Amplitude Analysis of $a_2 \to \eta\pi$ at GlueX

QNP 2022

Colin Gleason

Union College
on Behalf of the GlueX Collaboration

September 5, 2022

Overview

1. The $\eta\pi$ System
   - What we want to measure
2. The GlueX Experiment
   - Large acceptance detector
   - Polarized γ beam at 8.5 GeV
3. Amplitude Analysis of $\eta\pi$ at GlueX
   - $\gamma p \to \eta\pi^0 p$
   - $\gamma p \to \eta\pi^- \Delta^{++}$
4. Outlook

- The goal of GlueX is to map the spectrum of light hybrid mesons
- The $\eta^{(\prime)}\pi$ system is an ideal place to start
- For orbital angular momentum $L = 0, 1, 2, 3, ..$ of the $\eta(\prime)\pi$ system, we gain access to J^{PC}

L	S	P	D	F	...
J^{PC}	0^{++}	1^{-+}	2^{++}	3^{-+}	...

- $\eta\pi$ in a P–wave results in exotic quantum numbers (non $q\bar{q}$)

- The goal of GlueX is to map the spectrum of light hybrid mesons
- The $\eta^{(\prime)}\pi$ system is an ideal place to start
- For orbital angular momentum $L = 0, 1, 2, 3, ..$ of the $\eta(\prime)\pi$ system, we gain access to J^{PC}

L	S	P	D	F	...
J^{PC}	0^{++}	1^{-+}	2^{++}	3^{-+}	...

- $\eta\pi$ in a P–wave results in exotic quantum numbers (non $q\bar{q}$)

- Key questions:
  1. What is the nature and interpretation of the π_1 ($J^{PC} = 1^{-+}$)?
  2. How are hybrid states produced?

- The goal of GlueX is to map the spectrum of light hybrid mesons
- The $\eta^{(\prime)}\pi$ system is an ideal place to start
- For orbital angular momentum $L = 0, 1, 2, 3, ..$ of the $\eta(\prime)\pi$ system, we gain access to J^{PC}

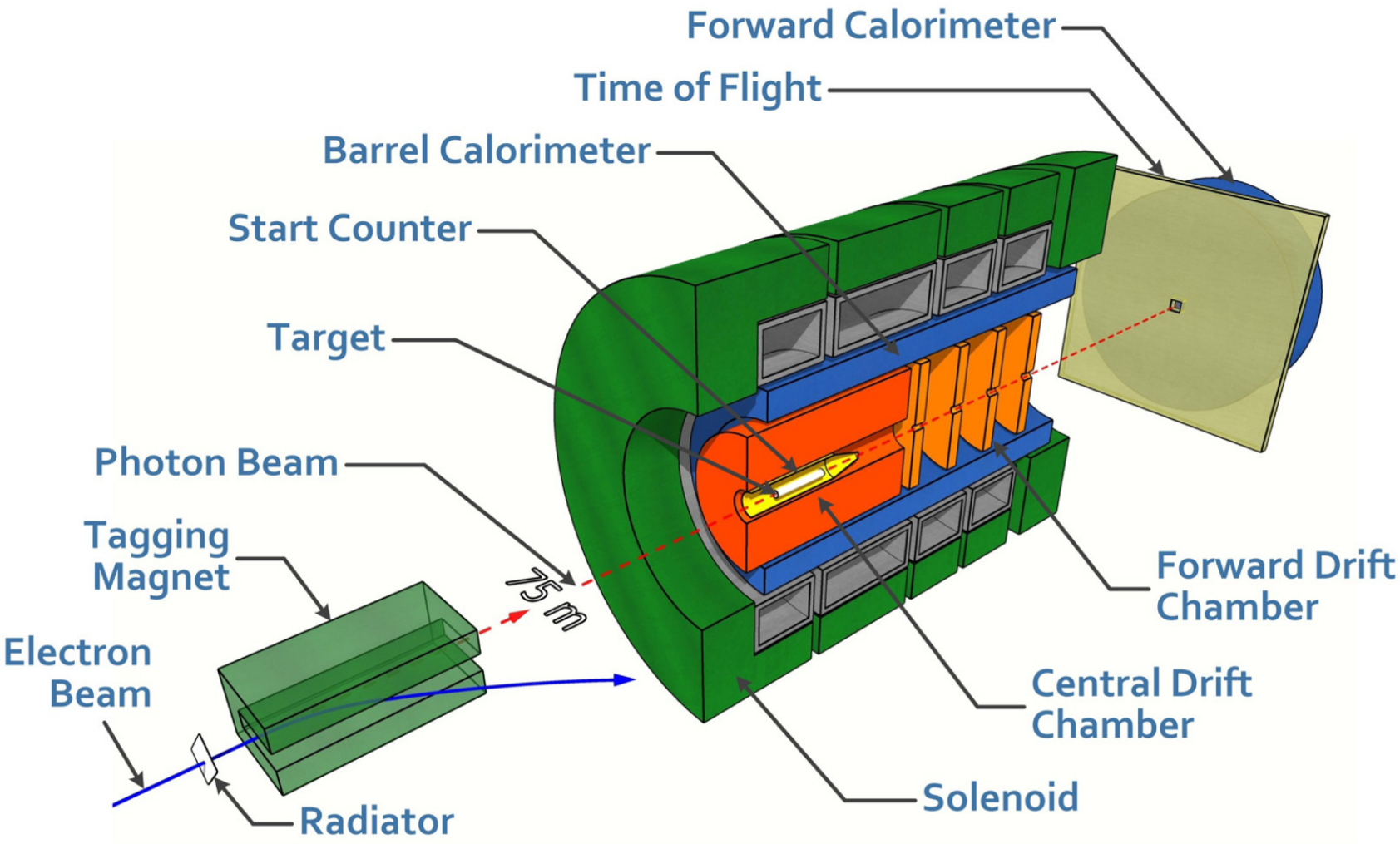
L	S	P	D	F	...
J^{PC}	0^{++}	1^{-+}	2^{++}	3^{-+}	...

- $\eta\pi$ in a P–wave results in exotic quantum numbers (non $q\bar{q}$)

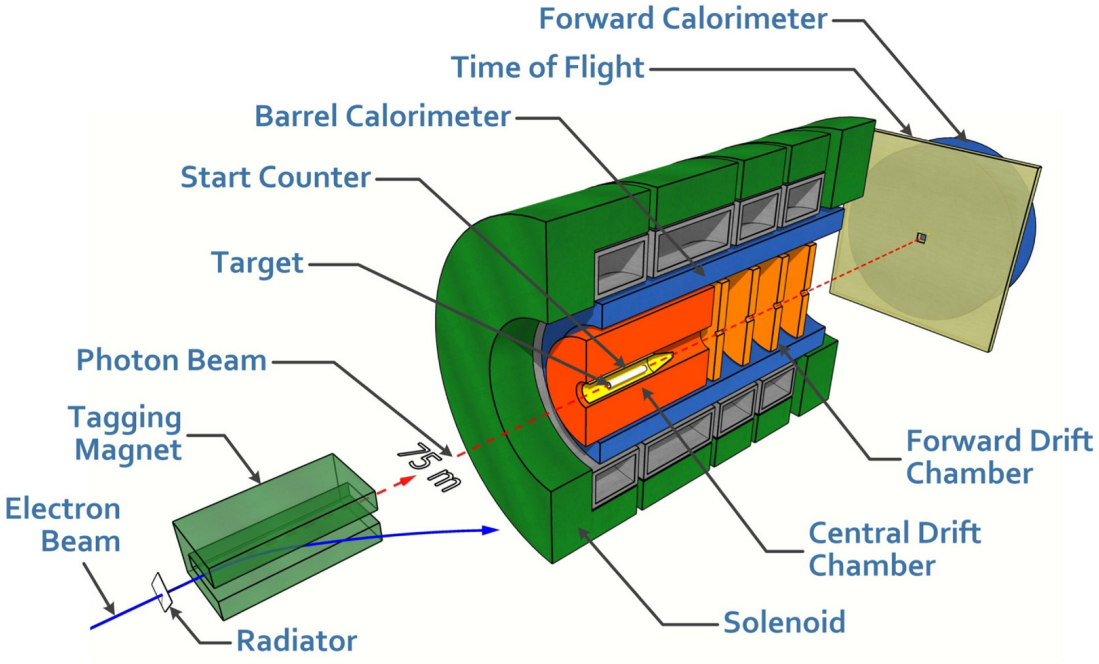
- Key questions:
  1. What is the nature and interpretation of the π_1 ($J^{PC} = 1^{-+}$)?
  2. How are hybrid states produced?

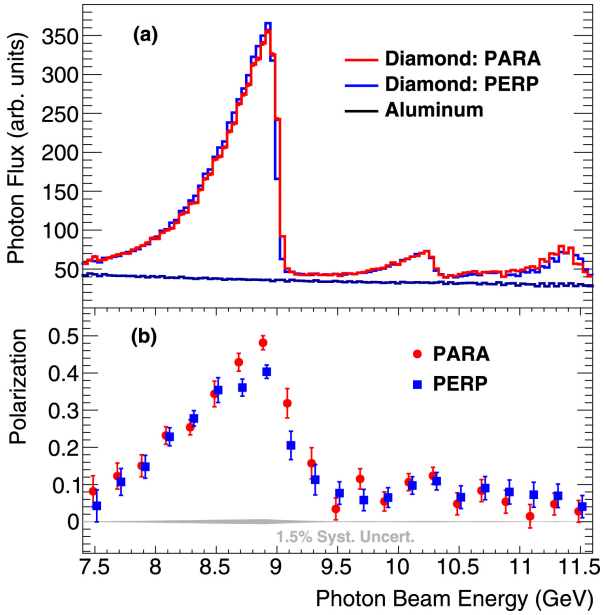
- Build foundation for hybrid searches by studying $\eta\pi$ system
- Focus of this talk is on $a_2(1320) \to \eta\pi$

The GlueX Experiment



The GlueX Experiment





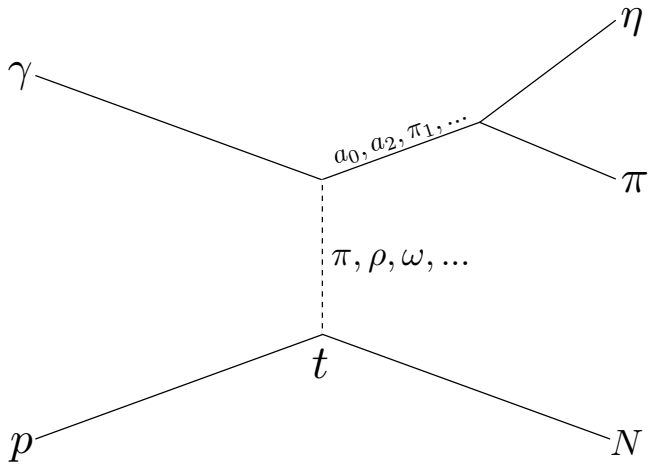
- Linearly polarized photon beam
- Large acceptance for charged and neutral final state particles
- 120 pb^{-1} data collected in GlueX Phase–1 ($E_\gamma = 8.2 - 8.8$ GeV)

$\eta^{(\prime)}\pi$ Systems With GlueX

First stage: study known resonances (e.g. $a_0(980) \to \eta\pi$, $a_2(1320) \to \eta\pi$) to build the foundation for hybrid meson searches at GlueX.

- Access to multiple channels:

1. $\gamma p \to \eta\pi^0 p$
   - $\eta \to \gamma\gamma$
   - $\eta \to \pi^+\pi^-\pi^0$
2. $\gamma p \to \eta\pi^- \Delta^{++}$
   - $\eta \to \gamma\gamma$
   - $\eta \to \pi^+\pi^-\pi^0$
3. $\gamma p \to \eta'\pi^0 p$,
   $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$
4. $\gamma p \to \eta'\pi^- \Delta^{++}$,
   $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$

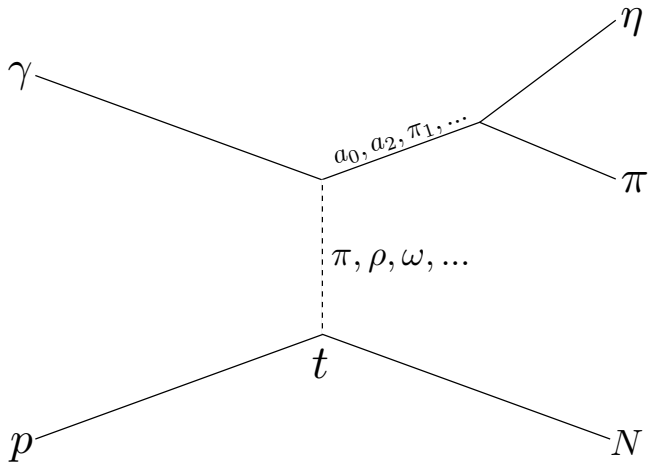


$\eta^{(\prime)}\pi$ Systems With GlueX

First stage: study known resonances (e.g. $a_0(980) \to \eta\pi$, $a_2(1320) \to \eta\pi$) to build the foundation for hybrid meson searches at GlueX.

- Access to multiple channels:

1. $\gamma p \to \eta\pi^0 p$
   - $\eta \to \gamma\gamma$
   - $\eta \to \pi^+\pi^-\pi^0$
2. $\gamma p \to \eta\pi^- \Delta^{++}$
   - $\eta \to \gamma\gamma$
   - $\eta \to \pi^+\pi^-\pi^0$
3. $\gamma p \to \eta'\pi^0 p$,
   $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$
4. $\gamma p \to \eta'\pi^- \Delta^{++}$,
   $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$

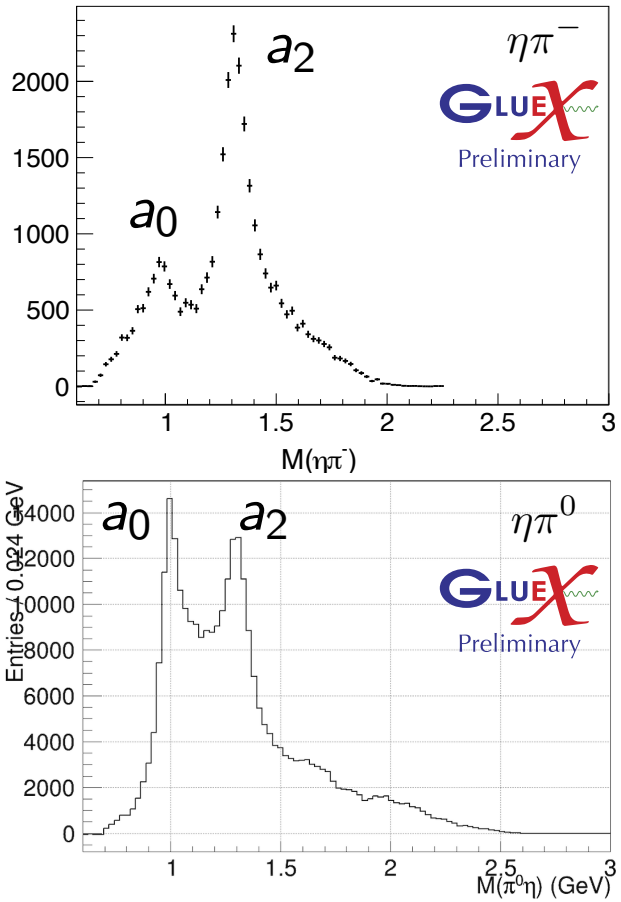


- Different decay modes should contain same physics
  - $\Rightarrow$ Understand Acceptance
  - $\Rightarrow$ Handling of backgrounds
- Charged and neutral decays are complementary

$\gamma p \to \eta\pi N$

$0.1 < -t < 0.3$ GeV^2

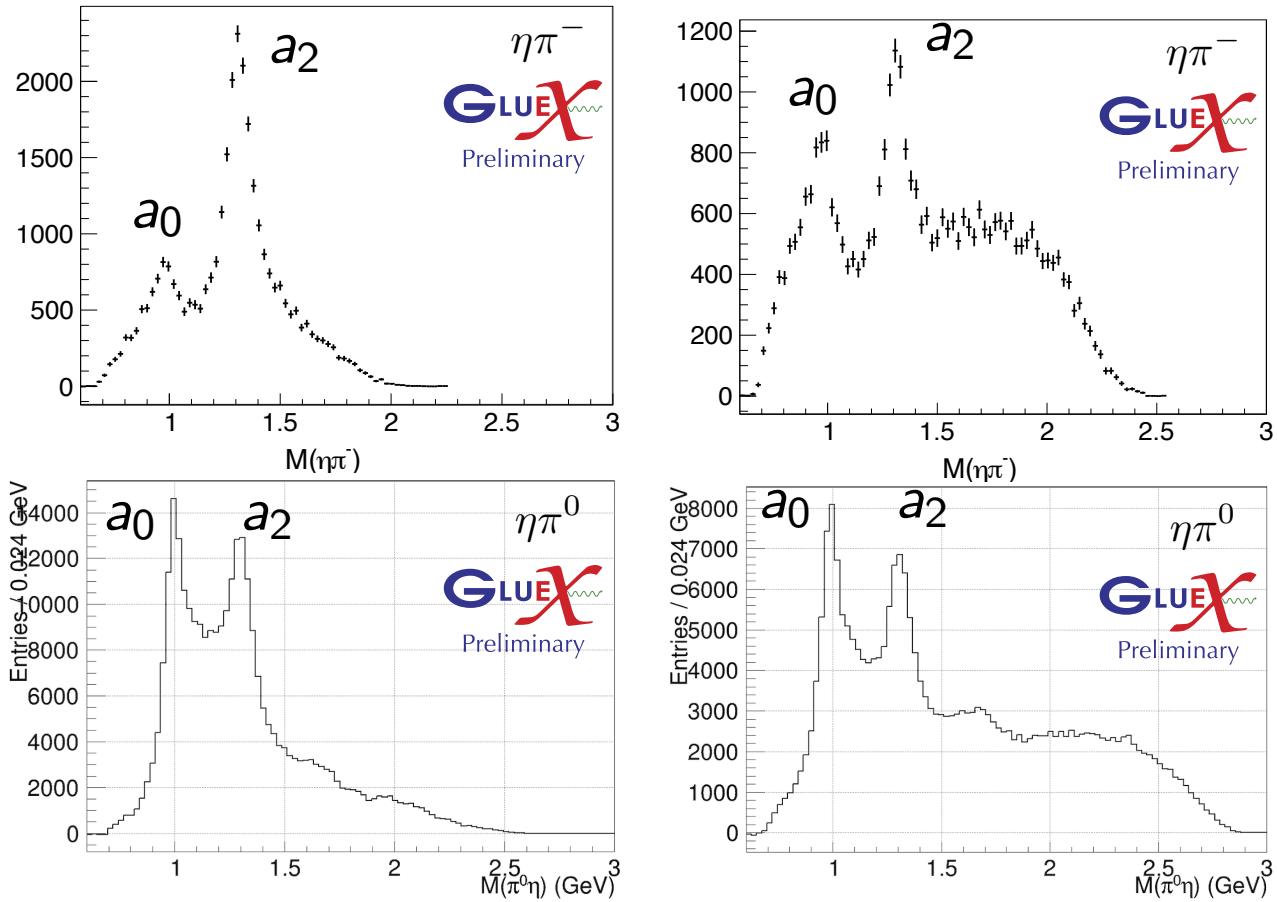
- Goal is to measure a_2 cross section as a function of t
- Mass distributions provide insight into how resonances and backgrounds evolve



$\gamma p \to \eta\pi N$

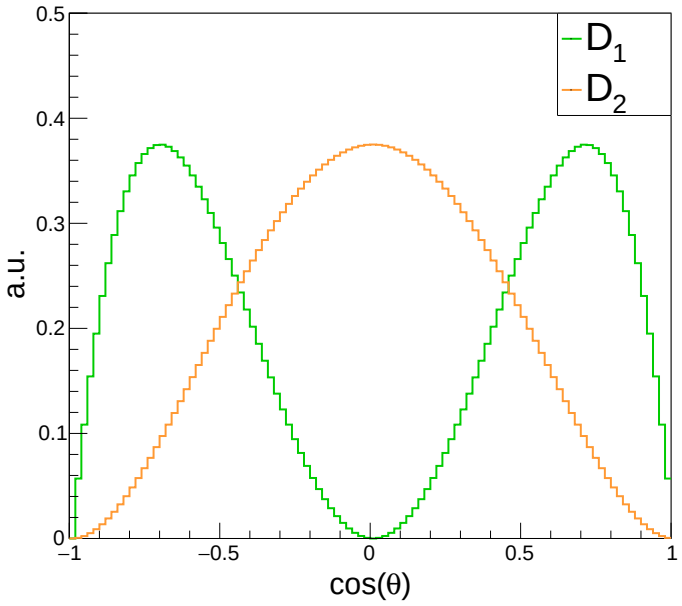
- Goal is to measure a_2 cross section as a function of t
- Mass distributions provide insight into how resonances and backgrounds evolve

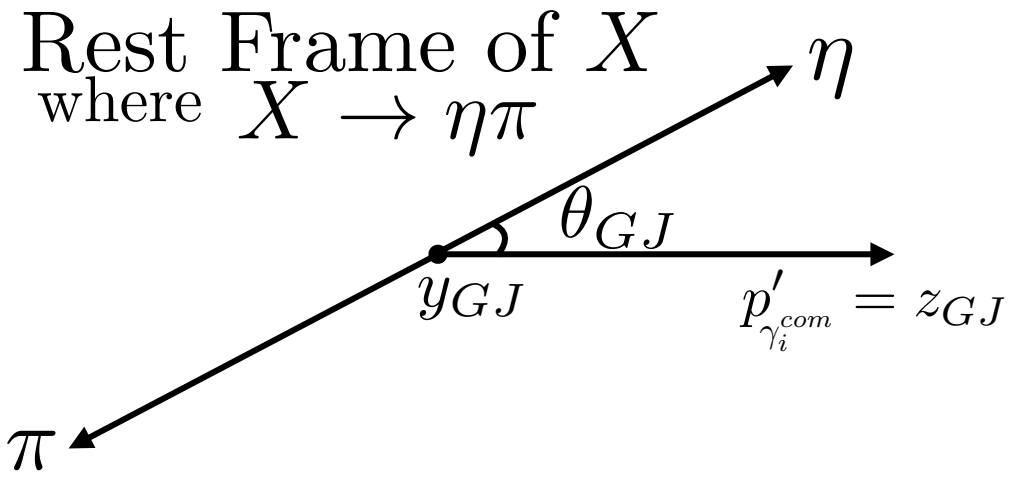
$0.1 < -t < 0.3$ GeV^2 $\quad$ $0.3 < -t < 0.6$ GeV^2



Angular Distributions in $\eta\pi$

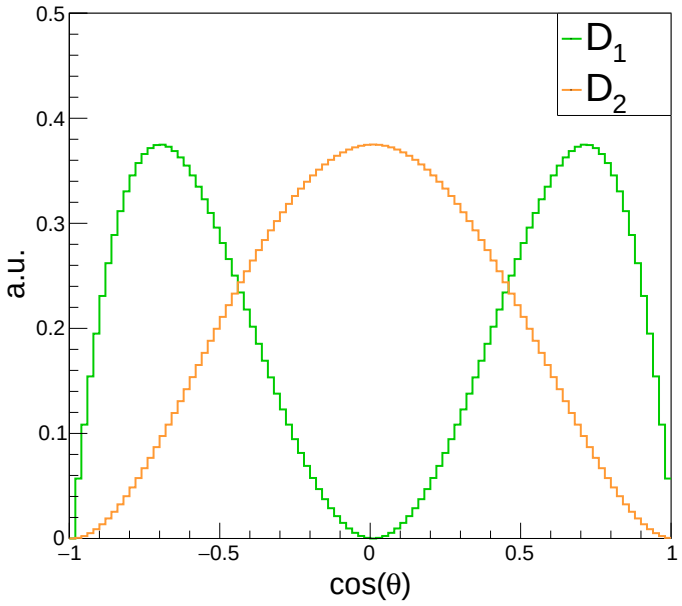
Gottfried-Jackson Frame

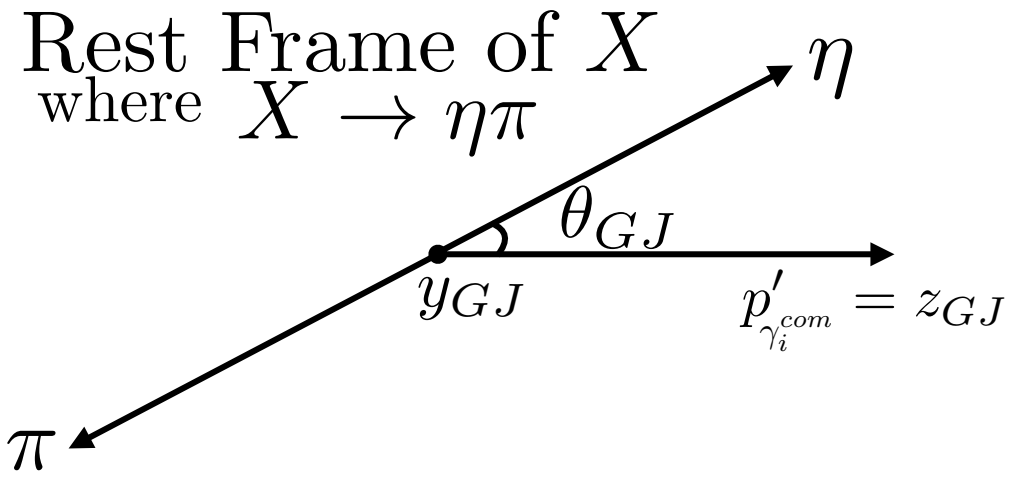


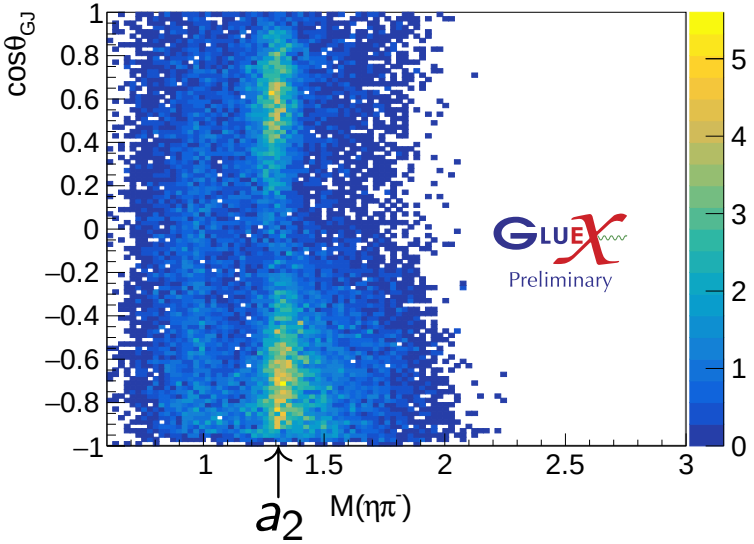


Angular Distributions in $\eta\pi$

Gottfried-Jackson Frame





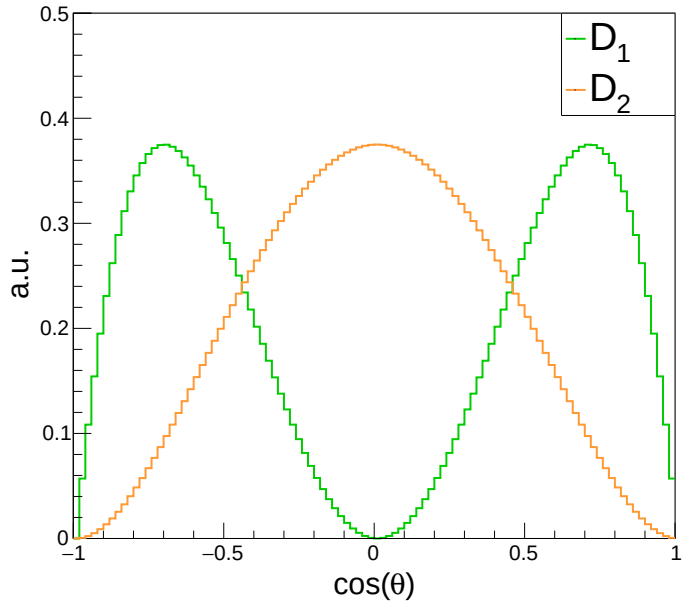


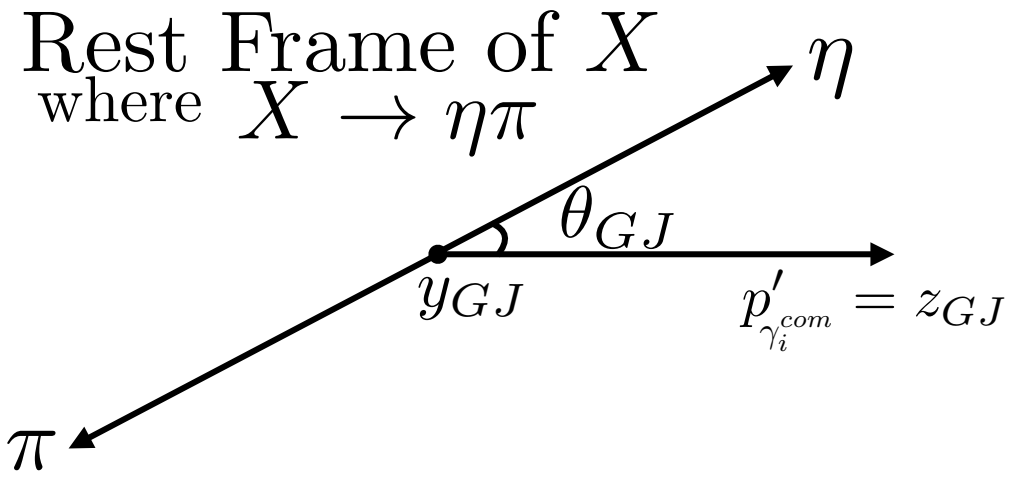
- D_1 ($L = 2,\ m = 1$) structure at ≈ 1300 MeV in $\eta\pi^-$ system ($a_2(1320)$)
- Similar to COMPASS D wave in $\eta\pi^-$

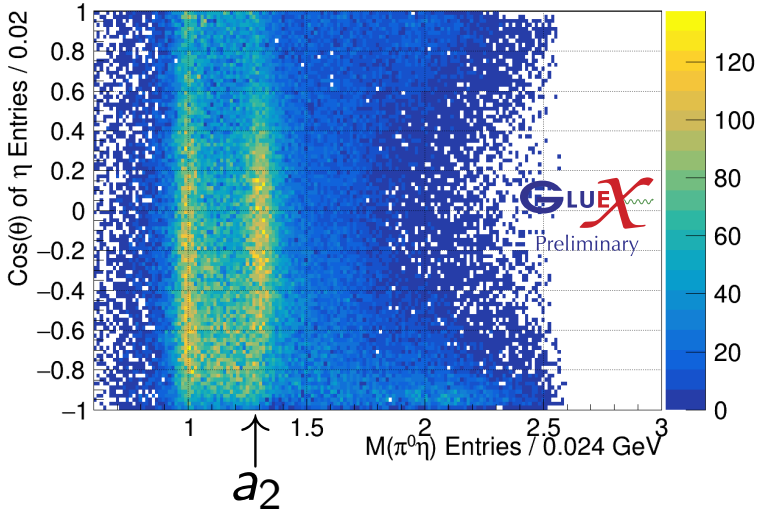
(PLB 740, 303 (2015))

Angular Distributions in $\eta\pi$

Gottfried-Jackson Frame







- D_2 ($L = 2,\ m = 2$) structure at ≈ 1300 MeV in $\eta\pi^0$ system ($a_2(1320)$)
- Belle: $\gamma\gamma \to \eta\pi^0$ sees a_2 produced in D_2 state (PRD 80, 032001 (2009))

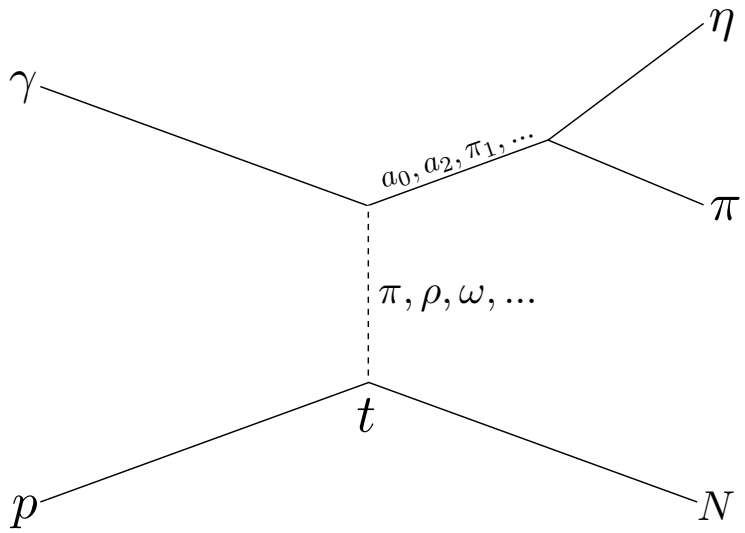
Amplitude Analysis on $\gamma p \to \eta\pi N$

Polarized Amplitudes (PRD 100 (2019) 5, 054017)

- Introduce polarized photoproduction amplitudes to incorporate beam polarization
- System described by $\Omega = \theta, \phi$ (in GJ or Helicity frame) and Φ, the polarization angle

$$\mathrm{I}(\Omega,\Phi) \propto (1-P_\gamma)\Big|\sum_\ell [\ell]_m^{(-)}\,\mathrm{Re}[Z_\ell^m(\Omega,\Phi)]\Big|^2 + (1-P_\gamma)\Big|\sum_\ell [\ell]_m^{(+)}\,\mathrm{Im}[Z_\ell^m(\Omega,\Phi)]\Big|^2$$
$$+\,(1+\mathrm{P}_\gamma)\Big|\sum_\ell [\ell]_m^{(+)}\,\mathrm{Re}[Z_\ell^m(\Omega,\Phi)]\Big|^2 + (1+P_\gamma)\Big|\sum_\ell [\ell]_m^{(-)}\,\mathrm{Im}[Z_\ell^m(\Omega,\Phi)]\Big|^2$$

- Basis: $Z_l^m(\Omega,\Phi) = Y_l^m(\Omega)e^{-i\Phi}$
- Fit $[\ell]_m^{\pm}$ coefficients to the data
  - $\pm$ corresponds to the naturality of exchange particle
  - $m = -\ell, ..., \ell$



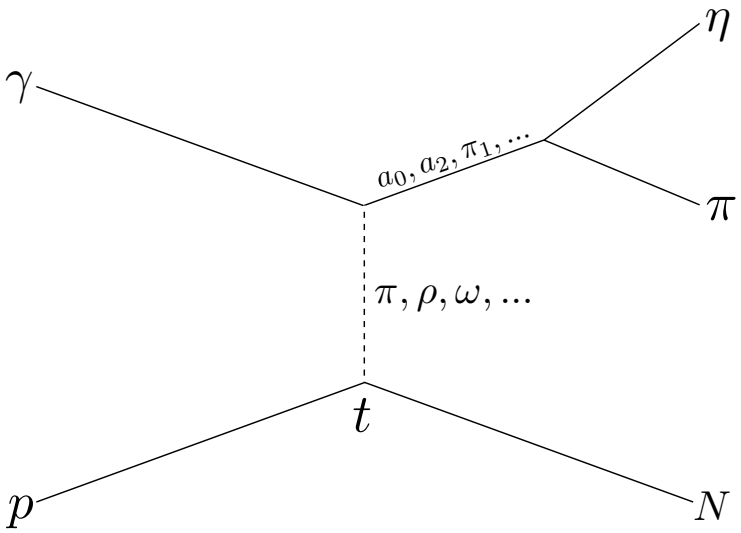
Amplitude Analysis on $\gamma p \to \eta\pi N$

Polarized Amplitudes (PRD 100 (2019) 5, 054017)

- Introduce polarized photoproduction amplitudes to incorporate beam polarization
- System described by $\Omega = \theta, \phi$ (in GJ or Helicity frame) and Φ, the polarization angle

$$\mathrm{I}(\Omega,\Phi) \propto (1-P_\gamma)\Big|\sum_\ell [\ell]_m^{(-)}\,\mathrm{Re}[Z_\ell^m(\Omega,\Phi)]\Big|^2 + (1-P_\gamma)\Big|\sum_\ell [\ell]_m^{(+)}\,\mathrm{Im}[Z_\ell^m(\Omega,\Phi)]\Big|^2$$
$$+\,(1+\mathrm{P}_\gamma)\Big|\sum_\ell [\ell]_m^{(+)}\,\mathrm{Re}[Z_\ell^m(\Omega,\Phi)]\Big|^2 + (1+P_\gamma)\Big|\sum_\ell [\ell]_m^{(-)}\,\mathrm{Im}[Z_\ell^m(\Omega,\Phi)]\Big|^2$$

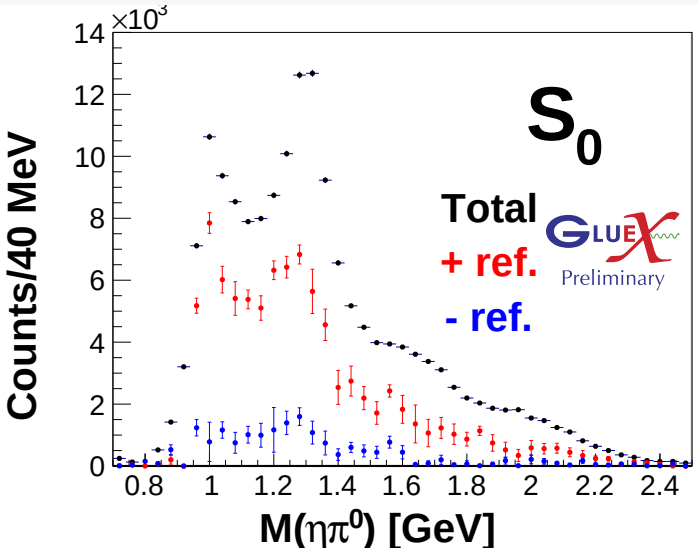
- Basis: $Z_l^m(\Omega,\Phi) = Y_l^m(\Omega)e^{-i\Phi}$
- Fit $[\ell]_m^{\pm}$ coefficients to the data
  - $\pm$ corresponds to the naturality of exchange particle
  - $m = -\ell, ..., \ell$



- Starting waveset ($S_0^{\pm}$, $D_{-1,0,1}^{\pm}$, D_2^{+}) set chosen from tensor meson decay model from JPAC (PRD 102 (2020))

Mass Independent Fit to $\gamma p \to \eta\pi^0 p$

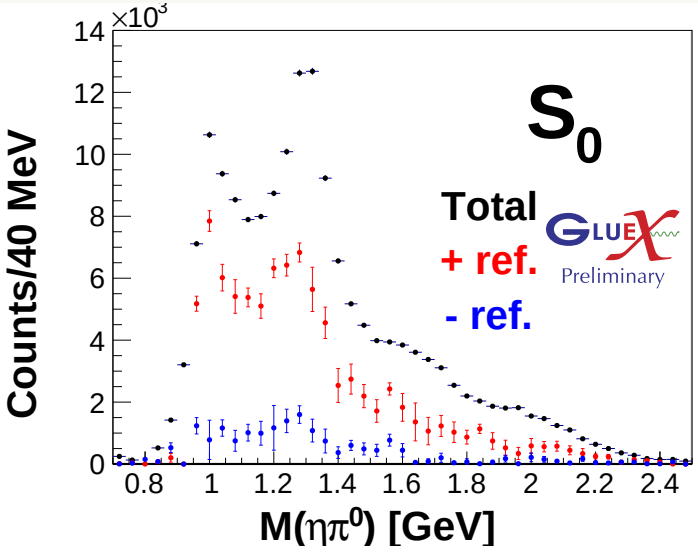
$0.1 < -t < 0.3$ GeV^2

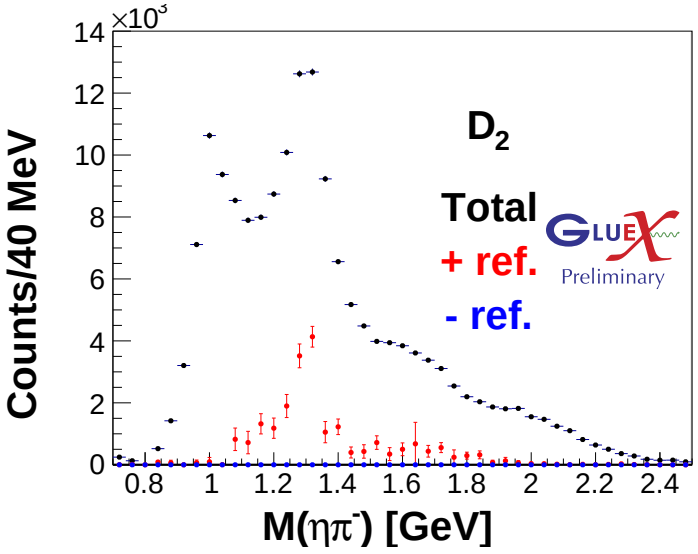


- Dominant structure in $a_0(980)$ is the S_0^+ wave ✓
- Large S_0^+ under $a_2(1320)$
  - Leakage or acceptance effect?
  - Contribution from other resonance?

Mass Independent Fit to $\gamma p \to \eta\pi^0 p$

$0.1 < -t < 0.3$ GeV^2



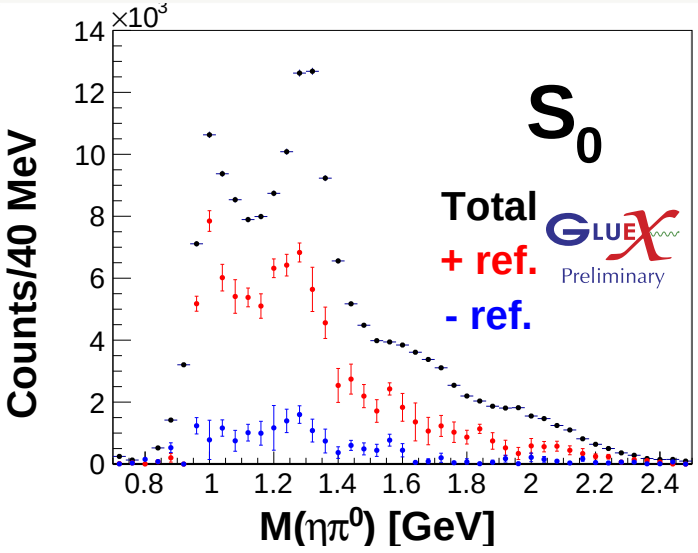


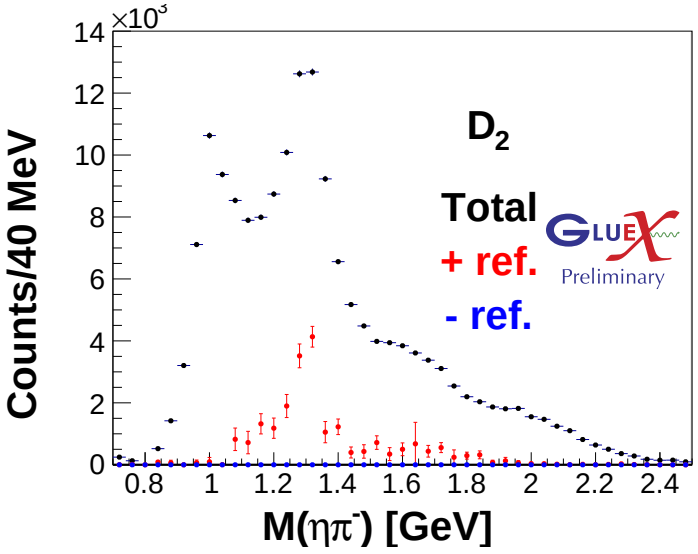
- Dominant structure in $a_0(980)$ is the S_0^+ wave ✓
- Large S_0^+ under $a_2(1320)$
  - Leakage or acceptance effect?
  - Contribution from other resonance?

- D_2^+ is the dominant D wave in the $a_2(1320)$ region at low $-t$ ✓
- Similar intensities of S_0^+ and D_2^+?

Mass Independent Fit to $\gamma p \to \eta\pi^0 p$

$0.1 < -t < 0.3$ GeV^2



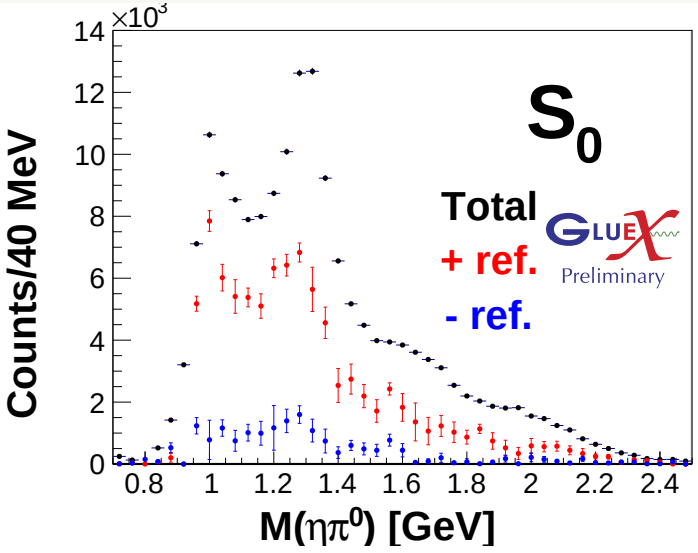


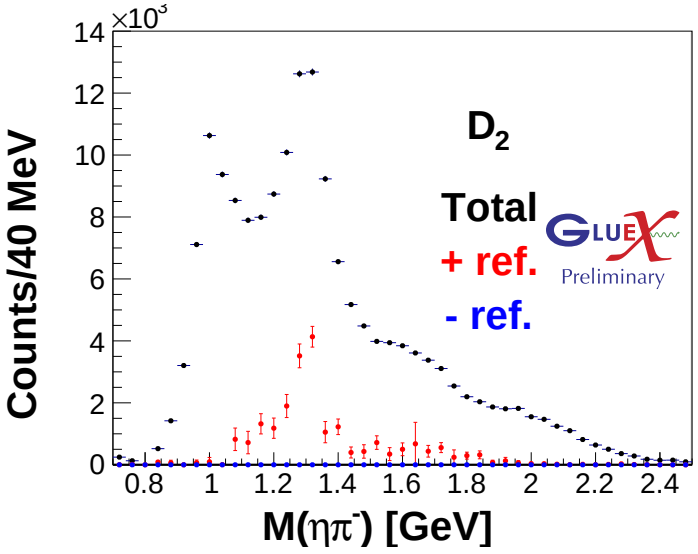
- Dominant structure in $a_0(980)$ is the S_0^+ wave ✓
- Large S_0^+ under $a_2(1320)$
  - Leakage or acceptance effect?
  - Contribution from other resonance?

- D_2^+ is the dominant D wave in the $a_2(1320)$ region at low $-t$ ✓
- Similar intensities of S_0^+ and D_2^+?
- Working on identifying $a_2(1700)$
  - Will need to identify correct waves and confirm phase motion for hybrid search

Mass Independent Fit to $\gamma p \to \eta\pi^0 p$

$0.1 < -t < 0.3$ GeV^2





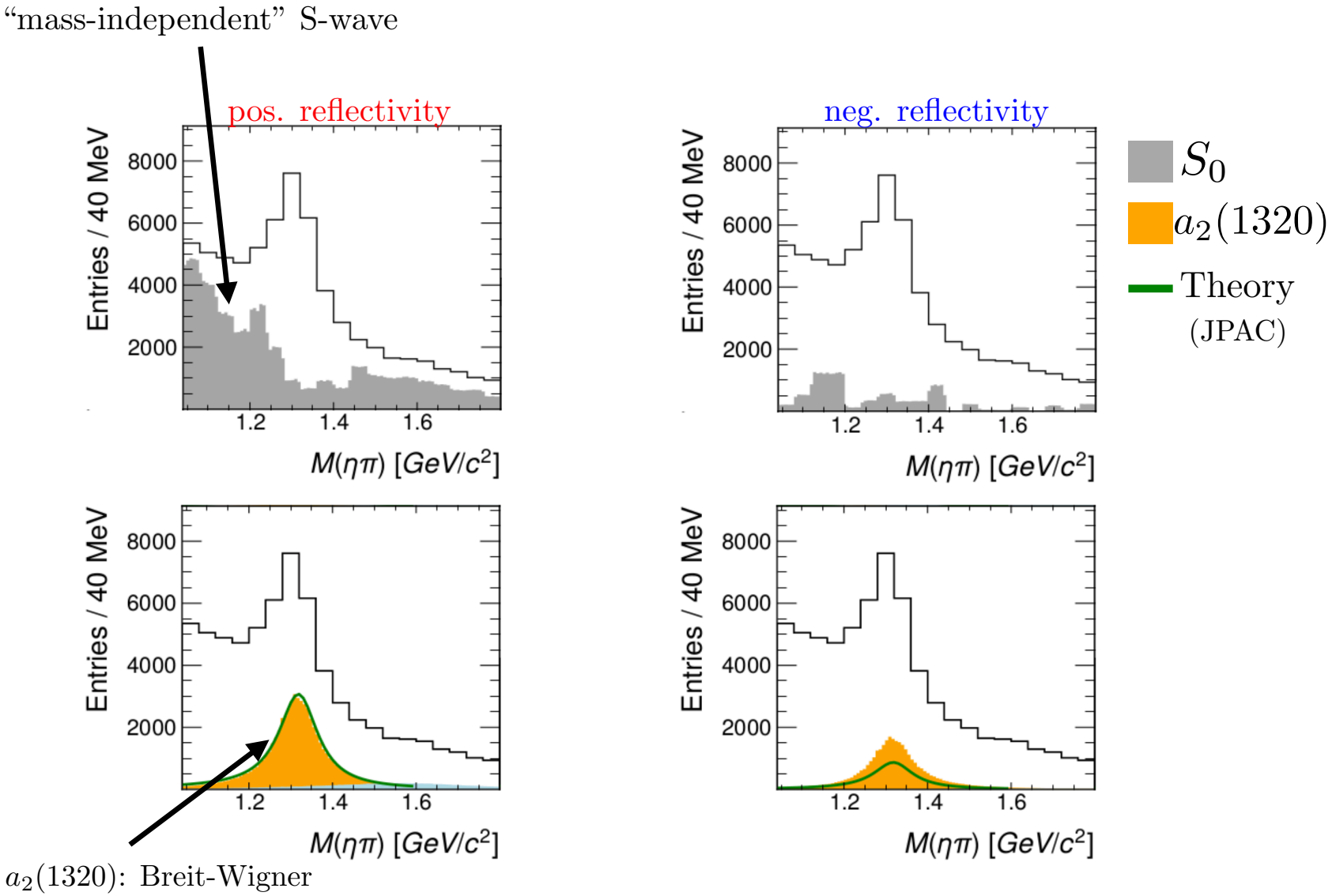
- Dominant structure in $a_0(980)$ is the S_0^+ wave ✓
- Large S_0^+ under $a_2(1320)$
  - Leakage or acceptance effect?
  - Contribution from other resonance?

- D_2^+ is the dominant D wave in the $a_2(1320)$ region at low $-t$ ✓
- Similar intensities of S_0^+ and D_2^+?
- Working on identifying $a_2(1700)$
  - Will need to identify correct waves and confirm phase motion for hybrid search
- How does D wave evolve as a function of $-t$?

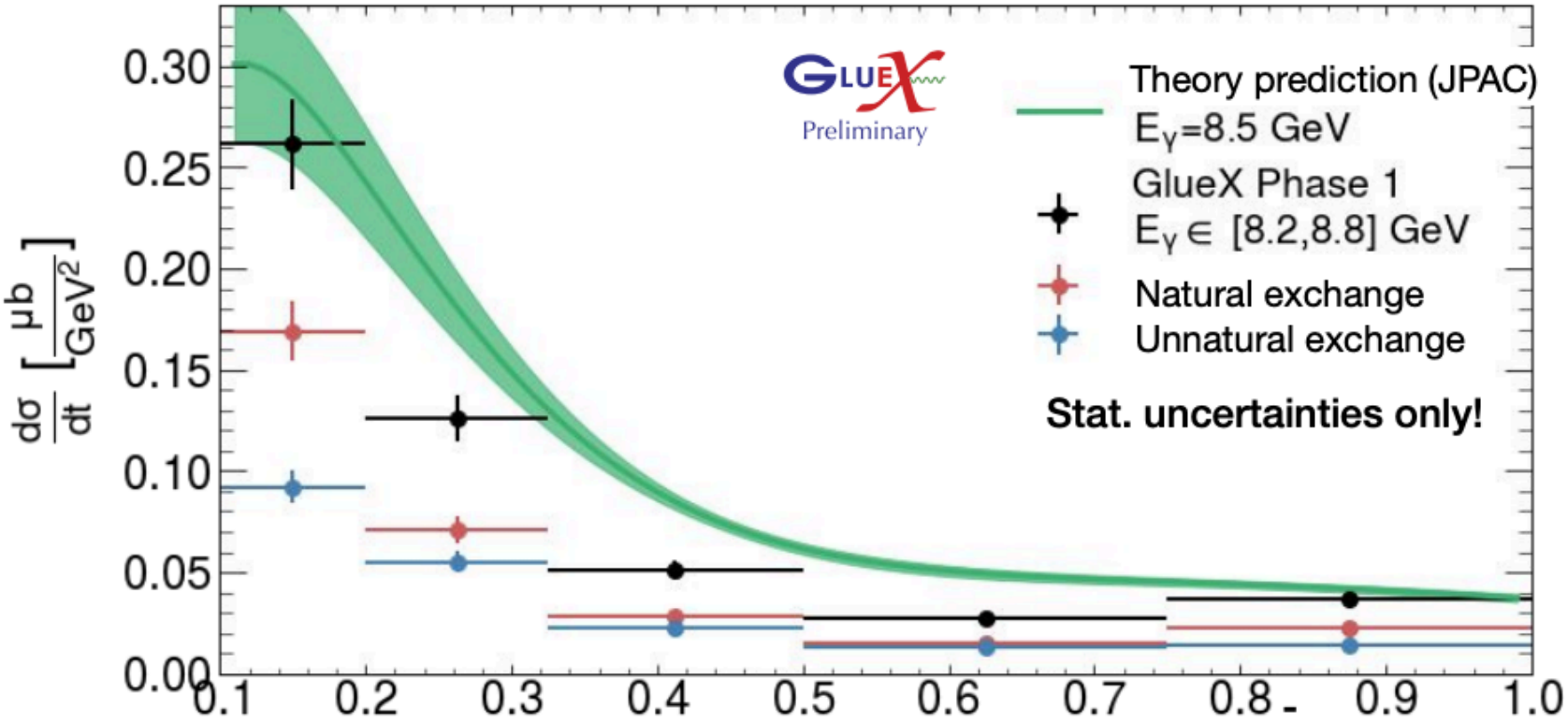
Model Semi-Independent Fit Approach

- Our goal is to try to extract t-dependent cross section of $a_2 \to \eta\pi$
- Initial strategy: mass independent fits to extract intensities, phase difference
  - Model independent, but challenges arise in waveset choice, ambiguities, leakage, etc.
- New approach: "Model Semi-Independent" fit
  - The $a_2(1320)$ is isolated, so we can limit the fit to the relevant mass range
  - Model $a_2(1320)$ with a relativistic Breit Wigner
  - Phase-motion of D-wave (BW) serves as anchor-point in these fits, may eliminate ambiguities
  - S_0 wave is fit on a bin by bin basis

$a_2(1320) \to \eta\pi^0$ Model Semi-Independent Fit

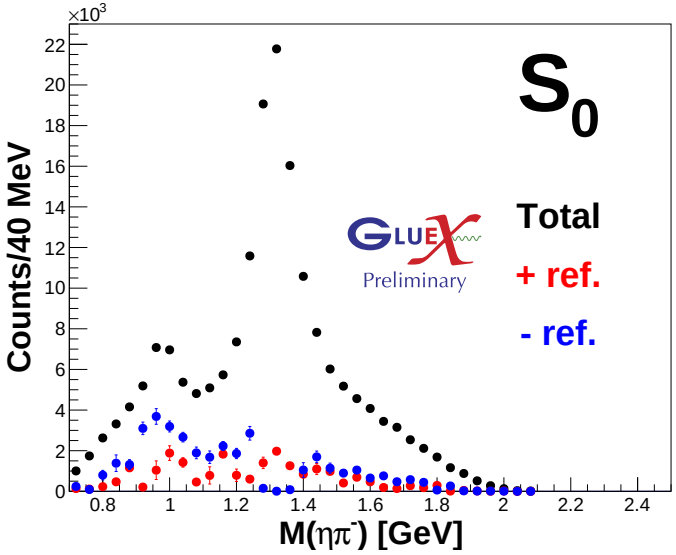


$a_2(1320) \to \eta\pi^0$ Cross Section



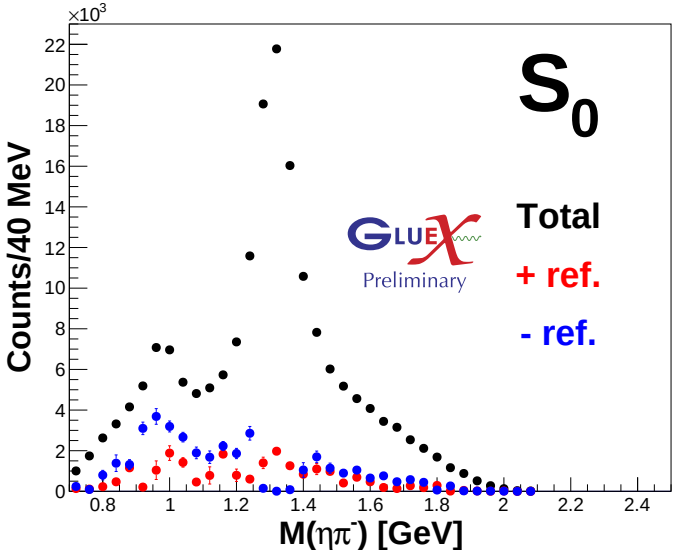
- Good agreement between theory and data
- Systematic studies underway
- Inclusion of $a2(1700)$ has significant impact on extracted cross section

Mass Independent Fits for $\gamma p \to \eta\pi^-\Delta^{++}$



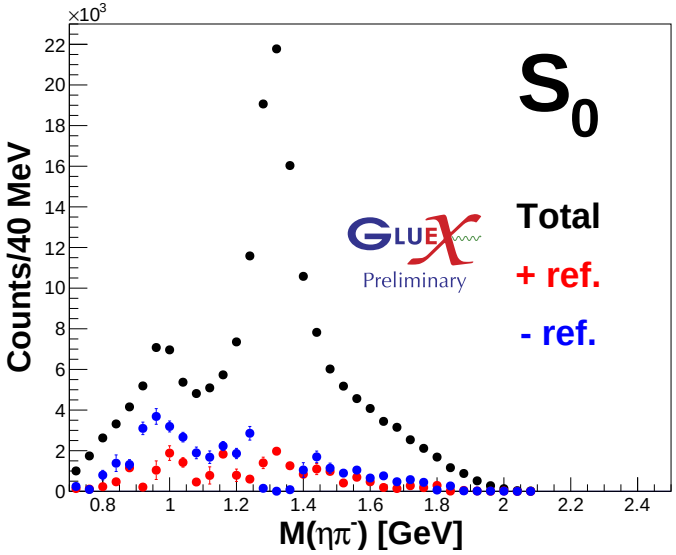
- Dominant structure in $a_0^-(980)$ is the S_0^- wave ✓
- Some S_0^+ under $a_2(1320)$

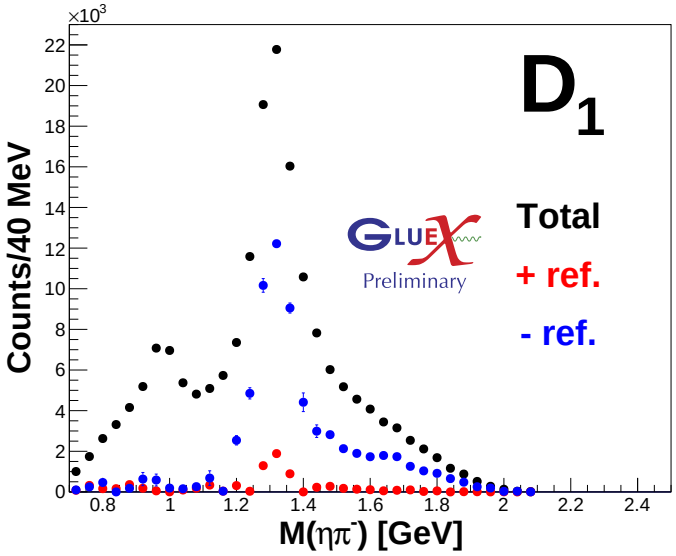
Mass Independent Fits for $\gamma p \to \eta\pi^-\Delta^{++}$



- Dominant structure in $a_0^-(980)$ is the S_0^- wave ✓
- Some S_0^+ under $a_2(1320)$
- $a_2^-(1320)$ should be dominated by D_1^-

Mass Independent Fits for $\gamma p \to \eta\pi^-\Delta^{++}$





- Dominant structure in $a_0^-(980)$ is the S_0^- wave ✓
- Some S_0^+ under $a_2(1320)$
- $a_2^-(1320)$ should be dominated by D_1^-

- Dominant structure is D_1^- ✓
  - unnatural (π) parity exchange expected to dominate at low $-t$
- D_0^- also has a large contribution
- Tail in D_1^- wave related to $a_2(1700)$?
- Progress being made on hybrid fits and cross sections in the channel

Comparison of the Neutral and Charged Channels

$a_2(1320) \to \eta\pi^0$

- Dominated by natural parity $(\rho,\ \omega)$ exchange at low t
- $m = 2$ wave has the largest contribution

Comparison of the Neutral and Charged Channels

$a_2(1320) \to \eta\pi^0$

- Dominated by natural parity ($\rho,\ \omega$) exchange at low t
- $m = 2$ wave has the largest contribution

$a_2(1320) \to \eta\pi^-$

- Dominated by unnatural parity (π) exchange at low t
- $m = 1$ wave has the largest contribution

Comparison of the Neutral and Charged Channels

$a_2(1320) \to \eta\pi^0$

- Dominated by natural parity (ρ, ω) exchange at low t
- $m = 2$ wave has the largest contribution

$a_2(1320) \to \eta\pi^-$

- Dominated by unnatural parity (π) exchange at low t
- $m = 1$ wave has the largest contribution

- Both channels have the D wave structure evolving with t
- Targeting $a_2(1320)$ production for a near term publication
- Laying the foundation for hybrid meson (P wave) searches at GlueX

Outlook

- Large, high-quality data set with access to multiple $\eta\pi$ channels
- Focusing on understanding a_2 production before moving onto weaker P wave
- Preliminary results are consistent with π, η production at low t
- Critical for us to understand $a_2(1700)$, phase motion, and alternative processes
- Close relationship with theorists (JPAC) on interpretation of results

Outlook

- Large, high-quality data set with access to multiple $\eta\pi$ channels
- Focusing on understanding a_2 production before moving onto weaker P wave
- Preliminary results are consistent with π, η production at low t
- Critical for us to understand $a_2(1700)$, phase motion, and alternative processes
- Close relationship with theorists (JPAC) on interpretation of results
- Building the foundation for hybrid searches in $\eta^{(\prime)}\pi$

- GlueX Acknowledgments: gluex.org/thanks