The Search for Hybrid Mesons at GlueX

Will Imoehl
Carnegie Mellon University
on behalf of the GlueX collaboration

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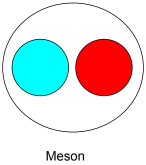
The Quark Model

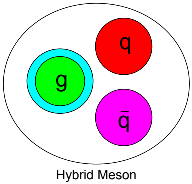
Want to know which types of hadrons exist in QCD

Conventional light mesons are $q\bar{q}$ states

- Allowed J^{PC} for conventional light mesons ($n = 0, 1, 2, ...$):

J^{PC}	$(2n)^{-+}$	$(2n+1)^{+-}$	$(n+1)^{--}$	n^{++}
Minimal Quark Content				
$u\bar{d}$, $u\bar{u}$-$d\bar{d}$, $d\bar{u}$ ($I = 1$)	π	b	ρ	a
$d\bar{d} + u\bar{u}$ and/or $s\bar{s}$	η, η'	h, h'	ω, ϕ	f, f'

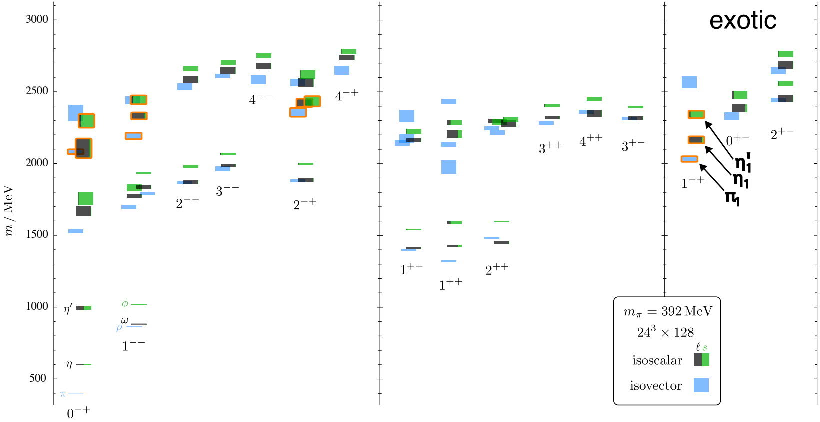




Hybrid mesons have gluonic excitations

- Hybrids can mix with conventional mesons
- Some hybrids have "exotic" J^{PC} not allowed for $q\bar{q}$ mesons

Lattice QCD Spectrum

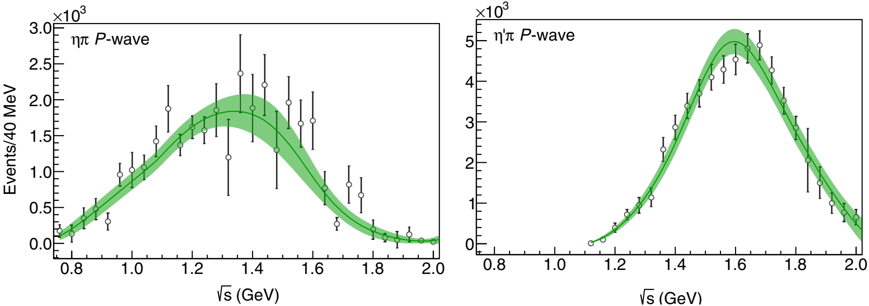


- Lightest hybrid meson predicted to be $I = 1$ $J^{PC} = 1^{-+}$ state
  - Likely the $\pi_1(1600)$, seen by multiple experiments
- BESIII observes $\eta_1(1855)$, candidate for either η_1 or η'_1

[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 $\eta'\pi$
- Joint Physics Analysis Center (JPAC) analysis of the COMPASS 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)

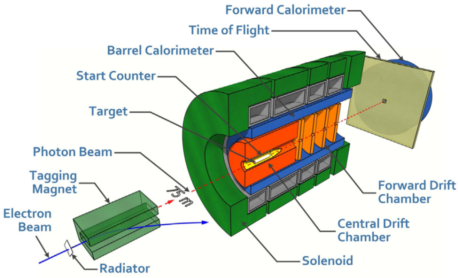
The GlueX Experiment

Photoproduction experiment located at Jefferson Lab

- Photoproduction has been predicted to copiously produce hybrid mesons in some models
- GlueX uses polarized photon beam - allows us to differentiate production mechanisms

Steps to studying the hybrid meson spectrum:

1. Demonstrate photoproduction produces hybrid mesons by confirming COMPASS result
2. Search for undiscovered hybrid mesons

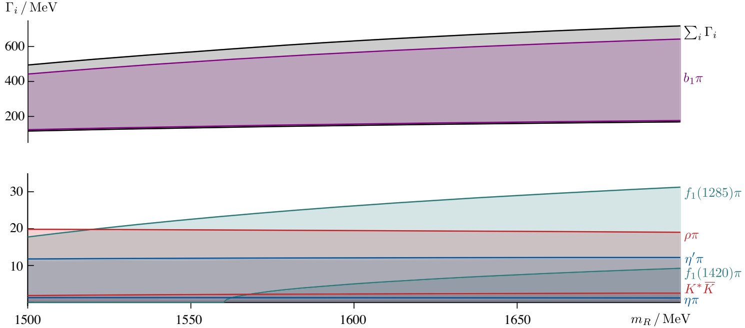


π_1 Branching Fractions from Lattice QCD

- Lattice QCD provides predictions for π_1 branching fractions

PRD **103** 054502 (2021)

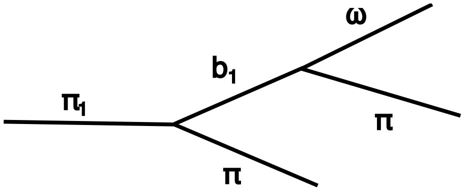
Decay	Width (MeV)	Branching Fraction
$\eta\pi$	$0 \to 1$	$0 \to 0.7\%$
$\eta'\pi$	$0 \to 12$	$0 \to 7.9\%$
$b_1\pi$	$139 \to 529$	$69.5 \to 100\%$
All others	$0 \to 48$	$0 \to 25.7\%$
Total	$139 \to 590$	-



GlueX Search Strategy for $\pi_1(1600)$

Two main goals:

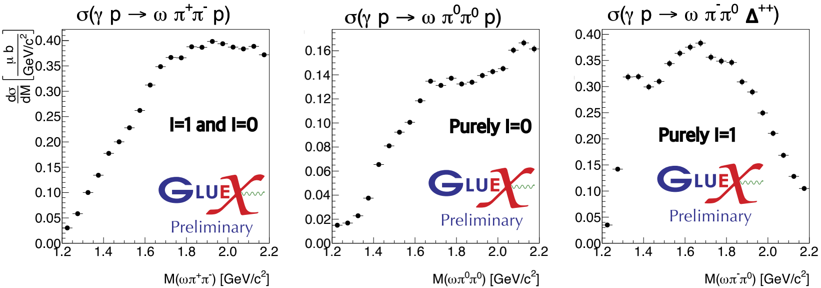
1. Set upper limit on photoproduction cross section of $\pi_1(1600)$
   - Never done before - use recent lattice calculations
   - Can be used to test discovery potential in different final states
   - Expect signals in $\pi_1^0 \to \omega\pi^+\pi^-$ and $\pi_1^- \to \omega\pi^-\pi^0$



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 $\pi_1(1600)$

$\pi_1(1600) \to \omega\pi\pi$ Search

- Measure $d\sigma/dM$ in 50 MeV$/c^2$ bins of $M(\omega\pi\pi)$



No obvious $\pi_1(1600)$ signal - set upper limit

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

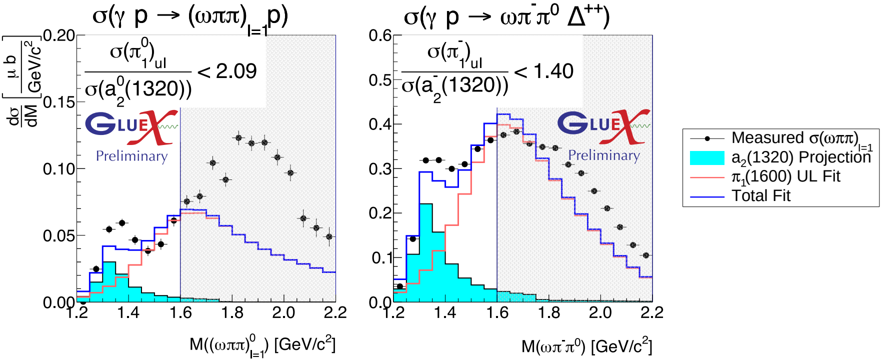
- Assume no $I = 2$ contributions to $\sigma(\omega\pi\pi)$
- $\sigma((\omega\pi\pi)^0)_{I=1} = \sigma(\omega\pi^+\pi^-) - 2\sigma(\omega\pi^0\pi^0)$
- $\sigma((\omega\pi\pi)^-)_{I=1} = \sigma(\omega\pi^-\pi^0)$

Know $a_2(1320)$ shape from PDG, π_1 shape from JPAC

Fit $I = 1$ cross sections with sum of these shapes

π_1 Upper Limit - Upper Limit Results

Measure ratio $\frac{\sigma_{ul}(\pi_1)}{\sigma(a_2(1320))}$

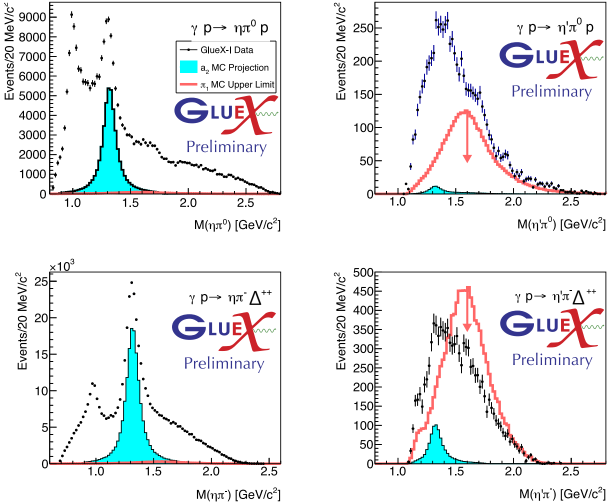


Analysis for $0.1 < -t < 0.5$ GeV^2 and $8 < E_\gamma < 10$ GeV using 28% of GlueX-I data

- $a_2(1320)$ size fixed to $\sigma_{\eta\pi}(a_2)\mathcal{B}_{PDG}(a_2 \to \omega\pi\pi)$
- 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 $\eta'\pi^-$

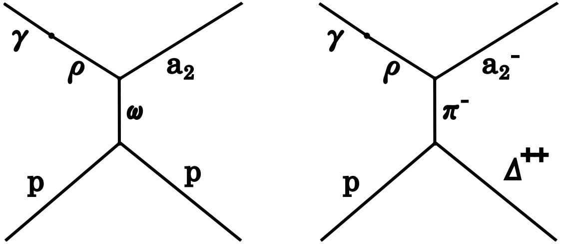
Projections for $0.1 < -t < 0.5$ GeV^2 and $8.2 < E_\gamma < 8.8$ GeV using full GlueX-I data

First limit on size of hybrid photoproduction cross sections

These projections guide the next steps of the search

Partial Wave Analysis of $\eta\pi$

- Beam polarization allows us to separate production mechanisms
- Natural parity exchange for $J^P = 0^+, 1^-, 2^+, ..$
- Unnatural parity exchange for $J^P = 0^-, 1^+, 2^-, ..$



Natural exchange

Unnatural exchange

- $\eta\pi$ is system of two pseudoscalars ($J^{PC} = 0^{-+}$)

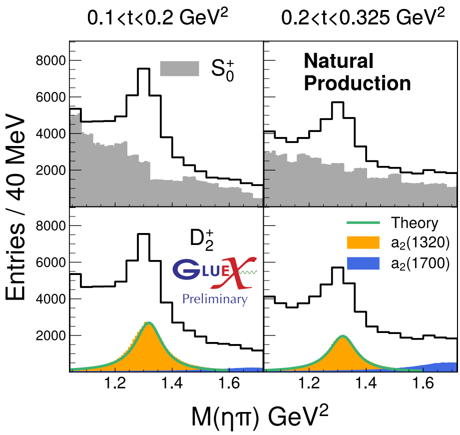
	$S-$wave ($\ell = 0$)	$P-$wave ($\ell = 1$)	$D-$wave ($\ell = 2$)
J^{PC}	0^{++}	1^{-+} (exotic)	2^{++}

Amplitudes function of production angle Φ and decay angles (ϕ, θ)

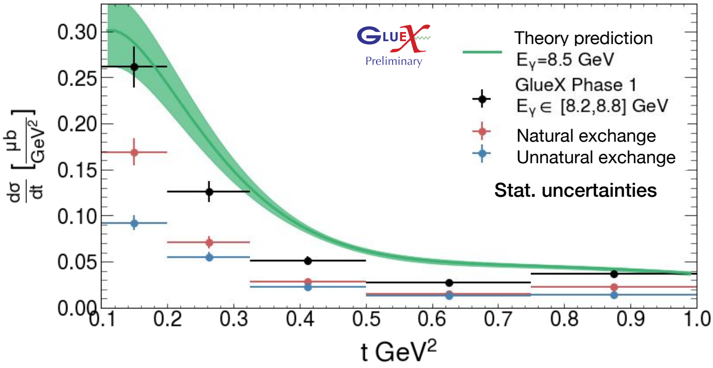
Semi-Mass Independent PWA on $\eta\pi^0$

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

- 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 $\frac{d\sigma(a_2)}{dt}$



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

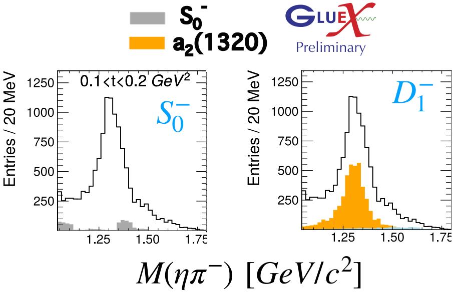


- First separation of natural and unnatural exchanges
  - Comes from polarized photon beam - unique to GlueX
- $\sigma(a_2(1320))$ measured here can be used as reference for $\eta'\pi$
- Results agree reasonably well with theory prediction
- Publication being prepared

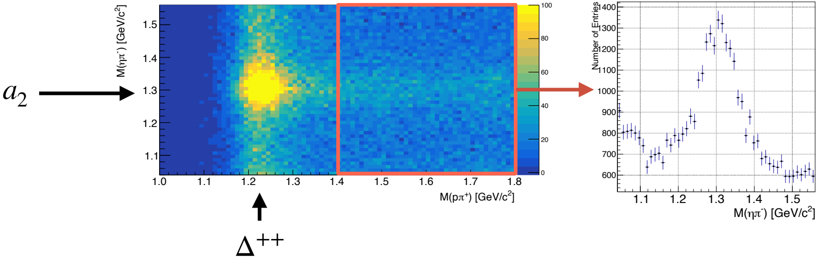
Semi-mass Independent PWA on $\eta\pi^-$

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

- 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



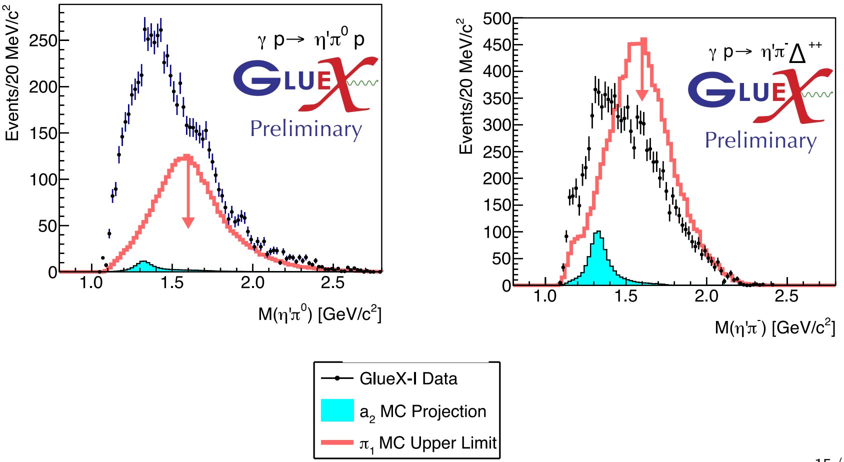
Complication: background from $\gamma p \to (a_2^- \pi^+) p \to \pi^+\pi^-\eta p$



Prospects for $\eta'\pi$

Analysis on $\eta'\pi$ being performed in parallel

- Expect best sensitivity to $\pi_1(1600)$ in $\eta'\pi$
- Less pronounced $a_2(1320)$ $\implies$ use $\eta\pi$ measurement as reference



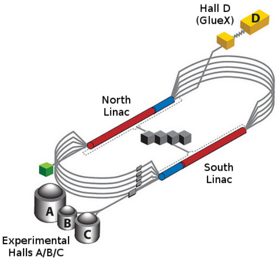
Summary

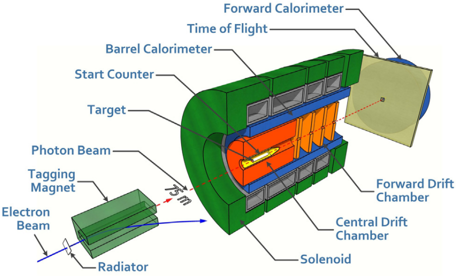
- GlueX provides a unique place to look for hybrid mesons
  - Beam polarization gives info on production mechanisms
  - Some models predict hybrids copiously produced in photoproduction
- We set first upper limit on π_1 photoproduction cross sections
  - $\eta'\pi$ final states have largest discovery potential
- $\eta\pi$ 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

Hall D at Jefferson Lab

- Hall D is one of four experimental halls at Jefferson Lab
- CEBAF accelerates electrons up to 12 GeV
- Electrons impinge on diamond wafer, creating linearly polarized photons via coherent bremsstrahlung
- Photon beam incident on liquid hydrogen target

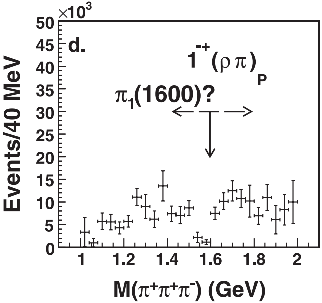




CLAS $\pi_1 \to 3\pi$ Upper Limit

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 $0 < \mathcal{B}(\pi_1 \to 3\pi) < 12.6\%$.