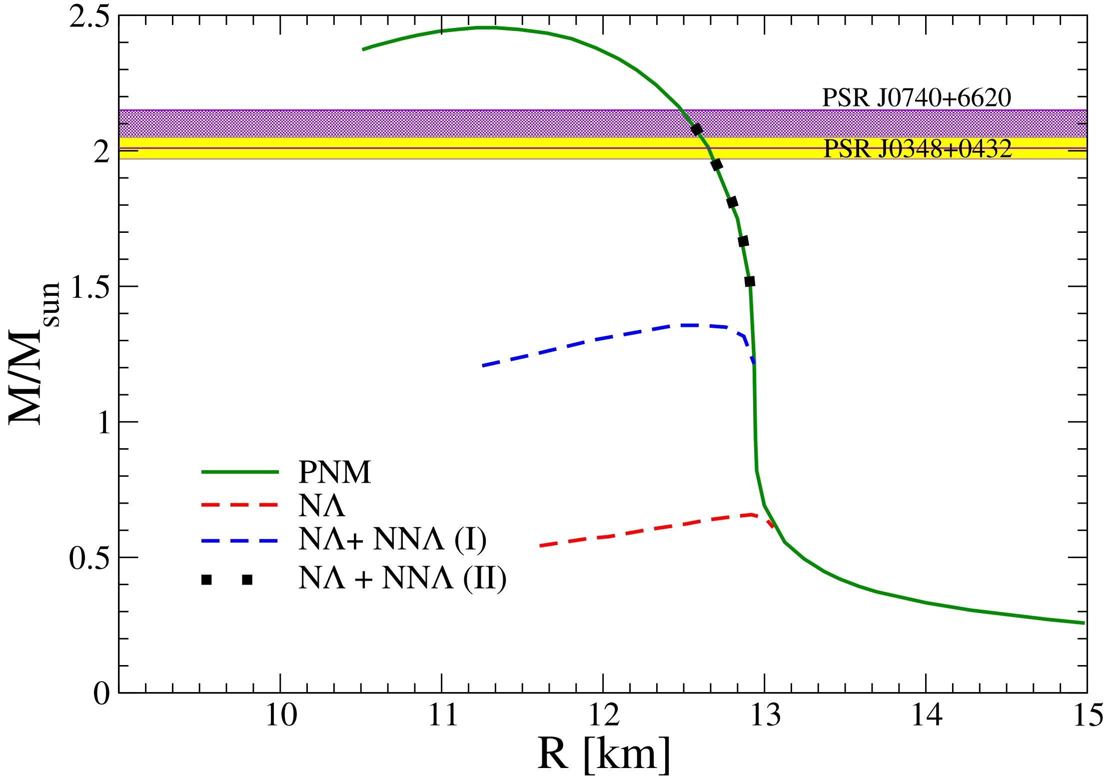


The Hyperon Puzzle

- Hyperons are expected to appear in the core of NS at $\rho \sim 2 - 3\ \rho_0$
- Hyperons soften the EoS → Reduction on maximum NS mass
- Observation of NS with $M_{ns}>2M_s$ is incompatible with such soft EoS → Hyperon Puzzle

Hyperon Puzzle: Possible solutions

- YY and YN forces
- YNN and YYN three body forces

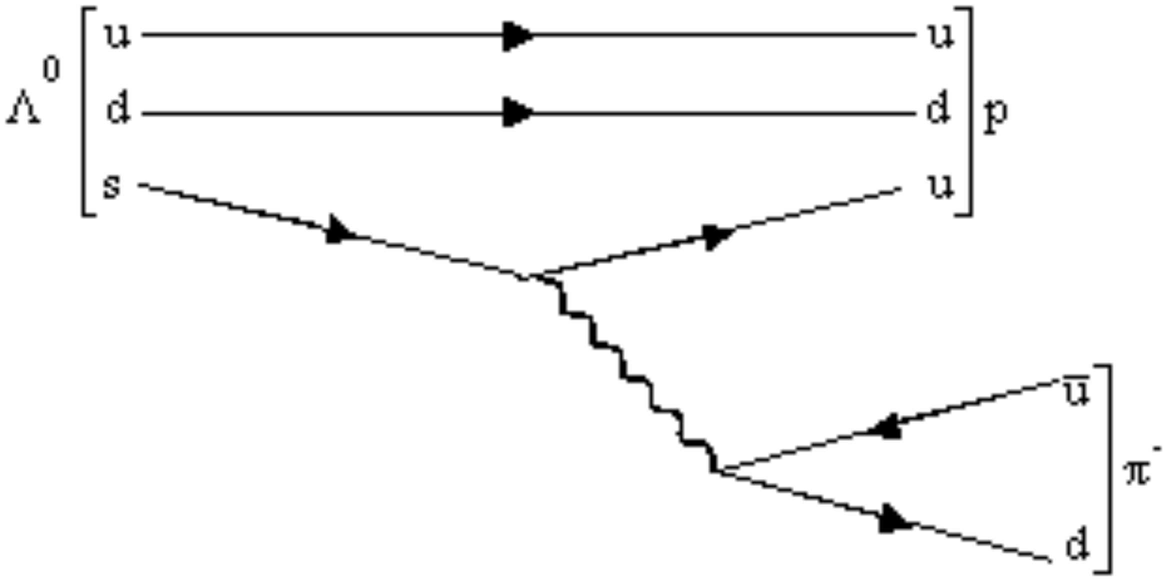


D. Lonardoni, Phys. Rev. Lett. 114, 092301 (2015)
J. Haidenbauer et al., Eur. Phys. J. A 53, 121 (2017)
I. Vidana, Proc. R. Soc. A 474, 20180145 (2018)

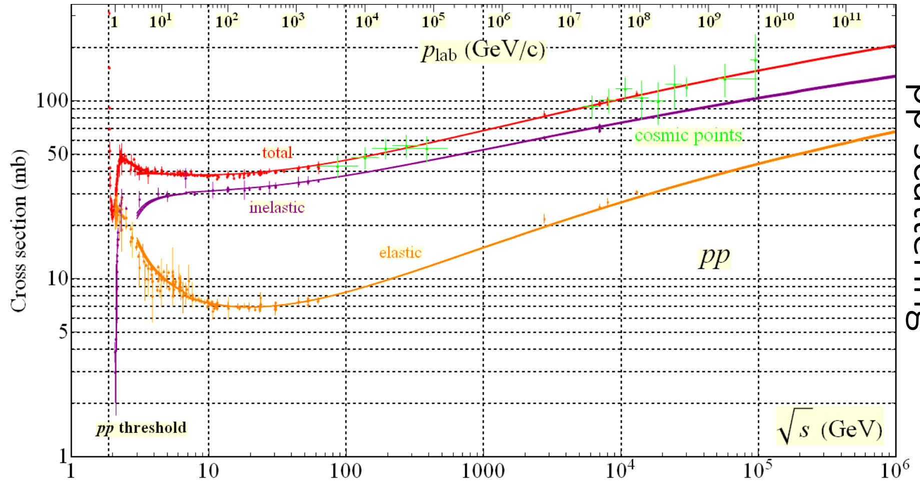
Current Challenges

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

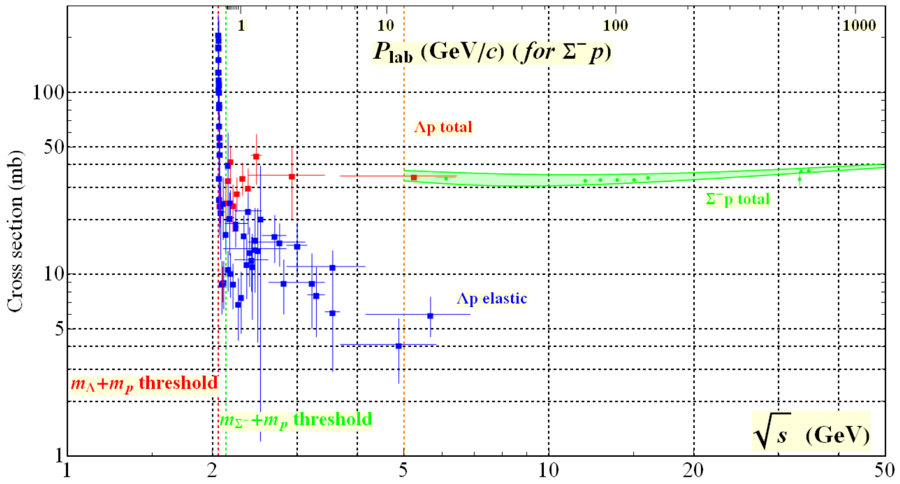
$$\tau_\Lambda = 2.6 \times 10^{-10}\ s$$
$$c\tau_\Lambda = 7.89\ cm$$
$$BR(p\pi^-) = 63.9\%$$



What is available?



pp scattering



Λp scattering

Best way to obtain information is through YN→YN

Total of <1300 observed Λp → Λp in 60 years

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

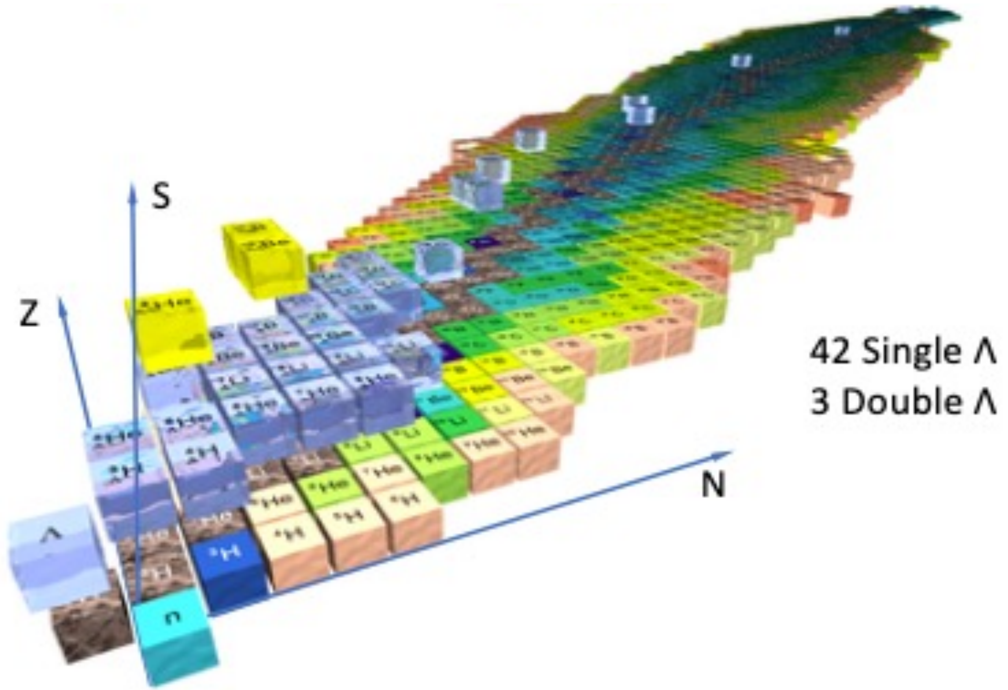
How do we address these challenges?

Recent advancements in Accelerator and Detector technologies allow complementary approaches to studying the hyperon-nucleon interaction via

- Hypernuclear physics
- Femptoscopy in high energy collisions
- Two-step processes and Final State Interaction

Hypernuclear Physics

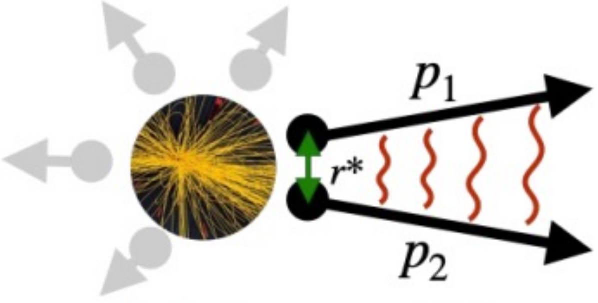
$$K^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$
$$\pi^+ + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + K^+$$
$$e^- + {}^{A}Z \rightarrow e^- + {}^{A}_{\Lambda}(Z-1) + K^+$$



Hypernuclear studies have uncertainties associated with medium modification as well as many-body effect

Femptoscopy Technique

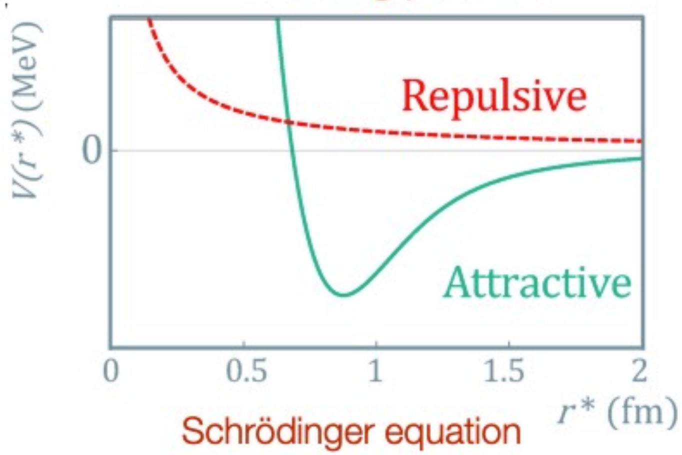
Slide from ALICE Collab. - Sarti Valentina Mantovani



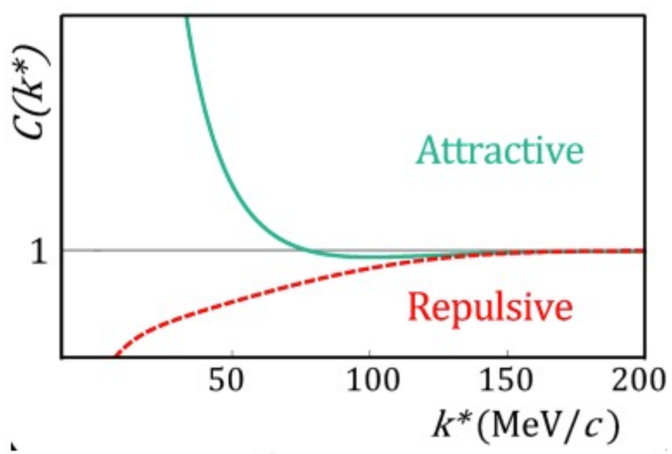
Emission source S(r*)

ALICE Collaboration
pΛ: PLB 833 (2022), 137272
pΣ⁰: PLB 805 (2020) 135419
pΞ/pΩ: Nature 588 (2020) 232-238
pφ: PRL 127 (2021), 172301
Kp: PRL 124 (2020) 09230,
PLB 822 (2021) 136708
arXiv: 2205.15176 [nucl-ex]
PRC 99 (2019) 2, 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRC 103 (2021) 5, 055201
PLB 829 (2022), 137060
arXiv: 2201.05352 [nucl-ex]
arXiv: 2204.10258 [nucl-ex]
STAR Collaboration
Nature 527 (2015) 345-348
PRL 114 (2015), 022301
PLB 790 (2019) 490-497
HADES Coll.
Phys. Rev. C 94 (2016)
……

Interacting potential



Correlation function



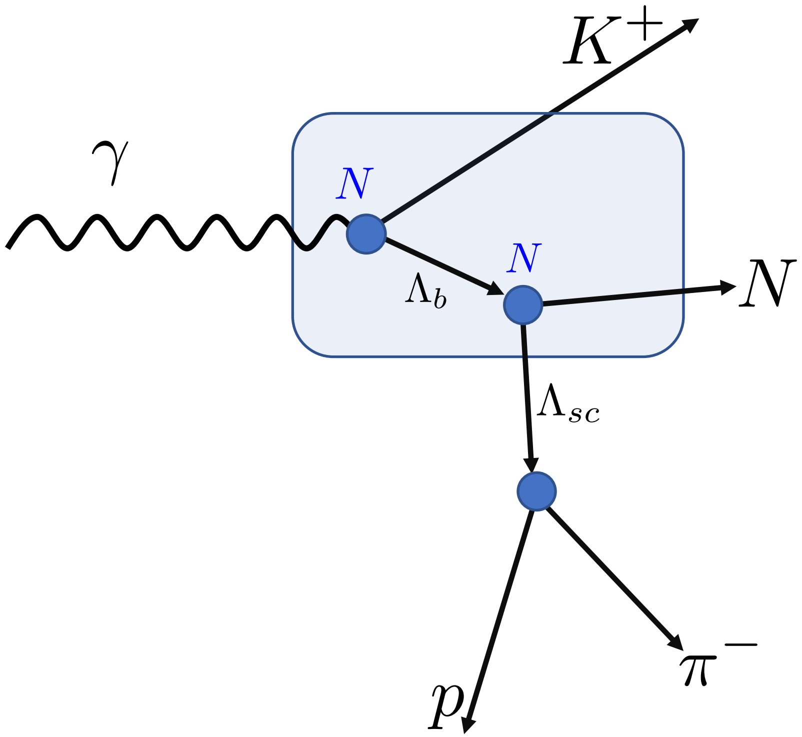
Schrödinger equation

Two-particle wave function

$$C(k^*) = \int S(\vec{r}^*) \left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^* = \mathcal{N}(k^*) \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

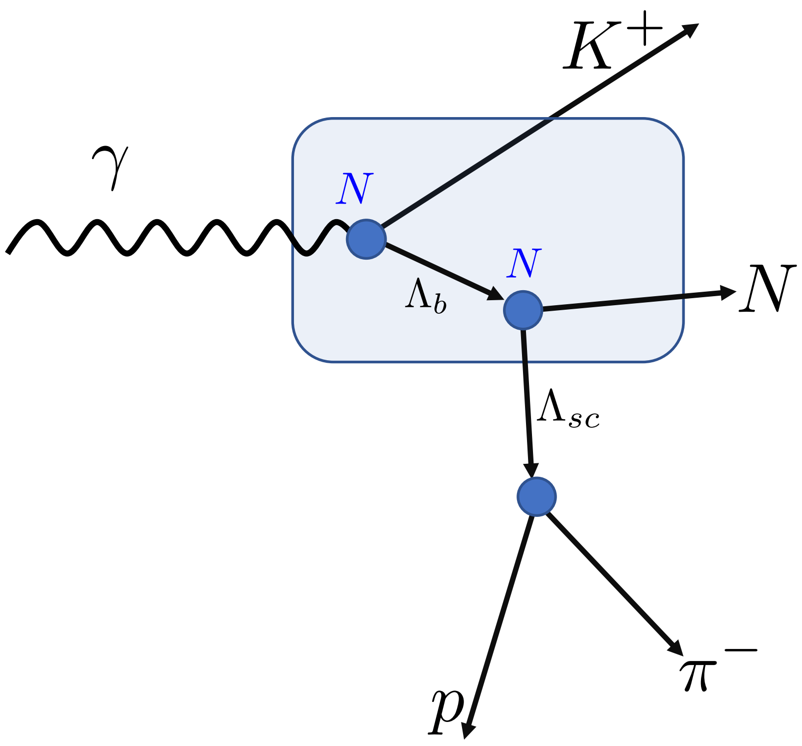
Measuring C(k*), fixing the source S(r*), study the interaction

Final State Interactions and Two-Step Processes



- 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

Final State Interactions and Two-Step Processes



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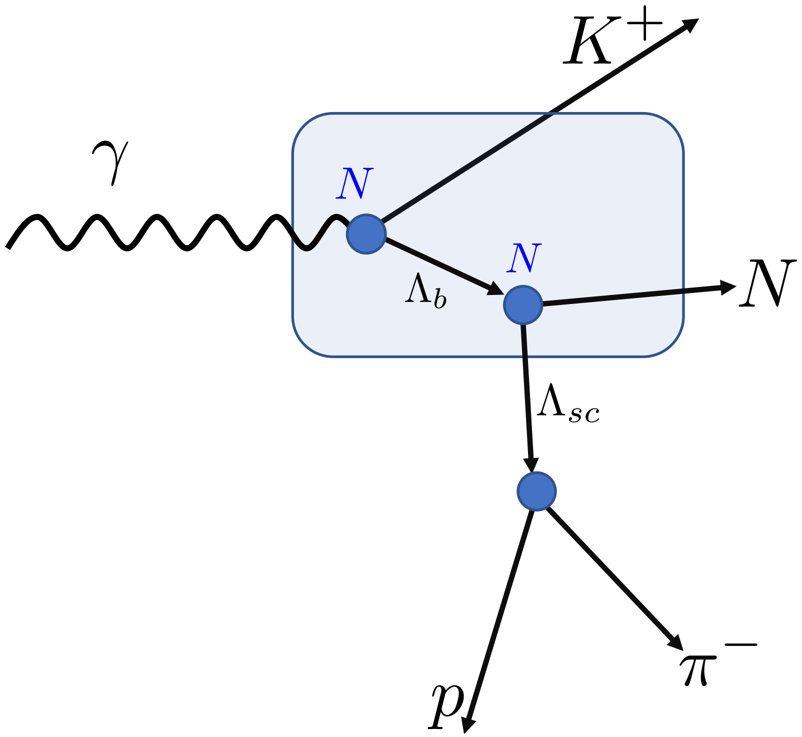
Cross sections

- Λp
- Σ^-p
- Σ^+p
- Λd

Cross section approach benchmarked using pp scattering

Final State Interactions and Two-Step Processes



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Cross sections
- Λp
- Σ^-p
- Σ^+p
- Λd

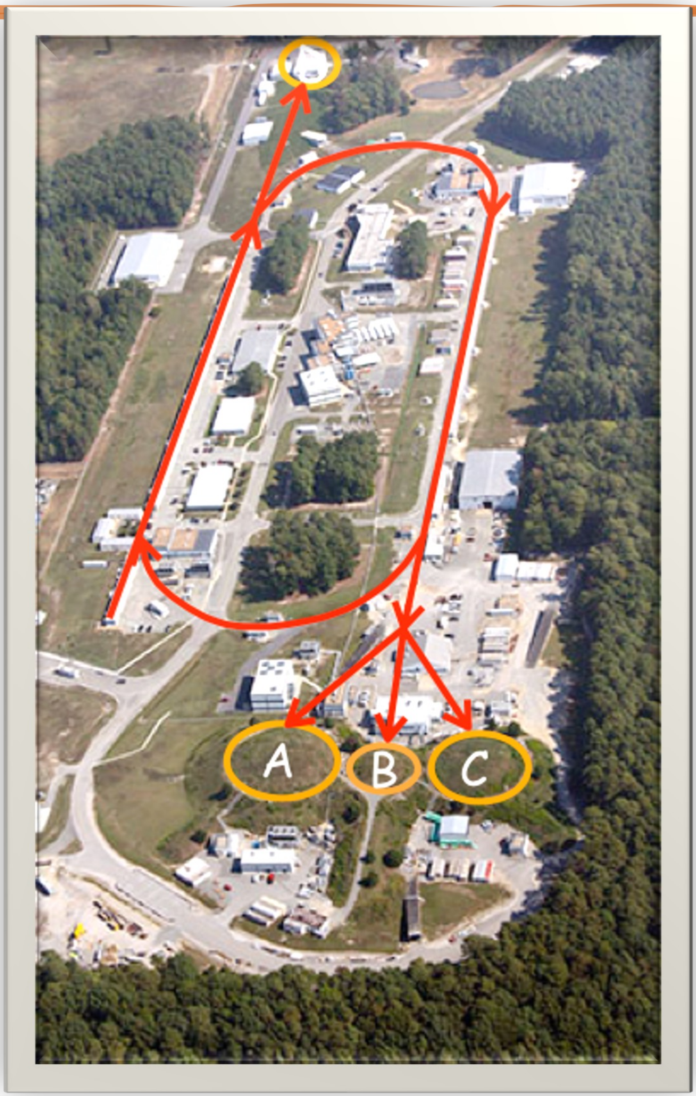
Polarization observables
- Λn
- Σ^-p
- Λd
- Λp

Cross section approach benchmarked using pp scattering

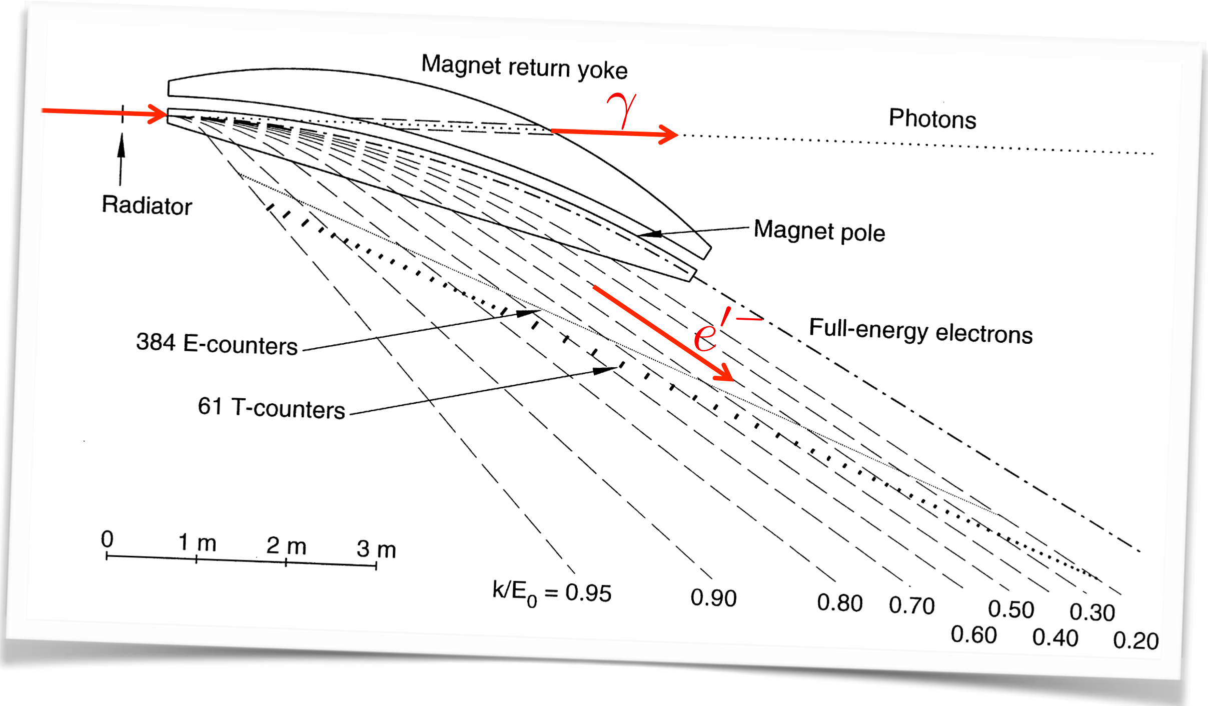
Thomas Jefferson Laboratory

6-GeV era: 1995-2012

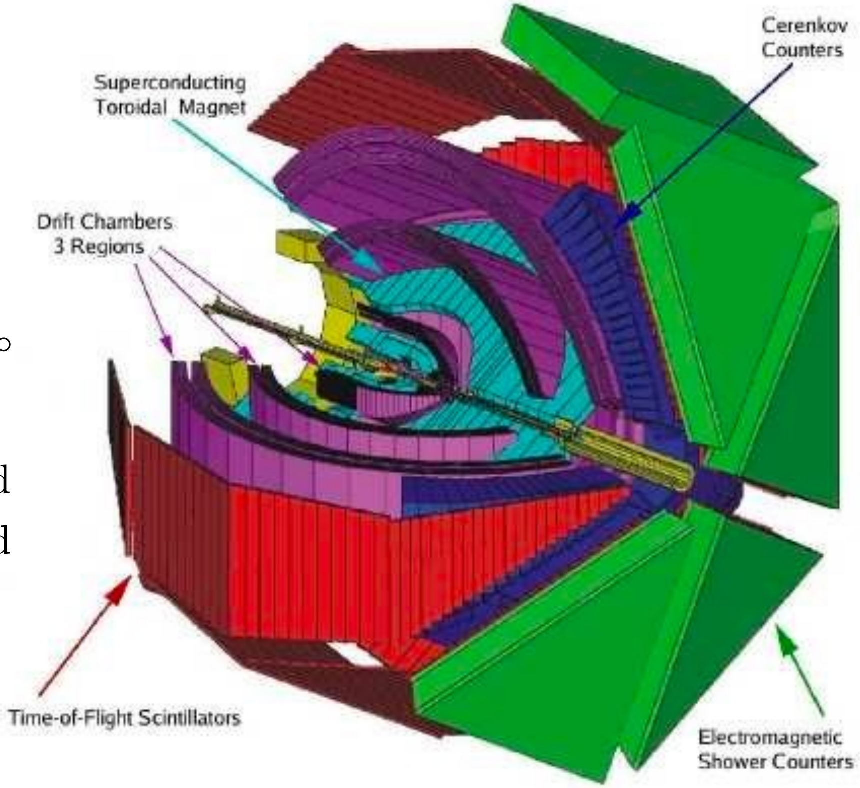
- C.W. electron beam: 2-ns wide bunch period, 0.2-ps bunch length
- Polarized Source: Pe ~ 86%
- Beam energies up to E_0 = 6 GeV
- Beam Current up to 200 μA



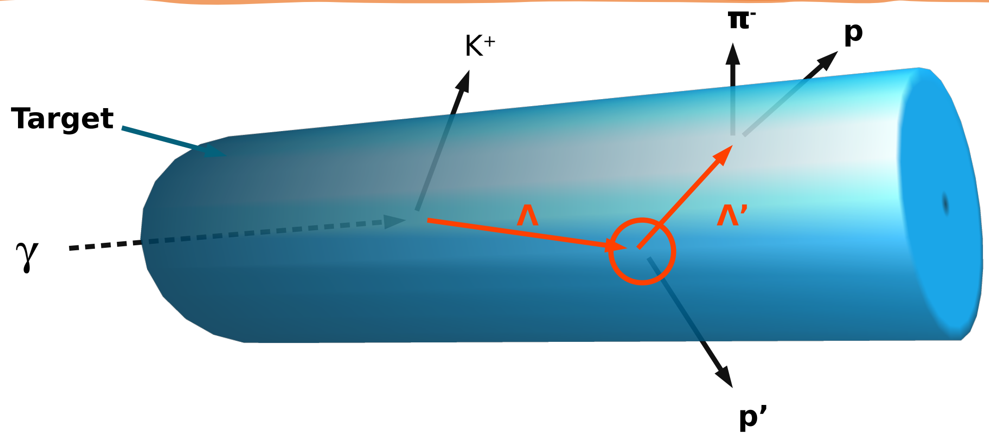
Hall-B: The CLAS detector and Tagger facility



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



Improved Λp Elastic Scattering Cross Sections



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

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

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

Cross section determination challenging

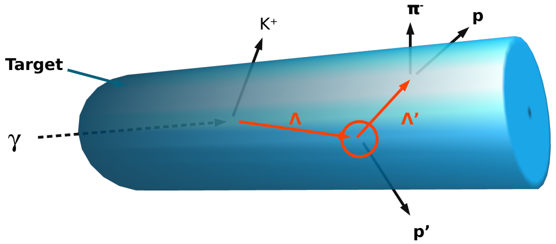
- Detector acceptance
- Detector efficiency
- **Hyperon beam luminosity**

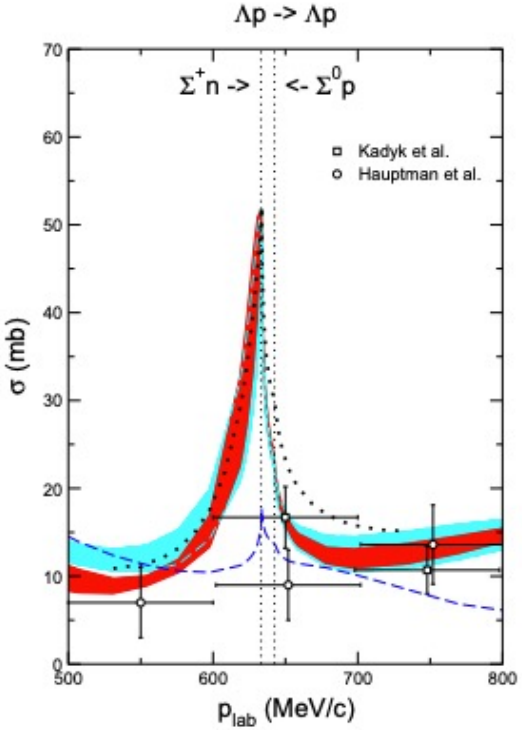
Order of magnitude higher statistics

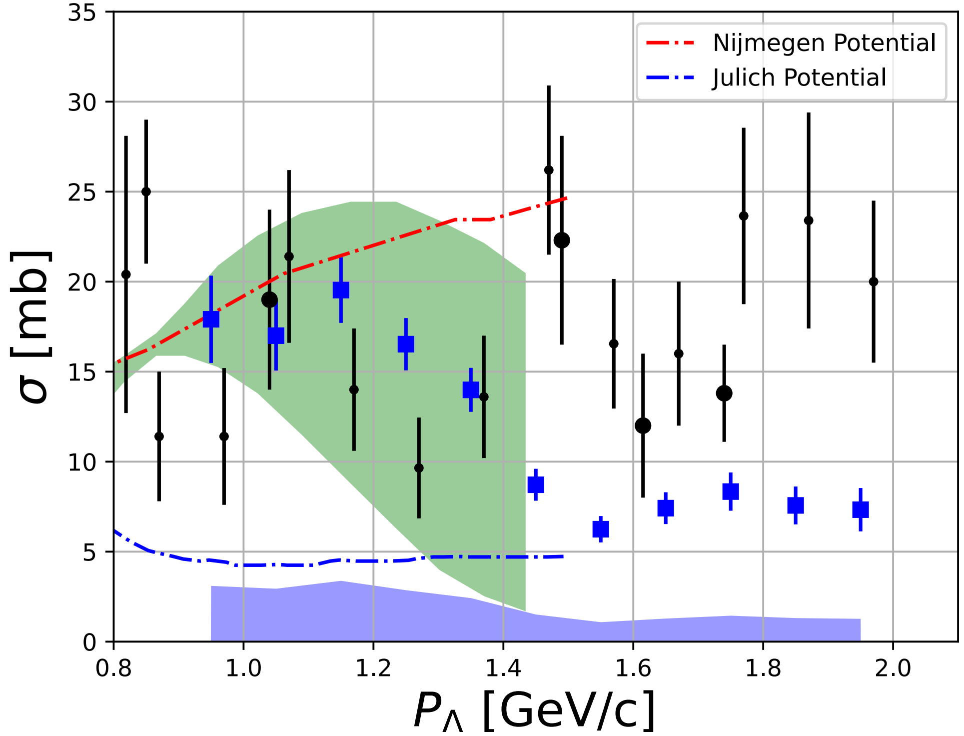
L: Path length determined from realistic simulations, accounting for beam size and kinematic dependence of the photoproduction cross section, as well as the decay length of hyperons

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

Improved Λp Elastic Scattering Cross Sections







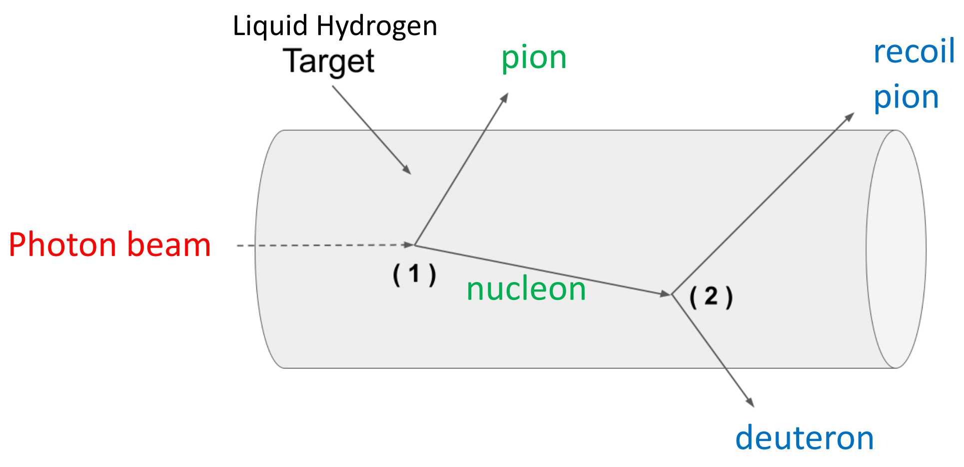
Calculation at next to leading order from chiral effective field theory (Haidenbauer *Eur. Phys. J. A* **56,** 91 (2020))

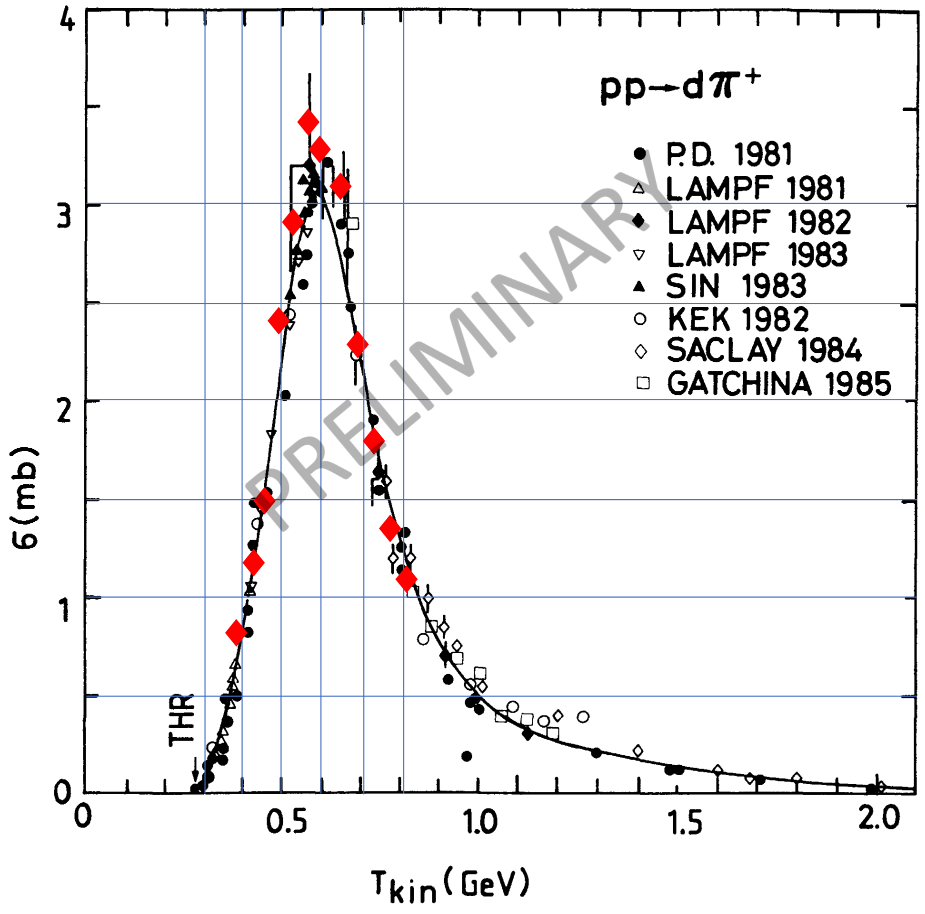
J. Haidenbauer and U.-G. Meißner, Phys. Rev. C 72, 044005 (2005)

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

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

Approach confirmation via pp scattering

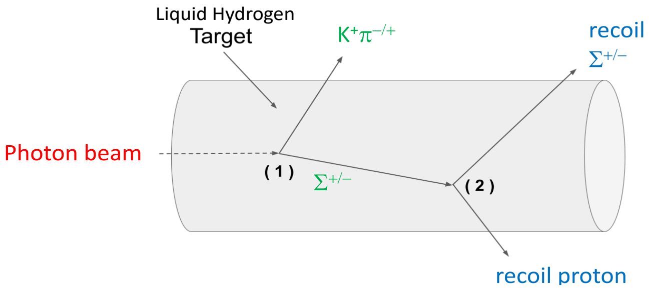




Statistical uncertainties -> size of marker
Systematic uncertainties of the order of 10%
Additional points at higher energies -- TBD

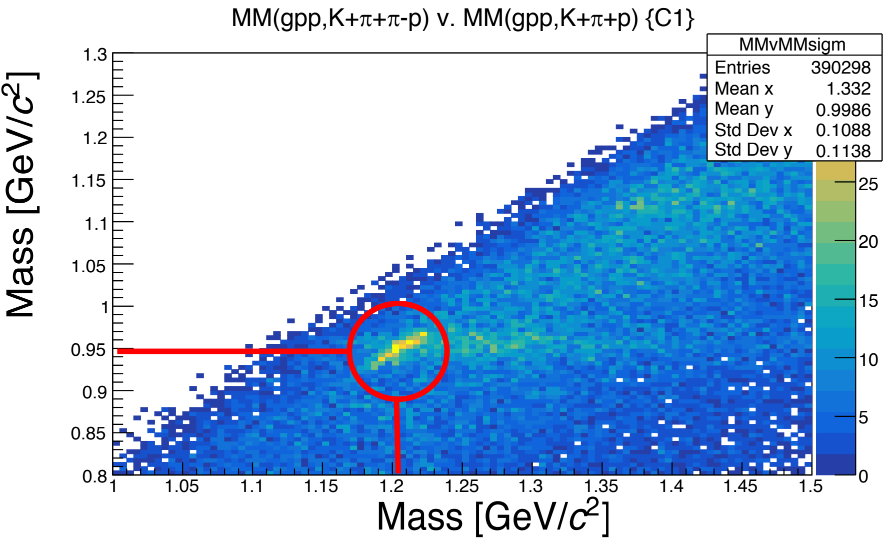
Σp Elastic Scattering Cross Sections

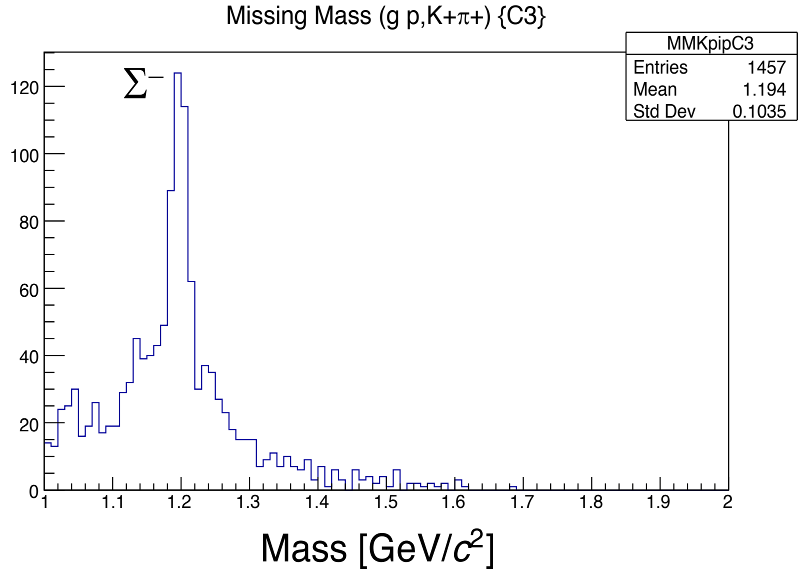
Approach identical to Λp channel

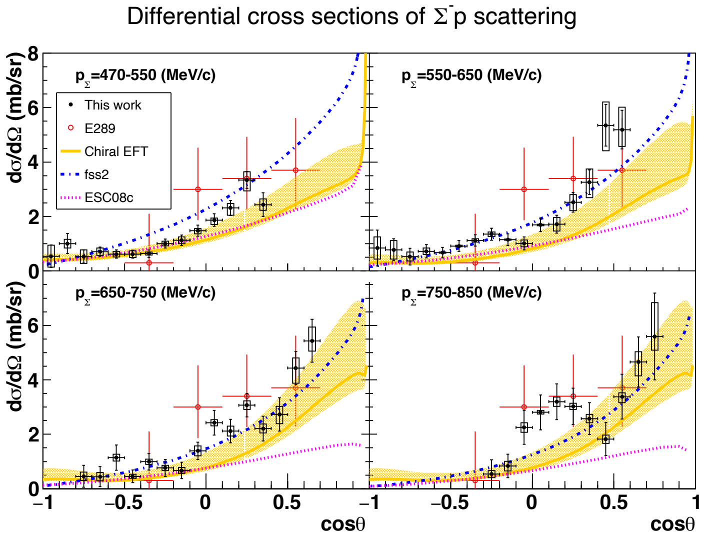


Recent results from JPARC Phys. Rev. C **104**, 045204

Extend momentum range

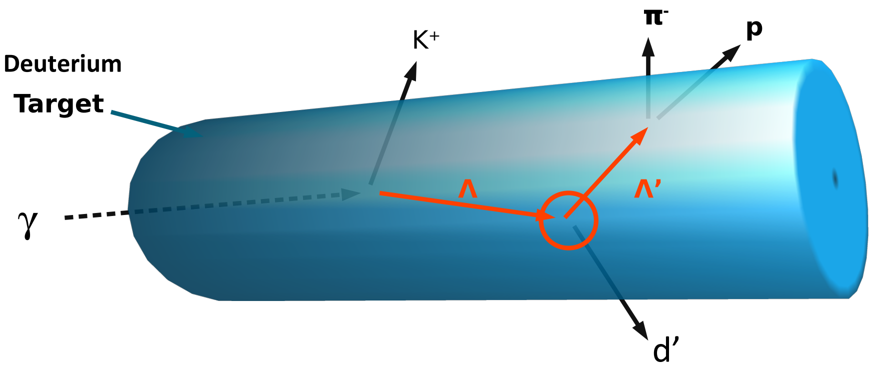


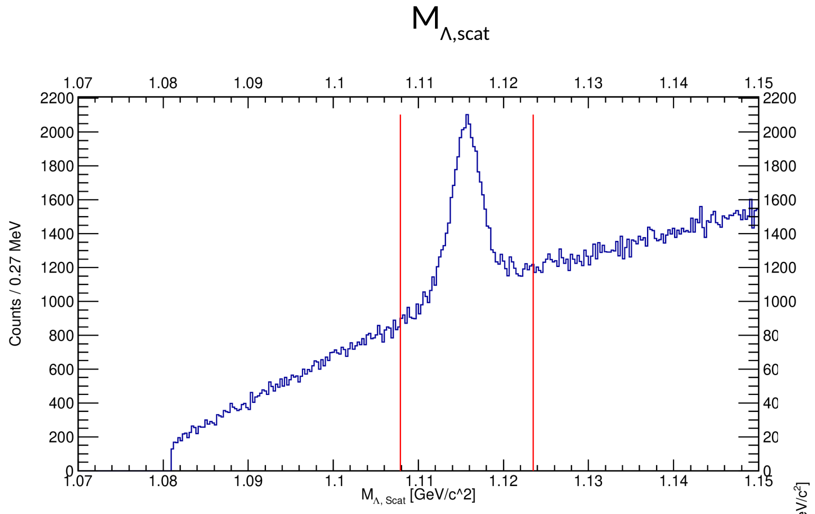


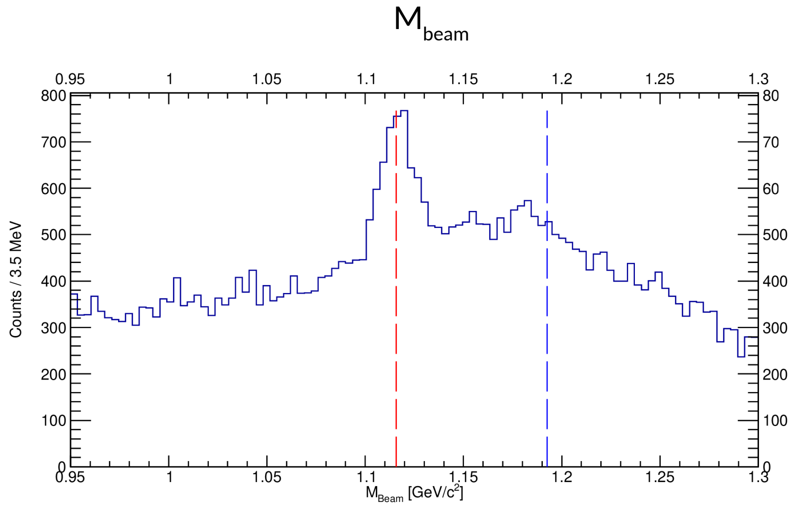


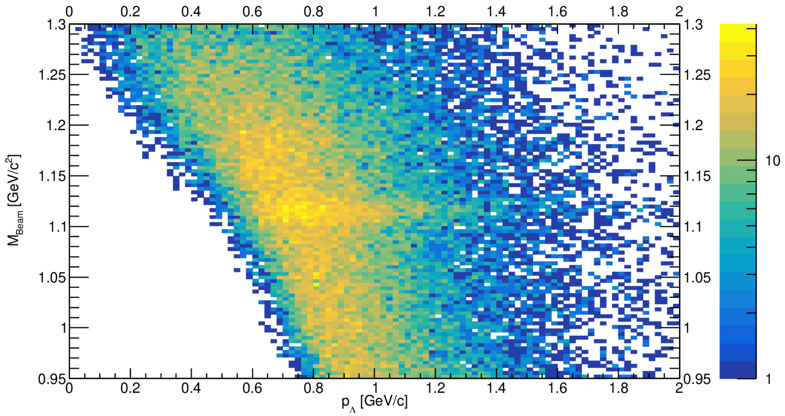
ΛNN Elastic Scattering Cross Section via Λd

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





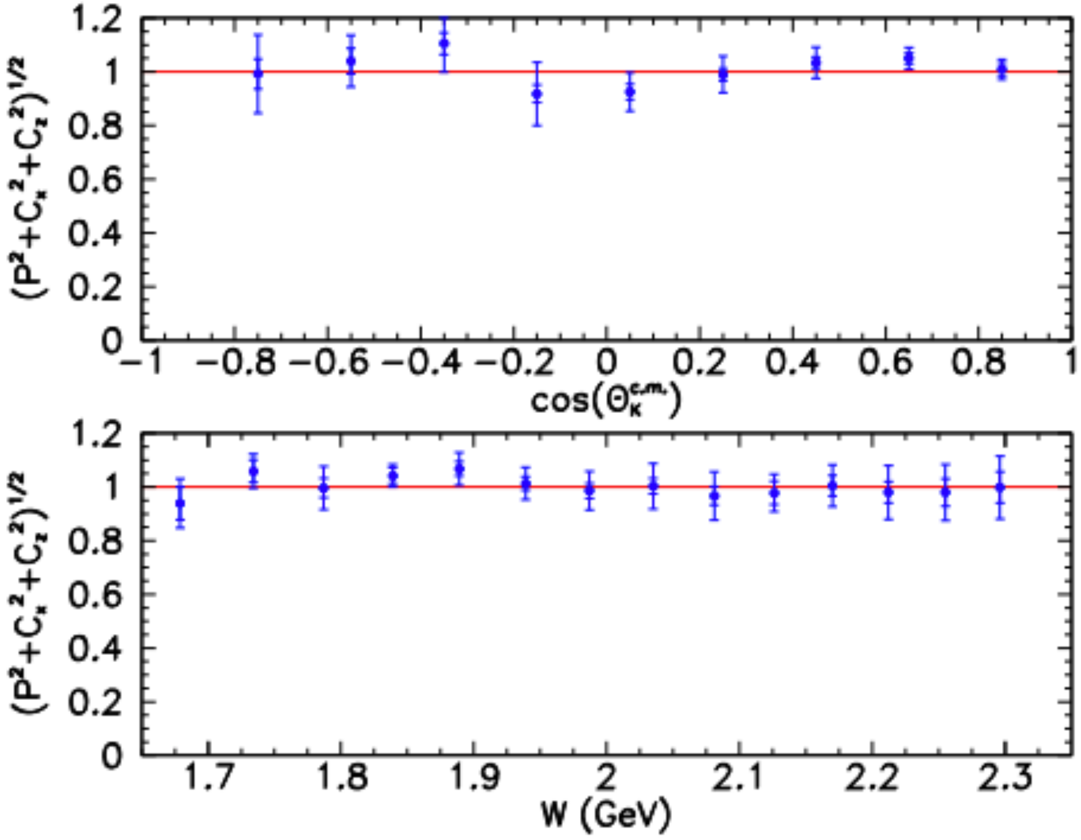




Additional Constraints on the YN interaction

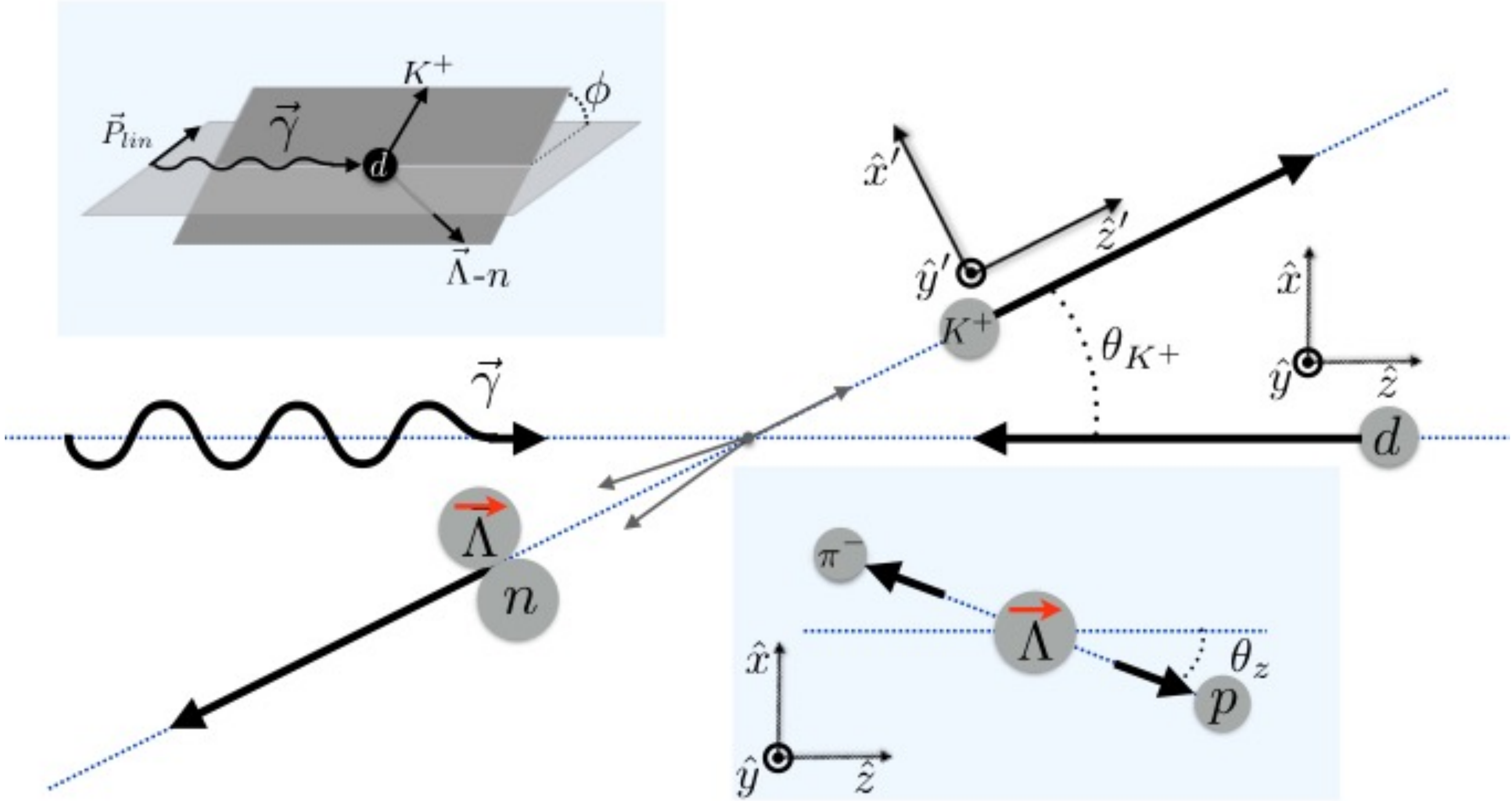
- Hyperons are photoproduced with R=1
- Utilize to study polarization effects in YN interaction
  - further constraints on the underlying dynamics.

PHYSICAL REVIEW C 75, 035205 (2007)



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

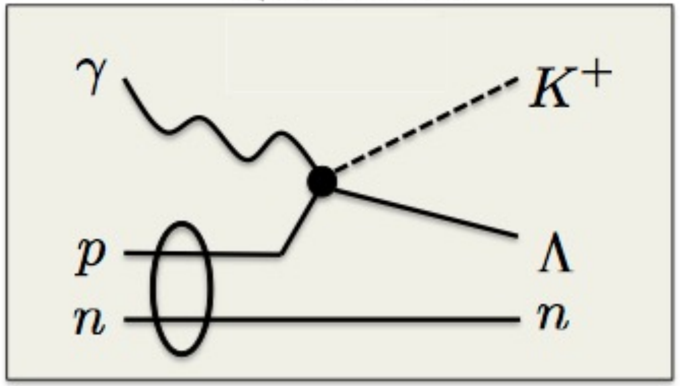
Λ Recoil Polarisation

Self-analysing power

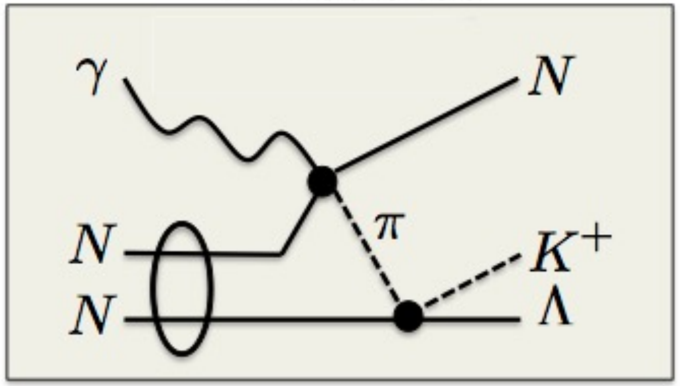
α=0.75

Hyperon Nucleon via FSI

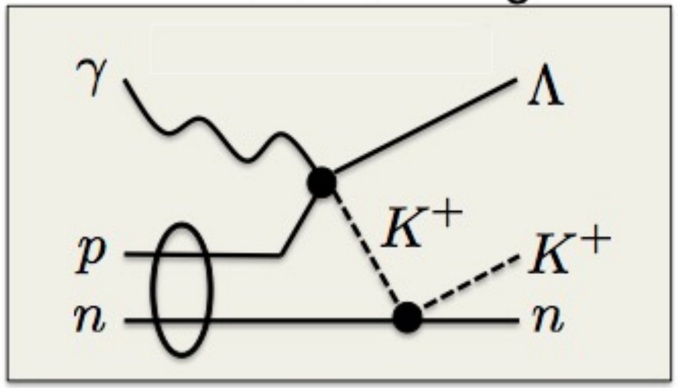
Quasi-free



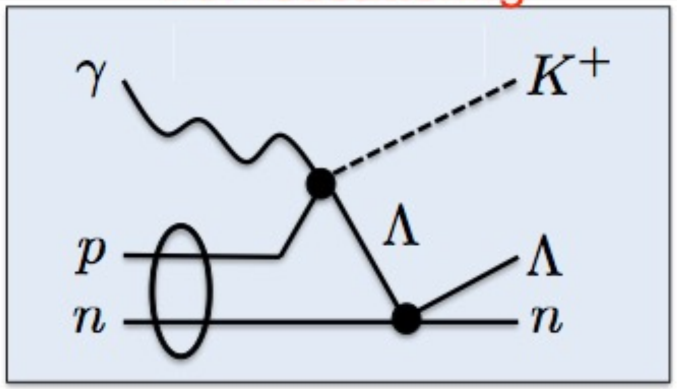
π-mediated



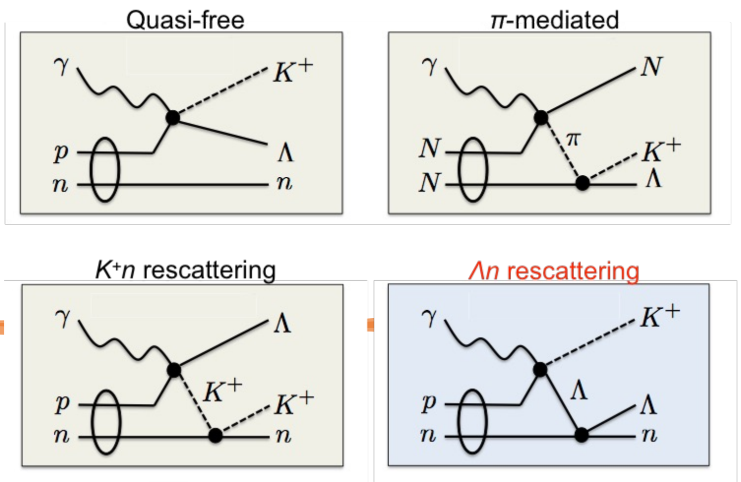
K^+n rescattering



Λn rescattering

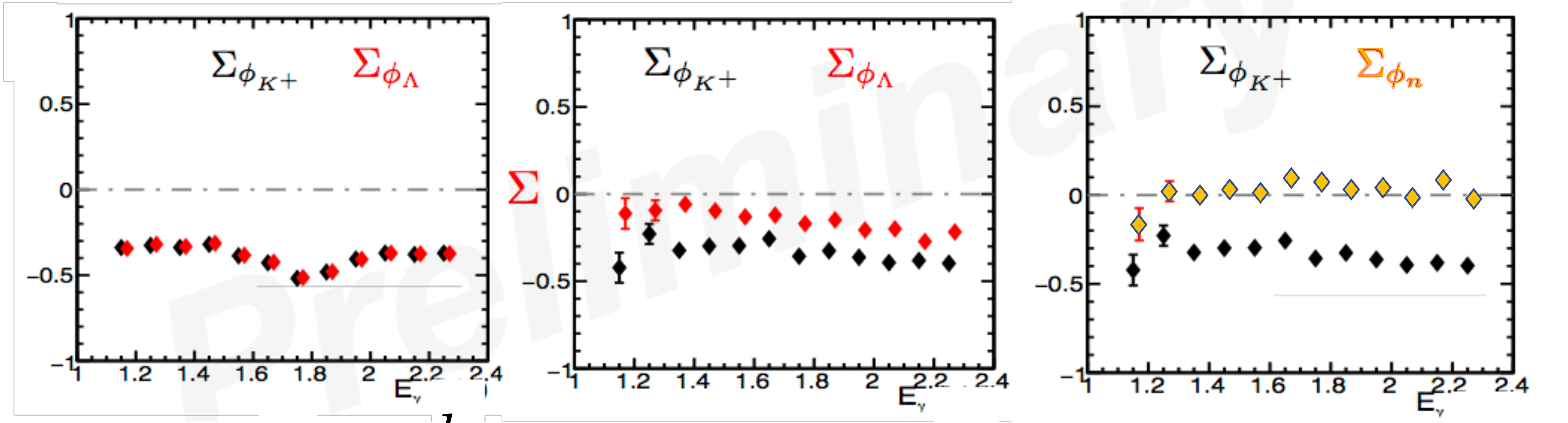


Hyperon Nucleon vis FSI



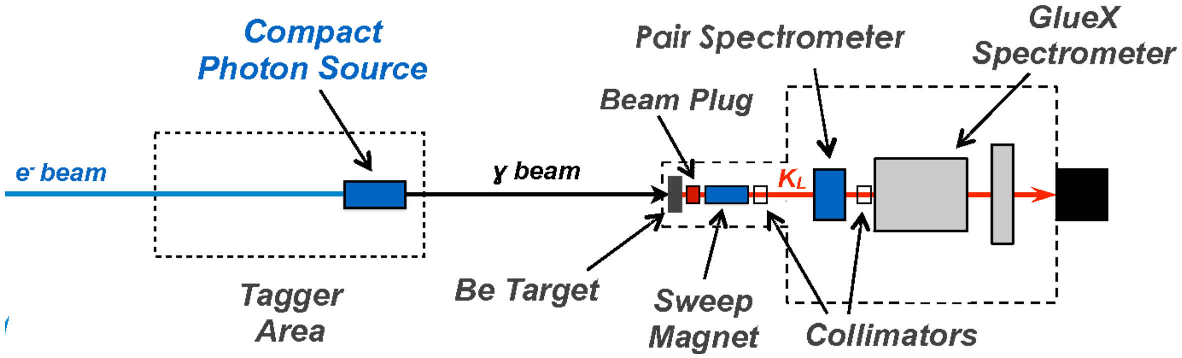
QuasiFree data

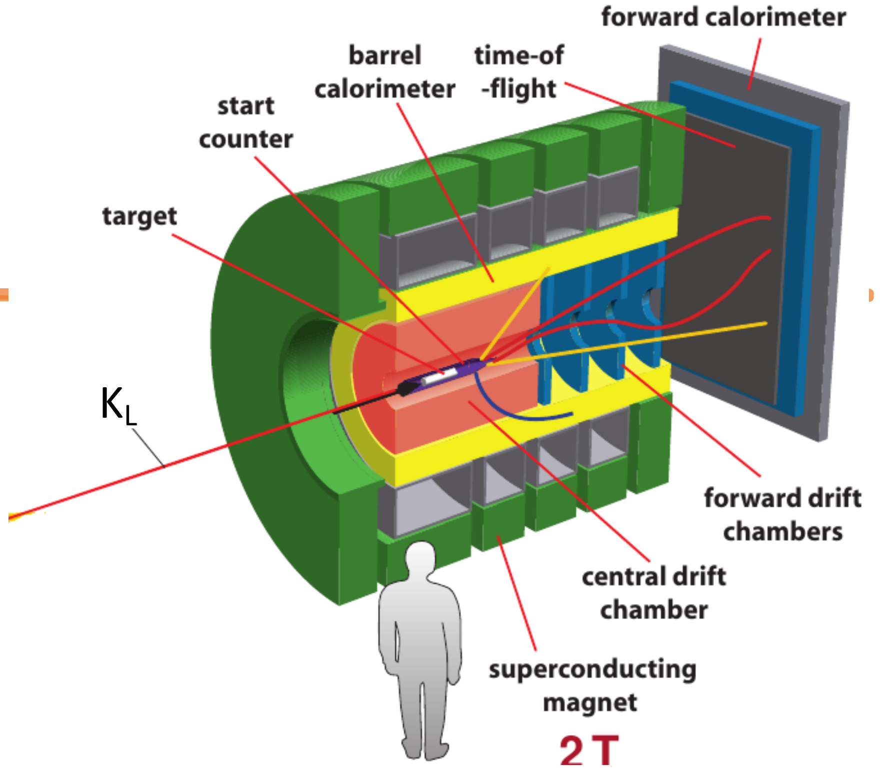
FSI data



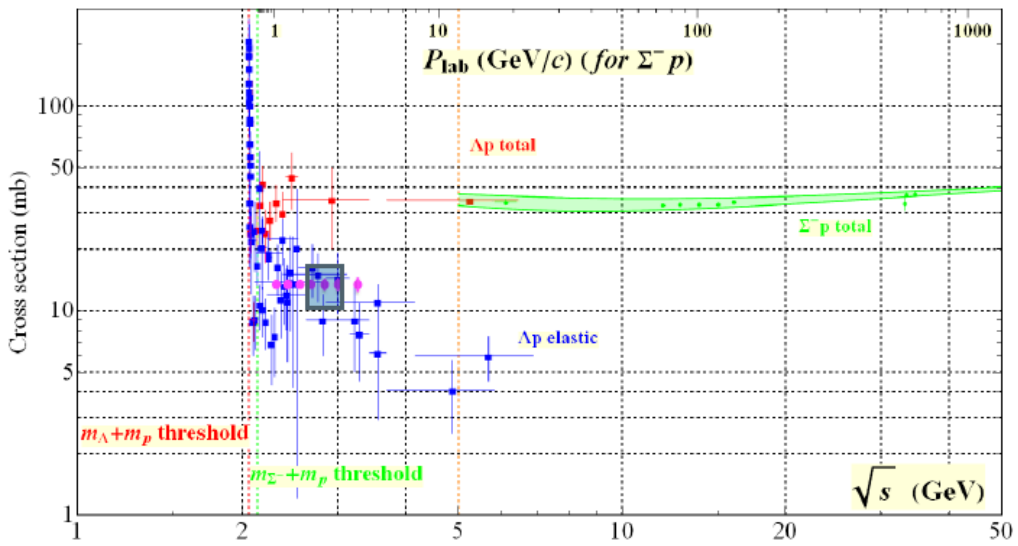
$$\frac{d\sigma}{d\Omega} = \sigma_0(1 - P_{lin}\Sigma\cos 2\phi)$$

Coming Up





- K-Long facility approved – Online 2025
- Compact photon source – 6 OOM higher luminosity
- 3 OOM higher cross section for hyperon production
- Access to ΞN 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
- KL facility to open door for doubly strange hyperon interactions with nucleons.
- Exciting results in the pipeline!!!

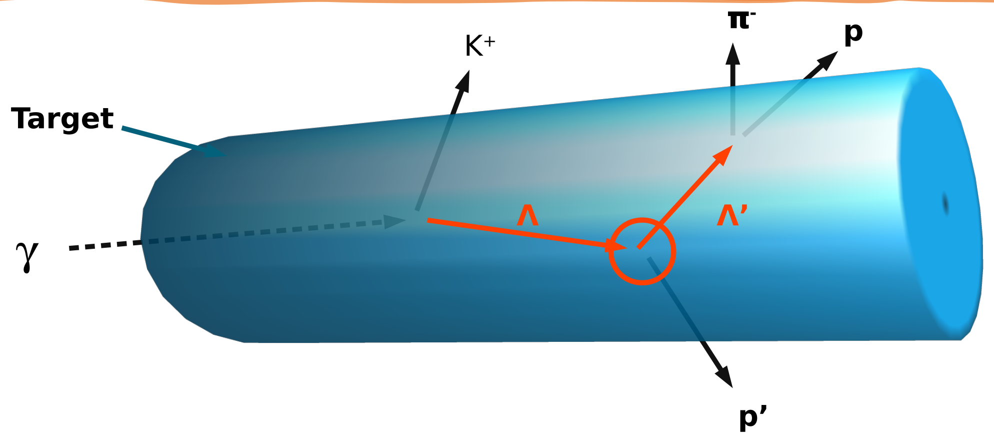
Thank you

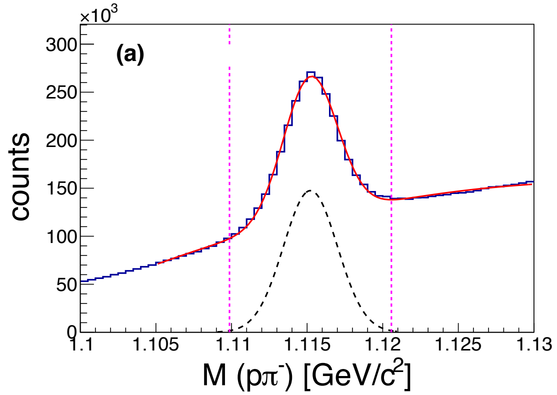


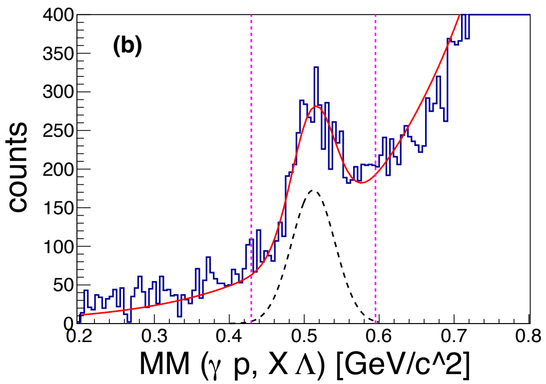


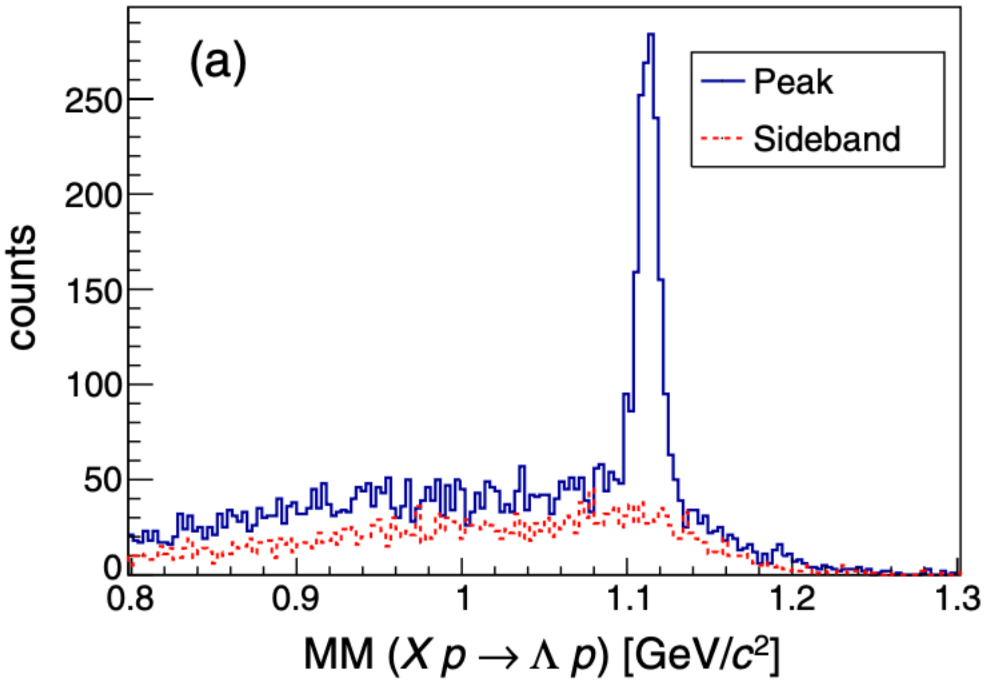


Improved Λp Elastic Scattering Cross Sections









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

Improved Λp Elastic Scattering Cross Sections

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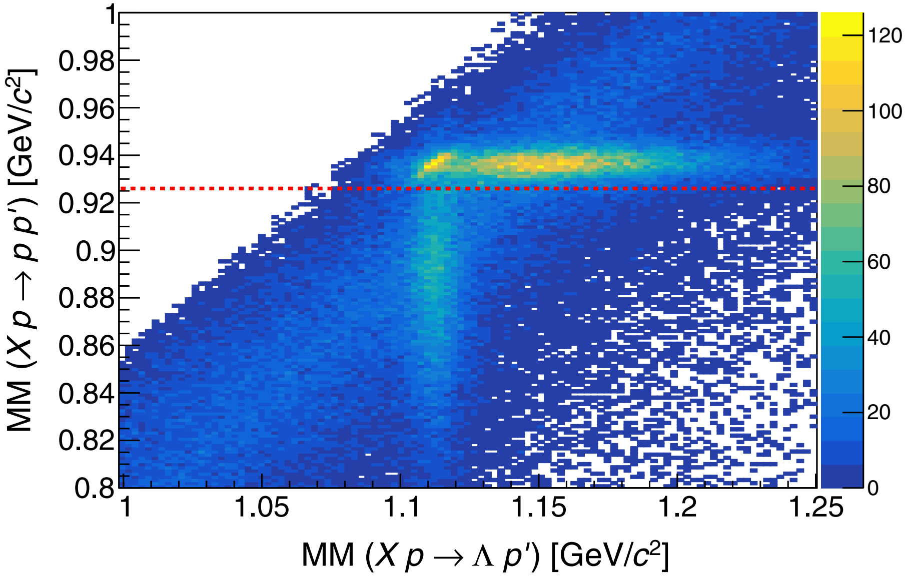
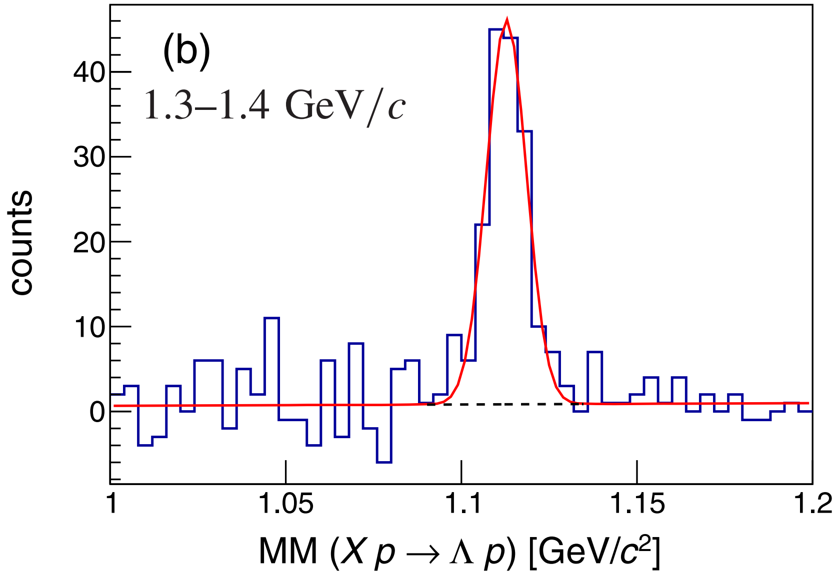
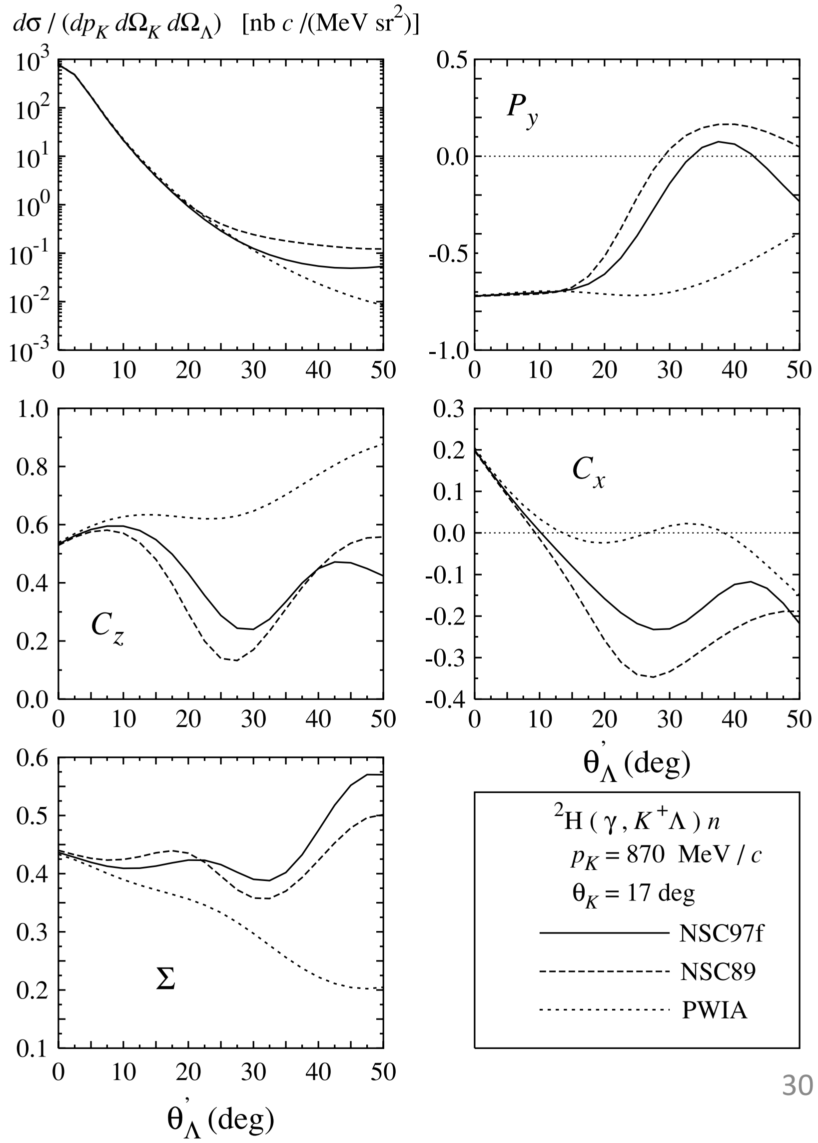
- Background contribution
  - $\gamma p \rightarrow p\,\pi^+\pi^-$
  - $\gamma p \rightarrow K^+\Sigma^0\ (\Lambda\gamma)$
  - $p(\Lambda)p \rightarrow pp$





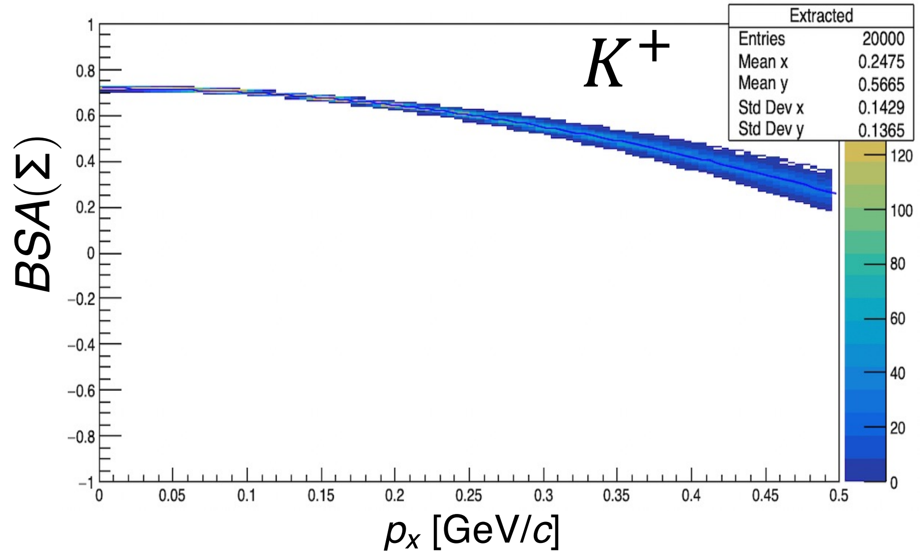
Polarisation Observables Λn

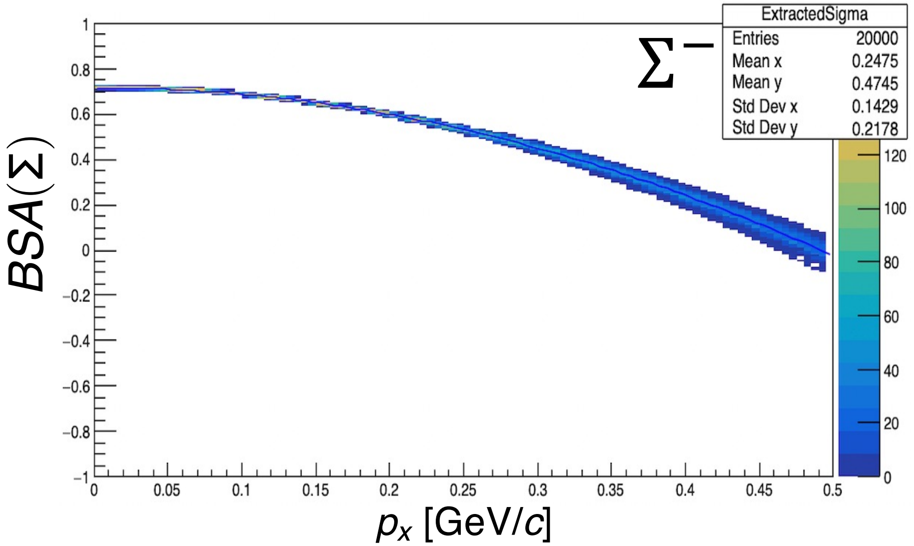
K. Miyagawa et al., Phys. Rev. C 74, 034002 (2006)

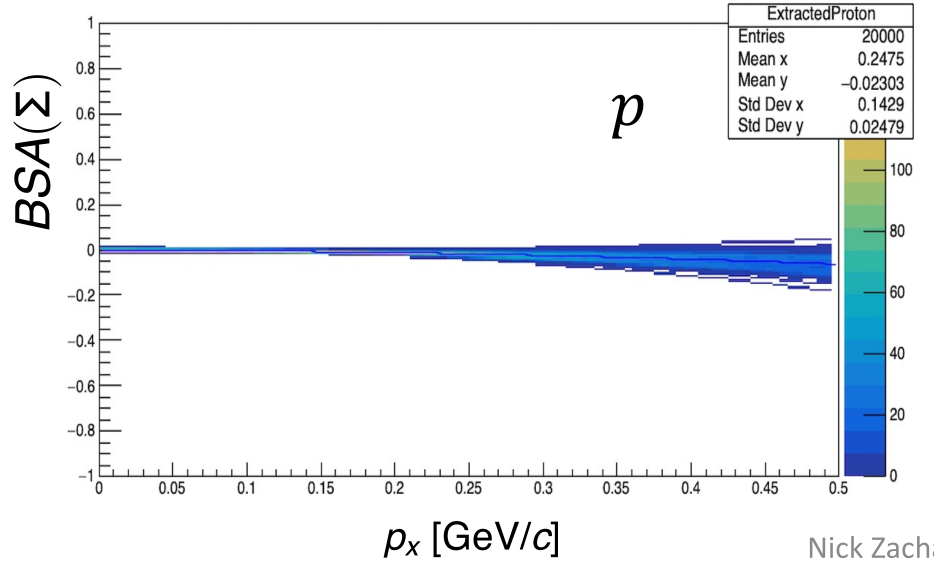


- Existing *YN* models allow the calculation of single and double polarization observables
- Two *YN* potentials (NSC97F and NSC89) give the correct hypetrition binding energy
- NSC97F and NSC89 lead to very different predictions of polarisation observables at some kinematics

Polarisation Observables Σp



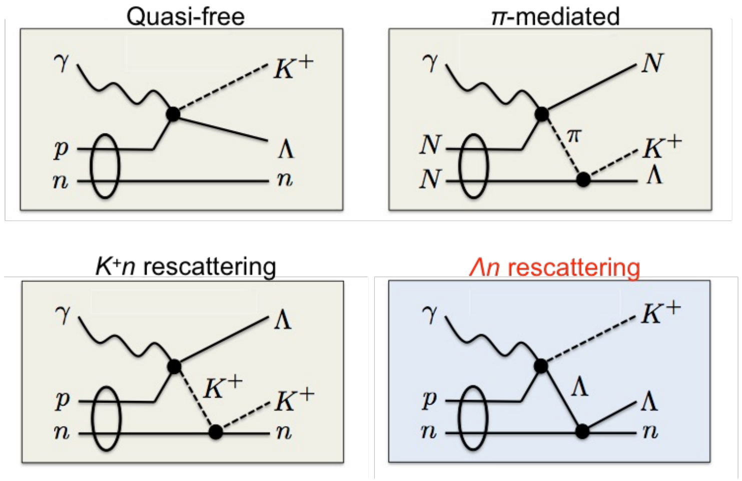




- Results extrapolated to zero missing-momentum agree with QF study
- Large dilutions at higher missing momenta due to FSI
- Relative dilutions can be attributed to the various FSI contributions
- Different reaction mechanisms cause unique combinations of
- $\Sigma_K(p_x)$, $\Sigma_\Lambda(p_x)$, and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

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