Beam Asymmetries from Light Scalar Meson Photoproduction on the Proton at GlueX

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Abstract. The GlueX facility, featuring a linearly polarized 9 GeV real photon beam delivered to a large-acceptance detector system, has recently completed its first phase of running, and analysis efforts of this dataset are well underway. It has been suggested that at GlueX energies, quark systems beyond the three quark and quark-antiquark systems of baryons and mesons, such as hybrid mesons, tetraquarks and glueballs, should exist, and studies of these systems could shed new light on how quarks combine under the strong force, particularly the role played by gluons.

GlueX data encompasses final states at energies where photoproduction of light scalar mesons, such as $a_0(980)$ and $f_0(980)$, can provide discriminatory evidence between various models, manifested in experimental observables such as the cross section and beam asymmetry, however many of these analyses comprise multi-particle final states, which can arise from numerous intermediate resonances formed via different production mechanisms.

The work presented showcases efforts to measure the beam asymmetry of the reaction $\gamma p \rightarrow p\eta\pi$, with a particular interest in future studies of the $a_0(980)$ meson, and discusses the application of longitudinal phase space plots, originally introduced by van Hove fifty years ago, as a means of optimizing event selection. This technique has found traction in several multi-particle final state analyses in GlueX, and provides an effective additional means of separately visualising meson and baryon production events with the same final state.

INTRODUCTION

At present, the structure of light scalar mesons, states with spin zero and even parity, is poorly understood. These states have large widths, and significant overlap with background, as well as being in close proximity to $K\bar{K}$ and $\eta\eta$ thresholds, which has so far made determination of their properties difficult [1]. The latest generation of hadron physics experiments hopes to learn more about these states, by performing precision measurements of their properties, providing discriminatory power between models describing the light scalars and aiding our understanding of their production mechanisms and their natures in quark-gluon terms.

Phenomenological models describe the light scalars as anything from a simple $q\bar{q}$ pair to glueball and tetraquark states, with a model by Donnachie et. al. [2] using reggeised ρ and ω exchanges, with a small contribution from $b_1(1235)$ exchange, to calculate photoproduction amplitudes for $a_0(980)$ and $f_0(980)$. This model has made cross section predictions for light scalar meson production, and was recently extended to include beam asymmetries.

Colleagues at the Joint Physics Analysis Center (JPAC) describe photoproduction of the $\eta\pi$ system in terms of contributing waves from various mesons, with the possible influence of an exotic state expressible in terms of the beam asymmetry. When binned in small angles in the Gottfried-Jackson frame, approximating back-to-back $\eta\pi$ events in that frame, an exotic wave is shown to have a more pronounced effect on the measured beam asymmetry [3].

Recent studies in lattice QCD, where an S-wave scattering amplitude is computed via a coupled-channel lattice calculation, suggests that something significant happens at $K\bar{K}$ threshold. Even allowing for the unphysical quark masses used in these calculations, it is still possible to interpret this as an $a_0(980)$-like resonance, coupled to $K\bar{K}$ and $\eta\pi$, and studies of $\eta\pi$ experimental data may allow further interpretation of this result [4].

This work focuses on the $\eta\pi$ system, where the $a_0(980)$ is the light scalar state of interest. The dependence of the beam asymmetry on the $\eta\pi$ mass is presented as a step towards providing insights to descriptions of the production of the light scalars.

JEFFERSON LAB AND GlueX

The Thomas Jefferson National Accelerator Facility (JLab) is a US Department of Energy facility located in Newport News, Virginia. Its centerpiece machine is the Continuous Electron Beam Accelerator Facility (CEBAF), a superconducting RF accelerator, recently upgraded to deliver electron beams up to 12 GeV in energy simultaneously to up to four experimental halls. The four halls, named A, B, C, and D, are host to a varied range of experimental equipment,

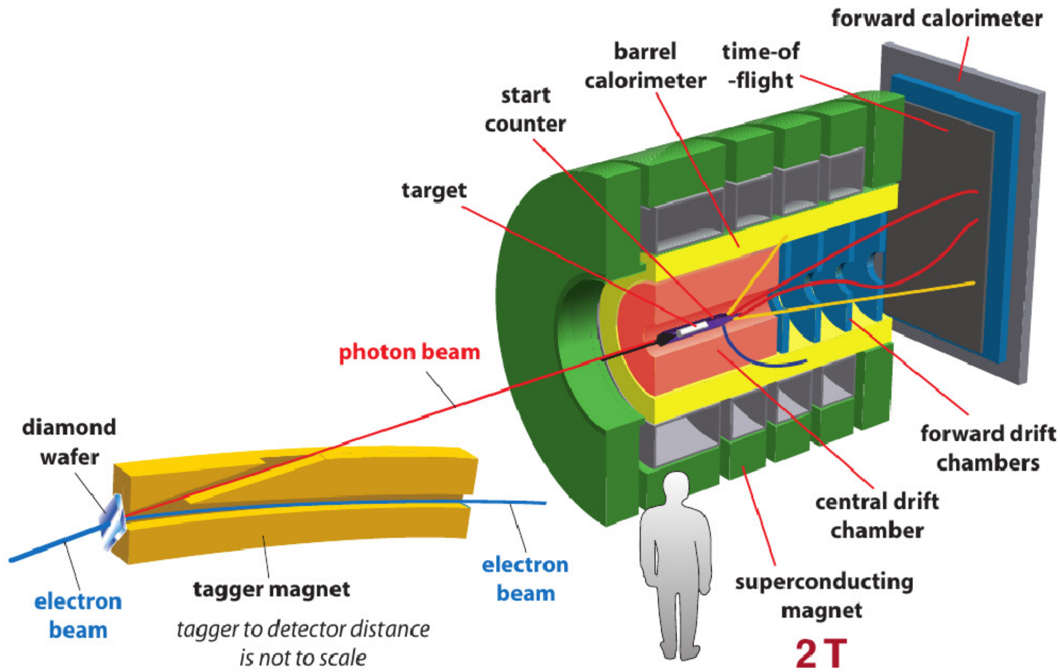

FIGURE 1. The GlueX detector and photon tagger.

supporting a diverse physics program, with Hall D focused on experiments using a real photon beam produced from the primary CEBAF beam via the bremsstrahlung process.

The Hall D photon beam facility produces real, linearly polarized photon beams in the tagger hall, a separate building to Hall D. The primary electron beam from CEBAF impinges on a radiator and produces photons via the bremsstrahlung process. The energy-degraded electrons are swept out of the beamline by the tagger magnet, and the photon beam continues to the experimental hall. The beam is collimated then enters the main experimental hall, passing through devices designed to monitor the flux and polarization of the beam, before interacting with the target at the center of the GlueX spectrometer.

When a diamond radiator is used, the resulting photon beam is linearly polarized in one of two orientations, referred to as PARA or PERP, parallel or perpendicular to the floor of the experimental hall. This 90 degree rotation of the polarization planes is utilized in the computation of the beam asymmetry, which will be discussed later in these proceedings.

The GlueX detector in Hall D is a hermetic, solenoid based detector, comprising two tracking systems, two calorimeters and time-of-flight scintillator paddles. This provides good charged and neutral particle identification, with uniform acceptance over 4π solid angle. Experimental operations with GlueX commenced in 2016, and its first phase of running concluded in the fall of 2018.

ANALYSIS

This work focuses on studying beam asymmetries of the $\eta\pi$ channel, where η and π each decay to a pair of photons. A kinematic fit is used to identify particles and filter data, with cuts applied on vertex position, energy loss in the drift chamber for proton tracks, and photon beam energy. Candidate $\eta\pi$ events are subjected to further processing to select event samples corresponding to meson photoproduction processes.

Even assuming perfect particle identification, different processes can result in the same final state. This is particularly true as the number of particles in the final state increases. In the reaction $\gamma p \to p\eta\pi$, as well as non-resonant background processes, the final state particles could arise from the production of an intermediate meson (e.g. $a_0(980) \to \eta\pi$), or a baryon (e.g. $\Delta^+ \to p\pi$).

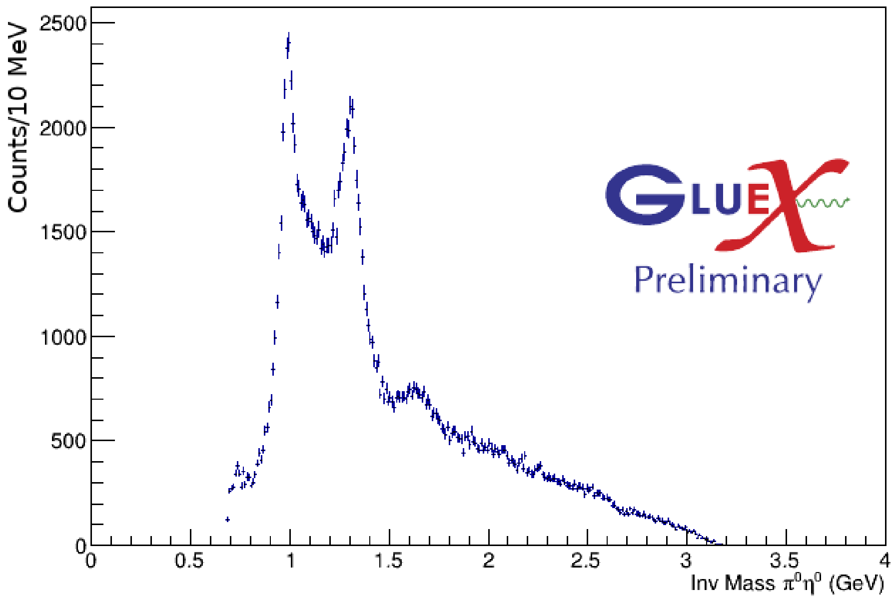

FIGURE 2. Invariant Mass of $\eta\pi$ after initial event selection, including cuts to veto baryon events.

To attempt to remove unwanted baryon events from our data, and retain the meson production events of interest, further cuts are applied to the invariant masses of $p\eta$ and $p\pi$. Figure 2 shows the $\eta\pi$ invariant mass after this initial event selection.

Longitudinal Phase Space Plots

The competing baryonic and mesonic processes have very different reaction kinematics, making it possible to separate them by studying these events in the center of mass frame. This idea was first proposed and studied fifty years ago by Leon van Hove, whose basic premise was that at sufficiently high center-of-mass energy, phase space is dominated by longitudinal components of particle momenta [5]. Transverse components can be neglected, reducing dimensionality of phase space. This gives rise to the Longitudinal Phase Space plot, also known as a van Hove plot, a way of visualising reaction kinematics of an n-particle final state in an n-1 dimensional plane. For example, in a three particle final state, the longitudinal phase space can be represented on a two dimensional plane. We can define co-ordinates on the van Hove plot analogously to polar co-ordinates via the longitudinal momentum components of the final state particles

$$X = q\,cos(\omega) \tag{1}$$
$$Y = q\,sin(\omega) \tag{2}$$

The axes on the van Hove plot divide the longitudinal phase space into six sectors, with each sector corresponding to specific directions of travel of the final state particles in the center of mass frame. These sectors can be seen in the van Hove plots for $\eta\pi$ in Figure 3. In this system, the bottommost sector of the Van Hove plot has $\eta\pi$ going forward and proton going backward, corresponding to a meson decay, such as $a_0(980)$.

By examining events in longitudinal phase space, we have an additional means of verifying our event selection, particularly the cuts applied to veto baryon production events. Figure 3 shows that the initial baryon veto cuts also remove a significant proportion of the meson events of interest, while Figure 4 shows how a plot of the van Hove angle versus invariant mass can be used to optimize a cut, in this case, the $p\pi$ invariant mass cut used to veto baryon resonances.

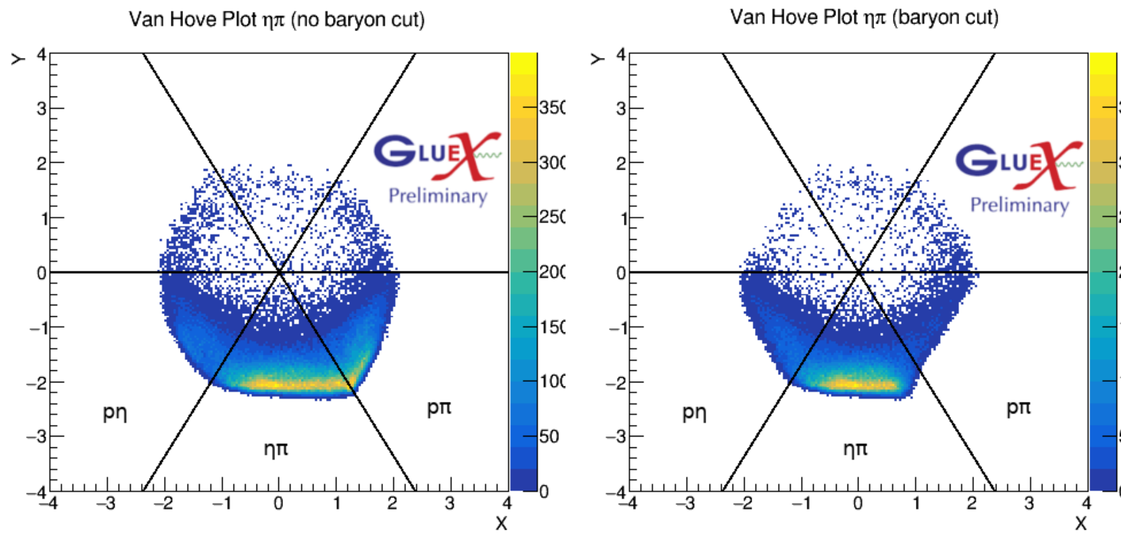

FIGURE 3. Longitudinal phase space plots of the $\eta\pi$ system, without (left) and with (right) cuts to veto baryon events. The initial baryon veto cuts also remove events corresponding to the meson production processes of interest.

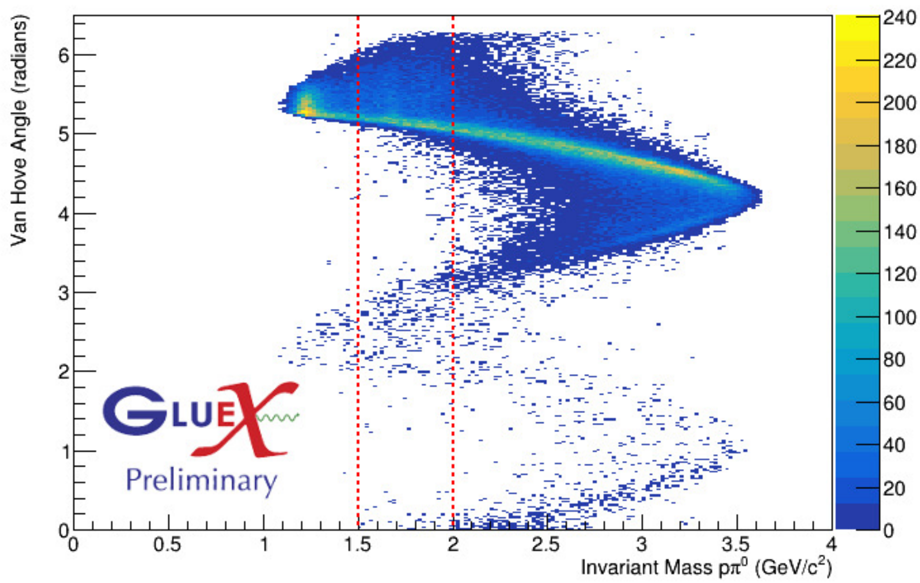

FIGURE 4. $p\pi$ invariant mass versus van Hove angle, showing the optimization of the applied cut. An initial cut at 2.0 GeV removes a significant amount of meson production events, while changing it to 1.5 GeV restores many of these events and still removes the main baryonic contribution.

Beam Asymmetries

The beam asymmetry, Σ, can be expressed in terms of the reduced cross section

$$\sigma = \sigma_0[1 - P_\gamma \Sigma cos(2(\phi - \phi_\gamma))] \quad (3)$$

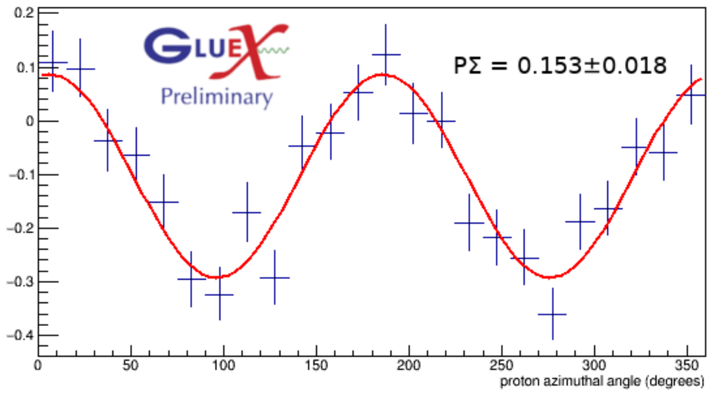

FIGURE 5. Example asymmetry fit for the $\eta\pi$ mass bin spanning the $a_0(980)$ meson. The magnitude of the $cos(2\phi)$ term of the fit corresponds to the beam asymmetry, modulated by the magnitude of photon beam polarization.

To measure it, we can take the difference over the sum of events with PARA and PERP beam polarization

$$A(\phi) = \frac{N(PARA) - N(PERP)}{N(PARA) + N(PERP)} \approx P_{lin}\Sigma cos(2\phi) \tag{4}$$

By doing this using the proton azimuthal angle distributions for PARA and PERP data in a number of $\eta\pi$ invariant mass bins, we can fit a function of the form of equation 4 to these asymmetry distributions. The beam asymmetry (more accurately, the beam asymmetry, modulated by the degree of photon polarization) is then extracted from the magnitude of the $cos(2\phi)$ term.

RESULTS

Figure 6 shows preliminary results for the beam asymmetry versus $\eta\pi$ invariant mass for the entire range of Gottfried-Jackson angles. The vertical error bars represent statistical uncertainties only. No obvious exotic signature is discernible, and due to limited statistics, the asymmetry is not shown for ranges of small Gottfried-Jackson angles, where comparisons to the JPAC model could determine the signature of an exotic state [3].

CONCLUSION

We present preliminary measurements of the beam asymmetry for the four photon final state of the $\eta\pi$ system, having applied longitudinal phase space plots to the optimization of selecting meson production events in this system. No obvious exotic signal is seen, however follow up measurements binned in Gottfried-Jackson angle, using experimental moments to overcome the limited statistics available at smaller angles, may provide additional insights. This measurement is also a first step toward several follow up measurements that GlueX will make in this system that may provide further insights into understanding the nature and production mechanisms of light scalar mesons in this reaction topology. These will include the $a_0(980)$ beam asymmetry and cross section, and full partial wave analysis of the $\eta\pi$ system.

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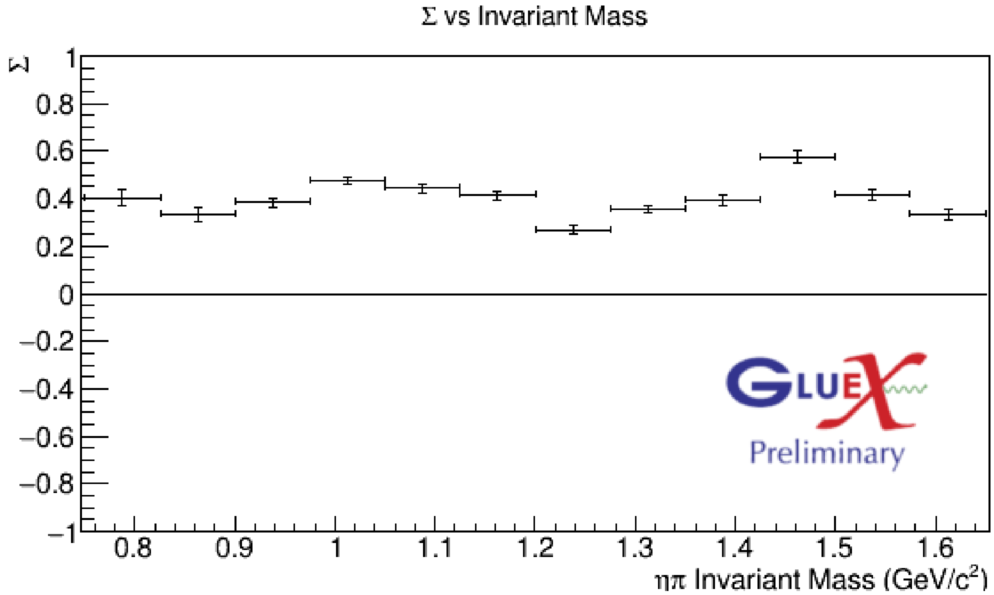

FIGURE 6. Beam asymmetry, Σ, versus $\eta\pi$ invariant mass. Errors are statistical only.

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