Experimental Aspects of Hyperon-Nucleon interactions

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STRONG 2020

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UNIVERSITY of York

Outline

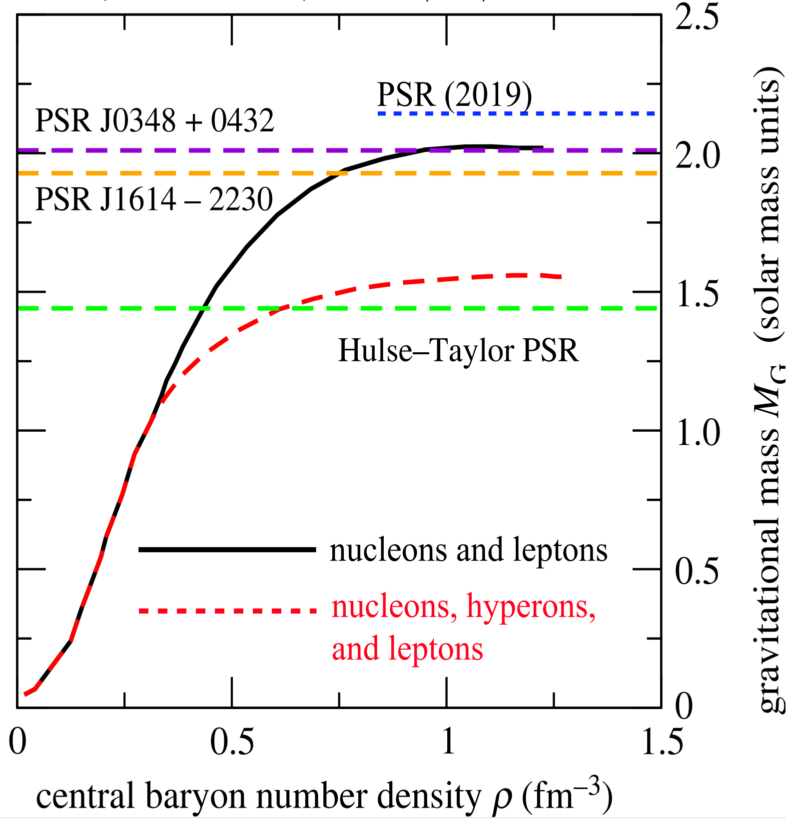
- Why study interactions between hyperons and nucleons?
- What has been done before?
- Thomas Jefferson Laboratory and CLAS
- Current status
- Future studies

Why Hyperon-Nucleon Interaction?

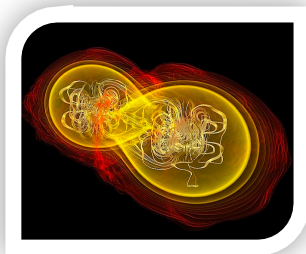
- The understanding of both nucleon-nucleon (NN) and hyperon-nucleon (YN) potential is necessary in order to have a comprehensive picture of the strong interaction
  - Understand composition of neutron stars
  - Understand hypernuclear structure and hyperon matter
  - Extend NN to a more unified picture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

The Hyperon Puzzle

I. Vidana, Proc. R. Soc. A 474, 20180145 (2018)



- 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 $M_G > 2M_s$ is incompatible with such soft EoS → Hyperon Puzzle



Artist rendition of NS merger

MSP M_G=2.14 +/- 0.1 M_s Nat Astron (2019) doi:10.1038/s41550-019-0880-2

The Hyperon Puzzle

YN interaction is poorly constrained: Difficulties associated with performing high-precision scattering experiments with hyperon beams

- Large uncertainties in the scattering lengths

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

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

Hyperon Puzzle: Possible solutions

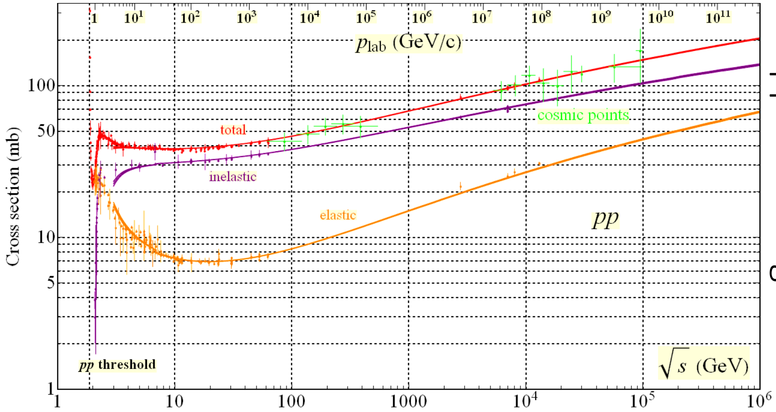
- YY and YN forces
- YNN and YYN three body forces

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)

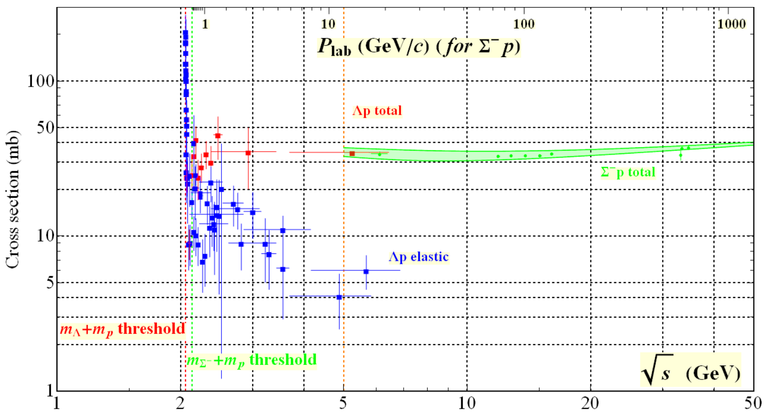
Experimental data are needed to place constraints on the interaction

What is available?

Best way to obtain information is through YN→YN



pp scattering



Λp scattering

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

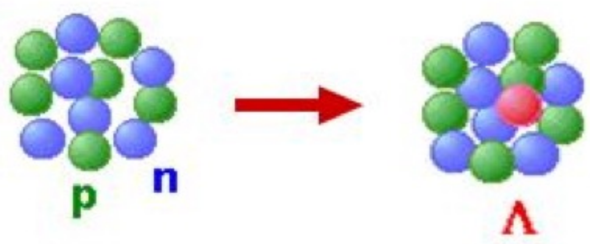
Difficulties performing high-precision scattering experiments with short-lived beams

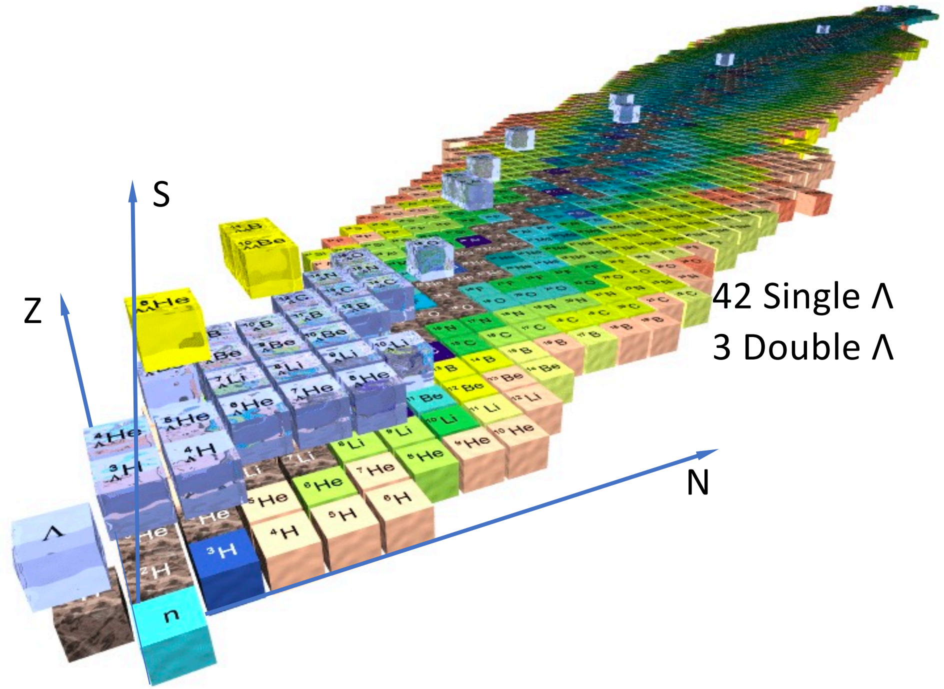
YN interaction – Complementary approaches

$$K^- + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$$

$$\pi^+ + {}^AZ \rightarrow {}^A_\Lambda Z + K^+$$

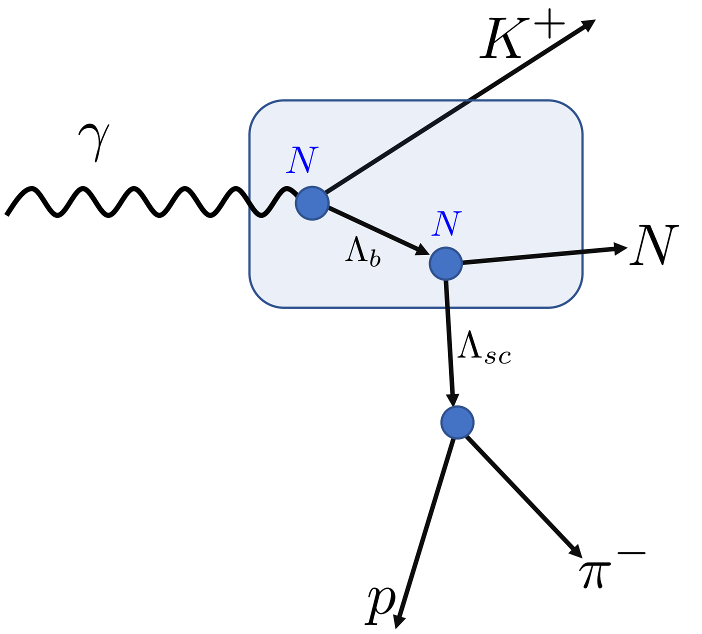
$$e^- + {}^AZ \rightarrow e^- + {}^A_\Lambda(Z-1) + K^+$$





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

Secondary hyperon beams in exclusive photoproduction



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

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

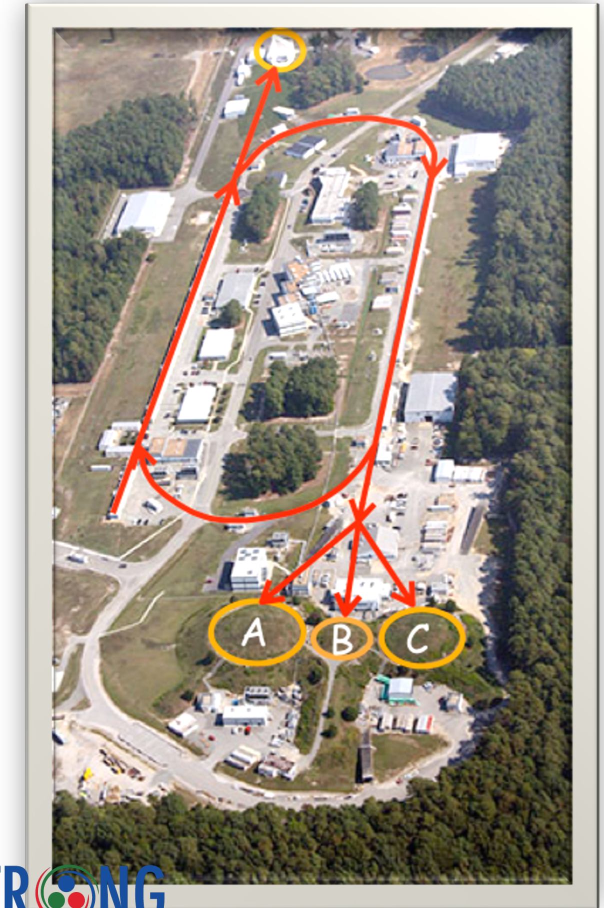
- Two-step process where Hyperon rescatters with secondary nucleon
- Kaon identification allows tagging of hyperon beam
- 4π detector allows full reconstruction of the event
- Hydrogen and deuterium targets

Cross sections measurements
- **Λp**
- Σ^-p
- Λd

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

Cross section approach benchmarked using pp scattering

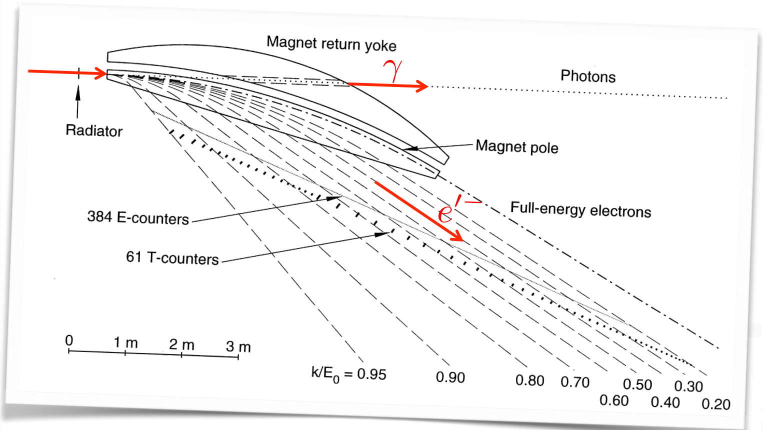
Experimental Facility: CLAS @ Jefferson Lab

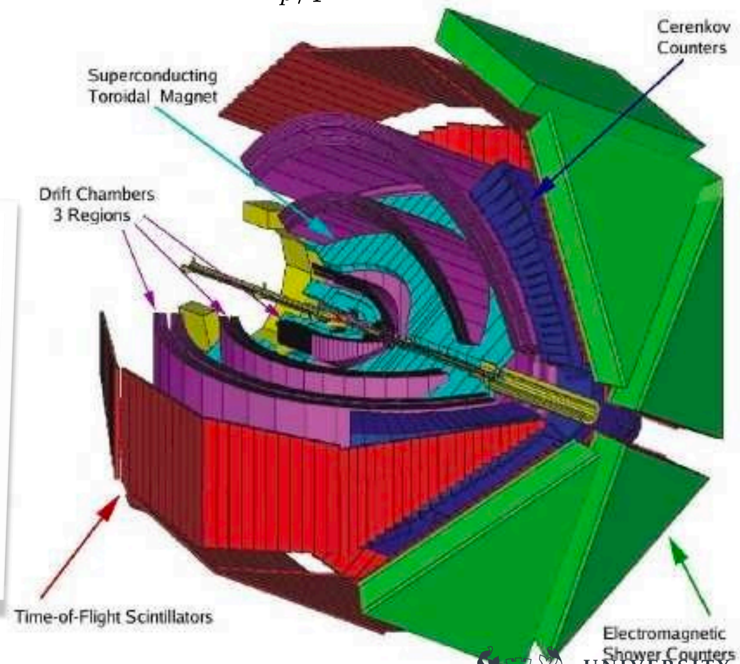


6-GeV era: 1995-2012

- 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

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





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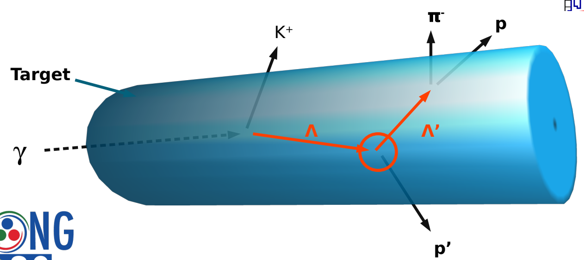
Hyperon-proton interaction – Λ

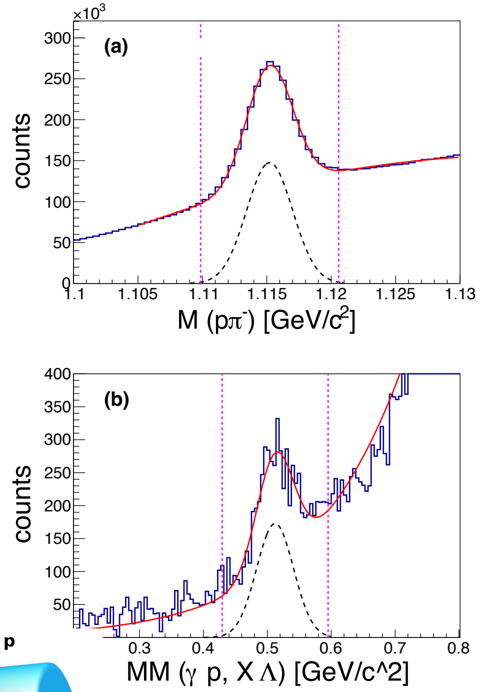
Cross section determination Challenging

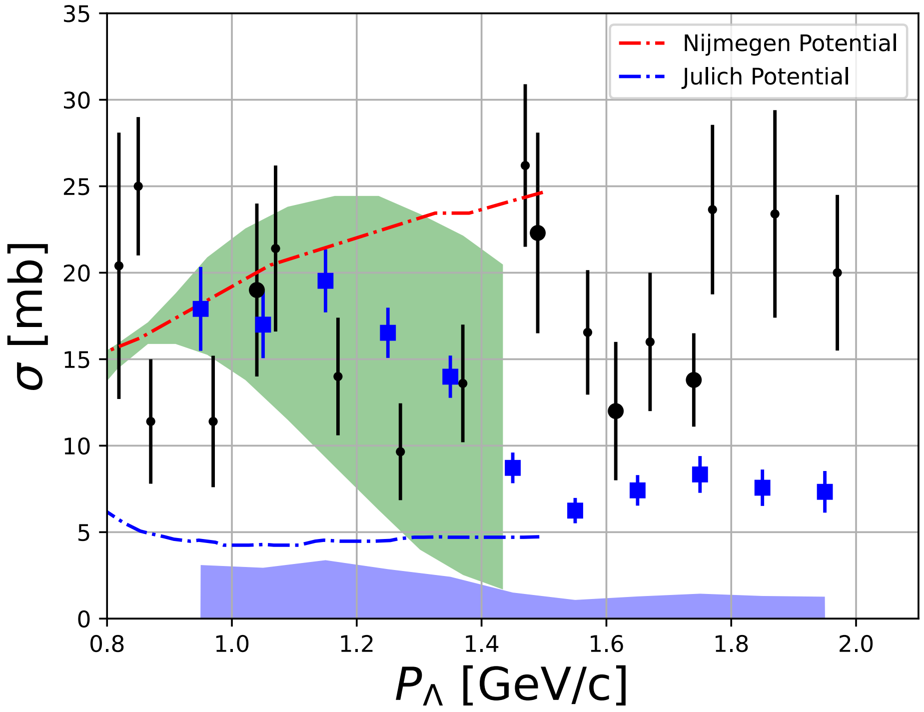
$$\mathcal{L}(E_\Lambda) = \frac{N_A \times \rho_T \times l}{M} N_\Lambda(E_\Lambda)$$

Order of magnitude higher statistics

New stringent constraints





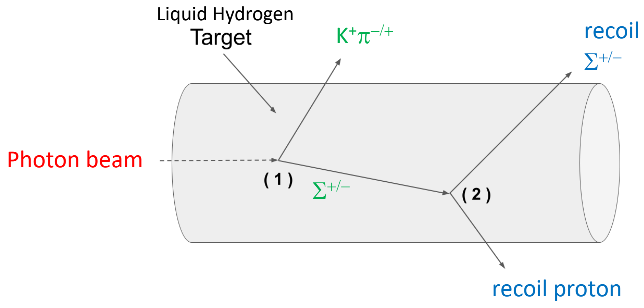


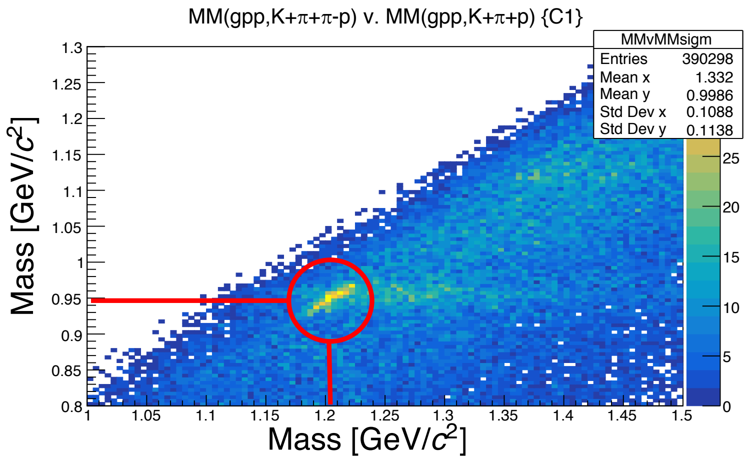
Submitted to Phys. Rev. Letters arxiv:[2108.03134](2108.03134)

Joey Rowley - OU

Hyperon-proton interaction – Σ

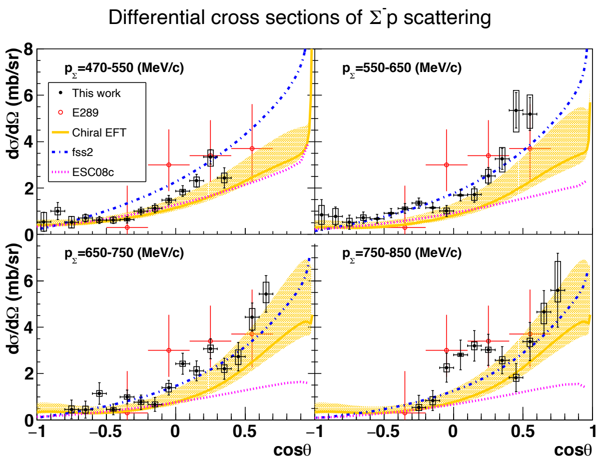
Approach identical as Λp channel

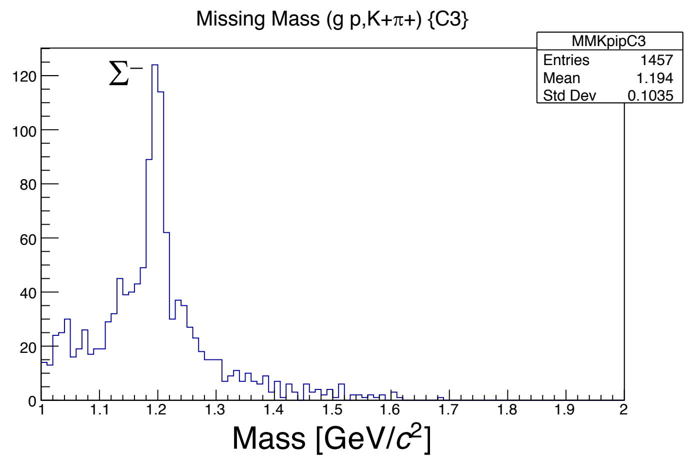




Recent results from JPARC [arXiv:2104.13608v2](https://arxiv.org/abs/2104.13608v2)

Extend momentum range



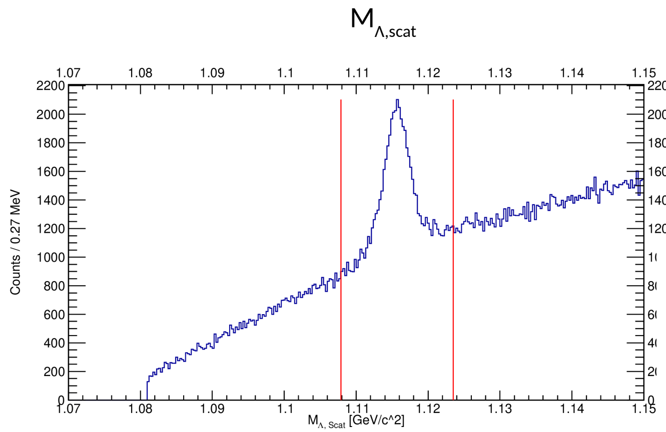


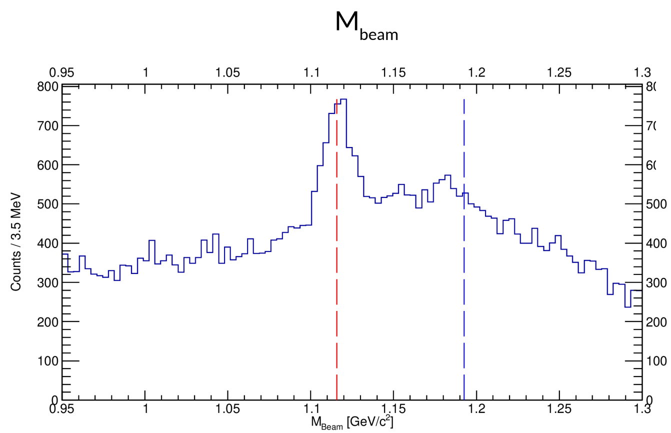
Ken Hicks - OU

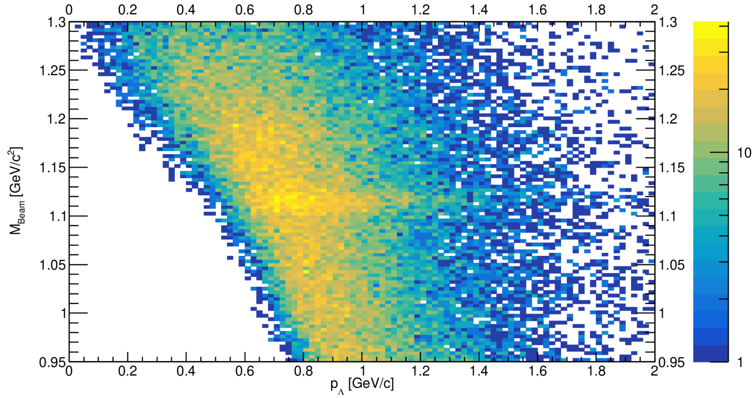
Hyperon-deuteron interaction – Λ

Cross section determination:

- p_Λ >0.7 GeV/c
- cos(θ) between -0.6 and 0.9
- Expected 4000 events

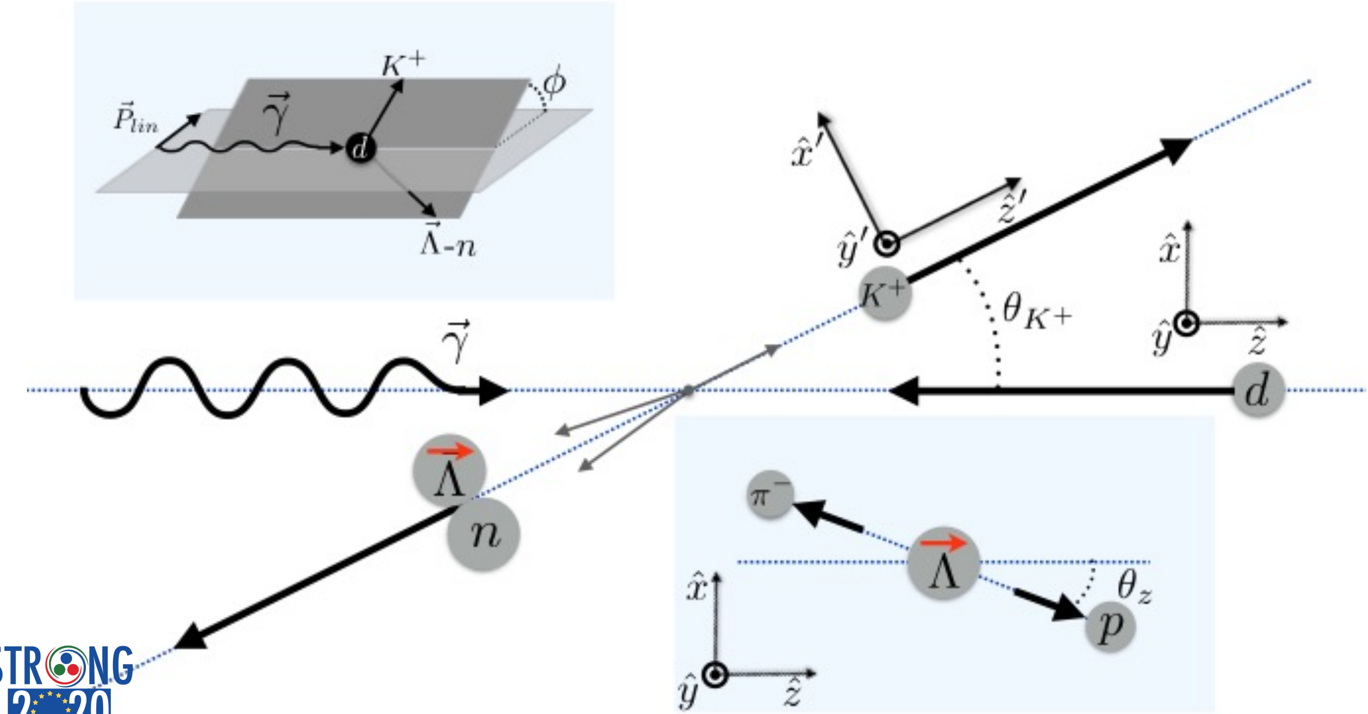






Polarisation observables General

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



Beam Polarisation

Linearly polarized

Circularly polarized

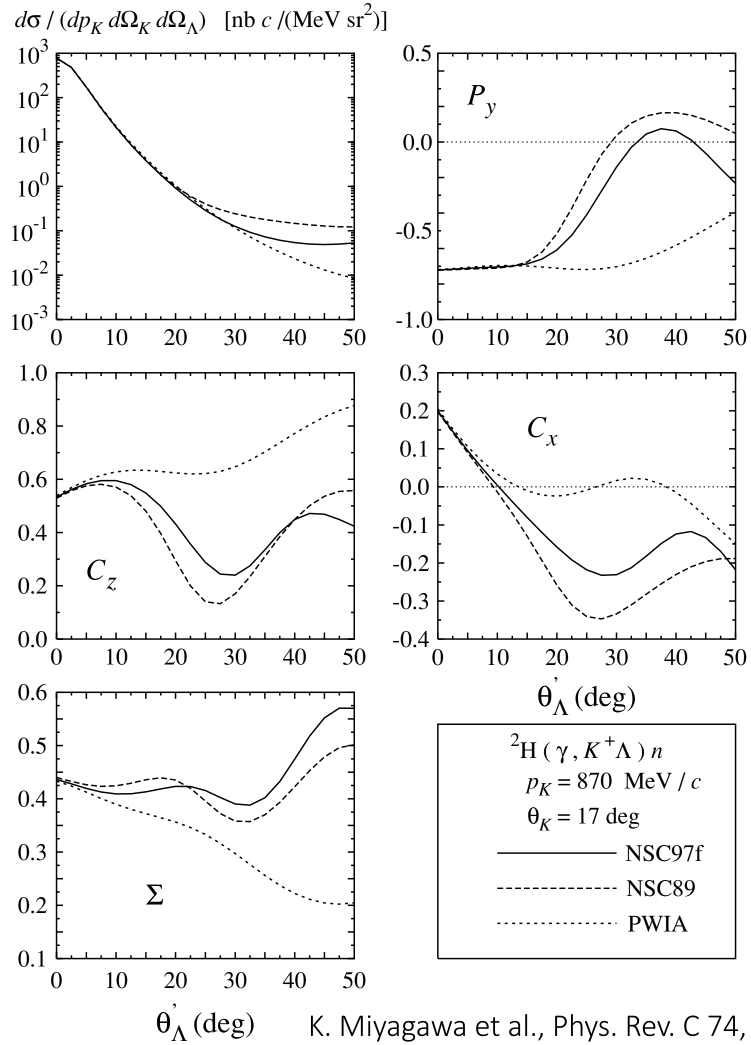
Λ Recoil Polarisation

Self-analysing power

α=0.75

Polarisation observables Yn

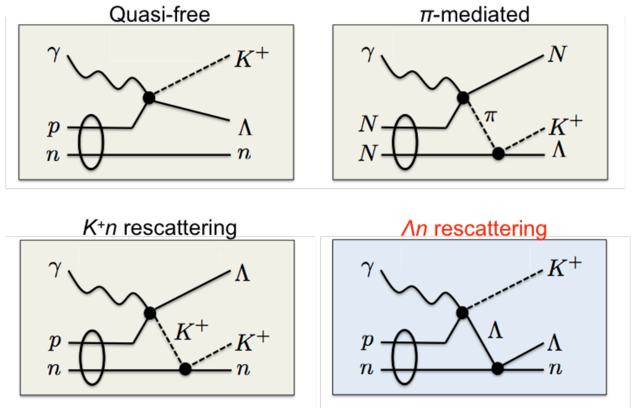
- Existing *YN* models allow the calculation of single and double polarization observables
- Two *YN* potentials (NSC97F and NSC89) give the correct hypetrition binding energy
- NSC97F and NSC89 lead to very different predictions of polarisation observables at some kinematics



Determination of scattering lengths
Phys. Rev. C **95**, 034001

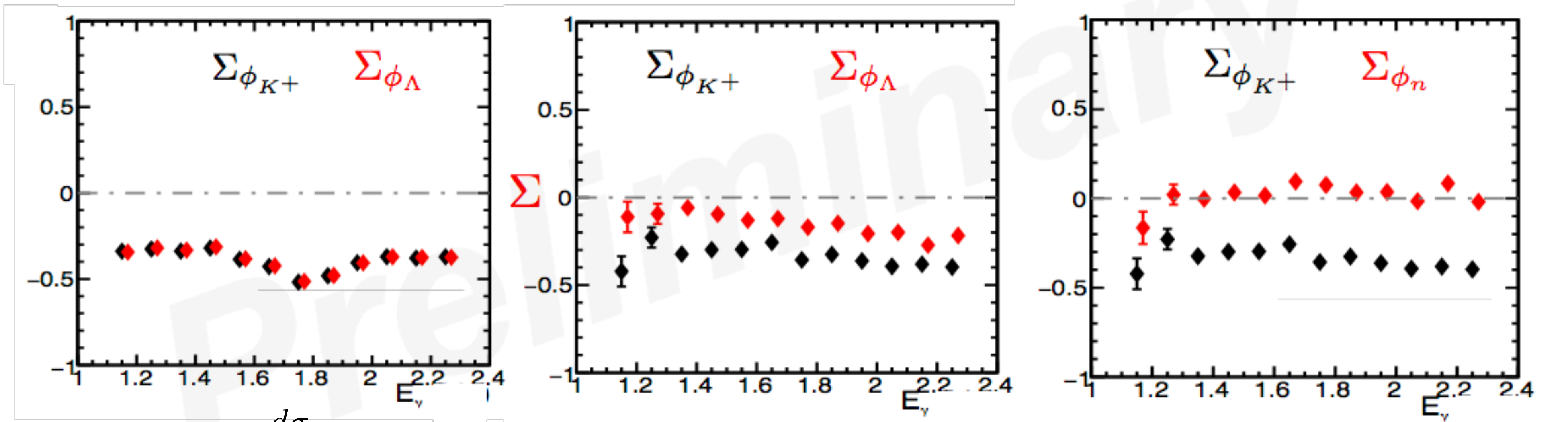
K. Miyagawa et al., Phys. Rev. C 74, 034002 (2006)

Polarisation observables Λ-n



QuasiFree data

FSI data

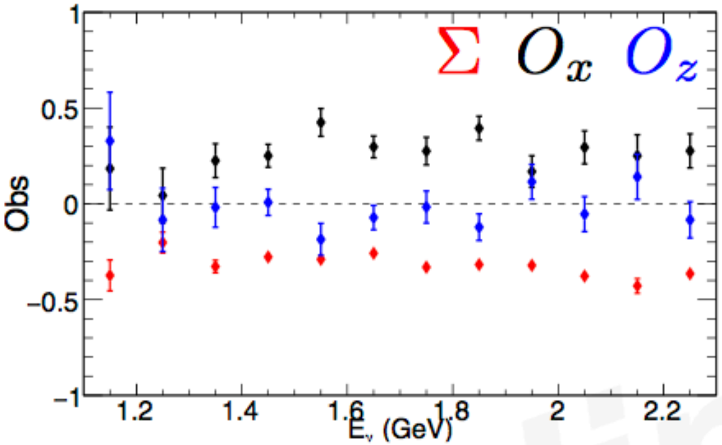


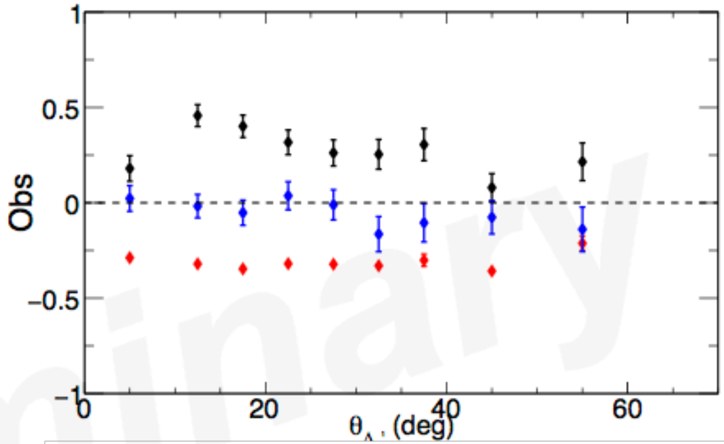
$$\frac{d\sigma}{d\Omega} = \sigma_0\{1 - P_{lin}\Sigma\cos 2\phi + \alpha\cos\theta_x(-P_{lin}O_x\sin 2\phi - P_{circ}C_x)$$

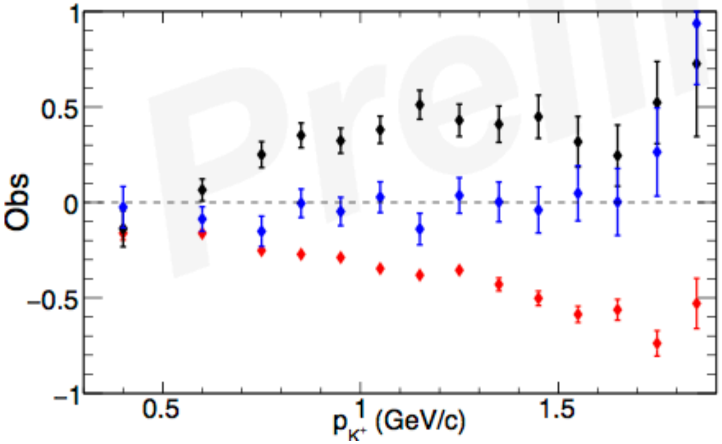
$$- \alpha\cos\theta_y(-P_y + P_{lin}T\cos 2\phi) - \alpha\cos\theta_z(P_{lin}O_z\sin 2\phi + P_{circ}C_z)\}$$

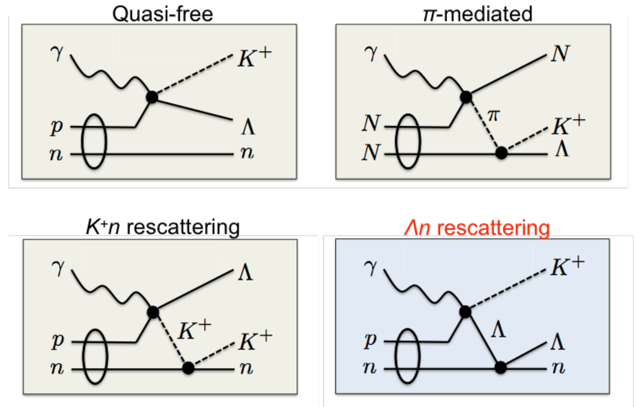
Polarisation observables Λ-n

FSI Results





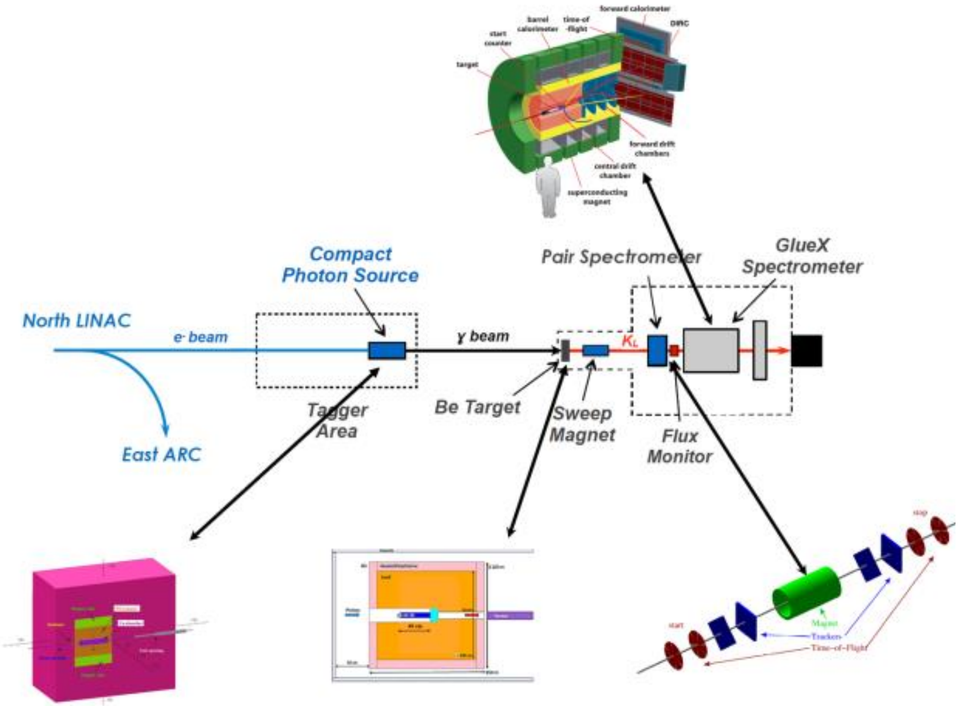


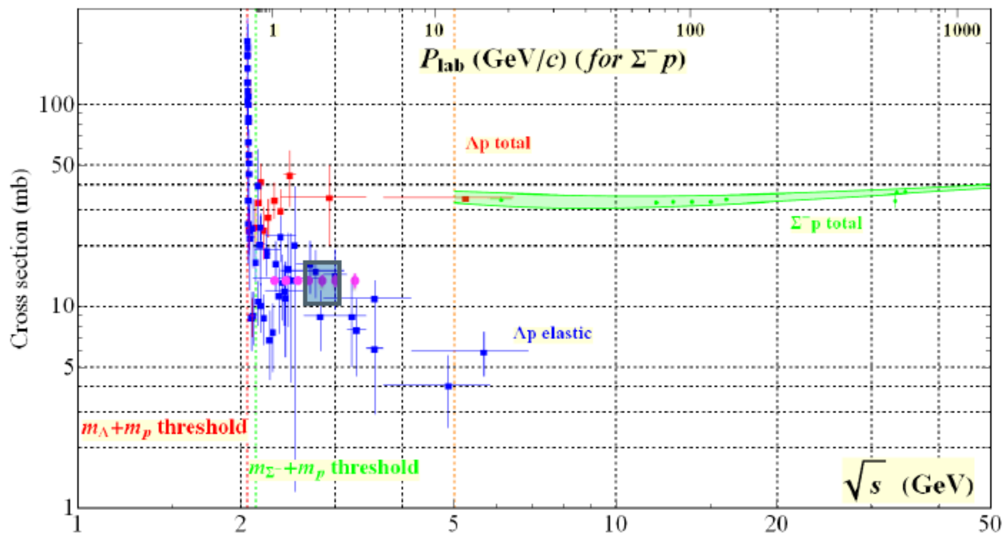


High statistics for extracting observables 2-fold and 3-fold differential

Work with theorist to interpret data and better tune free parameters of YN potentials

K-Long Facility at Jefferson Lab





Summary and conclusion

- FSI provides access to study YN with unprecedented statistics
- Polarisation observables are key in
  - Identifying YN dominating kinematic regimes
  - Separation between FSI mechanism and reduction in the model dependence interpretation
- Cross section measurements

$$\Lambda p \rightarrow \Lambda p \qquad \Sigma^- p \rightarrow \Sigma^- p$$
$$\Lambda d \rightarrow \Lambda d \qquad \Lambda d \rightarrow \Lambda pn \qquad \Lambda d \rightarrow \Sigma^- pp$$

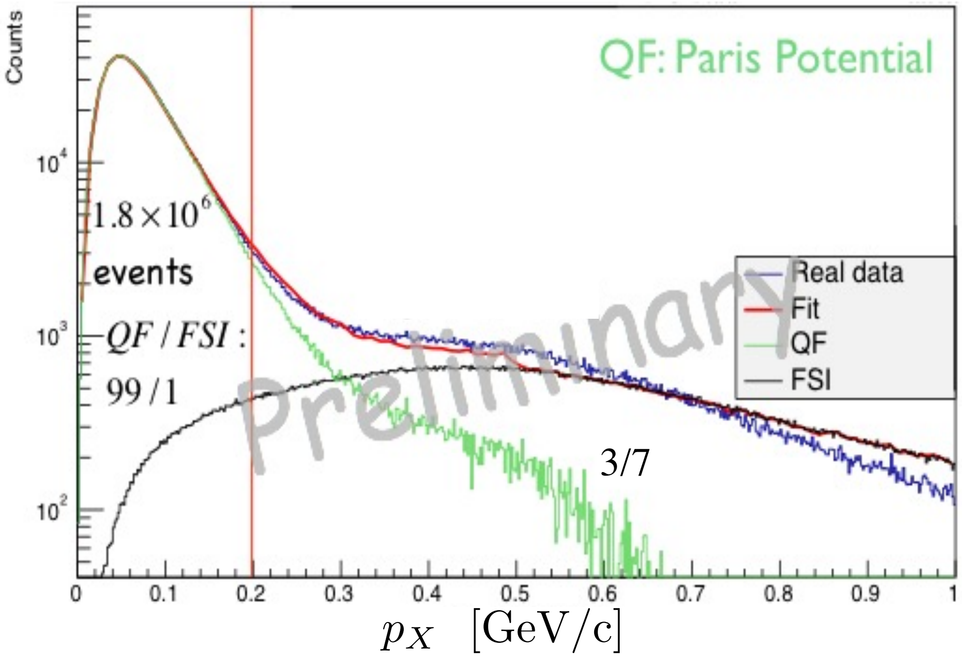
- Polarisation measurements

$$\Lambda n \rightarrow \Lambda n \qquad \Lambda p \rightarrow \Lambda p \qquad \Sigma^- p \rightarrow \Sigma^- p$$
$$\Lambda d \rightarrow \Lambda d$$

Thank you

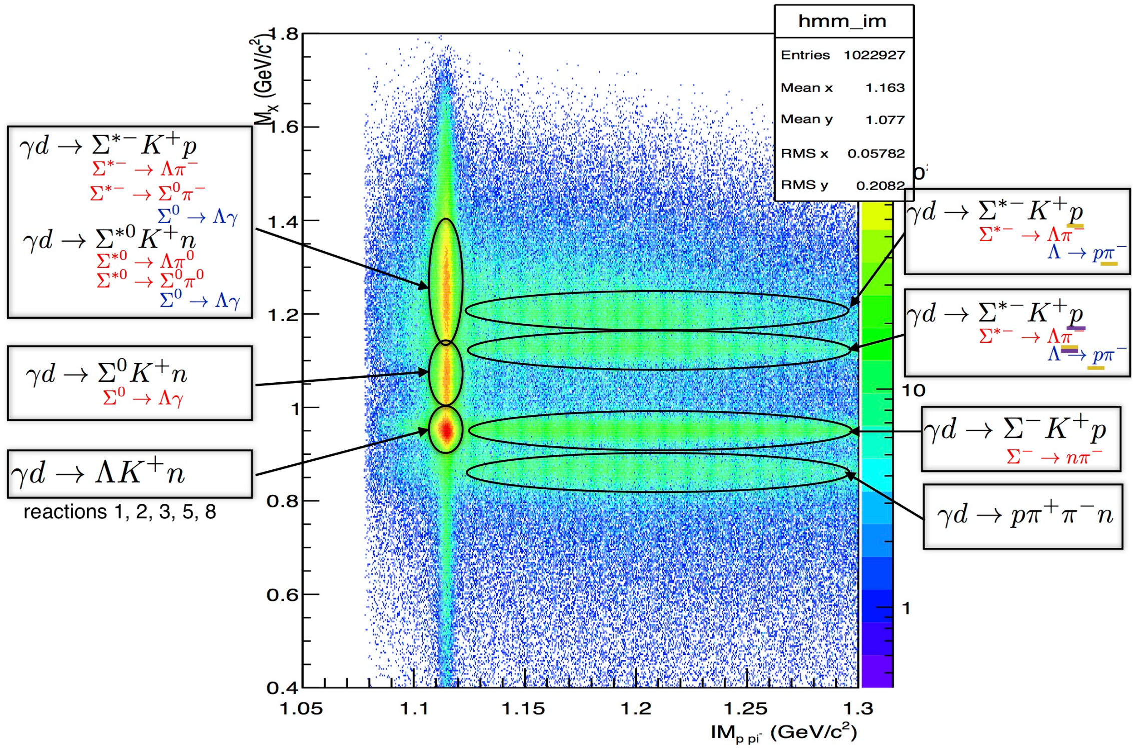
Exclusivity of the Reaction

Suppression of Quasi-free

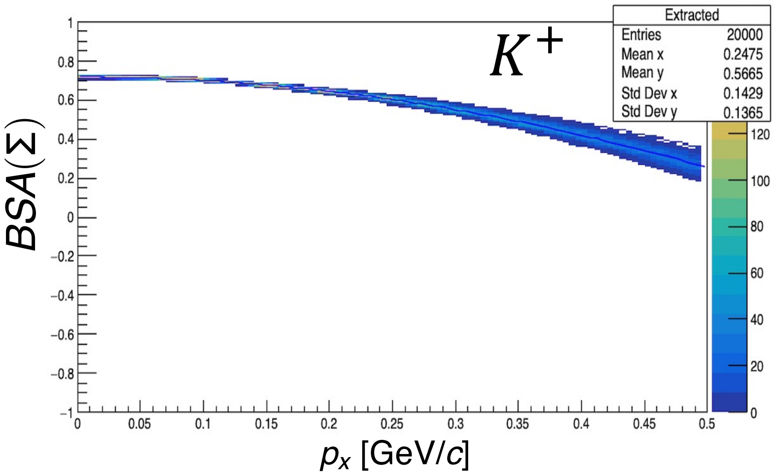


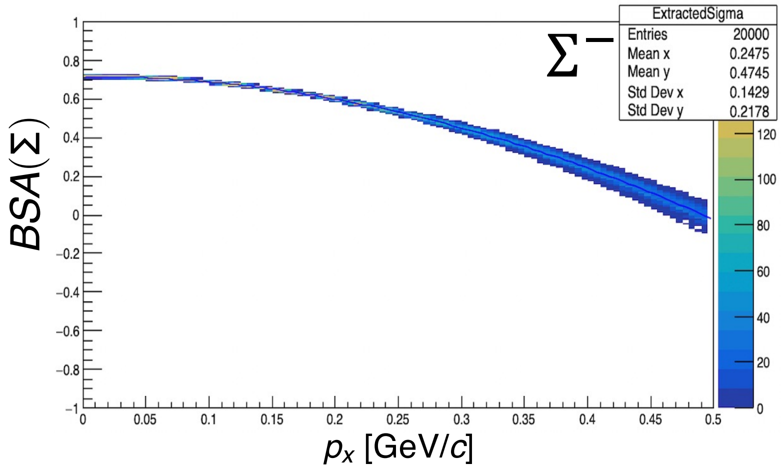
$$\gamma d \rightarrow K^+ \Lambda(n)$$
$$\hookrightarrow p\pi^-$$

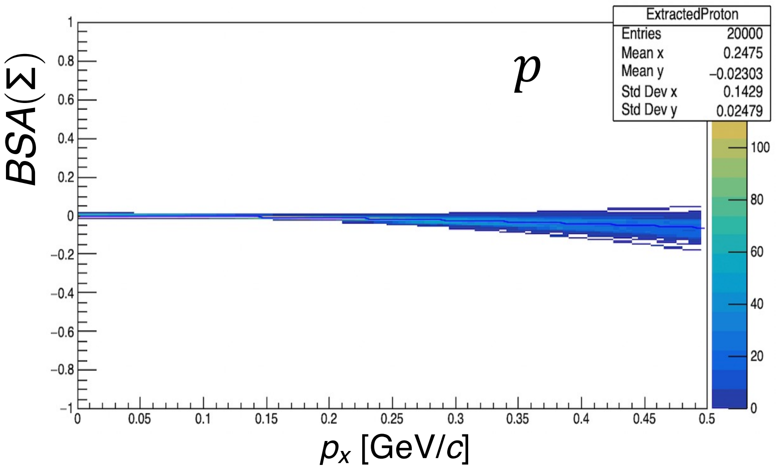
Reaction Reconstruction



Polarisation observables Σ-p







Results extrapolated to zero missing-momentum agree with QF study (submitted to PLB)

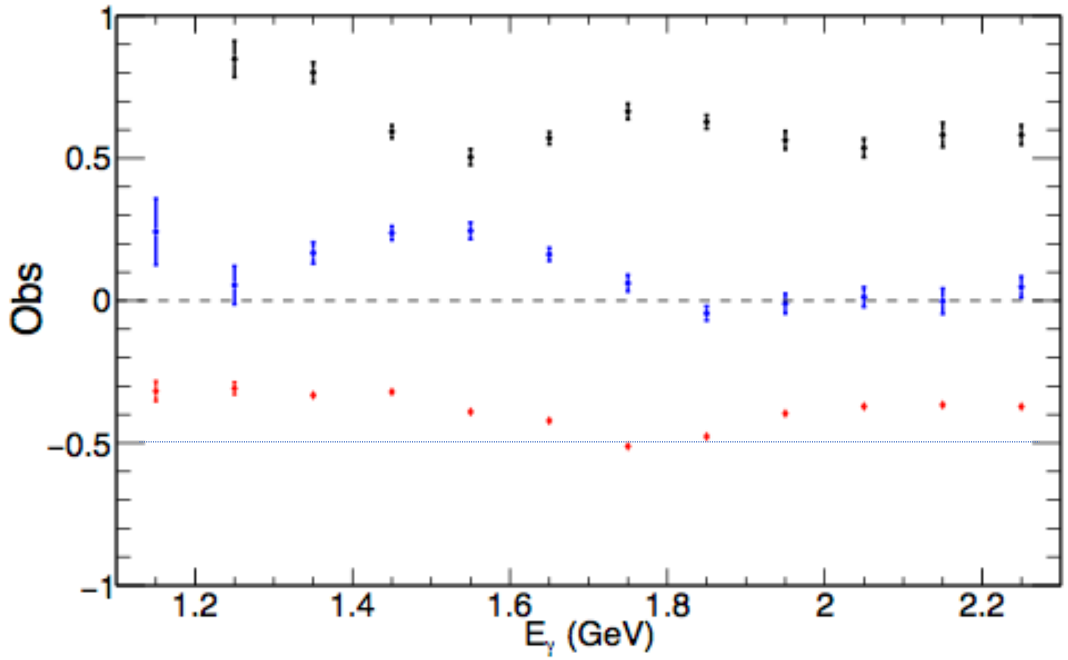
Large dilutions at higher missing momenta due to FSI

Relative dilutions can be attributed to the various FSI contributions

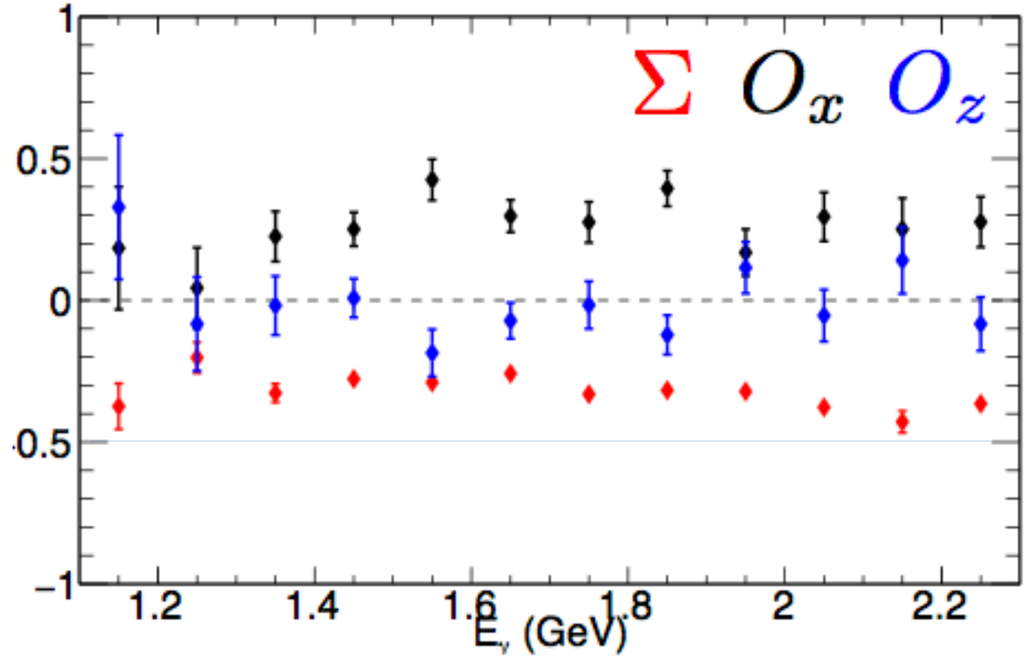
Preliminary Results

From 1250 events from BC to 10^5 from FSI

Quasi-free p_x< 200 MeV/c



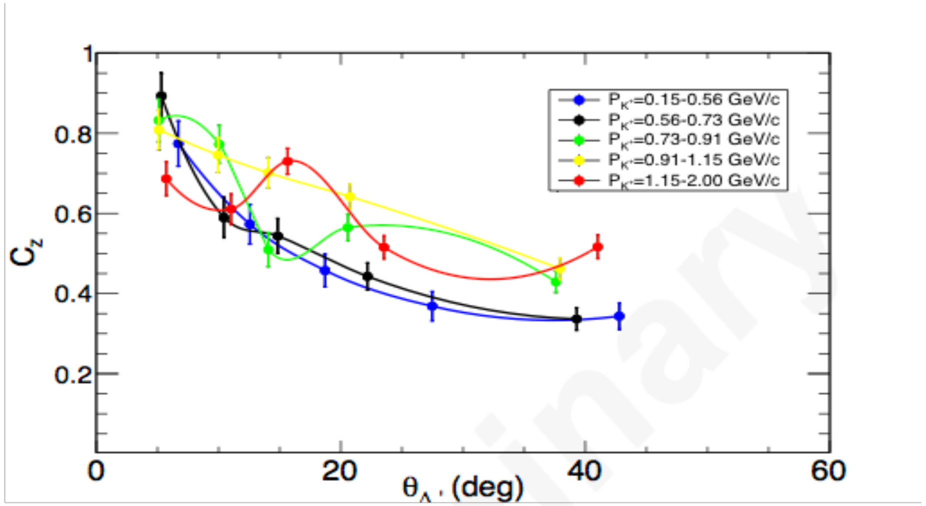
Final-state Int. p_x >200 MeV/c

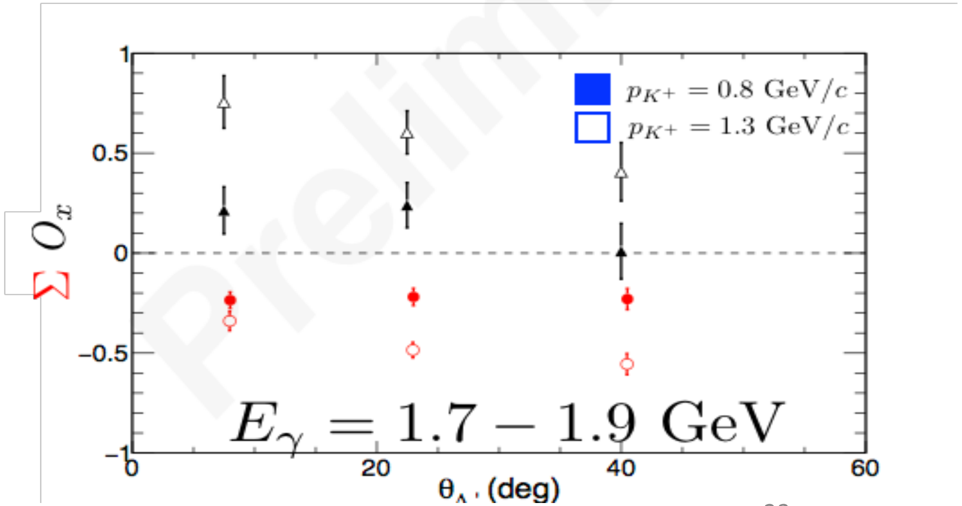


Sizable effects from FSI

Preliminary Results

- Adequate statistics for extracting observables 2-fold and 3-fold differential
- Goal is to better tune the free parameters of *YN* potentials
- Work with theorists to interpret the data





Interpretation studies $\gamma d \rightarrow K^+ \Lambda n$

- Single polarization observable → Smallest statistical uncertainty

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 - P_{lin} \Sigma \cos 2\phi + ...]$$

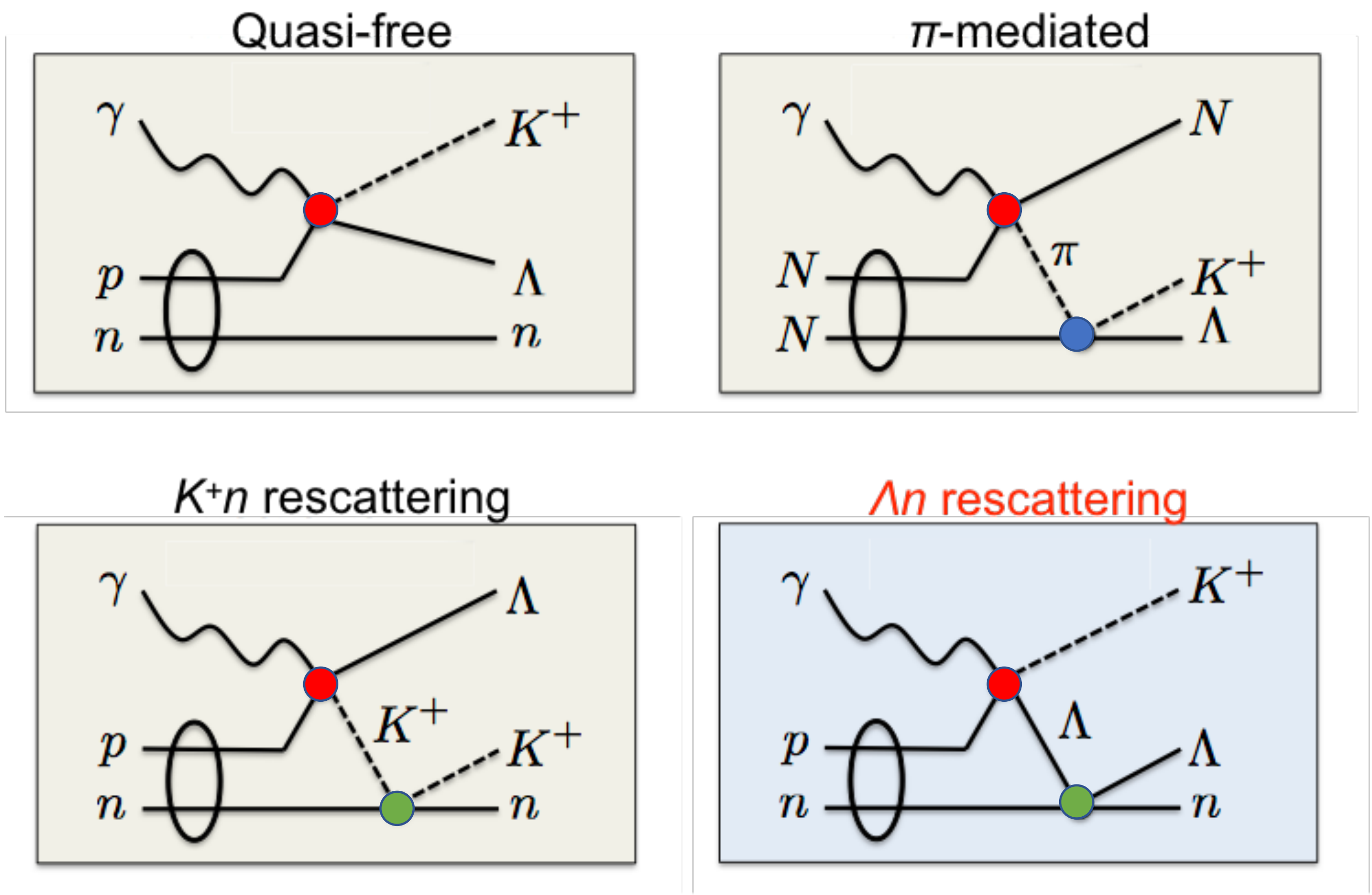
- For the $K^+ \Lambda n$ final state the azimuthal angle ϕ is not uniquely defined
  - ϕ_K, ϕ_Λ, ϕ_n, $\phi_{\Lambda n}$, ϕ_{Kn}, $\phi_{\Lambda K}$

Beam-spin asymmetry can be used as a probe to disentangle FSI

Interpretation studies

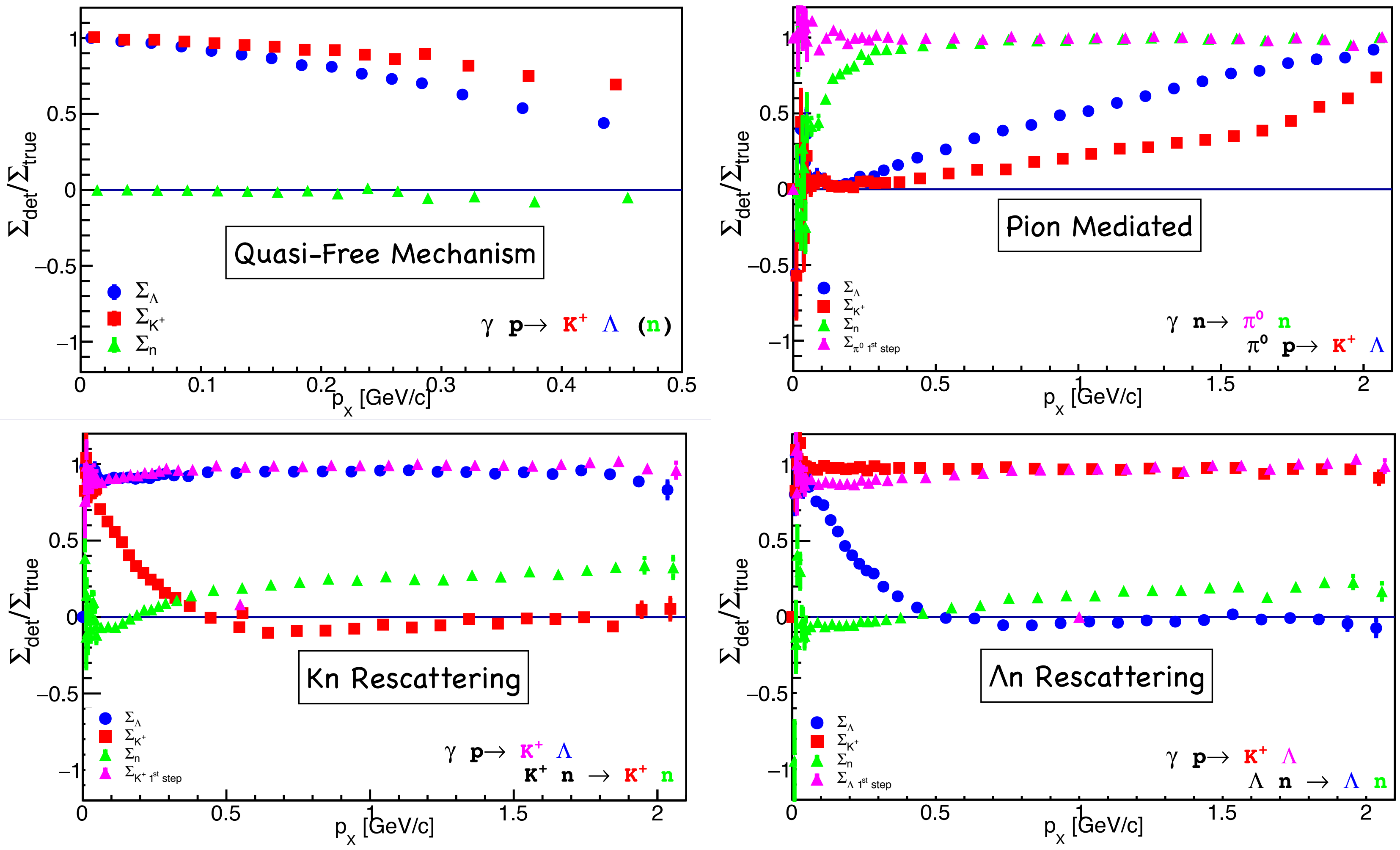
Generated Samples

- Polarised differential cross section
- Unpolarised differential cross section
- Phase space



Interpretation studies

Simulation



Interpretation studies

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