

Recent results from GlueX

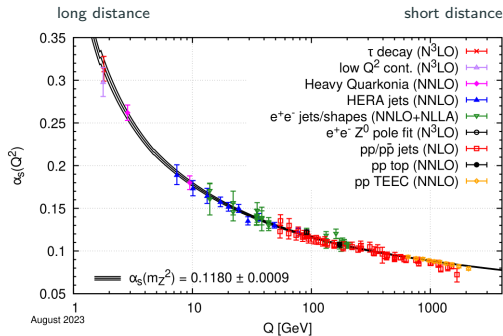
EINN Conference 2025

Farah Afzal for the GlueX Collaboration

Ruhr University Bochum

29.10.2025



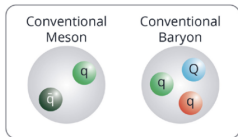


Quantum Chromodynamics (QCD): Theory of strong interactions

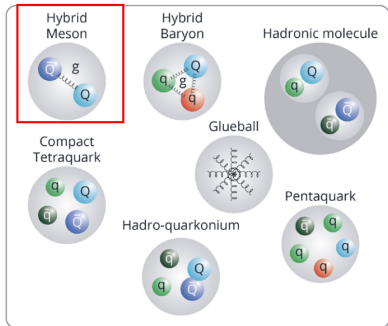
- Quarks are confined inside of **colorless hadrons**
- Hadrons $\leftrightarrow$ non-perturbative regime of QCD
 - $\rightarrow$ Challenging from experimental and theory side
 - $\rightarrow$ Theory side: Need to rely on quark models or Lattice QCD calculations
 - $\rightarrow$ Challenge in light hadron spectroscopy: Many broad and overlapping states in dense mass spectrum

Fundamental open questions in hadron physics:

- How do hadrons emerge?
- What is the role of gluons in the hadron spectrum?



Conventional Hadrons



Unconventional Hadrons

NUPECC, LRP 2024

Hadron spectrum

- Many conventional $q\bar{q}$ and qqq states have been observed
- QCD allows more complicated configurations as well, e.g. multi-quark states, hybrids, glueballs

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

... Baryons can now be constructed from quarks by using the combinations (qqq) , $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. ...

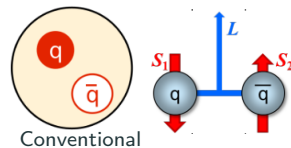
Phys.Lett. 8 214-215,1964

GlueX experiment:

- Unique opportunity to explore light hadron spectrum with focus on **hybrid mesons**

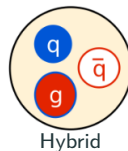
Conventional $q\bar{q}$ mesons:

- Quantum numbers: $J = L + S$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$
- Possible quantum numbers: $J^{PC} = 0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 2^{++}, \dots$



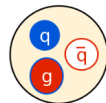
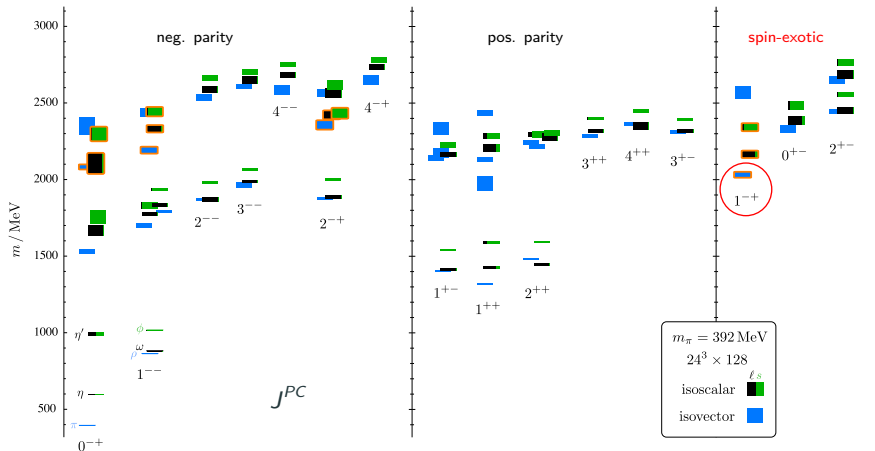
How to identify exotics in the meson spectrum?

- Supernumerary states
- Spin-exotic:** $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+} \dots$ (not allowed for $q\bar{q}$ states!)
 → "Smoking gun" for finding evidence for exotic mesons!



Experimental confirmation of exotic mesons is an essential direct test of QCD!

HadSpec: J. Dudek et al. PRD 88 094505 (2013)



Lightest hybrid mesons

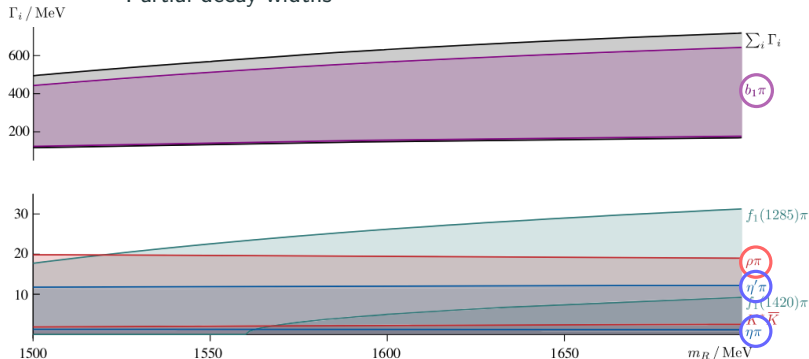
→ test gluonic degrees of freedom of QCD

Spin-exotic: $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, 3^{+-} \dots$ (not allowed for $q\bar{q}$ states!)

Clear signature for finding hybrid mesons!

Recent Lattice QCD calculation ($m_\pi \sim 700$ MeV): [Woss, Dudek et al., PRD 103 \(2021\) 054502](#)

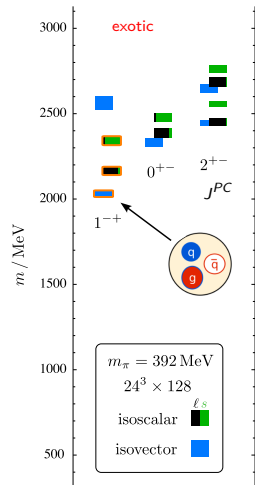
Partial decay widths



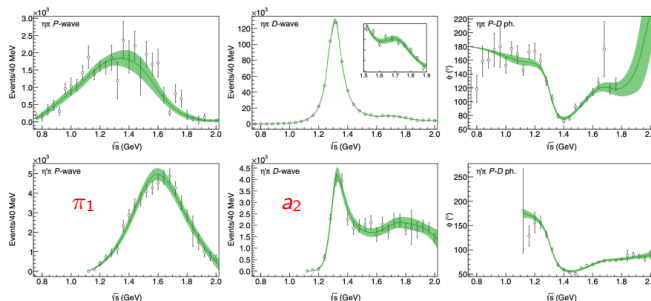
dominant decay mode: $b_1 \pi \rightarrow \omega \pi \pi$

other decay modes: $\rho \pi$, $\eta' \pi$, $\eta \pi$
 $\rightarrow$ experimental evidence exists

Important to measure different decay modes to compare to predictions from Lattice QCD!



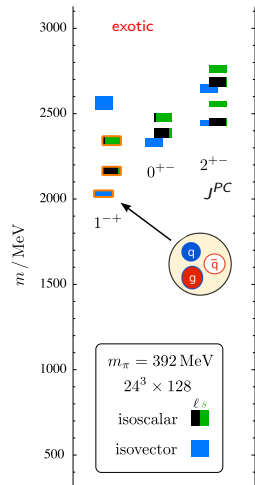
- Experimentally two hybrid meson candidates:
 $\pi_1(1400)$: GAMS, VES, E852, CBAR, COMPASS
 $\pi_1(1600)$: VES, E852, COMPASS
- JPAC: coupled channel analysis of $\eta\pi$ and $\eta'\pi$ requires only a **single pole**



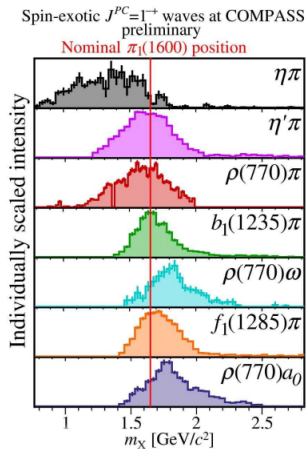
mass = $1564 \pm 24 \pm 86 \text{ MeV}$
width = $492 \pm 54 \pm 102 \text{ MeV}$

COMPASS: PLB 740 (2015) 303
JPAC: PRL 122 (2019) 042002

More recent progress



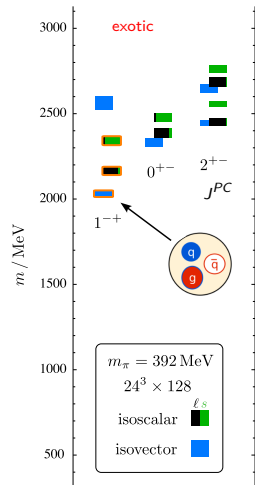
Multiple decay channels of π_1 measured



HADRON 2025 talk by J. Beckers

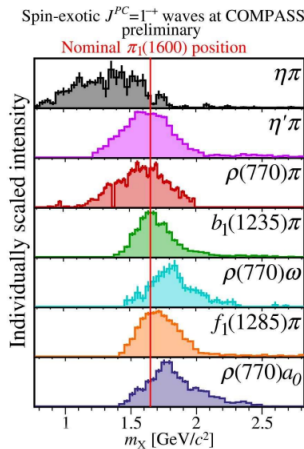
HadSpec: J. Dudek et al. PRD 88 094505(2013)

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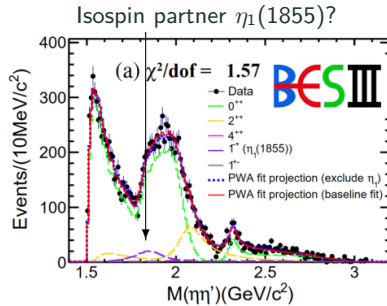


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HADRON 2025 talk by J. Beckers



BESIII: PRL 129, 192002 (2022)

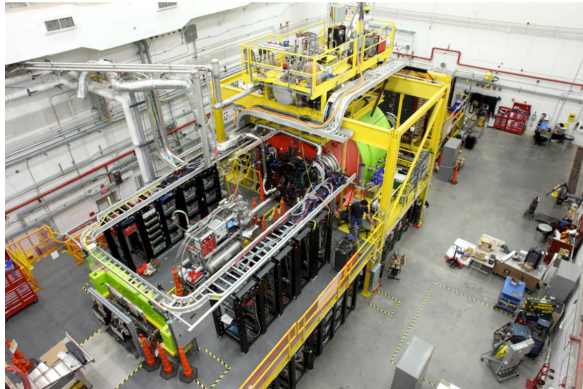
The GlueX experiment

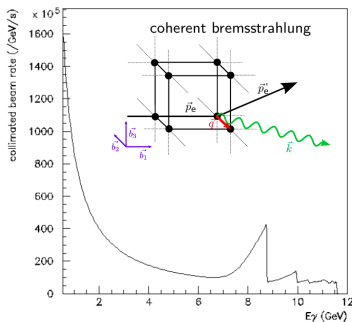
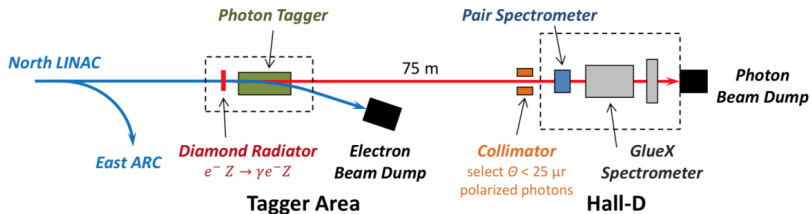
CEBAF accelerator



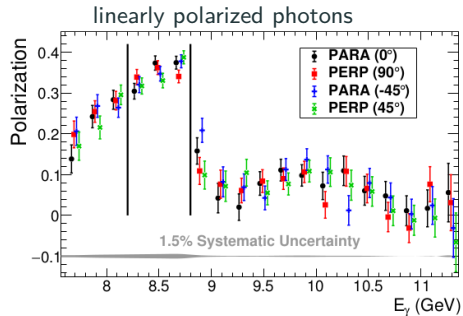
$E_{e^-} < 12 \text{ GeV}$

Hall D

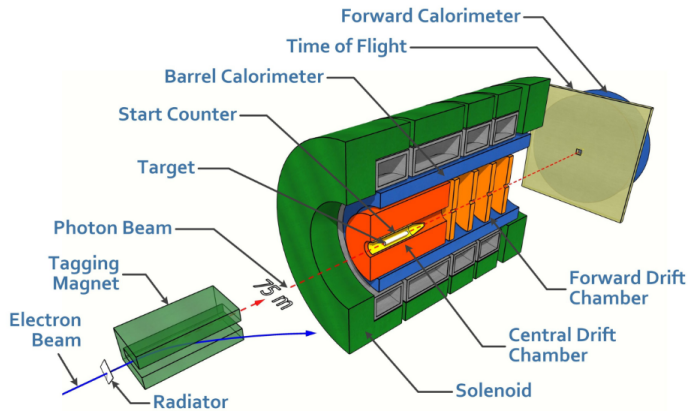




(b) Diamond radiator



Important for understanding production mechanism!

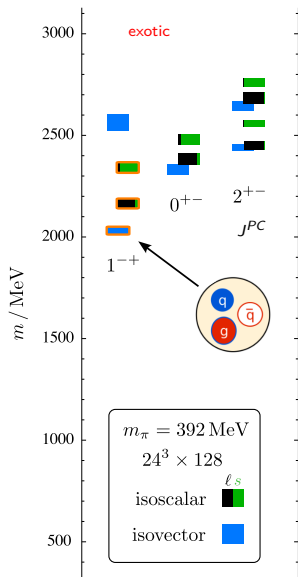


GlueX: NIMA 987 (2021) 164807

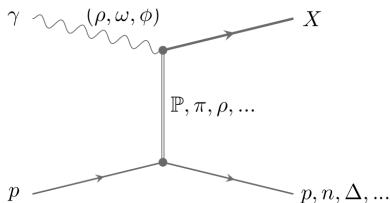
Year	Phase	$\int L(\text{pb}^{-1})$	Status
2017	I	22	analyzed
2018	I	103	analyzed
2020	II	132	analyzing
2023	II	~ 65	analyzing
2025	II	~ 140	calibrating
2026	II	~ 60	planned
?	III	800	proposed

70% GlueX-II data-taking completed!

- Nearly complete angular coverage for charged and neutral final states
→ Light meson spectroscopy with wide variety of final states possible!

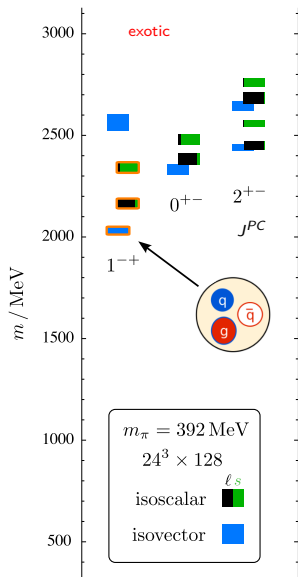


Photoproduction is **unique, complementary production mechanism**

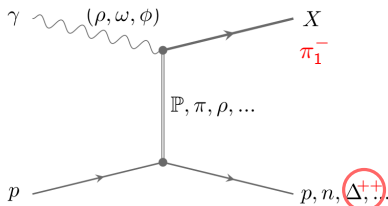


Exchange		Exotic Final States	
$\mathbb{P}$	0^{++}	b, h, h'	$2^{+-}, 0^{+-}$
π^0	0^{-+}	b_2, h_2, h'_2	2^{+-}
$\pi^\pm$	0^{-+}	$\pi_1^\pm$	1^{-+}
ω	1^{--}	π_1, η_1, η'_1	1^{-+}

Advantage: Access to **all exotic quantum numbers J^{PC}** !

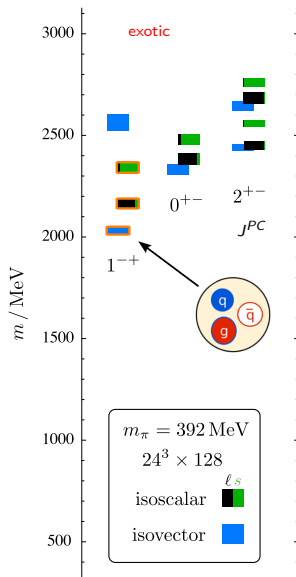


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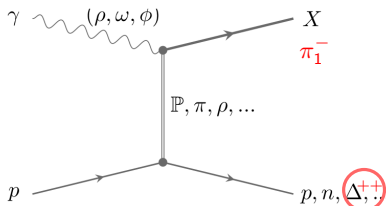


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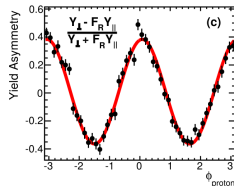
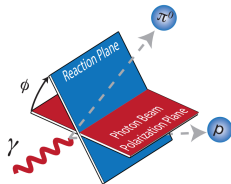
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Analysis approach to search for e.g. π_1 :

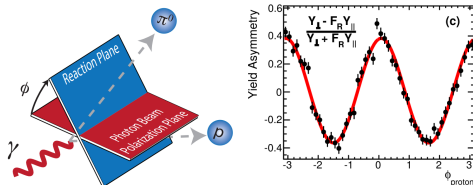
1. Study neutral and charge exchange mechanism
→ Linearly polarized photons help to disentangle different production mechanism
2. Study different decay modes of π_1 : e.g. $\pi\eta, \pi\eta', \pi\rho$
→ Disentangle different J^{PC} contributions in mass distributions
→ Develop formalism for amplitude analysis

Probing photoproduction mechanism with beam asymmetry Σ and Spin-Density Matrix Elements (SDMEs)

- Σ is sensitive to exchanged particle with J^{PC}
Sign of $\Sigma \rightarrow$ naturality: $\eta = P(-1)^J$
- **natural** parity exchange ($\eta = +1$):
 $J^P = 0^+, 1^-, 2^+ \dots$
- **unnatural** parity exchange ($\eta = -1$):
 $J^P = 0^-, 1^+, 2^- \dots$

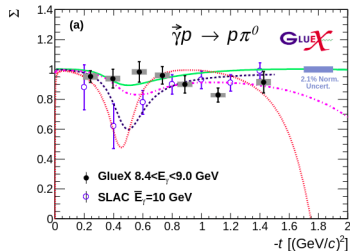


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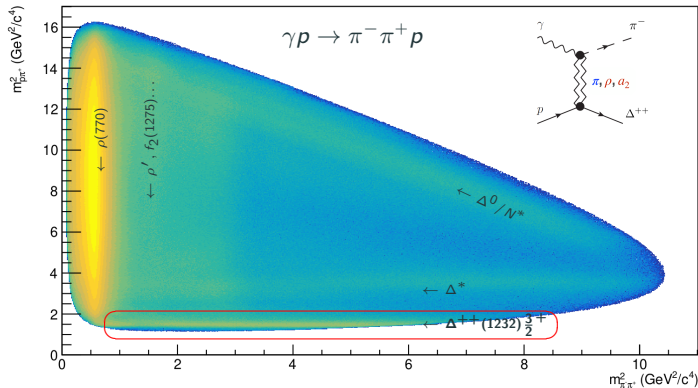
neutral exchange:

- $\pi^0 p$: natural parity (ρ, a_2) exchange dominates
- Similar observations ($\Sigma \approx 1$) for $\eta p, \eta' p, K^+ \Sigma^0$
GlueX: PRC 100, 052201 (2019)
GlueX: PRC 101, 065206 (2020)
- As well as for ρp and $\phi p \rightarrow K_S K_L p$
GlueX: PRC 108 055204 (2023)
GlueX: PRC 112, 025203 (2025)

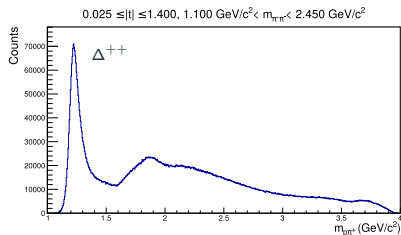


GlueX: PRC 95, 042201 (2017)

GlueX: Phys.Lett.B 863 (2025) 139368

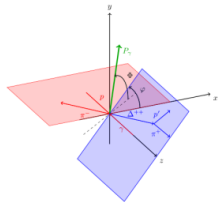


- High statistics available
- Clear Δ^{++} signal with small background contributions from $\pi^+ \pi^-$ system



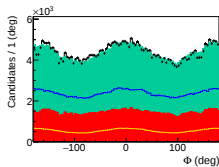
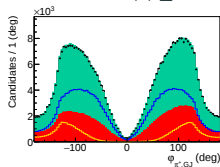
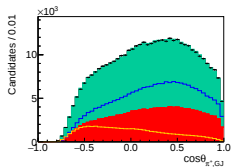
Analyzing decay angles of $\Delta^{++} \rightarrow p \pi^+$ gives access to Spin-density matrix elements!

Study of exchange mechanism with SDMEs in $\gamma p \rightarrow \pi^- \Delta^{++} \rightarrow \pi^- \pi^+ p$



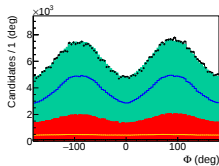
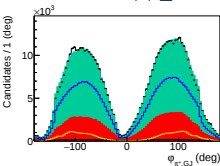
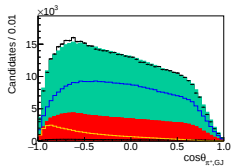
$$W(\theta, \varphi, \Phi) = \frac{3}{4\pi} (\rho_{33}^0 \sin^2 \theta + \rho_{11}^0 \left(\frac{1}{3} + \cos^2 \theta \right) - \frac{2}{\sqrt{3}} \text{Re}[\rho_{31}^0 \cos \varphi \sin 2\theta + \rho_{3-1}^0 \cos 2\varphi \sin^2 \theta]) - P_\gamma \cos 2\Phi \left[\rho_{33}^1 \sin^2 \theta + \rho_{11}^1 \left(\frac{1}{3} + \cos^2 \theta \right) - \frac{2}{\sqrt{3}} \text{Re}[\rho_{31}^1 \cos \varphi \sin 2\theta + \rho_{3-1}^1 \cos 2\varphi \sin^2 \theta] \right] - P_\gamma \sin 2\Phi \frac{2}{\sqrt{3}} \text{Im}[\rho_{31}^2 \sin \varphi \sin 2\theta + \rho_{3-1}^2 \sin 2\varphi \sin^2 \theta])$$

$0.100 < |t| \leq 0.125$



data
acc. MC + accid. bg
accid. background
acc. MC ($\pi^- \Delta^{++}$)
acc. MC ($p(\pi^+ \pi^-)$)

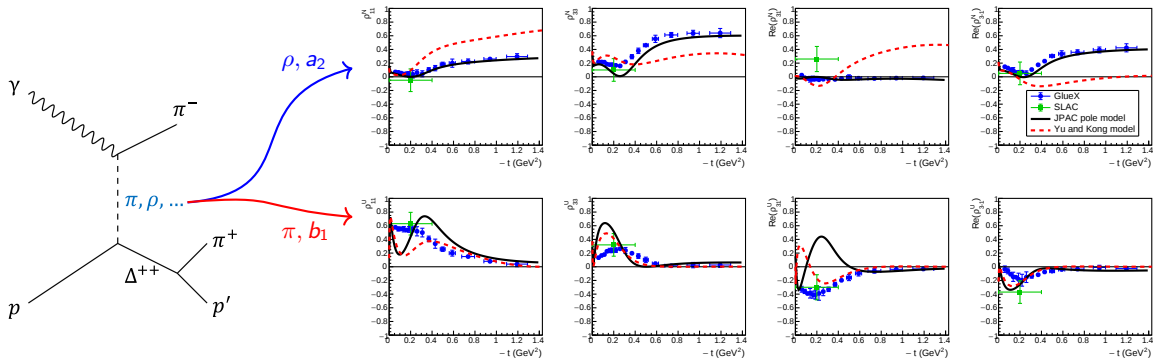
$0.640 < |t| \leq 0.850$



Exchange changes from
low t to high t region!

- Separation of unnatural-parity (U) and natural-parity (N) exchanges

$$\rho_{ij}^{N/U} = \rho_{ij}^0 \pm \rho_{ij}^1$$



GlueX: Phys.Lett.B 863 (2025) 139368

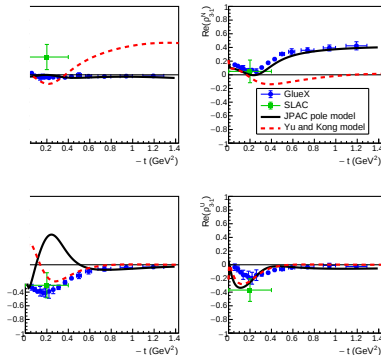
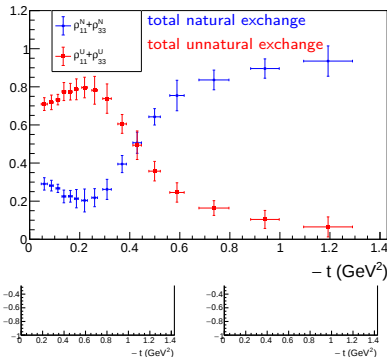
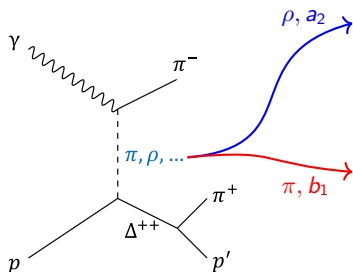
— JPAC: Phys. Lett. B 779, 77-81 (2018)

--- Yu and Kong: PLB 769, 262-266 (2017)

- JPAC model: π (a_2) is the dominant **unnatural** (**natural**) exchange
- Important for charge-exchange reactions e.g. $\gamma p \rightarrow \eta' \pi \Delta^{++}$, $\gamma p \rightarrow 3\pi \Delta^{++}$

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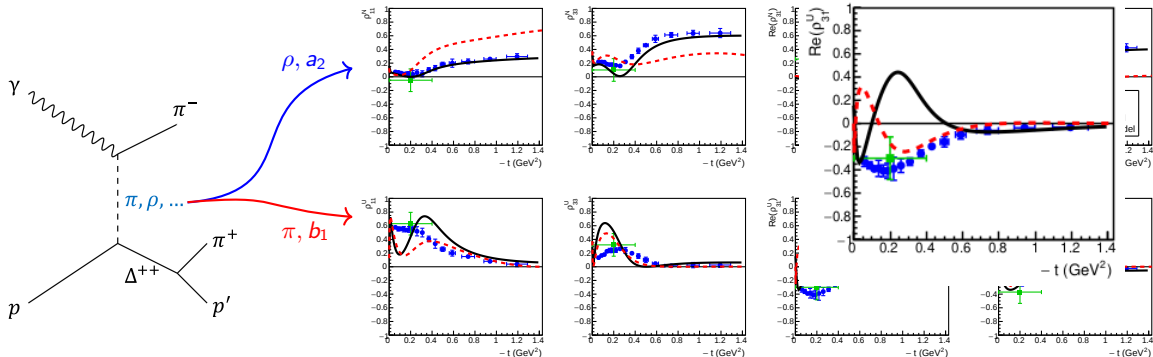
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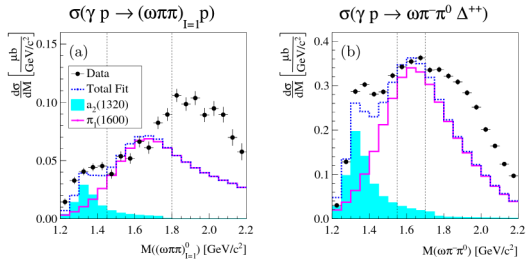
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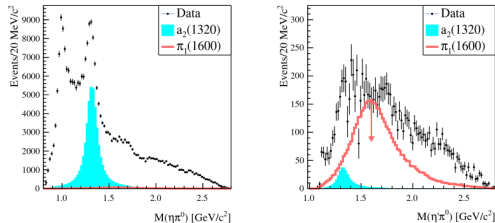
Towards hybrids at GlueX

GlueX: Phys.Rev.Lett. 133 (2024) 26, 26

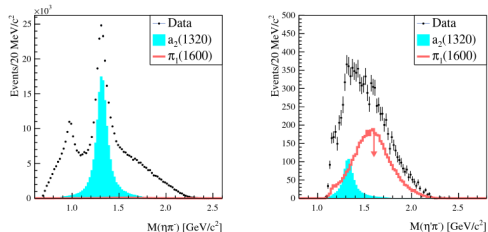


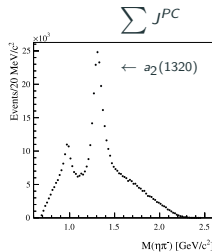
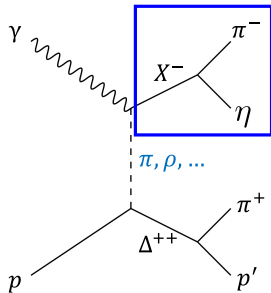
- Upper limit for photoproduction cross section $\gamma p \rightarrow p\pi_1^0(1600)$ and $\gamma p \rightarrow \Delta^{++}\pi_1^-(1600)$ using $\pi_1 \rightarrow b_1\pi \rightarrow \omega\pi\pi$
- Fit $\sigma(\omega\pi\pi)_{I=1}$ with fixed BW shapes for a_2 (PDG) and π_1 (JPAC)
- π_1 BR taken from lattice QCD

Projections for $\gamma p \rightarrow p\eta^{(\prime)}\pi^0$

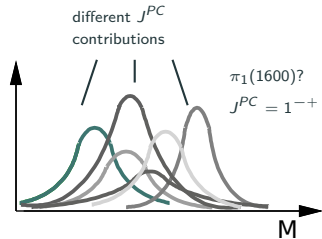


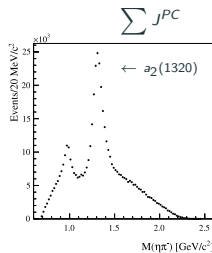
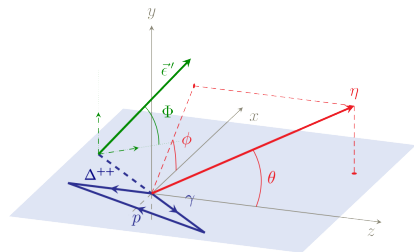
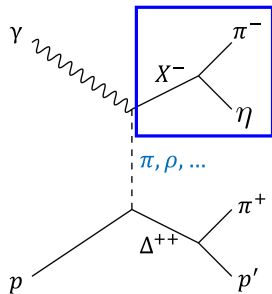
Projections for $\gamma p \rightarrow \Delta^{++}\eta^{(\prime)}\pi^-$



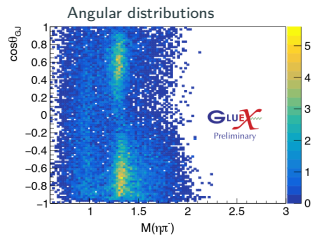
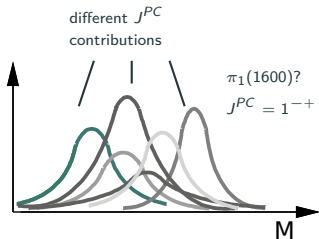


disentangle





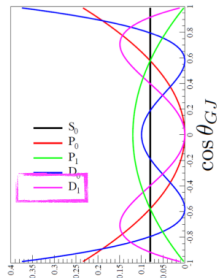
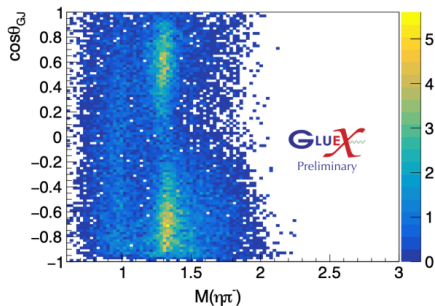
disentangle



Angular pattern $\leftrightarrow J^{PC}$

$$I(\theta, \phi, \Phi) \propto \left| \sum_{\ell, m} [l]_m^\epsilon Y_\ell^m(\theta, \phi) e^{-i\Phi} \right|^2$$

Production mechanism of $\gamma p \rightarrow a_2^-(1320)\Delta^{++}$



$$I(\theta, \phi, \Phi) \propto \left| \sum_{\ell, m} [\ell]_m^\epsilon Y_\ell^m(\theta, \phi) e^{-i\Phi} \right|^2$$

ℓ : orbital angular momentum

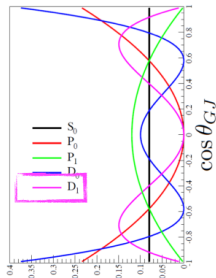
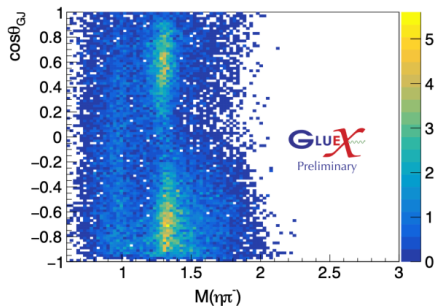
m : spin projection

ϵ : reflectivity - product of naturalities of exchanged particle and prod. res.

$[\ell]_m^\epsilon$: (interfering) partial waves

$$S_0^\pm, P_{-1,0,1}^\pm, D_{-2,-1,0,1,2}^\pm, \dots$$

Production mechanism of $\gamma p \rightarrow a_2^-(1320)\Delta^{++}$



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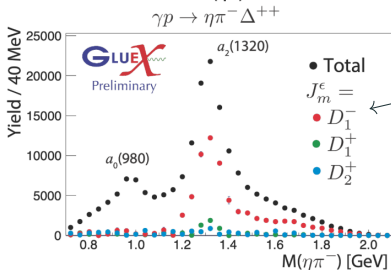
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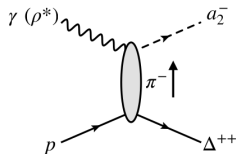
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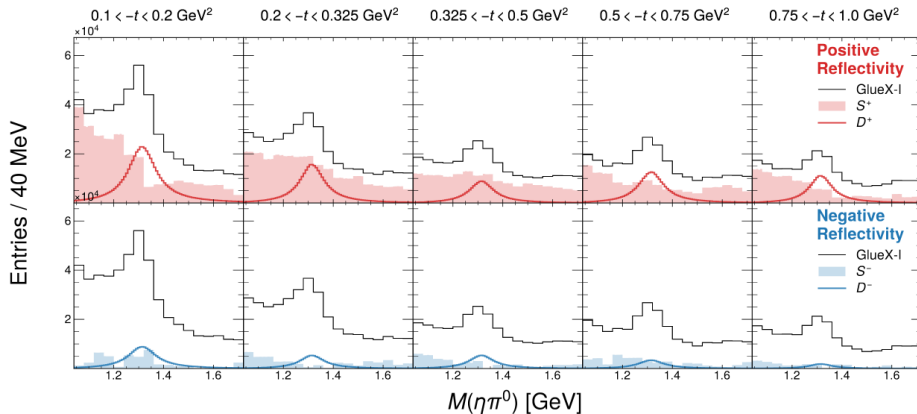


a_2^- is dominantly produced by **unnatural parity** ($\epsilon = -$) exchange

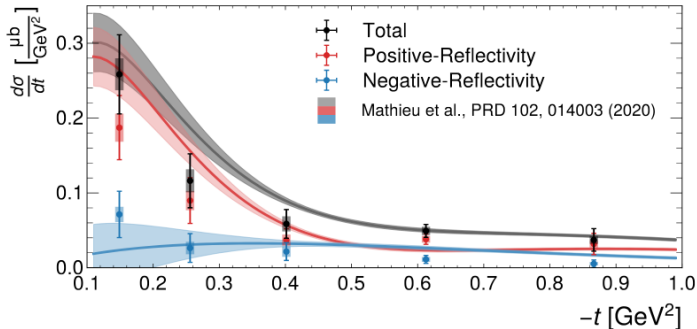


Production mechanism of $\gamma p \rightarrow a_2^0(1320)p$

- Semi-mass dependent method using Breit-Wigner to model $a_2^0(1320)$
- $a_2^0(1320)$ is dominantly produced by **natural parity** exchange (D_2^+)
- Polarized photoproduction cross section agrees well with theory (tensor meson dominance model)



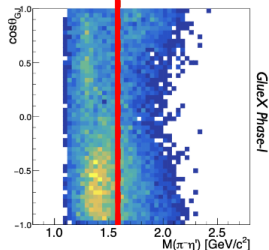
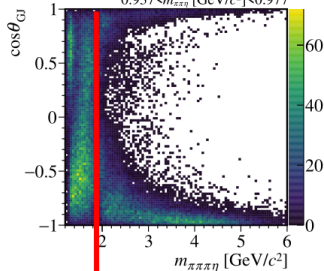
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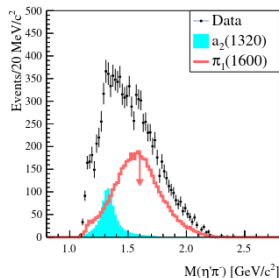
Serves as reference in search
for $\pi_1(1600)$ in $\eta'\pi$

Talk by Spülbeck, Hadron 2025

COMPASS preliminary
 $0.937 < m_{\pi\pi\eta} [\text{GeV}/c^2] < 0.977$



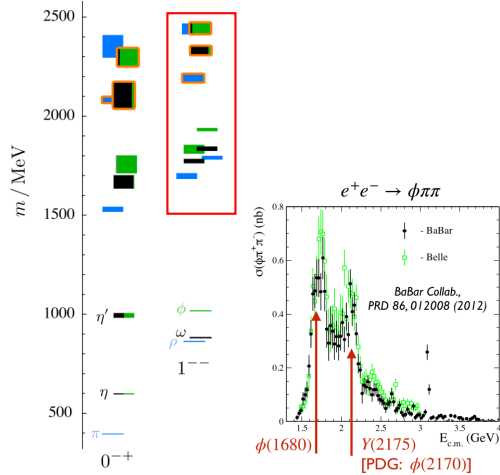
$\gamma p \rightarrow \eta' \pi^- \Delta^{++}$



GlueX: Phys.Rev.Lett. 133 (2024) 26, 26

- Similar forward/backward asymmetry seen in GlueX data consistent with COMPASS data
- Potential indication for **interference** between odd (π_1 **P-wave**) and even (a_2 **D-wave**) partial waves

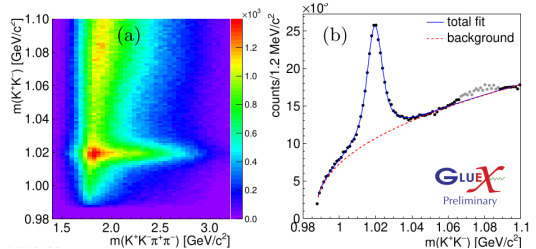
Search for " $Y(2175)$ " / $\phi(2170)$



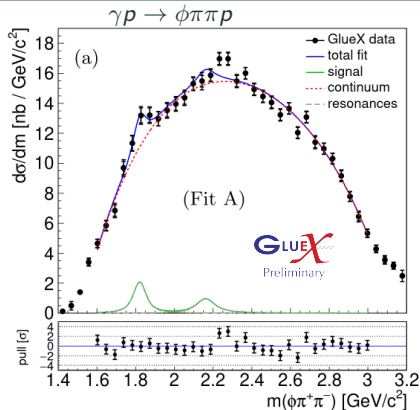
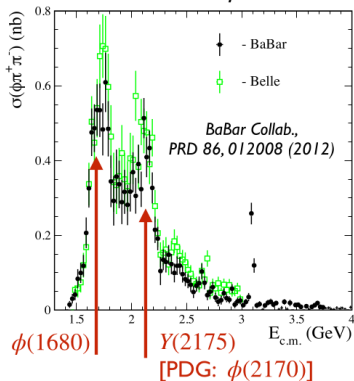
HadSpec: J. Dudek et al. PRD 88 094505(2013)

- $Y(2175)$ ($J^{PC} = 1^{--}$) observed in e^+e^- collisions, e.g. $e^+e^- \rightarrow \phi \pi \pi$
- Possible strange partner of the charmonium-like " $Y(4260)/\phi(4230)$ " state
- Possible interpretations: $s\bar{s}g$ hybrid, $(s\bar{s}s\bar{s})$ tetraquark, $\Lambda\bar{\Lambda}$ baryonium, conventional $s\bar{s}$ state, etc.

GlueX search: $\gamma p \rightarrow \phi \pi^+ \pi^- p, \phi \rightarrow K^+ K^-$



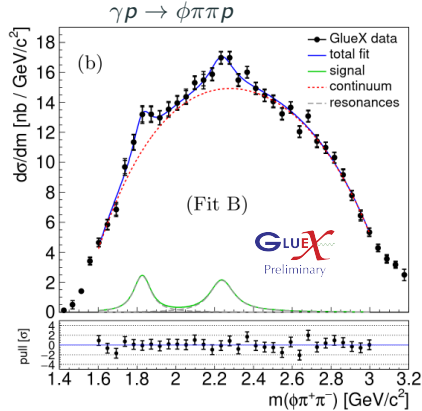
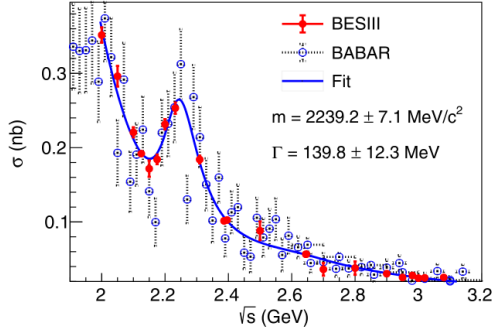
$e^+e^- \rightarrow \phi \pi \pi$



EPJ Web Conf. 291 (2024) 03011

- $\phi \pi \pi$ photoproduction spectrum looks completely different: e.g. no evidence for $\phi(1680)$
- Peaking structure at 1.8 GeV (3.4σ): parameters consistent with $\phi_3(1850)$
New decay mode $\phi_3(1850) \rightarrow \phi \pi \pi$?
Near $K^* K^*$ threshold $\rightarrow$ Rescattering effect?
- no evidence for " $Y(2175)/\phi(2170)$ ", 90% CL upper limit on cross section: < 272 pb for $|t| < 1$ GeV²

BESIII: Phys. Rev. D 99, 032001 (2019)

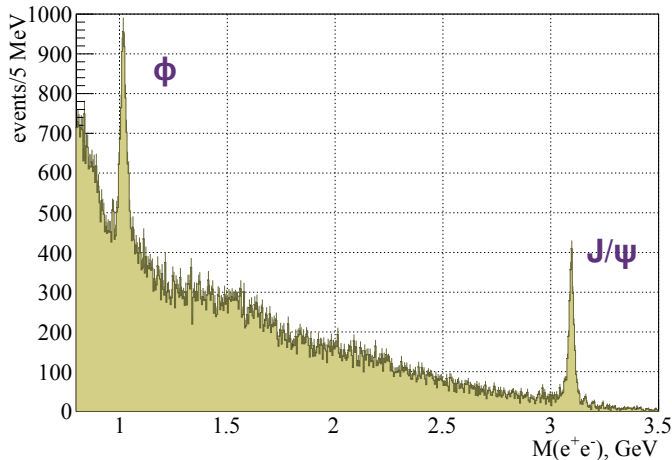


EPJ Web Conf. 291 (2024) 03011

- Fit quality improves when using BESIII parameters for $Y(2239)$ observed in $e^+e^- \rightarrow K^+K^-$
- GlueX observes structure at $m(\phi\pi^+\pi^-) = 2.24 \text{ GeV}/c^2$ with a statistical significance of about 5σ
- More studies needed in the future to understand both e^+e^- and photoproduction data

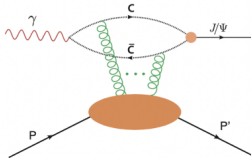
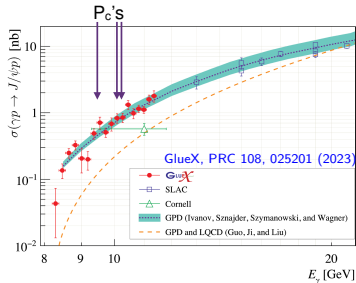
J/ψ Photoproduction at GlueX

$$\gamma p \rightarrow p \quad J/\psi \rightarrow p \quad e^+ e^-$$

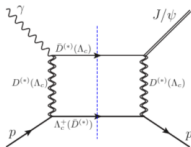
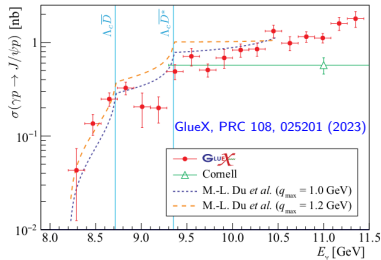


- Full GlueX-I data yields $2270 \pm 58 J/\psi$'s
- J/ψ production near threshold ($E_\gamma = 8.2 - 11.8 \text{ GeV}$)
 → probe of proton structure, search for P_c resonances, etc.

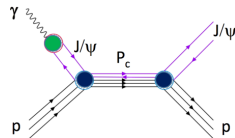
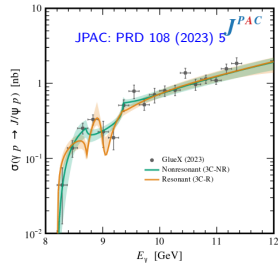
dip structure significance of 2.6σ



Cusps near open charm thresholds?

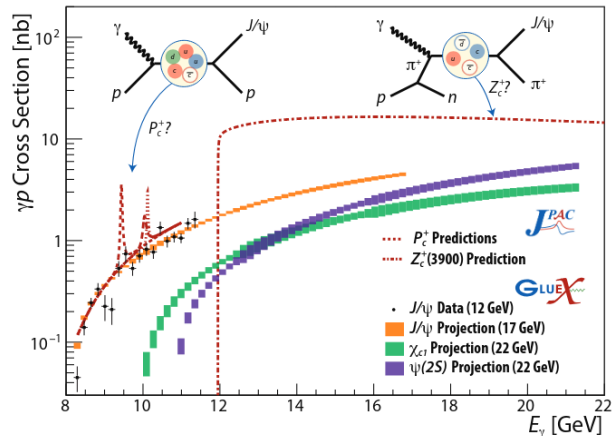


Resonant P_c contribution?



- More data taking (GlueX-III) planned in the future
- Polarization observables desirable to study production mechanism

A natural continuation to the charmonium sector: Spectroscopy of exotic states with $c\bar{c}$



A. Accardi et al., arXiv:2306.09360v2

- Many unexpected resonances XYZ observed in e^+e^- collisions and B decays; decay mostly into charmonium and light quarks
- Not much consistency between different production mechanisms
→ Are these states resonances?
- Photoproduction is free from rescattering effects

- GlueX has measured a unique photoproduction data set to explore the light hadron spectrum
 - Complementary to other experiments (e.g. COMPASS, BESIII, LHCb, ...)
 - Essential for global progress in hadron spectroscopy
- Developing amplitude analysis formalism and studying production mechanisms in parallel
 - Started with two-pseudoscalar final states: $\pi\pi$, $\eta\pi$, $\eta'\pi$, $K\bar{K}$, $K\pi$, ...
 - Natural extension of formalism to vector-pseudoscalar final states: $\omega\pi$, $\omega\eta$, ... and 3-body final states: 3π
- Many more exciting analyses ongoing: meson and baryon spectroscopy in strangeness sector, pentaquark and glueball searches, etc.
- GlueX gratefully acknowledges the support of several funding agencies and computing facilities:

gluex.org/thanks/

