Carnegie Mellon University

Jefferson Lab

GlueX – looking for exotic mesons with polarized photons

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for the GlueX Collaboration

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Universidad Técnica Federico Santa María, Valparaiso, Chile

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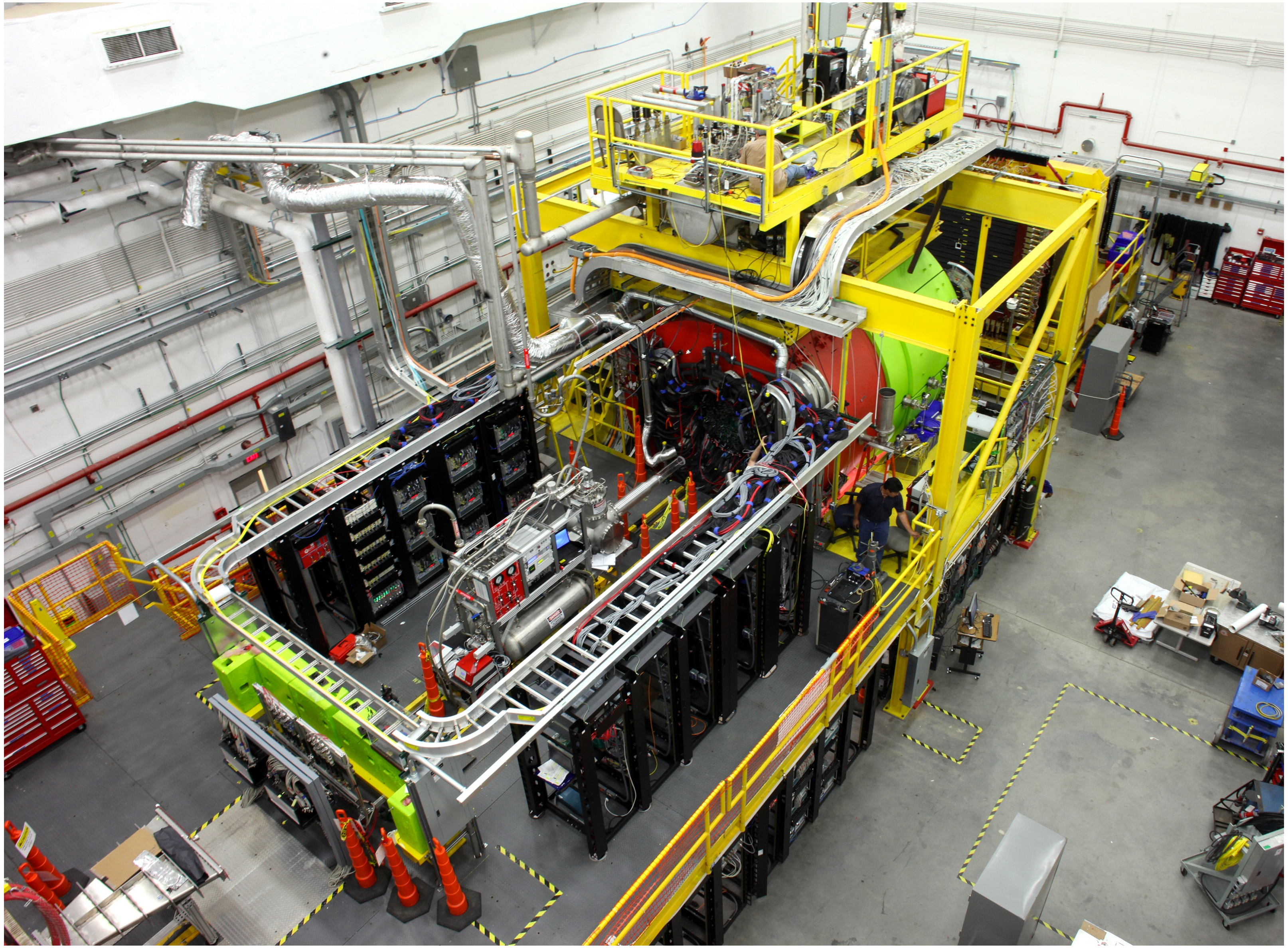
GlueX

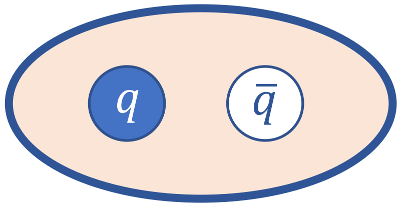
Outline

- Motivation
- GlueX beamline and spectrometer
- Some recent results



GlueX objective: find and study light exotic hybrid mesons

Quark model meson



Total intrinsic spin $\vec{S}$ = 0 or 1

Orbital angular momentum $\vec{L}$

Meson spin $\vec{J} = \vec{L} + \vec{S}$

Parity P $= (-1)^{L+1}$

Charge conjugation $C = (-1)^{L+S}$

Quantum numbers $J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{-+}$ …

Forbidden: $0^{--}, 0^{+-}, 1^{-+}$ …

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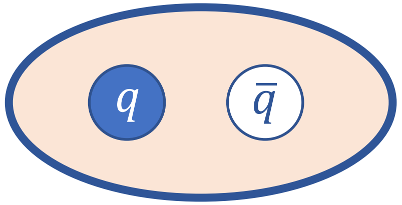
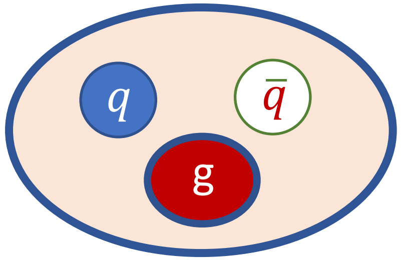


Hybrid meson



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Forbidden: $0^{--}, 0^{+-}, 1^{-+}$ …

QCD predicts excited gluonic field $J^{PC} = 1^{+-}$

This couples to the quark-antiquark pair

Meson QNs could be conventional or exotic

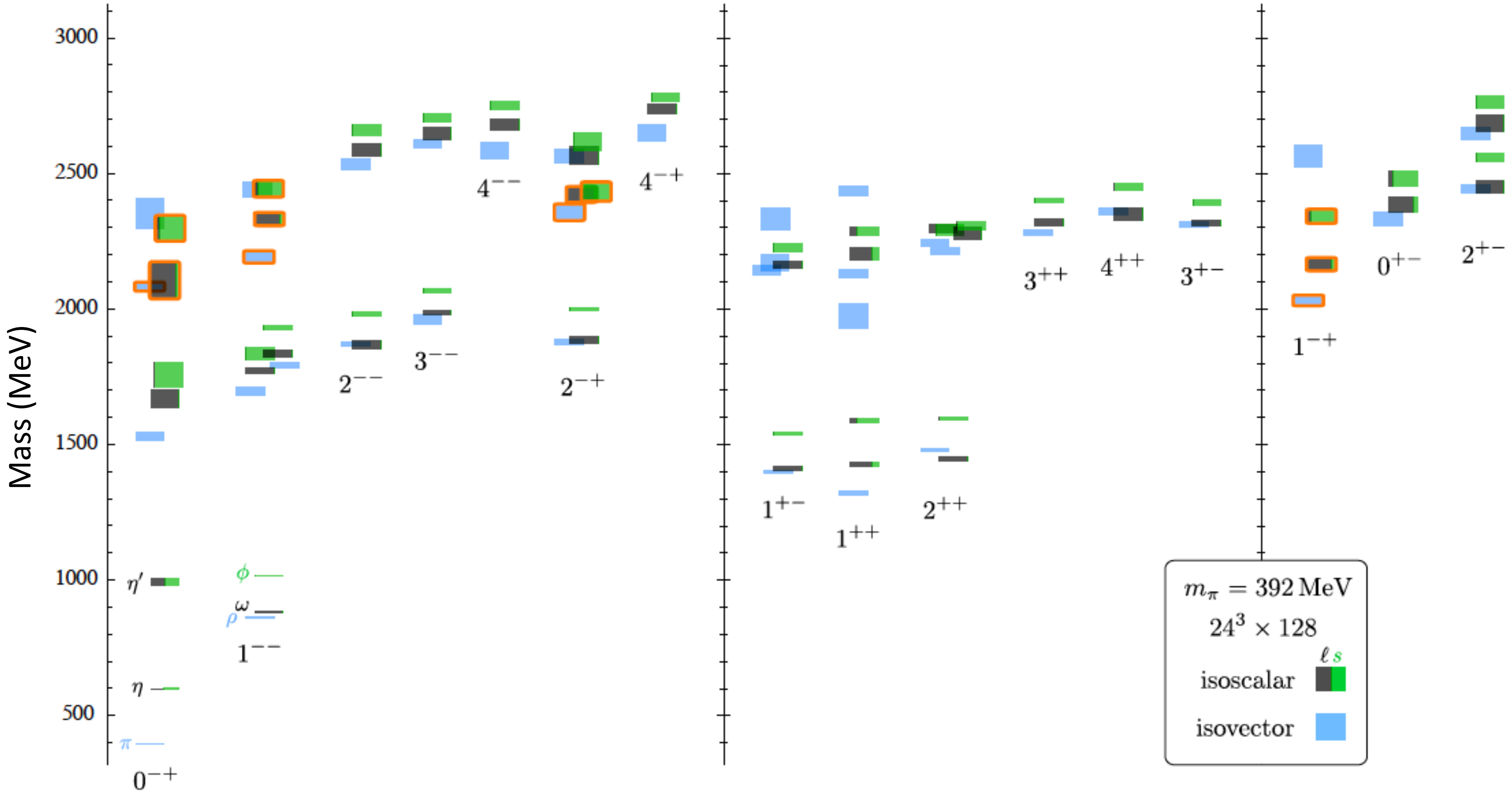
Exotics: J^{PC} forbidden by quark model but allowed by QCD

$J^{PC} = 0^{--}$, odd^{-+}, even^{+-}

Identification: strong evidence for gluonic excitations

Light Meson Spectrum from LQCD

Hadspec: Dudek et al PRD 88 (2013) 094505



Light Meson Spectrum from LQCD

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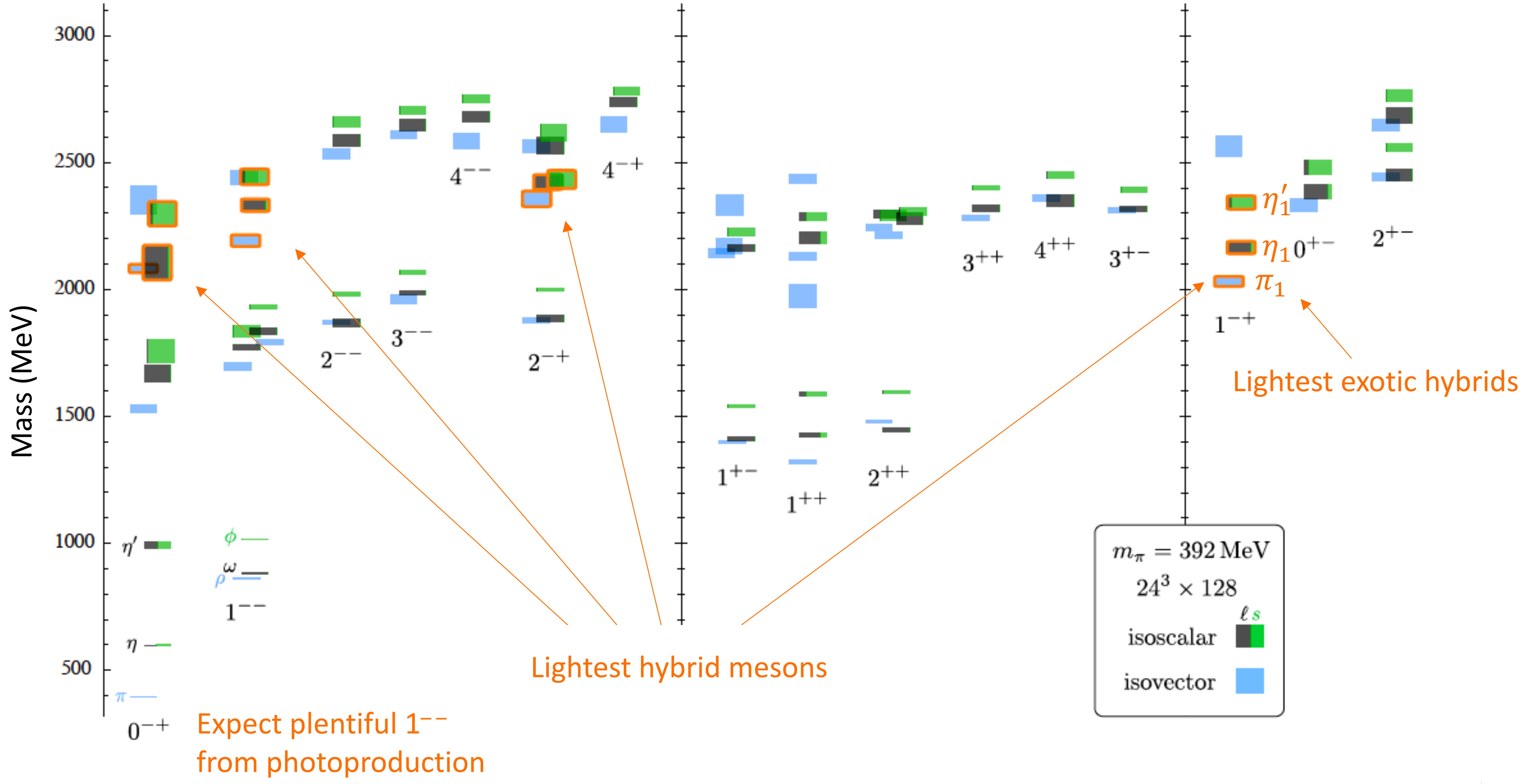
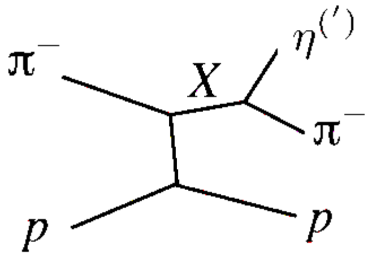
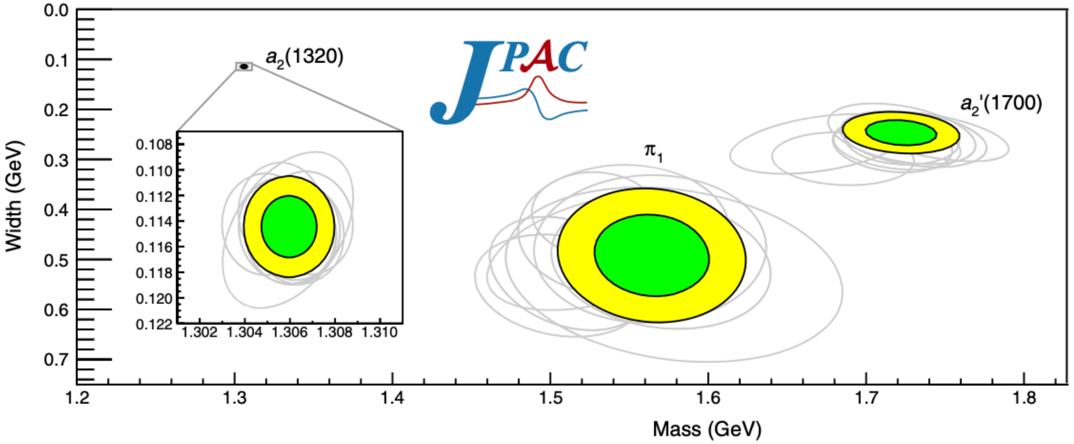


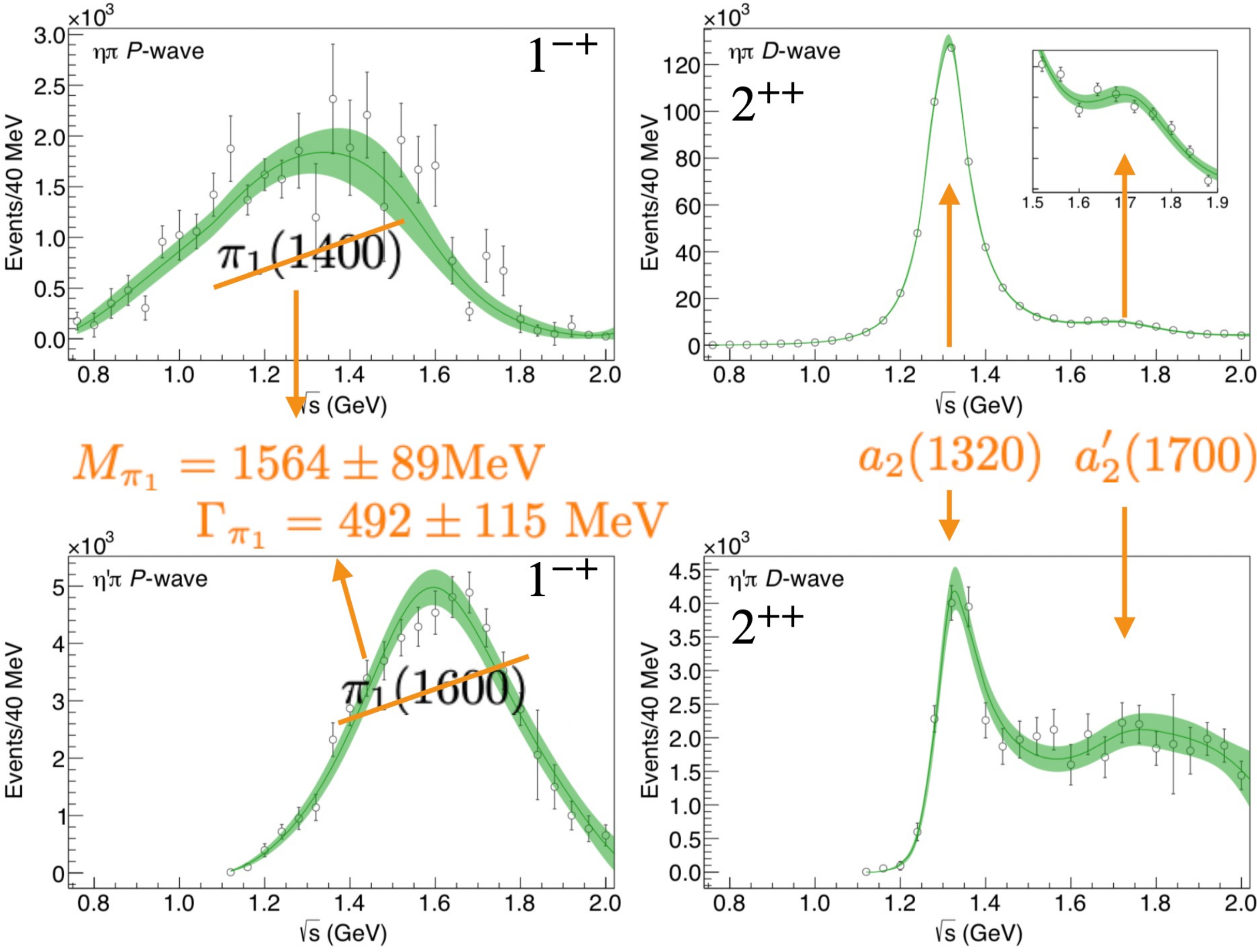
Existing evidence for exotic hybrids

- Long history of search for hybrid mesons
- Best evidence is for $\pi_1(1600)$ in data from COMPASS



- Published partial wave expansion analyzed by JPAC
  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





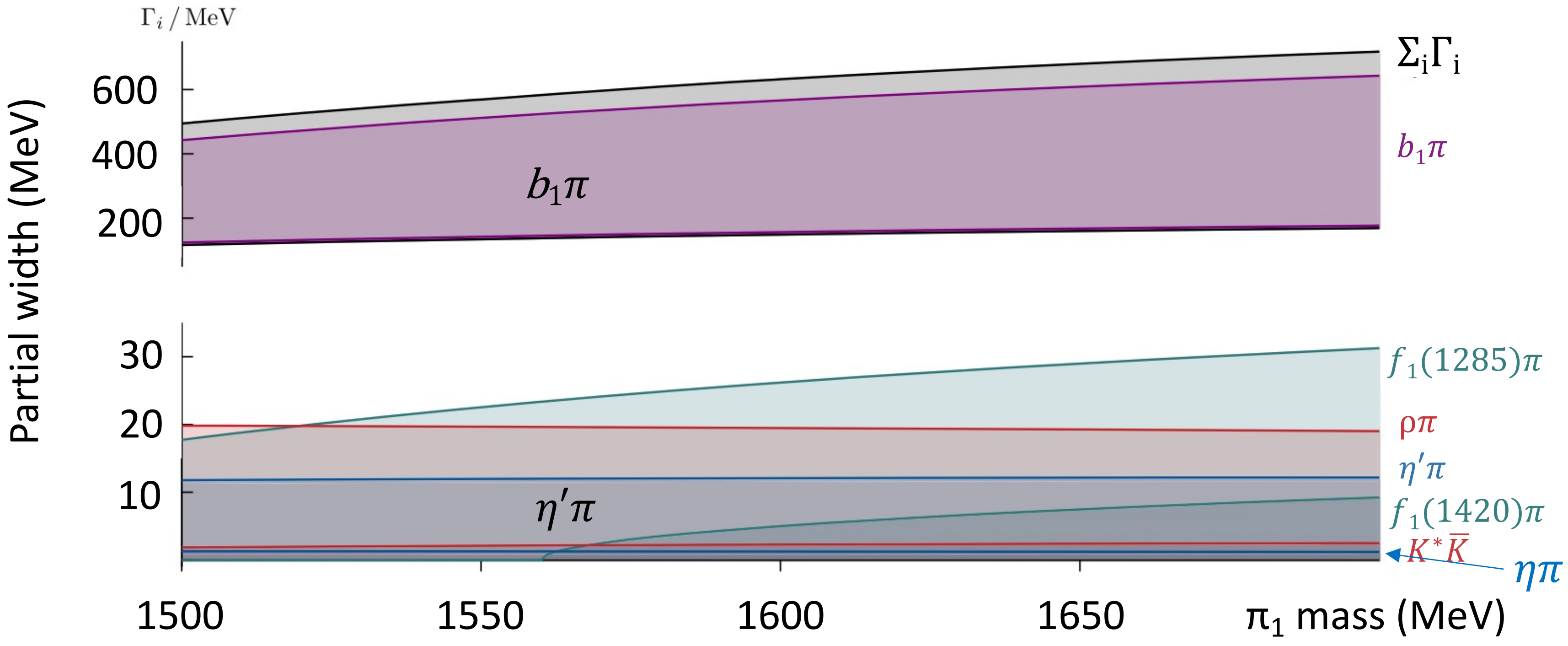
COMPASS: PLB 740 (2015) 303 JPAC Rodas et al: PRL 122 (2019) 042002

π_1(1600) partial decay width predictions

Hadspec: Woss et al PRD 103 (2021) 054502

Hadspec used lattice QCD to predict the decay widths of the π_1 as a function of mass.
Its decay channels are dominated by $b_1\pi$ (~95%).

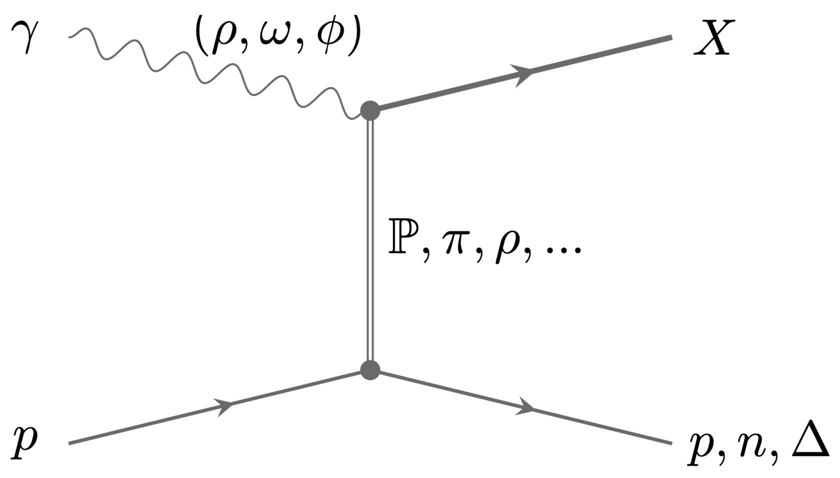
Less populated decay channels to $\eta^{(\prime)}\pi$ should be easier to identify.



All modes except $K^*\overline{K}$ observed
Meyer and Swanson PPNP 82 (2015) 21

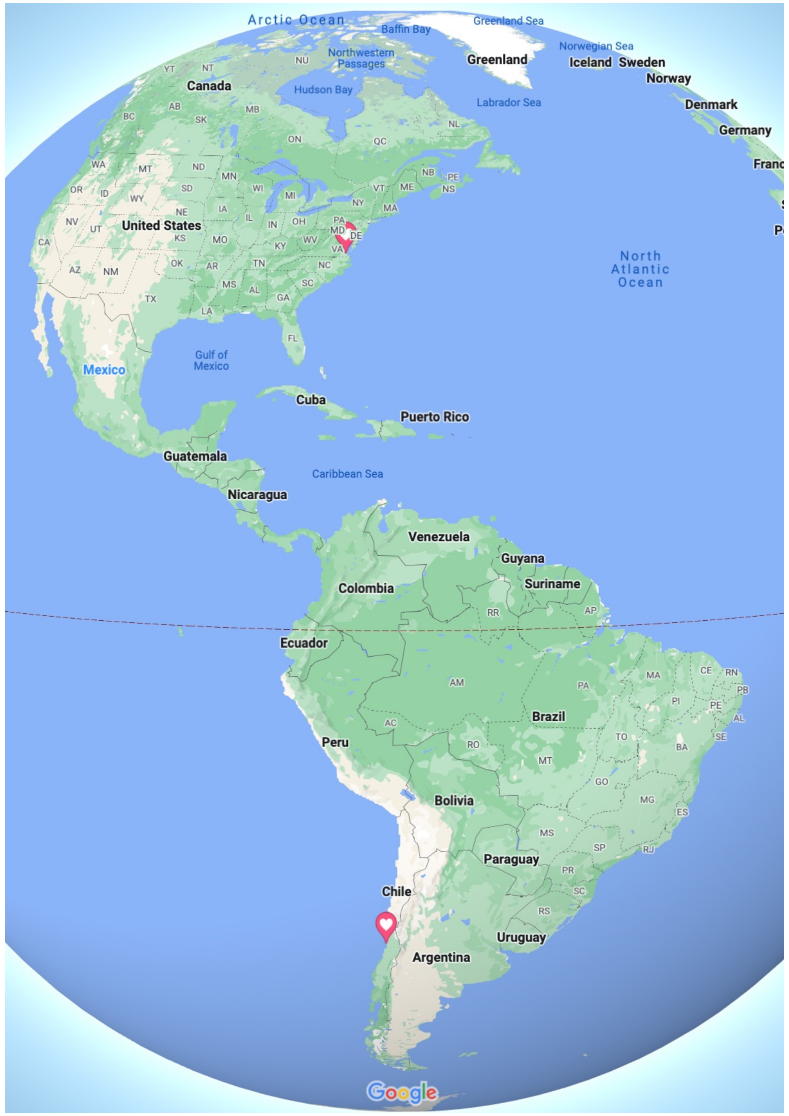
Photo-production with polarized beam

- 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, pi, rho, omega, …
- Polarization gives extra information on reaction mechanism
  - Extra constraint for amplitude analysis
- Little existing high-energy photoproduction data



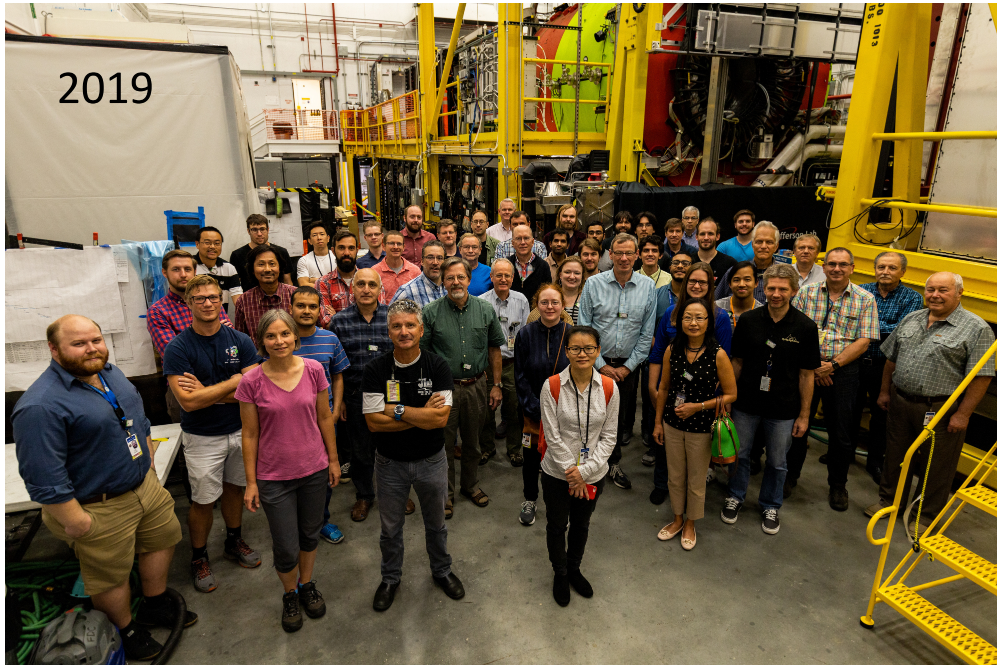
Exchange		Exotic Final States	
$\mathbb{P}$	0^{++}	b, h, h'	$2^{+-}, 0^{+-}$
π^0	0^{-+}	b_2, h_2, h_2'	2^{+-}
$\pi^\pm$	0^{-+}	$\pi_1^\pm$	1^{-+}
ω	1^{--}	π_1, η_1, η_1'	1^{-+}

GlueX Collaboration - Jefferson Lab, Newport News, VA, USA

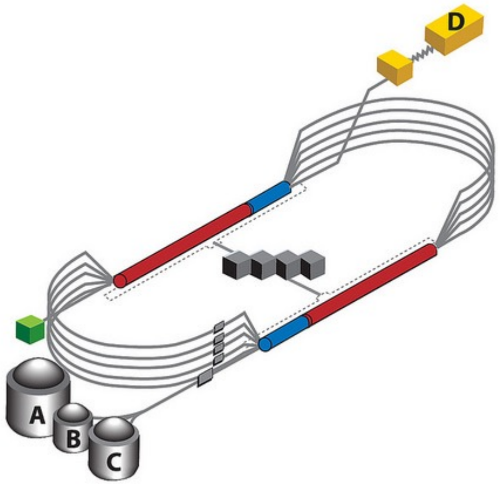


141 people from 32 institutions:

Arizona State U., U. of Athens, U. of Bonn, Carnegie Mellon U., Catholic U., U. of Connecticut, Duke U., Florida International U., Florida State U., George Washington U., U. of Glasgow, GSI, IHEP Chinese Academy of Sciences, Indiana U., ITEP Moscow, Jefferson Lab, Forschungszentrum Jülich, Lamar U., U. of Massachusetts Amherst, MIT, MEPhI, Mount Allison U., Norfolk State U., N Carolina A&T State, U. of N Carolina Wilmington, Old Dominion U., UT Federico Santa María, Tomsk State/Tomsk Polytechnic U., U. of Regina, William & Mary, Wuhan U., Yerevan Physics Institute



CEBAF and Hall D at Jefferson Lab



GlueX spectrometer located in Hall D

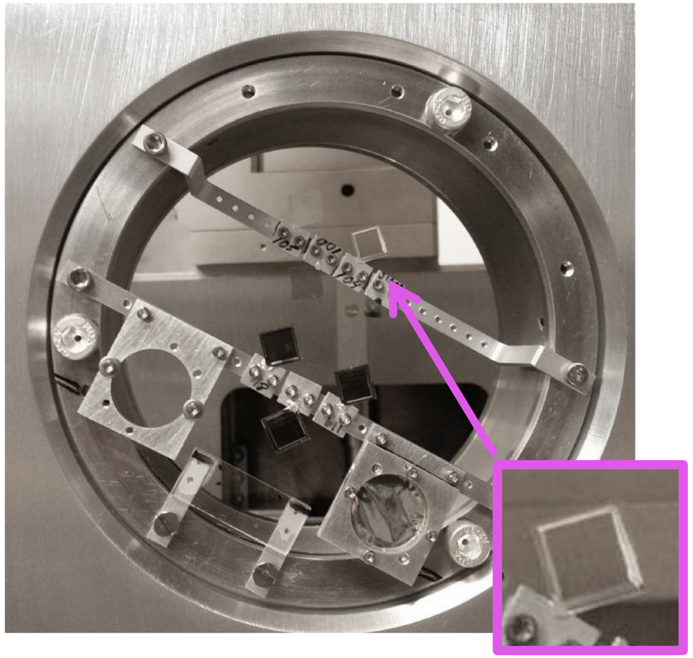
12 GeV electron beam from CEBAF
Continuous Electron Beam Accelerator Facility

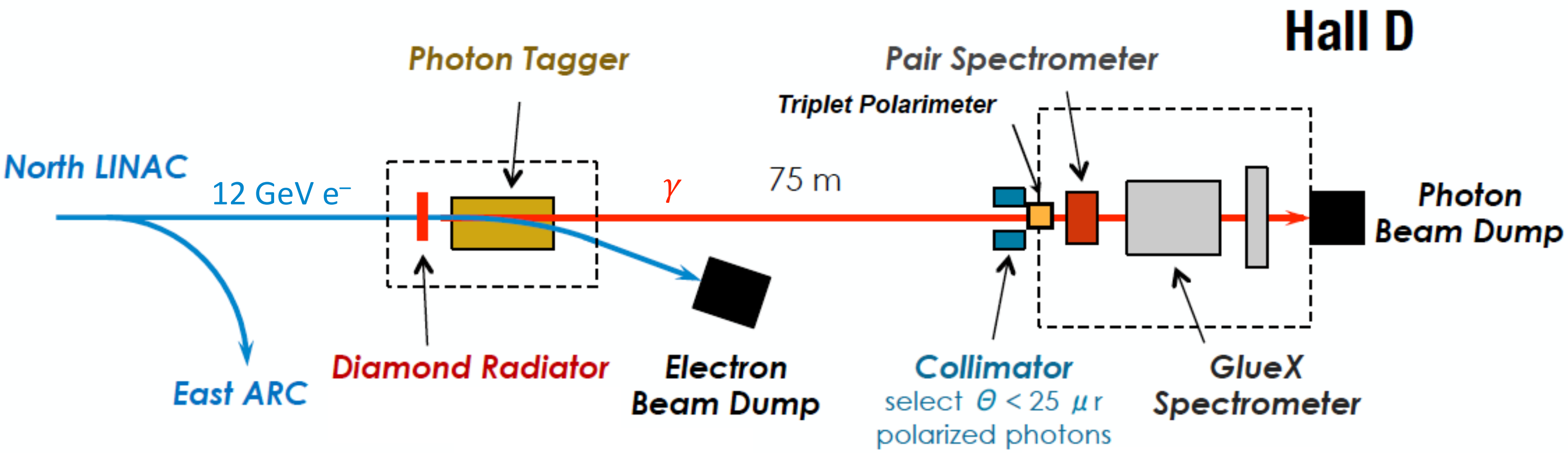
Polarized photon beam created in Tagger Hall

GlueX polarized photon beam

- 12 GeV e⁻ beam on thin diamond crystal (20-60 μm) produces 9 GeV linearly polarized photons via coherent Bremsstrahlung, intensity 5 x 10^7 γ/s
- Scintillator arrays measure energy of each scattered electron, to 'tag' its photon E_γ tagging precision ~ 0.1%   (resolution 5 MeV in coherent peak)

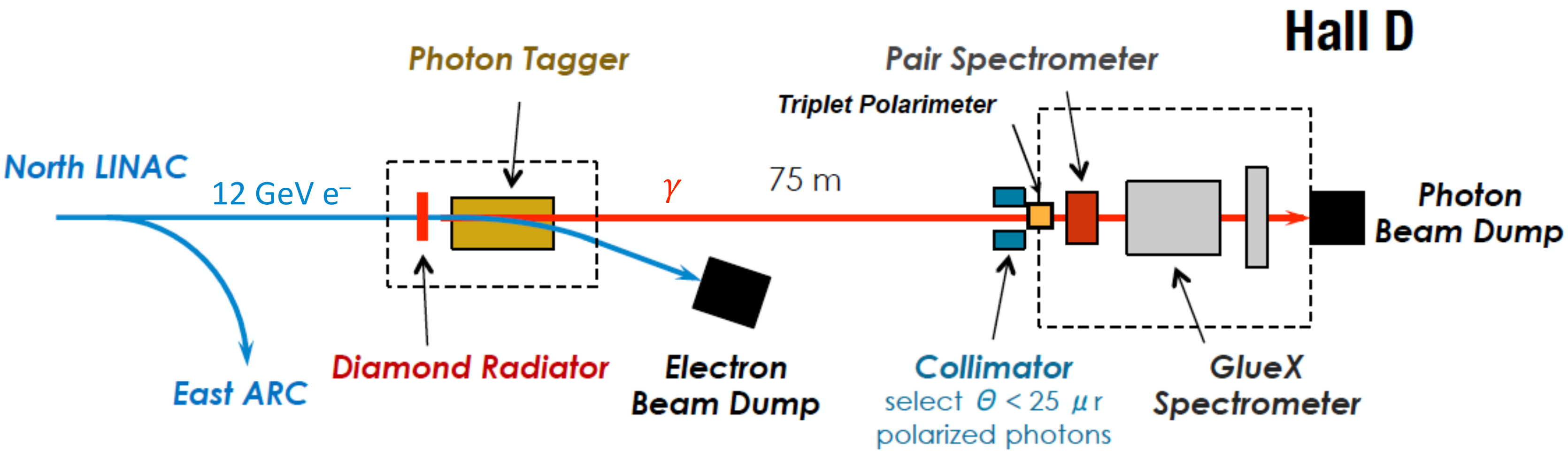
Radiators on goniometer



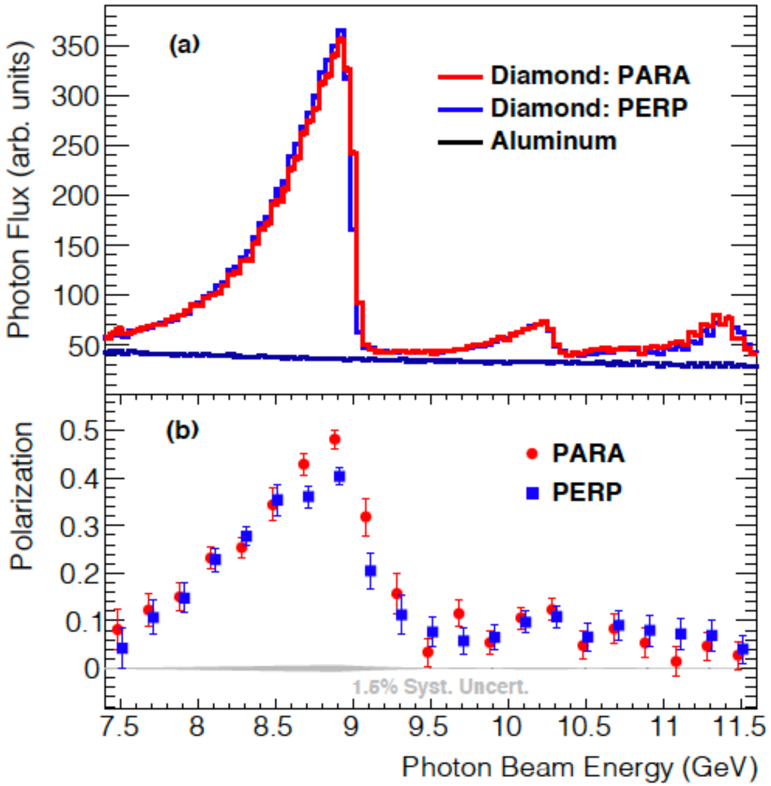


GlueX polarized photon beam

- 12 GeV e⁻ beam on thin diamond crystal (20-60 μm) produces 9 GeV linearly polarized photons via coherent Bremsstrahlung, intensity 5 x 10^7 γ/s
- Scintillator arrays measure energy of each scattered electron, to '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
- Four diamond orientations: 0°, 90°, -45°, 45°



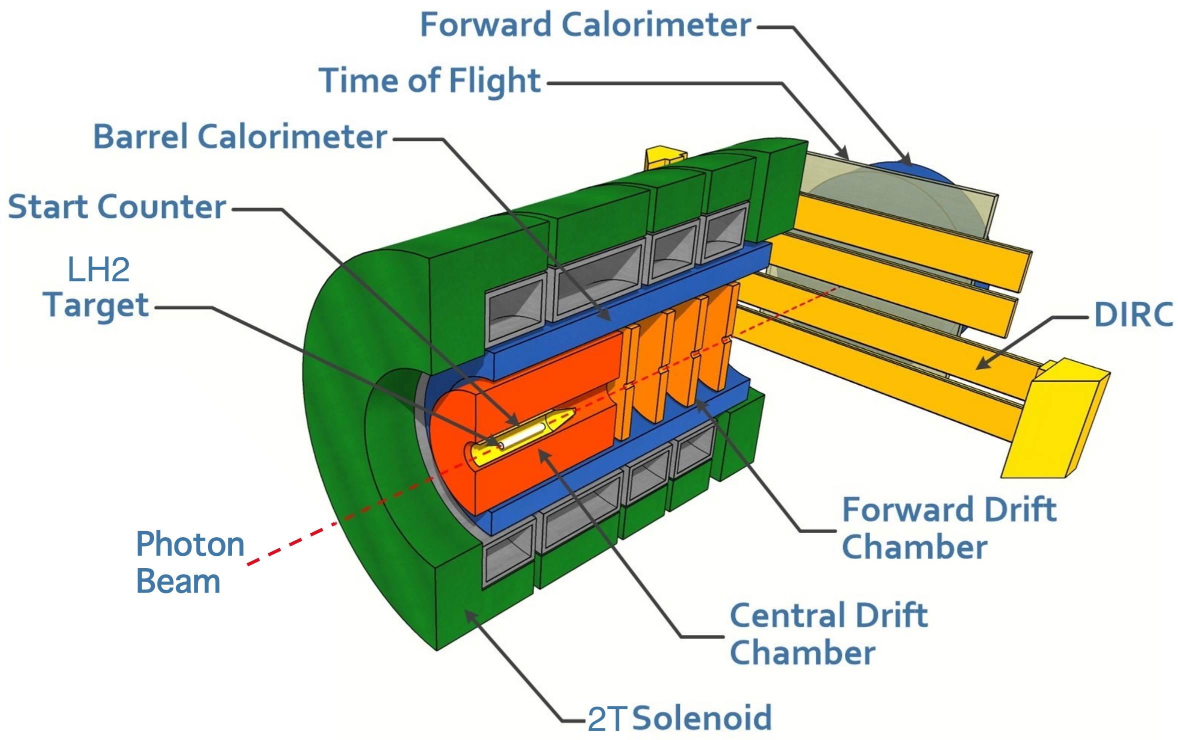
Photon flux and polarization



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

GlueX spectrometer

Large acceptance, optimized for light meson spectroscopy
Cerenkov detectors added in 2019



The GlueX Beamline and Detector
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Acceptance θ = 1–120°
Charged $\sigma_p/p \sim$ 1-5%
Neutral $\sigma_E/E = 6\% / \sqrt{E} \oplus 2\%$

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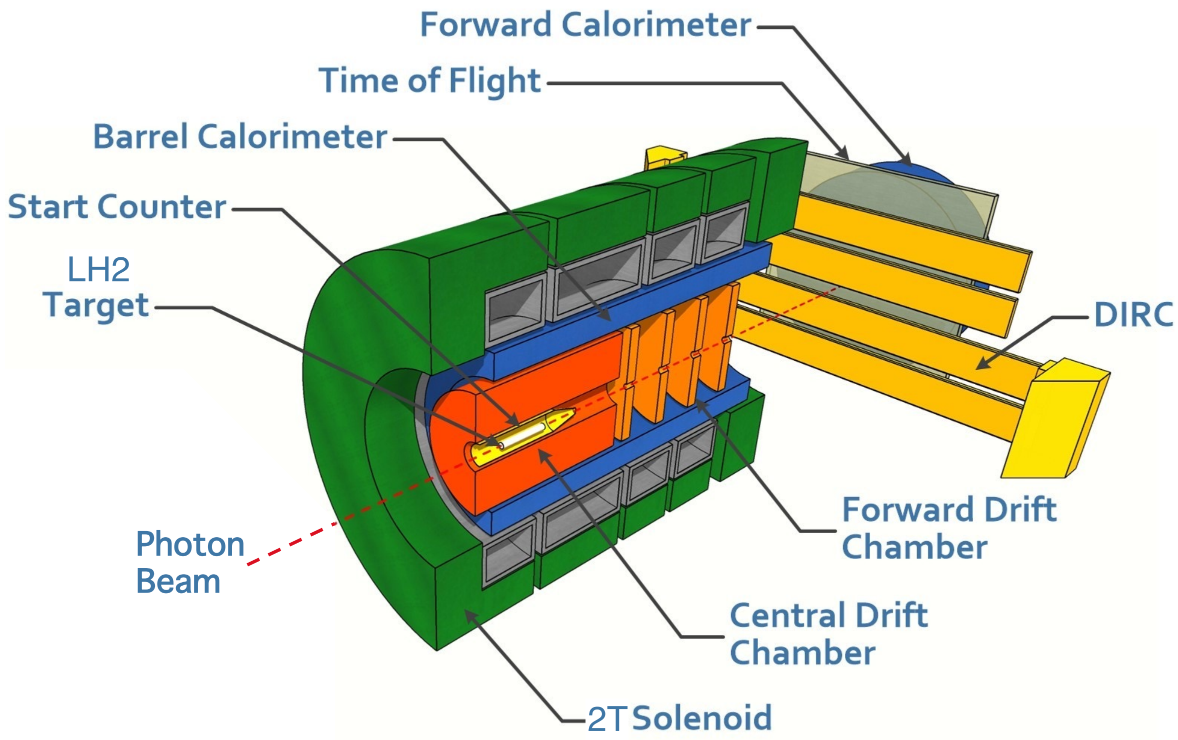

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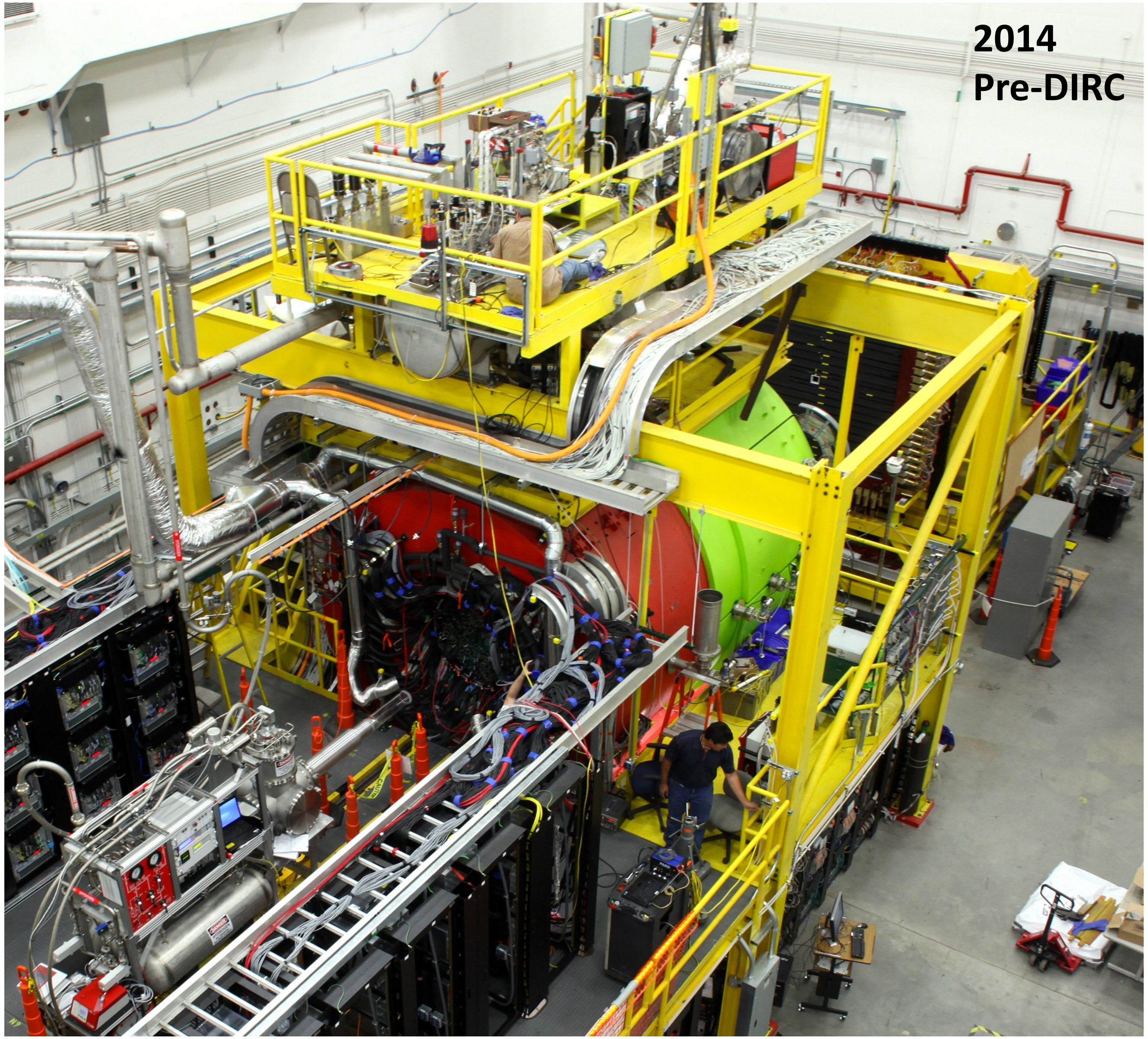
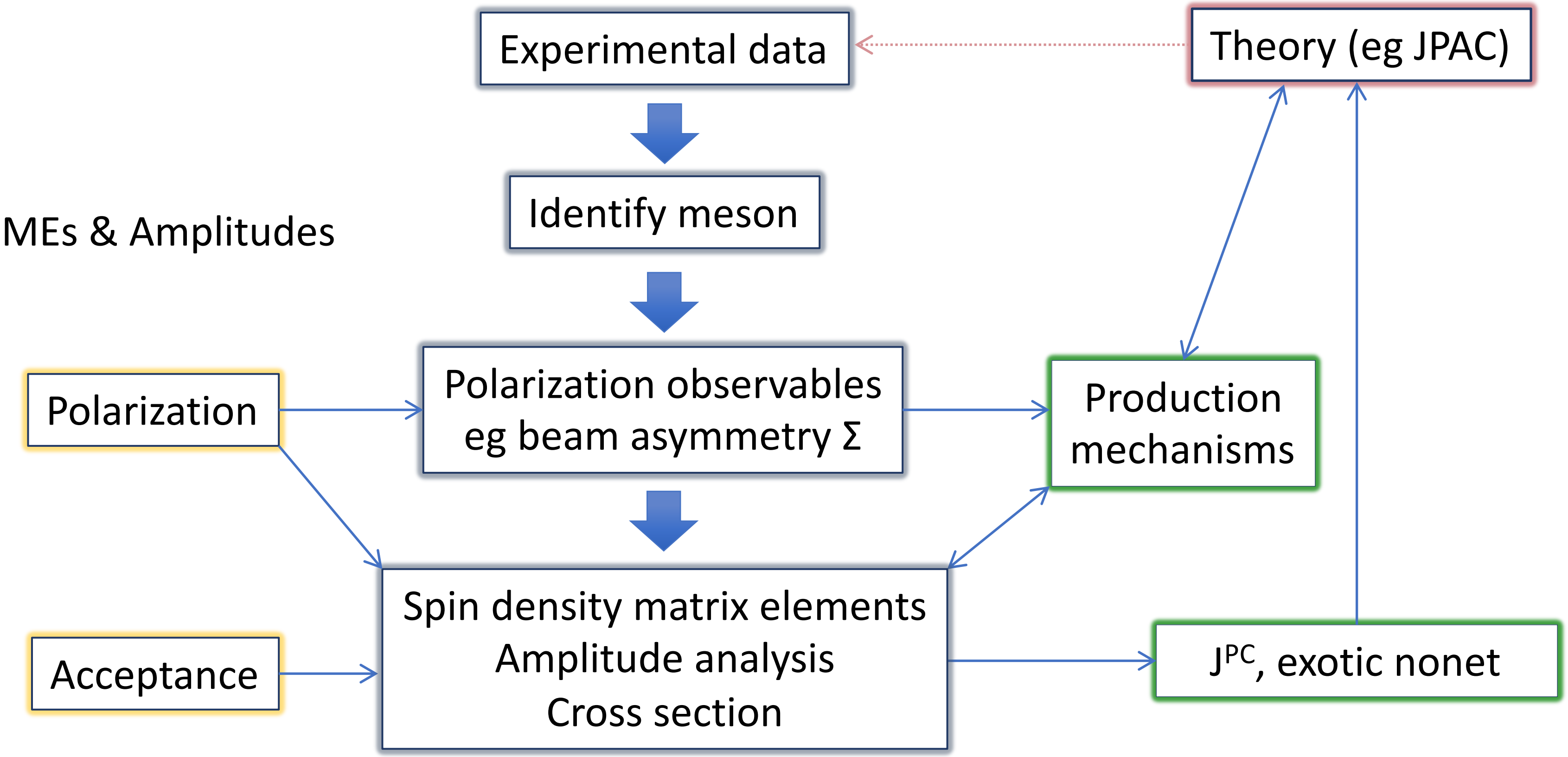


GlueX physics pathway

- Study known mesons
  Then look for exotics

- Same software for SDMEs & Amplitudes



- GlueX-I 2017 – 2018 125 pb^{-1} 8.2-8.8 GeV
- GlueX-II 2020 – 2025? Expect 3-4 x GlueX-I
- Publications listed on gluex.org

Selected results: SDME for ρ(770)
amplitude analysis $a_2(1320)$
J/ψ cross section
PrimEx-η

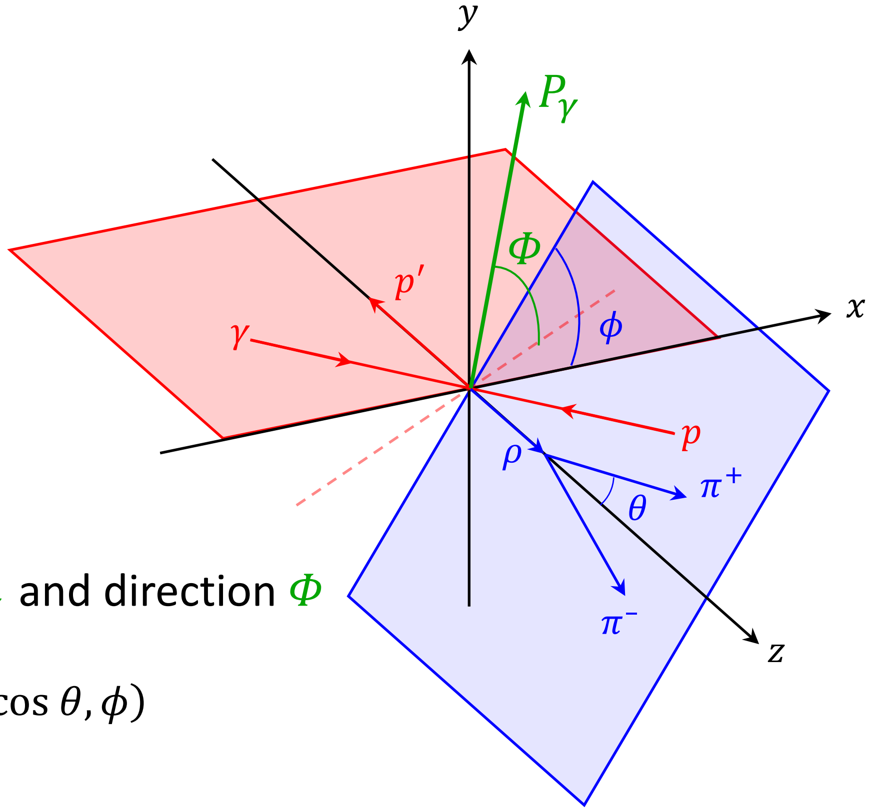
Spin Density Matrix Elements

Amplitude analysis

J/ψ cross section

PrimEx-η

Vector Meson Spin Density Matrix Elements



- Detailed theory predictions, but previous measurements limited
- Sensitive to angular components of detector acceptance
- Some channels have several decay modes

- SDMEs ρ_{ij}^{k} measured by angular distribution of decay products
- Linear beam polarization gives access to 9 SDMEs, input for production models
- Intensity expanded in $\cos\theta$, ϕ in helicity frame, beam polarization magnitude P_γ and direction Φ

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

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

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

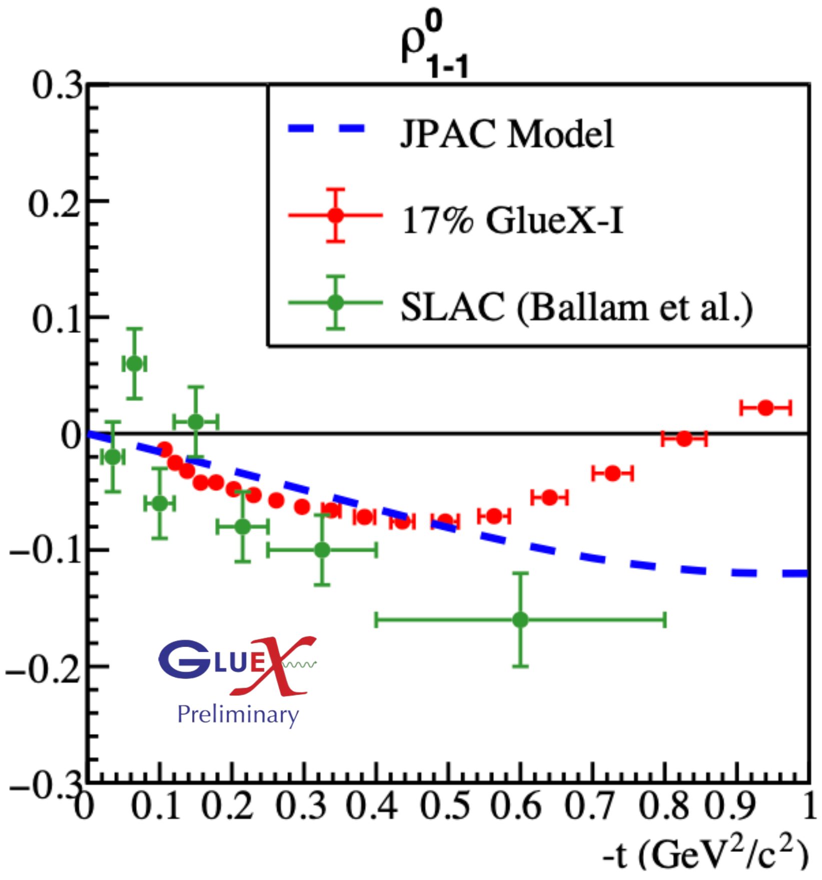
$$W^2(\cos\theta,\phi) = \frac{3}{4\pi}\left(\sqrt{2}\,\mathrm{Im}\,\rho_{10}^2\sin 2\theta\sin\phi + \mathrm{Im}\,\rho_{1-1}^2\sin^2\theta\sin 2\phi\right)$$

Schilling et al NPB15(1970)397

ρ(770) Spin Density Matrix Elements

Results:

- 2017 data ~ 10% of eventual dataset
- Combined fit of 4 orientations of polarization
- Statistical uncertainties nearly negligible
  → evaluation of systematic errors in progress
- Excellent agreement with previous measurements and model (where valid, t < 0.5 GeV)



JPAC model: Mathieu et al PRD 97 (2018) 094003

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

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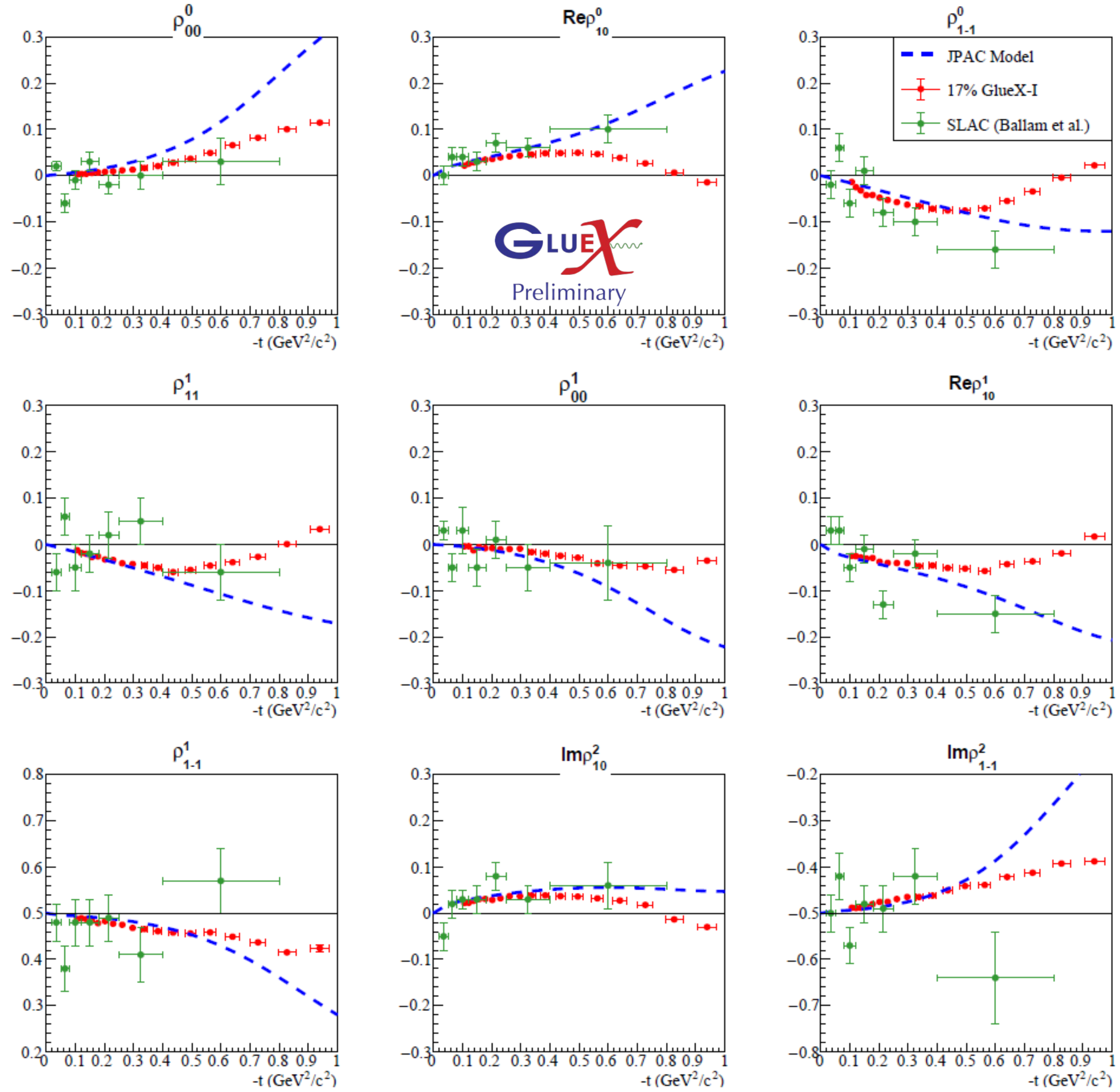


Parity asymmetry for ρ(770) photoproduction

- SDMEs describe combinations of natural & unnatural parity exchanges

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

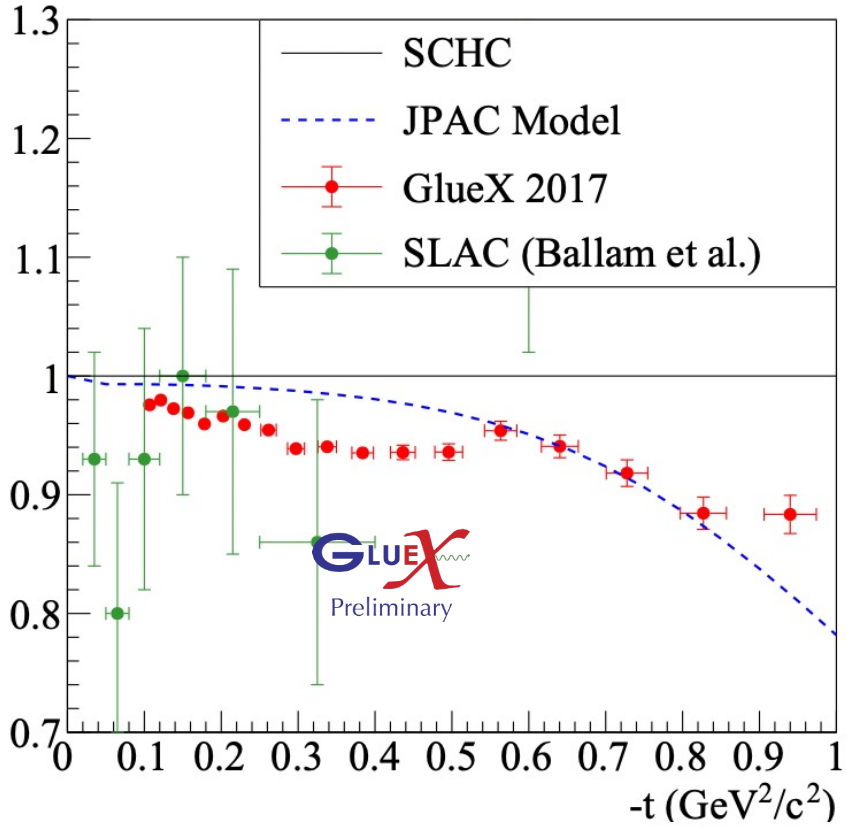
  $N = +1$ \`natural', eg 0^+ P, 1^- ρ

  $N = -1$ \`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



Relevance to exotic search:

- High-precision input for production models
- Improves our knowledge of data and acceptance
- Requires high-precision multi-dimensional fit procedures

Spin Density Matrix Elements

a_2(1320) amplitude analysis

J/ψ cross section

PrimEx-η

a_2(1320) strategy

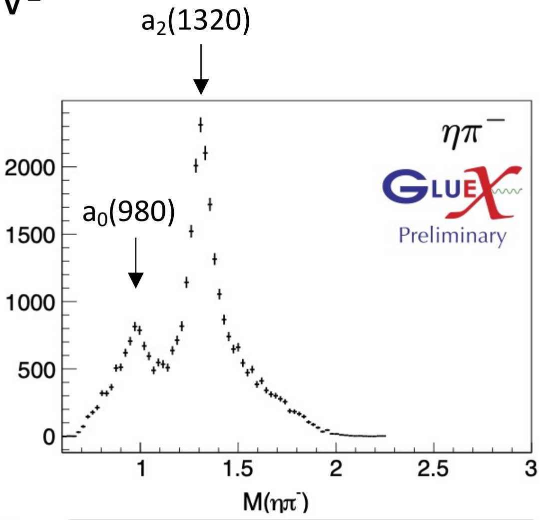
- a_2(1320) well-known non-exotic meson produced abundantly and decaying via ηπ
- Using this analysis to develop and refine software for large datasets
- Comparison between different decay modes helps to improve acceptance and background removal techniques
- Eventually use a_2(1320) as a standard reference for comparisons with smaller exotic contributions in η’π
- Key step towards analysis of η’π and other exotics

a_2(1320) in ηπ systems

- Clear signals at a_0(980) and a_2(1320) masses

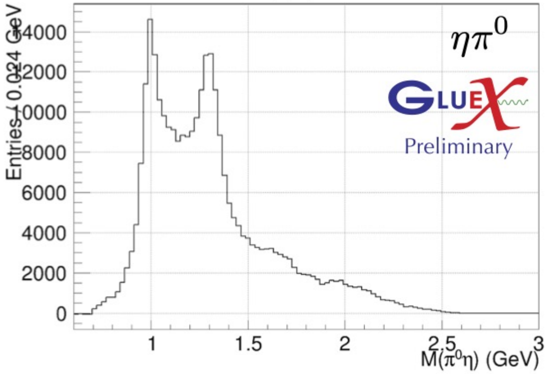
$0.1 < -t < 0.3$ GeV^2

ηπ⁻



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

ηπ^0



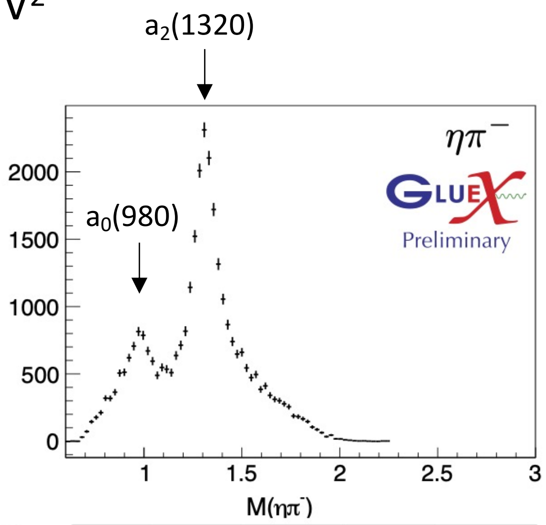
$$\gamma p \rightarrow \eta\pi^{0}p$$
$$\eta \rightarrow \gamma\gamma$$

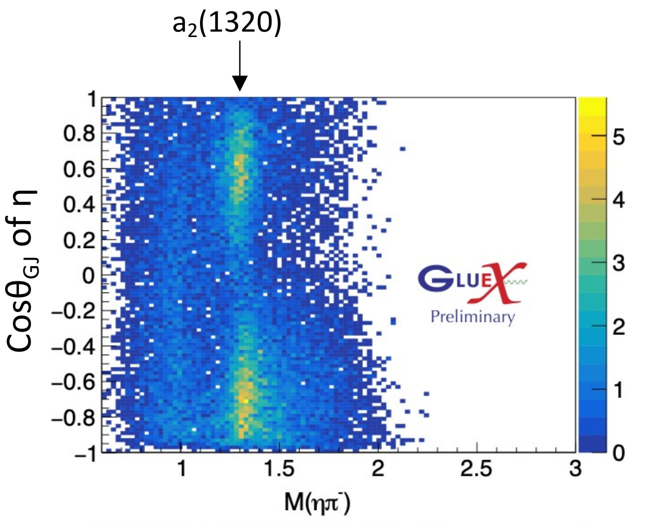
$a_2(1320)$ in $\eta\pi$ systems

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

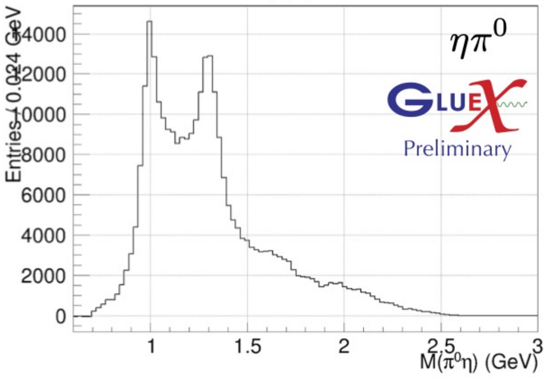
$0.1 < -t < 0.3$ GeV^2

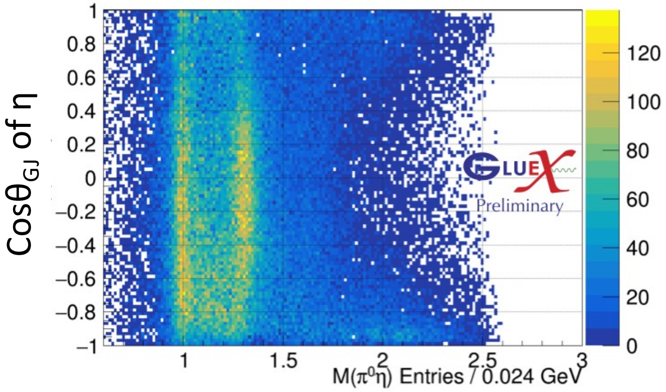
$\eta\pi^-$





$\eta\pi^0$





Different spin-projection states populated

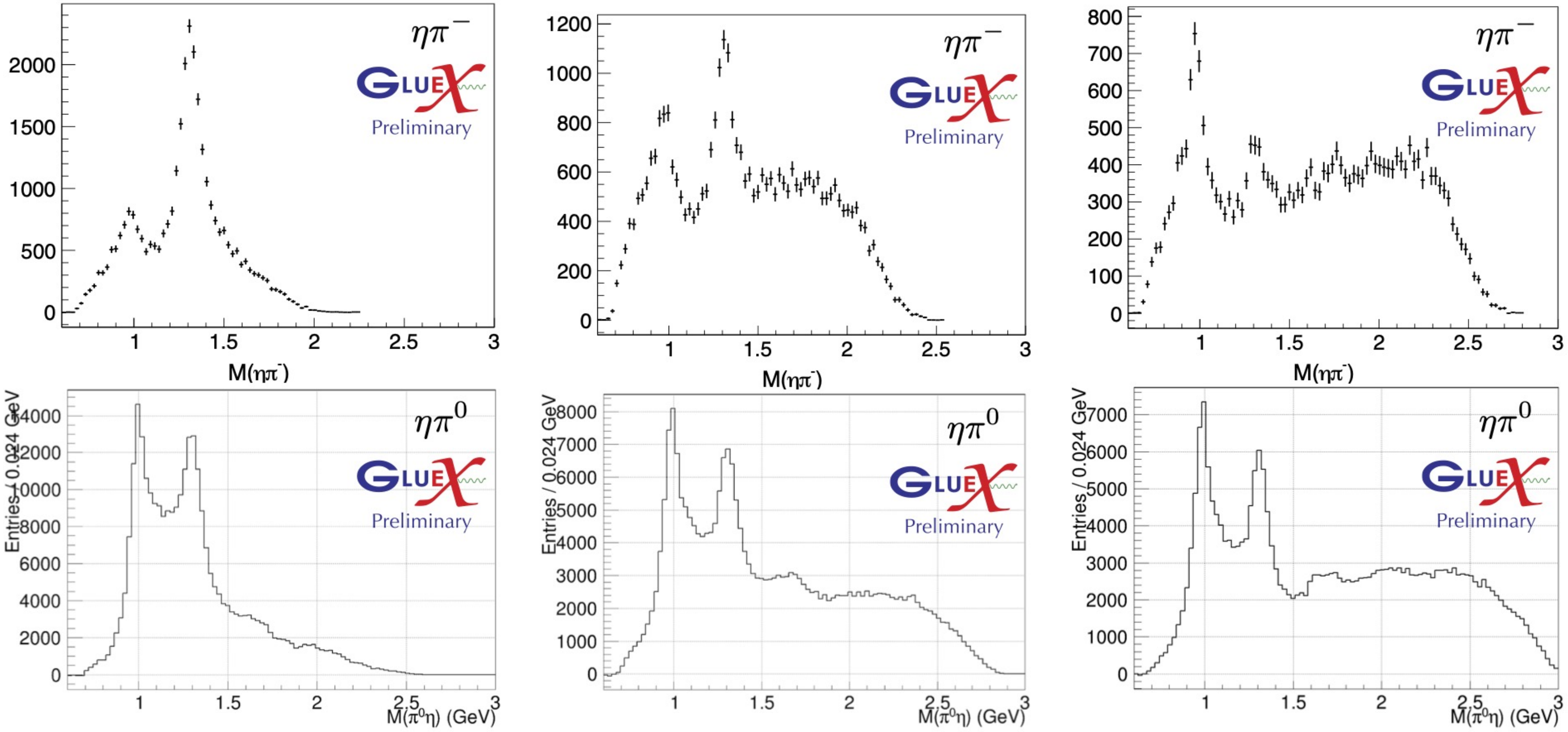
$a_2(1320)$ in ηπ systems

- 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

ηπ⁻

ηπ⁰



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

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

JPAC: Mathieu et al PRD 100 (2019) 054017

Intensity(Ω,Φ):

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

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

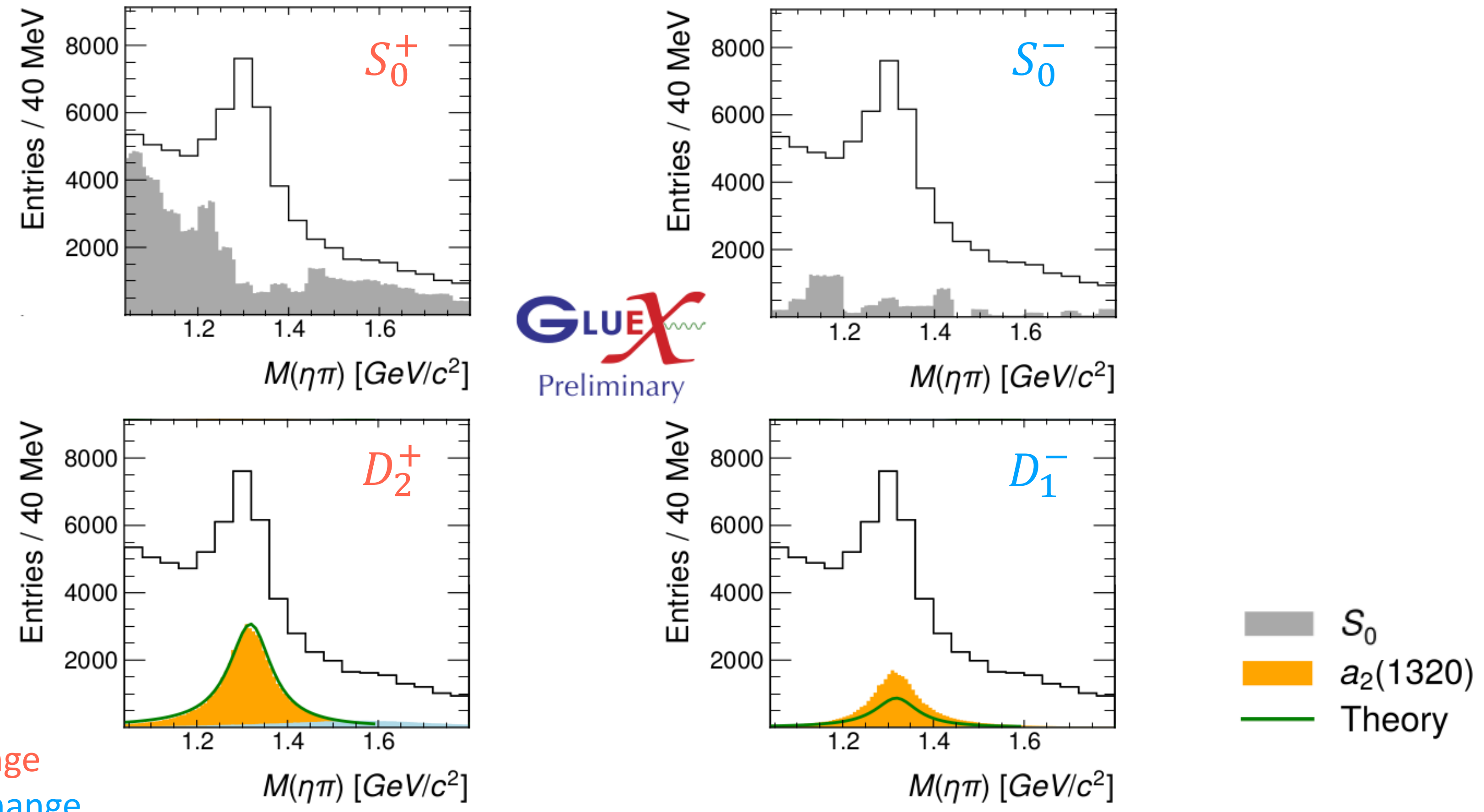
Naturality N = $P(-1)^J$ N=+1 'natural' for 0+ etc
Reflectivity = N(exchanged particle) x N(resonance)

Reflectivity + natural parity exchange
Reflectivity – unnatural parity exchange

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

- Choice of wave-set informed by TMD model from JPAC: Mathieu et al PRD 102 (2020) 014003
- Mass binned approach for the S-wave (non-trivial background includes double Regge + non-resonant processes)
- Model $a_2(1320)$ using a Breit-Wigner.

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

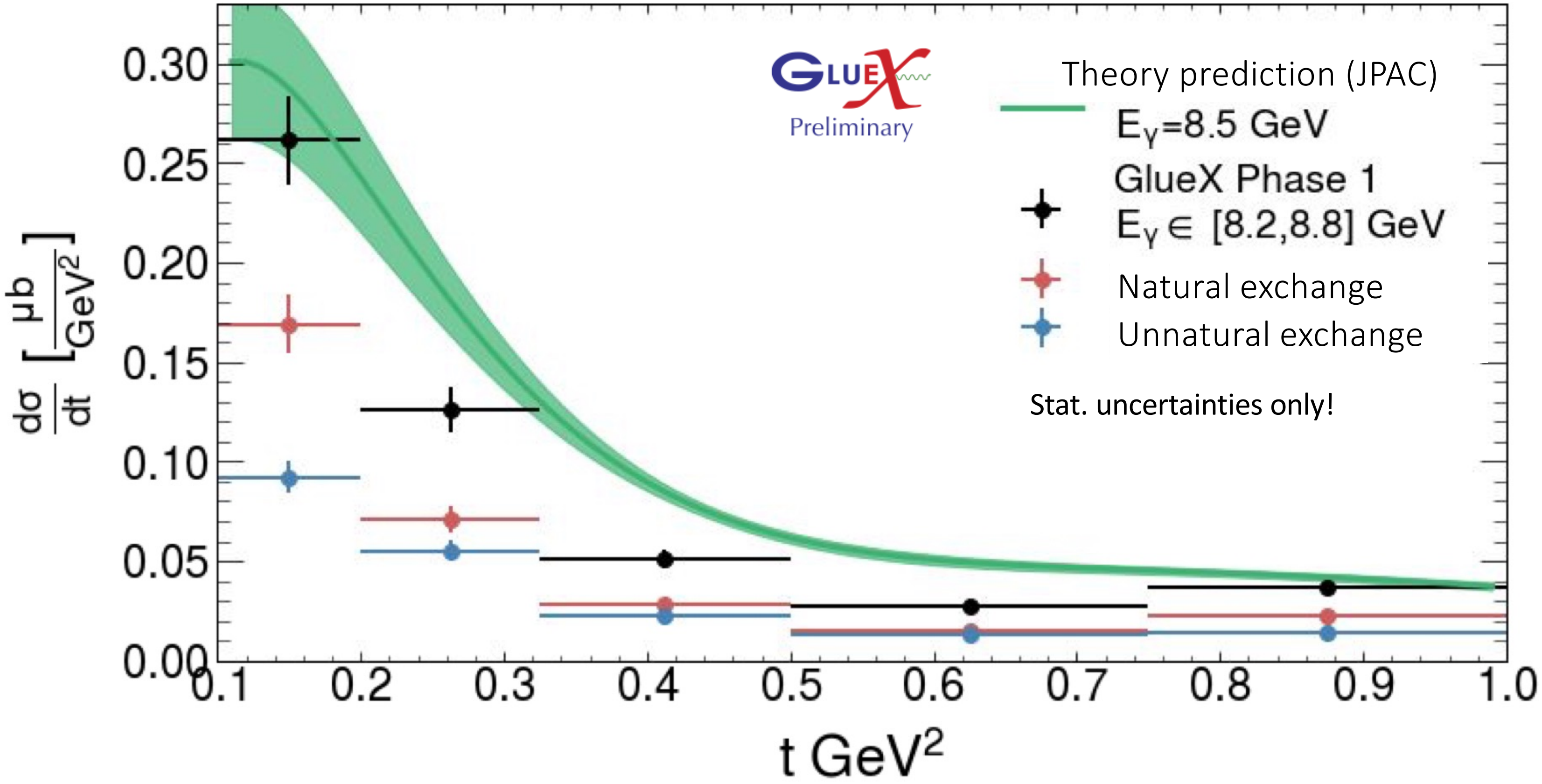


Reflectivity + natural parity exchange

Reflectivity − unnatural parity exchange

$a_2(1320)^0$ Differential cross-section

- Good agreement with theory
- Tail from $a_2(1700)$ extends beneath $a_2(1320)$ => more sophisticated model from JPAC being tested
- First step towards search for π_1
- Understanding the (large) contribution of a2(1320) to that mass region will help with analysis of spin-exotics



Spin Density Matrix Elements

Amplitude analysis

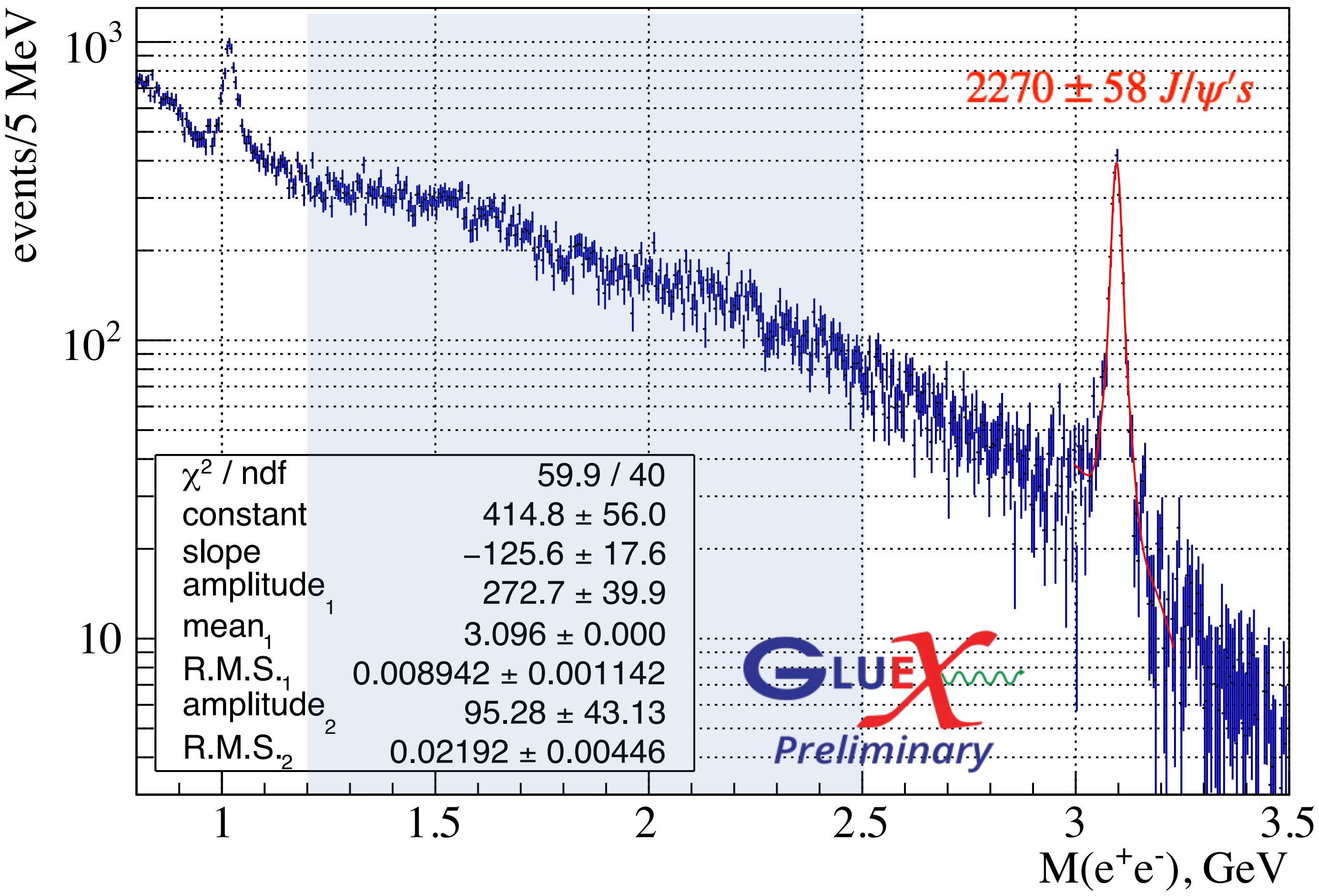
Cross section $\gamma p \rightarrow J/\psi\, p$

PrimEx-η

J/ψ photoproduction at GlueX

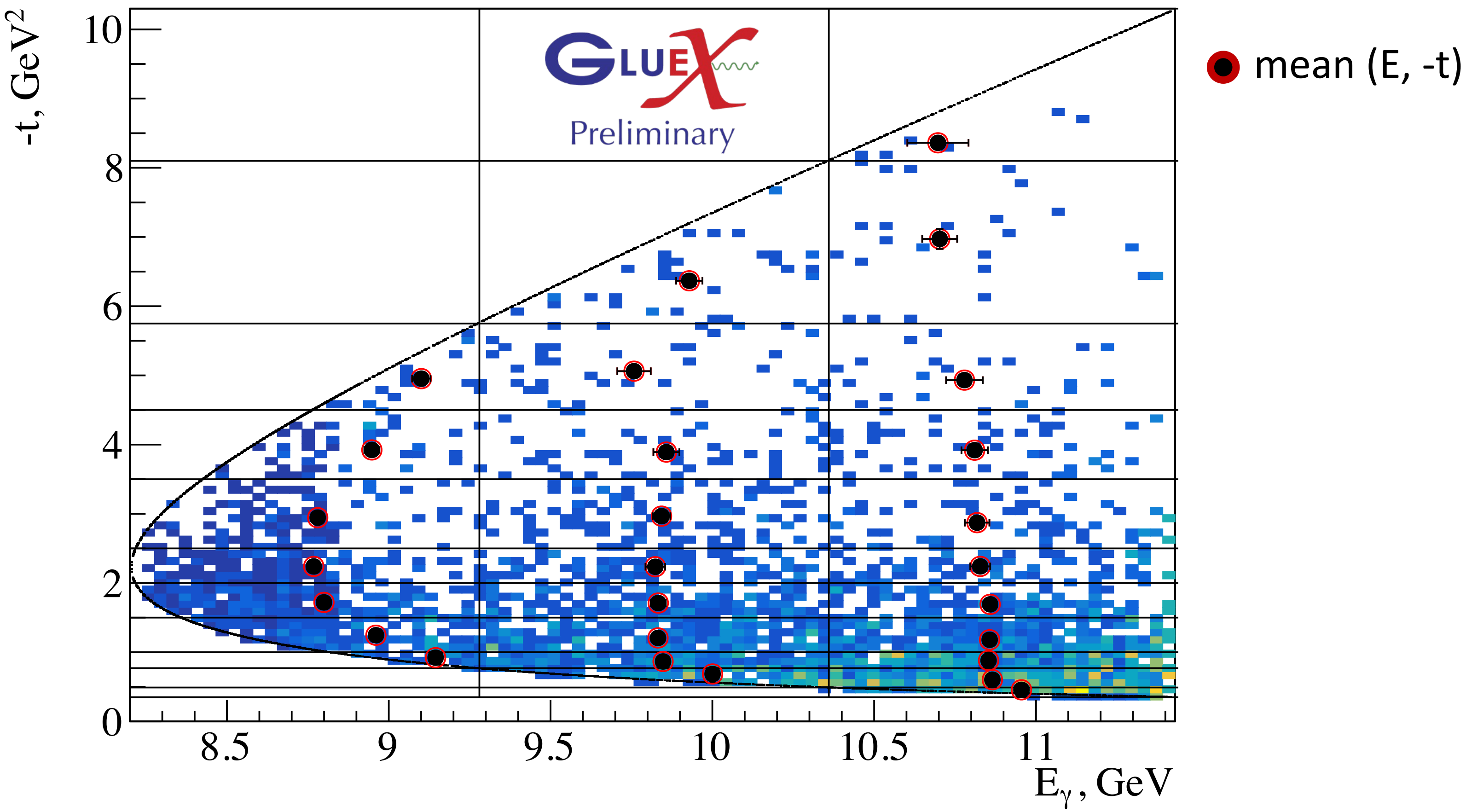
- Measured exclusive production
  $$\gamma p \rightarrow (J/\psi \rightarrow e^+e^-)p$$
- [Phys. Rev. Lett. 123 (2019) 072001](#) based on 2016-2017 data
- 2016 - 2018 data shown here, preliminary!
- 13 MeV mass resolution, no radiative tail.
- Yields extracted from fits
- Bethe-Heitler process (1.2 – 2.5 GeV) used for normalization

Invariant mass of e^+e^-



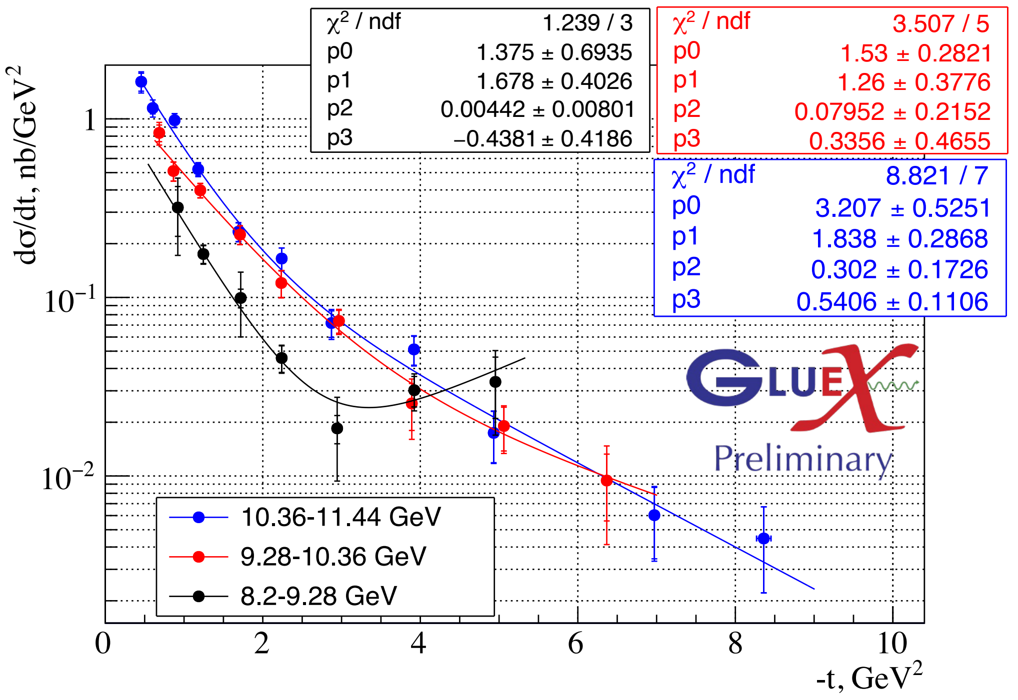
J/ψ differential cross-section

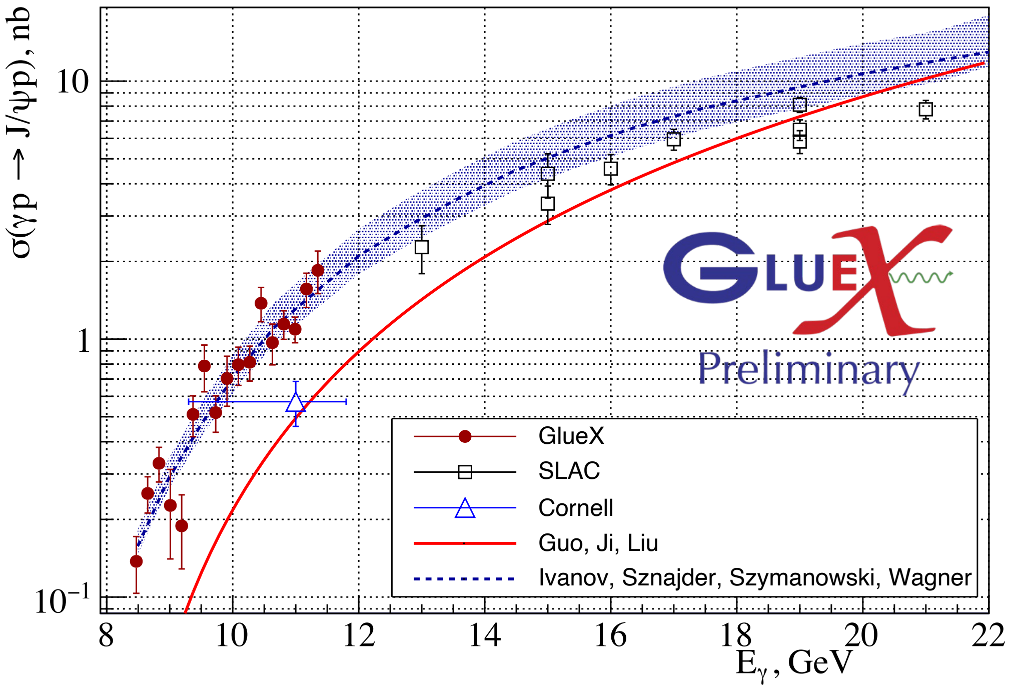
- Each event weighted by luminosity
- Most data close to threshold
- Deviations from bin averaging included in systematics



$$\frac{d\sigma}{dt}(E,t) = \frac{N_{J/\psi}}{L(E_\gamma)[nb^{-1}]/0.045GeV}\frac{1}{area(E,t)[GeV \cdot GeV^2]}\frac{1}{\varepsilon(E,t)}$$

Preliminary cross-section for $\gamma p \rightarrow J/\psi p$

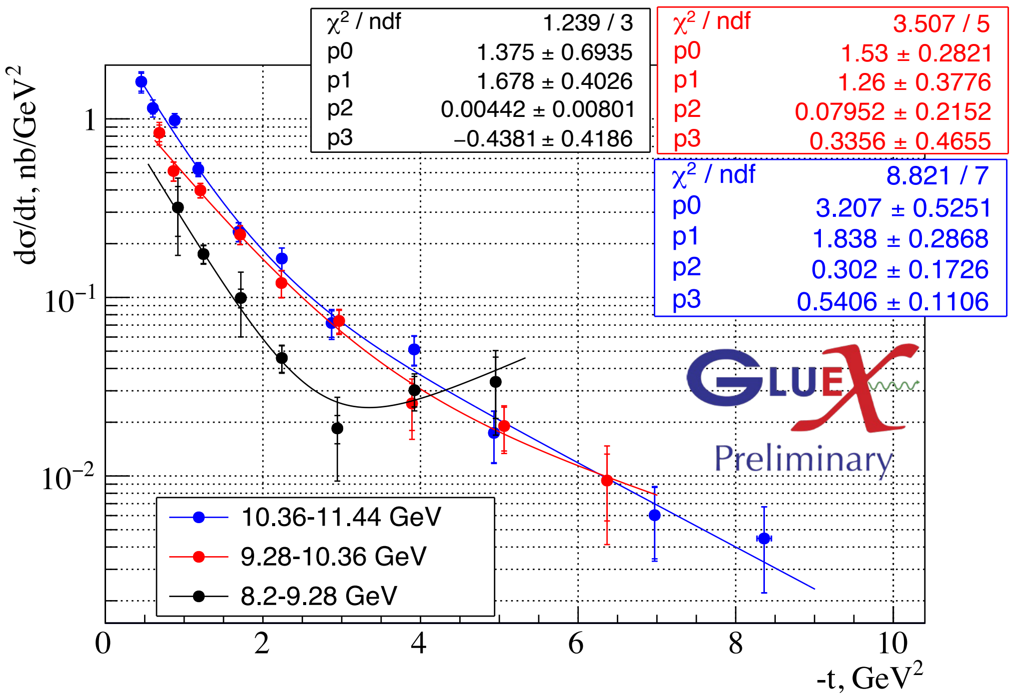


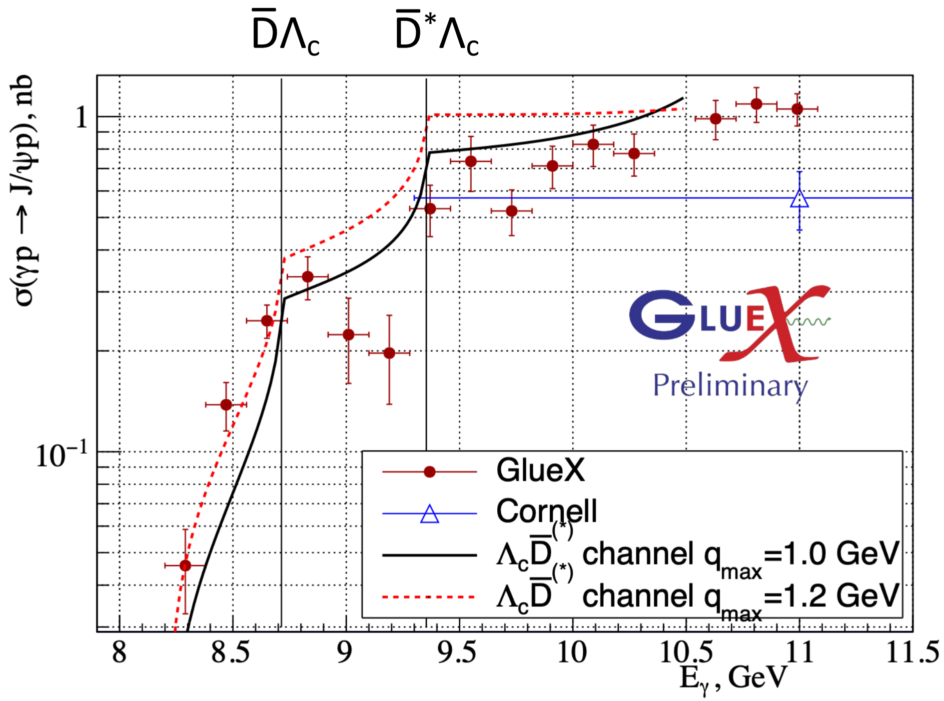


- Lowest beam energy dσ/dt has different t-dependence
- GlueX data compatible with older data, extend towards threshold
- QCD factorization models show good agreement with our data

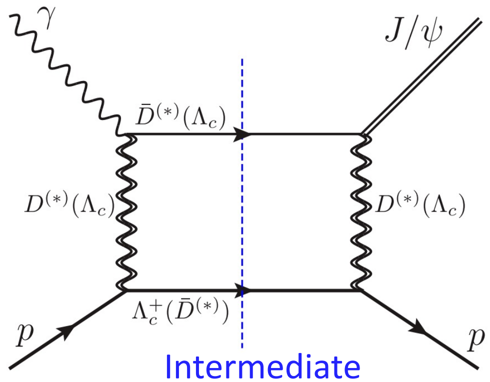
Guo, Ji, Liu PRD103 (2021) 096010
Ivanov, Sznajder, Szymanowski, Wagner (2022)

Preliminary cross-section for $\gamma p \to J/\psi p$





- Lowest beam energy $d\sigma/dt$ has different t-dependence
- Photoproduction model from Du et al EPJ C 80 (2020) 1053 predicts cusps in cross section at thresholds for $\bar{D}\Lambda_c$ and $\bar{D}^*\Lambda_c$
- Expect to have ~3 x this amount of data from GlueX I + II



Intermediate open-charm state

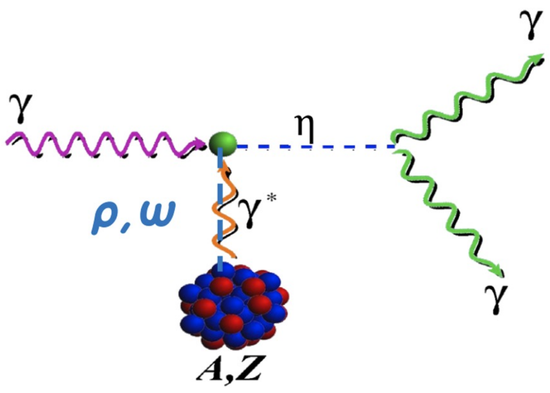
Spin Density Matrix Elements

Amplitude analysis

J/ψ cross section

PrimEx-η

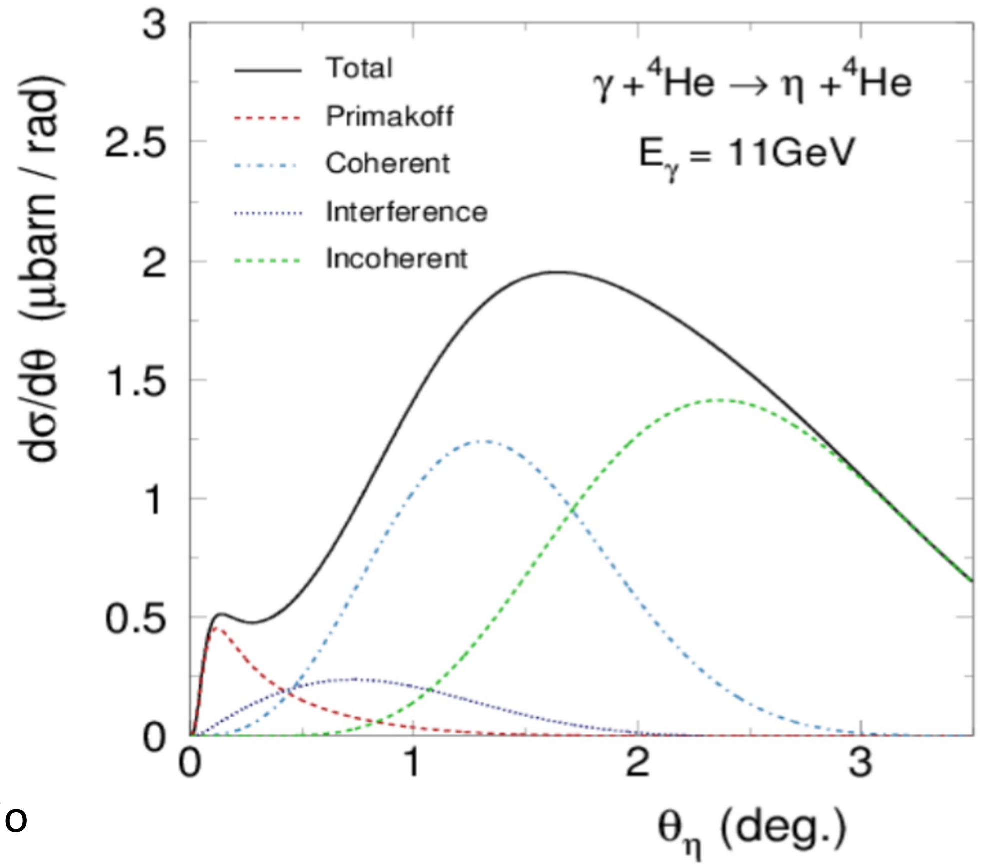
PrimEx-eta: Precision measurement of the η radiative decay width via the Primakoff Effect



- $\eta \to \gamma\gamma$ decay proceeds primarily via the chiral anomaly

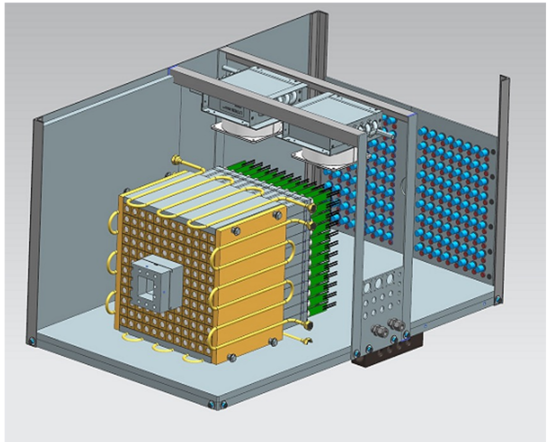
- Motivation for precise measurement of η radiative decay width:
  - Better knowledge of η-η' mixing angle
  - Improve all other partial decay widths of the η meson
  - Enable model-independent extraction of light quark mass ratio
  - Input to hadronic light-by-light contribution to g-2

- Target: Liquid ^{4}He (production) and ^{9}Be (luminosity normalization)



$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma(\eta \to \gamma\gamma)\ \frac{8\alpha Z^2}{m_\eta^3}\frac{\beta^3 E^4}{Q^4}|F_{em}(Q)|^2 \sin^2(\theta_\eta)$$

PrimEx-eta: Simultaneous measurement of Compton scattering, for systematics



Compton scattering on atomic electrons is a well-known QED process & useful reference

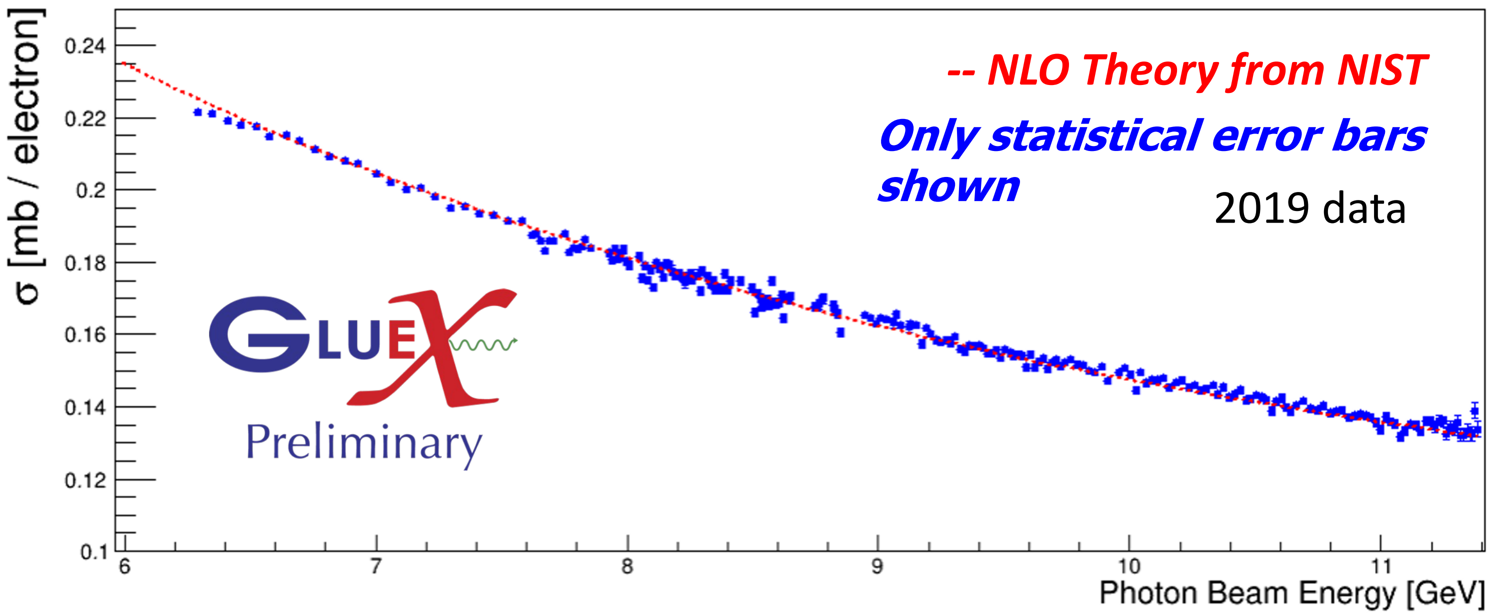
- Verify overall systematics in absolute cross section measurement
- Monitor changes in luminosity

Total uncertainty in Compton cross section ~3% (E_γ 6-11 GeV)

Excellent agreement with theory

Compton calorimeter $PbWO_4$ crystals
12.1 m from target, surrounds beamline
covers 0.19° – 0.8°

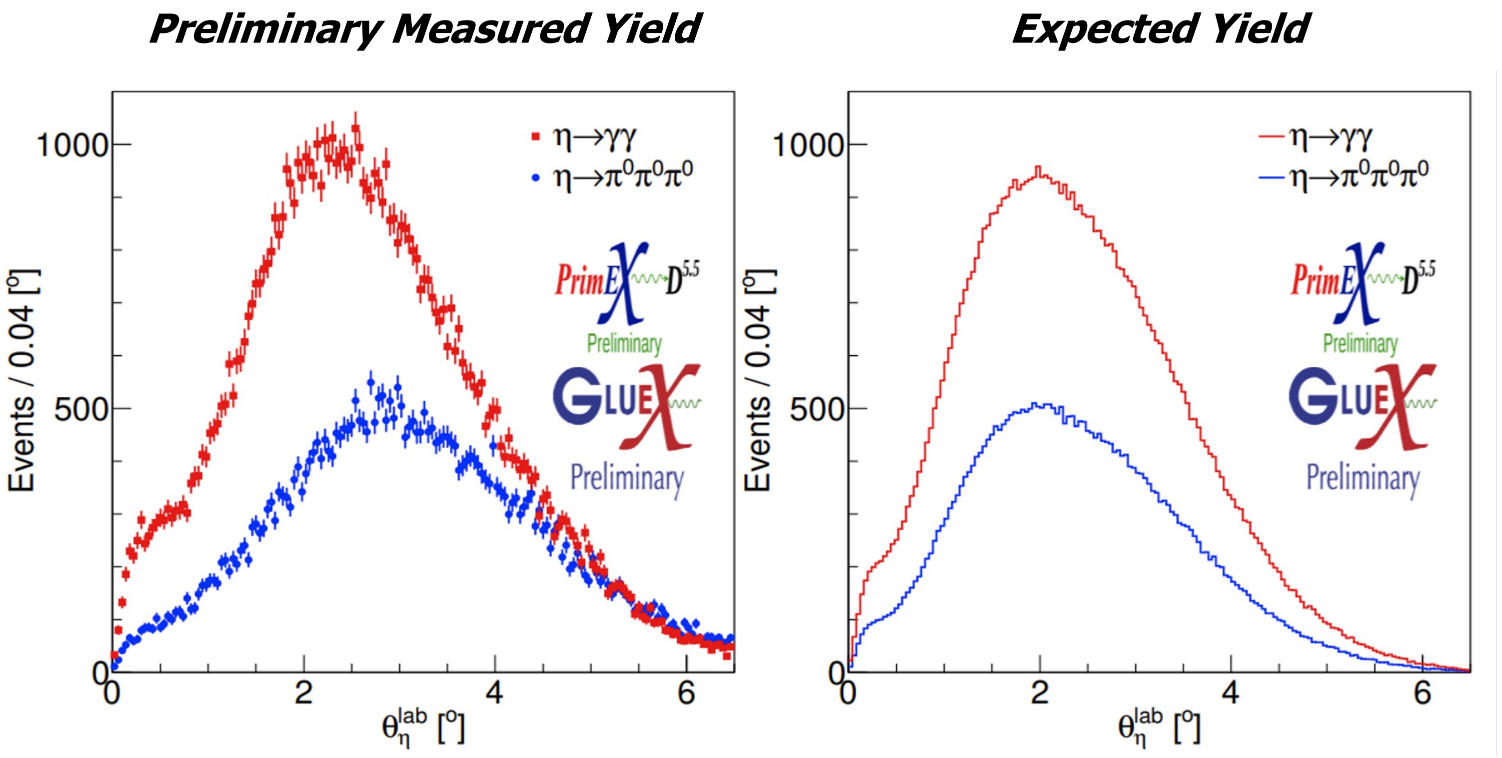
Total Compton Scattering Cross Section on ^{9}Be Target



PrimEx-eta: Angular yield of $\gamma p \rightarrow (\eta \rightarrow \gamma\gamma)p$ and $\gamma p \rightarrow (\eta \rightarrow 3\pi^0)p$

Measured yield shown is after subtraction of empty target background and accidentals
Expected yield is from simulation

2019 data



The cross section will be extracted independently from the 2γ, $3\pi^0$, and $\pi^0\pi^+\pi^-$ decay modes, with a simultaneous fit performed to extract the decay width.

Conclusion and Acknowledgements

We are looking forward to analysing our dataset with enhanced PID. Stay tuned for more GlueX publications.

Thank you for listening!

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

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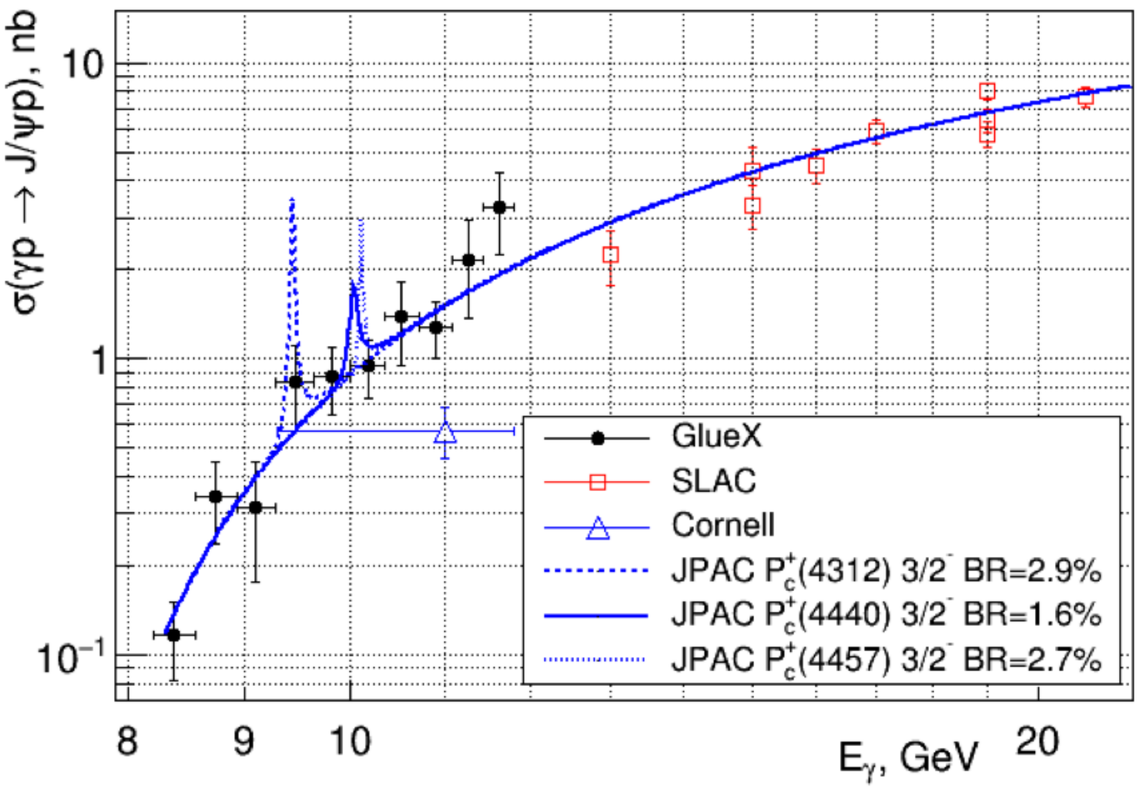
Backup slides

J/ψ cross-section, model-dependent upper limits for P_c



2016-7 data published in Phys. Rev. Lett. 123, 072001 (2019)

Assume all P_c independent, $J^P = 3/2^-$

s-channel model:

$\sigma(\gamma p \rightarrow P_c \rightarrow J/\psi p) \approx$

$0.35\ \mu b\ Br^2(P_c \rightarrow J/\psi p)\ (2J+1)$

JPAC model for t-channel: Pomeron and tensor part extracted at high energies

	$\mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, %		$\sigma_{\max} \times \mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, nb	
	p.t.p. only	total	p.t.p only	total
$P_c^+(4312)$	2.9	4.6	3.7	4.6
$P_c^+(4440)$	1.6	2.3	1.2	1.8
$P_c^+(4457)$	2.7	3.8	2.9	3.9

Upper limits at 90% confidence

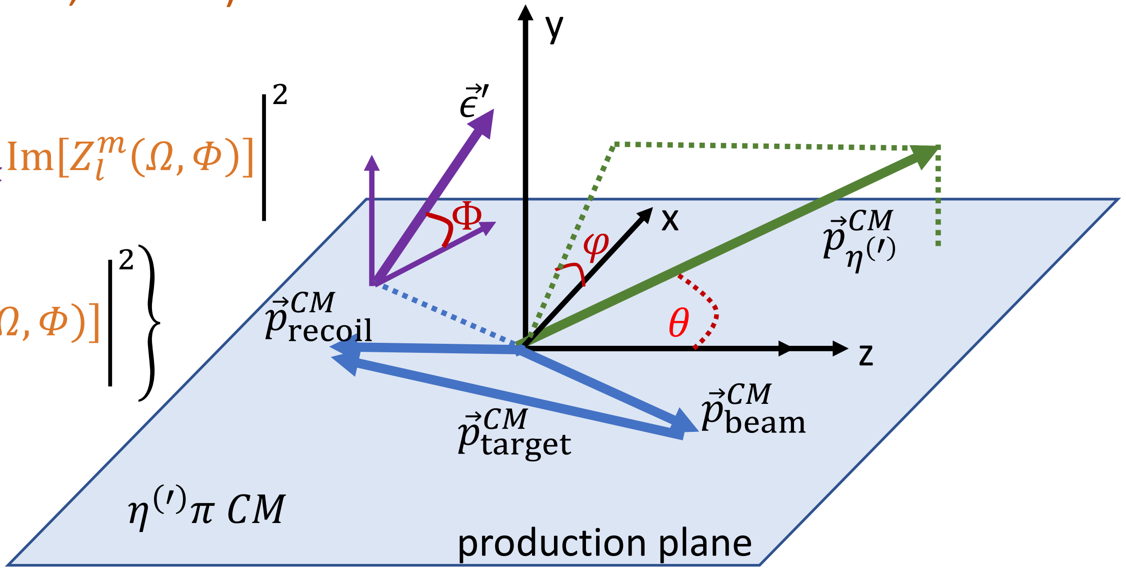
Model predicted number of events per unit phase space

Partial wave amplitudes (production of the wave)

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

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

Helicity frame (HX)



P_γ - degree of polarization

$Z^m_l(\Omega,\Phi) \equiv Y^m_l(\Omega)e^{-i\Phi}$

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

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)