ηπ Studies at GlueX
GlueX–Panda Workshop

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Overview

1. Why $\eta'\pi$?
   - What we want to measure
   - Status of the field

2. Status of current analyses at GlueX
   - $\eta\pi^-\Delta^{++}$
   - $\eta\pi^0 p$

3. Moving towards exotics
   - Putting AMPTOOLS to use
   - A look at $\eta'\pi$ final states

4. Challenges and Outlook
The $\eta(\prime)\pi$ System

- For orbital angular momentum $l = 0, 1, 2, 3, \ldots$ of the $\eta(\prime)\pi$ system, we gain access to $J^{PC}$

\[
\begin{array}{cccccc}
L & S & P & D & F & \ldots \\
J^{PC} & 0^{++} & 1^{--} & 2^{++} & 3^{--} & \ldots \\
\end{array}
\]

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

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The $\eta(\prime)\pi$ System

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<table>
<thead>
<tr>
<th>$L$</th>
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<th>$F$</th>
<th>$\ldots$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>1</td>
<td>2</td>
<td>3</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$J^{PC}$</td>
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- $\eta\pi$ in a $P$–wave results in exotic quantum numbers (non $q\bar{q}$)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam Momentum (GeV/c)</th>
<th>Reaction</th>
<th>Claim</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAMS</td>
<td>32, 38, 100</td>
<td>$\pi^- p \rightarrow \pi^0\eta n$</td>
<td>$\pi_1(1400)$</td>
</tr>
<tr>
<td>KEK</td>
<td>6.3</td>
<td>$\pi^- p \rightarrow \pi^-\eta p$</td>
<td>$\pi_1(1400/1600)$</td>
</tr>
<tr>
<td>E852</td>
<td>18</td>
<td>$\pi^- p \rightarrow \pi^-\eta(\prime)p$</td>
<td>$\pi_1(1400)$</td>
</tr>
<tr>
<td>Crystal Barrel</td>
<td>Annihilation</td>
<td>$\bar{p}n \rightarrow \pi^0\eta$</td>
<td>$\pi_1(1400)$</td>
</tr>
<tr>
<td>VES</td>
<td>37</td>
<td>$\pi^- p \rightarrow \pi^-\eta(\prime)p$</td>
<td>$\pi_1(1600)$?</td>
</tr>
<tr>
<td>COMPASS</td>
<td>190</td>
<td>$\pi^- p \rightarrow \pi^-\eta(\prime)n$</td>
<td>$??$</td>
</tr>
<tr>
<td>CLAS</td>
<td>5.5</td>
<td>$\gamma p \rightarrow \pi^-\eta\Delta^{++}$</td>
<td>(not published)</td>
</tr>
</tbody>
</table>

- Searches going on in other channels, but strongest evidence in $\eta'\pi$ and $\rho\pi$

- JPAC coupled channel fit to COMPASS PWA is the new gold standard
COMPASS Results for $\pi^- p \rightarrow \eta \pi^-$ and $\eta' \pi^-$

Rest Frame of $X$
where $X \rightarrow \eta' \pi^-$

$\cos \theta_{GJ}$

$\pi^-$
COMPASS Results for $\pi^- p \rightarrow \eta\pi^-$ and $\eta'\pi^-$

Rest Frame of $X$
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- Clear $D$–wave ($L = 2$) structure at
  $\approx 1300$ MeV in $\eta\pi^-$ system ($a_2(1320)$)
- Some $D$–wave structure around
  1500–2000 MeV $\rightarrow$ need PWA to understand

PLB 740, 303 (2015)
Rest Frame of $X$

where $X \rightarrow \eta'\pi^-$

- Forward/backward asymmetry attributed to interference between odd and even waves
COMPASS Results for $\pi^- p \rightarrow \eta\pi^-$ and $\eta'\pi^-$

- Forward/backward asymmetry attributed to interference between odd and even waves
- $L=1,3,5$ (exotic waves) suppressed in $\eta\pi^-$ with respect to $\eta'\pi^-$
- Only report $P$-wave amplitude
• Coupled channel fit to both $\eta\pi$ and $\eta'\pi$ amplitudes from COMPASS PWA

• Pole positions for $a_2$, $a'_2$, and $\pi_1$ (exotic $P$-wave) determined
  - $\pi_1$ consistent with lightest exotic in $J^{PC}$ and mass

• $\pi_1$ (exotic): $M = 1564 \pm 24 \pm 86$ MeV, $\Gamma = 492 \pm 54 \pm 102$ MeV
• The GlueX spectrometer provides access to multiple channels:

1. $\gamma p \rightarrow \eta \pi^0 p$, $\eta \rightarrow \gamma \gamma$
2. $\gamma p \rightarrow \eta \pi^0 p$, $\eta \rightarrow \pi^+ \pi^- \pi^0$
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6. $\gamma p \rightarrow \eta'\pi^-\Delta^{++}$, $\eta' \rightarrow \pi^+\pi^-\eta$, $\eta \rightarrow \gamma \gamma$

- Potentially could look at other $\eta(\prime)$ decay modes
- Studies would have to be done on $\gamma p \rightarrow \eta\pi^+ n$ or $\gamma p \rightarrow \eta\pi^+\Delta^0$
Brainstorming some early physics goals

- Need a strategy to publish physics results as we work towards an amplitude analysis of the full $\eta'(\pi)$ mass spectrum
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- Study $\frac{\sigma(a_0)}{\sigma(a_2)}$ as a function of $t$
  - JPAC interested in developing a model of $a_0$ and $a_2$ as a function of $t$

- WA102 performed PWA on $pp \rightarrow p\Delta^{++}\eta\pi^-$ and $pp \rightarrow pp\eta\pi^0$
  - Measured $\frac{\sigma(a_0 \rightarrow \eta\pi)}{\sigma(a_2 \rightarrow \eta\pi)} \approx 0.8 \pm 0.2$
  - $a_0$ and $a_2$ dependent on production mechanism
  - No evidence for higher mass states $a_0(1450), a_2(1700)$
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  - Beam asymmetries for $a_0$ (Stuart Fegan)
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So let’s go ahead and look at some distributions!
\[ \gamma p \rightarrow \eta \pi^- \Delta^{++}, \; \eta \rightarrow \gamma \gamma \; (2017 \; data) \]
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- $\frac{3}{7}$ of Spring 2018 data
- $\approx 116\%$ of 2017 dataset
- Remaining GlueX Phase–I data yet to be processed
- Similar features as in 2017
$M(\eta\pi^-)$ in $t$ bins (2017+2018)

- Clear $t$ dependence of $a_{0,2}$ production
- Extracting moments (or amplitudes) as a function of $t$ should be a short term target for early physics
- $\frac{\sigma(a_0)}{\sigma(a_2)}$ for both neutral and charged exchanges

Data  
---
Acceptance
\[ \gamma p \rightarrow \eta \pi^- \Delta^{++}, \quad \eta \rightarrow \pi^+ \pi^- \pi^0 \]
\( \gamma p \rightarrow \eta \pi^- \Delta^{++}, \ \eta \rightarrow \pi^+ \pi^- \pi^0 \)

- Less statistics, more background
- Angular distribution looks similar
- \( M(\eta \pi^-) \) looks similar for \( \eta \rightarrow \gamma \gamma \)
\( \gamma p \rightarrow \eta \pi^0 p, \ \eta \rightarrow \gamma \gamma \) (2017 data)
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- $D$–wave features not as prominent in $\eta \pi^0$
- Working on understanding acceptances
\( \gamma p \rightarrow \eta \pi^0 p, \ \eta \rightarrow \pi^+ \pi^- \pi^0 \) (2017 data)

- No noticeable \( a_0 \) and \( a_2 \) dependance on \( t \)
  - Suggests different production mechanisms between neutral and charged exchanges
- Similar features to what is seen in \( \eta \rightarrow \gamma \gamma \) decay
- \( \approx 100k \) events in this distribution (comparable to COMPASS)
Comparisons With Compass

- Comparable statistical precision with GlueX Phase 1 in $\eta \rightarrow \pi^+\pi^-\pi^0$
- Expect more in $\eta \rightarrow \gamma\gamma$ decay
• Goal: test amplitude analysis for $\gamma p \rightarrow \eta \pi^- \Delta^{++}$
• Generate $a_0(980)$ ($S$–wave) and $a_2(1320)$ ($D$–wave)
  • Do we get out what we put in?
  • Does the acceptance introduce any false waves?
Amplitude Analysis on Toy MC (Acceptance=1)

Invariant Mass [GeV/c]

$\pi\eta$

0.8 1 1.2 1.4 1.6 1.8 2

$S_0$

$P_0$

$P_1^-$

$P_1^+$

$D_0$

$D_1^-$

$D_1^+$

$\pi\eta$ All Waves

$cos(\theta)$ of Resonance Production

$S$-wave ($a_0$) dominate

$D$-wave ($a_2$) dominate

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Amplitude Analysis on Toy MC (GlueX Acceptance)

- Acceptance correction does not introduce any false $P$ waves
- Possible ambiguities in solution

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Moments on Data

- Moments provide the benefit of only having one unique solution
  - Downside is they’re hard to interpret
- Can extend moments to include beam polarization

\[
\begin{align*}
M(\eta\pi) \ [\text{GeV/c}^2] \\
\end{align*}
\]
\[ \gamma p \rightarrow \eta' \pi^- \Delta^{++} \]

- Currently processing Spring 2018 data \((\frac{3}{7}^{th}\) ready for analysis)
  - Have \(\approx 22.5k\) events
  - Expect to have \(\approx 45k\) for full dataset

2017

2018

![Graphs showing event distributions in mass and angle plots for 2017 and 2018 data.](image-url)
$M(\eta'\pi^-)$ vs. $\cos \theta_{GJ}$: Combined 2017+2018
$\gamma p \rightarrow \eta' \pi^0 p$ (2017 data)

Plot courtesy of Alex Austregesilo
Challenges

• Backgrounds
  • Baryons ($p\pi$ (Λ, $N^*$, Δ)’s) in both channels
    • Cuts on baryons, Van Hove
  • $\gamma p \rightarrow \eta\pi^- [\pi^+ p]$ more complicated due to $\rho \rightarrow \pi^+\pi^-$ and non-$\Delta^{++} \rightarrow p\pi^+$
    • Use weights (sWeights), hard cuts, or limit $t$ range
Challenges

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- **Monte Carlo**
  - Do we trust our MC to reproduce kinematics of reaction?
    - Proper generation and decay off \(\Delta^{++}\)
  - How well are our cuts mapped to MC?
  - Is the acceptance correct?

- **Amplitude Analysis**
  - Is what we’re extracting real?

- **Theorists (JPAC) will be crucial to understanding our results**
  - How do we best facilitate this relationship and what role do we want them to play?
Takeaways

- We have access to multiple $\eta(n)\pi$ channels
- Phase 1 should result in comparable statistics ($\approx 1.5 - 2x$) to COMPASS in $\eta'\pi$ and $\eta \rightarrow \pi^+\pi^-\pi^0$
  - We expect much more statistics in the $\eta \rightarrow \gamma\gamma$ decays
Takeaways

• We have access to multiple $\eta'(\pi)$ channels
• Phase 1 should result in comparable statistics ($\approx 1.5 - 2x$) to COMPASS in $\eta'\pi$ and $\eta \rightarrow \pi^+\pi^-\pi^0$
  • We expect much more statistics in the $\eta \rightarrow \gamma\gamma$ decays
• Early work has focused on looking at angular distributions and developing the amplitude analysis procedure
• Close work with theorists will be necessary