Partial Wave Analysis of Vector-Pseudoscalar Final States at GlueX

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for the GlueX Collaboration

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HADRON Conference 2023 – Genova, Italy

June 9th, 2023

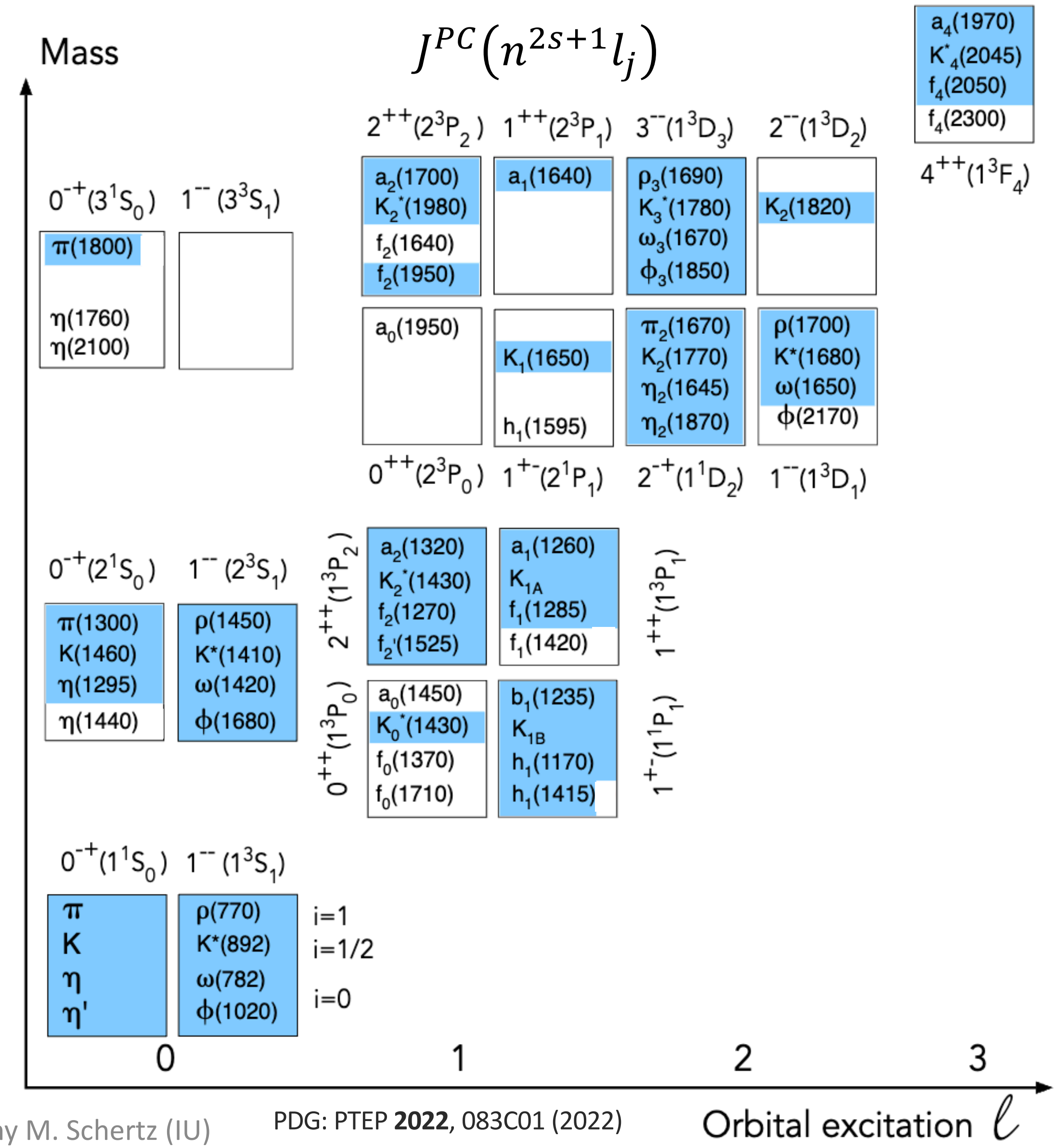
Quantum Numbers Accessible to Vec-PS

- The 0^{--} and 2^{+-} are exotic, not allowed by the quark model
- The 2^{--} is allowed, but has never been observed
- Understanding the 1^{+-} and 1^{--}, which have been observed, will assist us in our search for new and/or exotic states

l	J^{PC}
0	1^{+-}
1	$\boxed{0^{--}}, 1^{--}, \boxed{2^{--}}$
2	$1^{+-}, \boxed{2^{+-}}, 3^{+-}$
3	$2^{--}, 3^{--}, 4^{--}$

Meson Spectra

- Axial vector spectrum is largely unmapped
- One nonet each in 1^{++} and 1^{+-} established by PDG
- In contrast, three vector 1^{--} nonets are established
- Vector-pseudoscalar final states are an ideal place to search for both



PDG: PTEP **2022**, 083C01 (2022)

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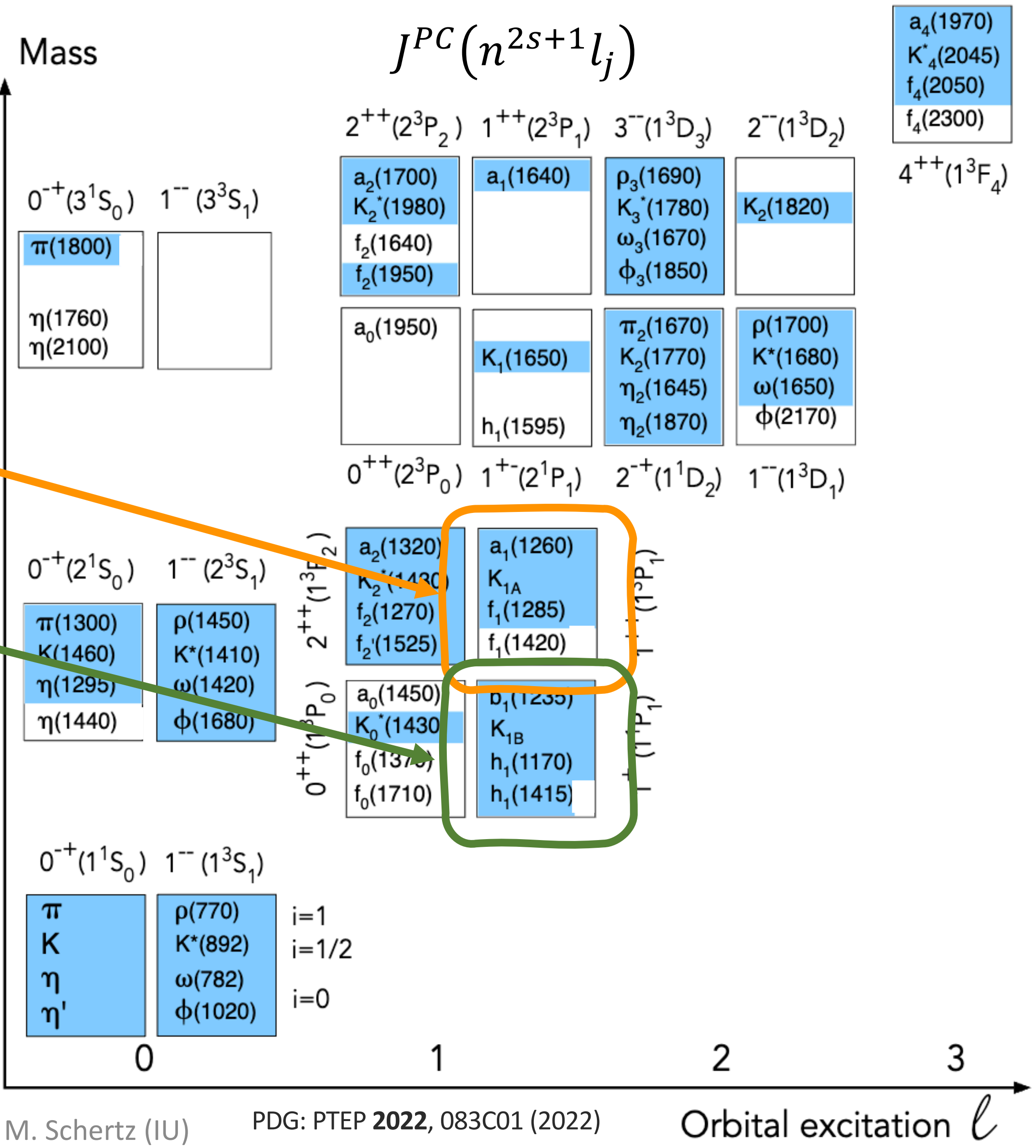

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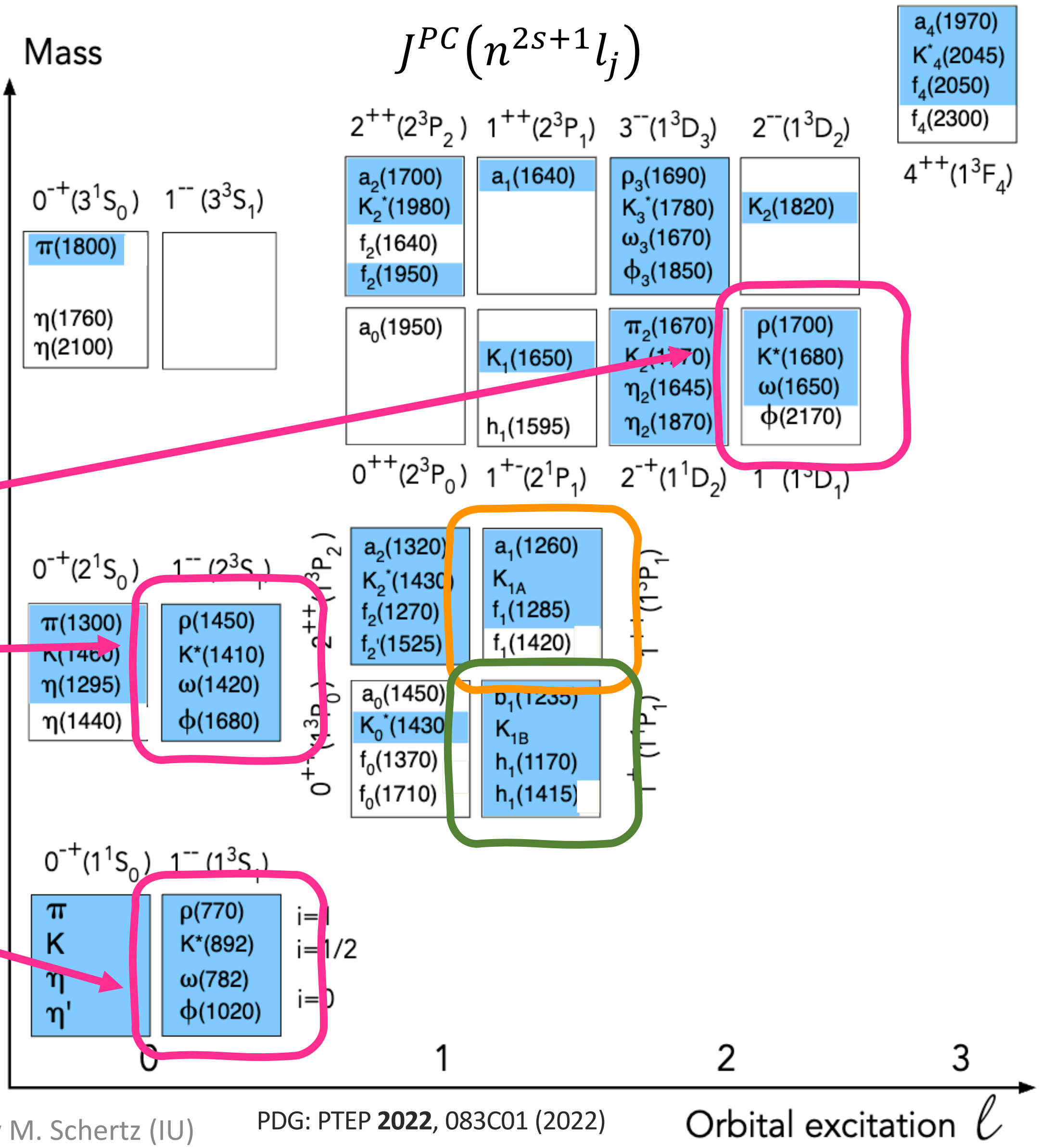

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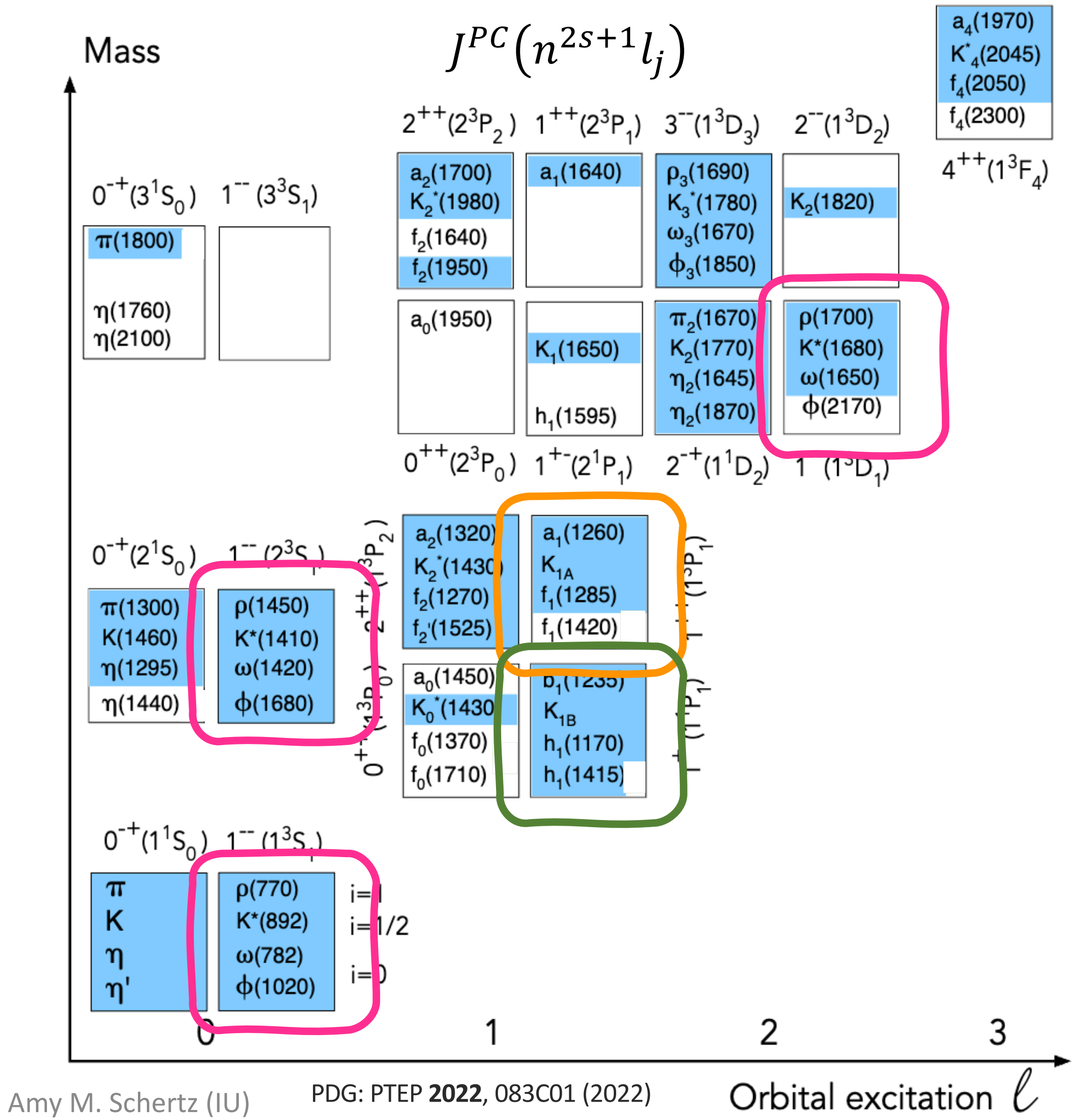
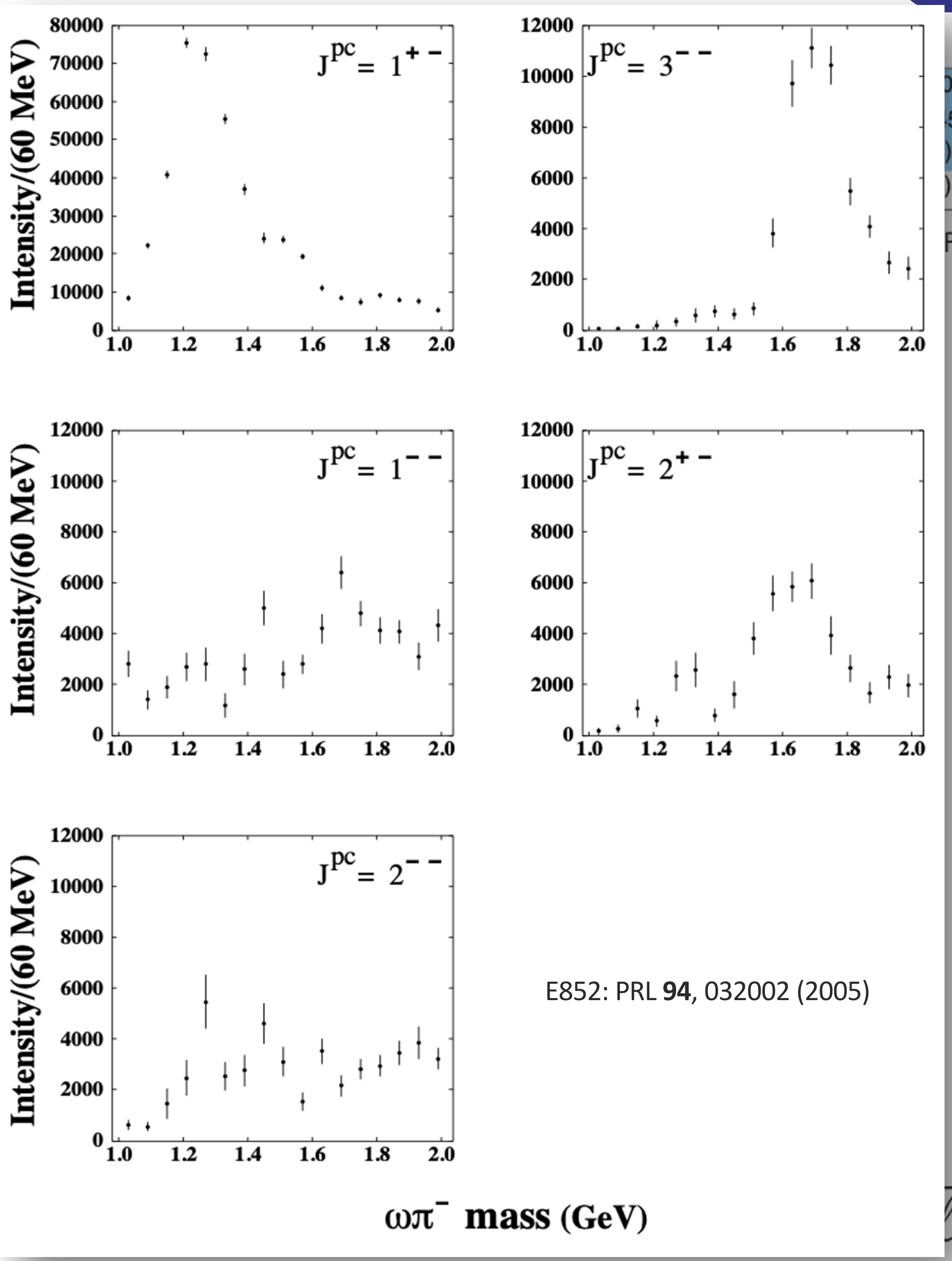


PDG: PTEP **2022**, 083C01 (2022)

$\omega\pi$ in π^- Production

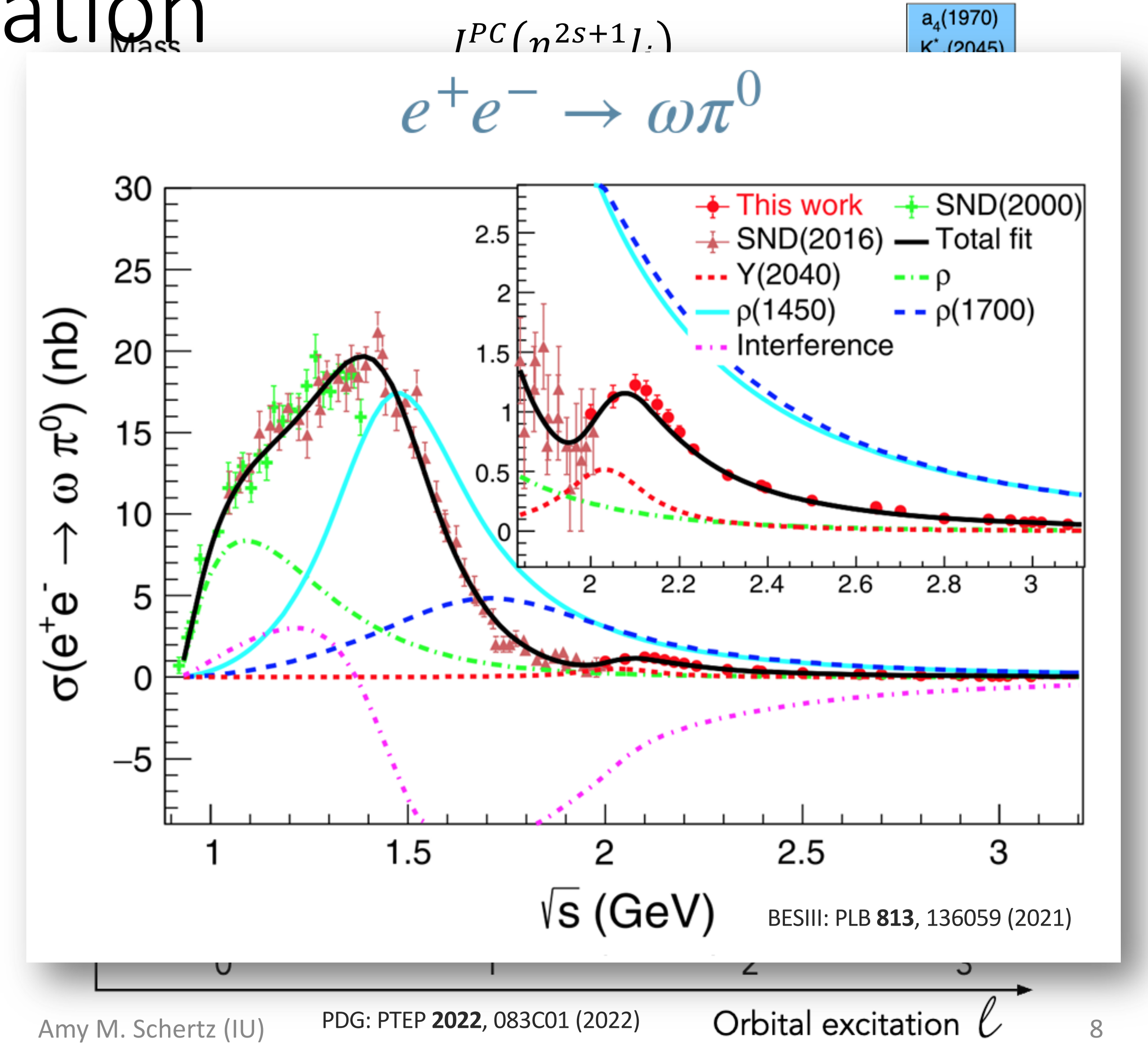
- E852 at BNL observed a dominant axial vector signal in $\omega\pi^-$, as well as a $\rho_3\ (3^{--})$
- Noted a significant enhancement in potentially exotic 2^{+-}



E852: PRL **94**, 032002 (2005)

$\omega\pi$ in e^+e^- Annihilation

- BESIII, which has access to only 1^{--}, has observed excited ρ states, as well as evidence for a $Y(2040)$

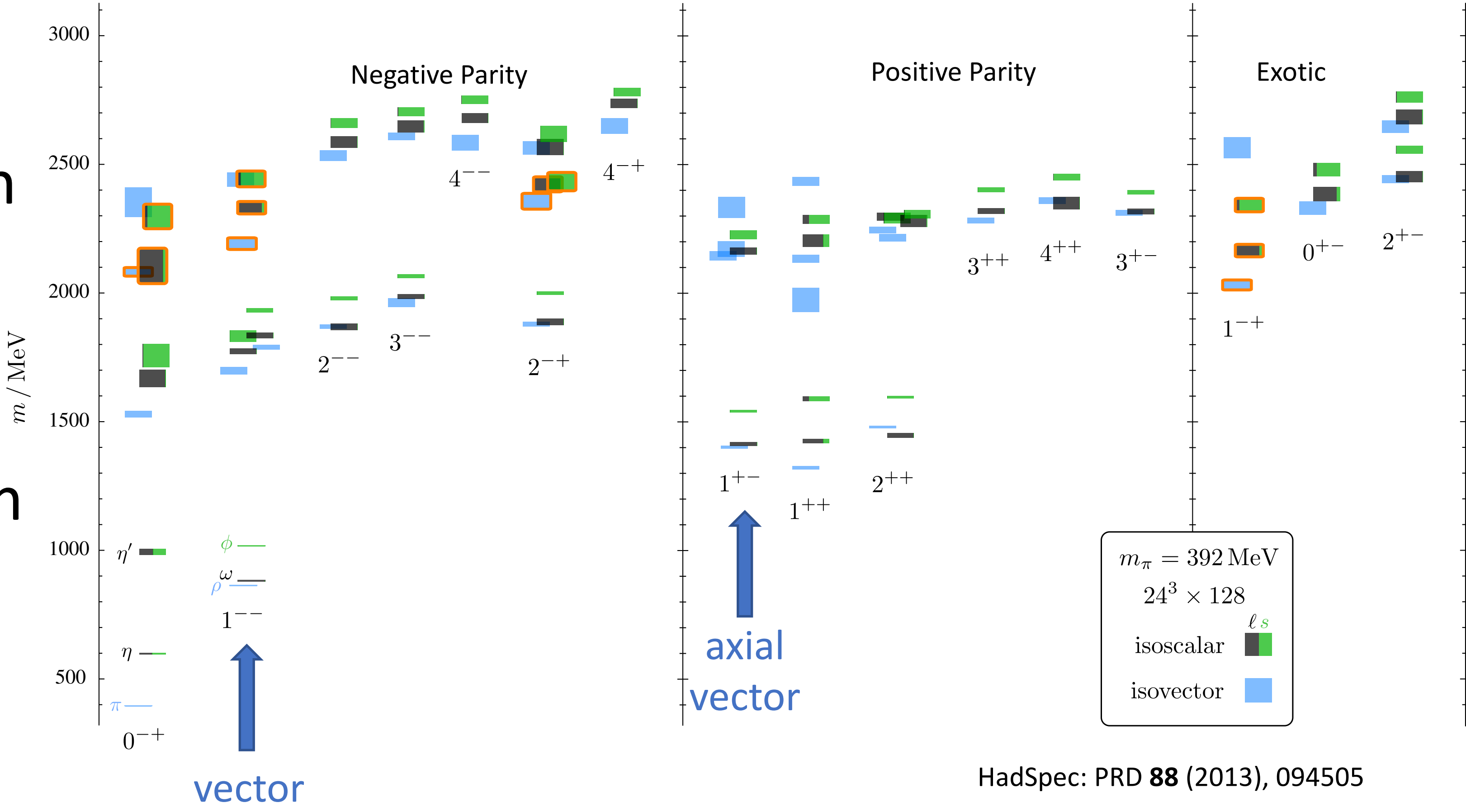


BESIII: PLB **813**, 136059 (2021)

PDG: PTEP **2022**, 083C01 (2022)

Meson Spectra

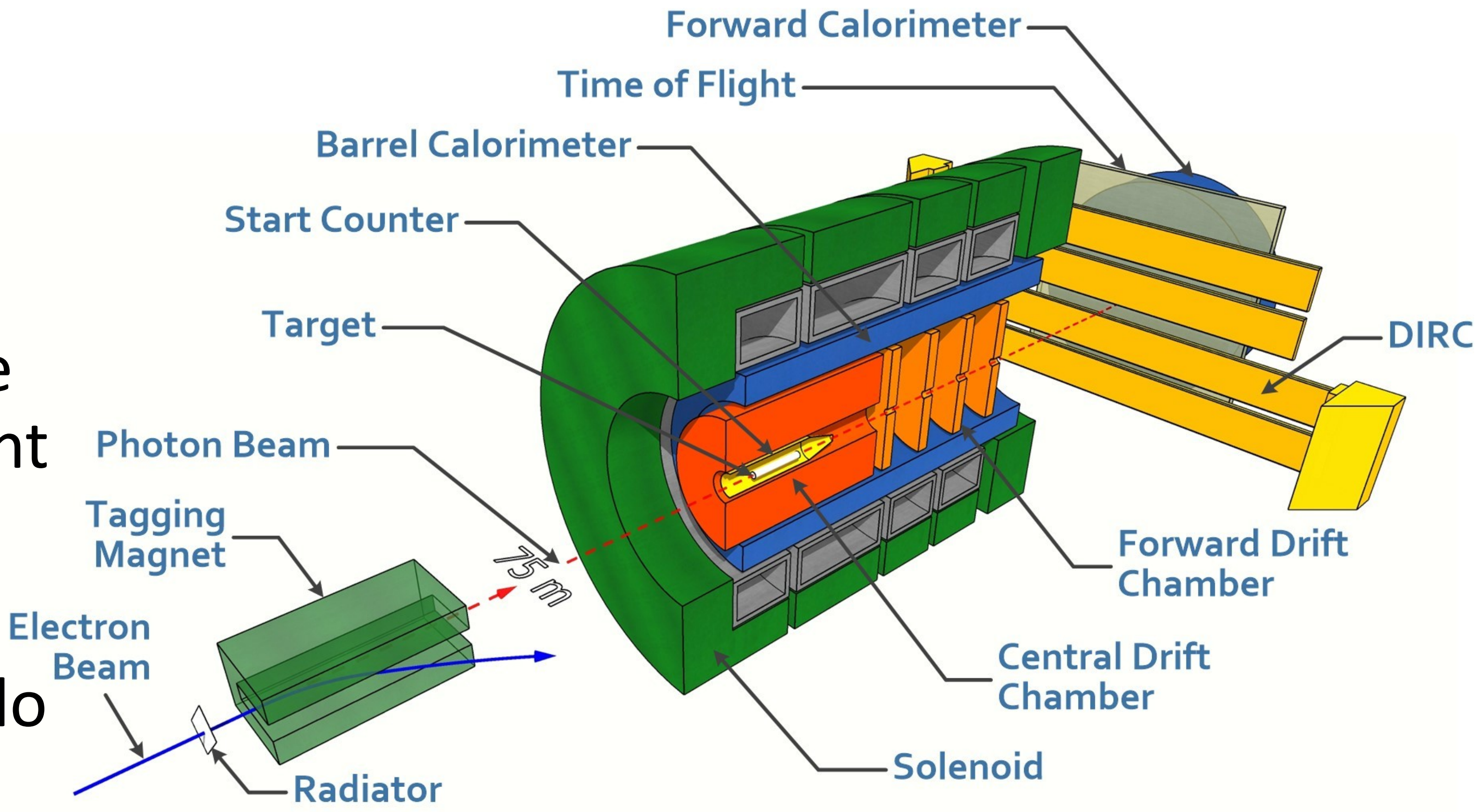
- Higher mass vector mesons may include gluonic contributions in their wavefunctions
- Not spin-exotic, but fill out the lightest predicted hybrid meson supermultiplet (along with π_1, η_1)



HadSpec: PRD **88** (2013), 094505

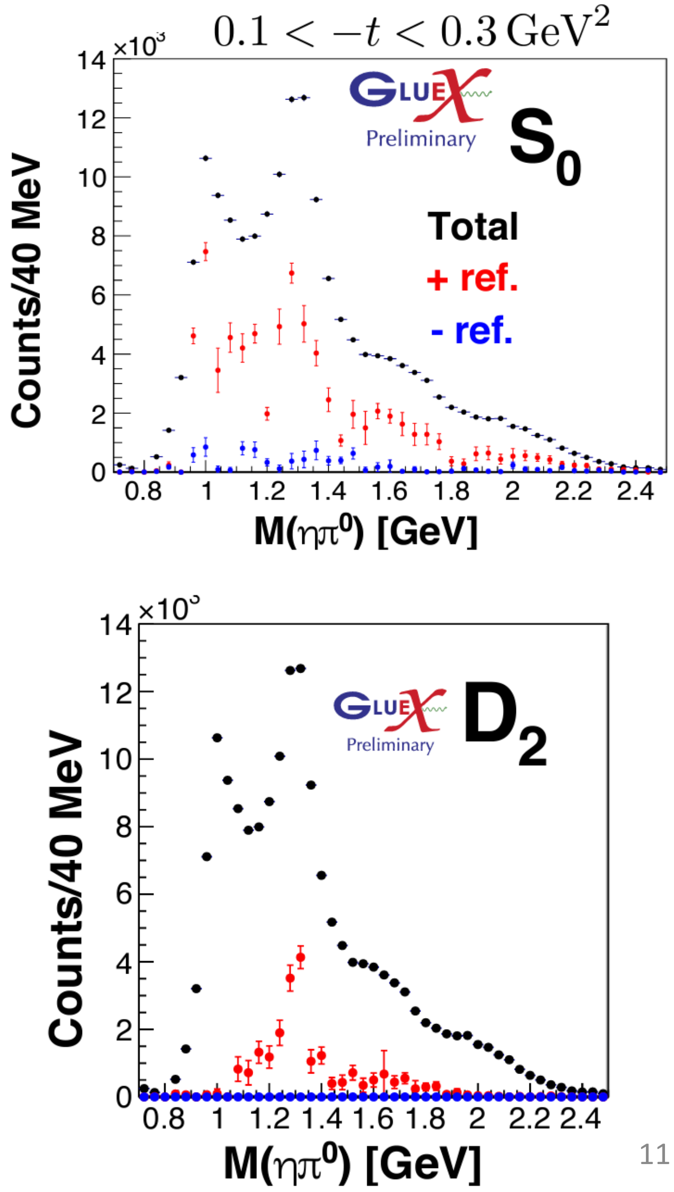
GlueX at Jefferson Lab

- Goal at GlueX: Measure spectrum of light quark mesons using polarized photoproduction
- Linear polarization of the photon beam gives insight into the production mechanism
- See talk by A. Austregesilo [This session, 9am]



Two-Pseudoscalar Production

- Two-pseudoscalar channels, such as $\eta\pi$ and $\eta'\pi$, are the first places to look when performing amplitude analyses
  - Relatively mathematically straightforward
  - Previous experiments have seen exotic signals
  - See talk by M. Albrecht [Tuesday, Exotic Hadrons]
- By considering channels where the final state consists of a vector and a pseudoscalar, we can access a broader range of intermediate resonances
  - Including excited vectors and axial vectors



From Two-Pseudoscalar to Vector-Pseudoscalar

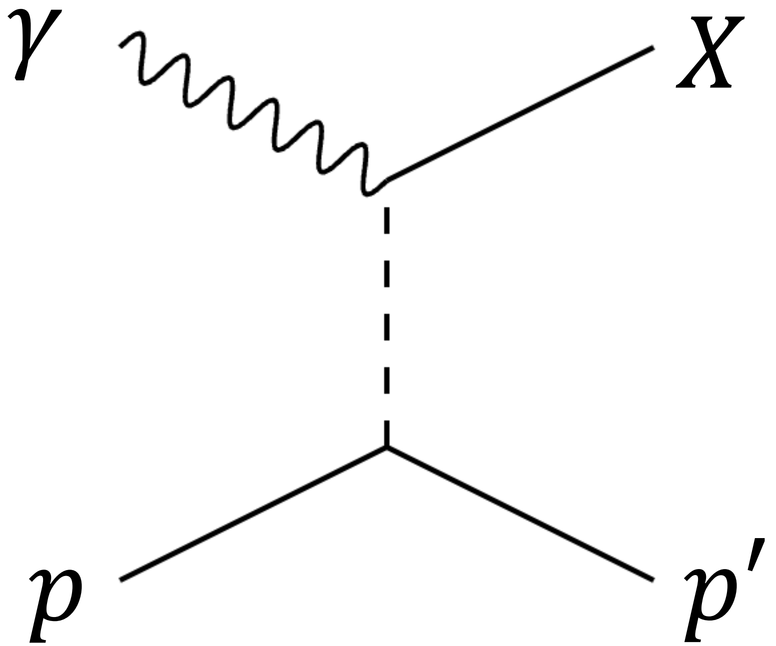
- Two-pseudoscalar ($X \to \eta^{(\prime)}\pi$)

$$A_{\lambda_\gamma} = \sum_{\ell,m} T^{\ell}_{\lambda_\gamma,m} Y^m_\ell(\Omega)$$

- Vector-pseudoscalar ($X \to \omega\pi$)

$$A_{\lambda_\gamma} = \sum_{i,m} T^{i}_{\lambda_\gamma,m} \sum_{\lambda} F^i_\lambda D^{J_i *}_{m,\lambda}(\Omega) Y^\lambda_1(\Omega_H) G$$

$i = J^P$ $\quad$ $m = -J_i \dots J_i$



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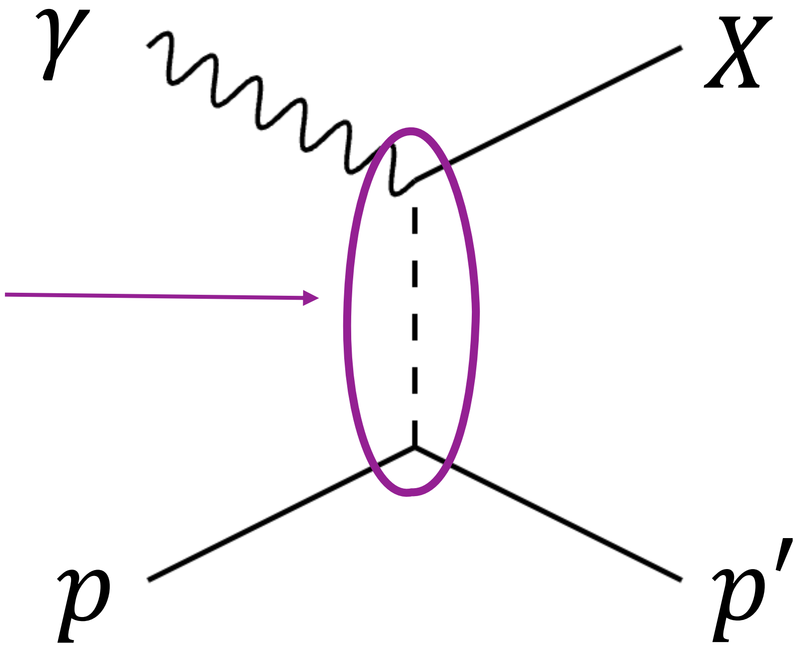
- Two-pseudoscalar ($X \to \eta^{(\prime)}\pi$)

$$A_{\lambda_\gamma} = \sum_{\ell,m} \boxed{T^{\ell}_{\lambda_\gamma,m}} Y^{m}_{\ell}(\Omega)$$

$\gamma p \to X p'$ production amplitude

- Vector-pseudoscalar ($X \to \omega\pi$)

$$A_{\lambda_\gamma} = \sum_{i,m} \boxed{T^{i}_{\lambda_\gamma,m}} \sum_{\lambda} F^{i}_{\lambda} D^{J_i *}_{m,\lambda}(\Omega) Y^{\lambda}_{1}(\Omega_H) G$$



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- Two-pseudoscalar ($X \to \eta^{(\prime)}\pi$)

$$A_{\lambda_\gamma} = \sum_{\ell,m} T^{\ell}_{\lambda_\gamma,m} \boxed{Y^m_\ell(\Omega)}$$

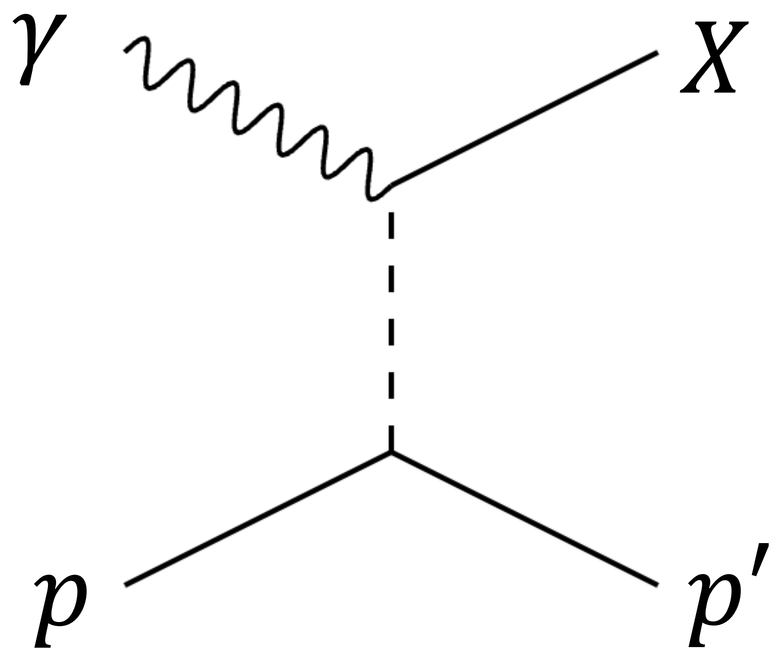
$\eta^{(\prime)}\pi$

decay amplitude of X

- Vector-pseudoscalar ($X \to \omega\pi$)

$\omega\pi$

$$A_{\lambda_\gamma} = \sum_{i,m} T^{i}_{\lambda_\gamma,m} \sum_{\lambda} \boxed{F^i_\lambda D^{J_i *}_{m,\lambda}(\Omega)}\, Y^\lambda_1(\Omega_H) G$$



From Two-Pseudoscalar to Vector-Pseudoscalar

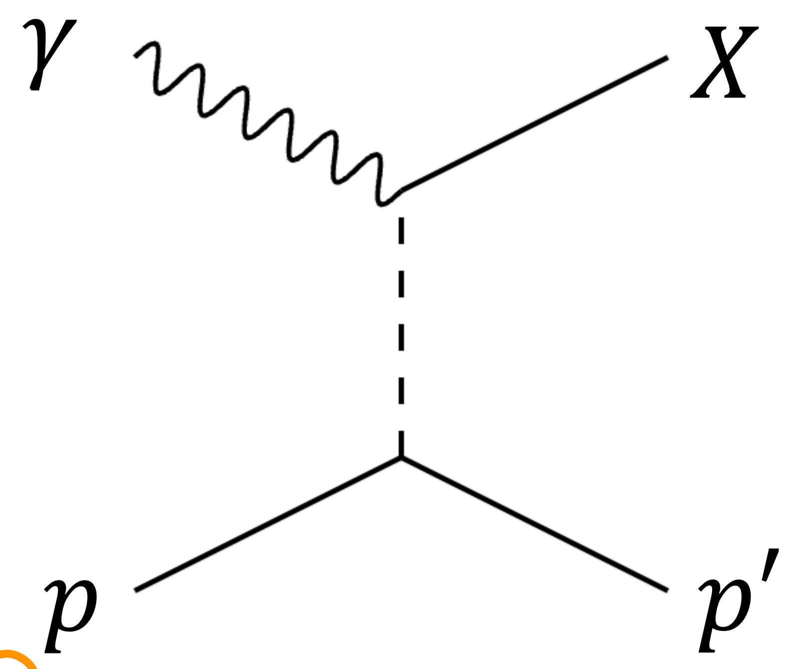
- Two-pseudoscalar ($X \to \eta^{(\prime)}\pi$)

$$A_{\lambda_\gamma} = \sum_{\ell,m} T^{\ell}_{\lambda_\gamma,m} Y^m_\ell(\Omega)$$

$\omega \to 3\pi$ decay amplitude

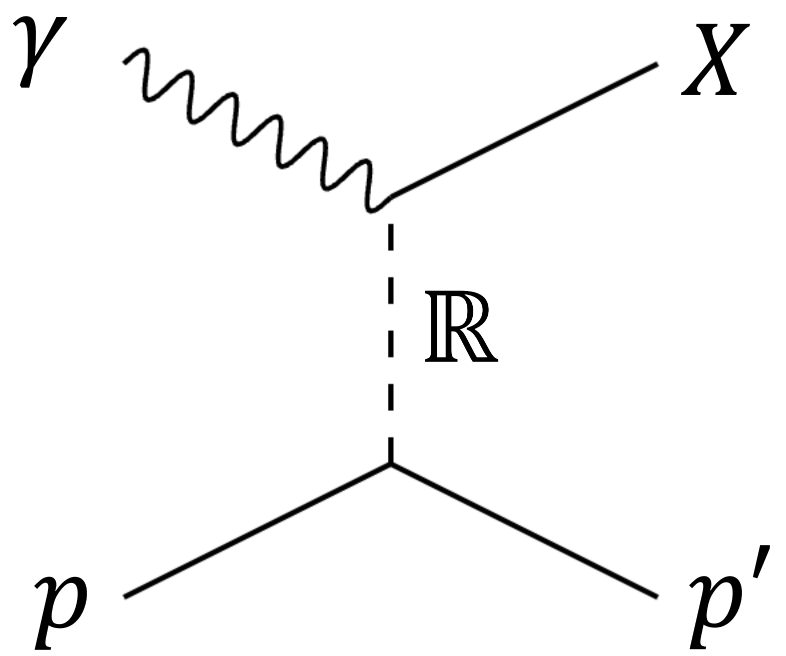
- Vector-pseudoscalar ($X \to \omega\pi$)

$$A_{\lambda_\gamma} = \sum_{i,m} T^{i}_{\lambda_\gamma,m} \sum_{\lambda} F^i_\lambda D^{J_i *}_{m,\lambda}(\Omega) \boxed{Y^\lambda_1(\Omega_H) G}$$



Partial Wave Analysis

- Decomposition of a measured intensity into its orthogonal angular momentum components, or partial waves
  - Can extract the spin and parity of the resonances contributing to a given final state
- At GlueX, we can perform PWA in the reflectivity basis to extract information on the exchange mechanism
  - The reflectivity operator, $\Pi_y = PR_y(\pi)$, reflects the reaction through the production plane



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

Reflectivity: $\varepsilon = \tau_{\mathbb{R}}\tau_X$

Reflectivity Basis Intensity

- The intensity function is written in terms of the reflectivity basis production amplitudes and phase-rotated decay amplitudes

$$I \propto (1-P_\gamma)\left[\left|\sum_{i,m}[J_i]^{(-)}_{m,k}\mathrm{Im}Z^i_m\right|^2+\left|\sum_{i,m}[J_i]^{(+)}_{m,k}\mathrm{Re}Z^i_m\right|^2\right]$$

$$+(1+P_\gamma)\left[\left|\sum_{i,m}[J_i]^{(+)}_{m,k}\mathrm{Im}Z^i_m\right|^2+\left|\sum_{i,m}[J_i]^{(-)}_{m,k}\mathrm{Re}Z^i_m\right|^2\right]$$

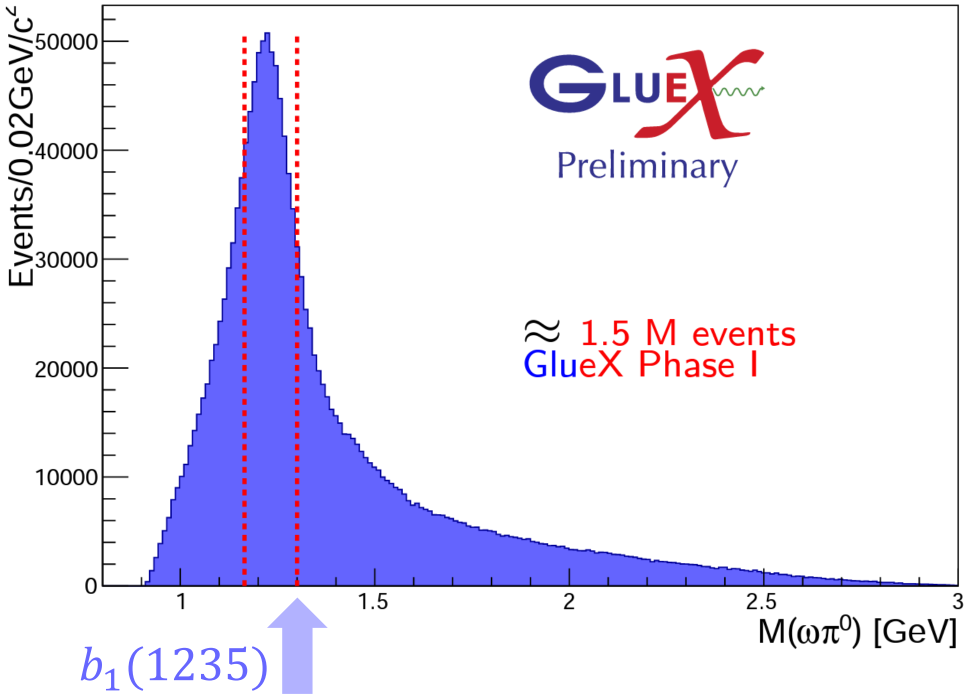
- All the angles are included in the Z^i_m decay amplitudes, and the $[J_i]^{(\epsilon)}_{m,k}$ are the free parameters in the fit

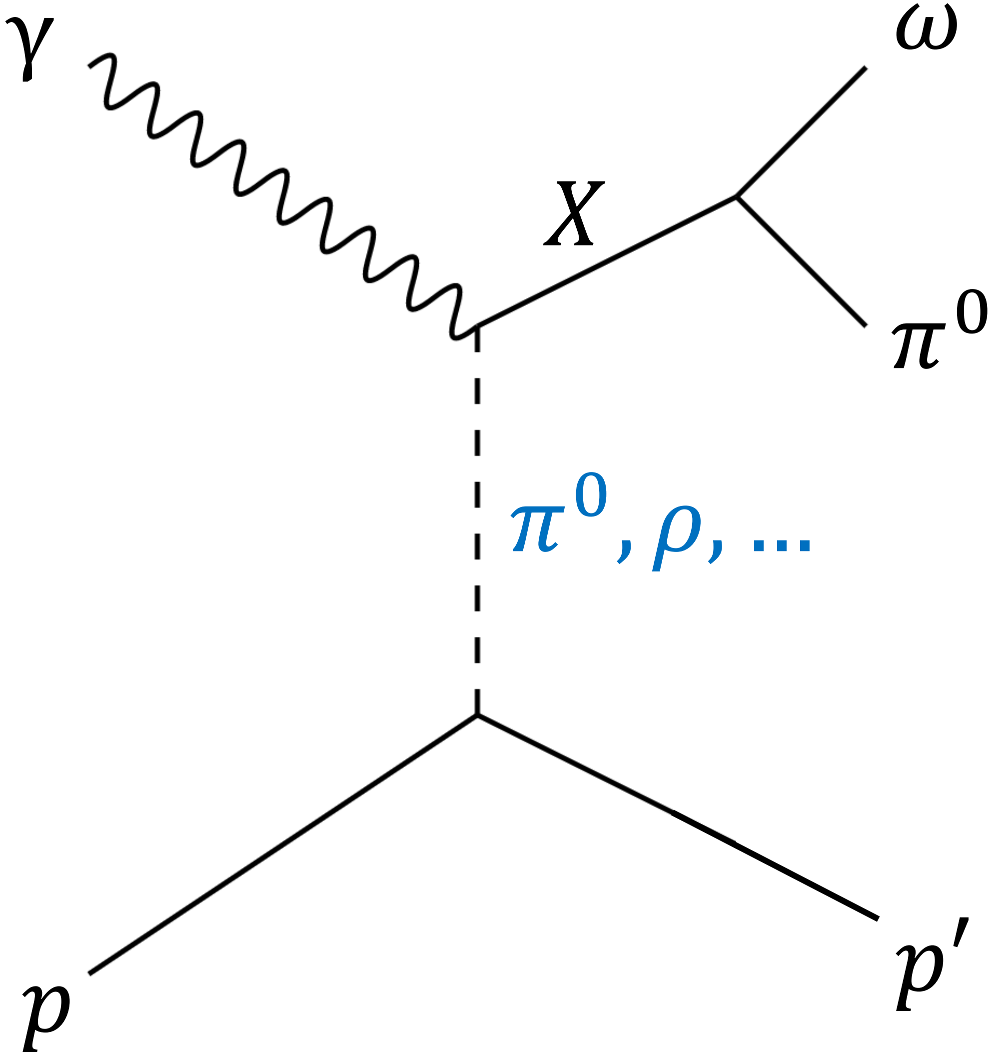
$$Z^i_m = e^{-i\Phi}\sum_\lambda F^i_\lambda D^{J_i *}_{m,\lambda}(\Omega)Y^\lambda_1(\Omega_H)G$$

$\omega\pi^0$ in Photoproduction

- A major contributor is the $b_1(1235)$
- Excited $\rho(1450, 1700)$ and $\omega(1420)$ mesons have been seen

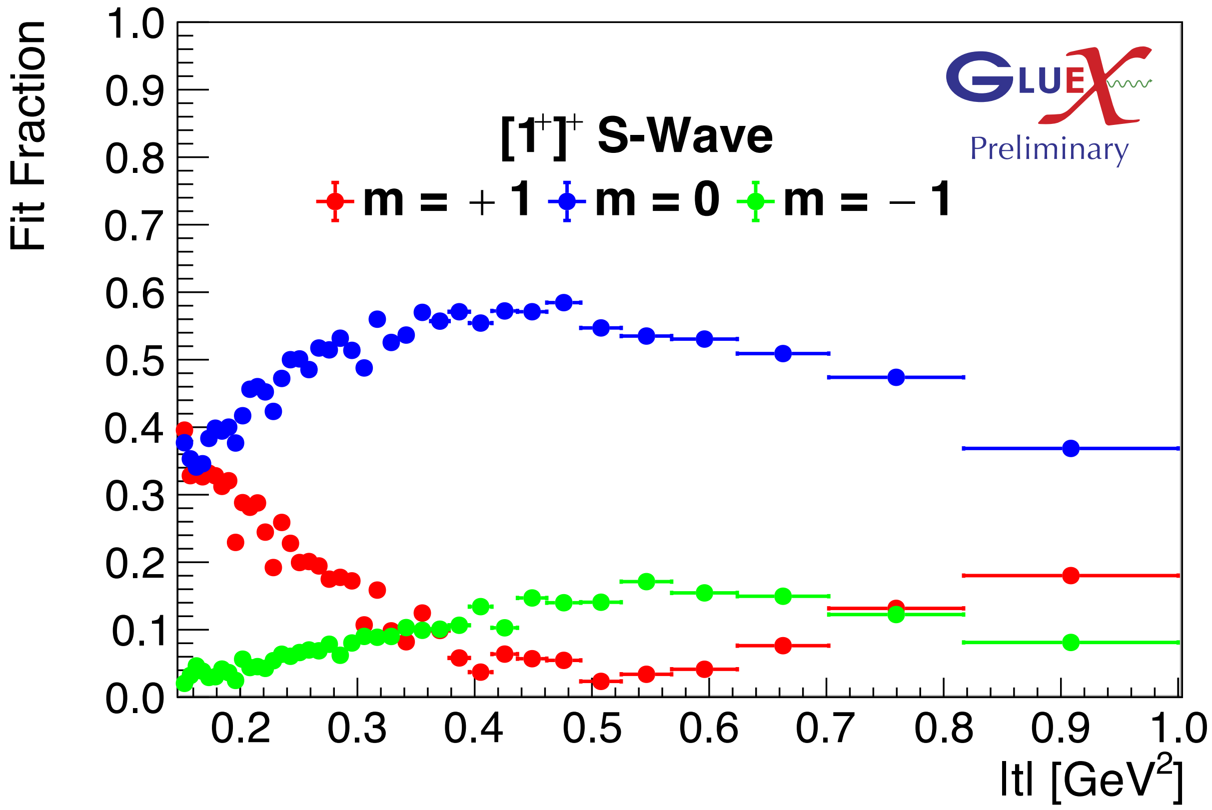
Reconstructed $\omega\pi^0$ events

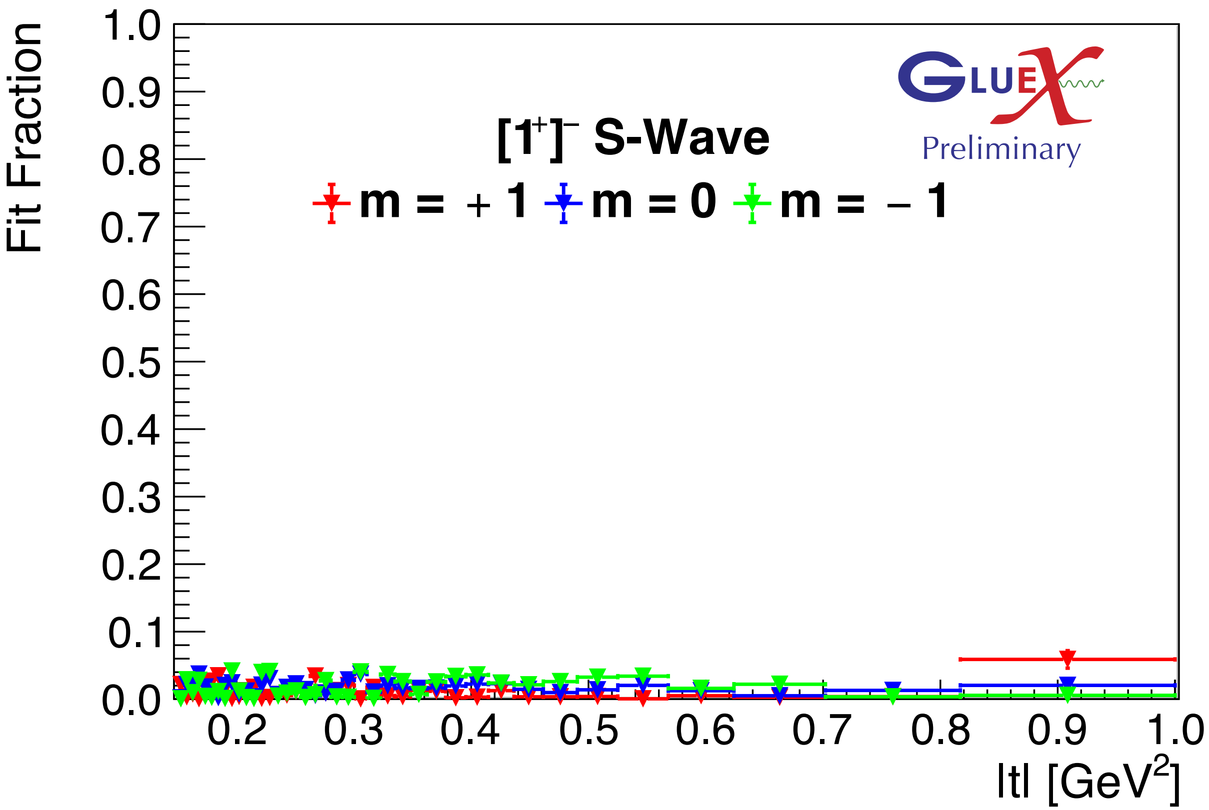




Preliminary $\omega\pi^0$ Results

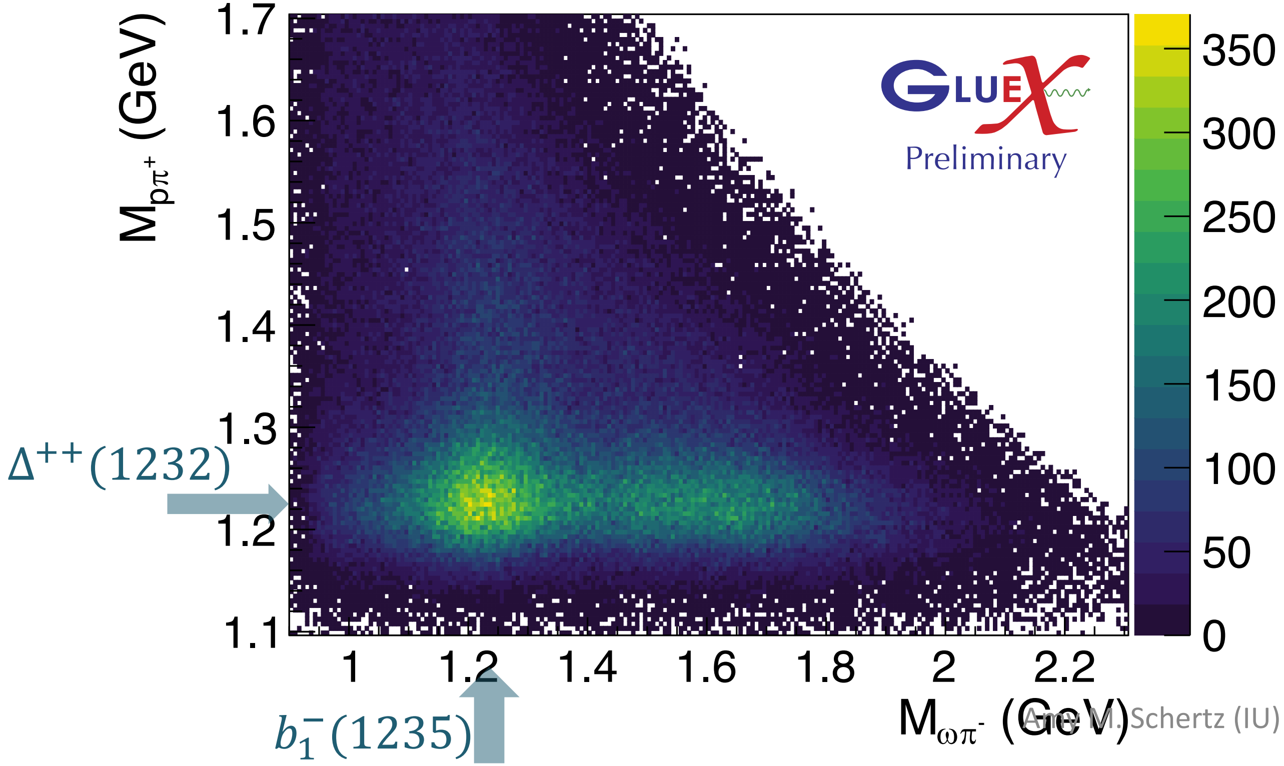
- Roughly 10% of the intensity is taken up by vector partial waves, the rest is axial vector (shown here)

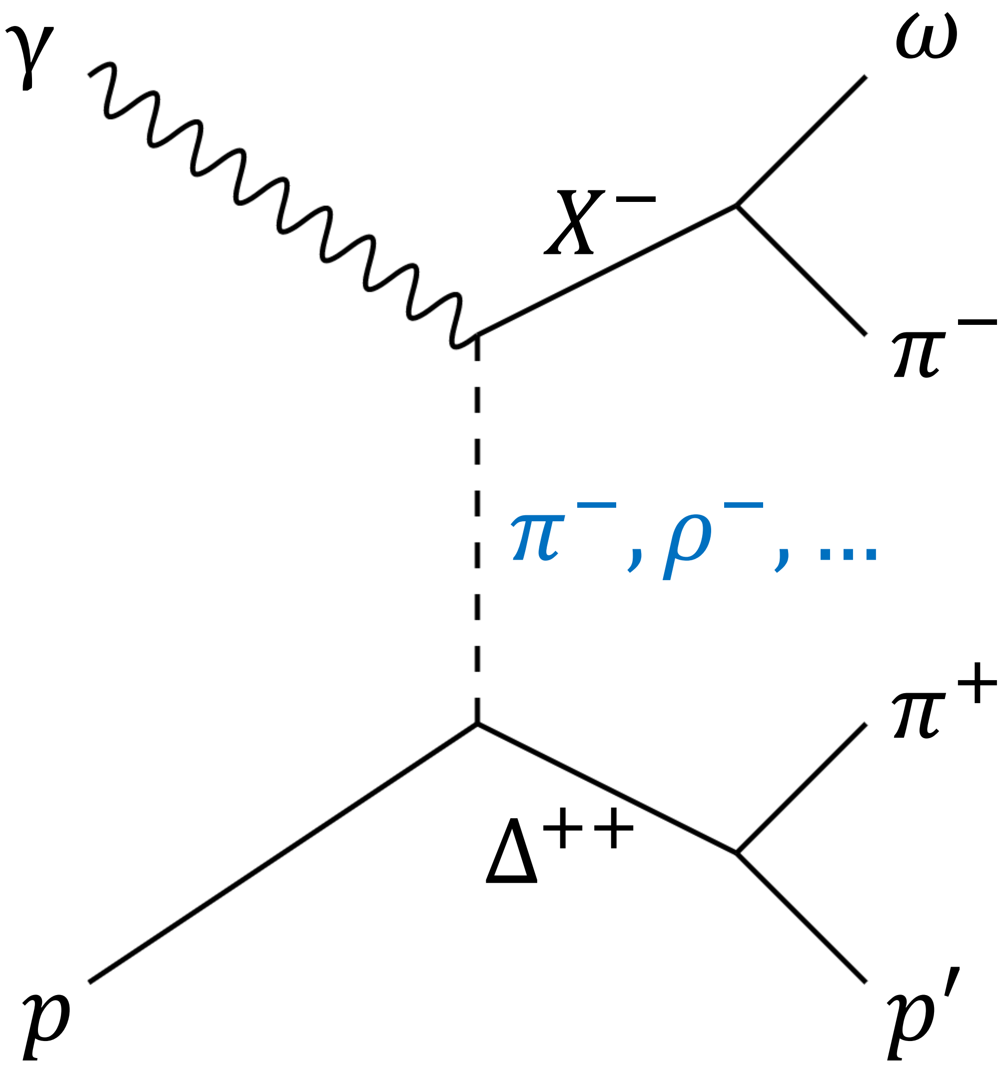




What about charged pions?

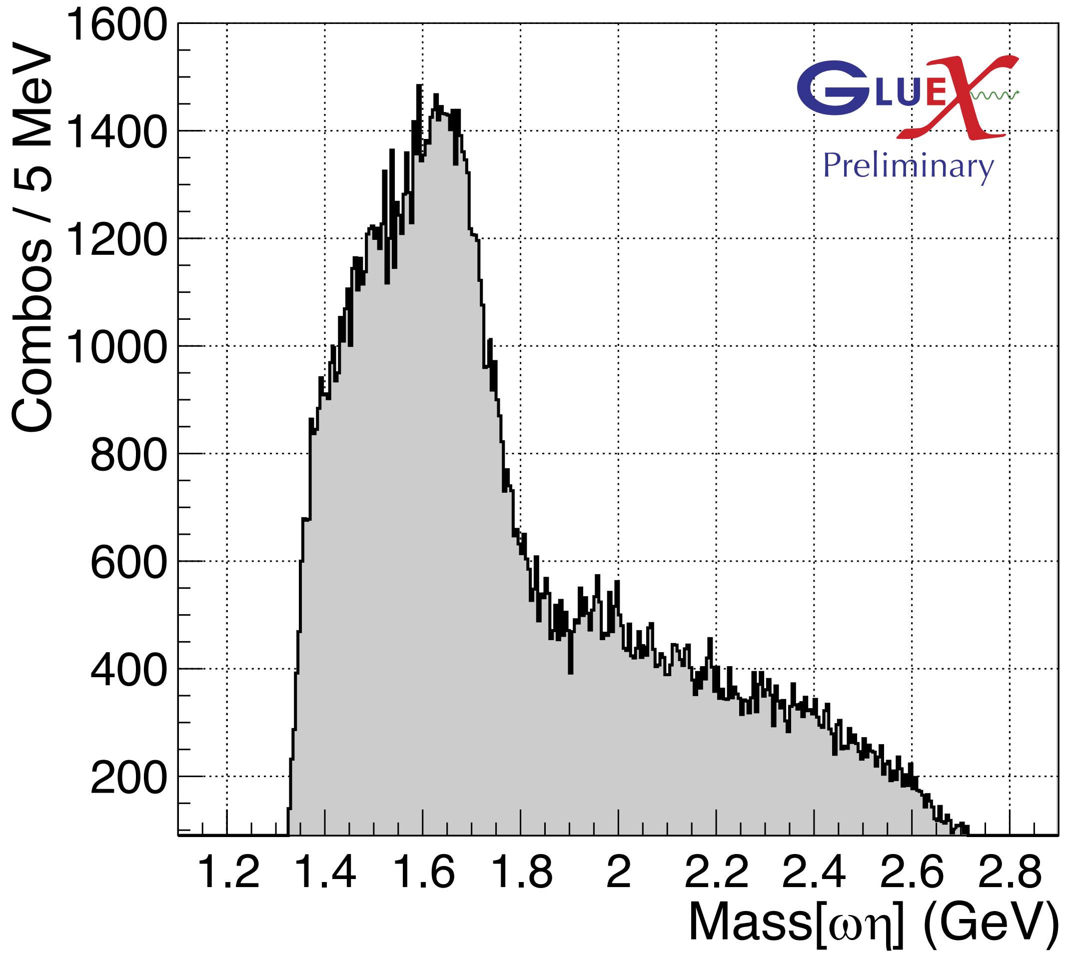
- Analysis of $\omega\pi^-$ system as well
- Can compare production mechanisms
- Unstable lower vertex adds complication





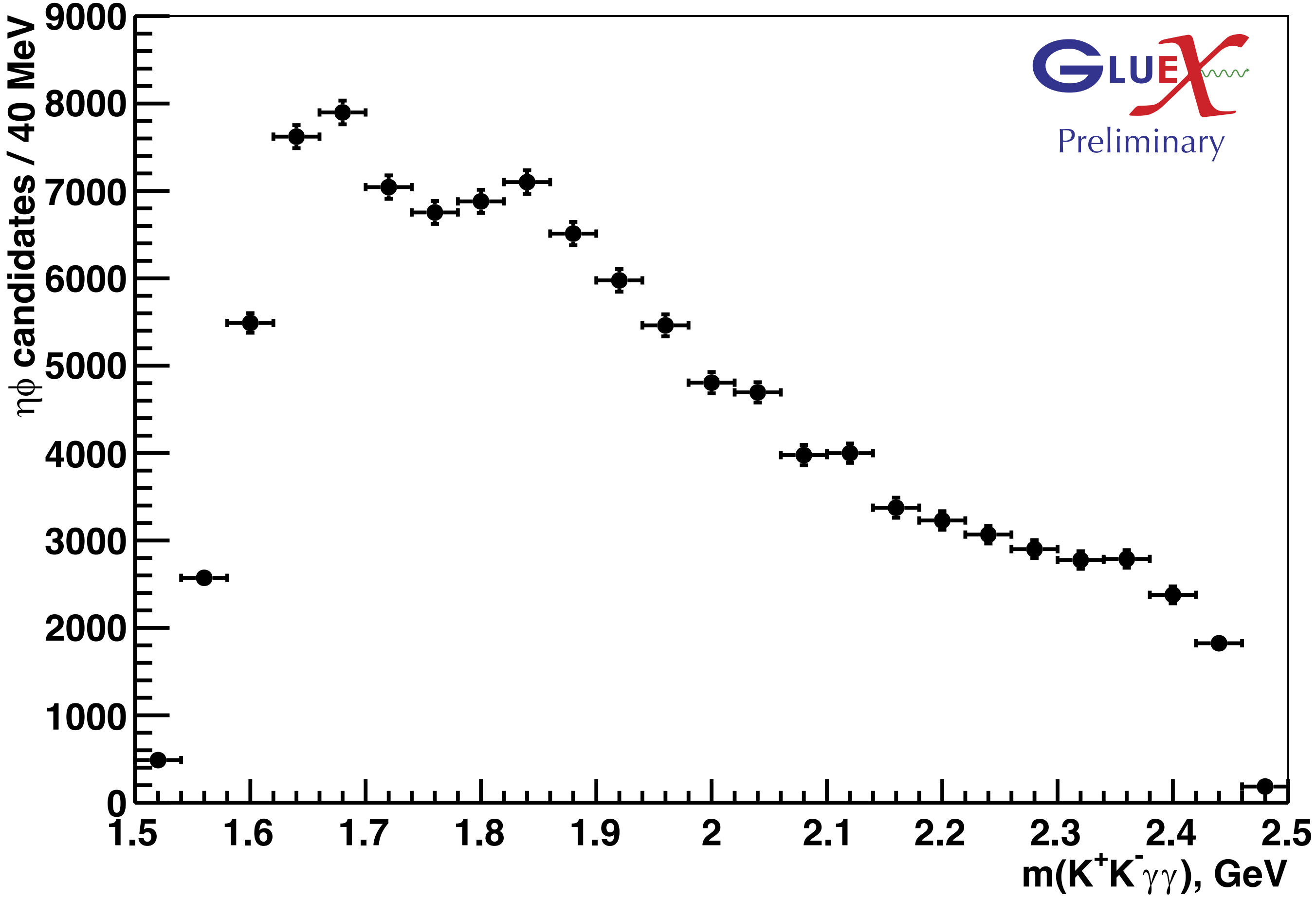
Other Vec-PS Channels: $\omega\eta$

- The $h_1(1595)$, (not PDG established), was seen in a PWA of $\omega\eta$ by E852
- Excited $\omega(1650)$ was seen in the same analysis
- Potential for excited ϕ at higher masses



Other Vec-PS Channels: $\phi\eta$

- Structures near $\phi(1680)$ and $\phi(1820)$
- Search ongoing for $Y(2175)$ in $\phi\eta$ using Vec-PS PWA
  - See talk by F. Nerling on the search for $Y(2175)$ in $\phi\pi\pi$ [Tuesday, Exotic Hadrons]



Summary/Outlook

- Partial wave analysis of vector-pseudoscalar final states is a pathway to a large set of interesting hadronic states (possibly including hybrids)
- Performing fits in the reflectivity basis provides information about exchange mechanism, and has never been done with a polarized beam
- Analyses of several vector-pseudoscalar channels are underway at GlueX – stay tuned!

- GlueX gratefully acknowledges the support of several funding agencies and computing facilities: gluex.org/thanks

Backup

Helicity to Reflectivity Basis

- Helicity basis amplitude

$$A_{\lambda_\gamma} = \sum_{i,m} T^i_{\lambda_\gamma,m} \sum_{\lambda} F^i_\lambda D^{J_i *}_{m,\lambda}(\Omega) Y_1^\lambda(\Omega_H) G$$

- Define reflectivity basis production amplitudes

$$^{(\epsilon)}V^i_m = \frac{1}{2}\left[T^i_{+,m} - \tau_i \epsilon (-1)^m T^i_{-,m}\right]$$

Helicity to Reflectivity Basis

- The phase-rotated helicity basis amplitudes can be written as sums and differences of the reflectivity production amplitudes

$$\tilde{A}_{+} = \sum_{i,m} \left({}^{(+)}V_m^i + {}^{(-)}V_m^i \right) Z_m^i$$

$$Z_m^i = e^{-i\Phi} \sum_{\lambda} F_\lambda^i D_{m,\lambda}^{J_i *}(\Omega) Y_1^\lambda(\Omega_H) G$$

$$\tilde{A}_{-} = \sum_{i,m} \left({}^{(+)}V_m^i - {}^{(-)}V_m^i \right) Z_m^{i*}$$

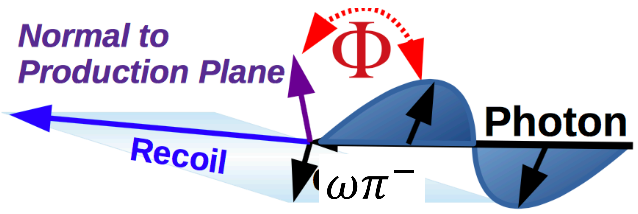
- The sum and difference of $\tilde{A}_{\pm}$ are used in the intensity equation

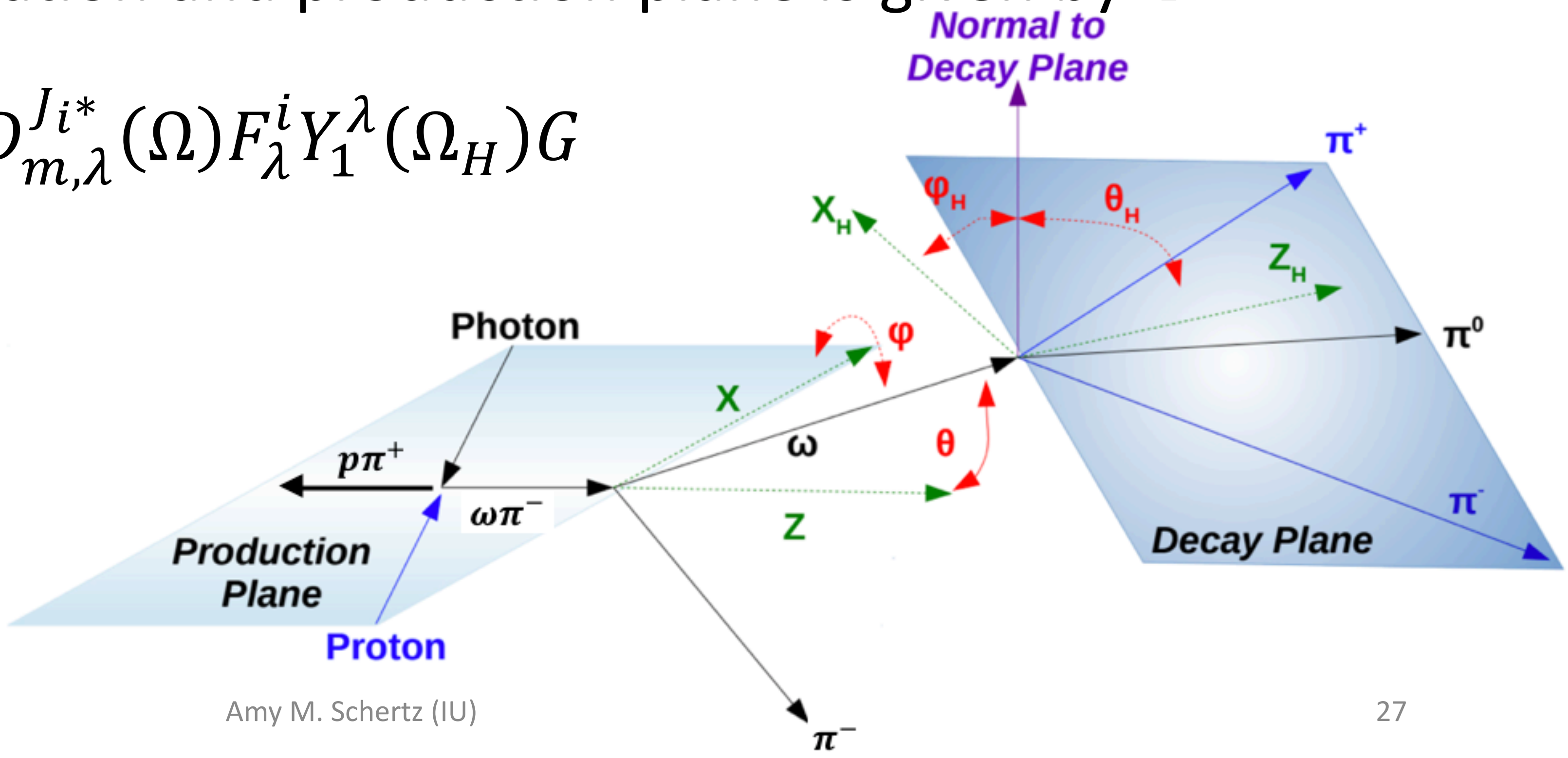
$$I = \frac{\kappa}{4} \sum_{\lambda_1 \lambda_2} \left[(1 - P_\gamma) \left| \tilde{A}_{+} + \tilde{A}_{-} \right|^2 + (1 + P_\gamma) \left| \tilde{A}_{+} - \tilde{A}_{-} \right|^2 \right]$$

$\omega\pi$ Production and Decay Angles

- Consider the reaction $\gamma p \to \Delta^{++} X^-$, where $X^- \to \omega\pi^-$ and $\omega \to 3\pi$
- The decay of the X^- can be described by 4 angles, two (Ω) to describe $X^- \to \omega\pi^-$, and two more (Ω_H) to describe $\omega \to 3\pi$ in the helicity frame
- Angle between polarization and production plane is given by Φ

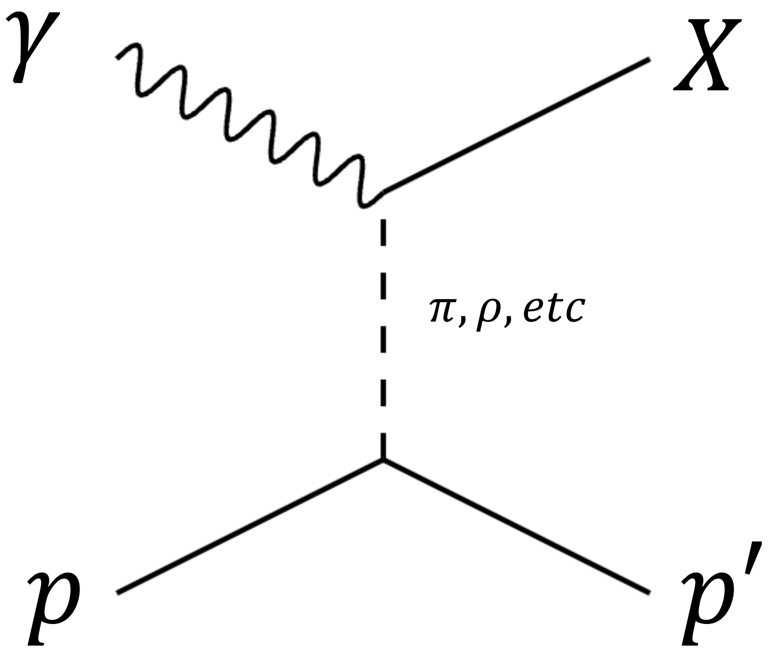
$$Z_m^i(\Phi, \Omega, \Omega_H) \propto e^{-i\Phi} \sum_\lambda D_{m,\lambda}^{J_i *}(\Omega) F_\lambda^i Y_1^\lambda(\Omega_H) G$$

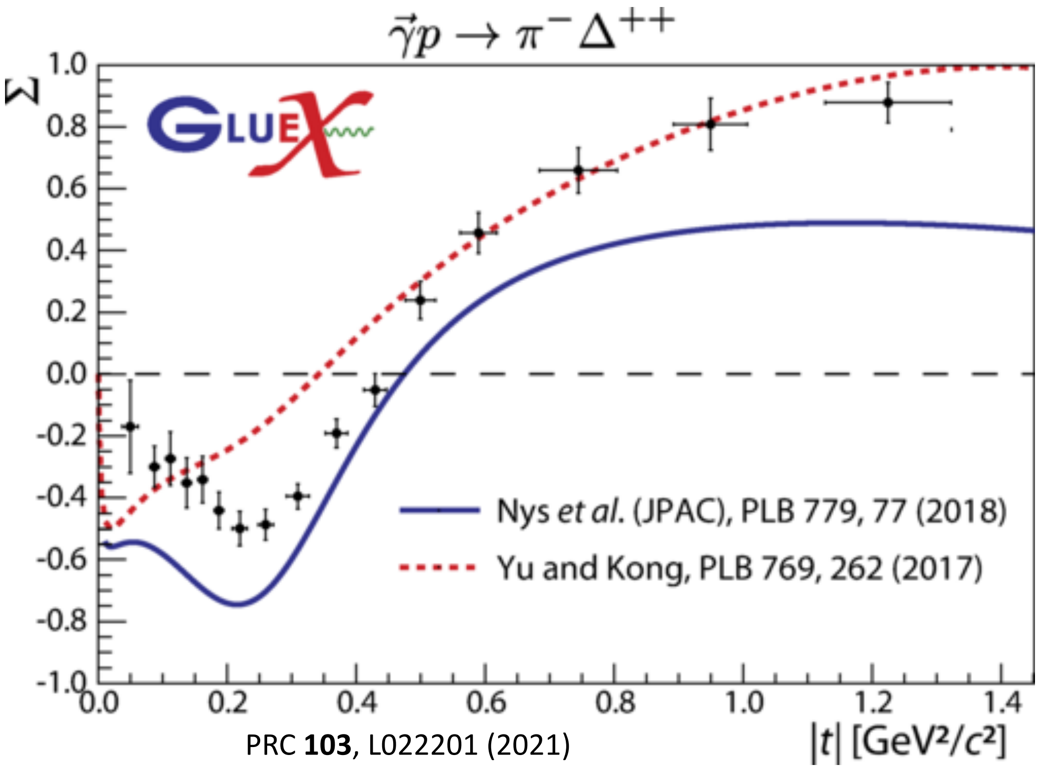




Polarized Photoproduction

- Polarization of the photon beam gives insight into the production mechanism via reflectivity measurements and beam asymmetries





PRC **103**, L022201 (2021)