Recent results from GlueX

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for the GlueX Collaboration

Exotic Hadron Spectroscopy 2024

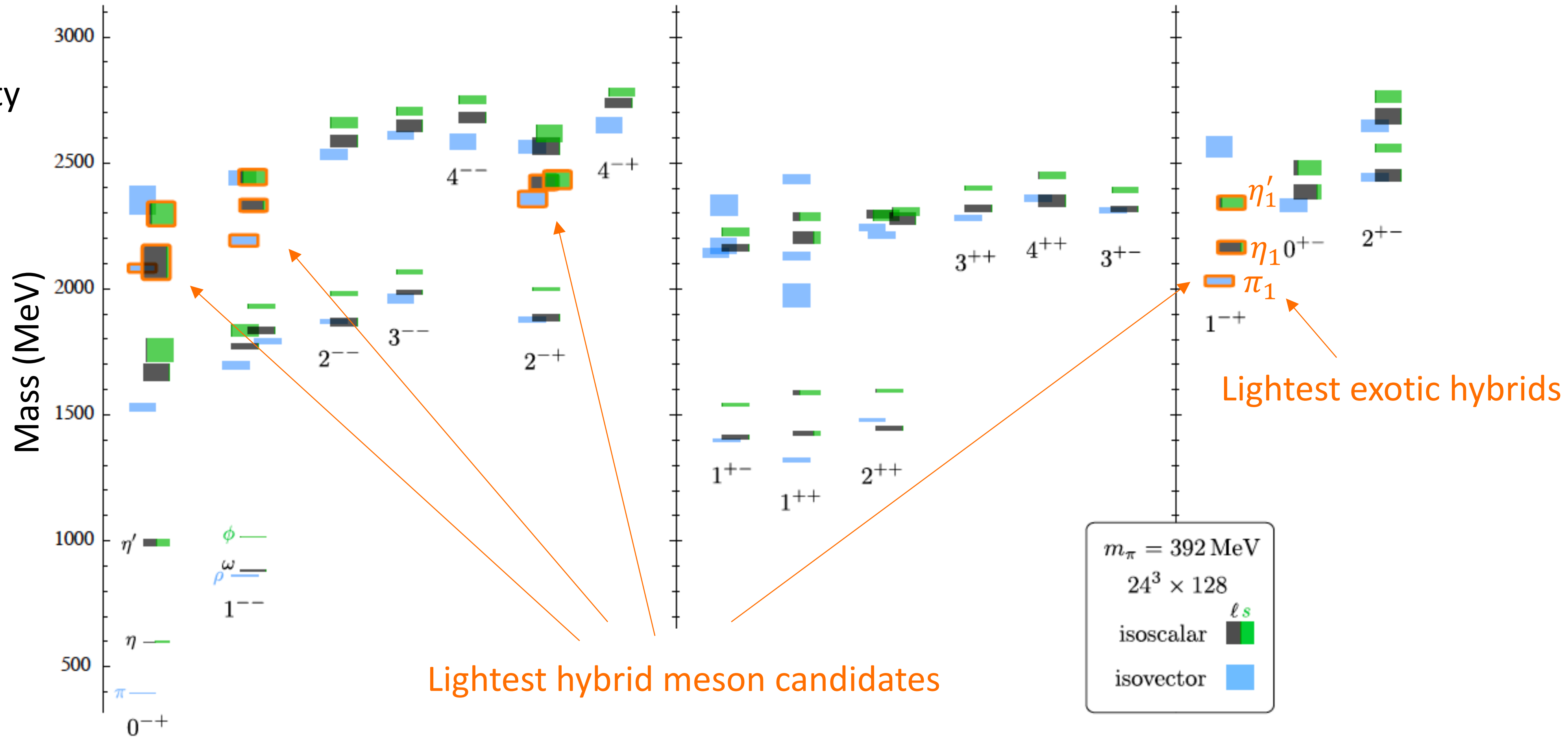
Swansea University, UK

July 2-4, 2024

GlueX objective: explore the light meson spectrum

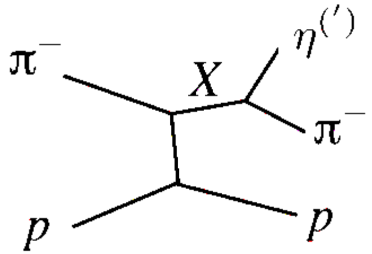
- Lattice QCD predictions from Hadron Spectrum collaboration: Dudek et al [PRD 88 (2013) 094505]

- Mass vs J^{PC}
- Box height: uncertainty
  Many states overlap
- Non-physical m_π

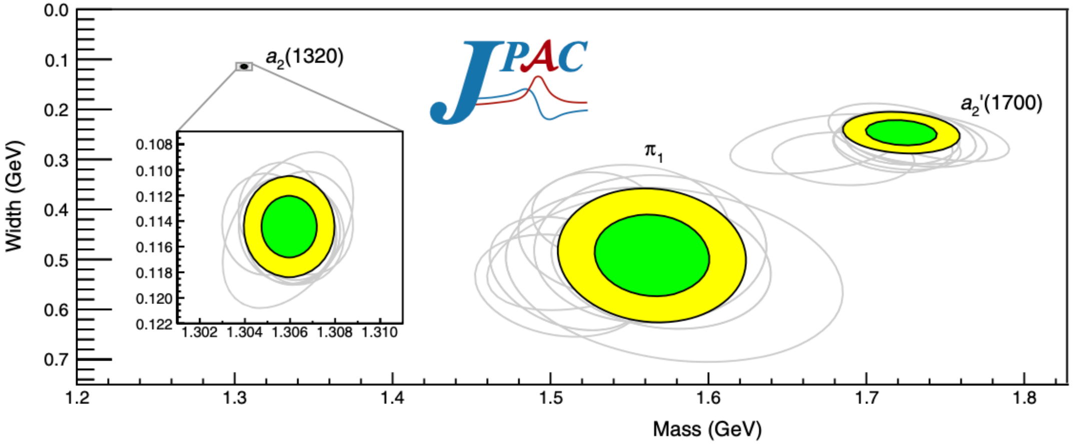


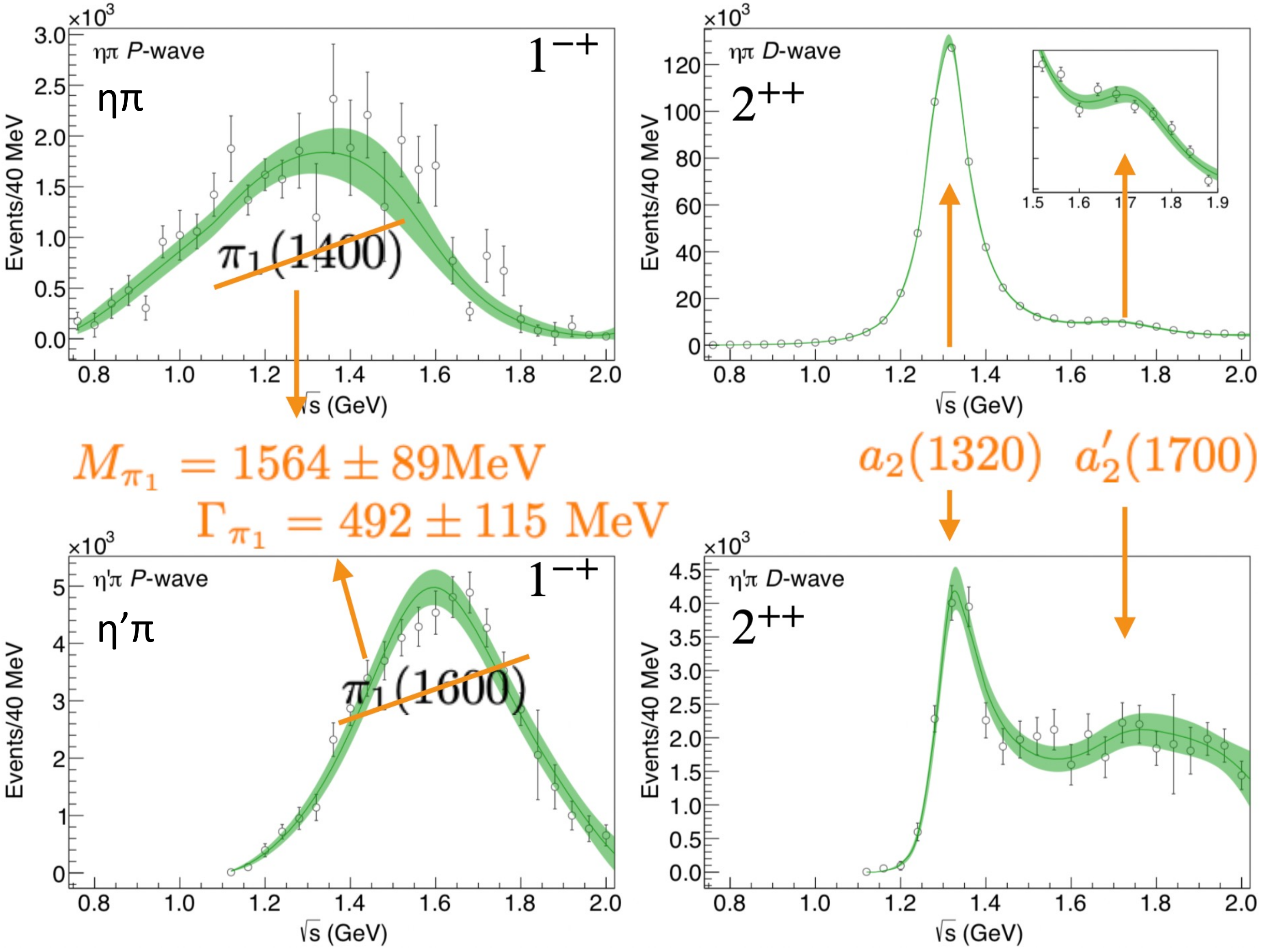
Evidence for exotic hybrid $\pi_1(1600)$

- Evidence for $\pi_1(1600)$ in data from COMPASS, 2015



- JPAC re-analyzed published PW expansions
- Coupled channel fit to ηπ and η'π partial waves
- Determined pole positions for $a_2(1320)$, $a_2'(1700)$ and single exotic π_1 pole at 1564 MeV

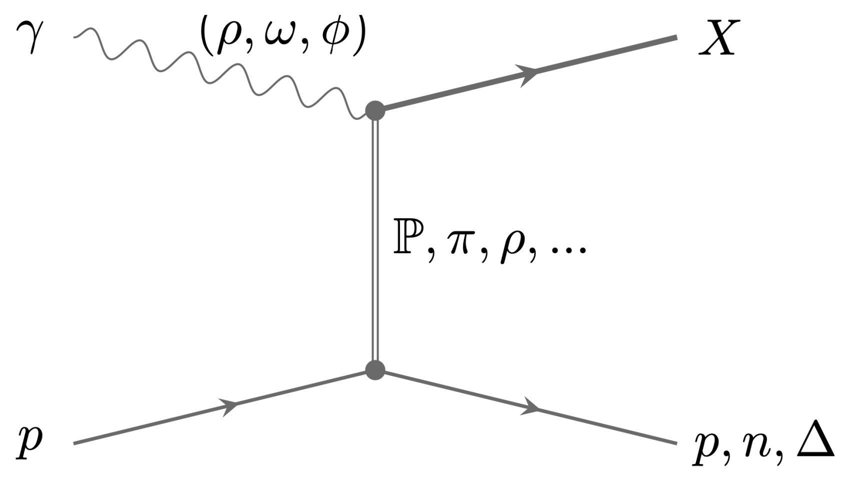




COMPASS: PLB 740 (2015) 303 JPAC Rodas et al: PRL 122 (2019) 042002

Motivation for studying meson photo-production with polarized beam

- Wide range of states is accessible, including all lightest hybrids
  - Photons oscillate to vector mesons (vector meson dominance)
  - Virtual particle exchanged with the target proton
  - Exchanged particle could be Pomeron, π, ρ, ω, …
- Polarization provides information on reaction mechanism
  - Extra constraint for amplitude analysis
- Little existing high-energy photoproduction data



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^{-+}

GlueX at Jefferson Lab, Newport News, VA, USA

- 12 GeV electron beam from CEBAF
  Continuous Electron Beam Accelerator Facility
- Polarized photon beam created in Tagger Hall
- GlueX spectrometer located in Hall D
- 5th pass beam

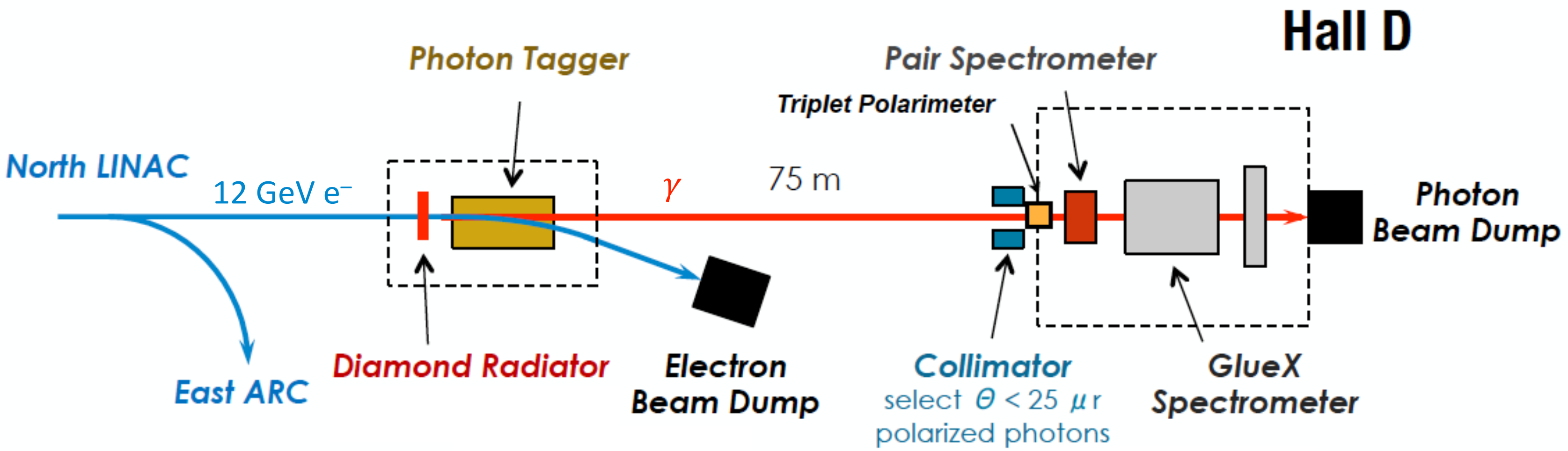
GlueX polarized photon beam

- 12 GeV e⁻ beam on thin diamond crystal
- 9 GeV linearly polarized photons via coherent Bremsstrahlung
- Intensity 5 x 10^7 γ/s in coherent peak

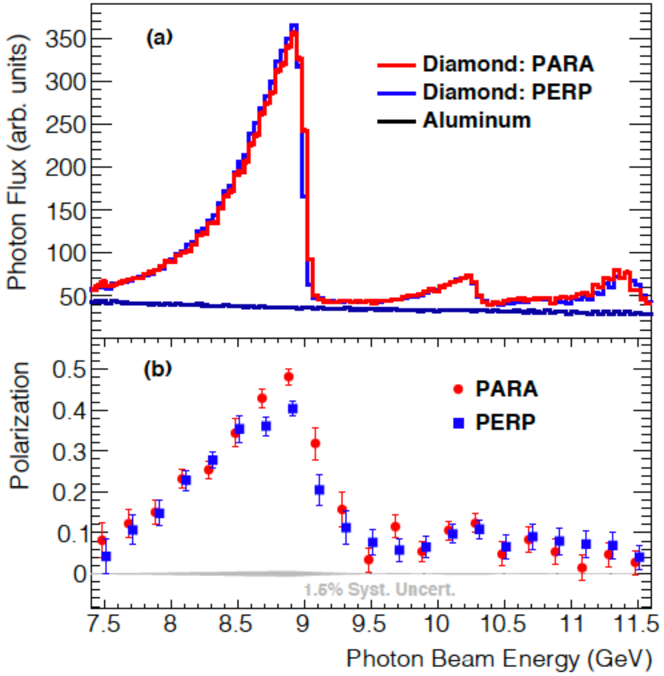
- Scintillator arrays measure energy of each scattered e⁻, 'tag' its photon E_γ
  tagging precision ~ 0.1% (resolution 5 MeV in coherent peak)

- ~ 40% linear polarization in coherent peak, measured in triplet polarimeter

Diamond
1cm x 1cm
x 20-70μm



Photon flux and polarization



[The GlueX Beamline and Detector NIM A 987 (2021) 164807]

GlueX spectrometer

- Optimized for light meson spectroscopy
- Large acceptance for charged & neutral

- Acceptance $\theta = 1-120°$
- Charged $\sigma_p/p \sim$ 1-5%
- Neutral $\sigma_E/E = 6\% / \sqrt{E} \oplus 2\%$

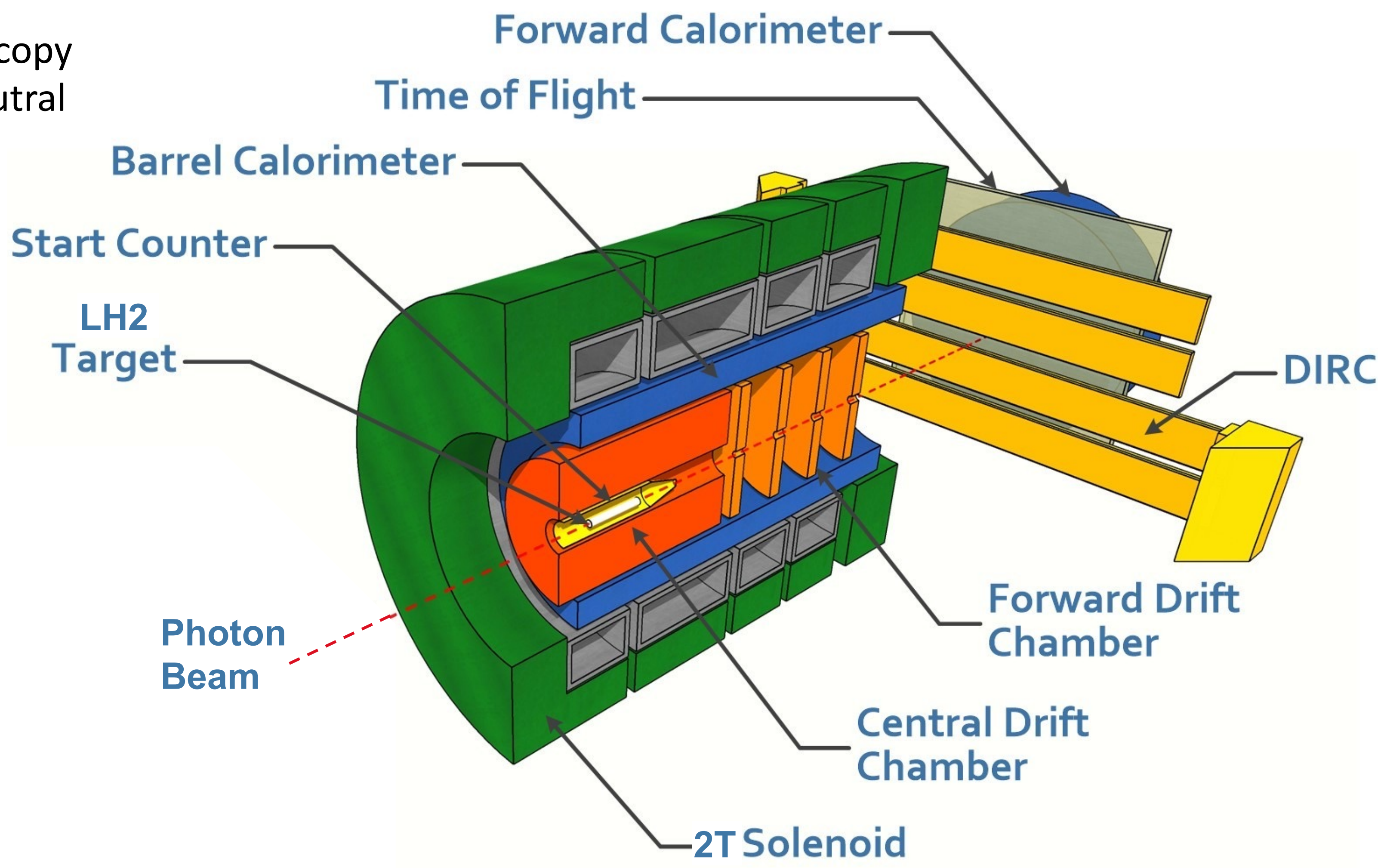
- GlueX-I 2017 – 2018

  125 pb^{-1} 8.2-8.8 GeV

- 2019 Added DIRC
- GlueX-II 2020 – 2025/6?

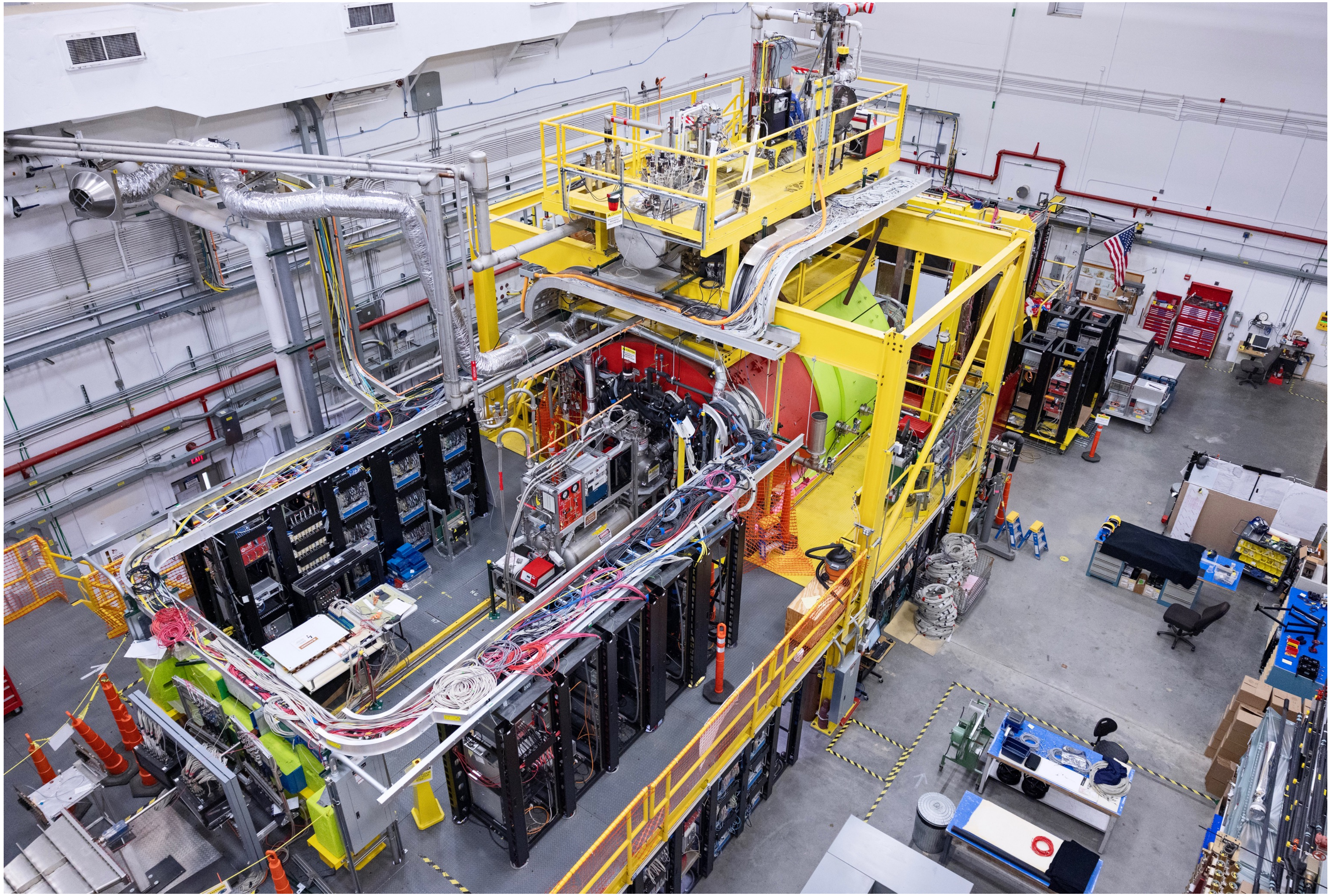
  Expect 3-4 x GlueX-I

- Publications listed on gluex.org



The GlueX Beamline and Detector
NIM A 987 (2021) 164807

GlueX spectrometer

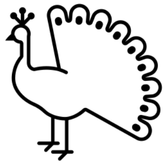


GlueX physics pathway – from familiar to exotic

- Goal: explore spectrum of light hybrid mesons

- Strategy:
  - study known mesons first
    - develop and refine software
    - improve knowledge of acceptance
    - learn about production mechanisms
    - talk to theorists

- look for exotics
  - keep talking to theorists



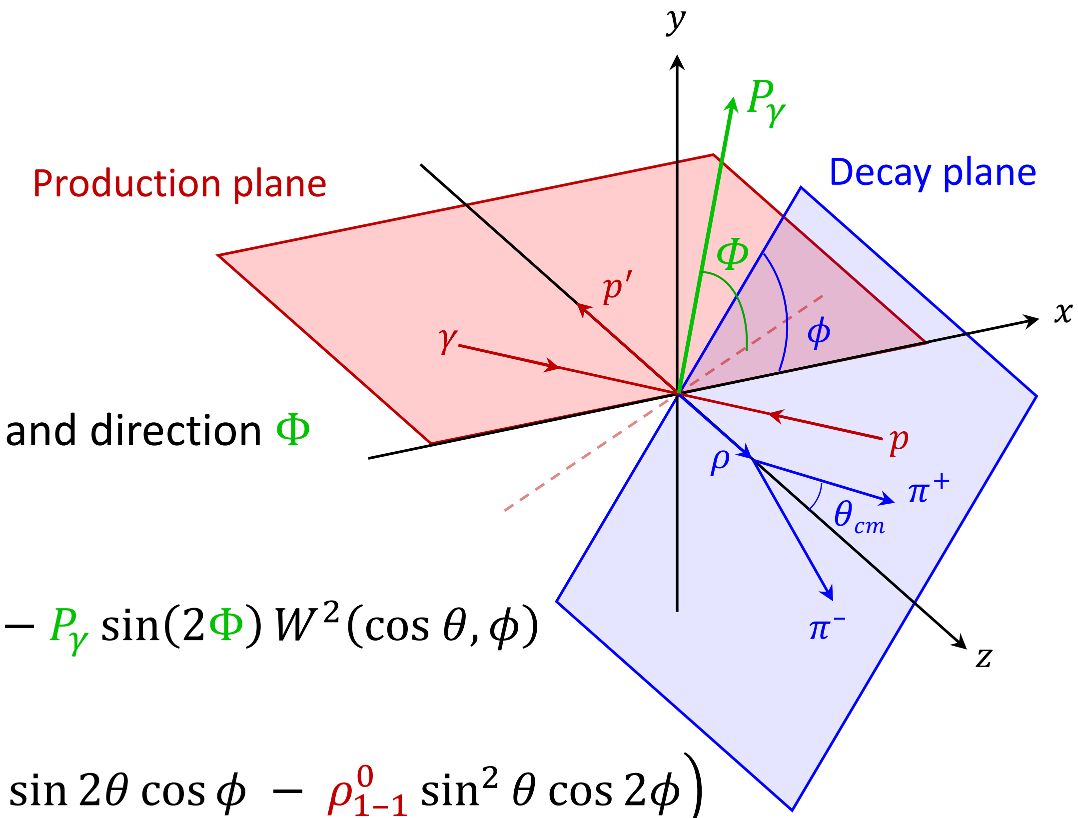
- Importance of Spin Density Matrix Elements (SDMEs):
  - useful observable
  - production mechanism info
  - input for theory and useful for modelling background processes
  - very sensitive to acceptance
  - amplitude analysis uses similar formalism and AmpTools software for multi-dimensional fits

- Published SDMEs: $\Lambda(1520)$ Phys.Rev. C105 (2022) 035201
  $\rho(770)$ Phys.Rev. C108 (2023) 055204

  Upcoming: $\Delta^{++}(1232)$ https://arxiv.org/abs/2406.12829
  Also working on $\phi(1020)$, $\omega(782)$

Vector Meson Spin Density Matrix Elements

- Detailed theory predictions, but previous measurements limited
- SDMEs ρ_{ij}^{k} measured by angular distribution of decay products
- Linear beam polarization gives access to 9 SDMEs
- Intensity expanded in $\cos\theta$, ϕ in helicity frame, beam polarization P_γ and direction Φ



$$W(\cos\theta,\phi,\Phi) = W^0(\cos\theta,\phi) - P_\gamma\cos(2\Phi)\,W^1(\cos\theta,\phi) - P_\gamma\sin(2\Phi)\,W^2(\cos\theta,\phi)$$

$$W^0(\cos\theta,\phi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00} - 1)\cos^2\theta - \sqrt{2}\,\mathrm{Re}\,\rho^0_{10}\sin 2\theta\cos\phi - \rho^0_{1-1}\sin^2\theta\cos 2\phi\right)$$

$$W^1(\cos\theta,\phi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \sqrt{2}\,\mathrm{Re}\,\rho^1_{10}\sin 2\theta\cos\phi - \rho^1_{1-1}\sin^2\theta\cos 2\phi\right)$$

$$W^2(\cos\theta,\phi) = \frac{3}{4\pi}\left(\sqrt{2}\,\mathrm{Im}\,\rho^2_{10}\sin 2\theta\sin\phi + \mathrm{Im}\,\rho^2_{1-1}\sin^2\theta\sin 2\phi\right)$$

Schilling et al NPB15(1970)397

$\rho(770)$ Spin Density Matrix Elements

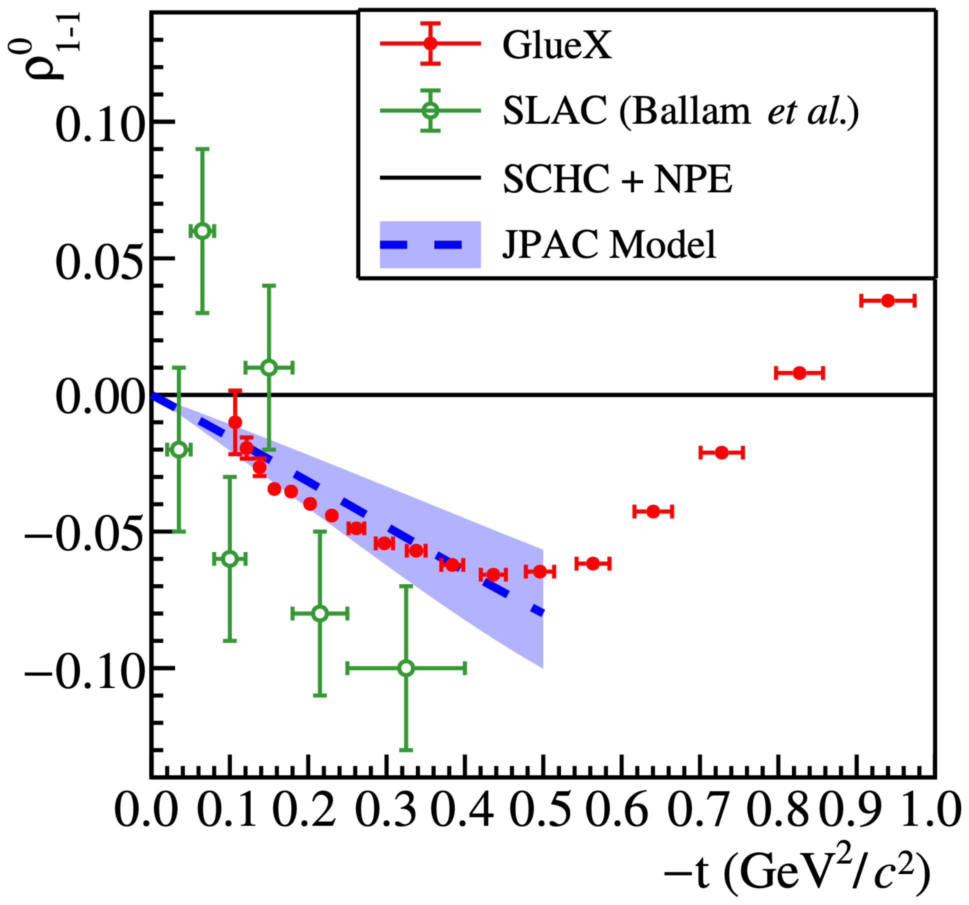
- 2017 data ~ 10% of eventual dataset
- Combined fit of 4 polarization orientations
- Consistent with previous measurements
- Consistent with JPAC Regge exchange model

GlueX data: Phys.Rev. C108 (2023) 055204

SLAC data: Ballam et al Phys. Rev. D7 (1973) 3150

JPAC model: Mathieu et al Phys. Rev. D97 (2018) 094003

ρ^0_{1-1} (helicity frame) from $\gamma p \to \rho(770) p \to \pi^+\pi^- p$



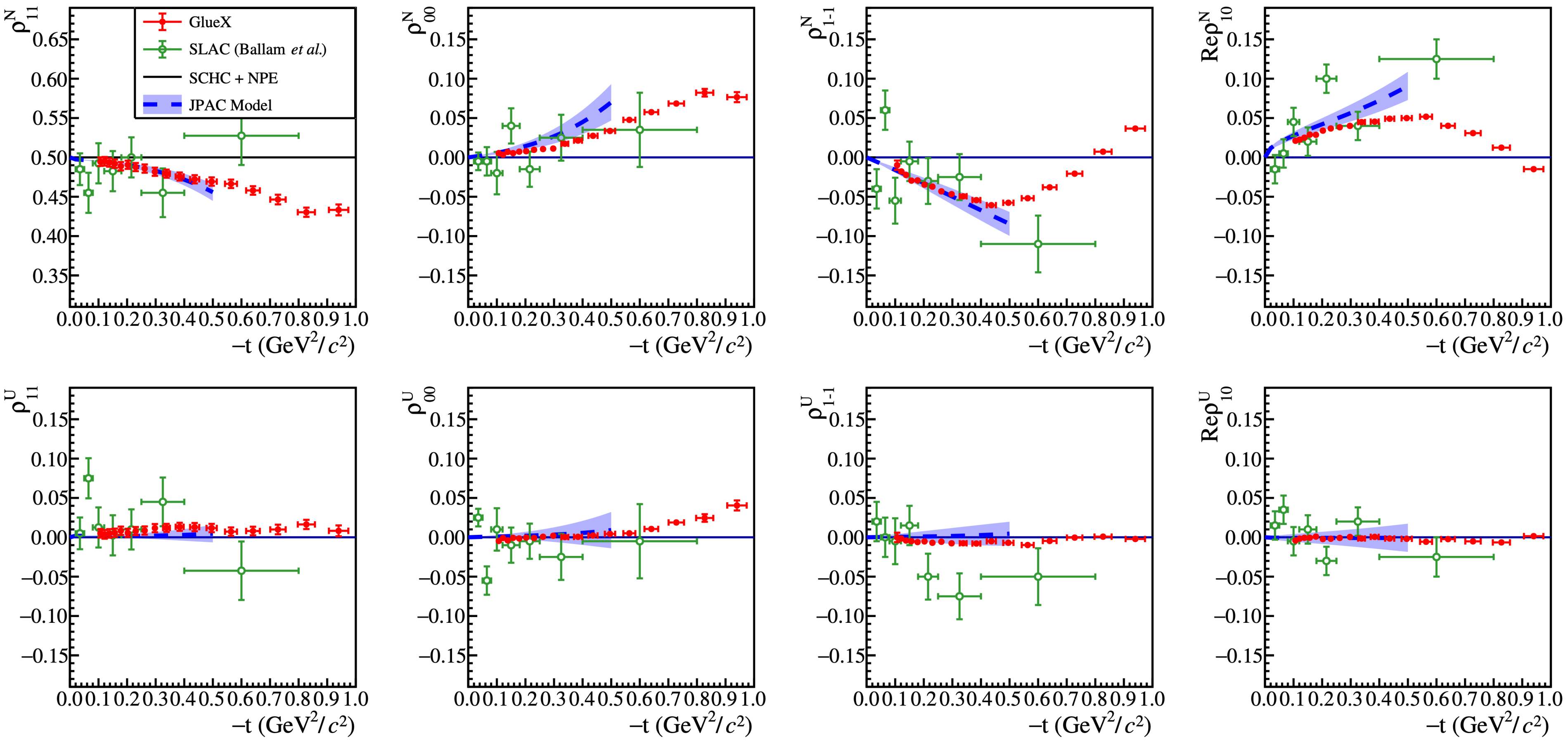
$\rho(770)$ Spin Density Matrix Elements

- SDMEs describe combinations of natural and unnatural parity exchange
- Unnatural parity components << natural parity components $\rho^N_{11} \sim 0.5$

GlueX PRC 108 (2023) 055204
SLAC PRD 7 (1973) 3150
JPAC PRD 97 (2018) 094003

Natural Parity Exchange
e.g. 0+ $\mathbb{P}$, 1− ρ

Unnatural Parity Exchange
e.g. 0− π



Using $a_2(1320)$ as a stepping-stone to spin-exotics

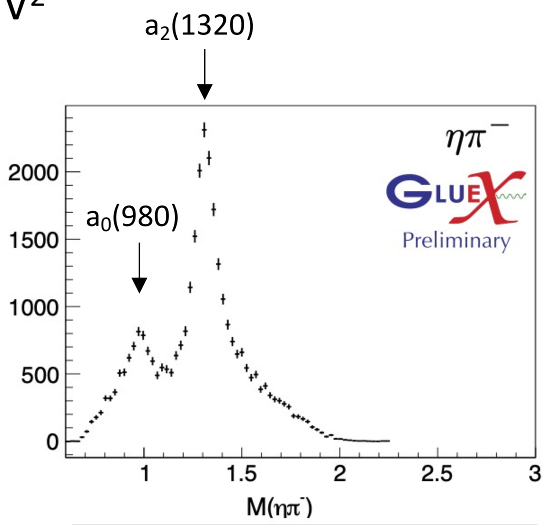
- Next progression in complexity is amplitude analysis of another non-exotic meson
- $a_2(1320)$ is well-known, not exotic, produced abundantly and decays via $\eta\pi$
- 2 decay modes - comparison helps to improve acceptance and background removal techniques
- Plan to use $a_2(1320)$ as a standard reference to compare with smaller exotic contributions to $\eta'\pi$
- Understanding the $a_2(1320)$ in $\eta\pi$ is a key step towards $\eta'\pi$ and exotics

a_2(1320) in ηπ

- Clear signals at a_0(980) and a_2(1320) masses (not acceptance-corrected)

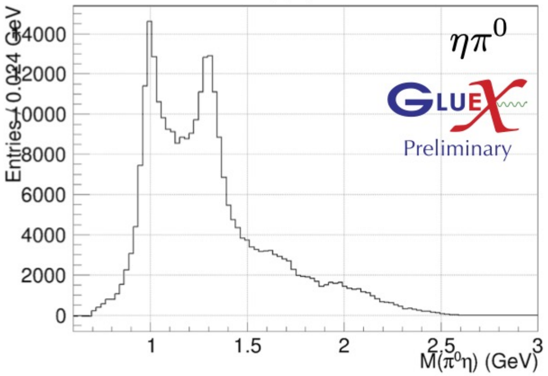
0.1 < –*t* < 0.3 GeV²

ηπ⁻



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

$\eta\pi^0$



$$\gamma p \rightarrow \eta\pi^0 p$$
$$\eta \rightarrow \gamma\gamma$$

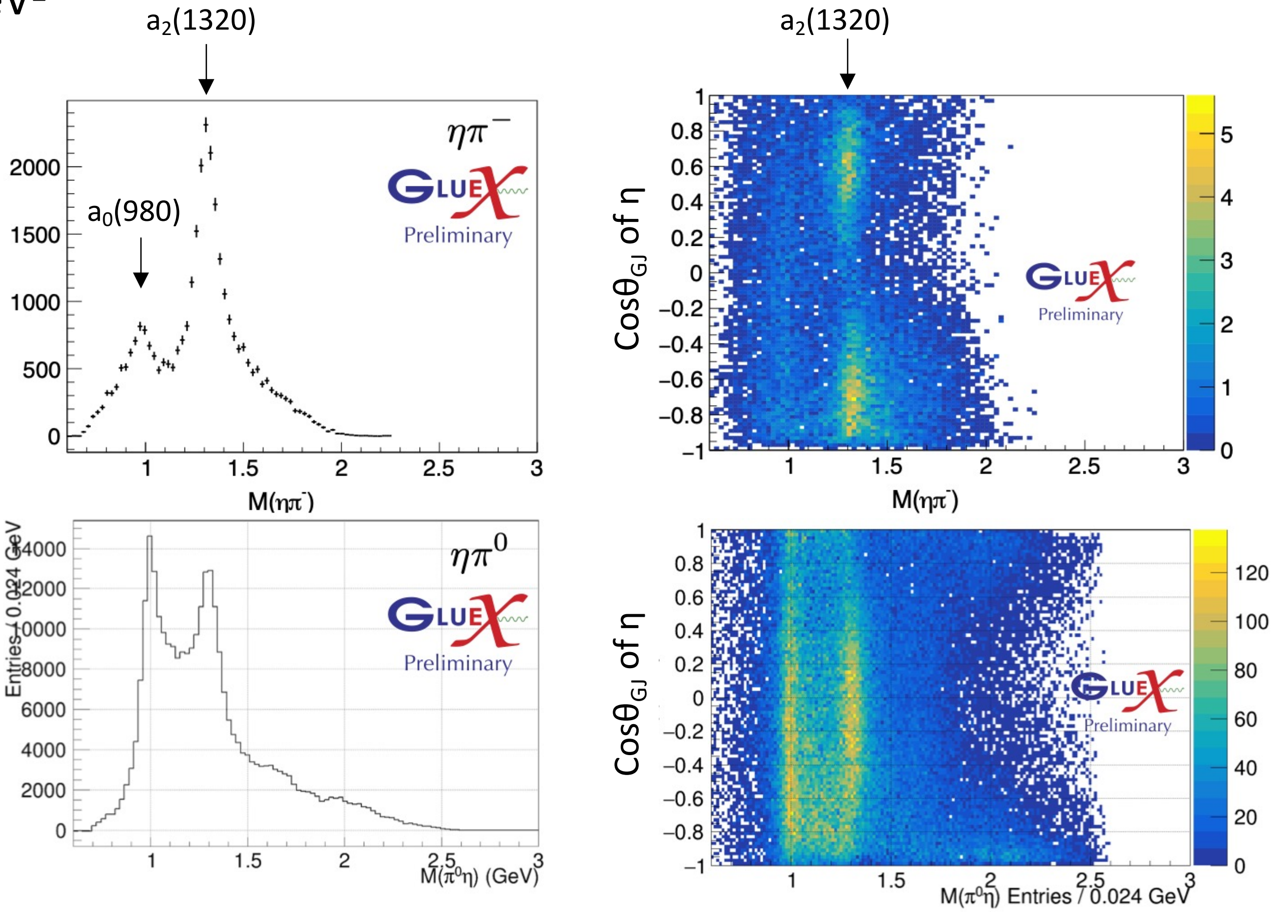
$a_2(1320)$ in $\eta\pi$

- Clear signals at $a_0(980)$ and $a_2(1320)$ masses
- $a_2(1320)$ angular distribution very different between charged and neutral decay modes

$0.1 < -t < 0.3$ GeV^2

$\eta\pi^-$

$\eta\pi^0$



Different spin-projection states populated

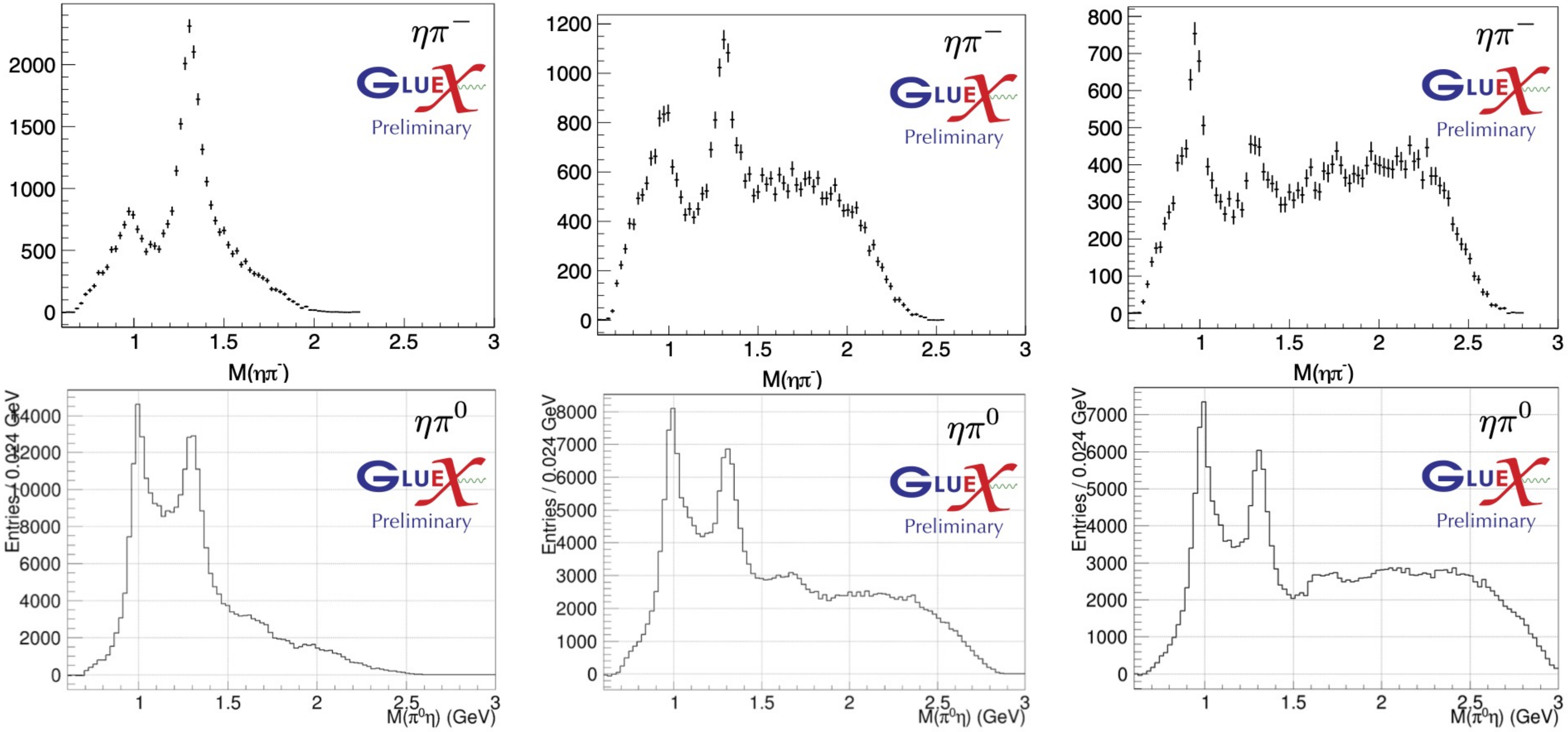
$a_2(1320)$ in $\eta\pi$

- Clear signals at $a_0(980)$ and $a_2(1320)$ masses
- $a_2(1320)$ angular distribution very different between charged and neutral decay modes
- Relative population changes with t

$0.1 < -t < 0.3$ GeV^2 | $0.3 < -t < 0.6$ GeV^2 | $0.6 < -t < 1.0$ GeV^2

$\eta\pi^-$

$\eta\pi^0$



$a_2(1320)$ in $\gamma p \to \eta\pi^0 p$ Semi-mass-independent amplitude analysis

- Amplitude formalism $Z_l^m(\Omega,\Phi) = Y_l^m(\Omega)\, e^{-i\Phi}$ JPAC: Mathieu et al PRD 100 (2019) 054017

$$\text{Intensity}(\Omega,\Phi) =$$

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

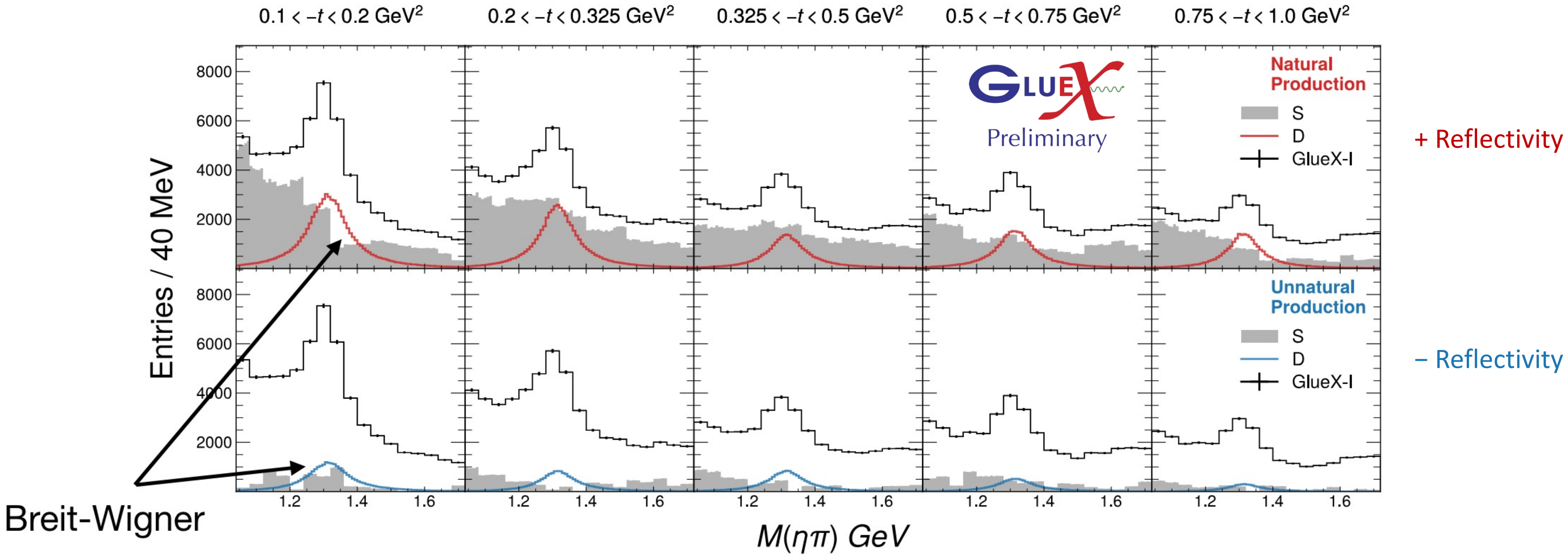
$$\left. + (1+P_\gamma)\left|\sum_{l,m}[l]_m^{(+)}\mathrm{Re}[Z_l^m(\Omega,\Phi)]\right|^2 + (1+P_\gamma)\left|\sum_{l,m}[l]_m^{(-)}\mathrm{Im}[Z_l^m(\Omega,\Phi)]\right|^2 \right\}$$

Reflectivity + natural parity exchange
Reflectivity − unnatural parity exchange

Naturality N = P$(-1)^J$ N=+1 ‘natural’ for 0+ etc
Reflectivity = N(exchanged particle) x N(resonance)

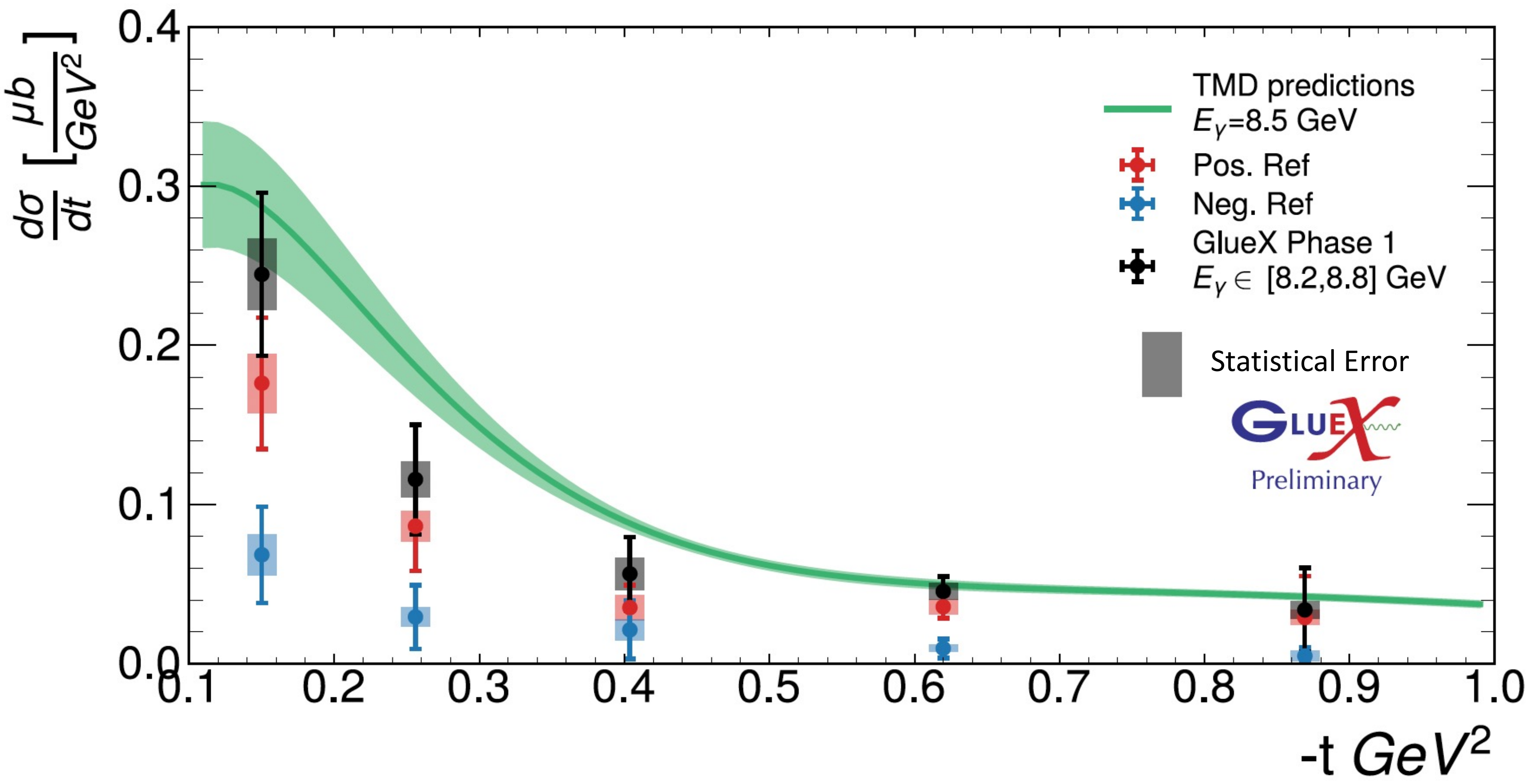
$a_2(1320)^0$ in $\gamma p \rightarrow \eta\pi^0 p$ Semi-mass-independent amplitude analysis

- Mass binned approach for the S-wave (complicated, includes double Regge + non-resonant processes)
- Model $a_2(1320)$ using a Breit-Wigner, as it is reasonably well isolated



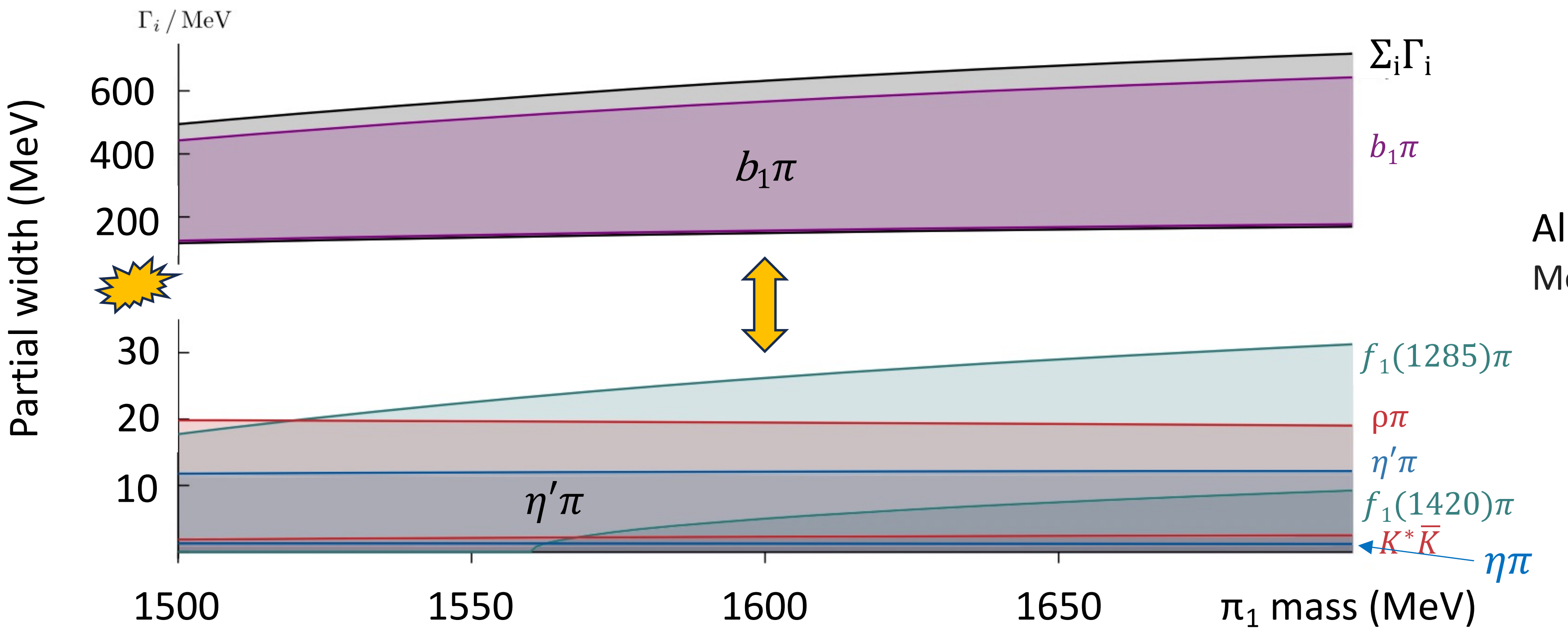
$a_2(1320)^0$ differential cross-section from $\gamma p \rightarrow \eta\pi^0 p$

- Good agreement with TMD theory from JPAC Mathieu et al PRD 102 (2020) 014003
- Predominantly + reflectivity, ie natural parity exchange, eg ρ, ω
- Publication in preparation



π_1(1600) partial decay width predictions

- HadSpec, Woss et al PRD 103 (2021) 054502
- Lattice QCD predictions of partial decay widths of π_1(1600) as a function of its mass
- π_1(1600) decay channels are dominated by $b_1\pi$ (~95%); decays to ωππ, final state 5π
- Experimentally, decay to ηπ and η'π might be easier to identify, although much less populated.



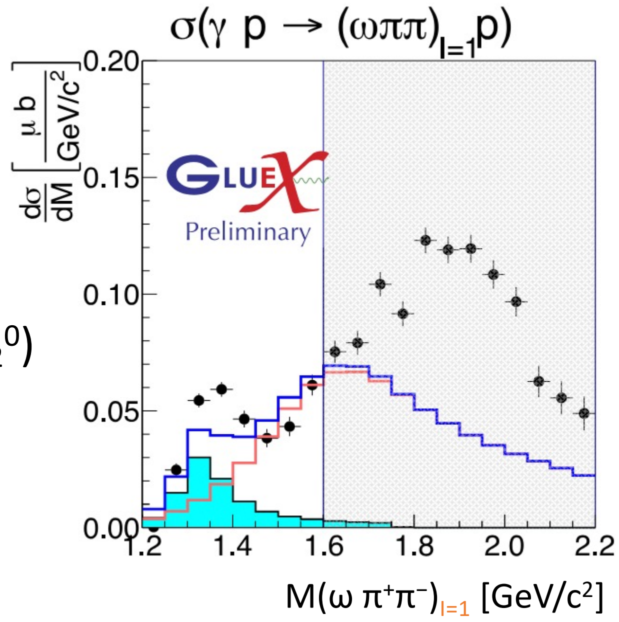
All modes except $K^*\bar{K}$ observed

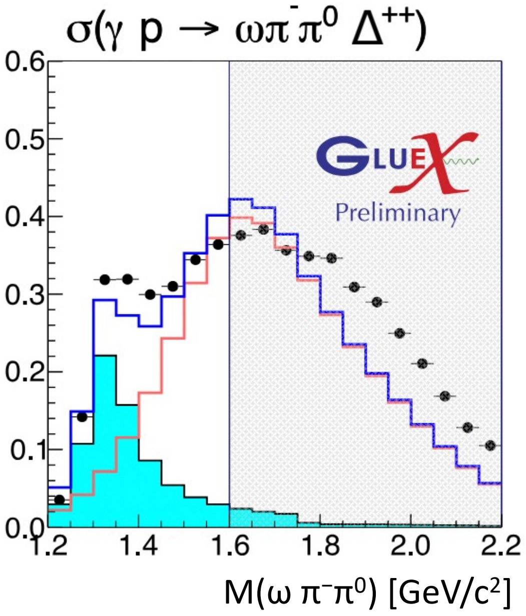
Meyer and Swanson PPNP 82 (2015) 21

$\pi_1(1600)$ cross-section upper limit

- π_1 has isospin 1, predicted to decay predominantly to $b_1(1235)\pi$, then to $\omega\pi\pi$
- Measured cross-sections for $\gamma\, p \rightarrow \omega\, \pi^+\pi^-\, p$ — $\omega\pi\pi$ isospin 0 and 1
  $\gamma\, p \rightarrow \omega\, \pi^0\pi^0\, p$ — $\omega\pi\pi$ isospin 0
- Used Clebsch-Gordan coefficients to obtain $\sigma(\omega\pi\pi)_{I=1} = \sigma(\omega\pi^+\pi^-) - 2\sigma(\omega\pi^0\pi^0)$
- Also measured cross-section for $\gamma\, p \rightarrow \omega\, \pi^-\pi^0\, \Delta^{++}$ — $\omega\pi\pi$ isospin 1
- Fit the I=1 cross-section **up to 1600 MeV** as $a_2(1320)$ + $\pi_1(1600)$ using Breit-Wigners (widths from PDG & JPAC)

Neutral mode
$\sigma(\pi_1^0) < 2.09\, \sigma(a_2^0)$

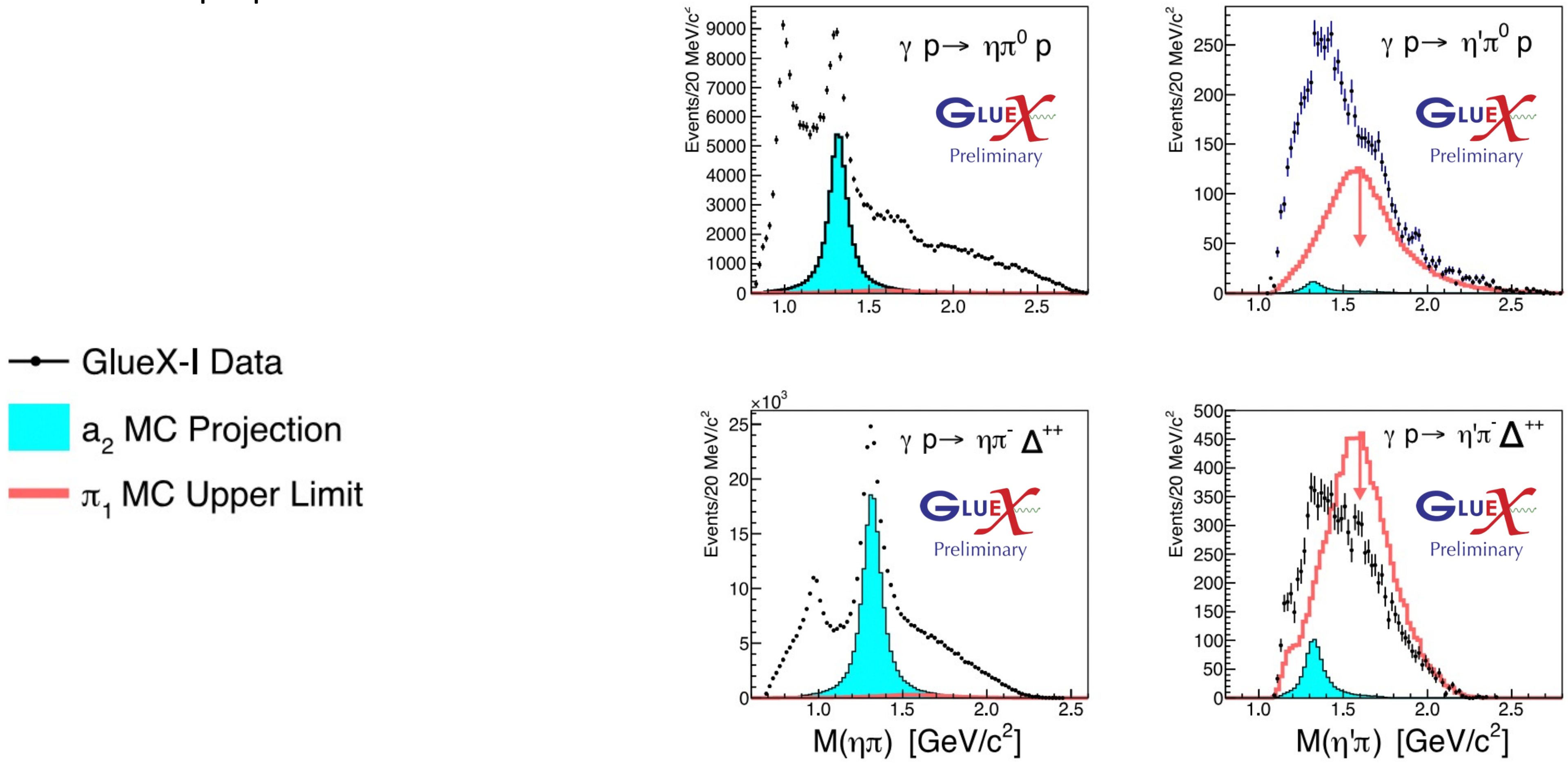




Charged mode
$\sigma(\pi_1^-) < 1.40\, \sigma(a_2^-)$

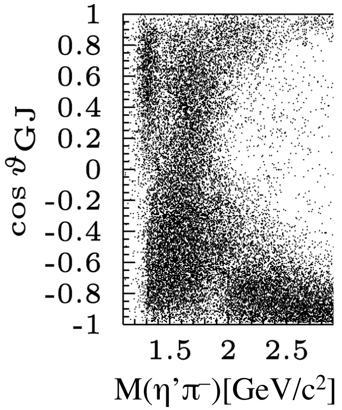
$\pi_1(1600)$ cross-section upper limit, projected into $\eta\pi$ and $\eta'\pi$

- Used decay widths from HadSpec PRD 103 (2021) 054502 to estimate upper limits for π_1 decaying to $\eta\pi$ and $\eta'\pi$
- Combined estimated maximum cross sections with GlueX luminosity and acceptance using Monte Carlo
- $\pi_1(1600)$ contribution appears to be small in $\eta\pi$, could be large in $\eta'\pi$
- Publication in preparation

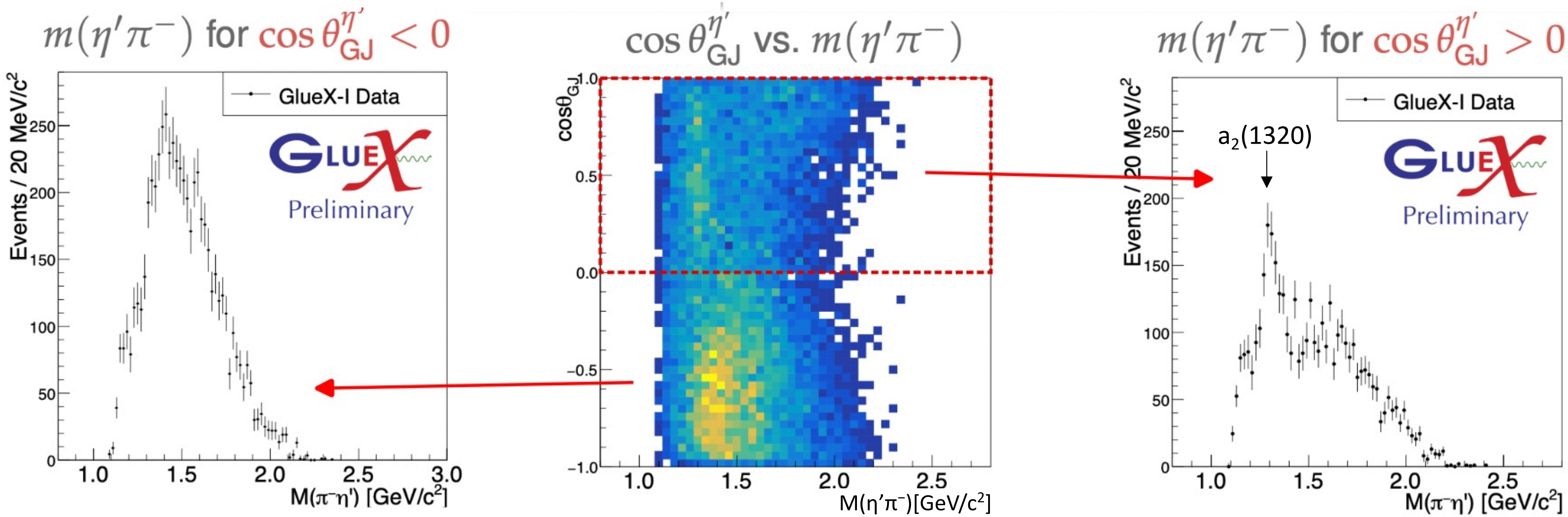


Analysis of $\gamma p \rightarrow \eta'\pi^-\Delta^{++}$

- Invariant mass of $\eta'\pi^-$ vs $\cos\Theta^{\eta'}_{GJ}$
- Striking forward/backward asymmetry, reminiscent of COMPASS data
- Amplitude analysis is ongoing



Phys Lett B 740 (2015) 303-311

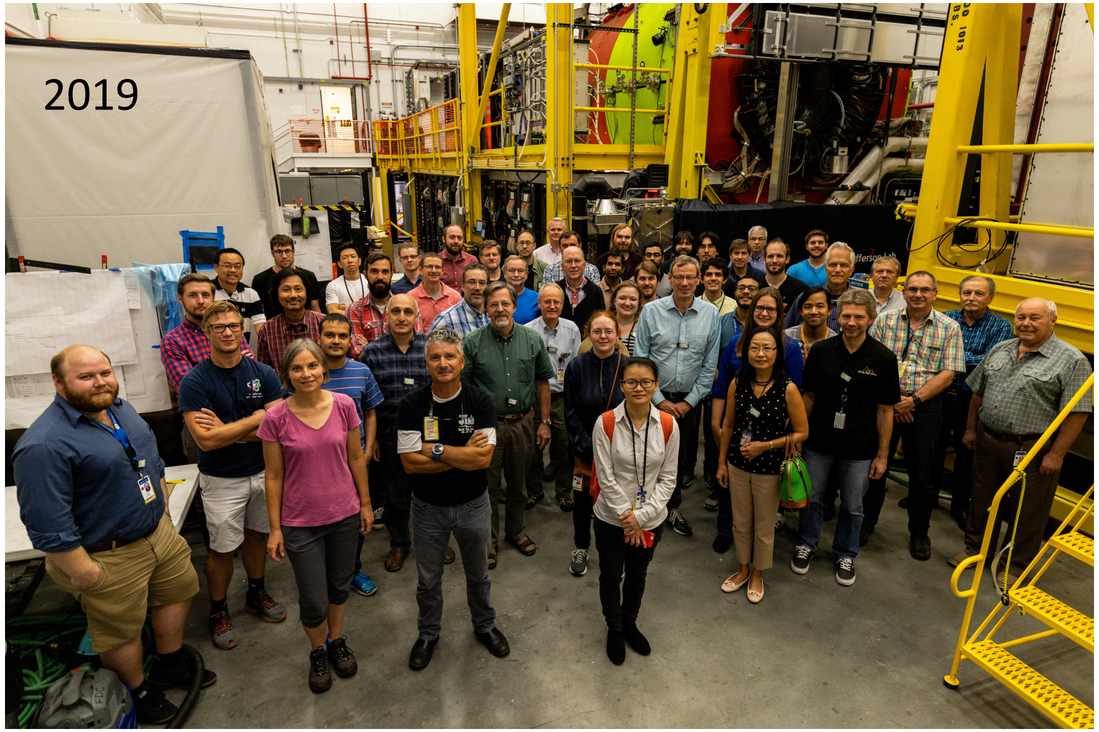


Conclusion and acknowledgements

Many GlueX analyses are in progress.

More publications are on the way.

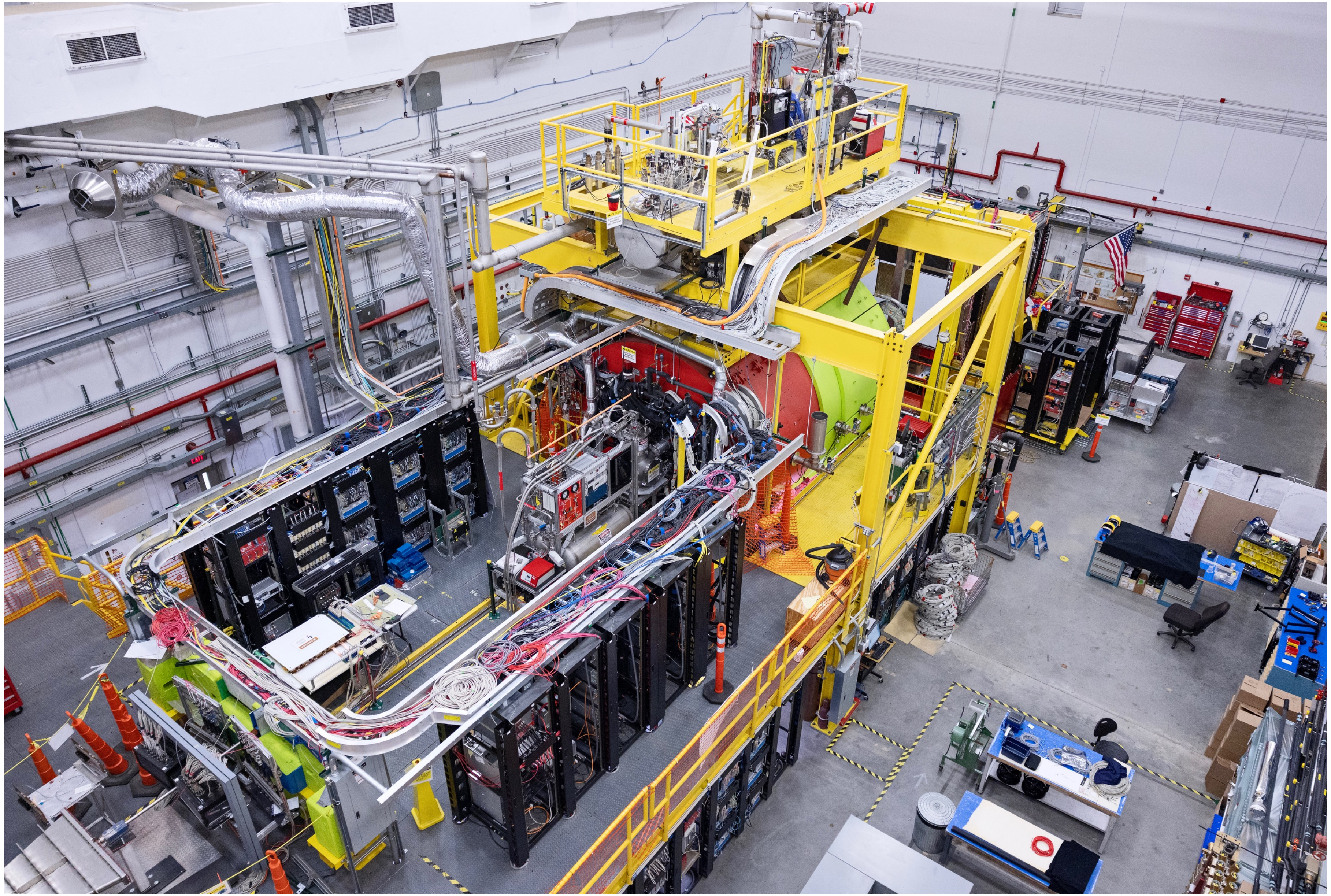
Thank you for listening!



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

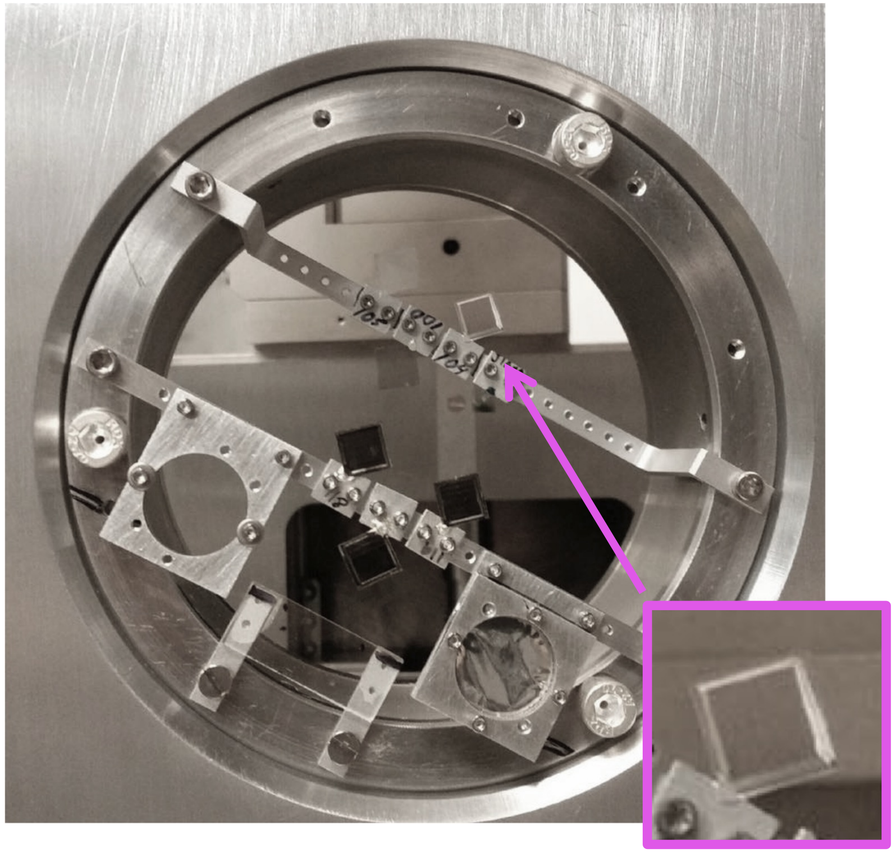
The Carnegie Mellon Group is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, DOE Grant No. DE-FG02-87ER40315.

Extra slides



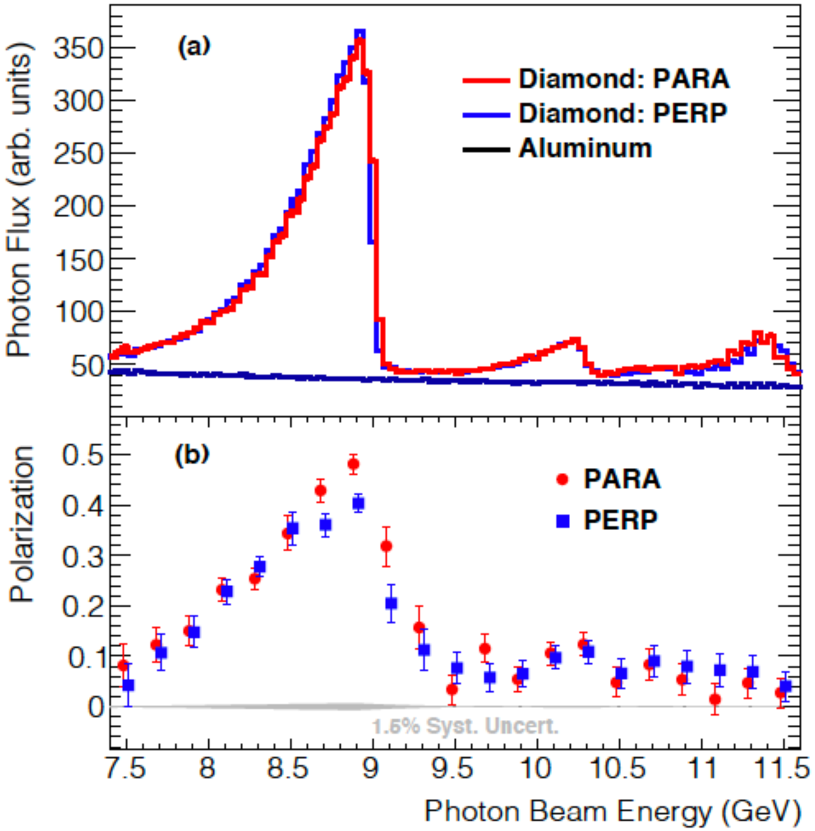
GlueX polarized photon beam

Radiators on goniometer



Diamond wafer size 1cm x 1cm x 20-70µm

Photon flux and polarization



The GlueX Beamline and Detector
NIM A 987 (2021) 164807

ρ(770) Spin Density Matrix Elements

- 2017 data ~ 10% of eventual dataset
- Combined fit of 4 orientations of polarization
- Good agreement with previous measurements and model
- Natural parity exchange dominates, exchanged virtual particle could be (eg) $\mathbb{P}$, ρ, ω …

GlueX data: Phys.Rev. C108 (2023) 055204

SLAC data: Ballam et al PRD 7 (1973) 3150

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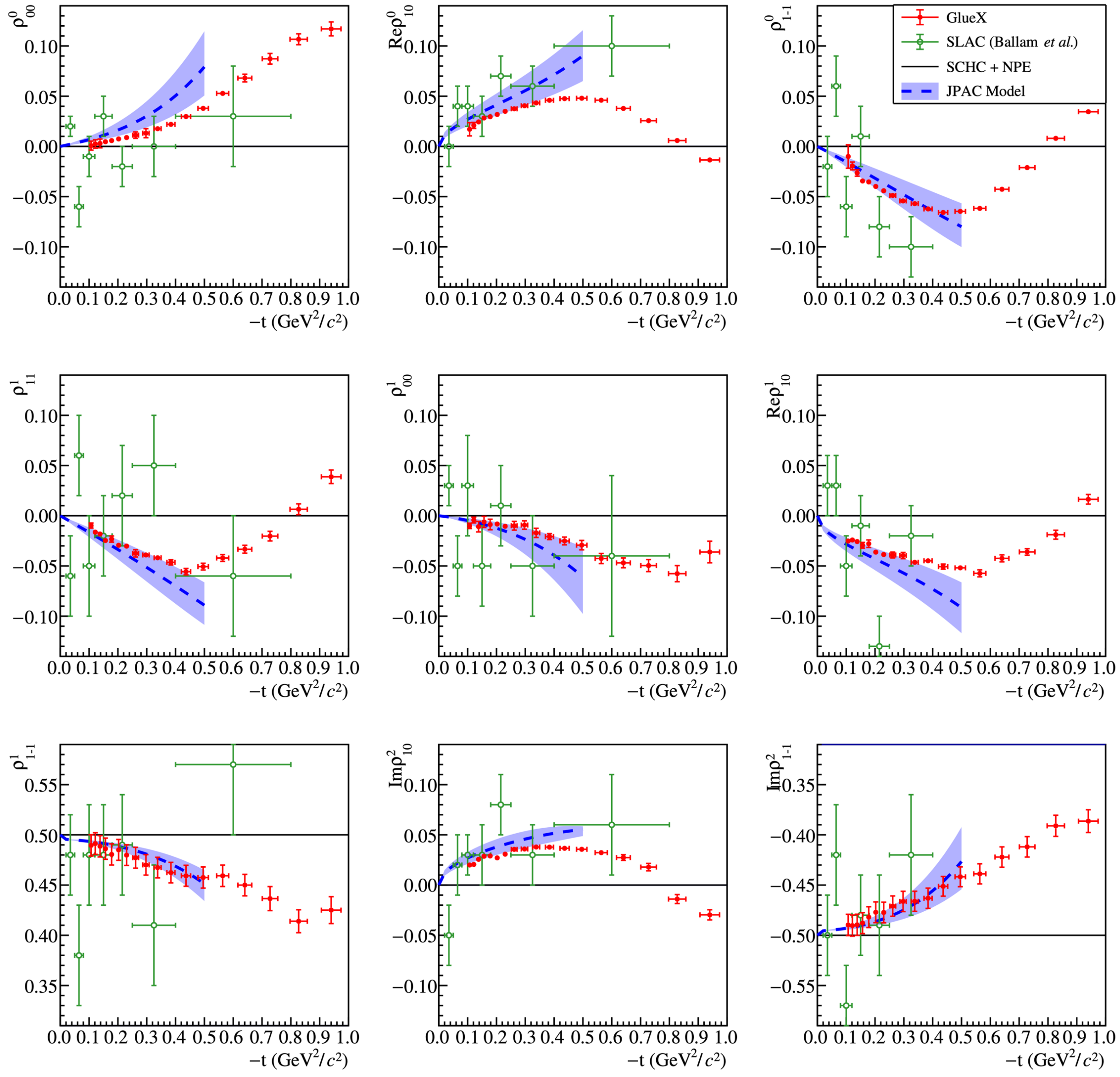


Parity asymmetry for $\rho(770)$ photoproduction

- SDMEs describe combinations of natural & unnatural parity exchanges

  Naturality of exchanged J^P $N = P(-1)^J$

  N = +1 `natural', eg 0^+ ℙ, 1^- ρ

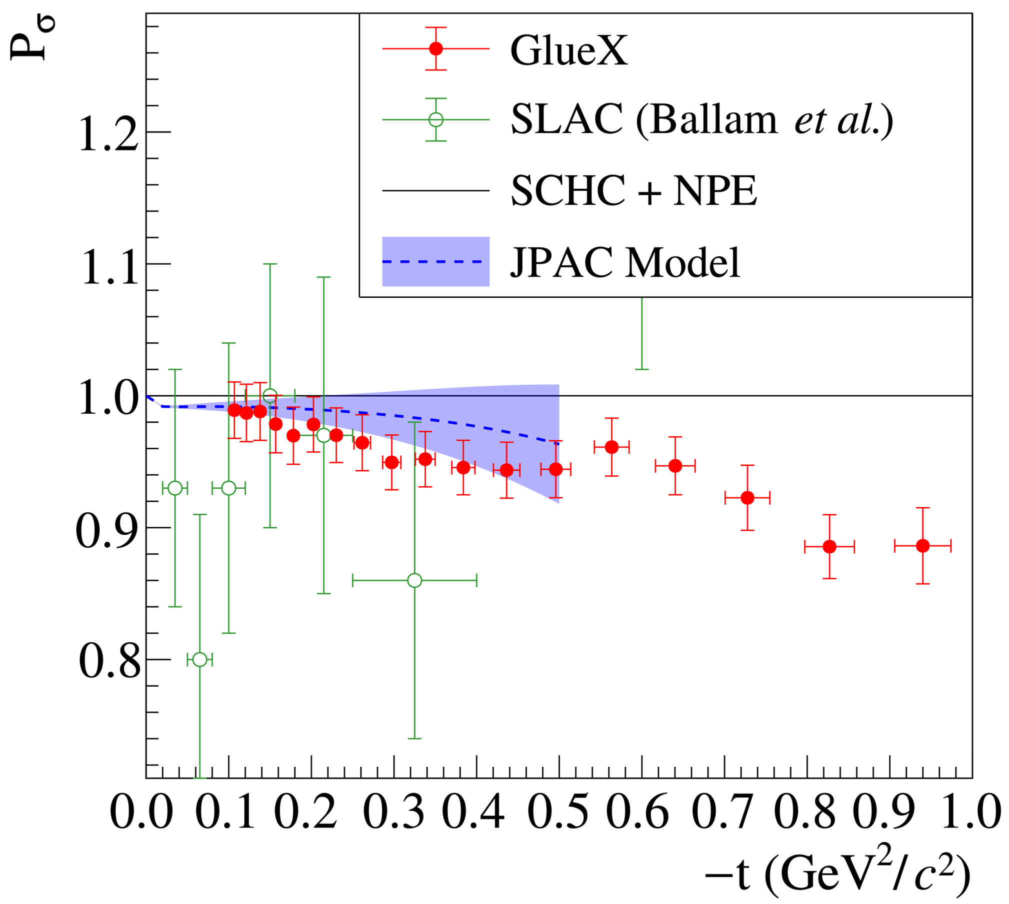
  N = –1 `unnatural', eg 0^- π

- Separate N and U from SDMEs to find parity asymmetry

$$P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U} = 2\rho^1_{1-1} - \rho^1_{00}$$

- Natural parity exchange dominates

P_σ for ρ(770) photoproduction



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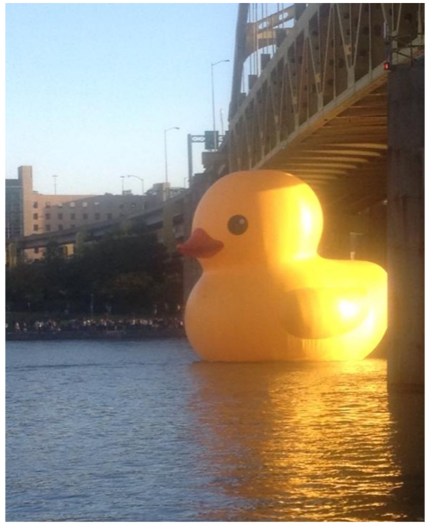

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- Published SDMEs: Λ(1520) Phys.Rev. C105 (2022) 035201; ρ(770) Phys.Rev. C108 (2023) 055204

  Upcoming: Δ++(1232) https://arxiv.org/abs/2406.12829
  Also working on ϕ(1020), ω(782)

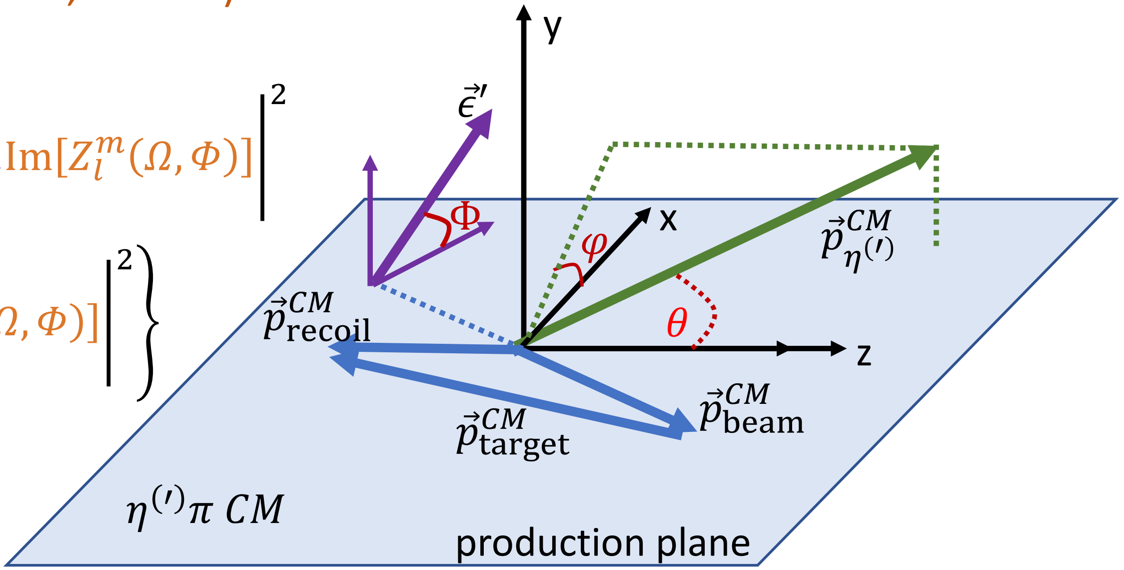
Model predicted number of events per unit phase space

Partial wave amplitudes (production of the wave)

Decay into two pseudo-scalars (parity constraints, L cons.)

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

Helicity frame (HX)



P_γ - degree of polarization

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

$\Omega = (\theta,\varphi)$

l, m- spin, its projection

$\vec{\epsilon}'$ - γ polarization vector

κ- kinematical factors

Nucleon spin flip k=1, non-flip k=0

Reflectivity ε=±1 corresponds to naturality of exchanged particle $\eta = P(-1)^J$

- natural parity $J^P = 0^+, 1^-, 2^+, \ldots$
- unnatural parity $J^P = 0^-, 1^+, 2^-$

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

Determine $[l]^{(-)}_{m;k}$, $[l]^{(+)}_{m;k}$ by fitting I_{EXP} using extended unbinned (in (θ,φ)) maximum likelihood method (AmpTools package https://github.com/mashephe/AmpTools)