Search for Exotic Hadrons at GlueX

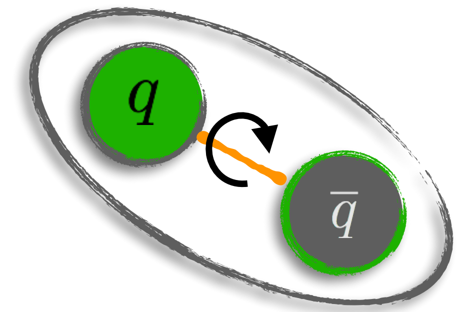
Malte Albrecht
for the GlueX Collaboration

Jefferson Lab

Exotic Heavy Meson Spectroscopy with EIC: Detector/Physics Simulations and Feasibility

04 / 16 / 2025

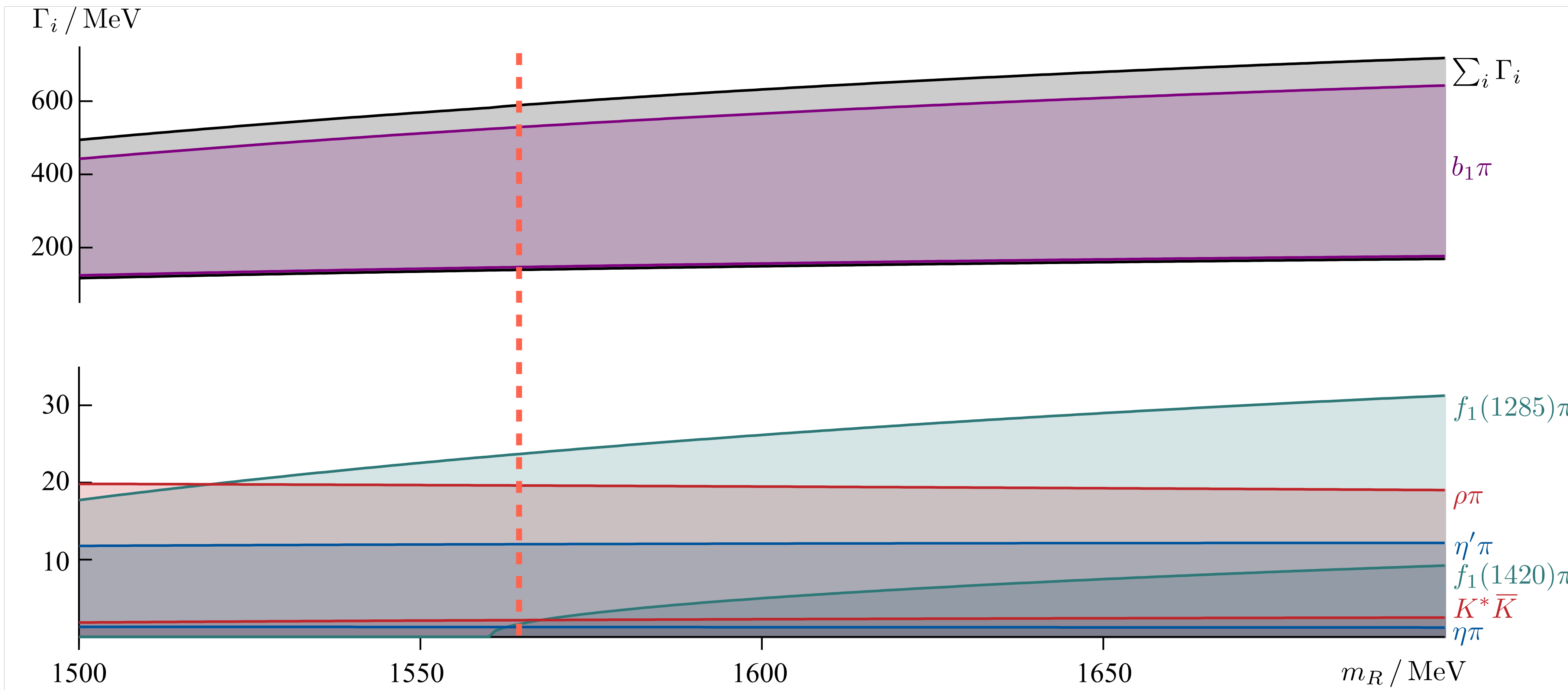
The Search for Hybrid Mesons



- **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 indispensa***
  - Achieving analysis goals depends on strong thec

Light Quark Mesons from Lattice QCD



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

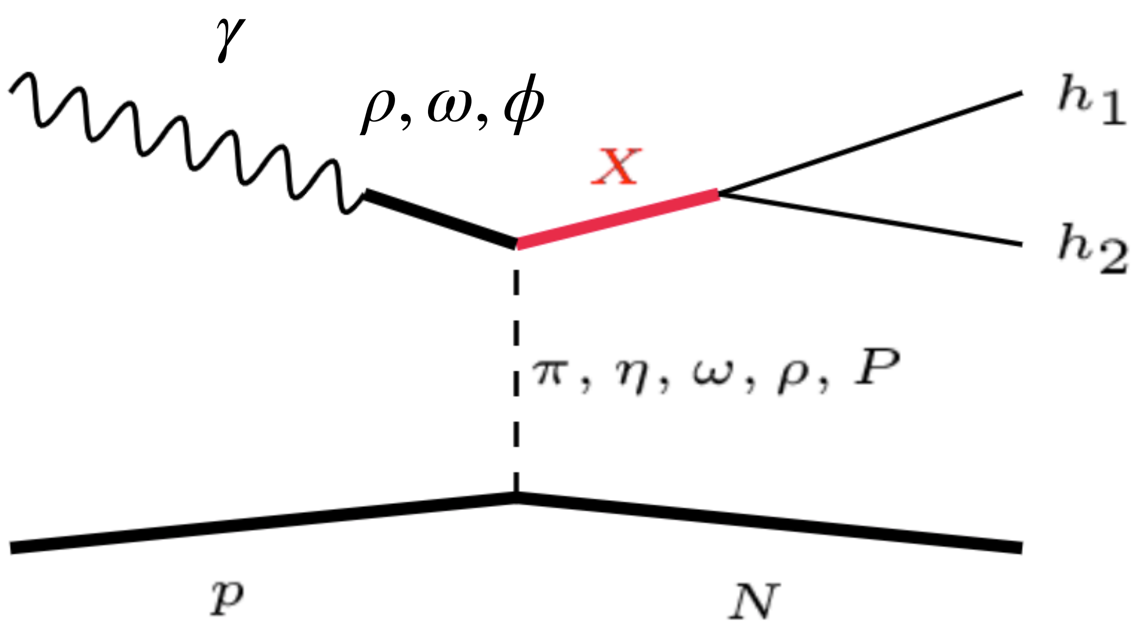
- Recent calculations: Large coupling of 1^{-+} state to axial vector-pseudoscalar channels
- Important to measure multiple decay modes to compare partial widths

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

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

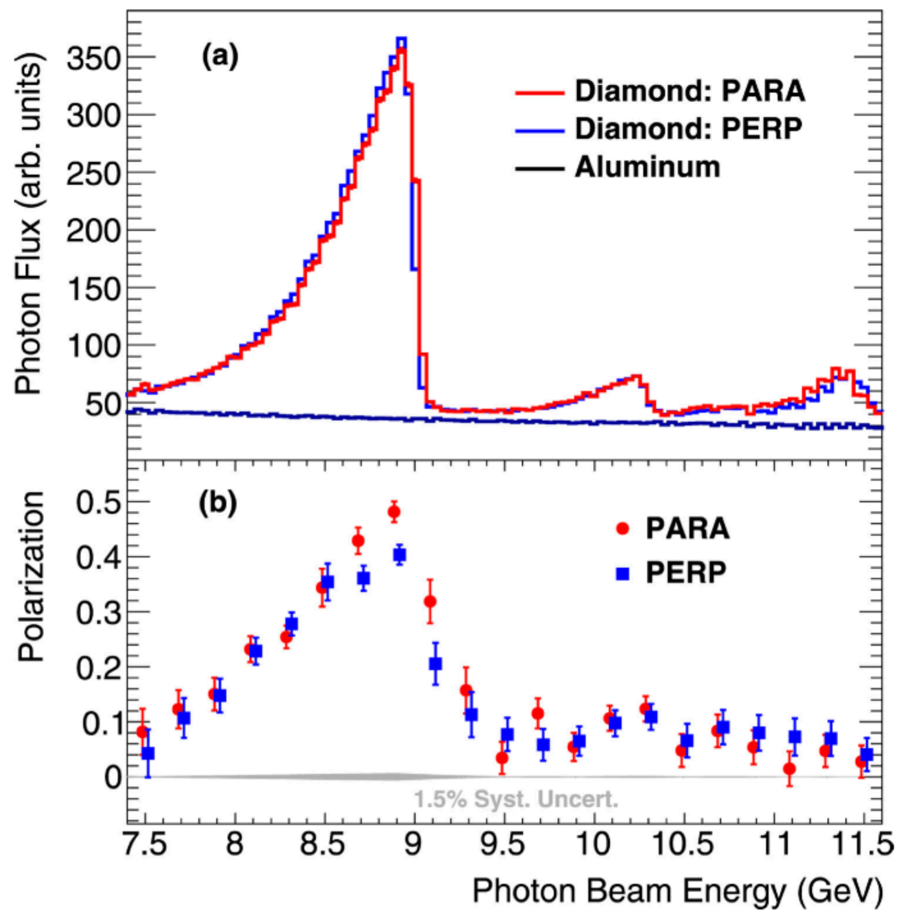
The Route to Exotics with GlueX

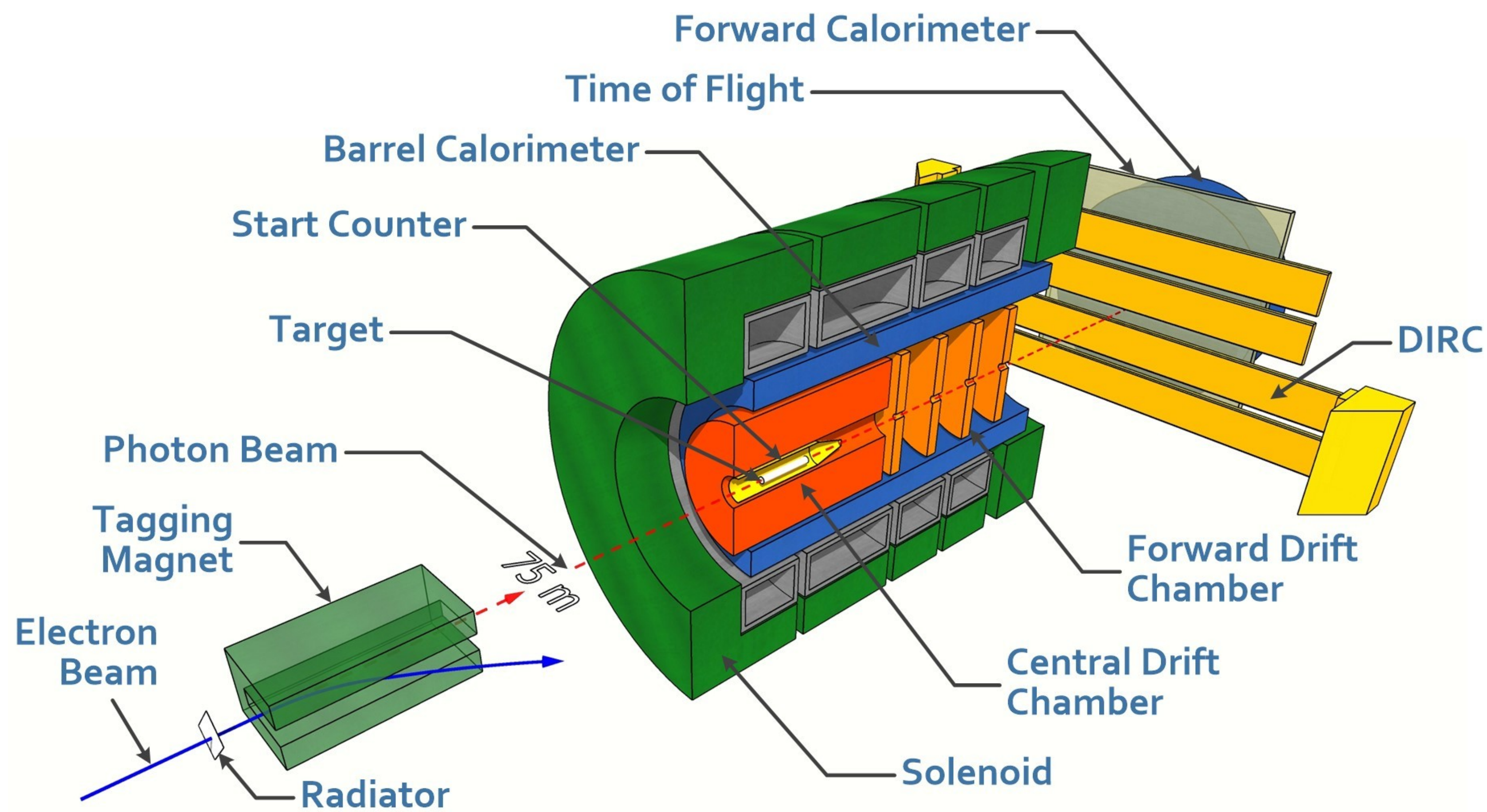
- **Photoproduction - a versatile process:**
  - Incoming photon may oscillate to vector meson
  - Production of mesonic resonances as well as target excitations
  - Complementary to πN reaction used by COMPASS, E852, VES
  - Allows coupling to all lightest hybrid nonet states



- 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), Δ^{++} PLB 863 (2025) 139368**)**
- 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 ($\omega\pi, \omega\eta, \phi\pi, \phi\eta, K^*K$)

The GlueX Experiment at Jefferson Lab



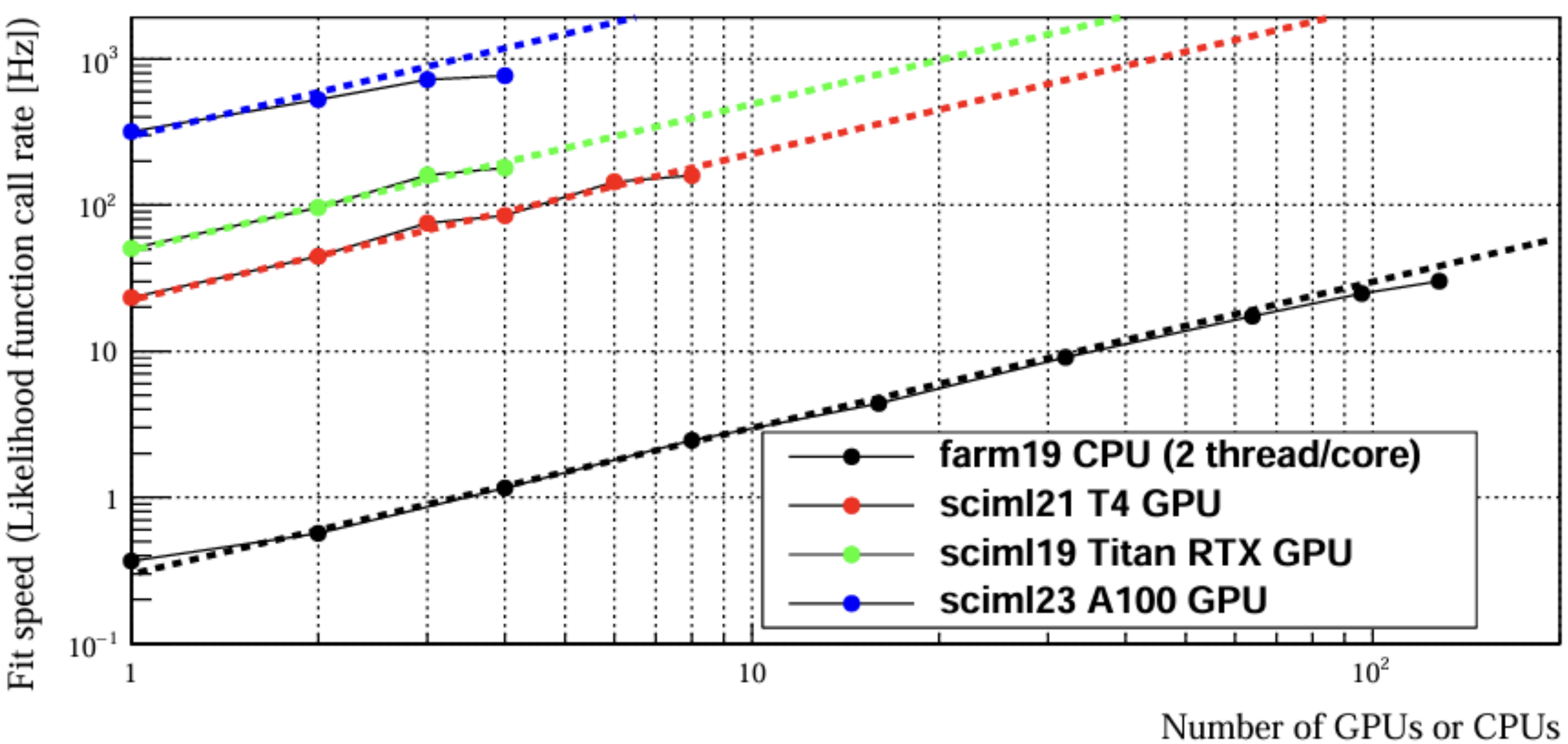


[(GlueX) NIMA **987** (2021) 164807]

- 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, $\int L = 125\,\mathrm{pb}^{-1}$), Phase II ongoing (expect 3-4 times Phase I data), Phase III approved by PAC

PWA with AmpTools

- AmpTools is a set of C++ classes that can be used for amplitude analyses
- Separate physics from computing
- The “user” provides:
  - an algorithm to unpack four-vectors from a file
  - algorithms to compute various physics amplitudes from four-vectors
  - a recipe for assembling the amplitudes into an intensity
- AmpTools provides:
  - general framework (no assumptions about experiment or physics model)
  - set of core libraries optimized for unbinned likelihood fitting and parallel processing
  - MPI parallelization
  - GPU acceleration per process (multiple GPUs supported)
  - modular code that can also be used for MC generation and displaying fit results



github.com/mashephe/AmpTools

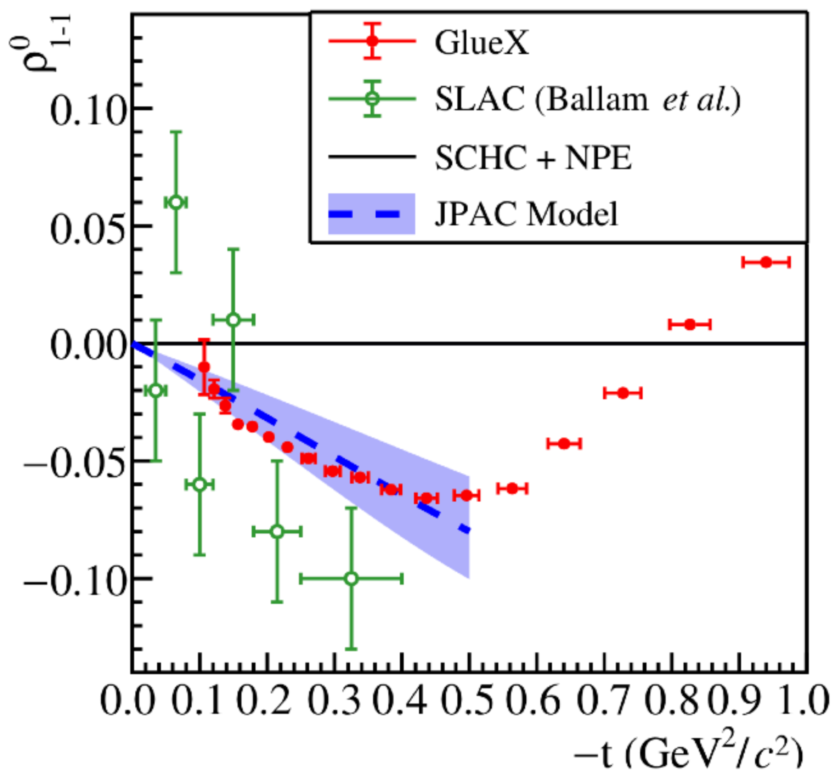
New Developments and Tools

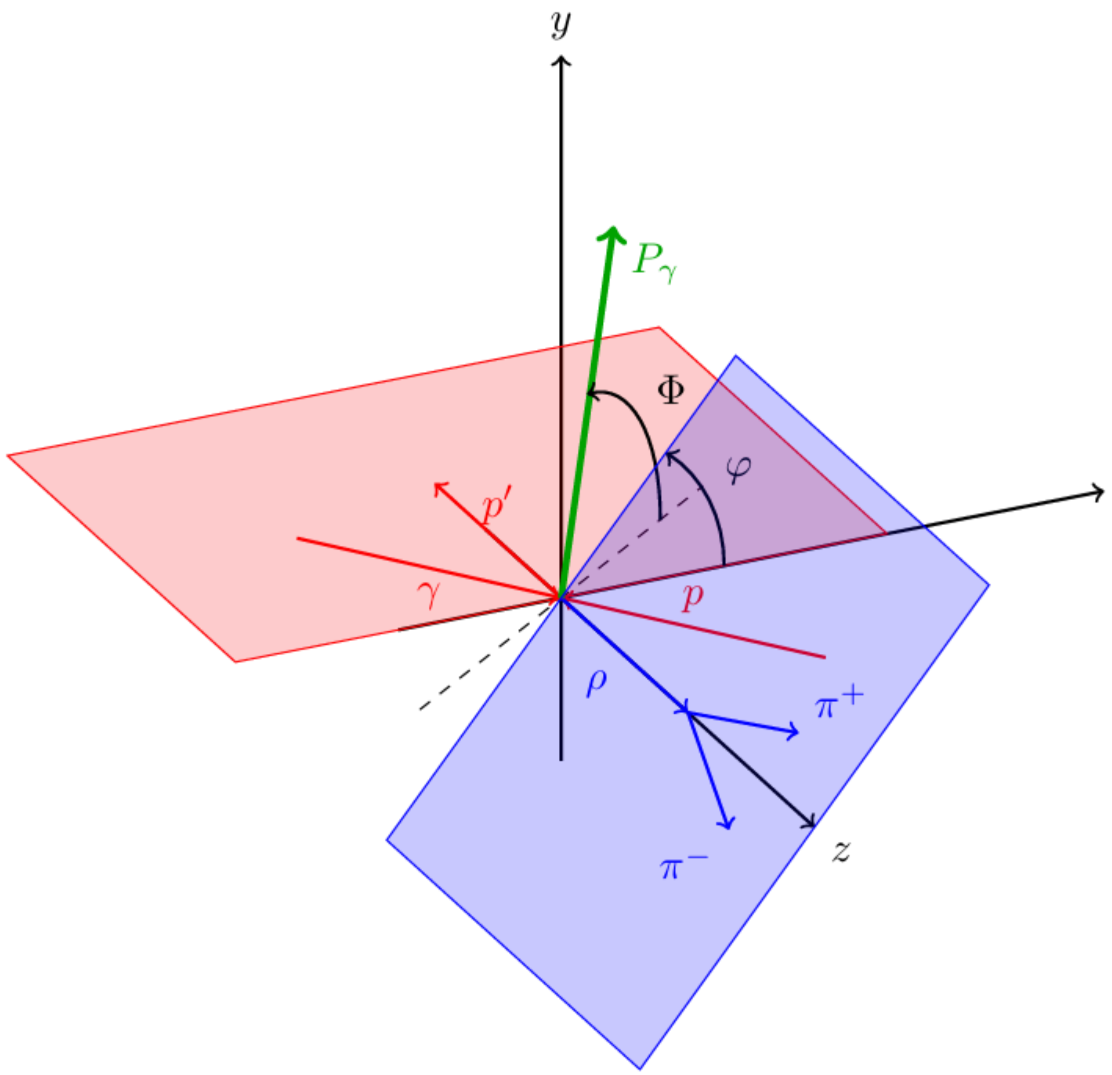
- Different implementations for mass dependent fits under development:
  - K-Matrix implementation
  - Non-parametric models using NIFTy (Information Field Theory for PWA)

- Python bindings for AmpTools
  (see https://lan13005.github.io/PyAmpTools):
  - Usage of all AmpTools features
  - Access to Python ecosystem
- Capability to switch minimizer (Markov chain MC, …)

Spin Density Matrix Elements

- Full angular distribution of vector meson production and decay is described by Spin Density Matrix Elements ρ^k_{ij}
- Linear beam polarization gives access to nine independent SDMEs





$$W(\cos\vartheta,\varphi,\Phi) = W^0(\cos\vartheta,\varphi) - P_\gamma\cos(2\Phi)W^1(\cos\vartheta,\varphi) - P_\gamma\sin(2\Phi)W^2(\cos\vartheta,\varphi)$$

$$W^0(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\vartheta\cos\varphi - \rho^0_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

$$W^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

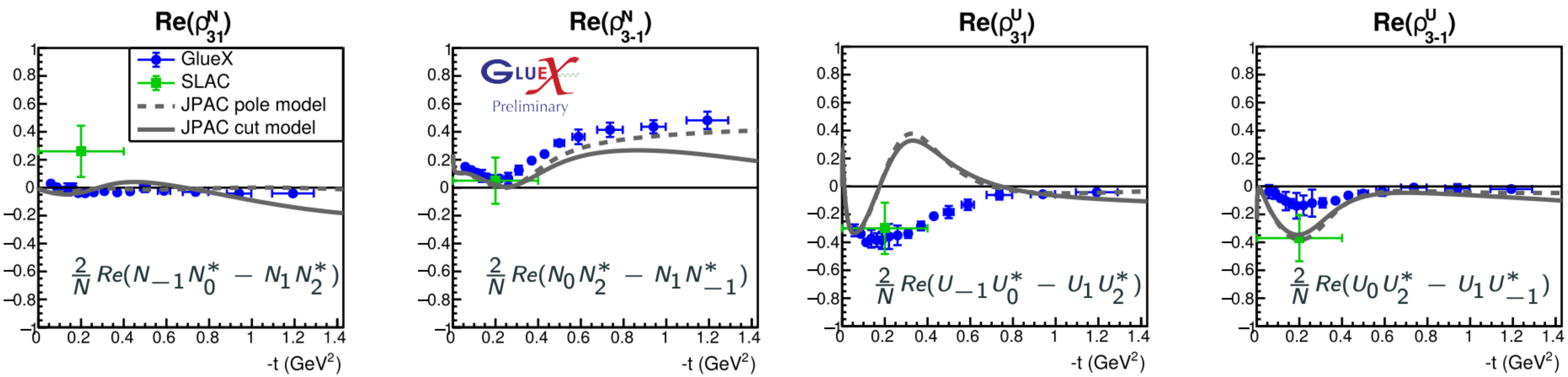
$$W^2(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\right)$$

Schilling *et al.* [Nucl. Phy. B, 15 (1970) 397]

Δ^{++} SDMEs

PLB 863 (2025) 139368

- 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:



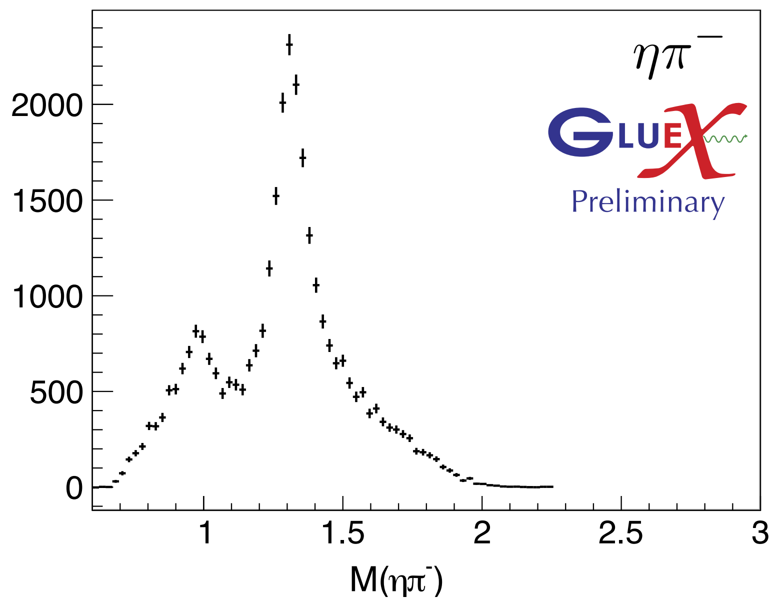
    - Include Δ^{++} decay angles in amplitude model, extract $a_2^-(1320)$ cross section in $\gamma p \to \eta \pi^- \Delta^{++}$
    - Use findings for analysis of $\gamma p \to \eta' \pi^- \Delta^{++}$, which seems to be most promising avenue for exotics search

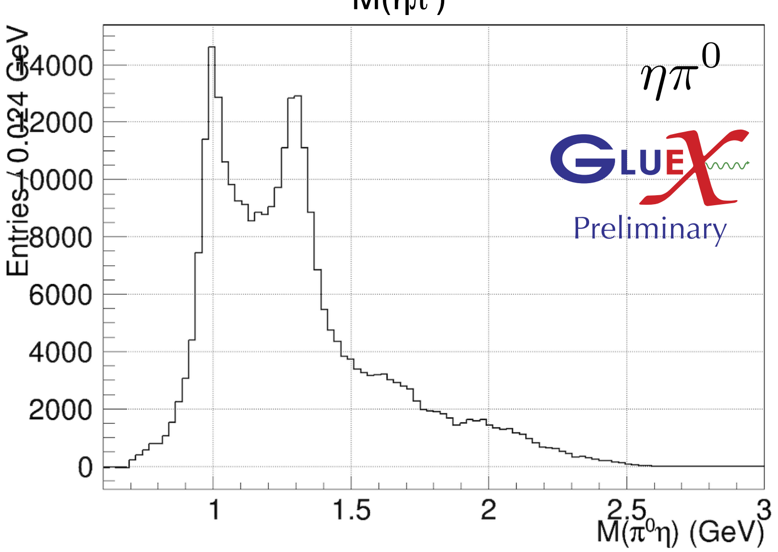
$\gamma p \to \pi\eta N$ at GlueX

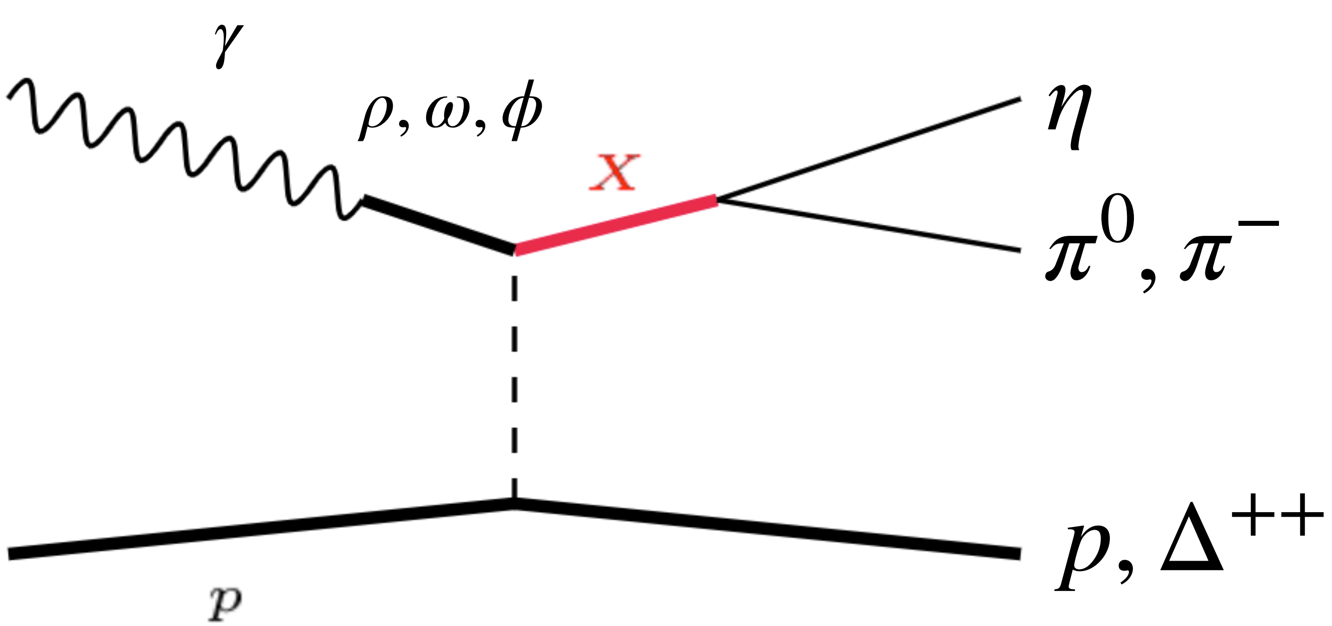
- Evidence for spin-exotic contribution from other experiments
  → Key channel for GlueX

- 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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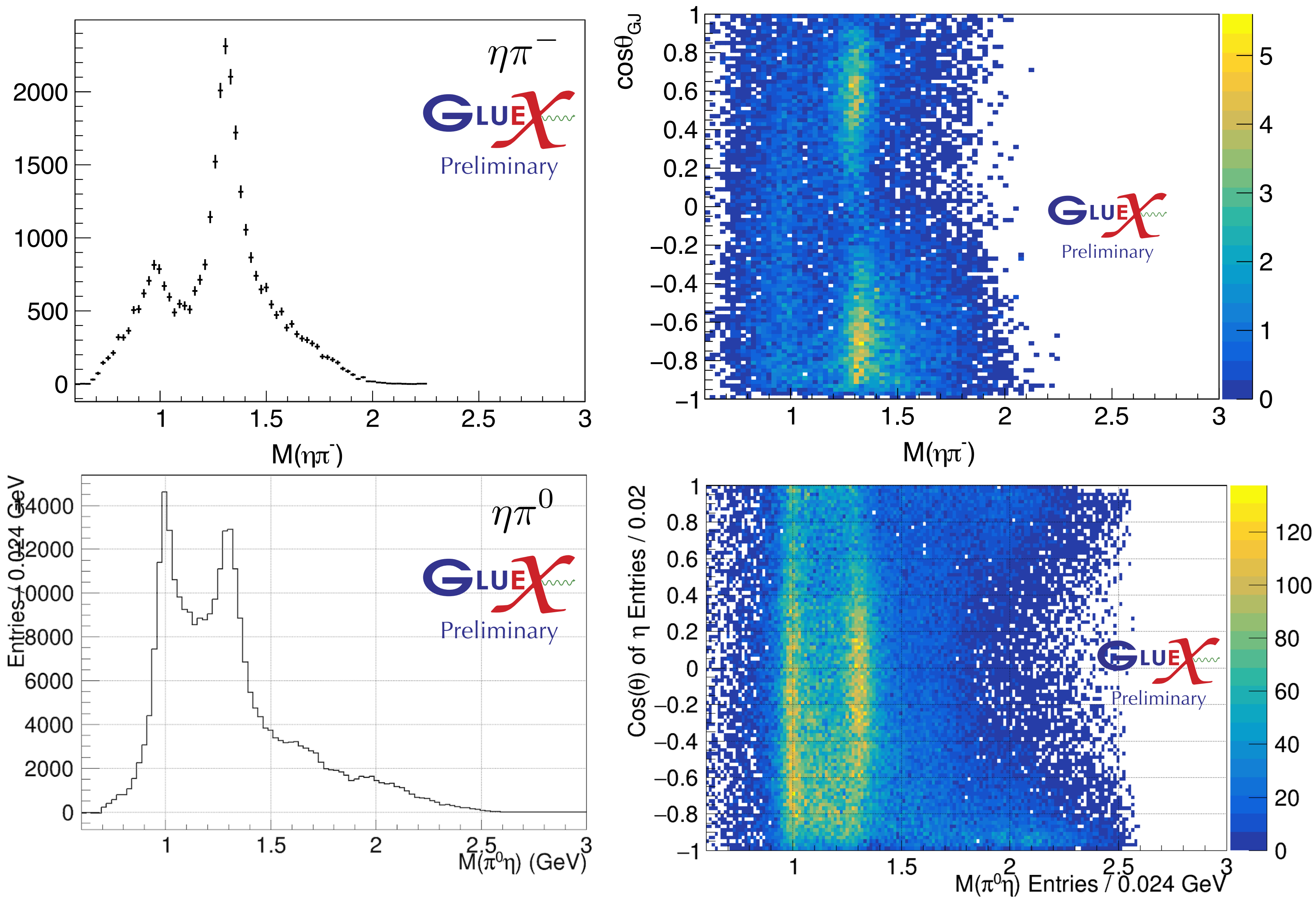


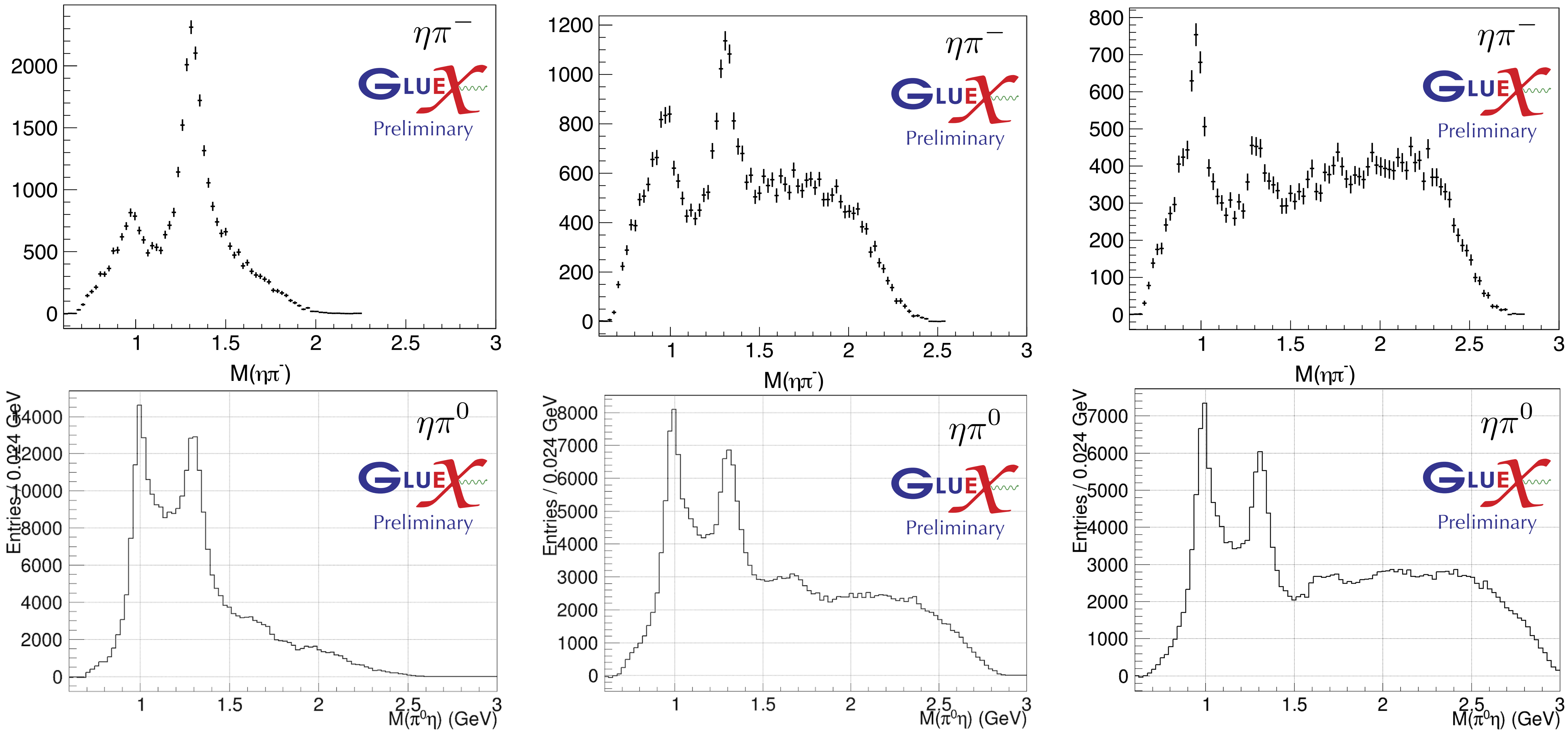
- Angular distribution of $a_2(1320)$ signal clearly different between charged and neutral channels

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

$\gamma p \to \pi\eta N$ 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)*

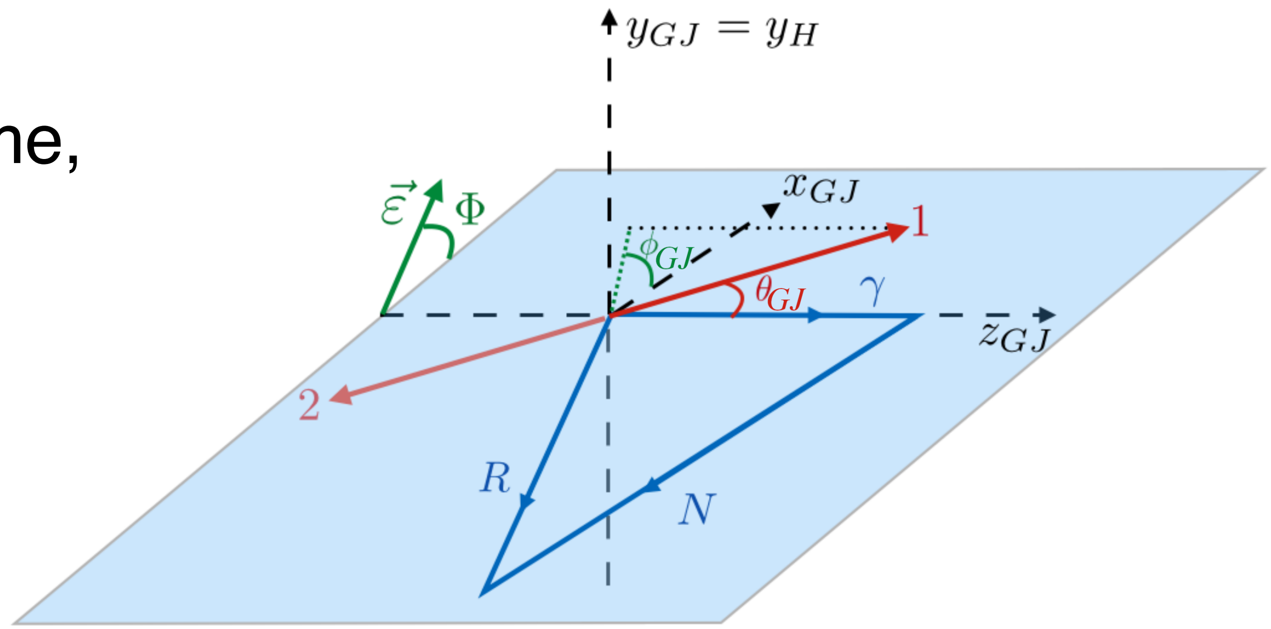
$0.1 < -t < 0.3$ GeV^2 $\quad$ $0.3 < -t < 0.6$ GeV^2 $\quad$ $0.6 < -t < 1.0$ GeV^2



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]

- 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

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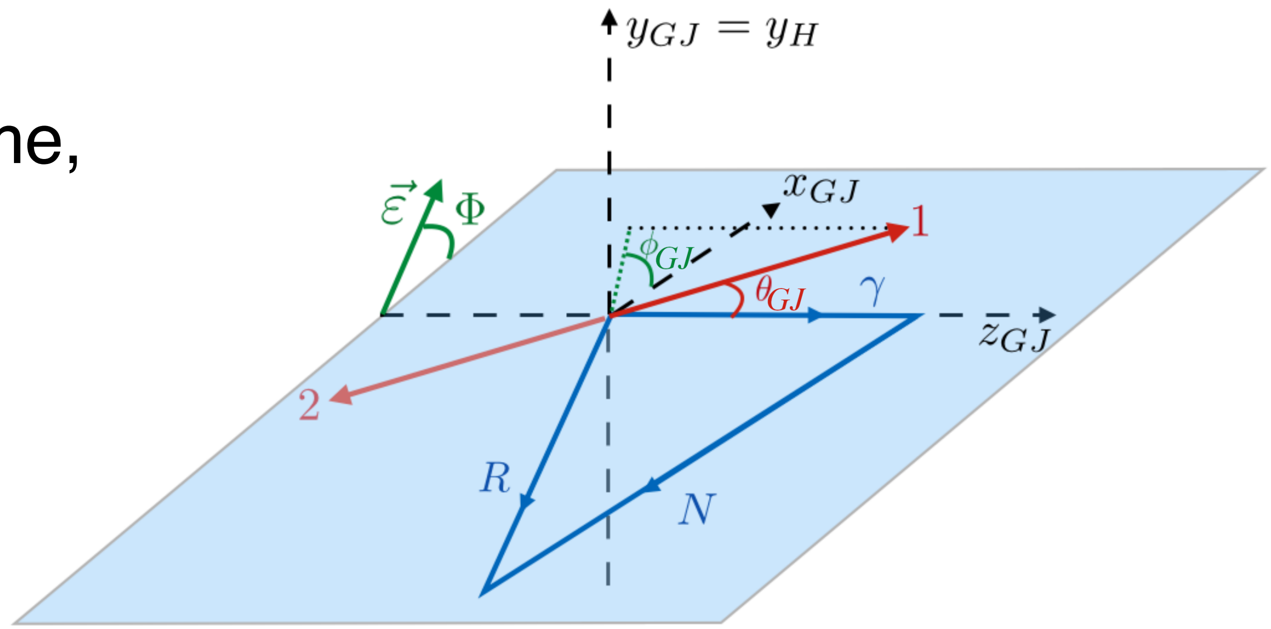


[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

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

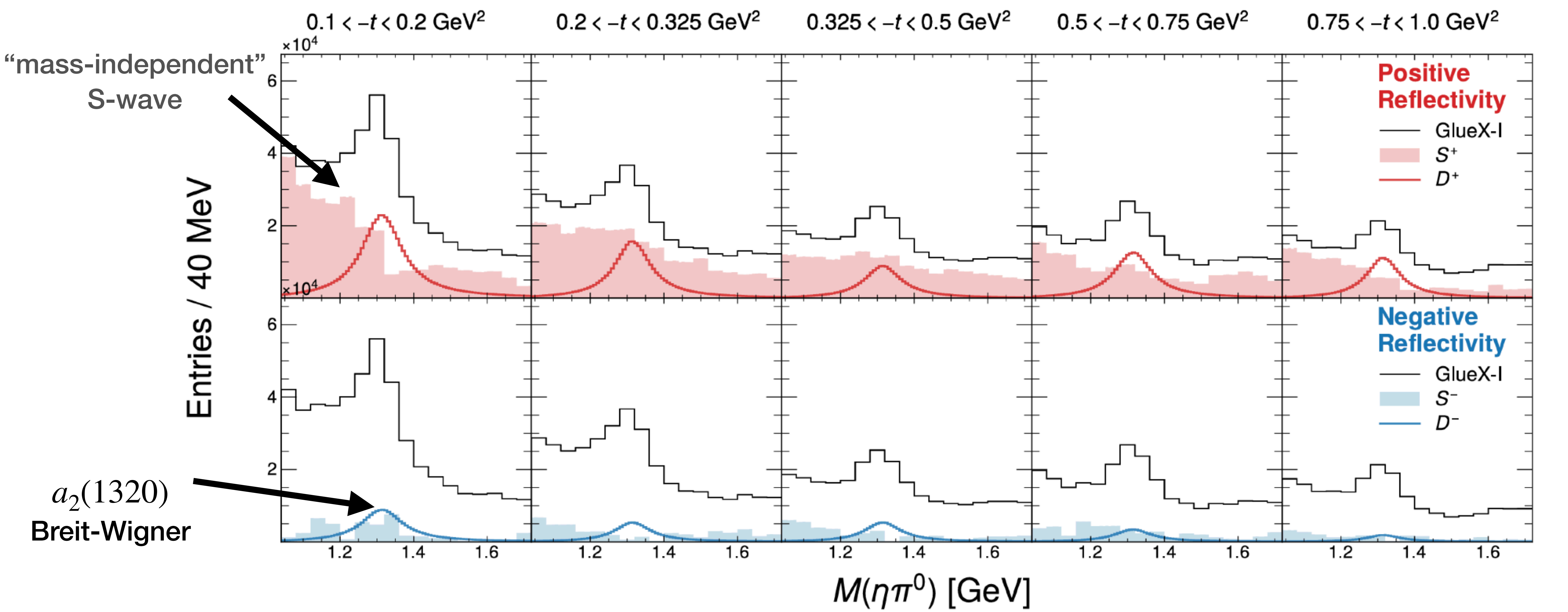
$$I(\Omega,\Phi) = 2\kappa \sum_k \Big\{ (1-P_\gamma) \Big| \sum_{\ell,m} [\ell]^{(-)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)] \Big|^2 + (1-P_\gamma) \Big| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Im}[Z^m_\ell(\Omega,\Phi)] \Big|^2 + (1+P_\gamma) \Big| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)]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

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

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

arXiv:2501.03091

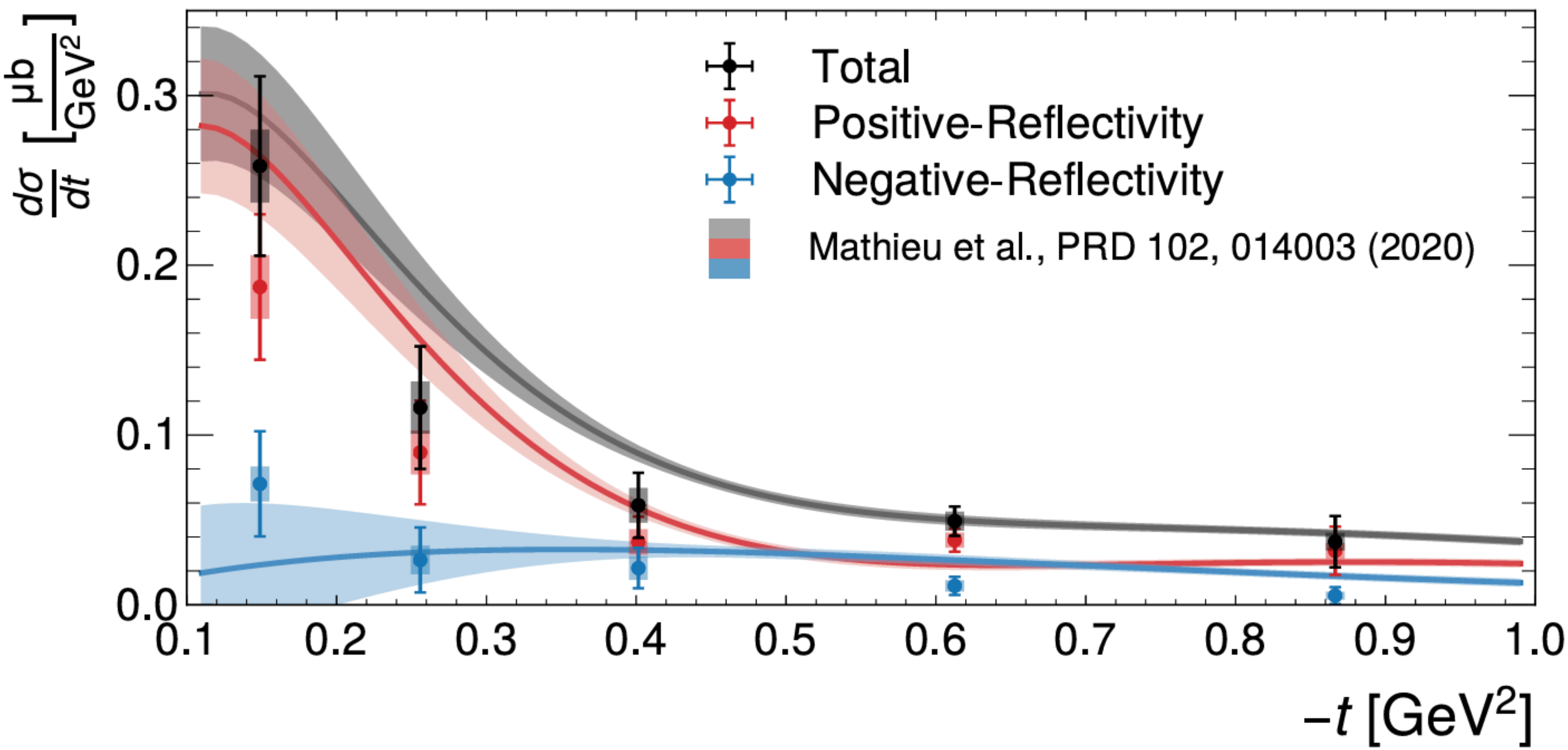
- Simplify problem by introducing physics constraint:
- $a_2(1320)$ reasonably isolated → Well described by Breit-Wigner function
- S-wave has complex structure → keep "mass-independent" parameterisation
- Eliminates leakage between waves, ensures continuity of solution
- Major contributions consistent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



Differential $a_2(1320)^0$ Cross Section

arXiv:2501.03091

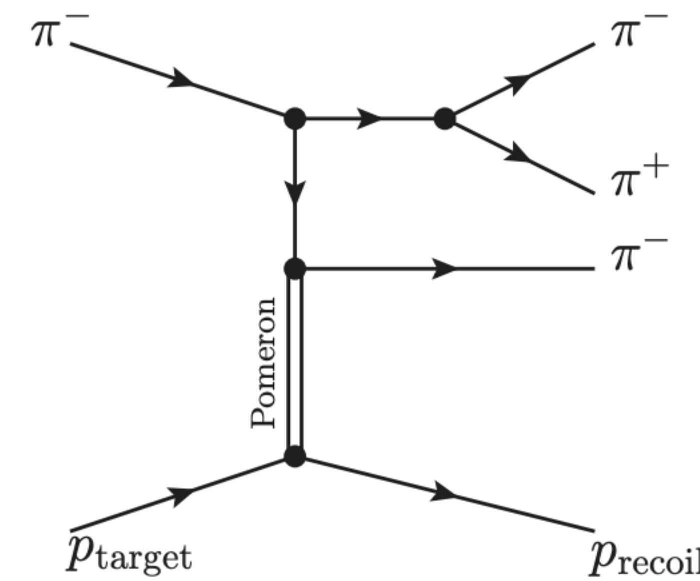
- Reasonable agreement with JPAC prediction
- We observe dominance of natural parity exchange $(\rho, \omega, \ldots)$
- Submitted to Phys. Rev.



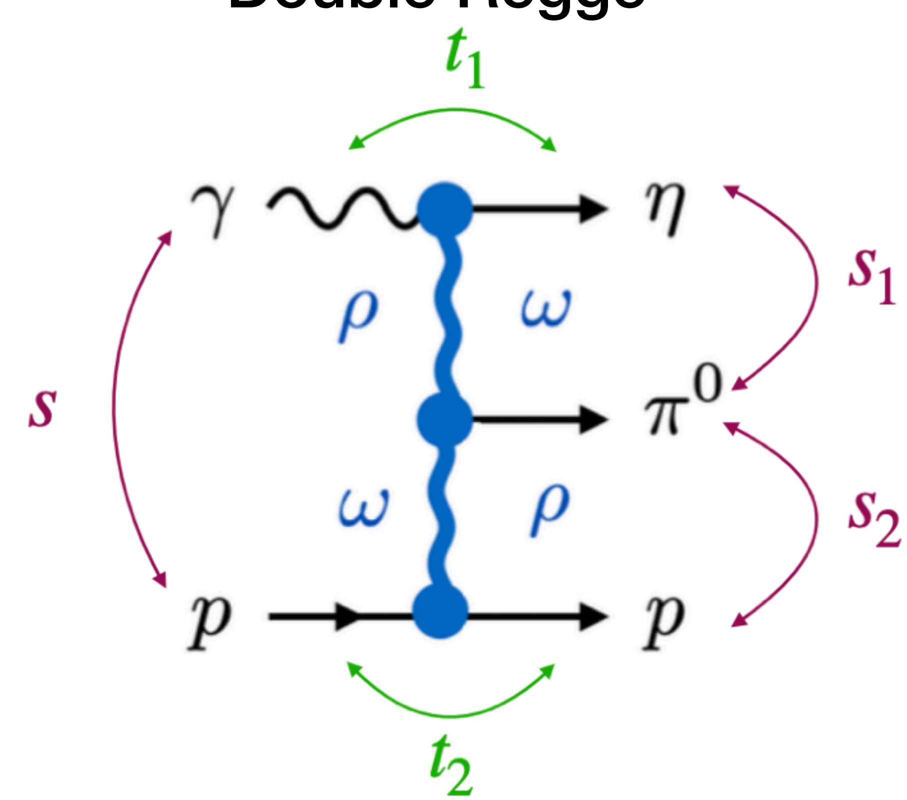
Double Regge Process

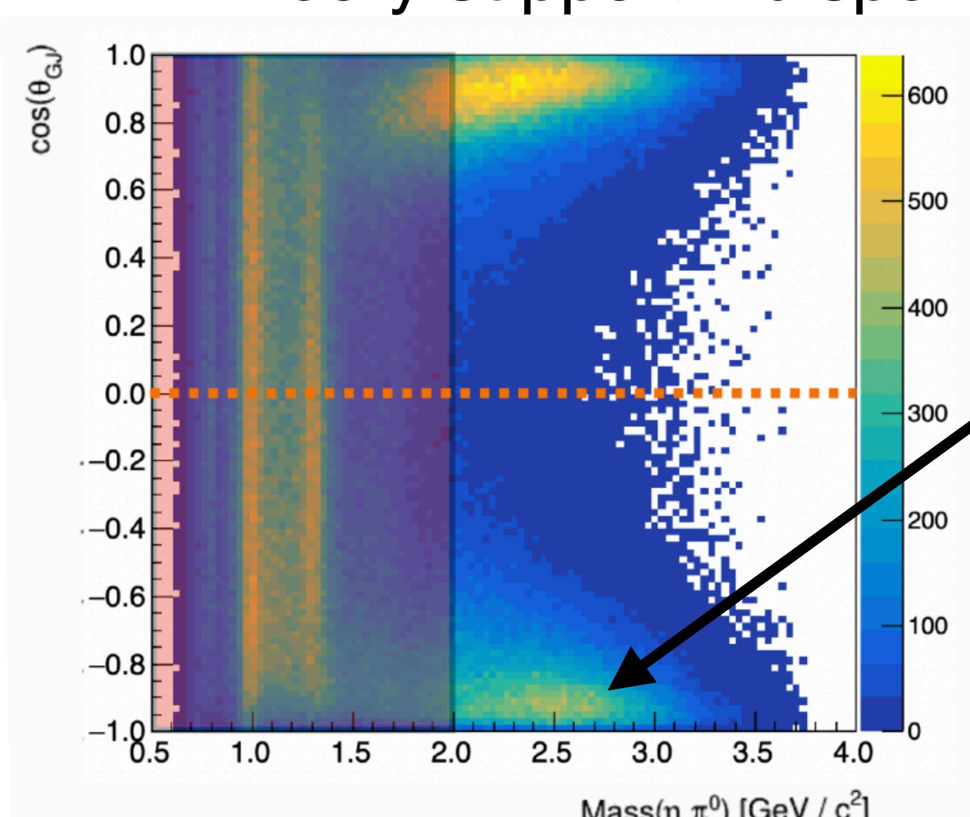
- Double-Reggeon exchange process
  (similar to Deck-contribution at COMPASS)
  - Dominant at high invariant mass
  - Extends down into resonance region, will overlap with (broad) π_1 signal, if present
  - Can enhance odd partial waves
    → mimic exotic signal
  - Important to understand and model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

Deck-Effect



Double Regge



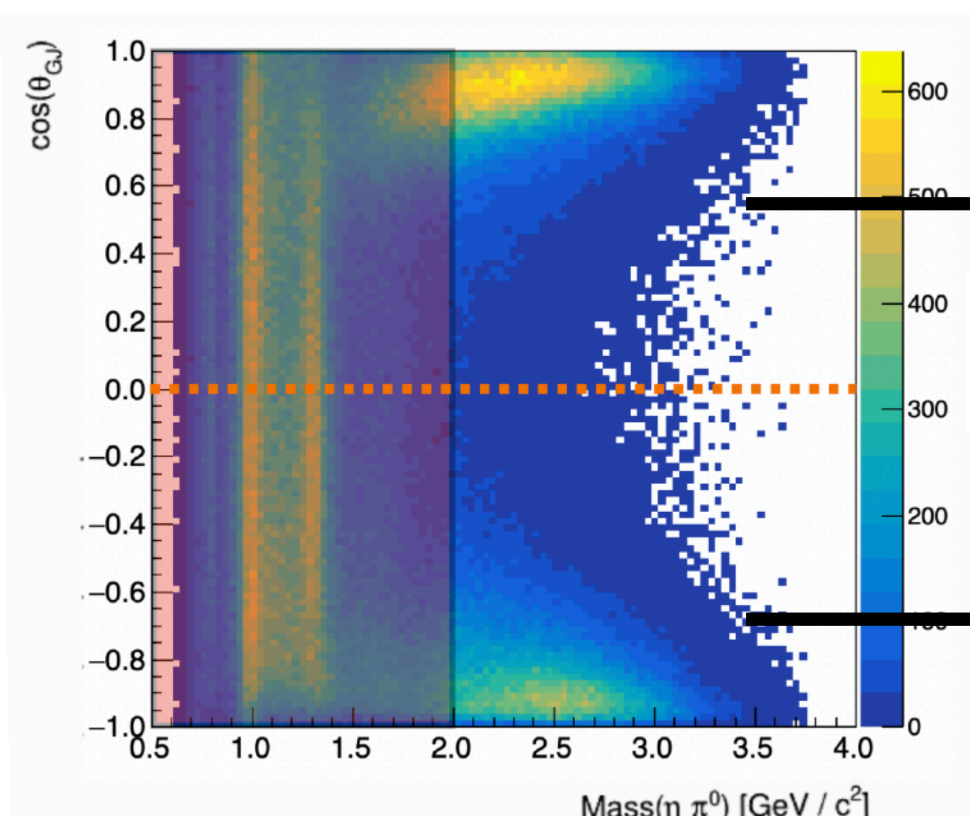


Baryon background and Double Regge exchange?

Improved Double Regge Process Modeling

- 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?



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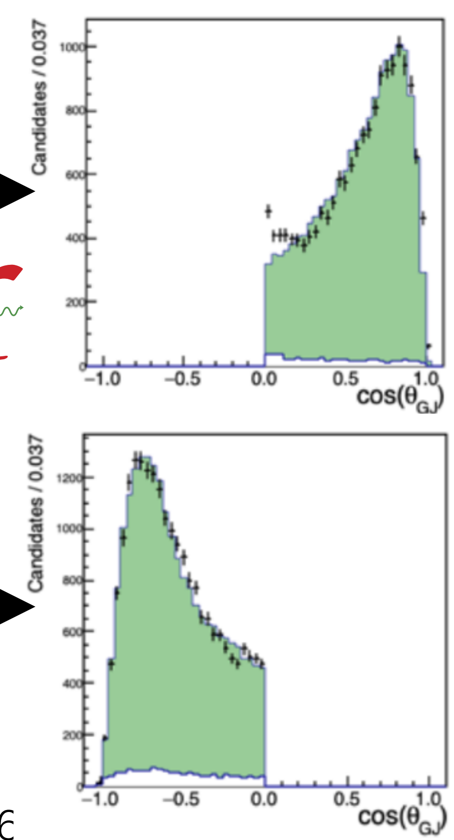
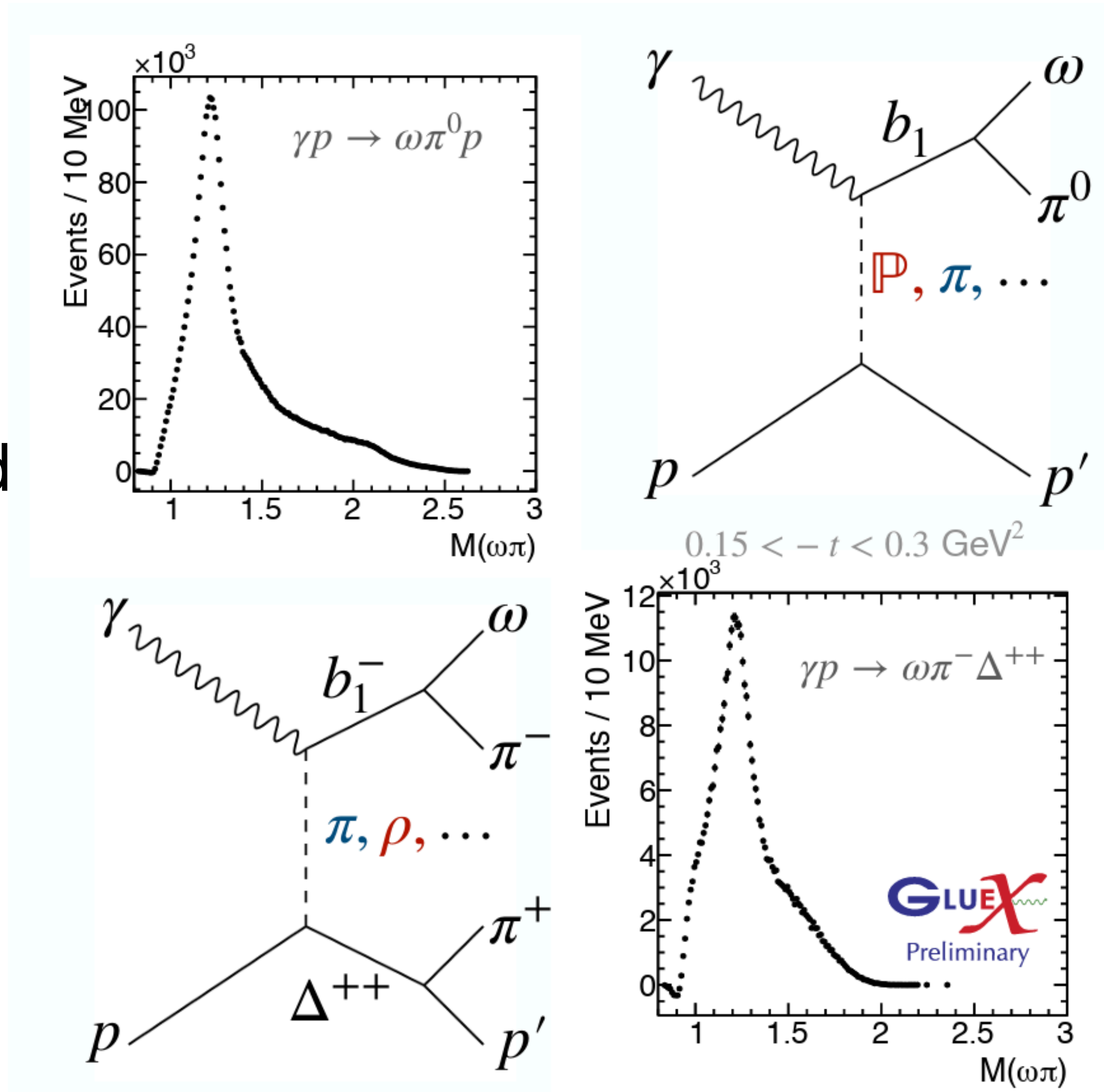
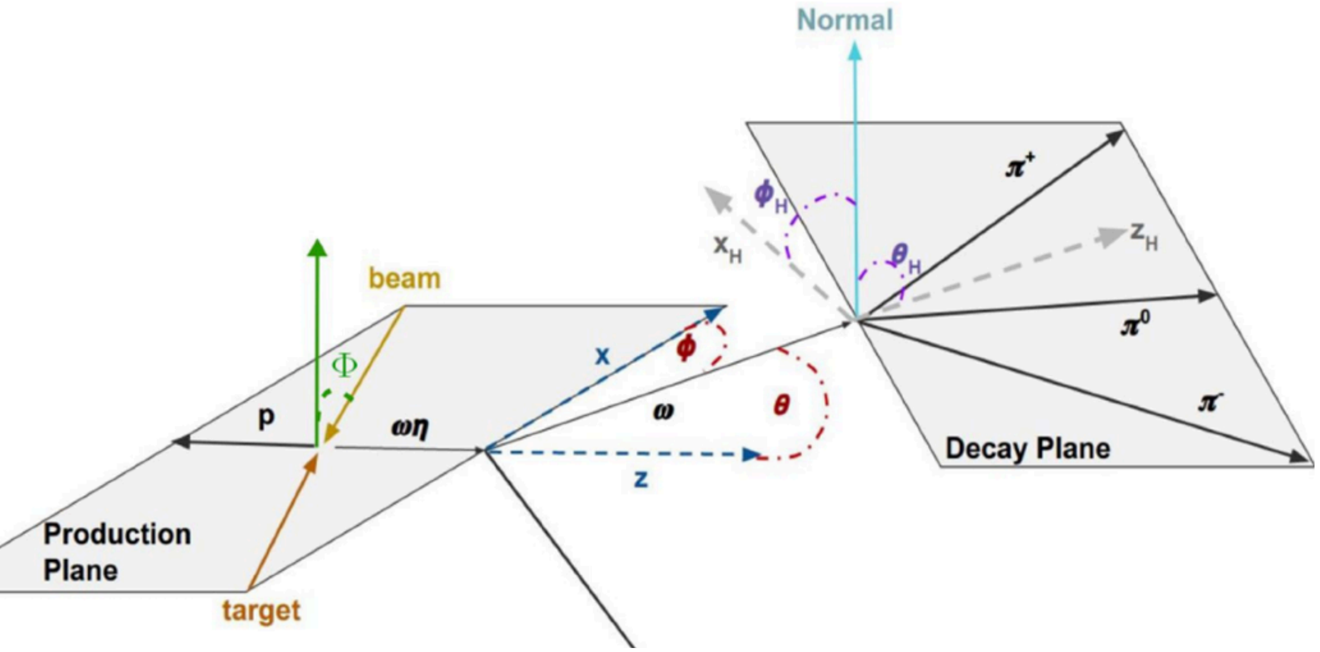


Towards Vector-Pseudoscalar Channels

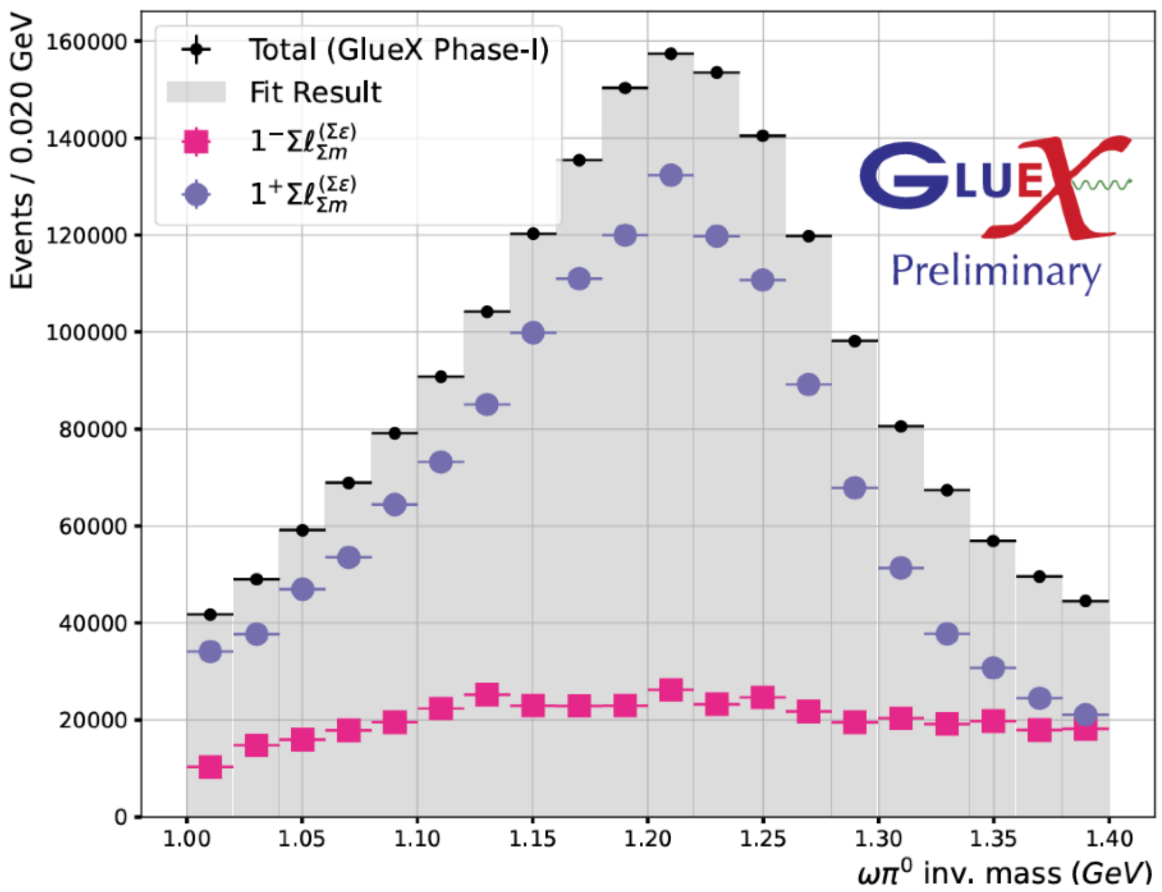
- Study vector-pseudoscalar channels in parallel
- Investigate production of b_1:
  - Clean samples for neutral and charged channels
  - High statistics
  - b_1 acts as reference for other resonances decaying to $\omega\pi$



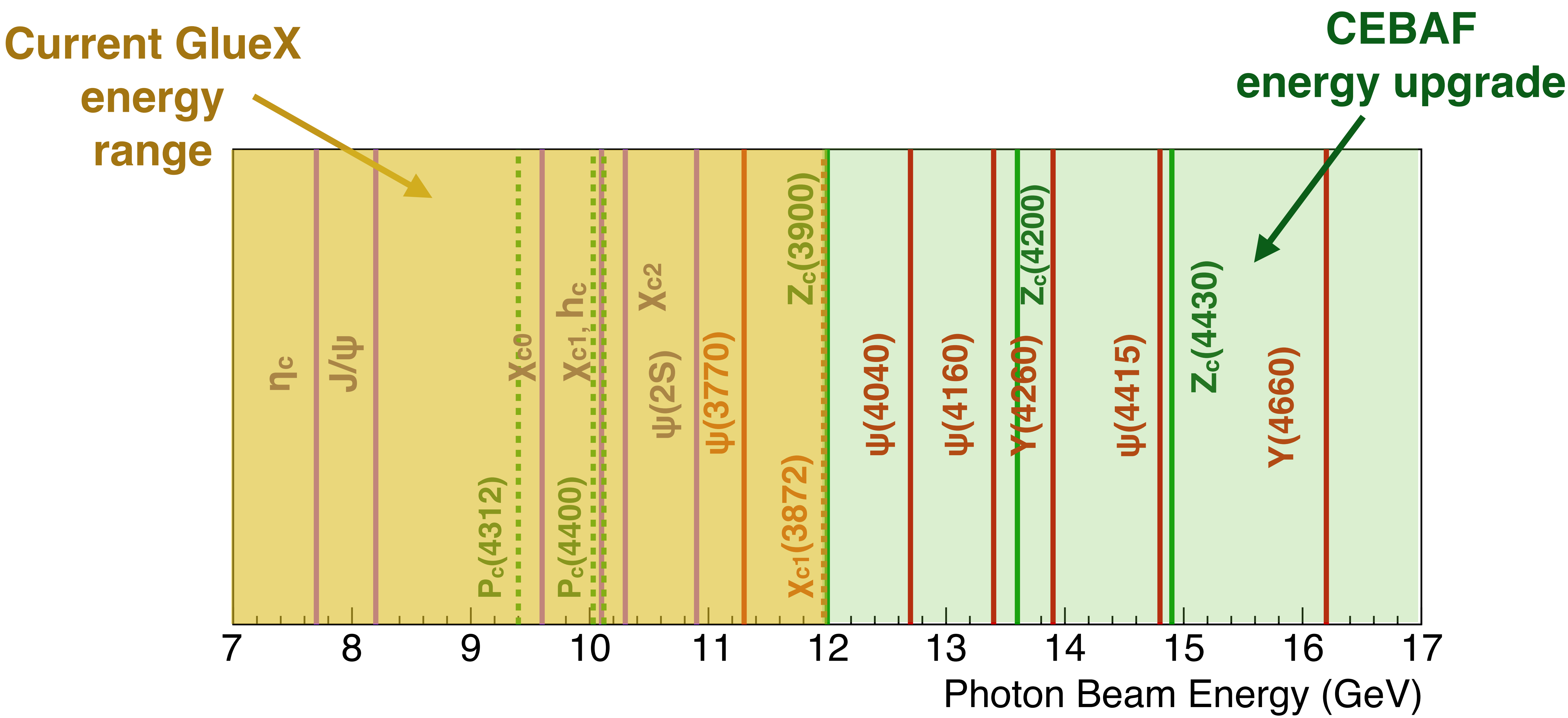
PWA of $\gamma p \to \omega\pi^0 p$



- Ω: Decay of the resonance
- Ω_H: Decay of the vector meson
- Φ: Orientation of polarization plane
- Clear separation of $b_1(1235)$ (1^+) and $\rho(1450)(1^-)$
- Production dominated by natural parity exchange



Charmonium and beyond at GlueX

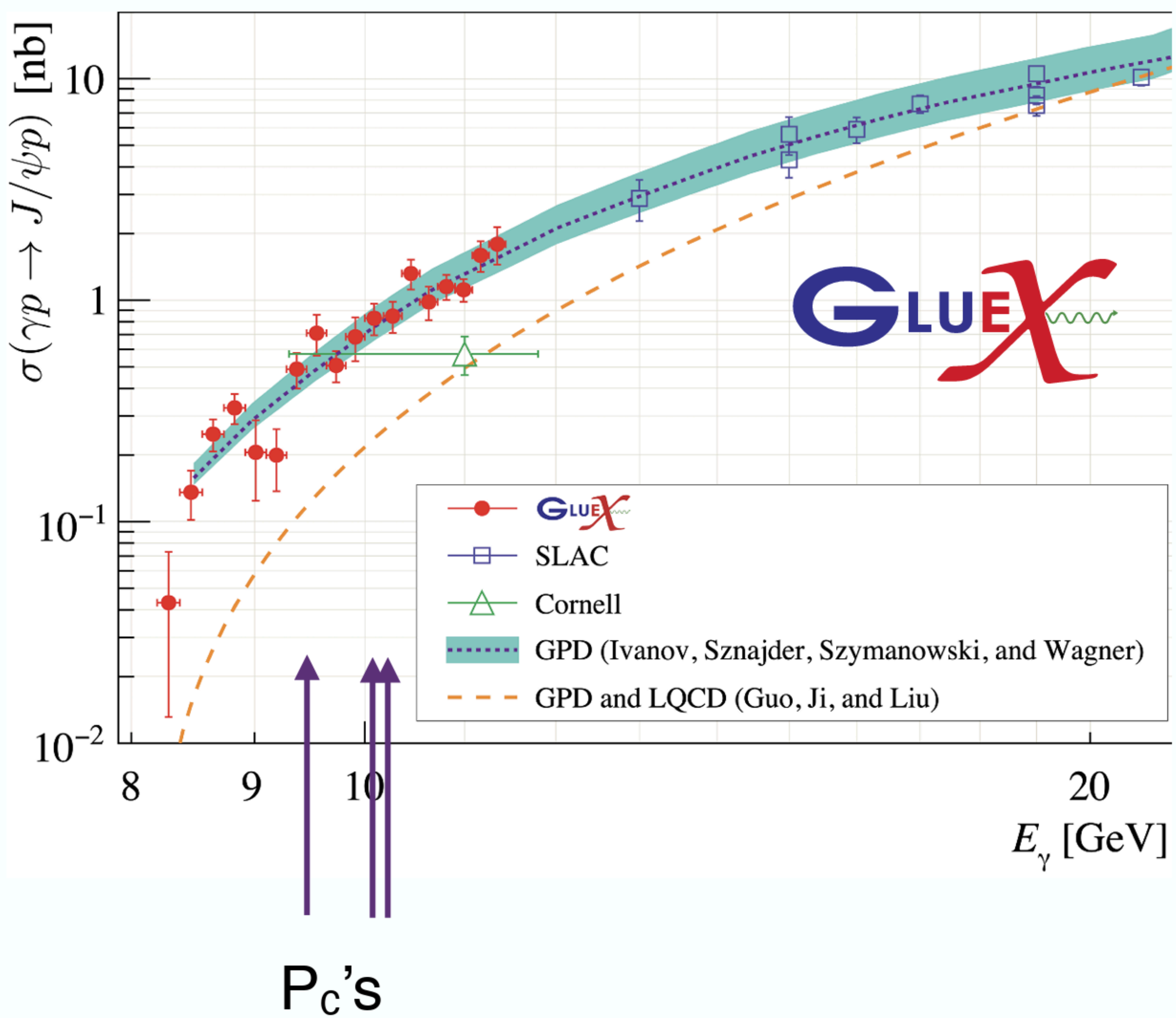


- Current max CEBAF energy allows study of bound $c\bar{c}$, P_c states
- 22 GeV e- gives access to most exotic states, good phasespace, linear polarization

GlueX-I Results on J/ψ Photoproduction

- Full GlueX-I data yields 2270 ± 58 J/ψ's
- Overall normalization uncertainty ~20%
- "Dip" above 9 GeV has 2.6σ (1.3σ) local (global) significance
- No evidence of narrow P_c production, tension with molecular interpretation?
- Differential cross sections generally consistent with expectations of gluonic exchange, except near threshold

GlueX, PRC 108, 025201 (2023)



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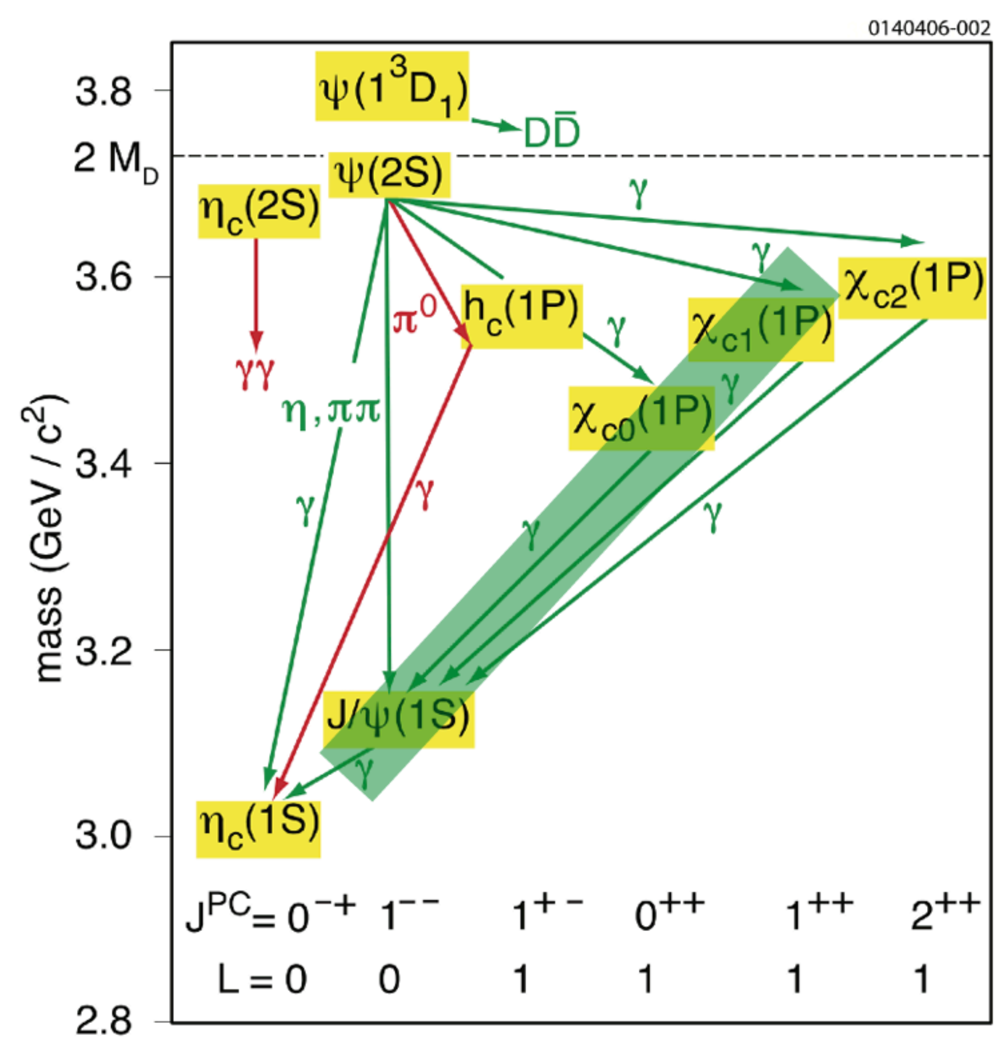
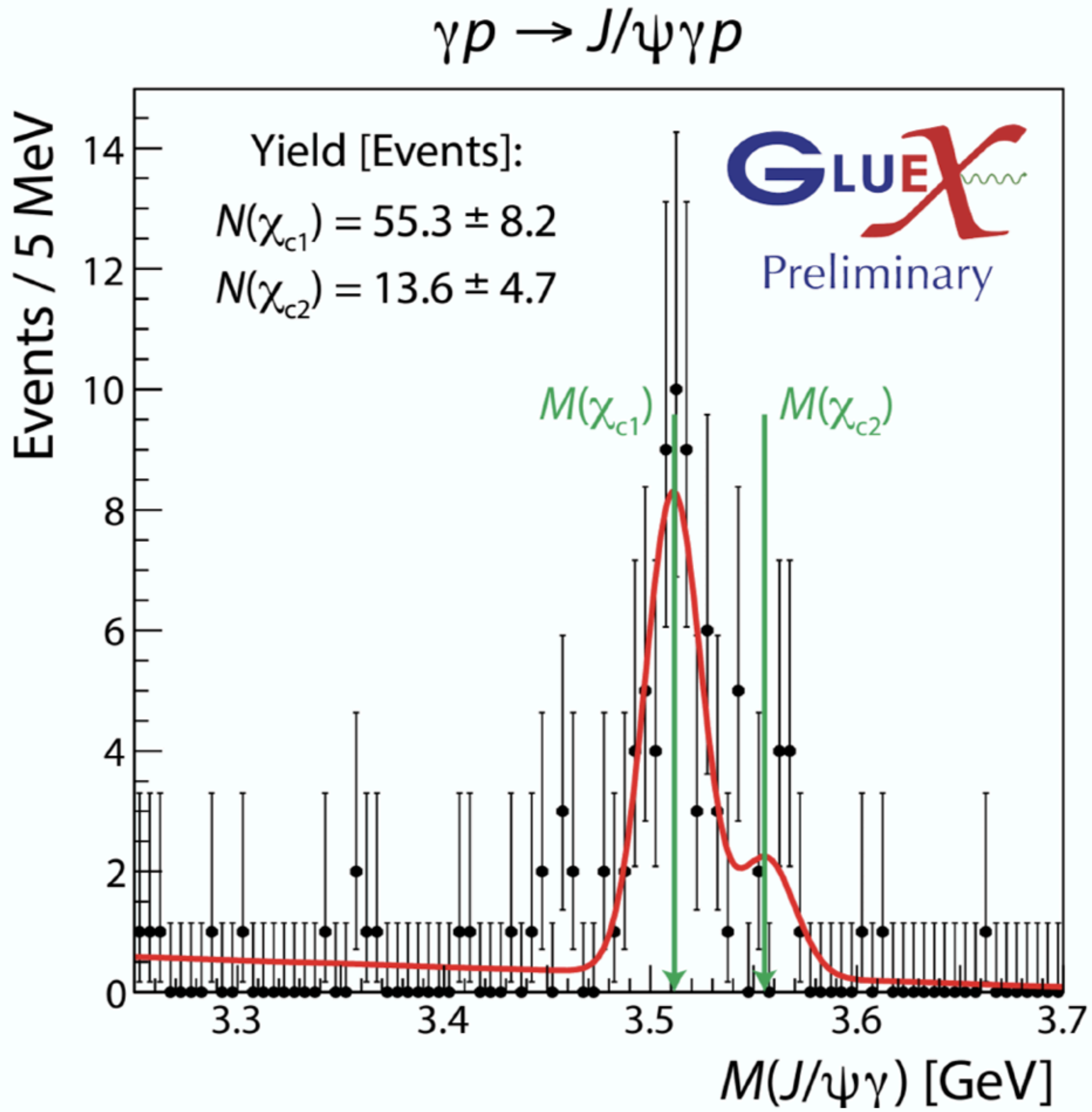
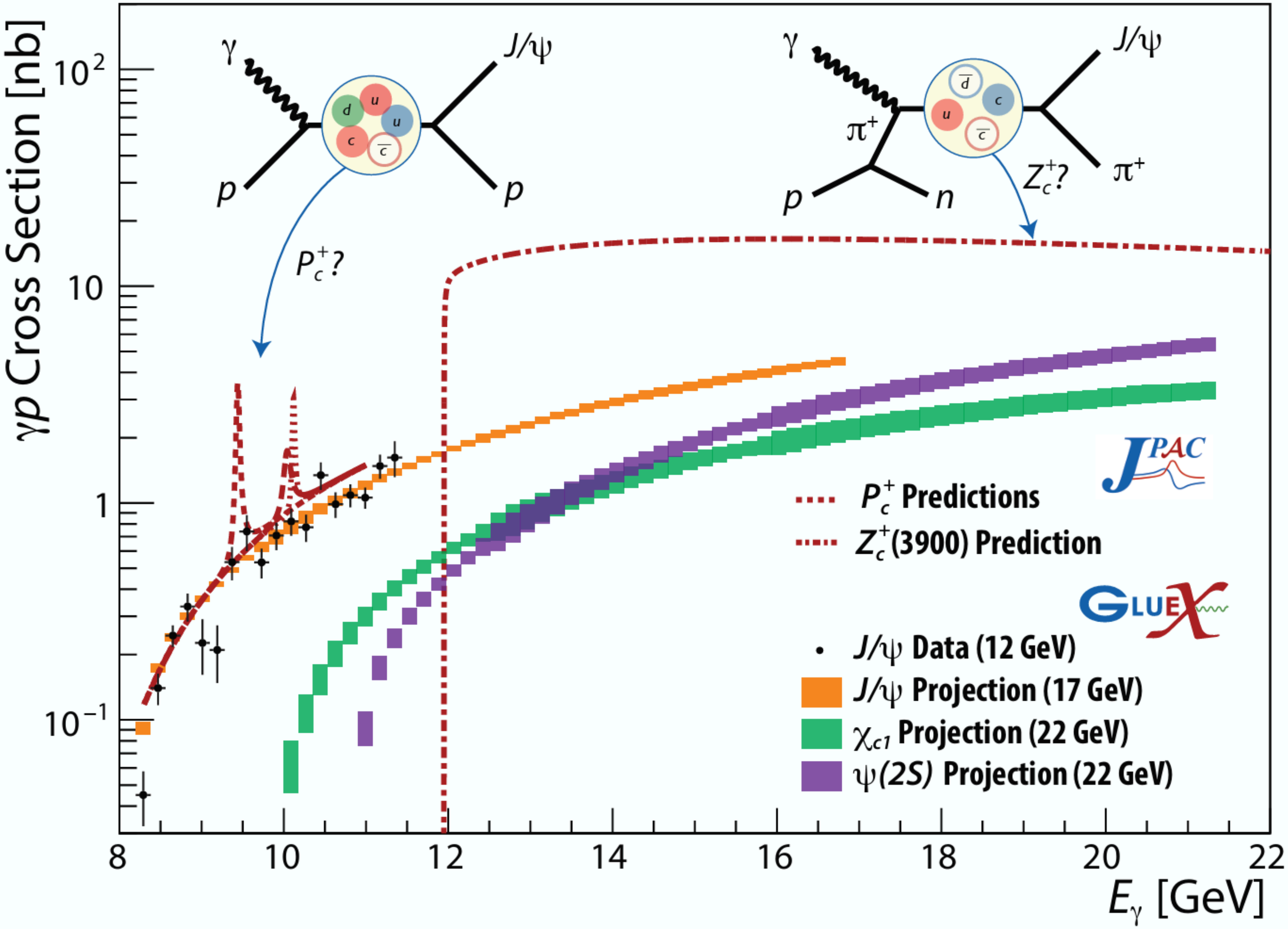




- $\chi_{c1}(1^{++})$ photoproduction: probe of different parity C=+
- Test of “Odderon-like” couplings and fixed-spin exchange models
- Look for $\gamma p \to \chi_{cJ} p \to (\gamma J/\psi) p \to (\gamma e^+ e^-) p$

JPAC, PRD 108, 054018 (2023)

Projections for Future JLab Upgrade

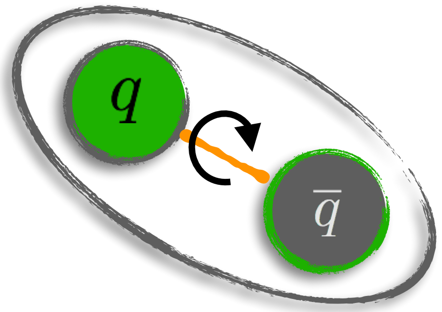


Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab, EPJA 60, 9 (2024)

- Projections for GlueX measurements with upgraded CEBAF allow for precision study of charmonium and charmonium-like states with linearly polarized photons

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
  - 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**

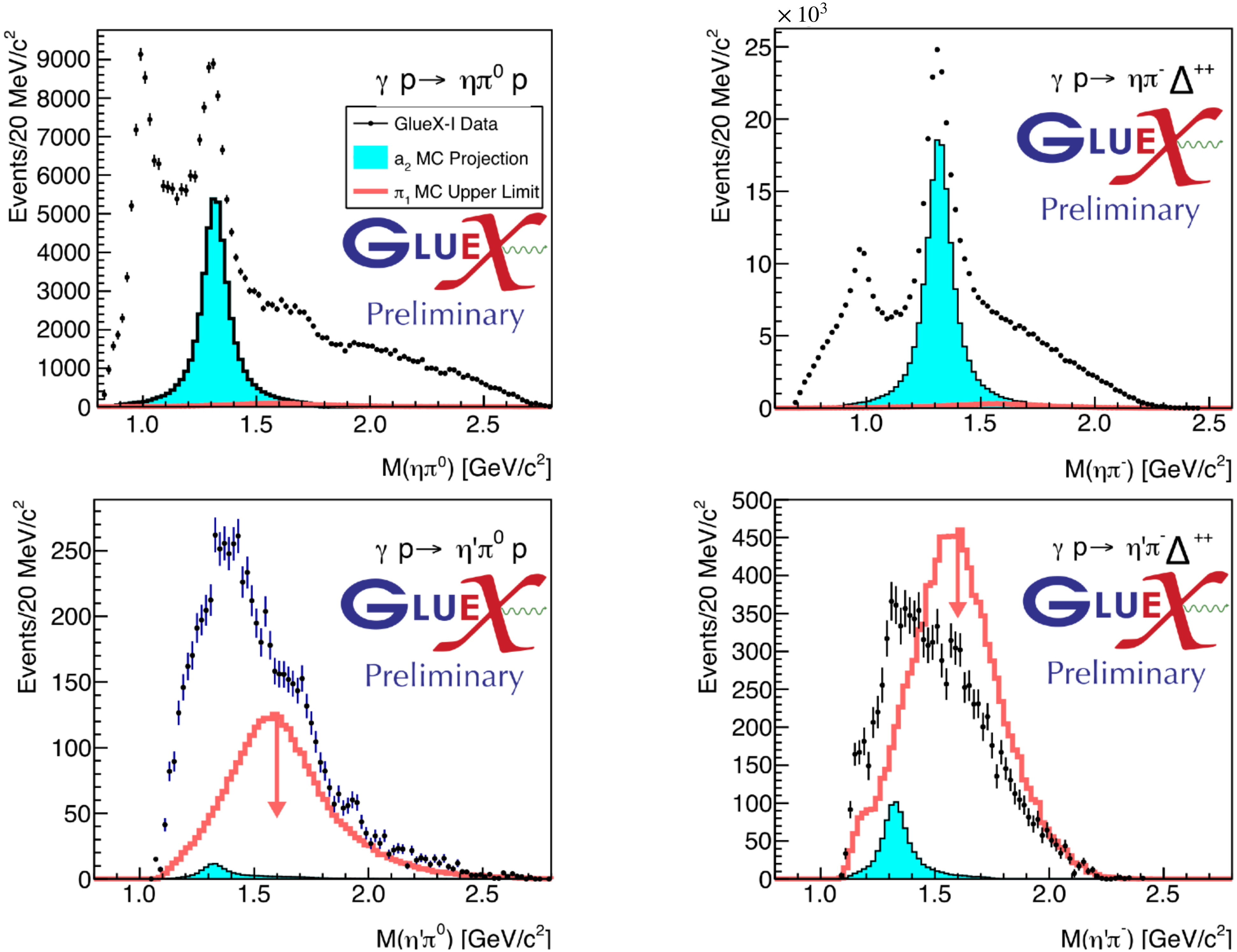


En route to first results on exotic mesons with GlueX!

gluex.org/thanks

Backup

Analysis of $\eta'\pi$ Channels



- 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

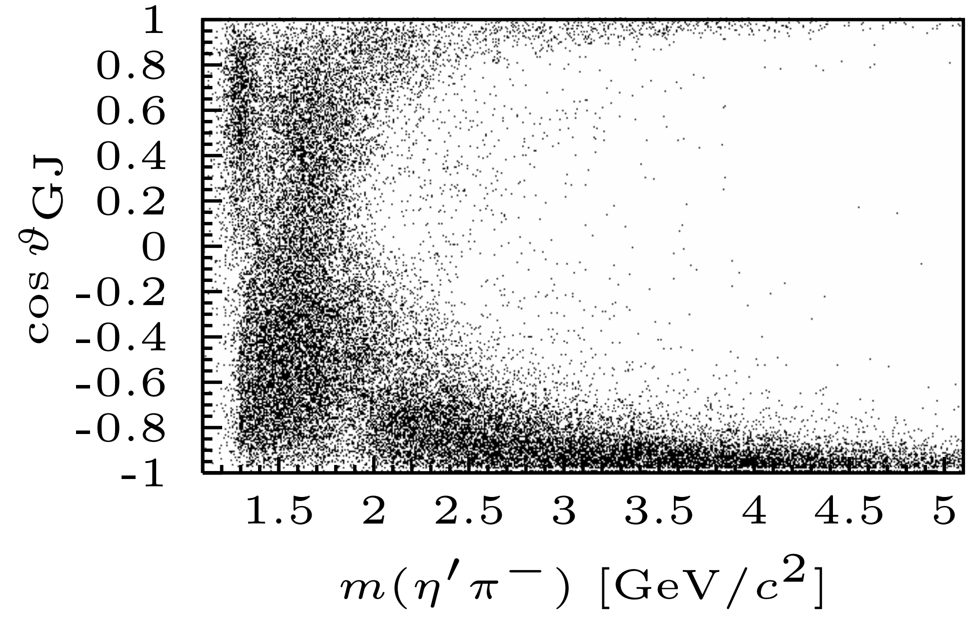
Closeup of $\eta'\pi^-$ Spectra

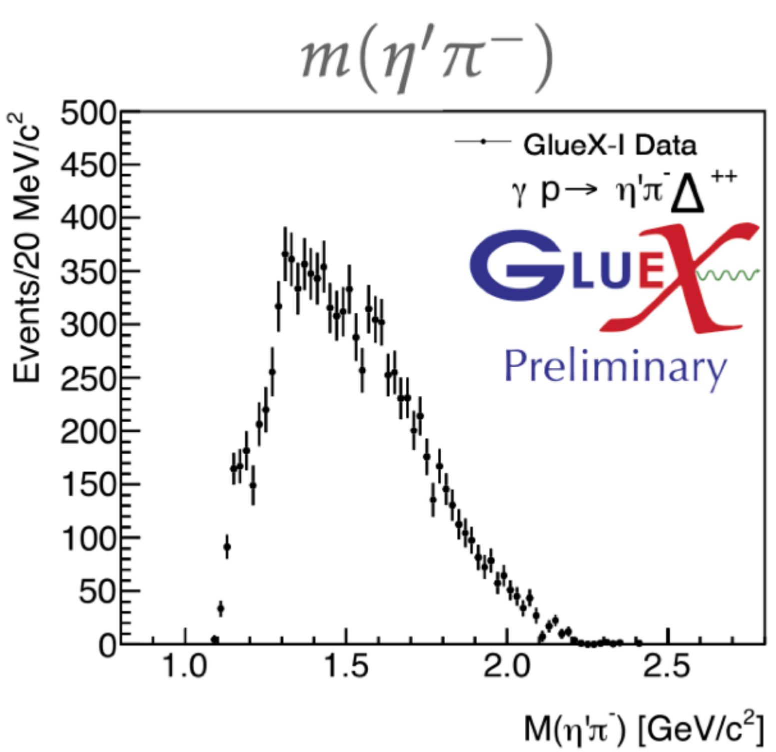
- Projections look intriguing
- Interesting interference pattern visible

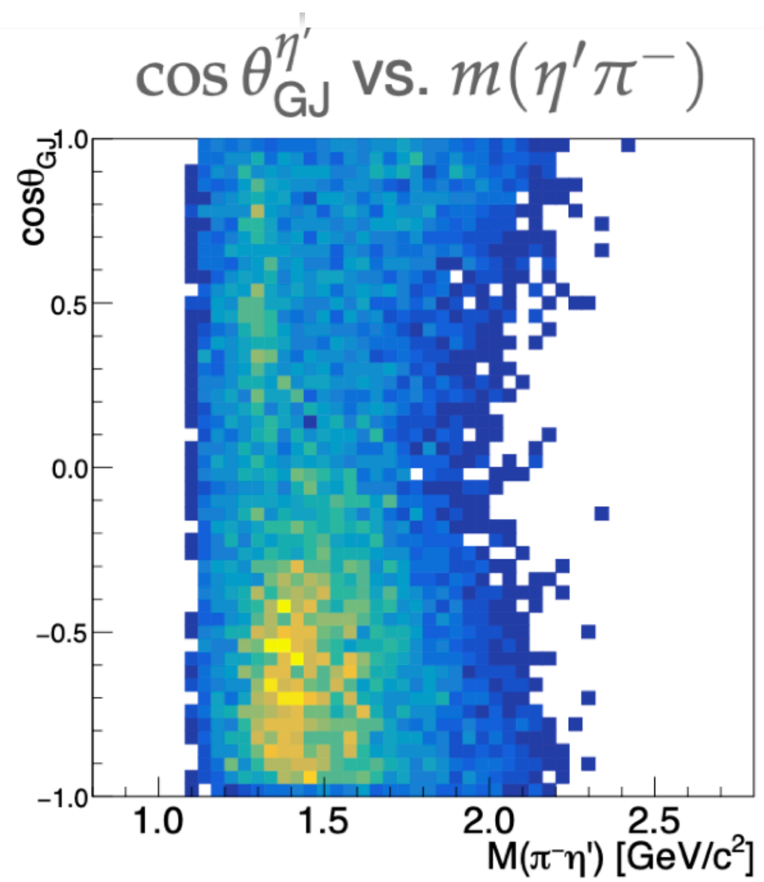
→ Constructive / destructive interference of odd and even wave contributions in different $\cos\theta_{GJ}$ regions?

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

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







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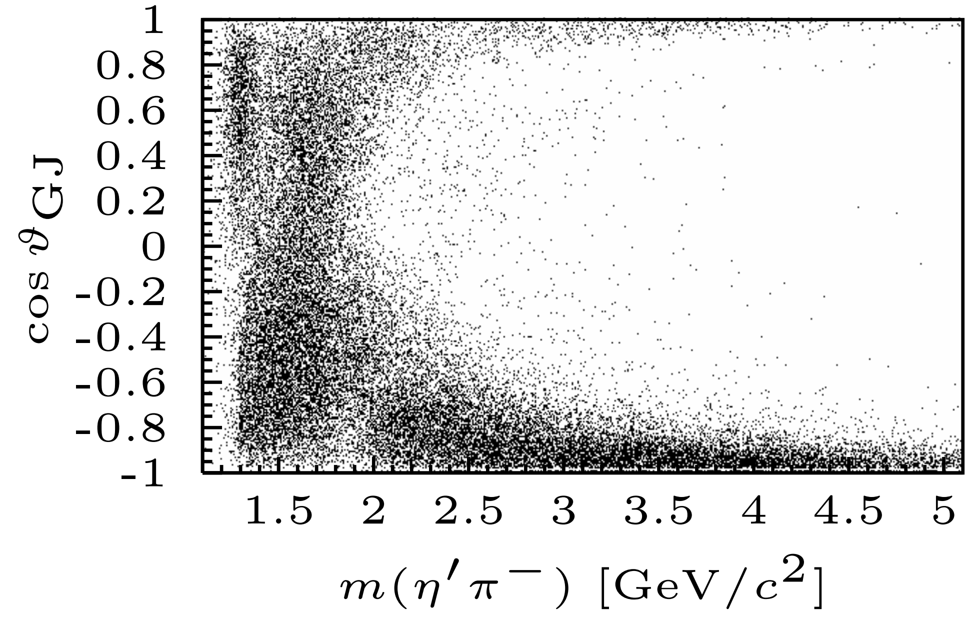
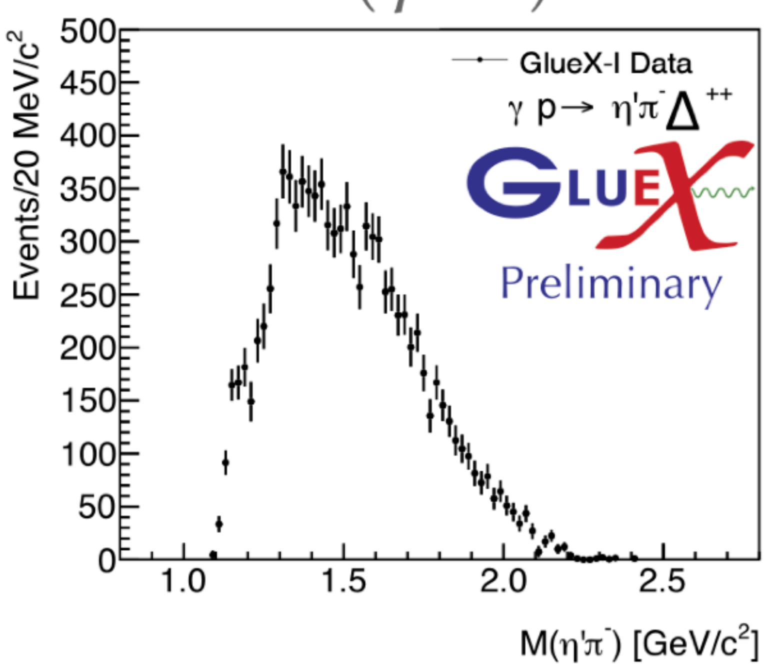
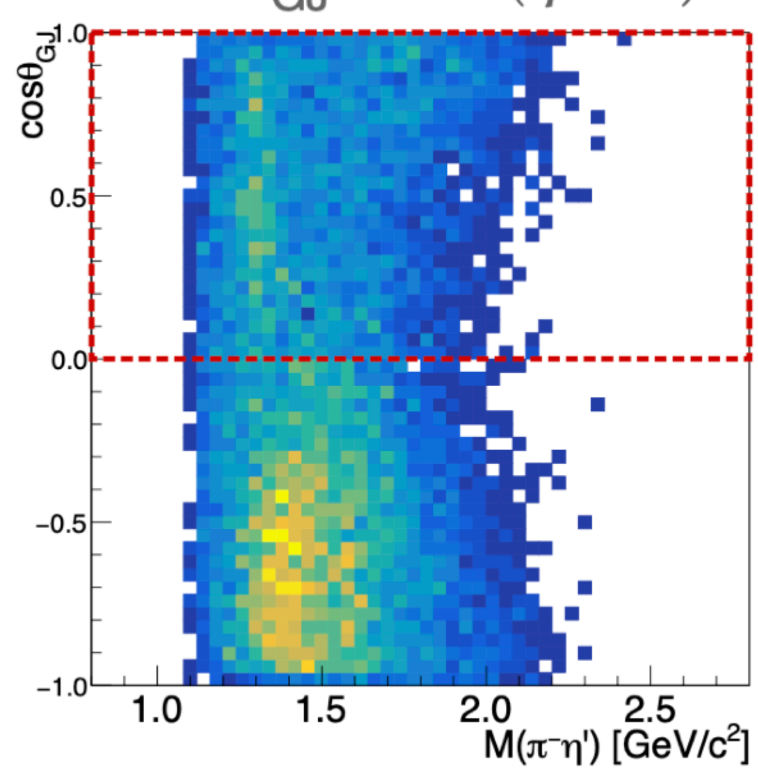


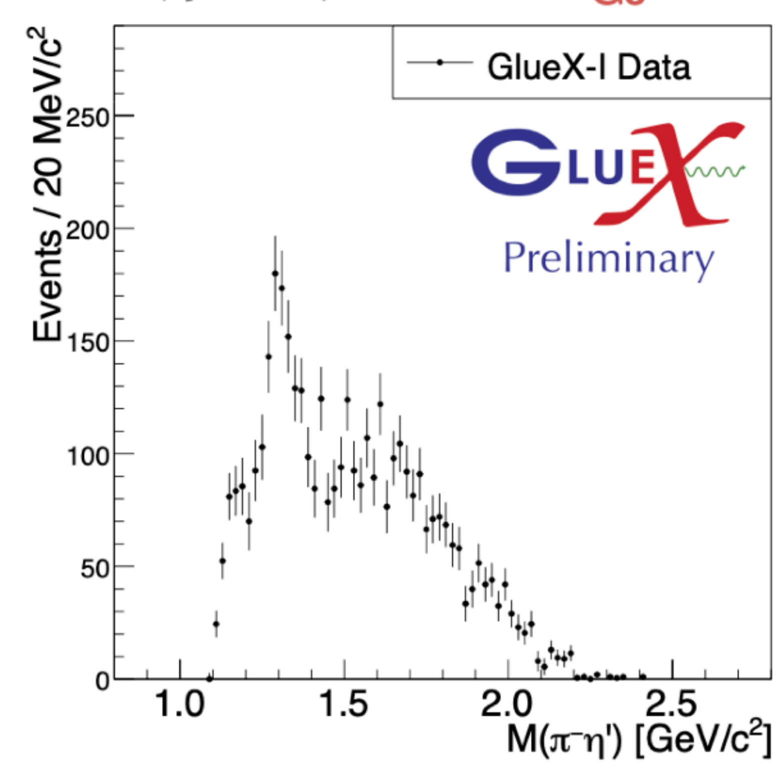
$m(\eta'\pi^-)$



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



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



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

- 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

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