Update on the Search for π_1 at GlueX

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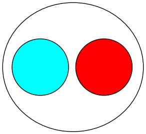
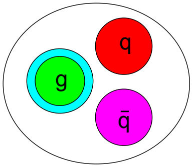
June 25, 2023

The Quark Model

Want to know which types of hadrons exist in QCD

- Simplest bound states are mesons ($q\bar{q}$) and baryons (qqq)
- Mesons in quark model have $P = (-1)^{\ell+1}$ and $C = (-1)^{\ell+s}$
- Some J^{PC} combinations are forbidden for $q\bar{q}$ states
  - Forbidden $q\bar{q}$ J^{PC}: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}...
- The forbidden J^{PC} can be accessed if there are additional degrees of freedom in the final state
  - Additional quarks: tetraquarks or molecular mesons
  - Gluonic excitations: glueball state or a hybrid meson

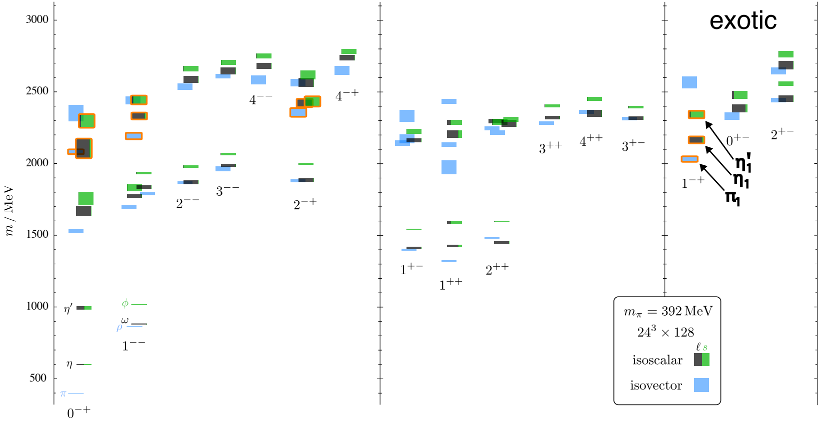

Meson



Hybrid Meson

Studying hybrid mesons can tell us how the gluon contributes to properties of bound states in QCD

Lattice QCD Spectrum



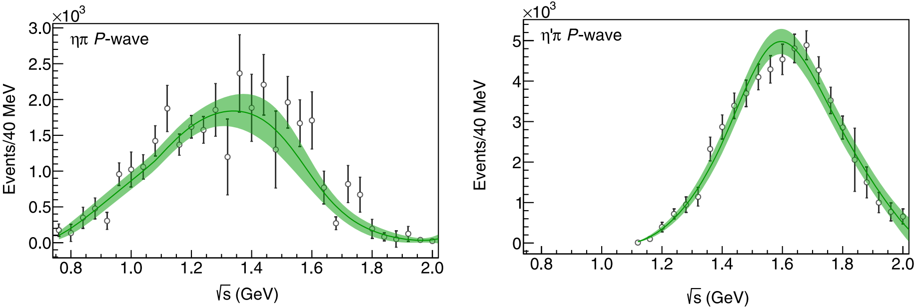
- Lightest hybrid meson predicted to be $I = 1$ $J^{PC} = 1^{-+}$ state
  - Likely the $\pi_1(1600)$, seen by multiple experiments
- BESIII observes $\eta_1(1855)$, candidate for either η_1 or η_1'

[PRD **88** 094505(2013)]

Recent Experimental Results on Lightest Hybrid Meson

Previous experiments find $\pi_1(1400)$ in $\eta\pi$ and $\pi_1(1600)$ in $\eta'\pi$

- COMPASS extracted $\eta(')\pi$ P-wave using pion production
- $\eta\pi$ P-wave corresponds to 1^{-+} resonance
- Joint Physics Analysis Center (JPAC) fit to the data only requires one resonance
  - $M = 1564 \pm 24 \pm 86$ MeV and $\Gamma = 492 \pm 54 \pm 102$ MeV



Analysis: A. Rodas *et al.* PRL **122** 042002 (2019)

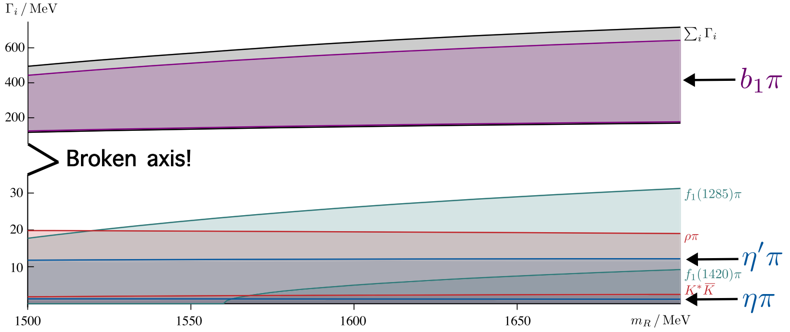
Data: C. Adolph *et al.* (COMPASS) PLB **740** 303-311 (2015)

This tells us where to look

π_1 Branching Fractions from Lattice QCD

- Lattice QCD predicts widths for π_1 decays

PRD **103** 054502 (2021)



- $b_1\pi$ predicted to be dominant decay mode, but b_1 is broad
- $\eta\pi$ is system of two pseudoscalars ($J^{PC} = 0^{-+}$)

	$S-$wave ($\ell = 0$)	$P-$wave ($\ell = 1$)	$D-$wave ($\ell = 2$)
J^{PC}	0^{++}	1^{-+} (exotic)	2^{++}

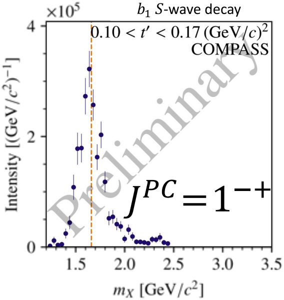
π_1 Branching Fractions from Lattice QCD

- Use predicted widths to get decay branching fractions

PRD **103** 054502 (2021)

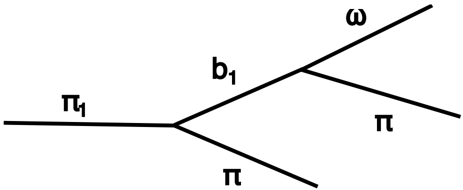
Decay	Width (MeV)	Branching Fraction
$\eta\pi$	$0 \to 1$	$0 \to 0.7\%$
$\eta'\pi$	$0 \to 12$	$0 \to 7.9\%$
$b_1\pi$	$139 \to 529$	$69.5 \to 100\%$
All others	$0 \to 48$	$0 \to 25.7\%$
Total	$139 \to 590$	-

- COMPASS recently showed preliminary $b_1\pi$ PWA results
- They find a 1^{-+} peak consistent with the π_1



GlueX Hybrid Meson Search Strategy

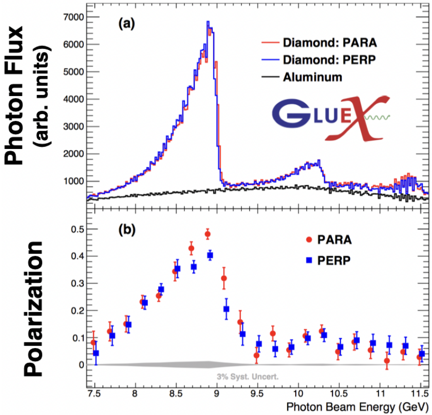
1. Set upper limit on photoproduction cross section of $\pi_1(1600)$
   - First limit using recent lattice calculations
   - Can be used to test discovery potential in different final states
   - Expect signals in $\pi_1^0 \to \omega\pi^+\pi^-$ and $\pi_1^- \to \omega\pi^-\pi^0$

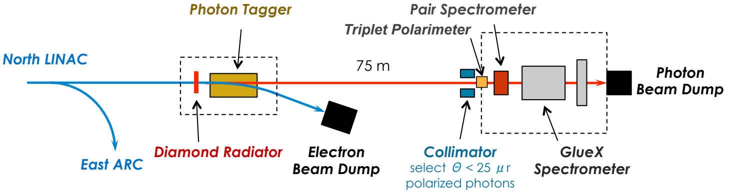


2. Confirm state found in COMPASS data:
   - Perform partial wave analyses on $\eta\pi$ and $\eta'\pi$
   - $\pi_1(1600)$ would appear in P-wave
   - $\eta\pi$ has stronger coupling to $a_2(1320)$
   - $\eta'\pi$ has stronger coupling to $\pi_1(1600)$
3. Search for new hybrid mesons

Hall D

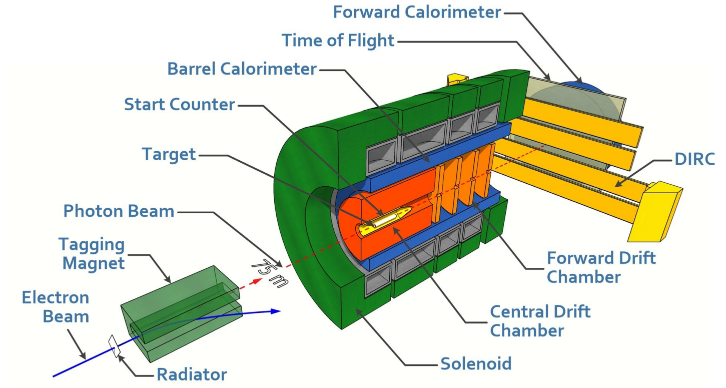
- CEBAF accelerates electrons up to 12 GeV
- Electrons impinge on diamond wafer, creating linearly polarized photons via coherent bremsstrahlung
- Photon energy tagged with high precision (< 25 MeV)
- Photon beam incident on liquid hydrogen target





The GlueX Experiment

Nearly hermetic detector can detect charged and neutral particles



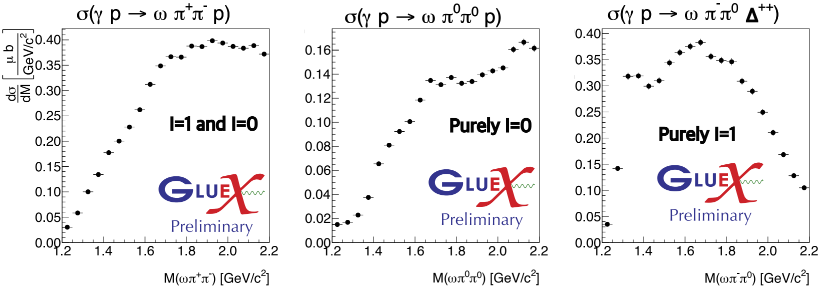
DIRC installed in 2019 to help with kaon identification

Data Sample	Dates	Integrated Luminosity (pb^{-1})
Phase 1	2017 – 2018	125
Phase 2	2020 – 2025?	375 – 500

Upper Limit Using $\pi_1(1600) \to b_1\pi$

Signal: $\pi_1 \to b_1\pi$, $b_1 \to \omega\pi$, $\omega \to \pi^+\pi^-\pi^0$

- Measure $\sigma(\omega\pi\pi)$ by fitting ω yield in 50 MeV/c^2 bins of $M(\omega\pi\pi)$

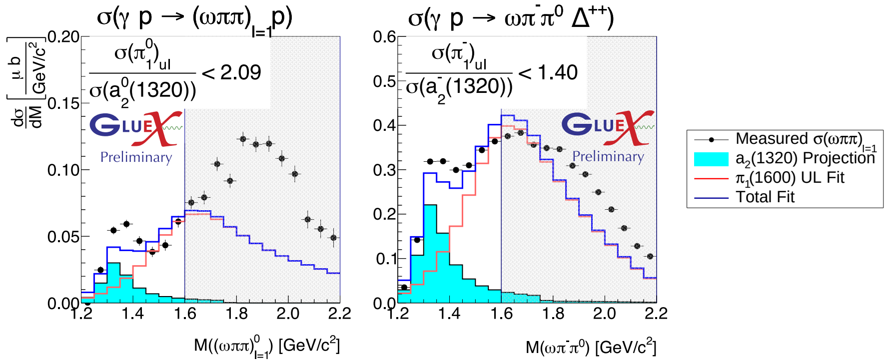


Analysis for $0.1 < -t < 0.5$ GeV^2 and $8 < E_\gamma < 10$ GeV using 28% of GlueX-I data

π_1 is $I = 1$ - isolate $\sigma(\omega\pi\pi)_{I=1}$ using Clebsch-Gordan coefficients:

- Assume no $I = 2$ contributions to $\sigma(\omega\pi\pi)$
- $\sigma((\omega\pi\pi)^0)_{I=1} = \sigma(\omega\pi^+\pi^-) - 2\sigma(\omega\pi^0\pi^0)$
- $\sigma((\omega\pi\pi)^-)_{I=1} = \sigma(\omega\pi^-\pi^0)$

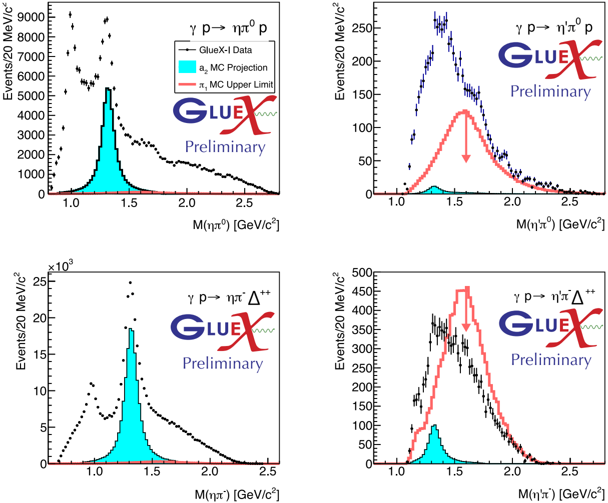
π_1 Upper Limit - Fits to $\sigma(\omega\pi\pi)_{I=1}$



- Know $a_2(1320)$ shape from PDG, π_1 shape from JPAC
- $a_2(1320)$ size fixed to $\sigma_{\eta\pi}(a_2)\mathcal{B}_{PDG}(a_2 \to \omega\pi\pi)$ from $\eta\pi$ PWA
- Fit $I = 1$ cross sections with sum of these shapes
- Fit $M(\omega\pi\pi)_{I=1} < 1.6$ GeV$/c^2$ using $\pi_1(1600)$ (pink) shape
- **Only free parameter in fit is the π_1 normalization**

$\pi_1(1600)$ upper limit is of similar size to the $a_2(1320)$ cross section

π_1 Upper Limit - Projections to $\eta\pi$ and $\eta'\pi$



Do not expect large $\pi_1(1600)$ in $\eta\pi$

$\pi_1(1600)$ could be the dominant contribution in $\eta'\pi^-$

Projections for $0.1 < -t < 0.5$ GeV^2 and $8.2 < E_\gamma < 8.8$ GeV using full GlueX-I data

These projections guide the next steps of the search

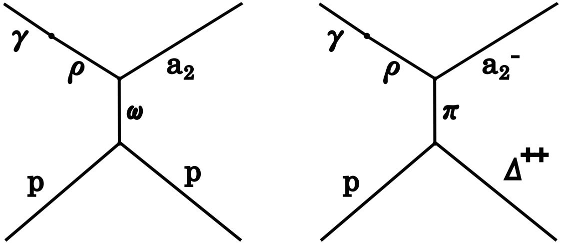
Publication being prepared for this analysis

Partial Wave Analysis of $\eta\pi$ and $\eta'\pi$

Looking for broad overlapping resonances $\Longrightarrow$ need to do PWA
Define naturality: $\eta = P(-1)^J$

- Natural ($\eta = 1$) parity exchange for $J^P = 0^+, 1^-, 2^+, ..$
- Unnatural ($\eta = -1$) parity exchange for $J^P = 0^-, 1^+, 2^-, ..$

Reflectivity is product of exchange and produced meson naturalities



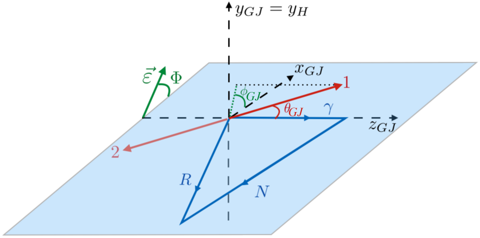
Natural exchange
Positive reflectivity

Unnatural exchange
Negative reflectivity

Definition of Amplitudes

Three angles describe the decay:

- Angle Φ between polarization vector and production plane
- Angles θ_η and ϕ_η in the $\eta\pi$ rest frame



[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

Use Z_ℓ^m amplitudes: $Z_\ell^m(\Omega, \Phi) = Y_\ell^m(\Omega) e^{-i\Phi}$

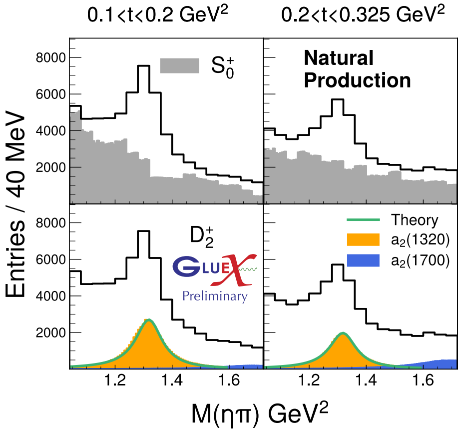
$$I(\Omega, \Phi) = 2\kappa \sum_k \Bigg\{ (1 - P_\gamma) \left| \sum_{\ell,m} [\ell]^{(-)}_{m;k} \mathrm{Re}[Z_\ell^m(\Omega, \Phi)] \right|^2 + (1 - P_\gamma) \left| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Im}[Z_\ell^m(\Omega, \Phi)] \right|^2 + (1 + P_\gamma) \left| \sum_{\ell,m} [\ell]^{(+)}_{m;k}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

Can have $\pm$ reflectivity and $m = -\ell ... \ell$

Semi-Mass Independent PWA on $\eta\pi^0$

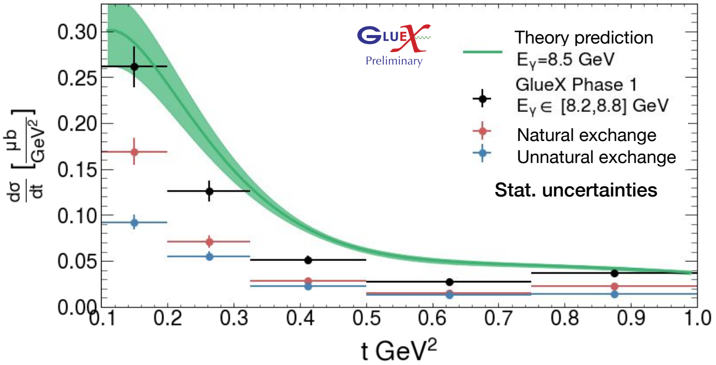
Signal process: $\gamma p \to a_2^0(1320)p$

- Ultimately want mass independent PWA to $\eta\pi$ and $\eta'\pi$
- Mass independent PWA has many parameters
- To stabilize fits, we add in physical constraints: model $a_2(1320)$ and $a_2(1700)$ as Breit-Wigner
- Use these results to measure $\frac{d\sigma(a_2)}{dt}$



Full GlueX-I data for $8.2 < E_\gamma < 8.8$ GeV

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



Theory curve: V.Mathieu et.al. (JPAC) PRD 102, 014003 (2020)

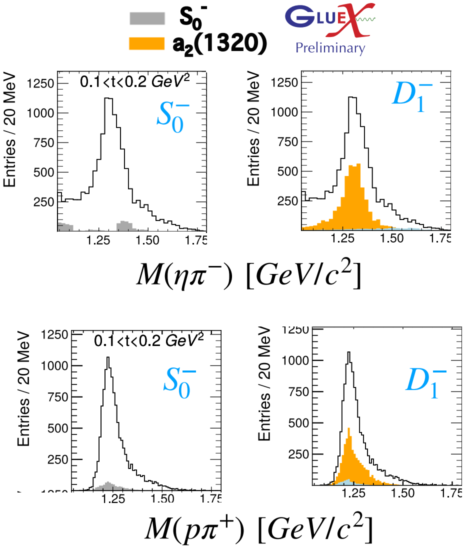
- First separation of natural and unnatural exchanges
  - Comes from polarized photon beam - unique to GlueX
- Theory curve from model fit to unpolarized CLAS data
- $\sigma(a_2(1320))$ measured here can be used as reference for $\eta'\pi$
- Publication being prepared

Semi-mass Independent PWA on $\eta\pi^-$

Process: $\gamma p \rightarrow \eta\pi^-\Delta^{++}$

- Use same method as $\eta\pi^0$
- $a_2(1320)$ appears in D_1^- wave $\Longrightarrow$ pion exchange with direct polarization transfer from γ to a_2

Want to measure $\frac{d\sigma(a_2)}{dt}$

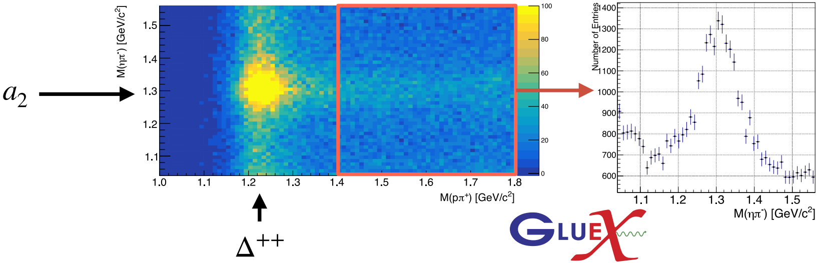


28% of GlueX-I data for $8.2 < E_\gamma < 8.8$ GeV

Semi-mass Independent PWA on $\eta\pi^-$

Complication: background from non-Δ^{++} events at higher $-t$

- Collaborating with JPAC on including the Δ^{++} in amplitudes



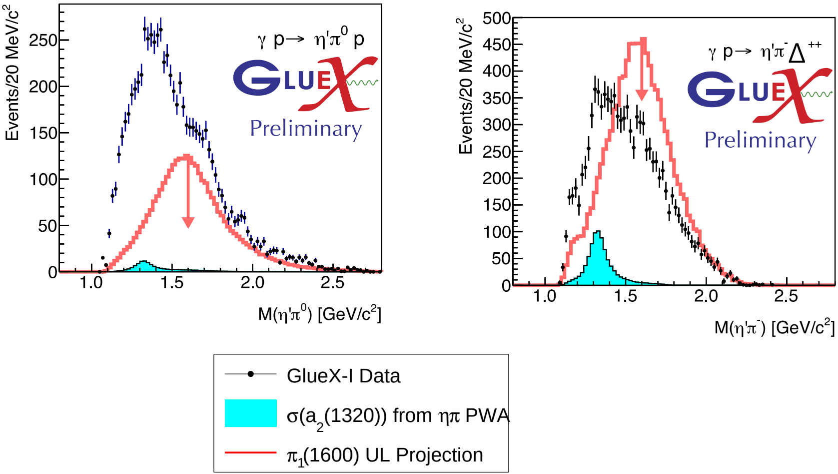
28% of GlueX-I data for $8.2 < E_\gamma < 8.8$ GeV

What we learn about Δ^{++} can be used for $\eta'\pi^-$ analysis

Prospects for $\eta'\pi$

Analyses on $\eta\pi$ and $\eta'\pi$ being performed in parallel

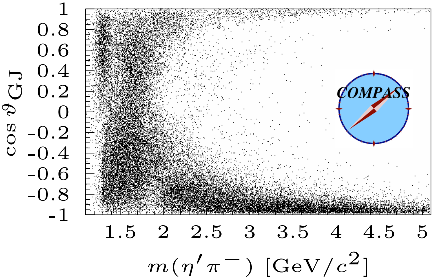
- Upper limit can't exclude π_1 being dominant feature in $\eta'\pi$
- Know $a_2(1320)$ is present - will interfere with π_1 signal

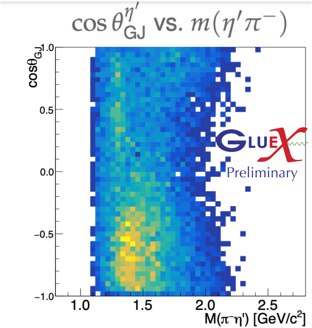


Prospects for $\eta'\pi$

COMPASS sees forward/backward asymmetry in $\cos\theta_{GJ}$ for $\eta'\pi^-$

- Caused by interference between even and odd (exotic) waves





- GlueX data has similar forward/backward asymmetry
- Caveats: no acceptance correction, double Regge and baryonic contributions need to be understood

Exploring moment analysis to probe possible exotic signal

Summary

- GlueX provides a unique place to look for hybrid mesons
  - Beam polarization gives info on production mechanisms
- We set a new upper limit on π_1 photoproduction cross sections
  - $\eta'\pi$ final states have largest discovery potential
  - Publication being prepared
- $\eta\pi$ PWA is being used to extract $\sigma(a_2(1320))$
  - Agrees well with theory predictions
  - Can be used as reference for $\eta'\pi$ analysis
  - Publication being prepared
- $\eta'\pi$ is most sensitive channel to $\pi_1(1600)$ at GlueX
  - PWA framework from $\eta\pi$ analysis can be used

Acknowledgements: gluex.org/thanks

Thoughts on π_1 Sensitivity

Question: Why do we expect to find π_1 in $\eta'\pi$ more easily than $b_1\pi$?

	$\pi_1 \to b_1\pi$	$\pi_1 \to \eta'\pi$
$\mathcal{B}(\pi_1)$	$> 70\%$	$0 - 8\%$
Widths	$\Gamma(b_1) = 142$ MeV	$\Gamma(\eta') = 0.188$ MeV
Partial Wave	S-wave	P-wave
Self-Interference*	Yes	No

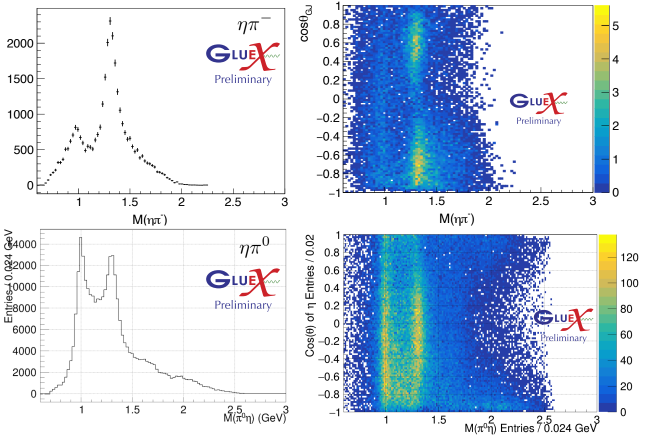
* $\pi_1 \to b_1\pi$ has destructive self-interference:

- $\pi_1^0 \to b_1^+\pi^-$ destructively interferes with $\pi_1^0 \to b_1^-\pi^+$
- $\pi_1^- \to b_1^0\pi^-$ destructively interferes with $\pi_1^- \to b_1^-\pi^0$
- Changes size and shape of π_1 signal

For $\eta'\pi$, expect $a_2(1320)$ signal and $\pi_1(1600)$
In this case, $P-$wave and $D-$wave interfere $\Longrightarrow$ forward/backward asymmetry in $\cos\theta$

Production of $a_2(1320)$ in $\eta\pi$

Clear signals for $a_0(980)$ and $a_2(1320)$ in $\eta\pi$



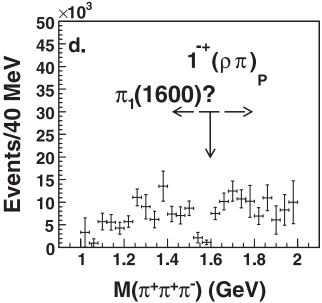
Full GlueX-I data for $8.2 < E_\gamma < 8.8$ GeV and $0.1 < -t < 0.3$ GeV^2

- Angular distributions look different for $a_2^0(1320)$ and $a_2^-(1320)$
- Different exchange mechanisms populate different spin projections

CLAS $\pi_1 \to 3\pi$ Upper Limit

CLAS sets an upper limit of $\sigma(\gamma p \to \pi_1^+ n) < 13.5$ nb.

- Lower photon beam energy: $4.8 < E_\gamma < 5.4$ GeV
- Different reaction - produced against a neutron

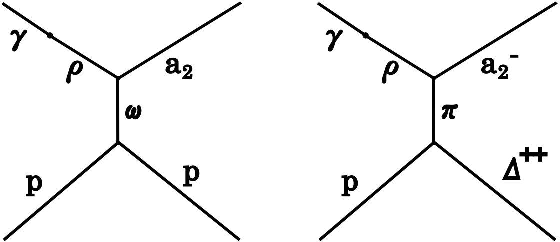


- Upper limit is really on $\sigma(\gamma p \to \pi_1^+ n)\mathcal{B}(\pi_1^+ \to \pi^+\pi^-\pi^+)$
- They used a model dependent central value for $\mathcal{B}(\pi_1)$
- Upper limit needs to include systematic uncertainty in $\mathcal{B}(\pi_1^+)$
- LQCD allowed values are $0 < \mathcal{B}(\pi_1 \to 3\pi) < 12.6\%$.

Reflectivity

Define naturality: $\eta = P(-1)^J$

- Reflectivity is product of exchange particle and produced resonance nautralities
- Nautrality of a_2 is $+1$



Natural exchange
Positive reflectivity

Unnatural exchange
Negative reflectivity

- Amplitudes are eigenstates of reflectivity - allows us to incorporate beam polarization