



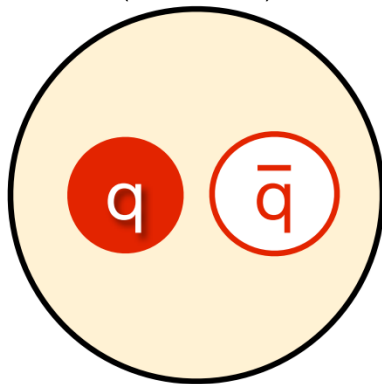
Searches for Exotic Mesons: Perspective from the GlueX Experiment

March 9, 2023
Jon Zarling

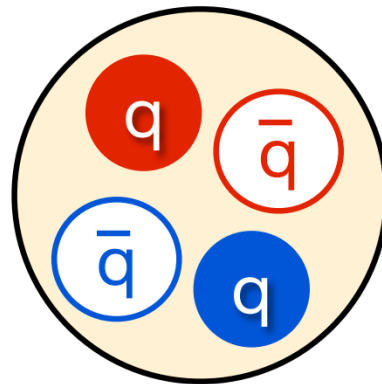


Hadrons by Constituents

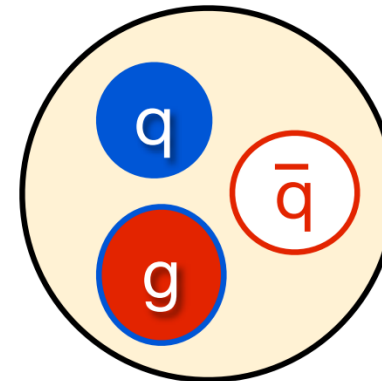
Meson
(conventional)



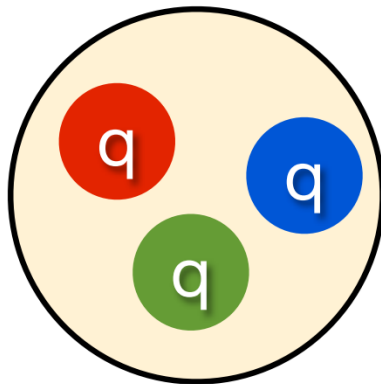
Tetraquark



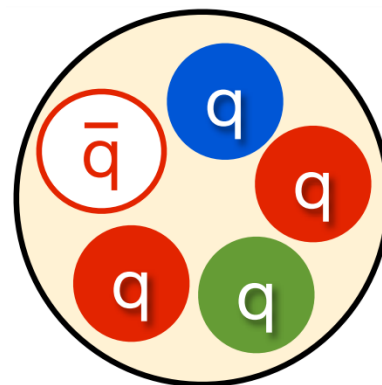
Hybrid meson



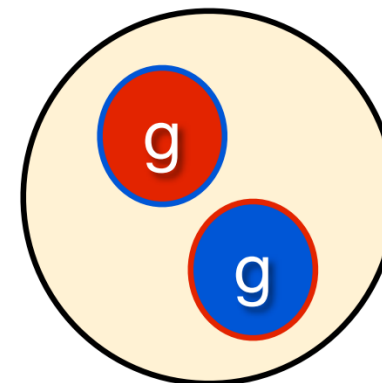
Baryon
(conventional)



Pentaquark



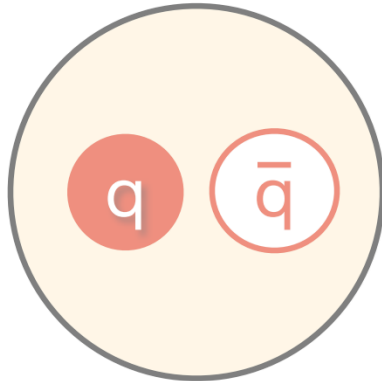
Glueball



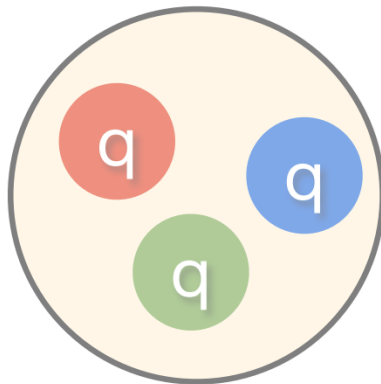


Hadrons by Constituents

Meson
(conventional)



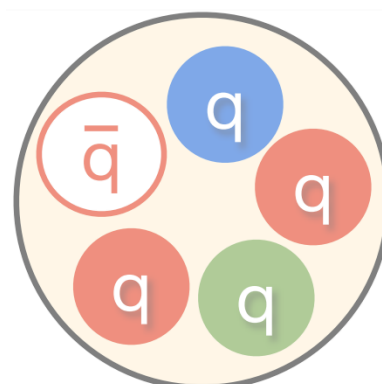
Baryon
(conventional)



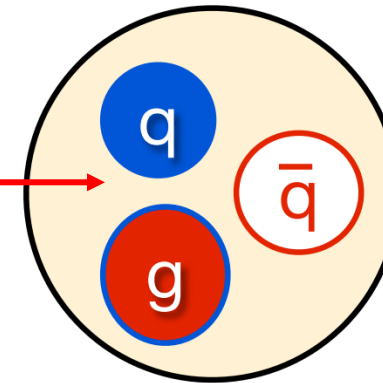
Tetraquark



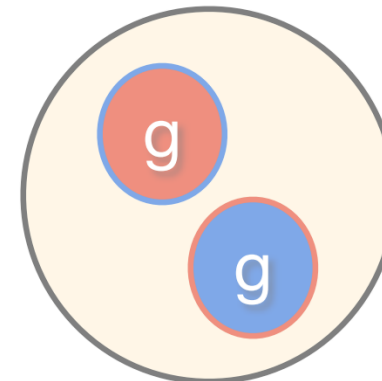
Pentaquark



Hybrid meson



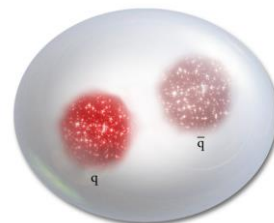
Glueball





Constituent Model Mesons

Quark Model Meson

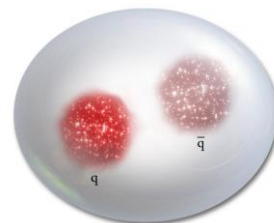


- $q\bar{q}$ pair
 - Meson as simple two-fermion system
- Quantum numbers J^{PC} :
 - J : total angular momentum, whole integer
 - P : parity, $(-1)^{L+1}$
 - C : charge conjugation $(-1)^{L+S}$
- Some quantum numbers unreachable:
 - $0^{+-}, 1^{-+}, 2^{+-}, \dots$



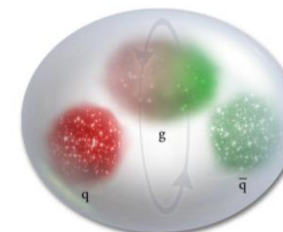
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Hybrid Meson

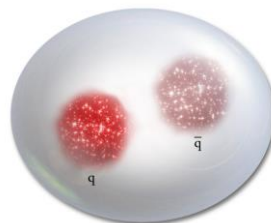


- $q\bar{q}g$ constituents
 - Add “dressed” gluon constituent
- Quantum numbers J^{PC} :
 - Same rules, but with added gluon
 - g contributes $J^{PC} = 1^{+-}$
- Now reachable:
 - $0^{+-}, 1^{-+}, 2^{+-}, \dots$



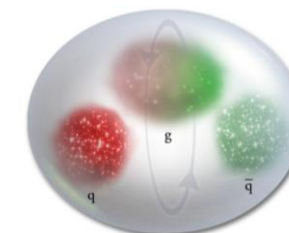
Constituent Model Mesons

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If observed, cannot be $q\bar{q}$ meson, call these “exotic”

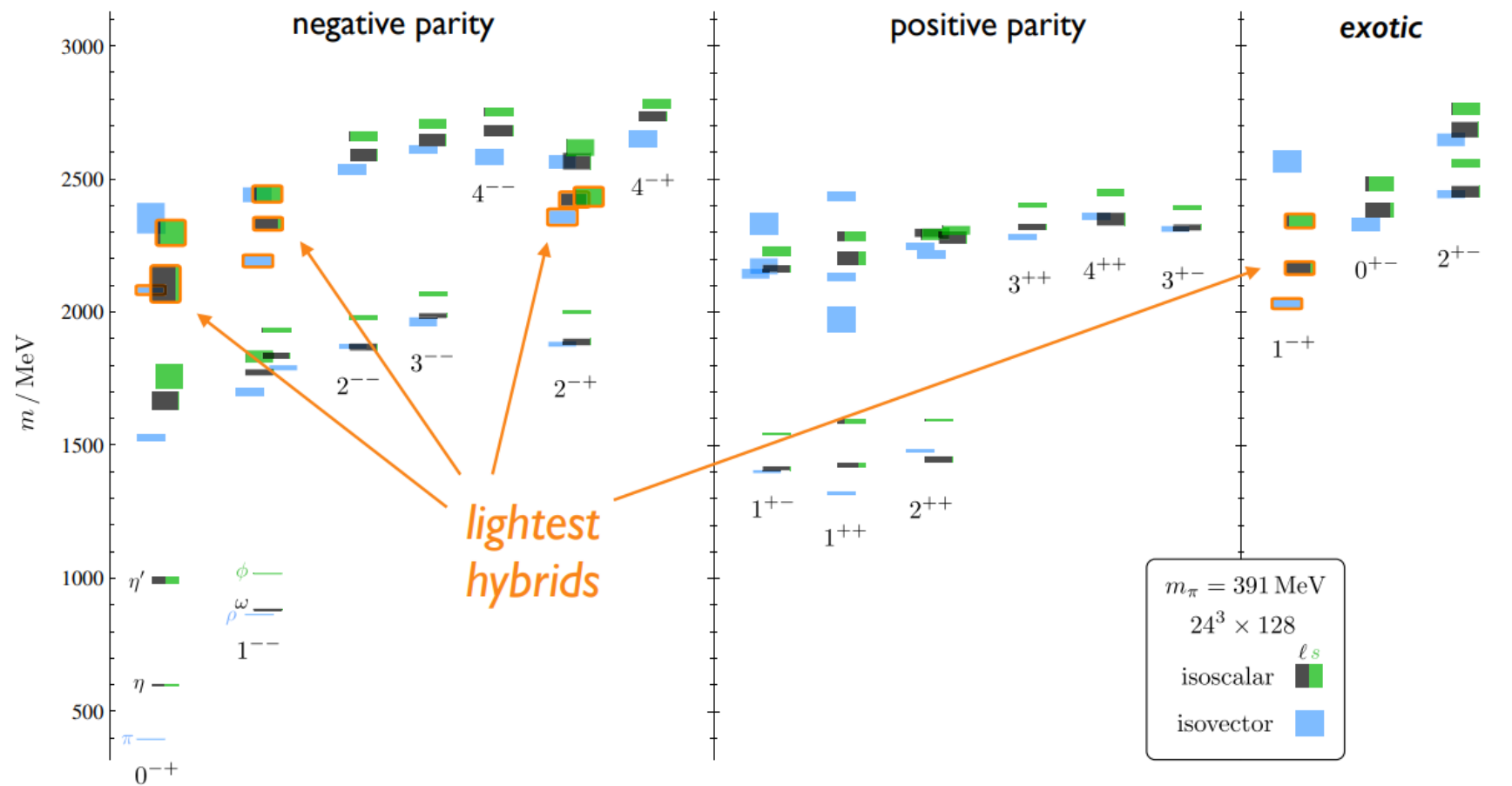




Predictions from Lattice QCD

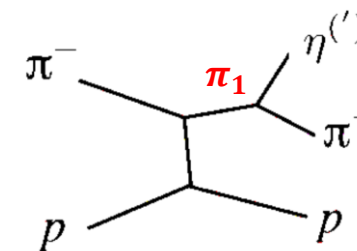
had spec

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



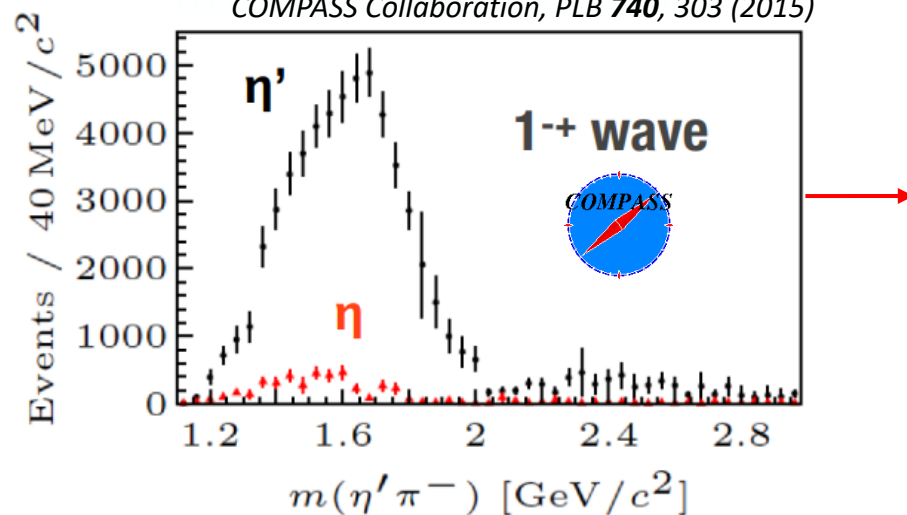
Evidence for Exotics?

- Best evidence exists for a $\pi_1(1600)$ exotic meson
- Recent evidence from COMPASS experiment
 - A state decaying to $\pi \eta^{(\prime)}$ with angular momentum 1 must be exotic

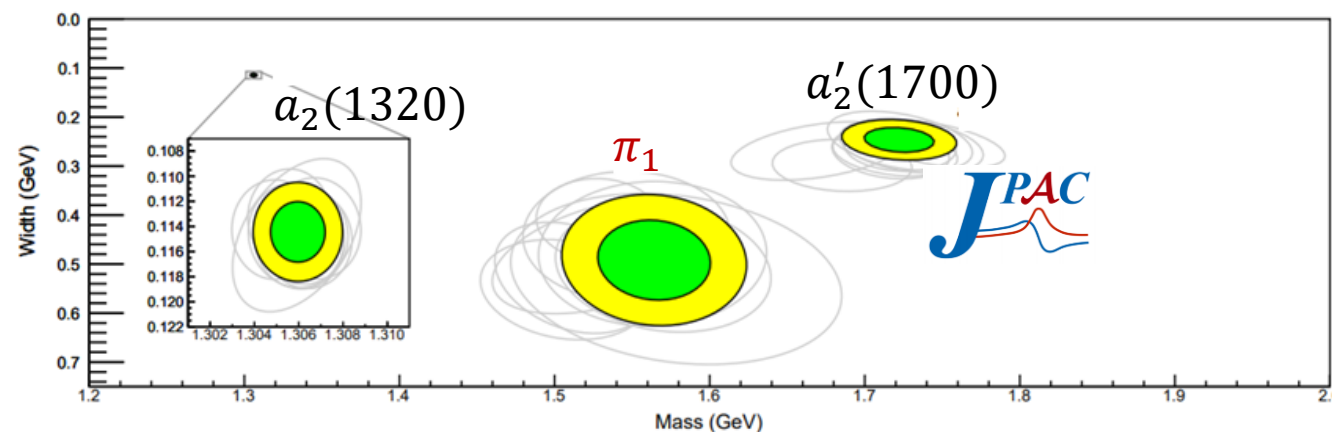


$$\pi^- p \rightarrow \pi^- \eta^{(\prime)} p$$

COMPASS Collaboration, PLB **740**, 303 (2015)



A. Rodas et al. (JPAC), PRL **122**, 042002 (2019)





Exotic Hybrid Decay Modes

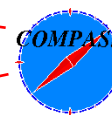
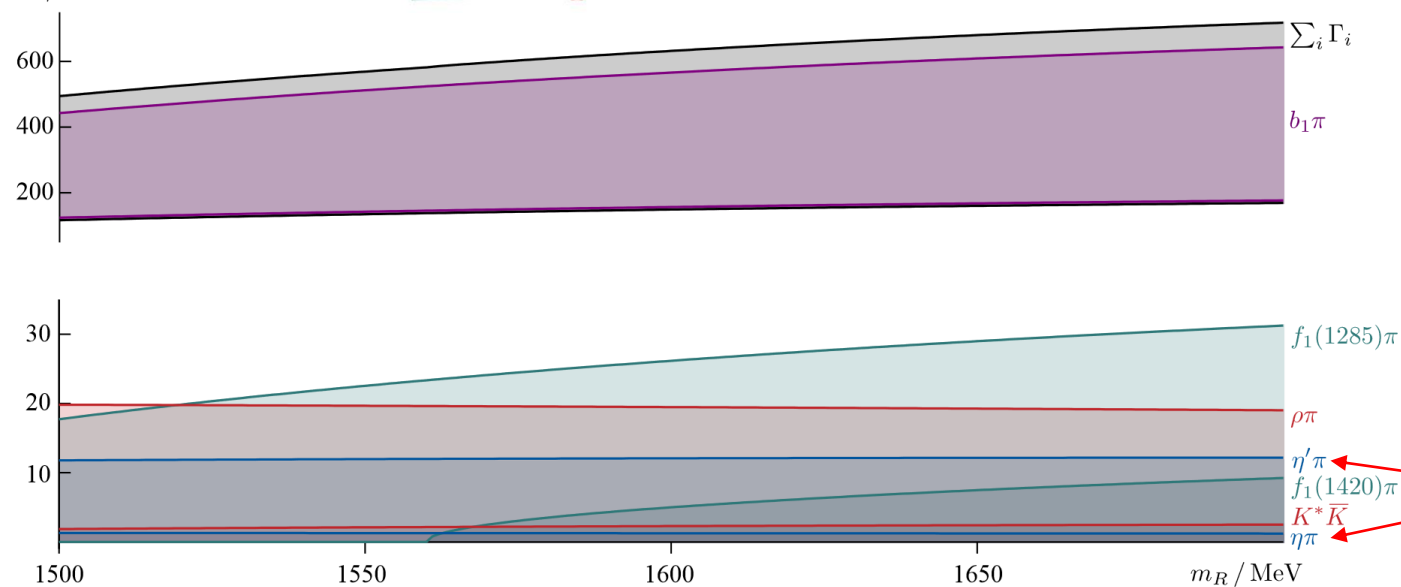
Lattice QCD calculation of lightest exotic hybrid (i.e. $\pi_1(1600)$)

- A number of significant decay modes + relative rates
- $b_1\pi$ decay dominant
- COMPASS $\eta^{(\prime)}\pi$ results may only be small fraction of $\pi_1(1600)$

had spec

Woss, *et al.* PRD **103**, 054502 (2021)

Γ_i / MeV





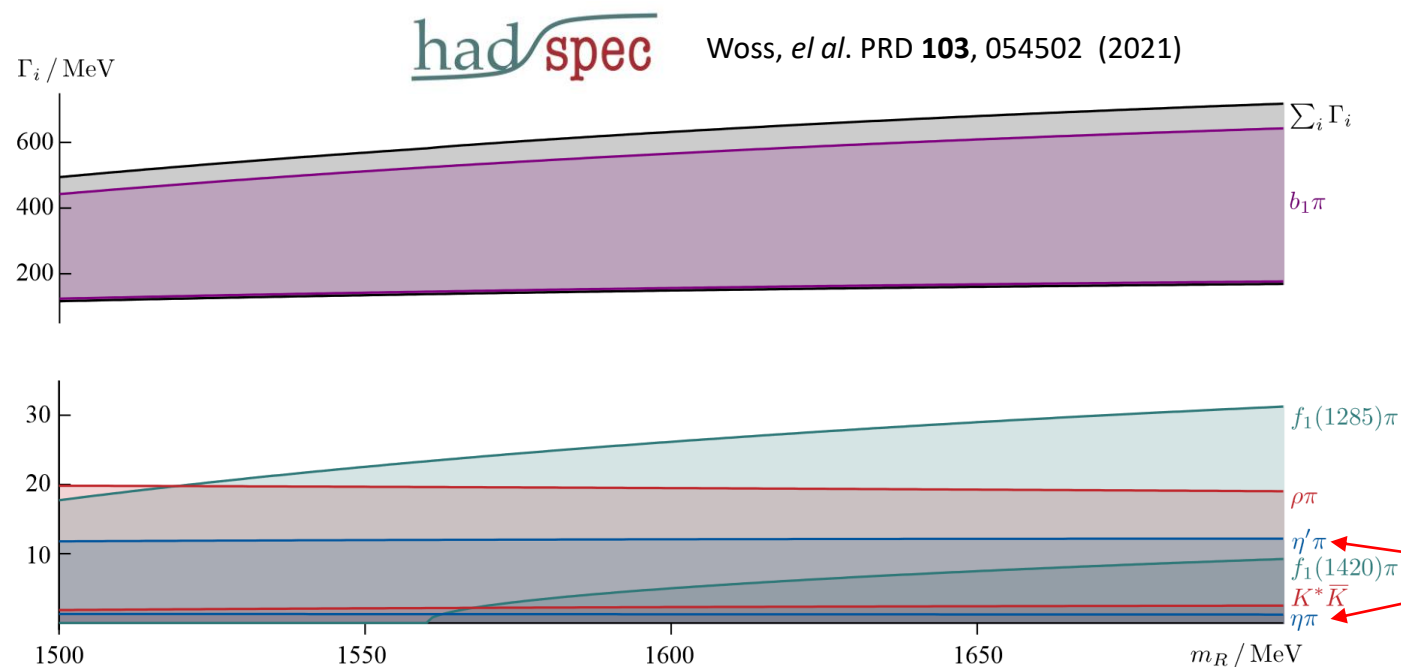
Exotic Hybrid Decay Modes

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Experimental results:

- Exotic signals reported in most modes
- See review: *Meyer and Swanson PPNP 82, 21 (2015)*

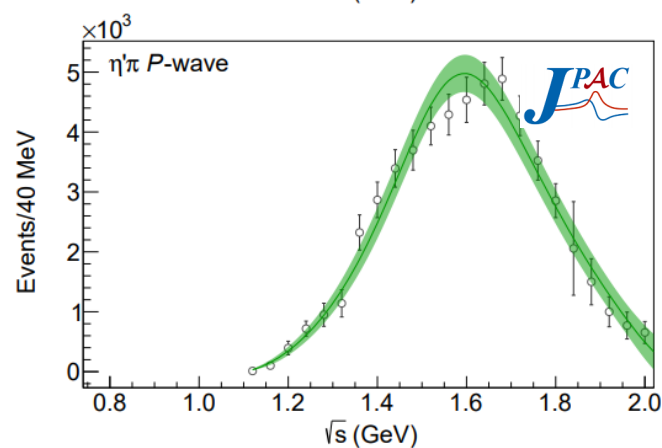
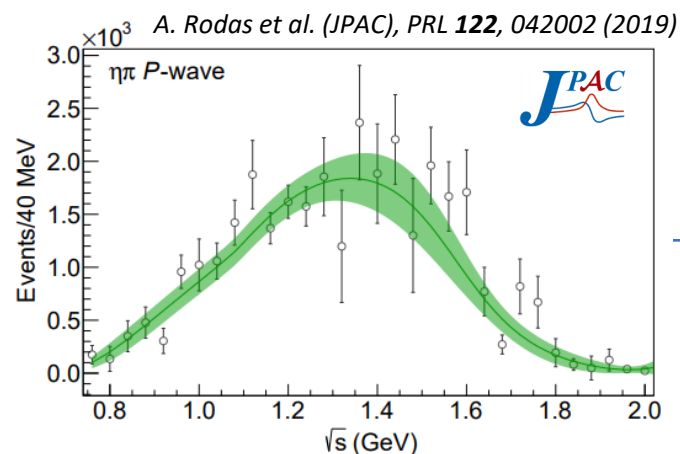


Decay Mode	1^{-+} Signal Reported?
$b_1\pi$	✓ (E852, VES, CBAR)
$f_1(1285)\pi$	✓ (E852, VES)
$\rho\pi$	✓ (E852, COMPASS, Obelix, CBAR)
$\eta'\pi$	✓ (E852, VES, COMPASS, CLEO-c)
$f_1(1420)\pi$	
$K^*\bar{K}$	
$\eta\pi$	✓ (many)



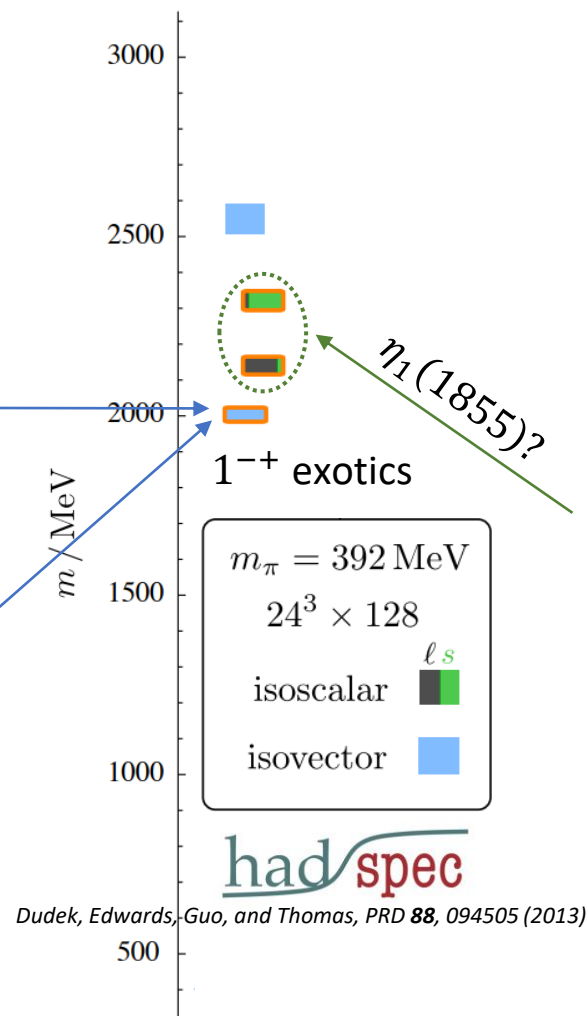
Another New Exotic Candidate?

Isovector ($I=1$)

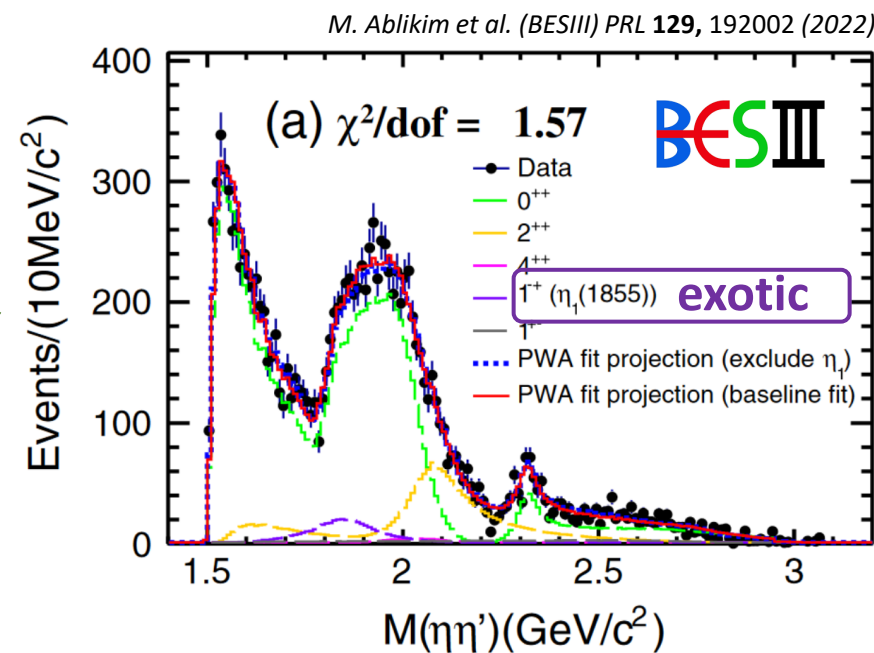


$\pi_1(1600)$

$\pi_1(1600)$



Isoscalar ($I=0$)



- Potential isoscalar partner found?
- Not yet confirmed in other experiments

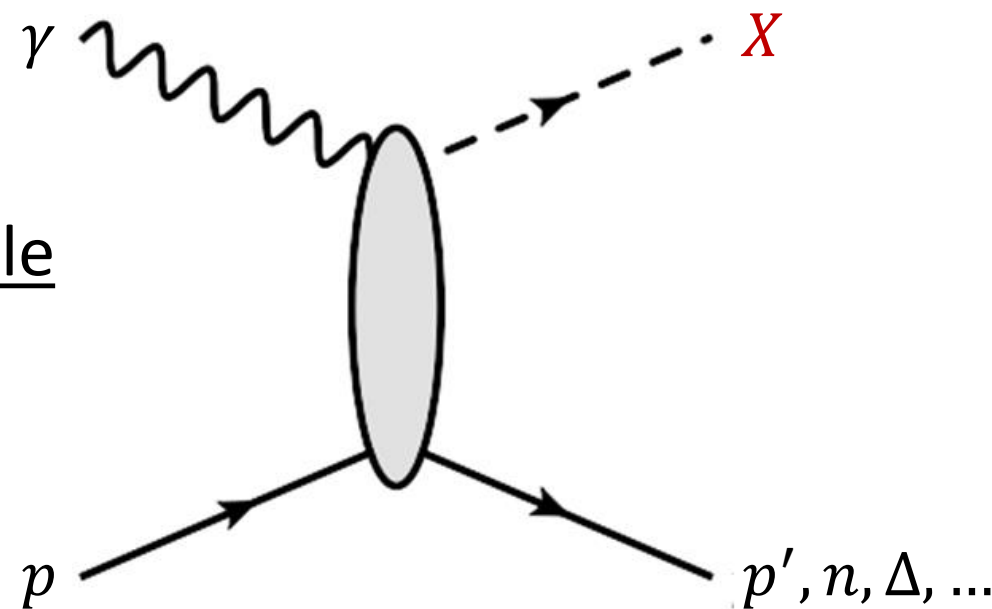


Photoproduction Reactions

Why study γp interactions?

- Compliment, cross check πp measurements
- Polarized photon beam: additional observable
- Many J^{PC} states X directly accessible

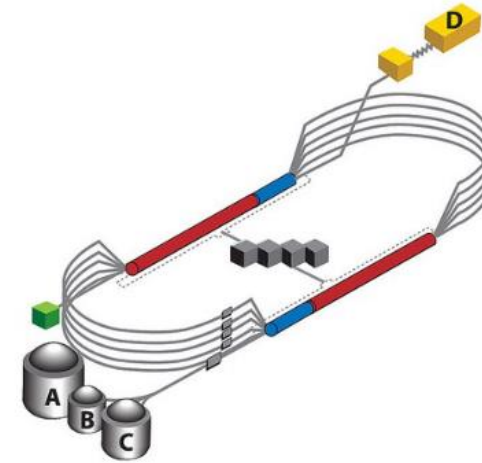
- Past measurements:
 - Bubble chambers from ~ 1970 s
 - No neutral detection
 - Statistics: orders of magnitude improvement possible today





GlueX at **Jefferson Lab**

- Newport News, Virginia, USA
- 12 GeV electron accelerator
- Secondary Photon beam \sim 3-12 GeV



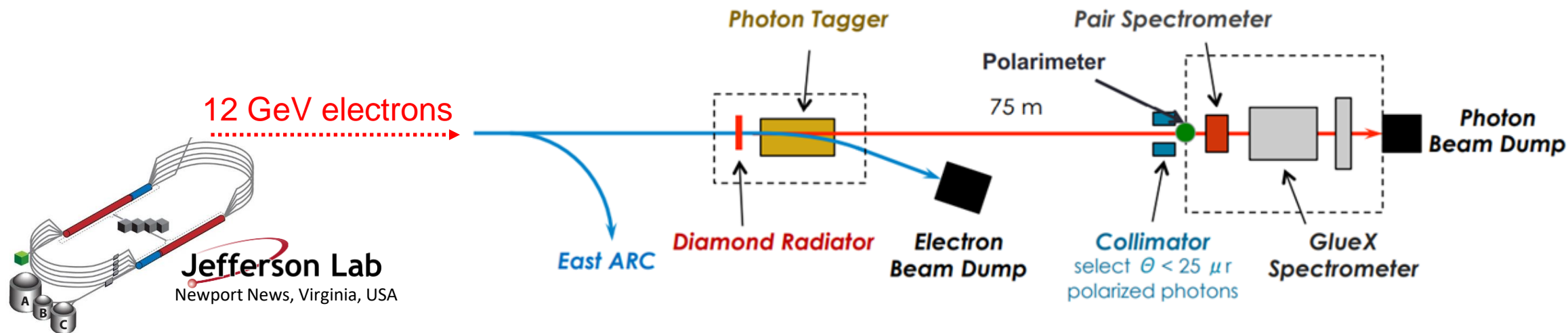
Tagger Hall (photon beam)

GlueX Detector Hall



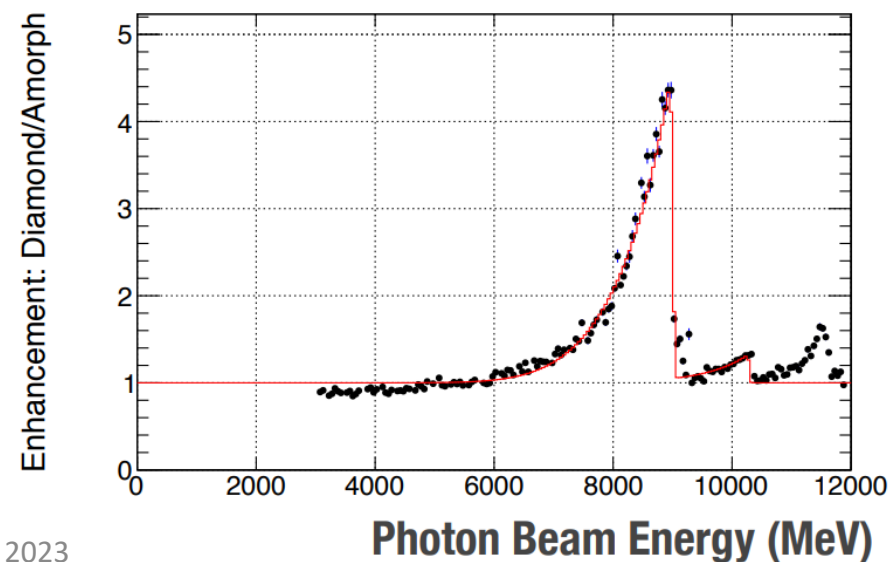


GlueX Polarized Photon Beam



Beam photons:

- Energy inferred from outgoing electrons
- Wide spectrum of energies (3-12 GeV)
- Enhancement at ~ 9 GeV:
 - Increases beam flux
 - Roughly 35% linear polarization



GlueX Detector

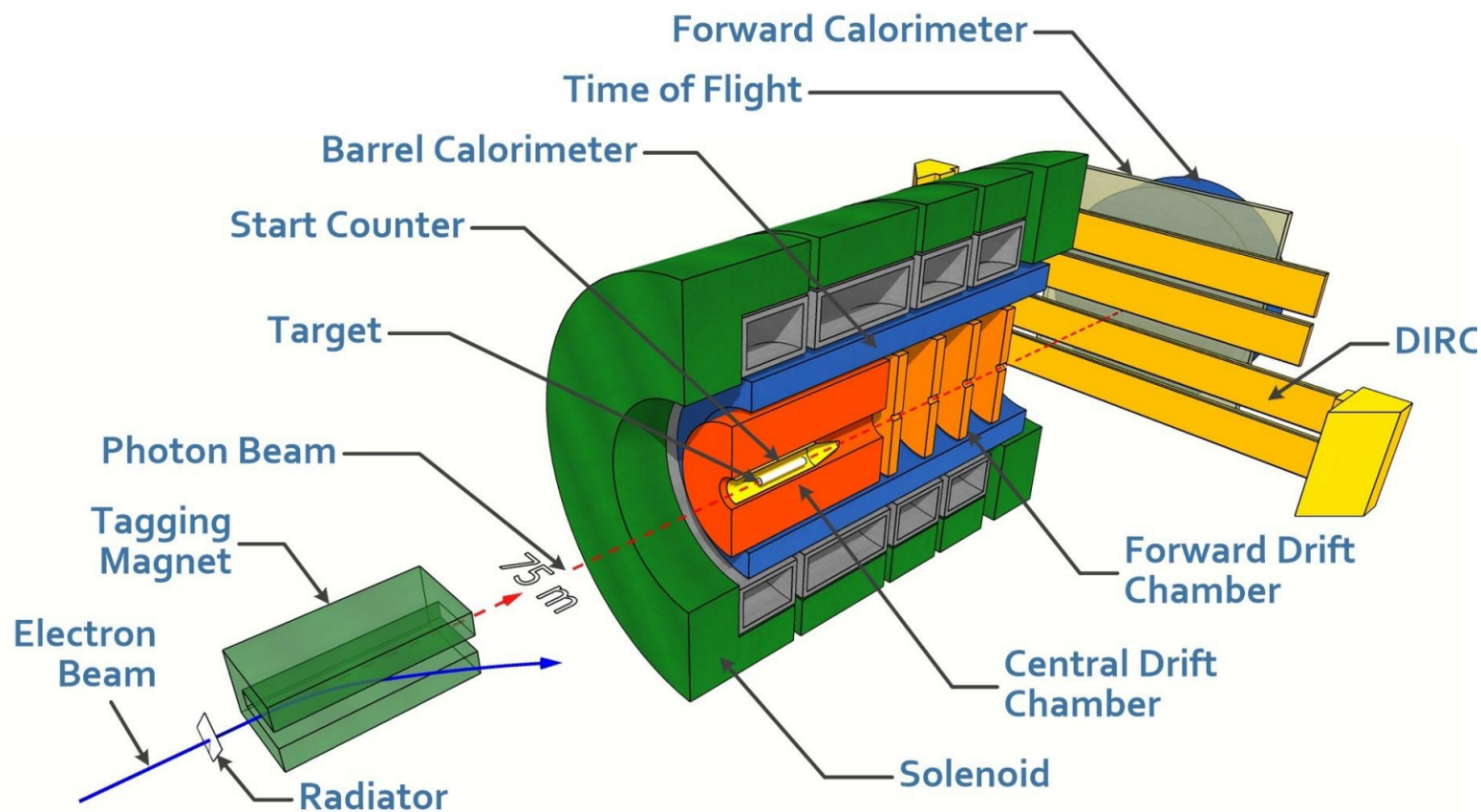
- Key features

- Wide acceptance
- Charged particle detection
- Photon detection

- GlueX-I dataset:

- 2016-2018 data collection
- Four directions of linear polarization
- 125 pb^{-1} ($8.2 < E_\gamma < 8.8 \text{ GeV}$)

- GlueX-II (ongoing): expect 3-4× stats





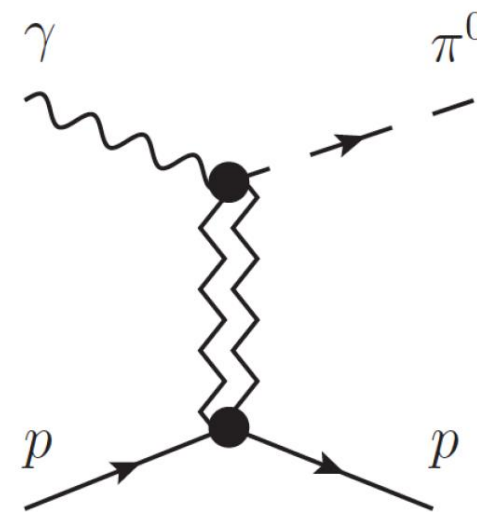
Production Mechanisms

Common features of production:

- Meson exchange(s) in t-channel (for relevant energies)
- Contributions vary over Mandelstam t
- Theory modeling: determine exchanges
 - Known mesons that couple to system
 - Reflectivity: new quantum number $P(-1)^J$
 - + or - reflectivity

Spin-0 example:

- ρ, ω, b, h could contribute



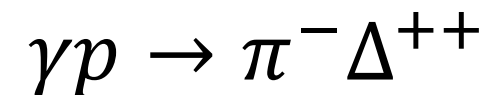
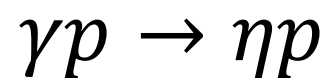
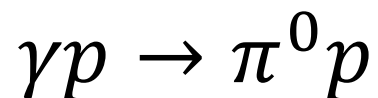
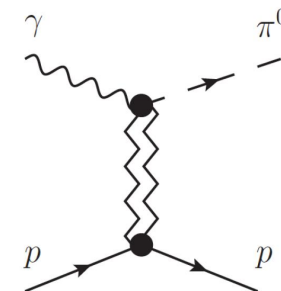
Exchange J^{PC}

$1^{--} : \rho, \omega$

$1^{+-} : b_1, h_1$

Production Mechanisms: Spin-0 Case

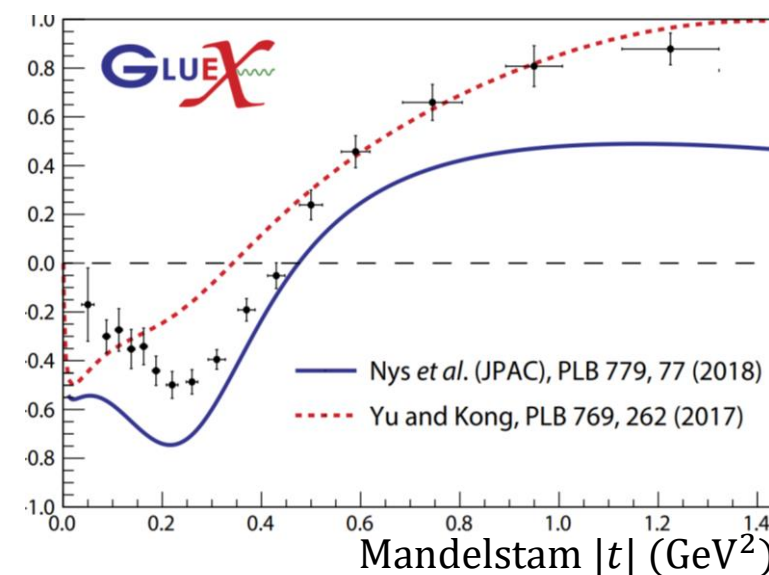
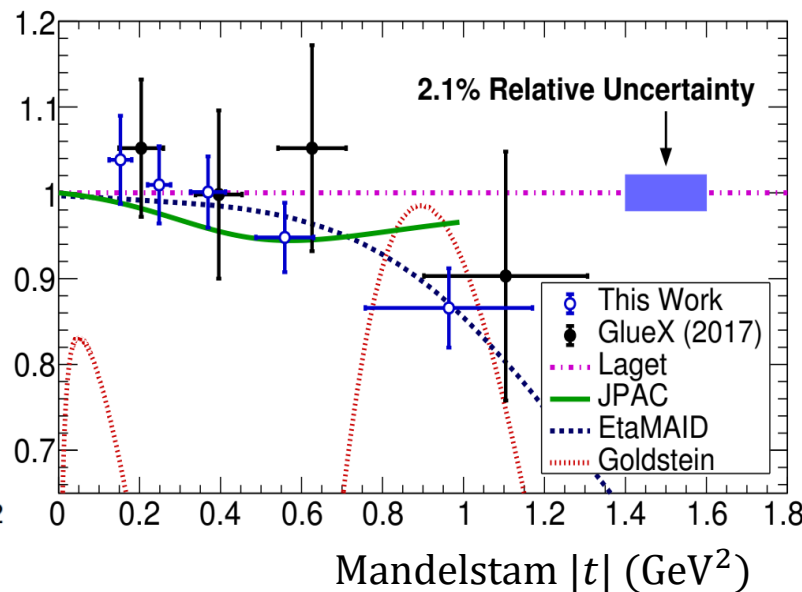
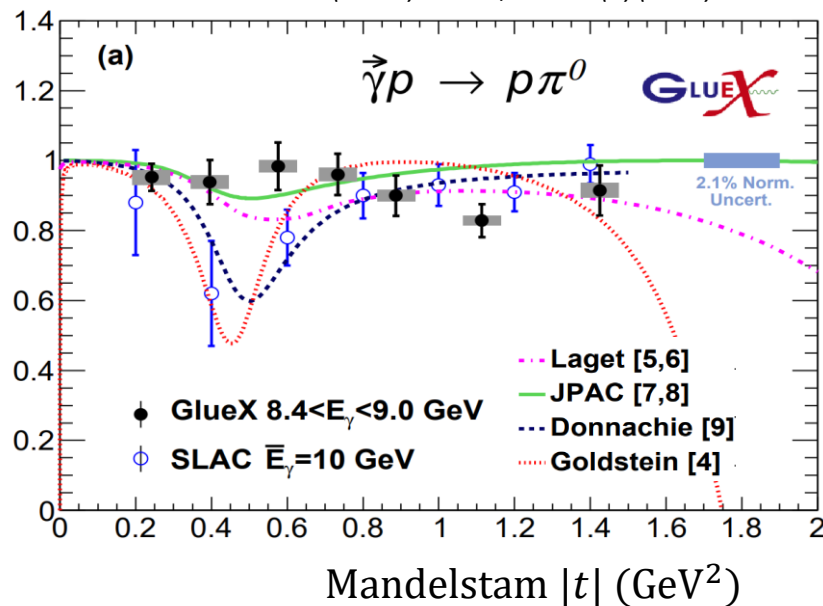
- Observable Σ : **+1** for pure natural exchange, **-1** for unnatural
- Several publications constraining spin-0 meson production



H. Al Ghoul et al. (GlueX) PRC **95**, 042201(R) (2017)

S. Adhikari et al. (GlueX) PRC **100**, 052201(R) (2019)

S. Adhikari et al. (GlueX) PRC **103**, L02201 (2021)

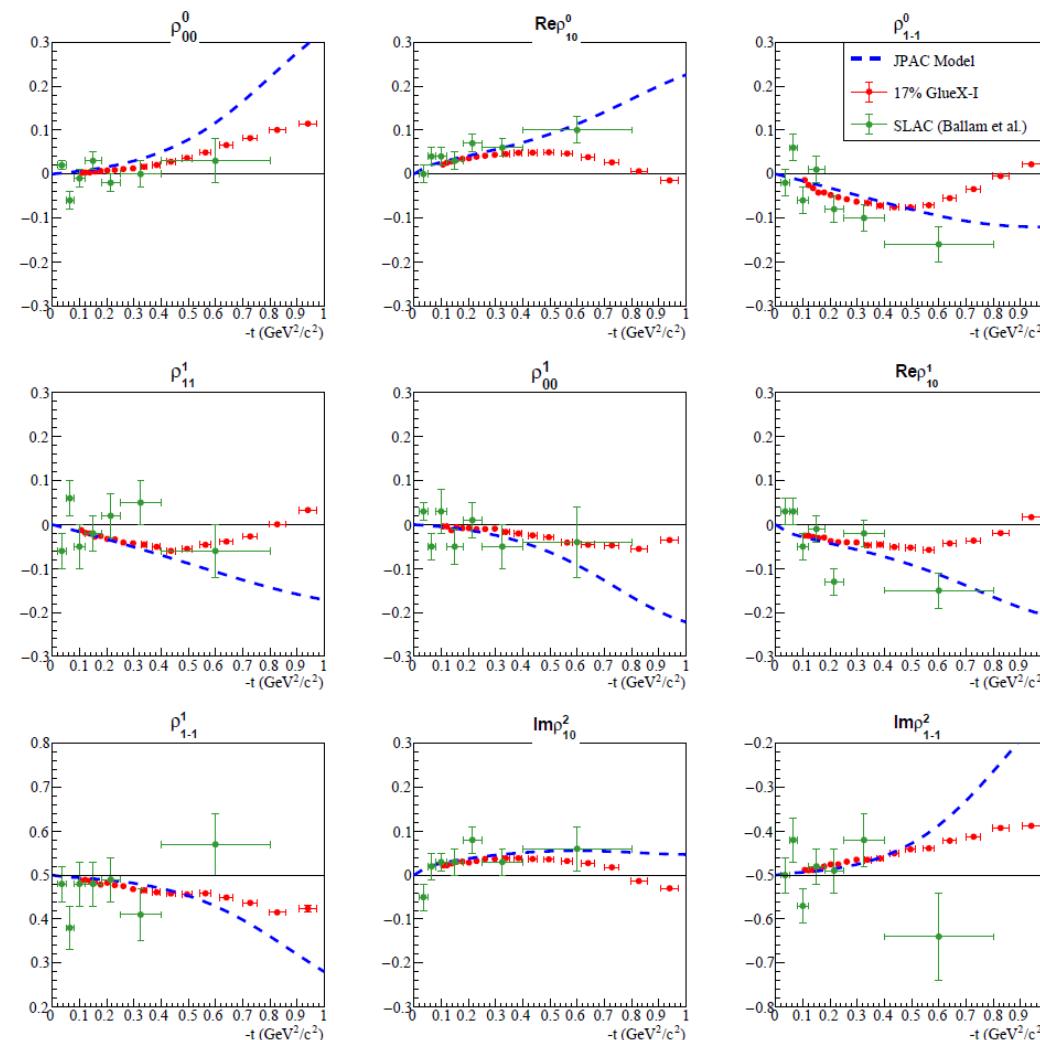
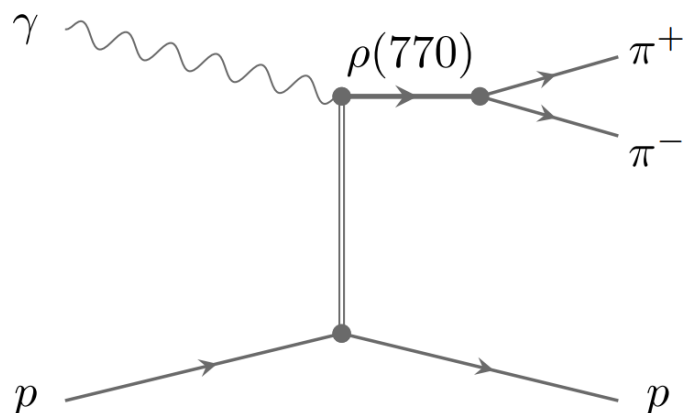




Production Mechanisms: Spin-1 Case

ρ_{ji}^k Elements over $|t|$

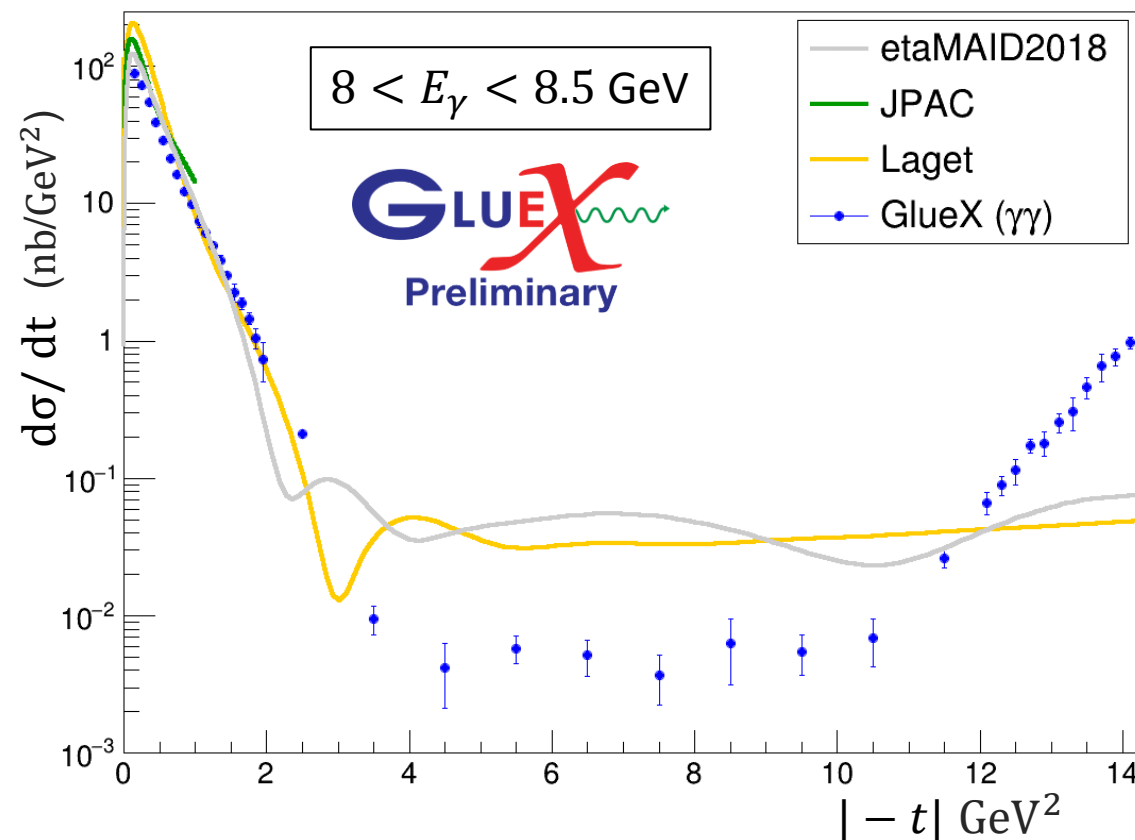
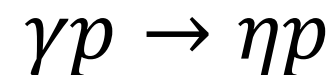
- Study angular dependence in c.m. decay angles(θ, ϕ) and polarization magnitude, direction P_γ, Φ
- Parameterized by 9 linearly independent ρ_{ji}^k
- Theory phenomenology: **Regge + pomeron exchange**
- ρ meson case: paper undergoing internal review
 - Well modeled for $|t| < 0.5 \text{ GeV}^2$
- ω, ϕ vector mesons: also under study





Exclusive η Mesons Production

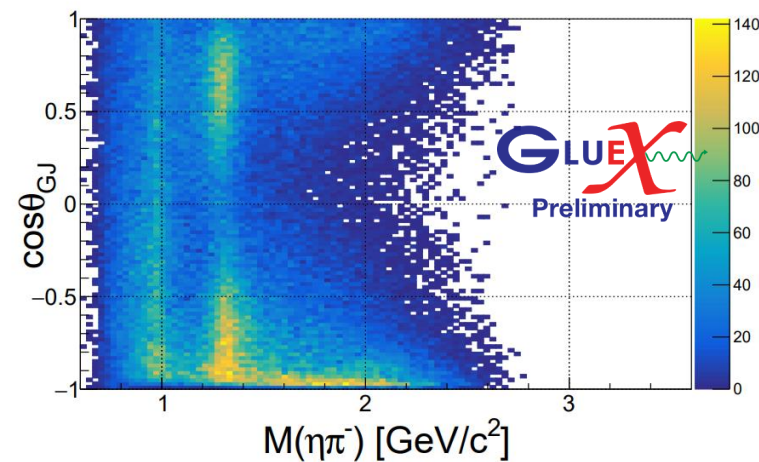
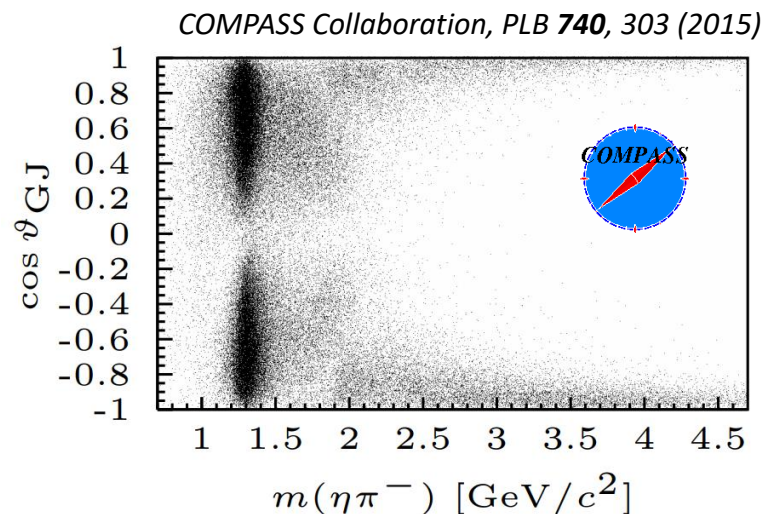
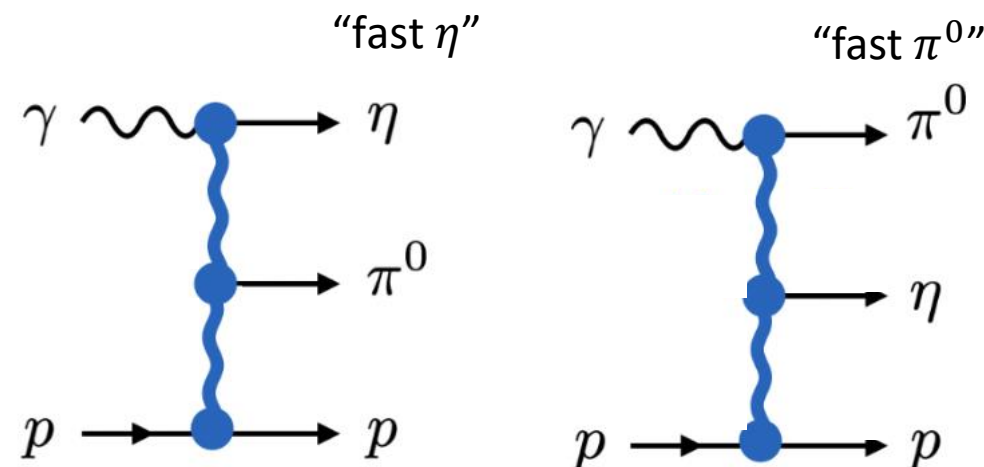
- Excellent coverage to far-backward angles
- Further constrain production descriptions
- Near-term publication



Non-resonant Production

Hybrid searches using $\pi \eta^{(\prime)}$:

- Non-resonant features near $\cos \theta = \pm 1$
- Parameterize, constrain to data
- Under detailed study at GlueX



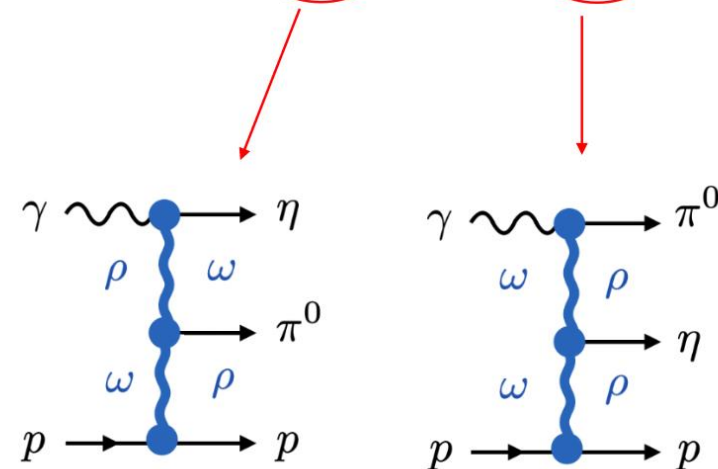


Non-resonant Production

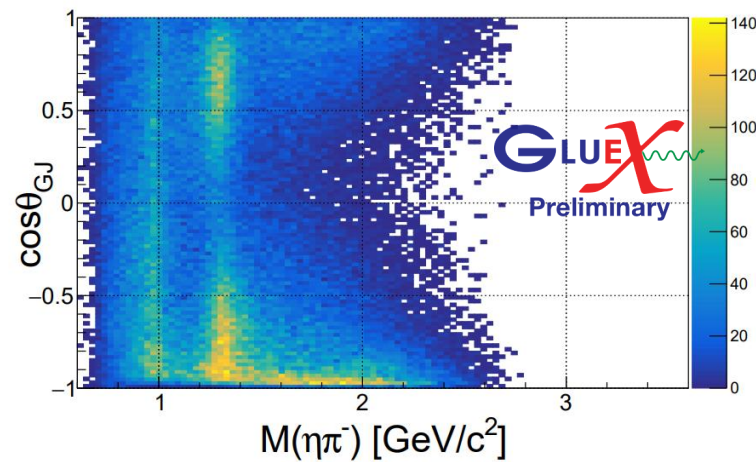
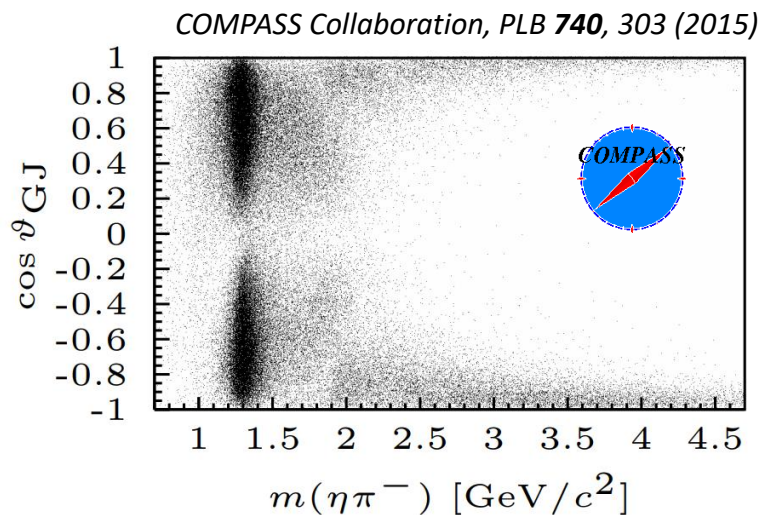
Hybrid searches using $\pi \eta^{(\prime)}$:

- Non-resonant features near $\cos \theta = \pm 1$
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$$A_{\lambda\gamma\lambda\lambda'}^{\gamma p \rightarrow \eta \pi p} = a_\eta e^{b_\eta t_\eta} A_{\lambda\gamma\lambda\lambda'}^{\eta\pi} + a_\pi e^{b_\pi t_\pi} A_{\lambda\gamma\lambda\lambda'}^{\pi\eta}$$

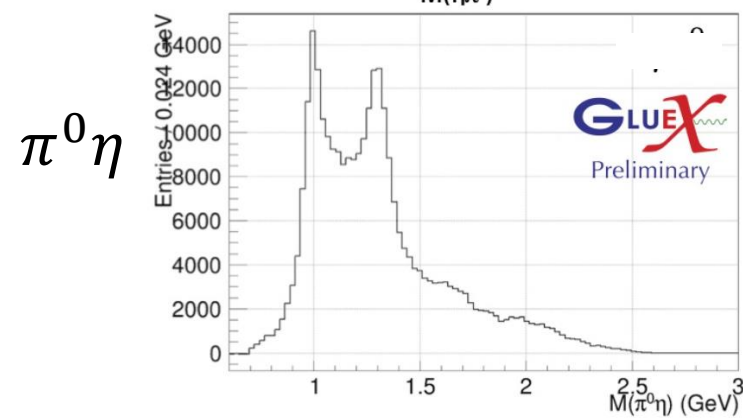
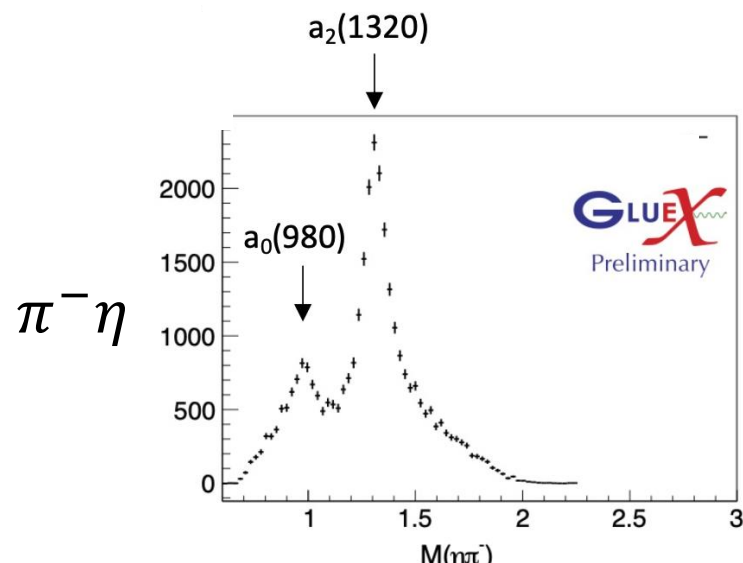


Formalisms from JPAC theory group





The $\pi\eta$ Spectrum at GlueX



[low momentum transfer]

Mass independent intensity fits with formalism:

Amplitude formalism $Z_l^m(\Omega, \Phi) = Y_l^m(\Omega, \Phi) e^{-i\Phi}$

JPAC: Mathieu et al [PRD 100 \(2019\) 054017](https://arxiv.org/abs/1905.04017)

Intensity(Ω, Φ):

$$2\kappa \left\{ (1 - P_\gamma) \left| \sum_{l,m} [l]_m^{(-)} \text{Re}[Z_l^m(\Omega, \Phi)] \right|^2 + (1 - P_\gamma) \left| \sum_{l,m} [l]_m^{(+)} \text{Im}[Z_l^m(\Omega, \Phi)] \right|^2 \right. \\ \left. + (1 + P_\gamma) \left| \sum_{l,m} [l]_m^{(+)} \text{Re}[Z_l^m(\Omega, \Phi)] \right|^2 + (1 + P_\gamma) \left| \sum_{l,m} [l]_m^{(-)} \text{Im}[Z_l^m(\Omega, \Phi)] \right|^2 \right\}$$

Naturality $N = P(-1)^J$ $N=+1$ 'natural' for $0+$ etc

Reflectivity = $N(\text{exchanged particle}) \times N(\text{resonance})$

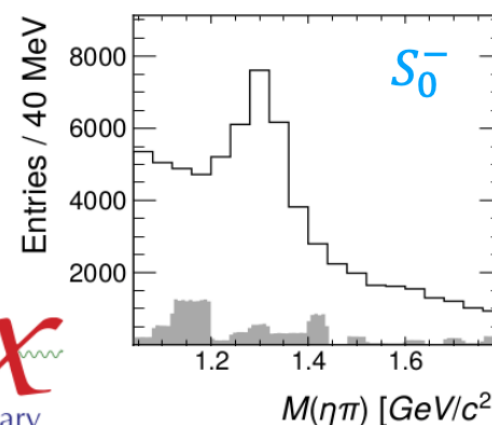
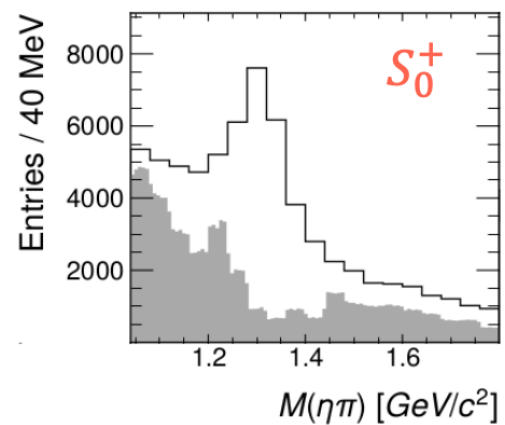
Reflectivity + natural parity exchange

Reflectivity - unnatural parity exchange

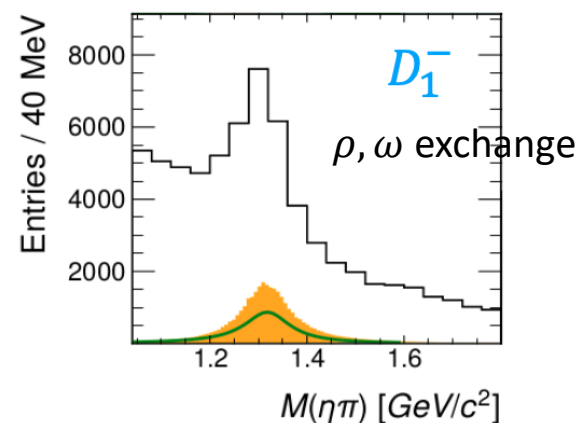
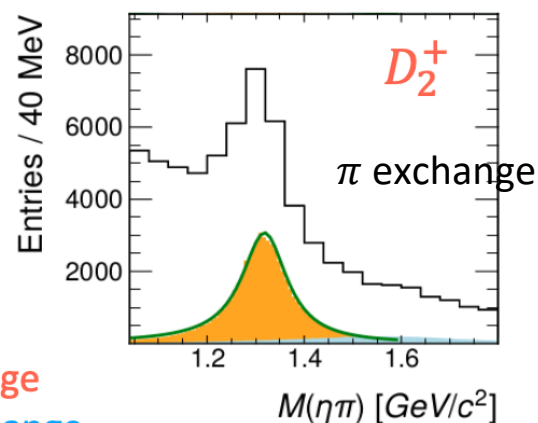


The $a_2(1320)$ meson in $\gamma p \rightarrow \pi \eta p$

Invariant mass($\eta\pi^0$) $0.1 < |t| < 0.2 \text{ GeV}^2$



Preliminary



■ S_0
■ $a_2(1320)$
— Theory

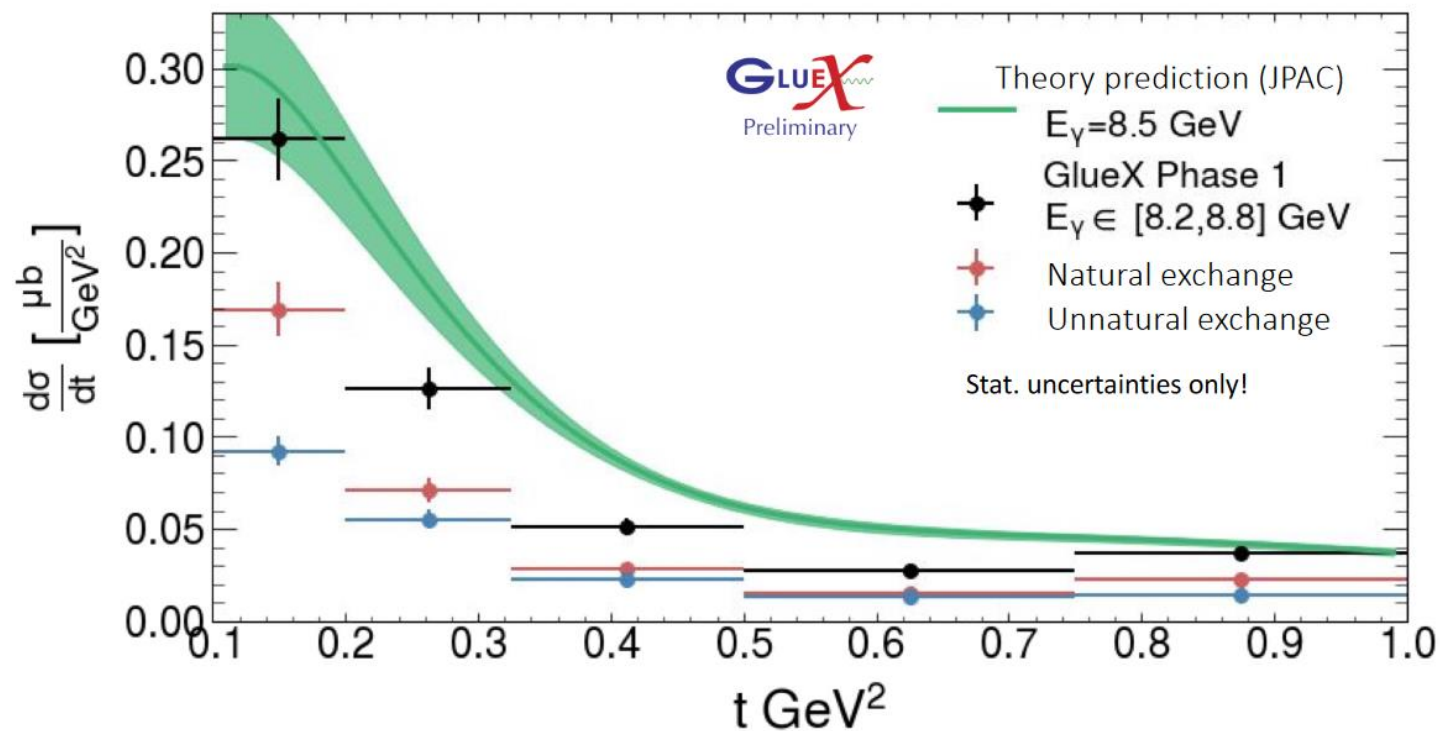
Reflectivity + natural parity exchange
Reflectivity - unnatural parity exchange



Outlook for $\gamma p \rightarrow \pi \eta^{(\prime)} p$

Near-term publication on $a_2(1320)$

- Amplitude analysis
- Differential cross section
- Same approach to be used for hybrid search

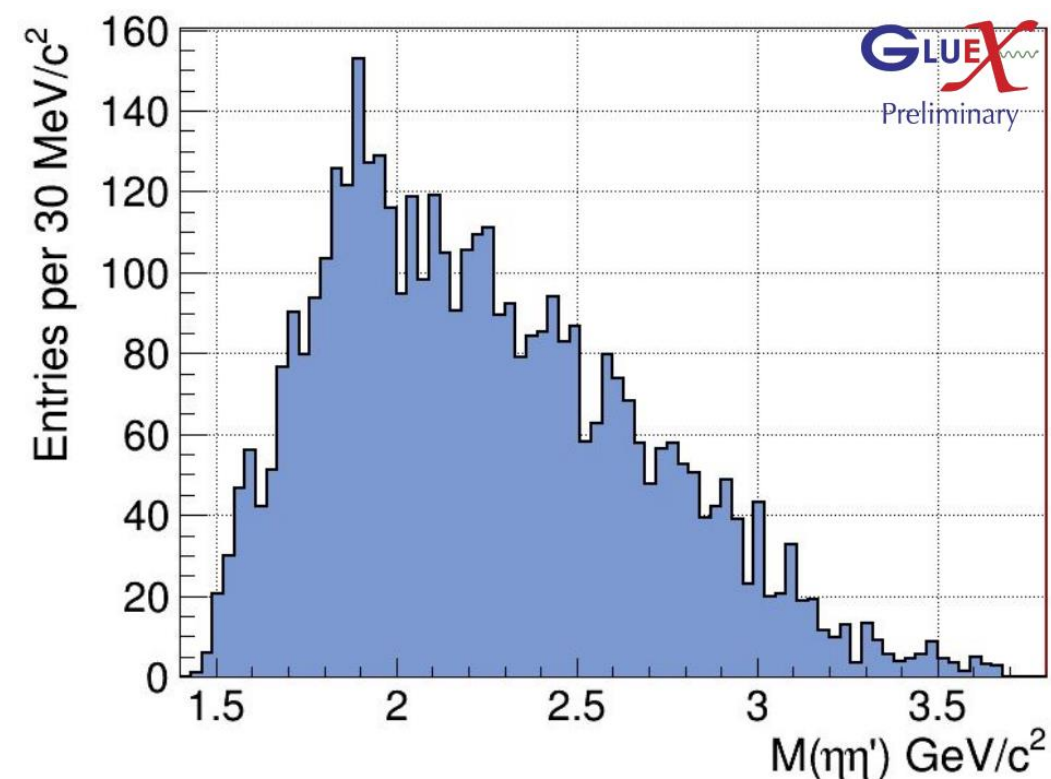
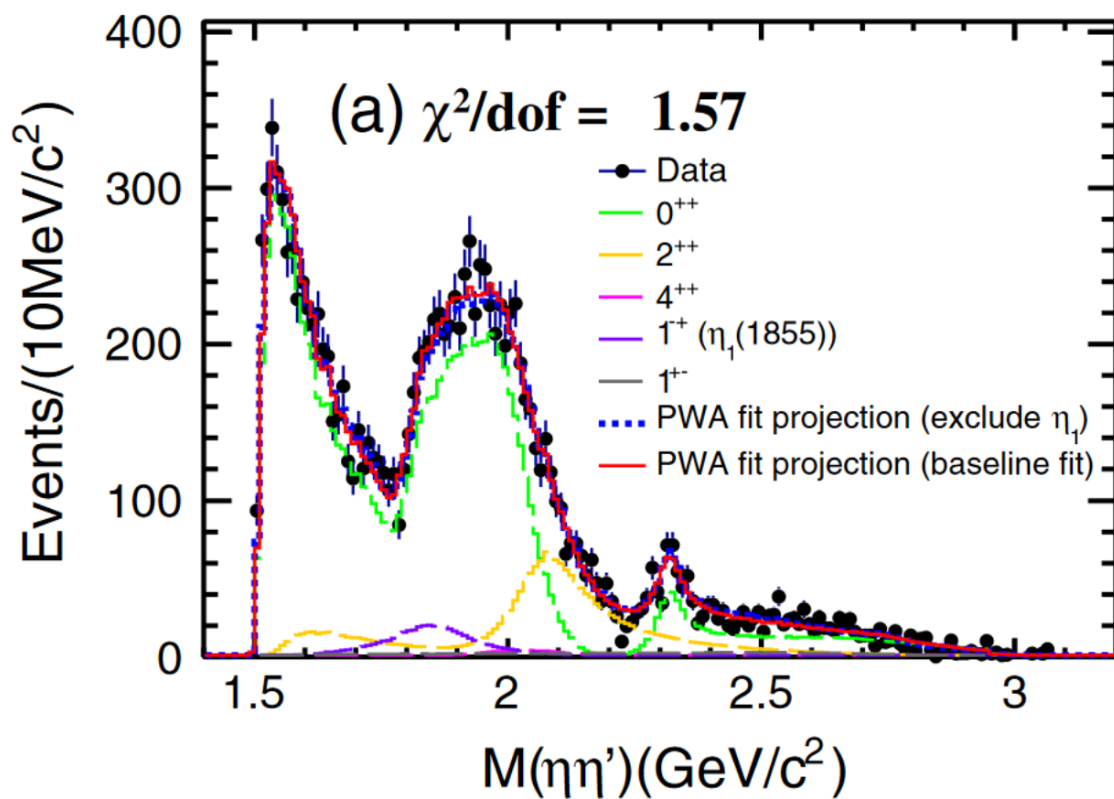




Isoscalar Hybrid at GlueX?

GlueX-II dataset needed, but will have comparable statistics to BESIII

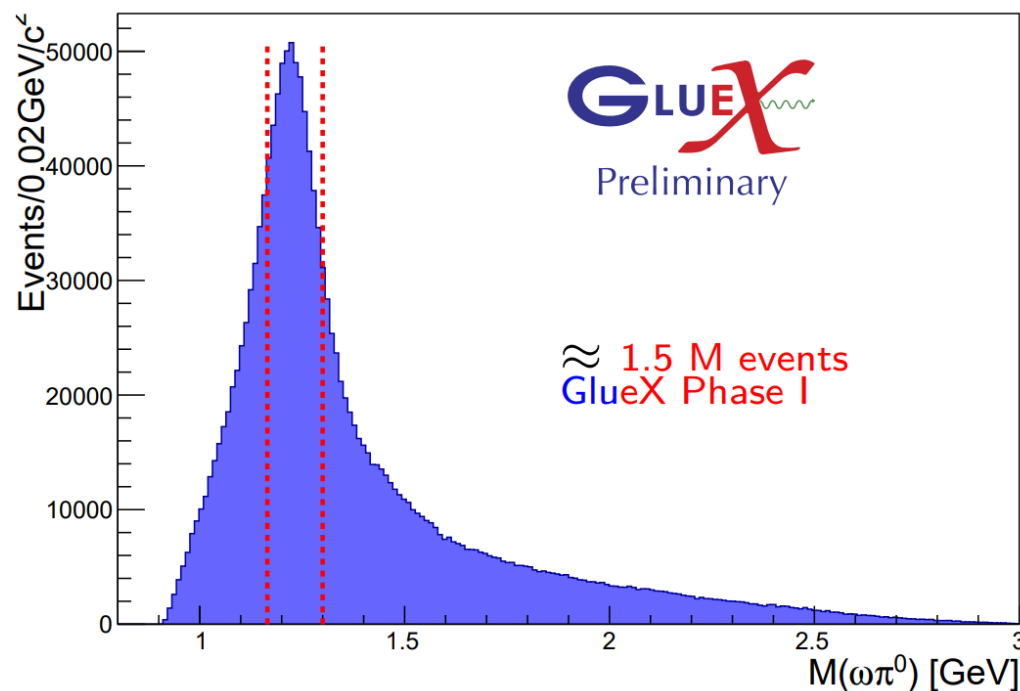
M. Ablikim et al. (BESIII) PRL 129, 192002 (2022)



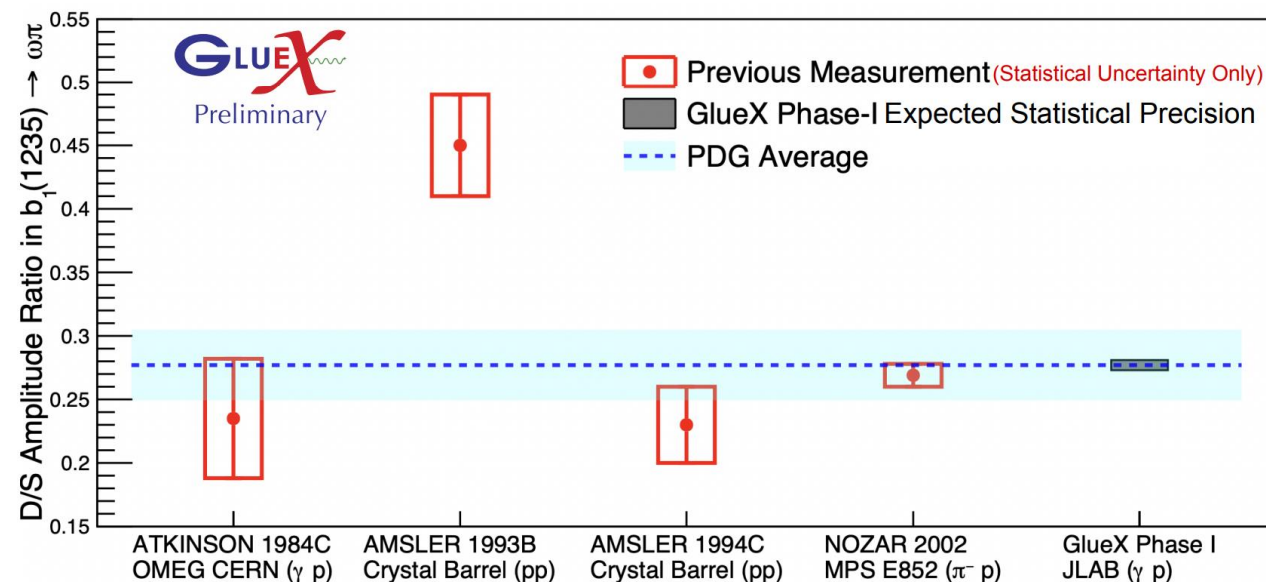


Understanding b_1 Photoproduction

Reconstructed $\omega\pi^0$ events



Focus: D/S ratio

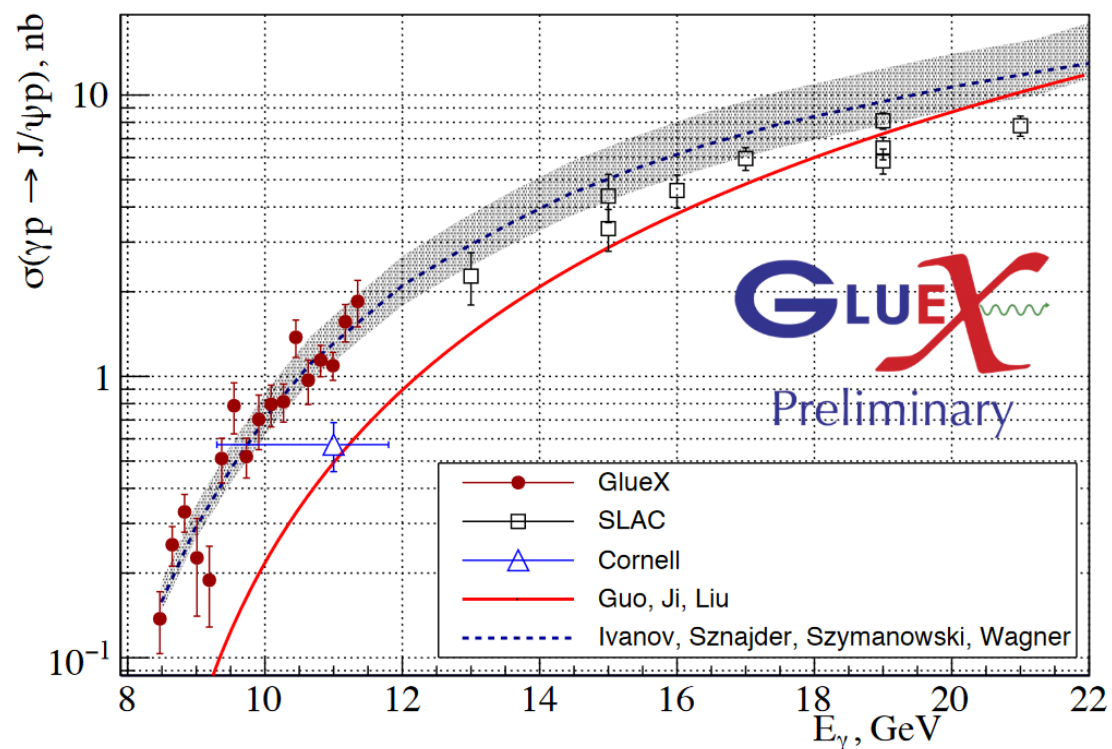




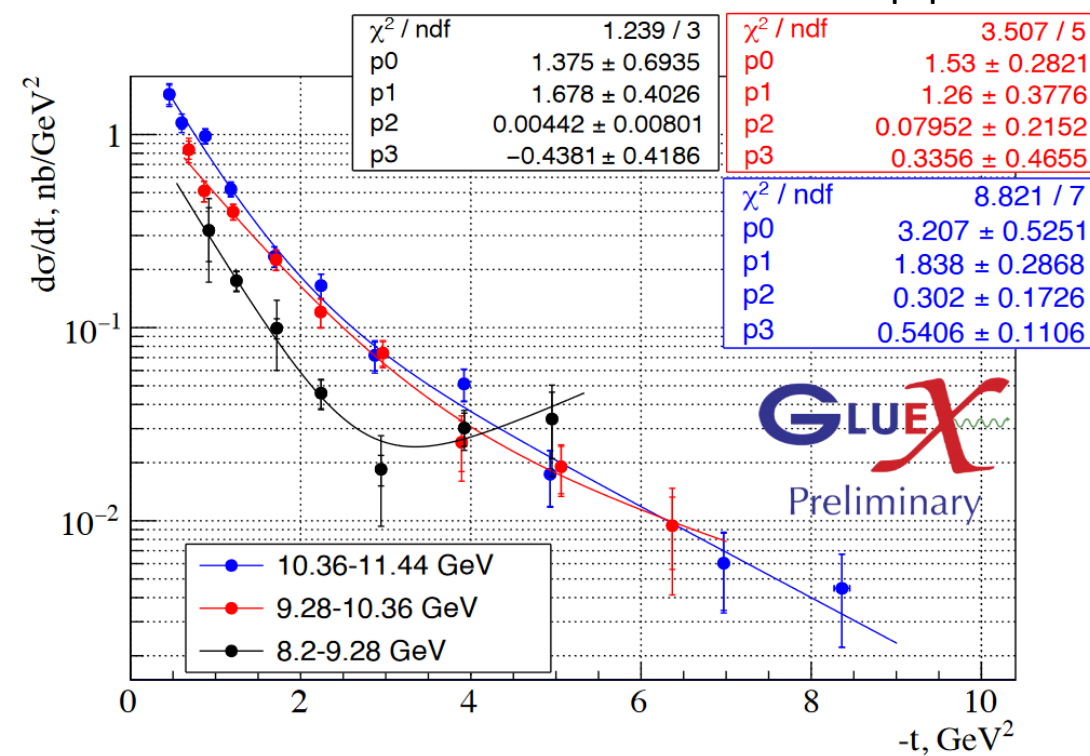
Exclusive J/ψ Cross Section

- Most cited GlueX result to date
- Another publication ready to submit w/ improved statistics

Total cross section over beam energy

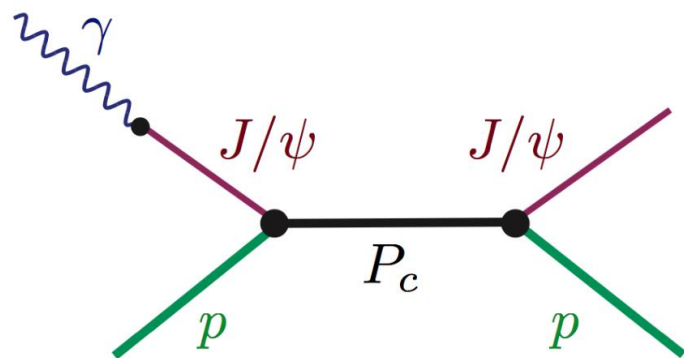


Differential Cross Section in $|t|$

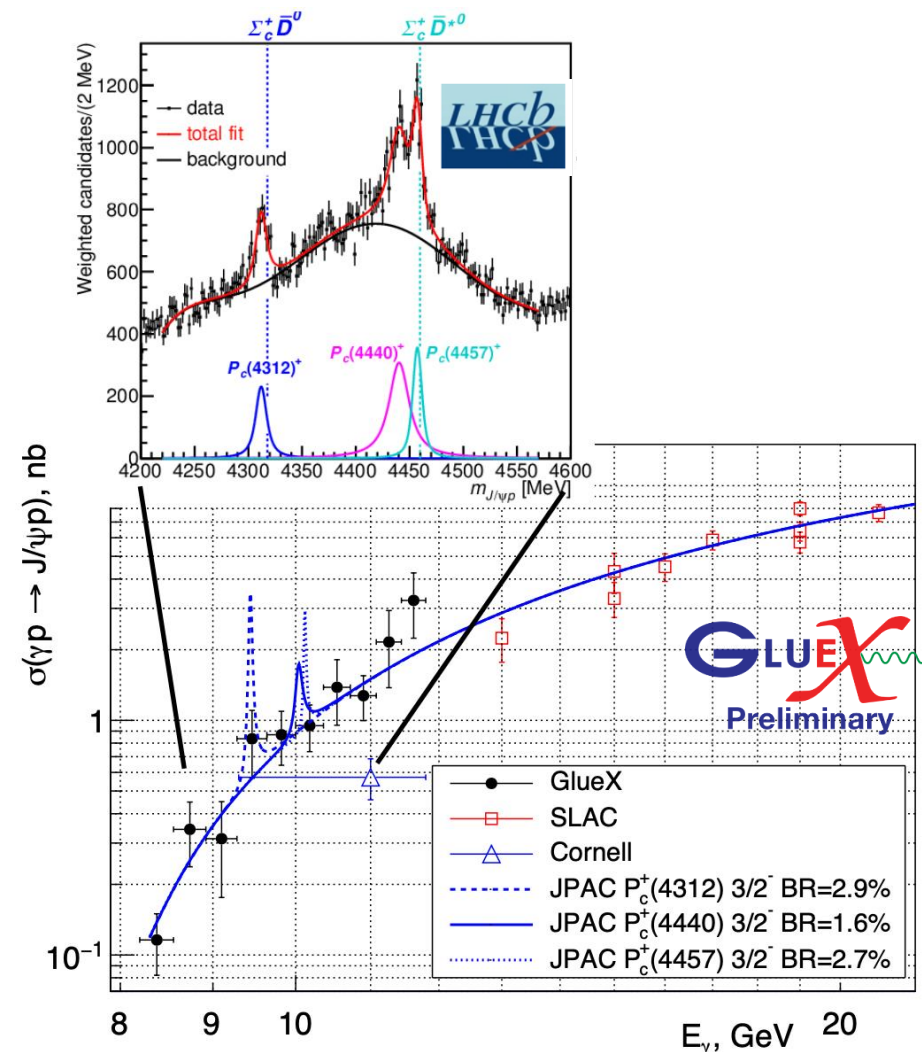




Search For LHCb Pentaquark?

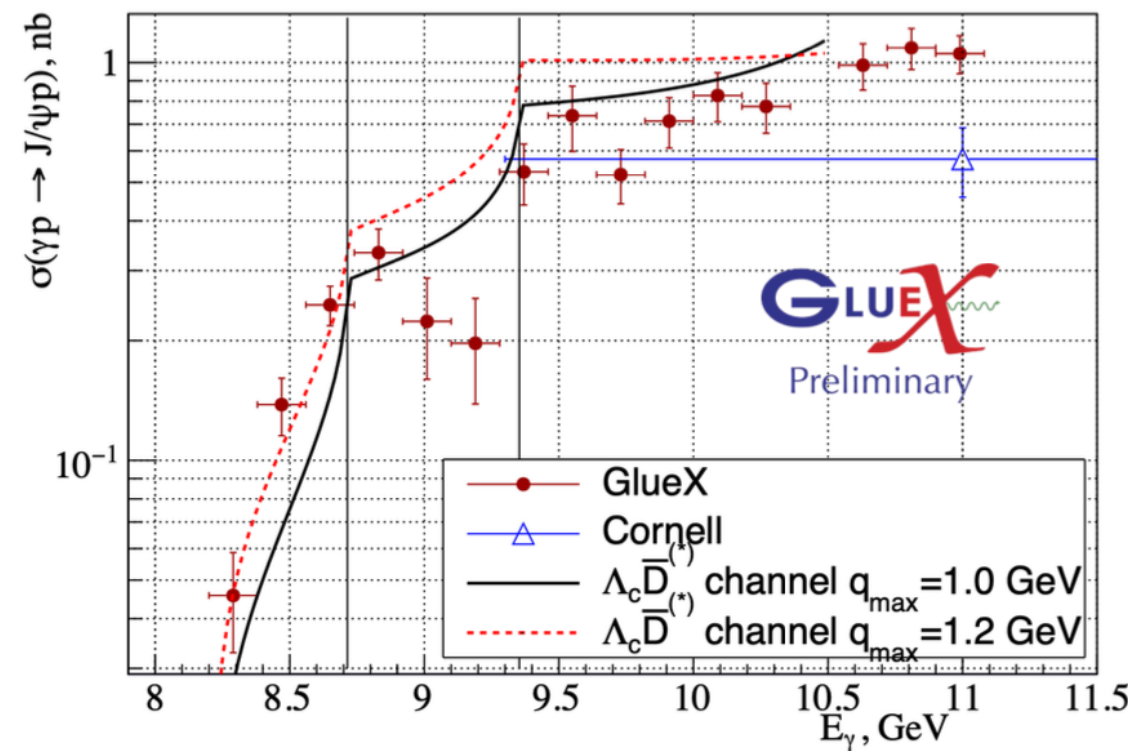
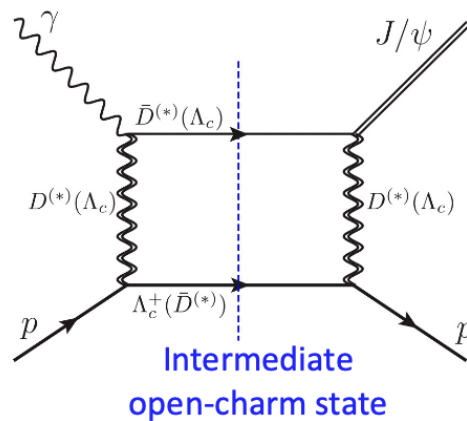
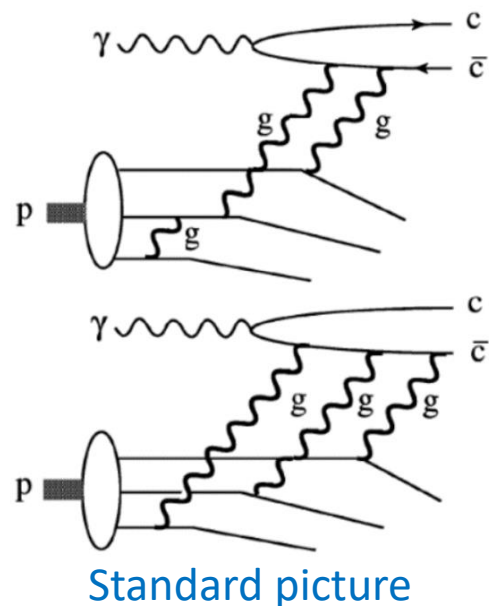


- Model-dependent upper limits at 90% CL: $J^P = 3/2^-, L = 0$
- $\text{Br}(P_c(4312) \rightarrow J/\psi p) < 4.6\%$
- $\text{Br}(P_c(4440) \rightarrow J/\psi p) < 2.3\%$
- $\text{Br}(P_c(4457) \rightarrow J/\psi p) < 3.8\%$



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Exclusive J/ψ Photoproduction



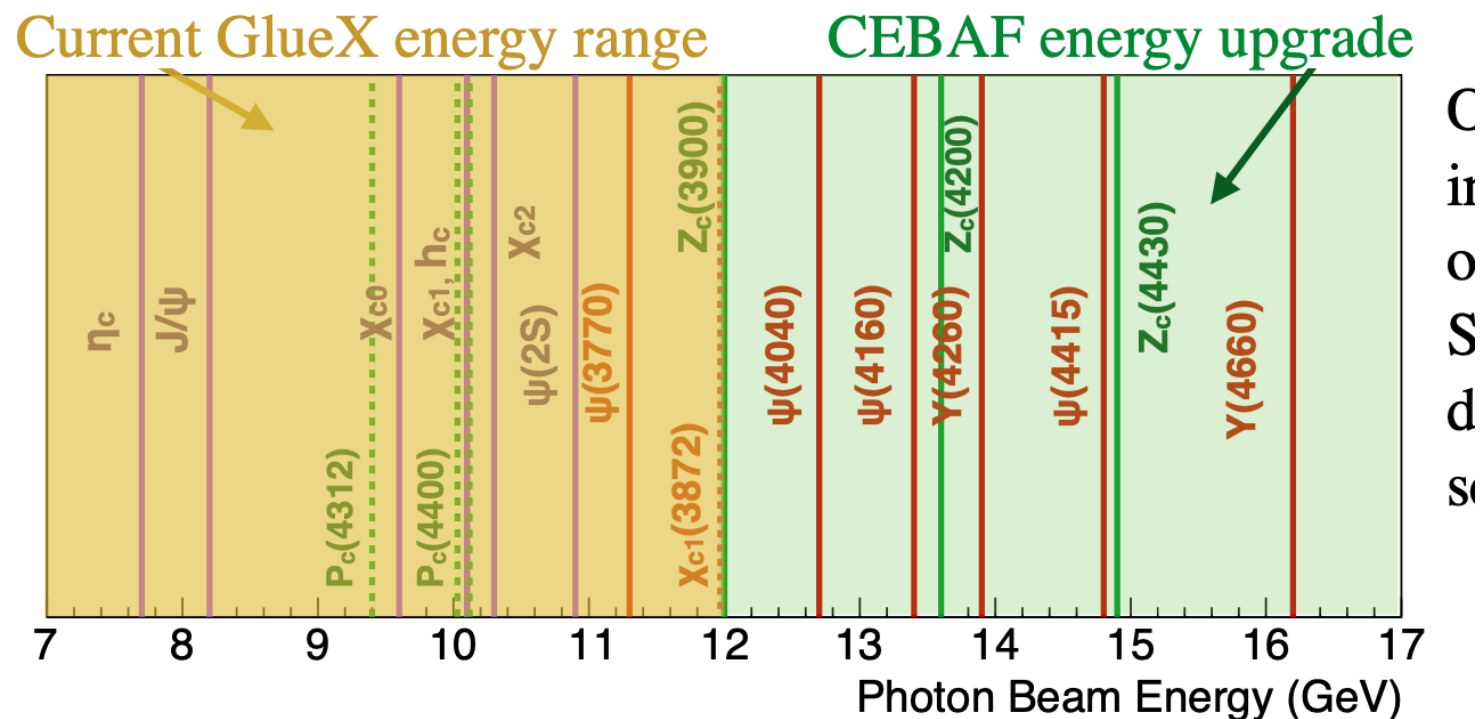
Potential structure in cross section?

- $D^{(*)}\Lambda$ threshold effect?
- 2.6σ significance
- 1.3 if “look elsewhere” effect used



Additional $c\bar{c}$ States at GlueX

- More states, e.g. ψ' , within energy reach (can't say more today)
- Exotic $c\bar{c}$ candidates could be reached with proposed upgrade



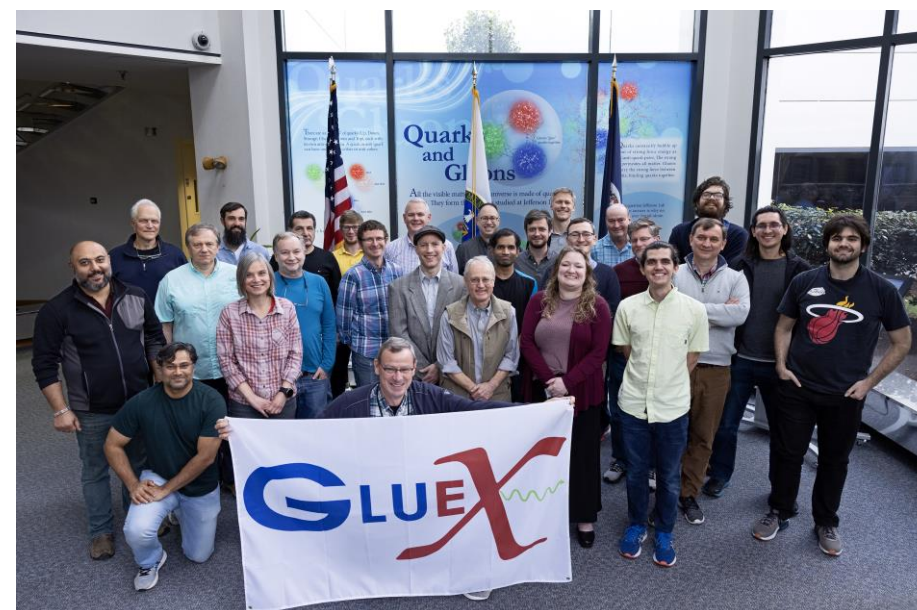


Conclusion

<http://gluex.org/thanks/>



- GlueX has collected unprecedented photoproduction statistics
- Program: confirm, extend list of candidates for non- $q\bar{q}$ mesons
 - Well underway
 - Production well constrained
 - Amplitude analysis of known states
 - Stay tuned!



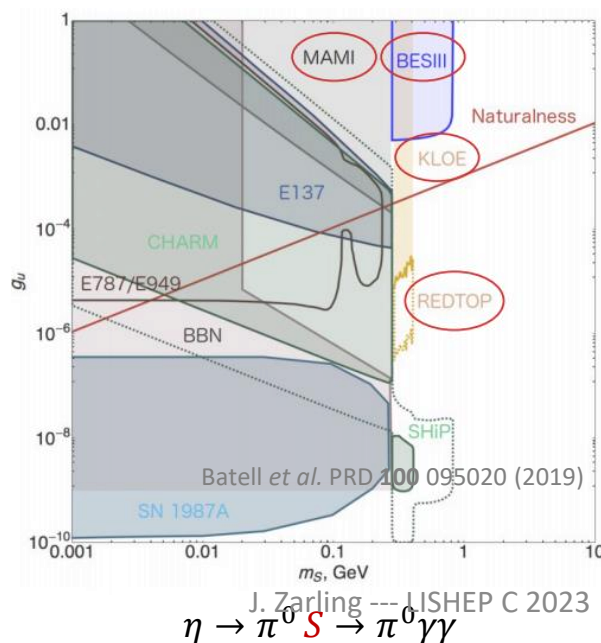
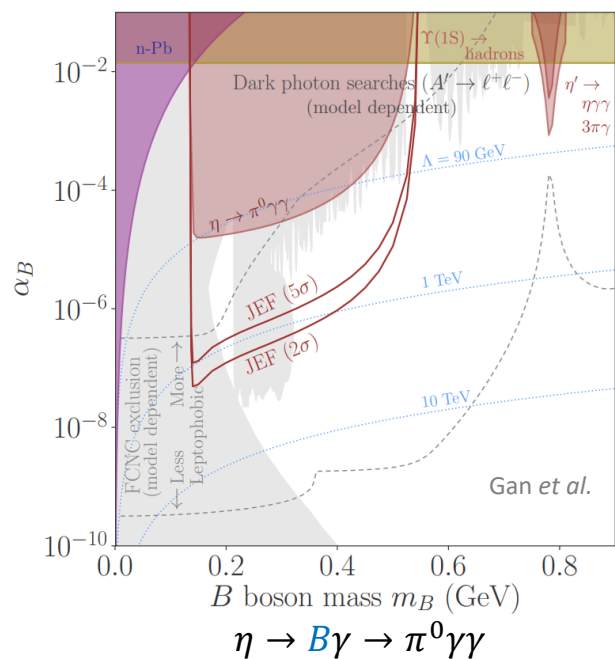


Backup: Probing the Dark Sector w/ η Mesons

Interest in new sub-GeV dark sector:

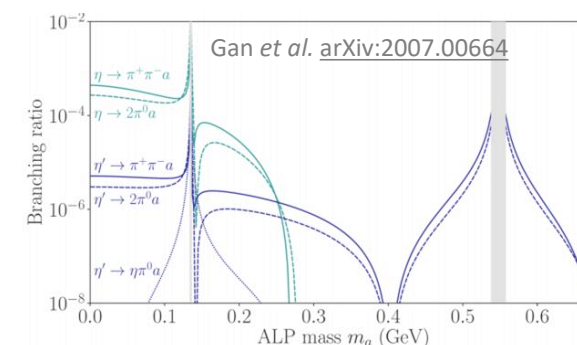
- Vector, scalar, axion-like candidates
- X(17) protophobic boson candidate

Main search channel: $\eta \rightarrow \gamma\gamma\pi^0$



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$\eta \rightarrow ALP + \dots$



$\eta \rightarrow X(17)\gamma \rightarrow e^+e^-\gamma$

