Search for Exotic Hadrons in $\eta^{(\prime)}\pi$ at GlueX

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for the GlueX Collaboration

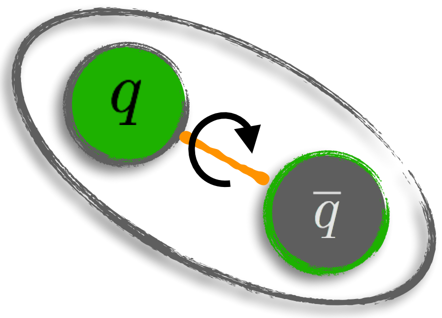
Jefferson Lab

International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy (PWA13/ATHOS8)
College of William & Mary, Williamsburg, VA

28 / 05 / 2024

The $\eta^{(\prime)}\pi$ System

- **Ongoing quest:**
  - What are the correct degrees of freedom to describe the hadron spectrum?
  - How do gluons contribute to the structure of hadrons?

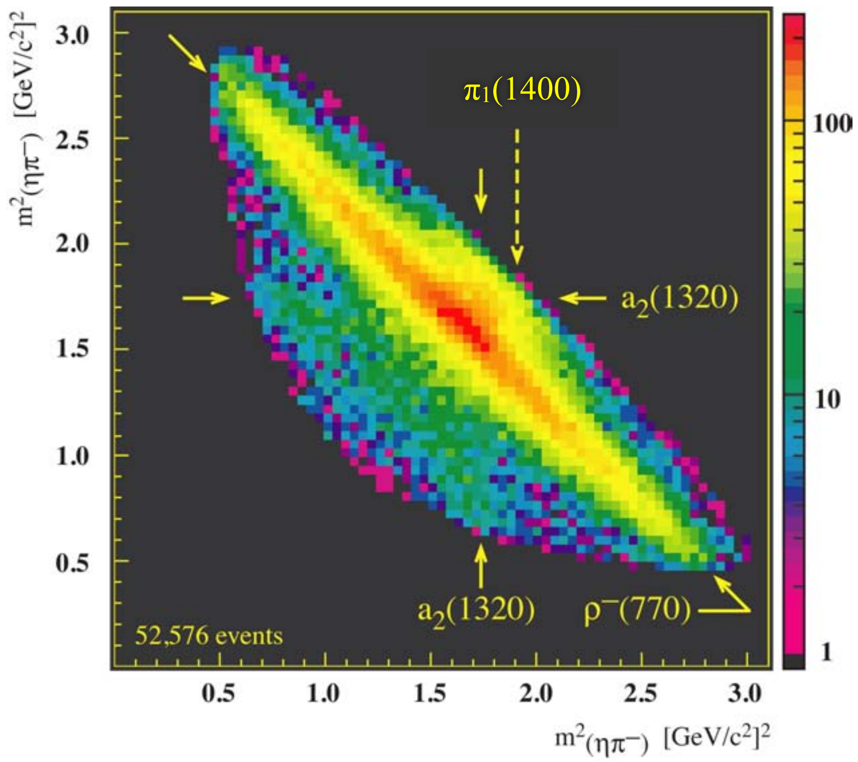


- **Mapping out the spectrum of light hybrids:**
  - Evidence in multiple channels, consistent results
  - Search for partner states, regular J^{PC} hybrids, higher mass nonets
  - Partial Wave Analysis (PWA) is an indispensable tool
  - Achieving analysis goals depends on strong theory-experiment collaboration

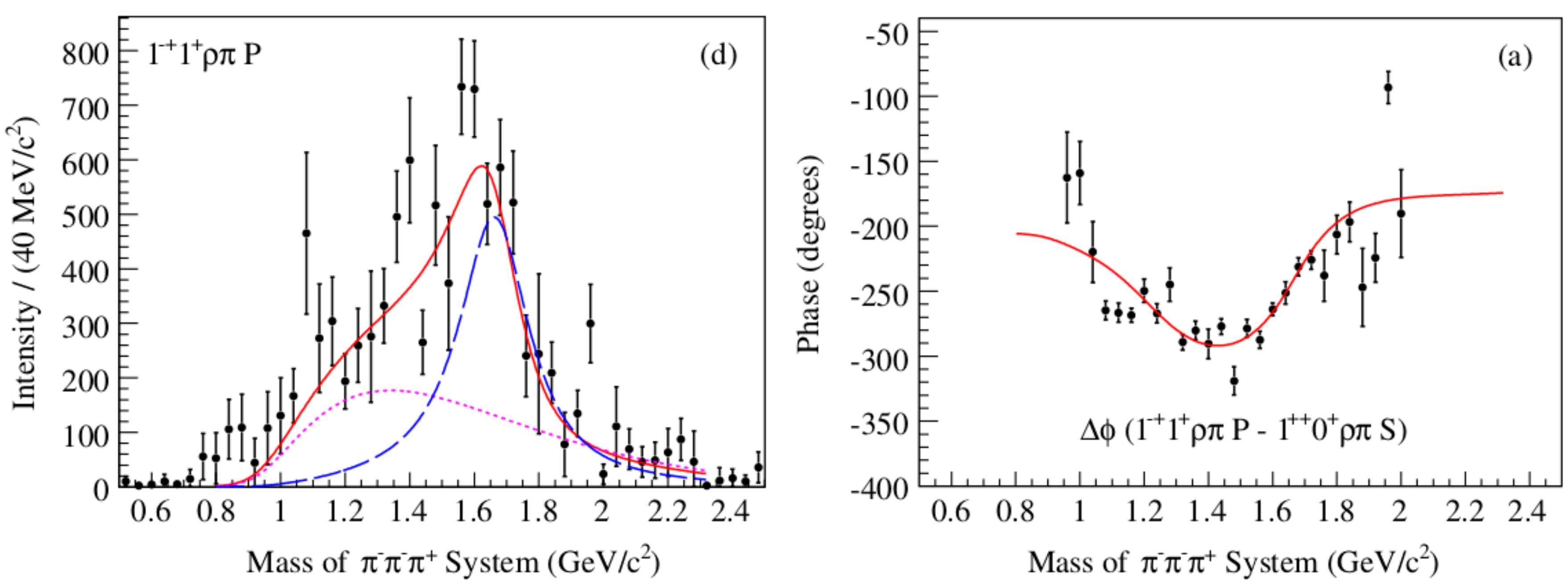
- **Strongest experimental evidence so far in $\eta^{(\prime)}\pi$ channels**
  → High priority for GlueX
  → Investigating in parallel:
  $\gamma p \to \eta\pi^0 p,\ \eta\pi^-\Delta^{++},\ \eta'\pi^0 p,\ \eta'\pi^-\Delta^{++}$

Hybrid Mesons

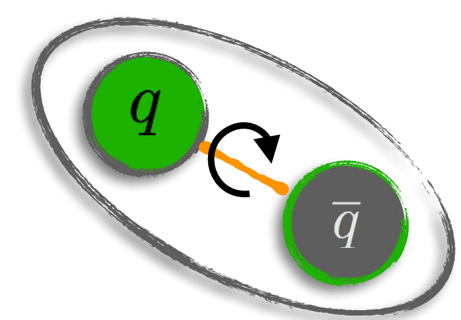
PLB 423, 175-184 (1998), Crystal Barrel



PRL 104, 241803 (2010), COMPASS



- Hints for spin-exotic states already in 1980s
- Observed at various experiments
- From PWA: $J^{PC} = 1^{-+}$
  - $\pi_1(1400)$ in $\eta\pi$
  - $\pi_1(1600)$ in $\eta'\pi, \rho\pi$
- Clear contribution of exotic wave
- Two genuine resonances?

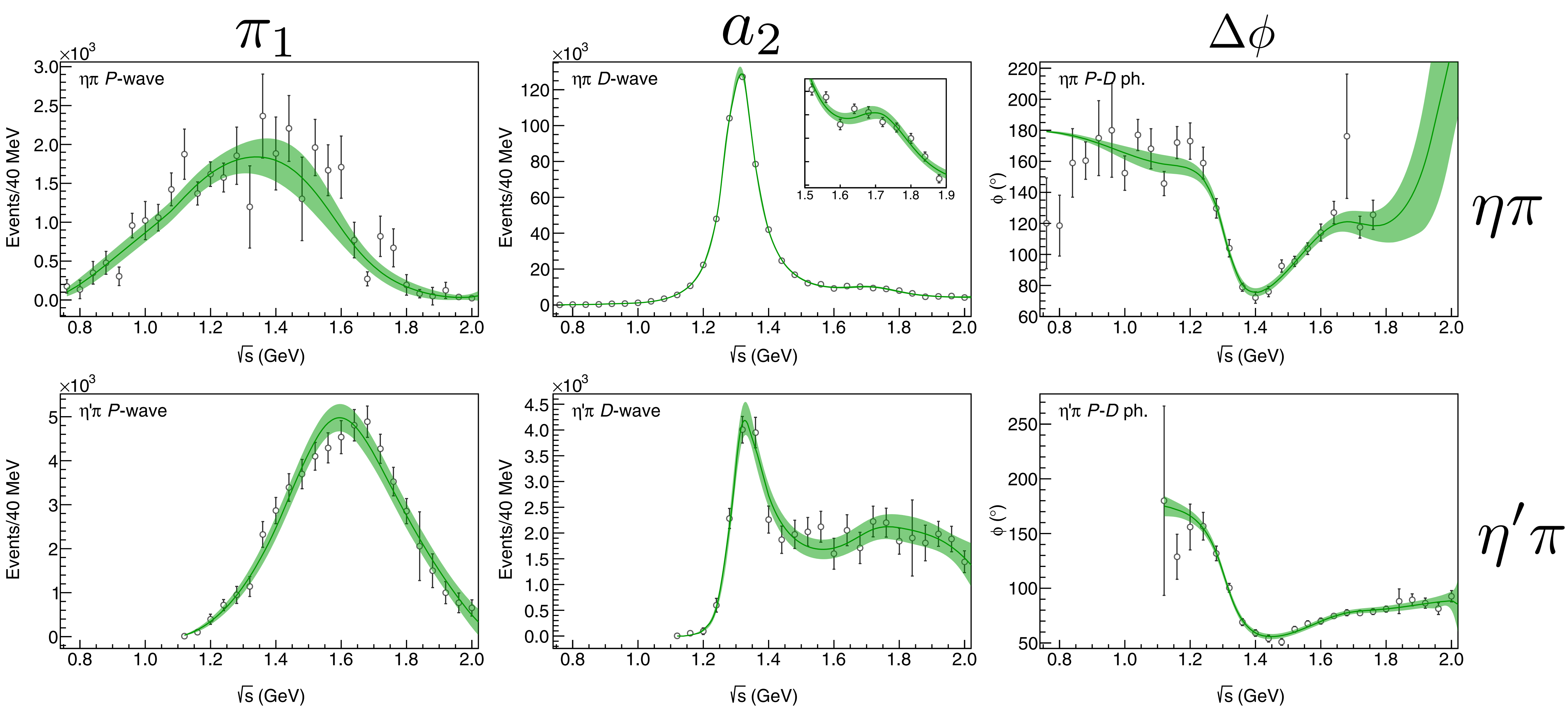


Two Hybrid Mesons?

- Analysis of COMPASS data from JPAC, recently extended with $\bar{p}p$ data:
  [A.Rodas et.al. PRL 122, 042002 (2019), B.Kopf et.al. Eur.Phys.J.C 81, 1056 (2021)]

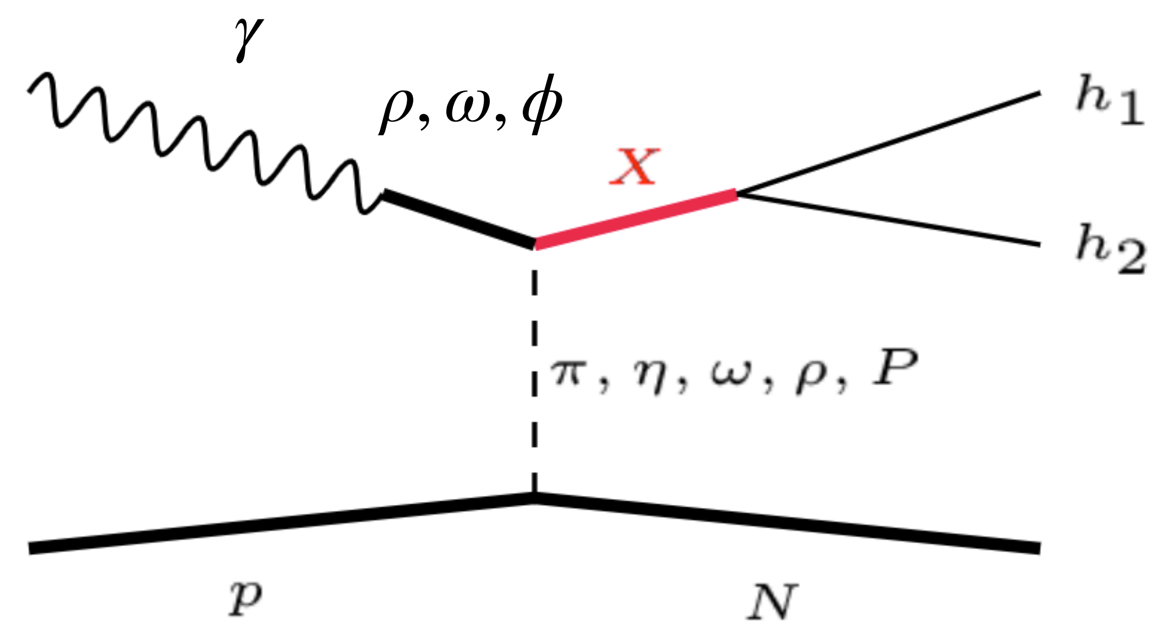
- Sophisticated description of 1^{-+} wave with 1-pole, coupled channels

- Observed structures described by a single resonance



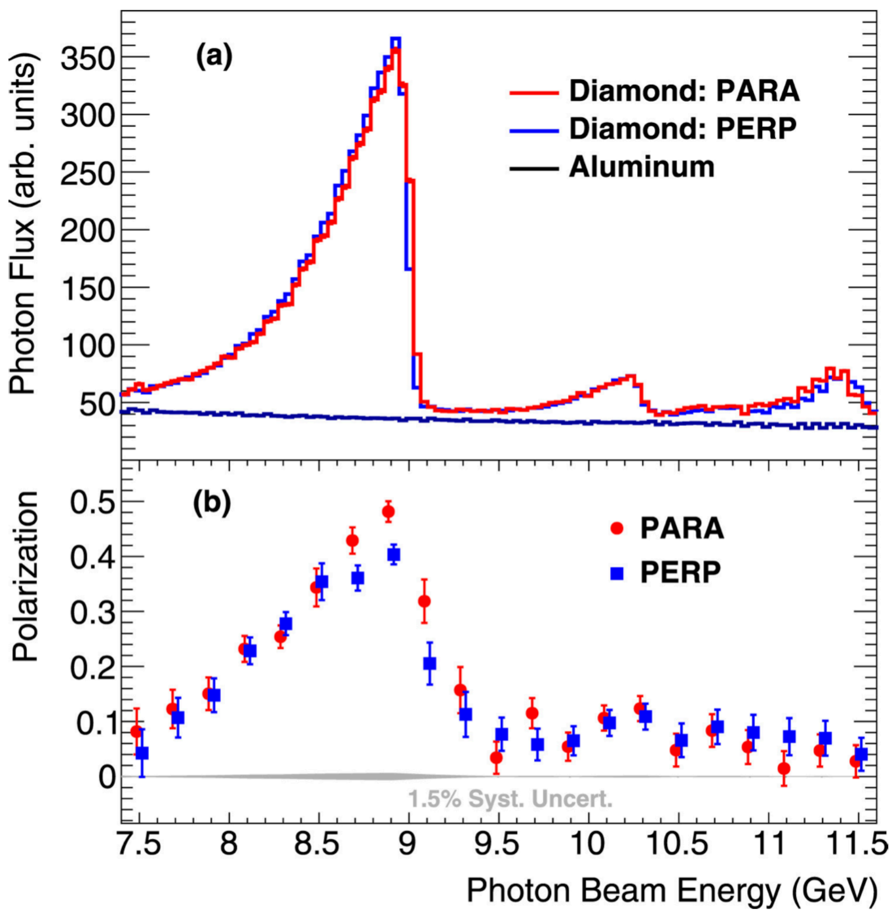
The Route to Exotics with GlueX

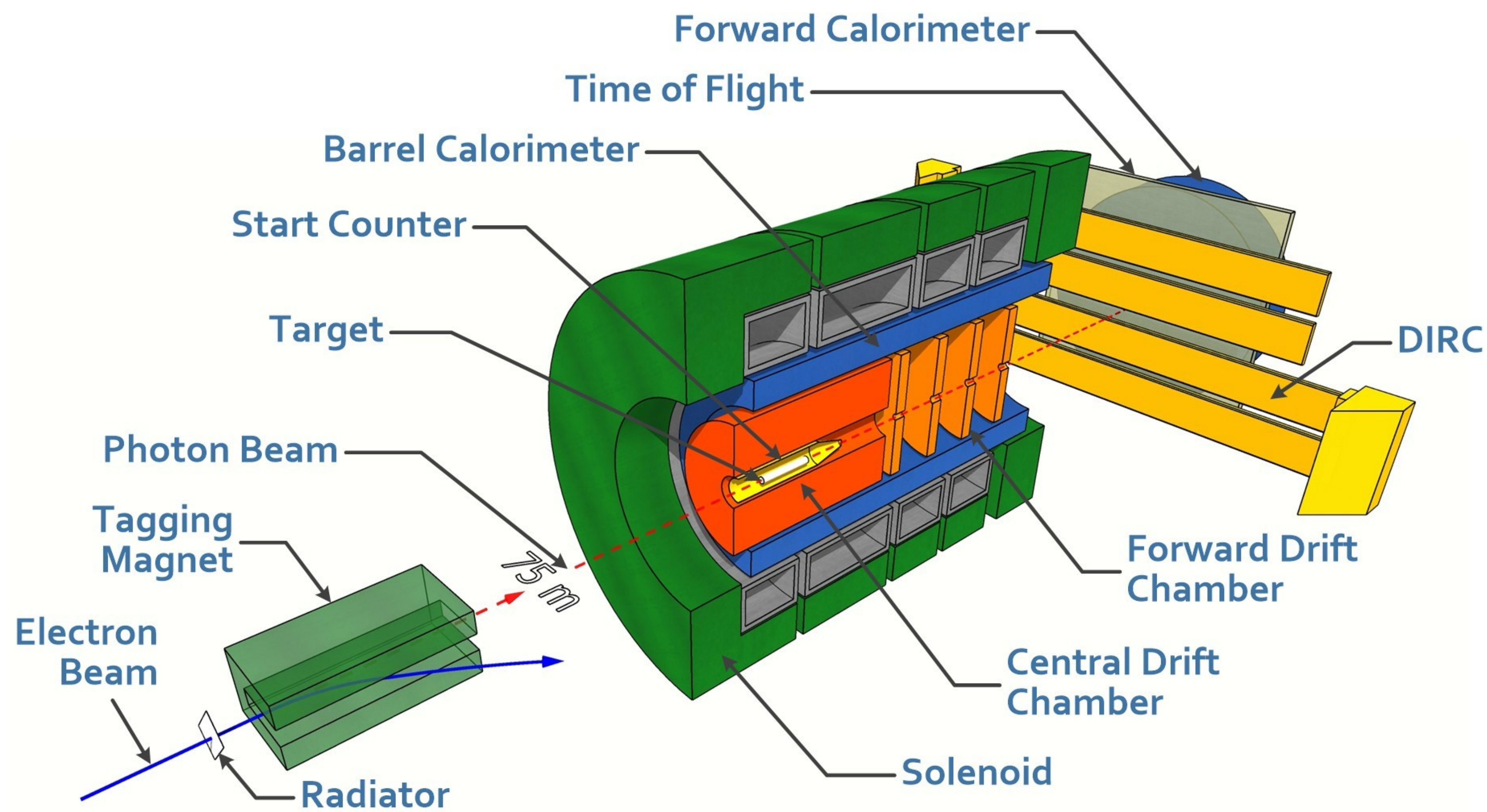
- **Photoproduction - a versatile process:**
    - Incoming photon may oscillate to vector meson
    - Production of mesonic resonances as well as target excitations
    - Complementary to πN reaction used by COMPASS, E852, VES
    - Allows coupling to all lightest hybrid nonet states



- Understand (polarized) production of “simple” hadrons - increase complexity stepwise
- 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 ($\omega, \varphi, \Lambda(1520)$ -** PRC 105, 035201 (2022), ρ - PRC 108, 055204 (2023)**)**
- Investigation of $\eta^{(\prime)}\pi$ channels
    - **Study production mechanism, cross section of known mesons first**
    - Charged and neutral modes, different sub-decays → acceptance, background handling
- Extend hybrid search to vector-pseudoscalar channels ($\omega\pi, \omega\eta, \phi\pi, \phi\eta, K^*K$)
  (see talk by Amy Schertz: Fri, 4:45pm!)

The GlueX Experiment at Jefferson Lab





[(GlueX) NIMA **987** (2021) 164807]

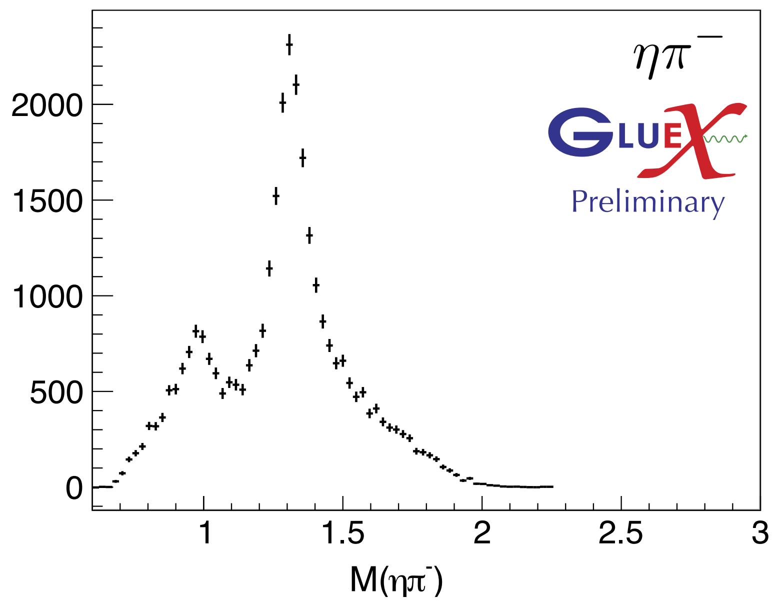
- Linearly polarized, tagged photon beam (P≈40%) impinging on Liquid Hydrogen Target
- Four polarization orientations, coherent peak: ~8.2-8.8 GeV
- Large acceptance for charged and neutral final state particles
- GlueX Phase I completed (2017-18, $\int L = 125\,\text{pb}^{-1}$), Phase II ongoing (expect 3-4 times Phase I data)

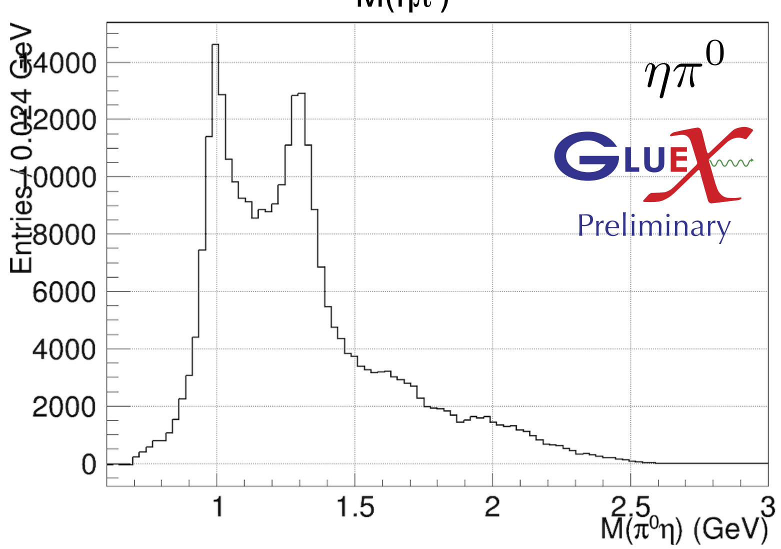
$\gamma p \to \pi \eta N$ at GlueX

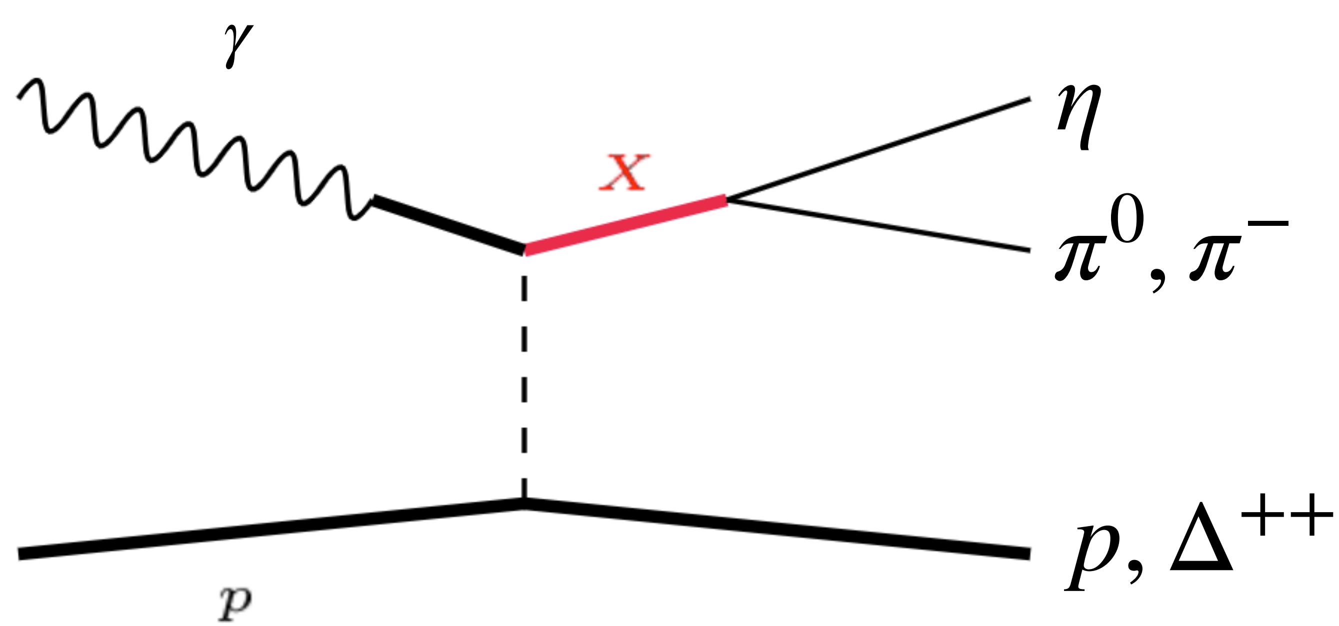
- Evidence for spin-exotic contribution from other experiments
  → Key channel for GlueX

- Clear signals at $a_0(980)$ and $a_2(1320)$ masses *(not acceptance corrected)*

$0.1 < -t < 0.3$ GeV^2







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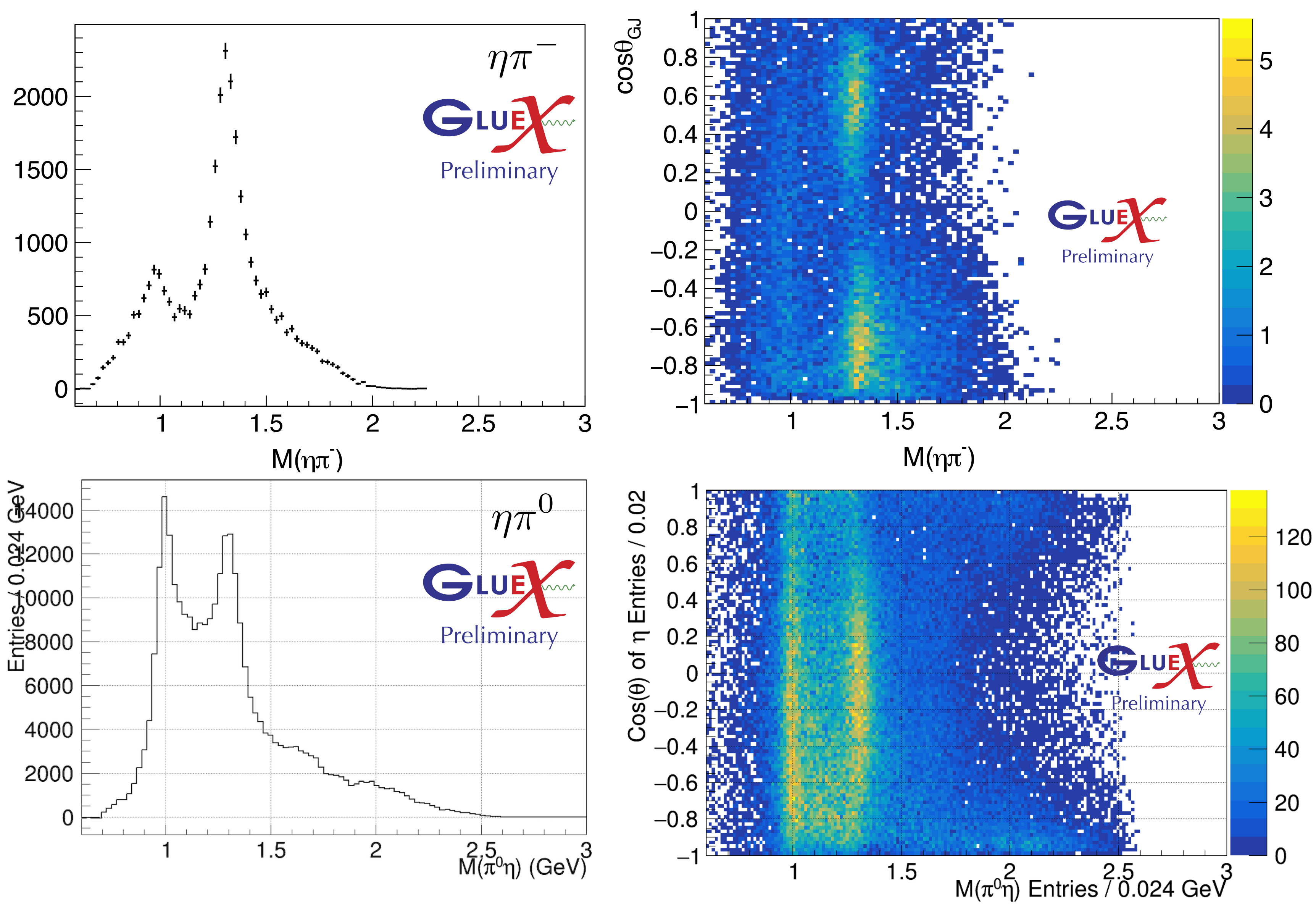


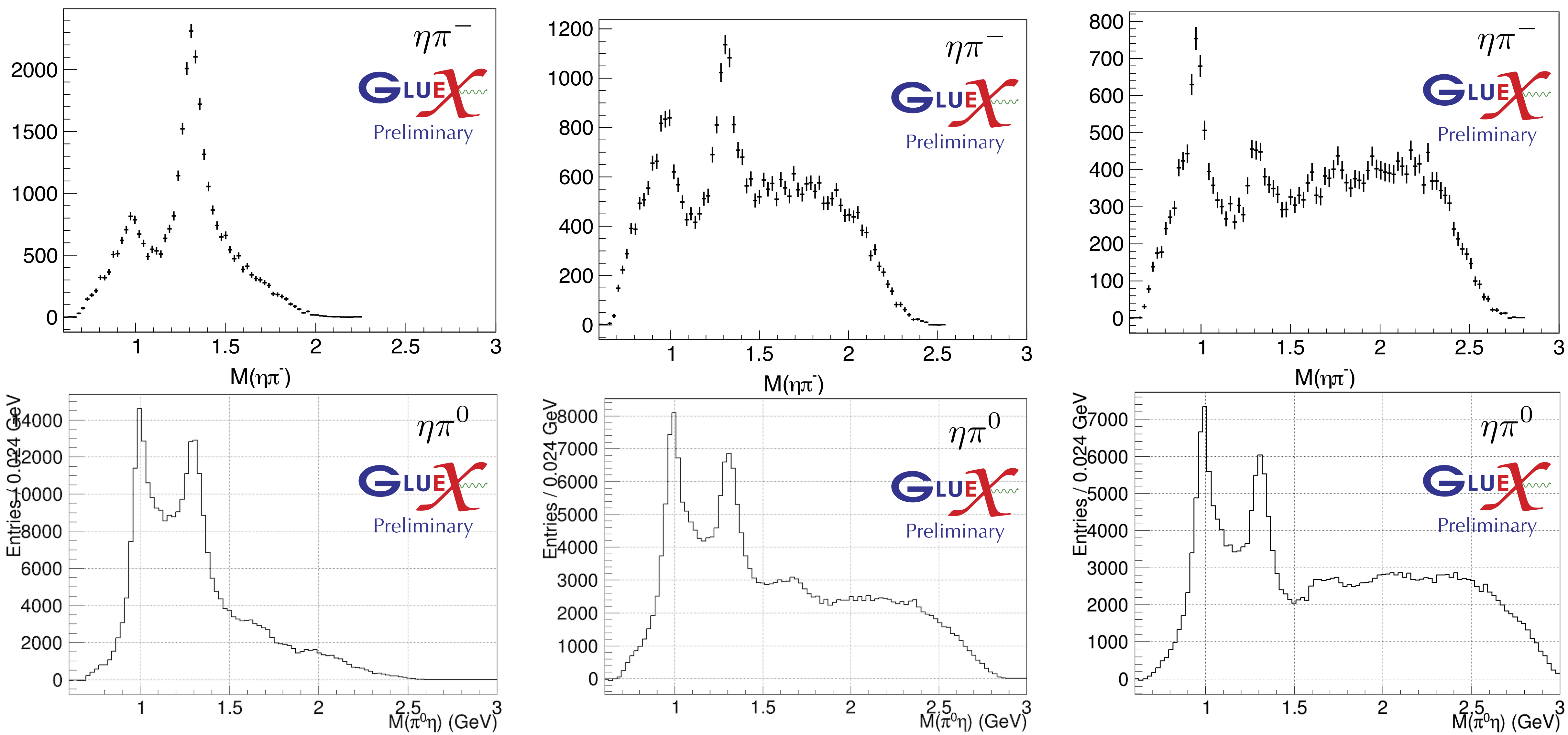
- Angular distribution of $a_2(1320)$ signal clearly different between charged and neutral channels

- Different spin-projection states populated in charged vs. Neutral channel

$\gamma p \rightarrow \pi \eta N$ 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 *(not acceptance corrected)*

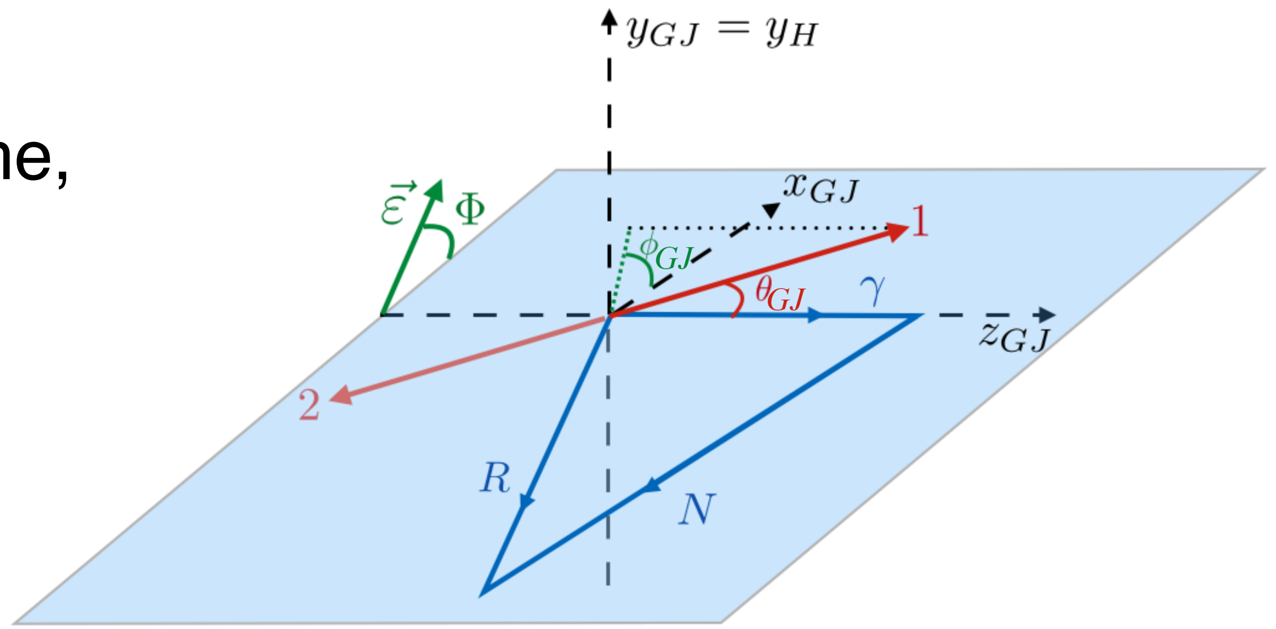
$0.1 < -t < 0.3$ GeV^2 | $0.3 < -t < 0.6$ GeV^2 | $0.6 < -t < 1.0$ GeV^2



Definition of Amplitudes

- Described by three angles:
  $\cos\theta_\eta$ and ϕ_η in the resonance 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

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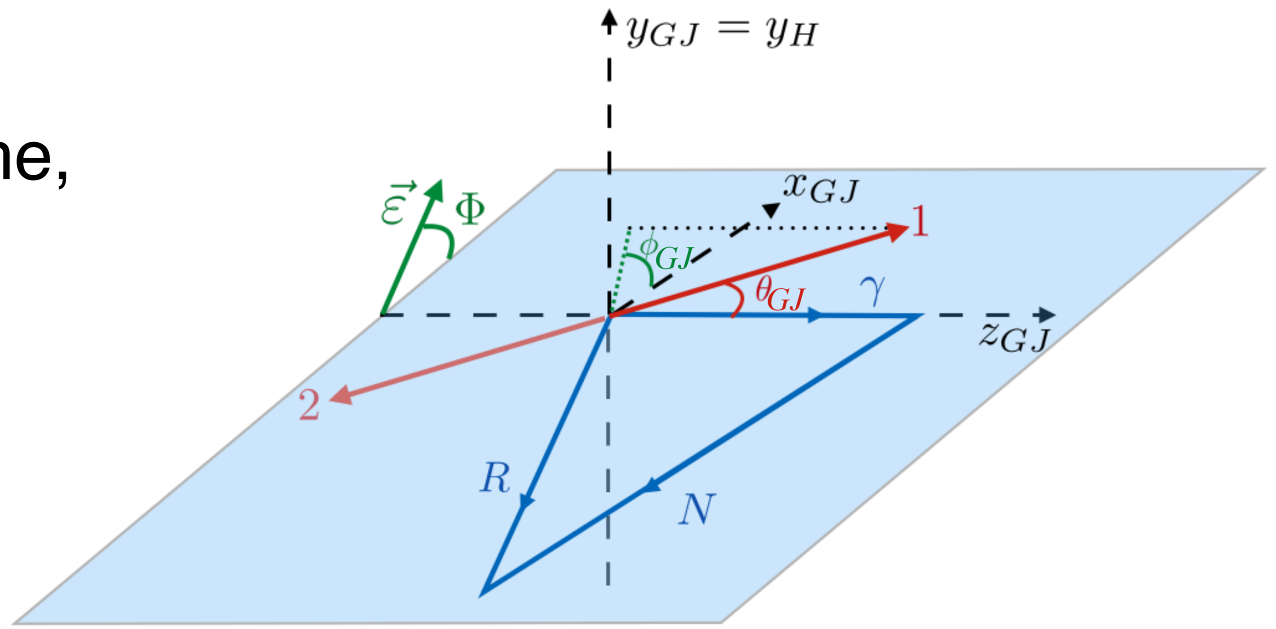


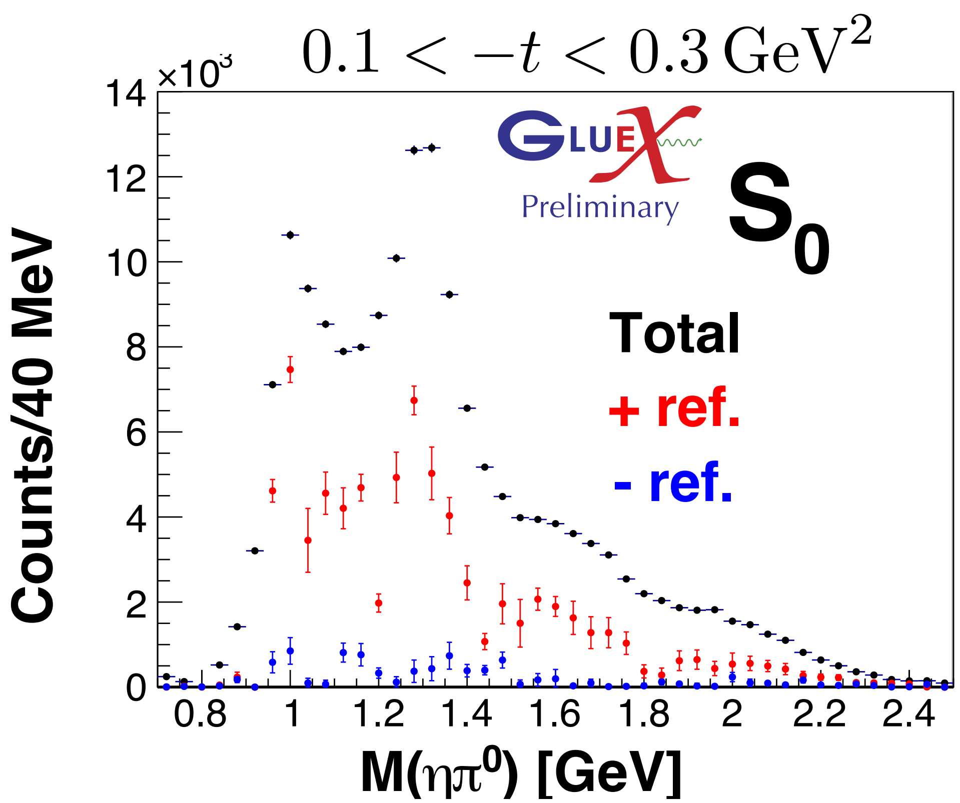
[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

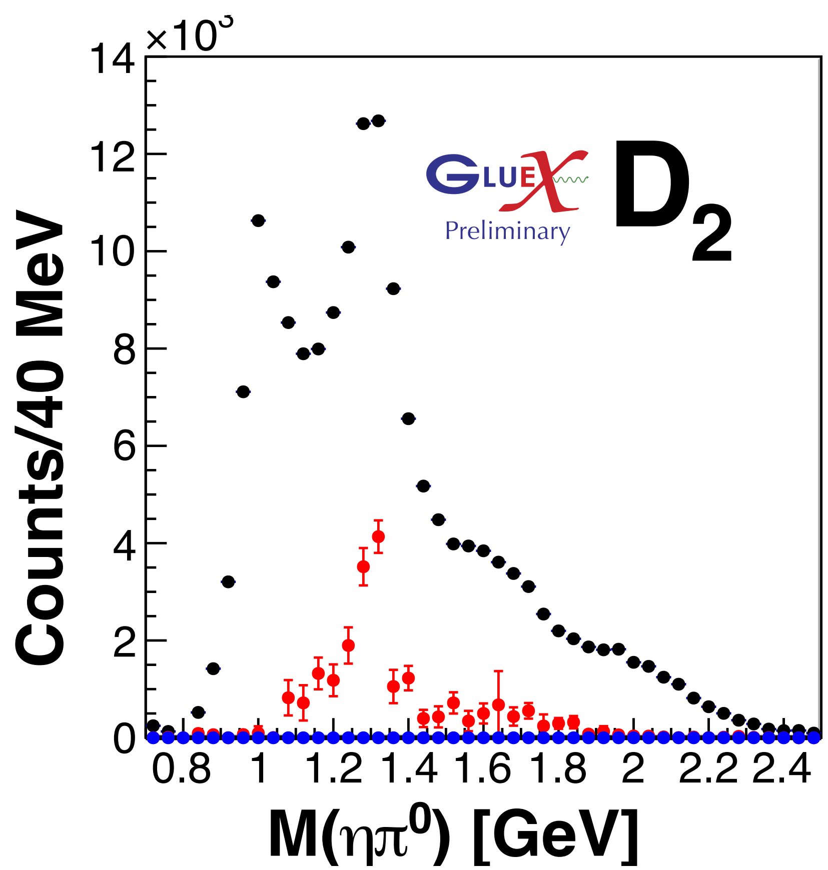
- Basis: Z_l^m amplitudes defined as $Z_l^m(\Omega, \Phi) = Y_l^m(\Omega) e^{-i\Phi}$

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

- Complexity: Reflectivity $\epsilon = \pm 1$ and spin projections $m = -l, \ldots, +l$ allowed
  - 4 times more amplitudes than with pion beam (with same truncation)

Mass-Indep. PWA of $\gamma p \to \eta\pi^0 p$





Work of L. Ng, M.A.

- Combined fit of all polarization orientations
- Large S-wave, positive reflectivity contribution
  - Non-resonant?
  - Contribution from other resonance(s)?
- Clear signal in $m = +2$ D-wave
- Waveset initially 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)]

- Persisting challenges:
  leakage between waves, fluctuations - especially for sub-dominant waves, ambiguities
  (More on ambiguities, non-parametric approaches: Edmundo's talk, Wed 4:15pm and Lawrence' talk Wed, 4.45pm!)

$\to$ **Perform semi - mass independent PWA to extract a_2 contribution**

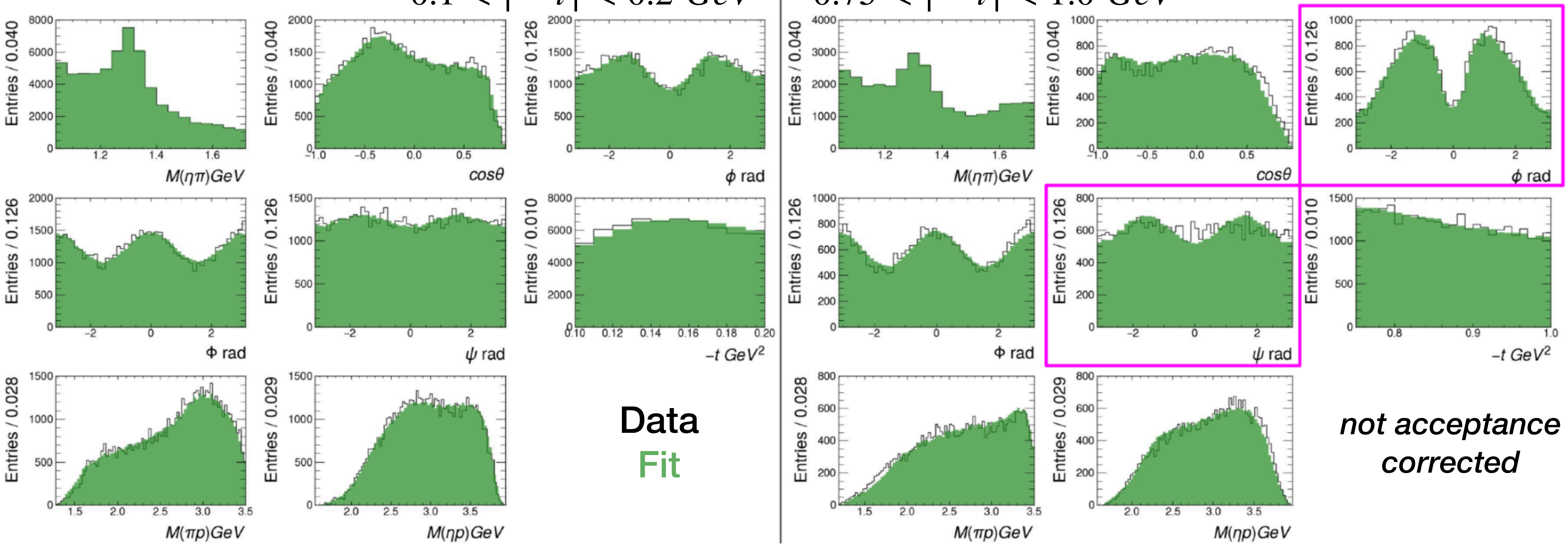
Validity of TMD Waveset

Work of L. Ng, M.A.

Internal

Nominal Fit Quality

$0.1 < |-t| < 0.2\ GeV^2$ | $0.75 < |-t| < 1.0\ GeV^2$



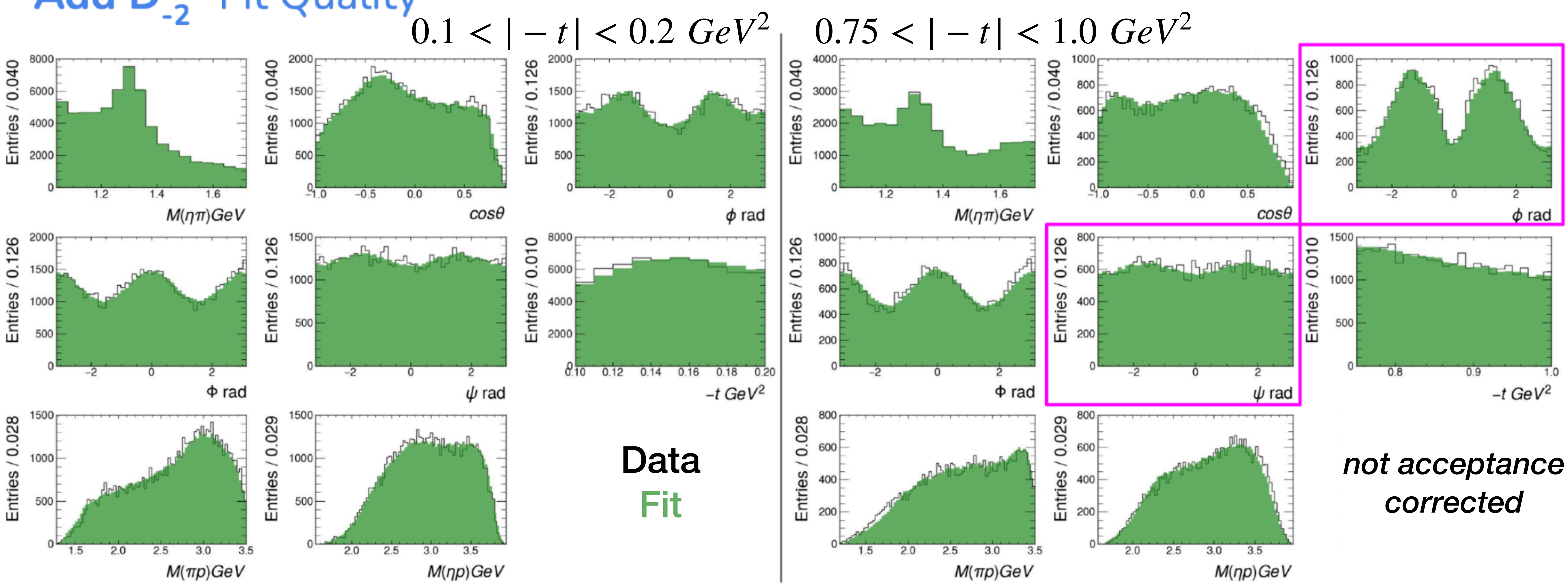
$$\textbf{Waveset: } L_m^{\epsilon} = S_0^{\pm}, D_0^{\pm}, D_1^{\pm}, D_2^{+}, D_{-1}^{-}$$

Extension of Waveset

Work of L. Ng, M.A.

GlueX Internal

Add D_{-2}^{+} Fit Quality



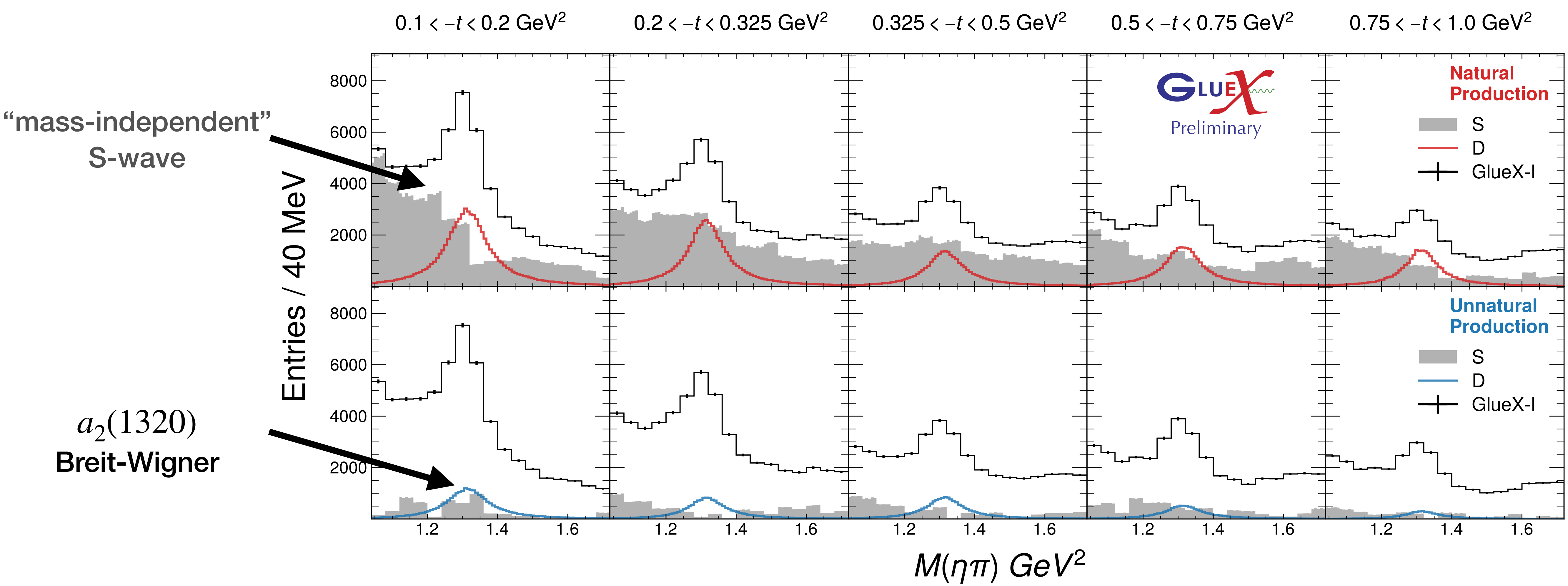
Waveset: $L_m^{\epsilon} = S_0^{\pm}, D_0^{\pm}, D_1^{\pm}, D_2^{+}, D_{-1}^{-}, D_{-2}^{+}$

For final results: Extended to full waveset

Semi-Mass Independent PWA ($\gamma p \to \pi^0 \eta p$)

Work of L. Ng, M.A.

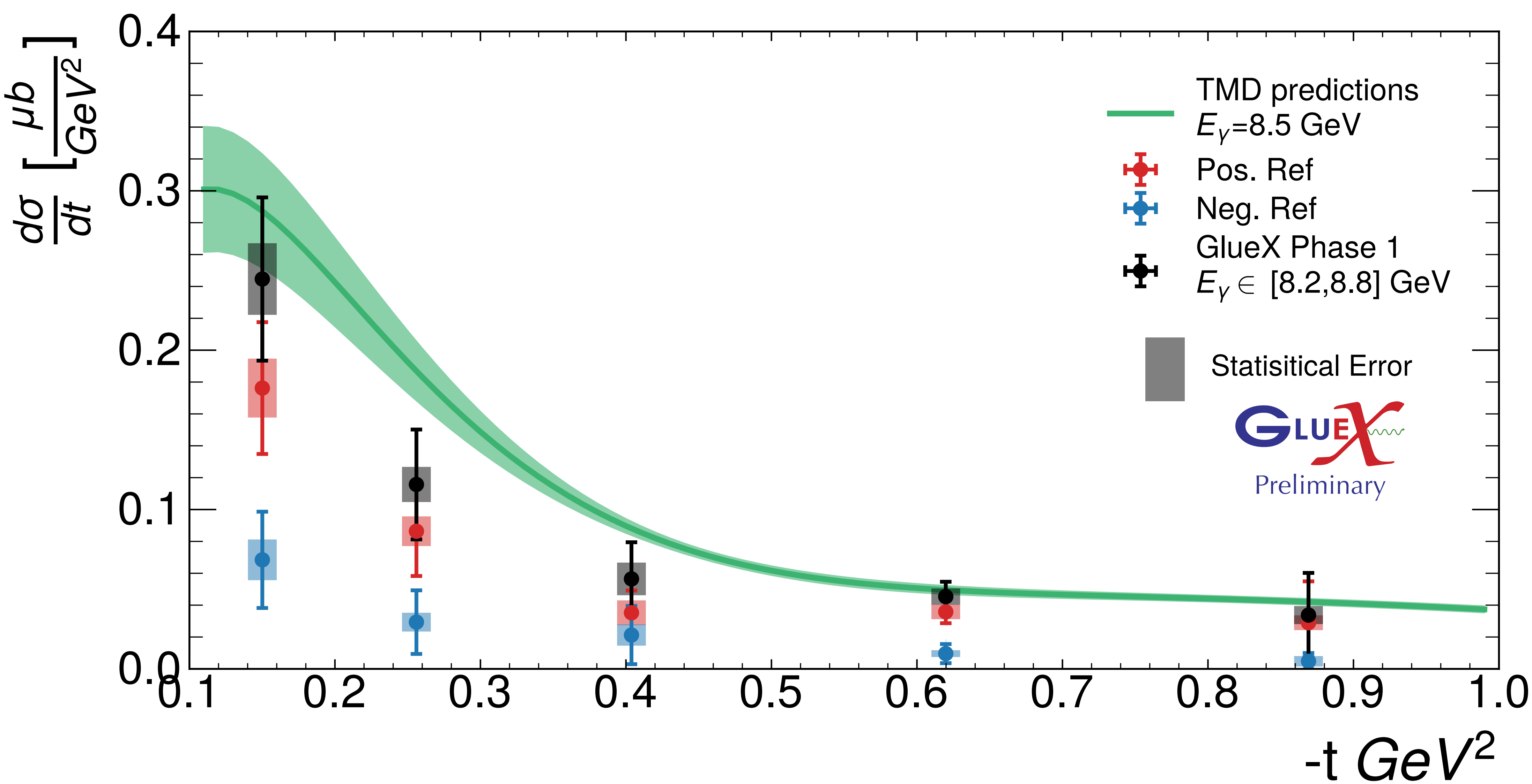
- Simplify problem by introducing physics constraint:
- $a_2(1320)$ reasonably isolated $\to$ Well described by Breit-Wigner function
- S-wave has complex structure $\to$ keep "mass-independent" parameterisation
- Eliminates leakage between waves, ensures continuity of solution
- Major contributions consistent with observations from mass independent PWA



Differential $a_2(1320)^0$ Cross Section

Work of L. Ng, M.A.

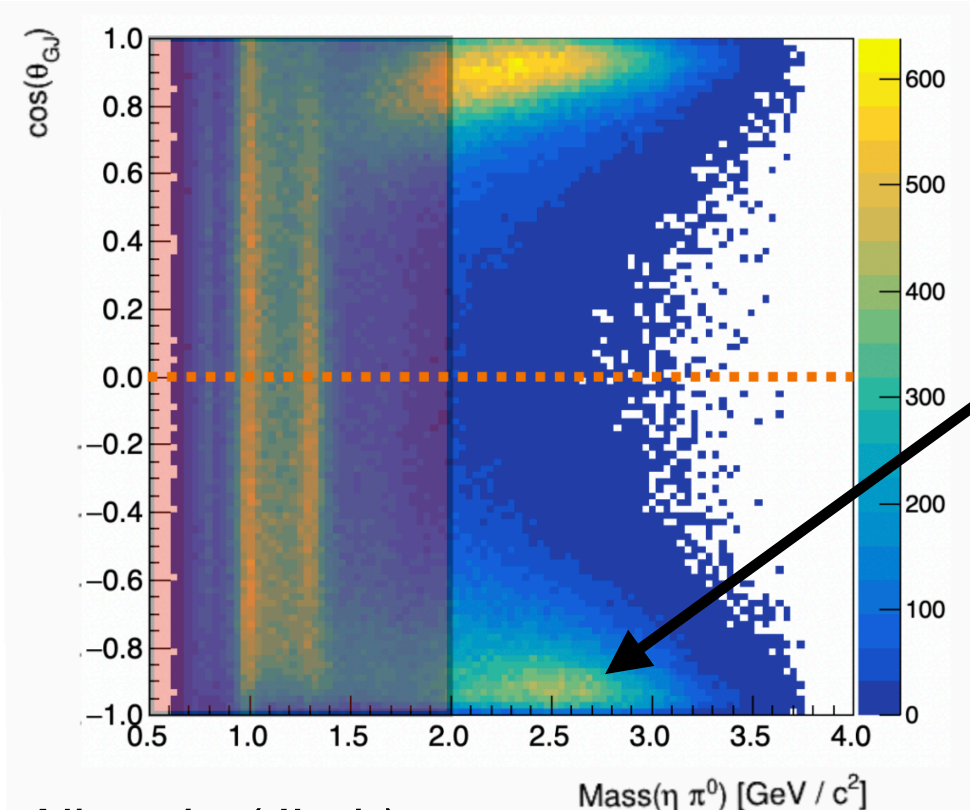
- Reasonable agreement with JPAC prediction
- We observe dominance of natural parity exchange $(\rho, \omega, \ldots)$
- Statistical uncertainties from bootstrapping, systematics finalized
- Publication in preparation (internal review)



Double Regge Process

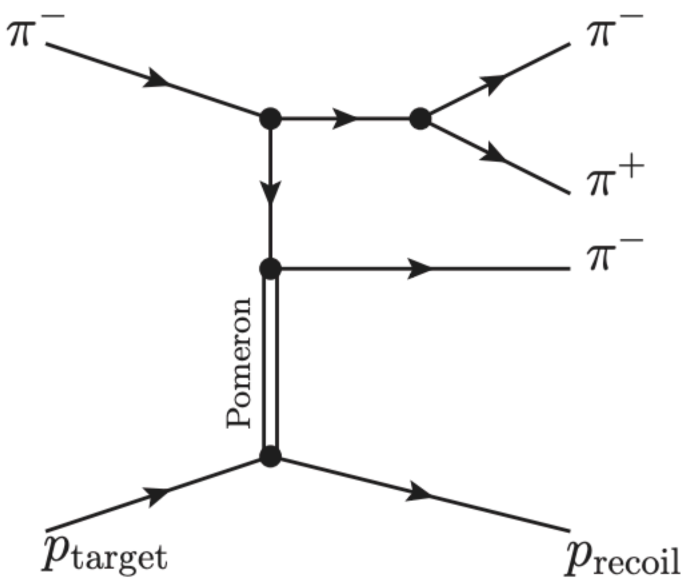
Work of R. Barsotti

- Double-Reggeon exchange process (similar to Deck-contribution at COMPASS)
  - Dominant at high invariant mass
  - Extends down into resonance region, will overlap with (broad) π_1 signal, if present
  - Can enhance odd partial waves → mimic exotic signal
  - Important to understand and model this process → Theory support indispensable

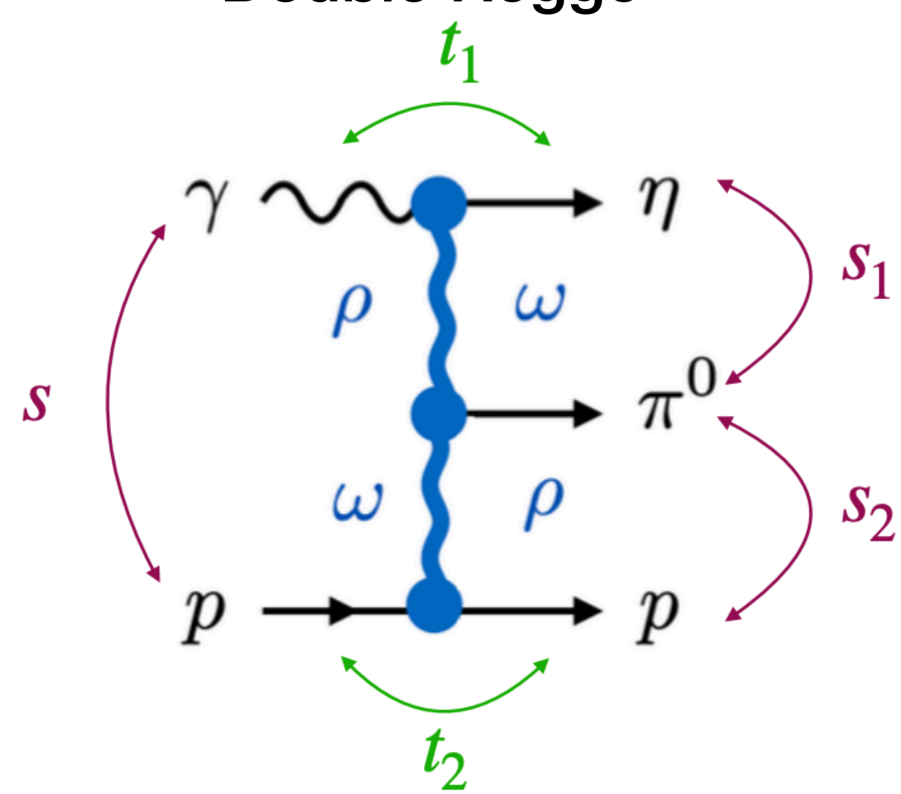


Baryon background and Double Regge exchange?

Deck-Effect



Double Regge

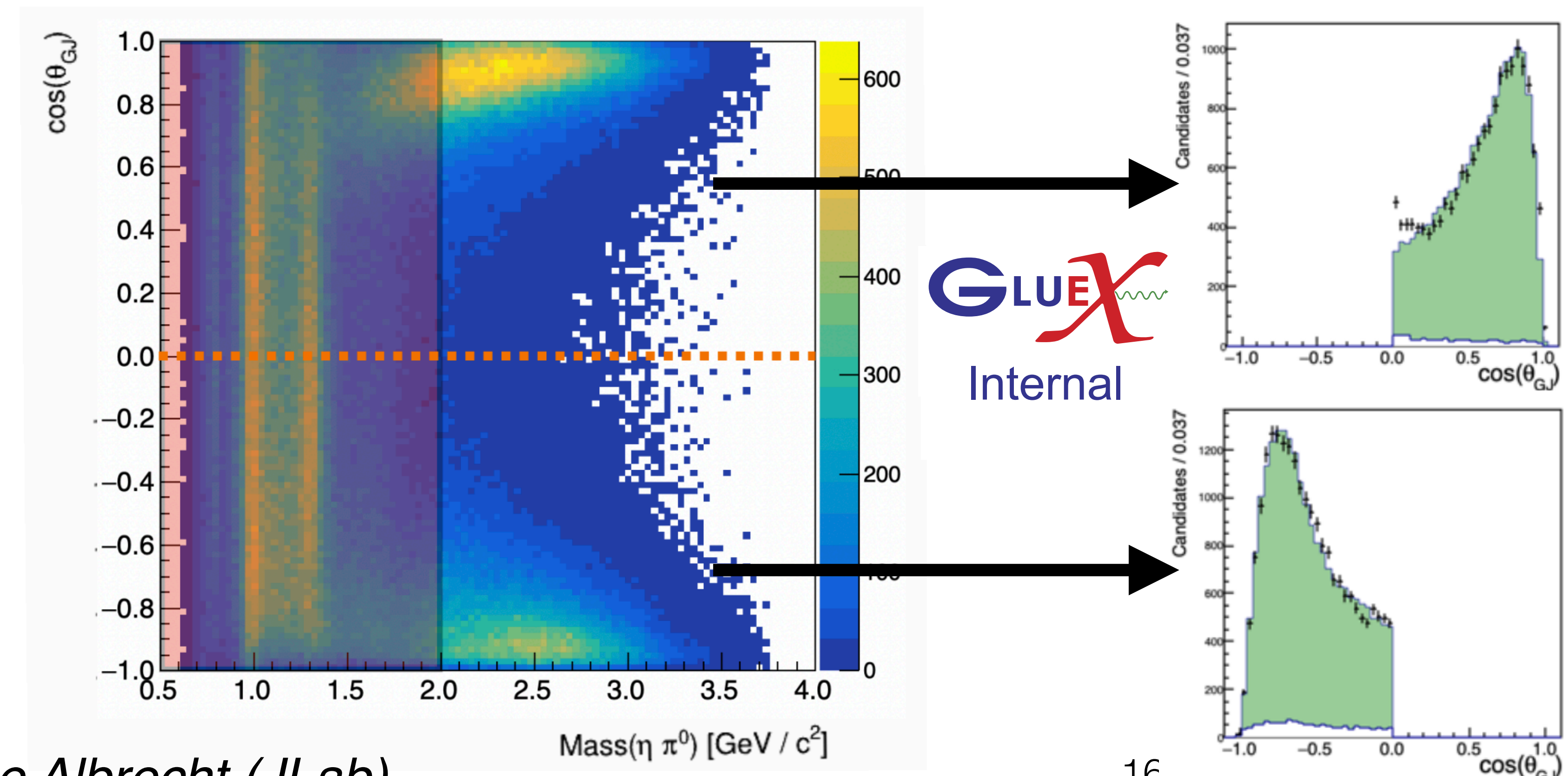


Improved Double Regge Process Modeling

Work of R. Barsotti

- Close collaboration with Theory/JPAC:
  - Original model was too simplistic
    (see also [L. Bibrzycky et. al. (JPAC), EPJ C 81, 647 (2021)])
  - Improved model available that involves better description of vertex factors, five parameters to describe kinematic distribution
- Monte Carlo study with updated model underway
- First fits to data promising, reasonable agreement in high mass region

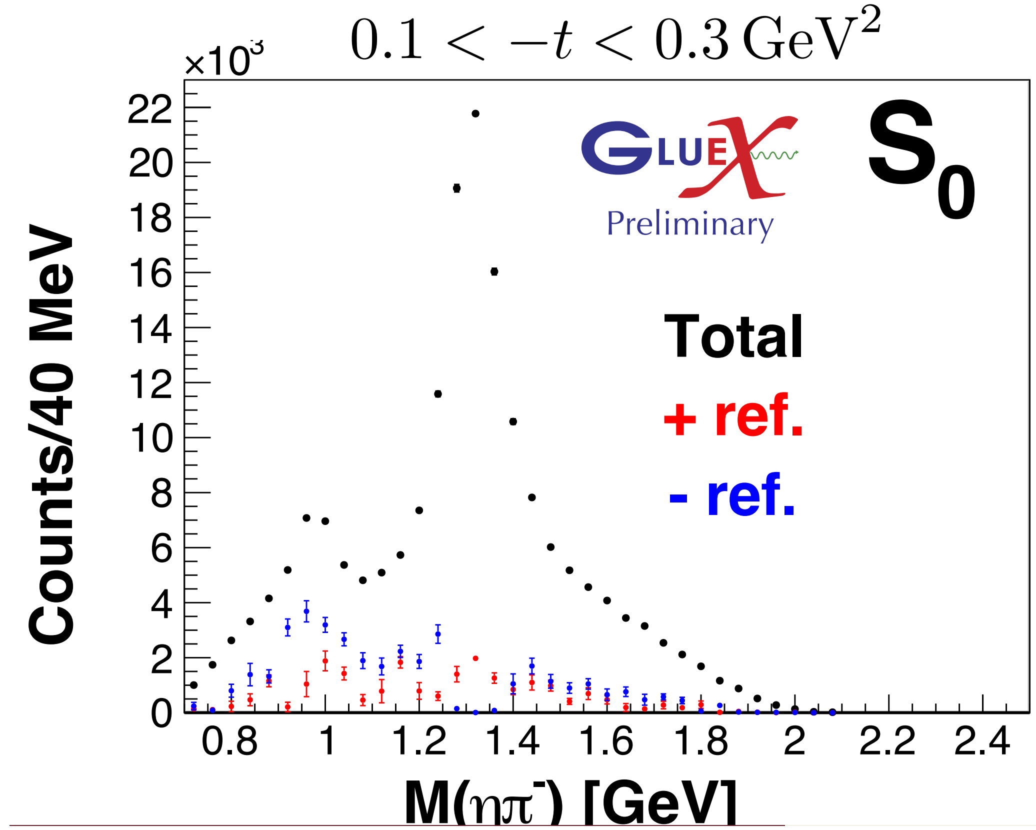
→ Can we extrapolate a model for Double Regge to the resonance region?

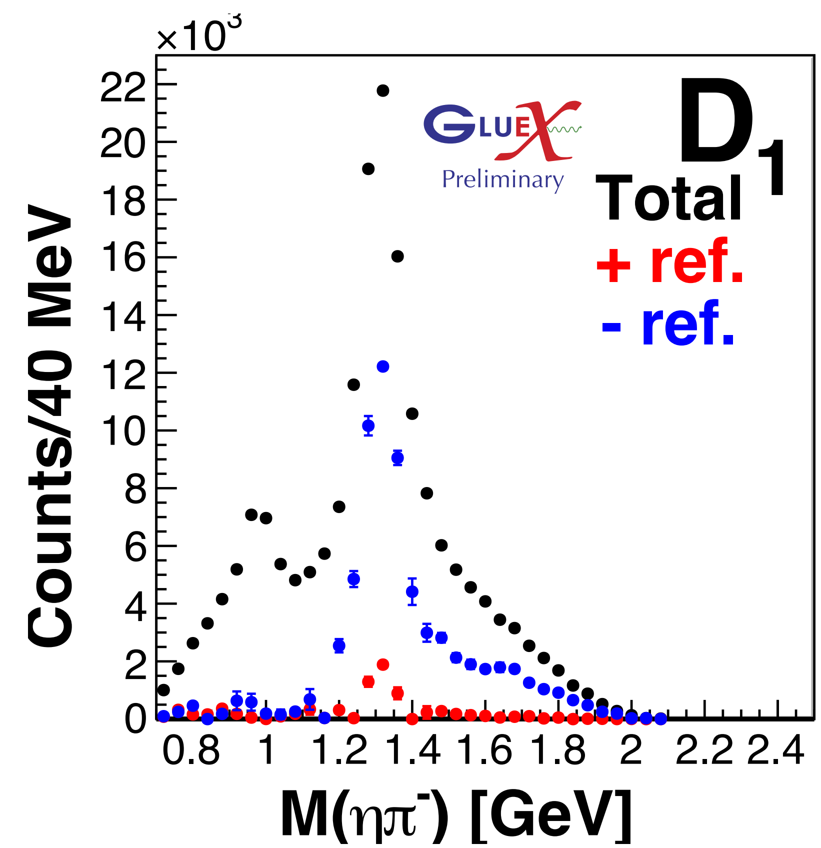


Mass Indep. PWA of $\gamma p \to \pi^- \eta \Delta^{++}$ at low t

- Combined fit of all polarization orientations
- Dominant S-wave contribution in negative reflectivity component
- Clear $a_2(1320)$ signal in $m = +1$ D-wave, negative reflectivity
  - Expected for unnatural parity exchange ***(pion exchange! Contrary to neutral channel)***
  - Same challenges with mass-independent fit as in neutral channel

→ Extract a_2 cross section with same semi mass-independent PWA stategy





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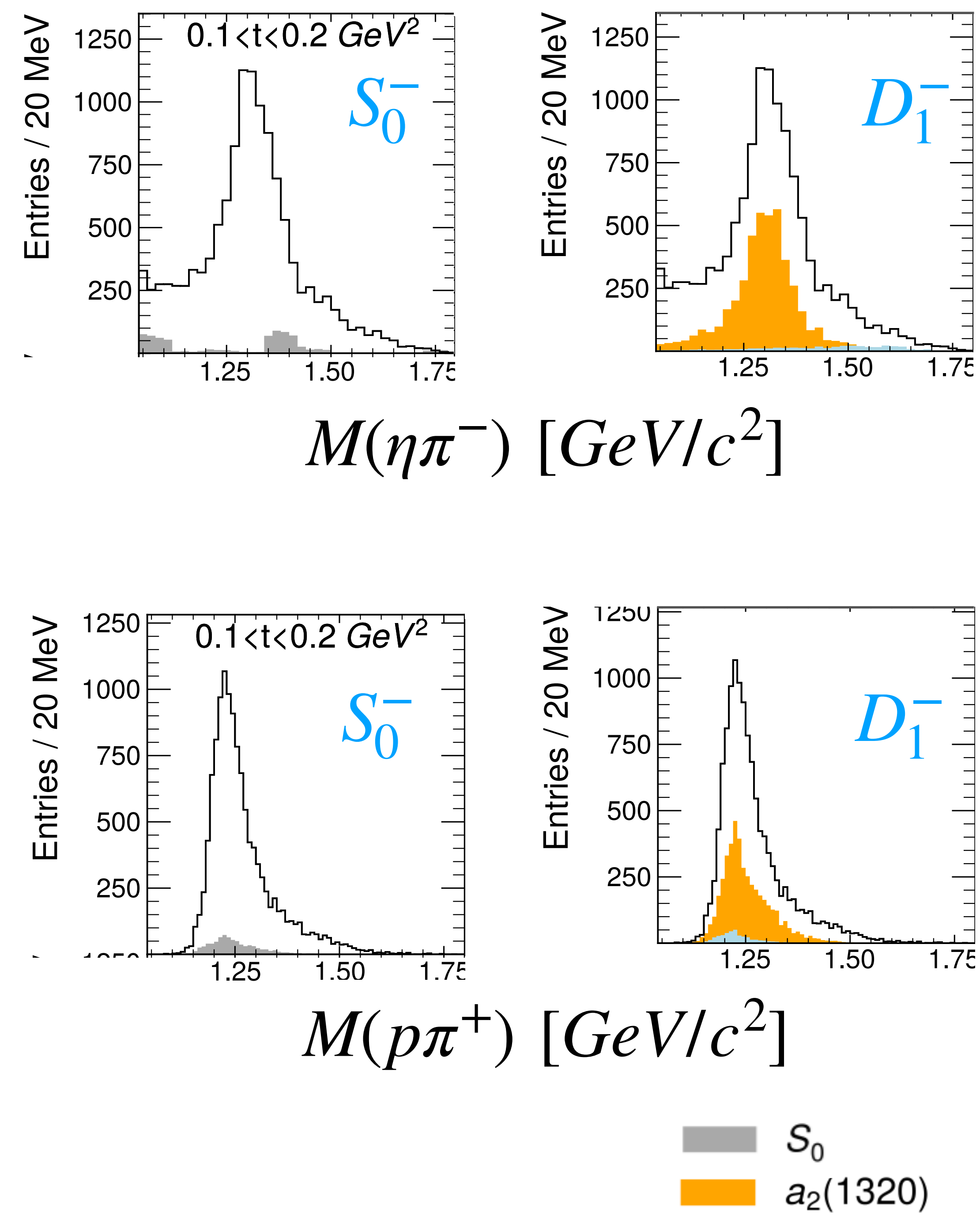
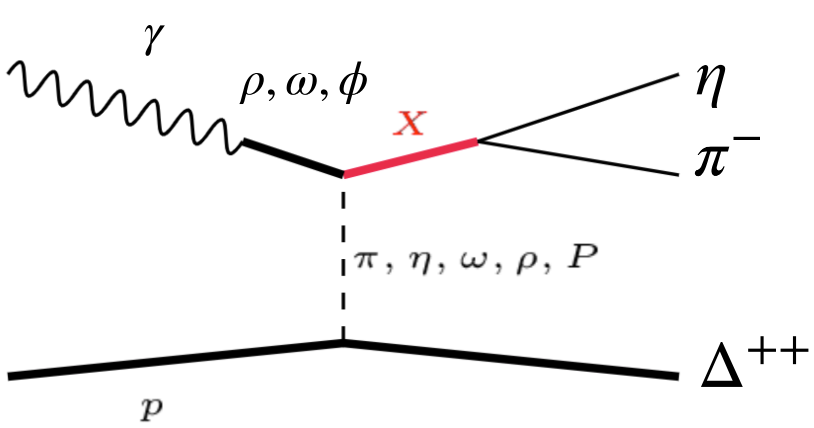
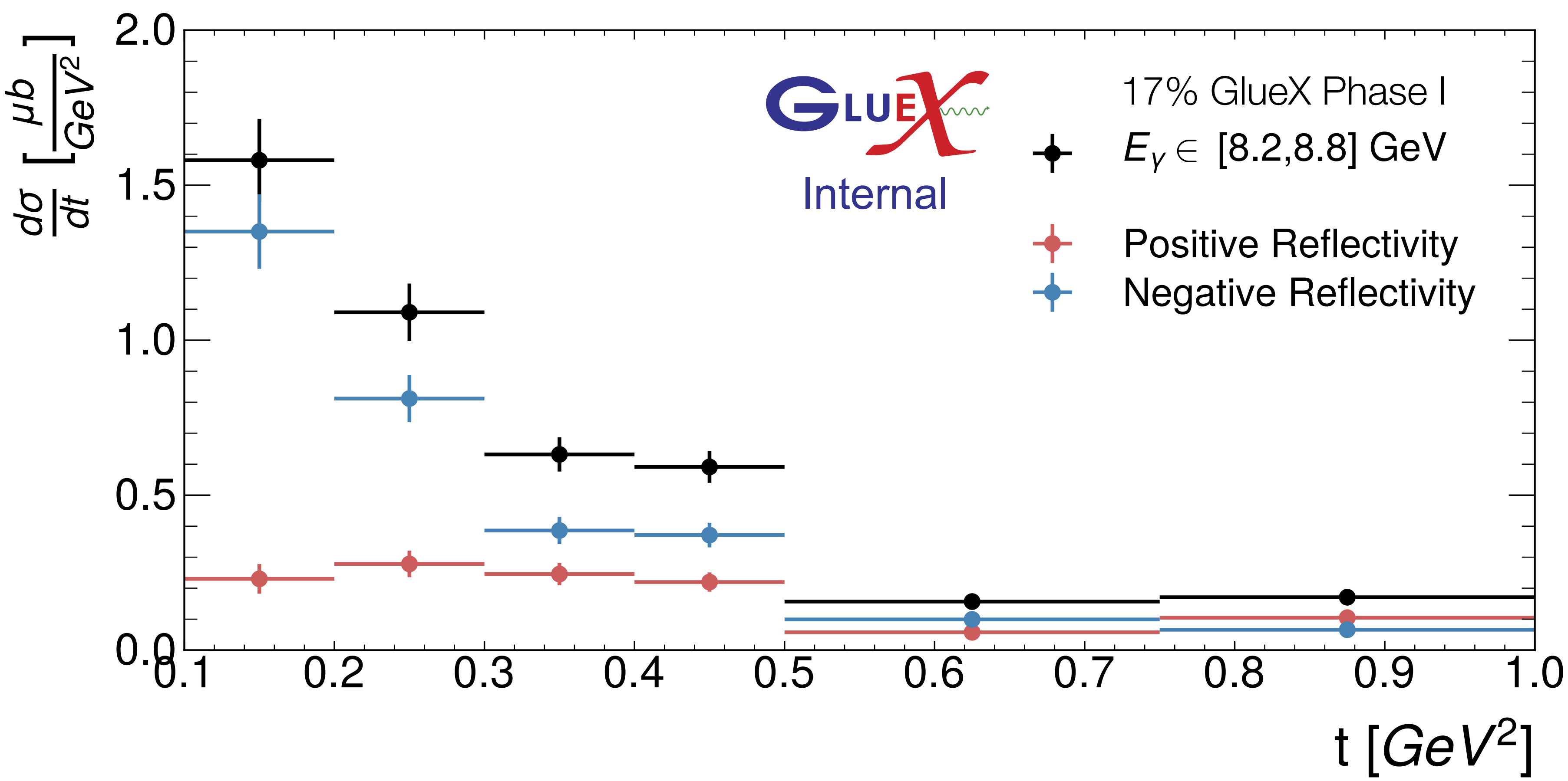
Example projections:



First Results for Differential a_2^- Cross Section

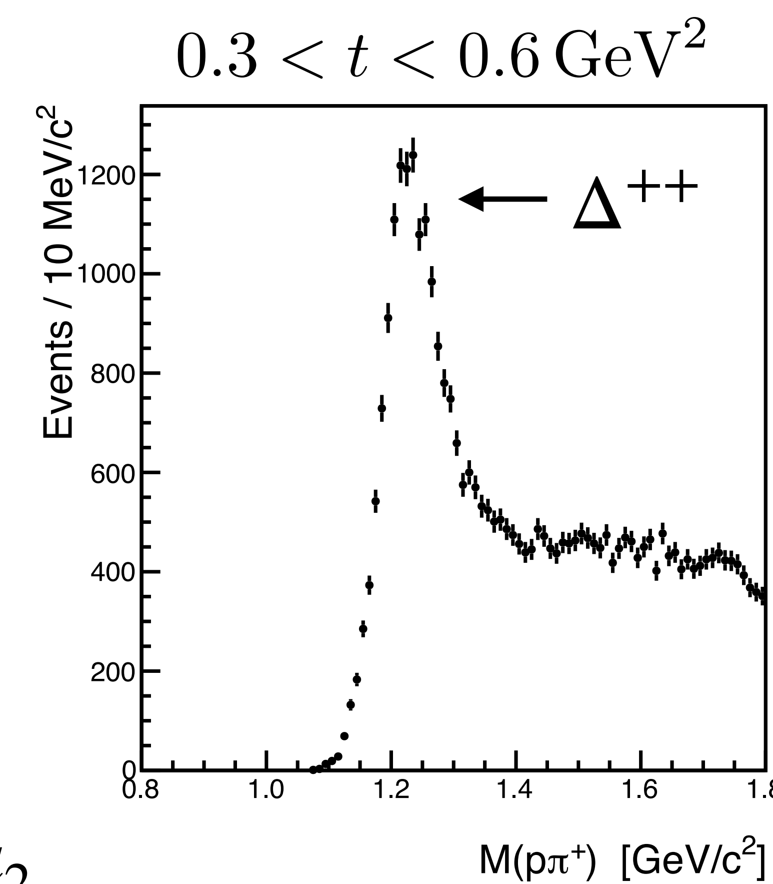


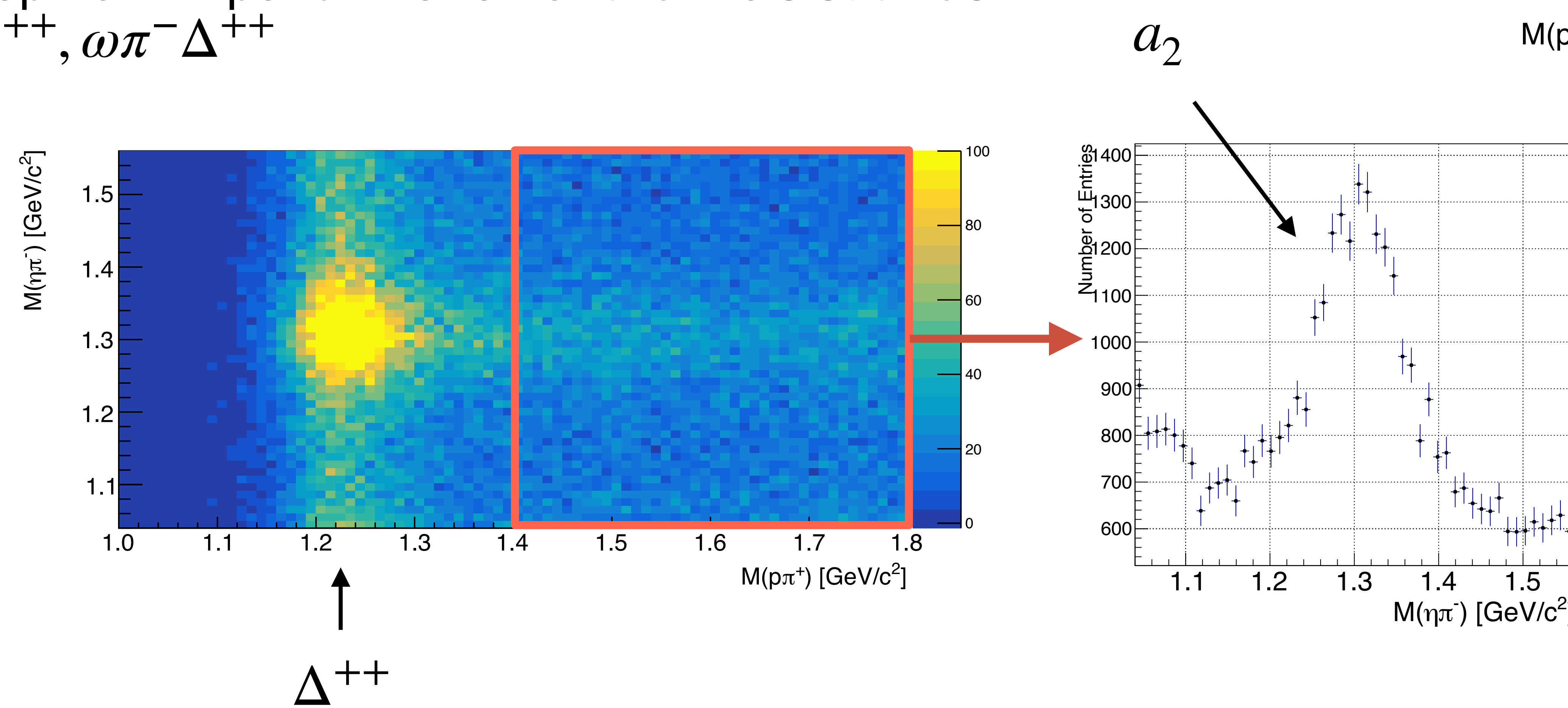


- PWA does not yet take Δ^{++} decay angular distributions into account
- Preliminary cross section results reasonable, in agreement with estimation from simple one-dimensional fit to mass spectrum

Non-Δ^{++} Background at higher |t|

- At higher t, non-Δ^{++} background important
- Contains peaking background under a_2 signal possibly from $\gamma p \to (a_2^- \pi^+)\ p \to \pi^+\pi^-\eta\ p$
- Strategy developed:
  - Include Δ^{++} in amplitudes → working with JPAC
  - Separate components in fit
- Development important for other channels such as $\eta'\pi^-\Delta^{++}, \omega\pi^-\Delta^{++}$

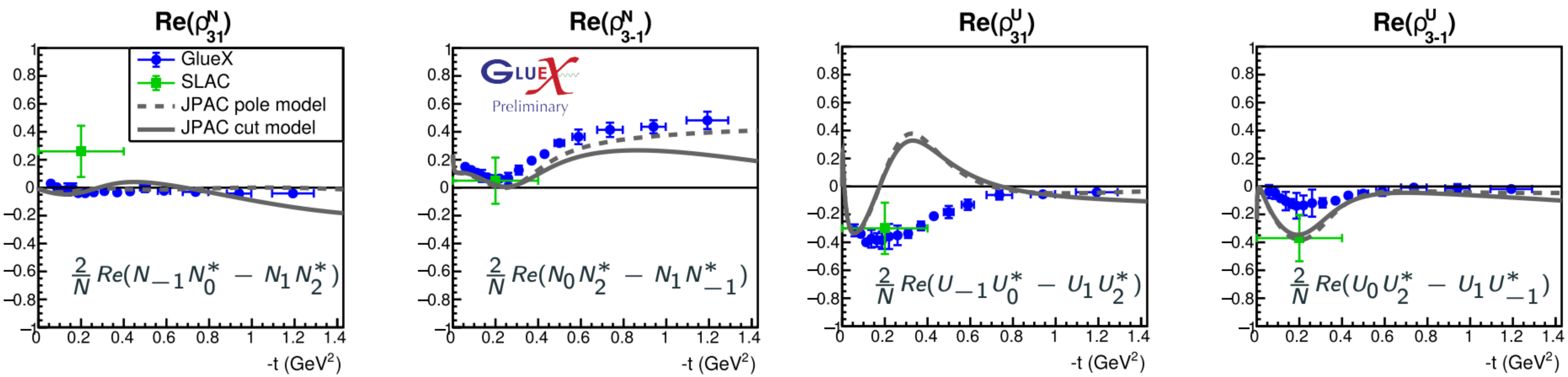




Δ^{++} SDMEs

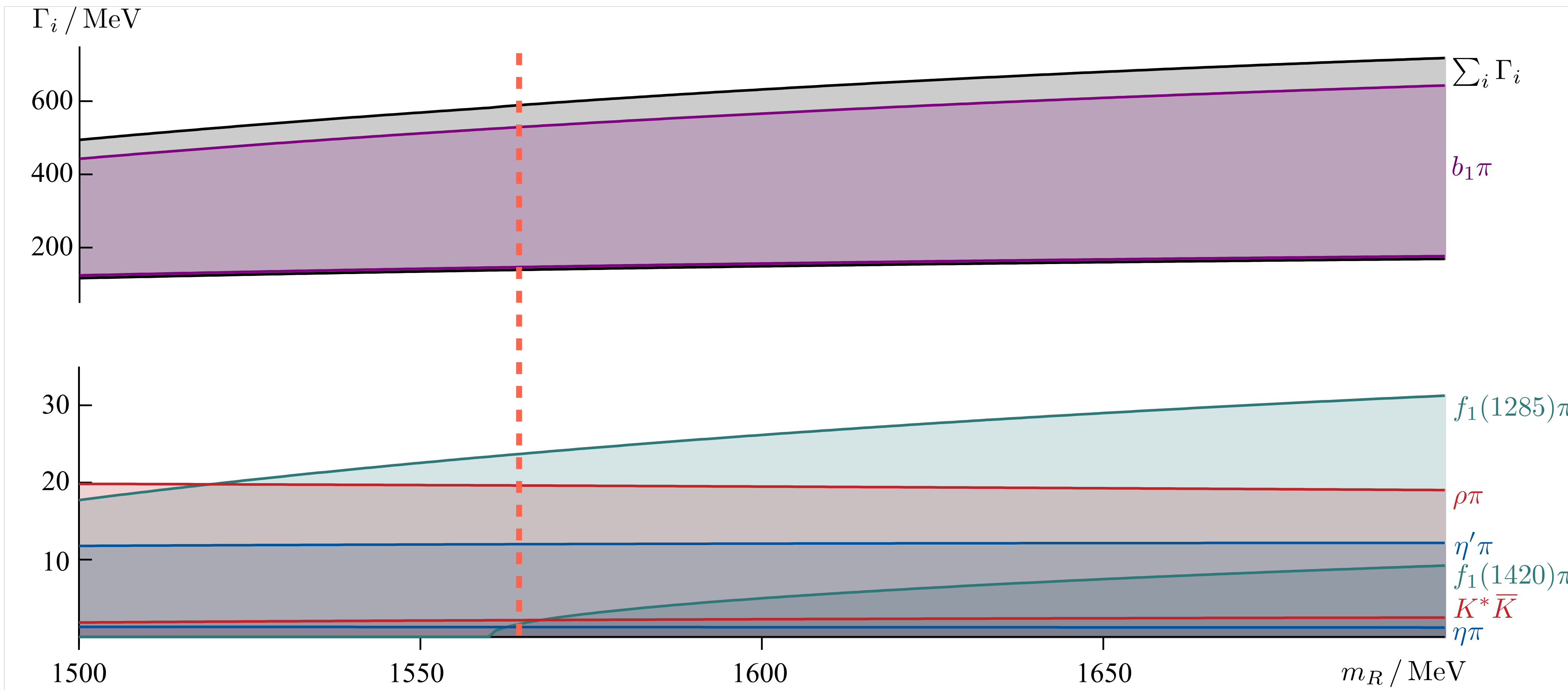
Work of F. Afzal

- Many channels rely on understanding and describing Δ^{++} at the lower vertex correctly
- Structured effort underway:
    - Extract Δ^{++} SDMEs in $\gamma p \to \pi^- \Delta^{++}$ first:
      (see talk by Vanamali, Sat. 11am!)



- Include Δ^{++} decay angles in amplitude model, extract $a_2^-(1320)$ cross section in $\gamma p \to \eta \pi^- \Delta^{++}$
- Use findings for analysis of $\gamma p \to \eta' \pi^- \Delta^{++}$, which seems to be most promising avenue for exotics search

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

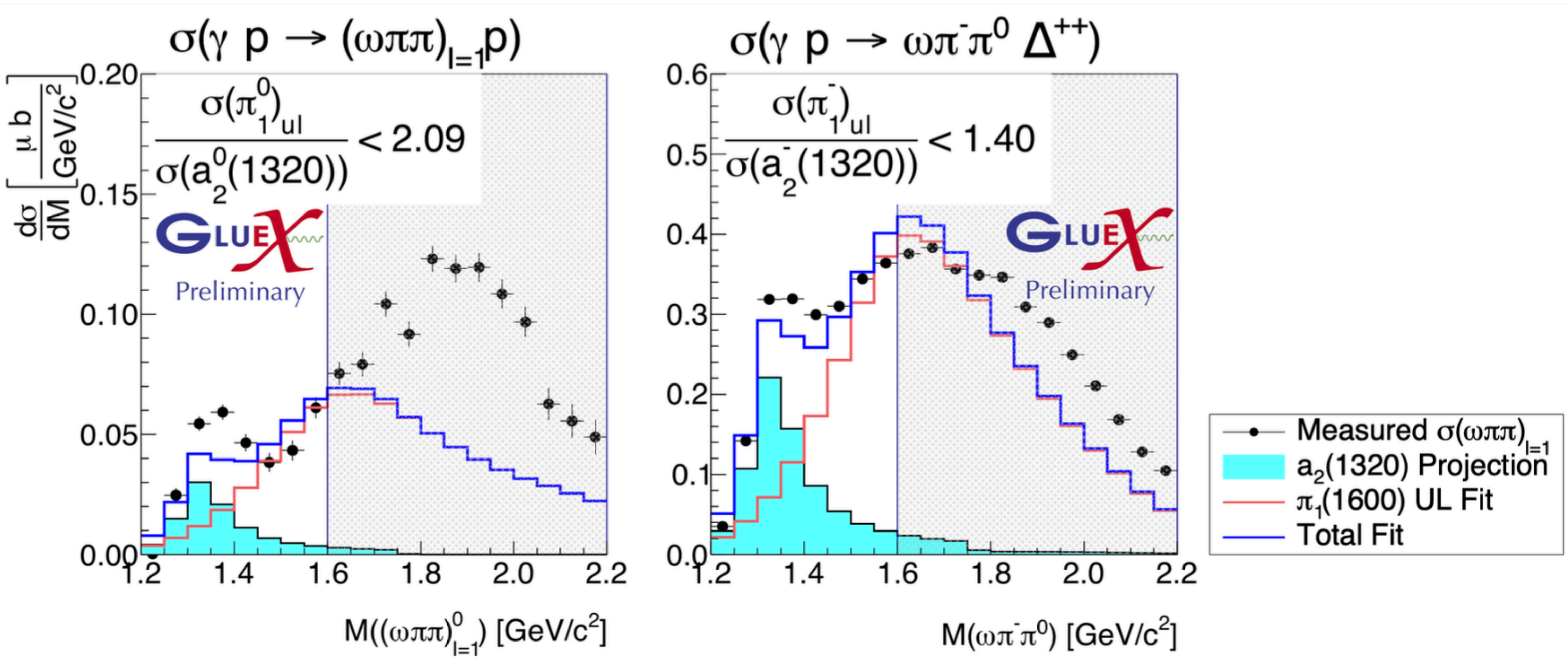
[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

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

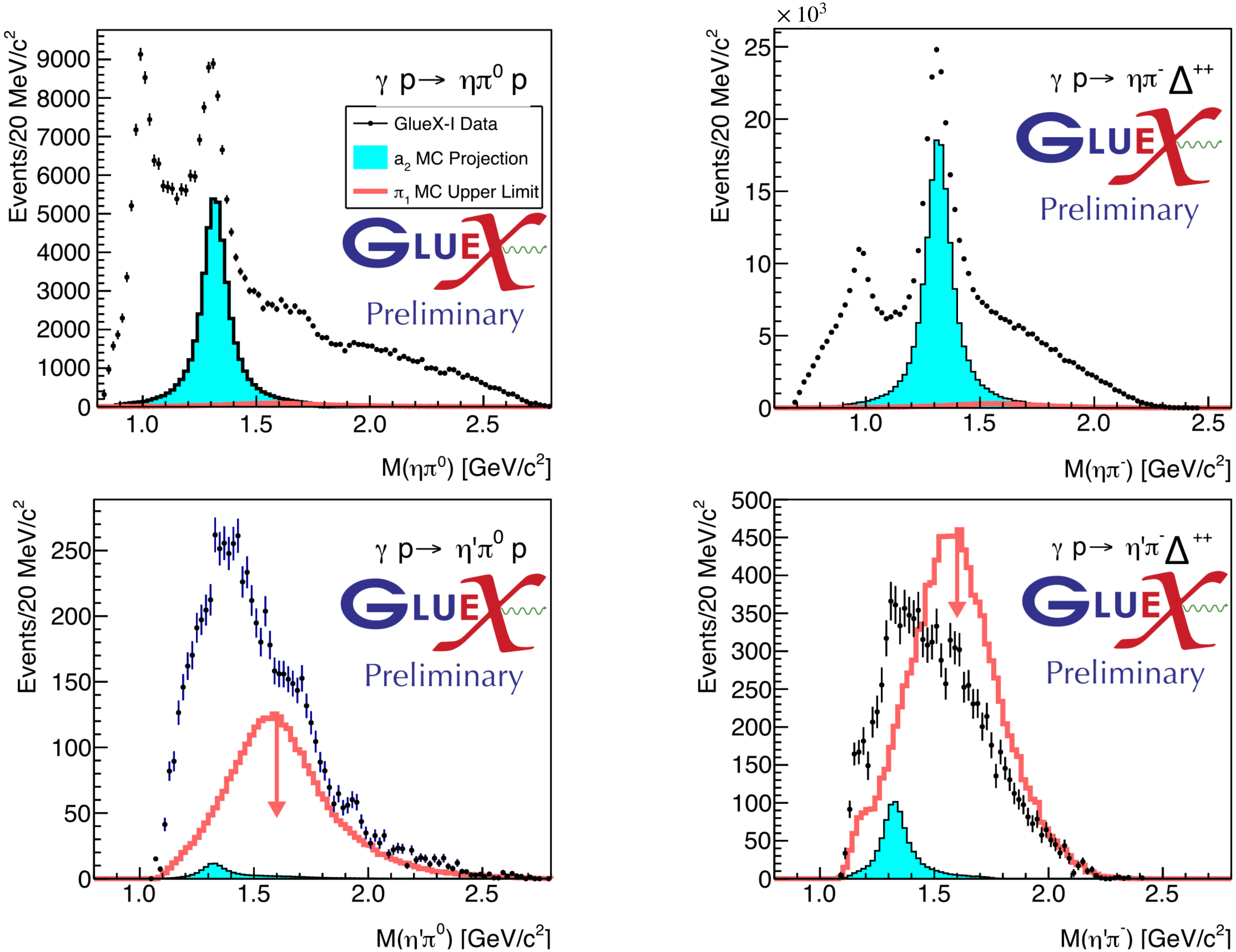
Projection for $\pi_1 \to \eta^{(\prime)}\pi$

Work of W. Imoehl

- Measurement of strong a_2 signal in $\eta\pi$ channels serves as reference
- Fit π_1 yield assuming signal saturates measured $I = 1 \quad \omega\pi\pi$ cross sections



Work of W. Imoehl, L. Ng, B. Grube, M.A.



- Based on upper limit for π_1 cross section from $\omega\pi\pi$:
- No large π_1 signal expected in $\eta\pi$
- Possibly dominant signal in $\eta'\pi$
- Publication on upper limit imminent

Closeup of $\eta'\pi^-$ Spectra

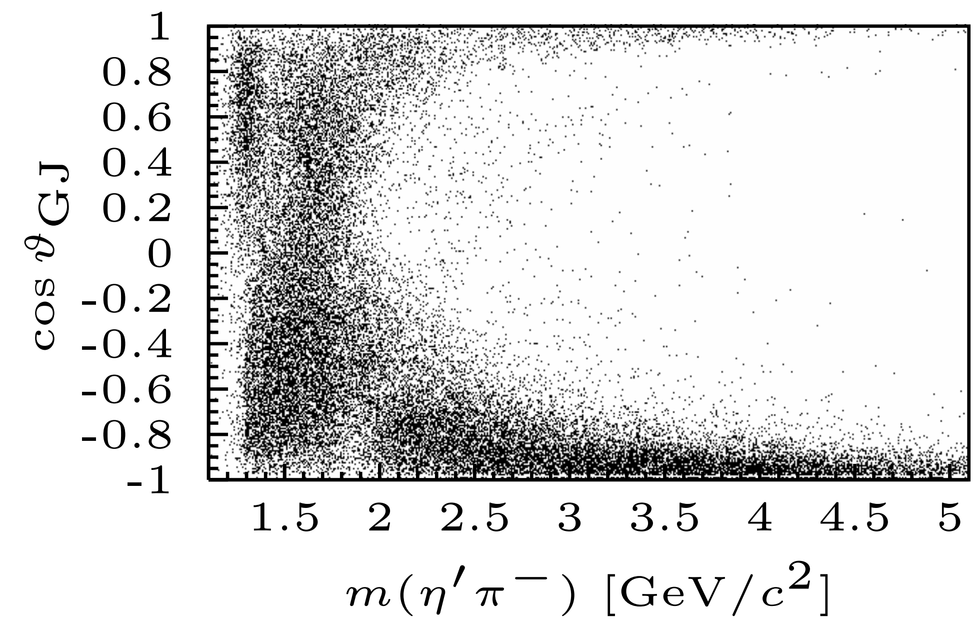
Work of W. Imoehl, L. Ng, B. Grube, M.A.

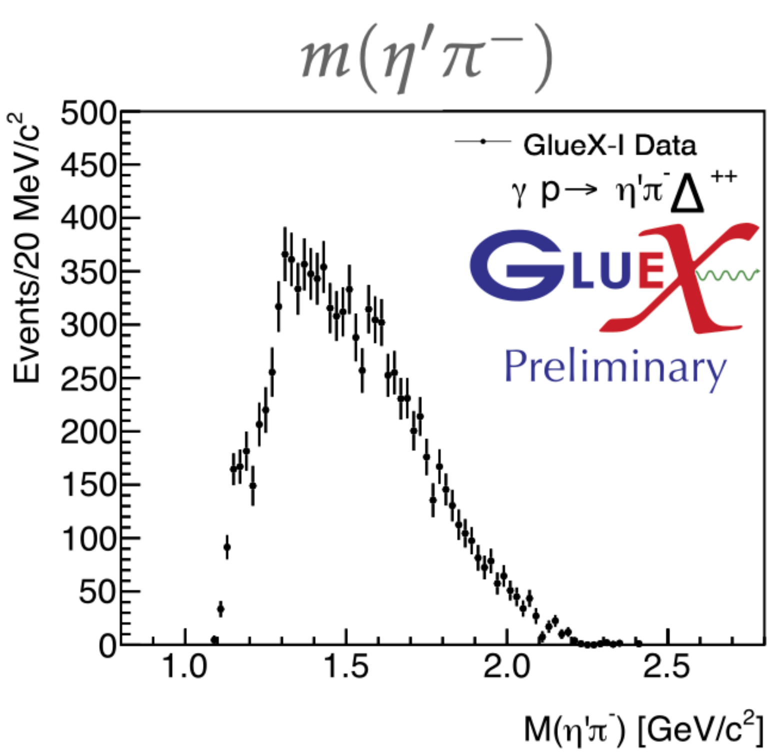
- Projections look intriguing
- Interesting interference pattern visible

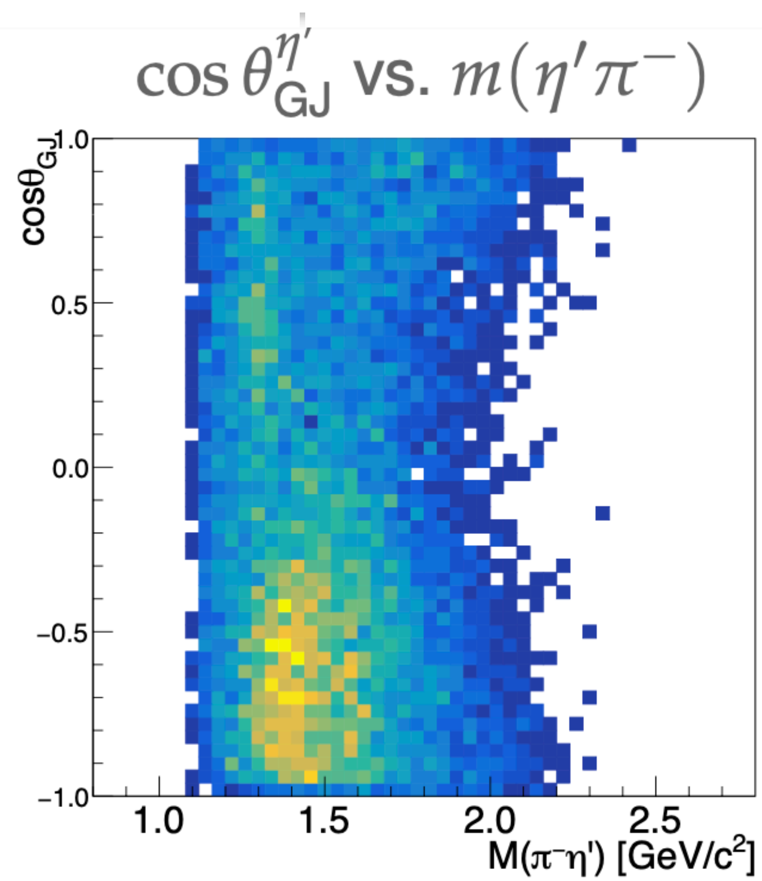
  → Constructive / destructive interference of odd and even wave contributions in different $\cos\theta_{GJ}$ regions?

- Using a_2 cross section measurements from $\eta\pi$ channels as important reference

[COMPASS, PLB 740(2015) 303-311]







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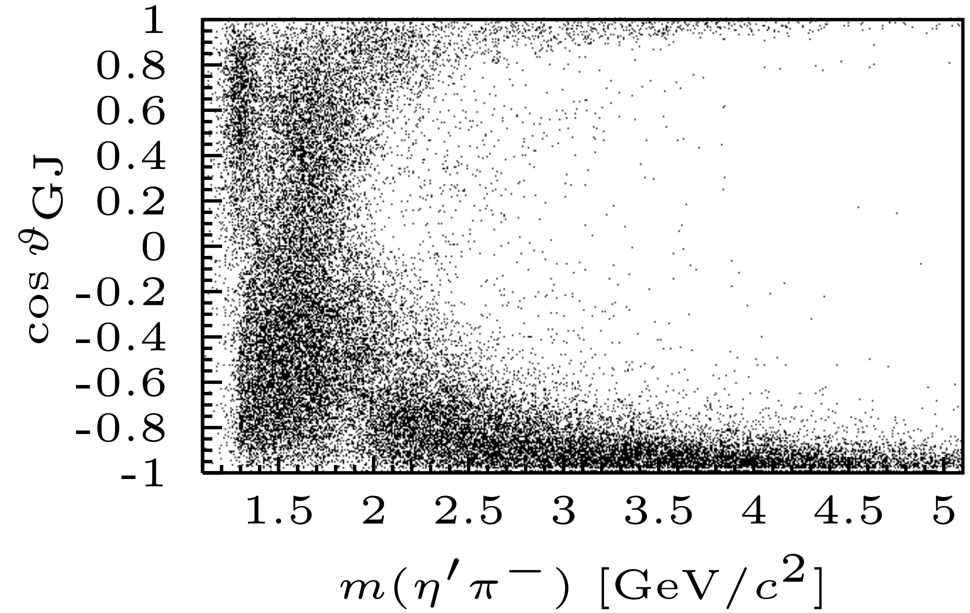
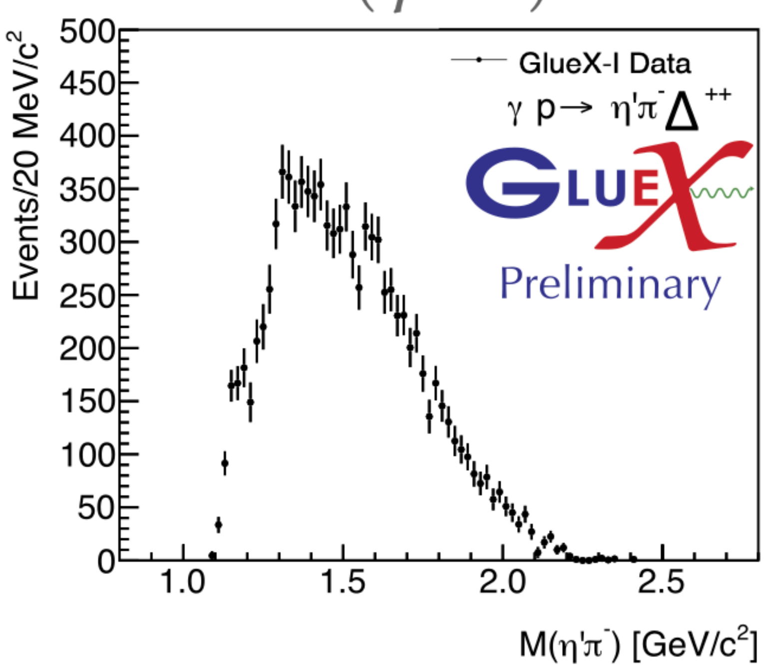
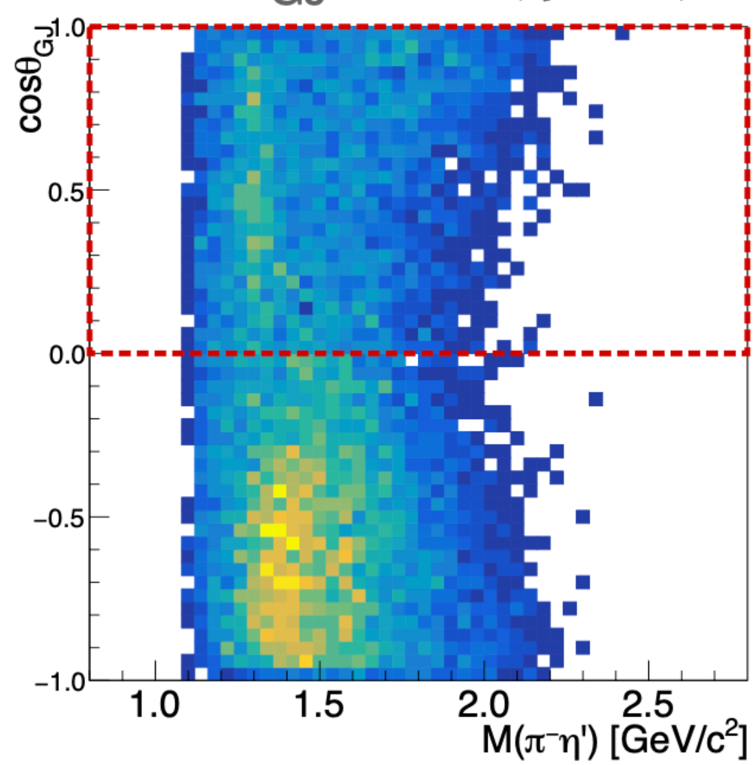


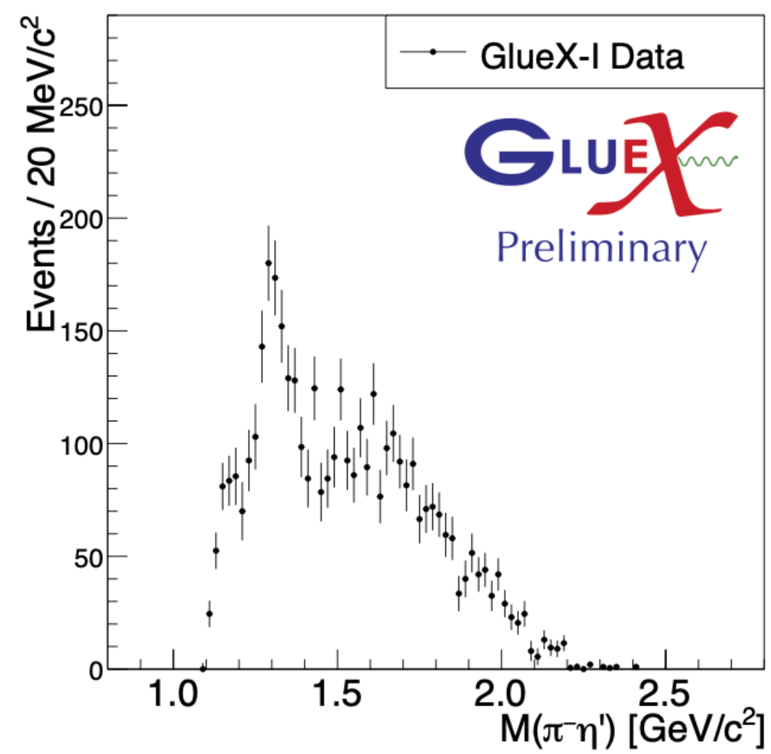
$m(\eta'\pi^-)$



$\cos\theta^{\eta'}_{GJ}$ vs. $m(\eta'\pi^-)$



$m(\eta'\pi^-)$ for $\cos\theta^{\eta'}_{GJ} > 0$



Closeup of $\eta'\pi^-$ Spectra

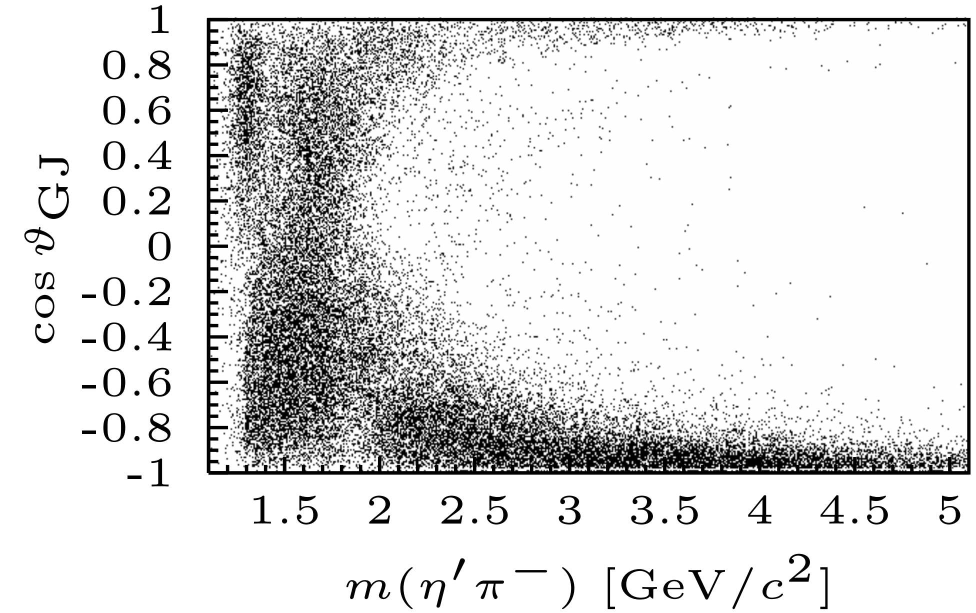
Work of W. Imoehl, L. Ng, B. Grube, M.A.

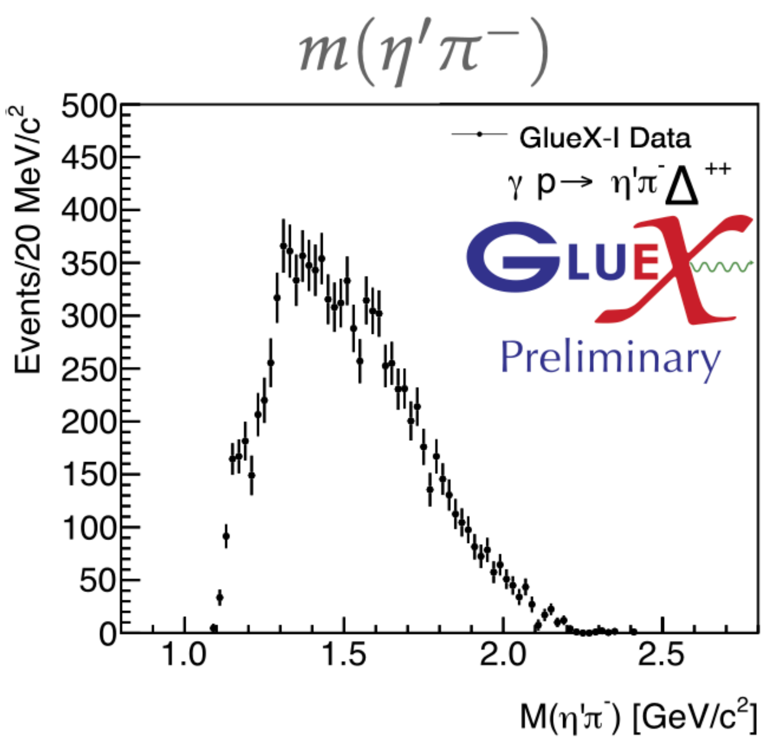
- Projections look intriguing
- Interesting interference pattern visible

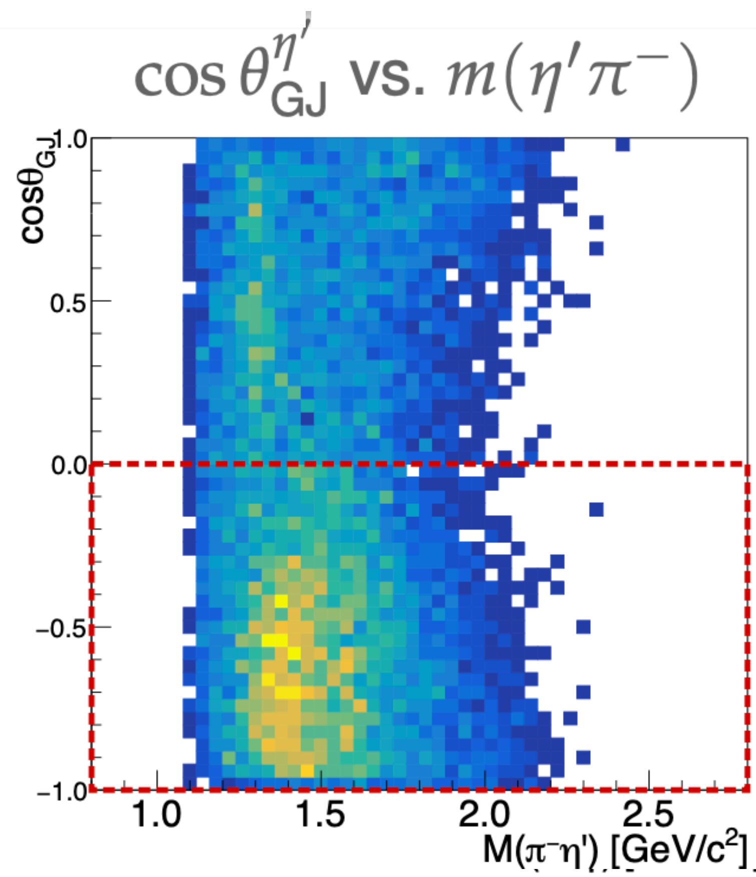
  → Constructive / destructive interference of odd and even wave contributions in different $\cos\theta_{GJ}$ regions?

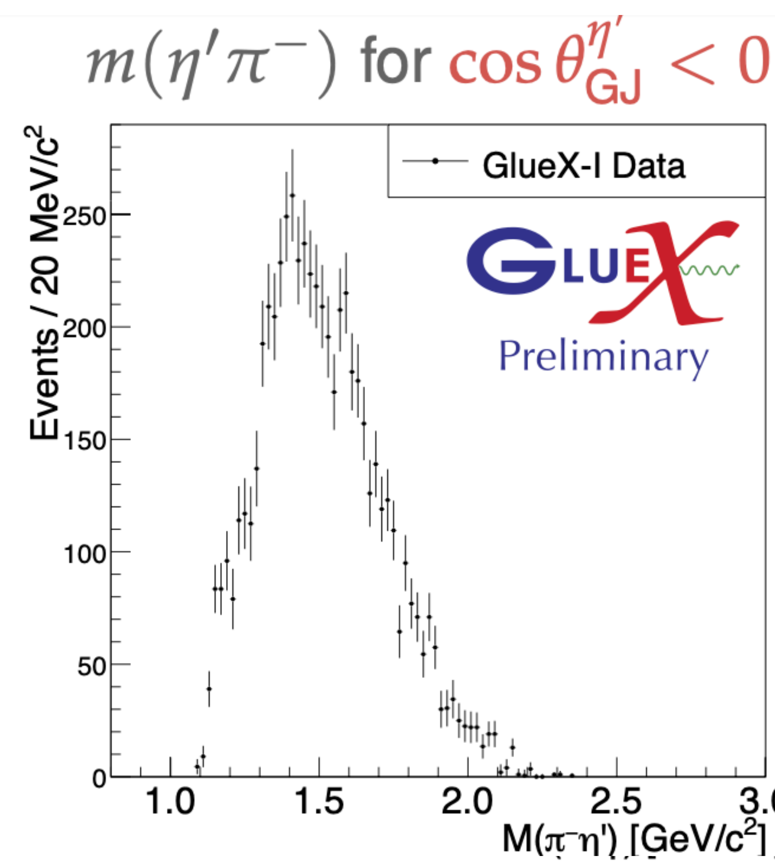
- Using a_2 cross section measurements from $\eta\pi$ channels as important reference

[COMPASS, PLB 740(2015) 303-311]



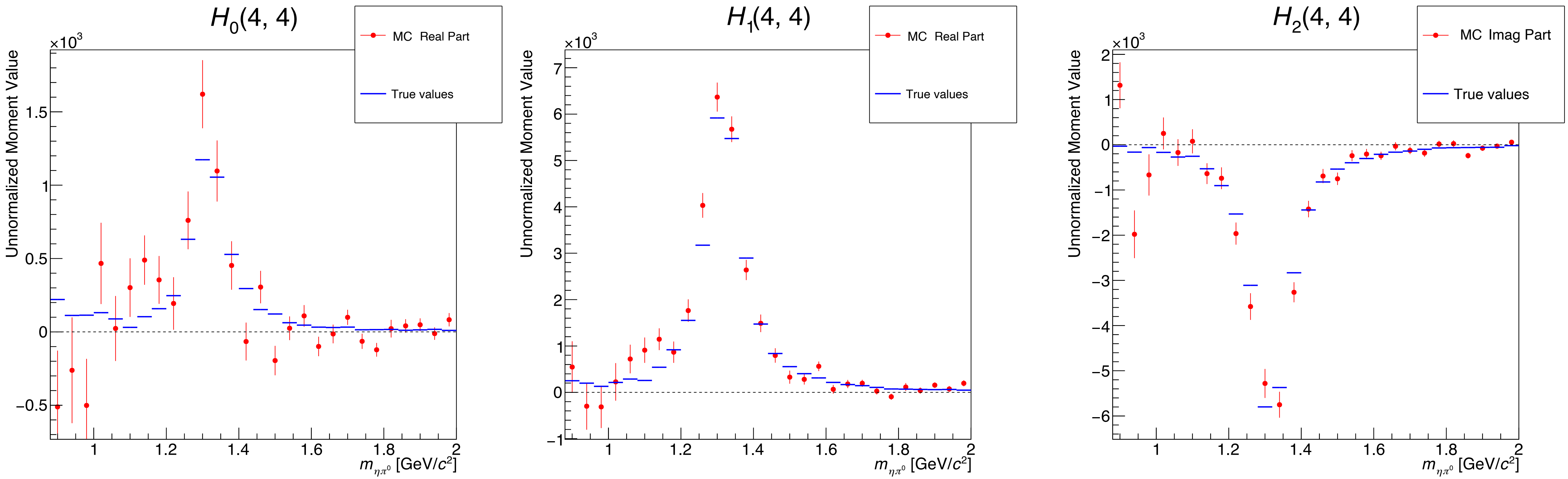






Moment decomposition

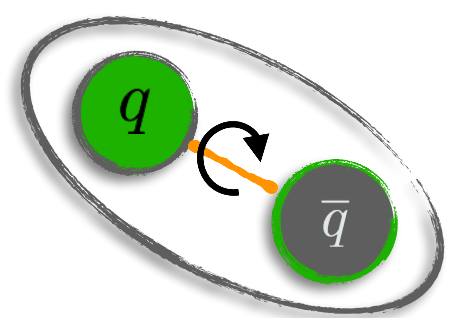
- Goal: Probe for presence of spin-exotic wave in η’π *Work of B.Grube*
- Challenge: Are we sensitive to an exotic contribution with this method?
- Multi-staged approach:
  - Code base for moment extraction developed
  - MC Input-Output studies using ρ(770), $a_2(1320) \rightarrow \eta\,\pi^0$ MC
  - Influence of real detector acceptance / efficiency based on $\eta\,\pi^0$ MC Extract moments of $a_2(1320)$, $\pi_1(1600)$ (MC study)



Summary and Outlook

- **High quality photoproduction data sets (GlueX Phase I) available, analyses underway**
  - Extract a_2 cross sections in high-statistics $\eta\pi$ channels using PWA and fits with physics constraints,
    use polarization information to investigate production mechanism
    (publication in preparation)
  - Route towards $\eta'\pi$ channels set, analyses underway
    → Use a_2 signal and cross section measurements as reference
  - Partial wave analysis tools being used and further developed
    → Future: Higher statistics (GlueX Phase II, coupling of channels, …)
    will allow to refine analysis strategy and possibly decrease model dependencies

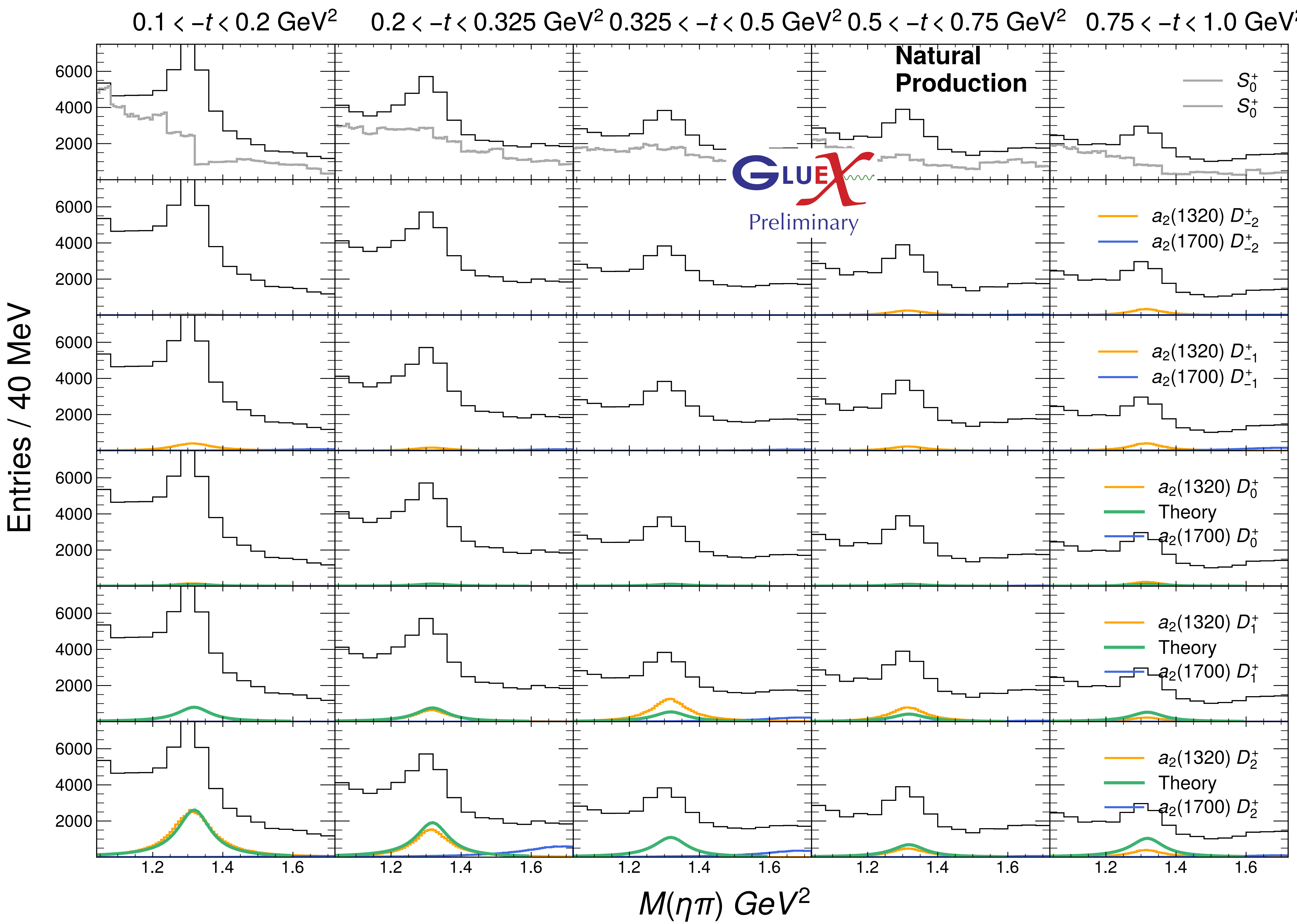
- **Highly productive collaboration with theory**



En route to first results on exotic mesons with GlueX!

Backup

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



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