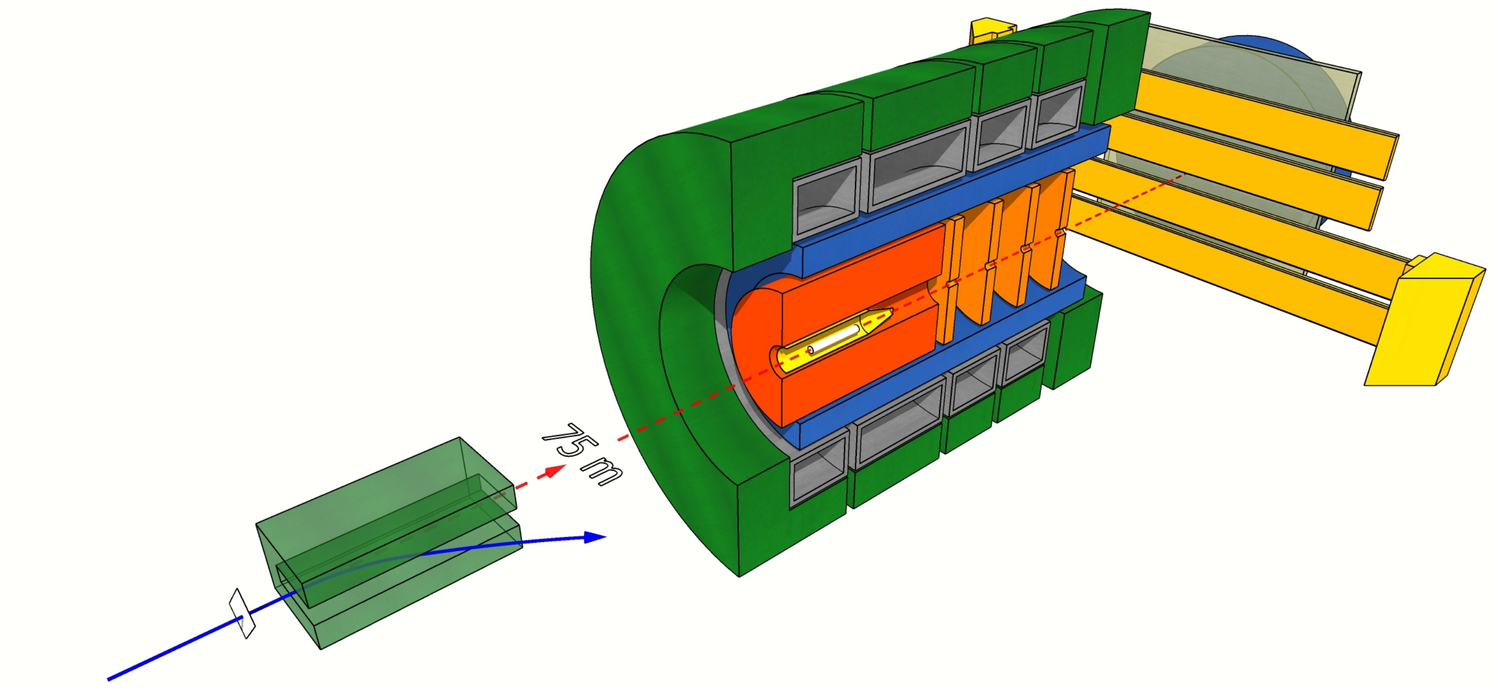
Meson Spectroscopy at GlueX

Will Imoehl on behalf of the GlueX Collaboration

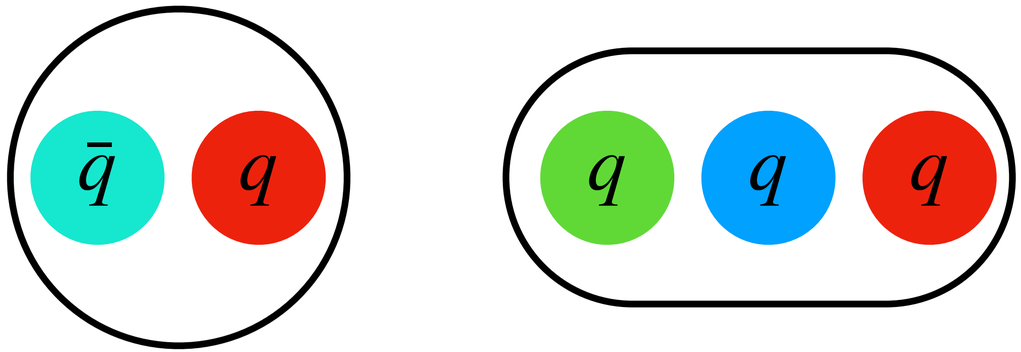


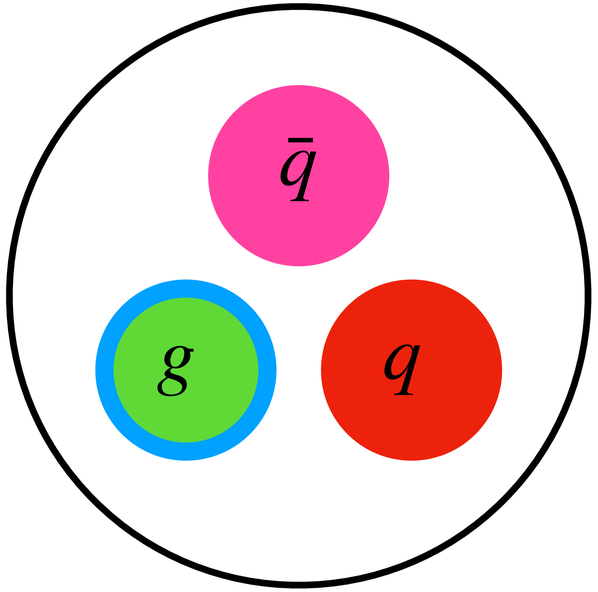
Carnegie Mellon University

Jefferson Lab Users Organization Annual Meeting

Exotic Hadrons in Quark Model

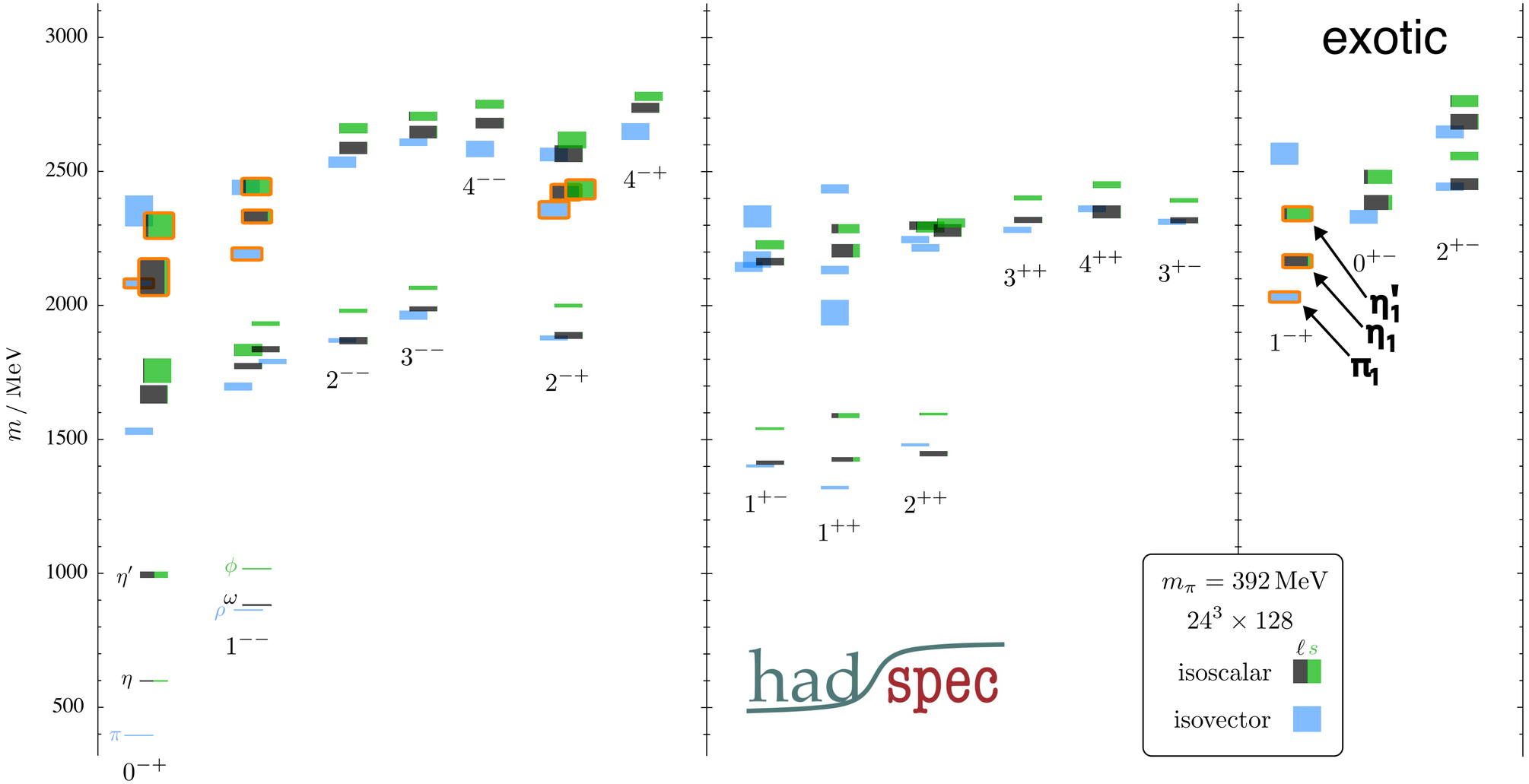
- Conventional hadrons are mesons ($q\bar{q}$) or baryons (qqq)





- Additional color singlet states allowed
- Hybrid mesons are unique probe for QCD
  - States are $q\bar{q}$ with excited gluonic field
  - Hybrid spectrum $\Longleftrightarrow$ gluon contribution to properties of hadrons
    - i.e. Mass, J^{PC}

Lattice QCD Light Meson Spectrum

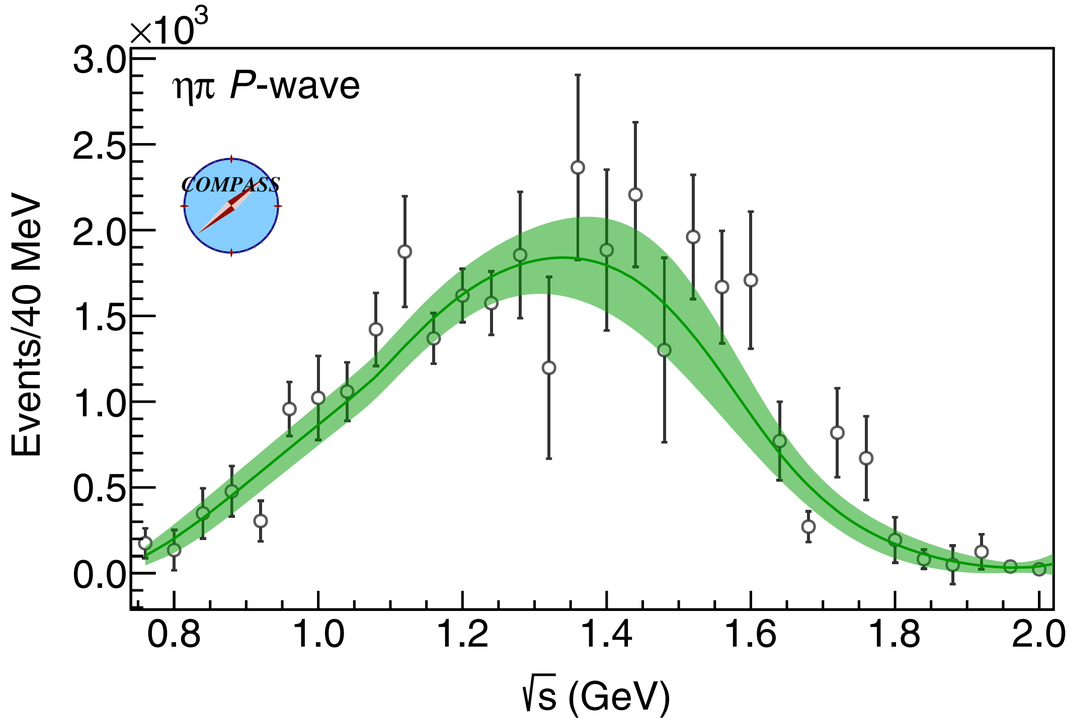


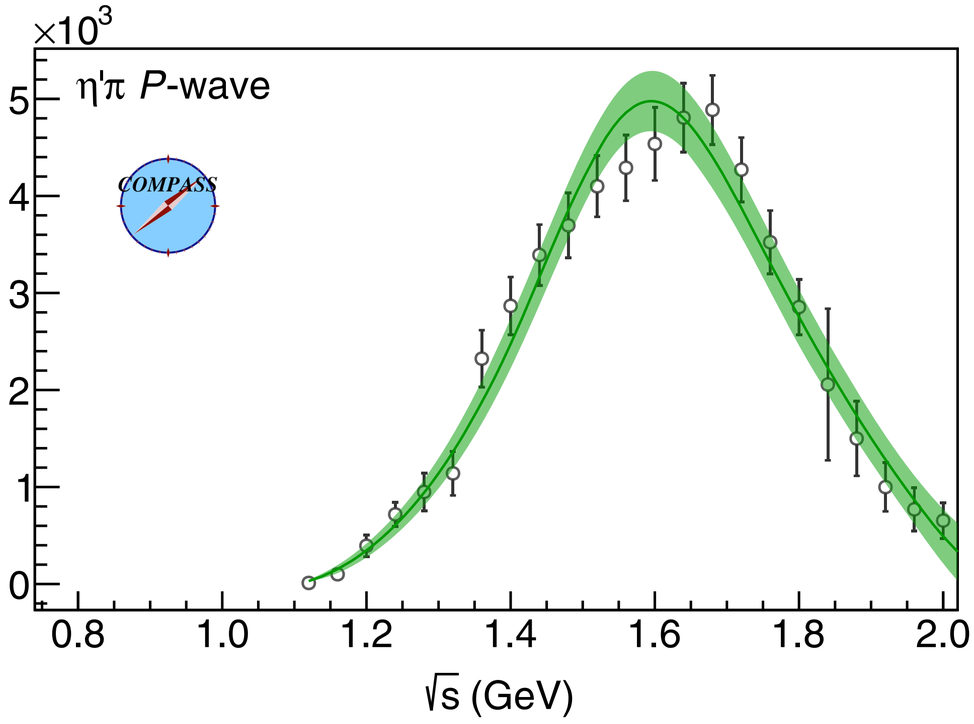
[Dudek, Edwards, Guo, Thomas, PRD 88 094505(2013)]

- Candidates for π_1 and either η_1 or η_1' have been observed

Hybrid Mesons - JPAC π_1 Result

- Only one $I = 1$ hybrid meson with $J^{PC} = 1^{-+}$ expected below 2.0 GeV/c^2
- Historically, $\pi_1(1400)$ found only in $\eta\pi$, $\pi_1(1600)$ found in $\eta'\pi$, $\rho\pi$, $f_1(1285)\pi$,
- JPAC coupled channel analysis only requires a single resonance pole (Adam's talk)



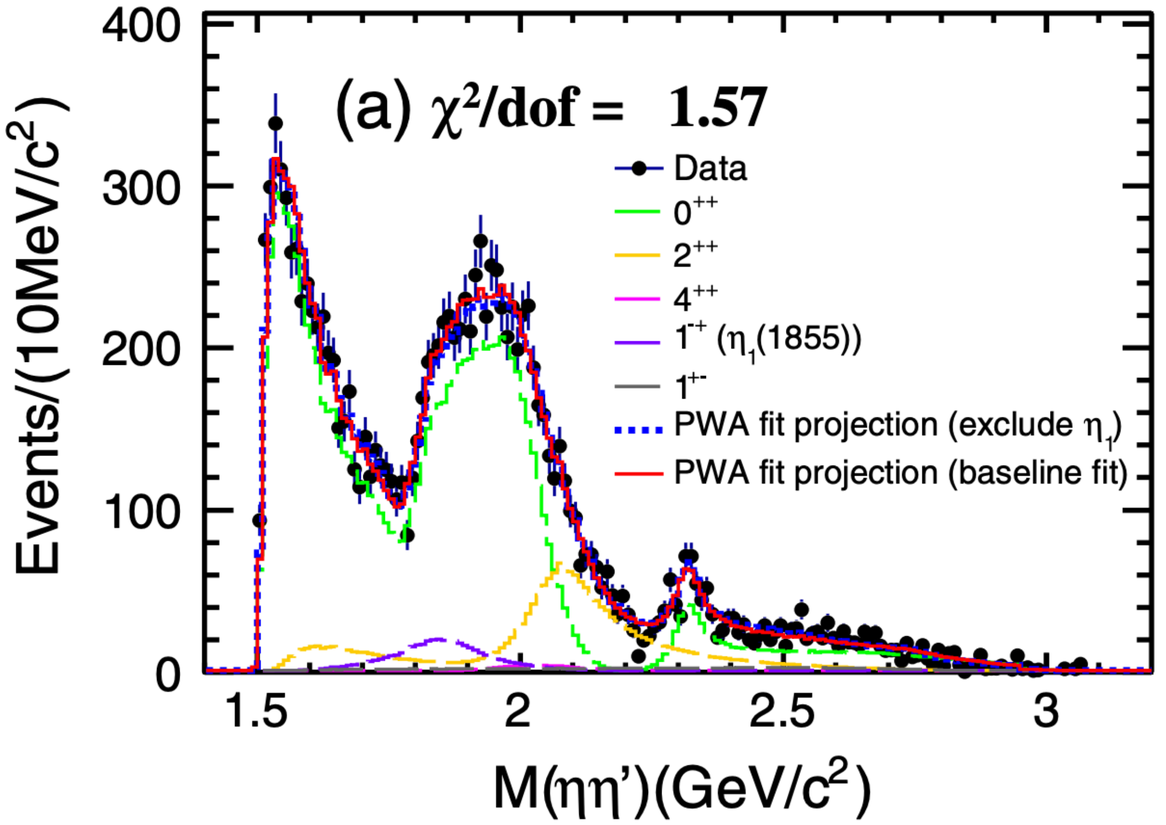


[A.Rodas et.al. PRL 122, 042002 (2019), B.Kopf et.al. Eur.Phys.J.C 81, 1056 (2021)]

Hybrid Mesons - BESIII $\eta_1^{(\prime)}$ Result

- BESIII studied the decay $J/\psi \to \gamma\eta\eta'$ using sample of 10 billion J/ψ
- PWA finds significant signal for and $I = 0, J^{PC} = 1^{-+}$ state
- Blue is fit without $\eta_1^{(\prime)}$, red is with $\eta_1^{(\prime)}$
- Fit to mass distribution looks unimpressive

[PRL 129 192002 (2022)].



PWA fits decay angles too, state may not peak in mass distribution

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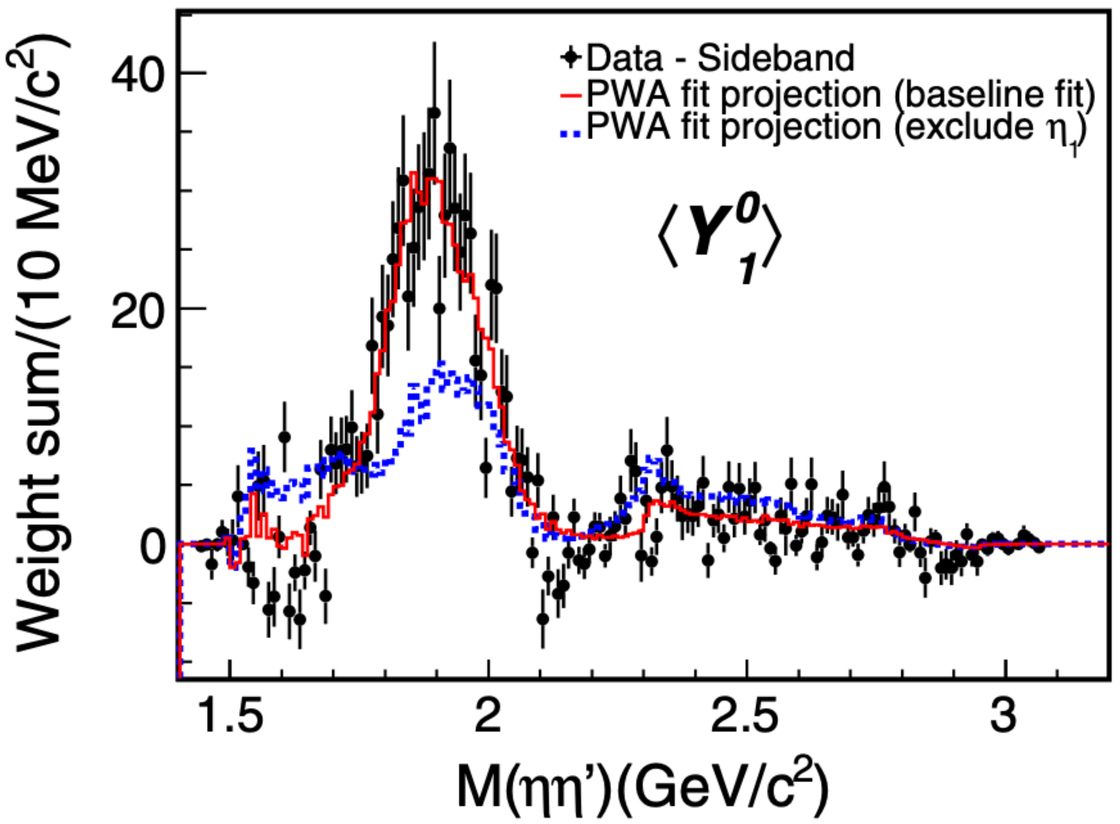
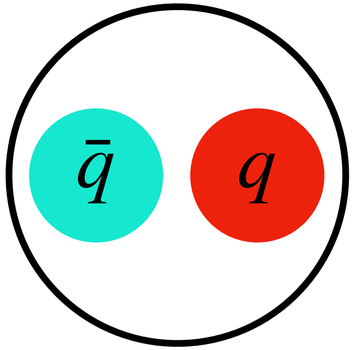
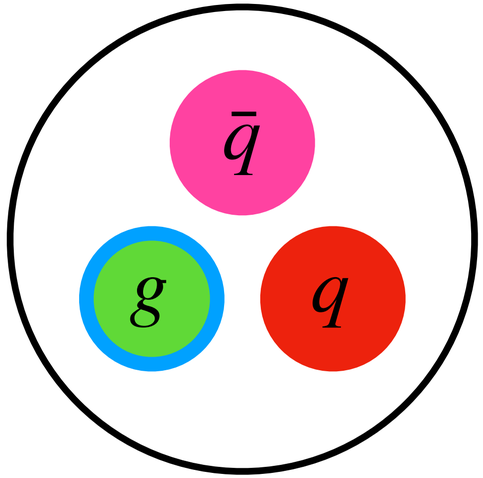


PWA fits decay angles too, state may not peak in mass distribution

The Path to Hybrid Mesons at GlueX

- Primary goal of GlueX is mapping out hybrid meson spectrum
- Understand production processes using conventional mesons
  - Study of beam asymmetries, SDMEs
- Identifying conventional mesons [like $a_2(1320)$] through PWA
- Use previous measurements and lattice results
  - $\pi_1(1600)$ is well established in several decay modes
  - Prediction of π_1 decay widths based on lattice QCD
- Ultimately want to establish spectrum of hybrid mesons





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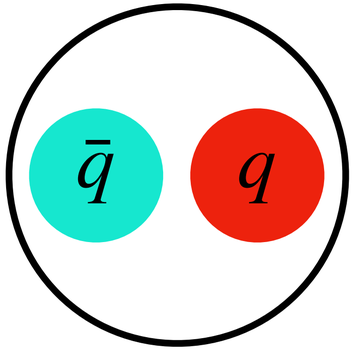
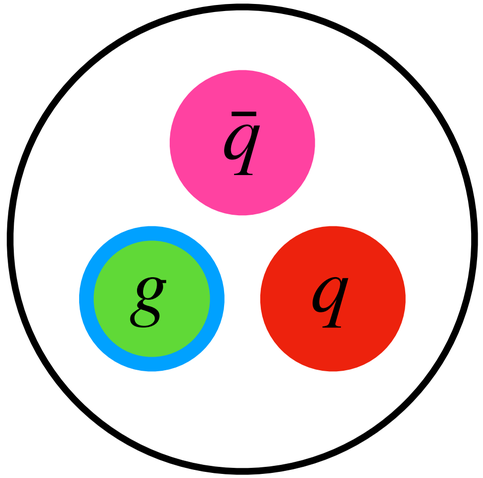
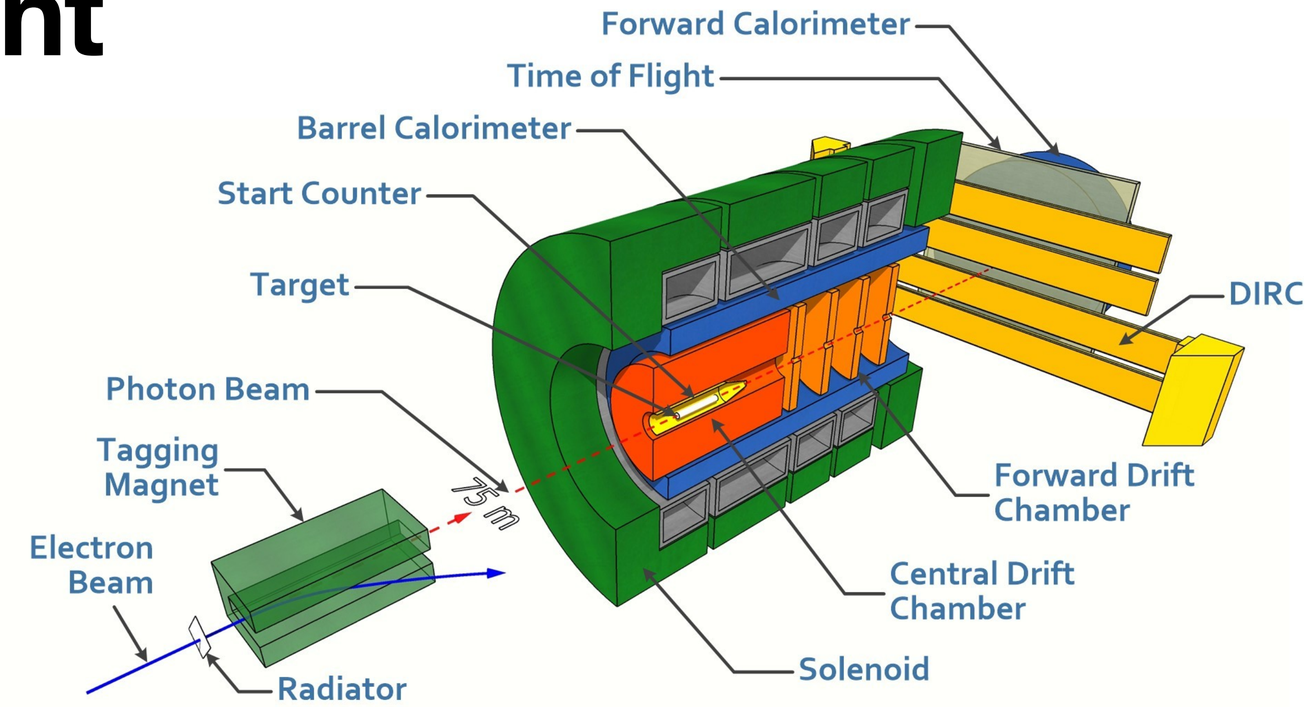




The GlueX Experiment

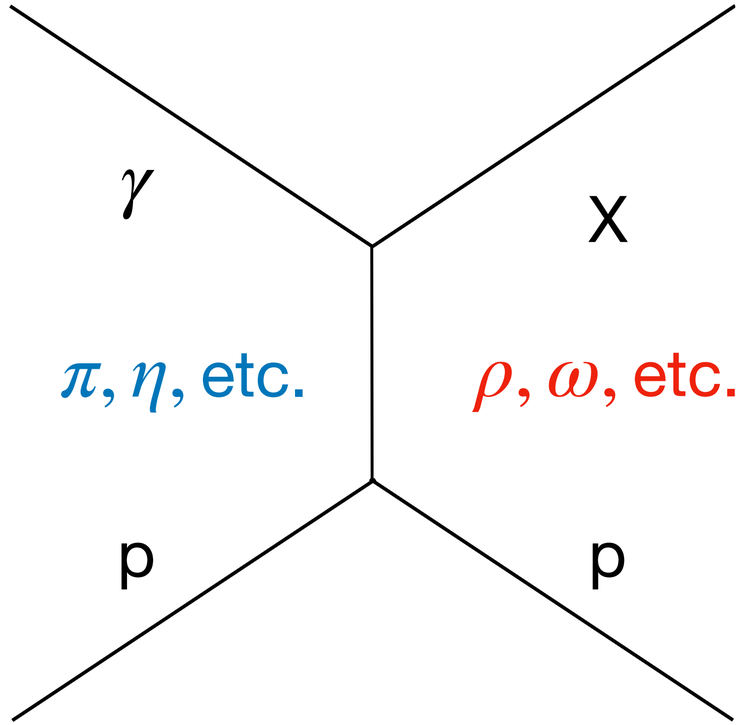
- CEBAF electrons impinge on diamond radiator
- Linearly polarized photons hit liquid hydrogen target
- Can reconstruct both charged and neutral particles



Data Set	Coherent Peak Luminosity	Luminosity for $E_\gamma > 6$ GeV	Percent Collected
GlueX Phase-I	125.0 pb^{-1}	439.6 pb^{-1}	100%
GlueX Phase-II	132.4 pb^{-1}	386.2 pb^{-1}	33%

PWA Amplitudes

- Broad overlapping states can interfere
- Perform partial wave analysis (PWA)
  - Fit angular distributions in data to determine J^{PC} of produced resonances
- t-channel production through natural or unnatural exchange particles
  - Natural for $J^P = 0^+, 1^-, 2^+, \ldots$
  - Unnatural for $J^P = 0^-, 1^+, 2^-, \ldots$

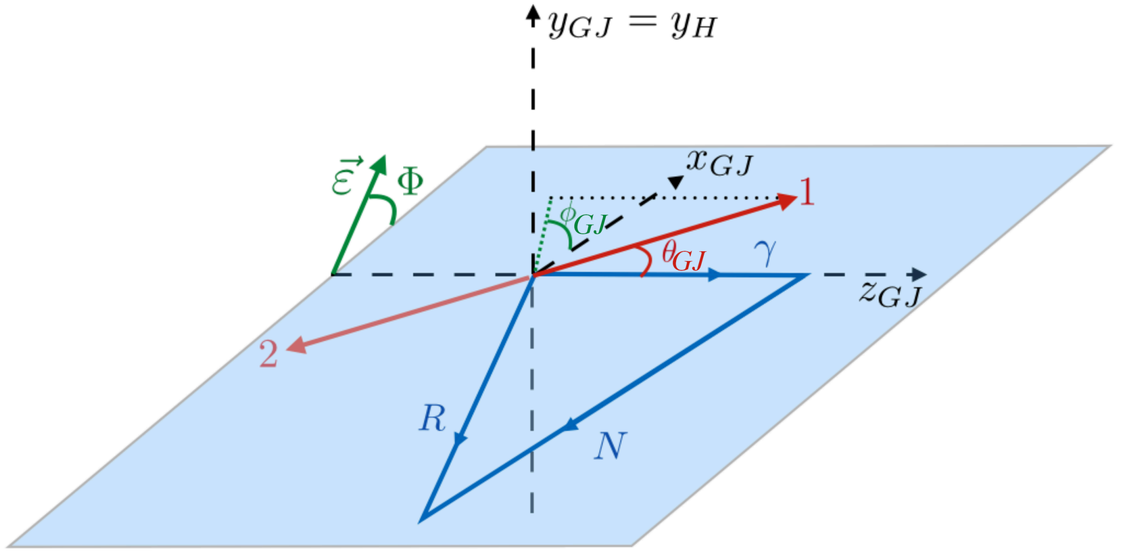


Sensitivity to naturality of exchange particle comes from photon polarization

	$S-$wave $(\ell = 0)$	$P-$wave $(\ell = 1)$	$D-$wave $(\ell = 2)$
J^{PC}	0^{++}	1^{-+} (exotic)	2^{++}

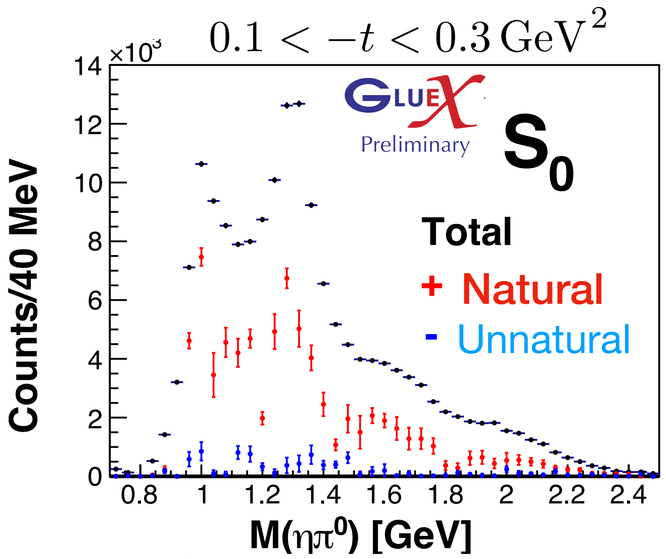
PWA Amplitudes

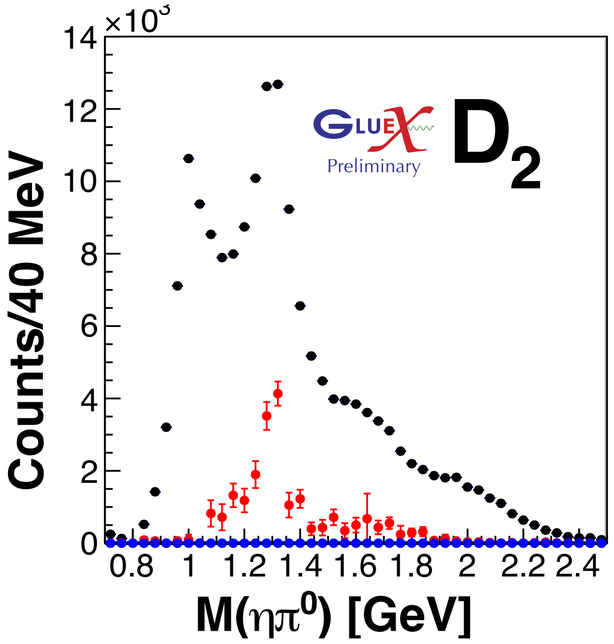
- Natural for $J^P = 0^+, 1^-, 2^+, \ldots$
- Unnatural for $J^P = 0^-, 1^+, 2^-, \ldots$
- $\cos\theta$ and ϕ describe resonance decay
- Φ angle between production plane and photon polarization vector
- Use Z_l^m amplitude basis: $Z_l^m(\Omega, \Phi) = Y_l^m(\Omega) e^{-i\Phi}$



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

Mass Independent PWA to $\eta\pi^0$ System





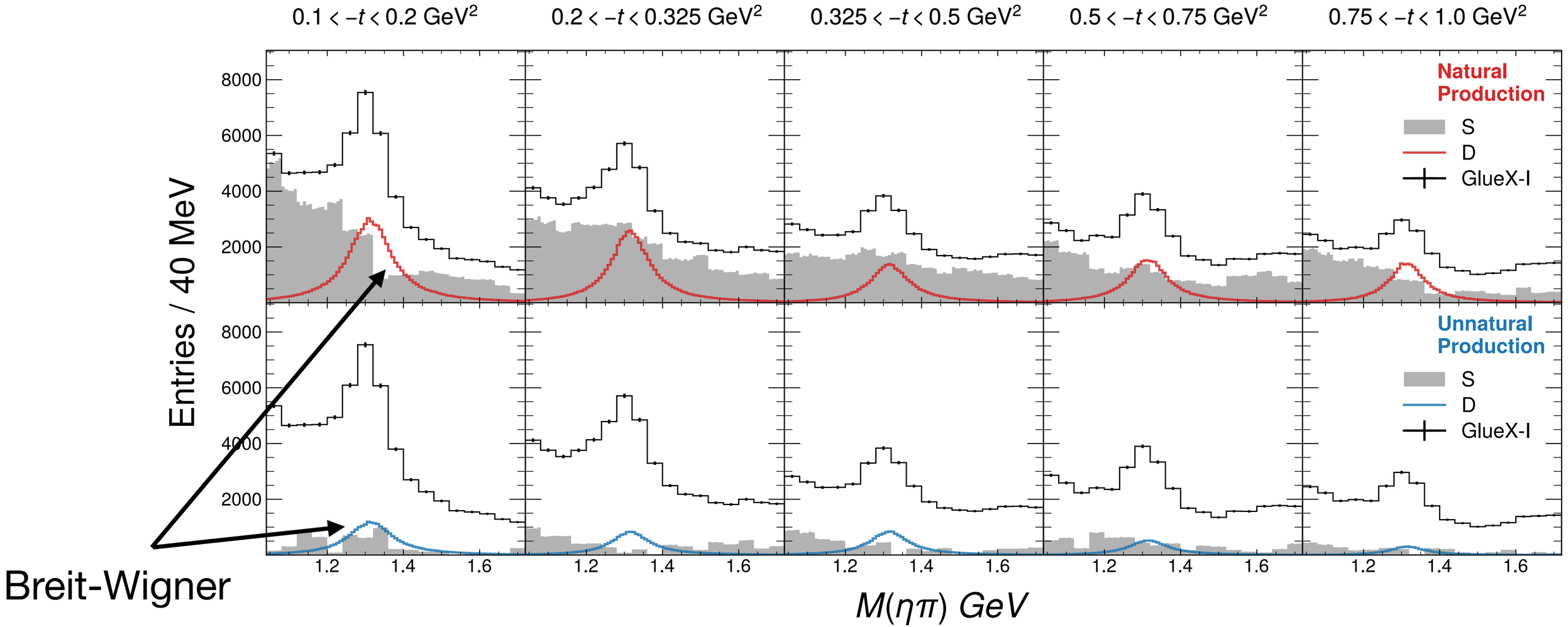
Study process $\gamma p \to \eta\pi^0 p$

- Each point in plots an independent fit to data
- Large S wave natural exchange contribution
- Clear $a_2(1320)$ signal in D_2^+ wave
- Use TMD 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)]

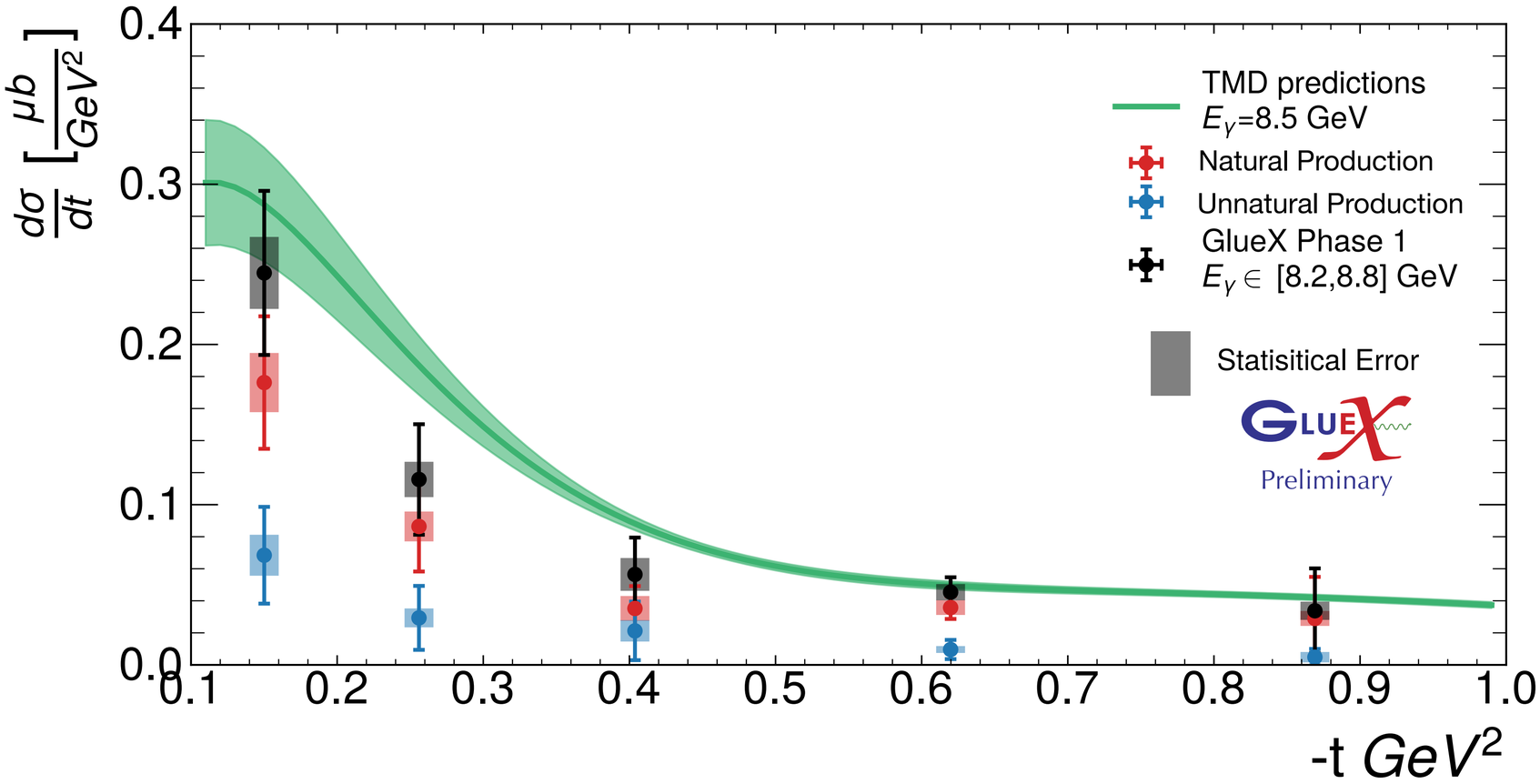
- Challenges: leakage between waves, ambiguities
- Number of fit parameters = $\sum_{\ell=0}^{\ell_{max}} 2 \cdot (2\ell + 1)$
- Add physical constraint to reduce complexity

Semi-Mass Independent PWA to $\eta\pi^0$ System



Showing coherent sum of all S wave and all D wave contributions

PWA of $\eta\pi^0$ System - $a_2^0(1320)$ Cross Section

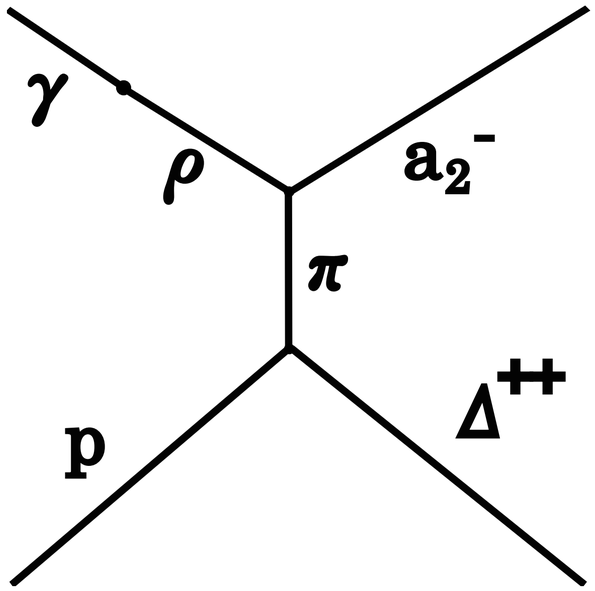


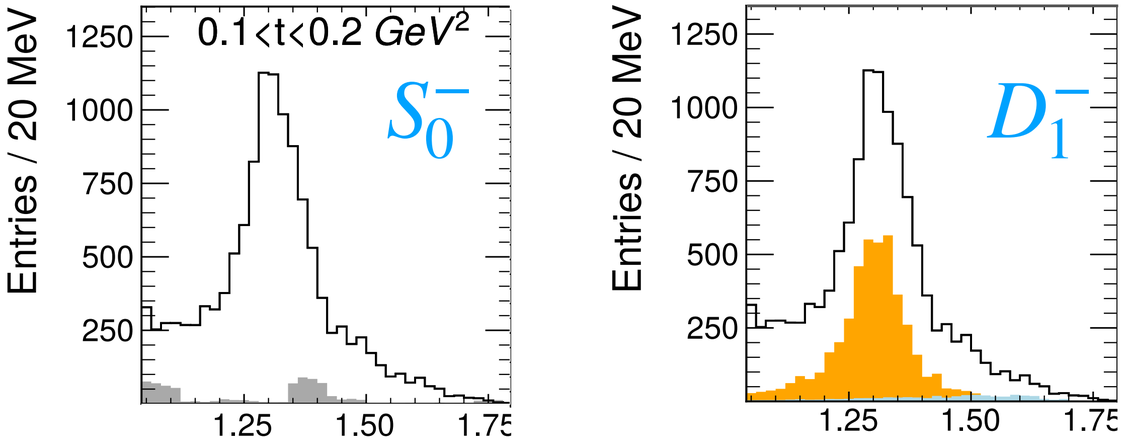
- Measured values agree well with TMD model (based on unpolarized CLAS data)
- First separation of natural and unnatural production mechanisms - publication in progress

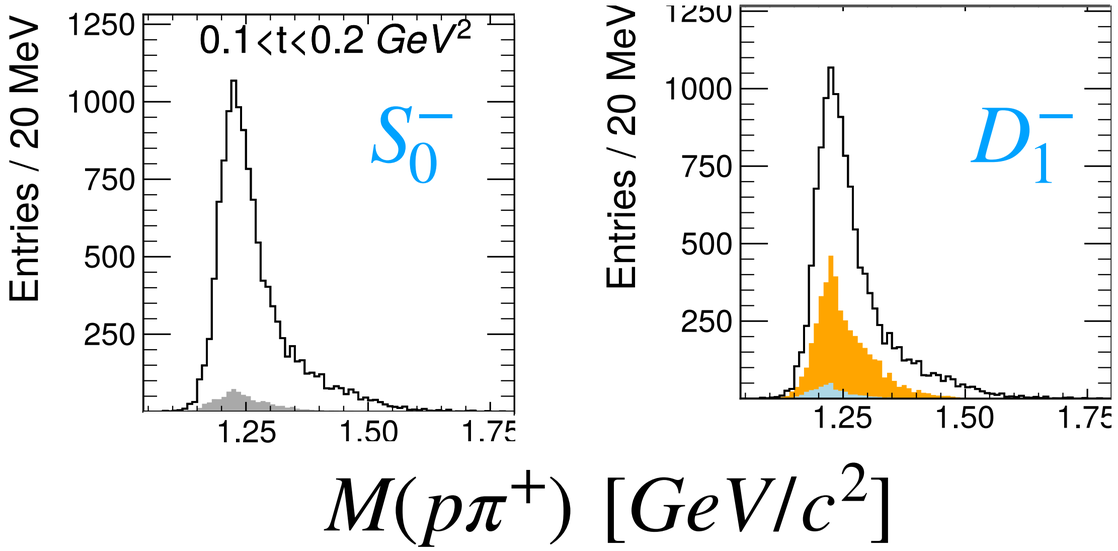
PWA of $\eta\pi^-$ System

$\gamma p \rightarrow \eta\pi^-\Delta^{++}$

- Same stability issues as $\eta\pi^0$
  - Use semi-mass independent fit
- Additional complications from Δ^{++}



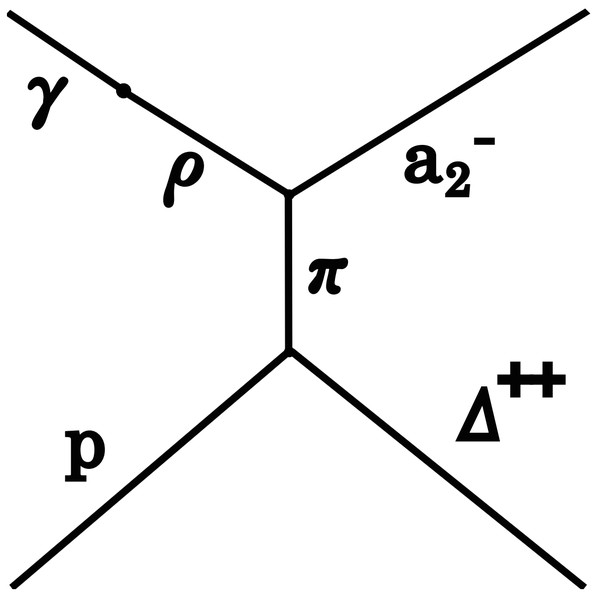


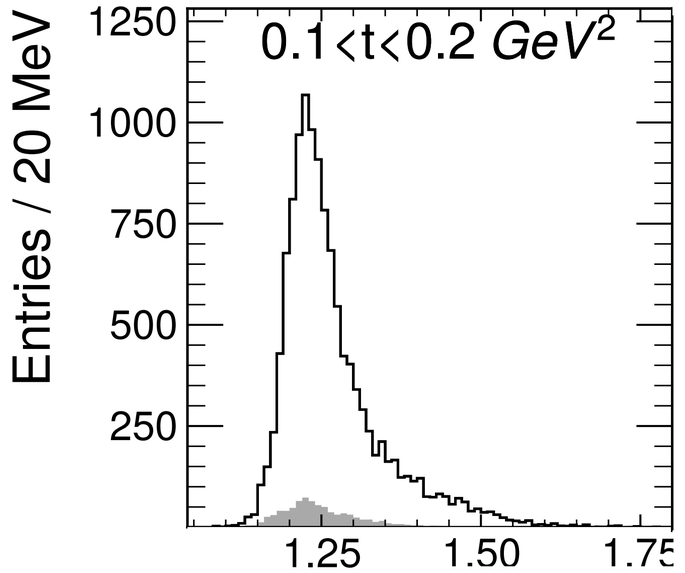


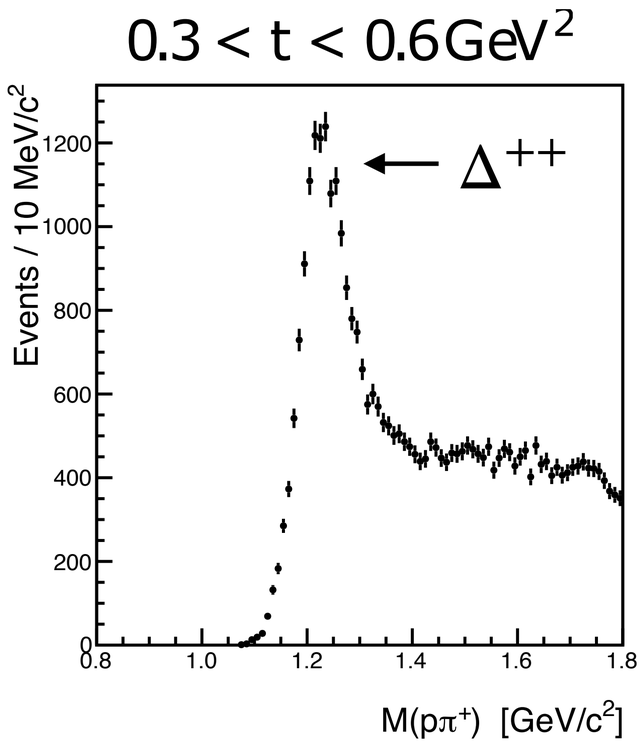
PWA of $\eta\pi^-$ System

$\gamma p \rightarrow \eta\pi^-\Delta^{++}$

- Additional complications from Δ^{++}
  - Additional decay angles
  - Background at larger -t

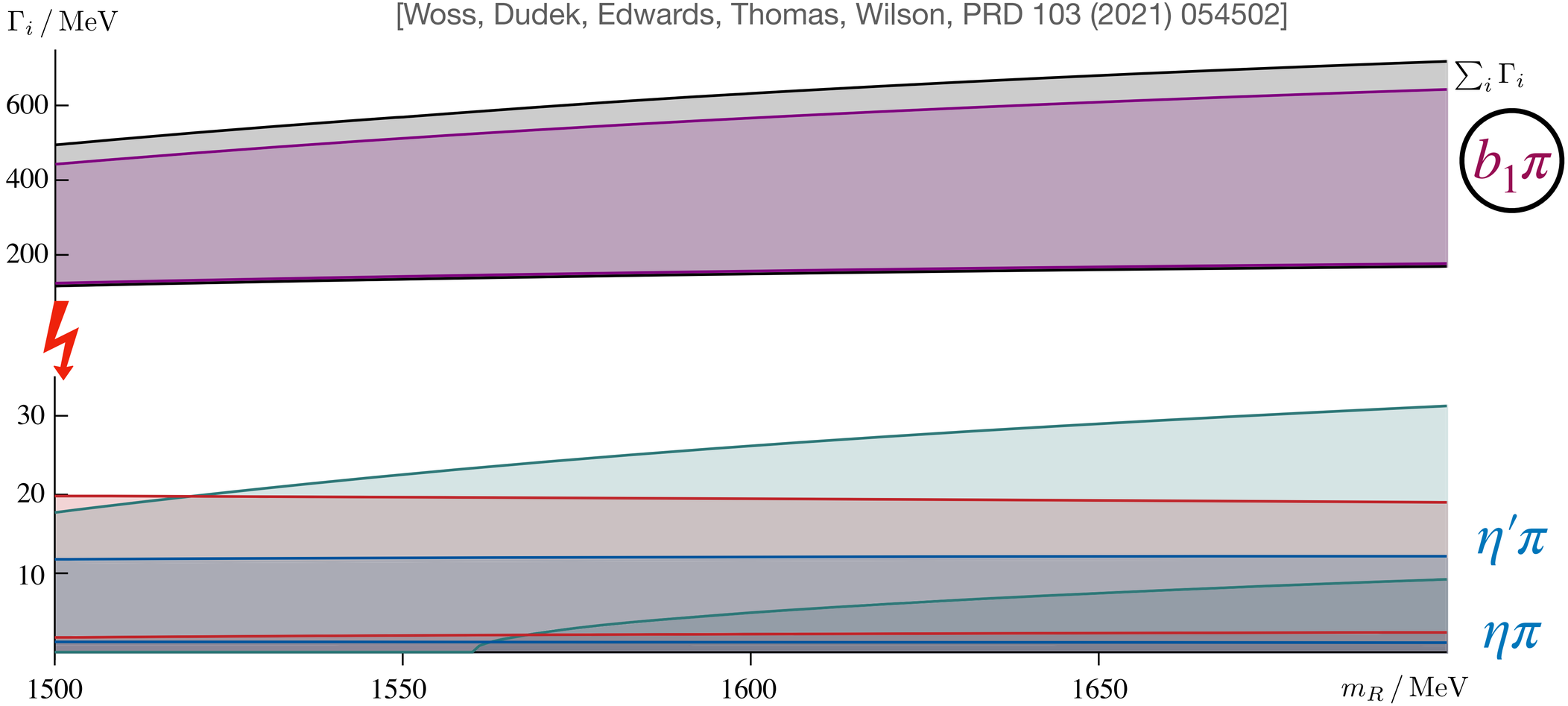






Lattice QCD Predicted π_1 Decay Widths

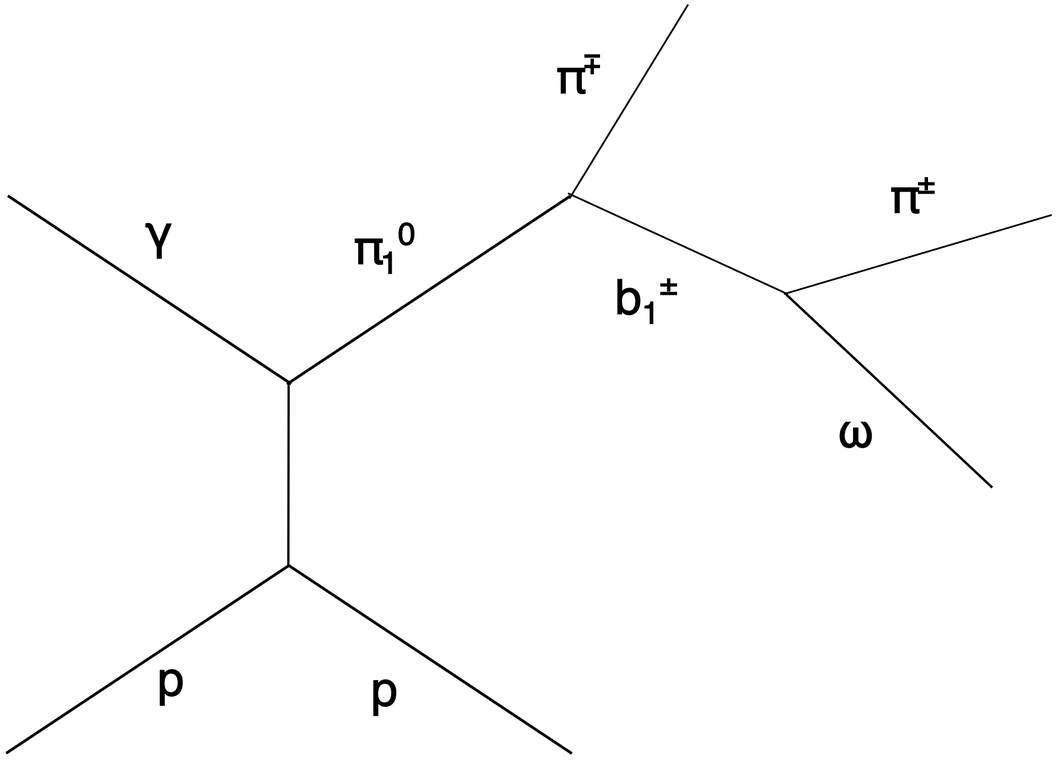
[Woss, Dudek, Edwards, Thomas, Wilson, PRD 103 (2021) 054502]

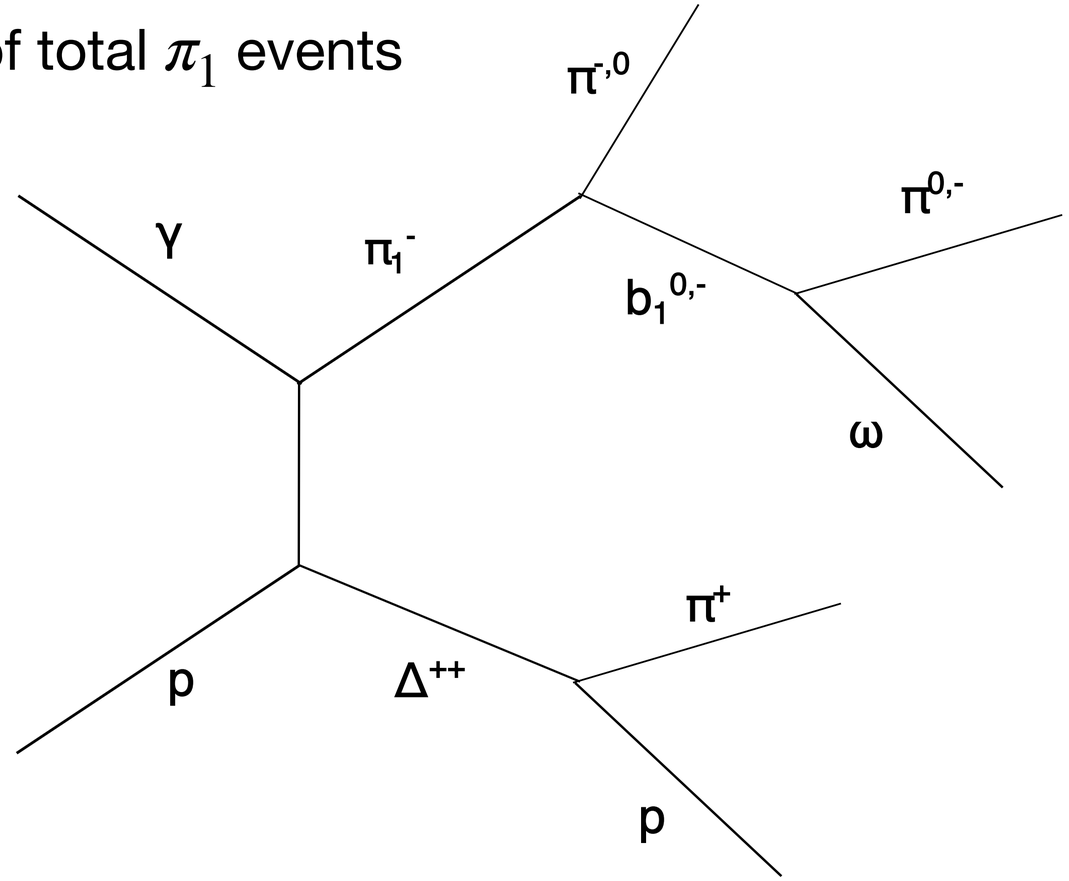


- Note: broken y-axis scale, $b_1\pi$ substantially larger than $\eta^{(\prime)}\pi$
- $b_1\pi$ PWA difficult - S-wave decay with broad b_1 isobar

What can we learn from $b_1\pi$?

- b_1 has large decay width to $\omega\pi$
- Expect $\pi_1 \to b_1\pi \to \omega\pi\pi$ to be large fraction of total π_1 events



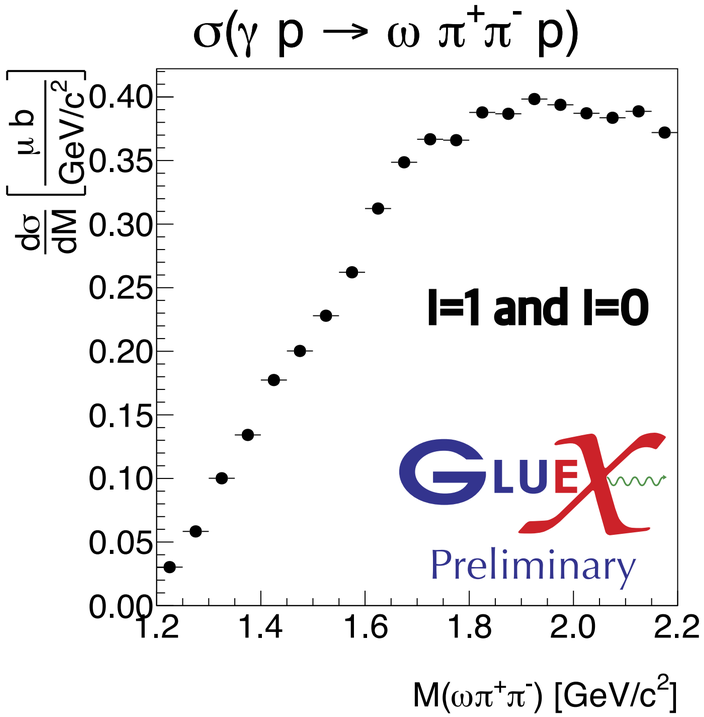


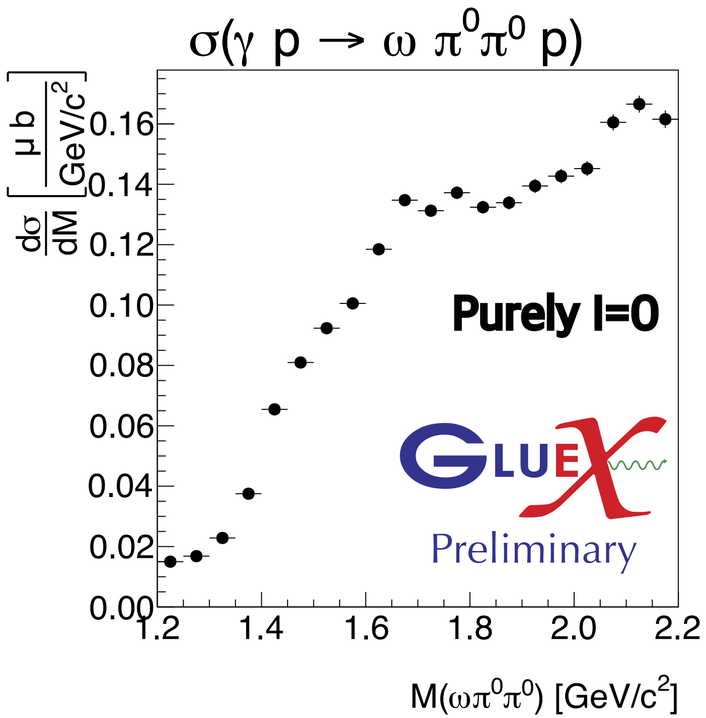
π_1^0 should contribute in $\gamma p \to \omega\pi^+\pi^- p$

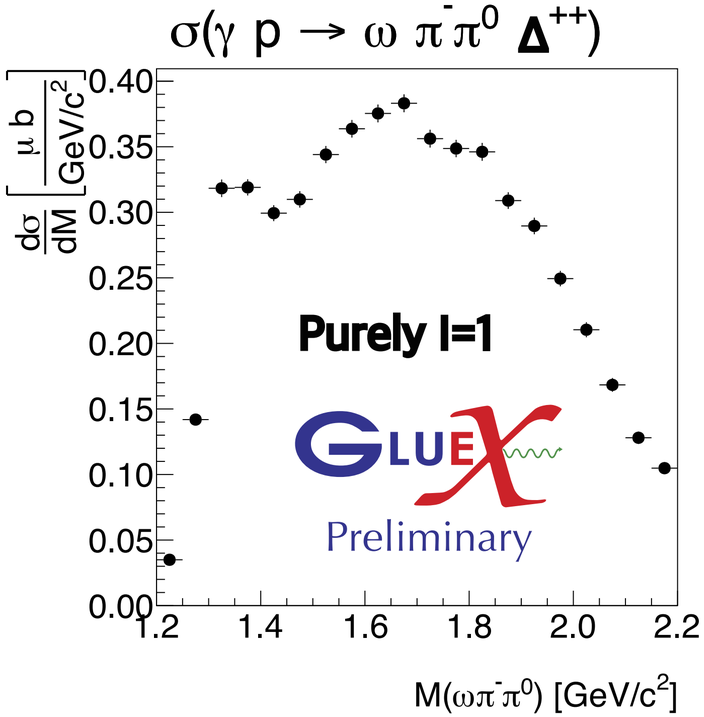
π_1^- should contribute in $\gamma p \to \omega\pi^-\pi^0\Delta^{++}$

Upper Limit on π_1 Photoproduction

- π_1 is isospin-1, but $\omega\pi^+\pi^-$ can have $I = 1$ and $I = 0$
- Use isospin conservation to separate $I = 1$ part of $\omega\pi^+\pi^-$
  - Assuming no $I = 2$, $\sigma(\omega\pi\pi)_{I=1} = \sigma(\omega\pi^+\pi^-) - 2\sigma(\omega\pi^0\pi^0)$





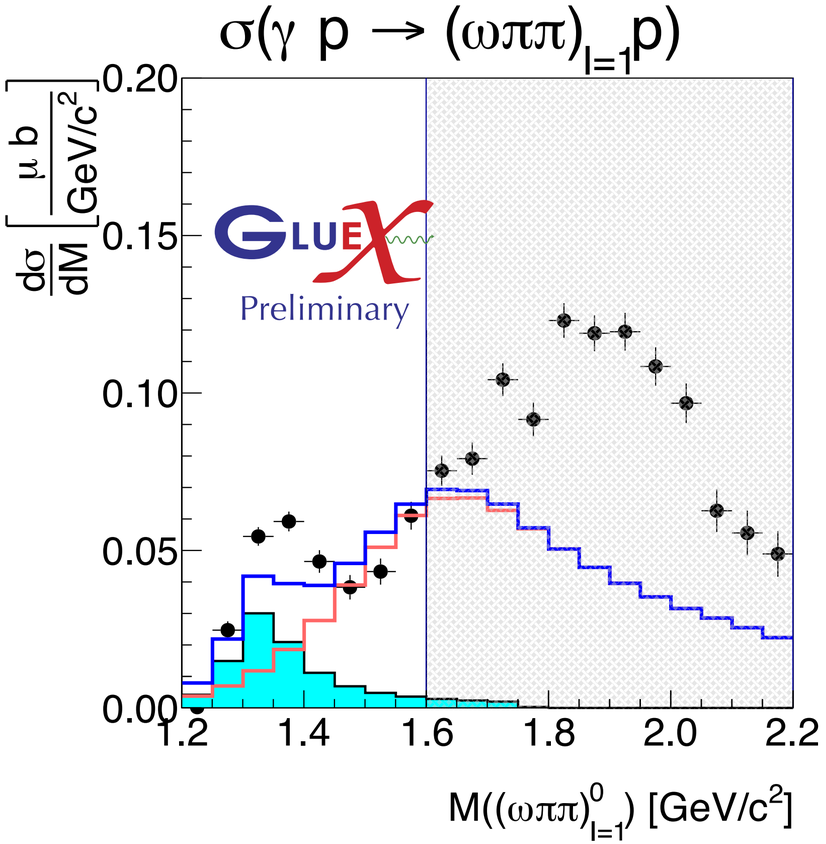


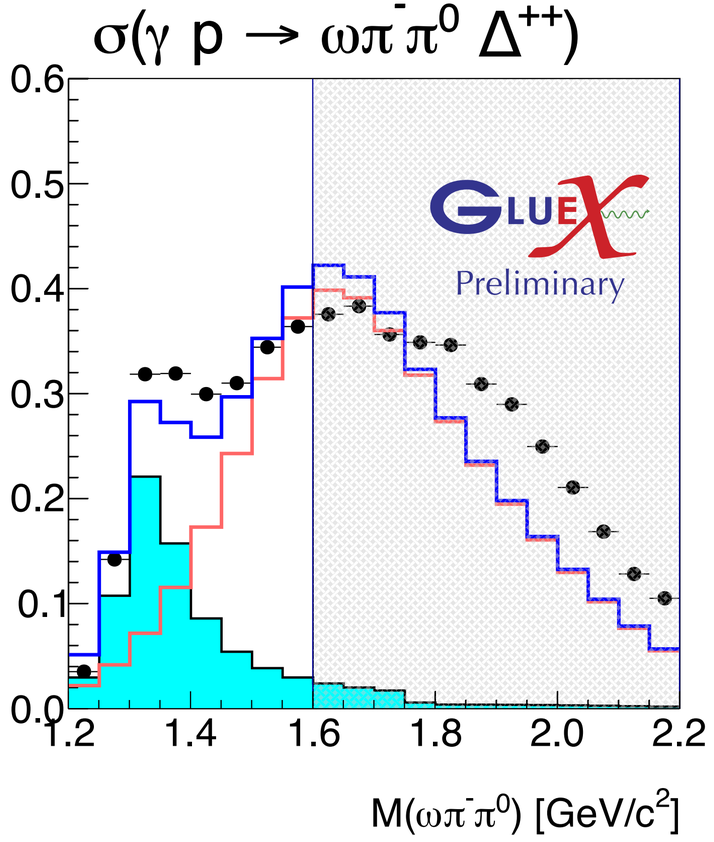
Fits to $I = 1$ $\omega\pi\pi$ Systems

- Expect $I = 1$ $\omega\pi\pi$ to have contribution from $a_2(1320)$
- Fit assuming just $a_2(1320)$ and $\pi_1(1600)$ contribute

$a_2(1320)$ Breit-Wigner [PDG]

$\pi_1(1600)$ Breit-Wigner [JPAC]

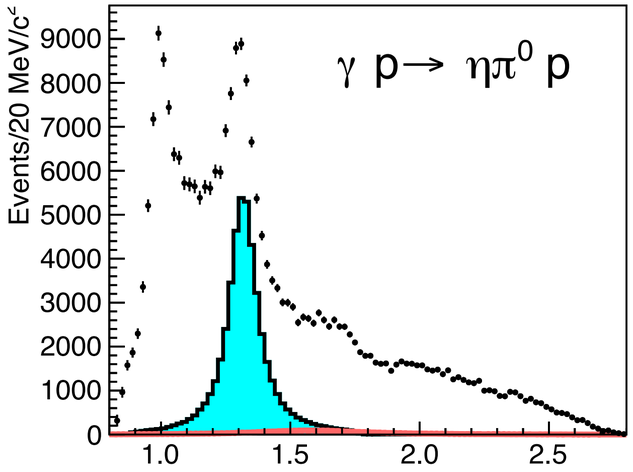


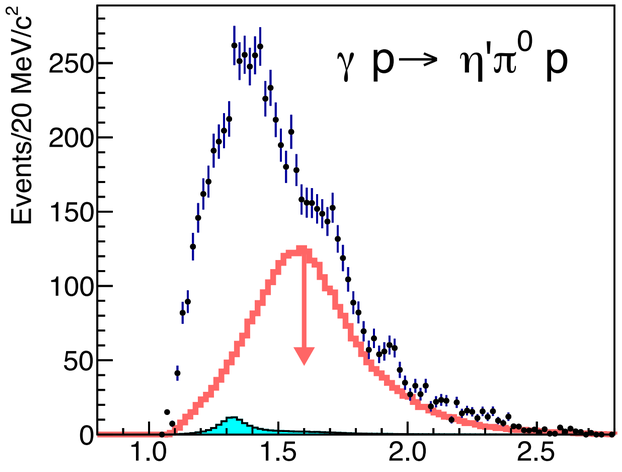


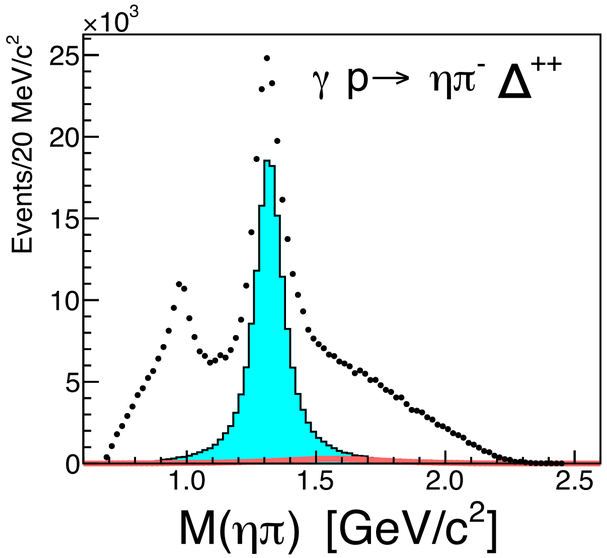
$$\frac{\sigma(\pi_1^0)_{ul}}{\sigma(a_2^0(1320))} < 2.09$$

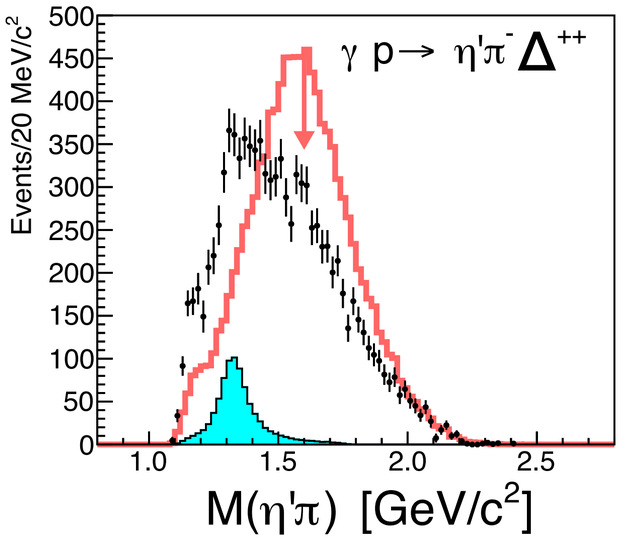
$$\frac{\sigma(\pi_1^-)_{ul}}{\sigma(a_2^-(1320))} < 1.40$$

Projecting π_1 Limit to $\eta^{(\prime)}\pi$ final states









- Use LQCD π_1 decay widths to estimate maximum π_1 in $\eta^{(\prime)}\pi$
- $\eta\pi$ expected to have at most percent-level contribution from $\pi_1(1600)$
- Cannot rule out large $\pi_1(1600)$ contribution in $\eta'\pi$
- Publication nearing submission!

GlueX-I Data

a_2 MC Projection

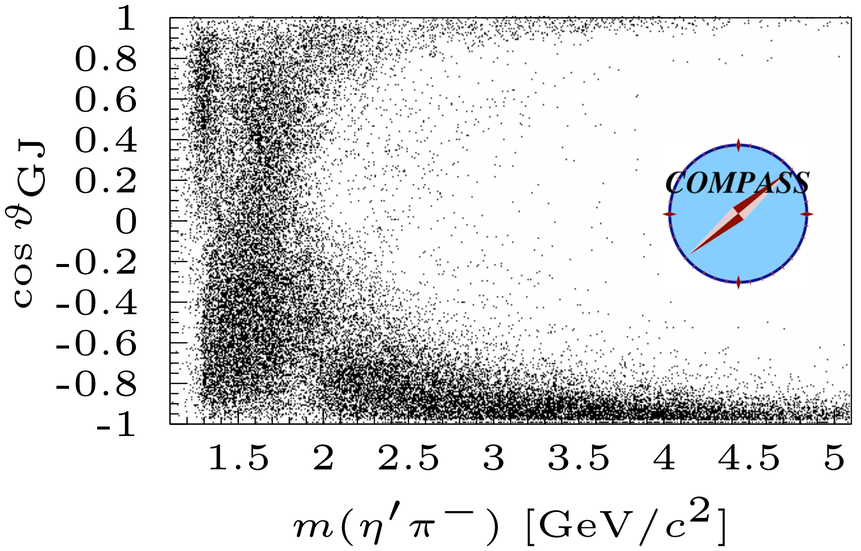
π_1 MC Upper Limit

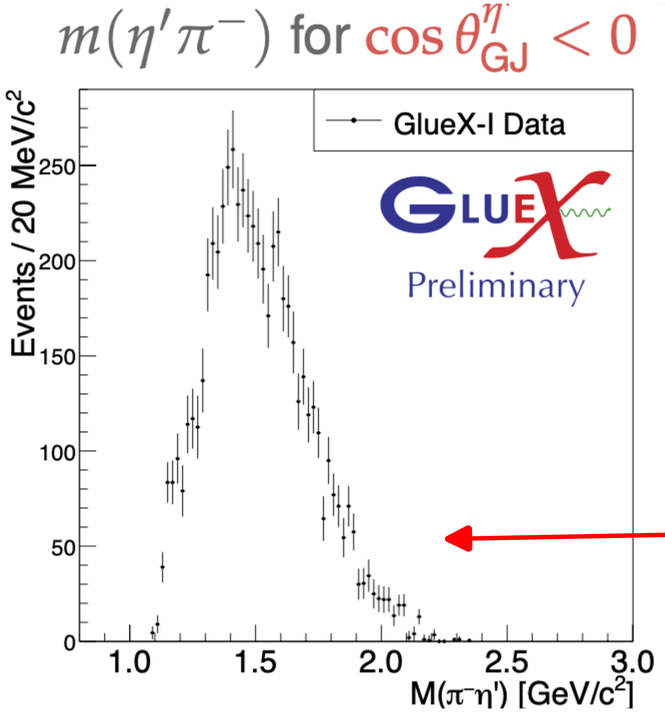
GLUEX

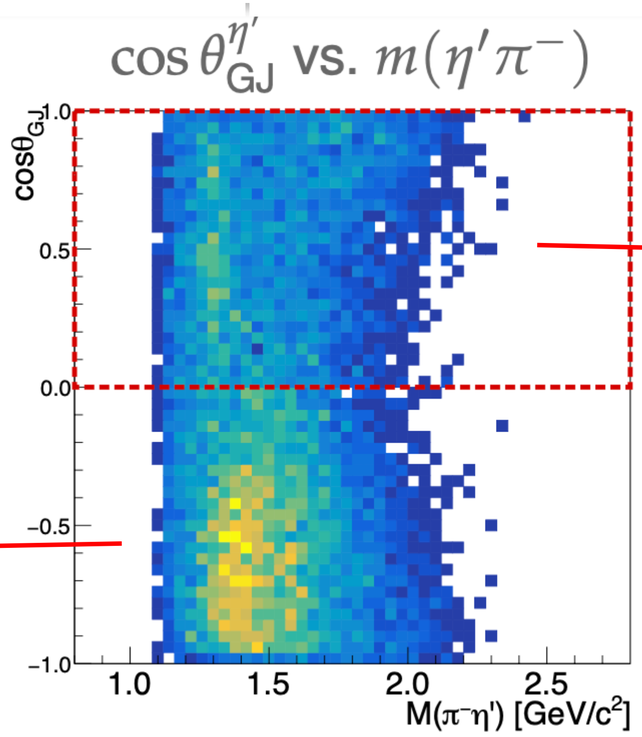
Preliminary

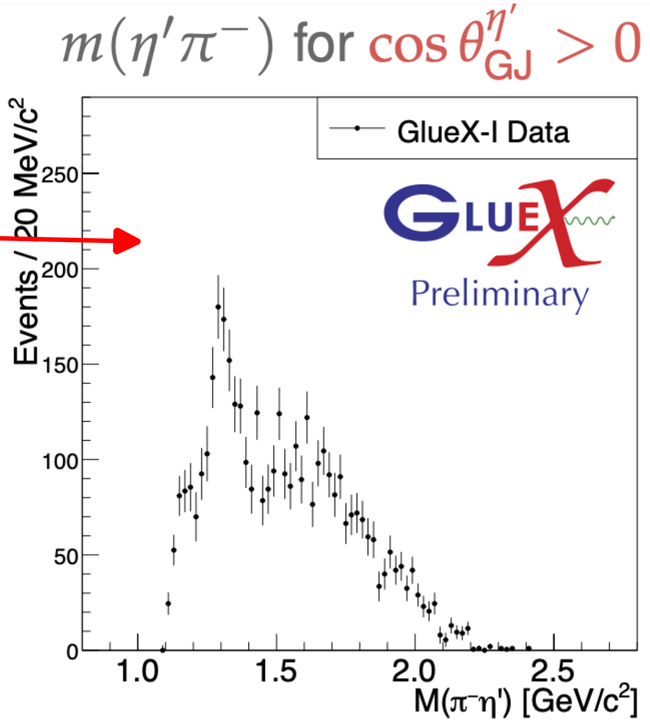
Prospects for $\eta'\pi^-$

- Clear forward/backward asymmetry
- Working on rigorous extraction of potentially exotic signal









Physics Outside the Hybrid Meson Search

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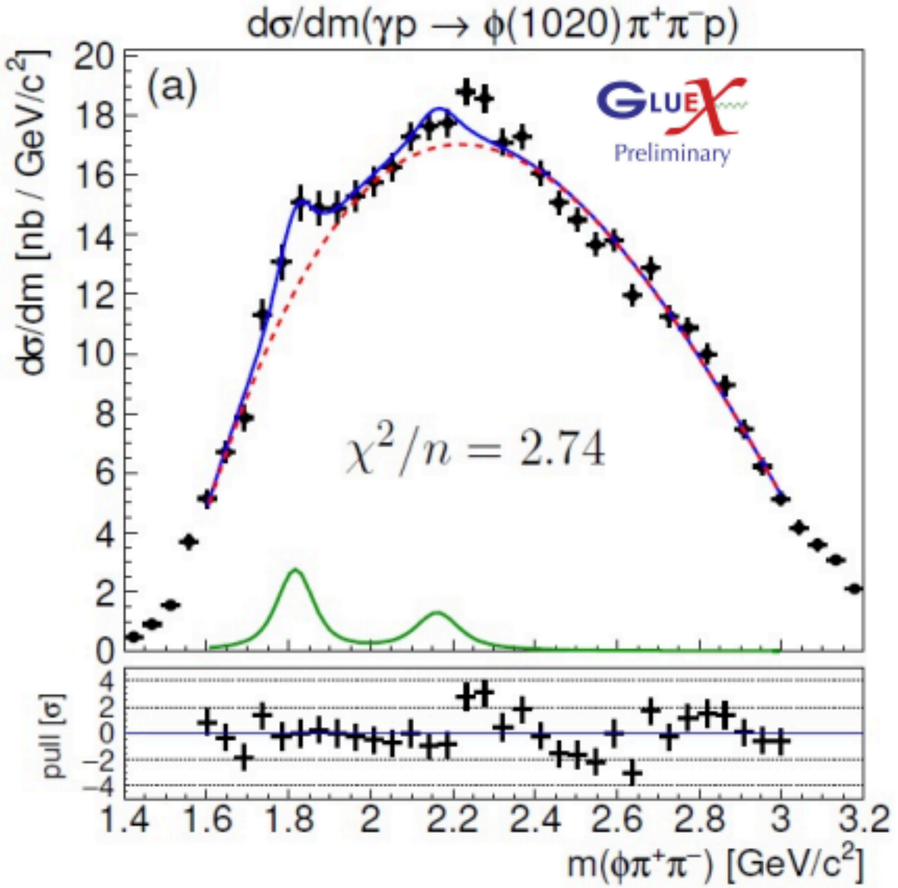
- Use previous measurements and lattice results
  - $\pi_1(1600)$ is well established in several decay modes
  - Prediction of decay widths based on lattice QCD
- Baryon anti-baryon (Hao), vector pseudo scalar analyses (Edmundo)
- Results on $\phi\pi\pi$, K_sK_s, K_sK_L

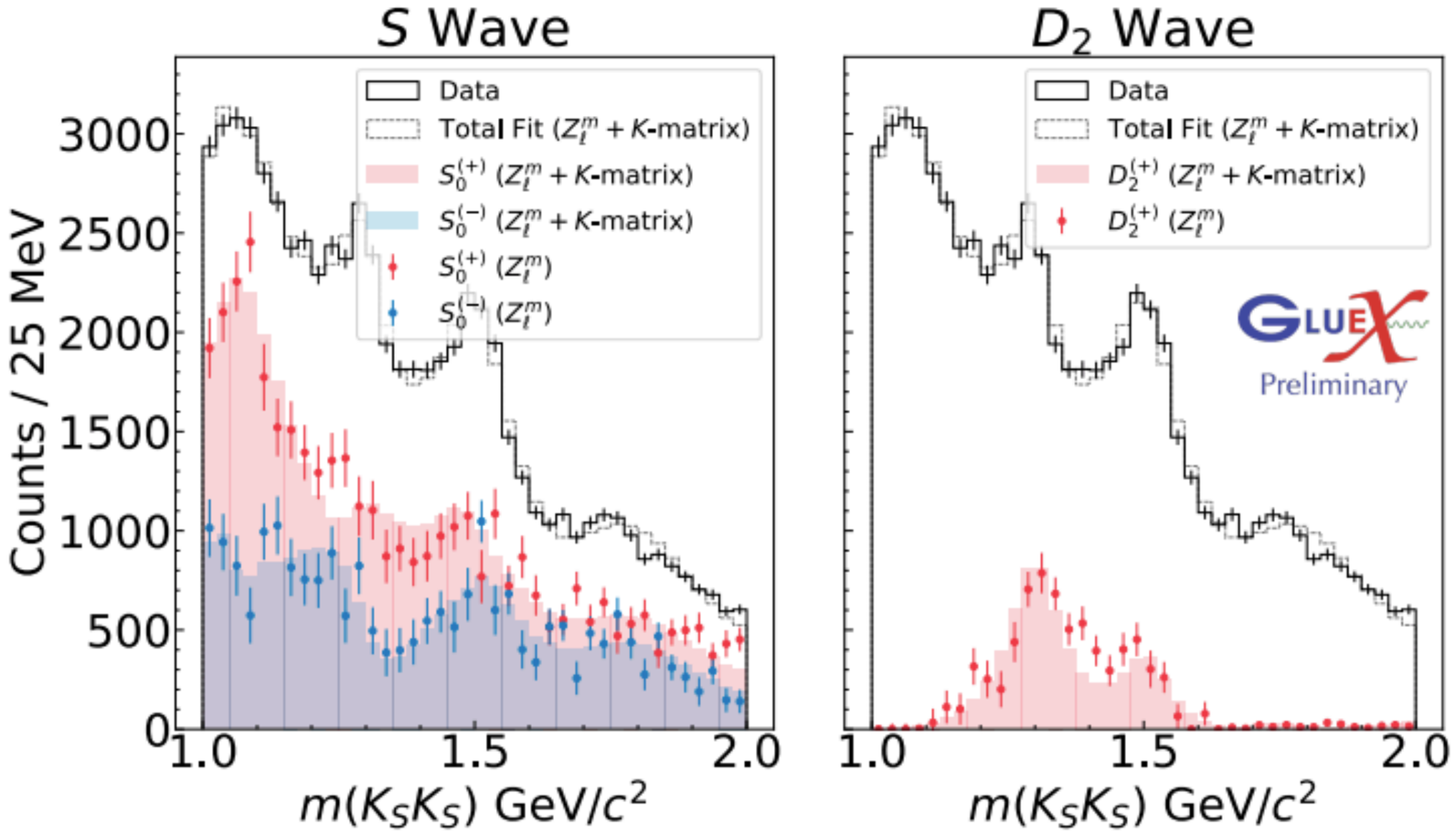
Search for $\phi(2170)$ in $\phi\pi\pi$

- Exotic meson candidate $Y(4230)$ found decaying to $\pi\pi J/\psi$
- $\phi(2170)$ believed to be strange equivalent
- Measure $\sigma(\gamma p \to \phi\pi\pi p)$ vs. $M(\phi\pi\pi)$
- Fit background poly + $\phi(2170)$ Voigtian
- Large background and systematics - set limit
- $\sigma(\gamma p \to \phi(2170)p) < 379$ pb at 90% CL



Studies on $K\bar{K}$

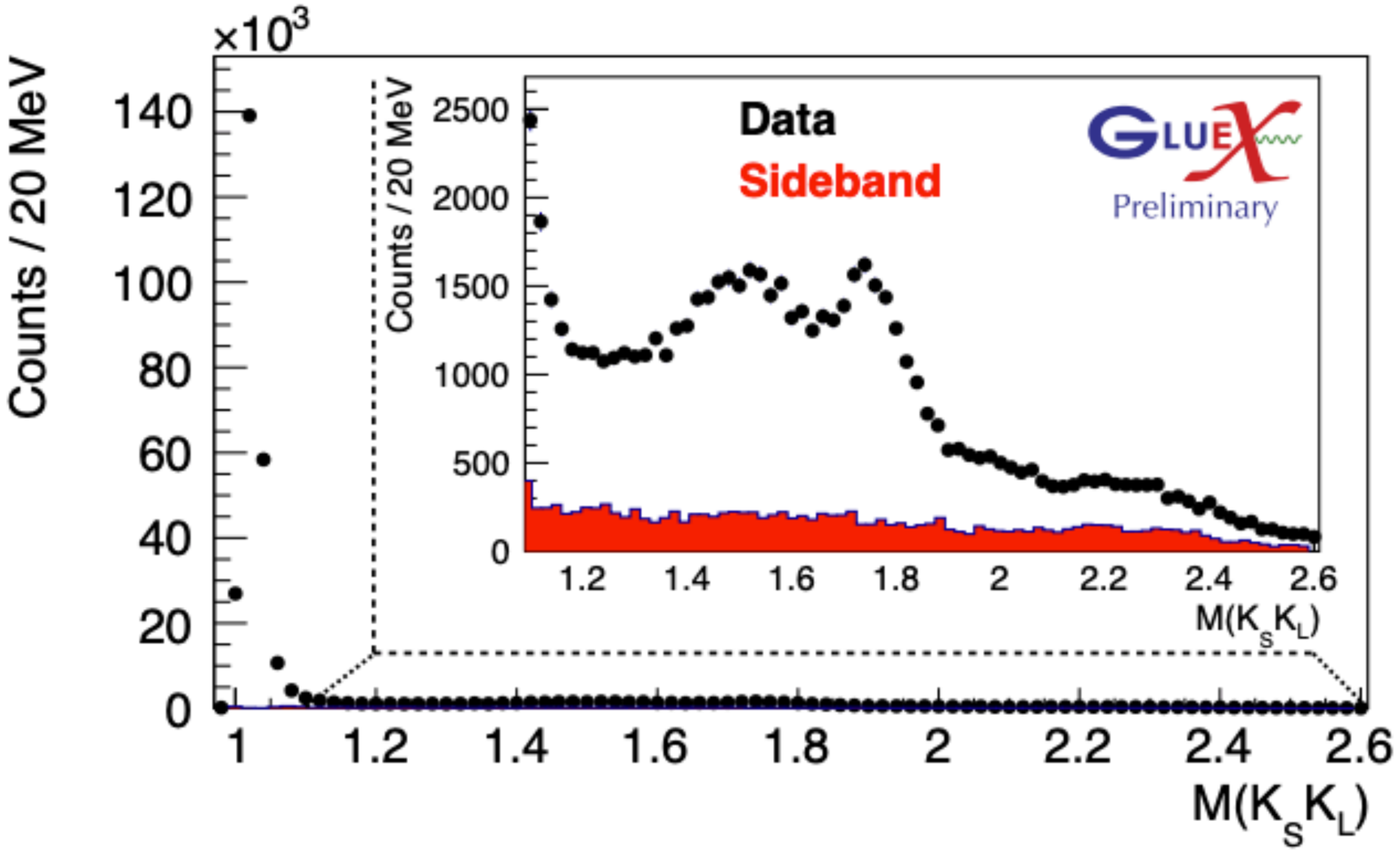
- K_sK_s has $J^{PC} = (0,2,...)^{++}$
  - Glueball candidates
- Preliminary PWA results



Structure visible in both S and D waves

Studies on $K\bar{K}$

- K_sK_L has $J^{PC} = (1,3,...)^{--}$
  - Vector meson hybrids
- Very preliminary results



Large peak from ϕ, additional structure at higher mass

PWA under way

Conclusion

- GlueX has very active spectroscopy program
  - Linearly polarized photon beam gives access to production mechanisms
- $\pi_1(1600)$ upper limit nearing submission
  - Determine largest discovery potential is in $\eta'\pi$ final state
- Neutral $a_2^0(1320)$ cross section nearing publication
  - First time production mechanisms have been separated
- Many interesting projects outside of the exotic hybrid meson search

Acknowledgements: gluex.org/thanks