Search for Exotic Hadrons at GlueX

Marciana 2025: Lepton Interactions with Nucleons and Nuclei

Farah Afzal for the GlueX Collaboration

Ruhr University Bochum

23.06.2025

Hadron spectrum

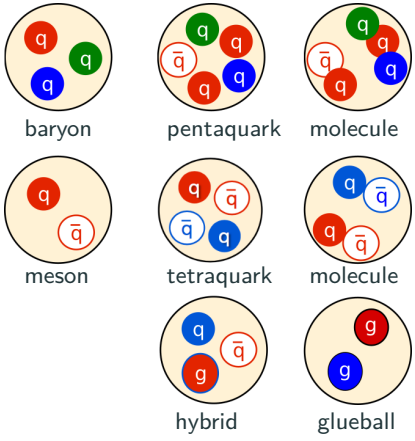
- Many conventional $q\bar{q}$ and qqq states have been observed
- QCD allows more complicated configurations as well, e.g. multi-quark states, hybrids, glueballs

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. ...

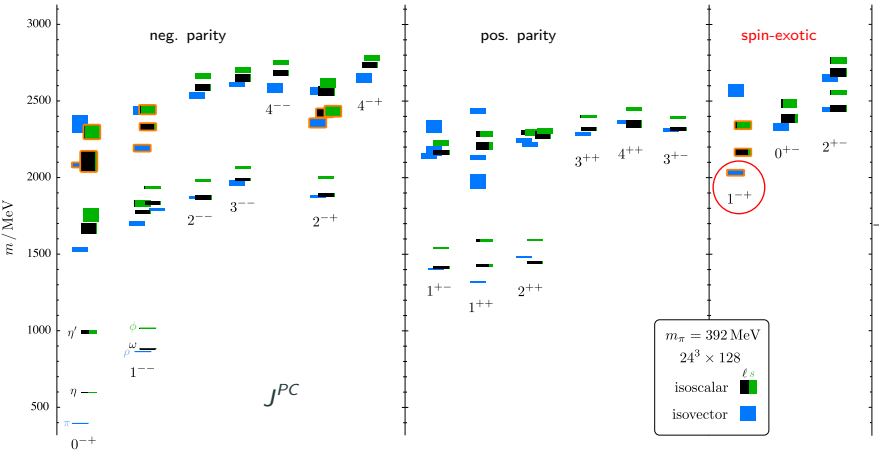
Phys.Lett. 8 214-215,1964

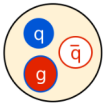


GlueX experiment: Probing hadron spectrum using photo-induced reactions
→ Focus on exotic hybrid mesons

Predicted light meson spectrum - Lattice QCD

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





Lightest hybrid mesons

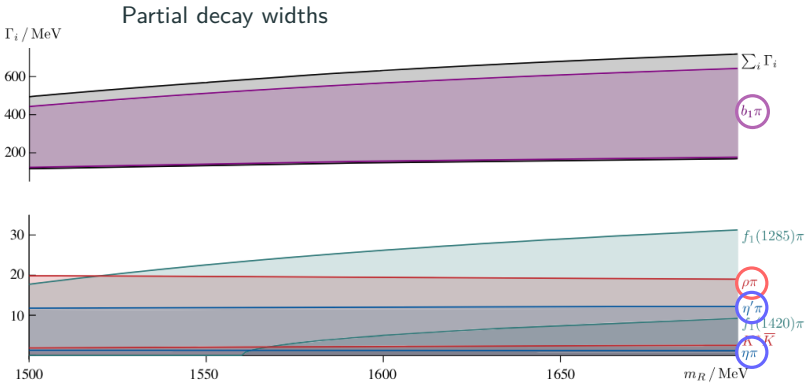
→ test gluonic degrees of freedom of QCD

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

Clear signature for finding hybrid mesons!

Expected decay modes of the lightest exotic hybrid meson

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

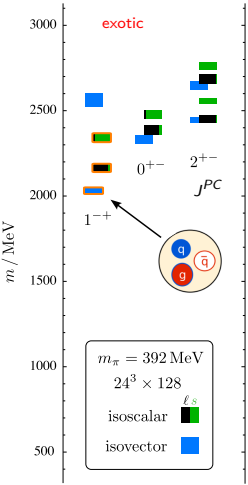


dominant decay mode: $b_1\pi \to \omega\pi\pi$

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

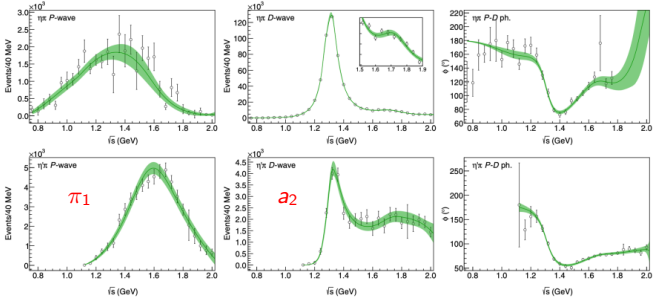
Important to measure different decay modes to compare to predictions from Lattice QCD!

Experimental evidence for light hybrid mesons



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

- 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**

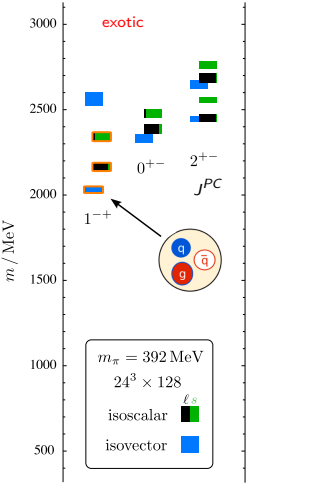


mass $= 1564 \pm 24 \pm 86$ MeV
width $= 492 \pm 54 \pm 102$ MeV

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

Experimental evidence for light hybrid mesons

More recent progress



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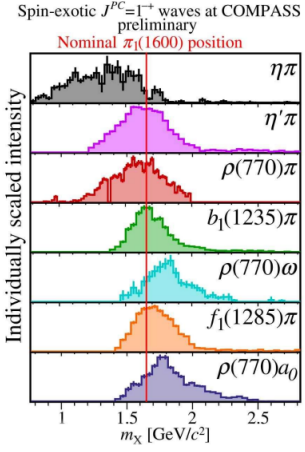
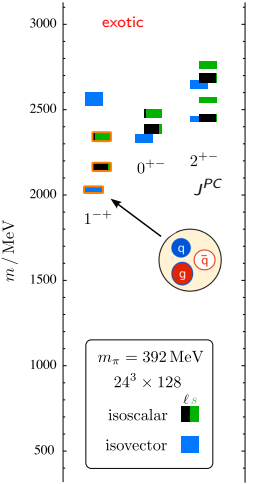
Multiple decay channels of π_1 measured



HADRON 2025 talk by J. Beckers

Experimental evidence for light hybrid mesons

More recent progress



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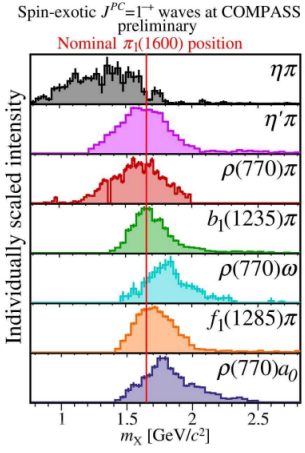
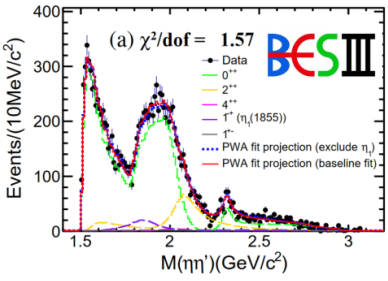


HADRON 2025 talk by J. Beckers

Isospin partner $\eta_1(1855)$?



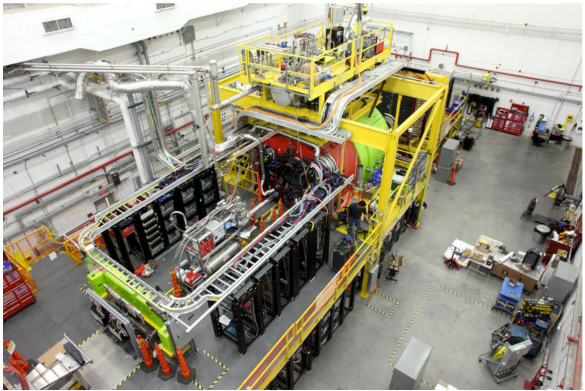
PRL 129, 192002 (2022)

The GlueX experiment

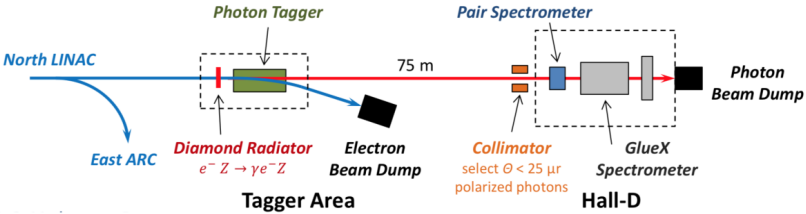
CEBAF accelerator

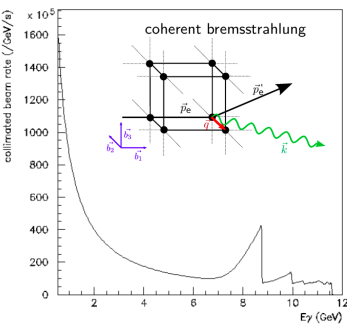
E_{e^-} <12 GeV

Hall D

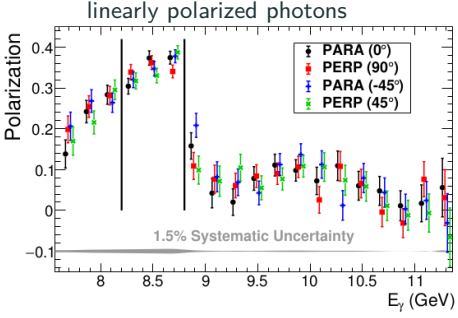


Linearly polarized photon beam



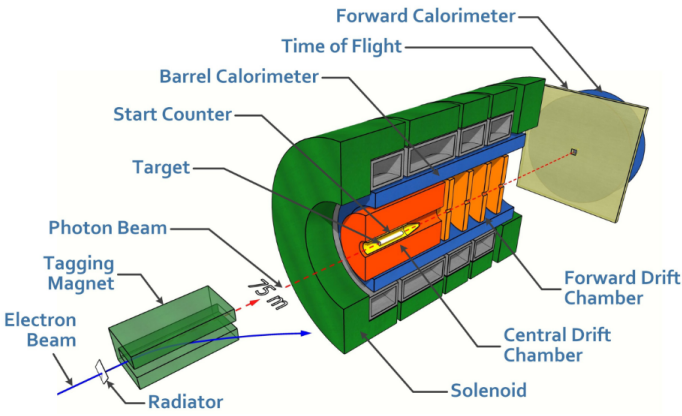


(b) Diamond radiator



Important for understanding production mechanism!

The GlueX experiment



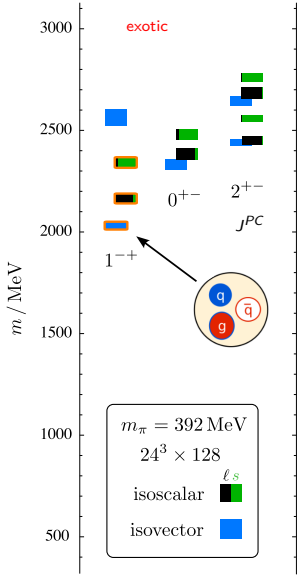
(GlueX) NIMA 987 (2021) 164807

Year	Phase	$\int L(\mathrm{pb}^{-1})$	Status
2017	I	22	analyzed
2018	I	103	analyzed
2020	II	132	analyzed
2023	II	$\sim$ 65	calibrating
2025	II	$\sim$ 200	running
?	III	800	proposed

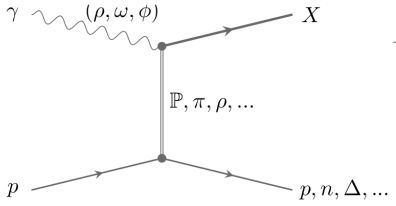
Currently GlueX-II data-taking ongoing!

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

Photoproduction of exotic final states



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}**!

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

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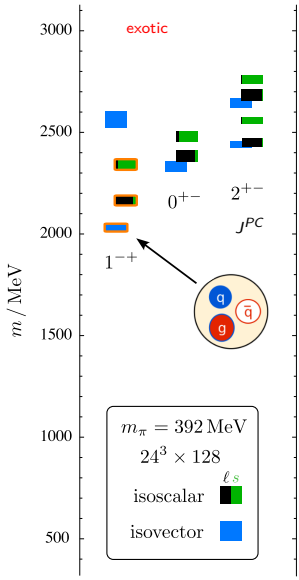

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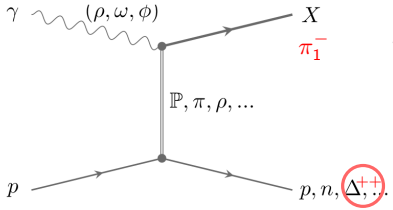

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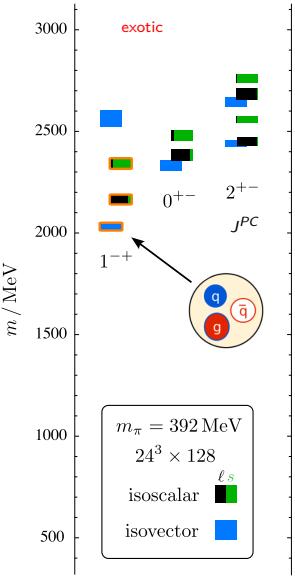

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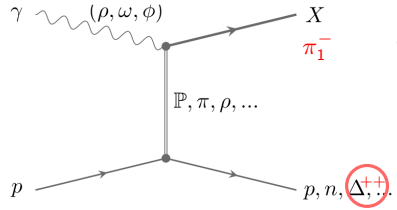

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Advantage: Access to **all exotic quantum numbers J^{PC}**!

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

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

Probing photoproduction mechanism with Σ and SDMEs

Probing photoproduction mechanism with Σ

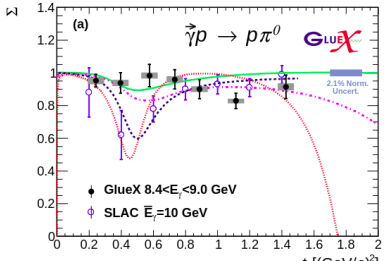
- Σ is sensitive to exchanged particle J^{PC}
  Sign of Σ → naturality: $\eta = P(-1)^J$
- **natural** parity exchange ($\eta = +1$):
  $J^P = 0^+, 1^-, 2^+ \ldots$
- **unnatural** parity exchange ($\eta = -1$):
  $J^P = 0^-, 1^+, 2^- \ldots$

neutral exchange:

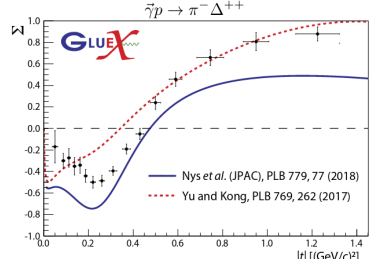
- $\pi^0 p$: natural parity (ρ, a_2) exchange dominates
- Similar observations ($\Sigma \approx 1$) for ηp, $\eta' p$ and $K^+\Sigma^0$
  GlueX: PRC 100, 052201 (2019)
  GlueX: PRC 101, 065206 (2020)

charge exchange:

- Low $-t$: unnatural exchange ($\Sigma < 0 \rightarrow \pi, b_1$) preferred
- High $-t$: natural exchange ($\Sigma > 0 \rightarrow \rho, a_2$) preferred



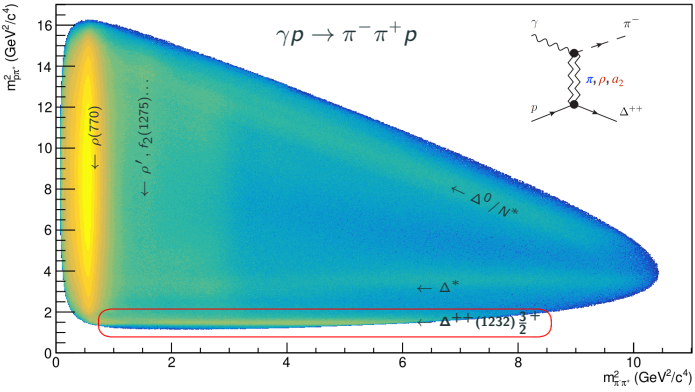
GlueX: PRC 95, 042201 (2017)



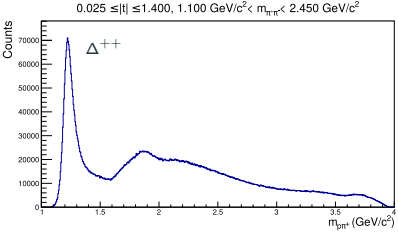
GlueX: PRC 103, 02201 (2021)

Study of charge exchange mechanism $\gamma p \to \pi^- \Delta^{++} \to \pi^- \pi^+ p$

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

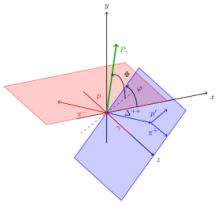


- High statistics available
- Clear Δ^{++} signal with small background contributions from $\pi^+\pi^-$ system



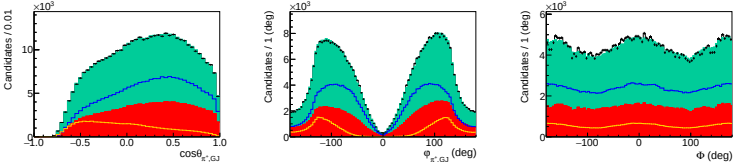
Analyzing decay angles of $\Delta^{++} \to p\pi^+$ gives access to Spin-density matrix elements!

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

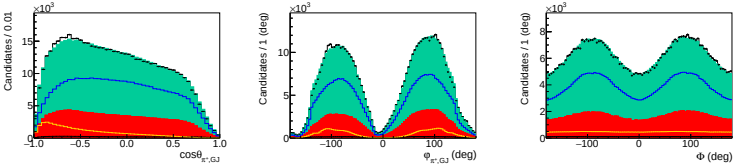


$$W(\theta, \varphi, \Phi) =$$
$$\frac{3}{4\pi}\left(\rho^0_{33}\sin^2\theta + \rho^0_{11}\left(\frac{1}{3} + \cos^2\theta\right) - \frac{2}{\sqrt{3}} Re[\rho^0_{31}\cos\varphi \sin 2\theta + \rho^0_{3-1}\cos 2\varphi \sin^2\theta]\right.$$
$$- P_\gamma \cos 2\Phi \left[\rho^1_{33}\sin^2\theta + \rho^1_{11}\left(\frac{1}{3}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

$0.100 < |t| \leq 0.125$



$0.640 < |t| \leq 0.850$



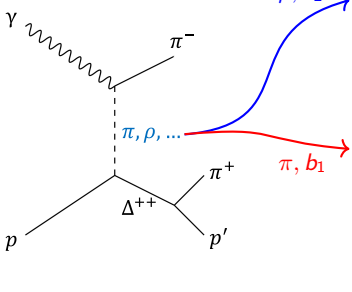
Exchange changes from low t to high t region!

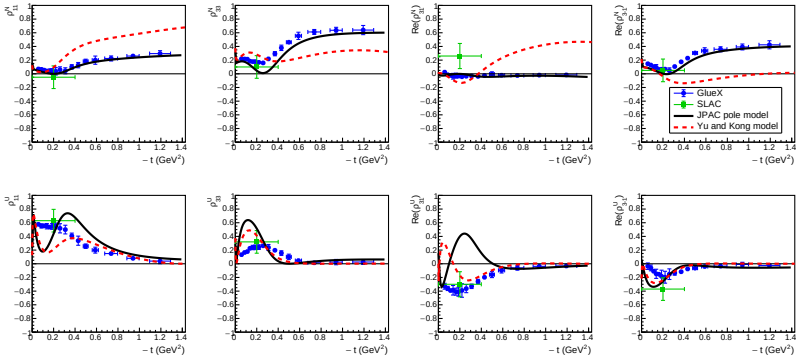
GlueX: Phys.Lett.B 863 (2025) 139368

Separation of natural and unnatural exchanges using combinations of SDMEs

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

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





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

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- Important for charge-exchange reactions e.g. $\gamma p \to \eta' \pi \Delta^{++}$, $\gamma p \to 3\pi\Delta^{++}$

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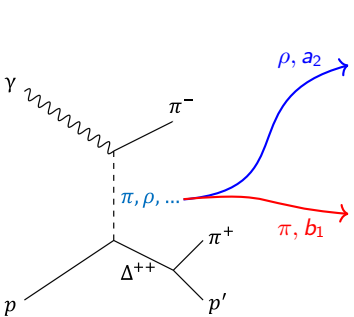

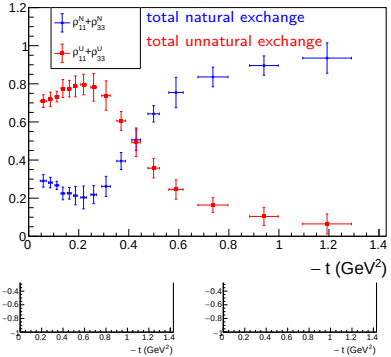

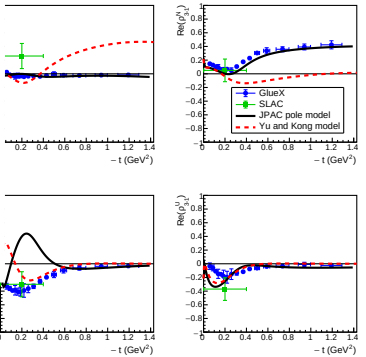

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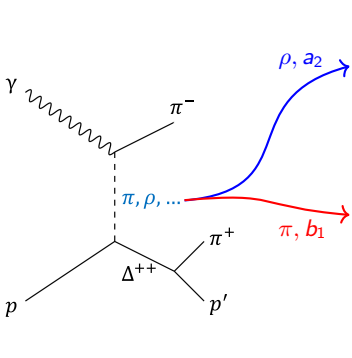

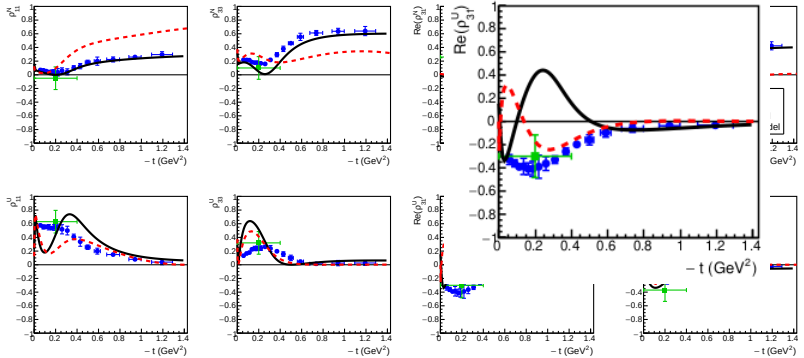

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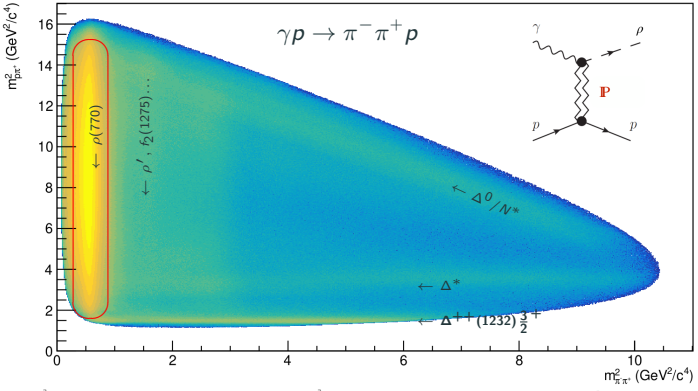
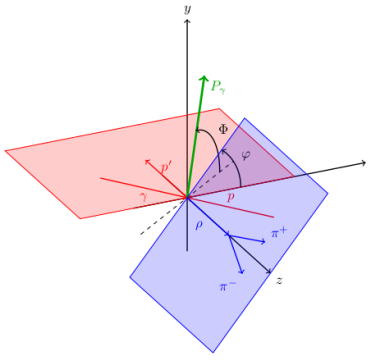
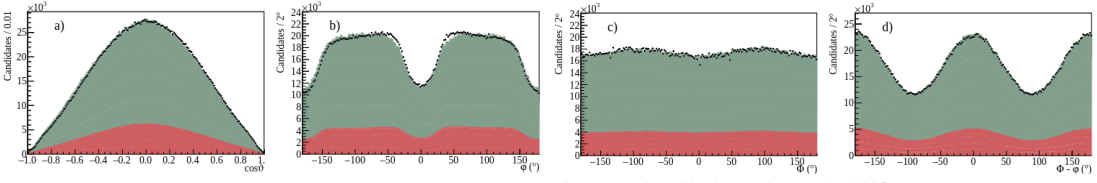
Spin-Density Matrix Elements in $\rho(770)$ production







GlueX: Phys.Rev.C 108 (2023) 5, 055204

• data accidental background weighted MC

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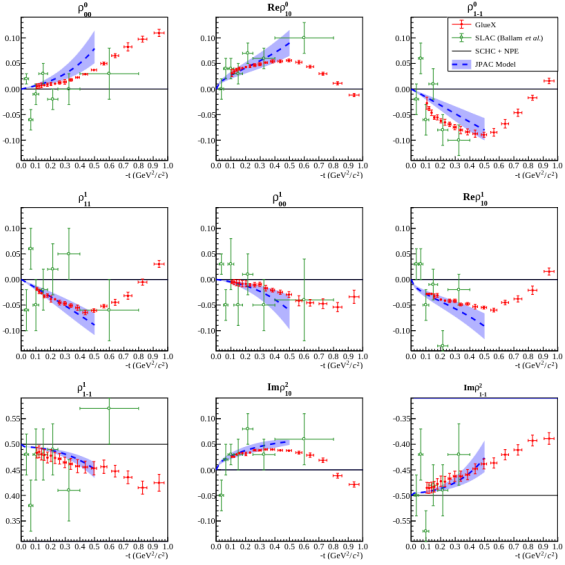
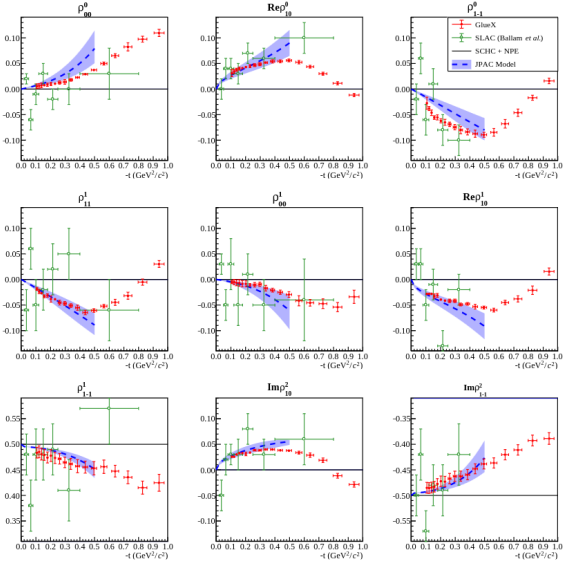


- High-precision data, uncertainties dominated by systematics
- s-channel helicity conservation: $\rho^1_{1-1} = 0.5$, $Im\rho^2_{1-1} = -0.5$ (valid at very low $-t$)
- Good agreement to JPAC: Regge model at low $-t$ [JPAC: PRD 97 094003 (2018)]
- Natural-parity exchange ($\mathbb{P}$) dominates

GlueX: Phys.Rev.C 108 (2023) 5, 055204

Spin-Density Matrix Elements in $\rho(770)$ production



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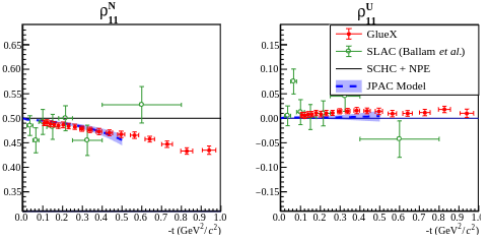
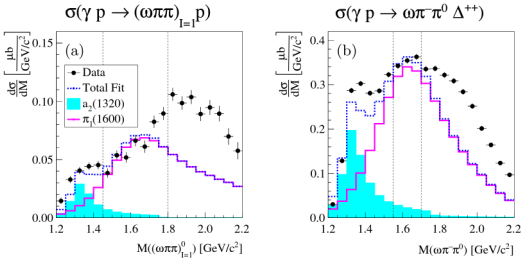


GlueX: Phys.Rev.C 108 (2023) 5, 055204

Towards hybrids at GlueX

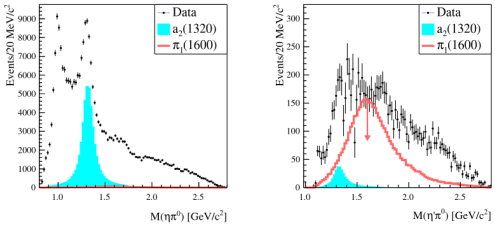
Guided search: $\pi_1(1600)$ photoproduction cross section upper limit

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

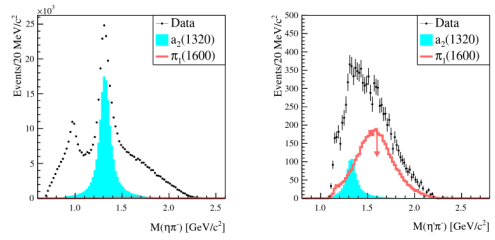


- Upper limit for photoproduction cross section $\gamma p \to p\pi_1^0(1600)$ and $\gamma p \to \Delta^{++}\pi_1^-(1600)$ using $\pi_1 \to b_1\pi \to \omega\pi\pi$
- Fit $\sigma(\omega\pi\pi)_{I=1}$ with fixed BW shapes for a_2 (PDG) and π_1 (JPAC)
- π_1 BR taken from lattice QCD

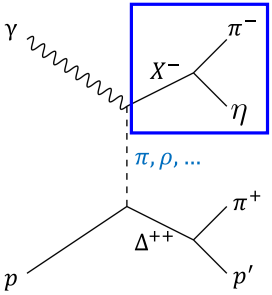
Projections for $\gamma p \to p\eta^{(\prime)}\pi^0$

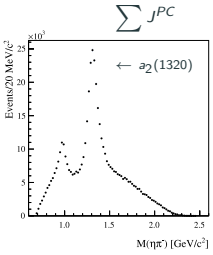


Projections for $\gamma p \to \Delta^{++}\eta^{(\prime)}\pi^-$

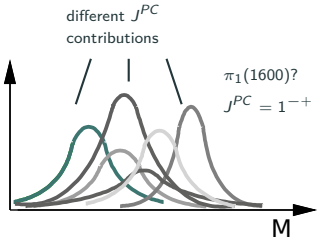


Disentangle different J^{PC} contributions in mass distributions





disentangle



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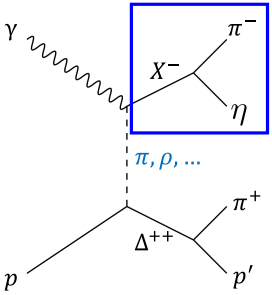
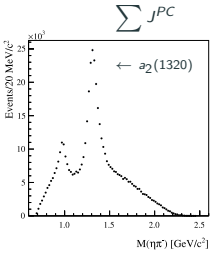
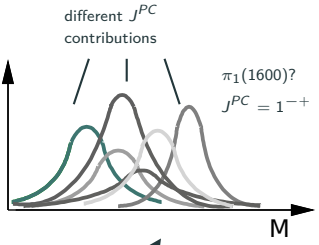
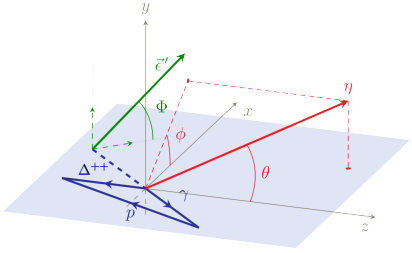


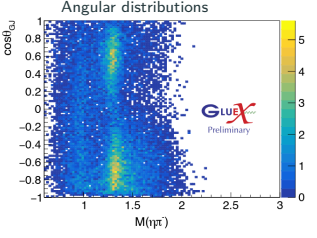


disentangle





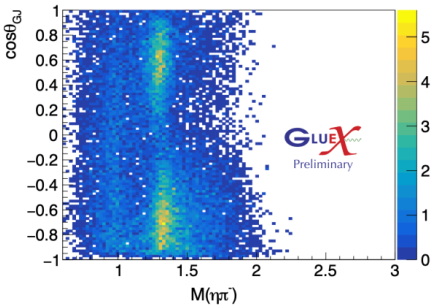
V. Mathieu et al., Phys.Rev.D 100, 054017 (2019)

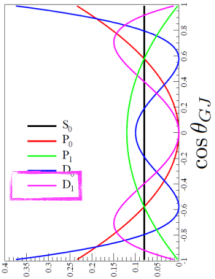


Angular pattern ↔ J^{PC}

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

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





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

ℓ: orbital angular momentum

m: spin projection

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

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

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

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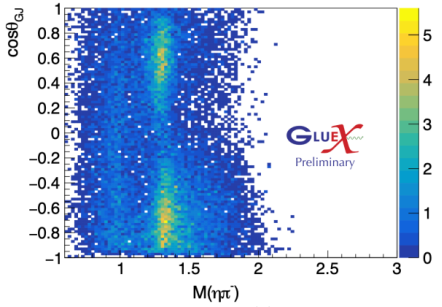

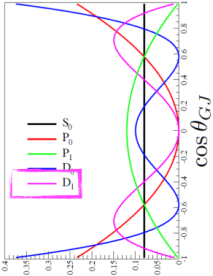

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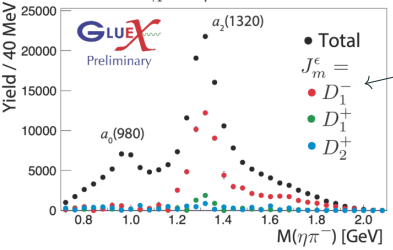
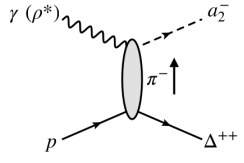
$\gamma p \to \eta\pi^-\Delta^{++}$

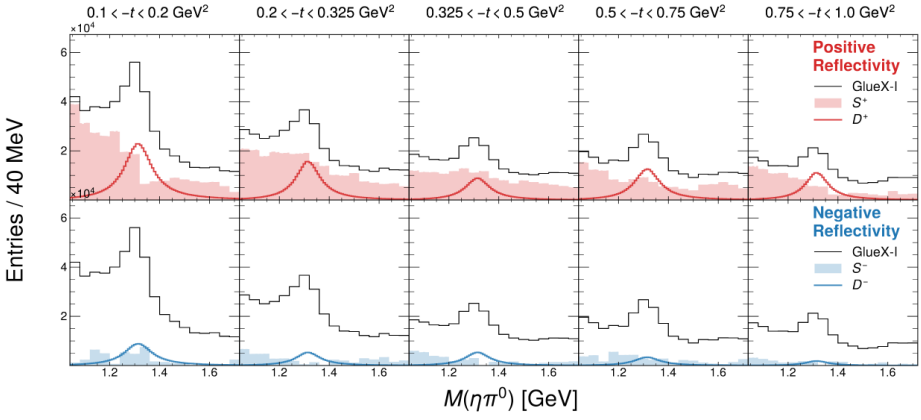


a_2^- is dominantly produced by unnatural parity ($\epsilon = -$) exchange



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 ($\boldsymbol{D_2^+}$)
- Polarized photoproduction cross section agrees well with theory (tensor meson dominance model)



GlueX: arXiv:2501.03091, Accepted in PRC

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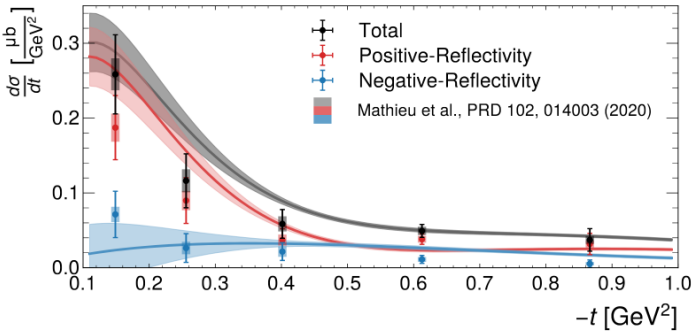
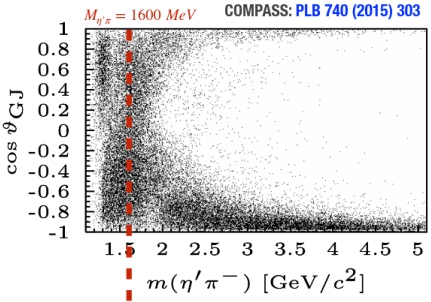
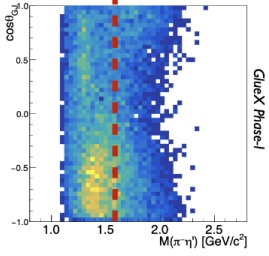


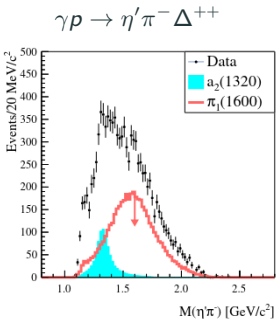
Serves as reference in search for $\pi_1(1600)$ in $\eta'\pi$

GlueX: arXiv:2501.03091, Accepted in PRC

Ongoing analysis for $\gamma p \to \eta' \pi^- \Delta^{++}$ at GlueX

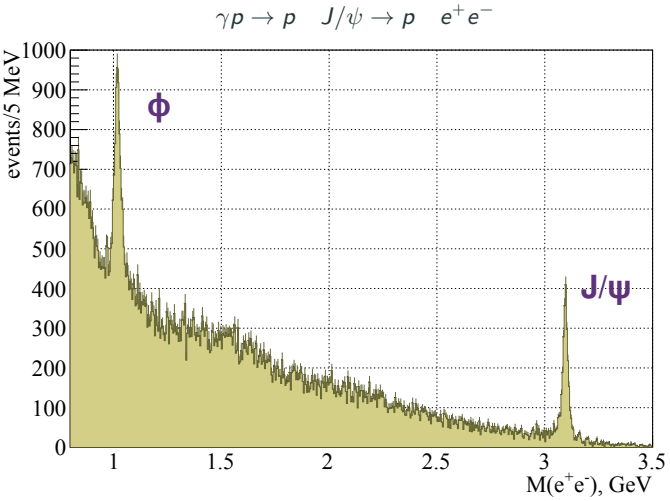






- Similar forward/backward asymmetry seen in GlueX data consistent with COMPASS data
- Potential indication for **interference** between odd (π_1 ***P*-wave**) and even (a_2 ***D*-wave**) partial waves

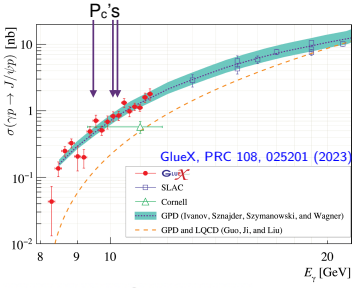
J/ψ Photoproduction at GlueX



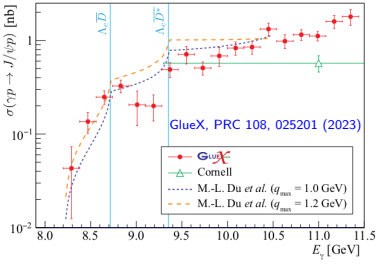
- Full GlueX-I data yields 2270 ± 58 J/ψ's
- J/ψ production near threshold ($E_\gamma = 8.2$ - 11.8 GeV)
  $\to$ probe of proton structure, search for P_c resonances, etc.

J/ψ Photoproduction at GlueX - Different possible production mechanisms

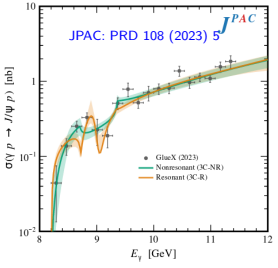
dip structure significance of 2.6σ

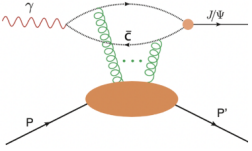


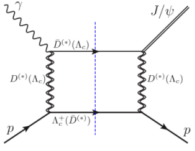
Cusps near open charm thresholds?

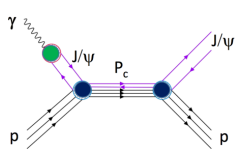


Resonant P_c contribution?





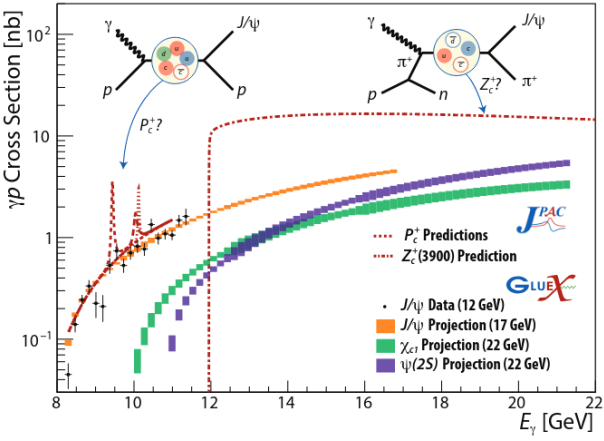




- More data taking (GlueX-III) planned in the future
- Polarization observables desirable to study production mechanism

Future Opportunities - JLab22 Upgrade

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
  $\rightarrow$ Are these states resonances?
- Photoproduction is free from rescattering effects

Summary

- GlueX has measured a unique data set with unprecedented statistical precision in the energy range between 6-12 GeV
- Developing amplitude analysis formalism and studying production mechanisms in parallel
- Σ, SDMEs provide important input for modeling exchange mechanism and search for exotic states
- $a_2^0(1320)$ results: first application of amplitude analysis formalism to linearly polarized photoproduction
- Upper limit of $\pi_1(1600)$ photoproduction cross section provides important guidance for future searches
  $\rightarrow$ Possible dominant contribution in $\eta'\pi$
  $\rightarrow$ First look at $\eta'\pi$ angular distributions looks promising
- GlueX has measured the first J/ψ photoproduction cross section in the energy range between 8.2-11.8 GeV
- No clear evidence of narrow P_c states, but dip structure at $E_\gamma = 9$ GeV with significance of 2.6σ observed
  $\rightarrow$ More data will be taken in the future
- GlueX gratefully acknowledges the support of several funding agencies and computing facilities:
  gluex.org/thanks/