Partial Wave Analysis of $\eta\pi$ at GlueX

Malte Albrecht
Indiana University

on behalf of the GlueX Collaboration

2022 JLUO Annual Meeting

06 / 14 / 2022

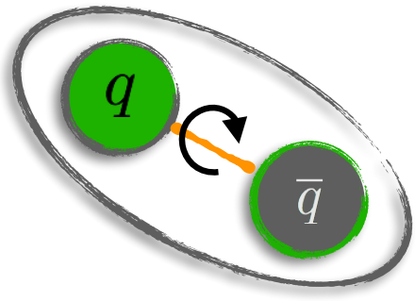
Beyond the Constituent Quark Model

- Minimal allowed bound states of QCD: Mesons ($q\overline{q}$) and baryons (qqq)
- For mesons: $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

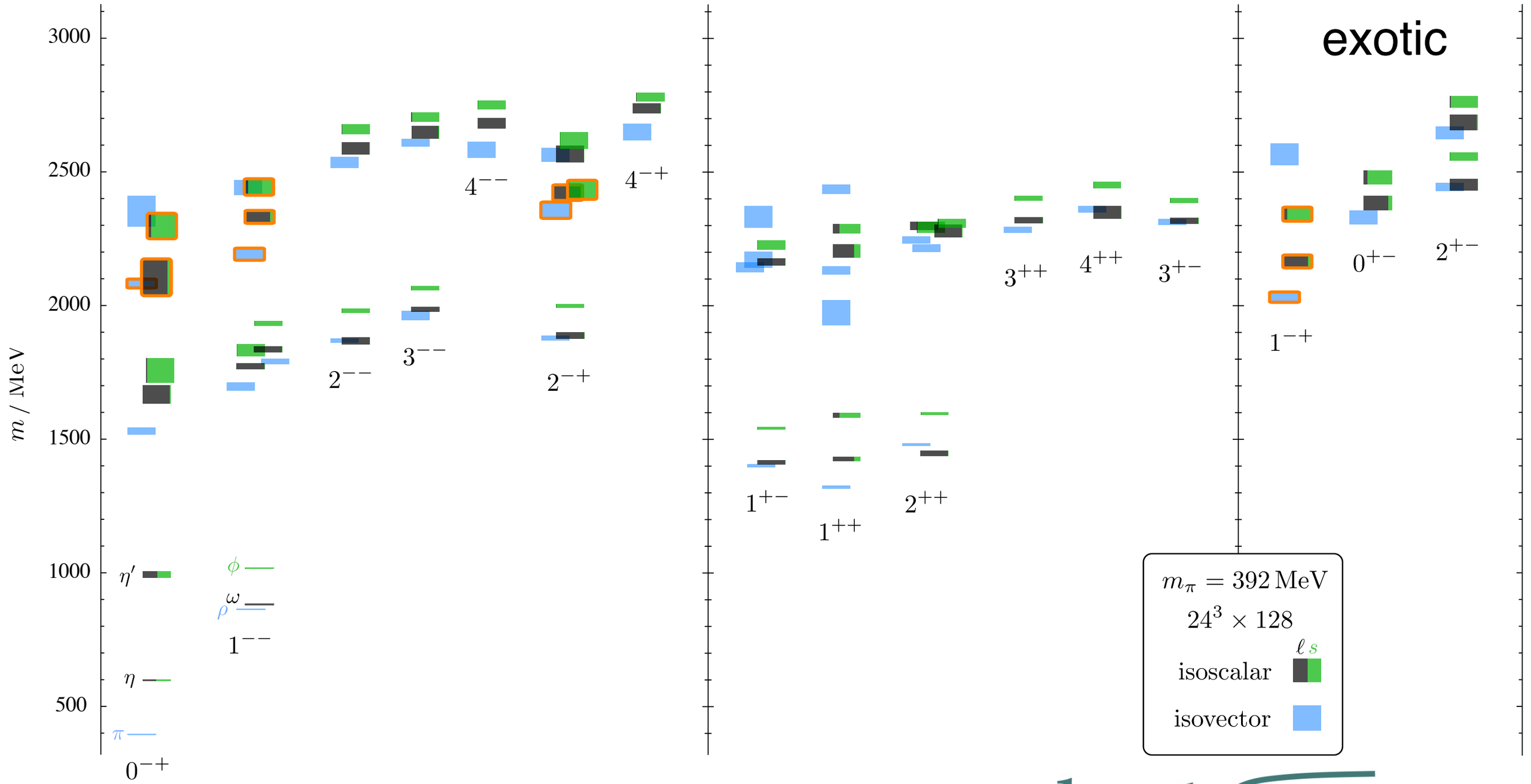
  Allowed: $J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, ...$
  Forbidden: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ...$

- Observation of state with J^{PC} forbidden for $q\overline{q}$: clear evidence for exotics
- Understanding QCD: **What is the role of gluons** (generation of mass, spin, …)?

- **Mapping out the spectrum of light hybrids:**
  - Evidence in multiple channels, consistent results
  - Establish partner states
  - Extend to regular J^{PC} hybrids, higher mass nonets
- Partial Wave analysis is an indispensable tool



Light Quark Mesons from Lattice QCD



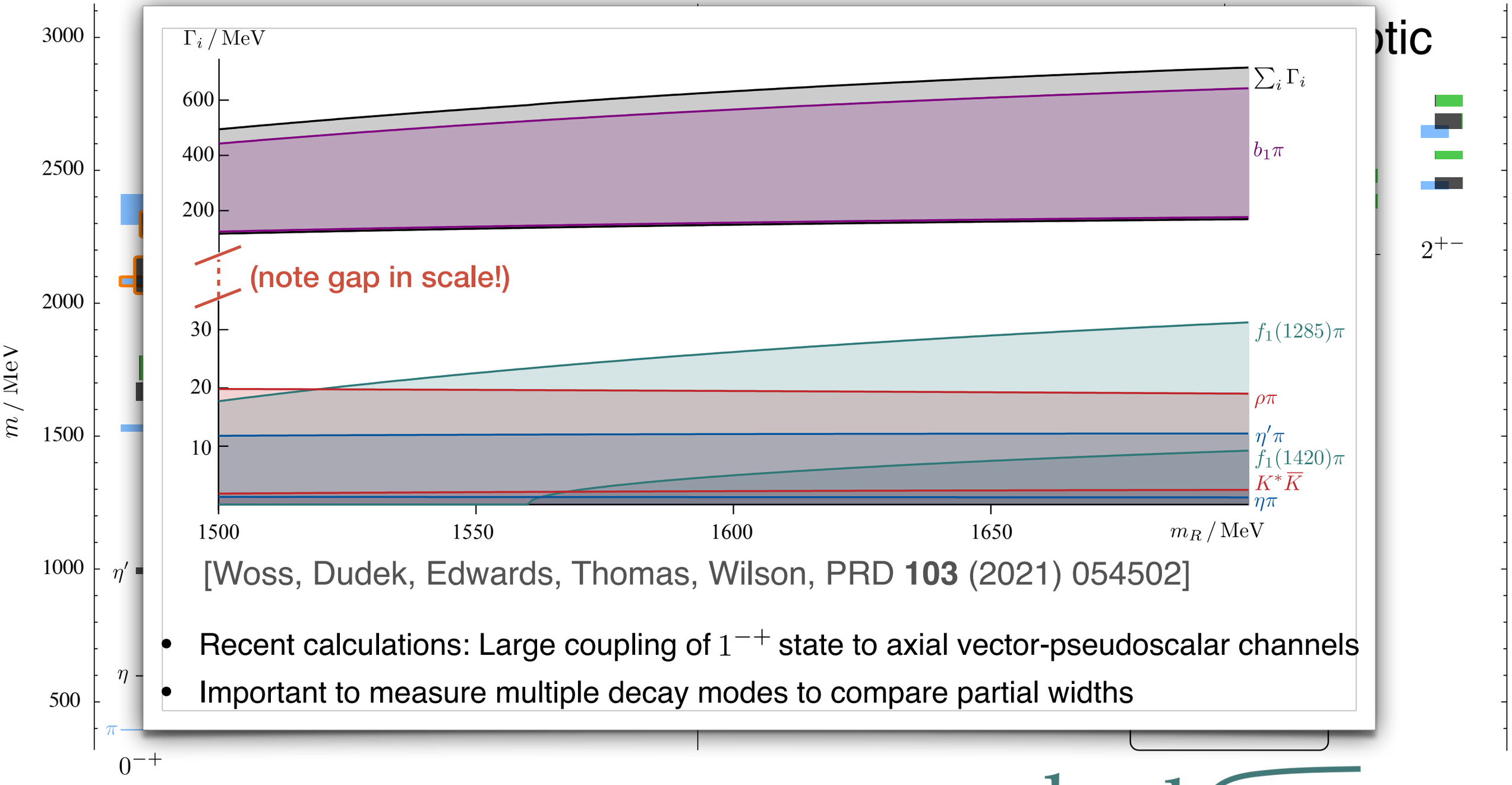
[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

had spec

- Lightest spin-exotic state: $J^{PC} = 1^{-+}$

→ **Talk by J. Dudek (Mon, 11:05am)**

Light Quark Mesons from Lattice QCD



[Woss, Dudek, Edwards, Thomas, Wilson, PRD **103** (2021) 054502]

- Recent calculations: Large coupling of 1^{-+} state to axial vector-pseudoscalar channels
- Important to measure multiple decay modes to compare partial widths

[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

had spec

- Lightest spin-exotic state: $J^{PC} = 1^{-+}$

→ **Talk by J. Dudek (Mon, 11:05am)**

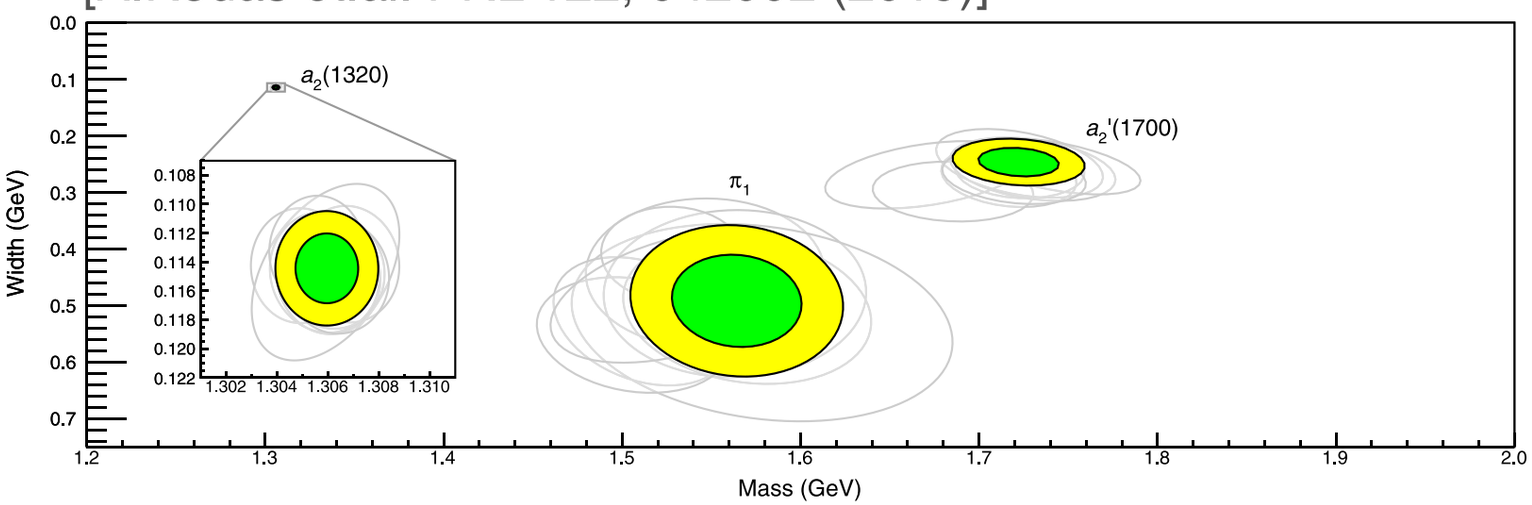
Two Hybrid Mesons?

- Recent analysis of COMPASS data in $\eta\pi, \eta'\pi$ channels from Joint Physics Analysis Center
- Sophisticated description of 1^{-+} wave with single pole coupling to two channels

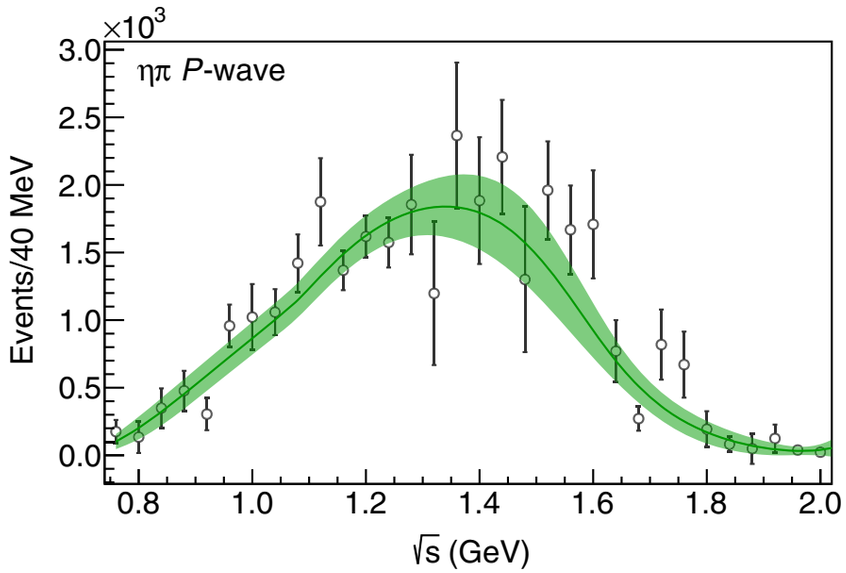
➡ Enhancements at 1.4GeV in $\eta\pi$, 1.6GeV in $\eta'\pi$ can be described by a single pole!

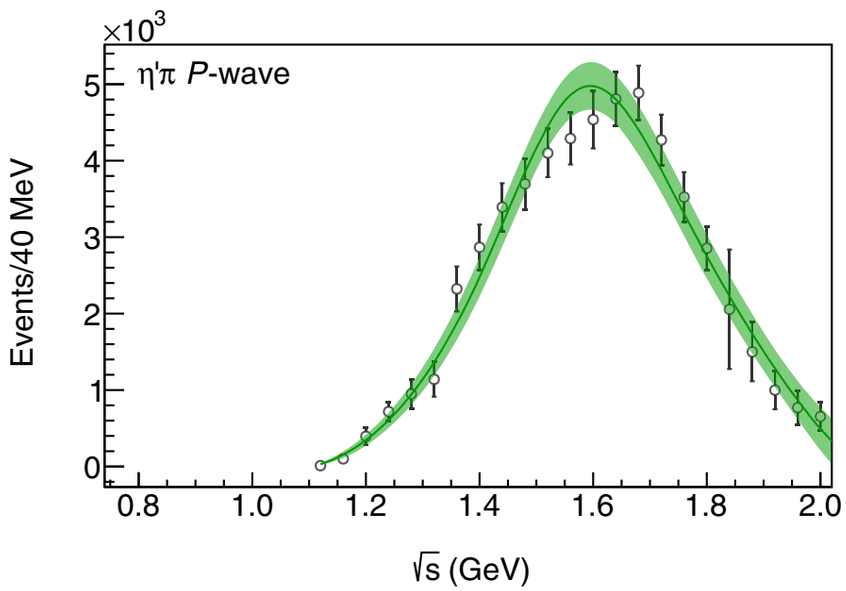
➡ $\pi_1(1400)$ and $\pi_1(1600)$ hybrid meson candidates are the same?

[A.Rodas et.al. PRL 122, 042002 (2019)]

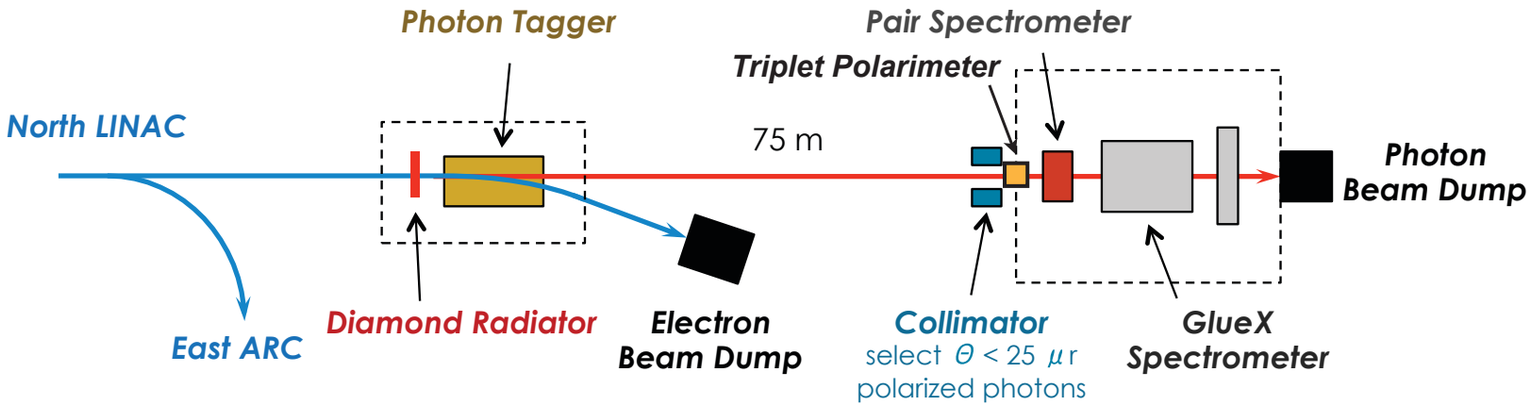


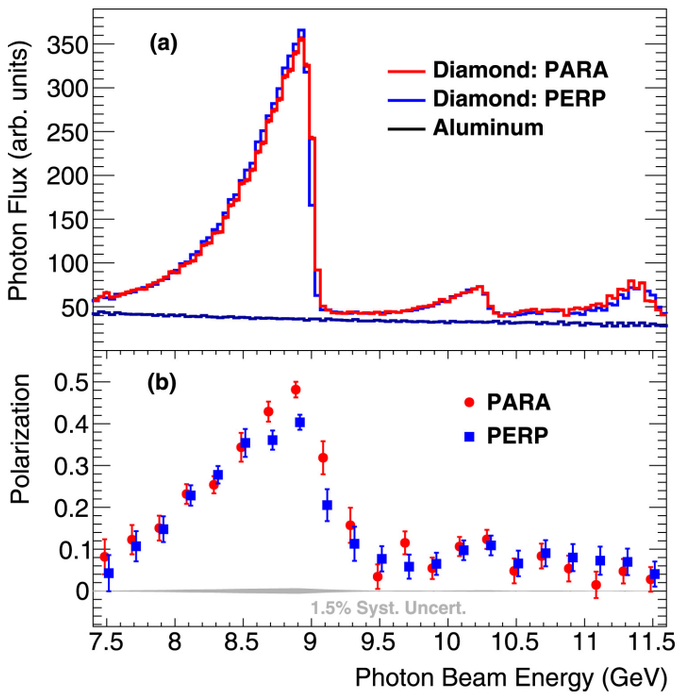
→ **Talk by V. Mathieu (Mon, 9:40am)**

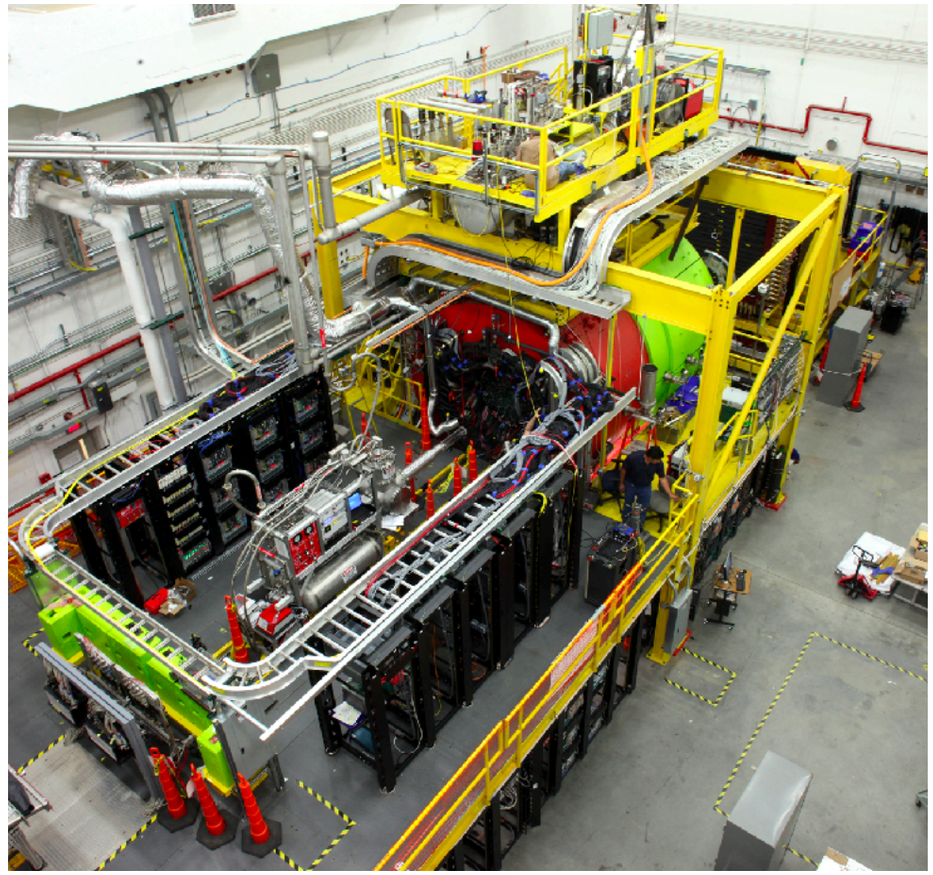




Hall-D at Jefferson Lab



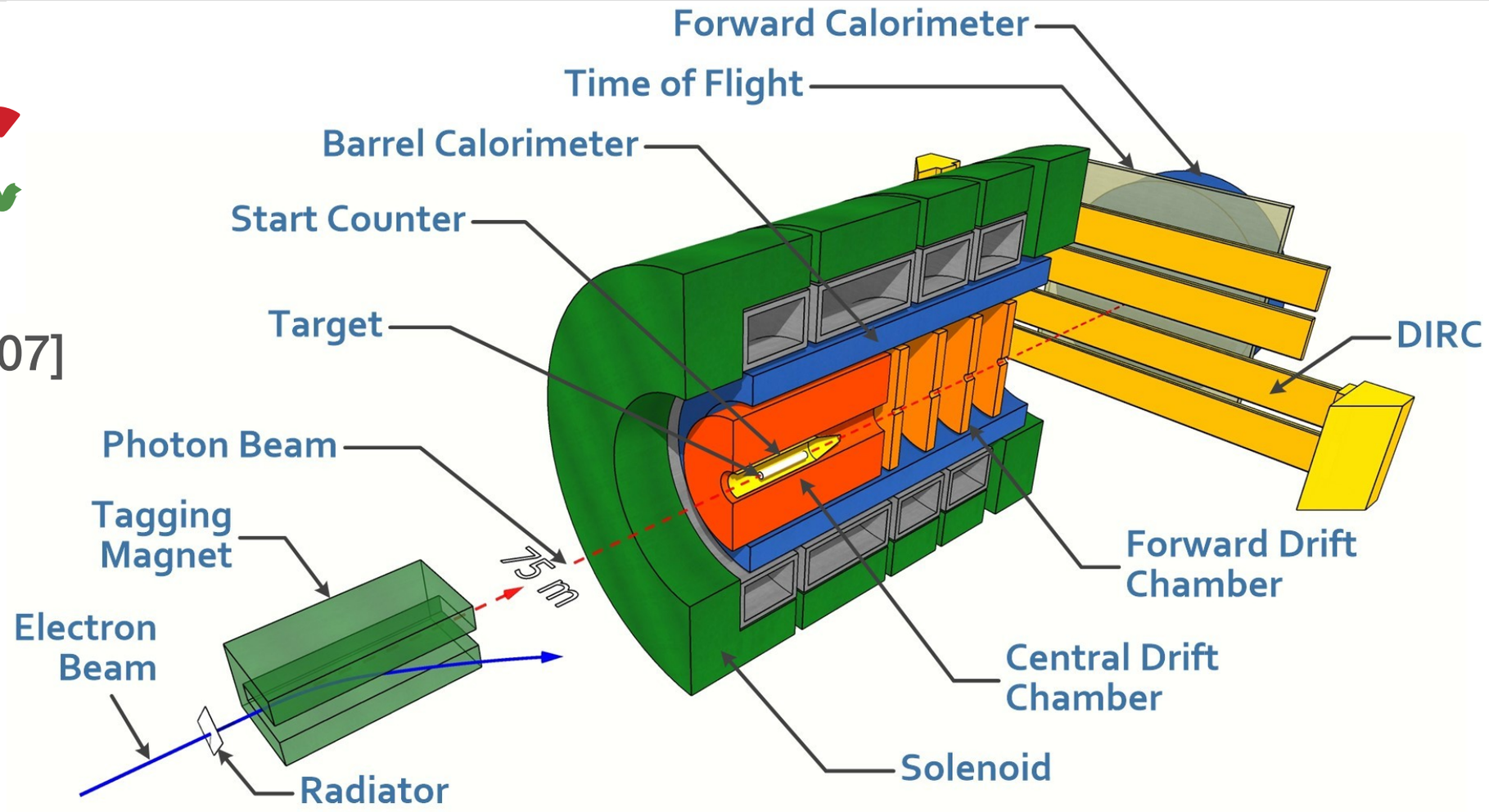




- CEBAF accelerator provides 12 GeV electron beam
- Hall-D: Linearly polarized photon beam produced via bremsstrahlung from thin radiator

The GlueX Experiment

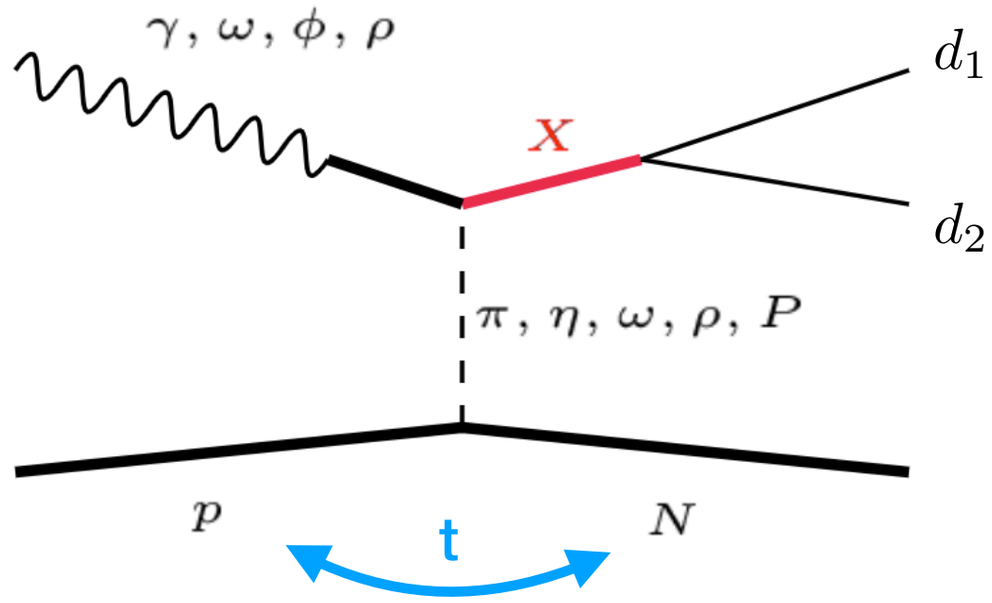
[NIM A 987 (2021) 164807]



- Linearly polarized, tagged photon beam (P≈40%) impinging on Liquid Hydrogen Target
- Four polarization orientations, coherent peak: ~8.2-8.8 GeV
- Analyses shown today use full GlueX Phase-I data sample $(125\,\mathrm{pb}^{-1})$
- GlueX Phase-II data taking will resume this summer
- Large acceptance for charged and neutral final state particles

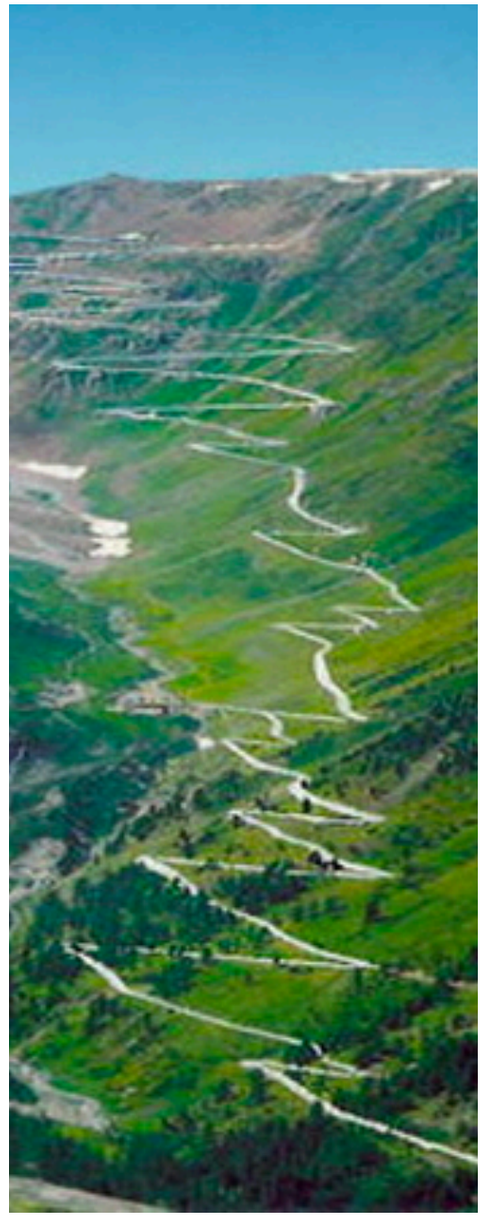
Spectroscopy using Photoproduction

- Versatile process:
  - Incoming photon interacts as ϕ, ω, ρ (Vector Meson Dominance)
  - Various exchange particles possible
    - Linear beam polarization filters naturality of exchanged particle
  - Allows coupling to all lightest hybrid nonet states
  - Production of mesonic resonances as well as target excitations
  - Ideal also for Baryon spectroscopy
    → background for meson production
- Complementary to πN reaction used by COMPASS, E852, VES



The Route to Exotics with GlueX

- Understand (polarized) production of “simple” hadrons
- Achieve good understanding of acceptance and backgrounds
  - Single pseudoscalar production asymmetries
    [GlueX, PRC 95 (2017) 042201; PRC, 100 (2019) 052201;
    PRC 103 (2021) 022201]
  - **Spin density matrix elements ($\rho, \omega, \Lambda(1520)$)**
    [GlueX, Phys.Rev.C 105, 035201]
- Investigation of $\eta^{(\prime)}\pi$ channels
  - **Study production mechanism, cross section of known mesons first**
  - Charged and neutral modes, different sub-decays under study
  - Provides check for acceptance, background handling
- Extend hybrid search to axial vector-pseudoscalar channels
  - **Study of b_1 production ongoing**, stepping stone towards hybrid search in $b_1\pi$

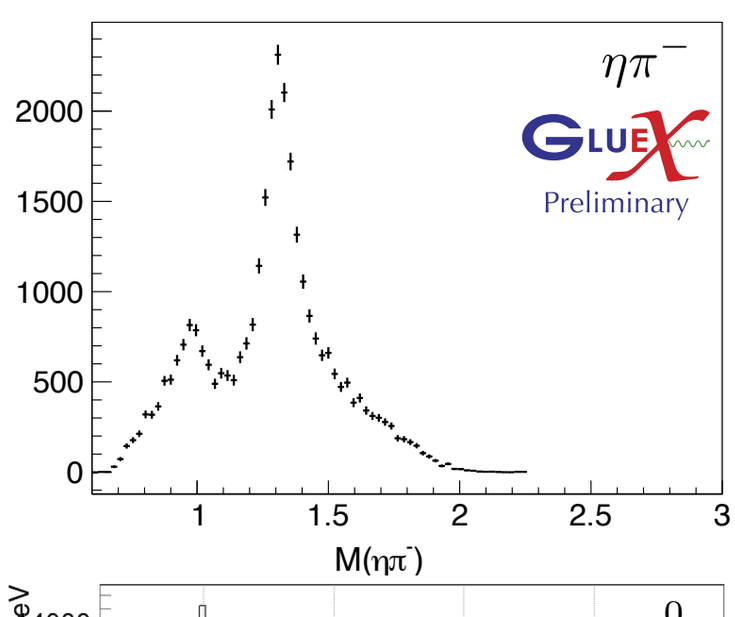


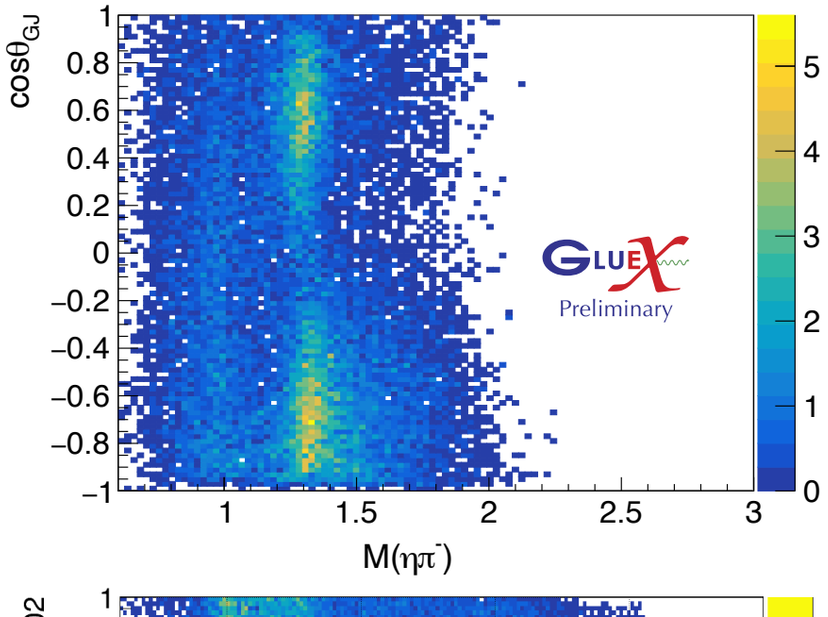
$\gamma p \to \pi\eta N$ at GlueX

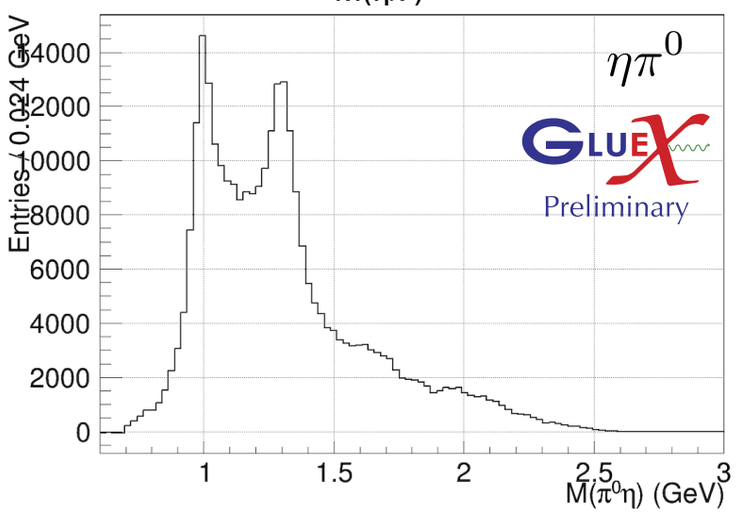
- Evidence for spin-exotic contribution from other experiments
  → Key channel for GlueX

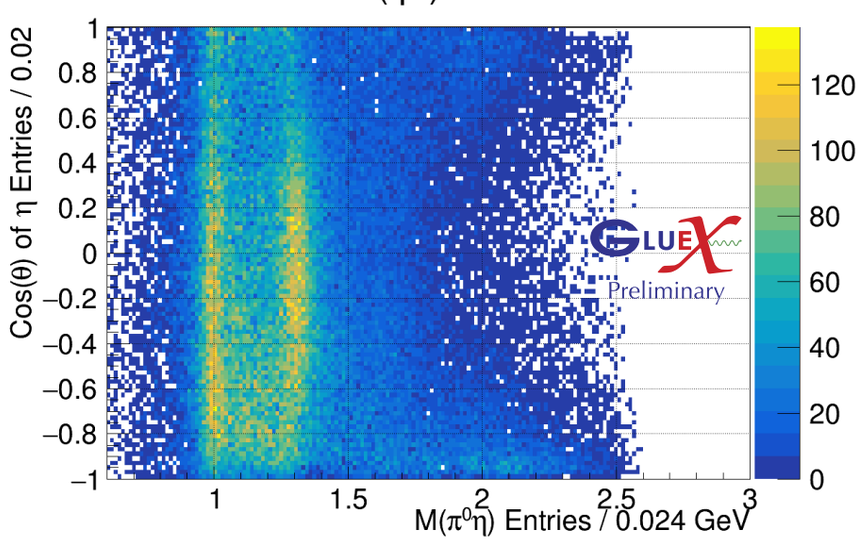
- Clear signals at $a_0(980)$ and $a_2(1320)$ masses

$0.1 < -t < 0.3$ GeV^2







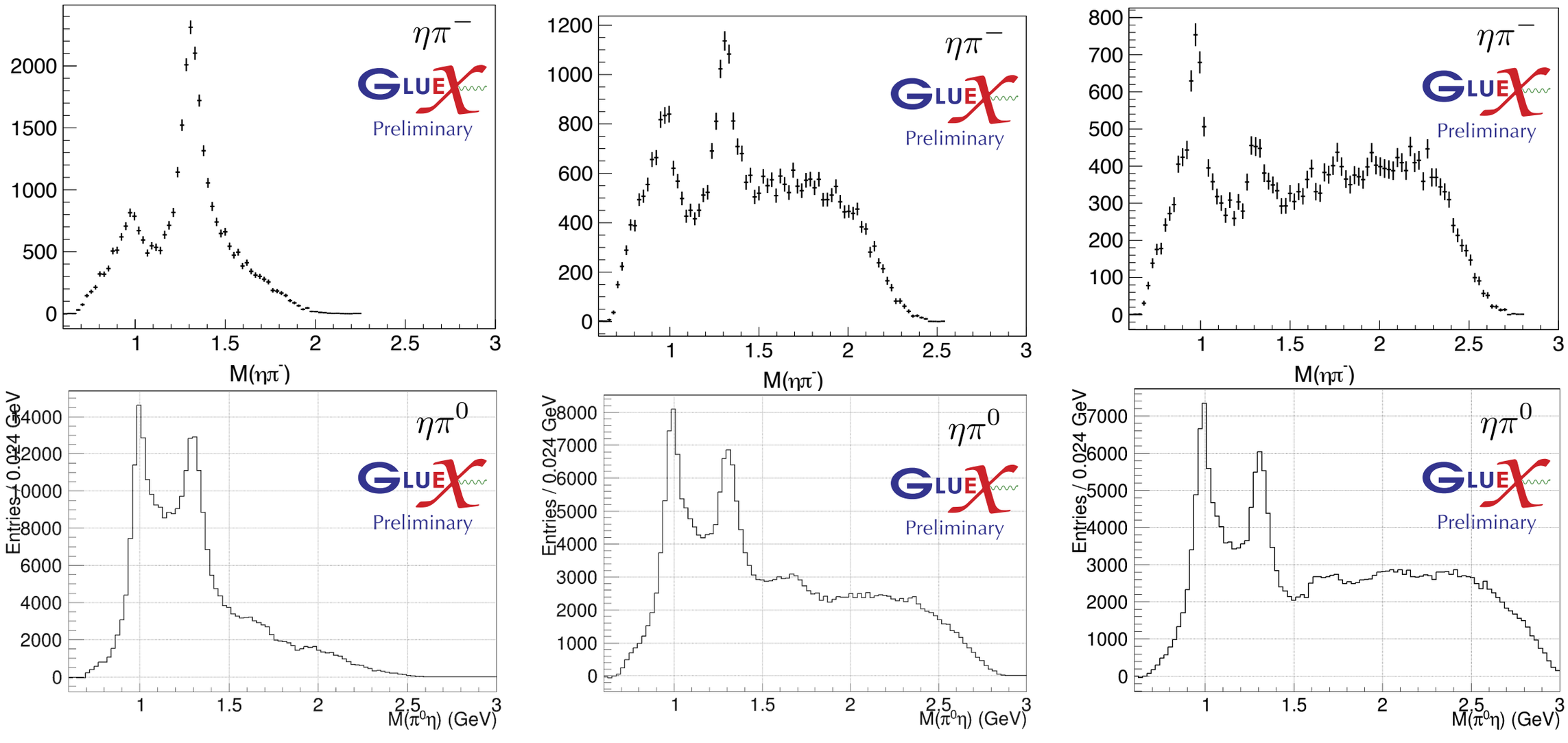


- Angular distribution of $a_2(1320)$ signal clearly different between charged and neutral channels

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

- Evidence for spin-exotic contribution from other experiments
  → Key channel for GlueX
- Clear signals at $a_0(980)$ and $a_2(1320)$ masses

$0.1 < -t < 0.3$ GeV^2 | $0.3 < -t < 0.6$ GeV^2 | $0.6 < -t < 1.0$ GeV^2



The Route to Exotics with GlueX

- Strong evidence for exotic in $\eta^{(\prime)}\pi$ channels - under investigation in parallel:

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

with

$$\eta \to \gamma\gamma, \eta \to 3\pi$$
$$\eta' \to \pi^+\pi^-\eta$$

Route to analyze $\eta'\pi$, where we expect larger exotic contribution, is through the study of $\eta\pi$ channels

- **Measure t-dependent cross section of known meson first**
  → $a_2(1320)$ is our 'standard candle' to validate results in other channels

- **Validate results across different final states**
  Consistency: different acceptance, background handling, …

- **Prove framework is working**
  achieve understanding of major contribution in hybrid mass region

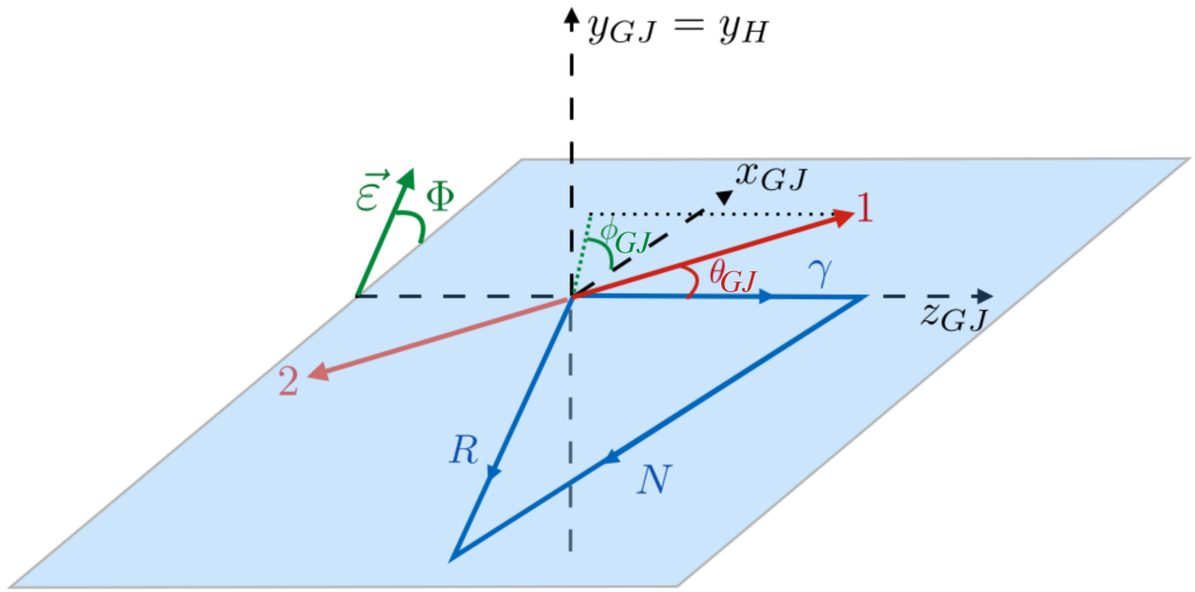
- **Enables reliable search for much smaller contributions**

- Challenges for fully mass-independent PWA:
  Fewer constraints, waveset selection, leakage, statistics, …

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]

- High-energy t-channel picture: ‘reflectivity’ fixes the product of naturalities of the exchange particle and the produced resonance

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

  natural parity $\eta = +1$ for: $J^P = 0^+, 1^-, 2^+, \ldots$

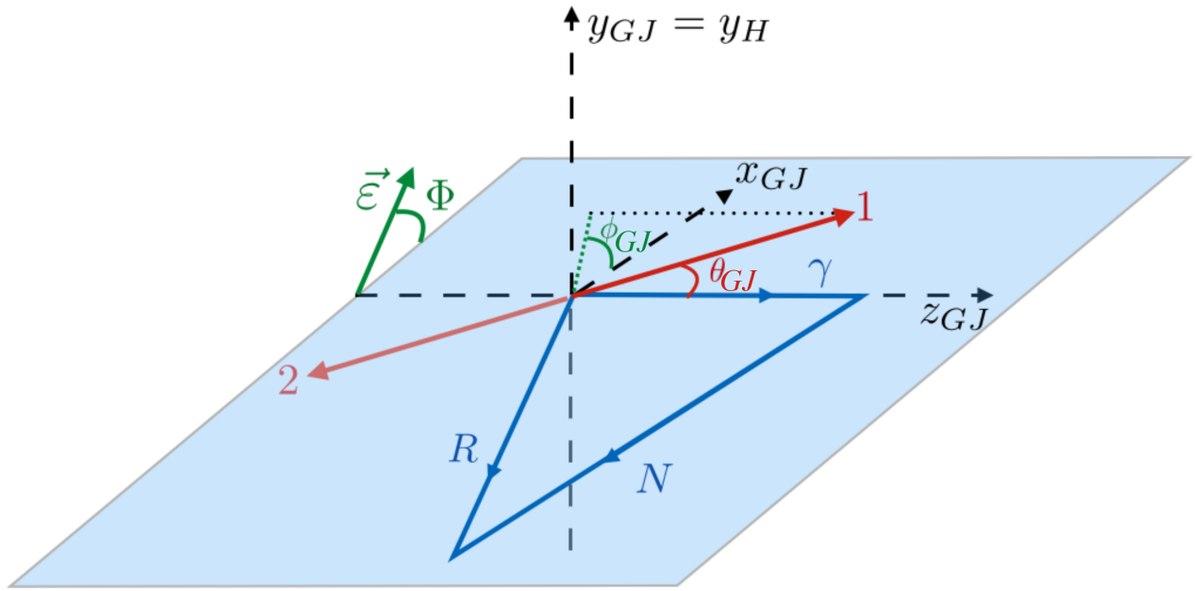
  unnatural parity $\eta = -1$ for: $J^P = 0^-, 1^+, 2^-, \ldots$

- In case of $\eta\pi$:
  positive (negative) reflectivity = natural (unnatural) parity exchange

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]

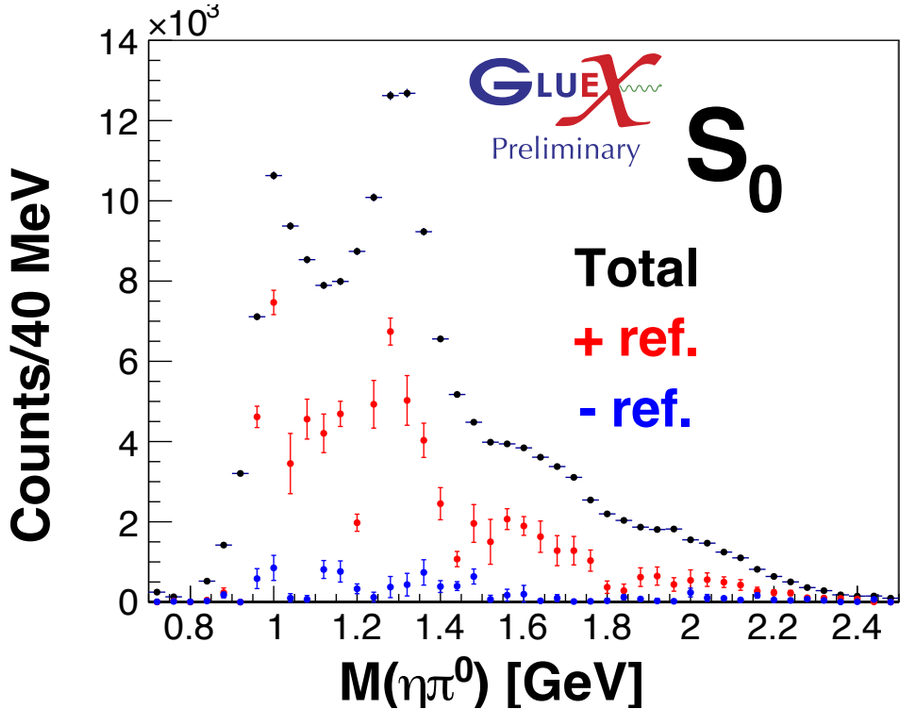
- Basis: Z_l^m amplitudes defined as $Z_l^m(\Omega, \Phi) = Y_l^m(\Omega) e^{-i\Phi}$

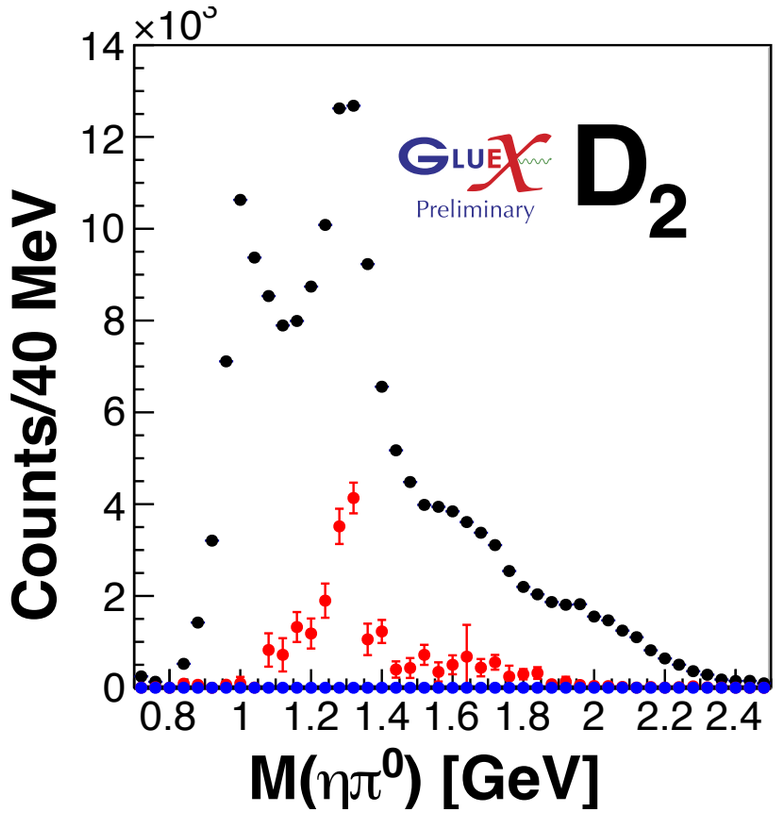
$$I(\Omega,\Phi) = 2\kappa \sum_k \Bigg\{ (1-P_\gamma) \left| \sum_{\ell,m} [\ell]^{(-)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)] \right|^2 + (1-P_\gamma) \left| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Im}[Z^m_\ell(\Omega,\Phi)] \right|^2 +$$
$$(1+P_\gamma) \left| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)]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

- Complexity: Positive and negative reflectivity, $m = -l ... l$ allowed

- Frequent exchange with JPAC

Fit to $\gamma p \to \pi^0 \eta p$ data ($0.1 < -t < 0.3\,\mathrm{GeV}^2$)



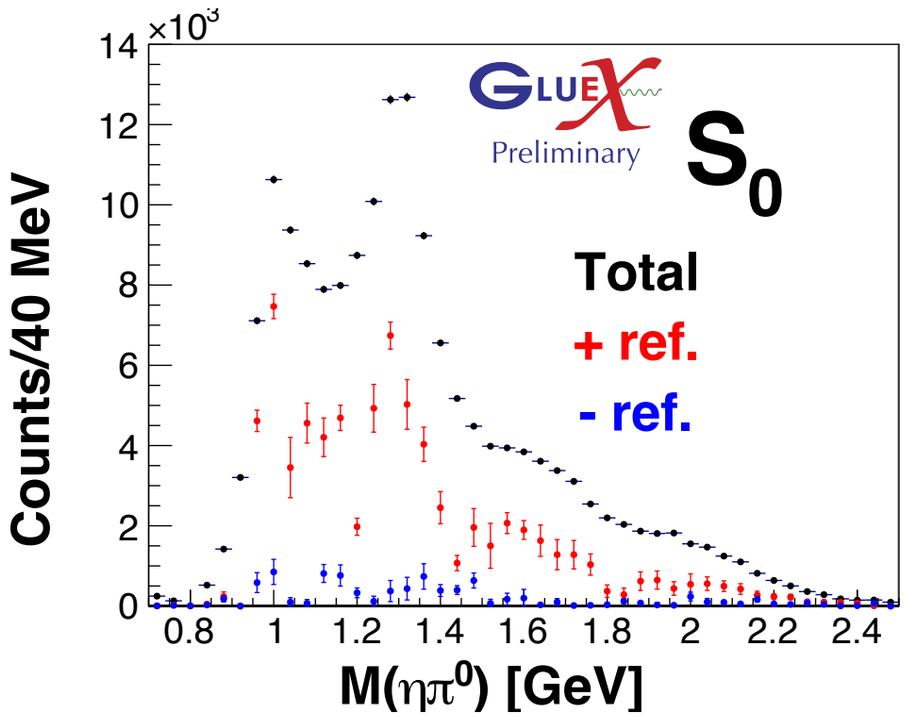


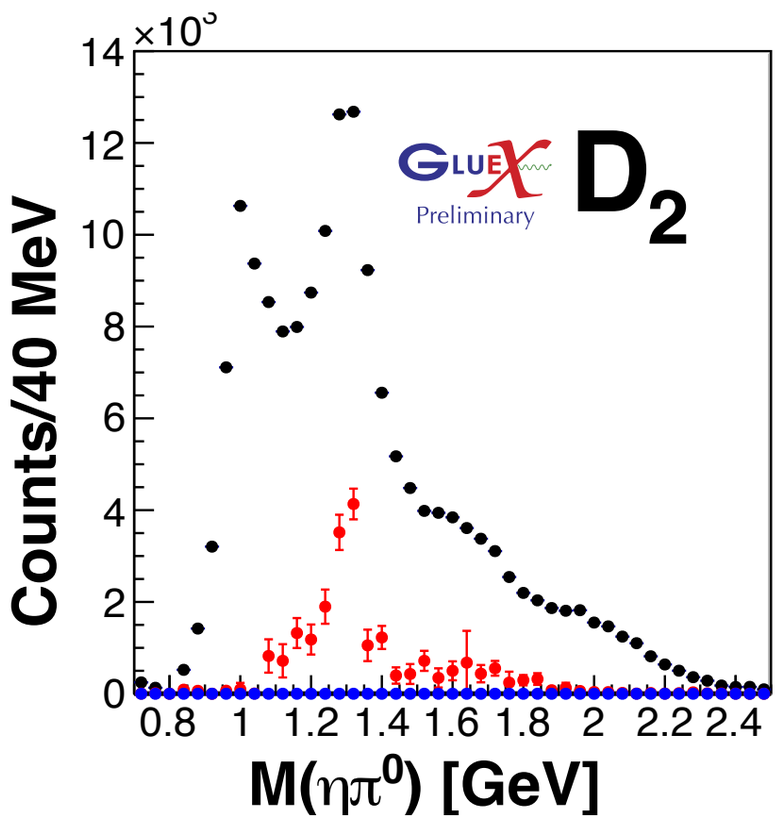
- Combined fit, all polarization orientations
- Large S-wave, positive reflectivity contribution
  - Non-resonant?
  - Contribution from other resonance(s)? ($a_2(1700), a_0(1450), \ldots$)
- Clear signal in $m = +2$ D-wave
- Waveset based on Tensor Meson Dominance model:

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

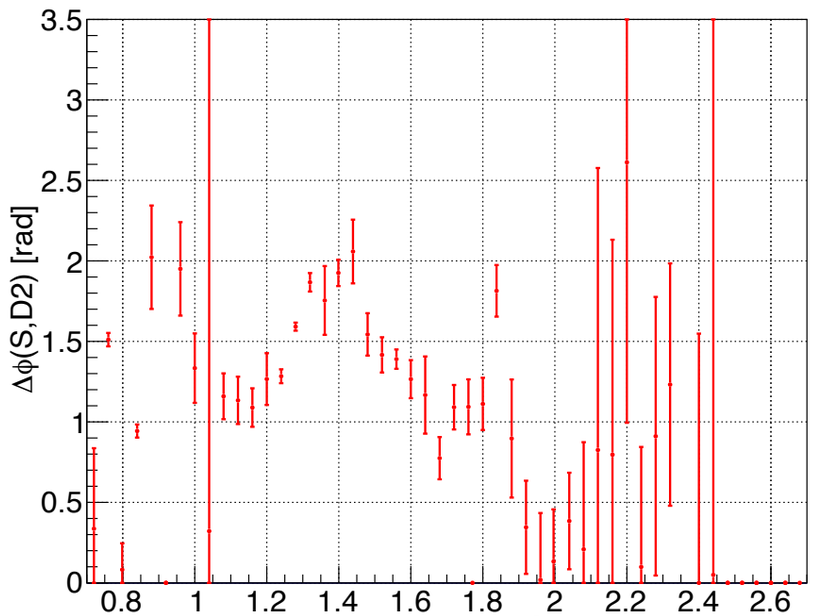
[V.Mathieu et.al. (JPAC) PRD 102, 014003 (2020)]

Fit to $\gamma p \to \pi^0 \eta p$ data ($0.1 < -t < 0.3\,\mathrm{GeV}^2$)





- Combined fit, all polarization orientations



- Statistical uncertainties (MINUIT) only
- Phase between S^+ and D_2^+ waves shows motion at $a_2(1320)$ position
- Depends on waveset
- **Perform semi - mass independent fit to extract a_2 contribution**

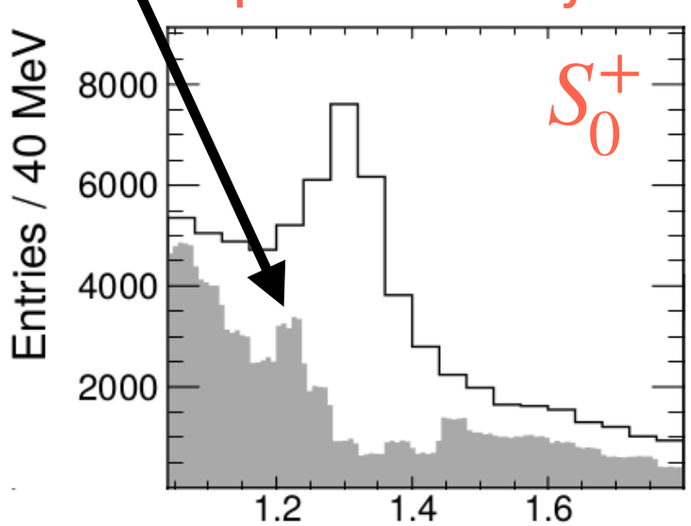
Semi-Model Independent Fit ($\gamma p \to \pi^0 \eta p$)

"mass-independent" S-wave

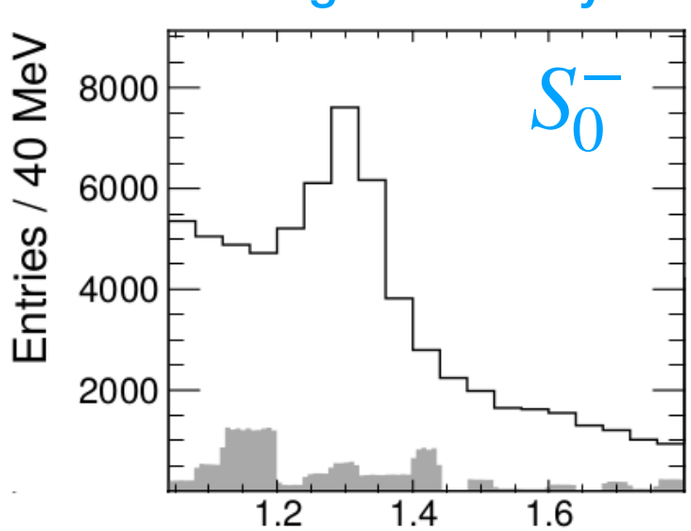
GlueX Preliminary

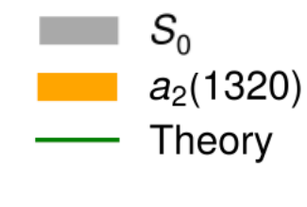
$0.1 < t < 0.2\ GeV^2$

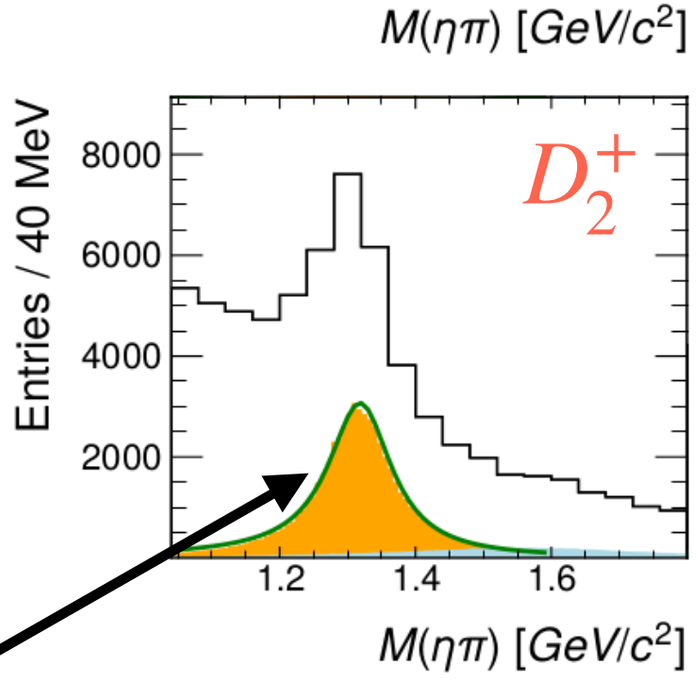
pos. reflectivity

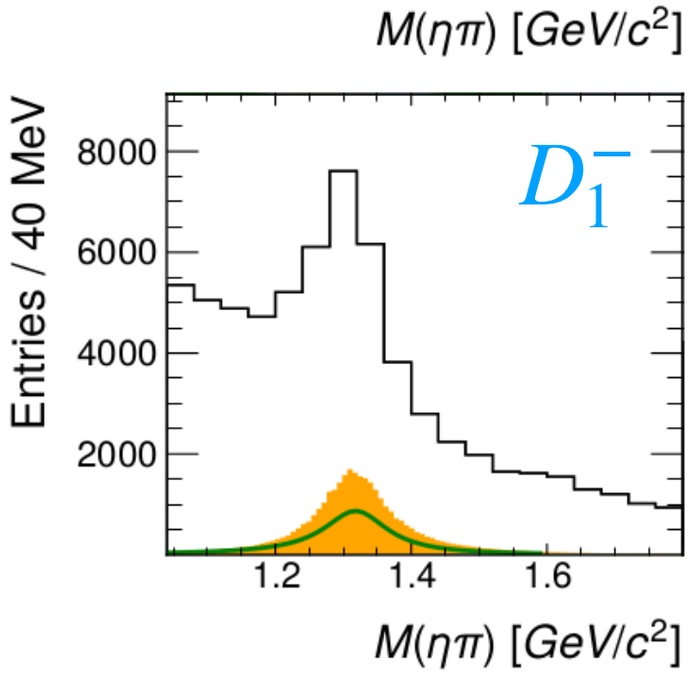


neg. reflectivity



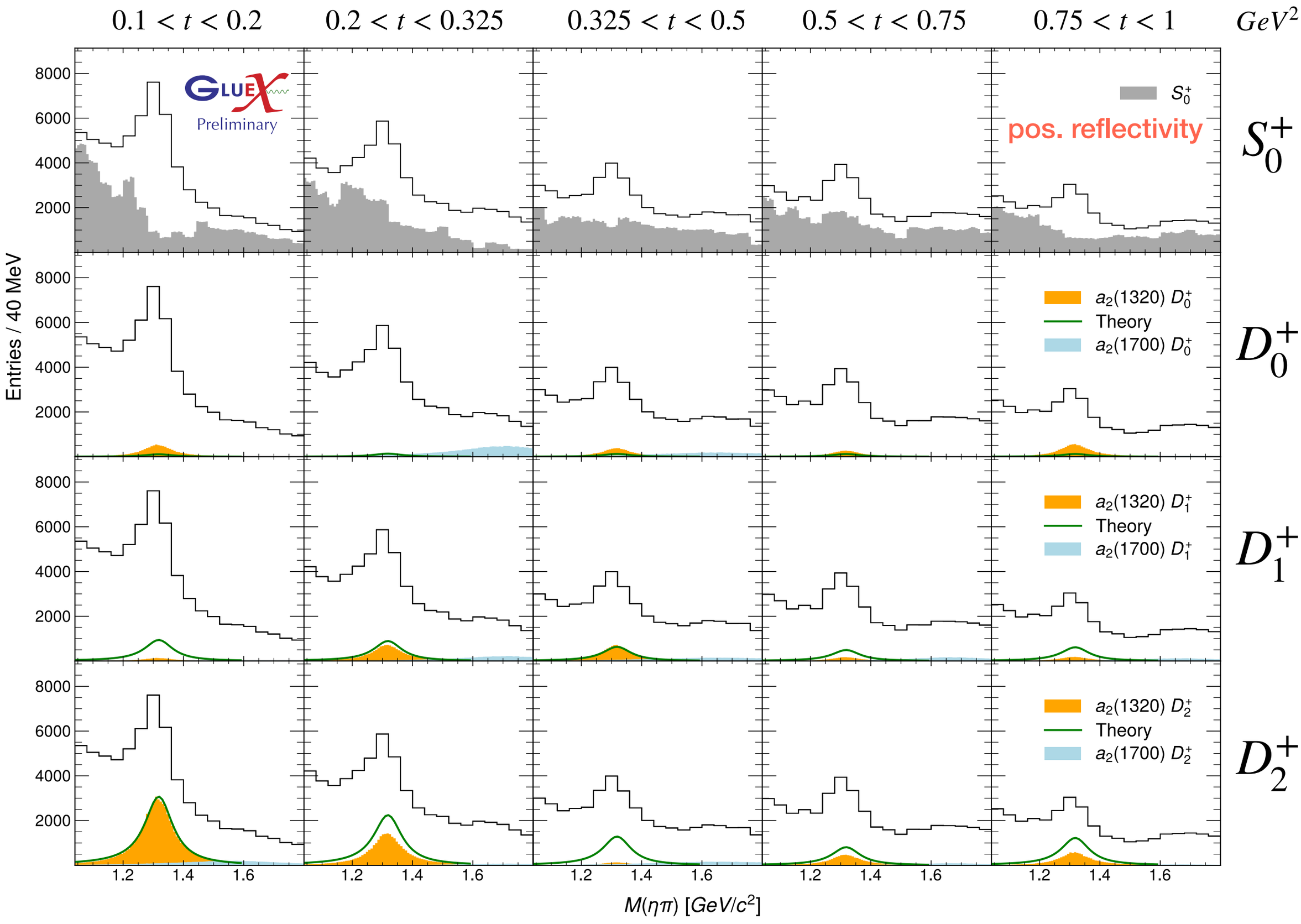




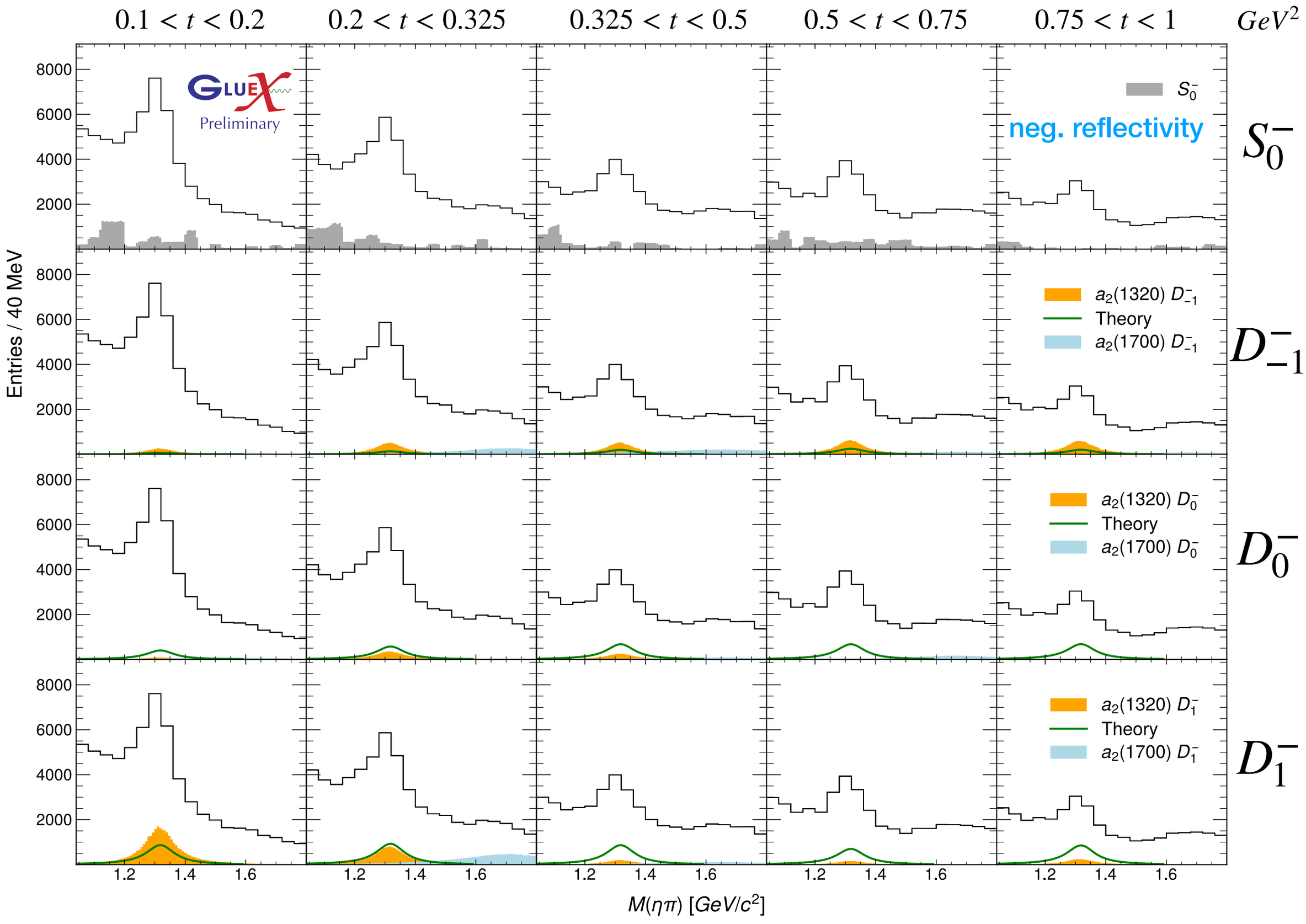


$a_2(1320)$: **Breit-Wigner**

Semi-Model Independent Fit ($\gamma p \to \pi^0 \eta p$)

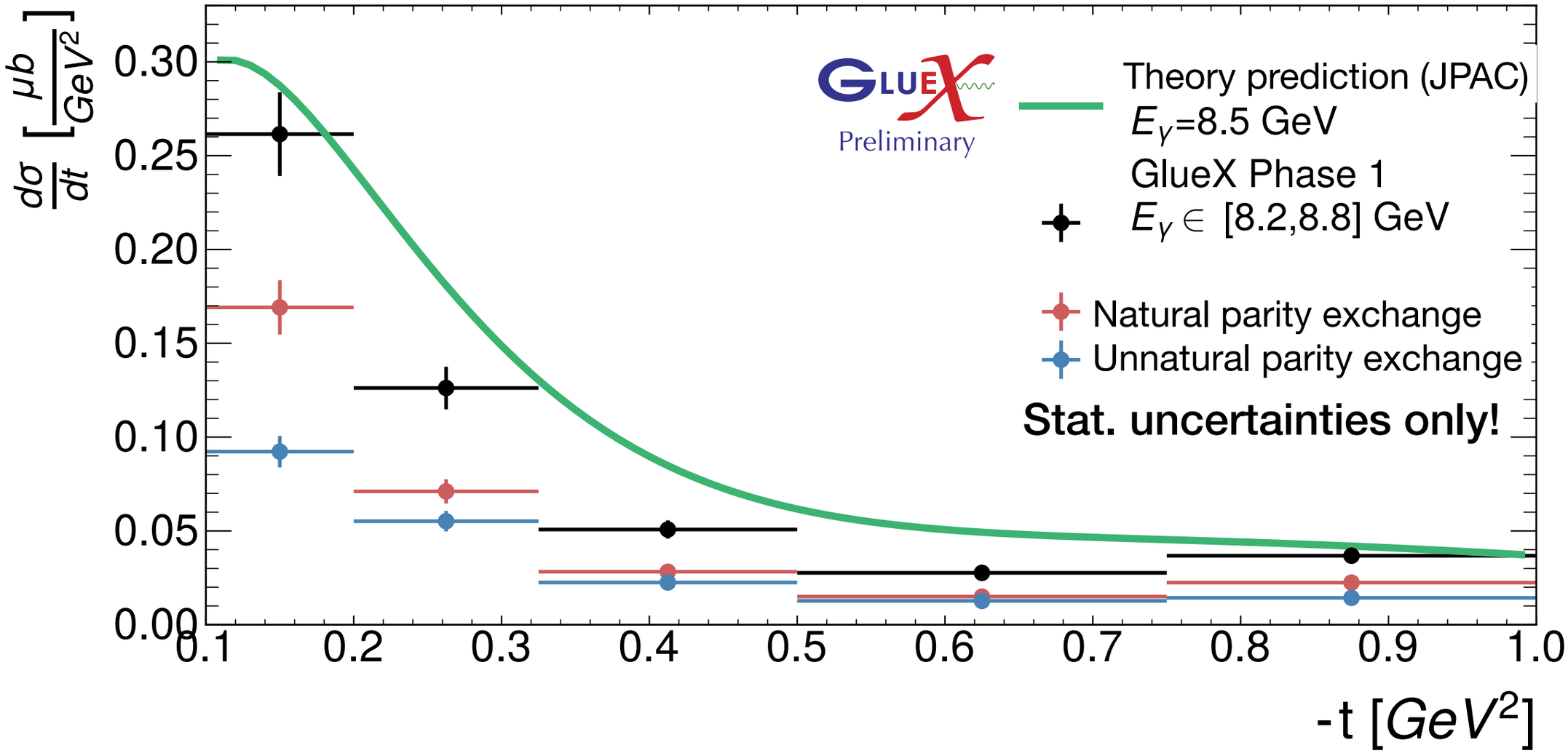


Semi-Model Independent Fit ($\gamma p \to \pi^0 \eta p$)



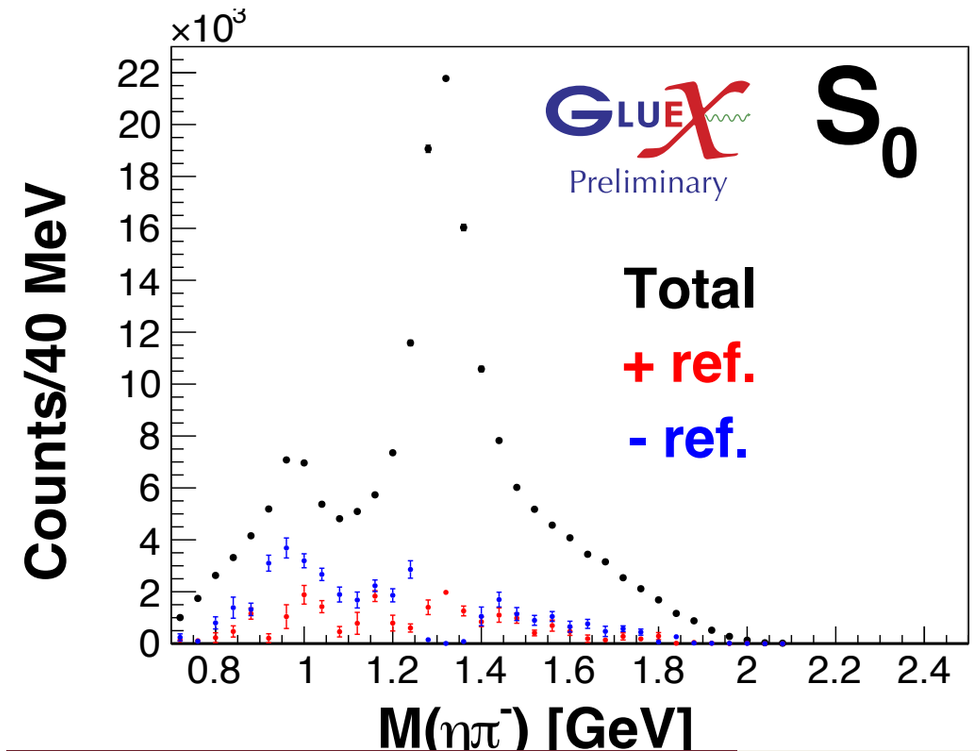
Extracted Cross Section

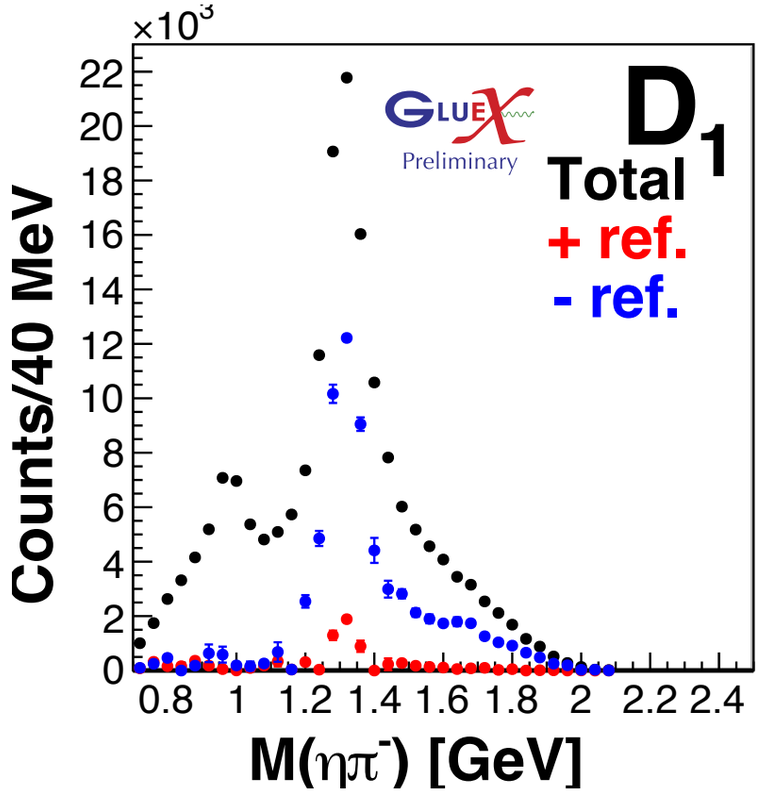
- Including $a_2(1700)$ has impact on result, tail underneath $a_2(1320)$
  → More sophisticated model being tested together with JPAC
- Good agreement with theory prediction
- Extraction of cross section well advanced, systematic checks started



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

- Combined fit, all polarization orientations
- Dominant S-wave contribution in negative reflectivity component
  - Large contribution in $a_0(980)$ mass region
- Clear signal in $m = +1$ D-wave ($a_2(1320)$), negative reflectivity
  - Expected for unnatural parity exchange (pion exchange)
  - Tail in D1 wave related to $a_2(1700)$?

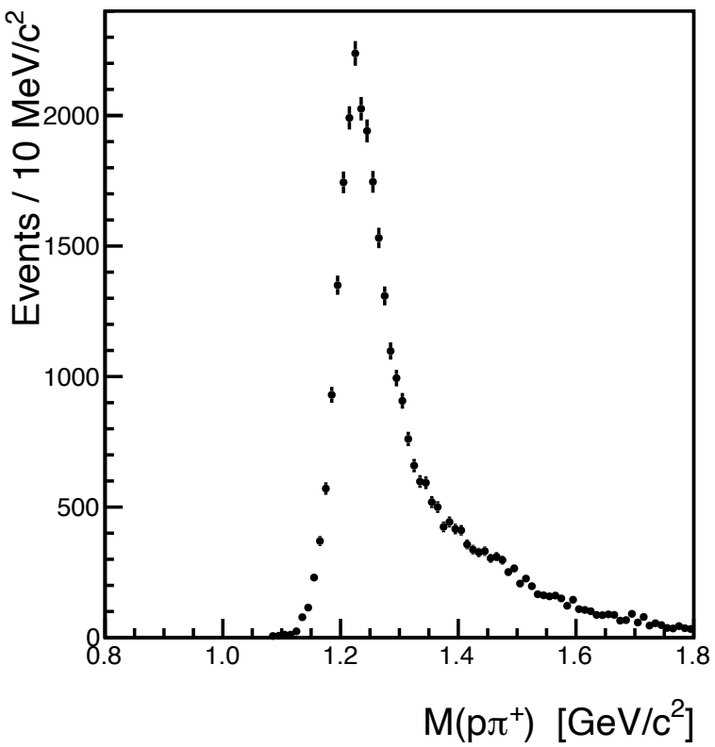




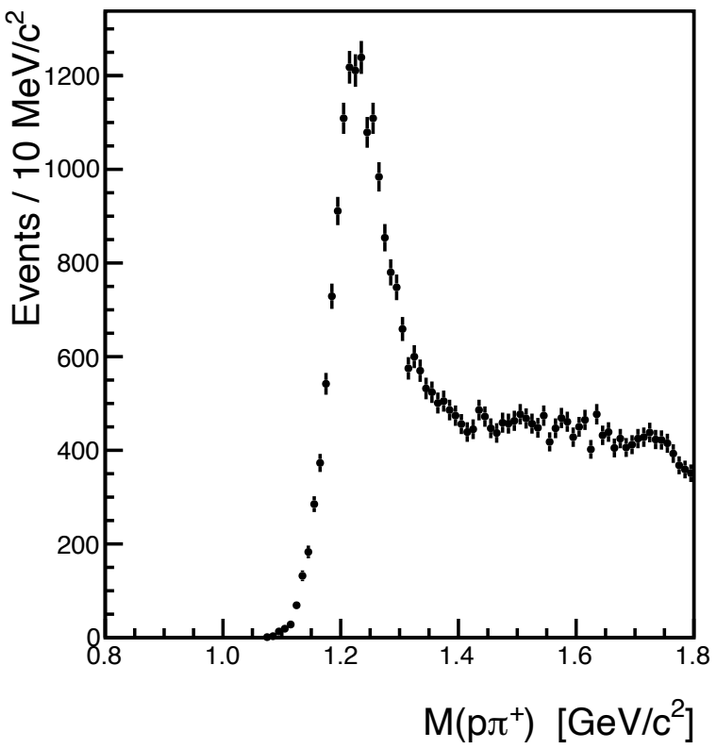
Non-Δ^{++} Background at higher t

- At higher t, non-Δ^{++} background important $\rightarrow$ contains a_2 signal
- Strategy developed:
  - Include Δ^{++} mass shape in amplitudes
  - Separate components in fit
- Development important also for other channels ($\eta'\pi^-\Delta^{++}, \omega\pi^-\Delta^{++}$)

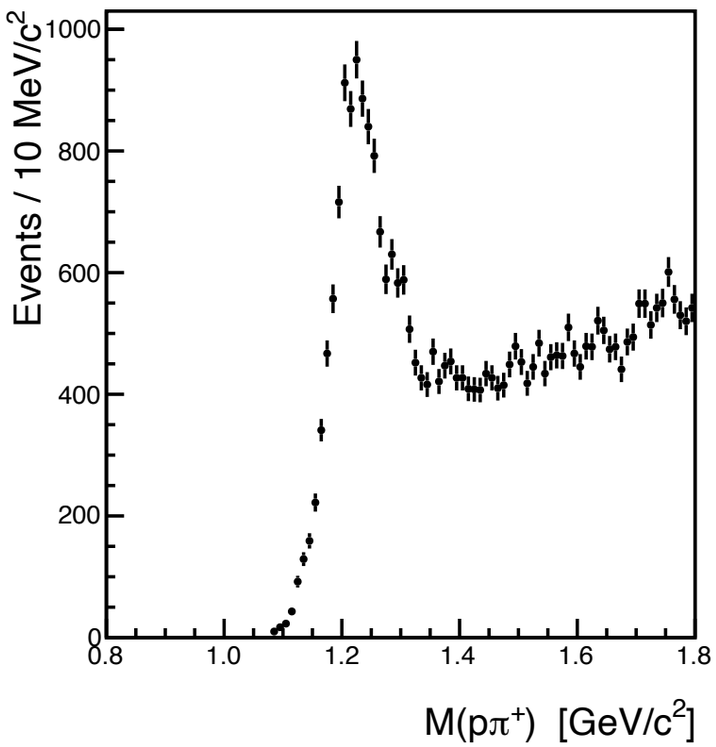
$0.1 < t < 0.3\,\mathrm{GeV}^2$



$0.3 < t < 0.6\,\mathrm{GeV}^2$



$0.6 < t < 1.0\,\mathrm{GeV}^2$



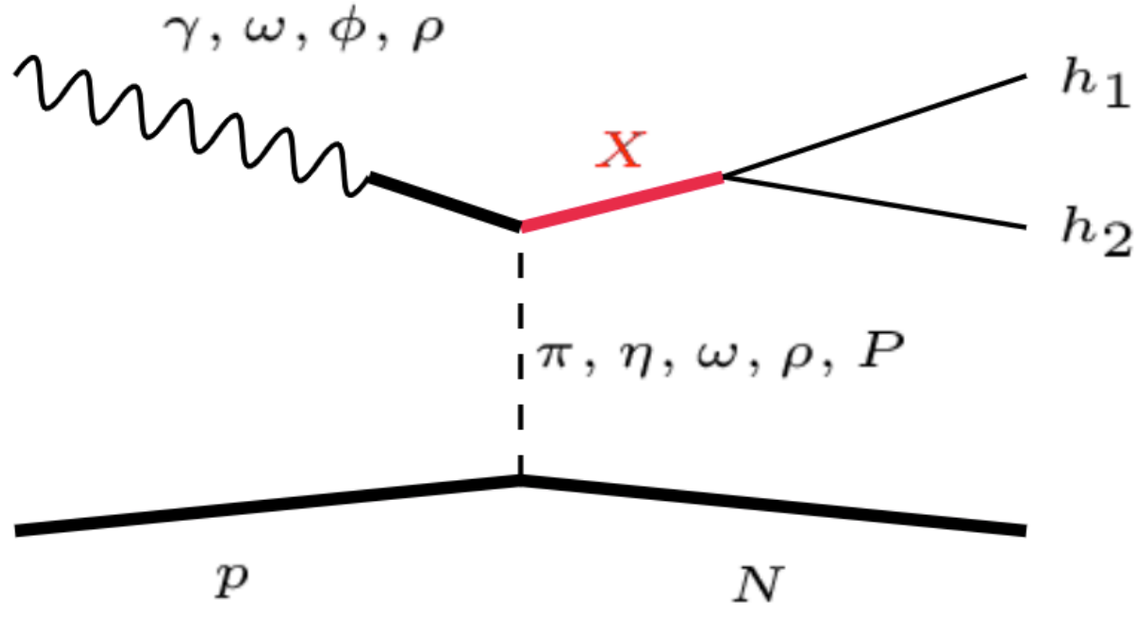
Comparison: Charged and Neutral Channels

$\eta\pi^0$:

- Dominated by positive reflectivity, $a_2(1320)$ signal in $m = 2$ wave at low t

➡ ρ, ω exchange (natural parity)

- Intriguing comparison: $a_2(1320)$ produced exclusively in helicity-2 state in $\gamma\gamma$-fusion
  [(L3) Phys.Lett.B 413(1997) 147;
  (Belle) Phys.Rev.D 80(2009), 032001]



$\eta\pi^-$:

- Dominated by negative reflectivity, $a_2(1320)$ signal in $m = 1$ wave at low t

➡ π exchange (unnatural parity)

- D-wave structure evolves with -t
- Investigation of a_2 production goal for near-term publication
- Groundwork for understanding weaker P-wave contribution

Where to Go from Here - The Big Picture

- Extraction of a_2 cross section against proton and Δ^{++} is first goal
  - Prompted code development, extension of amplitude library, performance enhancements, … useful for all amplitude analyses
  - Publication in preparation
- In parallel: preparing amplitude analysis for $\eta'\pi^-$ channel
  - Survey shows potential for large exotic contribution (using a_2 cross section from $\eta\pi^0$ as reference!)
- Near and far future:
  - Axial vector - pseudo scalar channels under investigation in parallel (largest hybrid branching fraction)
  - Search for partner states (e.g. in $\eta\eta'$ (recent BESIII hybrid result), hybrids with non-exotic quantum numbers, combine channels, …)
  - Future CEBAF energy upgrade: Benefits for spectroscopy program! → Suppression of double-regge contributions, accessibility of XYZ states, ….

Summary and Outlook

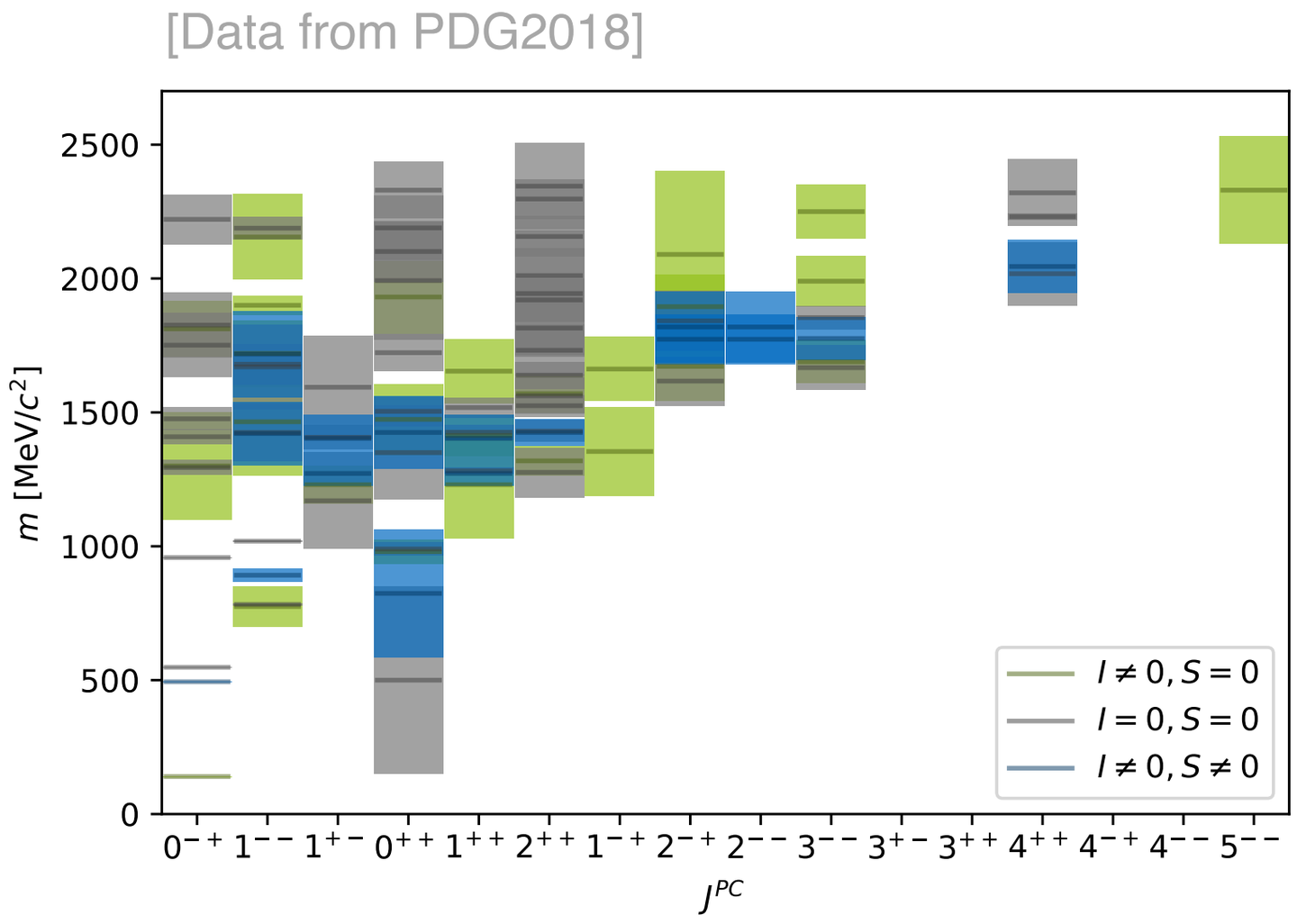
- **High quality photoproduction data sets available, analyses underway**
- **Partial wave analysis tools being used and further developed**
  - **Measurement of $a_2(1320)$ cross section in $\eta\pi$ demonstrates our ability to utilize beam polarization**
  - **Important stepping stone for hybrid search**
- **Highly productive and valuable collaboration with theory (JPAC)**
- **En route to first results on exotic mesons with GlueX!**

Acknowledgements: gluex.org/thanks

Backup

Challenges in Light Meson Spectroscopy

- Many broad and overlapping states discovered
- Assignment to multiplets ambiguous
- Fundamental to gain deeper understanding of strong interaction
- Ideally: Combine different **production** and **decay modes**



Modern experiments provide high statistics, clean data samples

⇒ Sophisticated methods needed to extract physics results