Search for exotic-quantum-number mesons with the GlueX experiment

Florida International University 2022

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Outline

1. Introduction to the GlueX experiment

   - Motivation: GlueX Physics
   - Experimental setup

2. Search for π_1 (1600) via Partial Wave Analysis (PWA) of $\eta^{(')}\pi$ system

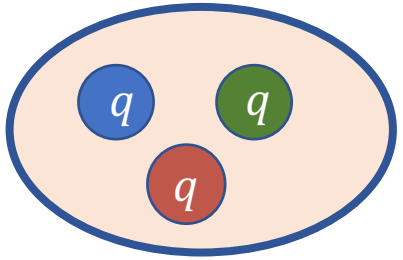
   - Newly developed model of intensity for $\eta(')\pi$ photoproduction
   - PWA studies of GlueX $\eta\pi^0$ and $\eta\pi^-$ data:
     - Studies of $a_2(1320)$ production mechanisms and cross section extraction
   - Ongoing PWA analysis of GlueX $\eta'\pi^0$ data

3. Summary

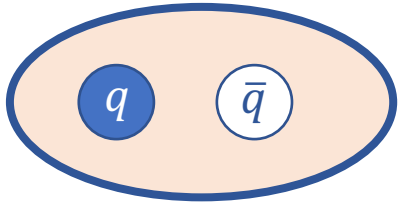
Motivation: Hadrons in Quantum chromodynamics (QCD)

Traditional hadrons:

Baryons



Mesons



QCD allows "colorless" hadronic states with different quark configurations:

A SCHEMATIC MODEL OF BARYONS AND MESONS *

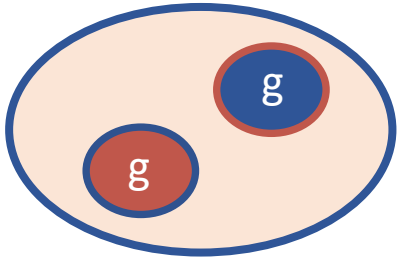
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

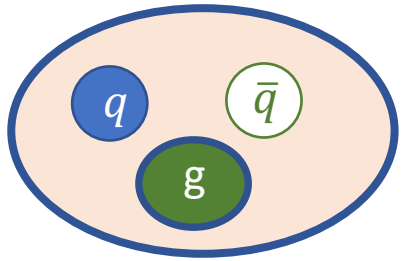
. . . Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. . . .

Lattice QCD (LQCD) also predicts a spectrum of bound states beyond the constituent quark model:

Glueball



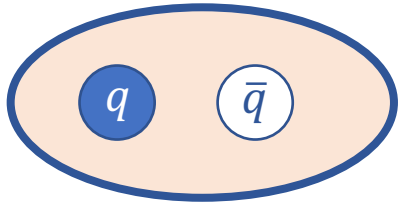
Hybrid mesons



GlueX studies production and structure of hadrons via photoproduction

Motivation: Hadrons in QCD

Mesons in standard quark model



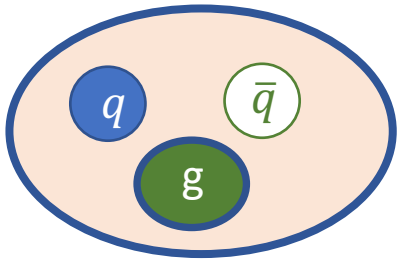
Classified as J^{PC} multiplets:

J- total angular momentum
S- total quark spin
L- orbital angular momentum between $q\bar{q}$ pair
P- parity
C- charge conjugation

$\vec{J} = \vec{L} + \vec{S}$,
$P = (-1)^{L+1} \rightarrow$ Spherical harmonics $(-1)^l$
$\times$ Product of individual parites of q,$\bar{q}$ (-1)
$C = (-1)^{L+S} \rightarrow$ Orbital angular momentum $(-1)^l$
$\times$ Flip of spin wavefunctions $(-1)^{S+1}$
$\times$ interchanging q and $\bar{q}$ (-1)

J^{PC}=$\mathbf{0}^{--}$, $\mathbf{odd}^{-+}$ and $\mathbf{even}^{+-}$ **"exotic"** quantum numbers are not available.

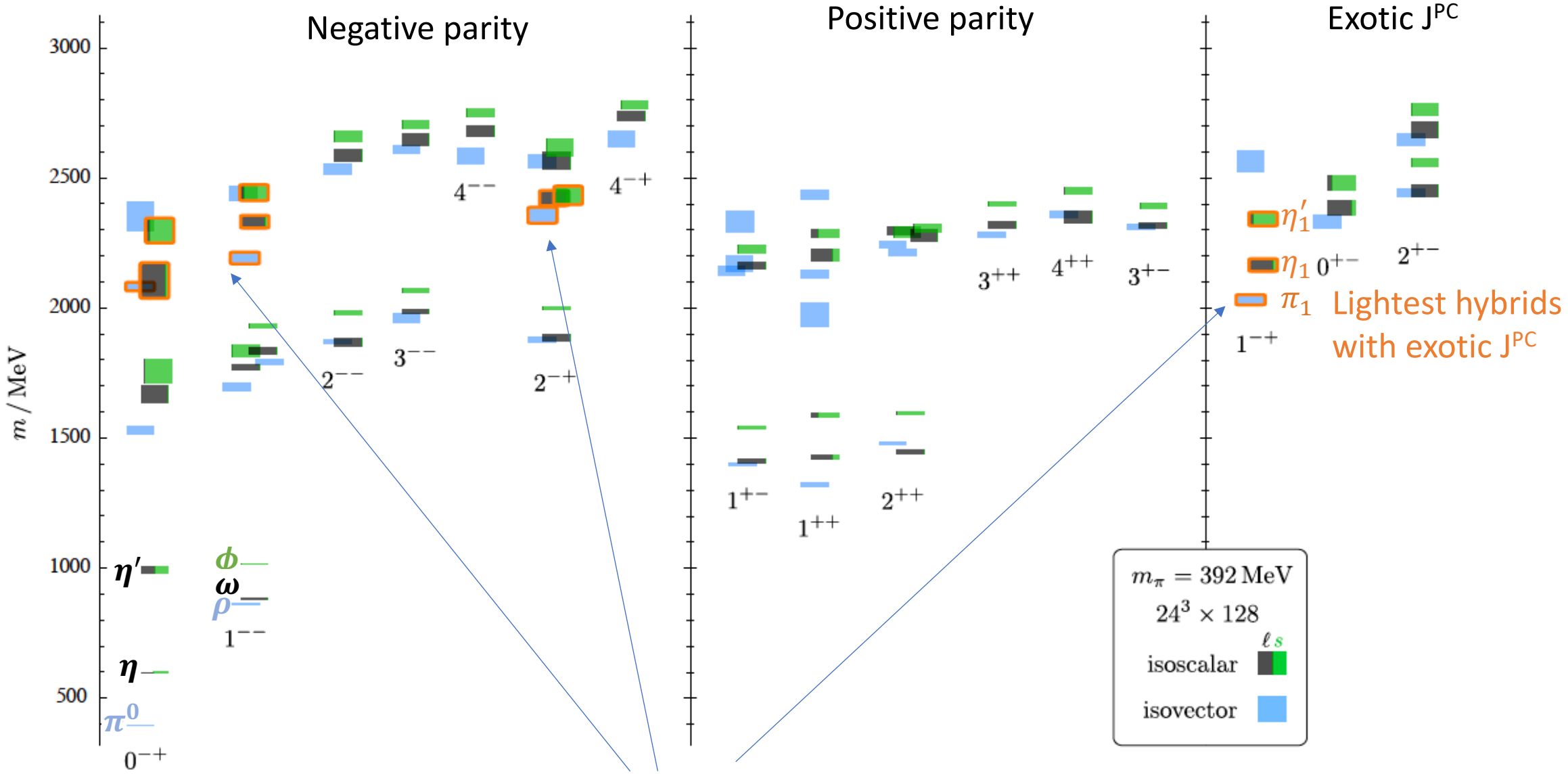
Hybrid mesons



Quark anti-quark pair coupled to valence gluon.
"Exotic" J^{PC} are also available.

Primary motivation of the GlueX is the search for light hybrid mesons.

Motivation: Isoscalar and isovector hybrid spectrum from Lattice QCD

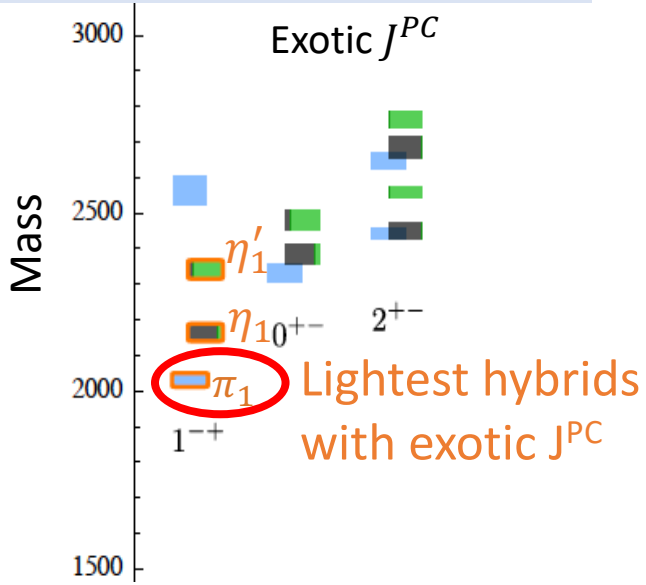


Phys. Rev. D 88, 094505 (2013)

Evidence for π_1 exotic 1^{-+} hybrid

Evidence for exotic $J^{PC} = 1^{-+}$ state from various experiments:

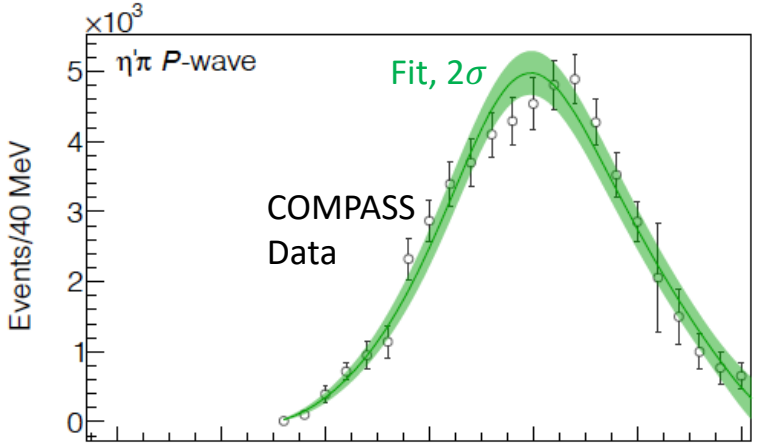
- π_1 (1400) in $\eta\pi$: GAMS, VES, E852, CBAR, COMPASS
- π_1 (1600) in $\eta'\pi$, $\rho\pi$: VES, E852, COMPASS

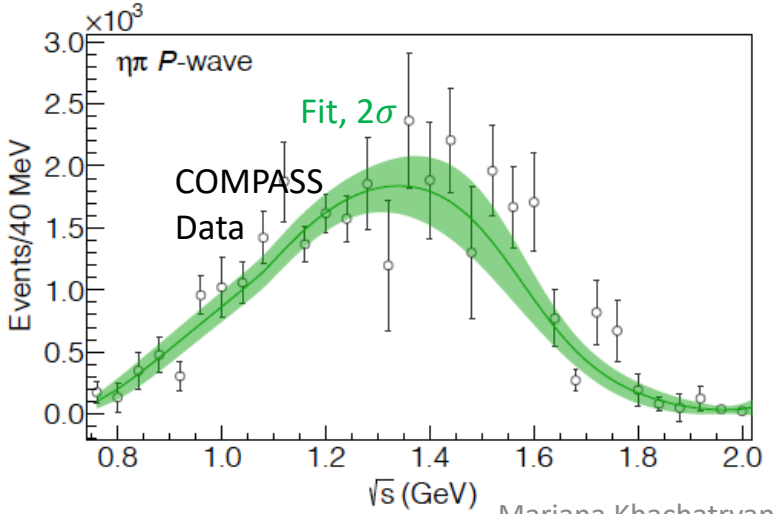


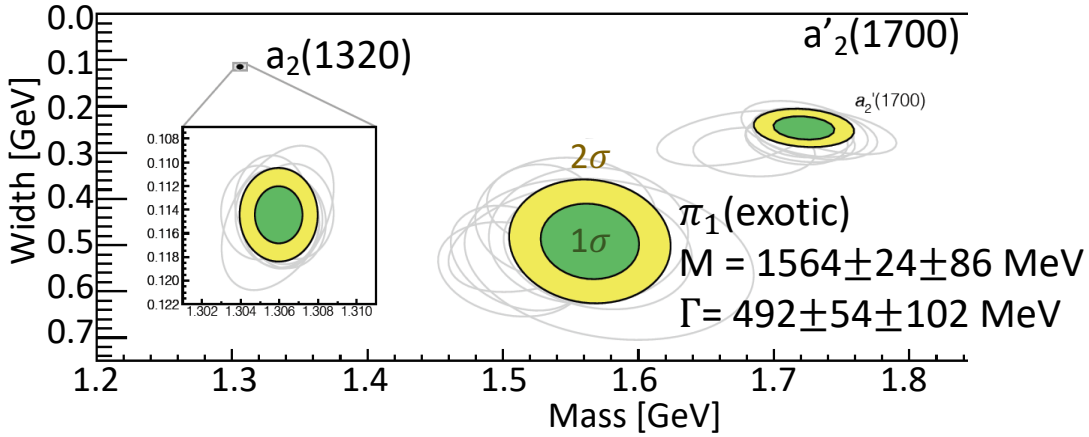
Joint Physics Analysis Center (JPAC)

Re-analyze COMPASS $\eta'\pi$ and $\eta\pi$ data

- Fit with amplitude model
- Extract resonance poles





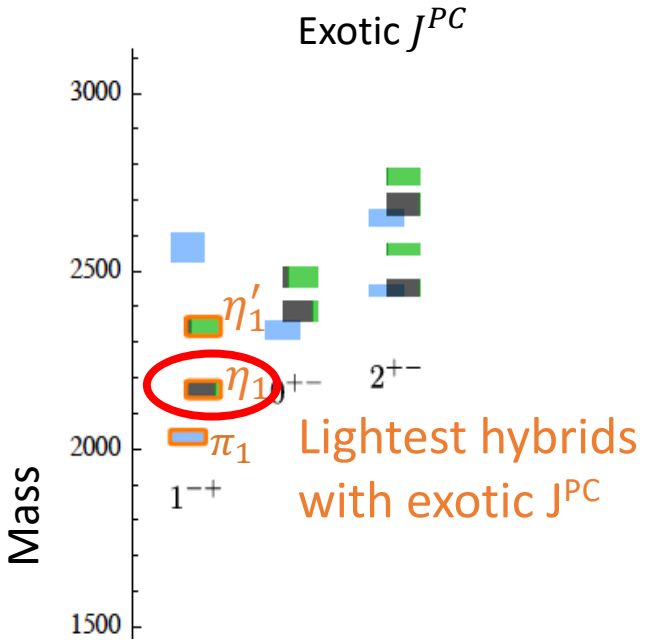


Single pole describing the 1^{-+} intensities

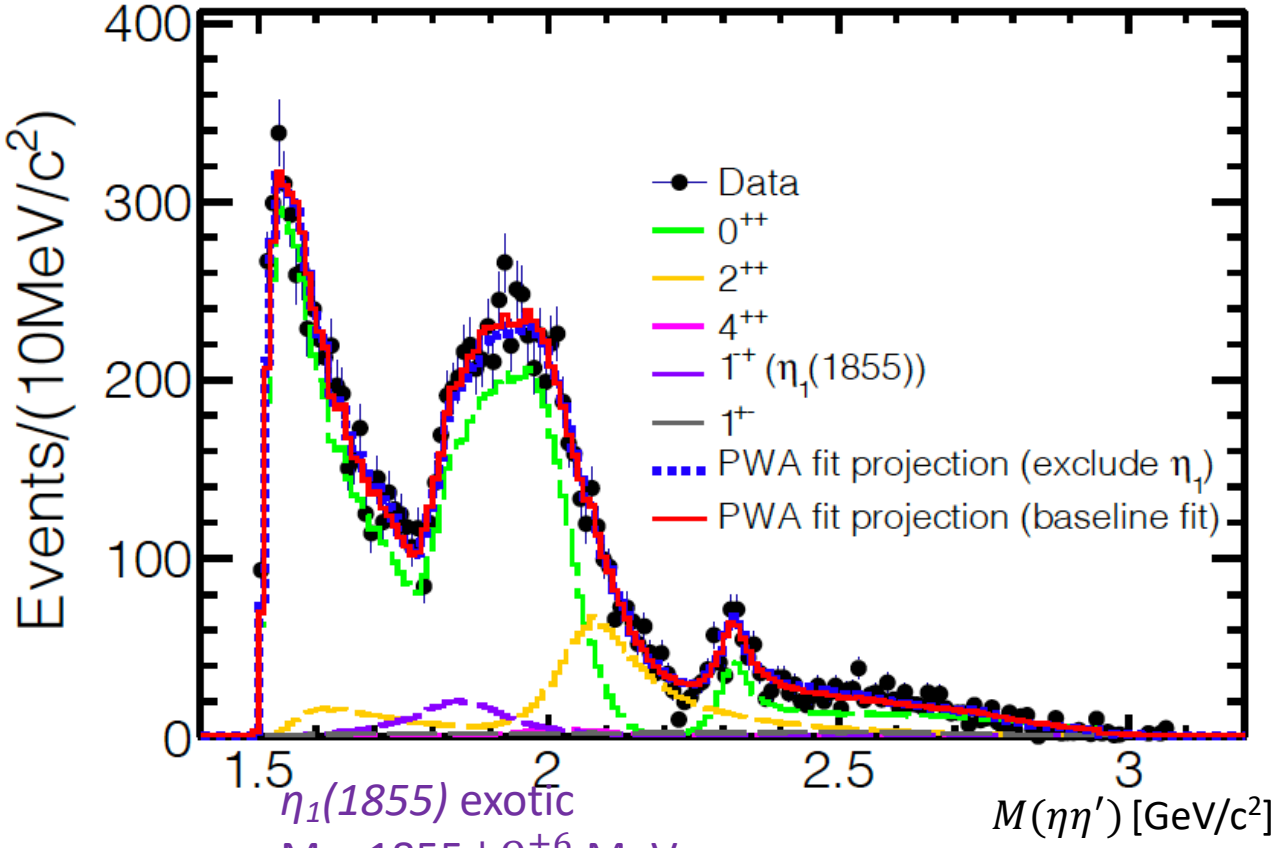
A. Rodas et al. [Joint Physics Analysis Center], PRL 122, 042002 (2019)

Evidence for isoscalar $\eta_1(1855)$ exotic 1^{-+} hybrid

- LQCD predicts that the exotic $J^{PC} = 1^{-+}$ nonet of hybrid mesons is the lightest
- There is evidence for the isovector member of the $J^{PC} = 1^{-+}$ nonet
- Finding an isoscalar 1^{-+} hybrid state is critical for establishing the hybrid multiplet



Partial wave analysis of $J/\psi \longrightarrow \gamma\eta\eta'$ data from BESIII

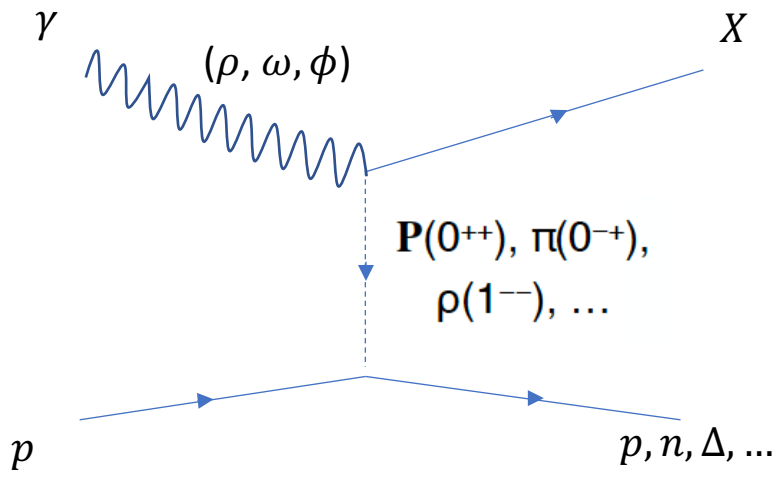


$\eta_1(1855)$ exotic
M = $1855 \pm 9^{+6}_{-1}$ MeV
Γ = $188 \pm 18^{+3}_{-8}$ MeV

arXiv:2202.00623v3

What can GlueX provide?

- No previous high precision photo-production data allowing PWA
- γ coupling via vector meson dominance (VMD) to wide variety of states (including exotic J^{PC})

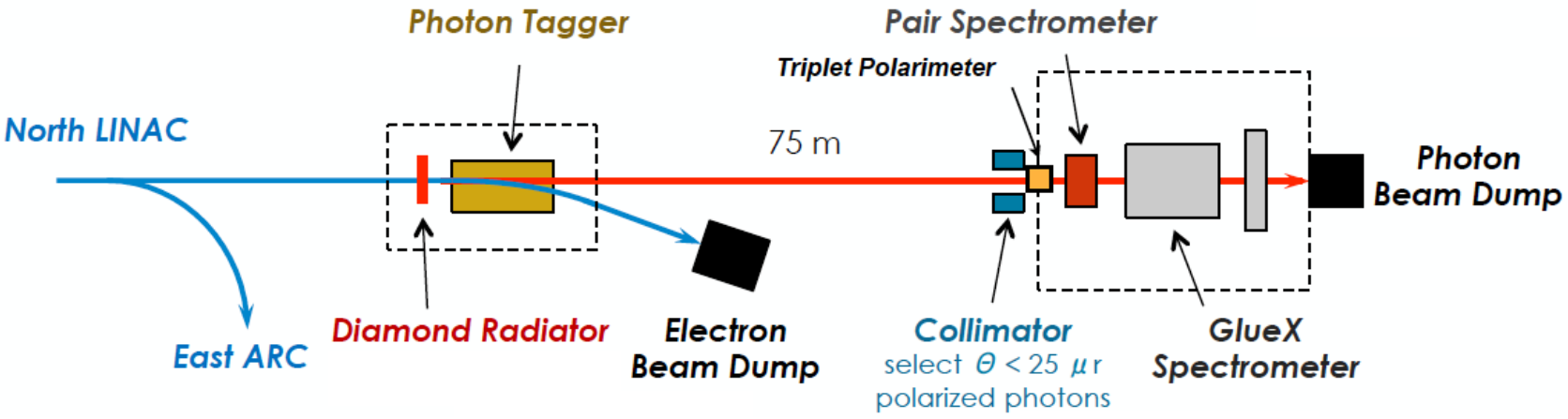


- γ beam polarization provides constraints for PWA

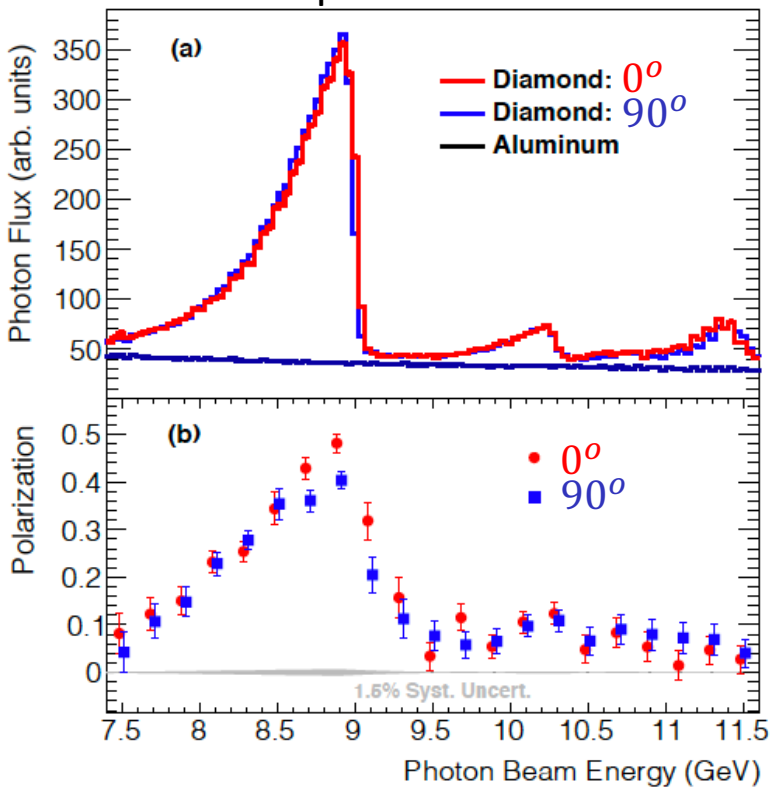
Linearly polarized photon beam production, Hall D complex

- The GlueX experiment is in the Hall-D complex at Jefferson Lab.
- Linearly-polarized photons via coherent bremsstrahlung on 20-60 μm thick diamond crystal radiator using 12 GeV e^- beam.
- 40% linear polarization in coherent peak (8-9 GeV)
- Four γ polarization plane angles relative to horizontal (0, 45, 90, 135°)
- Photon energy tagging precision ~0.1%

Hall D complex



Measured photon spectrum and degree of polarization



The GlueX spectrometer and phase I dataset

Hermetic detector.
Angular coverage:

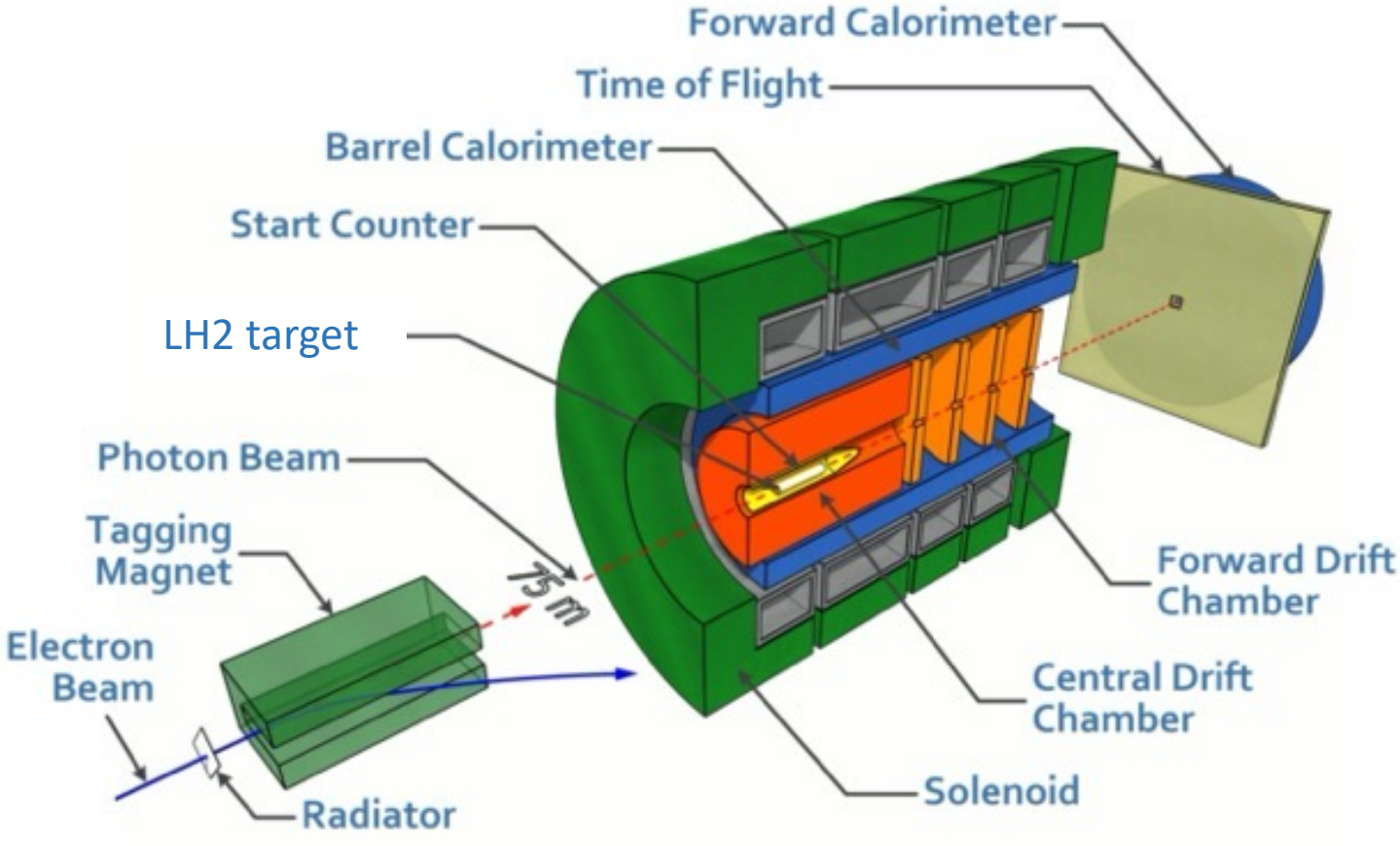
- full in φ
- $1^o < \theta < 120^o$

Charged particles:

- Drift chambers $\frac{\sigma_p}{p} \sim 1 - 3\%$

Photons:

- Electromagnetic calorimeters $\frac{\sigma_E}{E} = \frac{6\%}{\sqrt{E}}$

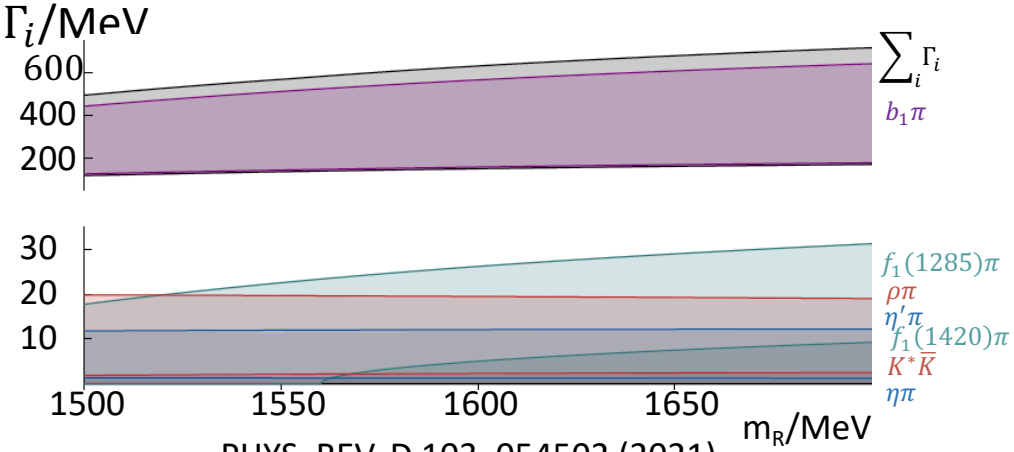


Run period	Coherent Peak Luminosity (pb^{-1})
GlueX phase I	125.0
GlueX phase II	132.4

Analysis of $\omega\pi$ system

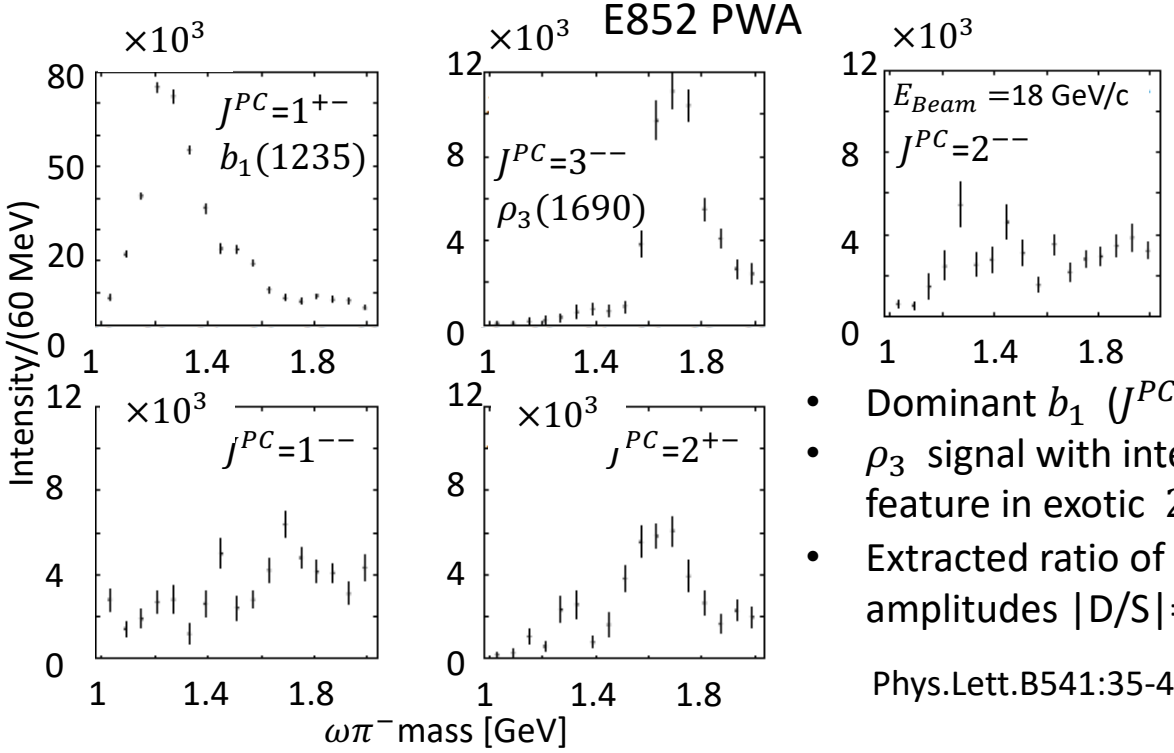
Studies of $b_1 \to \omega\pi$ system play important role in GlueX exotic search

Lattice QCD calculations by HadSpec:
π_1 exotic dominant decay - $b_1\pi$



PHYS. REV. D 103, 054502 (2021)

E852 PWA



- Dominant b_1 (J^{PC}=1^{+-})
- ρ_3 signal with interesting feature in exotic 2^{+-}
- Extracted ratio of $b_1 \to \omega\pi$ amplitudes |D/S|=0.269

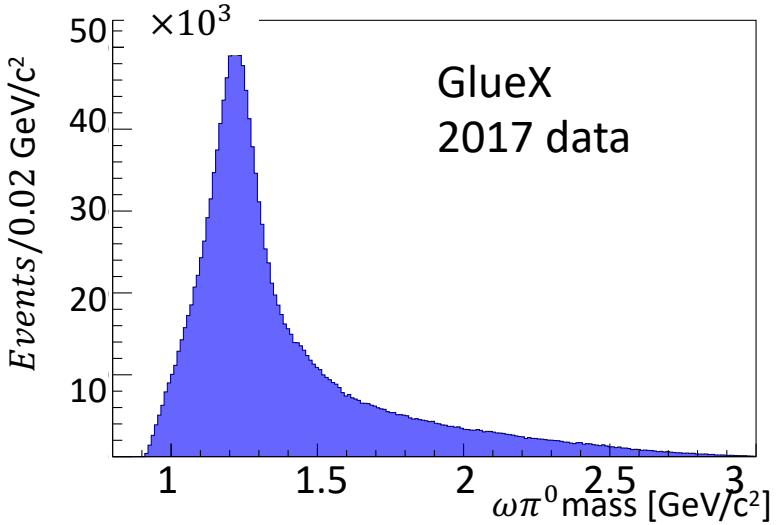
Phys.Lett.B541:35-44,2002

π_1 exotic dominant decay - $b_1\pi$

- ➢ Experimentally challenging
  - ▪ Current focus at GlueX on b1 (1235) : D/S ratio and production mechanism
    - Preliminary PWA analysis of GlueX data: b_1^0, b_1^-.
    - Preliminary D/S ratio for b_1^0

Start with $\eta^{(\prime)}\pi$ system

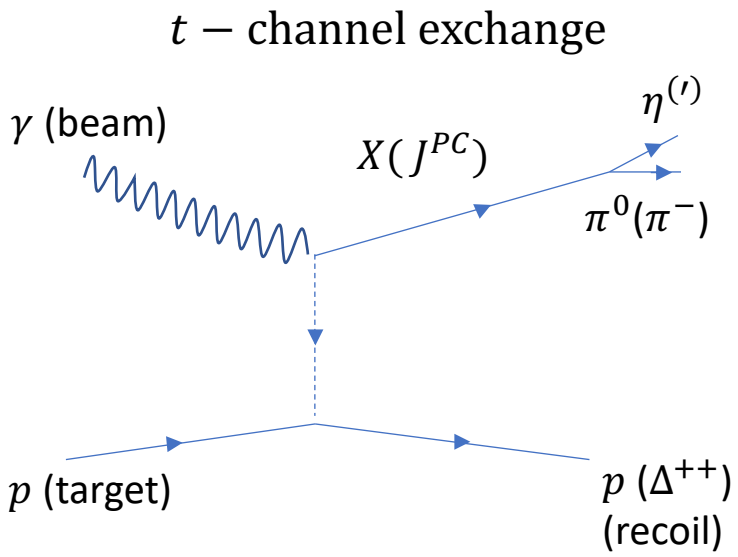
- ➢ Smaller expected branching ratio but large statistics



Search for exotic mesons via PWA of $\eta^{(\prime)}\pi$ system

- Focus of GlueX exotic search
- The odd waves (P, F, …) in $\eta^{(\prime)}\pi$ have exotic quantum numbers and the lowest (P) of them corresponds to exotic $\pi_1(1600)$
- Coupling of π_1 to $\eta'\pi$ expected to be larger than to $\eta\pi$
- Different aspects of various decay modes under investigation in parallel:

- $\gamma p \to p\boldsymbol{\eta\pi^0}$
- $\gamma p \to \Delta^{++}\boldsymbol{\eta\pi^-}$
- $\gamma p \to p\boldsymbol{\eta'\pi^0}$
- $\gamma p \to \Delta^{++}\boldsymbol{\eta'\pi^-}$



- Access to different production mechanisms
- Cross-check acceptance, systematics (includes $\eta \to \gamma\gamma$ and $\eta \to 3\pi$)
- Close collaboration with JPAC
- Learn about J^{PC} and production mechanism via PWA
  - New model of Intensity for $\eta^{(\prime)}\pi$ photoproduction at GlueX with polarized beam

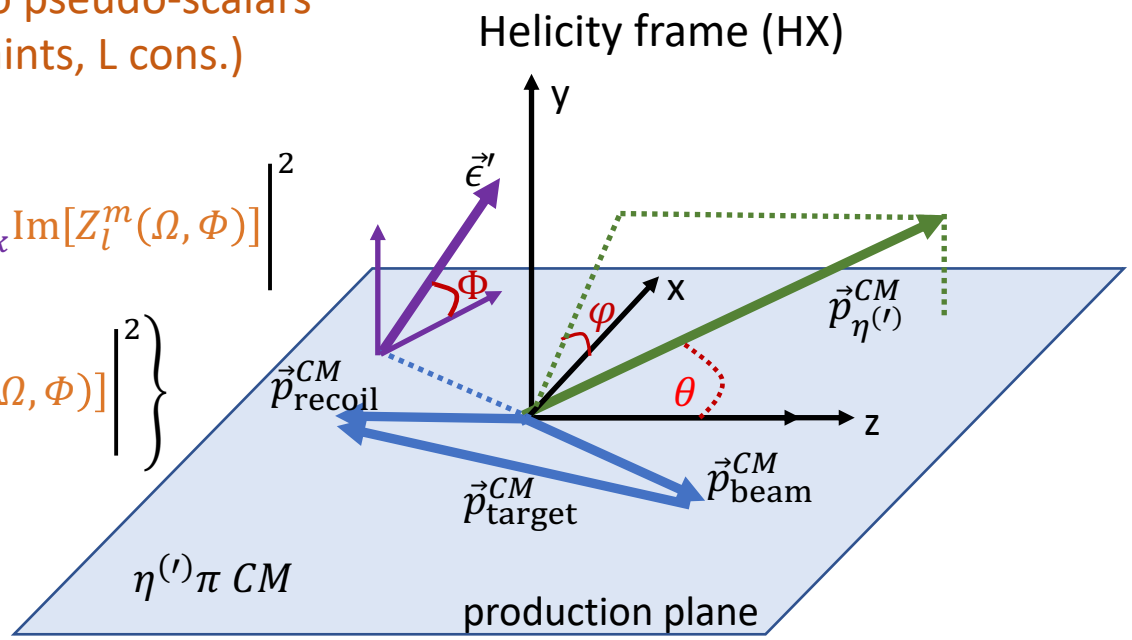
Search for exotic mesons via PWA of $\eta^{(\prime)}\pi$ system using new model of intensity

Model predicted number of events per unit phase space

Partial wave amplitudes (production of the wave)

Decay into two pseudo-scalars (parity constraints, L cons.)

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



P_γ - degree of polarization

$Z^m_l(\Omega,\Phi) \equiv Y^m_l(\Omega)e^{-i\Phi}$

$\Omega = (\theta,\varphi)$

l, m- spin, its projection

$\vec{\epsilon}'$ - γ polarization vector

κ- kinematical factors

Nucleon spin flip k=1, non-flip k=0

Reflectivity ε=±1 corresponds to naturality of exchanged particle $\eta = P(-1)^J$

- natural parity $J^P = 0^+, 1^-, 2^+, \ldots$
- unnatural parity $J^P = 0^-, 1^+, 2^-$

V. Mathieu et al. Phys. Rev. D 100, 054017 (2019)

Determine $[l]^{(-)}_{m;k}$, $[l]^{(+)}_{m;k}$ by fitting I_{EXP} using extended unbinned (in (θ,φ)) maximum likelihood method (AmpTools package https://github.com/mashephe/AmpTools)

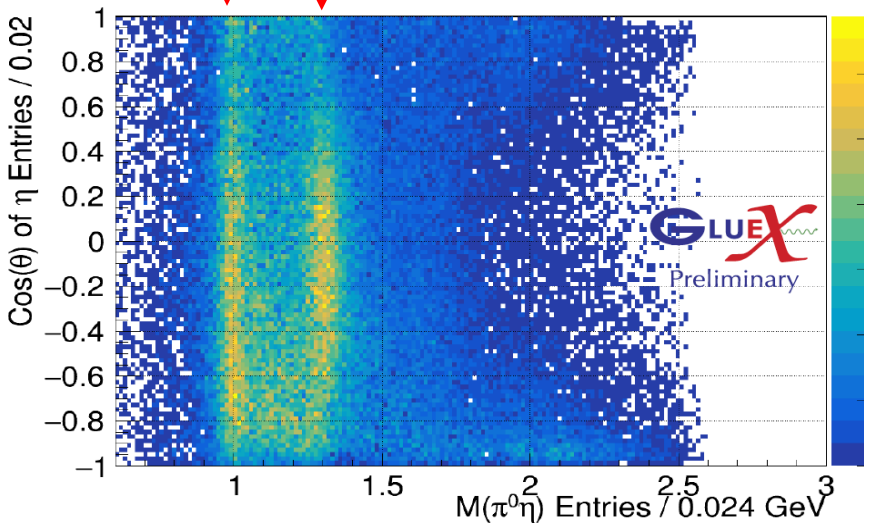
Search for exotic mesons via Partial Wave Analysis (PWA) of $p\eta^{(\prime)}\pi$ data

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

0.1<-t <0.3(GeV/c)^2

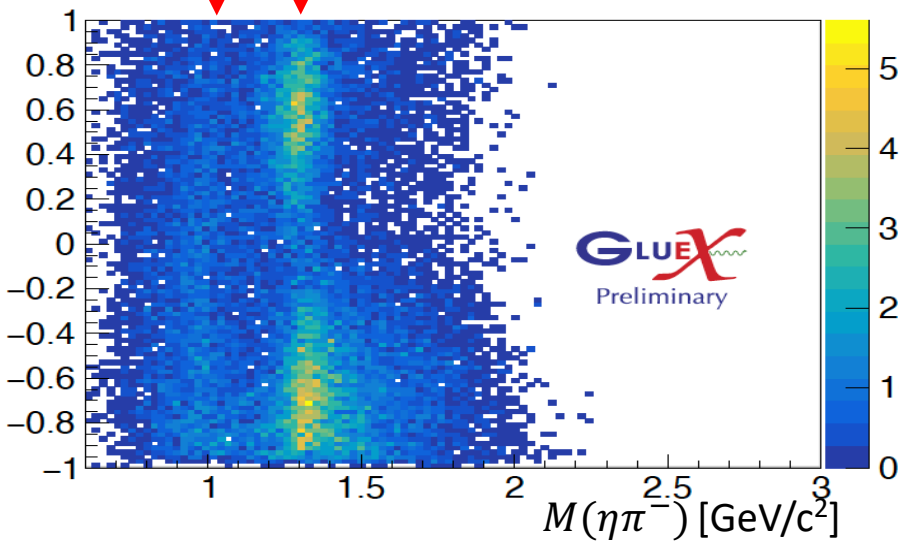
$\eta\pi^0$ $(\eta \to \gamma\gamma, \pi^0 \to \gamma\gamma)$

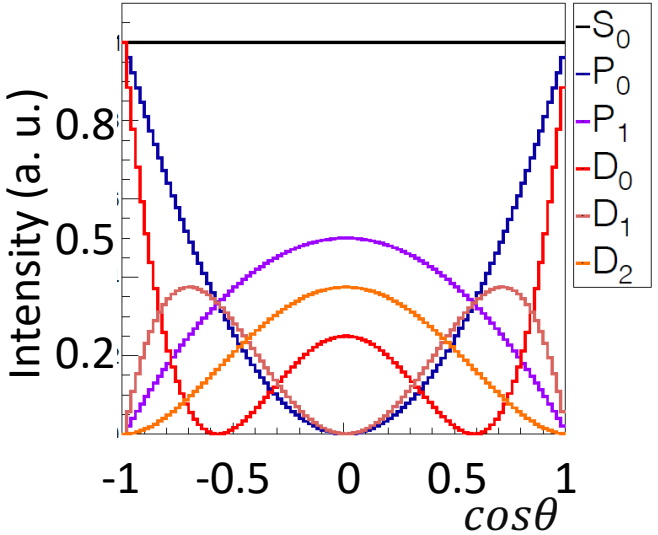
S/a_0 (980) D/a_2 (1320)

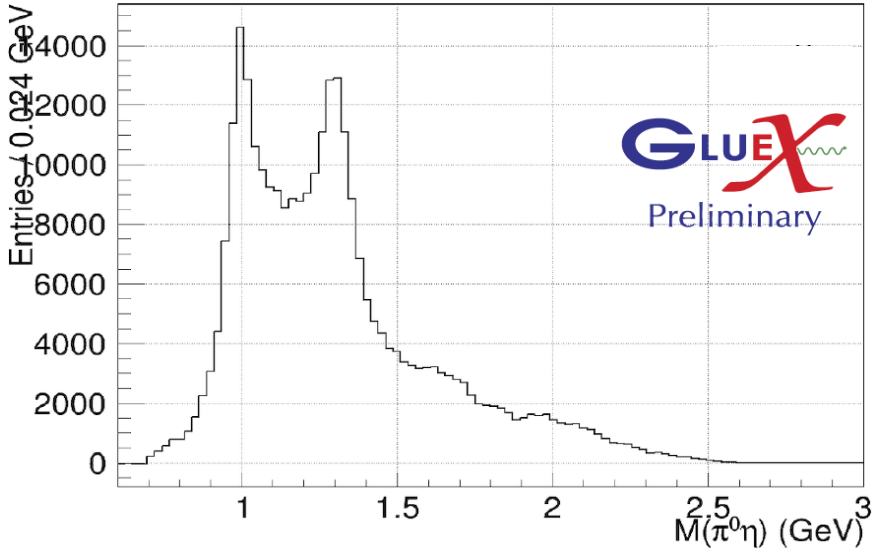


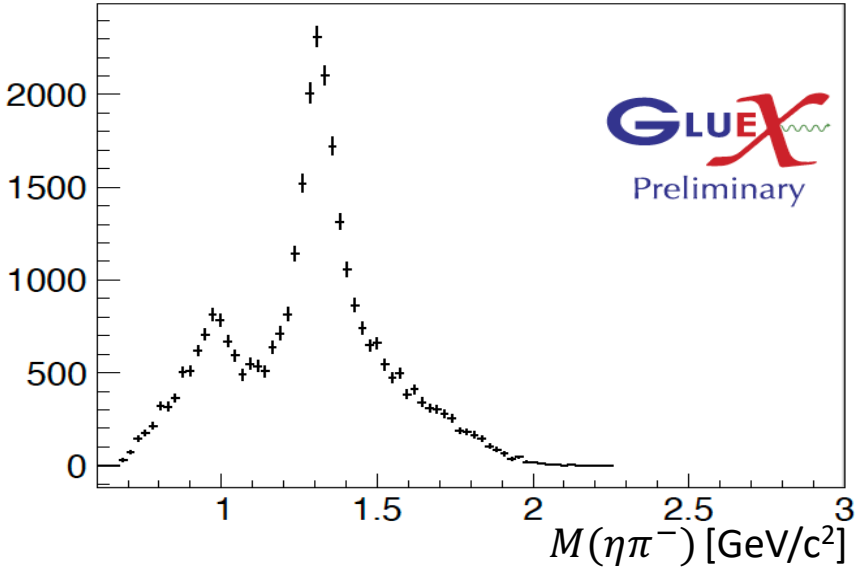
$\eta\pi^-(\eta \to \gamma\gamma, \Delta^{++} \to \pi^+ p)$

S/a_0 (980) D/a_2 (1320)







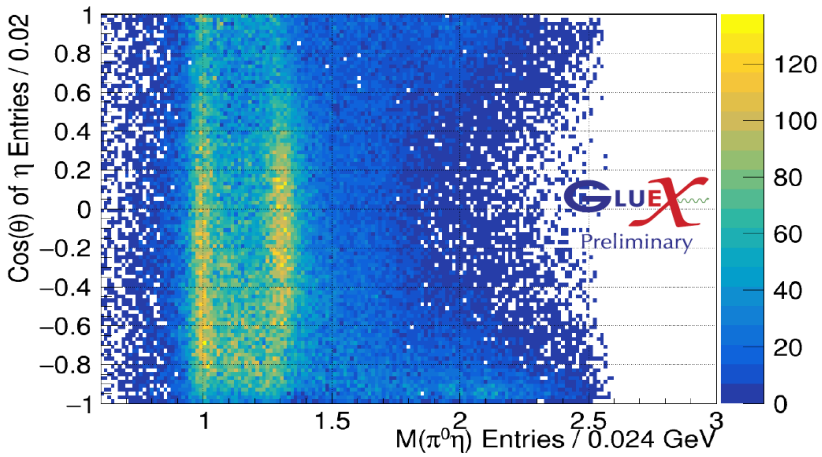


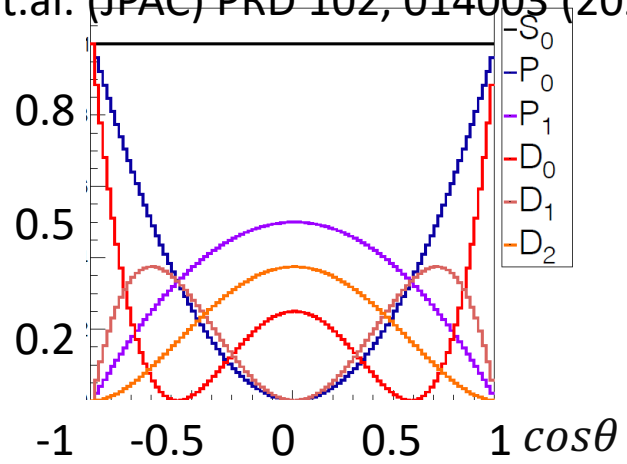
- Presence of a_0 (980) and a_2 (1320) signals
- Angular distribution of a_2 (1320) signal clearly different between charged and neutral channels

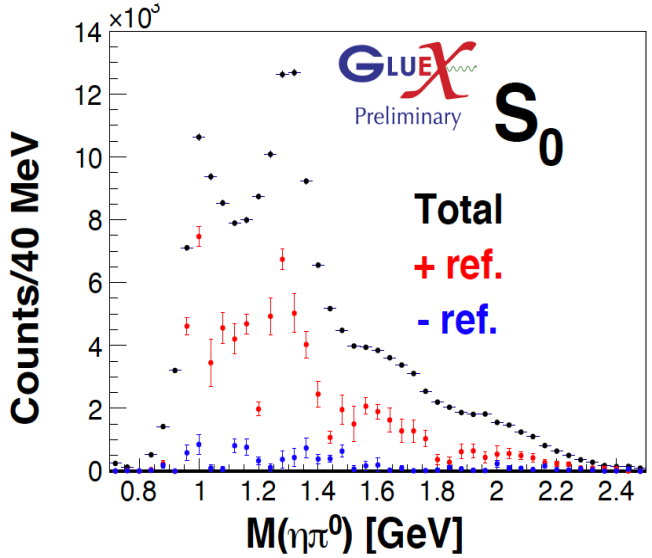
Fit to $\gamma p \rightarrow \pi^0 \eta p$ data (0.1<-t <0.3(GeV/c)^2)

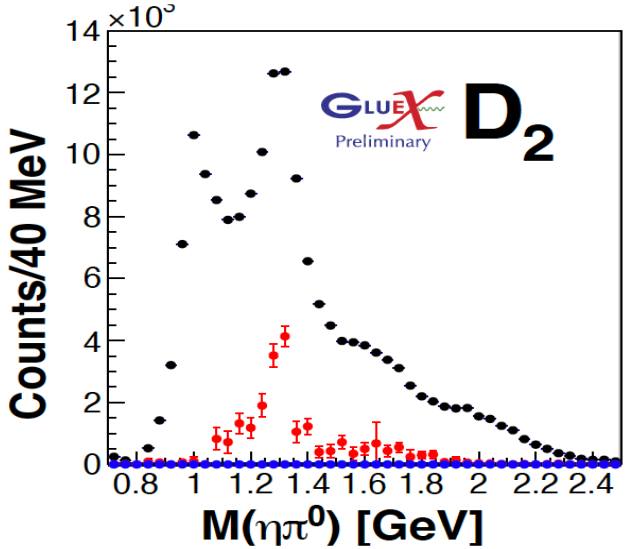
Waveset used in fitting based on Tensor Meson Dominance model (V.Mathieu et.al. (JPAC) PRD 102, 014003 (2020)):

$S_0^{\pm}, D_0^{\pm}, D_1^{\pm}, D_2^{+}, D_{-1}^{-}$









- Large S-wave, positive reflectivity contribution
- Non-resonant?
- Contribution from other resonance(s)? (a_2 (1700), a_0(1450), …)

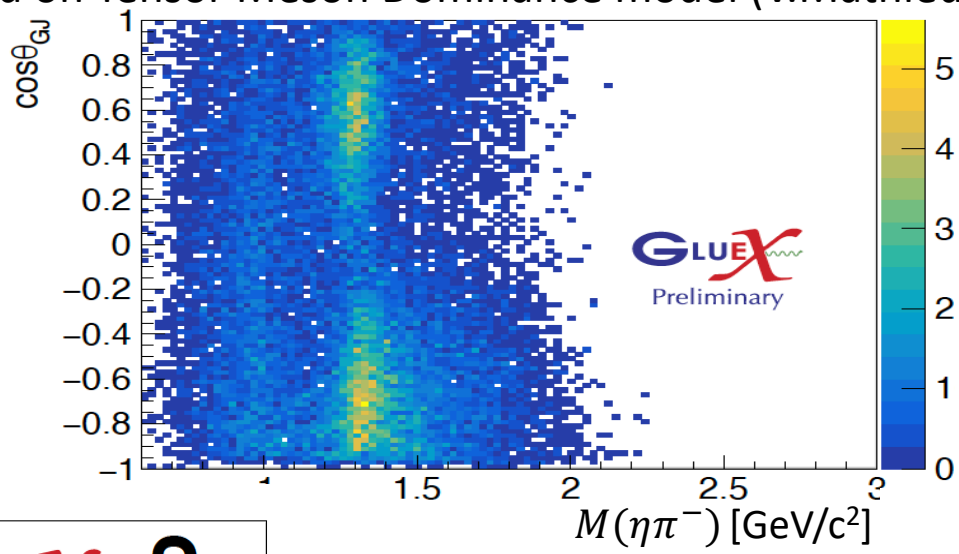
- a_2(1320) signal dominant in m=2 wave and positive reflectivity at low t:
  - ρ, ω exchange (natural parity)
- Extracted a_2(1320) cross section with semi - mass independent fit, systematic checks ongoing (see Colin Gleason's talk)

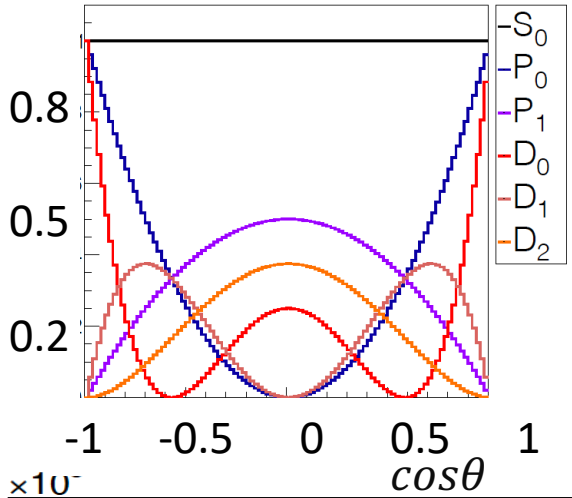
- ❑ D-wave structure evolves with -t
- ❑ Studying a_2(1320) production: Groundwork for understanding weaker P-wave contribution

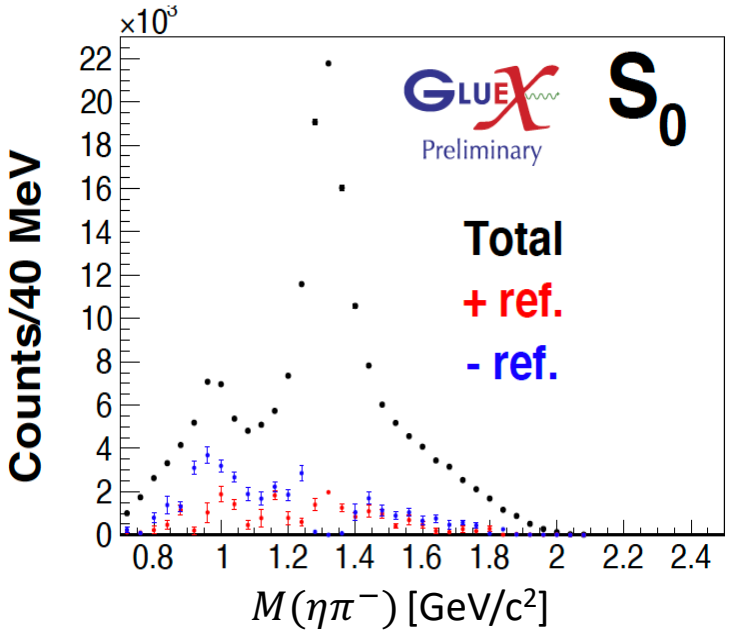
Fit to $\gamma p \rightarrow \pi^- \eta \Delta^{++}$ data (0.1<-t <0.3(GeV/c)^2)

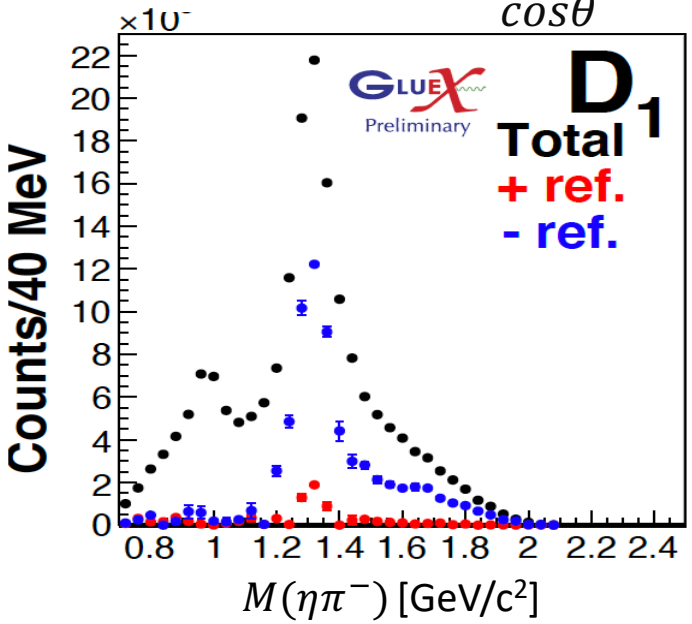
Waveset used in fitting based on Tensor Meson Dominance model (V.Mathieu et.al. (JPAC) PRD 102, 014003 (2020)):

$S_0^{\pm}, D_0^{\pm}, D_1^{\pm}, D_2^{+}, D_{-1}^{-}$









Large S-wave, negative reflectivity contribution

- Large $a_0(980)$ contribution
- Some signal under $a_2(1320)$

- $a_2(1320)$ signal dominant in m=1 wave and negative reflectivity at low t:
  - ➢ π exchange (unnatural parity)

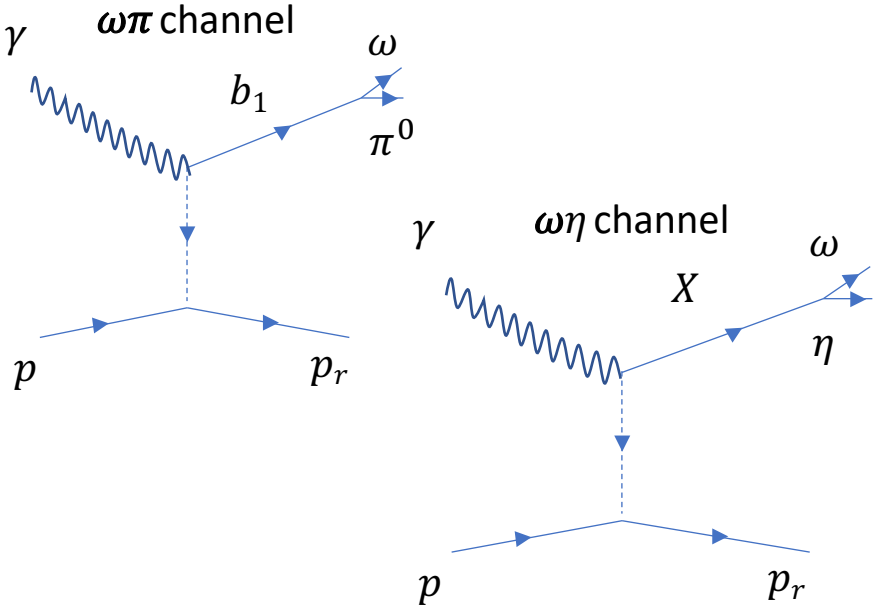
Search for exotic π_1 (1600) using the reaction $\gamma p \rightarrow p\eta'\pi^0$ in GLUEX

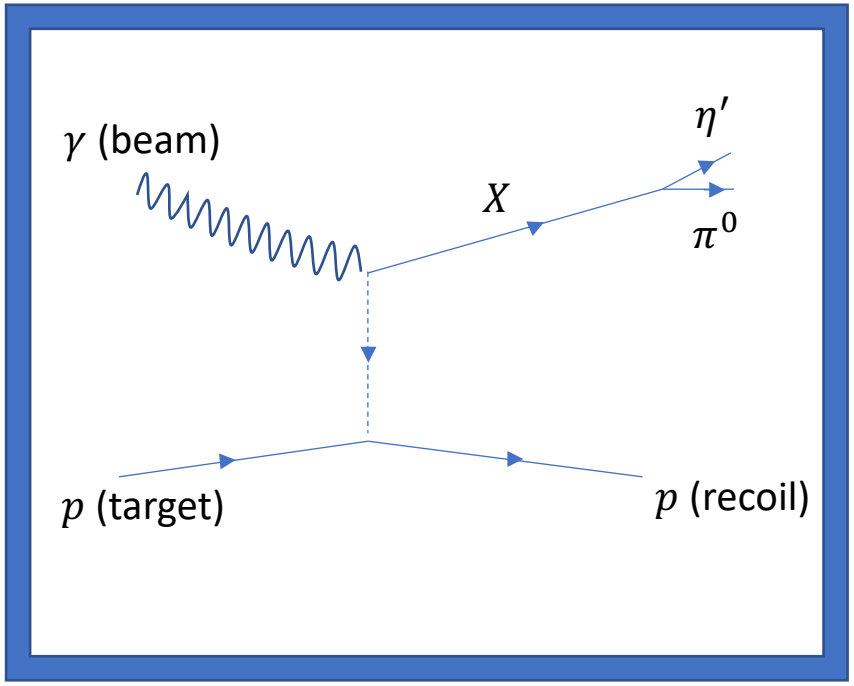
$\gamma p \rightarrow \eta' \pi^0 p \rightarrow (\pi^+ \pi^- \eta)(\gamma\gamma)p \rightarrow \pi^+ \pi^- \gamma\gamma\gamma\gamma p$

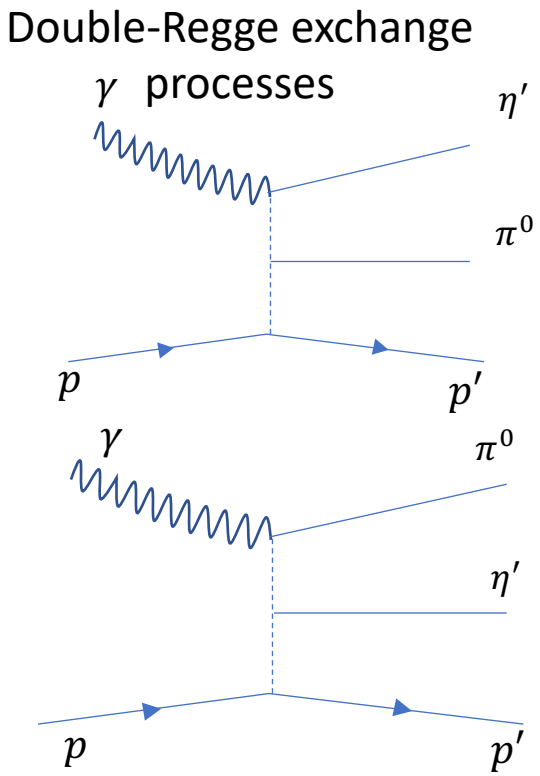
Alternate physics processes with same final state (Identified and rejected)

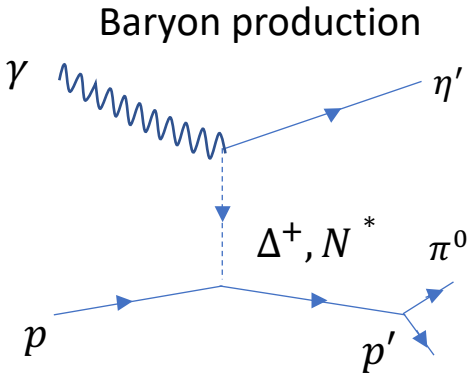
X : Probable resonance in $\eta'\pi^0$ system

Alternate physics processes with same final state (No quantitative analysis yet)









Critical to understand and model these backgrounds→ close collaboration with JPAC
Double Regge exchange (Deck effect) can enhance odd partial waves and mimic exotic signal

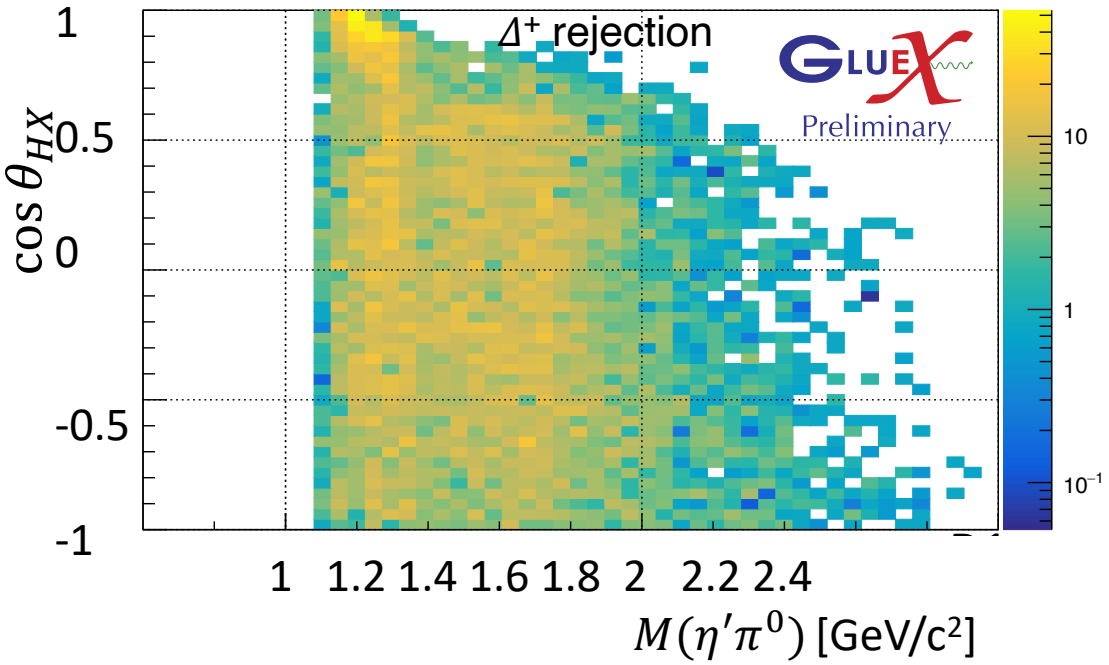
1

GlueX ($p\eta'\pi^0$) events for 4 γ polarization plane angles relative to horizontal (0, 45, 90, 135°)

Coupling of π_1 to $\eta'\pi$ expected to be larger than to $\eta\pi$
Lower statistics:

Number of signal events in selected beam energy range 6777

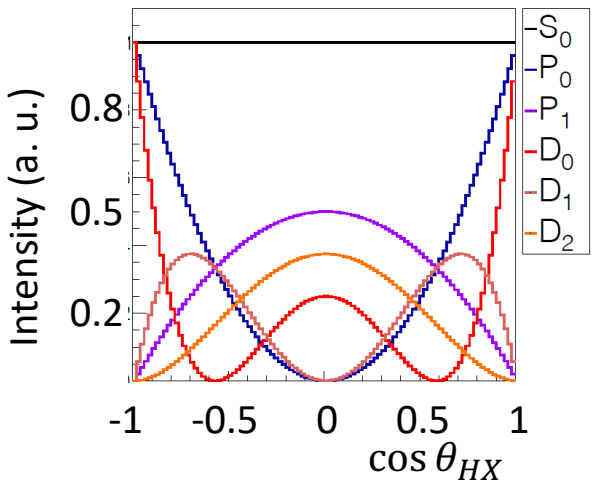
Looking for:
P/π_1(1600 MeV) (exotic)
D/a_2 (1320 MeV)
D/a_2' (1700 MeV)

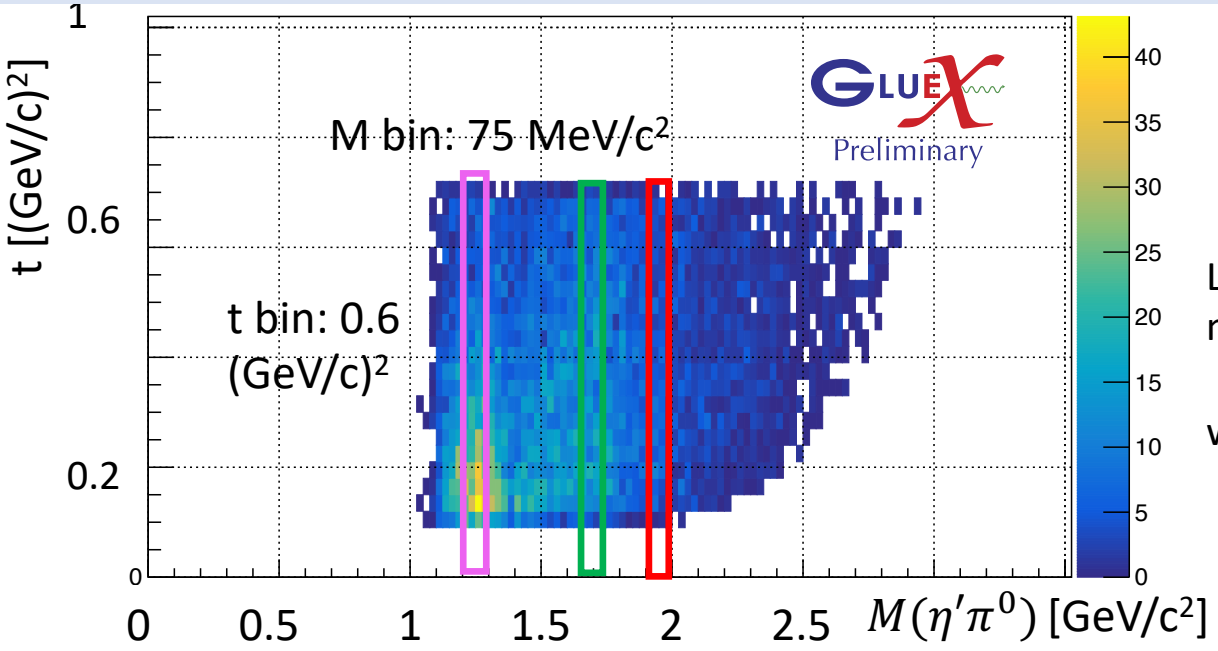


No obvious resonance structures

Partial Wave Analysis in bins of M and and t

$\cos\theta_{HX}$ distributions in different bins

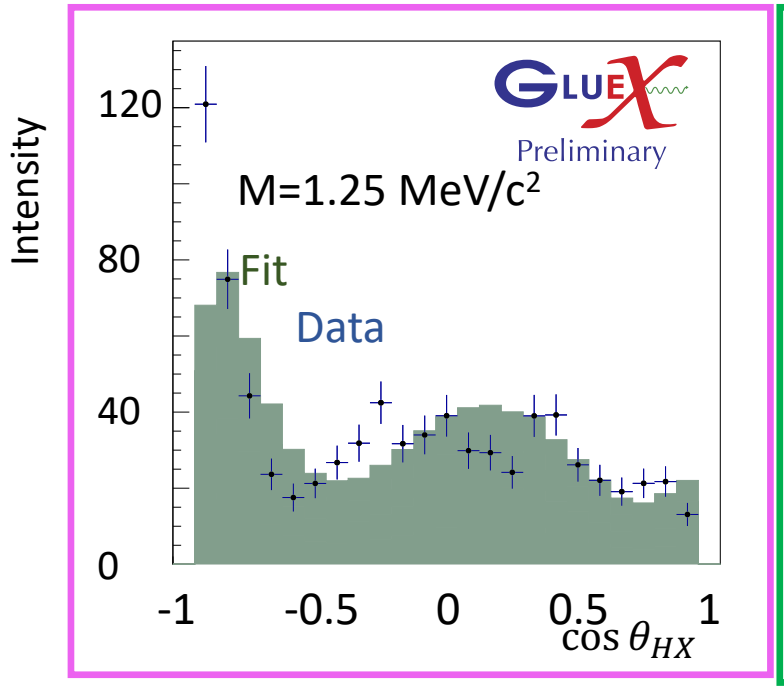


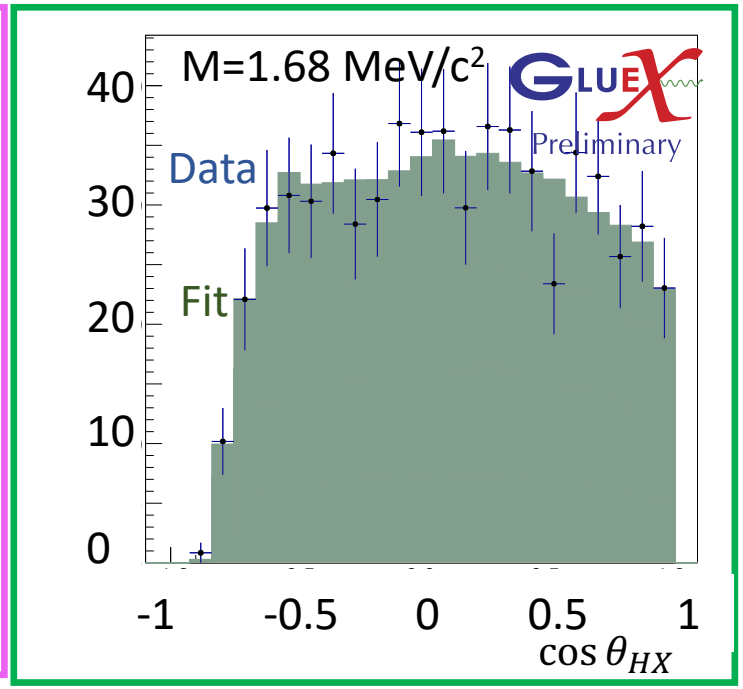


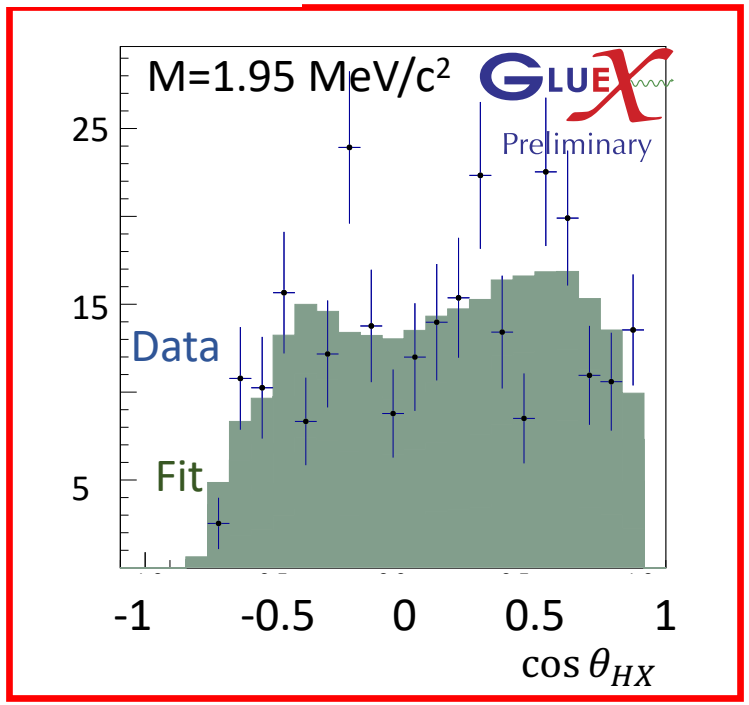
Low statistics makes it hard to make conclusions.

Future work: PWA of $\eta'\pi^0$ data with increased statistics

- Use data corresponding to broader energy range
- Add GlueX-II data set







Summary

- GlueX phase I data taking completed fall 2018

- Search for exotic mesons via PWA studies of $\eta^{(\prime)}\pi$ and $\omega\pi$ systems using newly developed model for photo-production via linearly polarized beam ongoing

- Have measured $a_2(1320)$ cross section from $\eta\pi^0$ PWA, systematic checks ongoing for near-term publication

- PWA studies of $\eta'\pi^0$ not conclusive due to low statistics:
  - Future work: PWA of GlueX $\eta'\pi^0$ data with increased statistics:
    - ➢ Use data corresponding to broader energy range
    - ➢ Add GlueX-II data set (near future double the statistics, full phase two will triple or quadruple the statistics)

- GlueX phase II data taking started in spring of 2020. Looking forward for new exciting results with high statistical power.

GlueX acknowledges the support of several funding agencies and computing facilities:

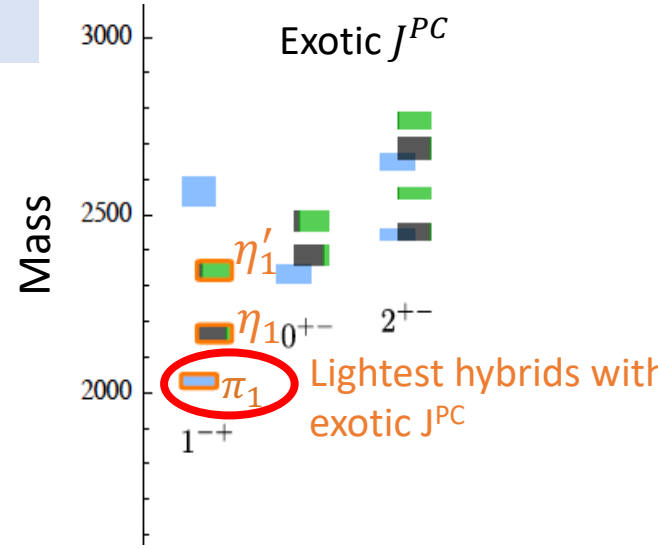
gluex.org/thanks

Backup slides

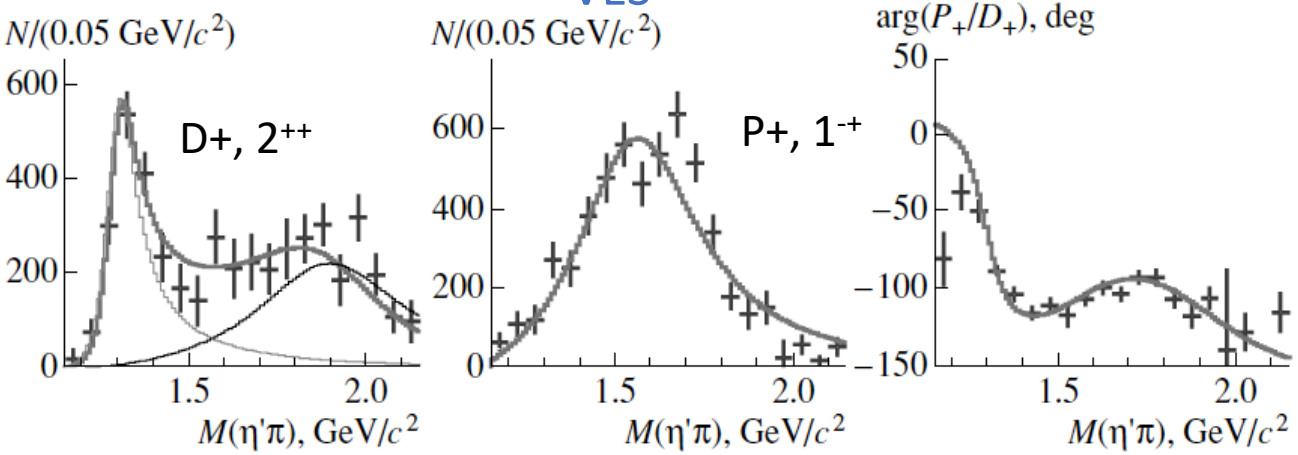
Evidence for π_1 exotic 1^{-+} hybrid from studies of $\eta^{(\prime)}\pi$ and $\rho\pi$ systems

Evidence for exotic J^{PC} =1^{-+} state from various experiments:

- π_1 (1400) in $\eta\pi$: GAMS, VES, E852, CBAR, COMPASS
- π_1 (1600) in $\eta'\pi$, $\rho\pi$: VES, E852, COMPASS

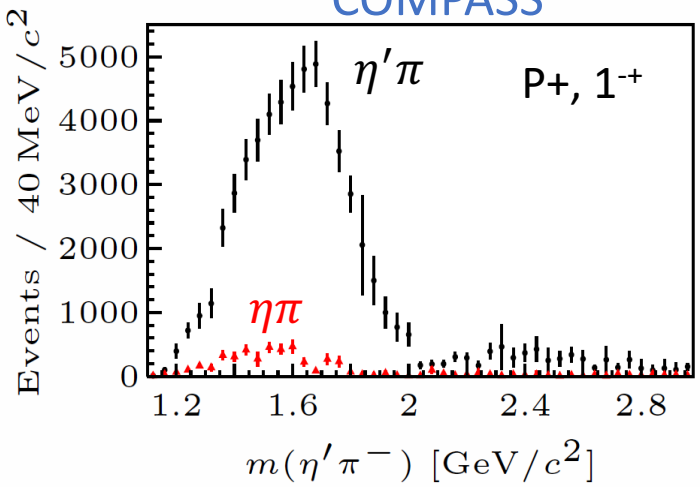


VES



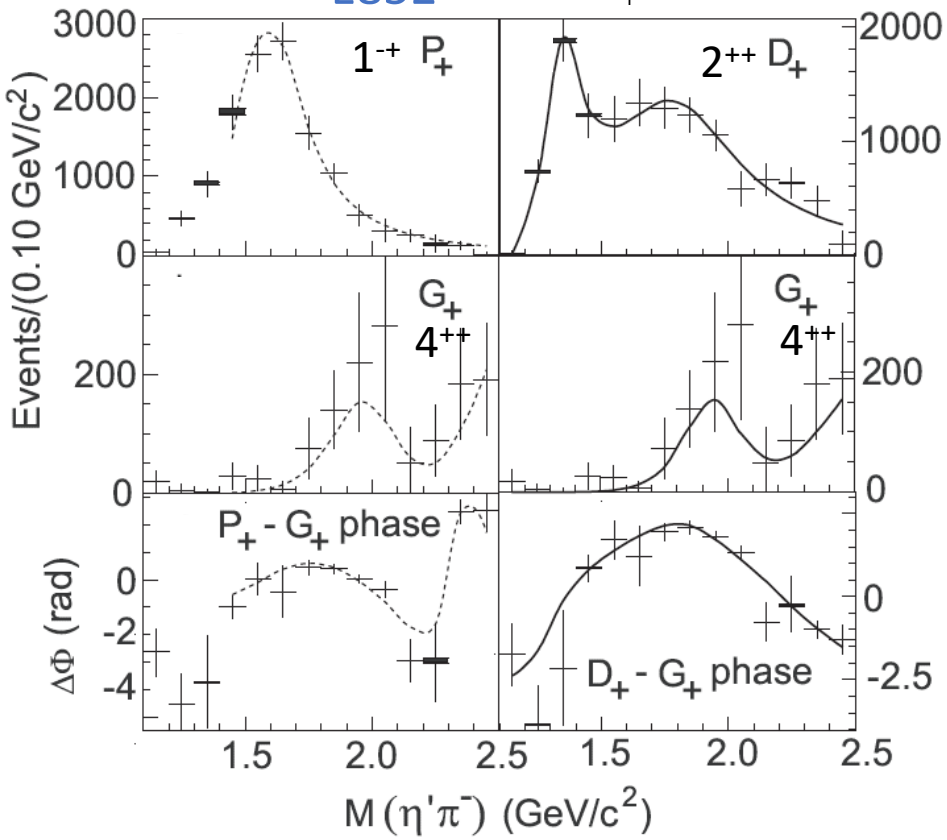
D. V. Amelin et al., Phys. Atom. Nucl. 68, 359 (2005)

COMPASS



C. Adolph, et al. [COMPASS Collaboration], Phys. Lett. B740, 303 (2015)

E852



E. I. Ivanov et al. [E852 Collaboration], Phys. Rev. Lett. 86, 3977 (2001)