

Recent Results and Future Prospects

from  GLUEX

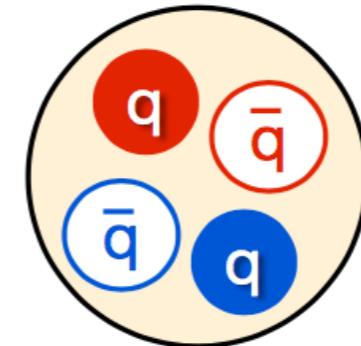
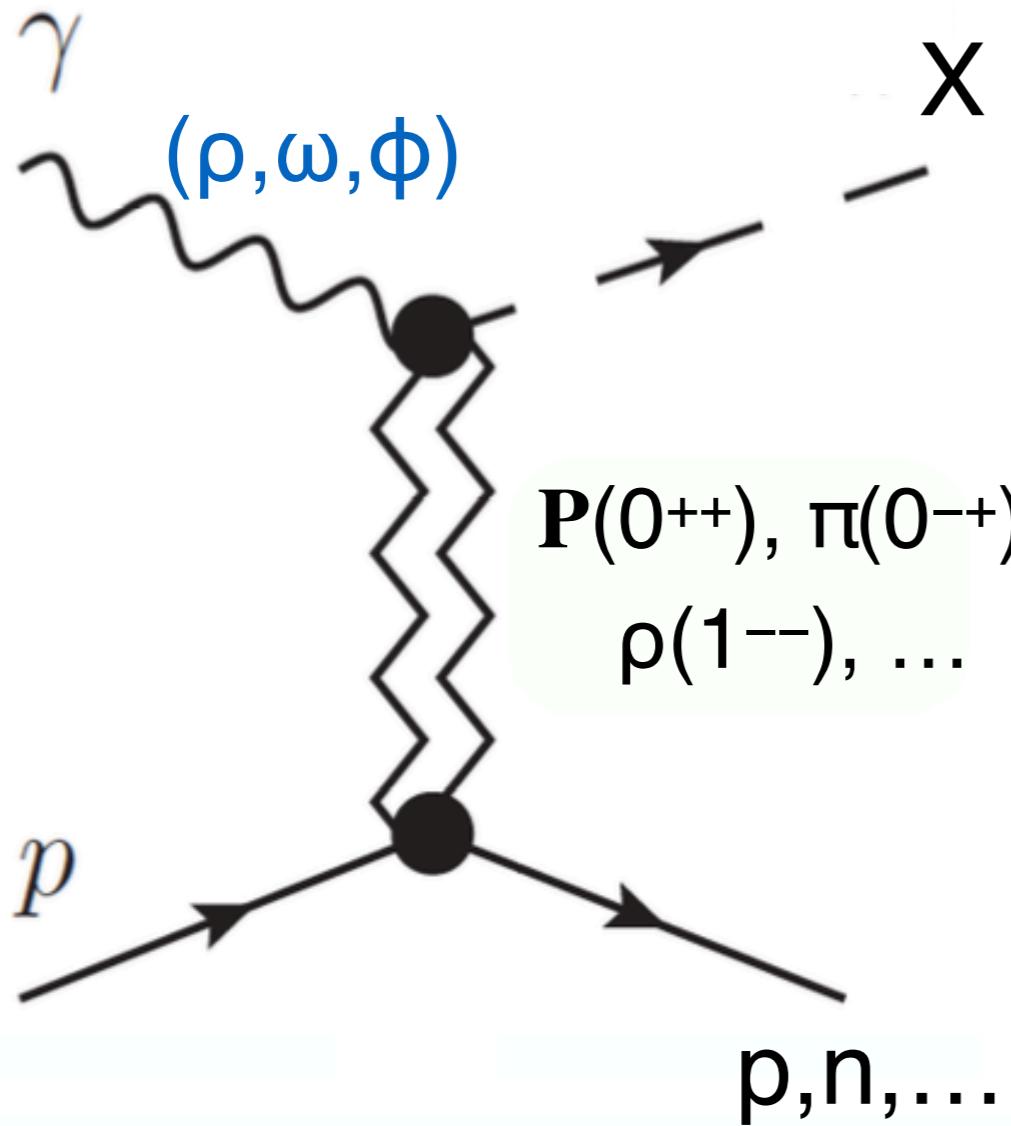
Sean Dobbs
Florida State U.

Hadron Spectroscopy: The Next Big Steps
March 22, 2022

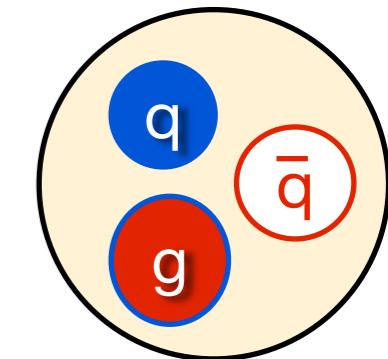


Hadron Spectroscopy and Photoproduction

- Photoproduction is an interesting process to search for exotic hadrons



tetraquark



hybrid meson

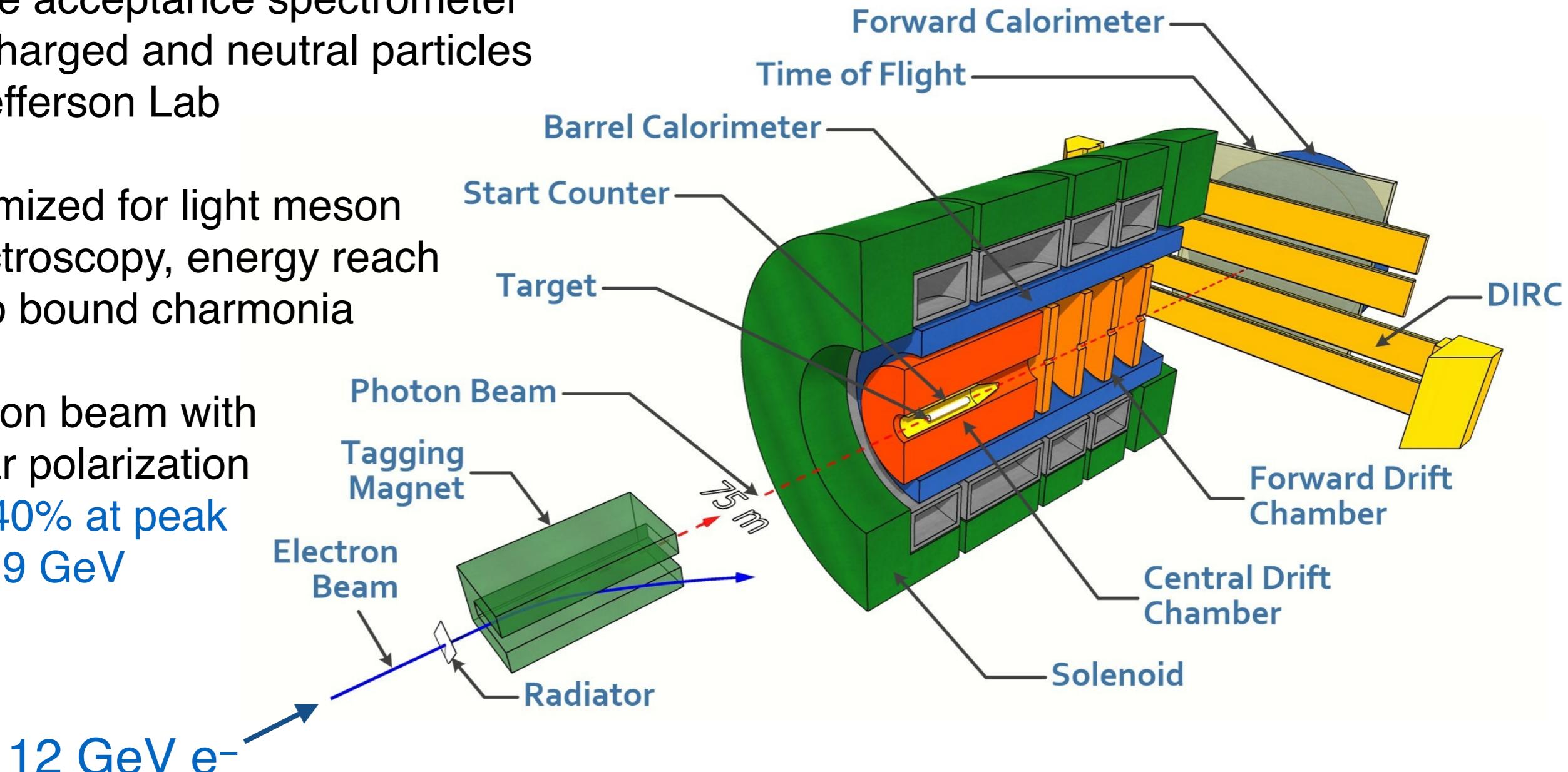
- Photon provides well-defined initial state, interacts through VMD
 - Photon polarization provides constraints on production processes, probe of hadron properties
- Photons couple to proton through exchanged QNs, can produce mesons of any J^{PC}

The GlueX Experiment

Large acceptance spectrometer
for charged and neutral particles
at Jefferson Lab

Optimized for light meson
spectroscopy, energy reach
up to bound charmonia

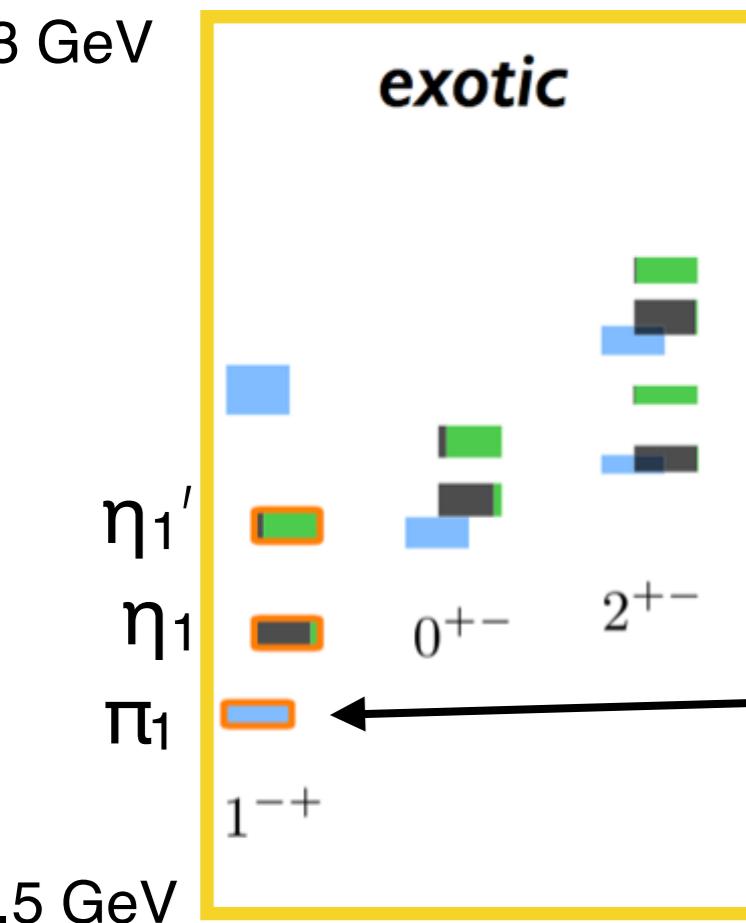
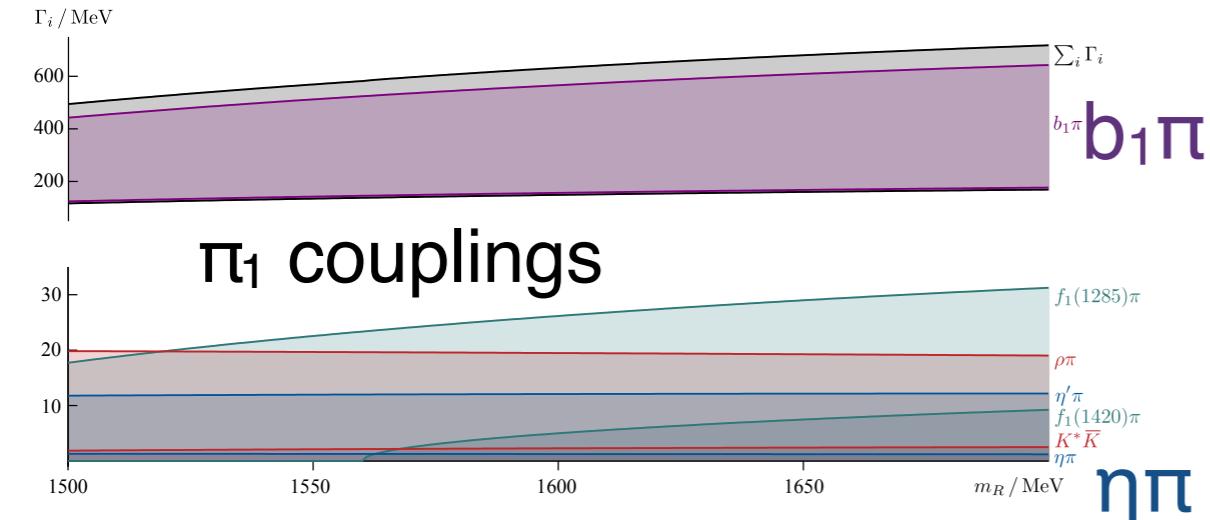
Photon beam with
linear polarization
 $P \approx 40\%$ at peak
 $E_\gamma \approx 9 \text{ GeV}$



- **GlueX-I (2017–2018): $L = 305 \text{ pb}^{-1}$ [$E_\gamma > 8 \text{ GeV}$]**
- **GlueX-II (2020–2025?): $L = 320 \text{ pb}^{-1}$ (so far)
expect 3-4x GlueX-I**

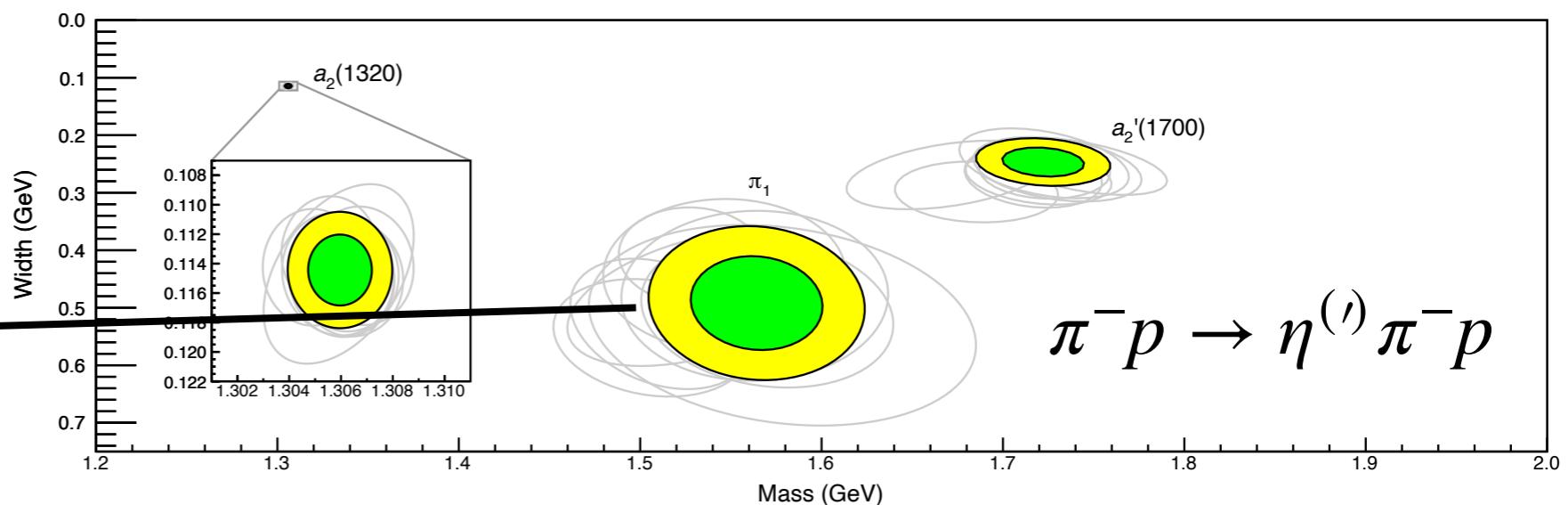
Hybrid Mesons

HadSpec: PRD 103, 054502 (2021)



HadSpec: PRD 88, 094505 (2013)

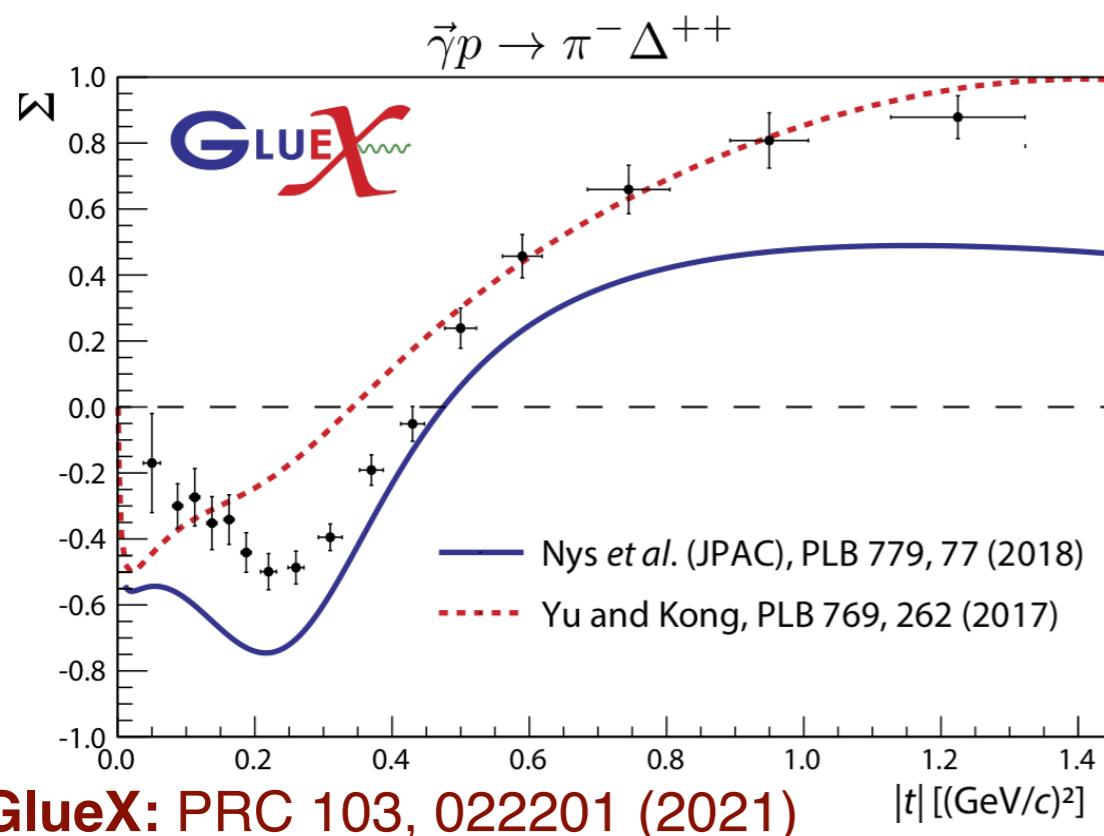
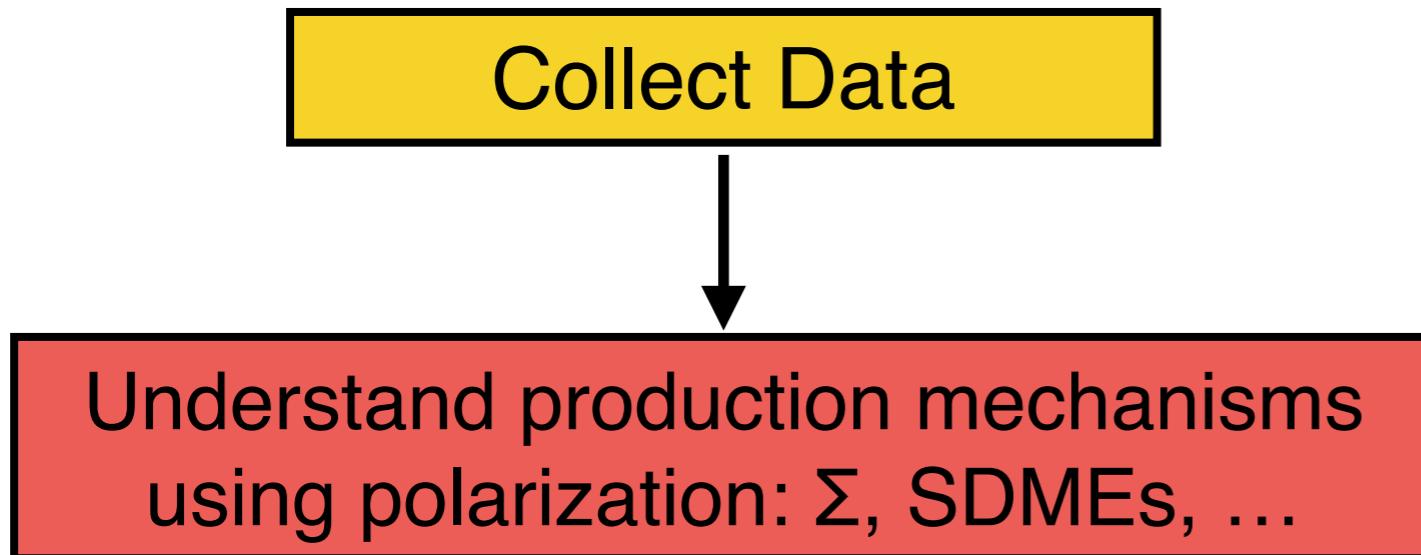
- Long history of search for “hybrid” mesons with gluonic excitations
- Best evidence is for $\pi_1(1600)$ in COMPASS pion-production data
- Recent evidence for $\eta_1^{(')}$ from BES-III in $J/\psi \rightarrow \gamma \eta \eta'$ [arXiv:2202.00621]
- Need to confirm π_1 and η_1 and establish the full light quark hybrid spectrum → insight to the heavy quark hybrid spectrum



JPAC: PRL 122, 042002 (2019)

Searching for Exotics in Photoproduction @ GlueX

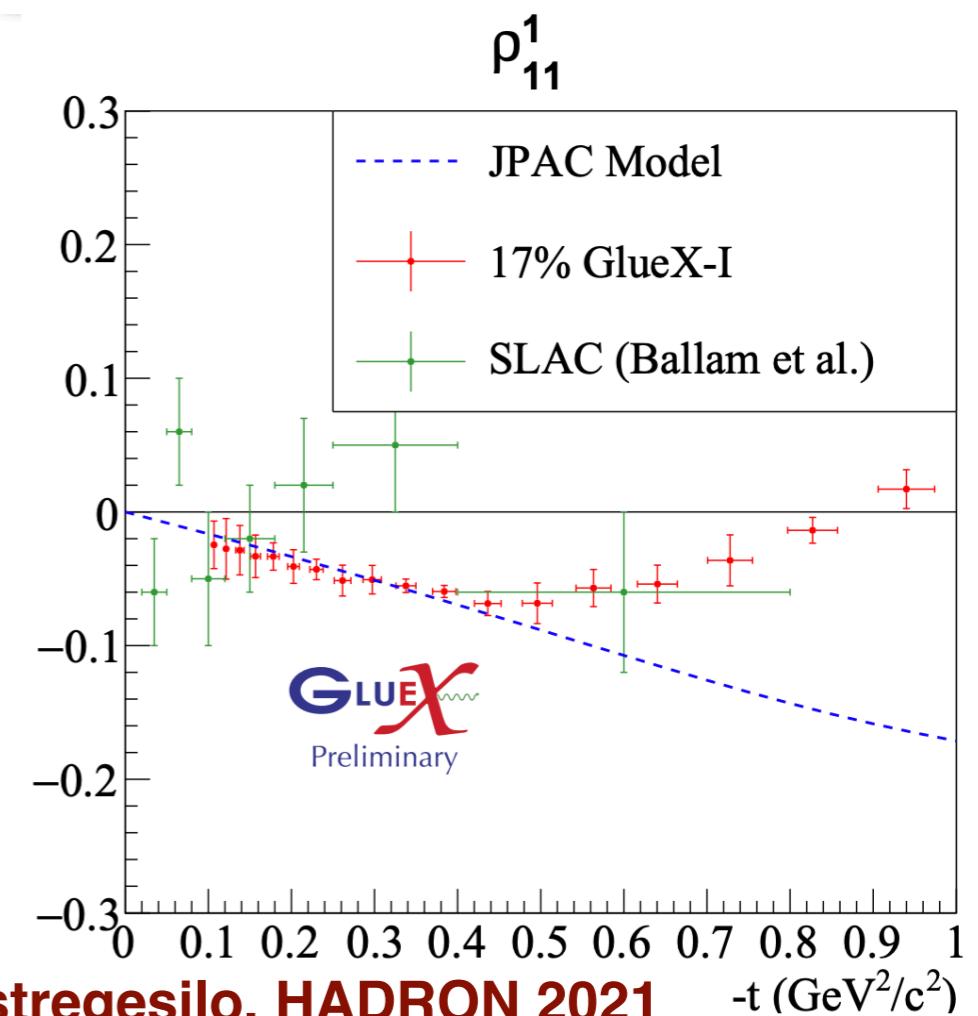
- Detailed understanding of light-quark meson spectrum requires amplitude analysis.



Beam Asymmetry Σ

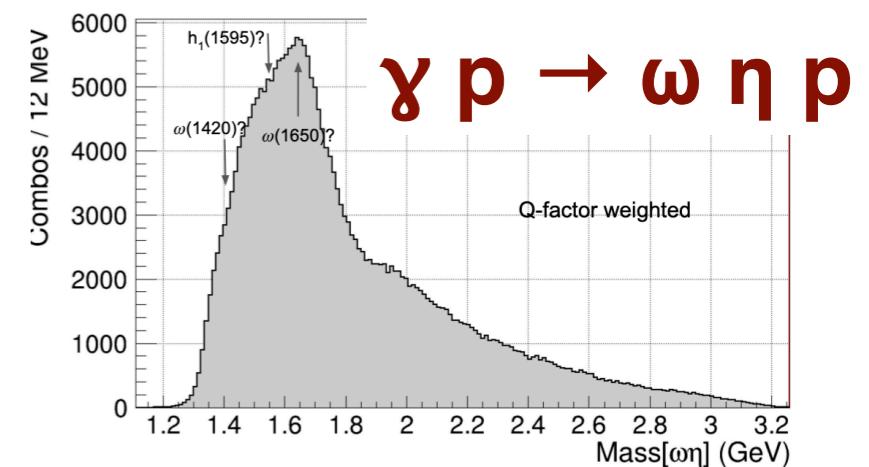
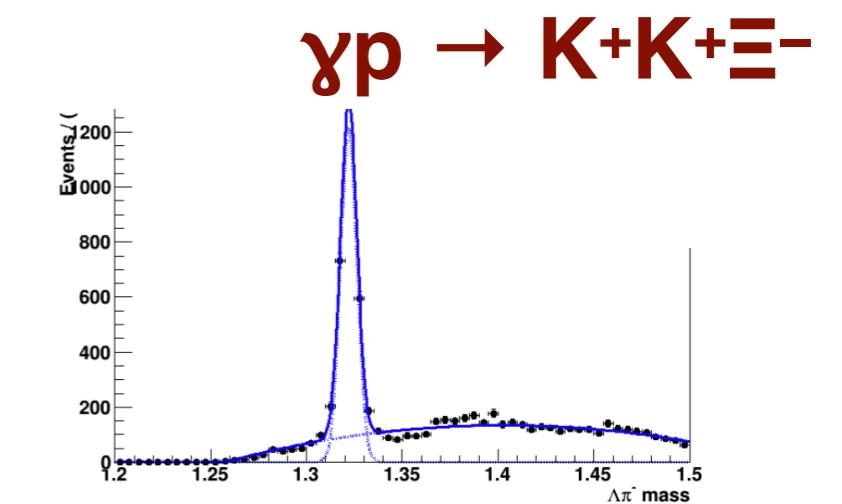
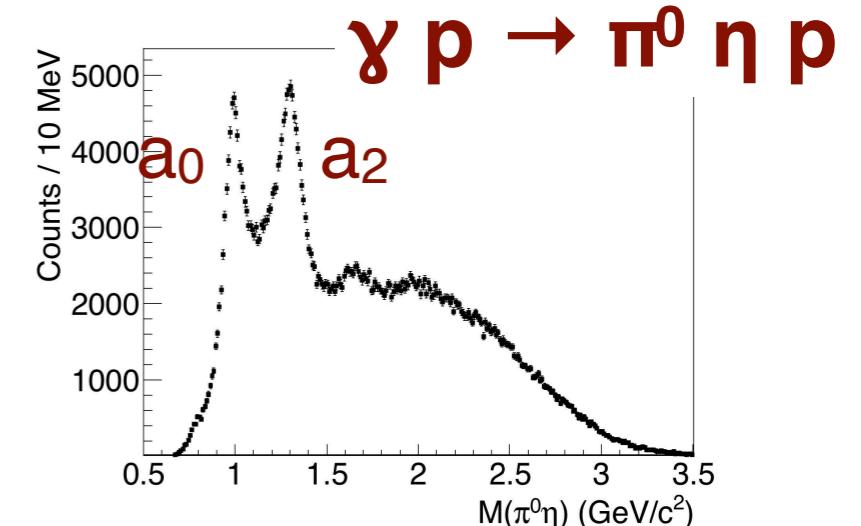
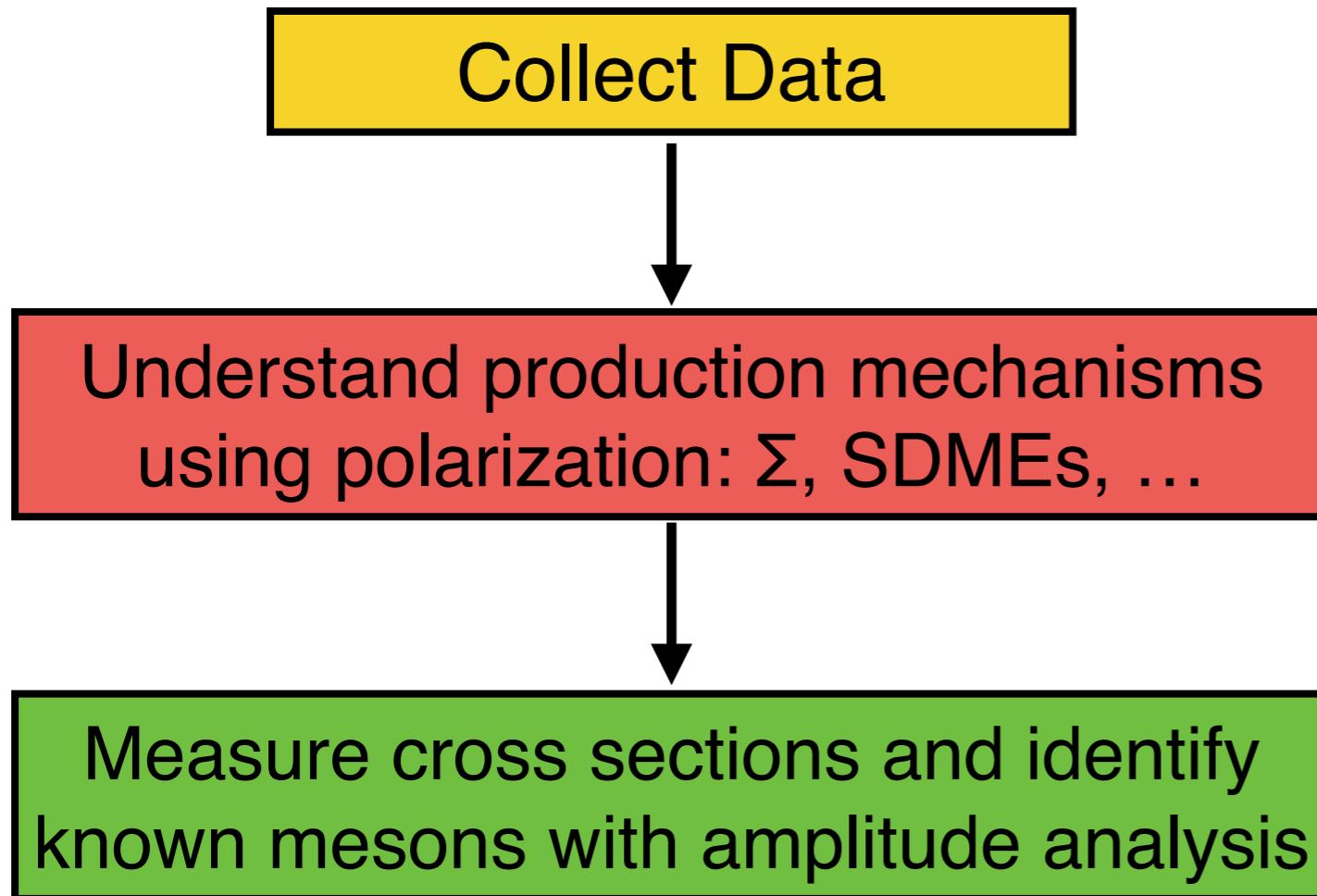
(π^0/η)p: Phys. Rev. C95, 042201 (2017)
(η/η')p: Phys. Rev. C100, 052201(R) (2019)
 $K^+\Sigma^0$: Phys. Rev. C101, 065206 (2020)
 $\pi^-\Delta^{++}$: Phys. Rev. C103, 022201 (2021)
 $K^+\Lambda(1520)$: sub. to PRC
More coming...

SDMEs: ρ , ω , ϕ in progress



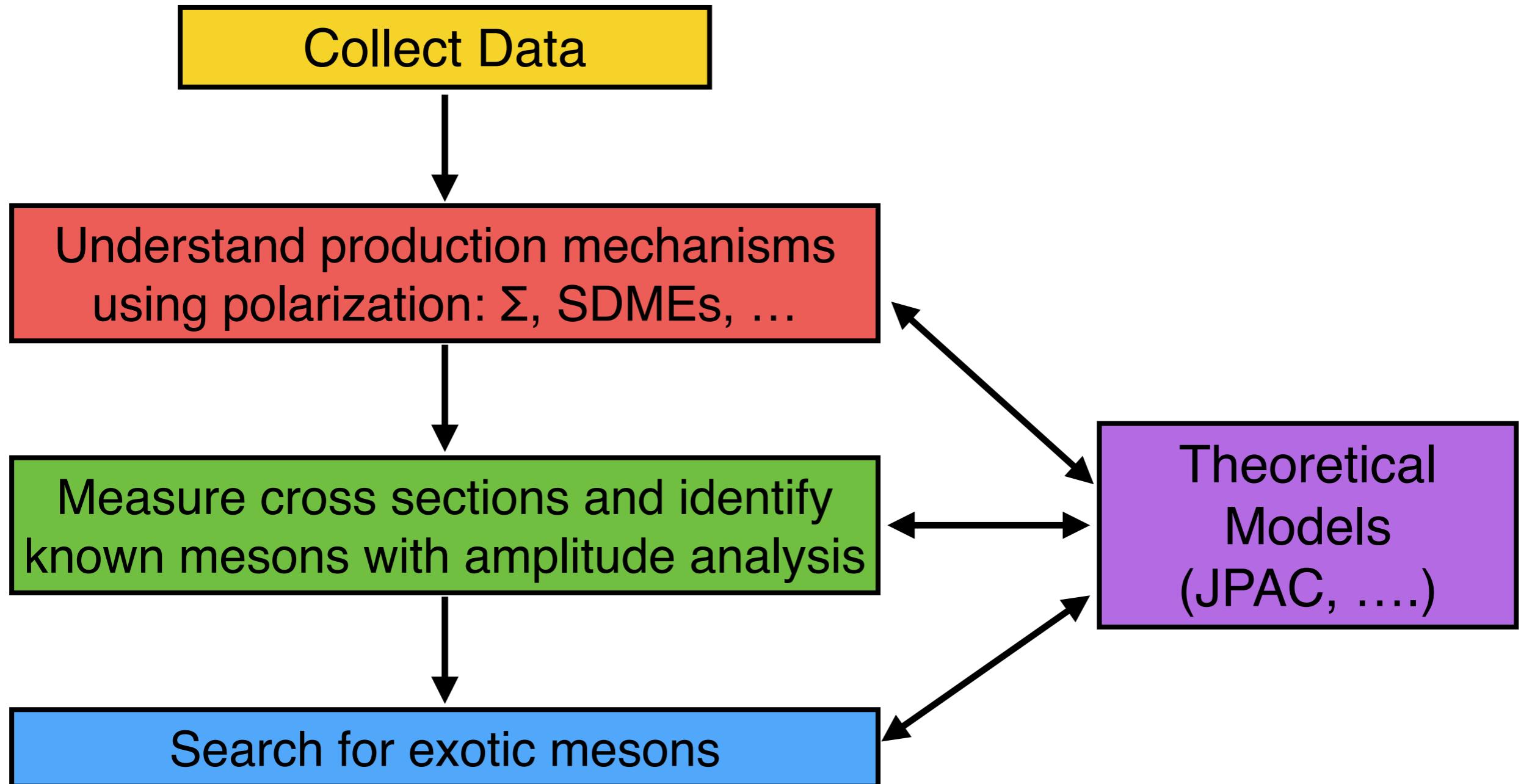
Searching for Exotics in Photoproduction @ GlueX

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.



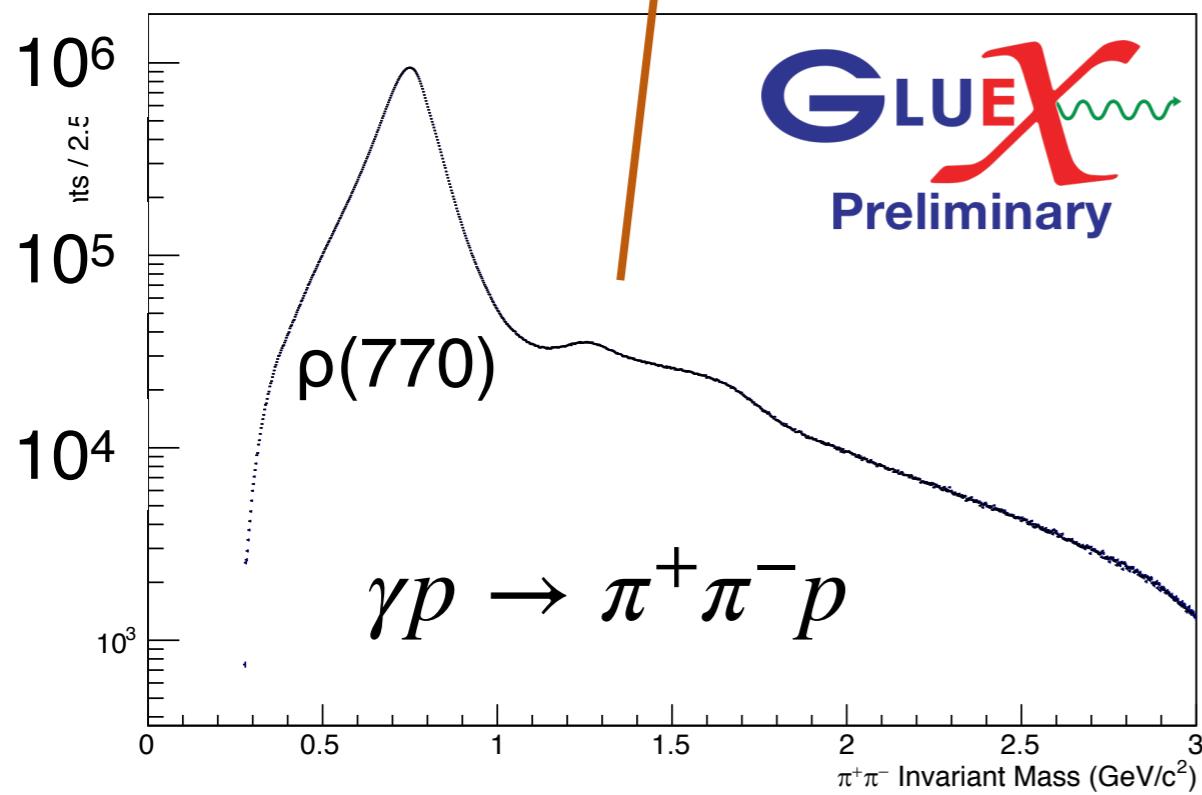
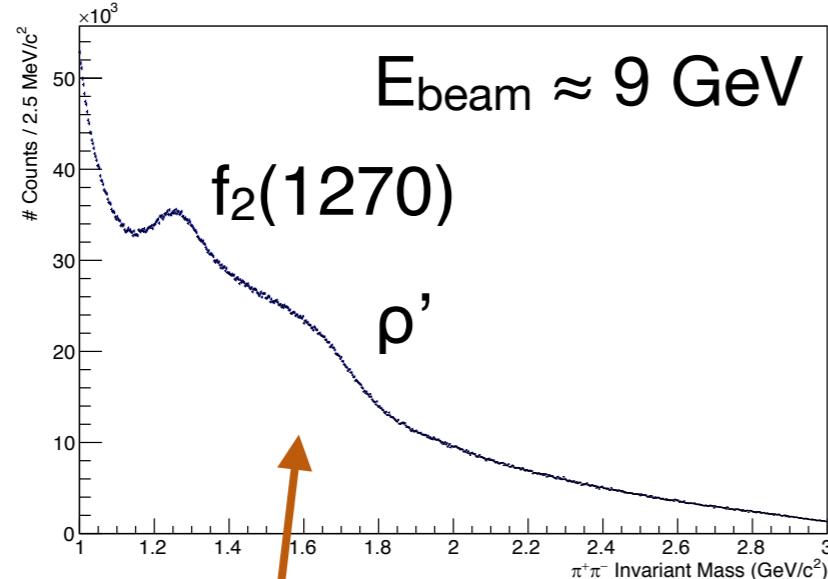
Searching for Exotics in Photoproduction @ GlueX

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

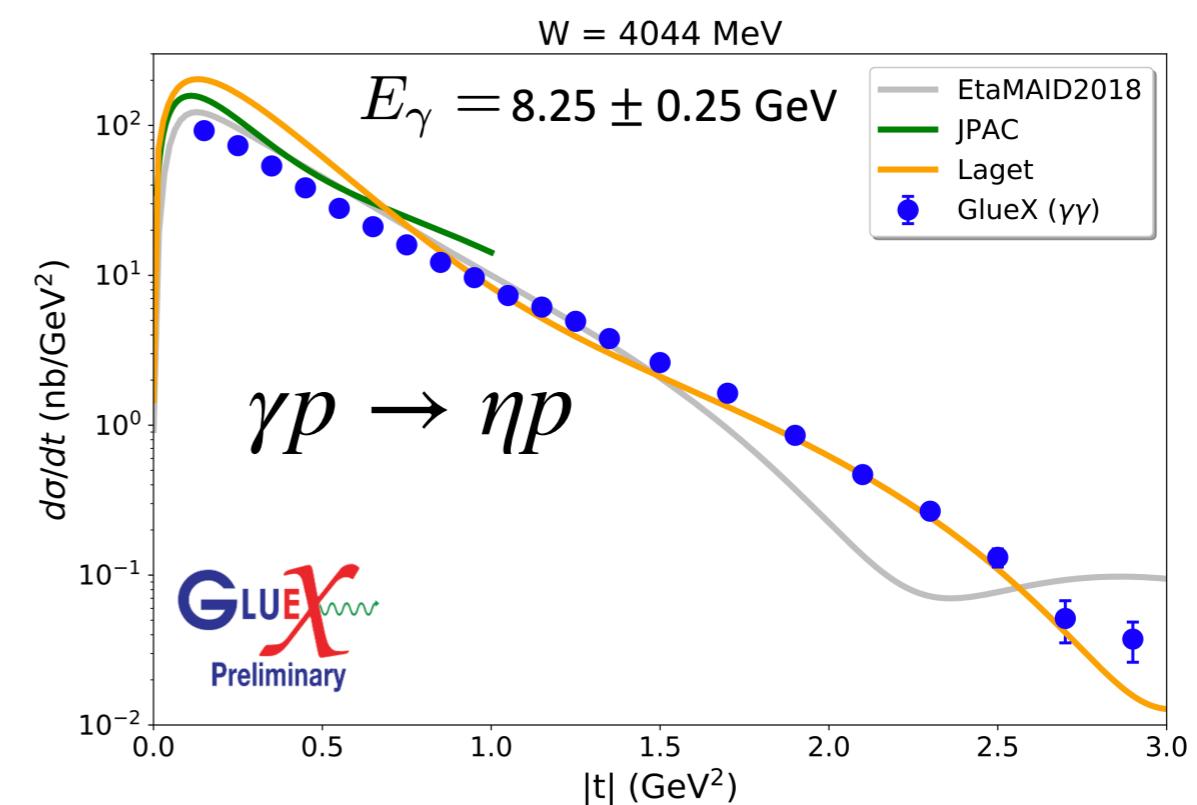


Start with $\eta\pi^0/\eta'\pi^0$ before moving to more complicated final states

GlueX: High Statistics Photoproduction Data



- GlueX has collected **orders of magnitude** more data than previous experiments at $E_\gamma \approx 9$ GeV
 - **> 5 times** more $\eta(\prime)\pi$ than COMPASS – amplitude analysis underway
- Hybrid search range allows searching for **strange XYZ partners**
 - $\phi(2170)$, Z_s , ...

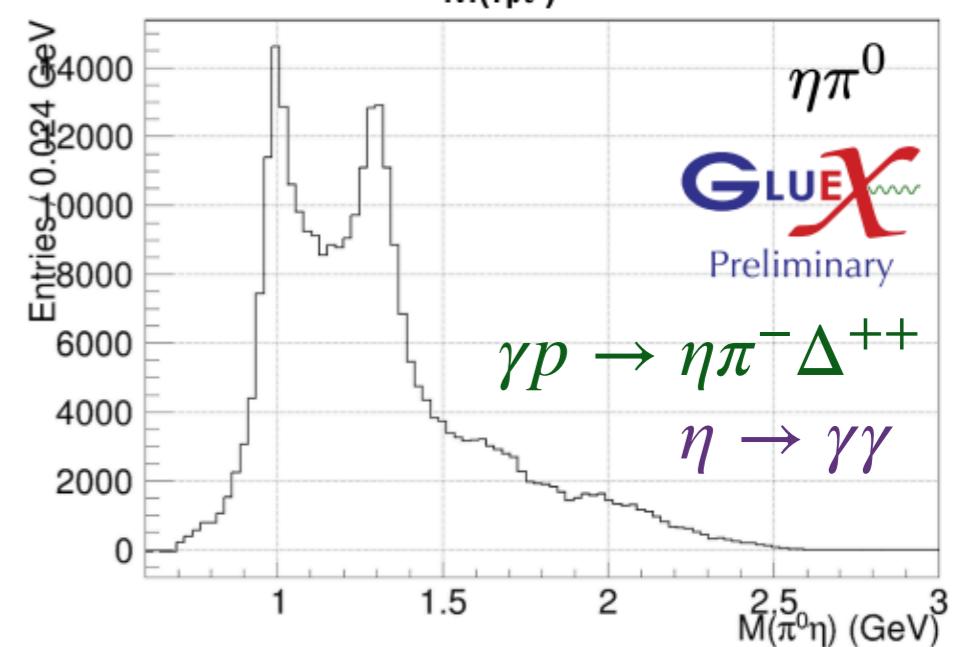
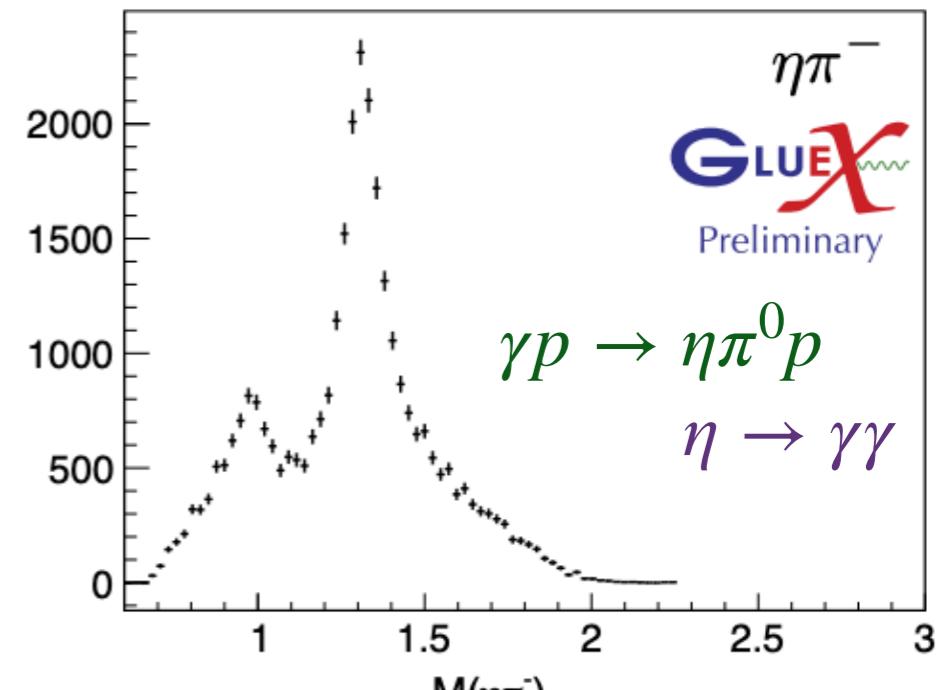


$\eta\pi$ Amplitude Analysis at GlueX

- $\pi\eta / \pi\eta'$ “golden channels” for π_1 search:
small b.f. but experimentally clean
 - Odd L $\pi\eta^{(1)}$ \rightarrow exotic JPC
 - Study known a_0/a_2 in $\pi\eta$ (focus here)
 - Apply analysis to $\pi\eta'$ with stronger π_1
- Can study several channels
 - $\gamma p \rightarrow \eta\pi^0 p$
 - $\gamma p \rightarrow \eta\pi^-\Delta^{++}$
 - Control understanding of production
- with multiple η decays
 - $\eta \rightarrow \gamma\gamma$
 - $\eta \rightarrow \pi^+\pi^-\pi^0$
 - Control understanding of acceptance and backgrounds

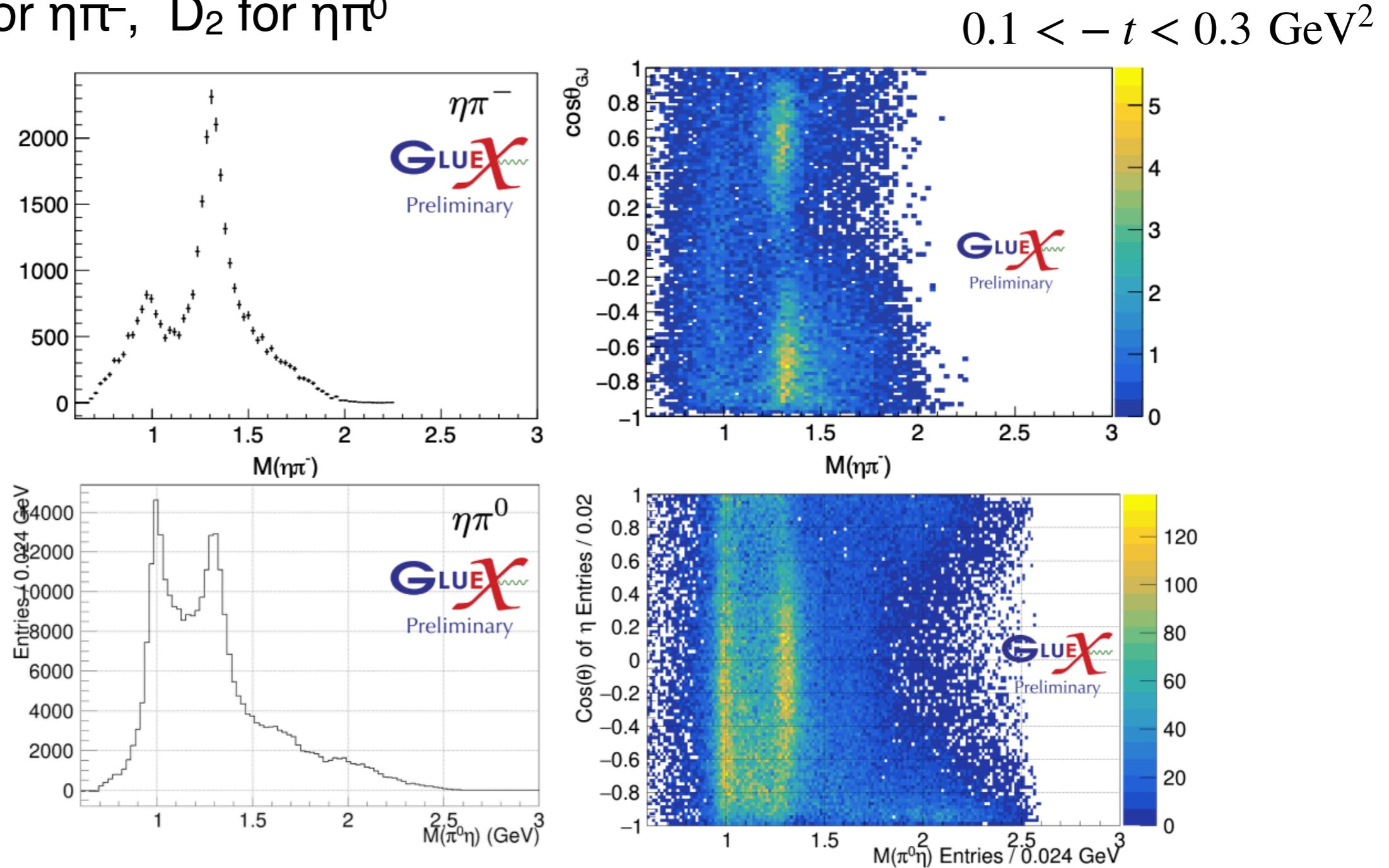
GlueX-I Data

$$0.1 < -t < 0.3 \text{ GeV}^2$$



$\eta\pi$ Amplitude Analysis at GlueX

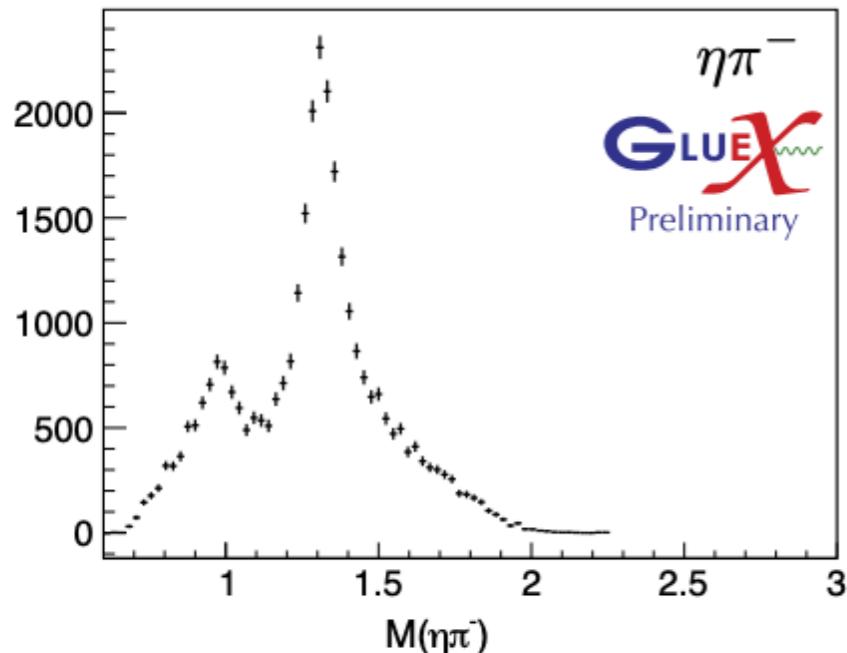
- Clear signals at $a_0(980)$ and $a_2(1320)$ masses
- Different angular dependence \rightarrow different dominant production wave
 - D_1 for $\eta\pi^-$, D_2 for $\eta\pi^0$



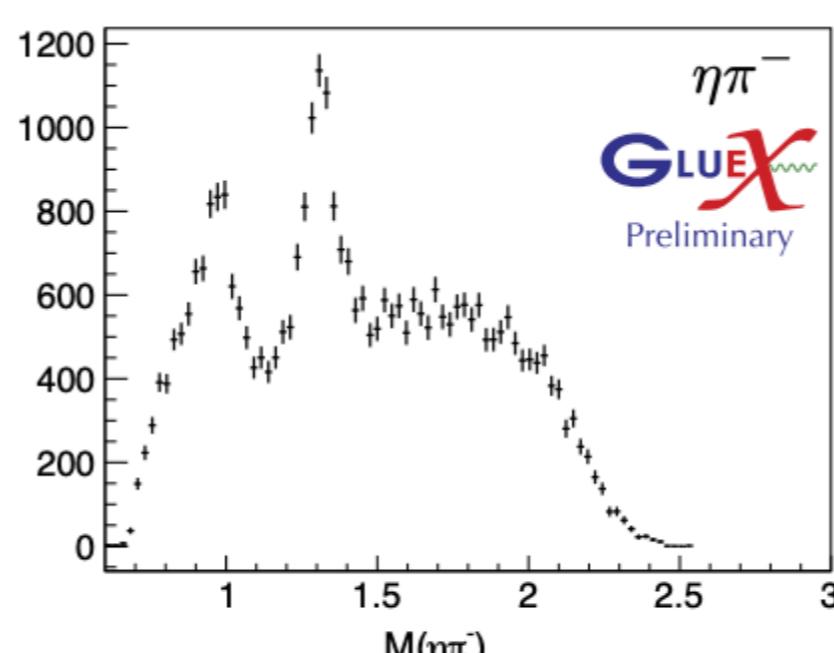
$\eta\pi$ Amplitude Analysis at GlueX

- Clear signals at $a_0(980)$ and $a_2(1320)$ masses
 - Peaks have different t -dependence

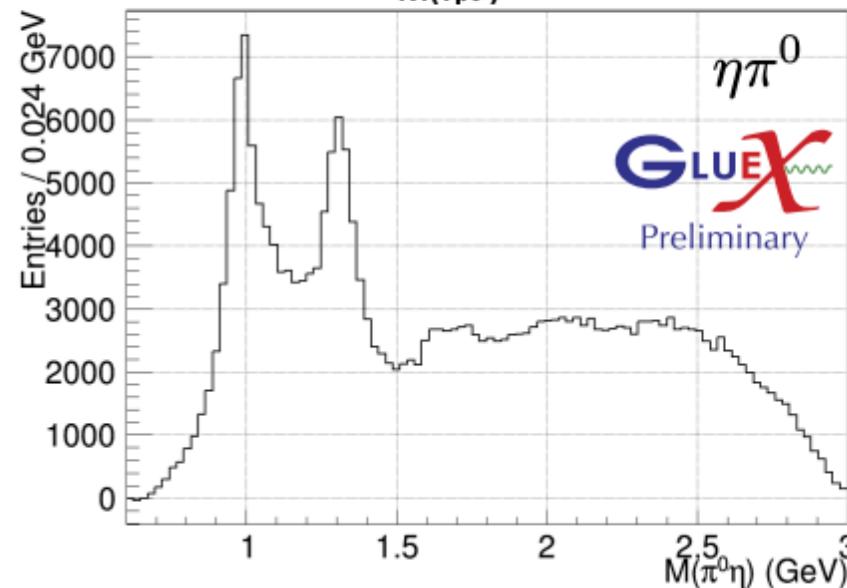
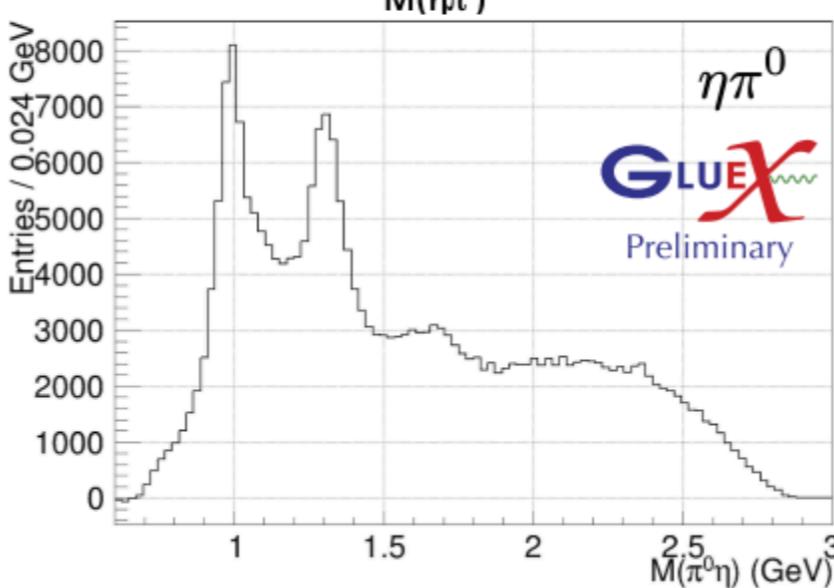
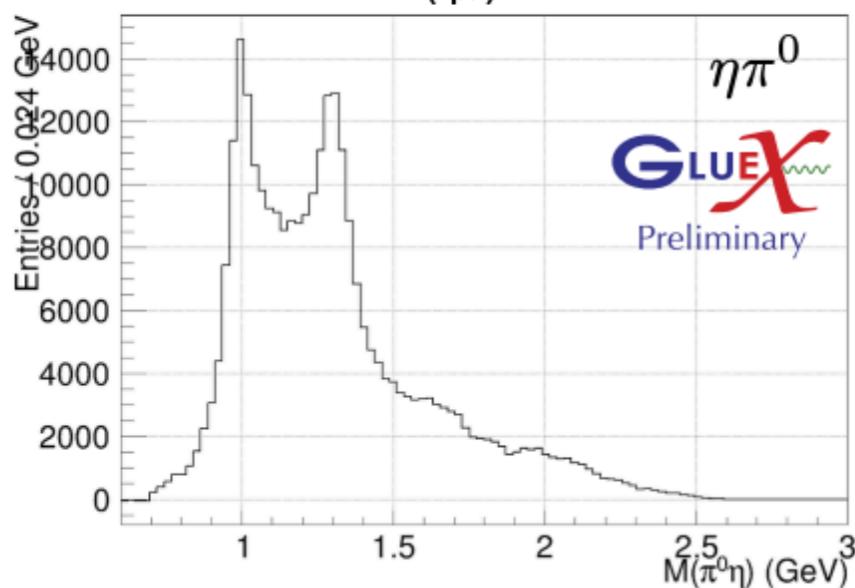
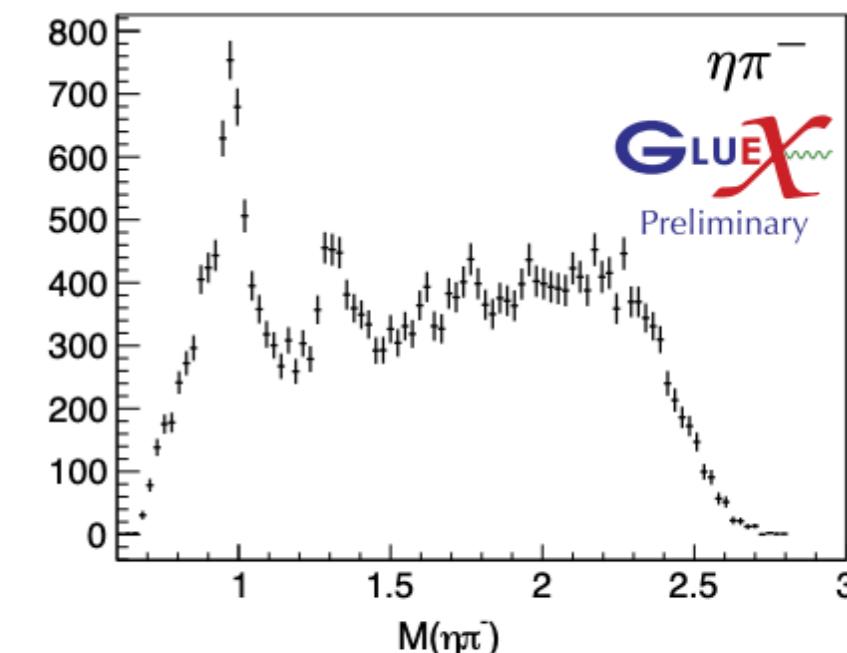
$$0.1 < -t < 0.3 \text{ GeV}^2$$



$$0.3 < -t < 0.6 \text{ GeV}^2$$

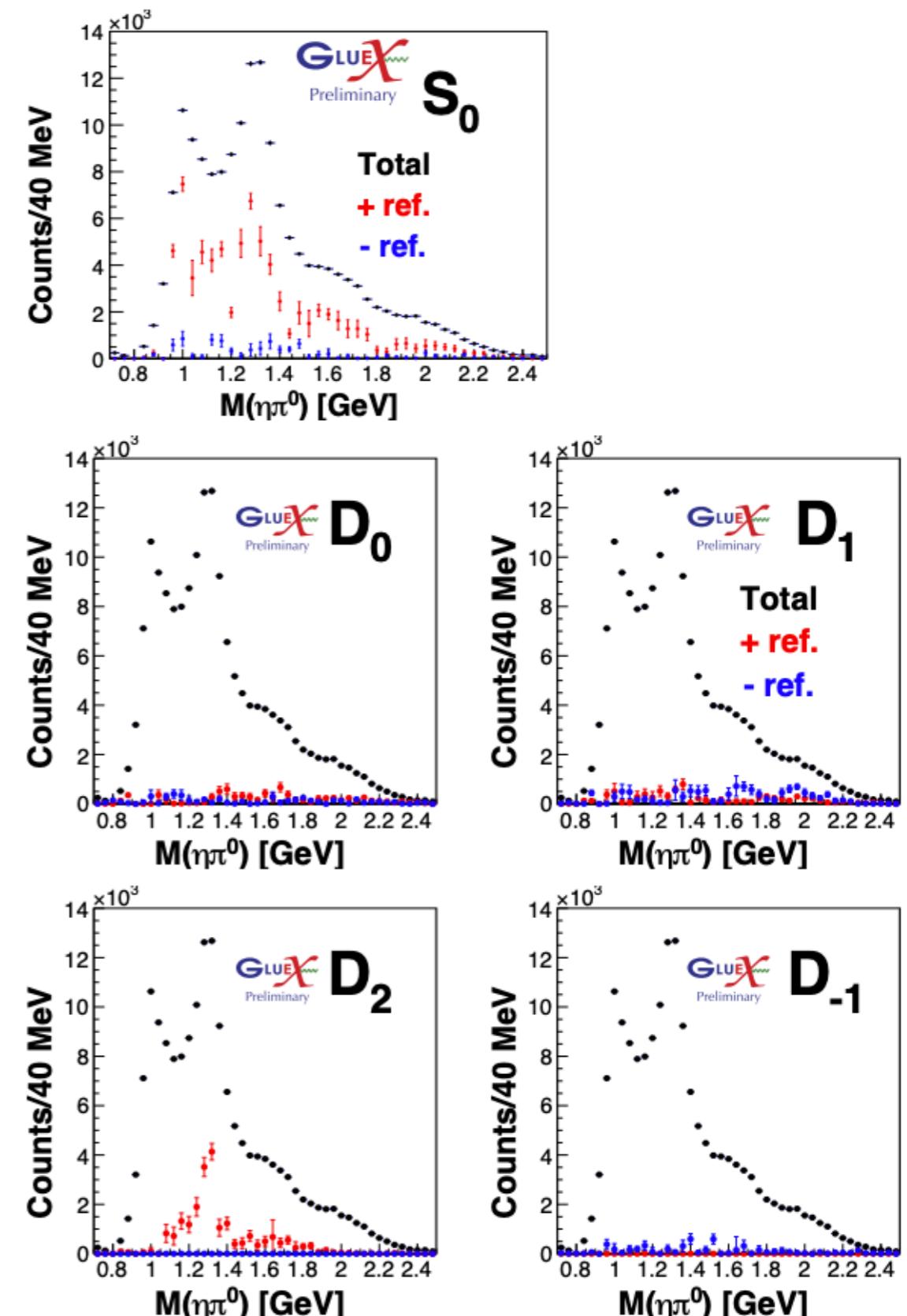


$$0.6 < -t < 1.0 \text{ GeV}^2$$



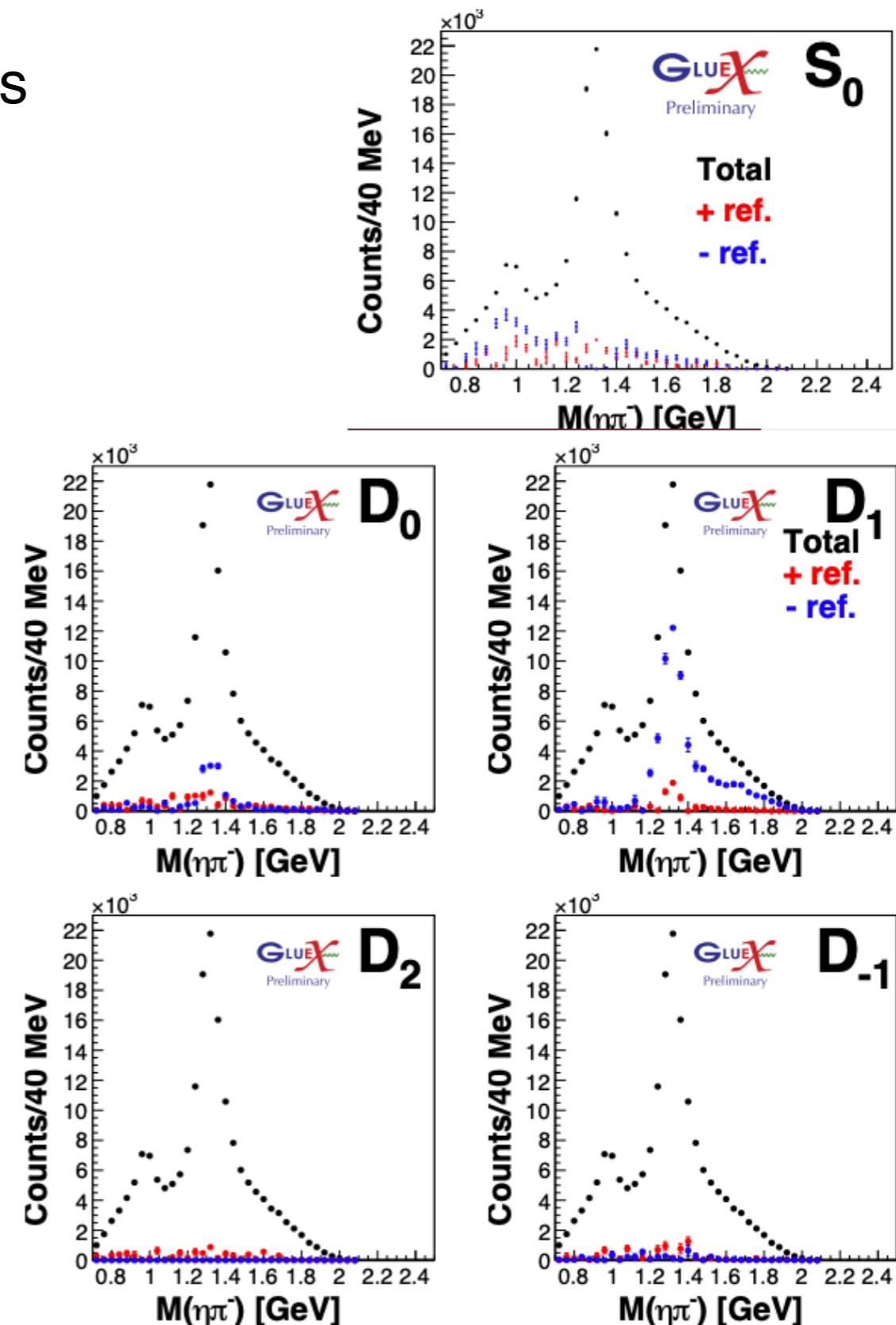
Fit to GlueX data for $\gamma p \rightarrow \eta\pi^0 p$ [$0.1 < -t < 0.3$ GeV 2]

- Preliminary fit to data allows us to start understanding features
- Combined fit to all polarization orientations with new photoproduction model
JPAC: PRD 100, 054017 (2019)
- Waveset based on TMD model
JPAC: PRD 102, 014003 (2020)
 - $S_0^\pm, D_0^\pm, D_1^\pm, D_2^+ D_{-1}^-$
- Large S-wave contribution
 - Non-resonant? a_0 's?
- Clear signal in $m=+2$ D-wave [[a₂\(1320\)](#)]
 - Dominant ρ/ω exchange
 - Similar to **helicity-2** dominance in $\gamma\gamma \rightarrow \eta\pi^0$ at Belle
- Systematic studies of wavelets, leakage, ambiguities, etc. ongoing



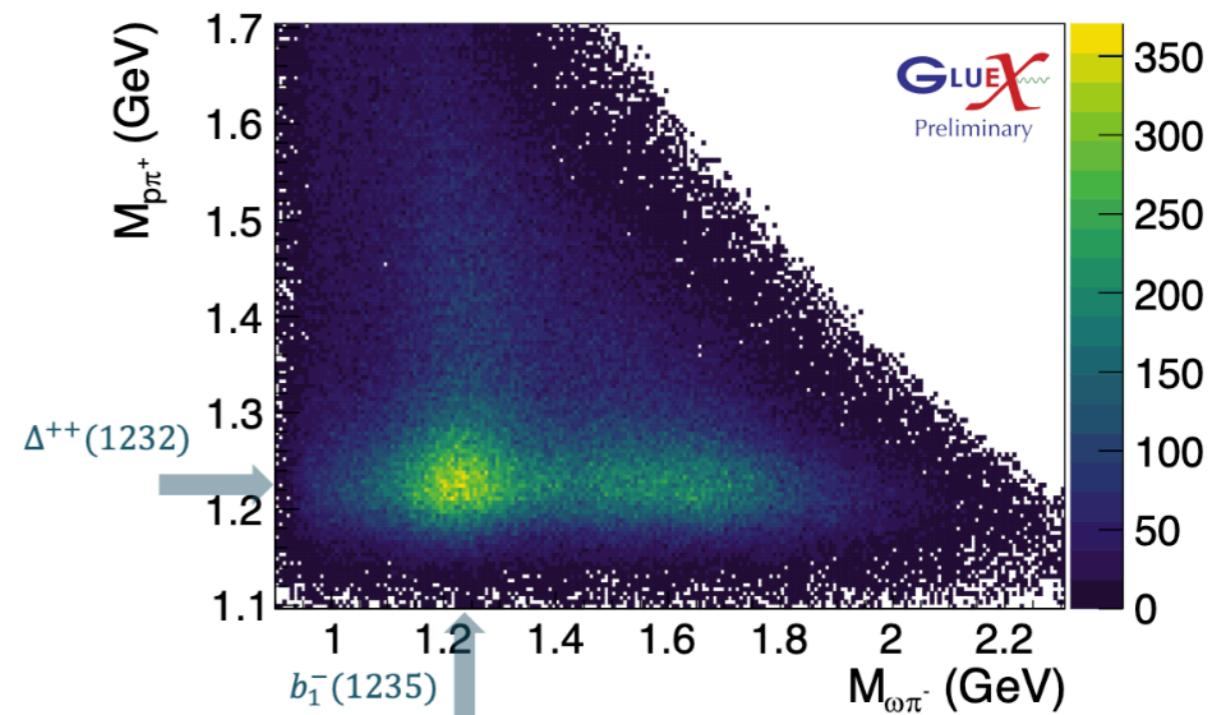
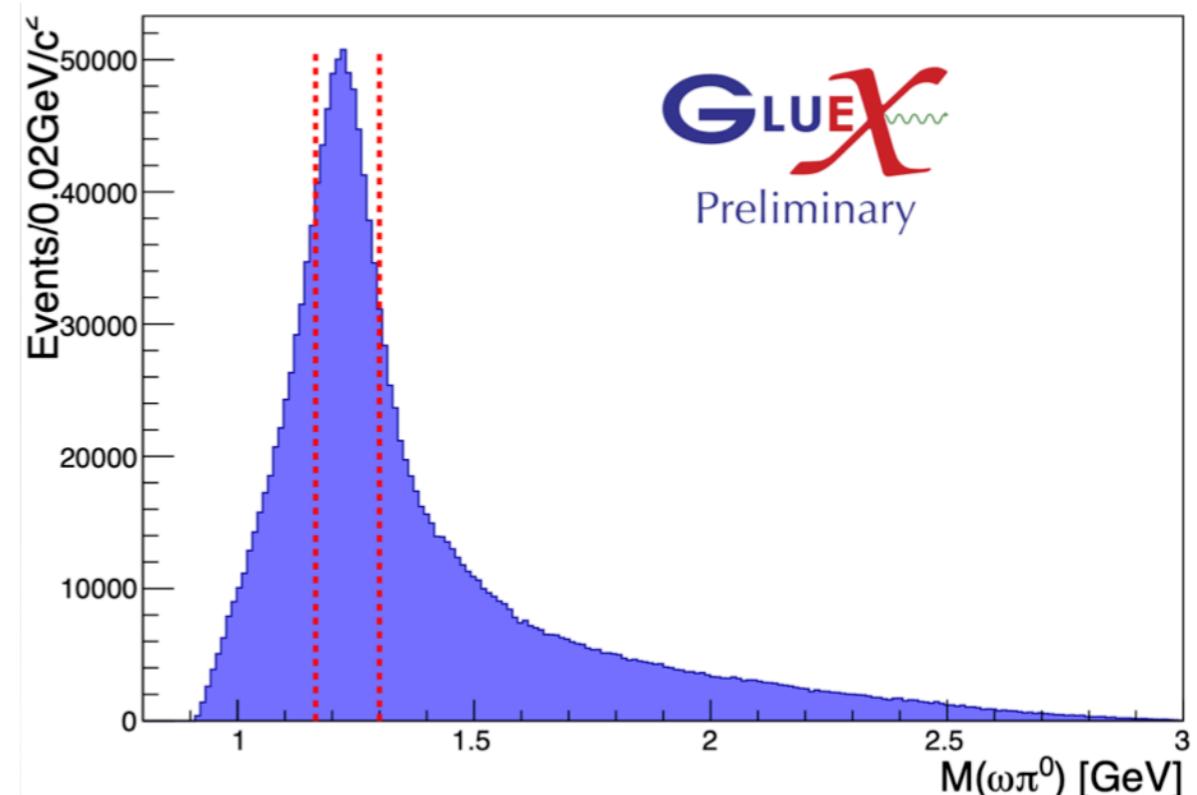
Fit to GlueX data for $\gamma p \rightarrow \eta\pi^-\Delta^{++}$ [$0.1 < -t < 0.3$ GeV 2]

- Combined fit to all polarization orientations with new photoproduction model
JPAC: PRD 100, 054017 (2019)
- Large S-wave contribution
 - Strongest in $a_0(980)$ region
- Clear signal in $m=-1$ D-wave [**$a_2(1320)$**], negative reflectivity
 - Dominant π exchange
 - Tail related to **$a_2(1700)$** ?
- Systematic studies ongoing
- Next steps:
 - Near-term goal: a_2 production studies
 - Understand other processes which could generate asymmetry, e.g., baryon prod., Double Regge exch.



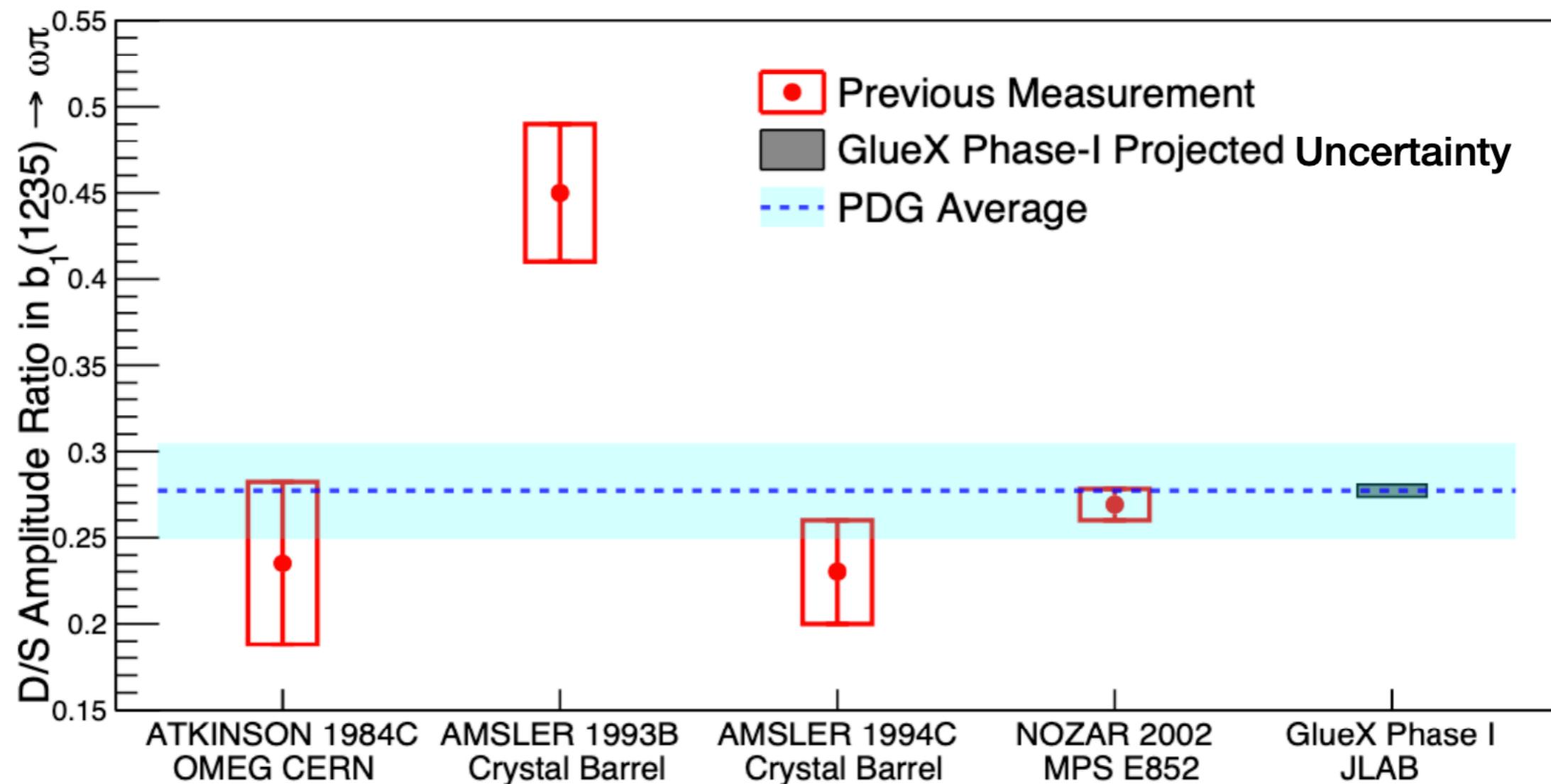
Study of $b_1(1235)$ at GlueX

- LQCD predicts dominant π_1 decay to be $b_1\pi$ ($\rightarrow 5\pi$)
- First step: understand b_1 production and decay to $\omega\pi$
 - Also search for excited vectors and others
 - Extend analysis to other VP channels ($\omega\eta$, $\phi\pi$, $\phi\eta$, ...)
- Access to charged and neutral b_1
 - $\gamma p \rightarrow b_1^0 p \rightarrow \omega\pi^0 p$
 - $\gamma p \rightarrow b_1^- \Delta^{++} \rightarrow \omega\pi^- \Delta^{++}$



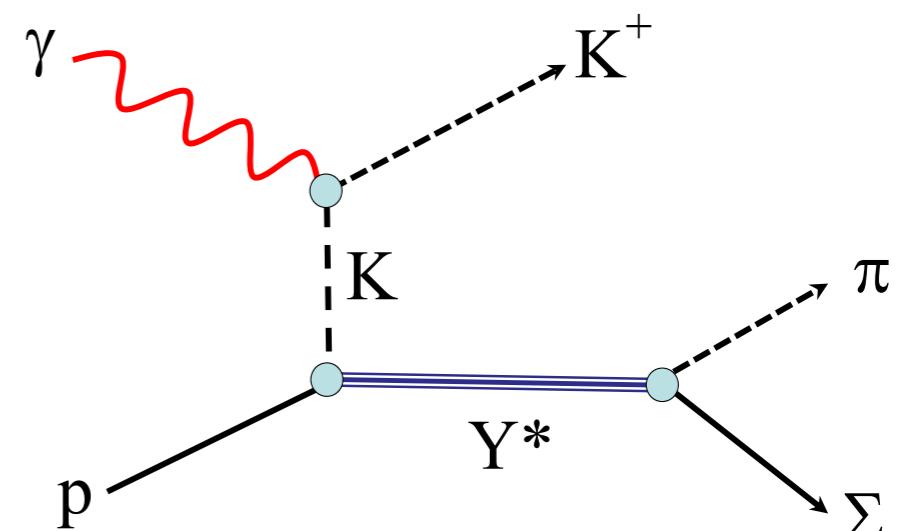
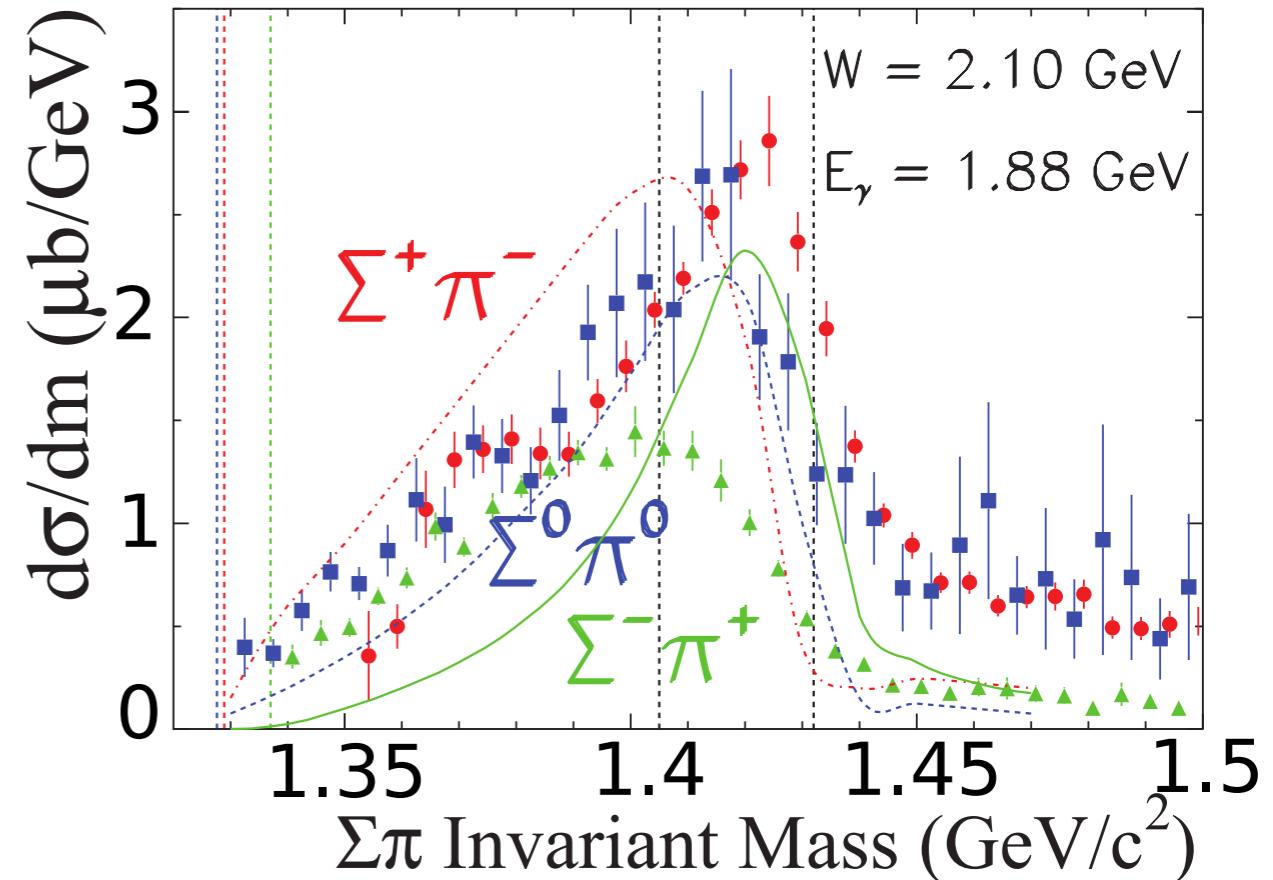
Study of $b_1(1235)$ at GlueX: S/D ratio

- Can use amplitude model for VP photoproduction to measure ratio of D/S amplitudes in $b_1 \rightarrow \omega\pi$
HadSpec: PRD 100, 054506 (2019)
LCQD: $|D/S| = 0.27(20)$
- First test of model finds good fits with 1^+ and 1^- waves near b_1 peak



$\Lambda(1405)$ in Photoproduction

- $\Lambda(1405)$ lies just below $\bar{K}N$ threshold
 - $I=0 \quad J^P = 1/2^-$
 - Decays to $\Sigma\pi$
- Lineshape not simple B-W
- Nature of state has been long discussed
 - 2 poles?
 - Something else?
- Current lineshape studies limited by knowledge of $\Sigma^0\pi^0$ channel
 - Pure $I=0$, no $\Sigma(1385)$ bkgd.

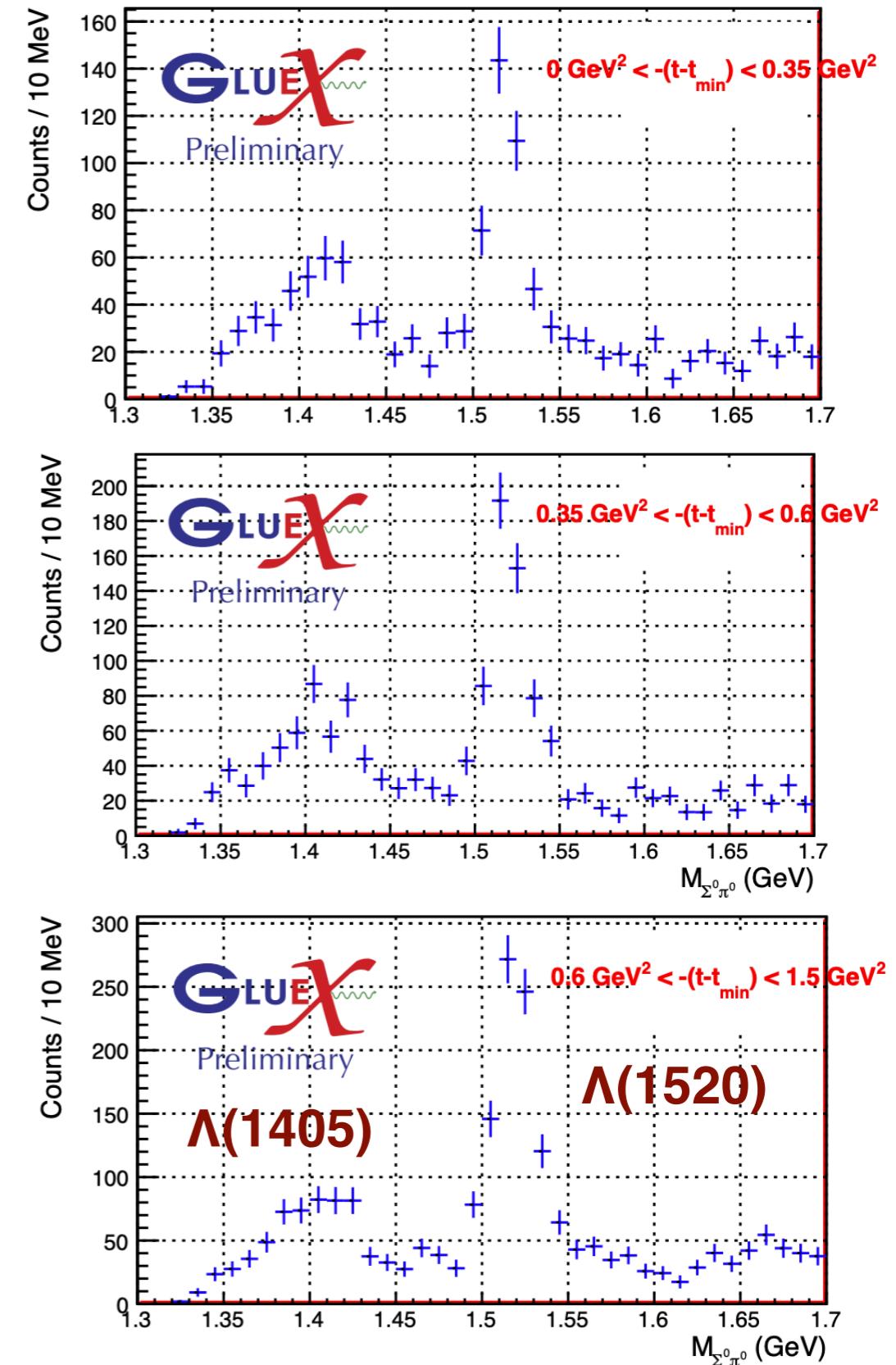


PPNP 120,103868 (2021)
EPJST 230, 1593 (2021)

CLAS, PRC 87, 035206 (2013)

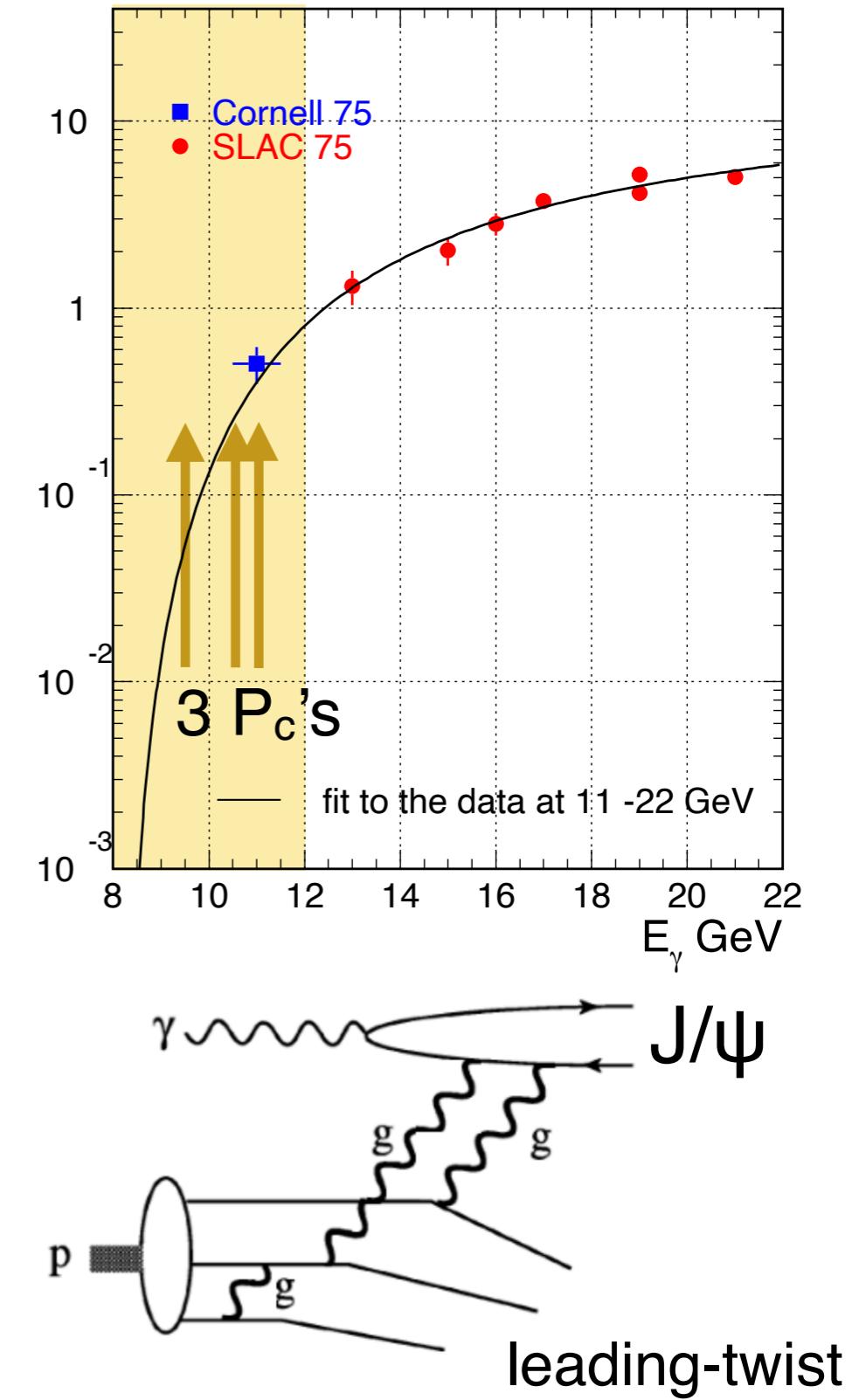
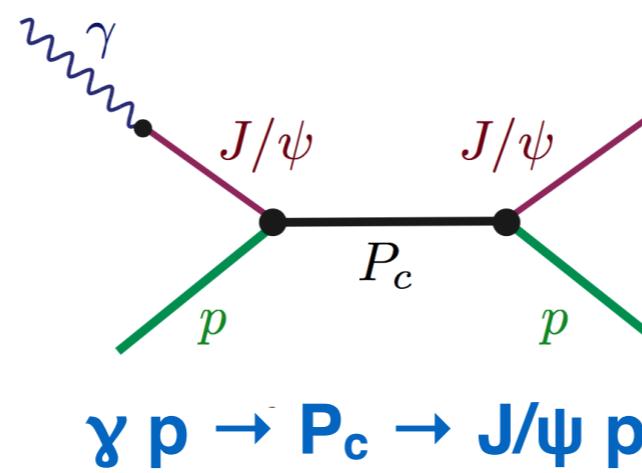
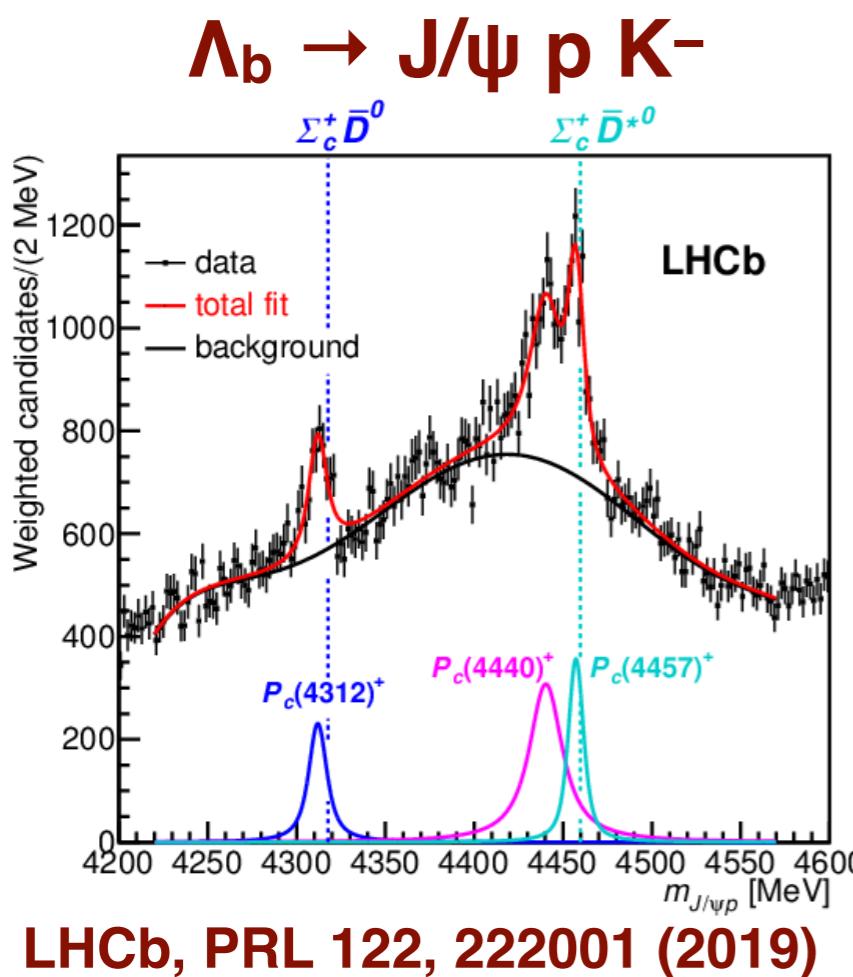
$\Lambda(1405)$ in Photoproduction @ GlueX

- Mass spectra shown for 20% of GlueX-I data in $\gamma p \rightarrow K^+ \Sigma^0 \pi^0$
- Yields shown in 3 t-bins without acceptance correction
 - Clear $\Lambda(1405)$ and $\Lambda(1520)$ signals
- With full GlueX-I data, we can study E_γ and t-dependence of lineshape using largest sample of $\Sigma^0 \pi^0$ available (>10k events in $\Lambda(1405)$ region)

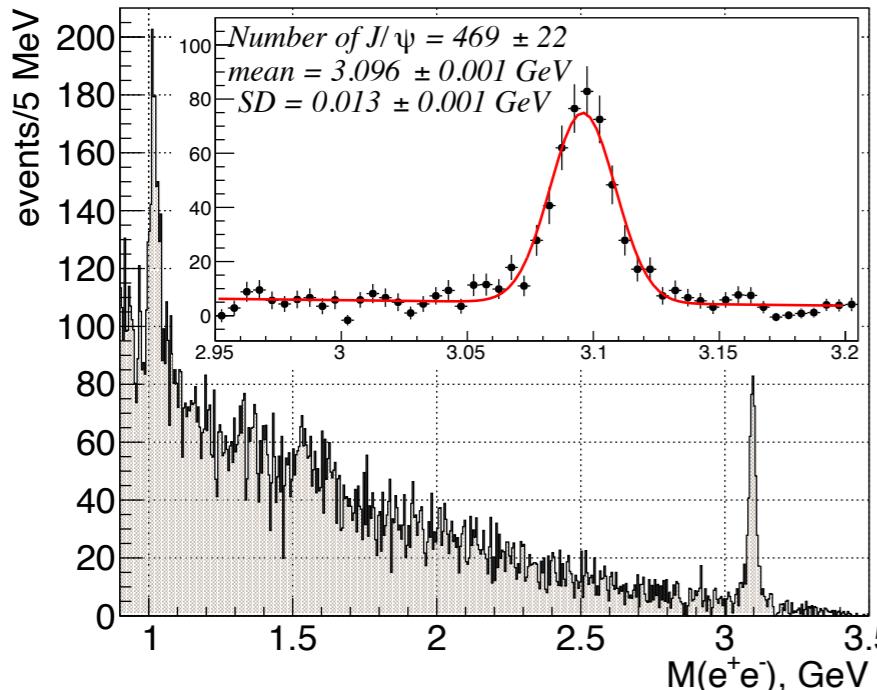


Charmonium Photoproduction Near Threshold

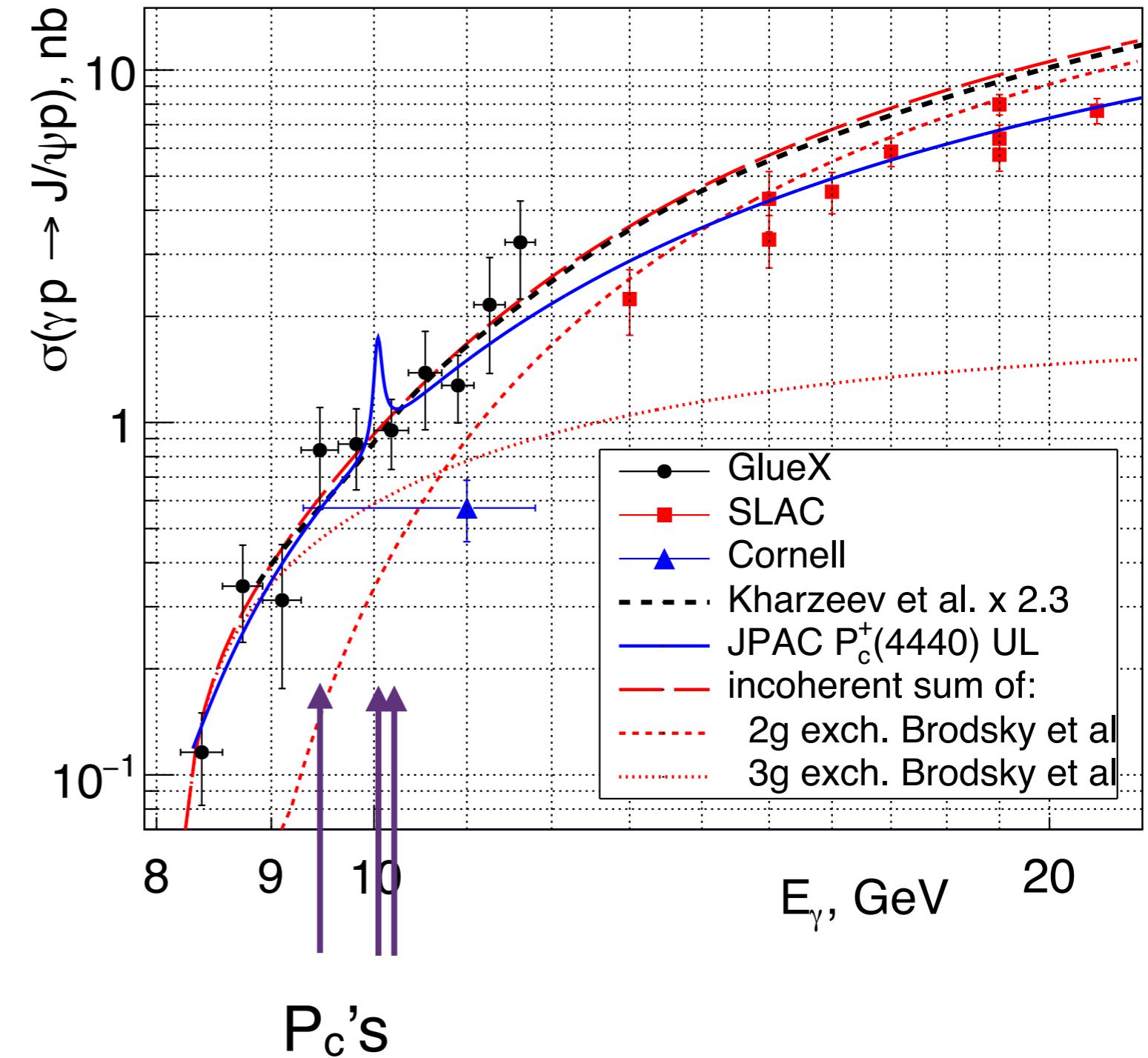
- Production of $c\bar{c}$ near threshold probes the distribution of gluons in the proton and the nature of the proton mass
- Can also look for s-channel production of resonant states



Published GlueX J/ ψ Photoproduction Results



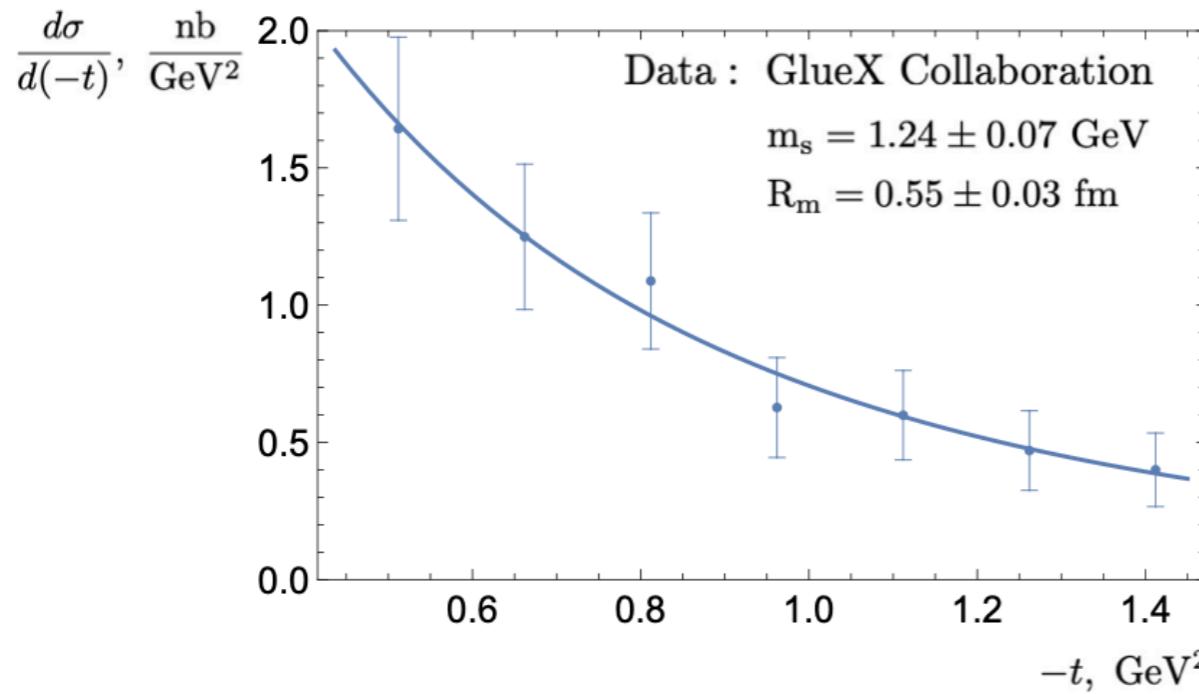
GlueX: PRL 123, 072001 (2019)



- Used portion of GlueX-I data [469 J/ ψ] to measure cross sections
- 27% normalization uncertainty
- Model-dependent limits set on P_c production

Interpretations of GlueX J/ ψ Photoproduction Results

Kharzeev, PRD 104, 054015 (2021)



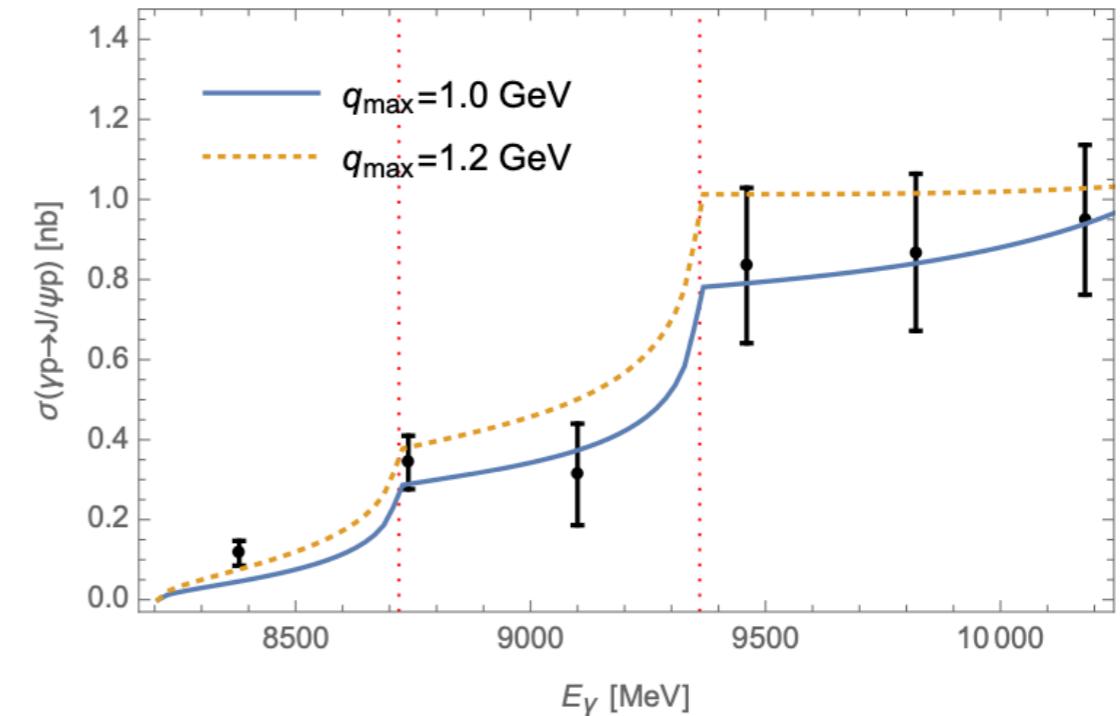
mass radius: $R_m = 0.55 \pm 0.03$ fm

charge radius: $R_c = 0.8409 \pm 0.0004$ fm

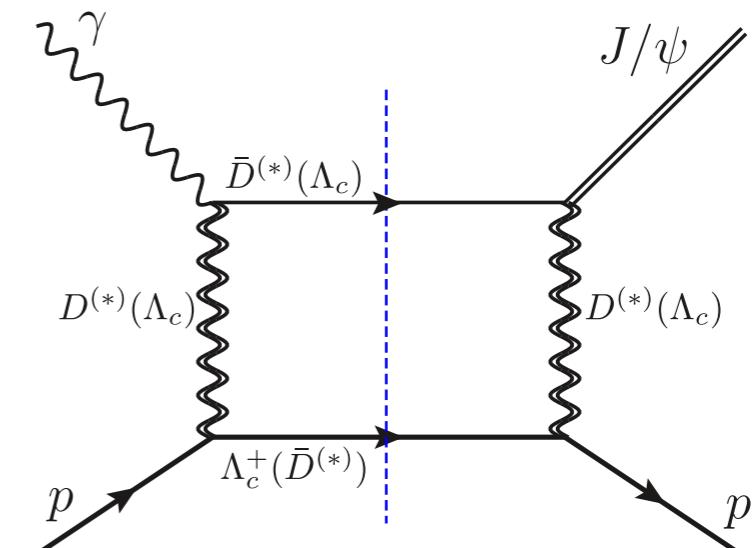
More data closer to the threshold is needed

- Interpretation depends on understanding production mechanism

Du et al., EPJC 80, 1053 (2020)

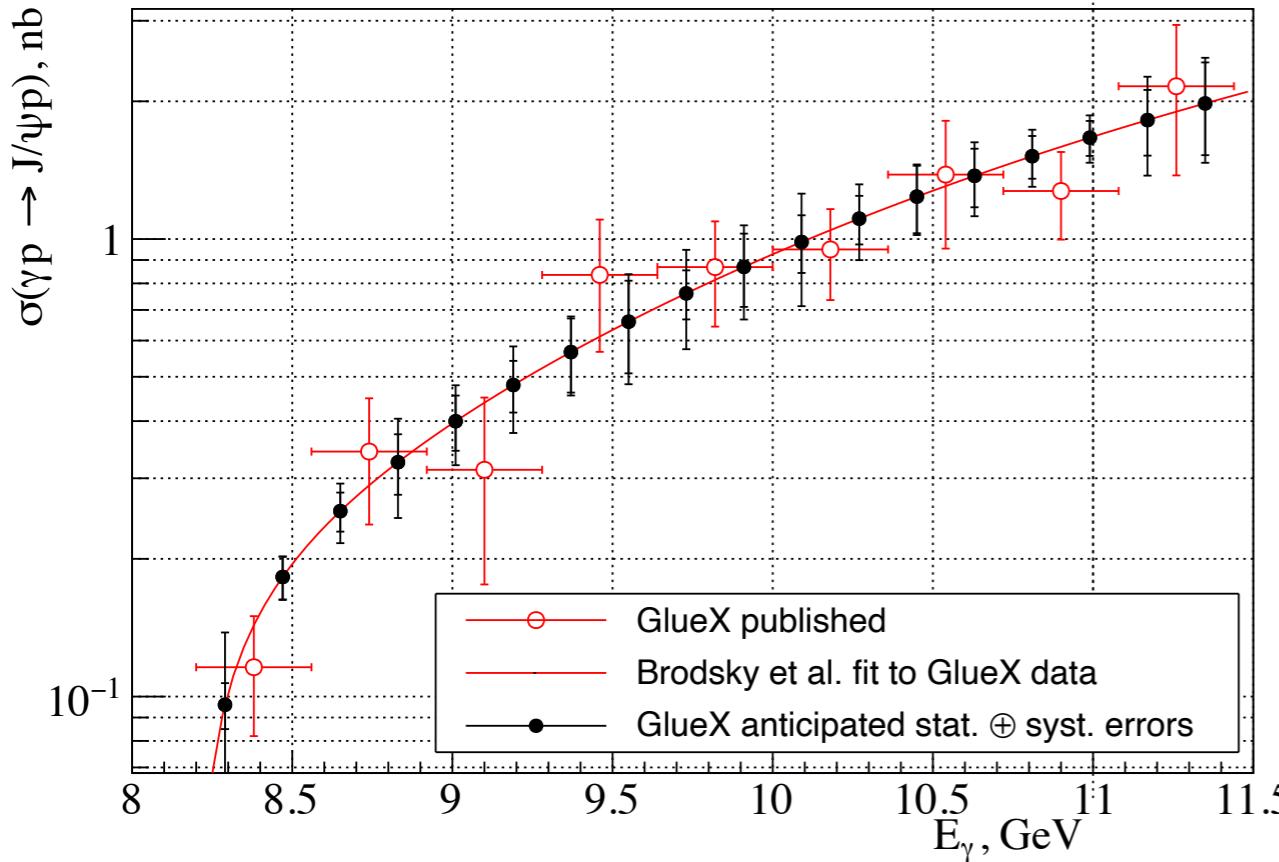


Implies dominance of open charm loops
Higher precision data is needed

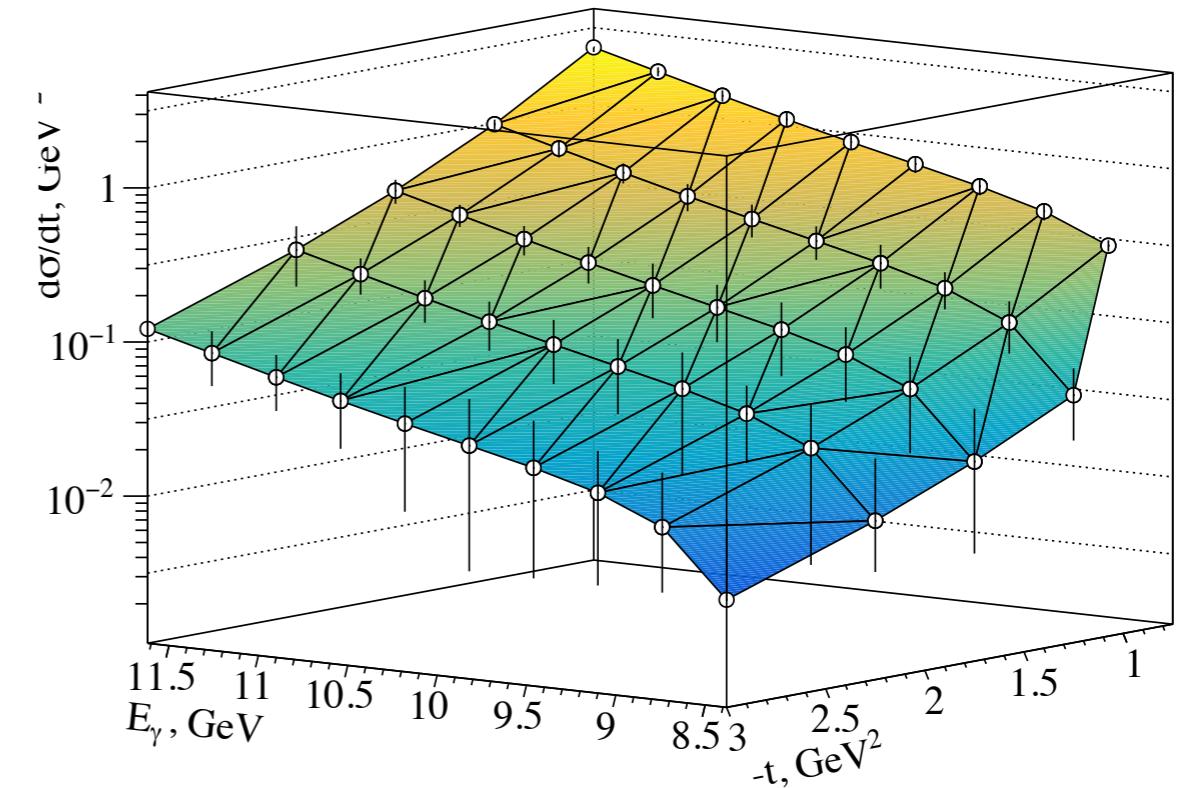


Projected GlueX-I J/ ψ Photoproduction Results

Estimated errors using full GlueX-I data



ERRORS ONLY shown for 2D differential cross-sections



Estimated errors using energy dependence from published results and dipole t-dependence

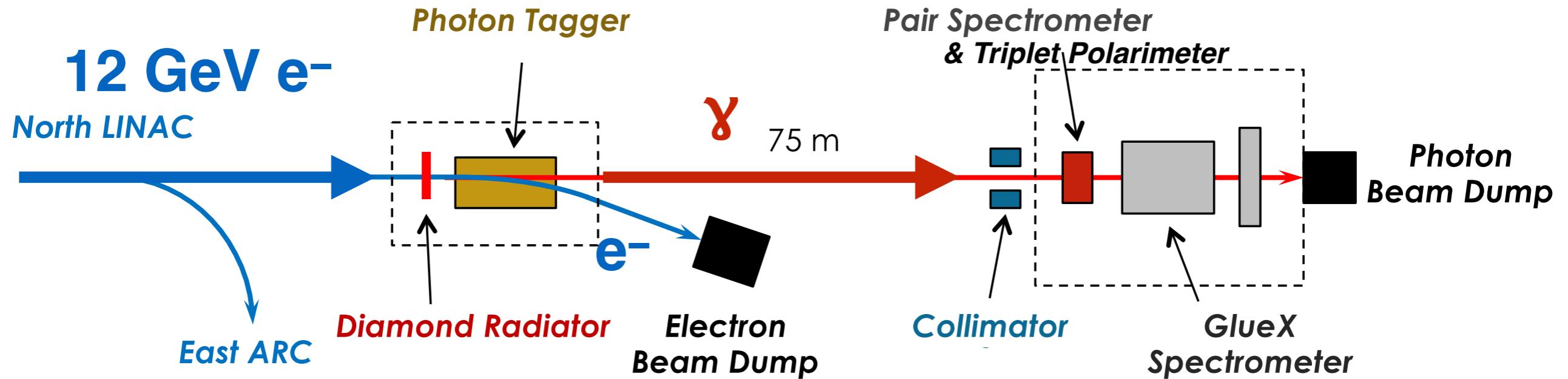
- Full GlueX-I run has **2k J/ ψ** , expect updated results soon!
- GlueX-II expected to provide additional 6k J/ ψ , results on χ_{c1} , $\psi(2S)$
- Open charm final states difficult to observe, but possible

Summary and Prospects

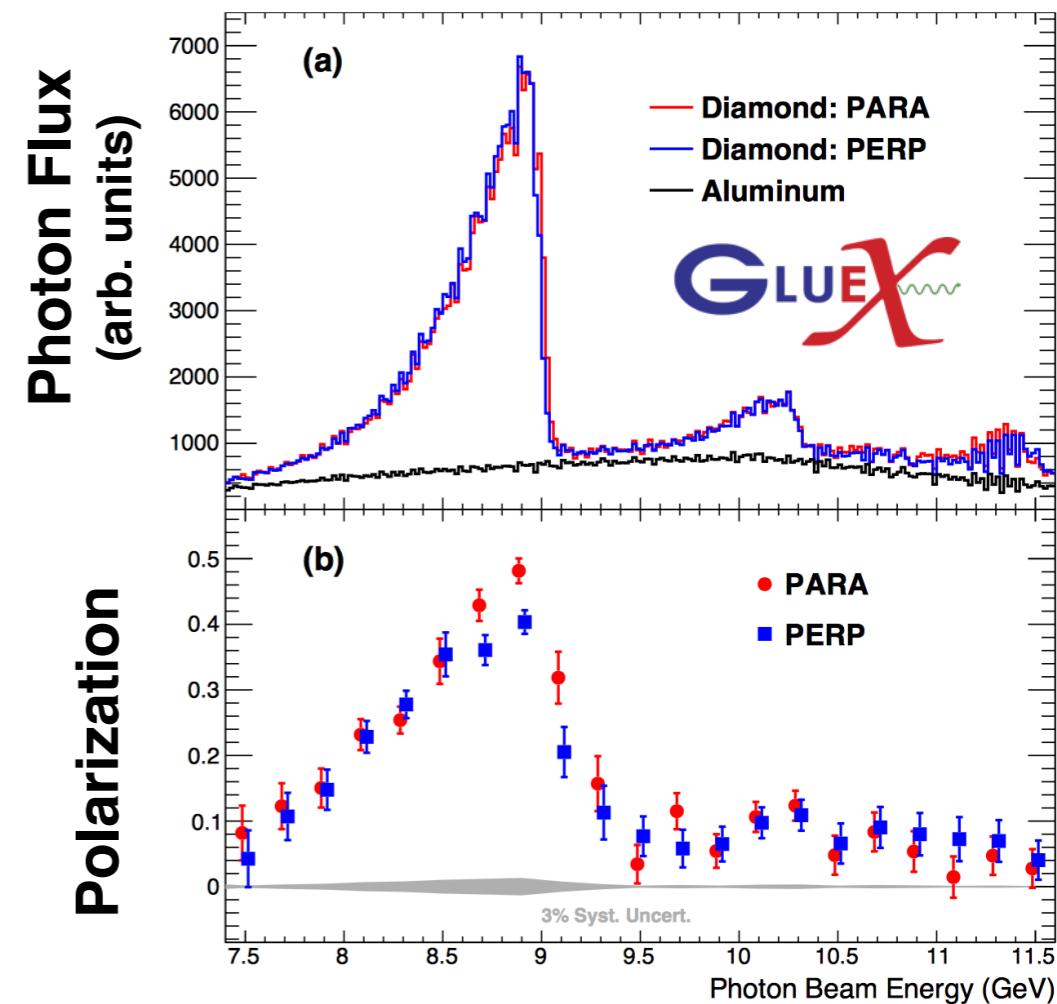
- Photoproduction is an interesting process to look for exotic hadrons — crucial to confirm their production in new processes
- GlueX has collected the world's largest photoproduction dataset
- First amplitude analyses of $\eta\pi$ and $\eta'\pi$ aim to identify the π_1 in photoproduction
 - Analysis of $\omega\pi$ focusing on study of b_1 and ρ 's
 - Next step: apply techniques to other PS-PS, V-PS final states
- First detailed studies of J/ψ photoproduction near threshold
- GlueX-II run in progress, planned to end around 2025
 - Other approved experimental programs includes spectroscopy with intense K_L beam ($\approx 10^4/s$), polarized target
- Spectroscopy of heavier states in photoproduction requires new experiments
 - Proposed JLab upgrade ideal for X, Z states [white paper: arXiv:2112.00060]
 - EIC ideal for Y states

Backup Slides

The GlueX Experiment: Photon Beam



- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
 - Energy measurement precision < 25 MeV
- Photon linear polarization $P_\gamma \sim 40\%$ in peak
- Intensity of $\sim 1-5 \times 10^7$ γ/s in peak



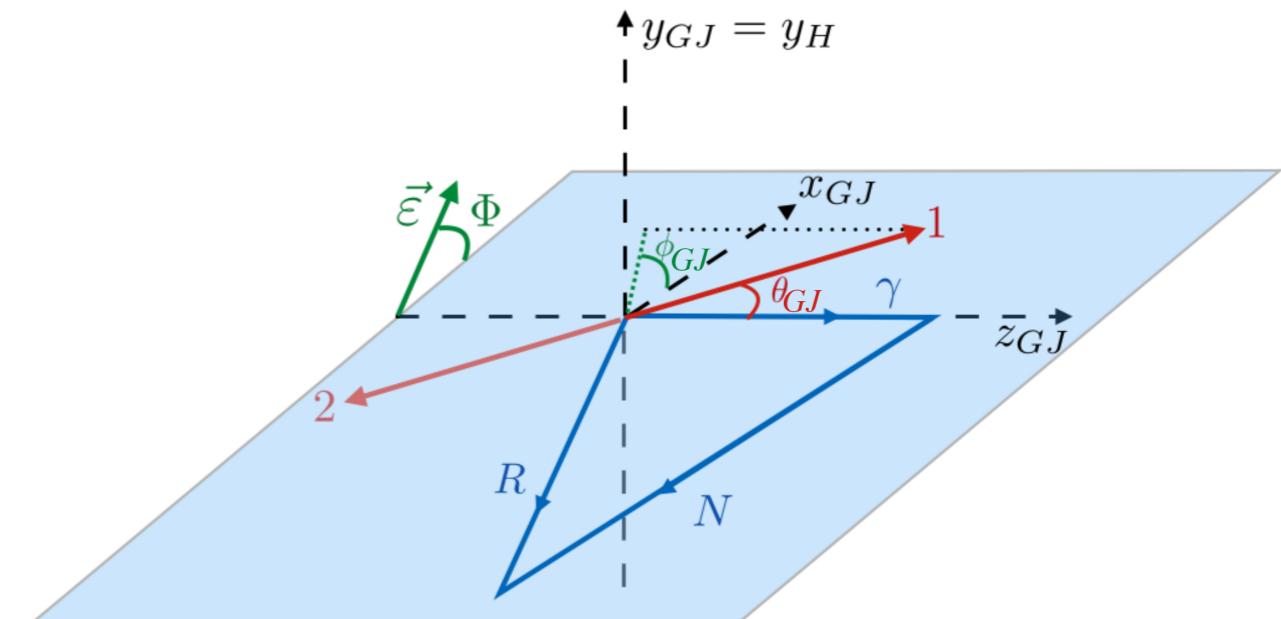
The GlueX Experiment in Hall D @ JLab

- The GlueX experiment is located in Hall D, newly constructed as part of the Jefferson Lab 12 GeV upgrade.
 - Large acceptance solenoidal spectrometer
 - Linearly polarized photon beam peaking at 9 GeV
 - Detects all decay products from full hadronic photoproduction rate
 - 100+ Collaborators from 26 institutions



Definition of Amplitudes

- Described by three angles:
 $\cos(\theta)_\eta$ and ϕ_η in the $\eta\pi$ rest frame,
angle Φ between polarization vector
and production plane
- Amplitudes incorporate beam
polarization, are eigenstates of
reflectivity $\epsilon = \pm 1$



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

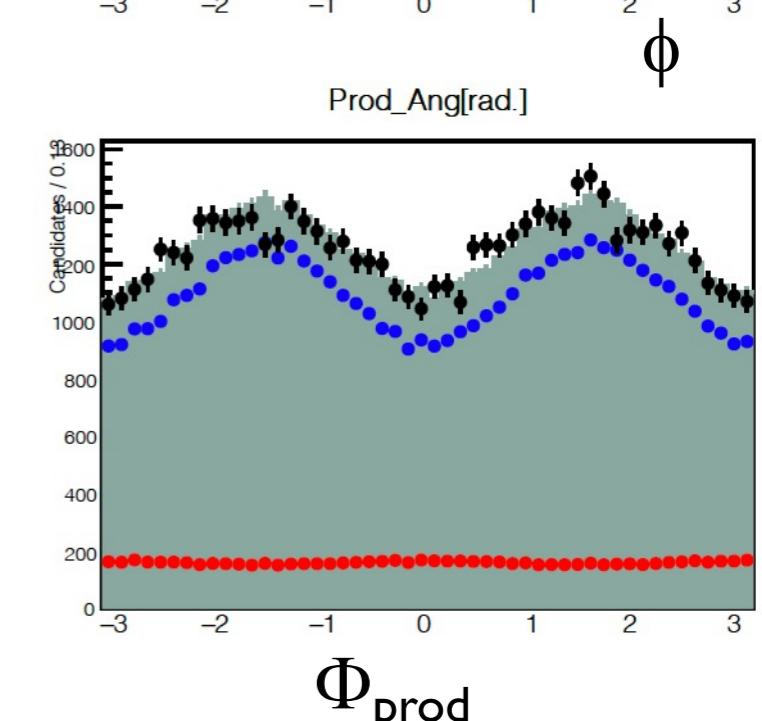
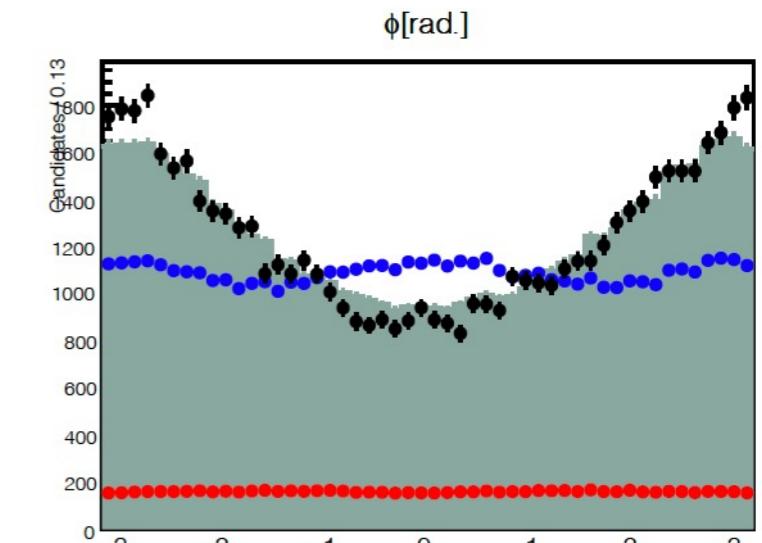
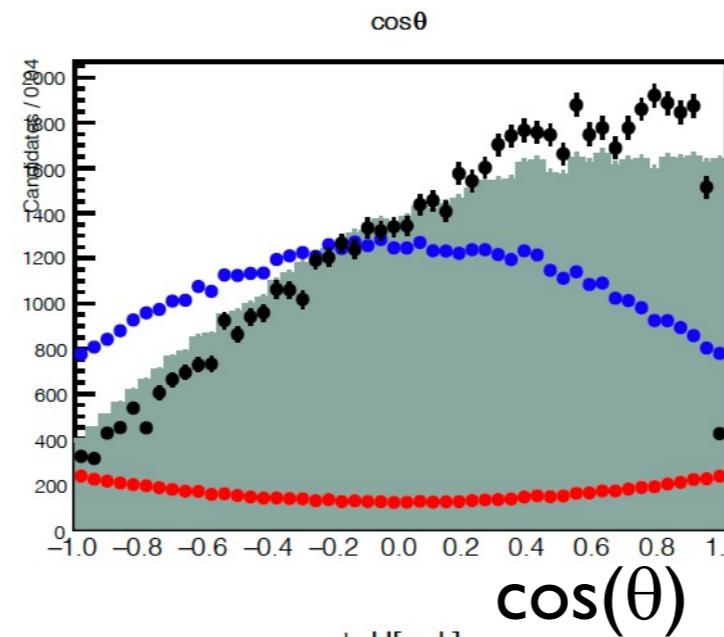
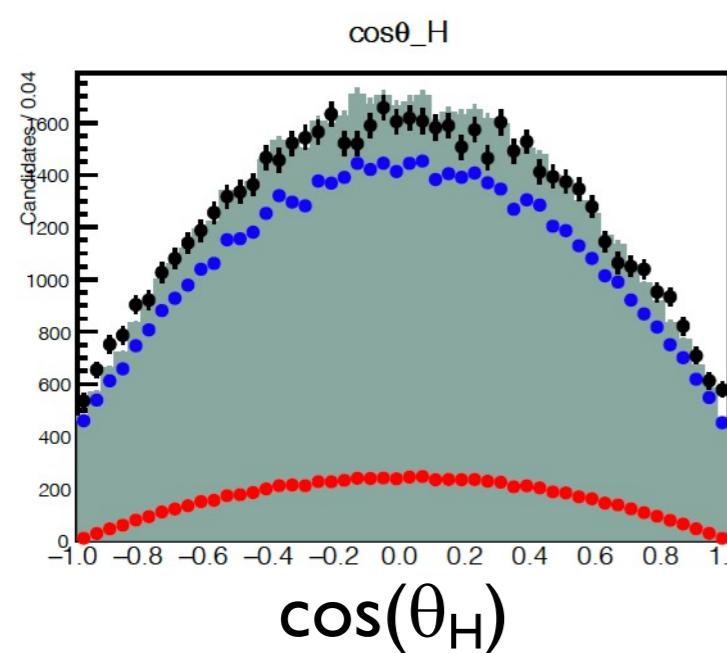
- Basis: Z_l^m amplitudes defined as $Z_l^m(\Omega, \Phi) = Y_l^m(\Omega)e^{-i\Phi}$

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

- Complexity: Positive and negative reflectivity, $m = -l \dots l$ allowed
- Frequent exchange with JPAC

Study of $b_1(1235)$ Decay: Example Fit

GlueX Data
Fit Results
 b_1 $[1^{\pm}]$ (S+D) GLUEX Preliminary
 ρ $[1^{\pm}]$ P



- Independent fits for each beam polarization orientation
- Inclusion of 1^- and 1^+ waves leads to good description of angular distributions