Beam Asymmetry from γp → ηΔ+ reaction at Jefferson Lab

Mac Thomson, Varun Neelamana, Zisis Papandreou

University of Regina

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On Behalf of the GlueX Collaboration

Physics Background

Properties
- Color confinement
- Asymptotic freedom
- Chiral symmetry breaking

Challenges
- Non-perturbative Regime
- Confinement

Explore Meson Spectrum
- Ground states → mesons
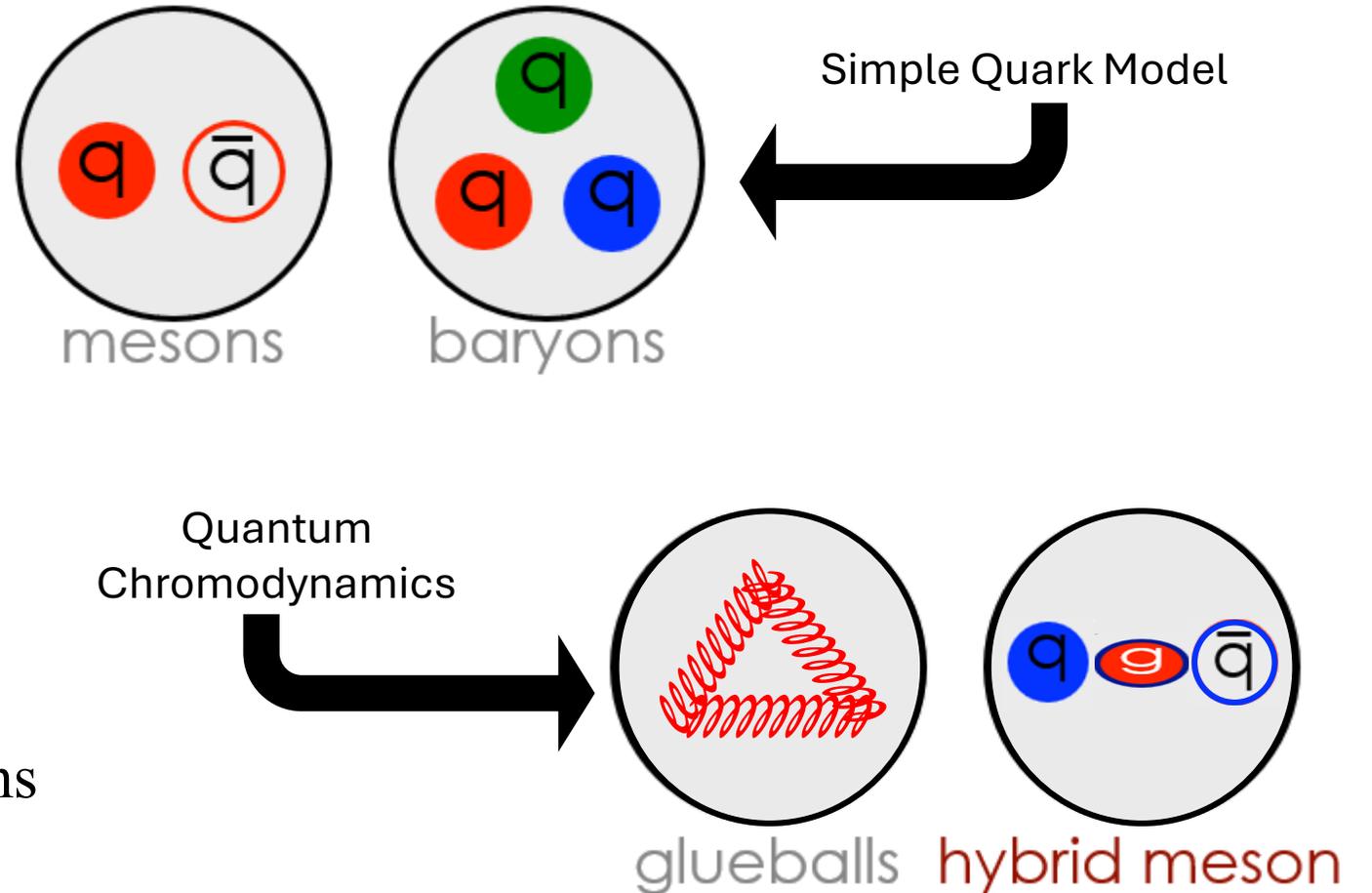- Excited states → hybrid mesons
- J^{PC} quantum numbers

Photo-Production and Beam Asymmetry

- **Conventional mesons**: gluons form flux tubes between the quark and anti-quark
- **Exotic mesons**: excitation of the flux tube
- Photo-production is more powerful than hadron probes, because no spin-flip is needed.

- **Beam Asymmetry** is an important polarization observable in photoproduction experiments
- It is relatively ease to access
- It provides information on the photoproduction mechanism
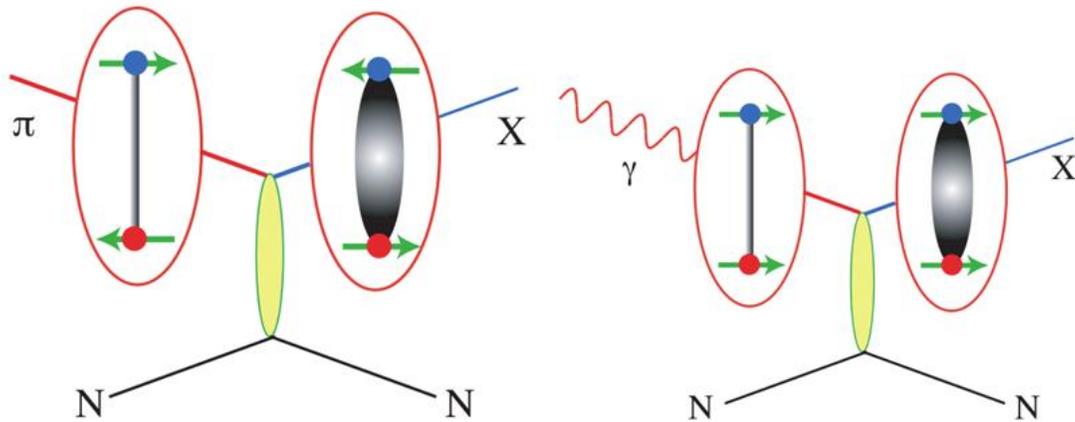
Hall D / GlueX Technical Design Report. Gluex-doc 2442, 2014

GlueX Publications

Measurement of the beam asymmetry Σ for π^0 and η photoproduction on the proton at $E_\gamma = 9$ GeV

H. Al Ghoul *et al.* (GlueX Collaboration)
Phys. Rev. C **95**, 042201(R) – Published 24 April 2017   Direct method

Beam asymmetry Σ for the photoproduction of η and η' mesons at $E_\gamma = 8.8$ GeV

S. Adhikari *et al.* (The GlueX Collaboration)
Phys. Rev. C **100**, 052201(R) – Published 27 November 2019   Direct method

Measurement of beam asymmetry for $\pi^- \Delta^{++}$ photoproduction on the proton at $E_\gamma = 8.5$ GeV
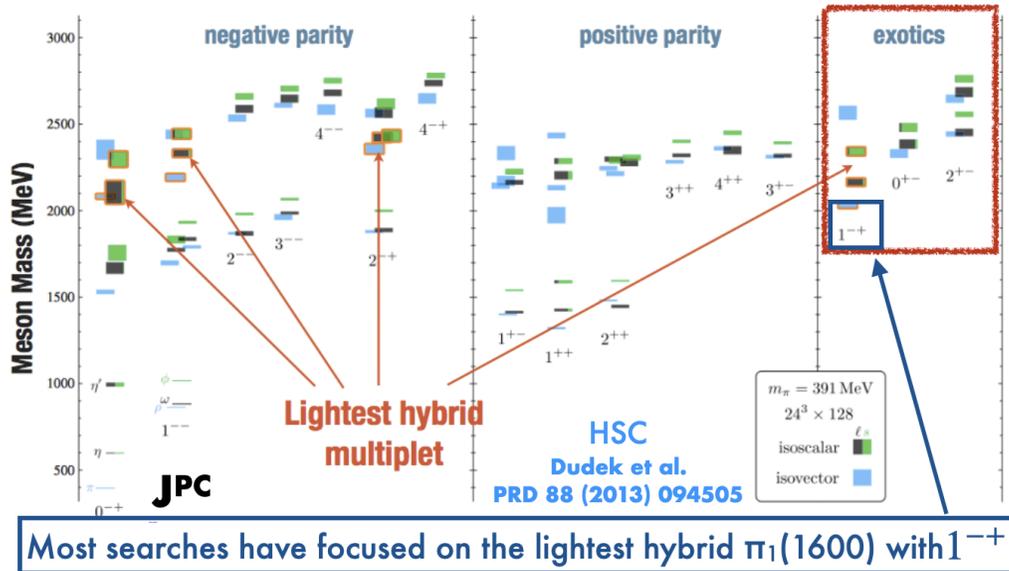
S. Adhikari *et al.* (The GlueX Collaboration)
Phys. Rev. C **103**, L022201 – Published 22 February 2021   Moment Yield method
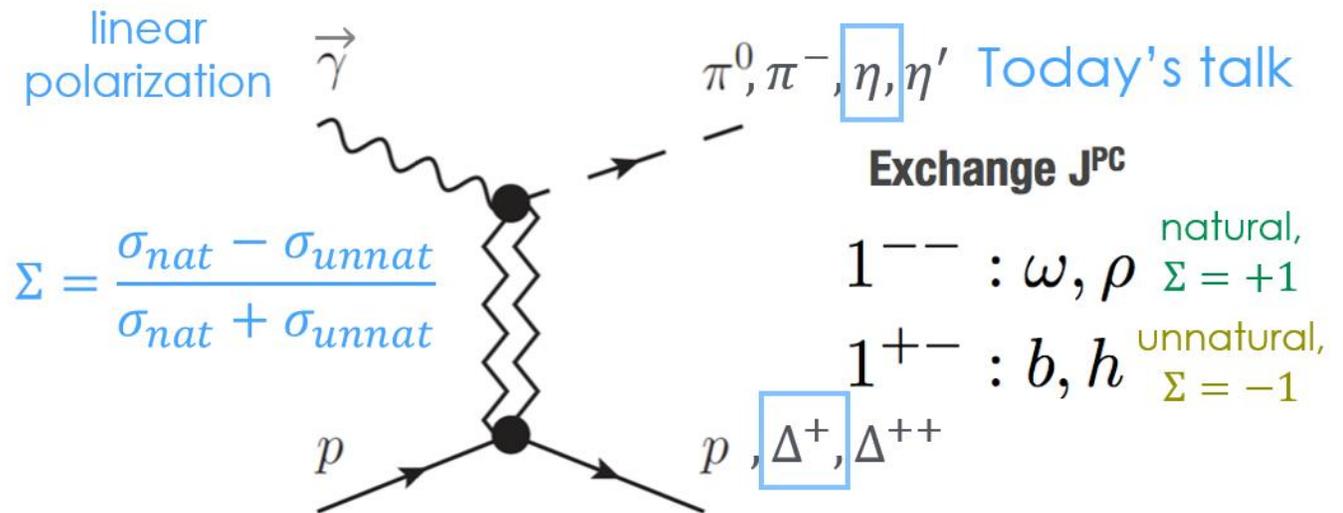
- Σ (-t) is needed as a constraint for complex Partial Wave Analyses used to to disentangle the quantum numbers of meson nonet patterns (normal and exotics)
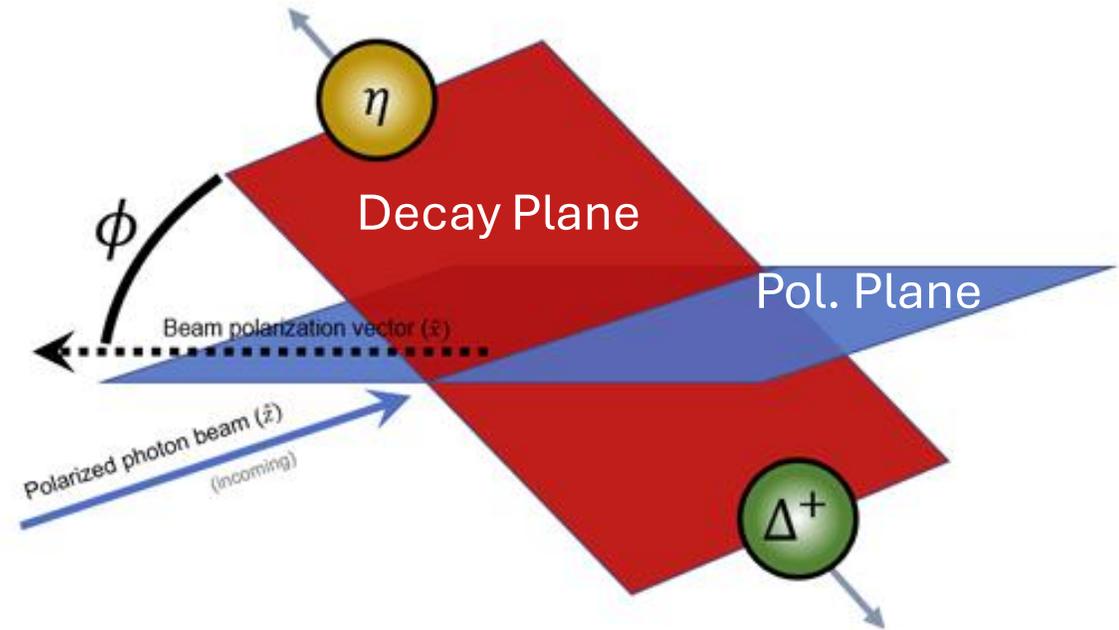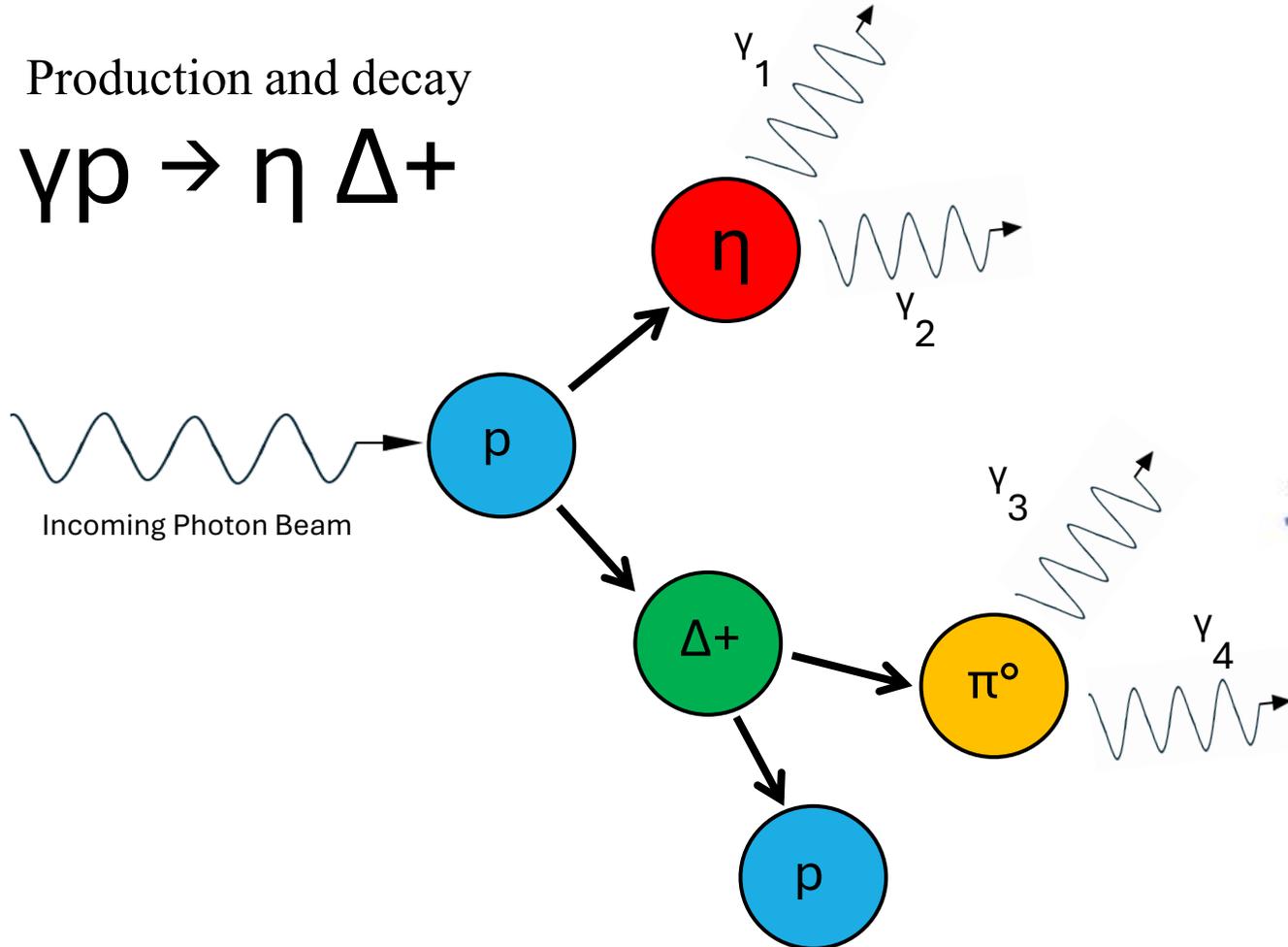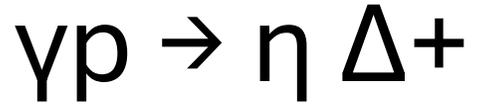

LQCD Meson Spectrum

Most searches have focused on the lightest hybrid $\pi_1(1600)$ with 1^{-+}

From Regge theory:

- Σ extensively studied in γp → **ηp**

- Expect Σ ≈ 1 for natural parity exchange (ρ, ω trajectories) for **ηp**. Past work: ratio Ση'/Ση shows no unnatural exchanges

- Question: is coupling at the lower vertex p vs Δ+ significant or different ? (**ηp** vs **ηΔ+**)

$$\Sigma = \frac{\sigma_{nat} - \sigma_{unnat}}{\sigma_{nat} + \sigma_{unnat}}$$

linear polarization $\vec{\gamma}$

$\pi^0, \pi^-, \eta, \eta'$ Today's talk

Exchange J^{PC}

1^{--} : ω, ρ — natural, $\Sigma = +1$

1^{+-} : b, h — unnatural, $\Sigma = -1$

p, Δ^+, Δ^{++}

Production and decay

γp → η Δ+

Incoming Photon Beam

γ₁

η

γ₂

p

γ₃

Δ+

π°

γ₄

p

φ

η

Decay Plane

Pol. Plane

Beam polarization vector (x̂)

Polarized photon beam (ẑ)
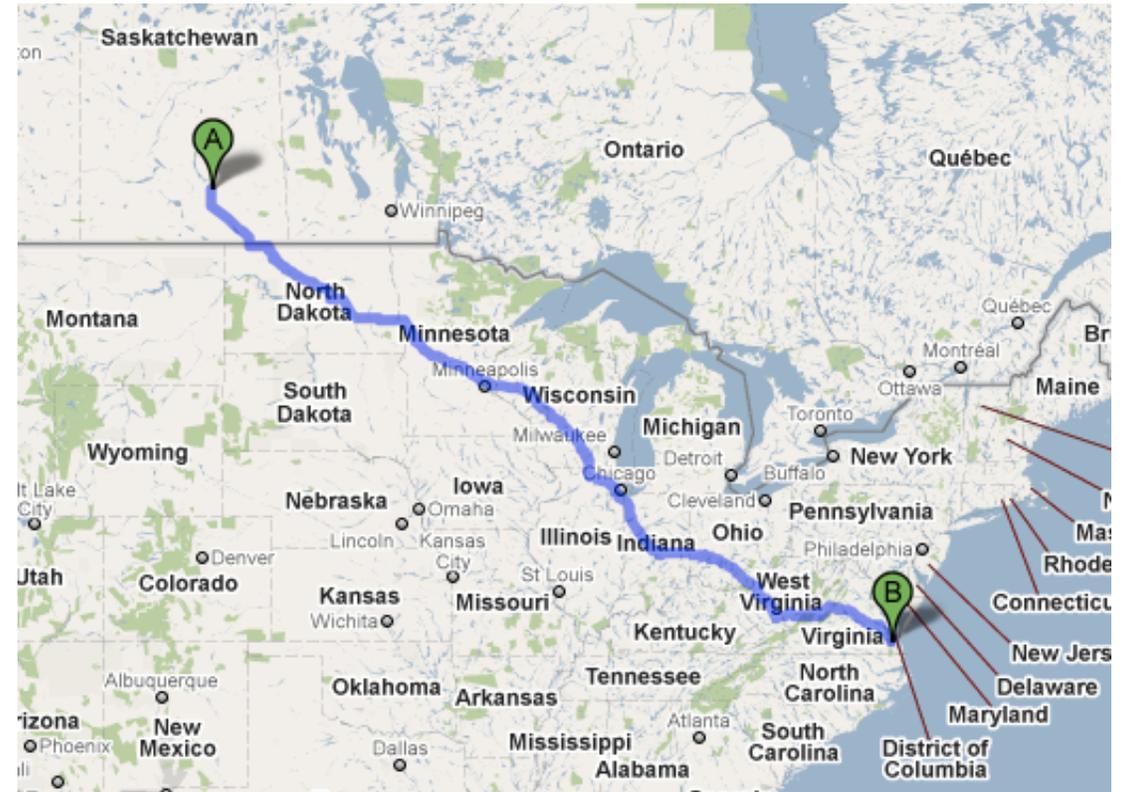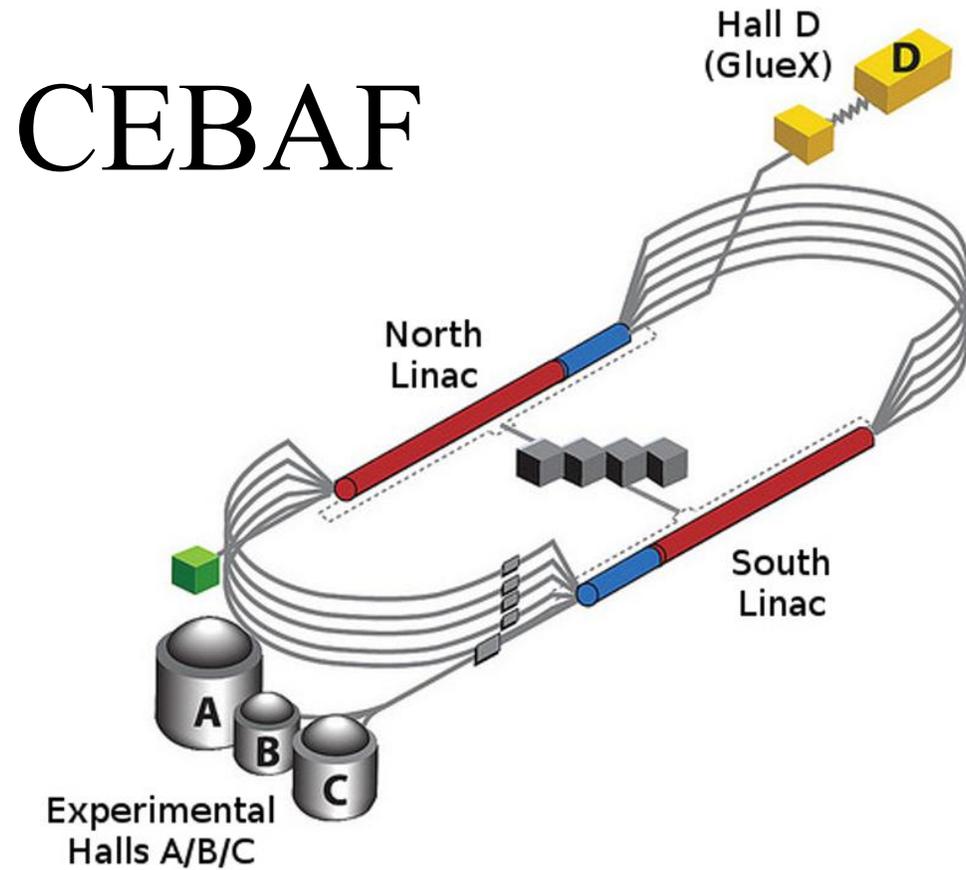(incoming)

Δ⁺

- Final (detected) state has 4 photons and 1 proton.
- Combinatorics are needed for the 4 γ

Electron Accelerator 12 GeV   Feeds Four Halls Simultaneously
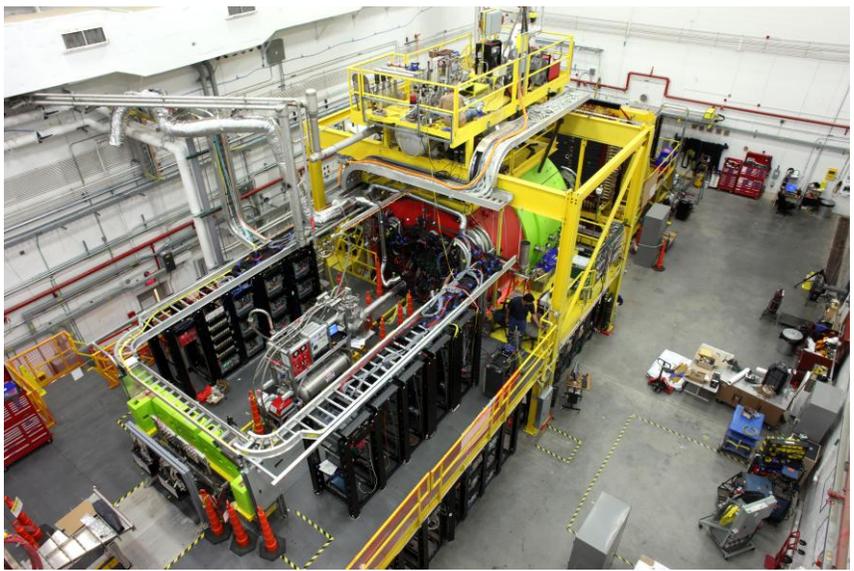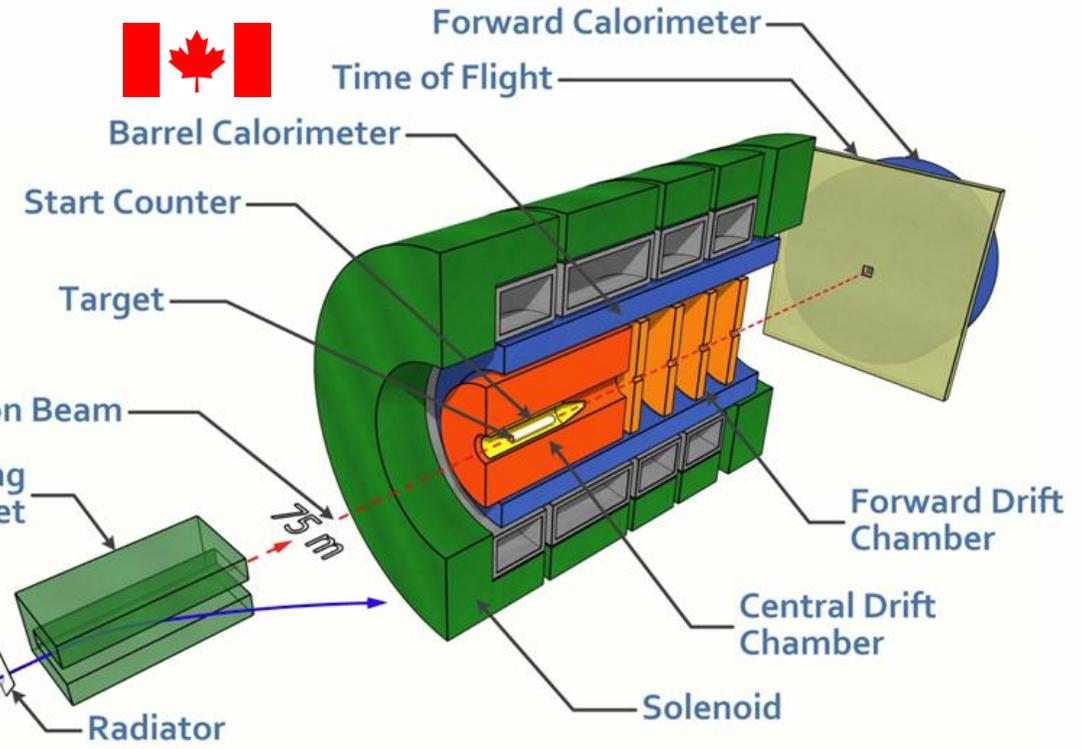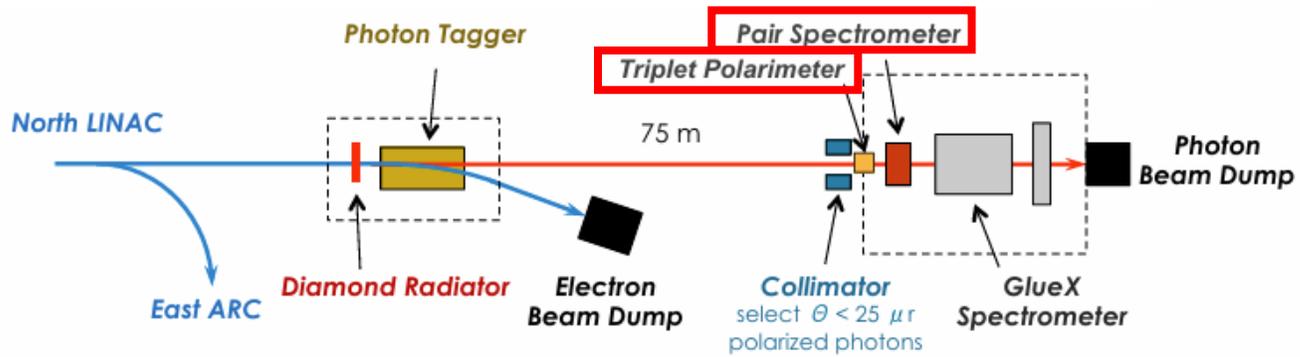
- Linearly polarized photons will be produced by coherent bremsstrahlung
- These photons from the crystal radiator are polarized; polarization vector depends on the orientation of the crystal (PARA or PERP)
- TPOL gives the polarization and PS gives the flux

Moment Yield Method

- Δ+ is a broad resonance

- Spectrum has background difficult to model -> Use moment yield method

- Asymmetry extraction- utilizing known invariant mass line shape with background present

$$\Sigma = \frac{N}{D} = \frac{Y_2^{\perp} - Y_2^{\parallel}}{\frac{P_{\parallel}}{2}\left(Y_0^{\perp} + Y_4^{\perp}\right) + \frac{P_{\perp}}{2}\left(Y_0^{\parallel} + Y_4^{\parallel}\right)}$$

$Y_n^{\parallel,\perp}$ - Yields from moment weighted (cos(nφ)) histograms. n=0,2,4...

$P_{\parallel}$ & $P_{\perp}$ - Polarization values of PARA and PERP from TPOL

Phys. Rev. C 103, L022201 (2021)
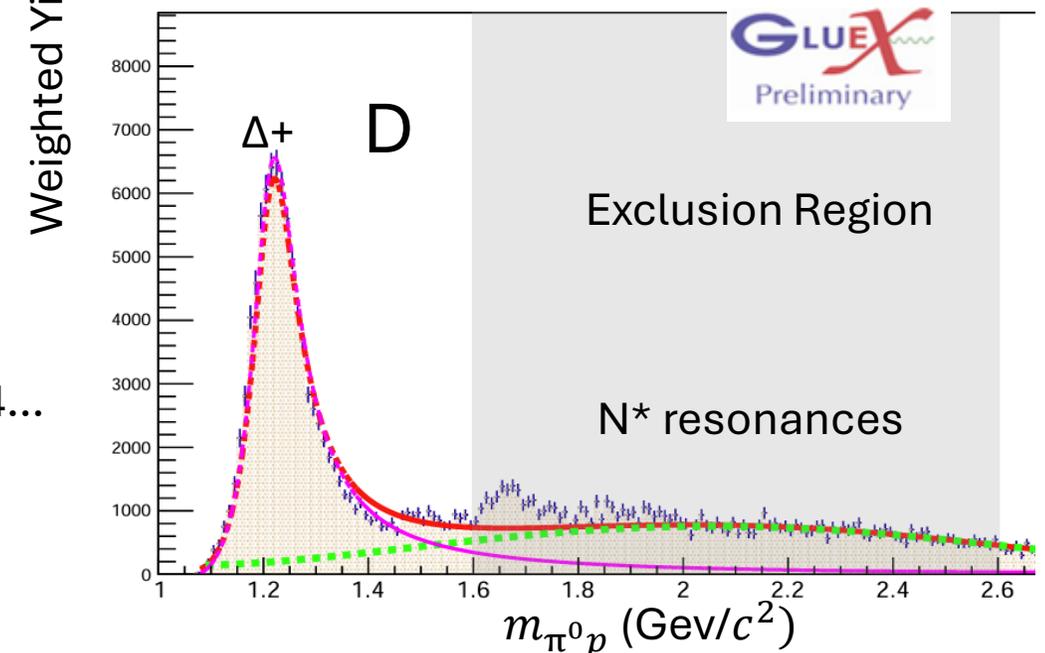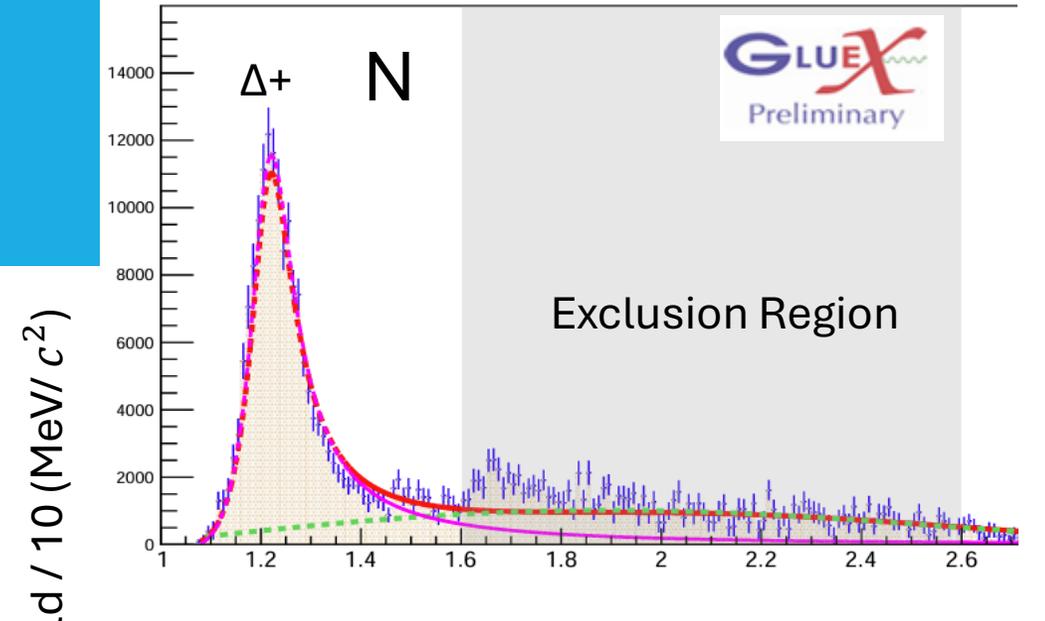
Analysis Workflow

- 50% of GlueX Phase I data (2018)

- Utilized both low-level cuts (beam energy, proton momentum, vertex position) and high-level cuts (missing mass squared and confidence level)

- Utilizing known invariant mass to extract the signal (N and D)

- Monte Carlo simulations used to extract the detector efficiency and make corrections

$$\Sigma = \frac{N}{D} = \frac{Y_2^\perp - Y_2^\parallel}{\frac{P_\parallel}{2}\left(Y_0^\perp + Y_4^\perp\right) + \frac{P_\perp}{2}\left(Y_0^\parallel + Y_4^\parallel\right)}$$

Σ Beam Asymmetry vs. -t
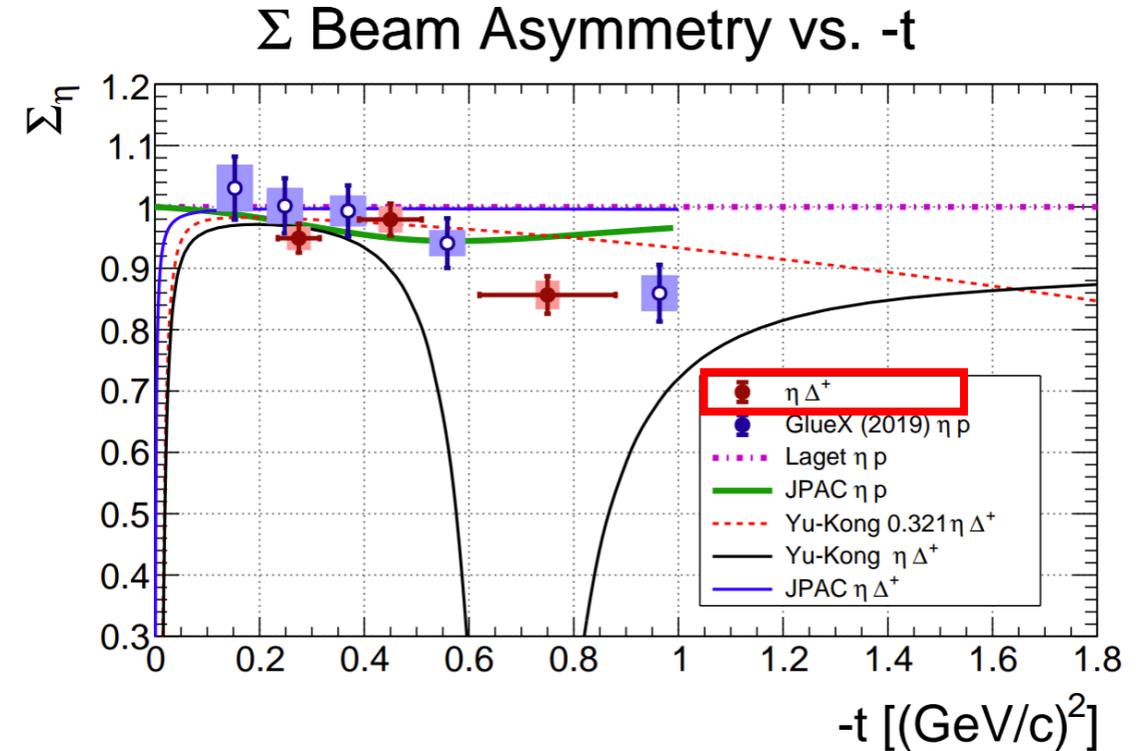
- **Purple**: published GlueX results from ηp
- **Red**: new results from ηΔ+ (under review)
- Theory curves are all Regge-based models from different groups with different parameters

Adding More Data

- Adding other two data sets of GlueX Phase I and the first data set of GlueX Phase II (2019 - Present)

- Currently being processed through analysis pipeline, but so far there is good agreement.

- Data now includes all of Phase I and ~25% of Phase II representing a >3x increase in events

$\pi^0 p$ Inv Mass

Spring 2017
Spring 2018
Fall 2018
Fall 2019

Weighted yield / (10 MeV/c^2)

$m_{\pi^0 p}$ (GeV/c^2)
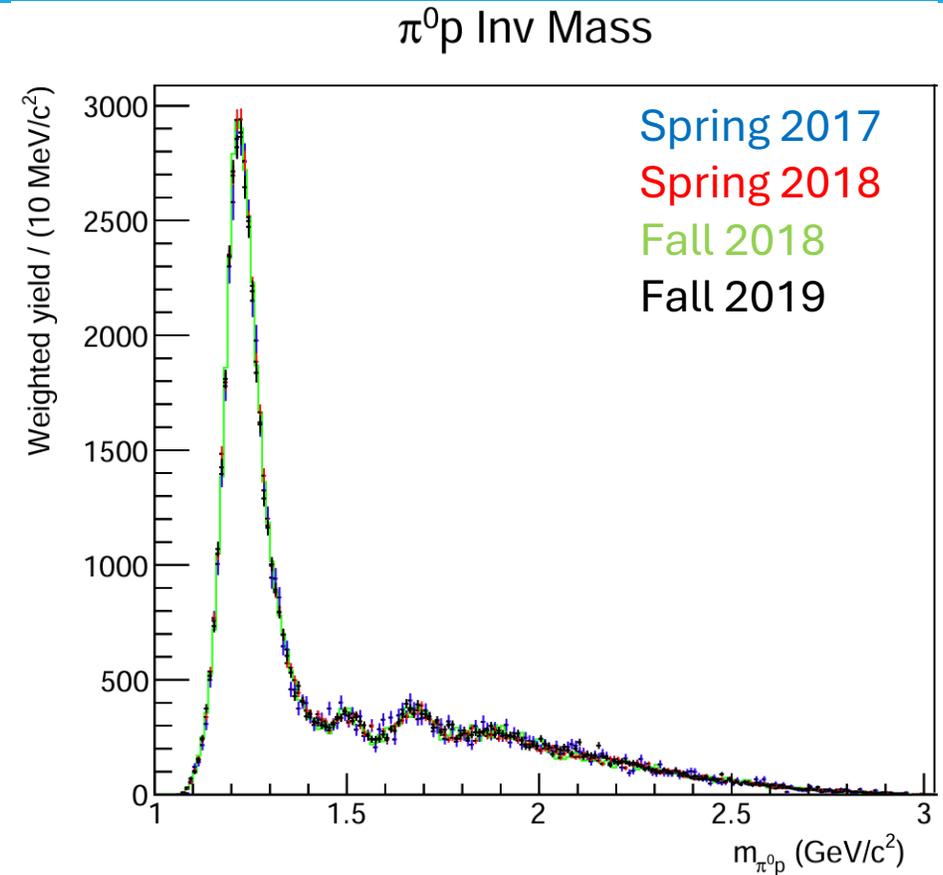
Example histogram of $\pi°p$ mass for several run periods normalized using integral of Fall 2018

Why More Data is Important

- Original analysis allowed only 3 Tbins due to limited statistics at higher t values

- New data set allows for finer bins in momentum transfer –t to probe regions where theory deviates from $\Sigma = +1$

Mandelstam **t** Distribution
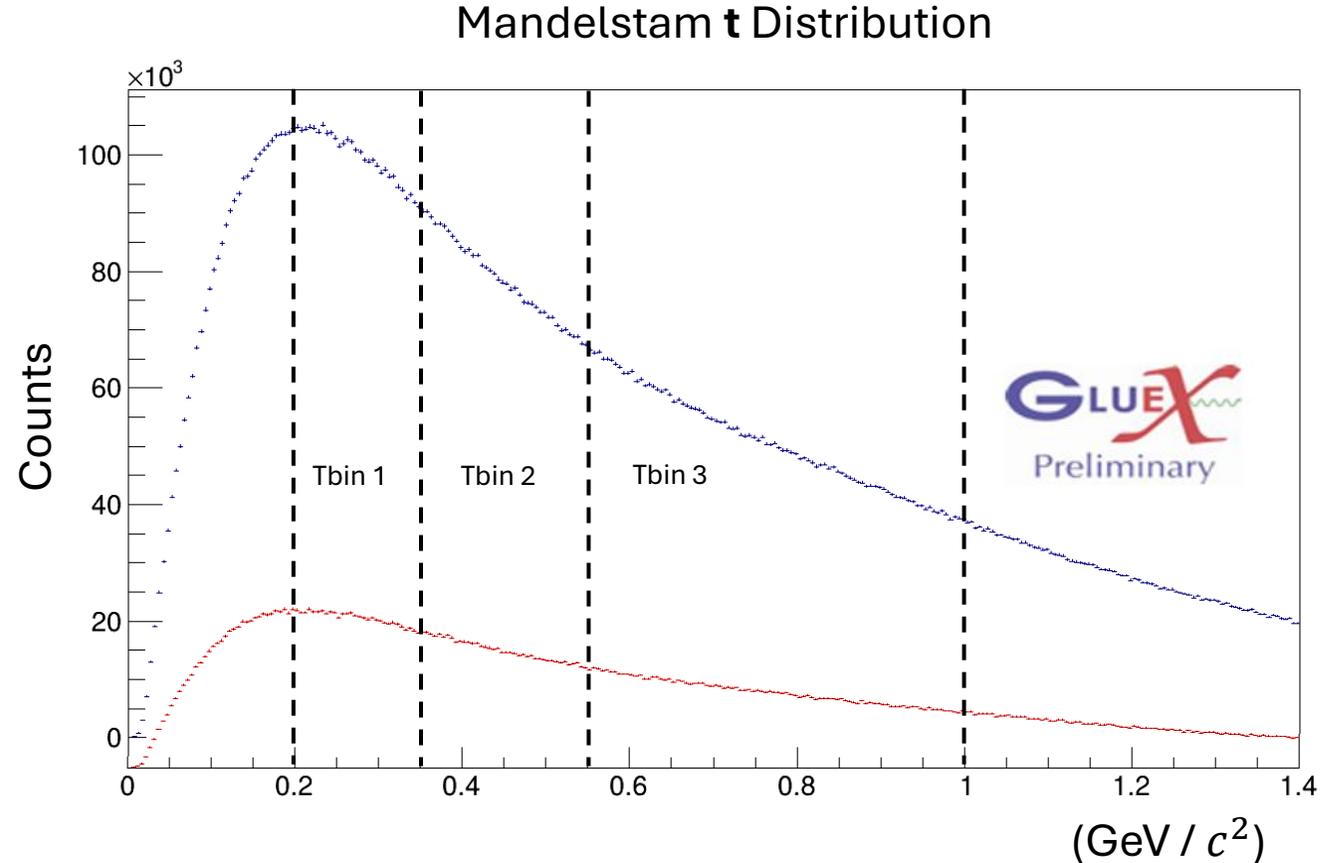
Graph of Counts by **t** distribution of original data (red) and combined data (blue)

Summary

Completed Analysis

V. Neelamana, PhD 2024

- Extracted Σ for the reaction γp → η Δ+ with systematics
- Shows natural parity exchanges are dominant
- Found slight deviation from theoretical models
- Gives more info on η photoproduction- shows polarization transfer doesn't depend on the lower vertex (η p, η Δ+)

Future Analysis

My MSc thesis

- Use a larger data set in order to increase precision
- Create finer Tbins, extend to higher t values, study regions Σ<1
- Investigate γp → η'Δ+ with the same analysis pipeline
- Working with Theorists to improve models

gluex.org/thanks.html

GlueXperiment

gluexexperiment

5.4.5 Additional Reparameterization

For the case of $\Sigma > 0$, the expected yield of $\tilde{Y}_2^{\parallel}$ should be negative. Similarly, when $\Sigma < 0$, the expected yield of $\tilde{Y}_2^{\perp}$ should be negative. Performing χ^2 minimization to determine a negative yield is suitable, however likelihood fitting cannot be used with negative yields. If χ^2 performed well, this would not be an issue. Unfortunately, χ^2 fitting with low statistics can be problematic: it tends to give poor parameter determination in the sample sizes of this analysis.

We found that fitting to the histogram combination $H_N (\equiv H_2^{\perp} - H_2^{\parallel})$ to determine $N (\equiv \tilde{Y}_2^{\perp} - \tilde{Y}_2^{\parallel})$ using likelihood fitting performed comparatively very well. However, this is only valid for $\Sigma > 0$. We expect both positive and negative asymmetries in this analysis.

Therefore, we solve for $\Sigma' \equiv \Sigma + 1$. This Σ' then ranges from 0 to 2 and should have positive amplitudes everywhere. In terms of the original method, we re-parameterize to solve for

$$\Sigma' = \frac{N'}{D} \equiv \frac{N + D}{D}. \tag{5.36}$$

Full Cuts

Cut	Range/Limit
Low-level Cuts	
Beam Energy (BE)	$8.2 < BE < 8.8$ GeV
Vertex Position (Z)	$52 < Z < 78$ cm
Vertex Radial Distance (R)	< 1 cm
Beam Hole Angle	$\eta p > 2.0°$, $\eta' p > 2.5°$
Photon Fiducial Cut	$10.3°$ to $11.5°$
Proton Momentum	> 0.30 GeV/c
Beam Hole Angle	$\eta \Delta^+ > 2.0°$
High-level Cuts	
$|M_{\pi^0}|$	$\in (0.125, 0.150 \, (GeV/c^2)) \approx 3\sigma$
$|M_\eta|$	$\in (0.50, 0.60 \, (GeV/c^2)) \approx 3\sigma$
Missing Mass Squared (MM^2)	$\in (-0.1, 0.1)$
Confidence Level $\eta \Delta^+$	$> 10^{-4}$

Beam Asymmetry - Publications

Measure Σ asymmetry of η' and η as functions of t

$\eta \to \pi^+\pi^-\pi^0$	$\eta \to 3\pi^0$	$\eta \to 2\gamma$	$\eta' \to \pi^+\pi^-\eta$
$\pi^0 \to 2\gamma$	$\pi^0 \to 2\gamma$		$\eta \to 2\gamma$
(BR ≈ 22.9 %)	(BR ≈ 32.7 %)	(BR ≈ 39.4 %)	(BR ≈ 42.9 % * 39.4 %)

Rapid Communication

(1) Measurement of the beam asymmetry Σ for π^0 and η photoproduction on the proton at $E_\gamma = 9$ GeV

H. Al Ghoul *et al.* (GlueX Collaboration)
Phys. Rev. C **95**, 042201(R) – Published 24 April 2017

Rapid Communication

(2) Beam asymmetry Σ for the photoproduction of η and η' mesons at $E_\gamma = 8.8$ GeV

S. Adhikari *et al.* (The GlueX Collaboration)
Phys. Rev. C **100**, 052201(R) – Published 27 November 2019

Letter

(3) Measurement of beam asymmetry for $\pi^-\Delta^{++}$ photoproduction on the proton at $E_\gamma = 8.5$ GeV

S. Adhikari *et al.* (The GlueX Collaboration)
Phys. Rev. C **103**, L022201 – Published 22 February 2021

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