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

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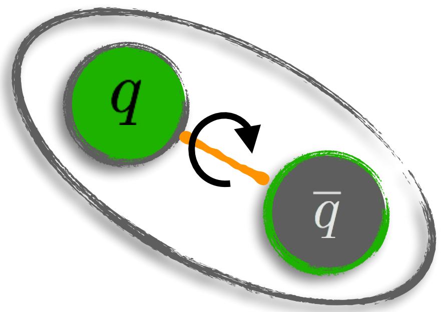
Thomas Jefferson National Accelerator Facility

4th Workshop on Future Directions in Spectroscopy Analysis (FDSA2022)

11 / 15 / 2022

Search for Exotic States in Photoproduction

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



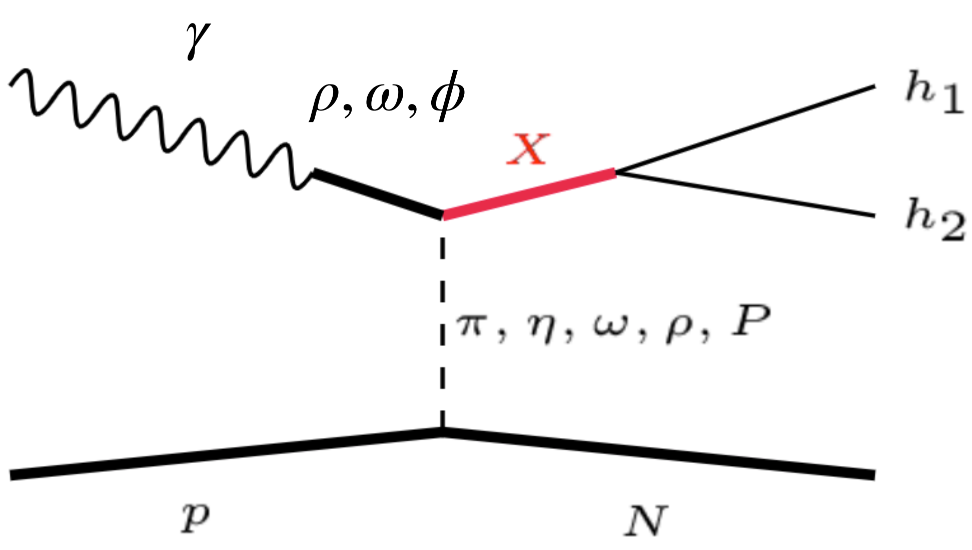
- **Mapping out the spectrum of light hybrids:**
  - Evidence in multiple channels, consistent results
  - Search for partner states, regular J^{PC} hybrids, higher mass nonets
  - Partial Wave Analysis (PWA) is an indispensable tool
  - *[see also talk by A. Austregesilo, Wed 2:05pm]*

- **Strongest experimental evidence so far in $\eta^{(\prime)}\pi$ channels**
  [see also talk by B. Grube, Tue 9:00am]

$\rightarrow$ **High priority for GlueX**
$\rightarrow$ **Investigating in parallel:** $\gamma p \rightarrow \eta\pi^0 p,\ \eta\pi^-\Delta^{++},\ \eta'\pi^0 p,\ \eta'\pi^-\Delta^{++}$

Search for Exotic States in Photoproduction

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



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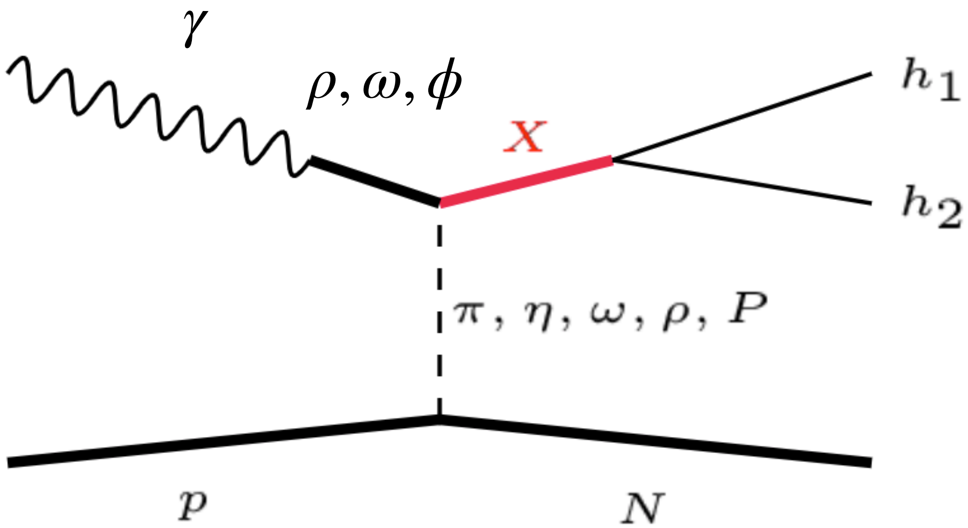
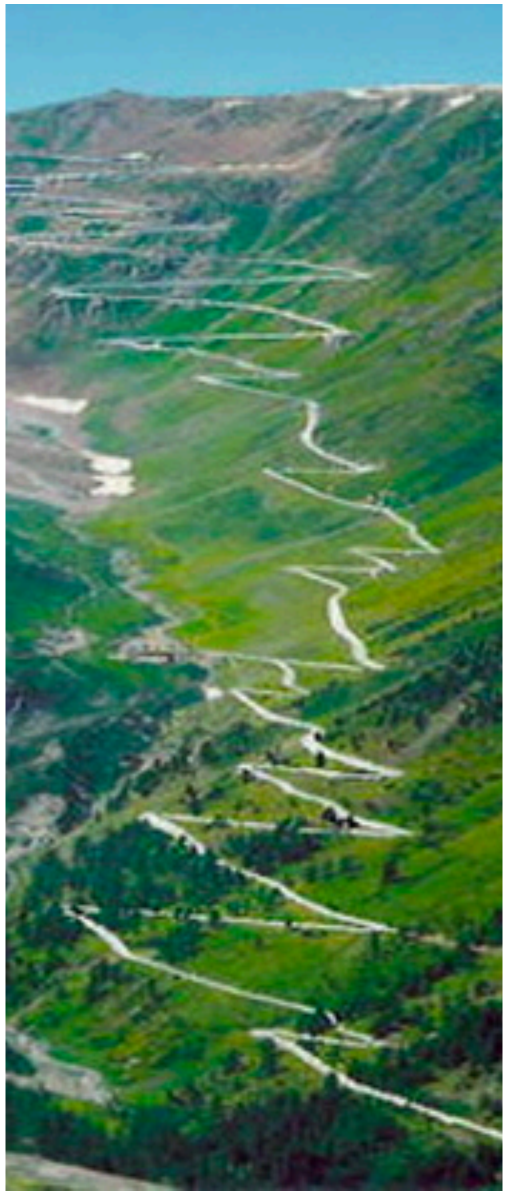
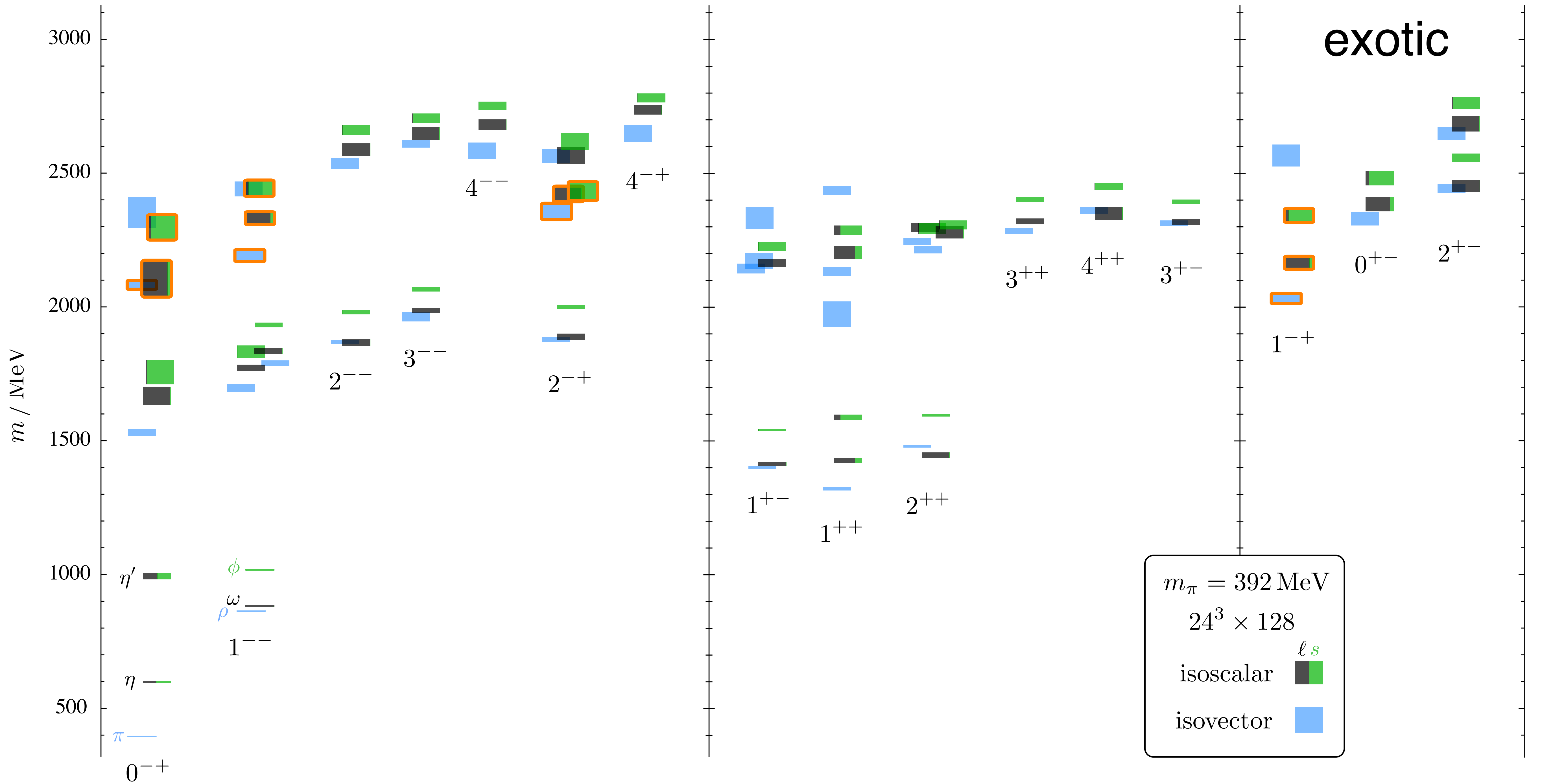


- **Structured investigation of $\eta^{(\prime)}\pi$ channels**
  - Route to analyze $\eta'\pi$ is through the study of $\eta\pi$ channels
  - Study (polarized) production, t-dependent cross section of known mesons
    - → $a_2(1320)$ is our 'standard candle'
    - → code development / extension, performance enhancements, …
    - → Understand major contribution in hybrid mass region
    - → *Publication in preparation*
  - Validate results across different final states
    Consistency: different acceptance, background handling, …
  - Enables reliable search for much smaller contributions
- **Extend hybrid search to other channels, quantum numbers, …**



Light Quark Mesons from Lattice QCD



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

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

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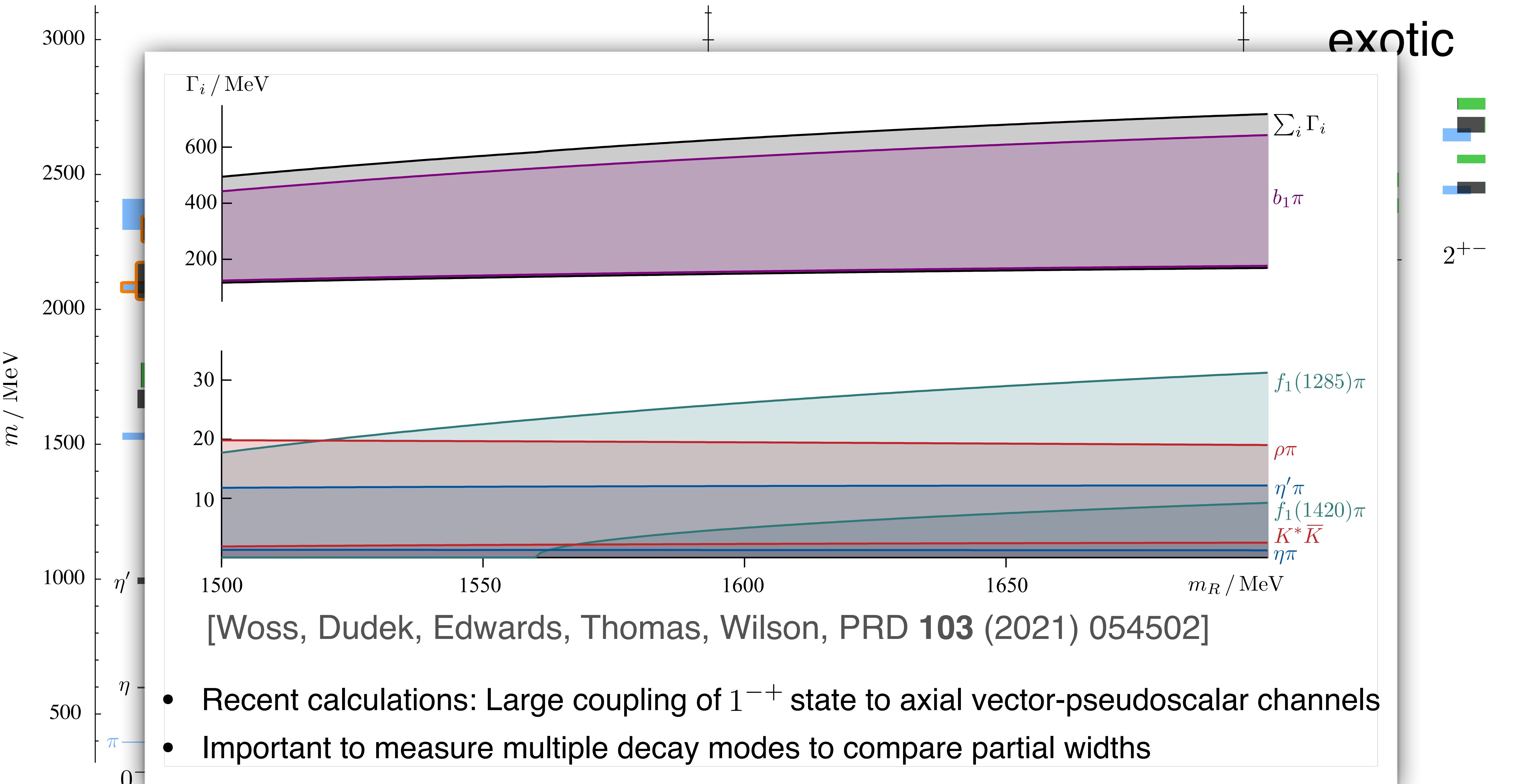


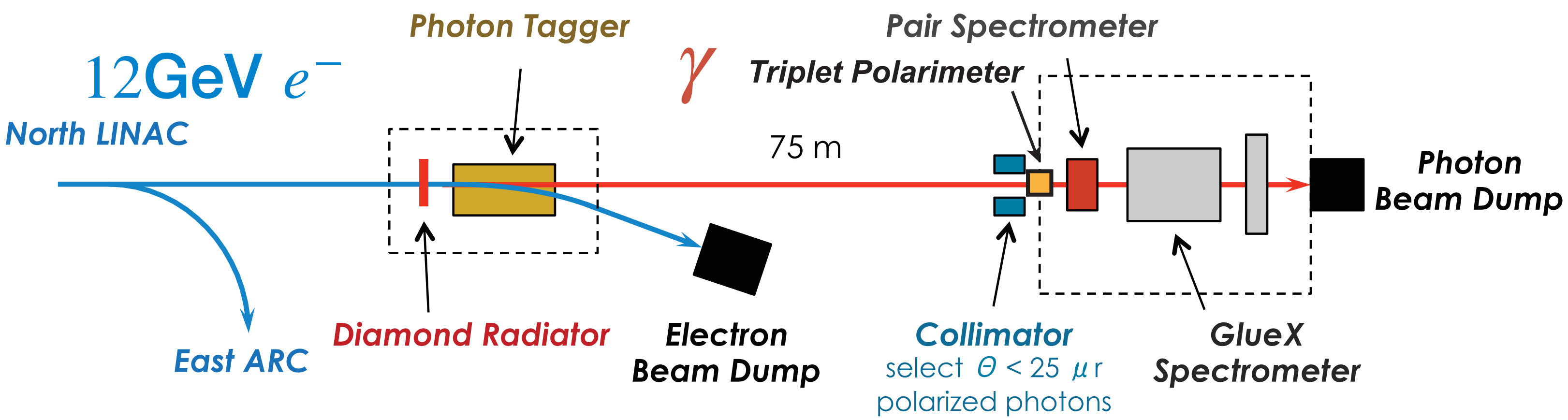
[Woss, Dudek, Edwards, Thomas, Wilson, PRD **103** (2021) 054502]

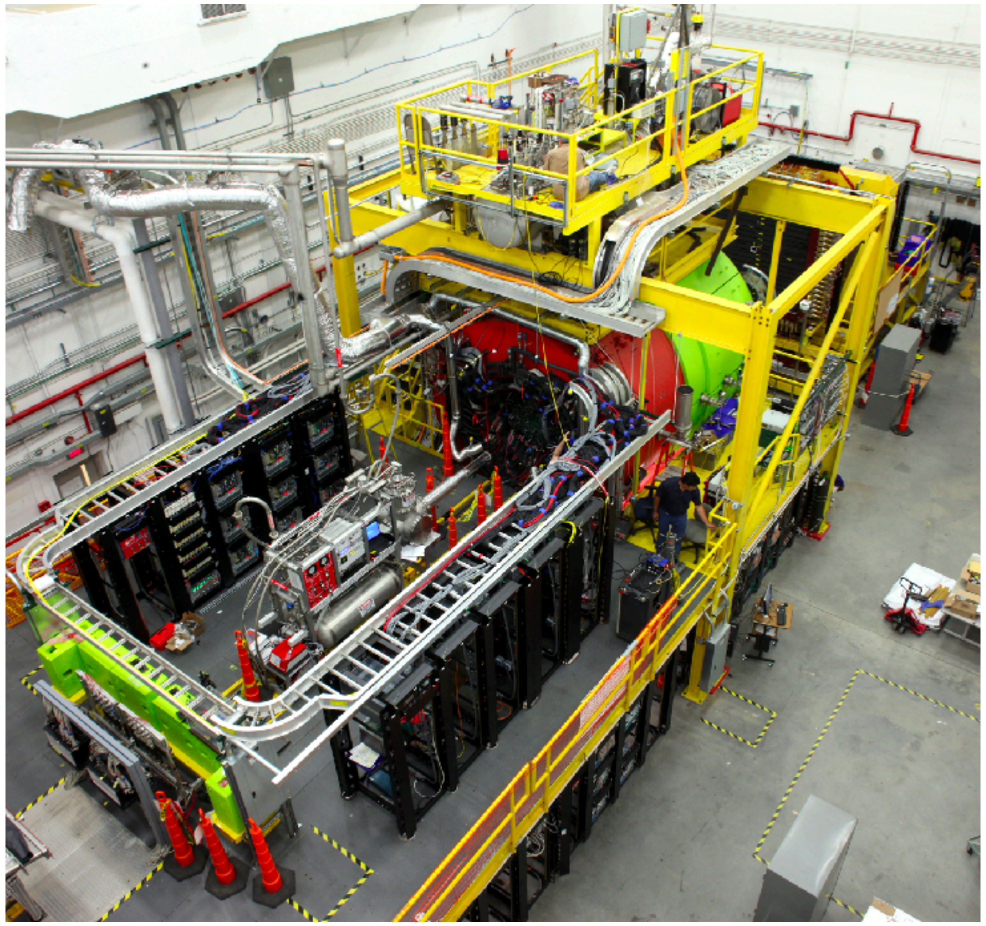
- Recent calculations: Large coupling of 1^{-+} state to axial vector-pseudoscalar channels
- Important to measure multiple decay modes to compare partial widths

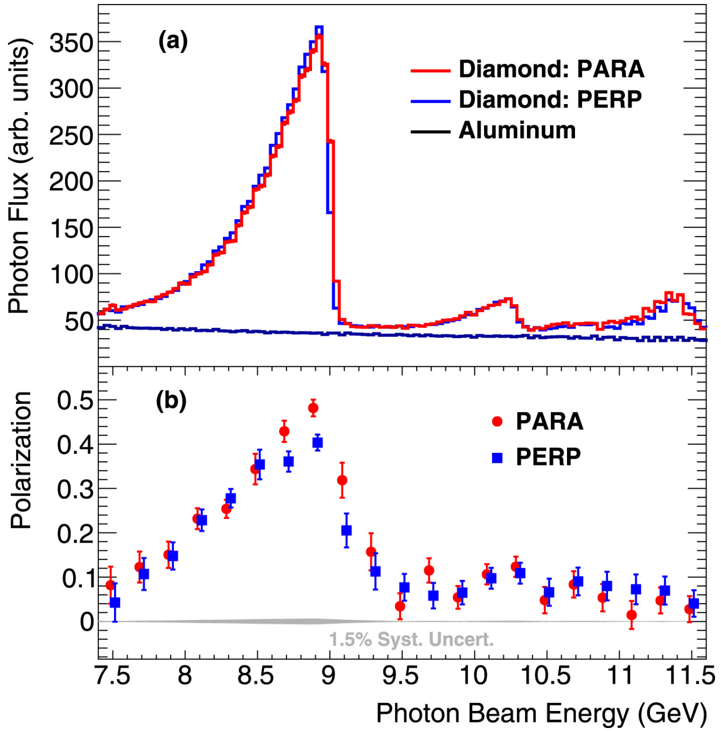
[Dudek, Edwards, Guo, Thomas, PRD **88** 094505(2013)]

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

Hall-D at Jefferson Lab

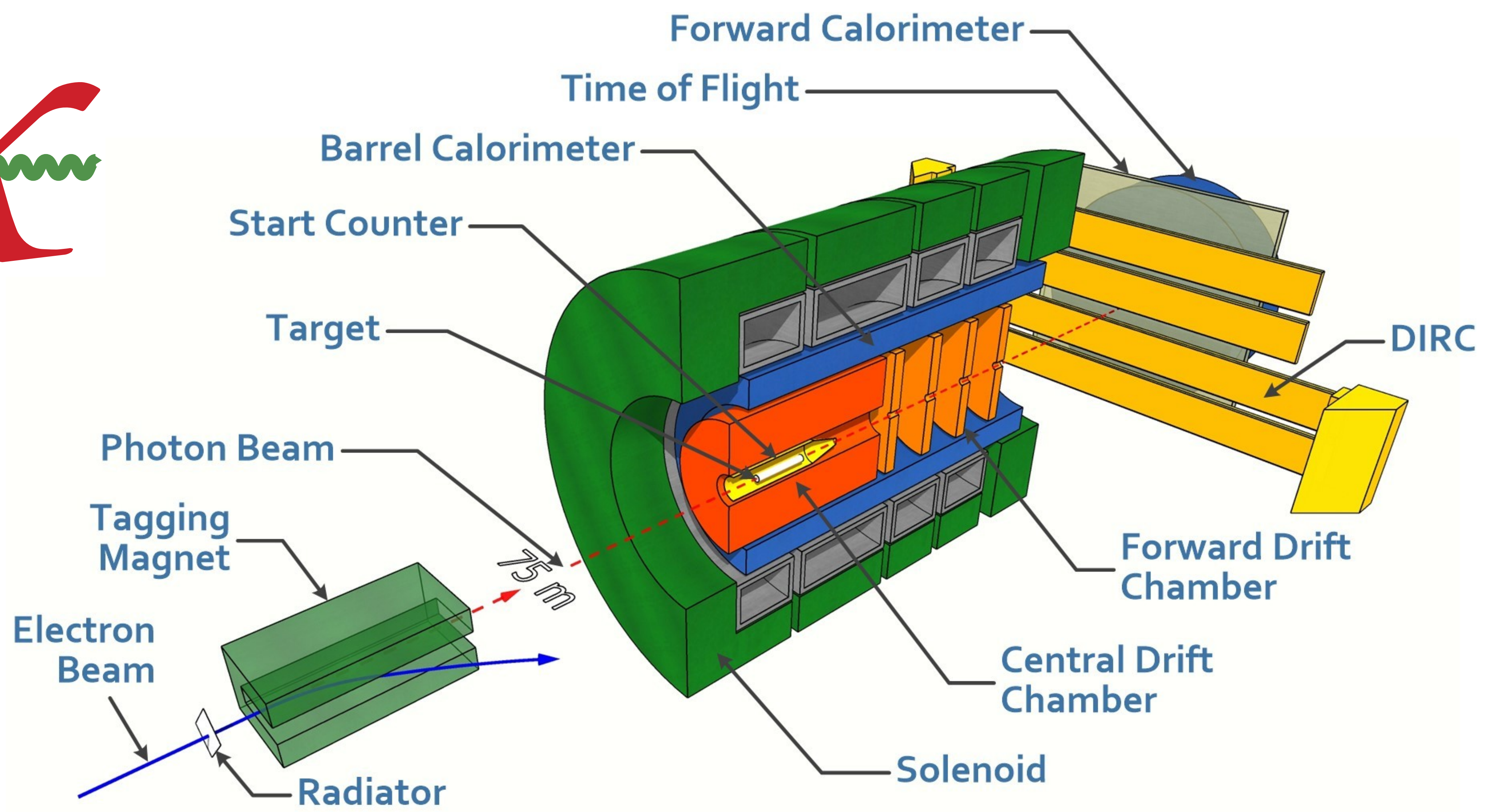






- JeffersonLab: Four main experimental halls
- CEBAF accelerator provides 12 GeV electron beam
- Hall-D: Linearly polarized photon beam produced via bremsstrahlung from thin radiator

The GlueX Experiment

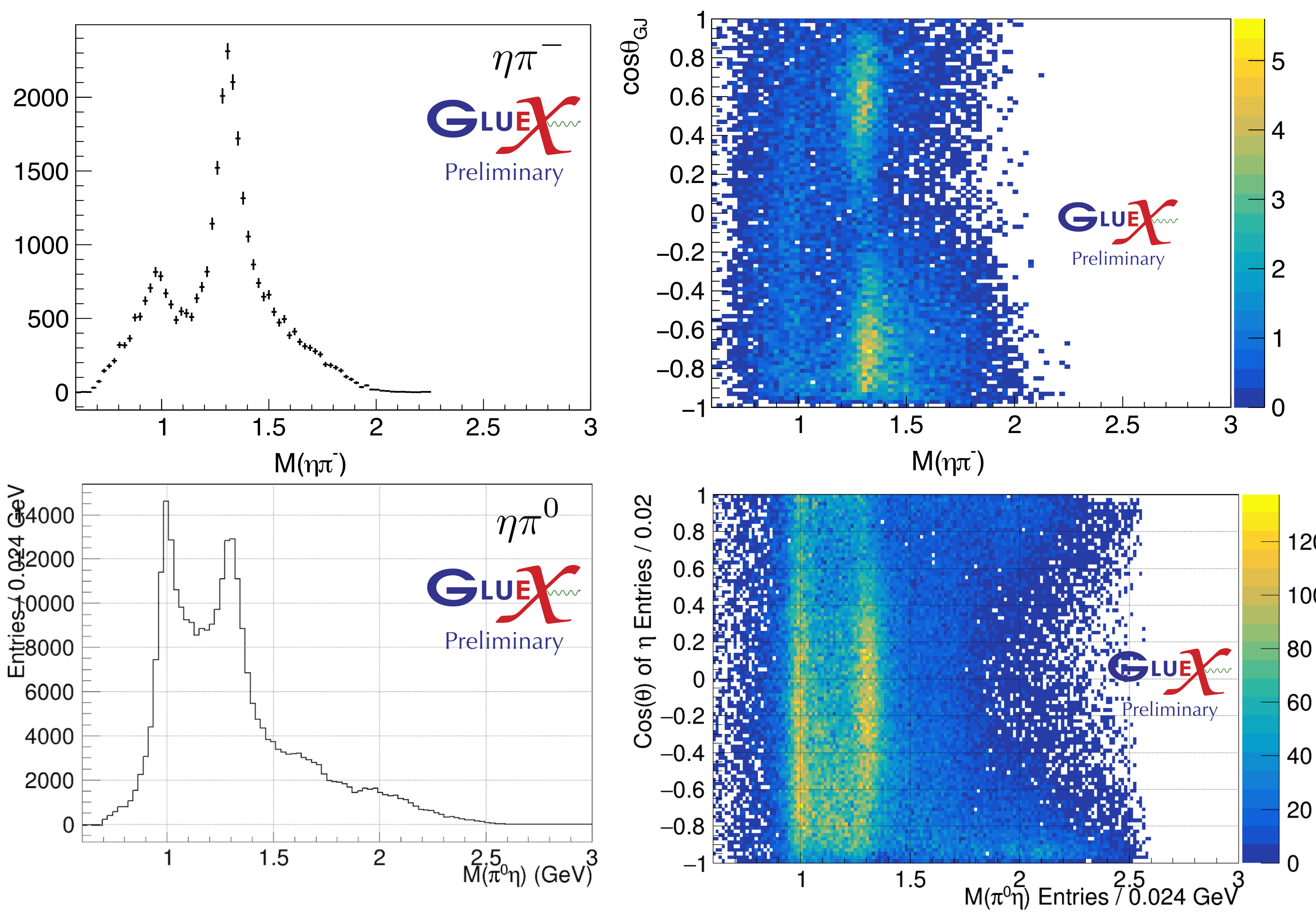


- Linearly polarized, tagged photon beam (P≈40%) impinging on Liquid Hydrogen Target
- Four polarization orientations, coherent peak: ~8.2-8.8 GeV
- Large acceptance for charged and neutral final state particles

$\gamma p \to \pi\eta N$ 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
- Different spin-projection states populated in charged vs. Neutral channel

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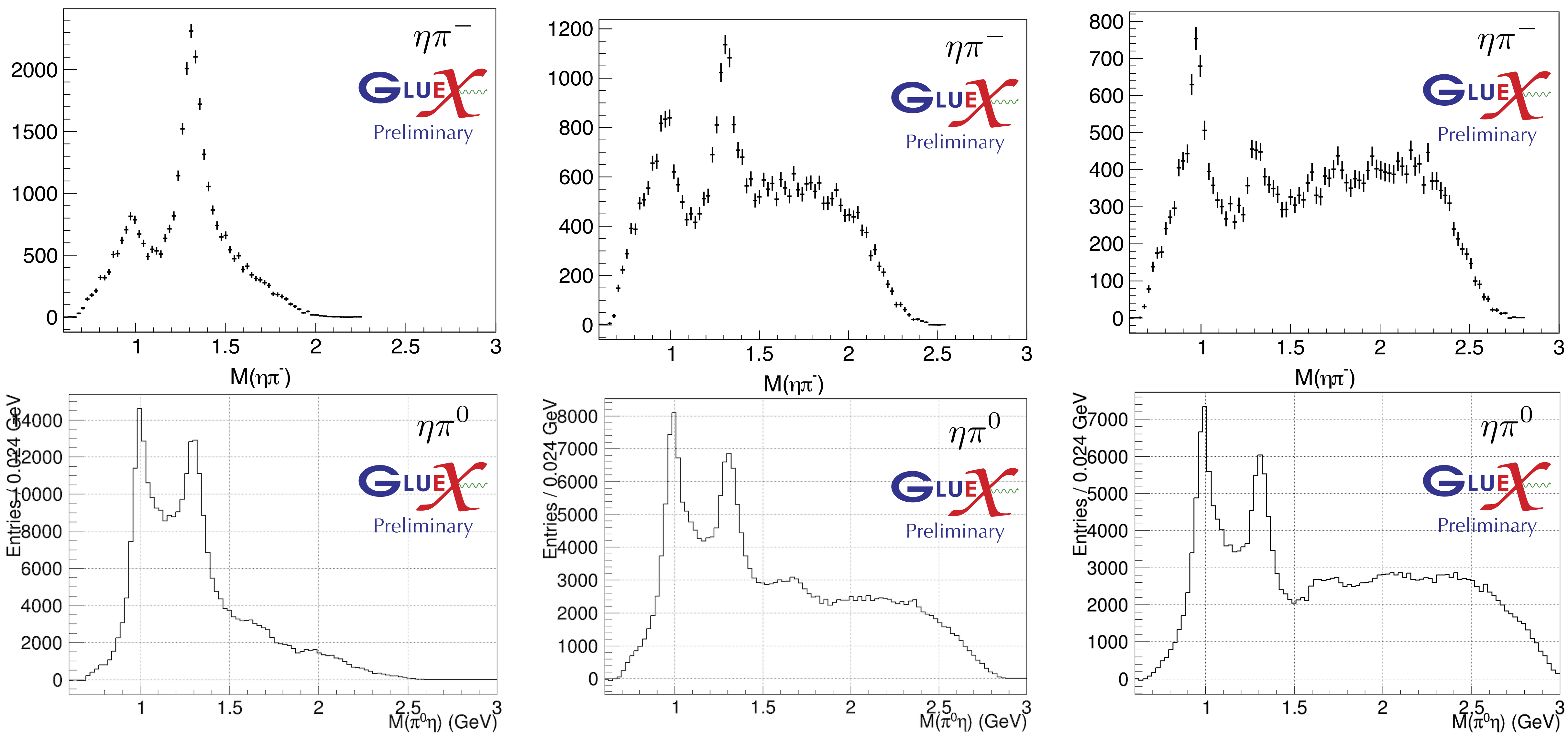
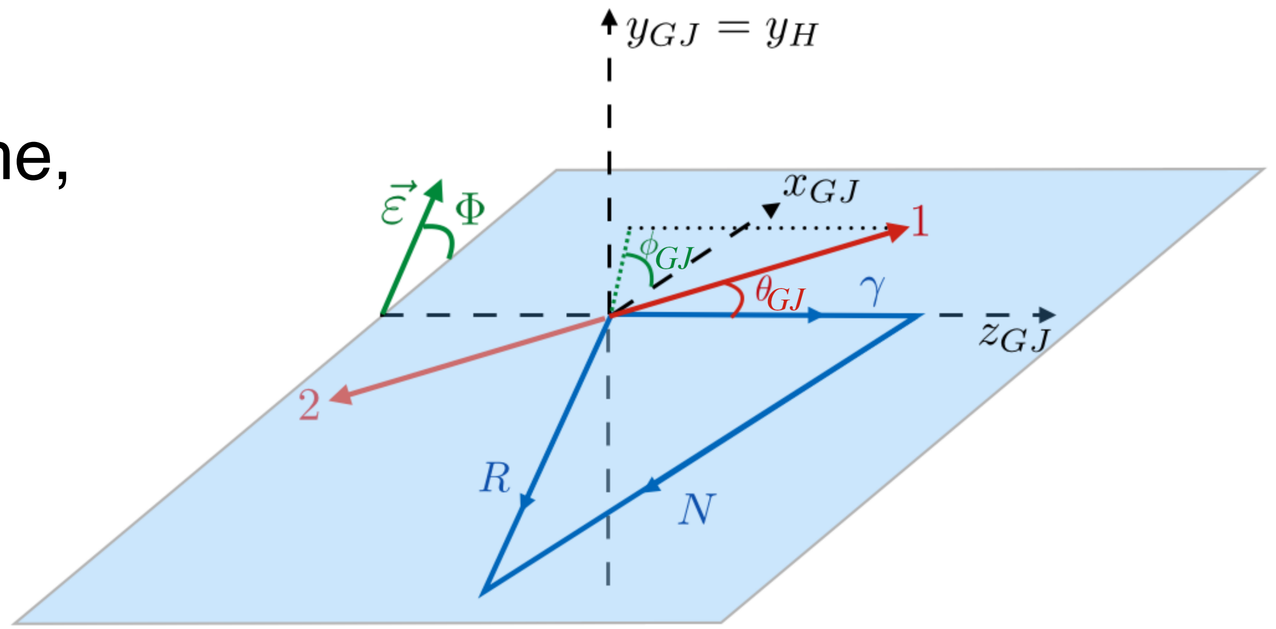
$0.1 < -t < 0.3$ GeV^2 $\quad$ $0.3 < -t < 0.6$ GeV^2 $\quad$ $0.6 < -t < 1.0$ GeV^2



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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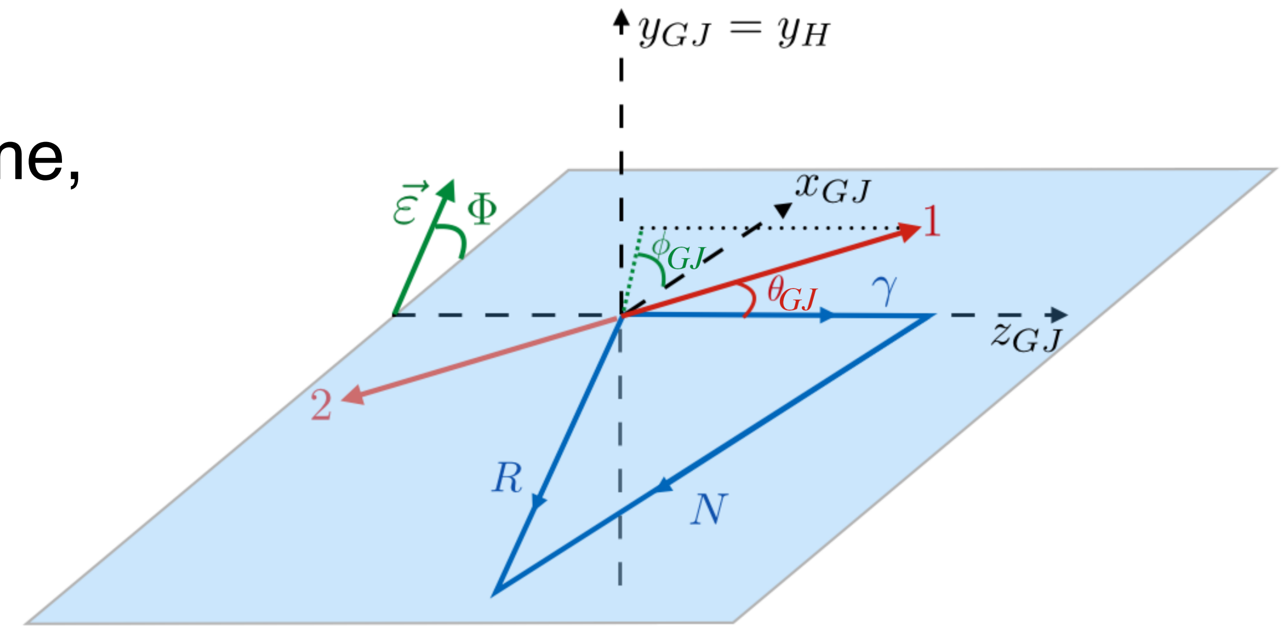


[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

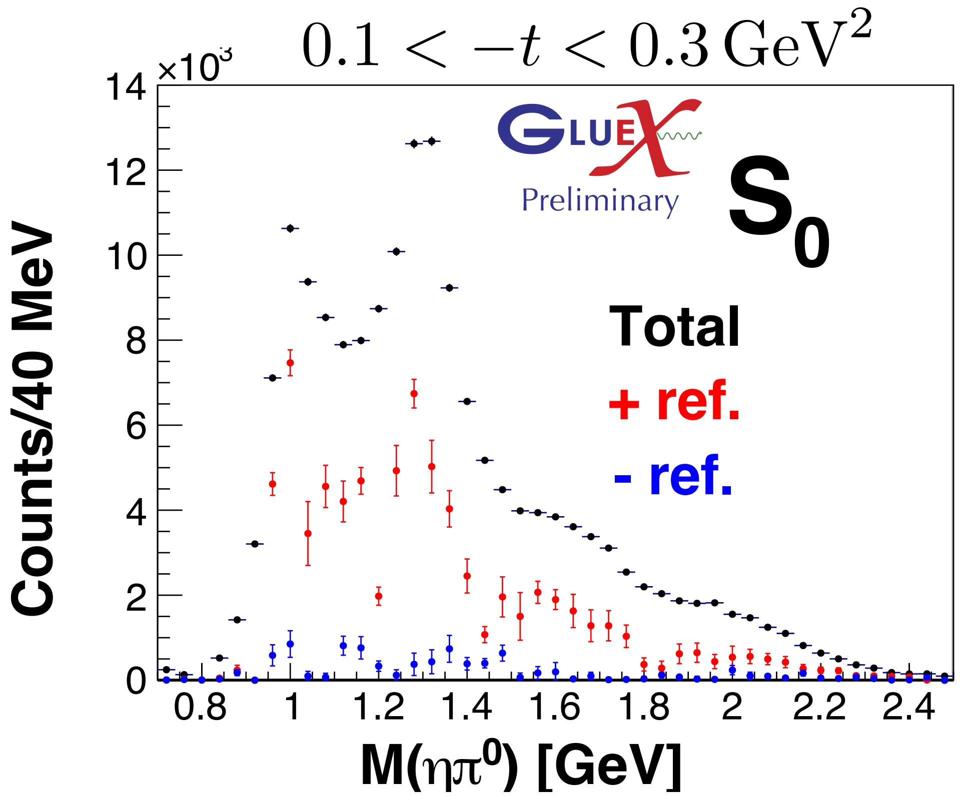
- Basis: Z_l^m amplitudes defined as $Z_l^m(\Omega, \Phi) = Y_l^m(\Omega)e^{-i\Phi}$

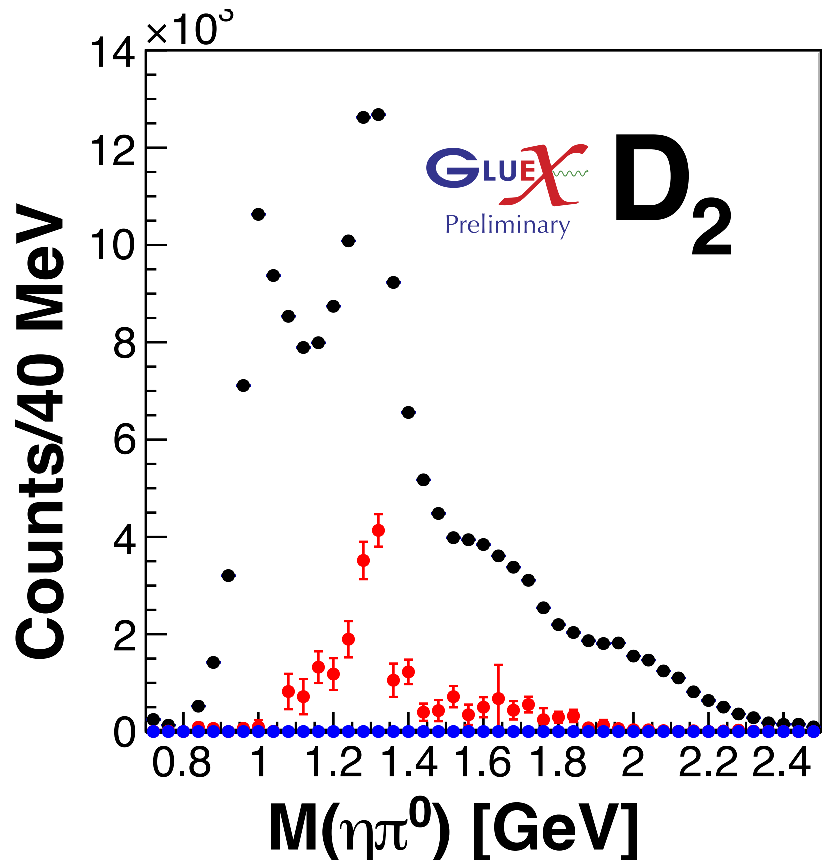
$$I(\Omega,\Phi) = 2\kappa \sum_k \Bigg\{ (1-P_\gamma) \left| \sum_{\ell,m} [\ell]^{(-)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)] \right|^2 + (1-P_\gamma) \left| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Im}[Z^m_\ell(\Omega,\Phi)] \right|^2 + (1+P_\gamma) \left| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)]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

- Complexity: Reflectivity $\epsilon = \pm 1$ and spin projections $m = -l, \ldots, +l$ allowed

- Frequent exchange with JPAC

Mass Independent PWA of $\gamma p \to \eta\pi^0 p$





- 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 based on Tensor Meson Dominance model:

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

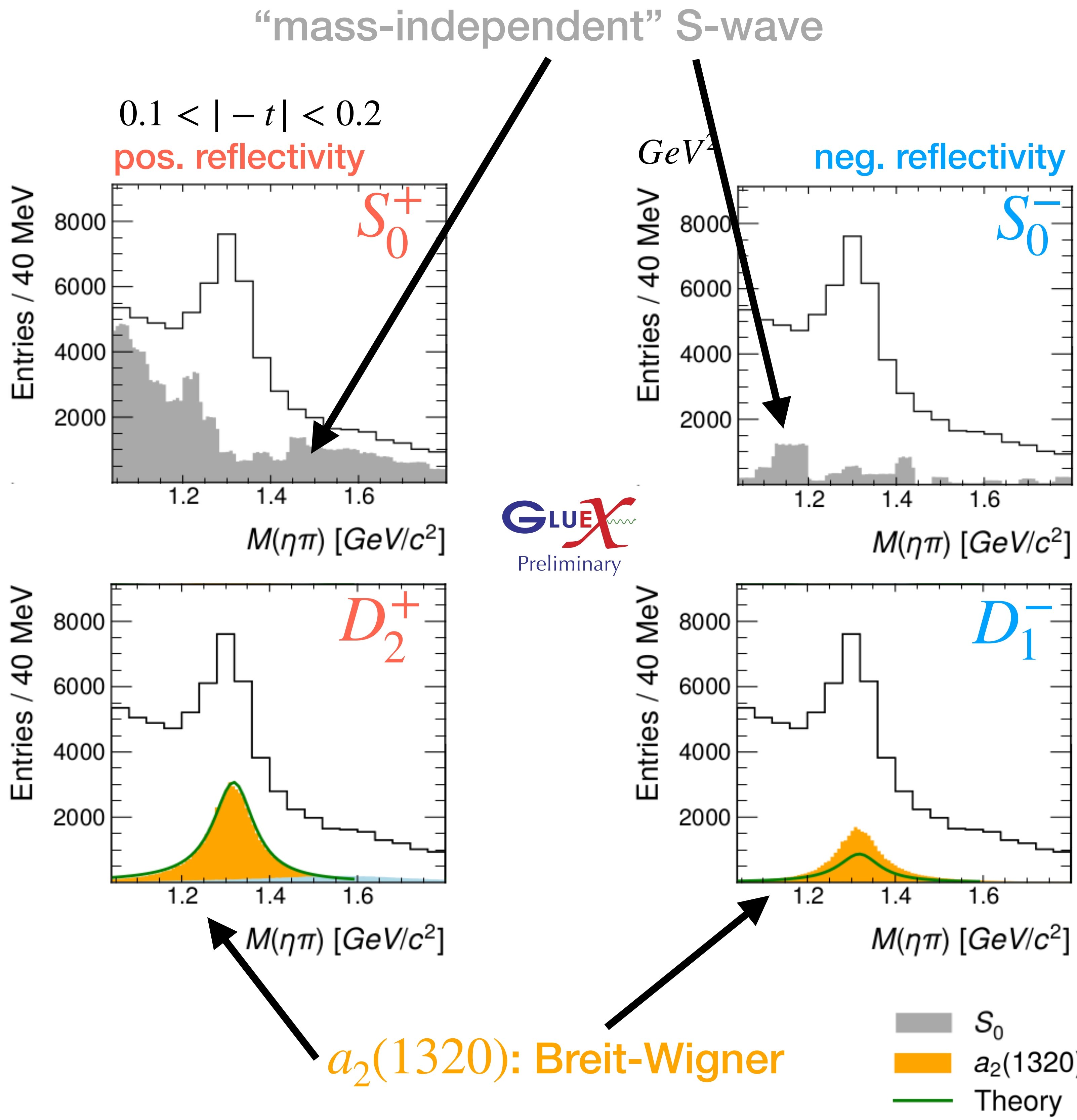
[V.Mathieu et.al. (JPAC) PRD 102, 014003 (2020)]

- Persisting challenges:
  leakage between waves, fluctuations - especially for sub-dominant waves

→ **Perform semi - mass independent PWA to extract a_2 contribution**

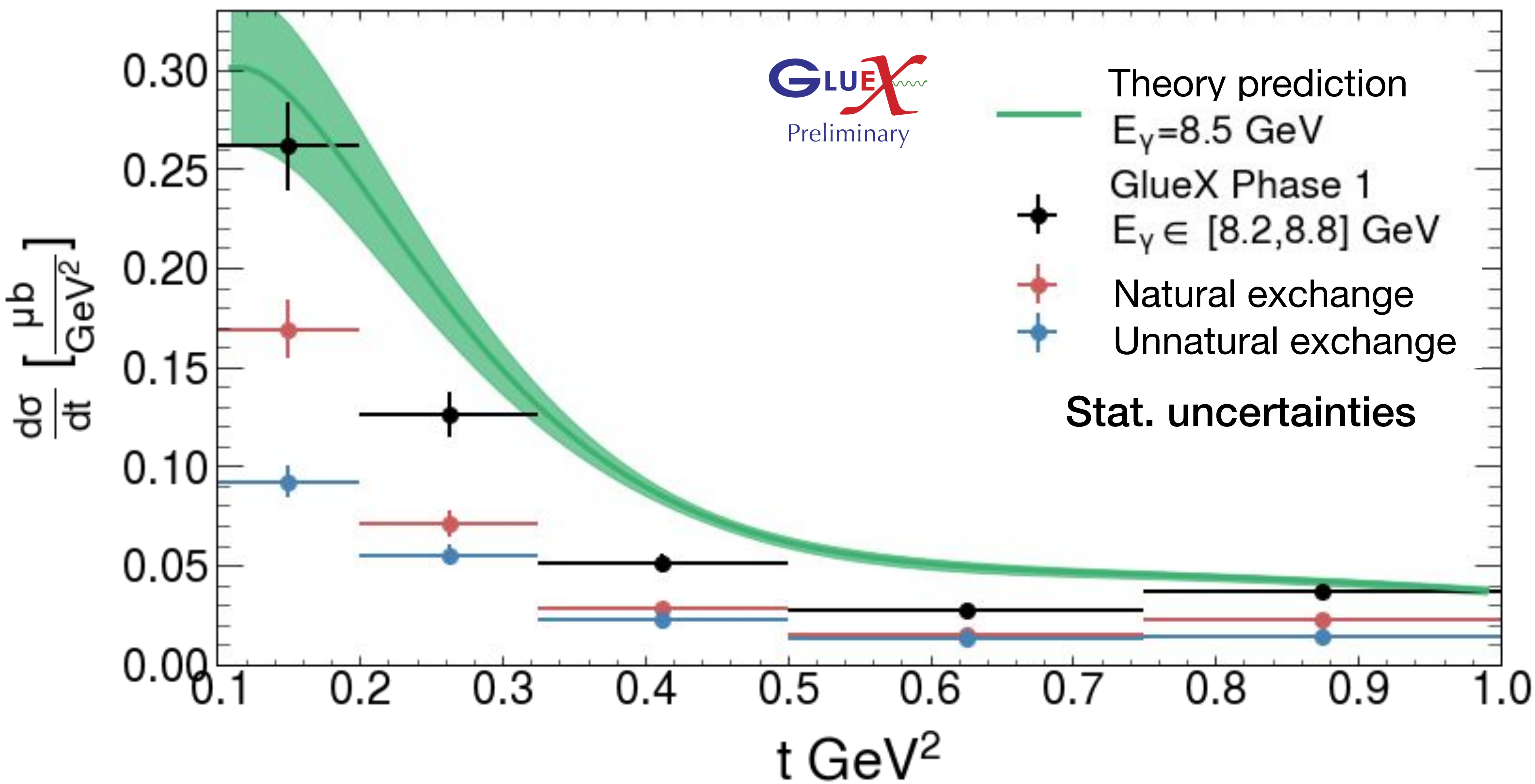
Semi-Mass Independent PWA $(\gamma p \to \pi^0 \eta p)$

- Simplify problem by introducing physics constraint:
- $a_2(1320)$ reasonably isolated
  → Well described by Breit-Wigner function
- S-wave has complex structure
  → 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

- 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
- Publication in preparation

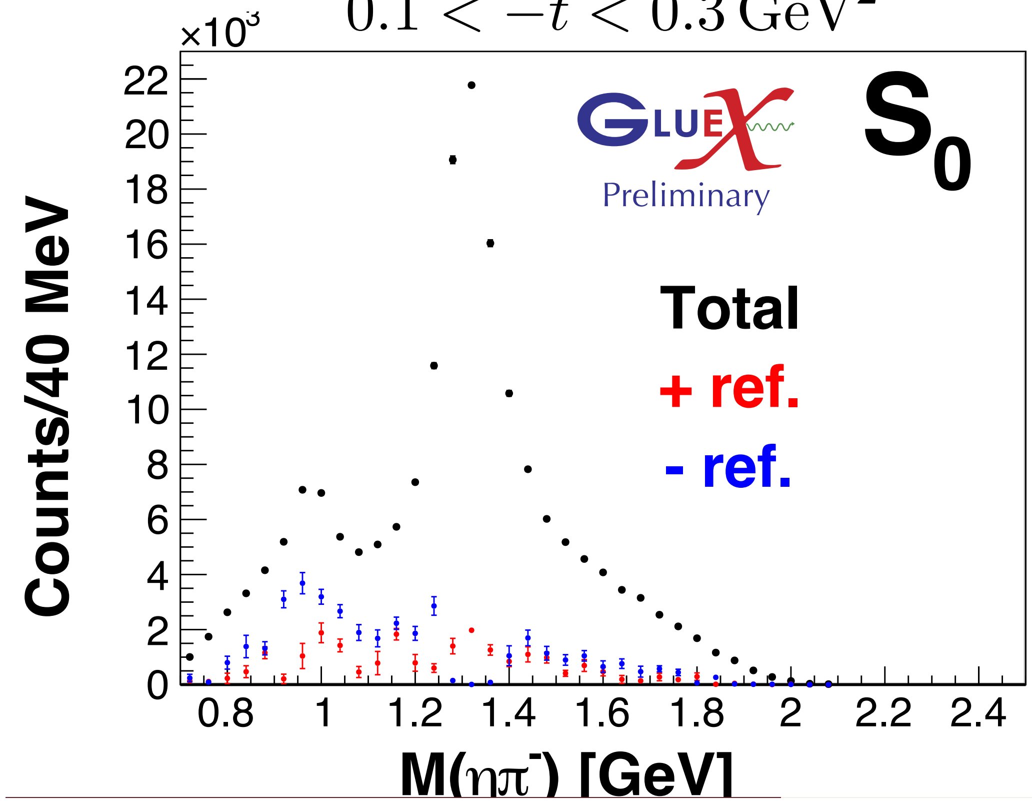


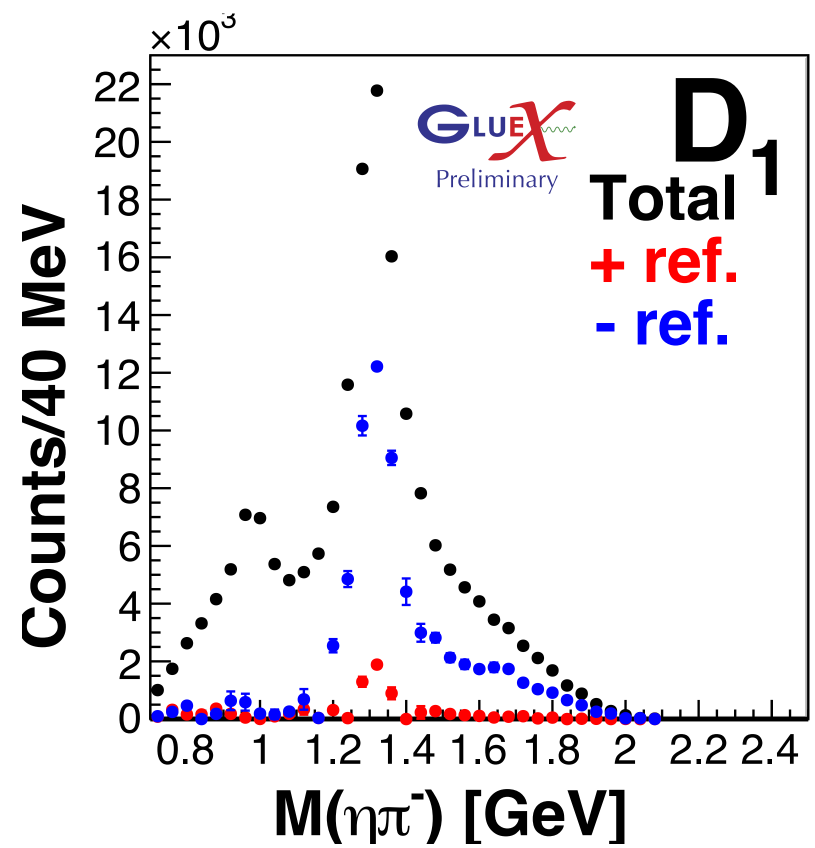
Mass Independent PWA of $\gamma p \to \pi^- \eta \Delta^{++}$

- 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)
  - Tail in D1 wave related to $a_2(1700)$?
  - Same challenges with mass-independent fit as in neutral channel

$\rightarrow$ Extract a_2 cross section with same semi mass-independent PWA stategy

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





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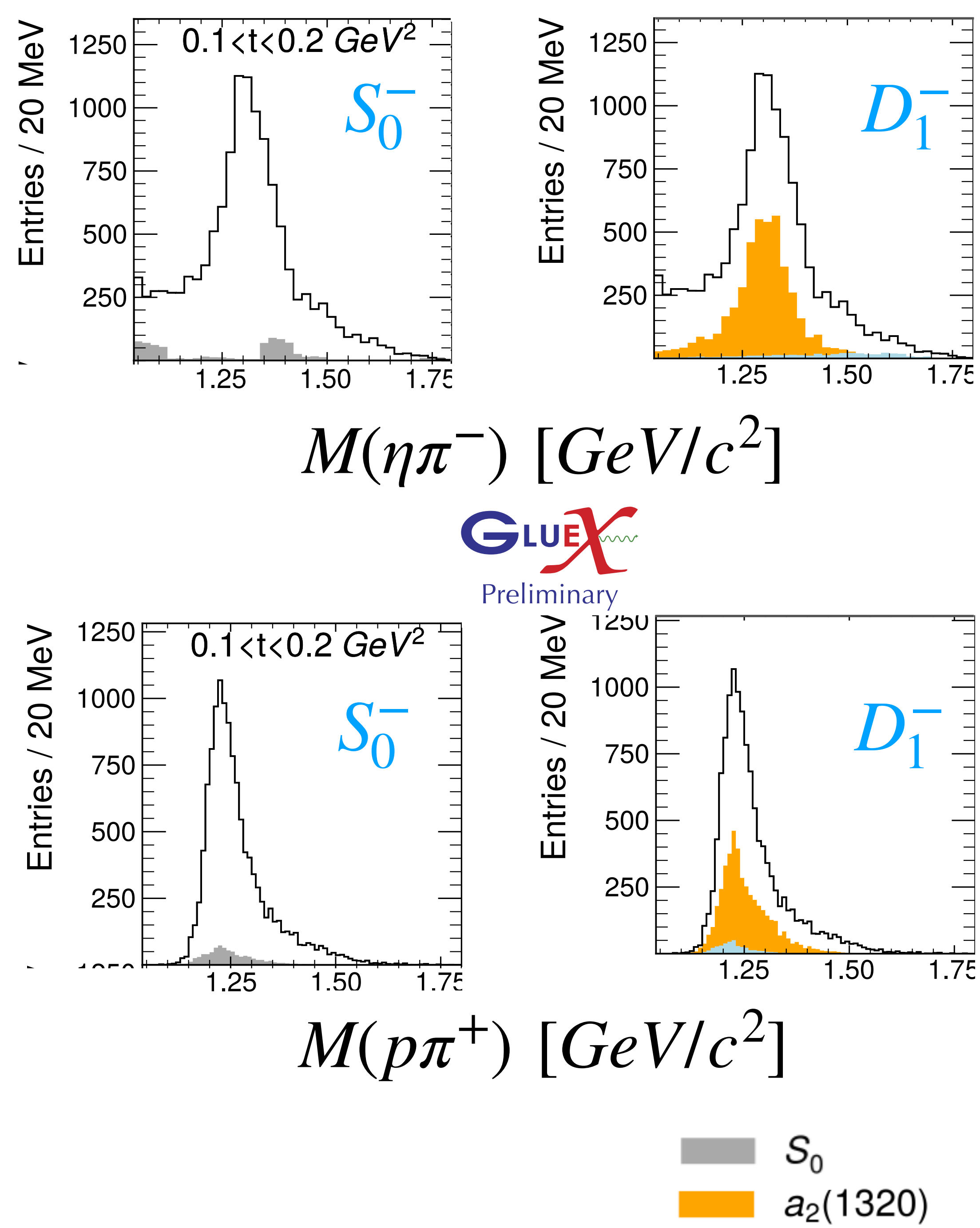
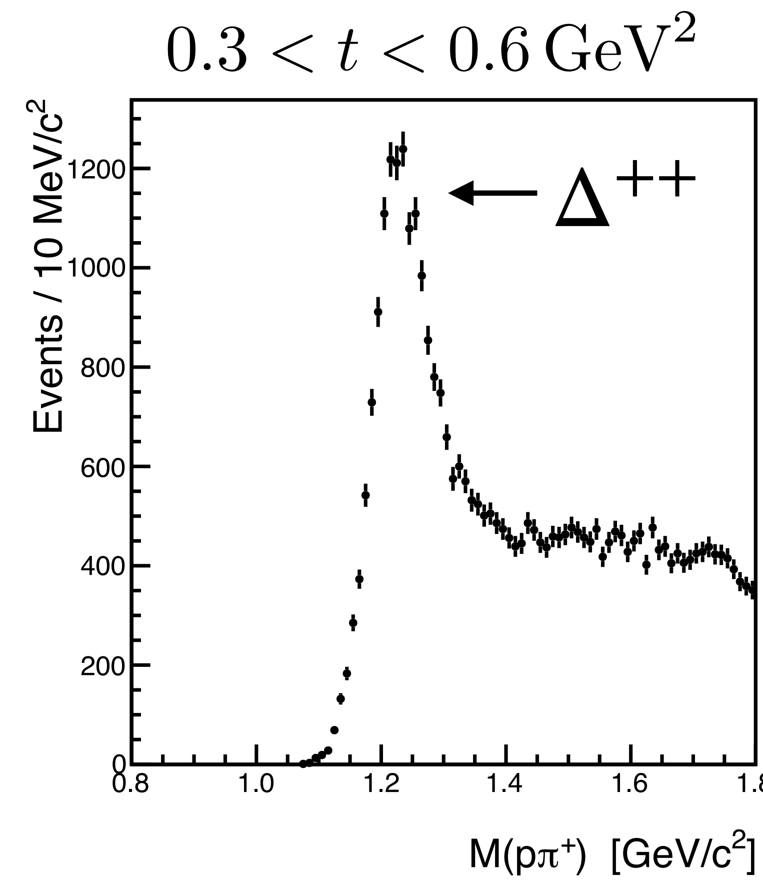
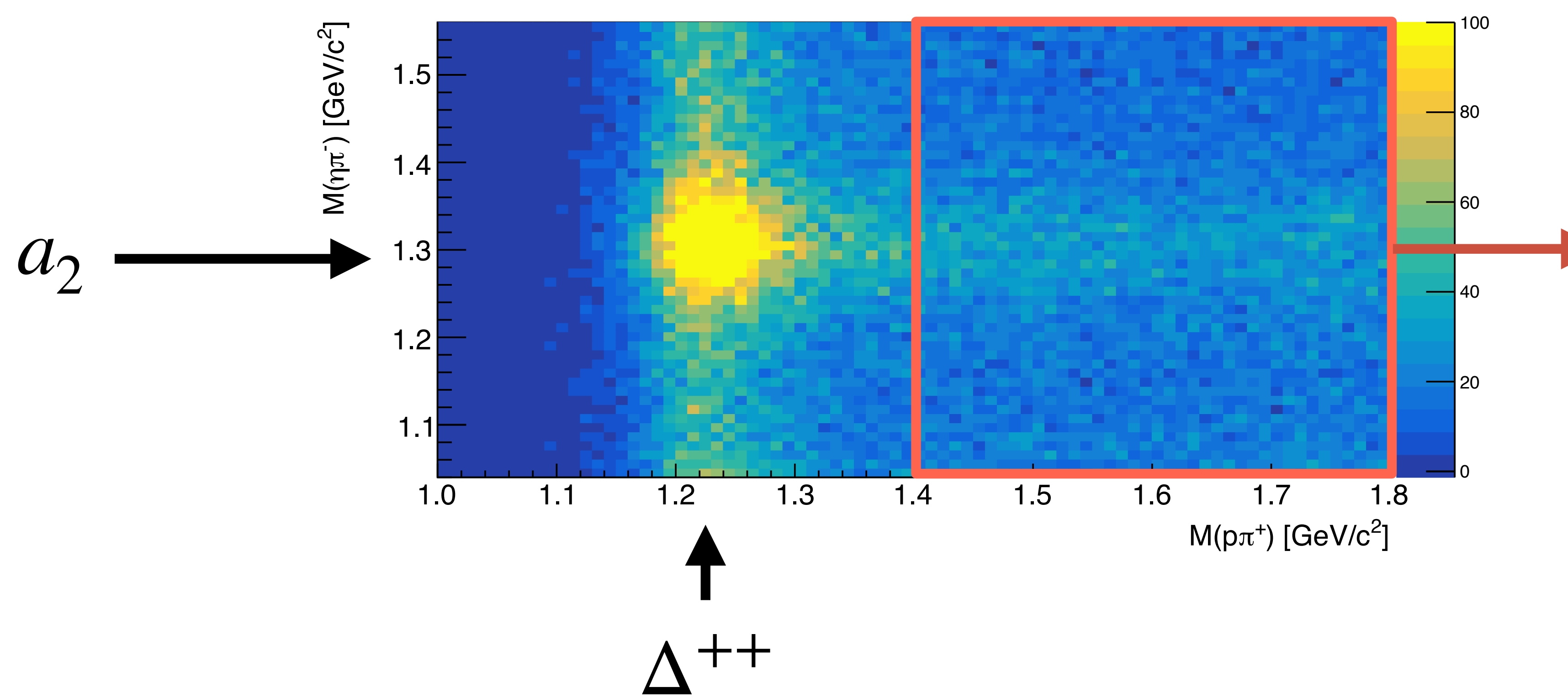
Example projections:

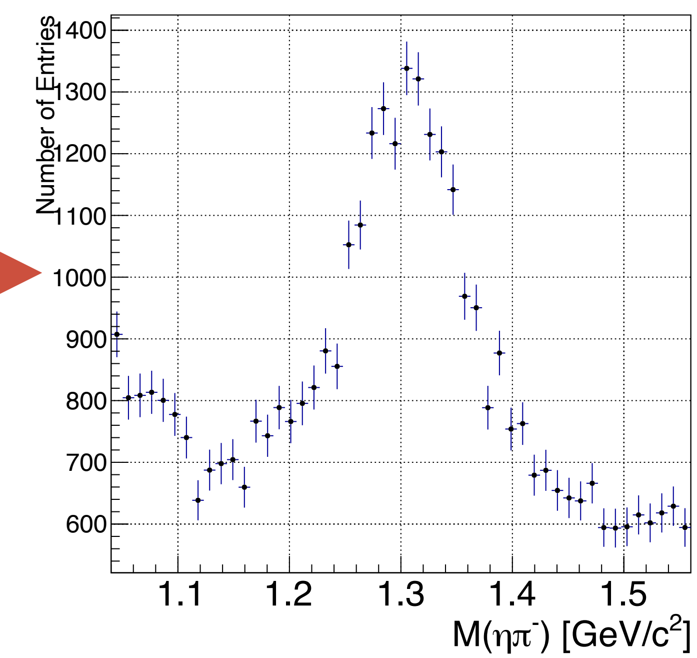


Non-Δ^{++} Background at higher |t|

- 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 $\eta' \pi^- \Delta^{++}, \omega \pi^- \Delta^{++}$

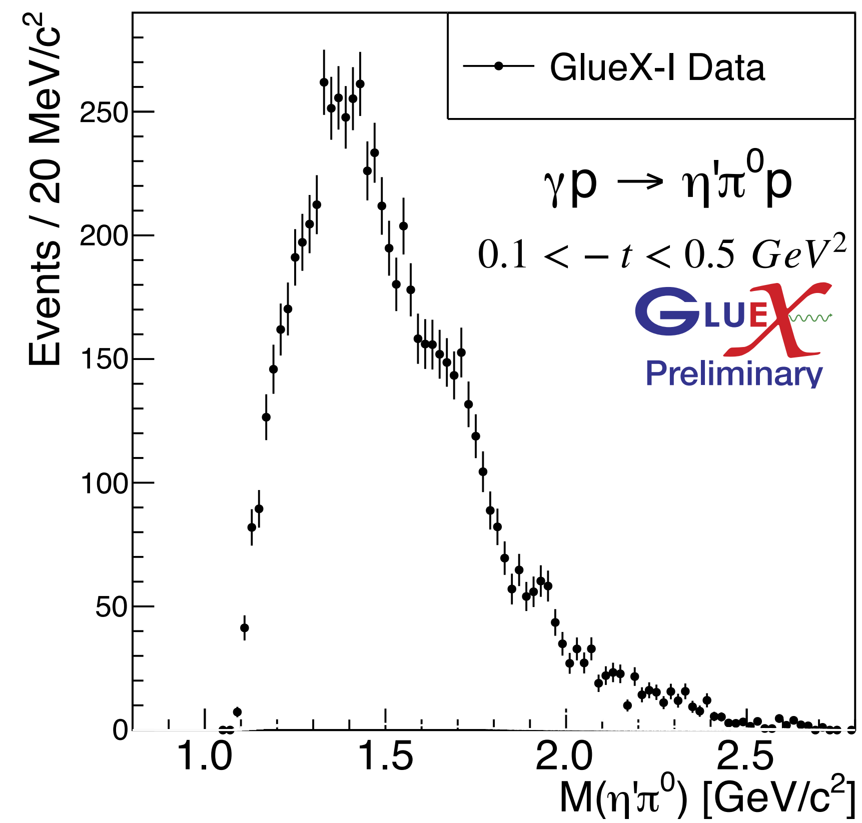


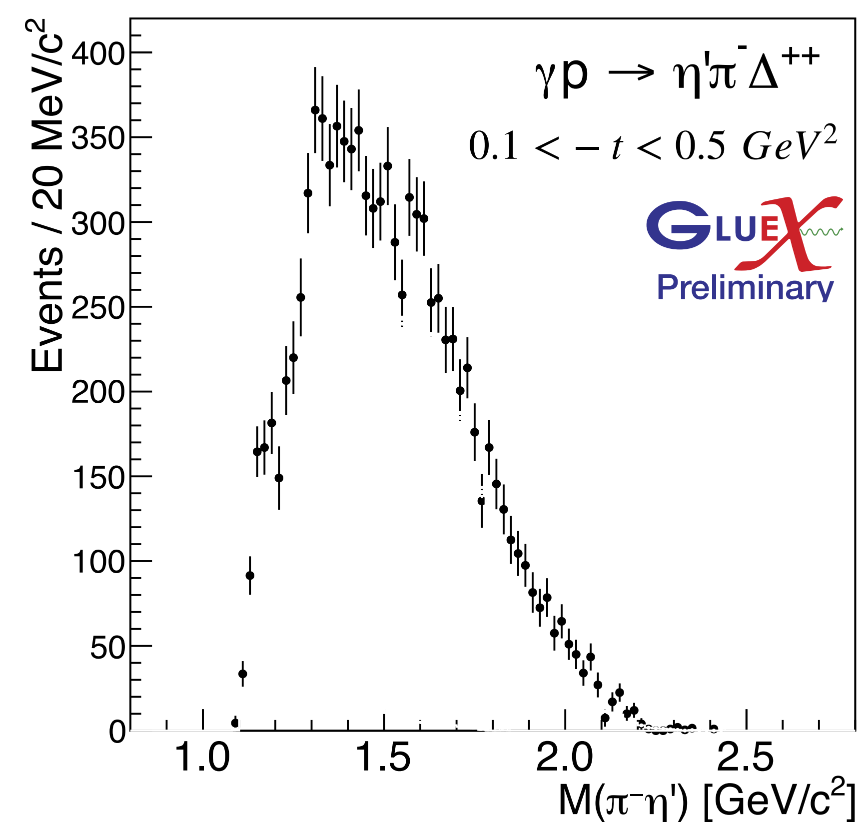




Analysis of $\eta'\pi$ Channels

- Channels under investigation in parallel
- Challenging backgrounds
    - Baryon excitations, channels with same final state (e.g. $\omega\eta \rightarrow \pi^+\pi^-\pi^0\eta$) (neutral), Δ^{++} (charged)
    - Combinatorics, Double-Regge contribution
- Smaller data samples and less pronounced a_2 signal, but coupling of π_1 expected to be larger
- Measurement of strong a_2 signal in $\eta\pi$ channels serves as reference





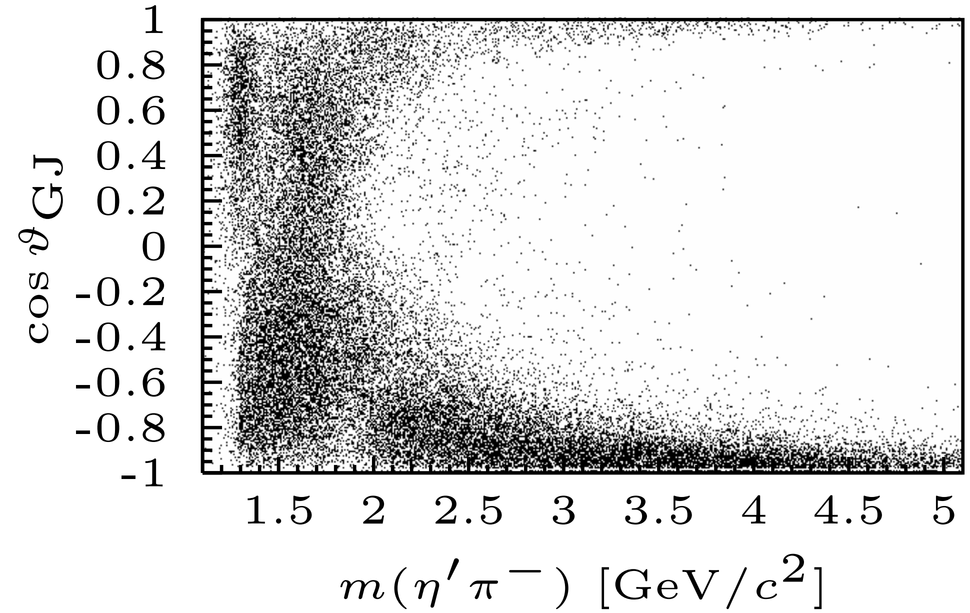
Closeup of $\eta'\pi^-$ Spectra

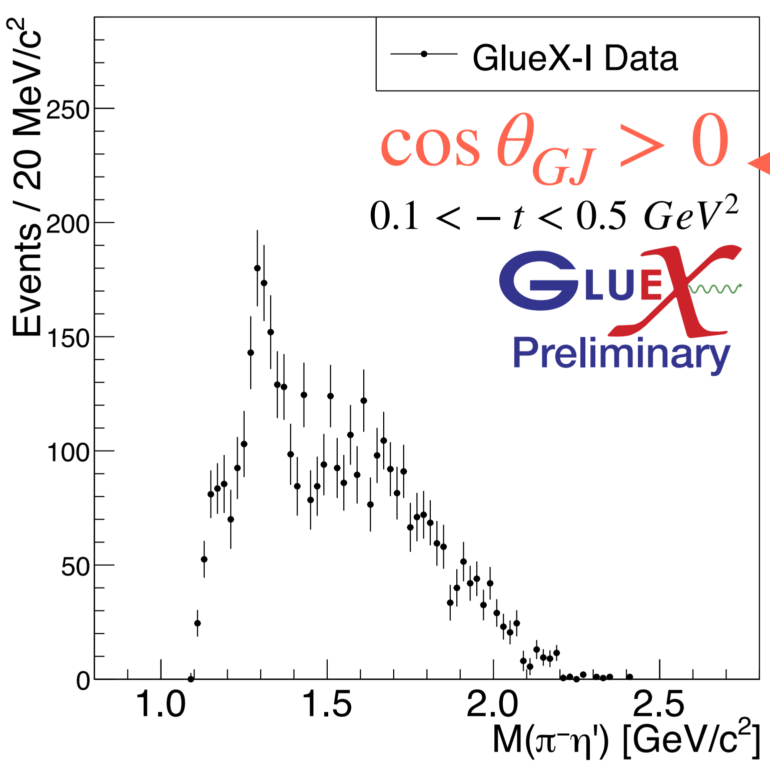
- Projections look intriguing
- Interesting interference pattern visible

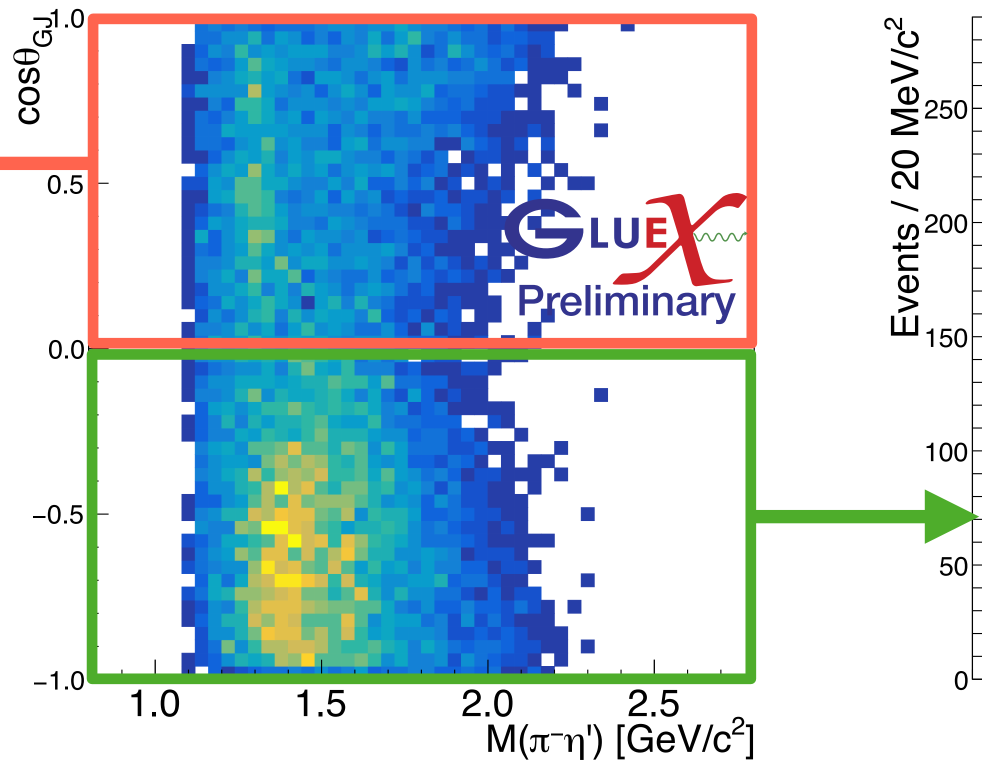
  → Constructive / destructive interference of odd and even wave contributions in different $\cos\theta_{GJ}$ regions?

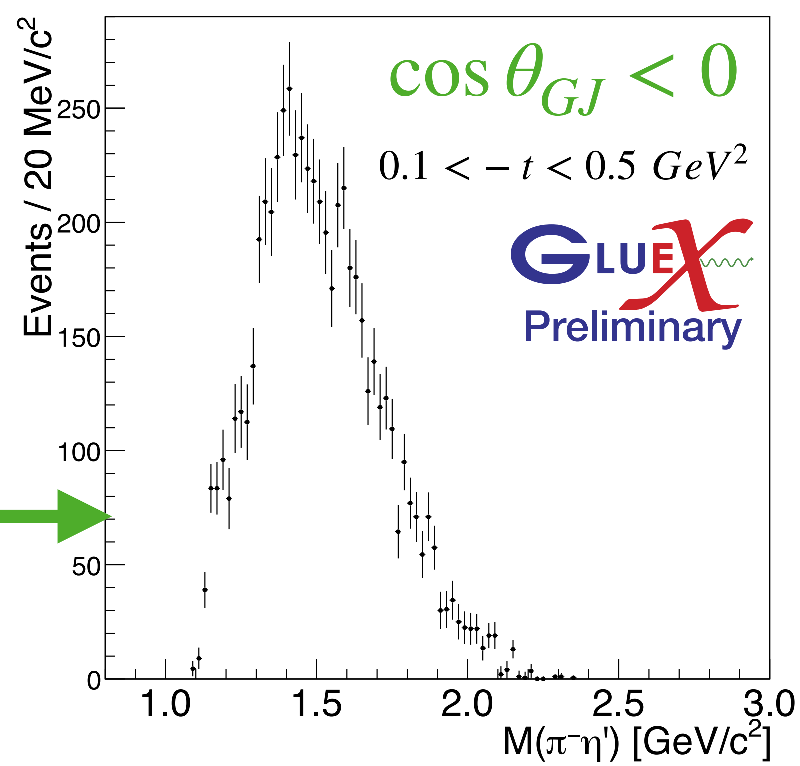
- Using a_2 cross section measurements from $\eta\pi$ channels as important reference

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



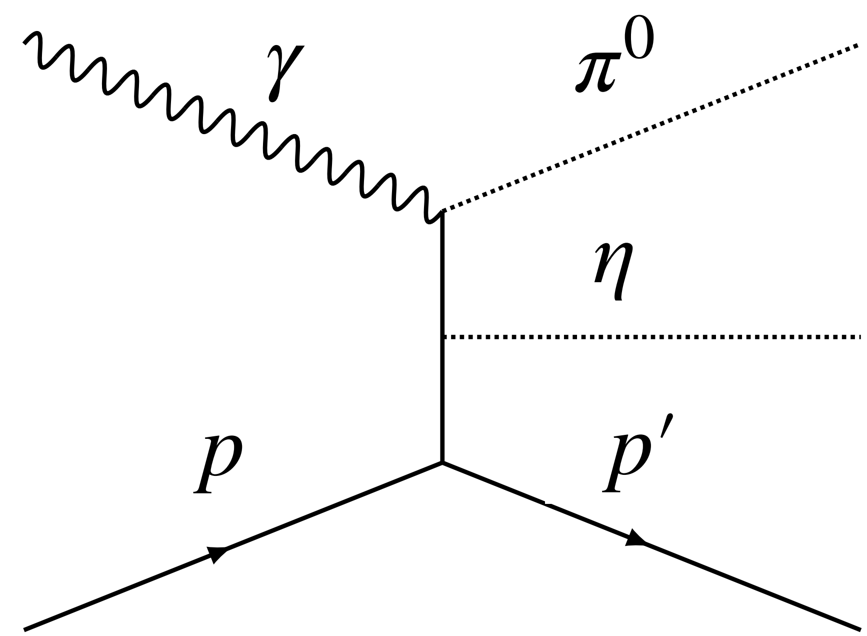


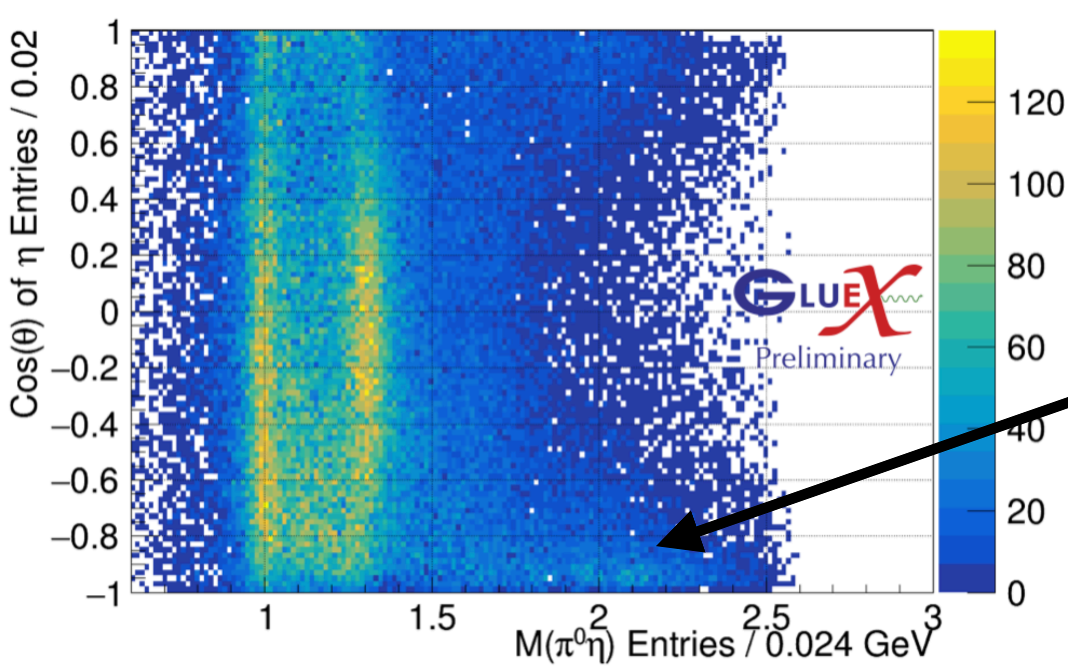




Double Regge Process

- Double-Reggeon exchange process (similar to Deck-contribution at COMPASS)
  - Dominant at high $|t|$ and 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



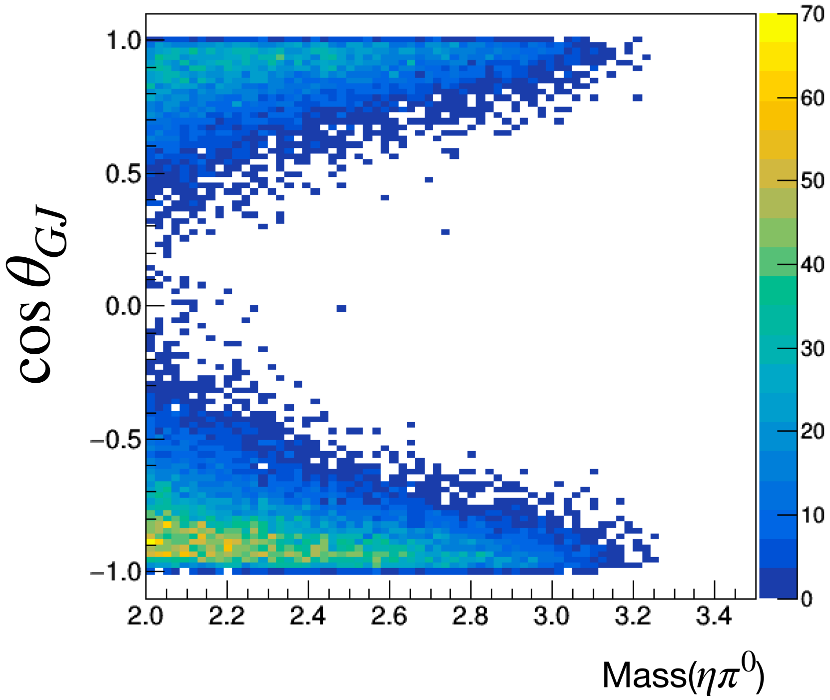


Improved Double Regge Process Modeling

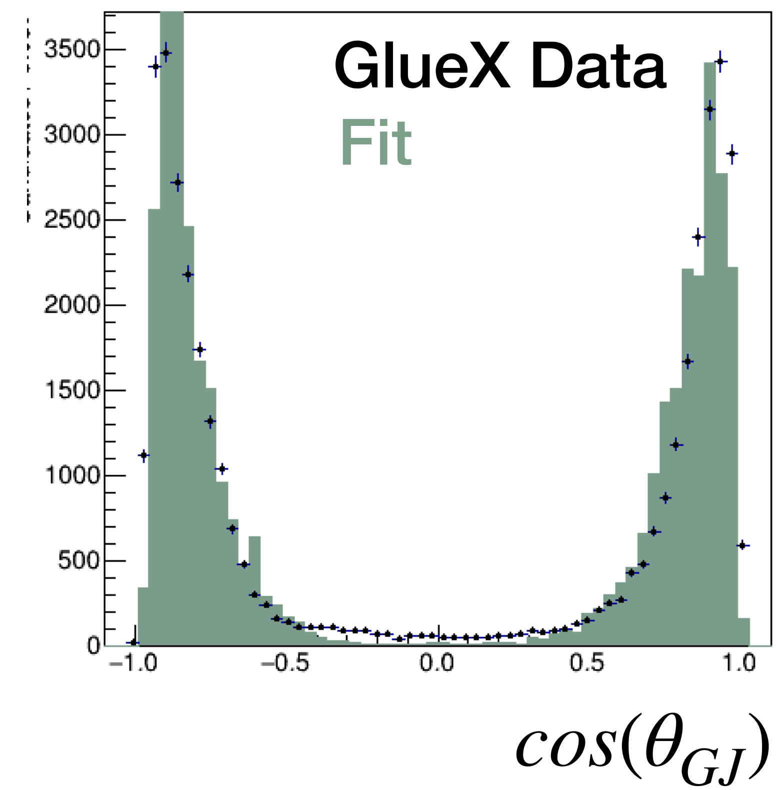
- Close collaboration with Theory/JPAC:
  - Original model was more simplistic
    (see also [L. Bibrzycky et. al. (JPAC), EPJ C 81, 647 (2021)])
  - Improved model available that involves better description of vertex factors, five parameters to describe kinematic distribution
- Monte Carlo study with updated model underway
  - Asymmetric $\cos\theta_{GJ}$ - shape can be reproduced
- First fits to data promising
  - Reasonable agreement in high mass region

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

Generated model MC:



Mass($\eta\pi$) : 2.6- 2.7 GeV

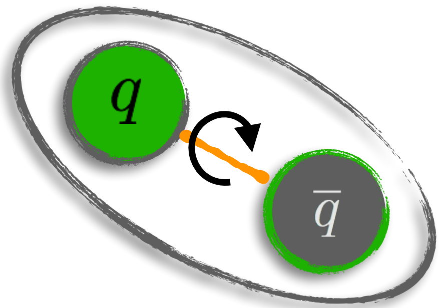


Summary and Outlook

- **High quality photoproduction data sets (GlueX Phase 1) 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 (JPAC) → continuous need for theory input**

En route to first results on exotic mesons with GlueX!



Backup

Improved Double Regge Model (JPAC)

- Original model too simplistic to describe the processes
- Fitted to five parameters as opposed to the original three
  - The fast η and fast π amplitudes each have their own b parameter instead of a shared one
  - Introduces a scaling factor S_0 which should be on order ~1.0 GeV
- More complex vertex factors
- Much more computationally expensive
  - Made GPU compatible

$$A^{\gamma p\to\eta\pi p}_{\lambda_\gamma\lambda\lambda'} = a_\eta e^{b_\eta t_\eta} A^{\eta\pi}_{\lambda_\gamma\lambda\lambda'} + a_\pi e^{b_\pi t_\pi} A^{\pi\eta}_{\lambda_\gamma\lambda\lambda'} \quad (4)$$

$$A^{\eta\pi}_{\lambda_\gamma\lambda\lambda'} = \frac{\sqrt{-t_\eta}}{m_\pi}\left(\frac{-t_p}{4m_p^2}\right)^{\frac{1}{2}|\lambda-\lambda'|} A^{DR,1}$$

$$A^{\pi\eta}_{\lambda_\gamma\lambda\lambda'} = \frac{\sqrt{-t_\pi}}{m_\pi}\left(\frac{-t_p}{4m_p^2}\right)^{\frac{1}{2}|\lambda-\lambda'|} A^{DR,2}$$

The double Regge amplitude is for fast eta:

$$A^{DR,1} = \Gamma(-\alpha_1)\Gamma(-\alpha_2)\left[(s/s_0)^{\alpha_1}(s_{\pi p}/s_0)^{\alpha_2-\alpha_1}\xi_1\xi_{21}V_1 + (s/s_0)^{\alpha_2}(s_{\eta\pi}/s_0)^{\alpha_1-\alpha_2}\xi_2\xi_{12}V_2\right] \quad (7a)$$

$$= \Gamma(-\alpha_1)\Gamma(-\alpha_2)(s_{\eta\pi}/s_0)^{\alpha_1}(s_{\pi p}/s_0)^{\alpha_2}\left[\eta^{\alpha_1}\xi_1\xi_{21}V_1 + \eta^{\alpha_2}\xi_2\xi_{12}V_2\right] \quad (7b)$$

$$\xi_1 = \frac{1}{2}\left(-1+e^{-i\pi\alpha_1}\right) \qquad \xi_{12} = \frac{1}{2}\left(1+e^{-i\pi(\alpha_1-\alpha_1)}\right) \quad (8a)$$

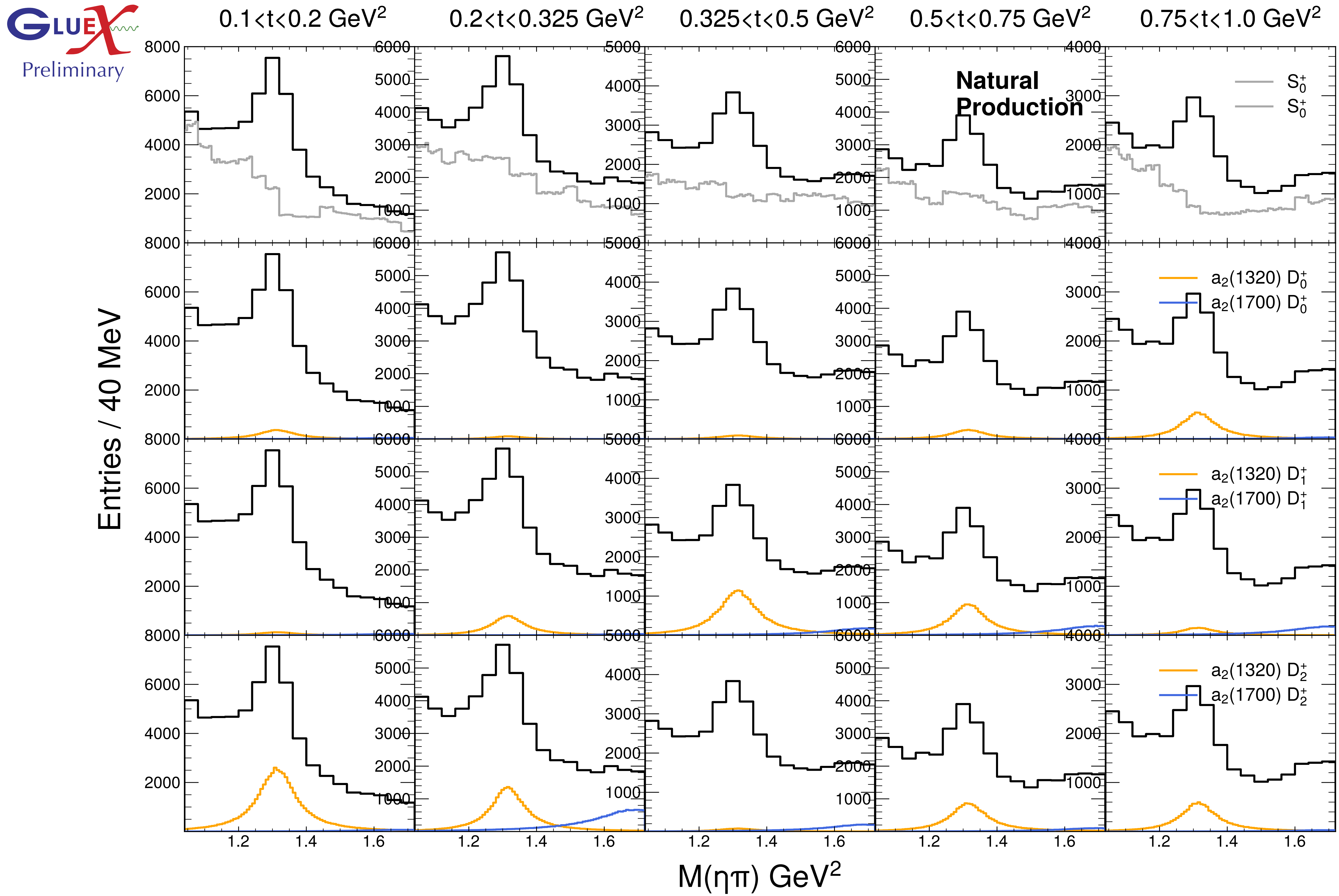
$$\xi_2 = \frac{1}{2}\left(-1+e^{-i\pi\alpha_2}\right) \qquad \xi_{21} = \frac{1}{2}\left(1+e^{-i\pi(\alpha_2-\alpha_1)}\right) \quad (8b)$$

$$V_1 = \frac{\Gamma(\alpha_1-\alpha_2)}{\Gamma(-\alpha_2)}\,{}_1F_1(-\alpha_1, 1-\alpha_1+\alpha_2, -\frac{1}{\eta}) \qquad \alpha_1 = \alpha(t_\eta) \quad (8c)$$

$$V_2 = \frac{\Gamma(\alpha_2-\alpha_1)}{\Gamma(-\alpha_1)}\,{}_1F_1(-\alpha_2, 1-\alpha_2+\alpha_1, -\frac{1}{\eta}) \qquad \alpha_2 = \alpha(t_p) \quad (8d)$$

$\eta = ss_0/(s_{\eta\pi}s_{\pi p})$ a dimensionless quantity.

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



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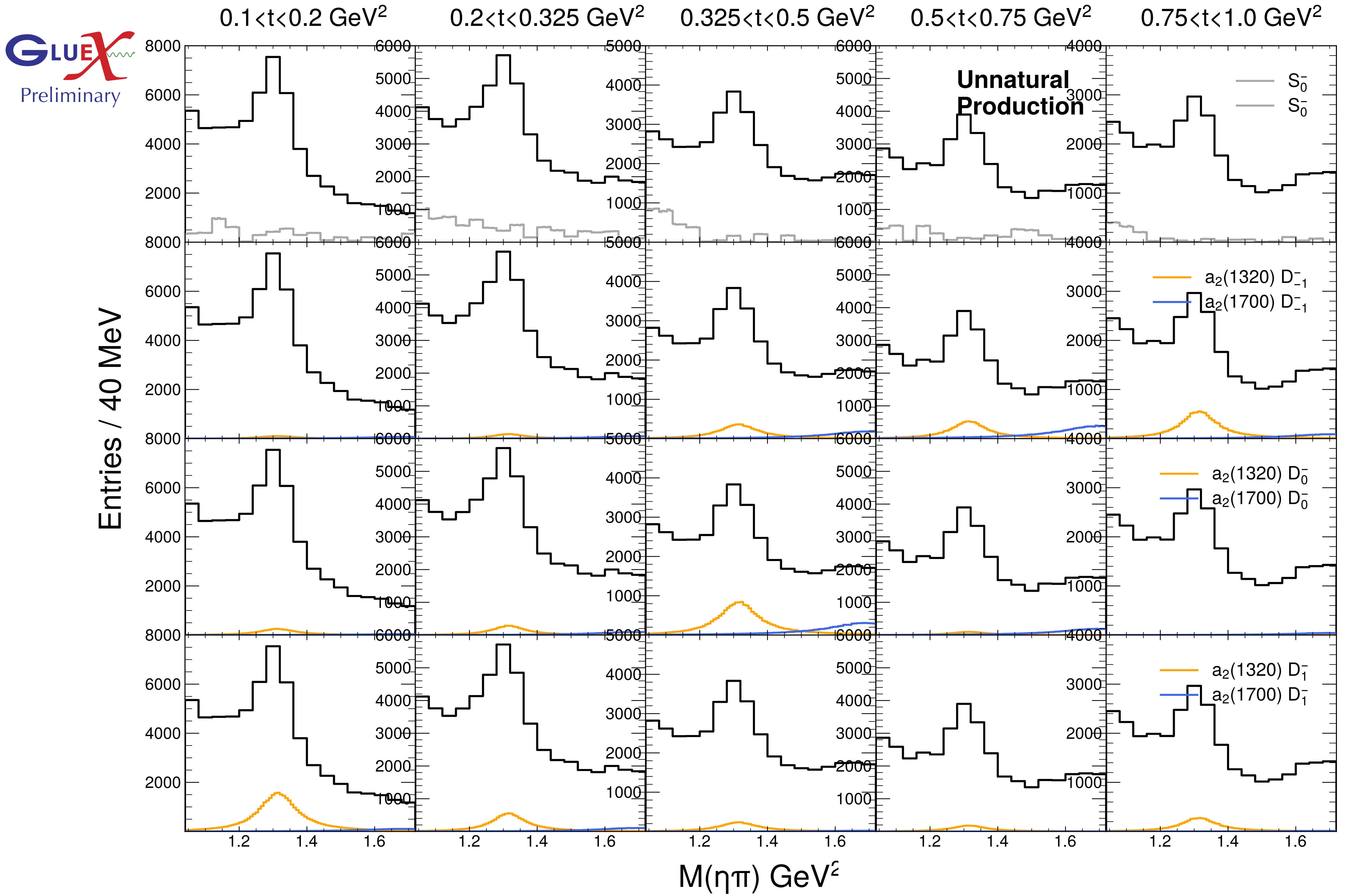


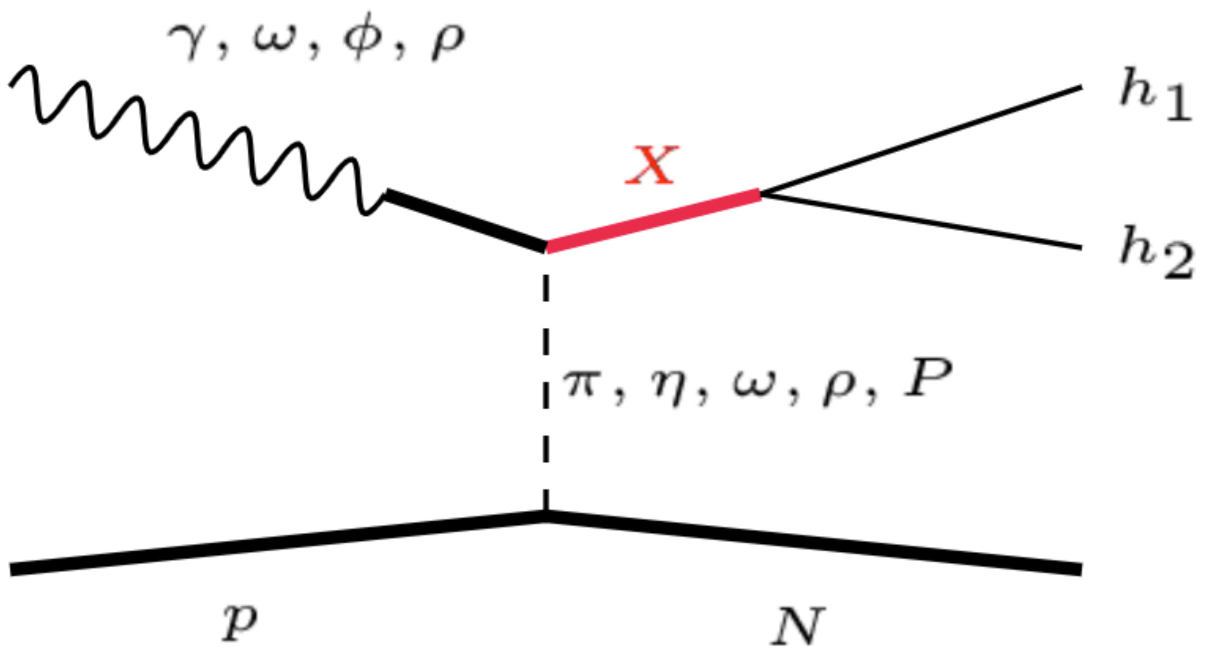
Comparison: Charged and Neutral Channels

$\eta\pi^0$:

- 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