The Search for Exotic Hadrons at GlueX

Alexander Austregesilo
for the GlueX Collaboration

The 10th International Conference on Quarks and Nuclear Physics
Barcelona, Spain
July 9th, 2024

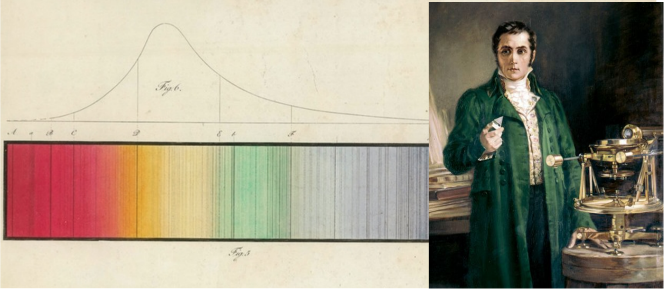
GlueX

Jefferson Lab

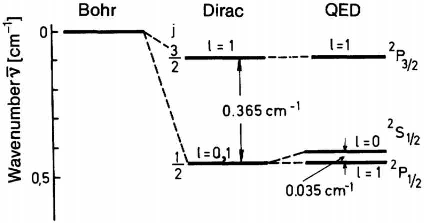
Outline

Spectroscopy

Jefferson Lab
Thomas Jefferson National Accelerator Facility



Joseph v. Fraunhofer, 1814



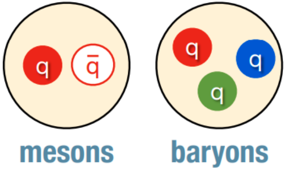
- Spectroscopy: study of the interaction between matter and electromagnetic radiation
- Precision measurements of the hydrogen atom spectrum ultimately lead to the development of QED
- Lasting impact on astro- and nuclear physics, solid state physics

The Strong Interaction

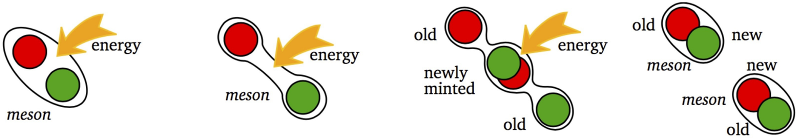
Quantum ChromoDynamics (QCD)

- Confinement: only color-neutral objects can be observed
- Baryons and mesons as the relevant degrees of freedom

Pion (π)
Eta (η)



Proton
Neutron

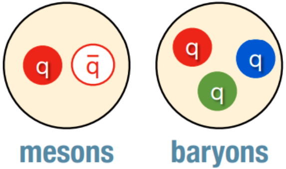


The Strong Interaction

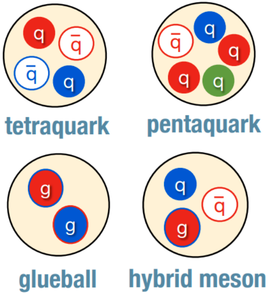
Quantum ChromoDynamics (QCD)

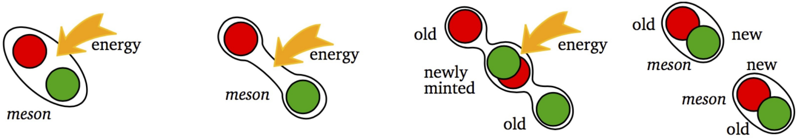
- Confinement: only color-neutral objects can be observed
- Baryons and mesons as the relevant degrees of freedom
- Exotic configurations permitted by QCD and predicted by many models

Pion (π)
Eta (η)



Proton
Neutron

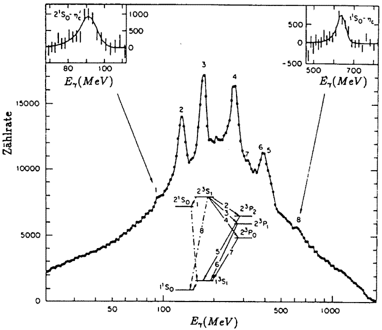


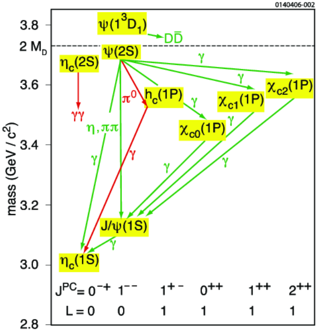


Exotic Hadrons

Quantum ChromoDynamics (QCD)

- Confinement: only color-neutral objects can be observed
- Baryons and mesons as the relevant degrees of freedom
- Exotic configurations permitted by QCD and predicted by many models

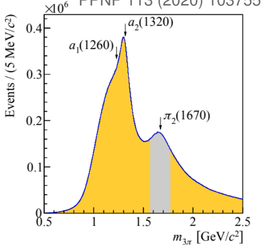




Spectroscopic Notation J^{PC}

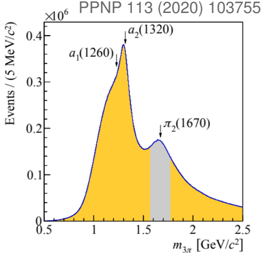
J:	Angular momentum
P:	Parity
C:	Charge conjugation

PPNP 113 (2020) 103755



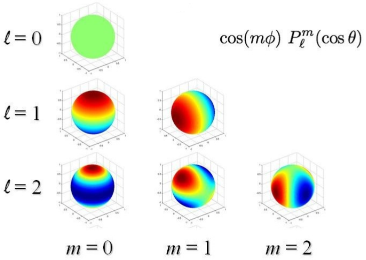
Meson Spectroscopy

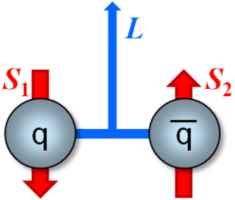
- Study of $q\bar{q}$ system: equivalent to the hydrogen atom
- Many broad and overlapping states in mass spectrum



Meson Spectroscopy

- Study of $q\bar{q}$ system: equivalent to the hydrogen atom
- Many broad and overlapping states in mass spectrum
- Characterize states by quantum numbers
- Disentangle states with angular distribution of decay

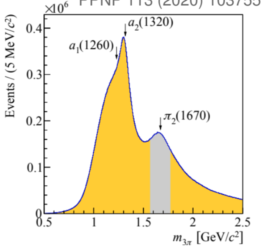


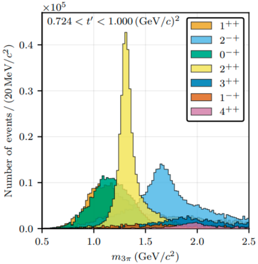


- Total angular momentum J: $\vec{J} = \vec{L} + \vec{S}$
- Parity P: $P = (-1)^{L+1}$
- Charge conjugation C: $C = (-1)^{L+S}$

Allowed J^{PC} for $q\bar{q}$ mesons: $\mathbf{0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 2^{++}, \ldots}$

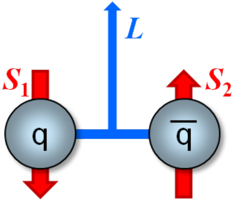
PPNP 113 (2020) 103755





Meson Spectroscopy

- Study of $q\bar{q}$ system: equivalent to the hydrogen atom
- Many broad and overlapping states in mass spectrum
- Characterize states by quantum numbers
- Disentangle states with angular distribution of decay
- Use interference to look for small signals



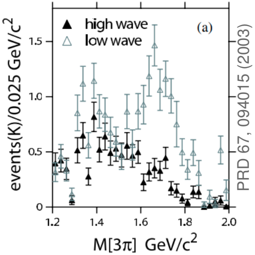
- Total angular momentum J: $\vec{J} = \vec{L} + \vec{S}$
- Parity P: $P = (-1)^{L+1}$
- Charge conjugation C: $C = (-1)^{L+S}$

Allowed J^{PC} for $q\bar{q}$ mesons: $\mathbf{0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 2^{++}, \ldots}$

Evidence for Exotic States

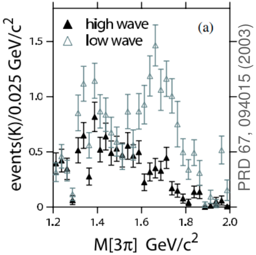
Experimental Status

- Forbidden J^{PC} for $q\bar{q}$ mesons: $\mathbf{0^{+-}, 1^{-+}, 2^{+-}, \ldots}$
- Smoking gun for states beyond the quark-antiquark model
- Lowest mass state $\pi_1(1600)$: $J^{PC} = 1^{-+}$
-



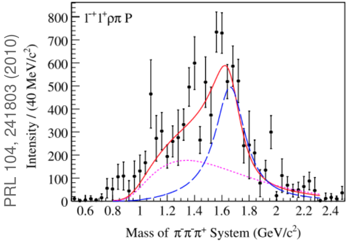
Evidence for Exotic States

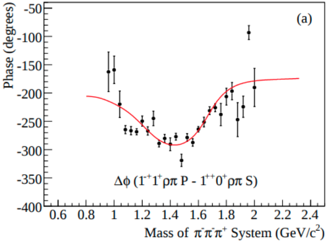
Jefferson Lab
Thomas Jefferson National Accelerator Facility

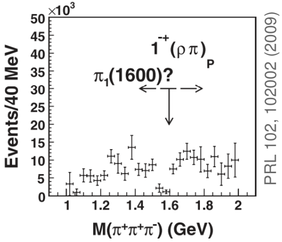


Experimental Status

- Forbidden J^{PC} for $q\bar{q}$ mesons: $\mathbf{0^{+-}, 1^{-+}, 2^{+-}, \ldots}$
- Smoking gun for states beyond the quark-antiquark model
- Lowest mass state $\pi_1(1600)$: $J^{PC} = 1^{-+}$
- Existence and interpretation debated for a long time



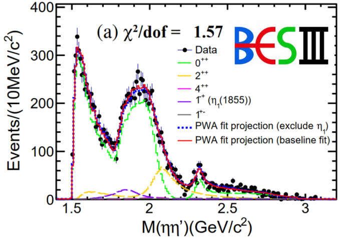




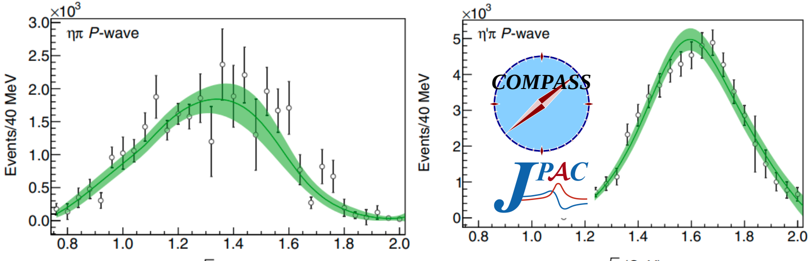
Evidence for Exotic States

Experimental Status

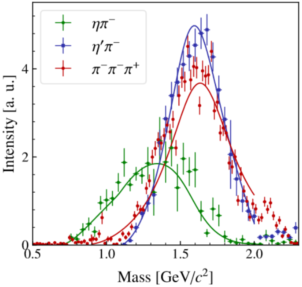
- Forbidden J^{PC} for $q\bar{q}$ mesons: $\mathbf{0^{+-}, 1^{-+}, 2^{+-}, \ldots}$
- Smoking gun for states beyond the quark-antiquark model
- Lowest mass state $\pi_1(1600)$: $J^{PC} = 1^{-+}$
- Significant progress in recent years, isospin-partner η_1**(1855)?**

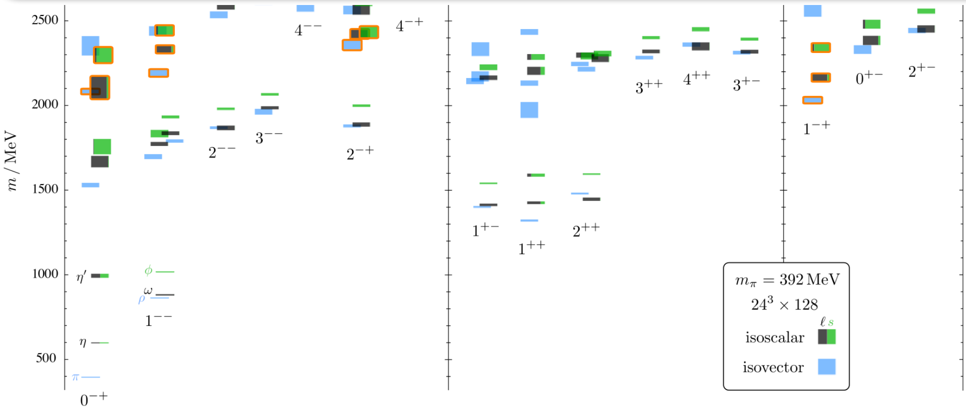


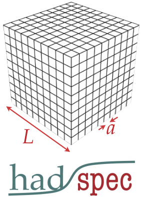
PRL 129, 192002 (2022)



PRL 122, 042002 (2019)







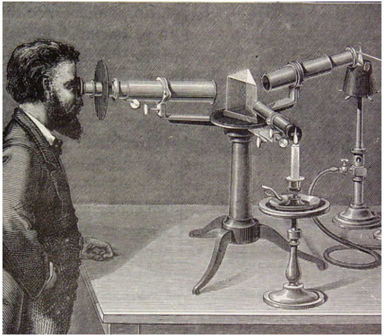
PRD 88, 094505 (2013)

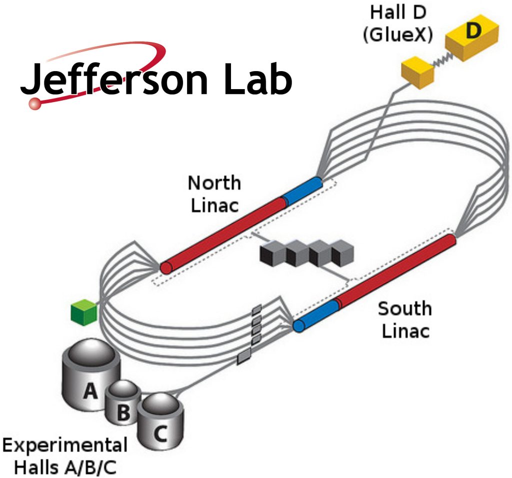
- Excited spectrum of states with identified spin, including exotic quantum numbers
- Tremendous progress in recent years: resonance parameters and decay modes
- Experimental results need to reach equivalent precision

The GlueX Experiment

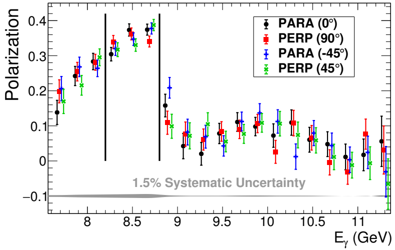
GLUEX

Gluonic Excitation Experiment

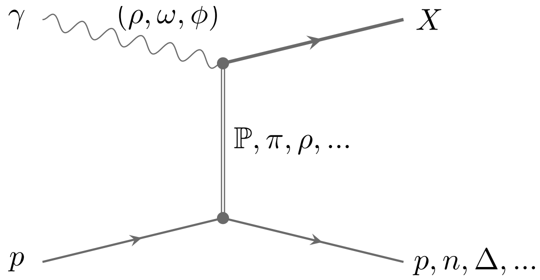




- 12 GeV electron beam from CEBAF accelerator
- Coherent Bremsstrahlung on diamond radiator
- Linear polarization peak $P_\gamma \sim 40\%$
- Photon energy tagged by scattered electrons
- Beam intensity: $1 - 5 \cdot 10^7\ \gamma/\text{s}$ in peak



Photoproduction



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^{-+}

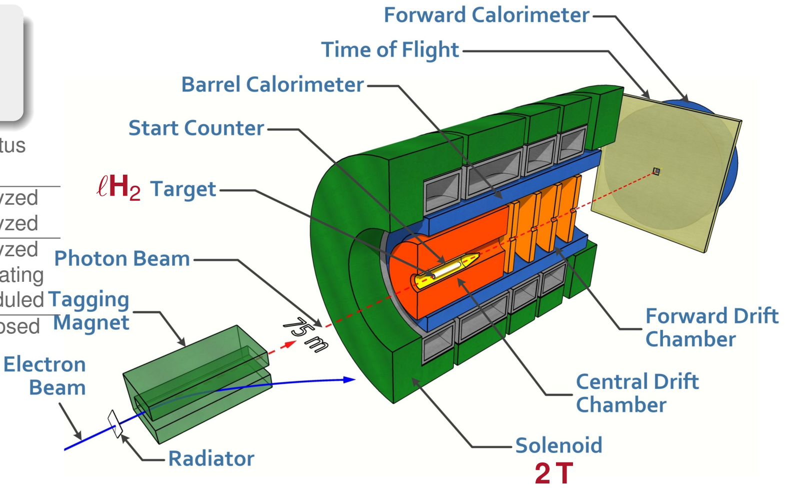
Complementary Production Mechanism

- Wide **variety of states** in spectrum accessible
- Photon polarization provides **constraints** on produced systems
- Understanding of **production mechanism** is prerequisite for interpretation
- Very limited photoproduction data existing at these energies

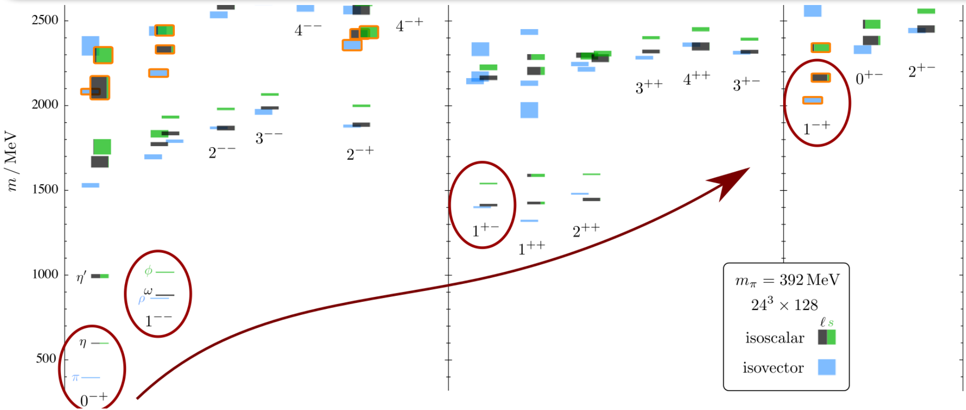
GlueX Detector

Light quark meson spectroscopy with **nearly complete coverage** for charged and neutral final states

Year	Phase	$\int \mathcal{L}$ (pb^{-1})	Status
2017	1	22	analyzed
2018	1	103	analyzed
2020	2	132	analyzed
2023	2	≈ 65	calibrating
2025	2	≈ 200	scheduled
?	3	800	proposed



The Path to Exotic Hadrons



ExoHad — Exotic Hadrons Topical Collaboration

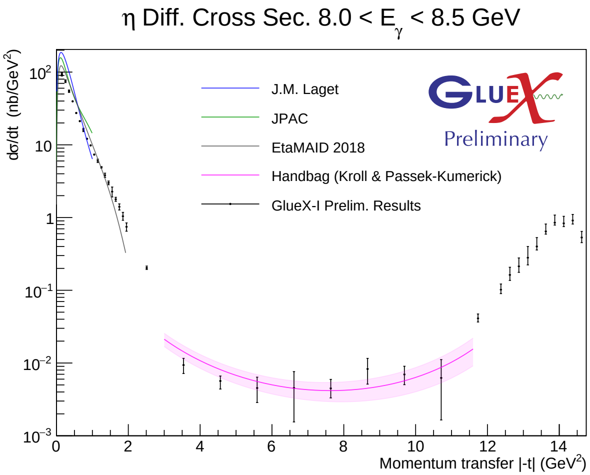
JPAC

hadspec

and many more...

Close Collaboration between GlueX Experiment and Theory / Phenomenology

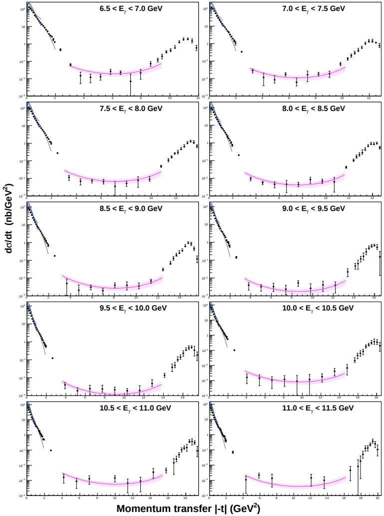
- Detailed study of photoproduction mechanism with polarization, robust theoretical models
- Develop capable analysis frameworks, evaluate with known states in the spectrum



$\gamma p \to \eta p$

- t-channel dominant, but coverage of entire kinematic regime
- Regge models at low $|t|$, Handbag for intermediate $|t|$

Cross Section Measurements



GlueX Preliminary

$\gamma p \to \eta p$

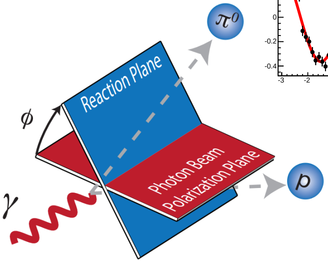
- t-channel dominant, but coverage of entire kinematic regime
- Regge models at low $|t|$, Handbag for intermediate $|t|$
- Energy coverage: $3 - 12\,\mathrm{GeV}$ Overlap with previous measurements

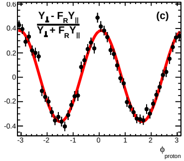
Many other channels

- Precise measurement for many different final states ongoing
- Consistency between decay modes limits systematic uncertainties

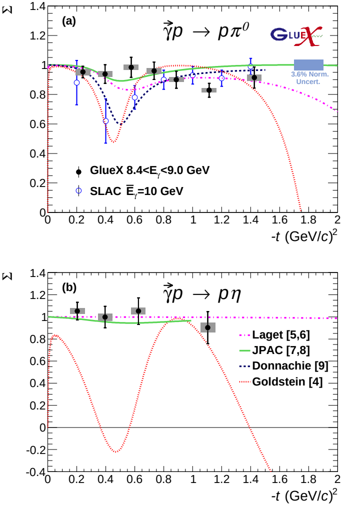
Polarization Transfer

First GlueX Publication: PRC 95, 042201 (2017)





$$\sigma_{\text{pol}}(\phi) = \sigma_{\text{unpol}}\left[1 - P_\gamma \Sigma \cos 2\phi\right]$$

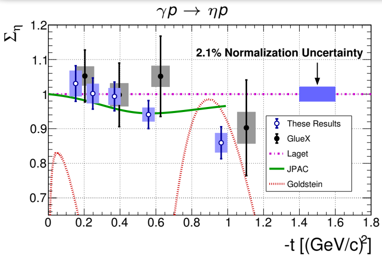


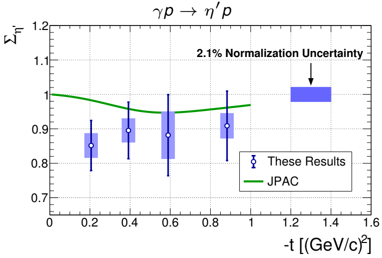
π^0 and η from 2016 Commissioning Data

- Modeling production mechanism: Σ sensitive to exchanged J^{PC}
- Cancel systematic effects by rotating polarization plane by 90°
- First measurement for η in this energy

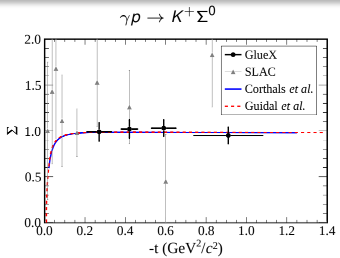
Pseudoscalar Meson Photoproduction

Jefferson Lab
Thomas Jefferson National Accelerator Facility

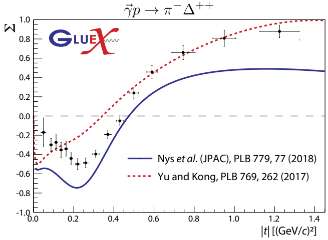




PRC 100, 052201 (2019)



PRC 101, 065206 (2020)



PRC 103, 02201 (2021)

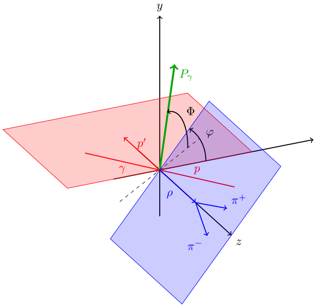
Beam Asymmetry Measurements

- η: significantly higher precision
- η': first measurement in this energy
- K^+: no visible t-dependence
- π^-: unnatural exchange important at small $-t$

Photoproduction

- Neutral exchange: **natural parity exchange** dominates
- Charge exchange: unnatural parity exchange for **small t**

- Full angular distribution of vector meson production and decay is described by **spin-density matrix elements ρ^k_{ij}**
- Linear beam polarization provides access to **nine** linearly independent SDMEs
- Intensity W is expressed as function of angles $\cos\vartheta, \varphi, \Phi$ and degree of polarization P_γ



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

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

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

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

Schilling *et al.* [Nucl. Phy. B, 15 (1970) 397]

Extraction of SDMEs
with Amplitude Analysis Technique

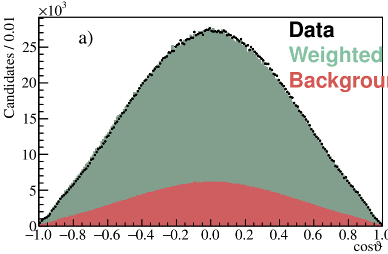
Extended Maximum-Likelihood Fit

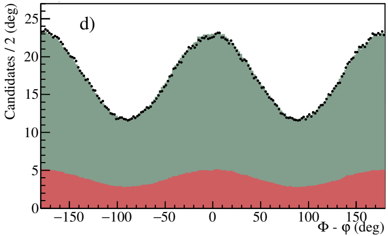
$$\ln L = \underbrace{\sum_{i=1}^{\text{events}} \ln \mathcal{I}(\tau_i)}_{\text{Experiment}} - \underbrace{\int d\Omega\, \mathcal{I}(\tau)\, \eta(\tau)}_{\text{Normalization Integral}}$$

- Choose SDMEs such that intensity fits the observed events
- Normalization integral evaluated by a phase-space Monte Carlo sample with the acceptance $\eta(\tau) = 0/1$

Analysis Strategy

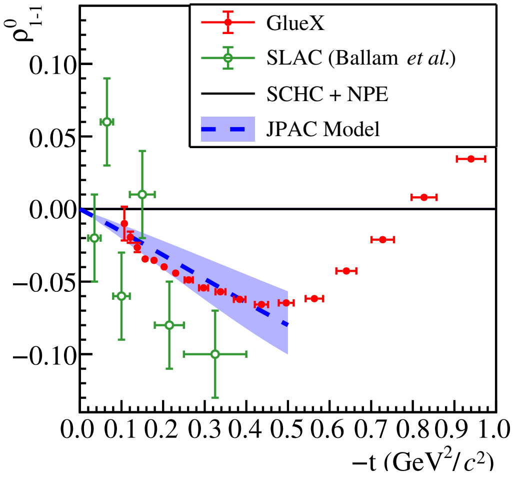
- Improve theoretical description of photoproduction process
- Understand and evaluate detector acceptance
- Prerequisites for amplitude analysis of possible exotic signals





$\rho(770)$ Meson SDMEs

PRC 108, 055204 (2023)



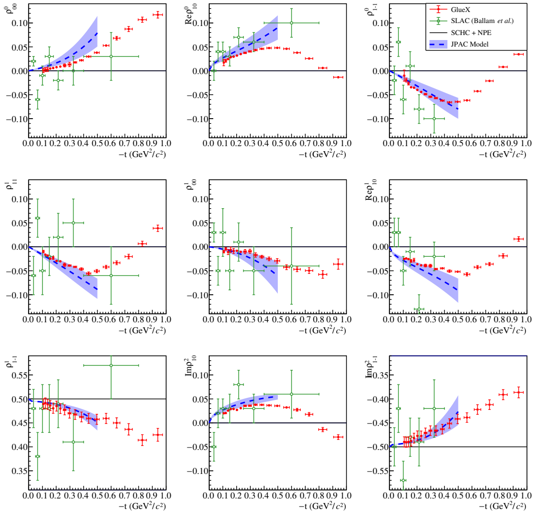
$\gamma p \to \rho(770) p$

- High precision with only fraction of data set
- Orders of magnitude more precise than previous measurements
- Uncertainties dominated by systematics
- Agree with Regge model up to $-t \approx 0.5\,\text{GeV}^2/c^2$ [JPAC, PRD 97 094003 (2018)]
- Studies of mass and energy dependence

$\rho(770)$ Meson SDMEs

PRC 108, 055204 (2023)

Jefferson Lab
Thomas Jefferson National Accelerator Facility

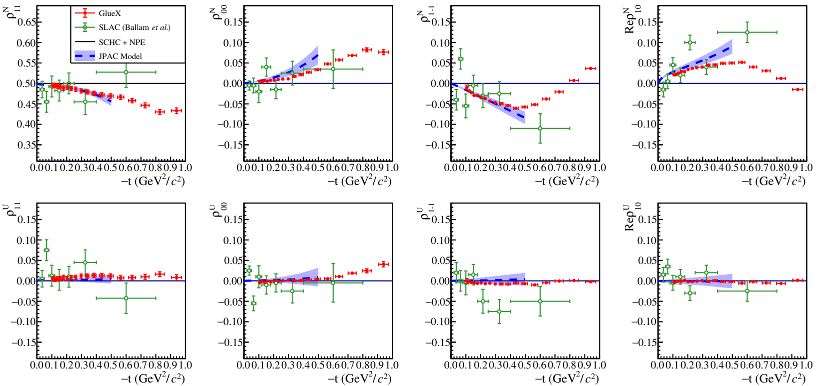


$\gamma p \to \rho(770)p$

- High precision with only fraction of data set
- Orders of magnitude more precise than previous measurements
- Uncertainties dominated by systematics
- Agree with Regge model up to $-t \approx 0.5\,\mathrm{GeV}^2/c^2$ [JPAC, PRD 97 094003 (2018)]
- Studies of mass and energy dependence

$\rho(770)$ Meson SDMEs

PRC 108, 055204 (2023)



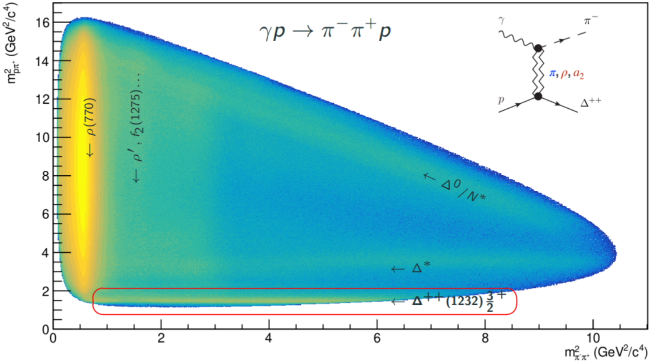
- Natural parity exchange dominates across t range
- Deviation from s-channel helicity conservation ($\mathbb{P}$) $\Rightarrow$ Contribution from f_2, a_2

Spin-Density Matrix Element Analysis for other Hadrons

- $\Lambda(1520)$ photoproduction [PRC 105, 035201 (2022)], analysis of $\omega(782)$, $\phi(1020)$ ongoing
- Improve theoretical description of photoproduction process and evaluate detector acceptance

Study of Charge Exchange Mechanism

Jefferson Lab
Thomas Jefferson National Accelerator Facility



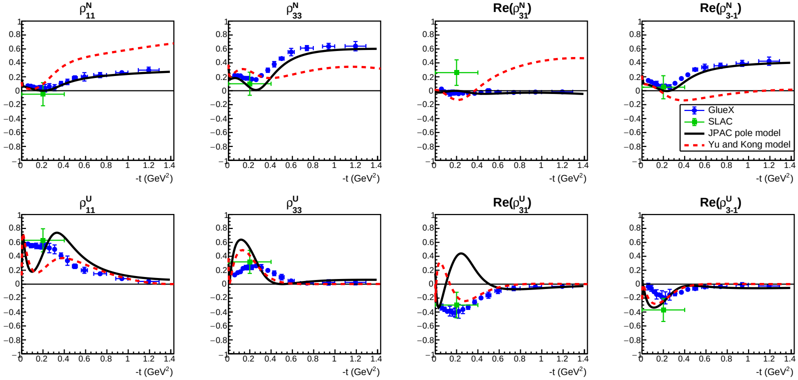
$\gamma p \to \pi^- \Delta^{++} \to \pi^- \pi^+ p$

- Only small overlap between $\rho(770)$ and $\Delta^{++}(1232)$ production in same final state
- Access to spin density matrix elements for $\Delta^{++}(1232)$ photoproduction
- High statistical precision

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

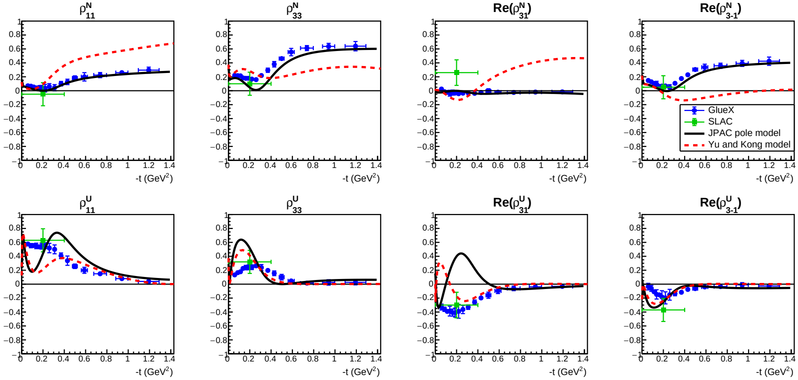
SDMEs in $\Delta^{++}(1232)$ Photoproduction

arXiv:2406.12829 (2024)

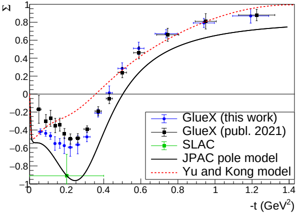


- Models under-constrained by previous measurements, do not describe unnatural parity exchange
- Sensitive to relative sign of exchange couplings

SDMEs in $\Delta^{++}(1232)$ Photoproduction
arXiv:2406.12829 (2024)



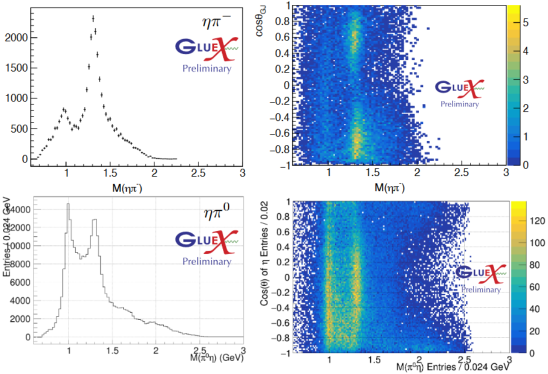
$$\Sigma = 2(\rho^1_{11} + \rho^1_{33})$$

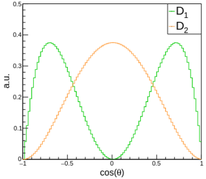


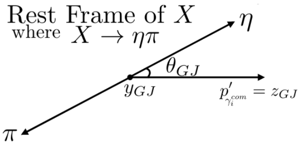
Systematic deviations in beam asymmetry Σ by Δ^{++} decay

- Models under-constrained by previous measurements, do not describe unnatural parity exchange
- Sensitive to relative sign of exchange couplings

- Strongest evidence for exotic $\pi_1(1600)$ from COMPASS in these channels
- Competitive statistical precision, but different production and multiple decay modes
- Collaboration with theory on development of amplitudes and models







- Clear signals for $a_0(980)$ and $a_2(1320)$
- Different angular distribution between charged (top) and neutral (bottom) final state
- Production mechanism populates states with different spin-projections

$\Rightarrow$ **Amplitude Analysis**

PWA with Beam Polarization

$$\mathcal{I}(\Omega,\Phi) = \mathcal{I}^0(\Omega) - P_\gamma \mathcal{I}^1(\Omega)\cos 2\Phi - P_\gamma \mathcal{I}^2(\Omega)\sin 2\Phi$$

- New amplitude formalism in reflectivity basis with $Z_\ell^m(\Omega,\Phi) = Y_\ell^m(\Omega)e^{-i\Phi}$: JPAC [PRD 100, 054017 (2019)]

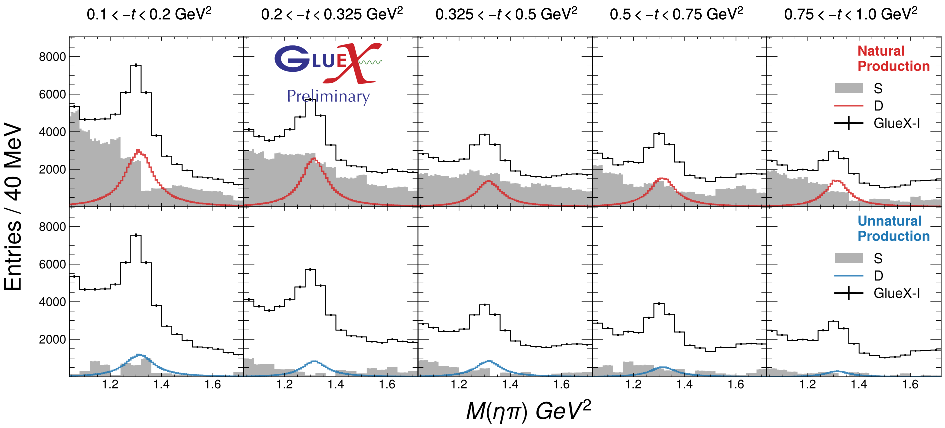
$$\mathcal{I}(\Omega,\Phi) \propto (1-P_\gamma)\left|\sum_{\ell,m}[\ell]_m^{(\varepsilon=-)}\mathrm{Re}Z_\ell^m(\Omega,\Phi)\right|^2 + (1-P_\gamma)\left|\sum_{\ell,m}[\ell]_m^{(\varepsilon=+)}\mathrm{Im}Z_\ell^m(\Omega,\Phi)\right|^2 +$$

$$+(1+P_\gamma)\left|\sum_{\ell,m}[\ell]_m^{(\varepsilon=+)}\mathrm{Re}Z_\ell^m(\Omega,\Phi)\right|^2 + (1+P_\gamma)\left|\sum_{\ell,m}[\ell]_m^{(\varepsilon=-)}\mathrm{Im}Z_\ell^m(\Omega,\Phi)\right|^2$$

- Reflectivity $\varepsilon = \pm$ corresponds to naturality of exchange
- Describes all two-pseudoscalar meson systems ($\pi\pi$, $K\bar{K}$, $\pi\eta$, etc.)

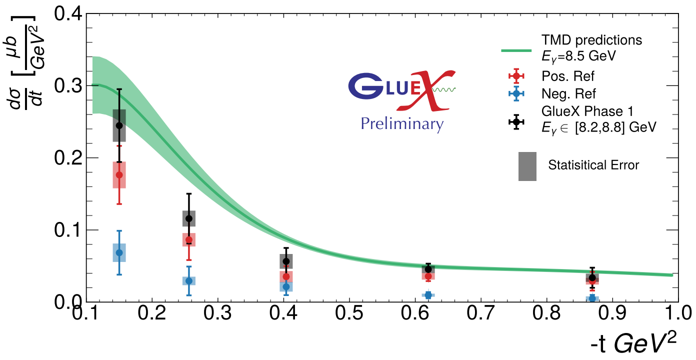
- Fully mass-independent analysis difficult due to complexity of wave set: $S_0^\pm$, $P_{-1,0,1}^\pm$, $D_{-2,-1,0,1,2}^\pm$, $\cdots$
- Require theory input to limit number of amplitudes or constrain mass dependence of known resonances

$a_2(1320)$ Cross Section



Semi-mass dependent method: impose Breit-Wigner shape for $a_2(1320)$

a_2(1320) Cross Section



Partial-Wave Analysis

- All possible S and D waves
- Shared phase between individual m projections

Prediction

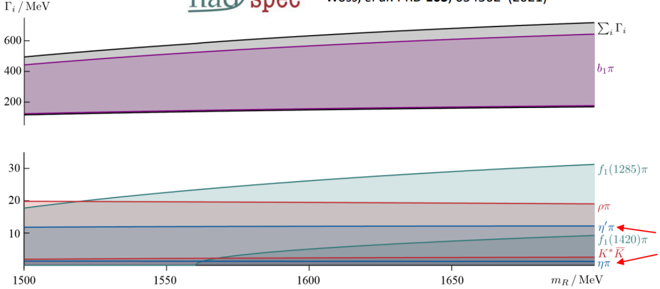
- Tensor Meson Dominance $S_0^{\pm}$, $D_{0,1}^{\pm}$, D_{-1}^{-}, D_2^{+}

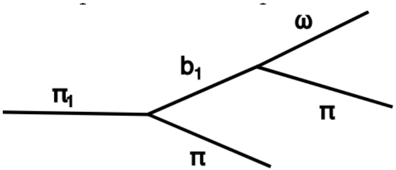
- Good agreement with theory prediction, demonstrate validity of method
- Separation of natural and unnatural parity exchange mechanisms, natural exchange dominant
- Reference for search for exotic $\pi_1(1600)$ in $\eta'\pi$

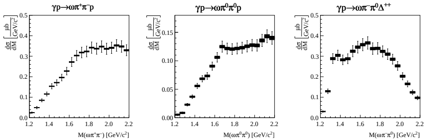
Projection for $\pi_1(1600) \to \eta^{(\prime)}\pi$

arXiv:2407.03316 (2024)

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







$\pi_1(1600)$ branching fractions from LQCD

Iso-vector ($I = 1$) $b_1\pi$ cross section

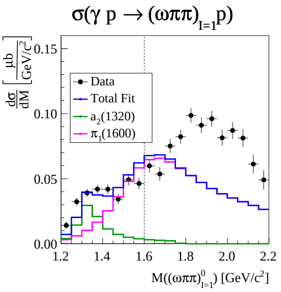
$\Rightarrow$ **First upper limit on the photoproduction cross section of the spin-exotic $\pi_1(1600)$**

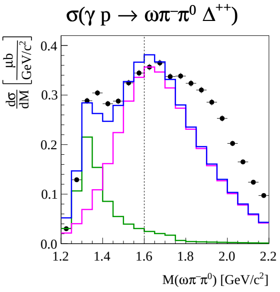
Projection for $\pi_1(1600) \to \eta^{(\prime)}\pi$

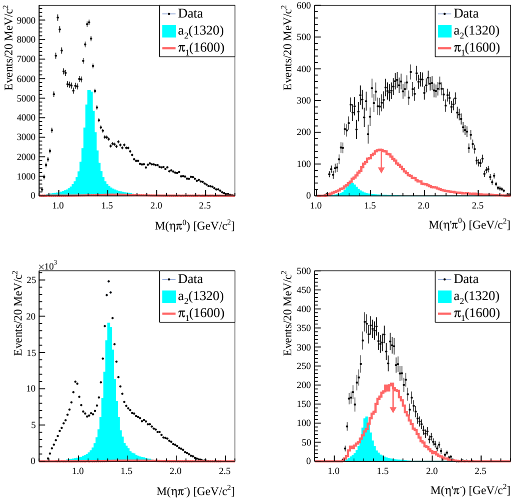
arXiv:2407.03316 (2024)

Jefferson Lab
Thomas Jefferson National Accelerator Facility

- Saturate measured $\omega\pi\pi$ cross section ($I = 1$) with $a_2(1320)$ and $\pi_1(1600)$ lineshapes





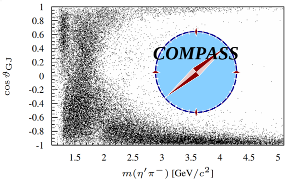


- Upper limit for photoproduction cross sections $\gamma p \to$ **π_1^0(1600)**p and $\gamma p \to$ **π_1^-(1600)**Δ^{++}
- Project this cross section into $\eta\pi$ and $\eta'\pi$
  $\Rightarrow$ Could **dominate $\eta'\pi^0$ and $\eta'\pi^-$ channels**

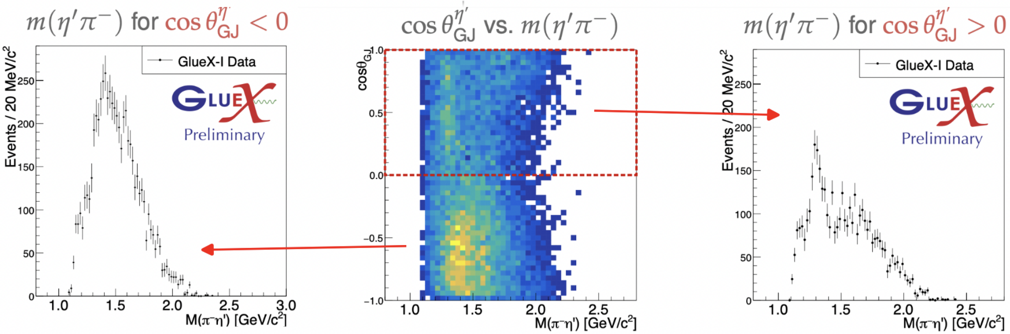
First look at $\gamma p \to \eta' \pi^- \Delta^{++}$

Invariant mass of $\eta' \pi^-$ vs $\cos\vartheta$

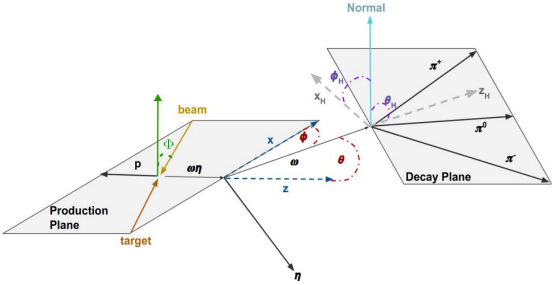
- Striking **forward/backward asymmetry**, similar to COMPASS observation
- Significant progress on PWA and moment analysis



PLB 740 (2015) 303



Vector-Pseudoscalar Meson Systems

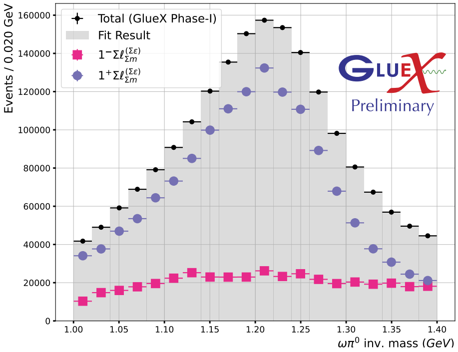


- Ω describes the decay of the resonance
- Ω_H describes the decay of the vector meson
- Φ indicates the orientation of the polarization plane
- All vector-pseudoscalar meson systems ($\omega\pi$, $\omega\eta$, $\phi\pi$, ...)

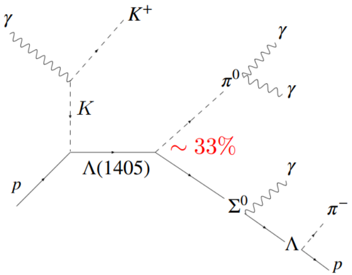
PWA of $\gamma p \to \omega\pi^0 p$

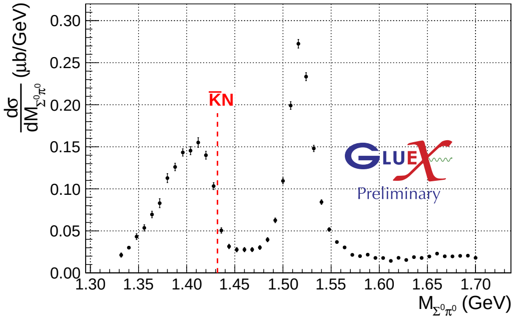
- High statistical precision
- Clear separation of b_1(1235) (1^+) and ρ(1450) (1^-)
- Production dominated by natural parity exchange

⇒ K. Scheuer (W&M), Session B



Study of $\Lambda(1405)$ Decay

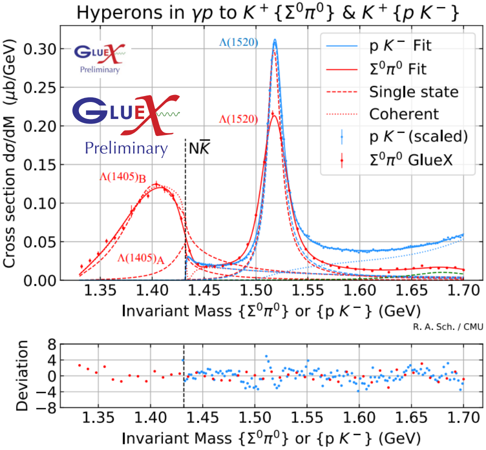




Differential Cross Section

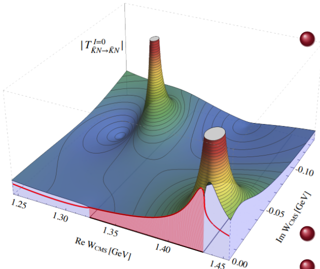
- Neutral $\Sigma^0\pi^0$ decay isolates isospin 0
- $\Lambda(1405)$ line shape deviates from pure Breit-Wigner form
- GlueX studies $\Lambda(1520)$ independently in $\gamma p \to K^+\Lambda(1502)$ [PRC 105, 035201 (2022)]

Study of Λ(1405) Decay



Two-Pole Hypothesis

- Simultaneous fit to both channels
- K-matrix parametrization for Λ(1405)
- Incoherent sum of Λ(1520) and background
- Fit favors two poles, currently working towards determination of pole positions



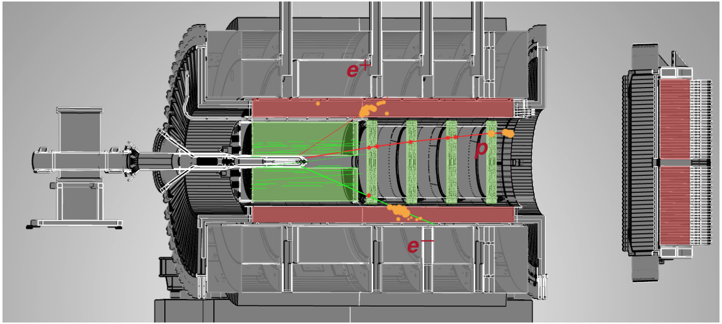
- Consistent with chiral unitary models (e.g. [EPJ A 51, 30 (2015)])
- Support from Lattice QCD
- PDG added Λ(1380) with **

J/ψ Photoproduction at Threshold

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

Threshold for J/ψ production: $E_\gamma = 8.22\,\text{GeV}$

$\gamma \to$



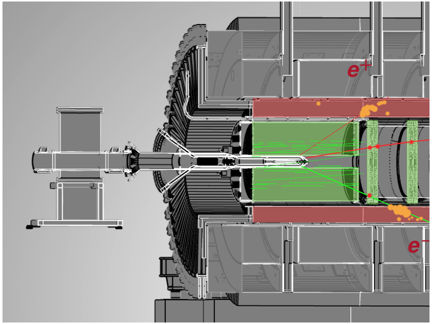
- Electron identification: E/p in calorimeters, pion background suppression by 10^{-4}
- Kinematic Fit with 0.1% precision on photon beam energy

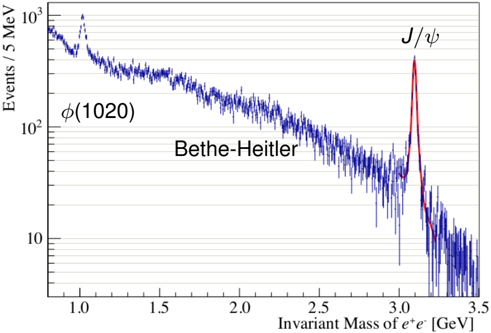
J/ψ Photoproduction at Threshold

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

Threshold for J/ψ production: $E_\gamma = 8.22\,\text{GeV}$

$\gamma \to$

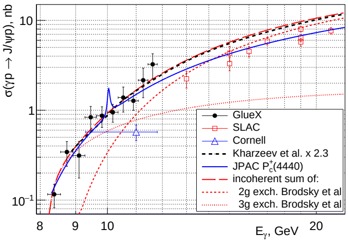




- Electron identification: E/p in calorimeters, pion background suppression by 10^{-4}
- Kinematic Fit with 0.1% precision on photon beam energy
- Cross section normalized by non-resonant e^+e^- production (Bethe-Heitler)

J/ψ Cross Section at Threshold

PRL 123, 072001 (2019)



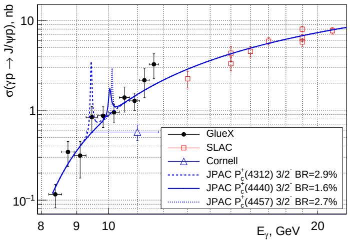
Energy dependence probes

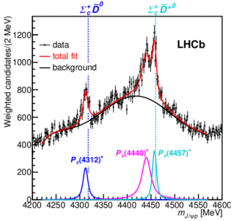
- Production dynamics
  Brodsky et al. [PRL 498 (2001)]
- Gluon distribution in proton
  Kharzeev et al. [NPA 661, 568 (1999)]

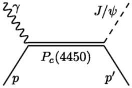
J/ψ Cross Section at Threshold

PRL 123, 072001 (2019)

Jefferson Lab
Thomas Jefferson National Accelerator Facility







LHCb, PRL 122, 222001 (2019)

JPAC, PRD 94, 034002 (2016)

Energy dependence probes

- Production dynamics
  Brodsky et al. [PRL 498 (2001)]
- Gluon distribution in proton
  Kharzeev et al. [NPA 661, 568 (1999)]

Search for Resonance in J/ψp

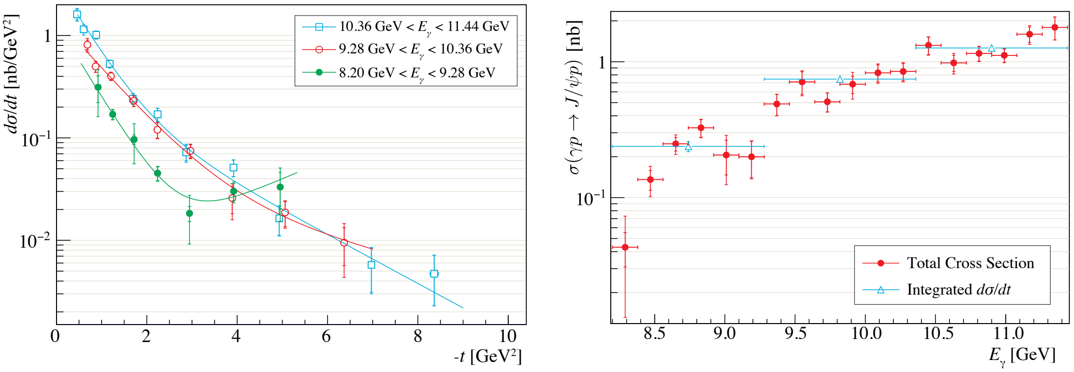
- No evidence for P_c^+ states
- Model-dependent upper limit for $J^{PC} = 3/2^-$

State	BR (90% CL)
$P_c^+(4312)3/2$-	$<$ 2.9%
$P_c^+(4440)3/2$-	$<$ 1.6%
$P_c^+(4457)3/2$-	$<$ 2.7%

- Disfavors hadrocharmonium and some molecular models

J/ψ Cross Section with GlueX-I Data

PRC 108, 025201 (2023)

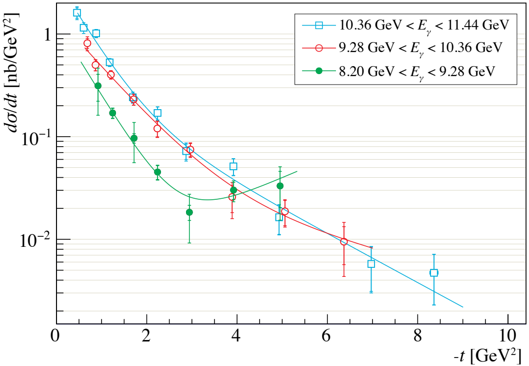


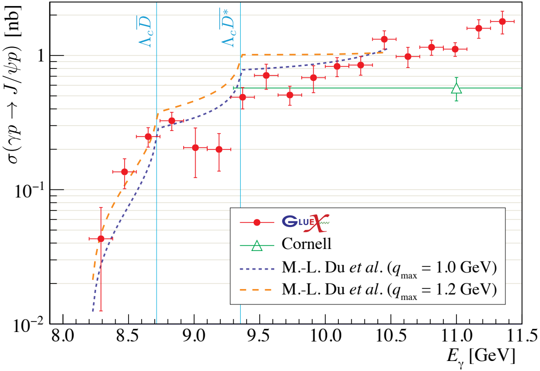
- 4 times more data, smaller systematic uncertainties, precise measurement of $d\sigma/dt$
- Results relevant for fundamental properties: proton mass, gravitational form factors, scattering length

J/ψ Cross Section with GlueX-I Data

PRC 108, 025201 (2023)

Jefferson Lab
Thomas Jefferson National Accelerator Facility



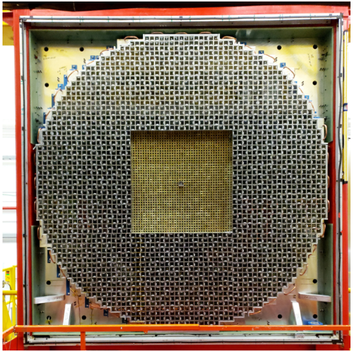


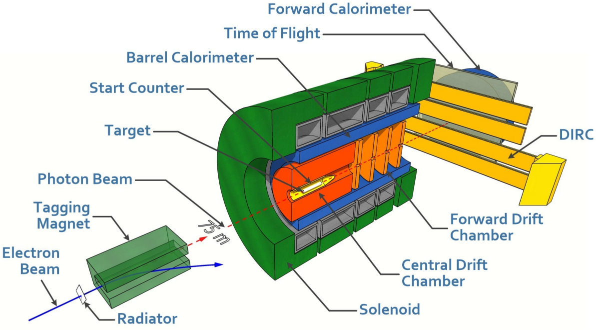
- 4 times more data, smaller systematic uncertainties, precise measurement of $d\sigma/dt$
- Results relevant for fundamental properties: proton mass, gravitational form factors, scattering length
- Possible evidence for contribution from open charm production

The Future of GlueX

Detector Upgrades

- DIRC: Extend kaon/pion separation (Fall 2019)
- FCal2: $PbWO_4$ insert with higher granularity
  Commissioned by the end of 2024



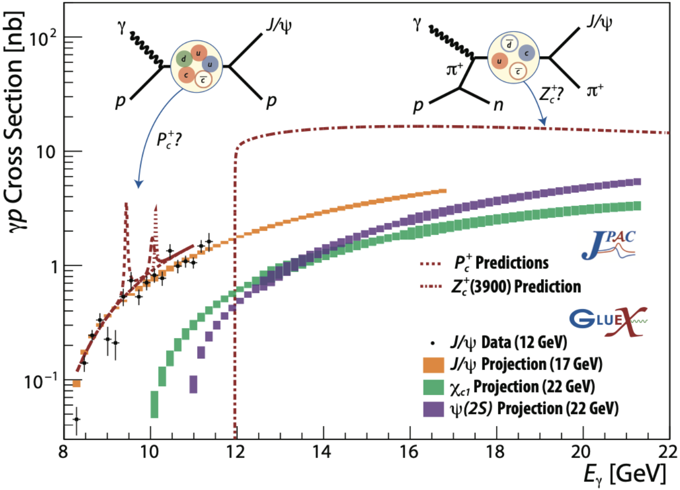


GlueX Phase II + JLab Eta Factory

- Started 2020, 2023, continue with FCal2 in 2025
- Emphasis on final states with strangeness
- Higher luminosity: rare processes

GlueX with CEBAF 22 GeV Upgrade

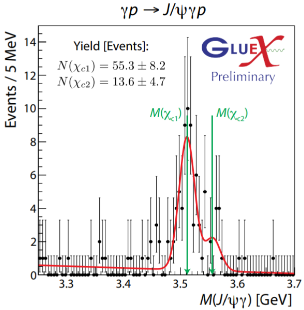
White Paper [arXiv:2306.09360]



Charmonium spectroscopy

- Exclusive photoproduction of J/ψ, χ_c and $\psi(2S)$
- Prediction for large cross section of $Z_c(3900)$ near threshold

JPAC, PRD 106, 094009 (2022)



Summary

Status of the GlueX Experiment

- Full data set for initial phase of GlueX **available** and under **active analysis**
- Several exciting **physics results**, many more to come
- GlueX Phase II in process: focus on meson spectrum with **strangeness** content

Summary

Status of the GlueX Experiment

- Full data set for initial phase of GlueX **available** and under **active analysis**
- Several exciting **physics results**, many more to come
- GlueX Phase II in process: focus on meson spectrum with **strangeness** content

Beyond GlueX

- Spectroscopy is active field of research with **global effort**
- Versatile GlueX detector used for **precision measurements** of QCD
- **Detector upgrades** for more science potential
- Development of **new programs**

Summary

Status of the GlueX Experiment

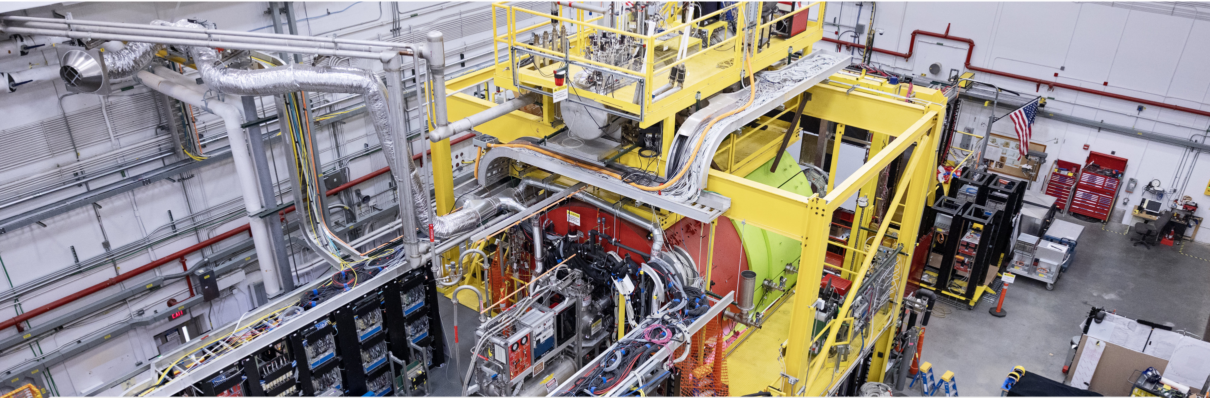
- Full data set for initial phase of GlueX **available** and under **active analysis**
- Several exciting **physics results**, many more to come
- GlueX Phase II in process: focus on meson spectrum with **strangeness** content

Beyond GlueX

- Spectroscopy is active field of research with **global effort**
- Versatile GlueX detector used for **precision measurements** of QCD
- **Detector upgrades** for more science potential
- Development of **new programs**

gluex.org/thanks

Dedicated GlueX Presentations



- Session B: Z. Baldwin: “Exploring Photoproduced $\eta^{(\prime)}\pi^0$ Systems in the Search for Exotic Hadrons at GlueX”
- Session C: I. Jaeglé: “The radiative decay width measurement of the η-meson at GlueX”
- Session B: K. Scheuer: “Amplitude Analysis of $\omega\pi^0$ Photoproduction at GlueX”

Backup

Step 1: Mass-Independent Partial-Wave Analysis (PWA)

- Partial wave $\psi_w(\tau)$: Complex-valued amplitude which describes angular distribution of decay products
- Constant in a narrow mass bin: model-independent
- Total intensity distribution $\mathcal{I}$ in each mass bin: coherent sum of amplitudes with production coefficients T_w

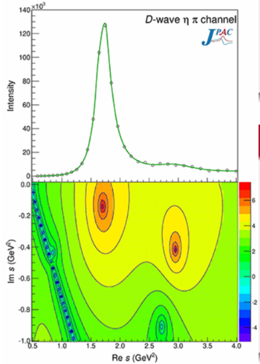
$$\mathcal{I}(\tau) = \left| \sum_{w}^{waves} T_w \, \psi_w(\tau) \right|^2$$

Amplitude Analysis

Step 1: Mass-Independent Partial-Wave Analysis (PWA)

- Partial wave $\psi_w(\tau)$: Complex-valued amplitude which describes angular distribution of decay products
- Constant in a narrow mass bin: model-independent
- Total intensity distribution $\mathcal{I}$ in each mass bin: coherent sum of amplitudes with production coefficients T_w

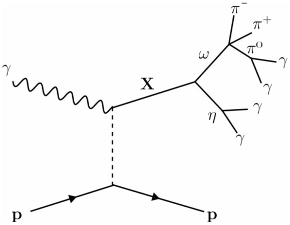
$$\mathcal{I}(\tau) = \left| \sum_{w}^{waves} T_w \, \psi_w(\tau) \right|^2$$

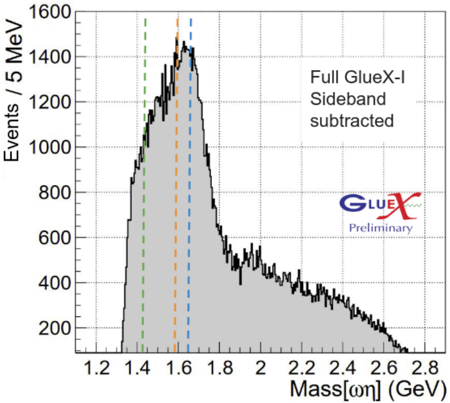


Step 2: Model for Mass Dependence for Results from Step 1

- Breit-Wigner function for narrow, isolated resonances
- Approximations for coupled channels: Flatté, K-matrix, ...
- Amplitudes for dynamical effects: triangle singularity, ...
- Treatment of background

Extraction of physical quantities: pole positions, coupling constants

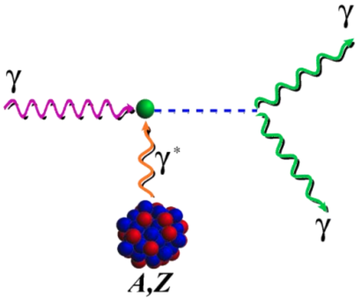


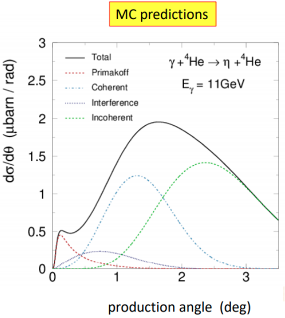


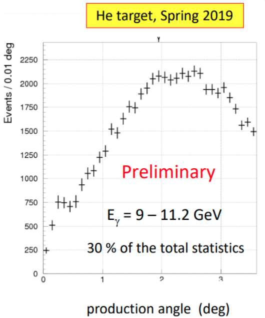
Accessible states:

- 1^{--}: $\omega(1650)$, $\omega(1420)$
- 1^{+-}: $h_1(1595)$ (needs confirmation)
- 0^{--} and 2^{+-}: exotic quantum numbers
- 2^{--}: never observed

Analysis of several Vector-Pseudoscalar Systems ongoing



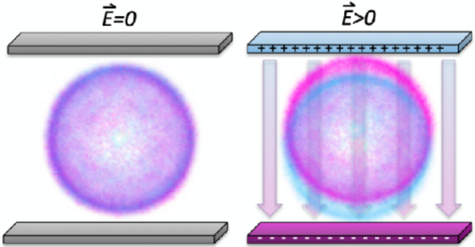




PrimEx-η: Precision measurement of η decay

- Primakoff production of η meson on nuclear target (Helium)
- Precise measurement of cross section at small production angles
- Experiment completed in three beam times 2019, 2021 and 2022
- Compton cross section measured simultaneously to verify systematic effects and monitor stability

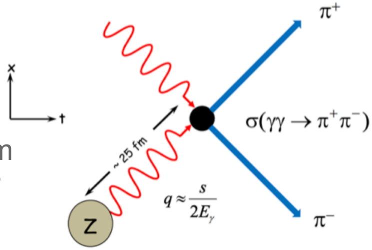
$\pi^{\pm}$ and π^{0} Polarizability



$$\vec{p} = -\alpha \vec{E}$$

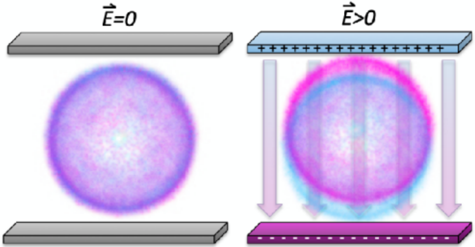
$$E \approx 10^{23}\mathrm{V/m}$$

$$\alpha \approx 10^{-4}\mathrm{fm}^3$$



Status and Projection for Sensitivity

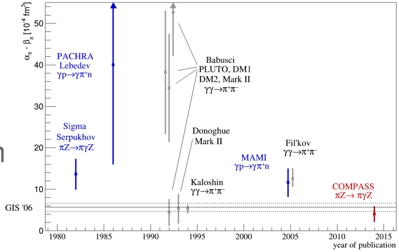
- Fundamental property of the strong interaction, precise predictions from χPT
- Primakoff production of $\pi^+\pi^-$ and $\pi^0\pi^0$ with 6 GeV polarized photon beam on Pb target
- New wire chambers behind forward calorimeter to detect muon background, data recorded in 2022



$$\vec{p} = -\alpha\vec{E}$$

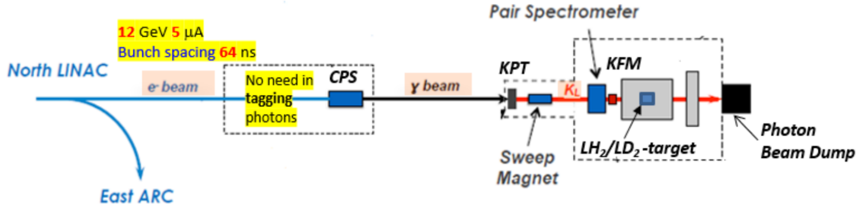
$$E \approx 10^{23}\,\mathrm{V/m}$$

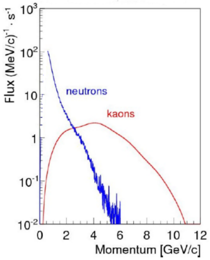
$$\alpha \approx 10^{-4}\,\mathrm{fm}^3$$



Status and Projection for Sensitivity

- Fundamental property of the strong interaction, precise predictions from χPT
- Primakoff production of $\pi^+\pi^-$ and $\pi^0\pi^0$ with 6 GeV polarized photon beam on Pb target
- New wire chambers behind forward calorimeter to detect muon background, data recorded in 2022
- Precision for $\pi^{\pm}$ estimated to be comparable with COMPASS, but different systematic effects
- Neutral pion polarizability has never been measured





Strange Hadron Spectroscopy with Secondary K_L Beam

- Use secondary photon beam to produce tertiary beam of neutral kaons
- GlueX detector with 4π acceptance for charged and neutral final states
- World-wide unique facility, planned to be ready after 2027
- Hyperon spectroscopy to identify missing baryon resonances, $K\pi$ scattering to study κ meson