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Exploring Photoproduced $\eta^{(\prime)}\pi^0$ Systems in the Search for Exotic Hadrons at GlueX

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Physicists have long been captivated by the spectrum of hadrons, aiming to better comprehend the fundamental building blocks of matter. While various experiments have laid the foundation for this spectrum, Lattice Quantum Chromodynamics has revealed new states with forbidden J^{PC} values. This has challenged the constituent quark model, suggesting *spin-exotic hybrid mesons* that could reshape our understanding of hadronic structure and quark-gluon interactions through gluonic excitations.

The GlueX experiment at Jefferson Lab has played a pivotal role in this pursuit, with its efforts centered on analyzing photoproduction data. In order to investigate the lightest predicted exotic state with $J^{PC} = 1^{-+}$, known as the $\pi_1(1600)$ meson, significant attention has been directed towards both $\eta\pi^0$ and $\eta'\pi^0$ systems. Detailed ongoing amplitude analysis studies of $\gamma p \to \eta^{(\prime)}\pi^0 p$, leveraging the polarization of the photon beam at the GlueX experiment will be highlighted. Furthermore, first studies on the moments of angular distributions for these channels will also be shown, along with the differential cross section results for the $a_2(1320)$ meson. These results aid in identifying the dominant production mechanisms and offer valuable insights into complex hadronic interactions. Ultimately, this contributes to the ongoing search for and future identification of exotic hybrid meson candidates.

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1. Introduction

The spectrum of hadrons that consist of quarks bound by the strong force continues to be a central focus for understanding the fundamental structure of matter. Hadrons are conventionally classified into the categories of mesons and baryons based on their intrinsic spin, with mesons being bosons and baryons being fermions. Within the framework of the constituent quark model, mesons are described as quark-antiquark ($q\bar{q}$) pairs, while baryons are composed of three quarks (qqq). While this model successfully describes a wide range of observed particles, it does not account for all theoretically possible states [1]. Recent advancements in Lattice Quantum Chromodynamics (Lattice QCD), predict the existence of hadronic states with unconventional quantum numbers – known as *spin-exotic hybrids* – which are forbidden to simple quark-antiquark configurations [2]. The most accessible of these is a hypothesized meson with quantum numbers $J^{PC} = 1^{-+}$, denoted as the $\pi_1(1600)$. This promising candidate is the lightest predicted state where excitations in the gluonic field contribute non-trivially to it's quantum numbers, challenging the traditional constituent quark model and offering a window into the dynamics of quark-gluon interactions.

Identifying this state has become a major goal in hadronic physics, with photoproduction experiments providing a powerful approach to this search. Specifically, using linearly polarized photon beams would enhance the ability to isolate specific production mechanisms, providing a compelling method for identifying and understanding potential exotic hybrid meson signals.

The ***Glu***onic ***Ex***citation (GlueX) experiment at Jefferson Lab was designed to explore these exotic meson states through photoproduction utilizing a 12 GeV linearly polarized photon beam produced by coherent bremsstrahlung [3]. This setup, with its large acceptance and capability to achieve precise measurements of both neutral and charged decay states, allows for detailed studies of exotic states by enabling high sensitivity to particular quantum number exchanges. To probe the promising $\pi_1(1600)$, an emphasis has been placed on studying the two pseudo-scalar final states, $\eta\pi^0$ and $\eta'\pi^0$. These channels are particularly attractive for initial studies since any signal observed in configurations with odd orbital angular momentum between the $\eta^{(\prime)}$ and the π^0 would be spin-exotic. Historically, two spin-exotic candidates, the $\pi_1(1400)$ and $\pi_1(1600)$, were identified as potential hybrid mesons. However, a recent coupled-channel analysis has consolidated evidence for only a single spin-exotic $\pi_1(1600)$ hybrid meson coupling to these final states [4], reinforcing the significance of GlueX's initial focus on this prominent and debated topic.

This work presents a detailed investigation of the reactions $\gamma p \to \eta^{(\prime)}\pi p$, contributing to the broader search for exotic hybrid mesons. A key focus in these studies lies on the well-established $a_2(1320)$ meson, which is a dominant resonance in the $\eta\pi^0$ final state and hence serves as a reference point for further analysis. This benchmark is essential, as any potential signal for the $\pi_1(1600)$ in these decay channels would overlap with the $a_2(1320)$ region. Alongside this, preliminary upper limits on the photoproduction cross section of the exotic hybrid $\pi_1(1600)$ meson are provided. Lastly, an introduction of the framework for photoproduction moment analyses at GlueX is shown. Such an analysis is crucial for refining production models and evaluating the experimental sensitivity to exotic contributions.

2. $\eta^{(\prime)}\pi^0$ channels at GlueX

At GlueX, various approaches are available for reconstructing $\eta^{(\prime)}\pi$ systems, with a particular focus placed on the $\eta^{(\prime)}\pi^0$ channels due to their comparatively lower complexity in relation to other potential final states.

Figure 1 presents the invariant mass distributions for $\eta\pi^0$ and $\eta'\pi^0$, where we use the decay channels with the highest branching fractions for each particle ($\eta \to \gamma\gamma$, $\eta' \to \pi^+\pi^-\eta$, and $\pi^0 \to \gamma\gamma$). Notably, while the $\eta\pi^0$ channel shows dominant peaks corresponding to the $a_0(980)$ and $a_2(1320)$ mesons, the $\eta'\pi^0$ system lacks any comparable structures. Examining the angular distributions in the Gottfried-Jackson reference frame provides initial insights into the contributions

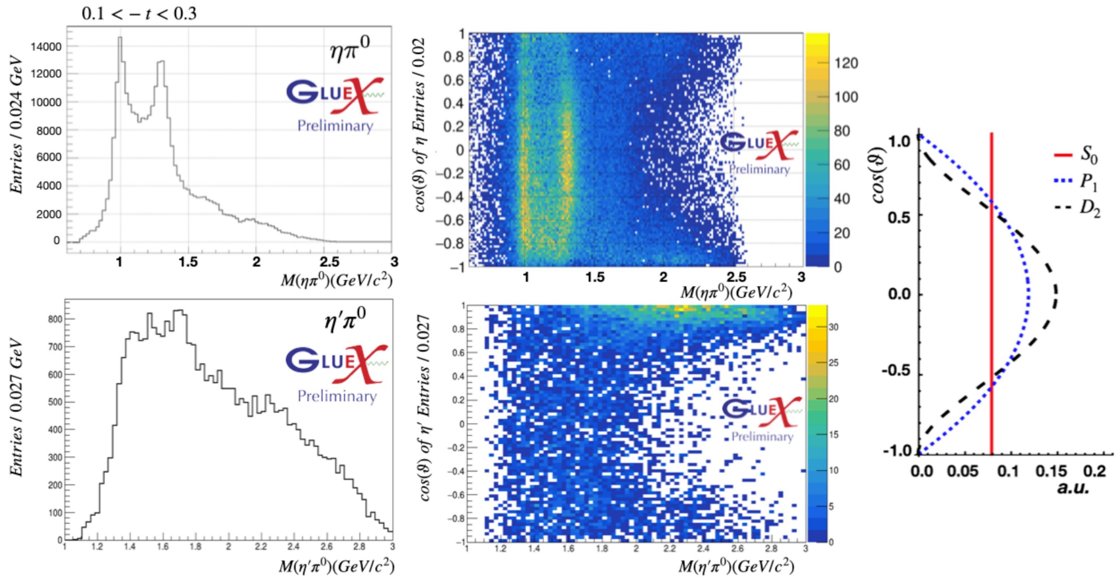

Figure 1: *Left:* Invariant mass spectrum of the $\eta^{(\prime)}\pi^0$ systems. *Right:* angular distributions of the respective $\eta^{(\prime)}$ meson in the Gottfried-Jackson reference frame.

associated with different partial waves. Specifically, comparing the $\eta\pi^0$ angular distributions in the 1 GeV and 1.3 GeV regions to projections of spherical harmonics Y^{ℓ}_{m} indicates contributions of two dominant partial waves: the S_0 wave for the $a_0(980)$ and the D_2 for the $a_2(1320)$ meson. In contrast, the $\eta'\pi^0$ channel does not exhibit any significant resonance band in the angular distribution, but a pronounced asymmetry is exhibited at high masses around $cos(\vartheta) = 1$. This effect is likely due to a combination of baryon background and non-resonant double-Regge exchange, which is currently under study.

3. Partial-Wave Analysis

Detailed studies of the production mechanisms of the $a_2(1320)$ are essential as a preparatory step for isolating contributions from the exotic $\pi_1(1600)$. This is due to the presence of overlapping conventional resonances in the same region. A partial-wave analysis (PWA) decomposes the data into individual interfering amplitudes with definite orbital angular momentum ℓ, helping to distinguish between well-known resonances and potential exotic signals.

Using the polarized photoproduction amplitudes developed by the Joint Physics Analysis Center (JPAC), we model the kinematic distribution of the events using the intensity function

$$\mathcal{I}(\Omega,\Phi) = 2\kappa\left\{(1+P_\gamma)\left|\sum_{\ell,m}[\ell]^{(+)}_{m;k}\,\mathrm{Re}\left[Z^m_\ell(\Omega,\Phi)\right]\right|^2 + (1-P_\gamma)\left|\sum_{\ell,m}[\ell]^{(+)}_{m;k}\,\mathrm{Im}\left[Z^m_\ell(\Omega,\Phi)\right]\right|^2 \right.$$
$$\left. +(1-P_\gamma)\left|\sum_{\ell,m}[\ell]^{(-)}_{m;k}\,\mathrm{Re}\left[Z^m_\ell(\Omega,\Phi)\right]\right|^2 + (1+P_\gamma)\left|\sum_{\ell,m}[\ell]^{(-)}_{m;k}\,\mathrm{Im}\left[Z^m_\ell(\Omega,\Phi)\right]\right|^2\right\} \quad (1)$$

Here, $Z_\ell^m(\Omega,\Phi)$ is a phase-rotated spherical harmonic function, Ω represents the polar $(cos(\vartheta))$ and azimuthal (ϕ) angles of the $\eta^{(\prime)}$ in the $\eta^{(\prime)}\pi^0$ helicity frame, and Φ is the angle between the production and polarization planes. P_γ denotes the photon polarization magnitude, while the real-valued κ represents the overall phase-space factor. Specifically, the $[\ell]_{m;k}^{(\epsilon)}$ are the partial-wave amplitudes that are fit to the data, where m is the projection of angular momentum. The superscript $\epsilon = \pm$ denotes the reflectivity, which corresponds to the naturality $\eta = P(-1)^J$ of the particle in the t-channel production process [5].

A fully mass-independent PWA was performed to study the $\eta\pi^0$ systems by analyzing the data independently in mass bins, allowing for an initial estimate of the relative strengths of each contributing wave. The results revealed a dominant D_2^+ wave contribution, prominently associated with the $a_2(1320)$. This suggests that there is a preference for natural-parity exchange mechanisms such as ω or ρ exchange. To further refine the extraction of the $a_2(1320)$ differential cross section as a function of momentum transfer, a semi-mass independent method was employed, where the D-waves were modeled in terms of $a_2(1320)$ and $a_2(1700)$ using Breit-Wigner amplitudes, while the binned formulation for all S wave contributions was kept [6].

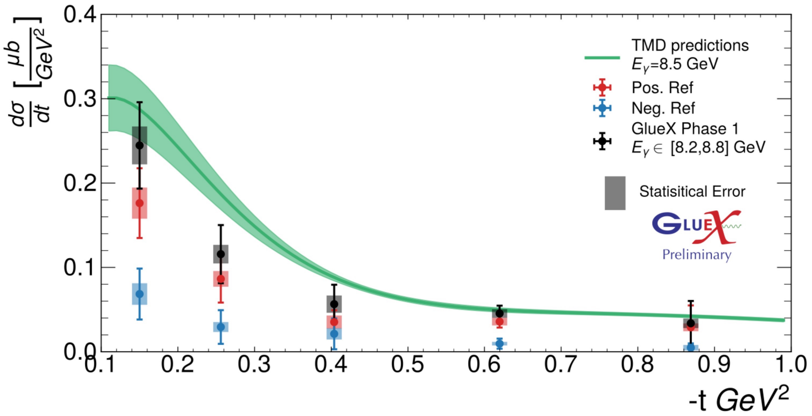

Figure 2: Differential cross section of photoproduced $a_2(1320)$ using PWA results in five bins of momentum transfer $-t$. Individual contributions of reflectivities are superimposed as well.

A primary focus of this analysis was to understand how the production mechanisms vary with t, as this dependence can provide insights into potential spin-exotic contributions. Distinct exchange mechanisms, such as natural and unnatural parity exchanges, show characteristic behaviors as functions of t, which can help distinguish conventional meson production from possible exotic signals. The results in Figure 2 highlight the dominance of natural-parity exchange at low t, aligning well with the theoretical predictions from a tensor meson dominance model [7]. Improved understanding of $a_2(1320)$ production in this context may assist theorists in refining predictions for exotic state production.

4. Upper Limits for $\pi_1(1600)$ photoproduction

To better understand how a $\pi_1(1600)$ signal might contribute to the $\eta^{(\prime)}\pi^0$ systems, we establish upper limits on the photoproduction cross sections of this exotic hybrid meson. The $a_2(1320)$ meson is utilized as a *standard candle* – a reliable, well understood resonance that serves both as a benchmark for the amplitude analysis and as a critical reference for channels where the spin-exotic contributions are not dominant. By measuring the cross section of the $a_2(1320)$ in the $\eta\pi^0$ channel and projecting this contribution into the invariant mass spectrum for the $\eta'\pi^0$ channel (as shown by the cyan-shaded region in Figure 3), we are able to scale the expectations and provide a comparison point for potential exotic states [8].

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To estimate the upper limit on the the exotic $\pi_1(1600)$ contribution, we began by assuming the $b_1\pi$ channel is the dominant decay mode, as predicted by Lattice QCD calculations [9]. While the analysis is based on data from the $\gamma p \to \omega\pi\pi p$ channel, we assume that the signal is dominated by contributions from the $b_1\pi$ decay. Using this assumptions, and considering the $\omega\pi\pi$ data to be saturated by contributions from the $a_2(1320)$ and the $\pi_1(1600)$, we extracted a production cross section ratio for these states. Specifically, we derived the branching ratio

$$R = \frac{\mathcal{B}(\pi_1(1600) \to \eta^{(\prime)}\pi)}{\mathcal{B}(\pi_1(1600) \to b_1\pi)} = \frac{\Gamma(\pi_1(1600) \to \eta^{(\prime)}\pi)}{\Gamma(\pi_1(1600) \to b_1\pi)},$$

based on Lattice QCD predictions of partial decay widths and branching fractions. This ratio, combined with the measured cross section for the $a_2(1320)$, was used to project an upper limit of the $\pi_1(1600)$ contribution to the $\eta^{(\prime)}\pi^0$ invariant mass spectra. The resulting projection, illustrated by the red curves in Fig. 3, represent the most conservative upper limits on the $\pi_1(1600)$ contribution, assuming the hybrid candidate's dominance in the $\gamma p \to \omega\pi\pi p$ channel.

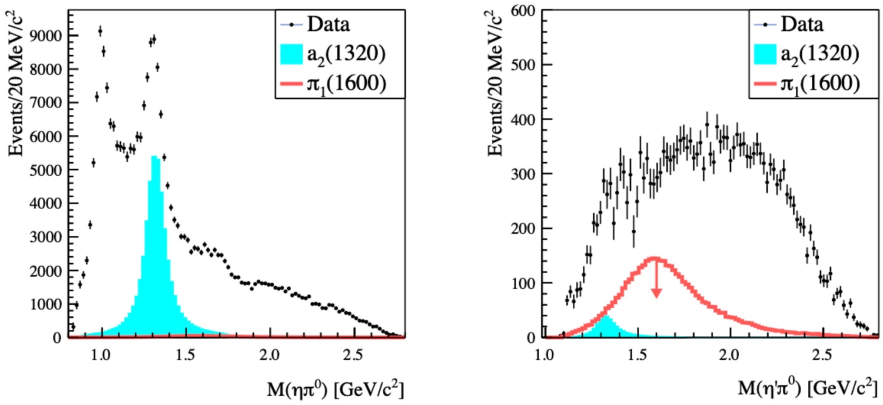

Figure 3: Invariant mass spectrum of both $\eta^{(\prime)}\pi^0$ with black points representing GlueX data, cyan shaded curve representing the $a_2(1320)$ contribution, and the red curve representing the projected upper limit of the $\pi_1(1600)$ contribution.

These projections indicate that while the $\pi_1(1600)$ contribution is expected to be less than 1% in the $\eta\pi^0$ system, it could be more substantial in the $\eta'\pi^0$. This suggests that the latter channel will offer enhanced sensitivity for exotic meson searches.

5. Moments Analysis

In photoproduction studies, a moment analysis serves as compelling method for exploring the angular components of meson production, potentially enabling the identification of possible exotic contributions [5]. By decomposing angular distributions into spherical harmonics, the analysis allows us to extract *moments*, coefficients which encode the underlying spin and parity of the contributing mesons, as well as the relative strengths of their partial waves [10]. Unlike a PWA, which isolates specific waves, a moment analysis captures the overall angular profile of meson production in a given system. The moments, defined by the equations

$$H_0(L,M) = \frac{1}{2\pi}\sqrt{\frac{4\pi}{2L+1}} \int_{4\pi} d\Omega \int_{-\pi}^{+\pi} d\Phi\, \mathcal{I}_0(\Omega,\Phi) Y_L^{M*}(\Omega) \tag{2}$$

and

$$H_i(L,M) = \frac{1}{\pi P_\gamma}\sqrt{\frac{4\pi}{2L+1}}\int_{4\pi} d\Omega \int_{-\pi}^{+\pi} d\Phi\, \mathcal{I}_i(\Omega,\Phi) Y_L^{M*}(\Omega) \times \begin{cases} \cos(2\Phi) & \text{for } i = 1, \\ \sin(2\Phi) & \text{for } i = 2. \end{cases} \tag{3}$$

represent the unpolarized and polarized moments, respectively, where further details can be found in Ref. [5]. More specifically, the terms of $\mathcal{I}_i$ in the moment equations are derived from the intensity equation

$$\mathcal{I}(\Omega,\Phi) = \mathcal{I}_0(\Omega) - \mathcal{I}_1(\Omega)P_\gamma \cos(2\Phi) - \mathcal{I}_2(\Omega)P_\gamma \sin(2\Phi) \tag{4}$$

where $\mathcal{I}_0$ represents the unpolarized component of the intensity, while $\mathcal{I}_1$ and $\mathcal{I}_2$ capture the polarization dependent contributions. This decomposition corresponds to three measurable moments, which reflect distinct aspects of the angular intensity in polarized states. These moments help reveal subtle patterns in the data, indicating contributions from both well-understood and exotic states, which allows for a refining of our understanding of the production dynamics.

This approach is particularly powerful for assessing the sensitivity of the system to spin-exotic mesons. Figure 4 illustrates the effectiveness of this method by showing the result from a Monte Carlo (MC) input-output study, where a clear $a_2(1320)$ signal emerges in $H_i(4,4)$ moments, highlighting the sensitivity of the analysis to resonant structures and the methods utility for isolating both established and exotic contributions [10].

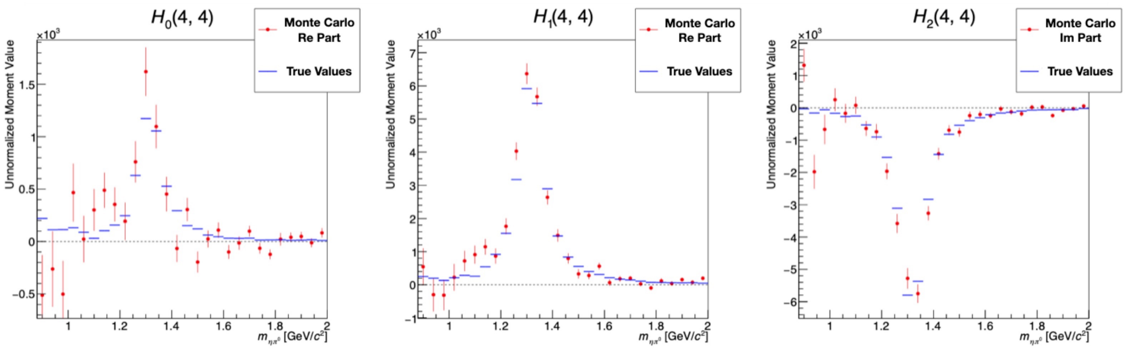

Figure 4: Moments calculated from MC data (red points) compared to the moment values used to generate the MC data (blue lines). Fair agreement of the output with the input values is observed.

6. Conclusions

The presented studies leverage the photoproduction data from the GlueX experiment to explore meson production mechanisms and search for spin-exotic hybrid mesons, particularly the $\pi_1(1600)$ with $J^{PC} = 1^{-+}$. By employing partial-wave analyses, the results highlight contributions from the well-established $a_2(1320)$ on the $\eta\pi^0$ final state, which serves as a crucial reference for exotic searches. Preliminary results for an upper limit of the photoproduction cross section of the $\pi_1(1600)$, indicate that the $\eta'\pi$ channel may contain a sizable π_1 signal. Additionally, moment analyses may help in the future to potentially isolate patterns suggestive of exotic states.

Further studies of the $\eta^{(\prime)}\pi^0$ channels, along with the corresponding respective charged channels $\eta^{(\prime)}\pi^-$, will help to provide deeper insights in exotic contributions arising from different production mechanisms. Additionally, continued collaboration with theorists will be important, particularly as coupled-channel fits are developed for these pseudo-scalar meson systems. These steps will be critical in advancing our understanding of gluonic excitations and exotic hadron structure.

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