Search for Hybrid Mesons at GlueX

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on behalf of the GlueX collaboration

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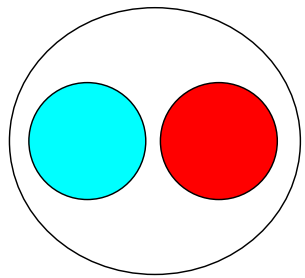
Hybrid Mesons

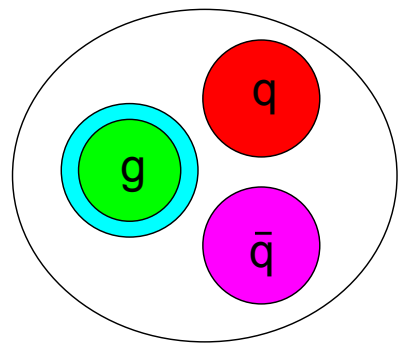
Goal: understand which types of hadrons are allowed in QCD

- Simplest bound states are mesons ($q\bar{q}$) and baryons (qqq)
- Tetraquark, pentaquark, glueballs, hybrid mesons also allowed

Our focus is on hybrid mesons - $q\bar{q}$ states with gluonic excitations



Meson



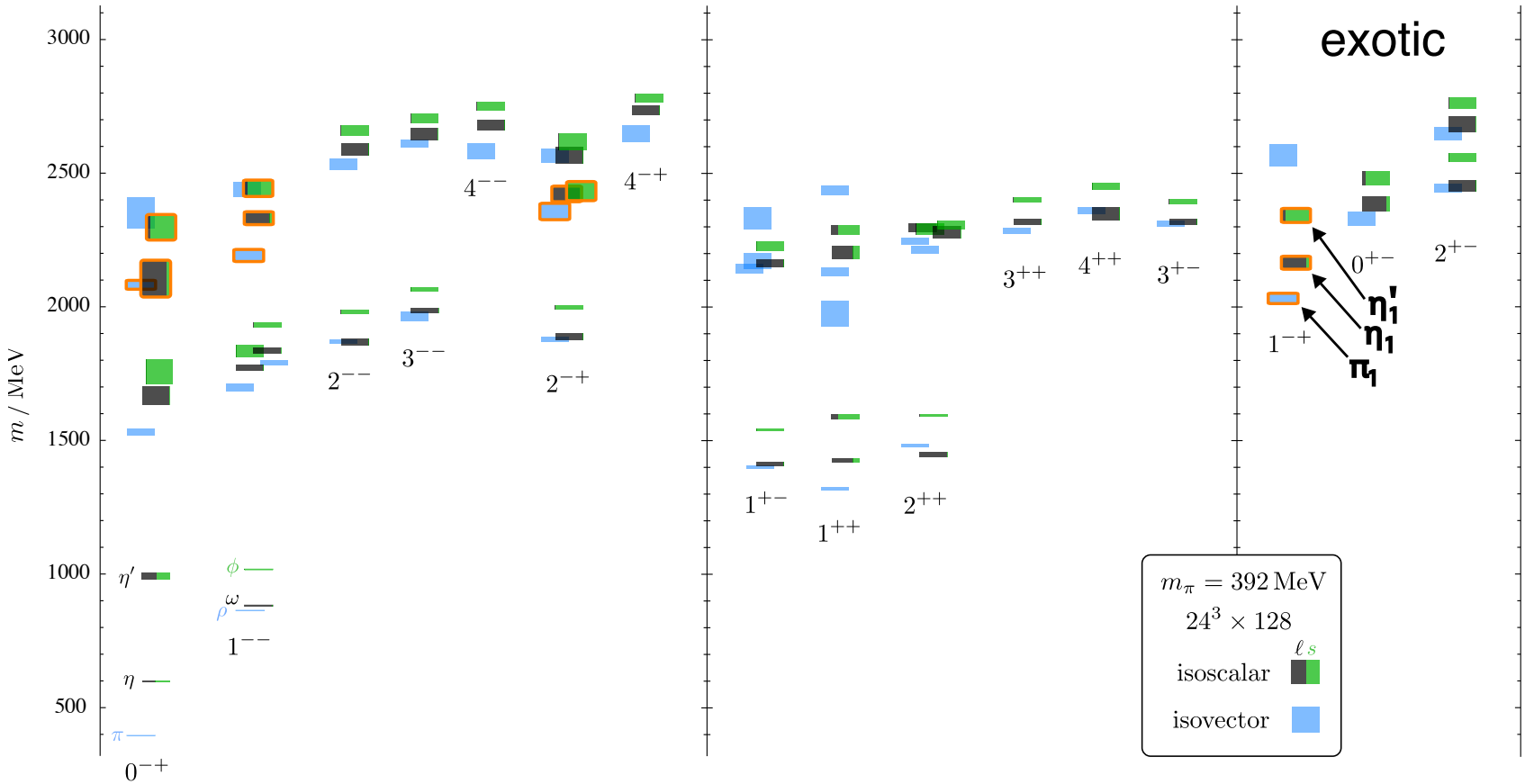
Hybrid Meson

Gluon directly contributes to properties of hybrid mesons

$\Longrightarrow$ spectrum tells us about the role of the gluon in QCD

- Some predicted to have J^{PC} allowed for conventional mesons
  - Can mix with conventional states - hard to distinguish
- Others predicted to have J^{PC} forbidden for $q\bar{q}$ states
  - Clear experimental signature for exotic states

Lattice QCD Spectrum



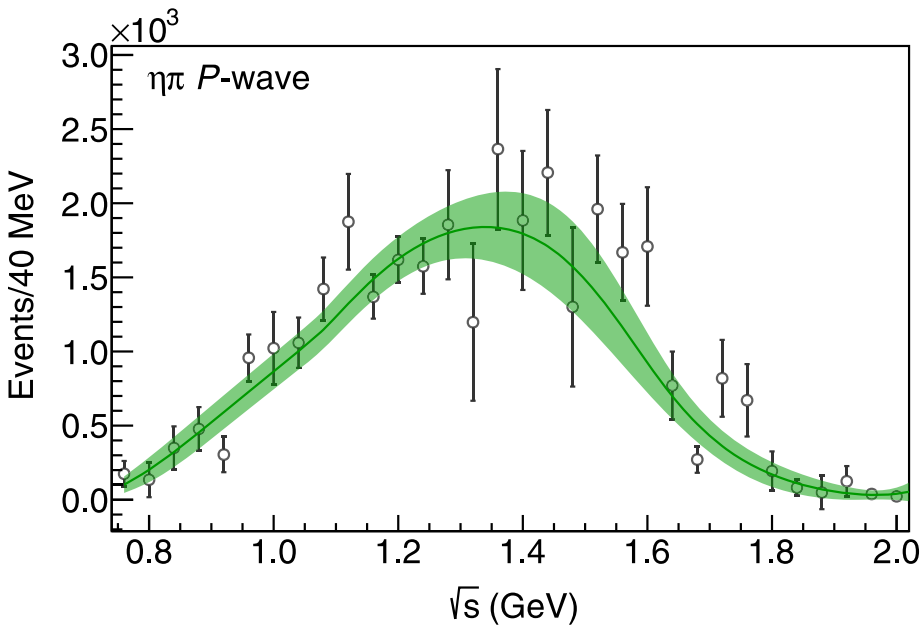
- Lightest hybrid meson predicted to be $I = 1$ $J^{PC} = 1^{-+}$ state
  - Likely the $\pi_1(1600)$, seen by multiple experiments
- BESIII observes $\eta_1(1855)$, candidate for either η_1 or η_1'

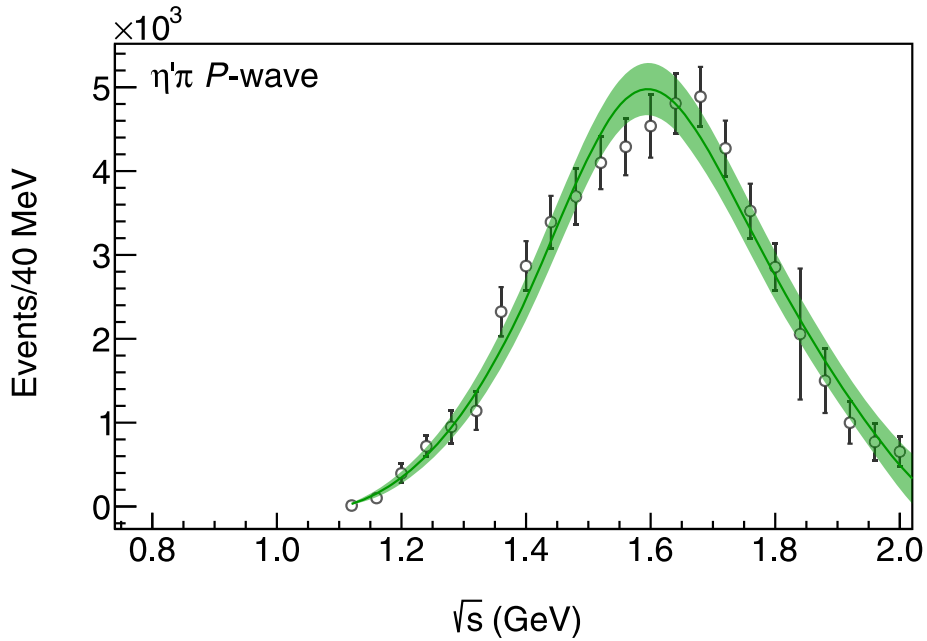
[PRD **88** 094505(2013)]

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
- 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)

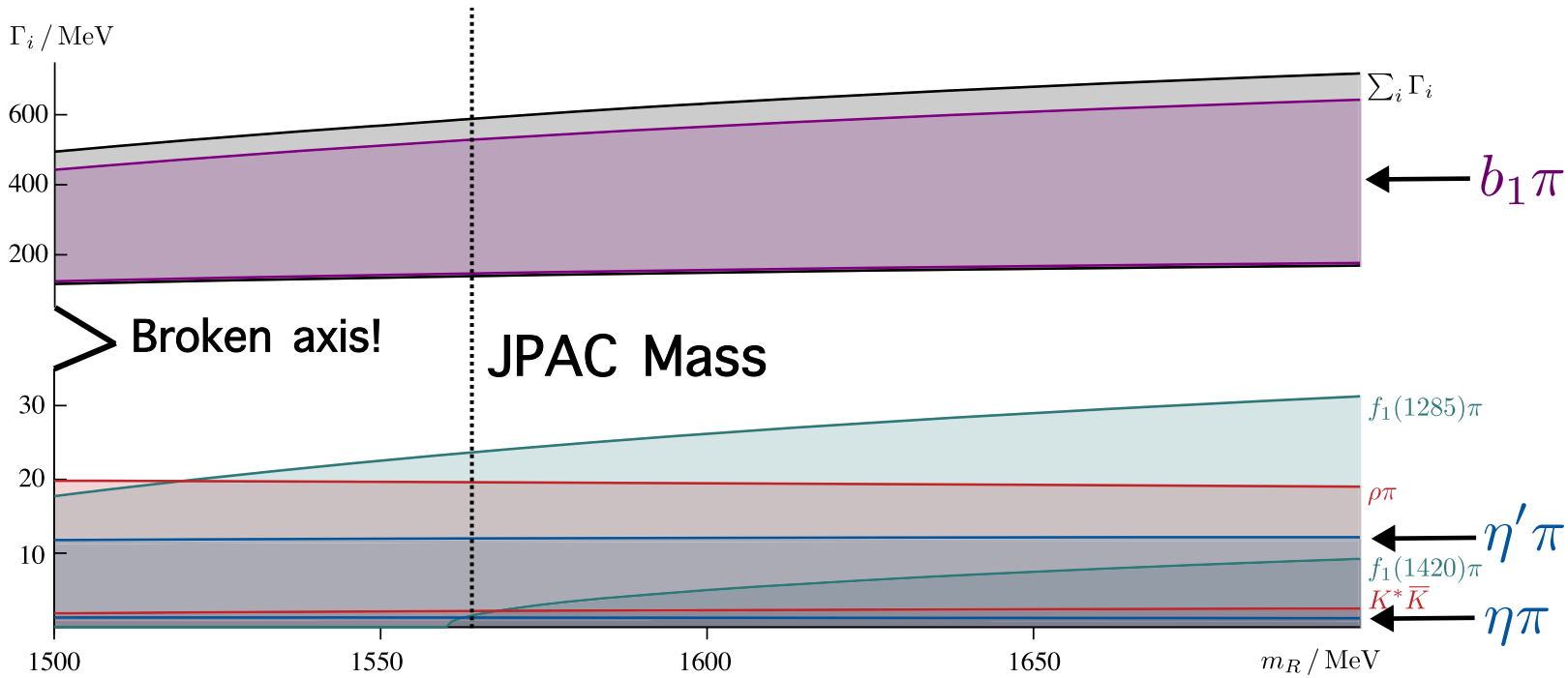
Data: C. Adolph *et al.* (COMPASS) PLB **740** 303-311 (2015)

π_1 Branching Fractions from Lattice QCD

- Lattice QCD predicts widths for π_1 decays

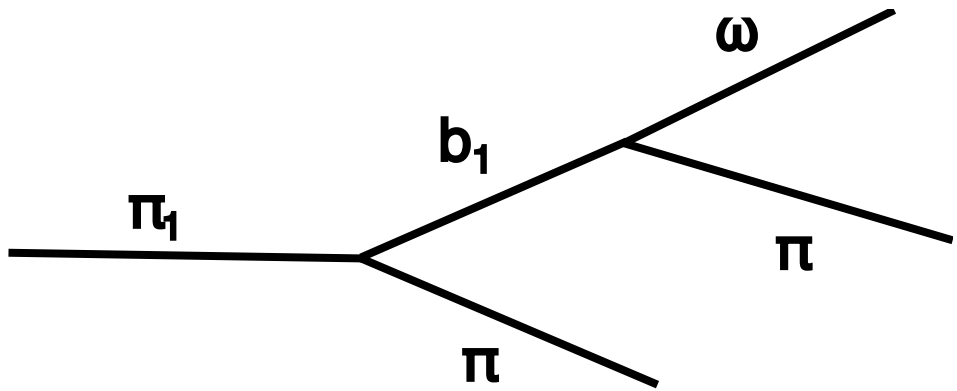
PRD **103** 054502 (2021)

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 Hybrid Meson Search Strategy

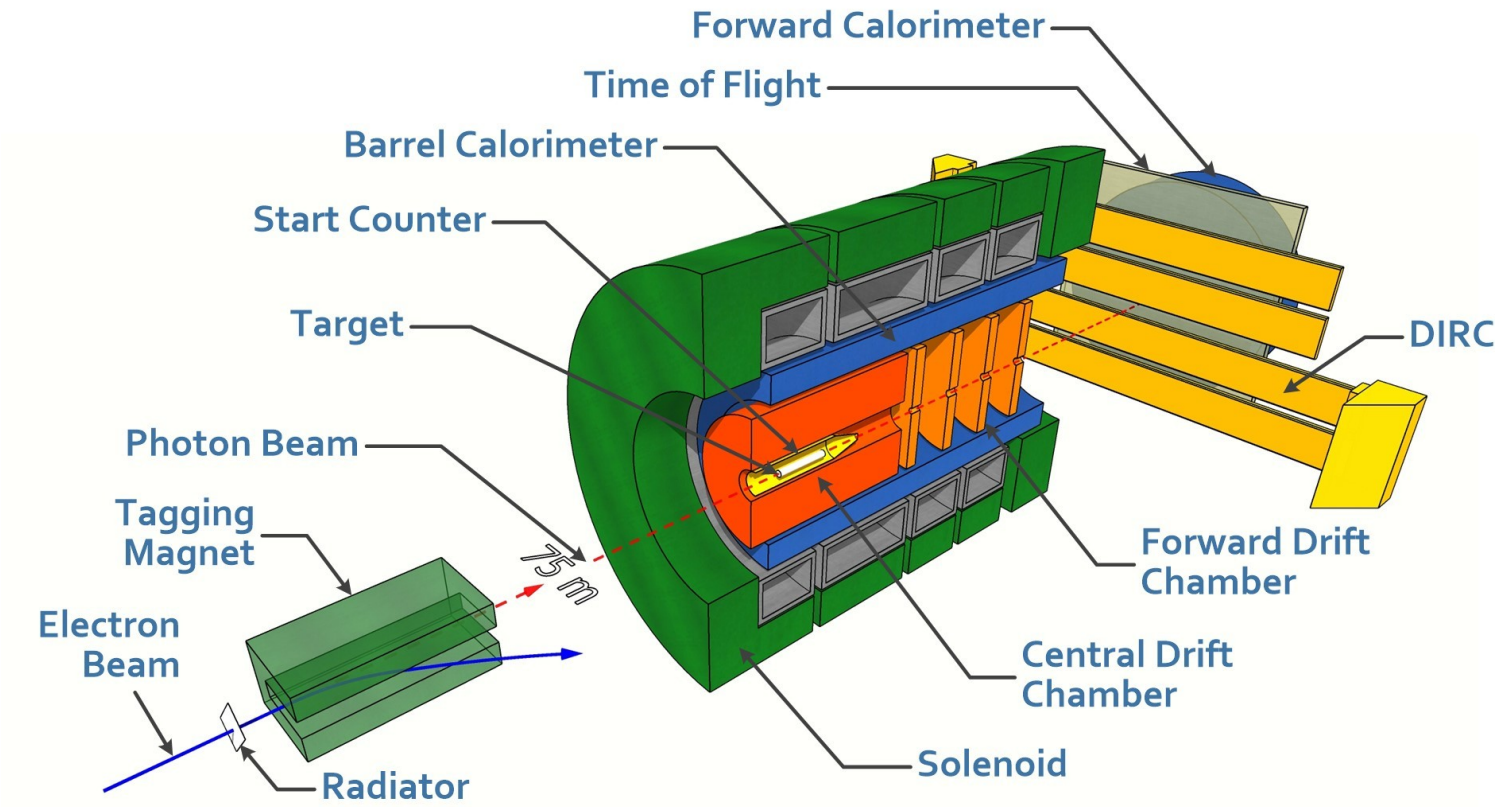
1. Set upper limit on photoproduction cross section of $\pi_1(1600)$
   - First limit using recent lattice calculations
   - Can be used to test discovery potential in different final states
   - Expect signals in $\pi_1^0 \to \omega\pi^+\pi^-$ and $\pi_1^- \to \omega\pi^-\pi^0$



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

The GlueX Experiment

Linearly polarized photon beam incident on liquid hydrogen target

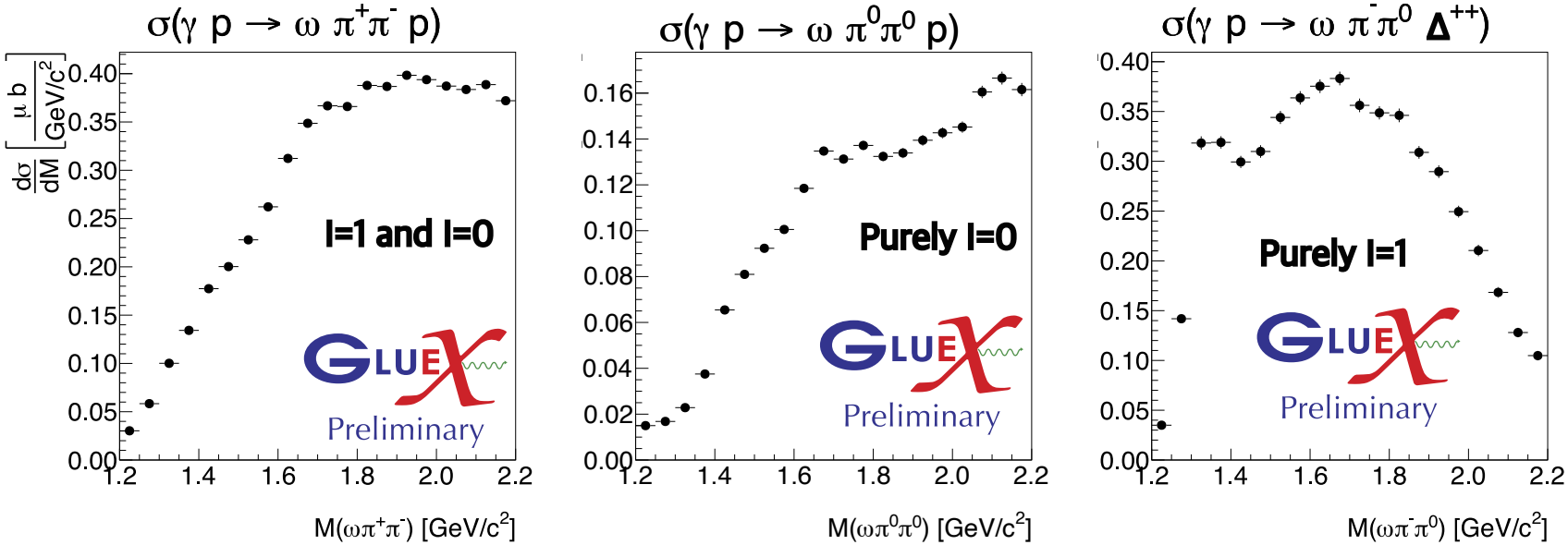


Nearly hermetic detector can detect charged and neutral particles
GlueX-I data: completed in 2018, 250 billion events

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 bins of $M(\omega\pi\pi)$

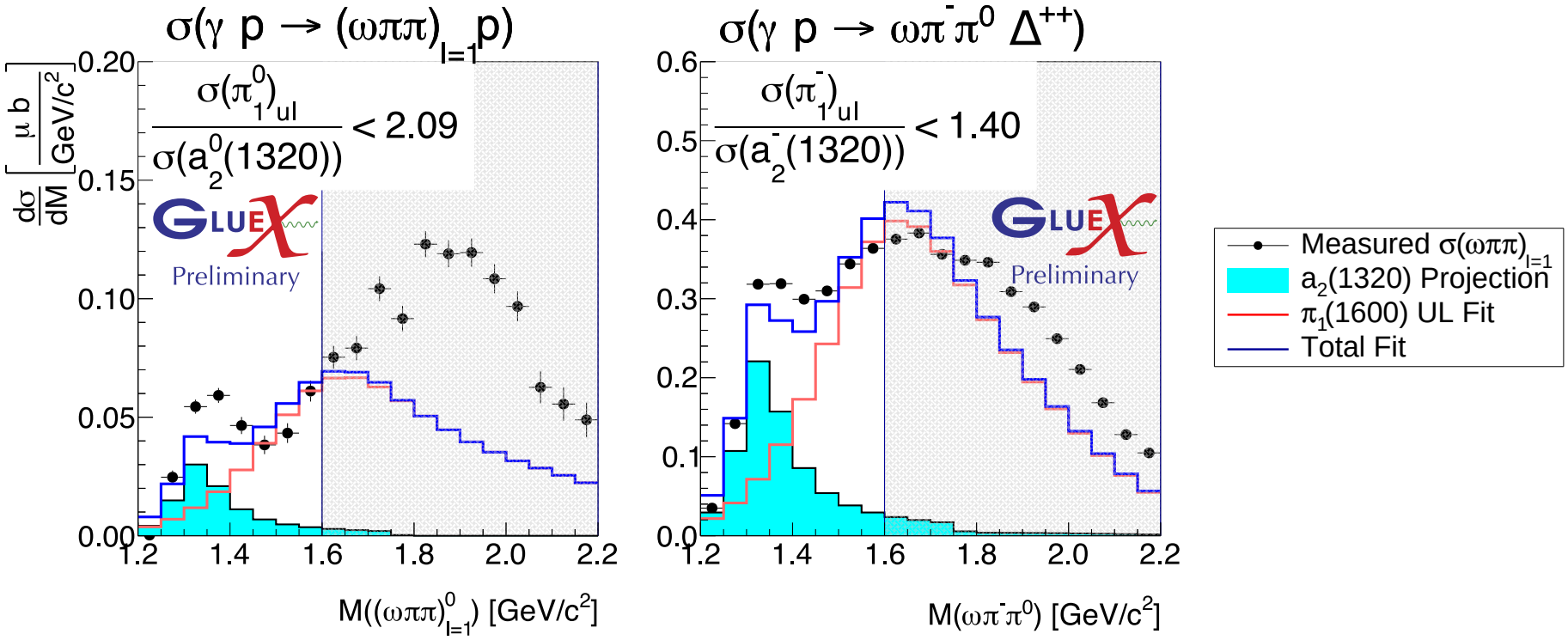


Analysis for $0.1 < -t < 0.5$ GeV^2 and $8 < E_\gamma < 10$ GeV using 28% of GlueX-I data

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

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

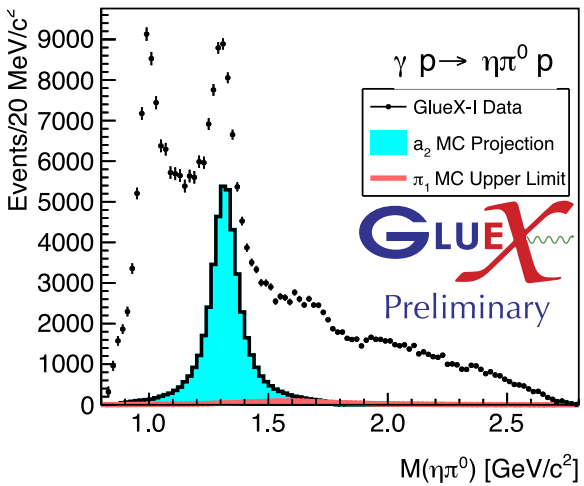
π_1 Upper Limit - Fits to $\sigma(\omega\pi\pi)_{I=1}$

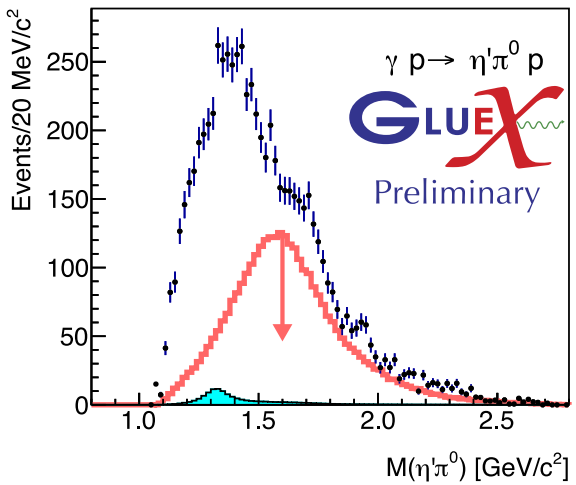


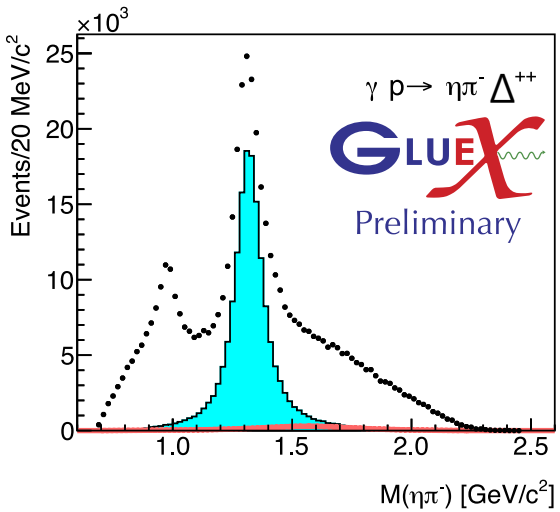
- Know $a_2(1320)$ shape from PDG, π_1 shape from JPAC
- $a_2(1320)$ size fixed to $\sigma_{\eta\pi}(a_2)\mathcal{B}_{PDG}(a_2 \to \omega\pi\pi)$ from $\eta\pi$ PWA
- Fit assuming $a_2(1320)$ and $\pi_1(1600)$ saturate $\sigma(\omega\pi\pi)_{I=1}$
- Fit $M(\omega\pi\pi)_{I=1} < 1.6$ GeV/c^2 using $\pi_1(1600)$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

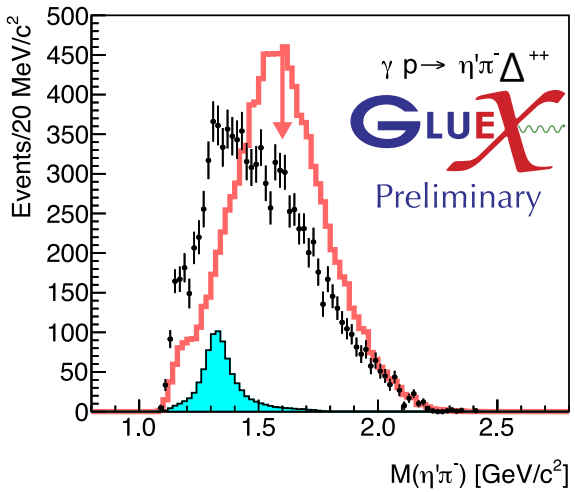
$\pi_1(1600)$ upper limit is of similar size to the $a_2(1320)$ cross section

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 $\eta'\pi^-$

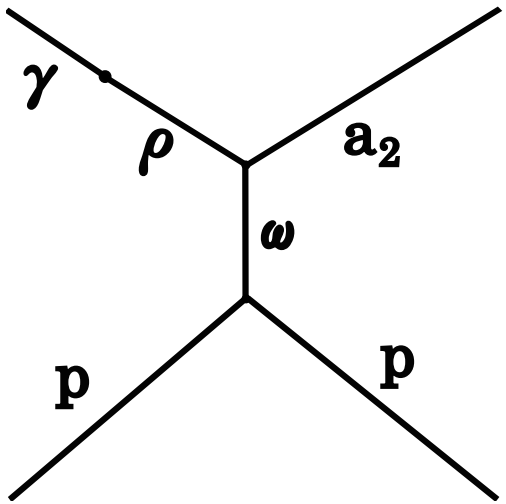
Projections for $0.1 < -t < 0.5$ GeV^2 and $8.2 < E_\gamma < 8.8$ GeV using full GlueX-I data

These projections guide the next steps of the search

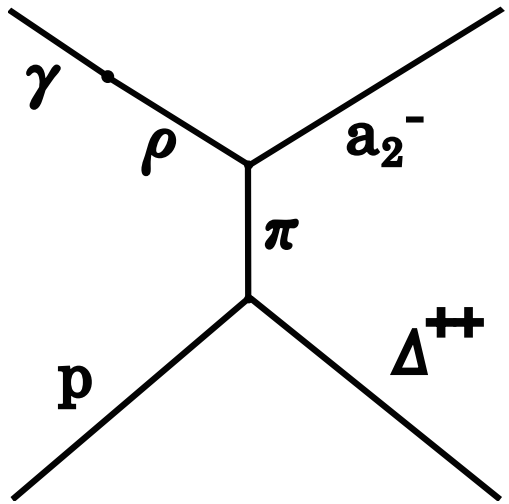
Publication being prepared for this analysis

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

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



Natural exchange



Unnatural exchange

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

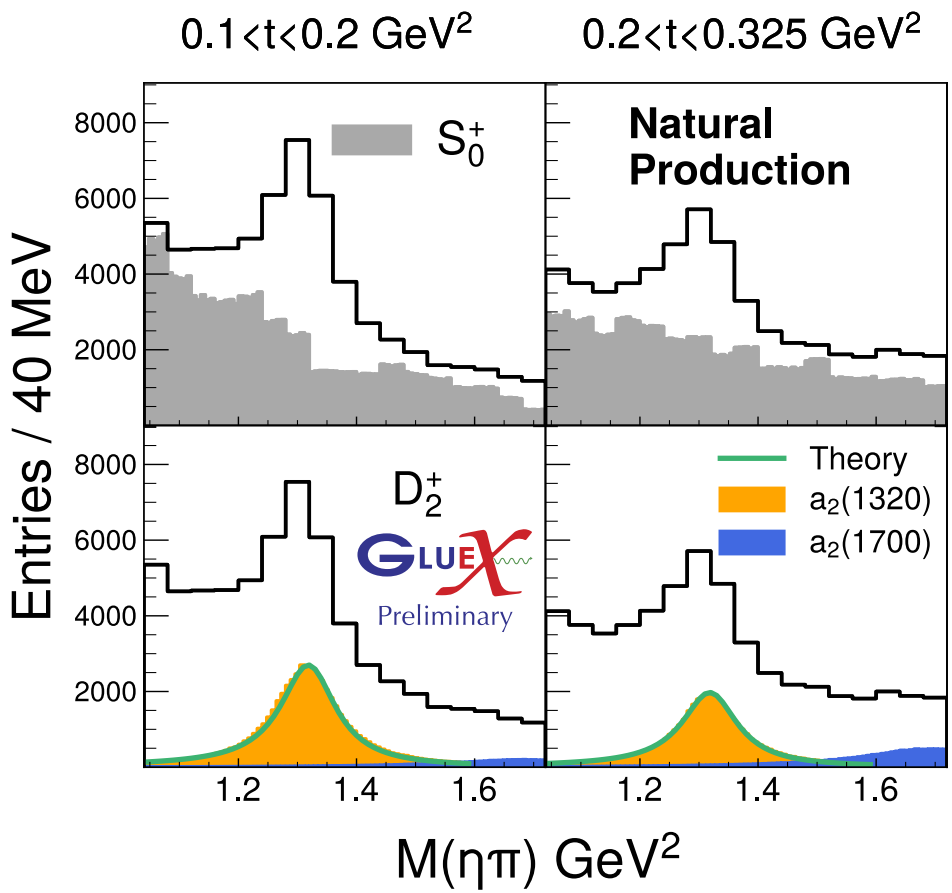
	$S-$wave ($\ell = 0$)	$P-$wave ($\ell = 1$)	$D-$wave ($\ell = 2$)
J^{PC}	0^{++}	1^{-+}	2^{++}

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

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

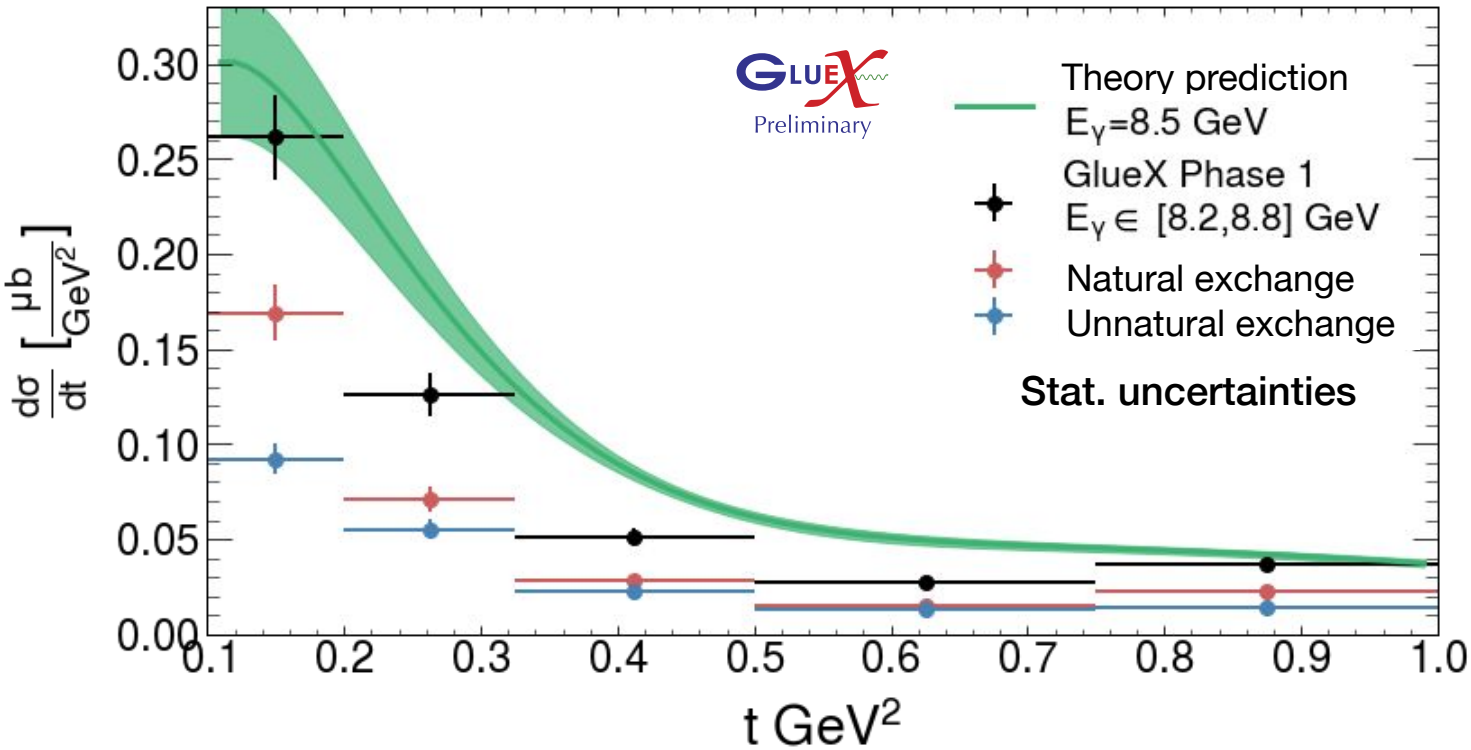
Signal process: $\gamma p \to \eta\pi^0 p$

- 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)

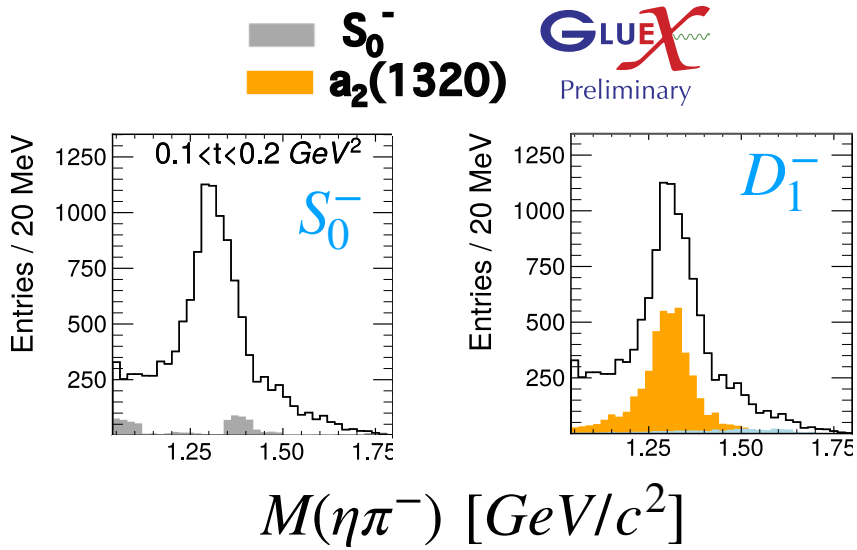
- First separation of natural and unnatural exchanges
  - Comes from polarized photon beam - unique to GlueX
- Theory curve from model fit to unpolarized CLAS data
- $\sigma(a_2(1320))$ measured here can be used as reference for $\eta'\pi$
- Publication being prepared

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

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

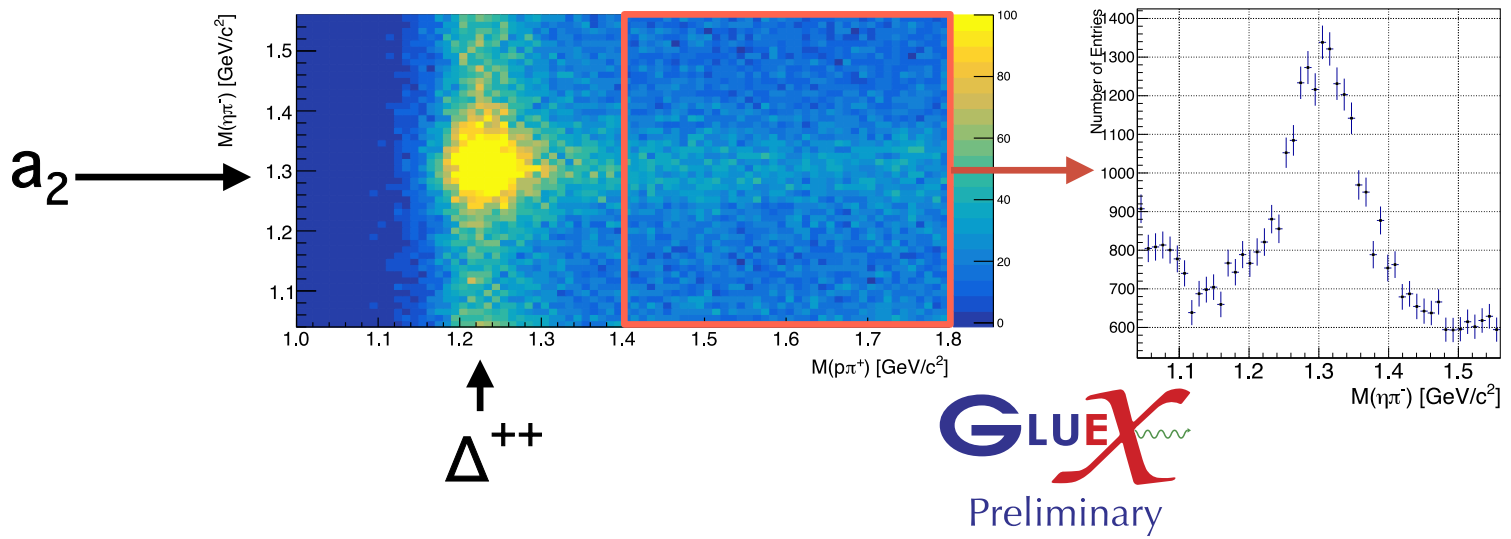
- Use same method as $\eta\pi^0$
- $a_2(1320)$ appears in D_1^- wave $\implies$ pion exchange with direct polarization transfer from γ to a_2

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



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

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

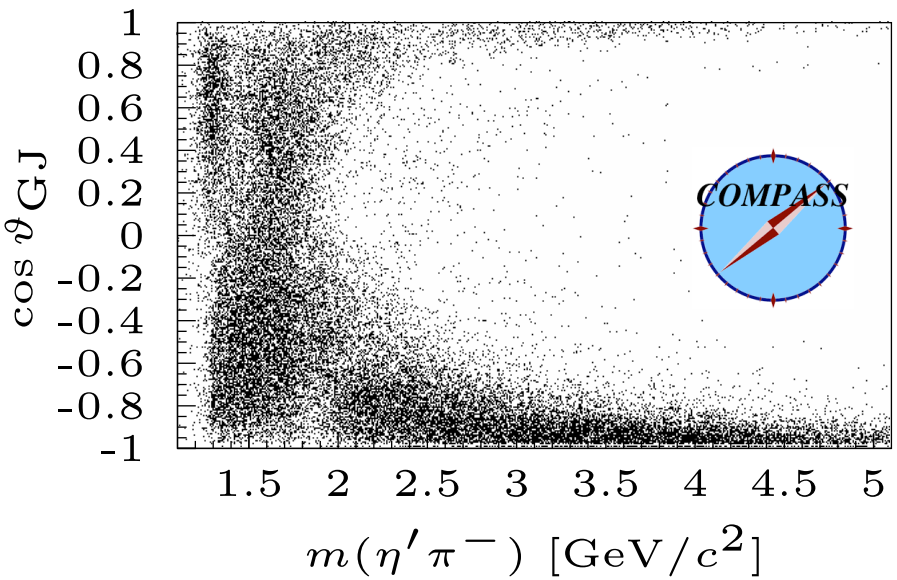


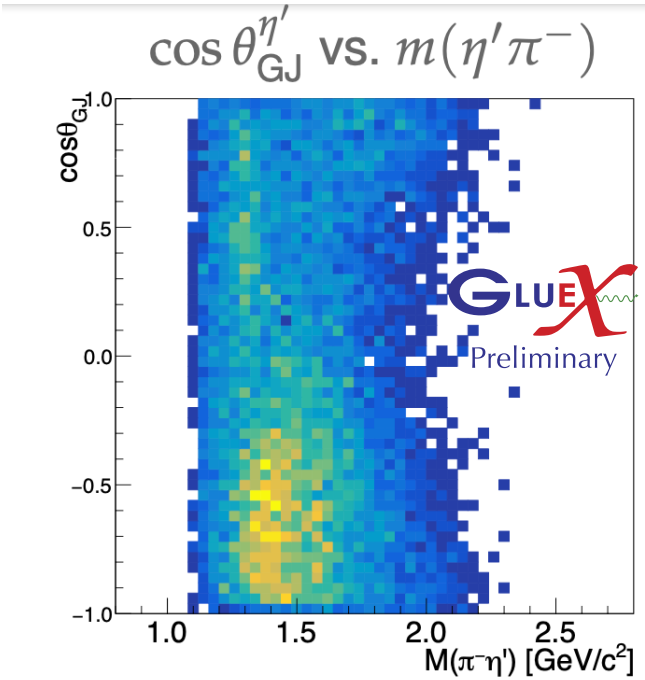
Prospects for $\eta'\pi$

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

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

PLB 740, 303-311 (2015)





- 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

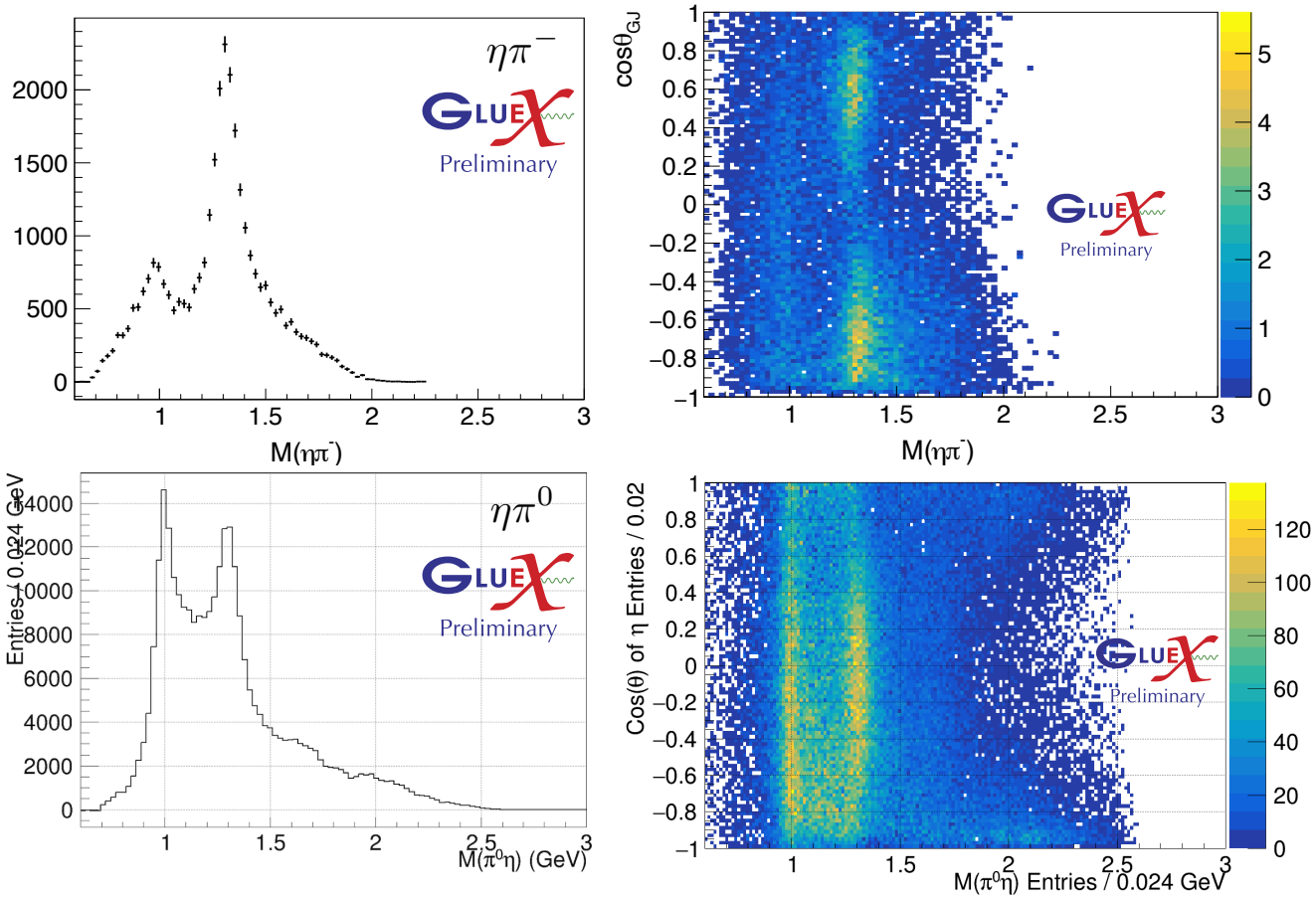
Summary

- 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 for $\eta\pi^0$
- $\eta'\pi$ is most sensitive channel to $\pi_1(1600)$ at GlueX
  - Working on moment analysis to probe potential exotic signal

Acknowledgements: gluex.org/thanks

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

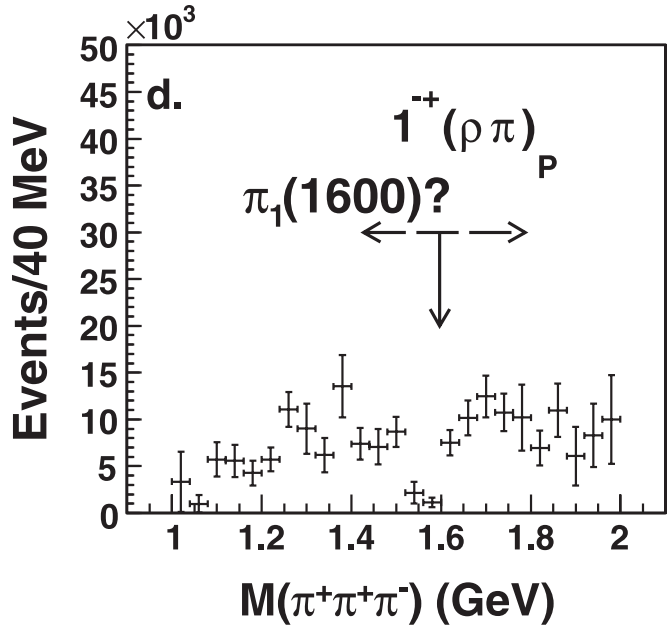
- Angular distributions look different for $a_2^0(1320)$ and $a_2^-(1320)$
- Different exchange mechanisms populate different spin projections

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

PRL 102, 102002 (2009)

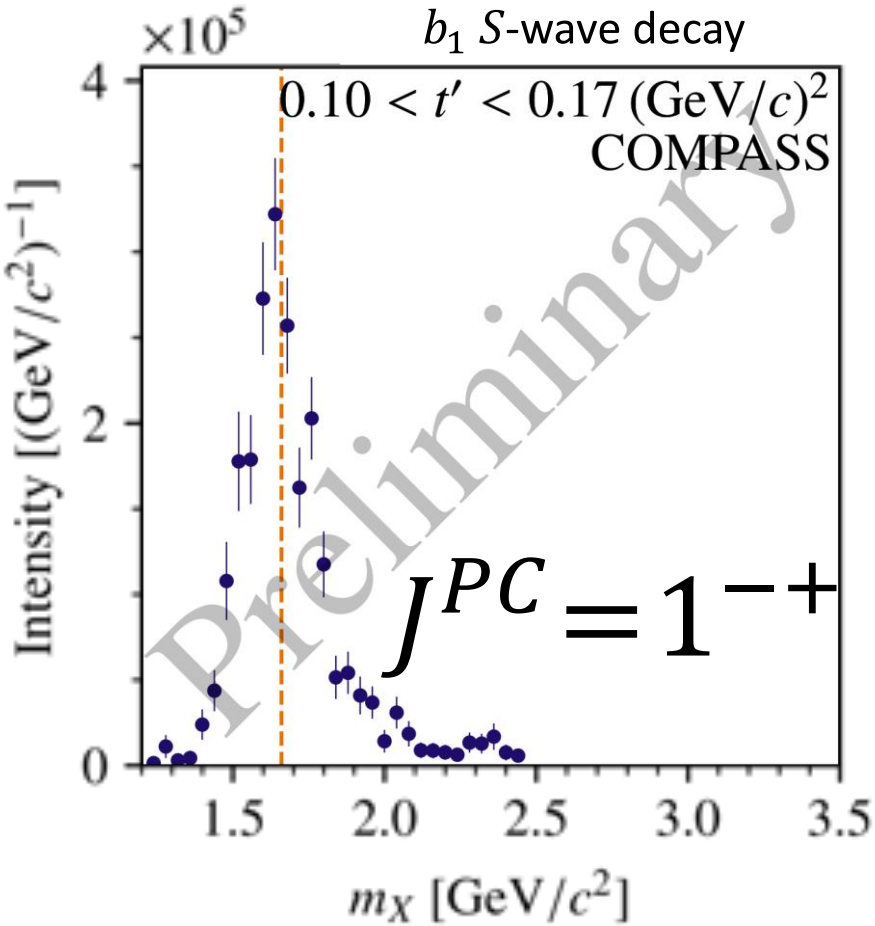


- Upper limit is really on $\sigma(\gamma p \to \pi_1^+ n)\mathcal{B}(\pi_1^+ \to \pi^+\pi^-\pi^+)$
- They used a model dependent central value for $\mathcal{B}(\pi_1)$
- Upper limit needs to include systematic uncertainty in $\mathcal{B}(\pi_1^+)$
- LQCD allowed values are $0 < \mathcal{B}(\pi_1 \to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

Recent Preliminary Result from COMPASS

- COMPASS recently showed preliminary $b_1\pi$ PWA results
- They find a 1^{-+} peak consistent with the $\pi_1(1600)$

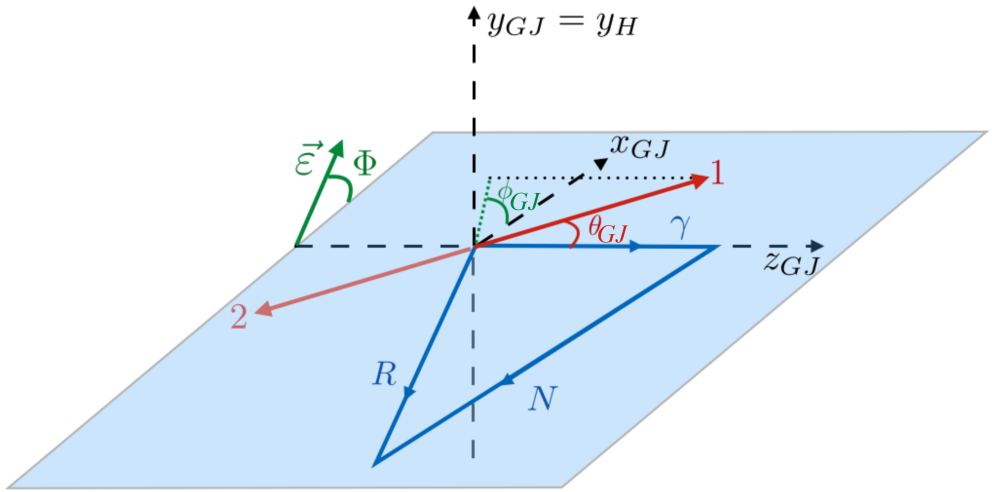
arXiv:2310.09148



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 $m = -\ell \ldots \ell$