Hyperons in Neutron Stars

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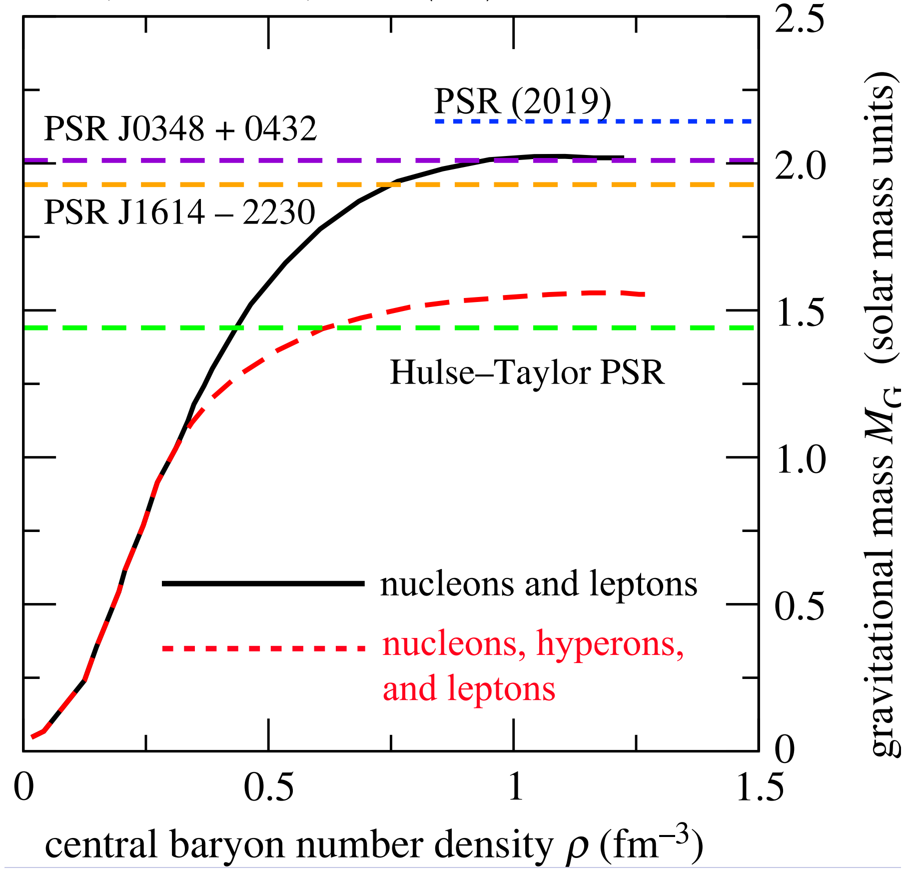
UNIVERSITY of York

Outline

- Why study the YN interaction
- Ongoing studies –
  - Exclusive hyperon photoproduction
- Summary and KLF

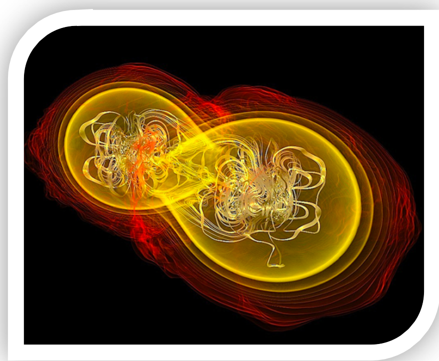
The Hyperon Puzzle

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



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

- Hyperons are expected to appear in the core of NS at $\rho \sim 2-3\ \rho_0$
- Hyperon 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

The Hyperon Puzzle

A comprehensive picture of the strong interaction is needed to understand both the NN and YN interactions

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

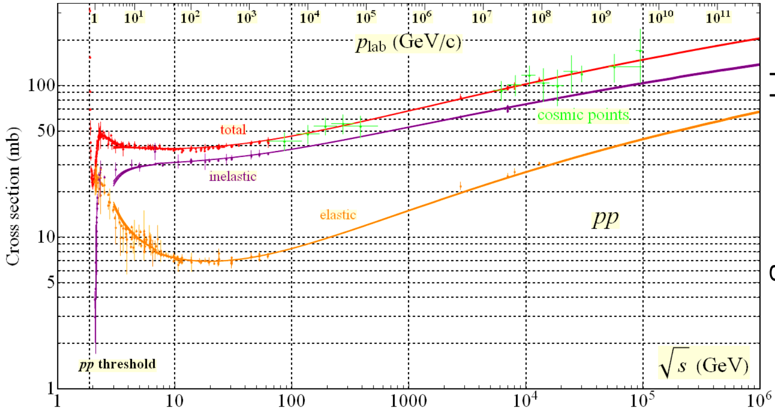
- YY and YN forces
- YNN and YYN three body forces

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)

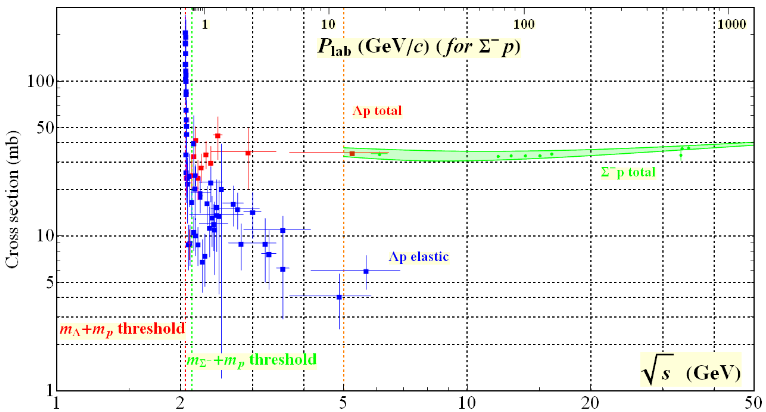
Experimental data are needed to place constraints on the interaction

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

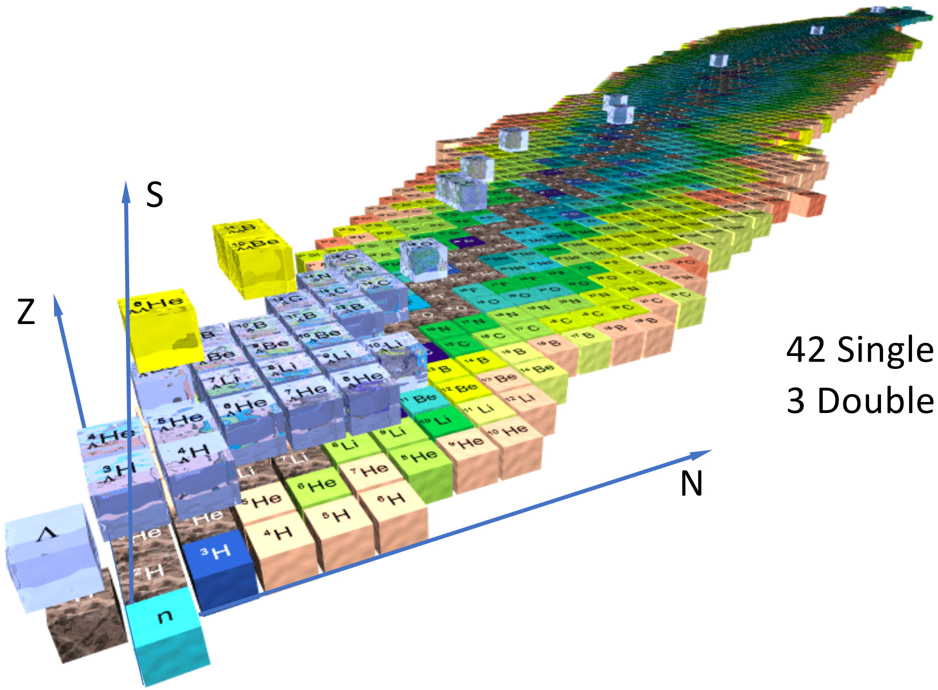
Hyperon Physics – Complementary approaches

Hyper-nuclear physics

$$K^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$

$$\pi^+ + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + K^+$$

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



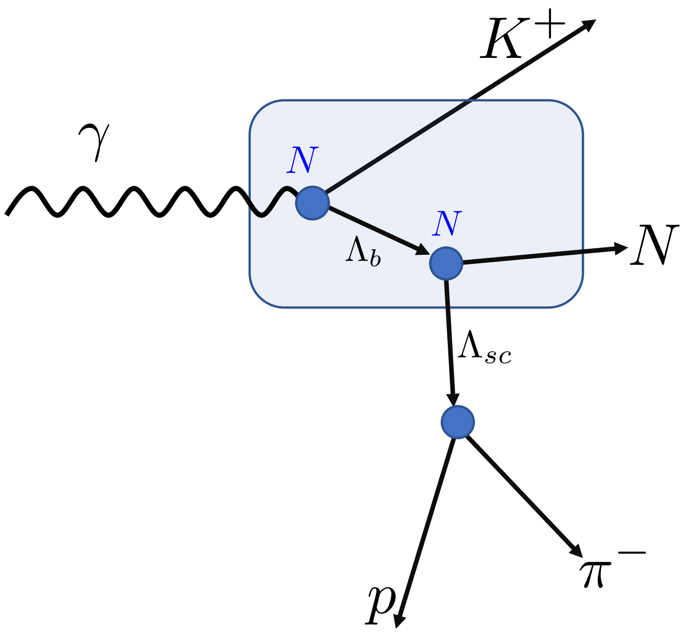
42 Single Λ
3 Double Λ

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

Hyperon Physics – Complementary approaches

Final State Interactions

$$\gamma N \rightarrow KY \quad YN \rightarrow \Lambda N$$
$$\gamma d \rightarrow KYN$$

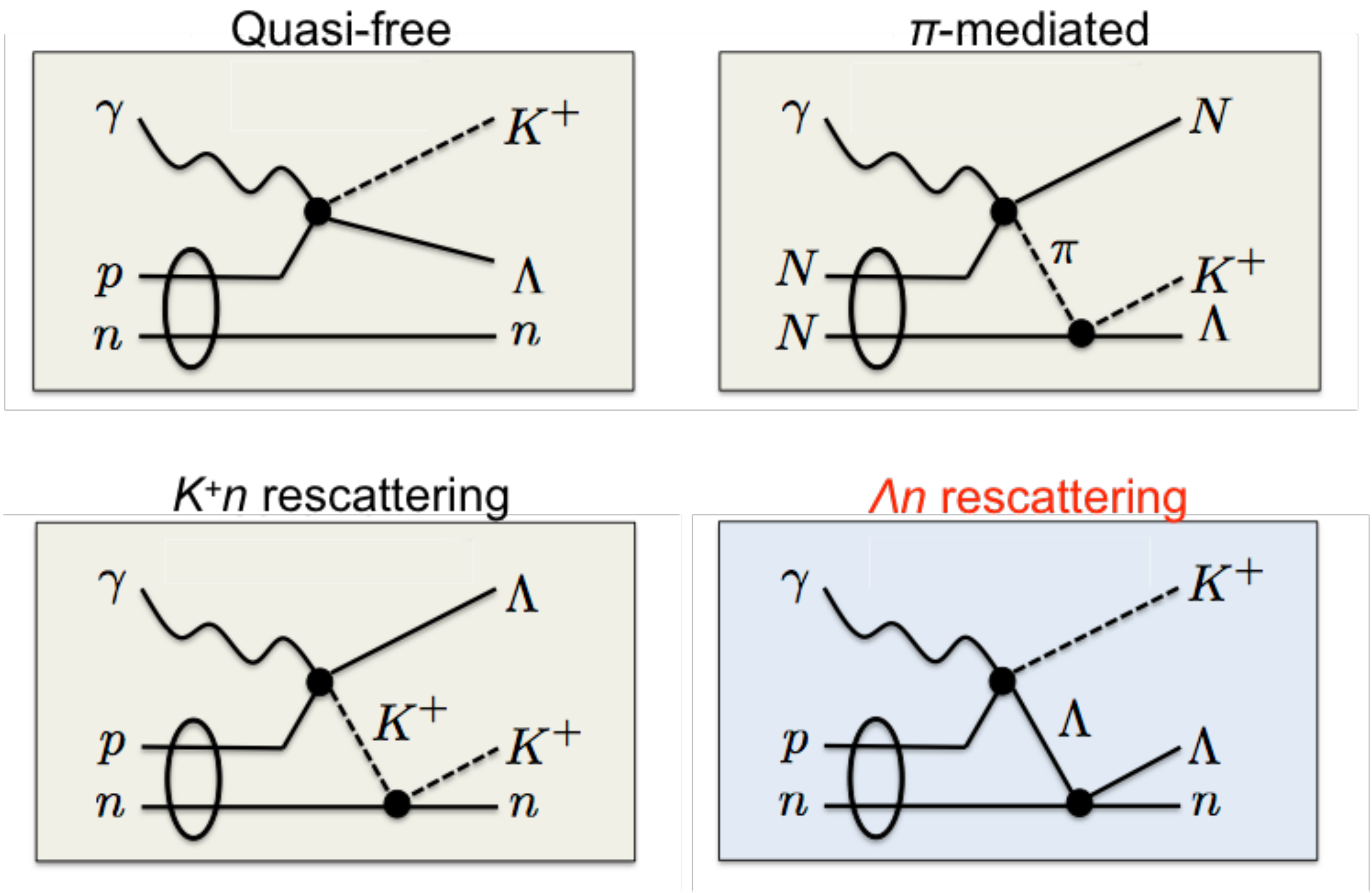


$\tau_\Lambda = 2.6 \times 10^{-10}\ s$
$c\tau_\Lambda = 7.89\ cm$

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

- 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

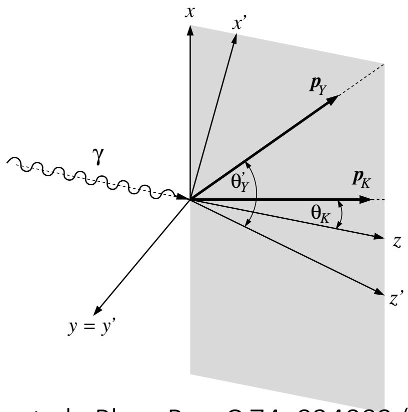
Exclusive hyperon Photoproduction off deuterium

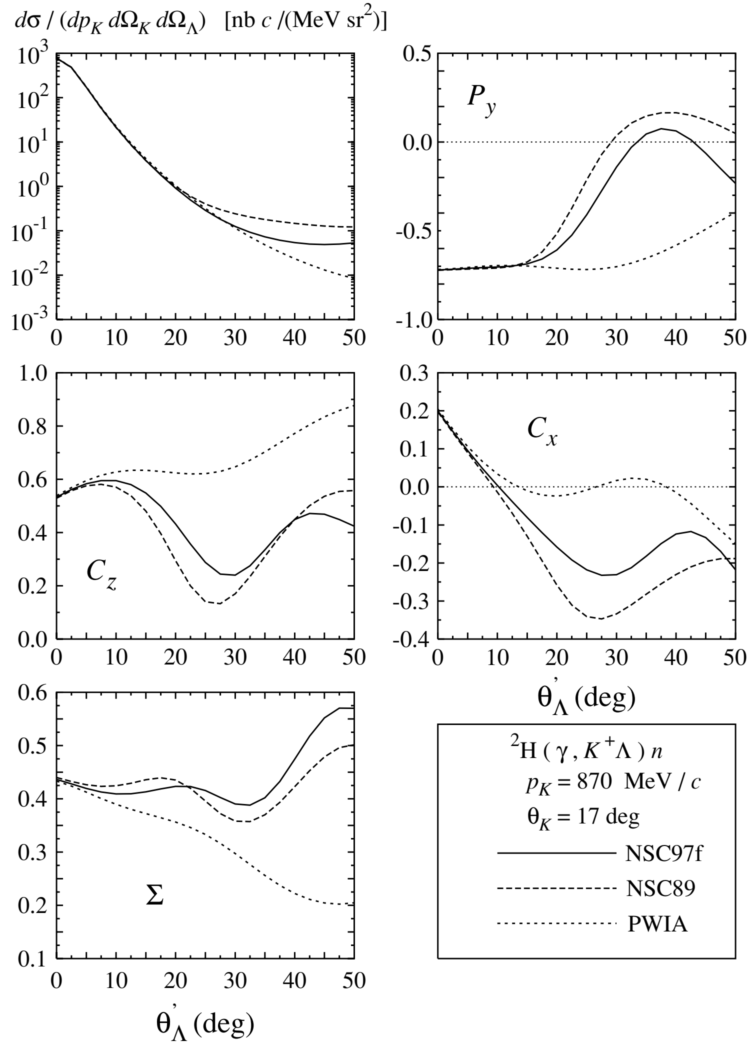


The QF events can be significantly reduced or enhanced experimentally, through kinematic constraints

Hyperon-Nucleon Theoretical studies $\gamma d \rightarrow K^+ \Lambda n$

- 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

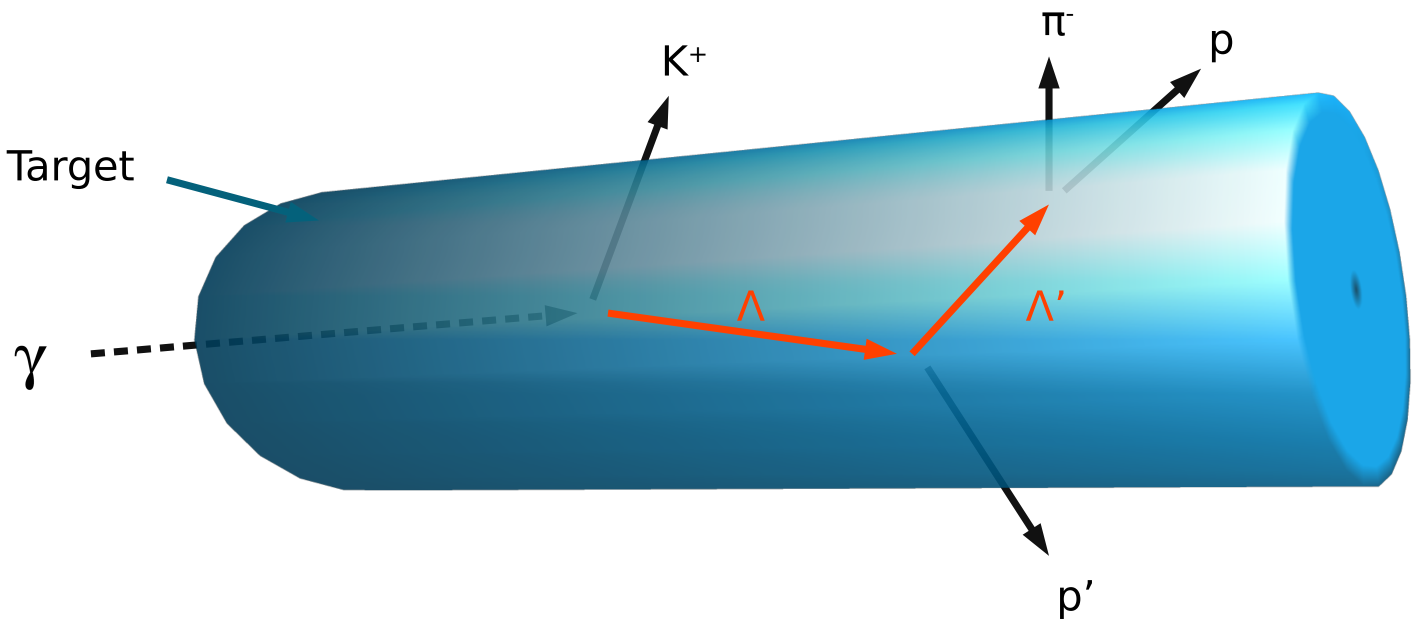




K. Miyagawa et al., Phys. Rev. C 74, 034002 (2006)

Ongoing studies: Cross Section Yp

CLAS Detector
g12 Data



- Liquid Hydrogen Target
- p, p', π^- detected
- Λp scatter elastically

$$\Lambda p \rightarrow \Lambda p$$

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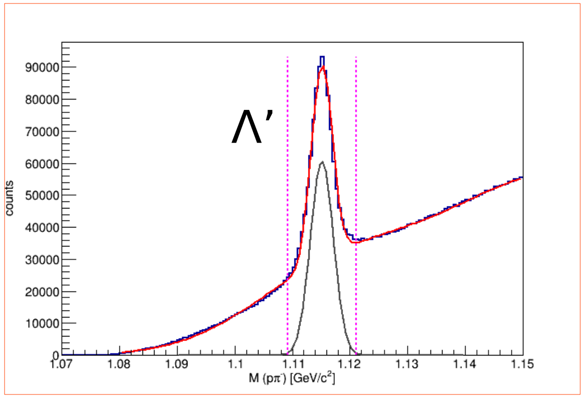
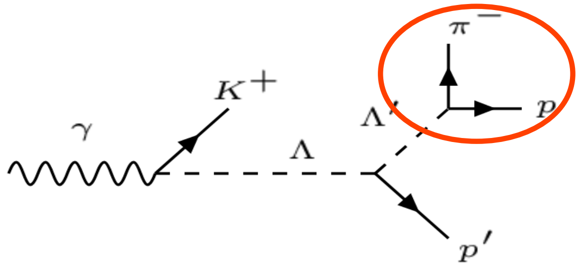
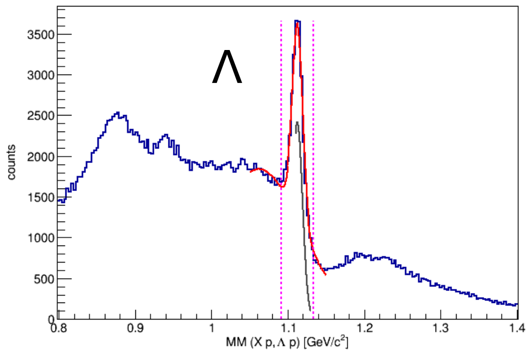
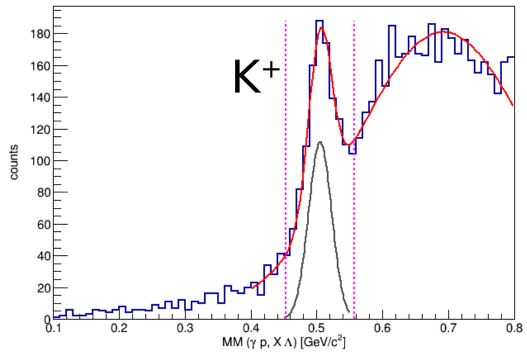
Ongoing studies: Cross Section Yp

CLAS Detector
g12 Data









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Ongoing studies: Cross Section Yp

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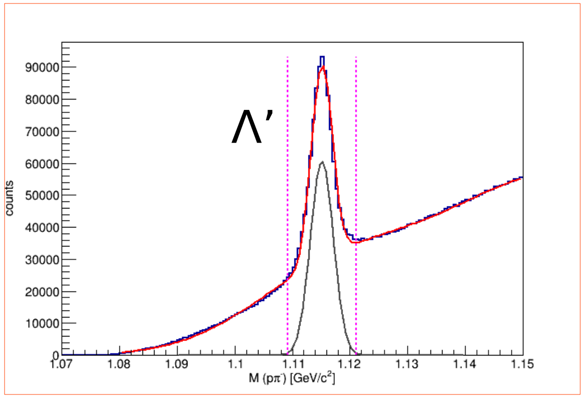

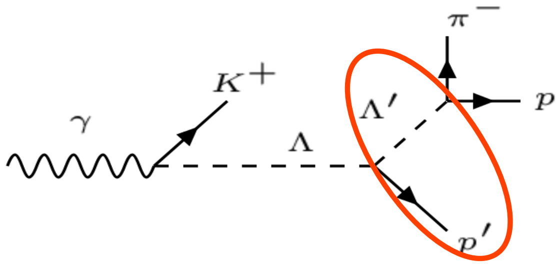

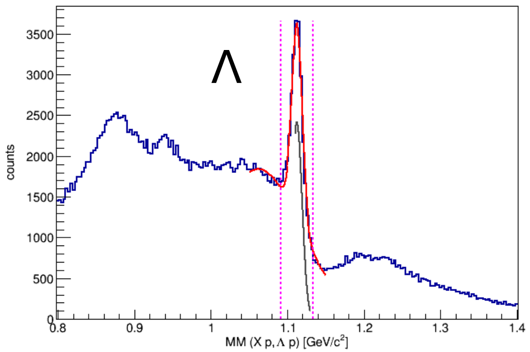

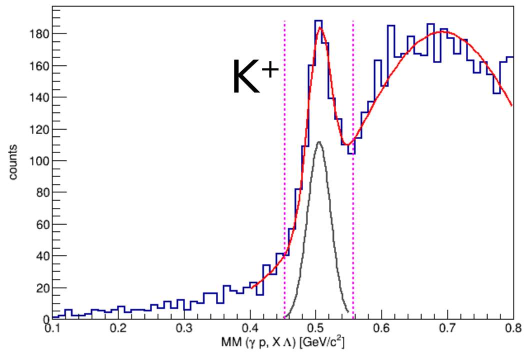

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Ongoing studies: Cross Section Yp

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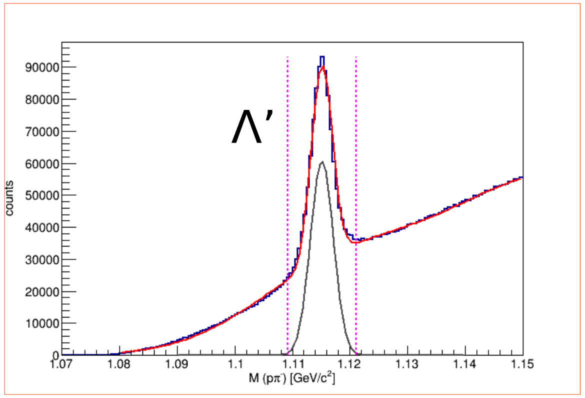

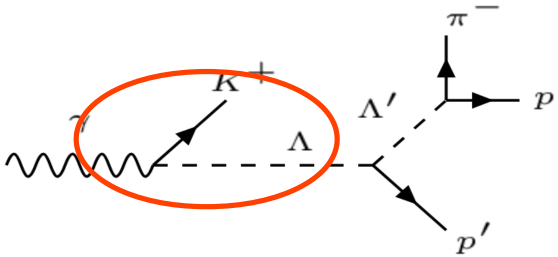

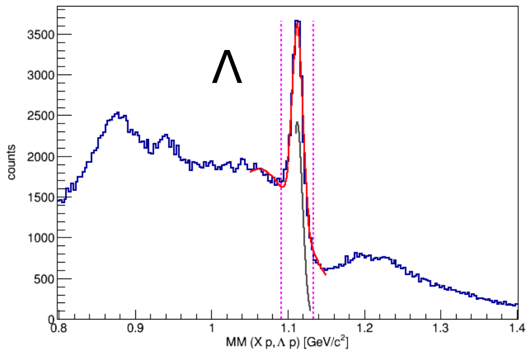

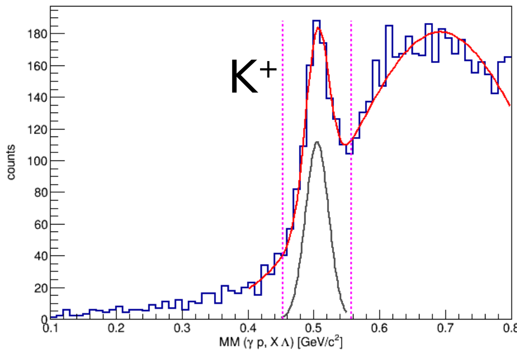

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Ongoing studies: Cross Section Yp

CLAS Detector
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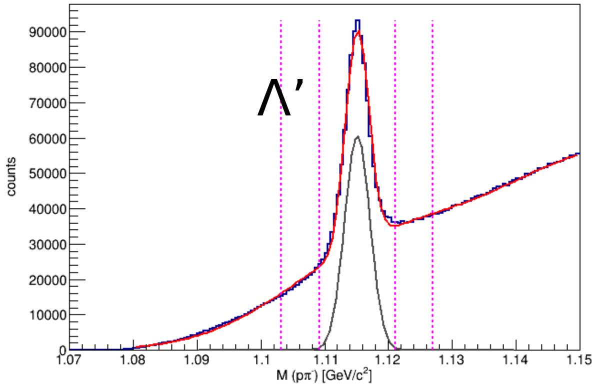

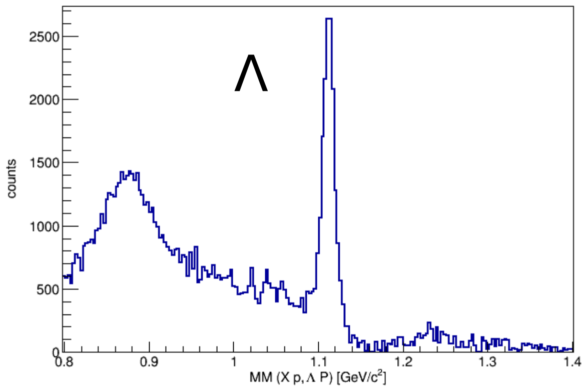

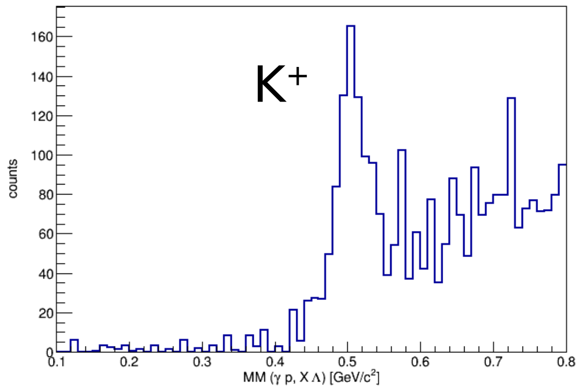

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Ongoing studies: Cross Section Yp

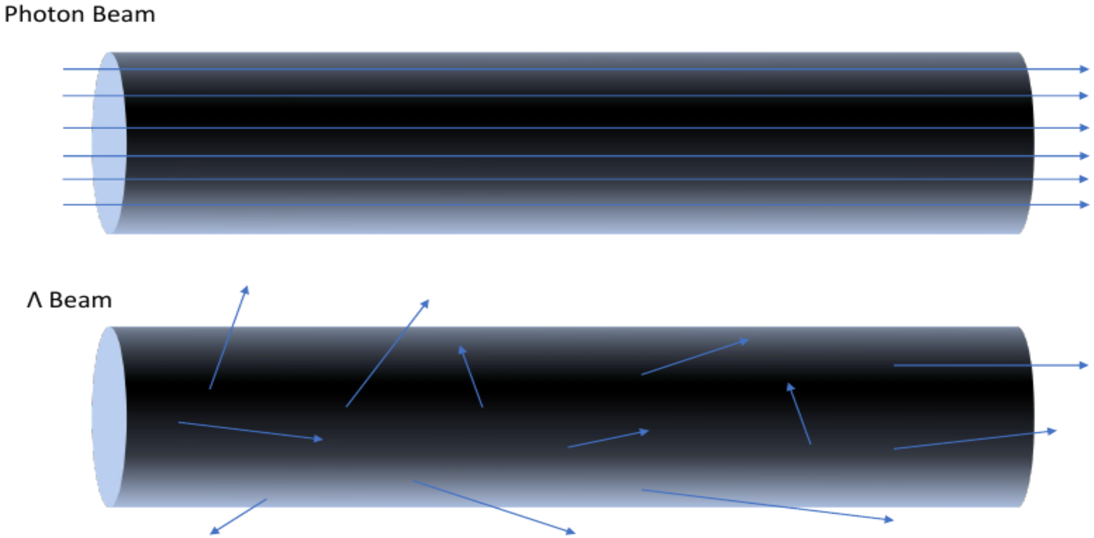
CLAS Detector
g12 Data

Luminosity

$$L_\Lambda(E_\Lambda) = \frac{\rho_T * N_A * l}{M} * N_\Lambda(E_\Lambda)$$

- ρ_T: density of the target
- N_A: Avogadro's number
- M: molar mass of Hydrogen
- l: travel distance of Λ
- $N_\Lambda(E_\Lambda)$: yield in a certain energy range

$$\frac{d\sigma}{d\Omega} = \frac{N_\Lambda}{2\pi * L_\gamma * \Delta\cos(\theta)}$$



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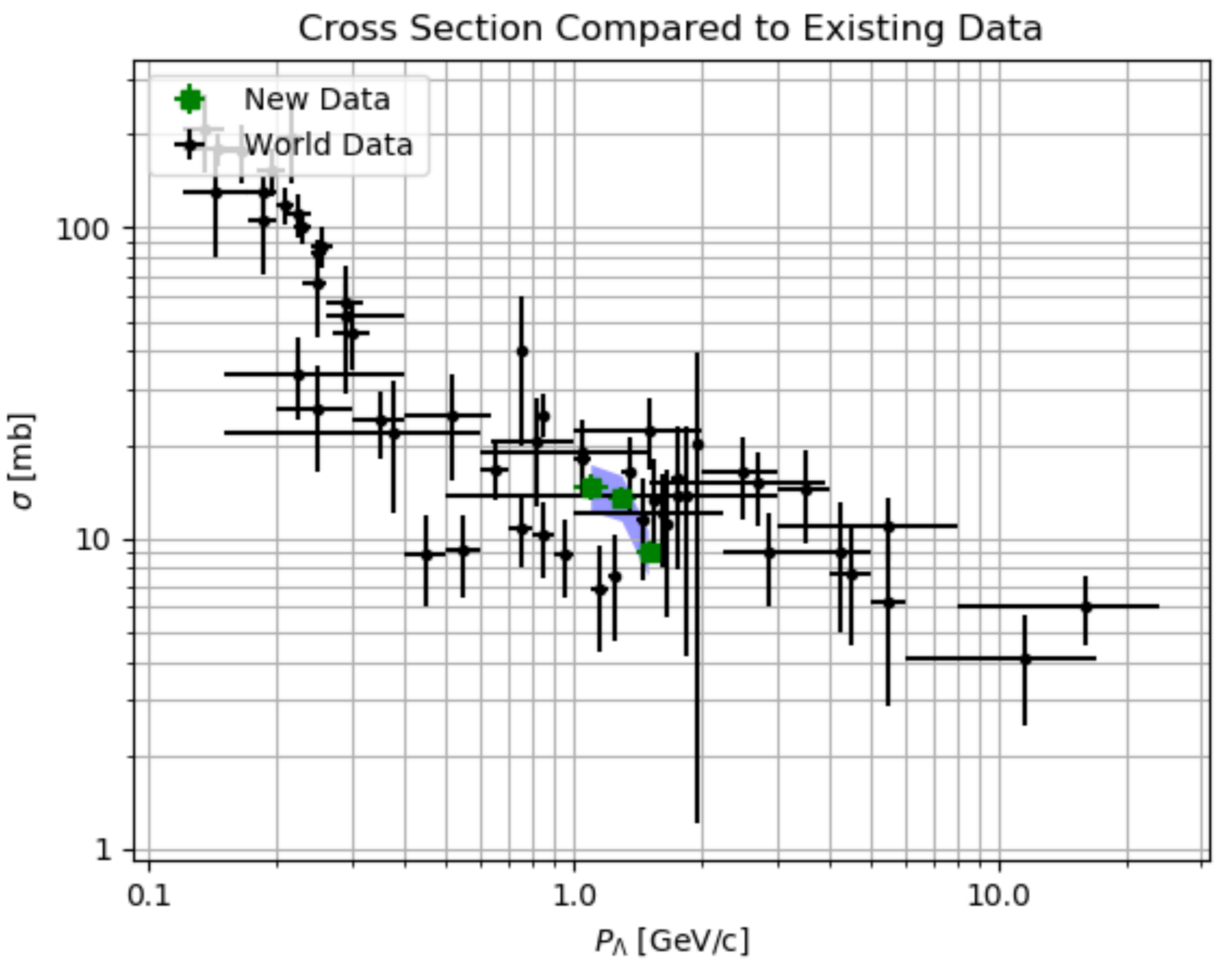
Preliminary Results

CLAS Detector
g12 Data



- Black: Existing data from PDG
- Green: Measurements from this study
- Blue: Systematic Errors

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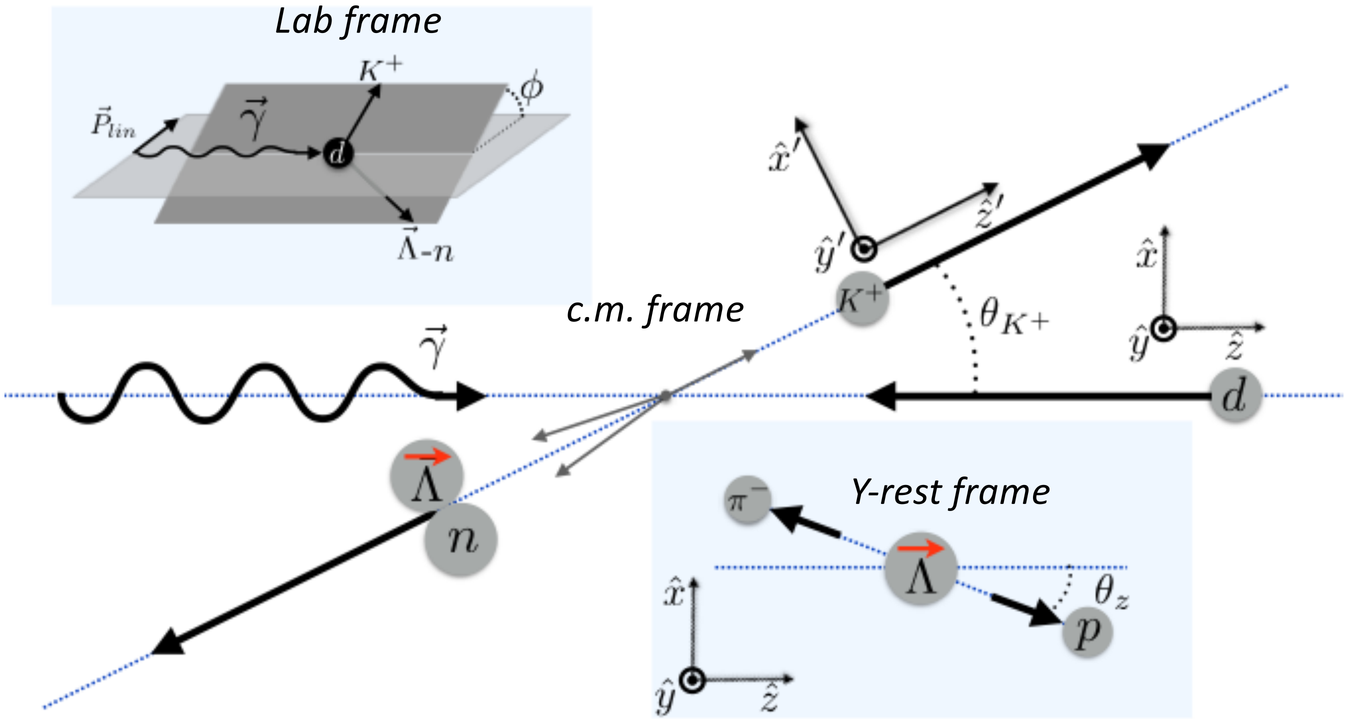
Polarisation observables $\gamma d \rightarrow K^+ \Lambda n$

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



Beam Polarisation

Linearly polarized

Circularly polarized

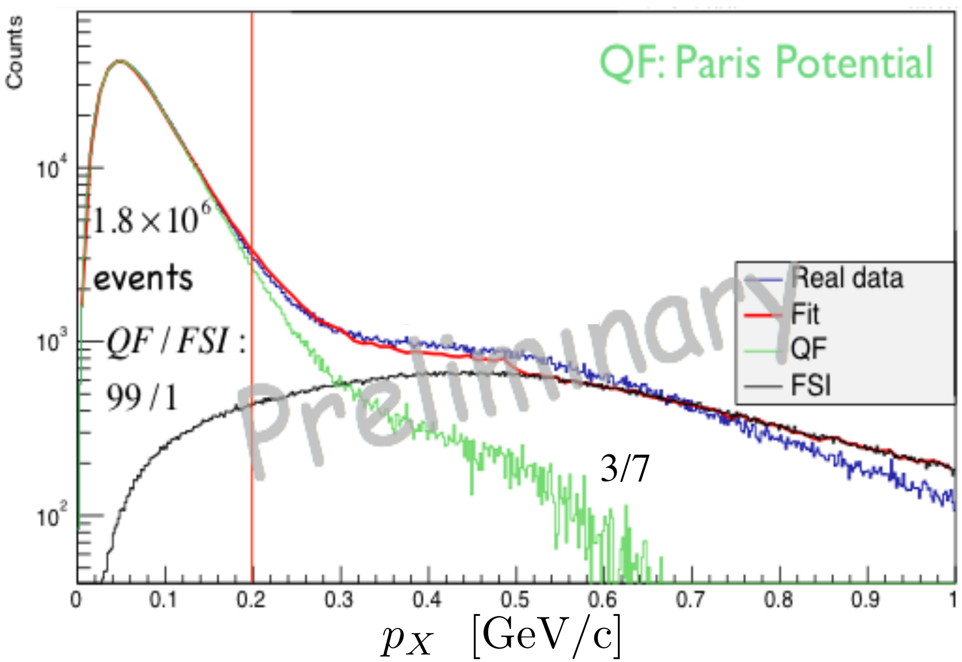
Λ Recoil Polarisation

Self-analysing power

α=0.75

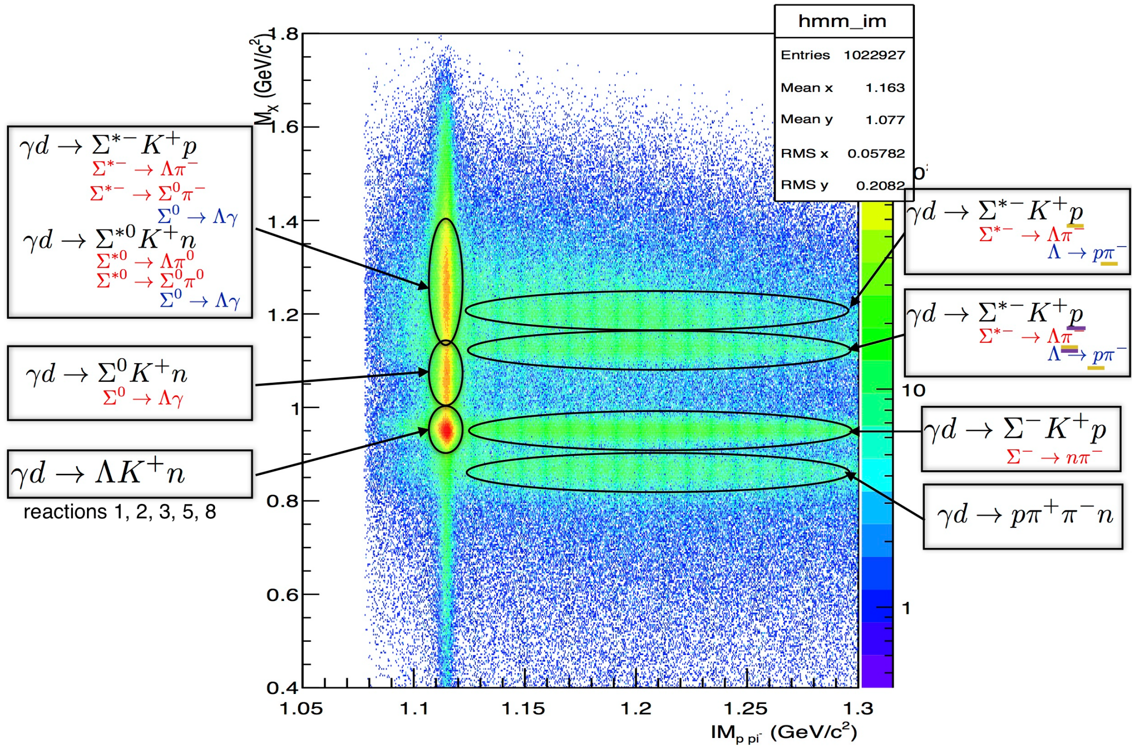
Exclusivity of the Reaction

Suppression of Quasi-free



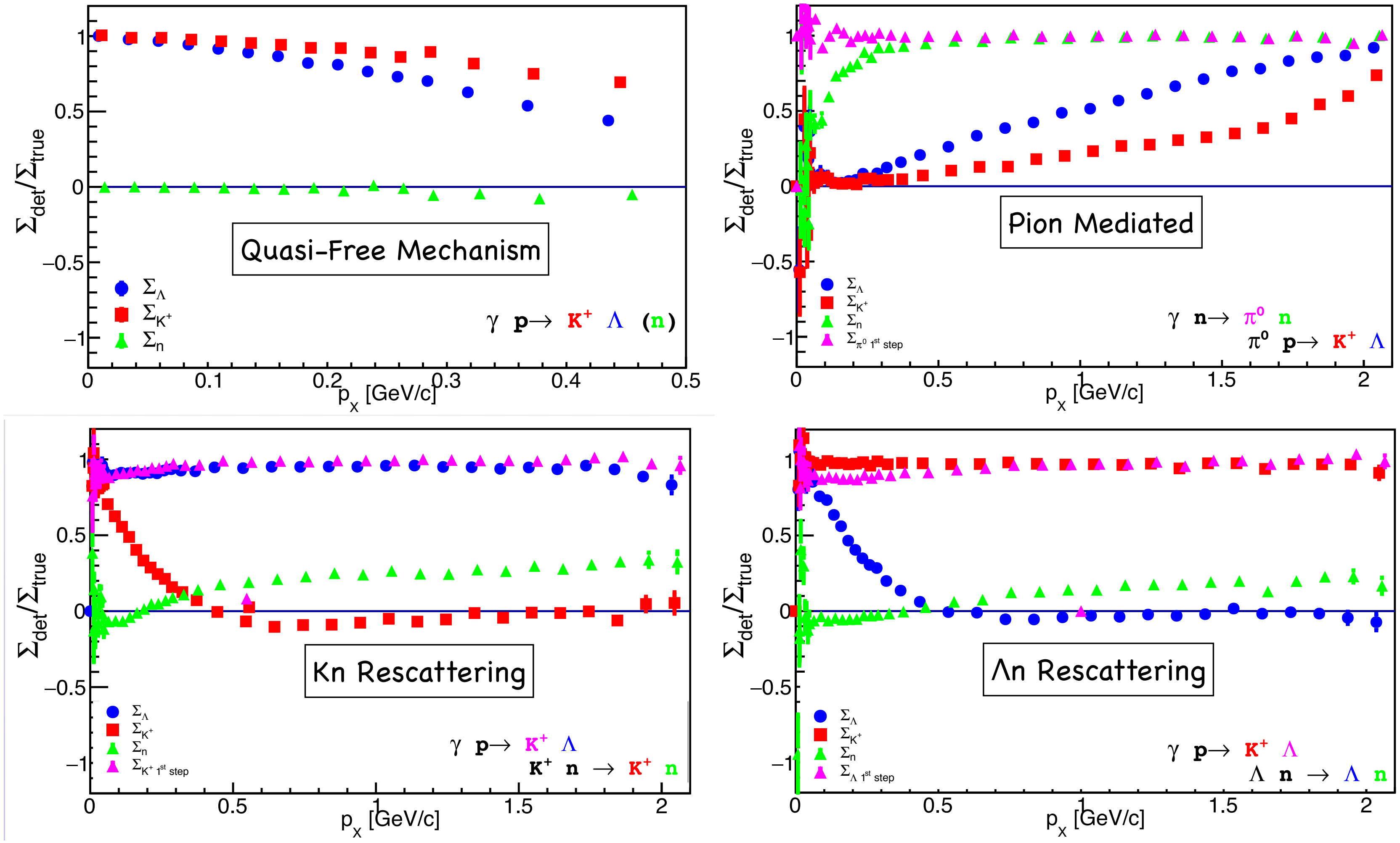
$$\gamma d \to K^+\Lambda(n)$$
$$\hookrightarrow p\pi^-$$

Reaction Reconstruction



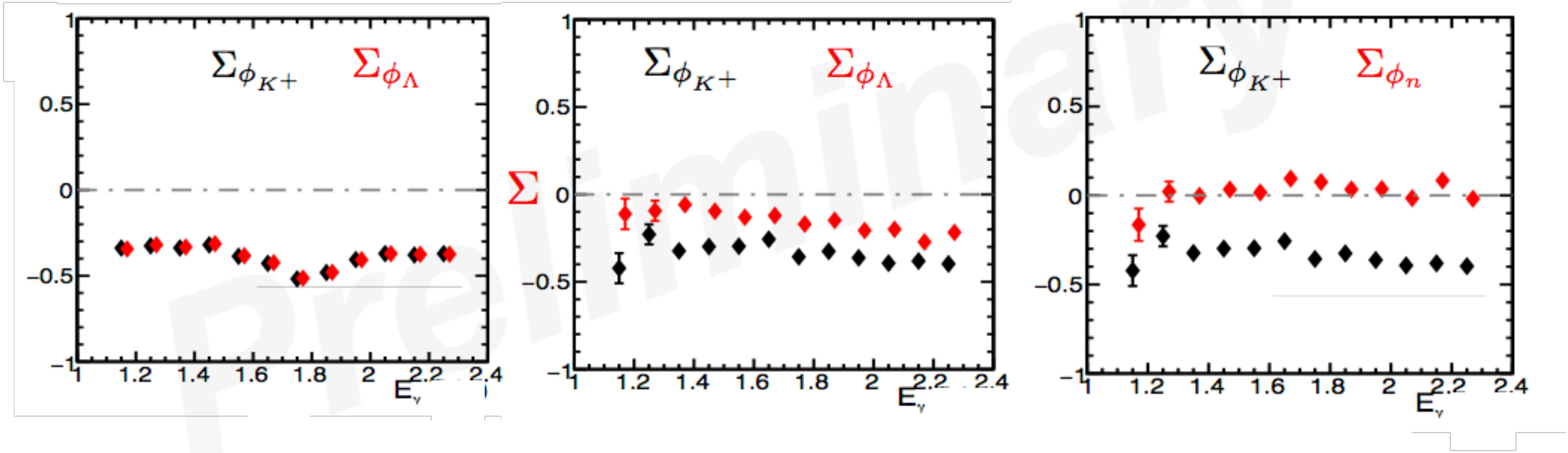
Interpretation studies

Simulation



Interpretation studies

QuasiFree data FSI data



KLF

- Precise measurement on YN interaction (~30 times higher statistics)
  - Cross section and polarization observables
- First measurement on double strangeness Xi-N interaction
- Access to three-body forces