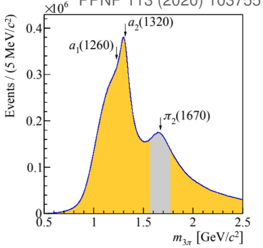
(Light) **Meson Spectroscopy with GlueX**
(and Beyond)

Alexander Austregesilo
for the GlueX Collaboration

20th International Conference on Hadron Spectroscopy and Structure
June 9th, 2023

Outline

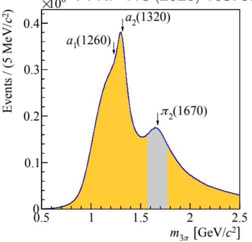
PPNP 113 (2020) 103755



Meson Spectroscopy

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

PPNP 113 (2020) 103755



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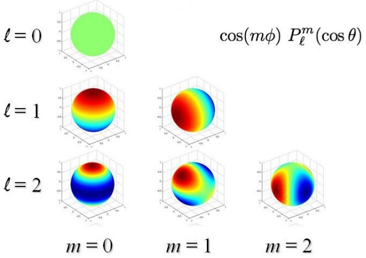
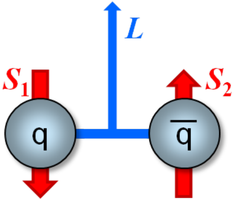
- Many broad and overlapping states in mass spectrum
- Characterize states by quantum numbers
- Disentangle states with angular distribution of decay



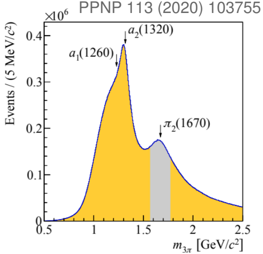


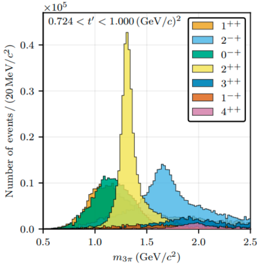
- Total angular momentum J: $\vec{J} = \vec{L} + \vec{S}$
- Parity P: $P = (-1)^{L+1}$
- Charge conjugation C: $C = (-1)^{L+S}$

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

Light Meson Spectroscopy

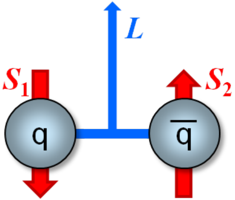
PPNP 113 (2020) 103755





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



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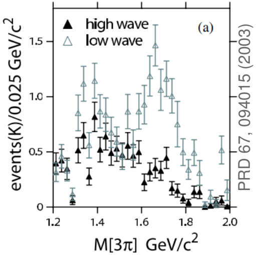
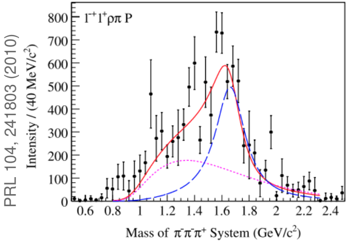
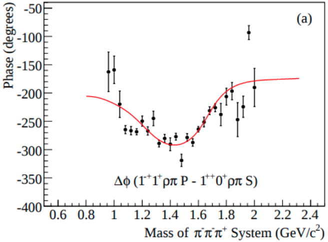
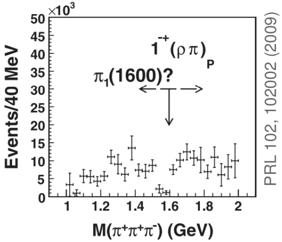
Evidence for Exotic States

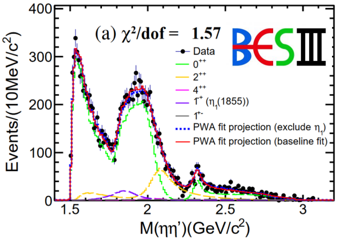
- Forbidden J^{PC} for $q\bar{q}$ mesons: $\mathbf{0^{+-}, 1^{-+}, 2^{+-}, \ldots}$
- Smoking gun for states beyond the quark-antiquark model
- Lowest mass state with $J^{PC} = 1^{-+}$: π_1
- Existence and interpretation still debated







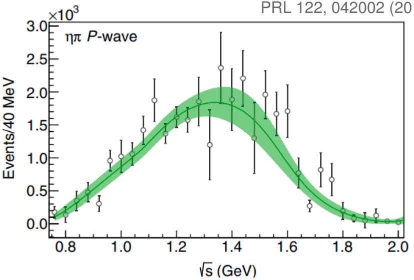


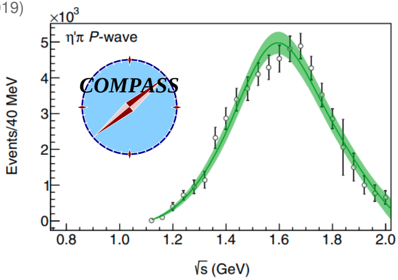


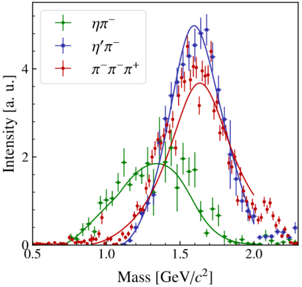
Evidence for Exotic States

- 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 with $J^{PC} = 1^{-+}$: π_1**(1600)**
- Significant progress in recent years, isospin-partner η_1**(1855)?**

PRL 122, 042002 (2019)

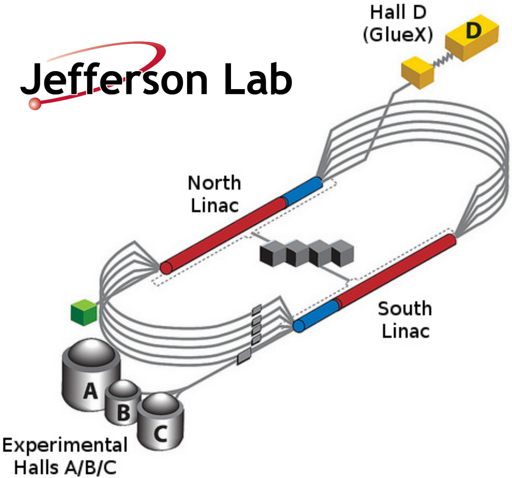




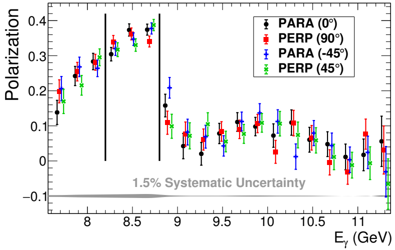


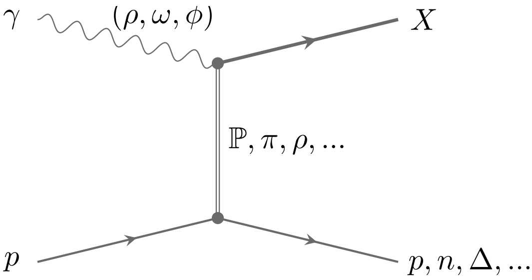
The GlueX Experiment

Gluonic Excitation Experiment



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





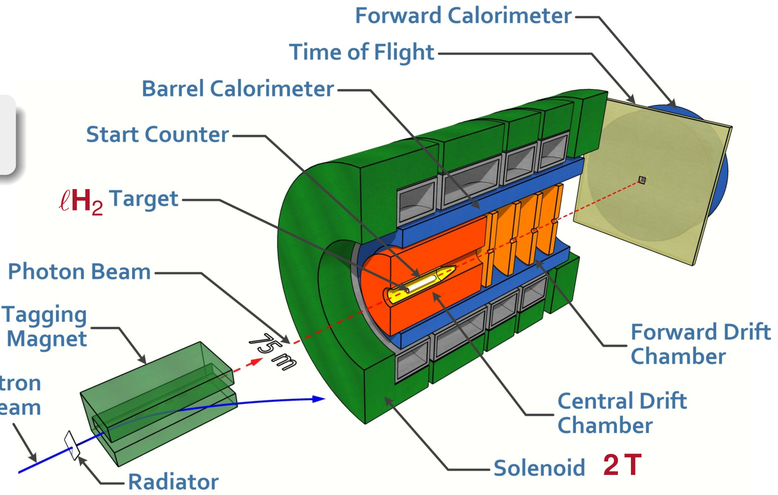
Exchange		Exotic Final States	
$\mathbb{P}$	0^{++}	b, h, h'	$2^{+-}, 0^{+-}$
π^0	0^{-+}	b_2, h_2, h'_2	2^{+-}
$\pi^\pm$	0^{-+}	$\pi_1^\pm$	1^{-+}
ω	1^{--}	π_1, η_1, η'_1	1^{-+}

Complementary Production Mechanism

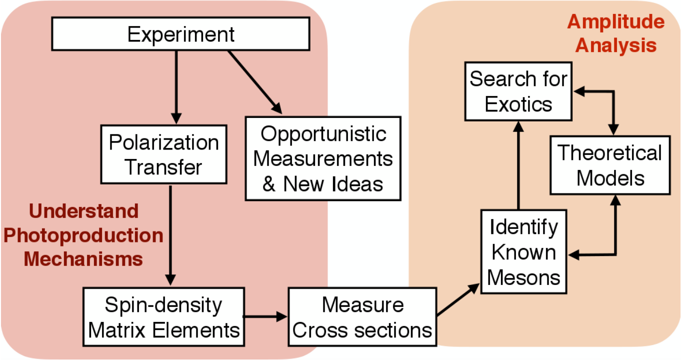
- Wide **variety of states** in spectrum accessible
- **Linear polarization** of photon provides constraints on produced system
- Understanding of **production mechanism** is prerequisite for interpretation
- Very limited photoproduction data existing at these energies

Light quark meson spectroscopy
with **nearly complete coverage**

Timeline	$\int \mathcal{L}$ (pb^{-1})	Status
2017	22	published
2018	103	analyzed
2020	132	analyzed
2023		calibrating
2024		scheduled
...		



Analysis Strategy

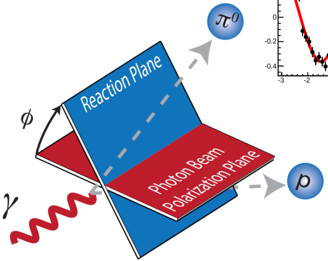


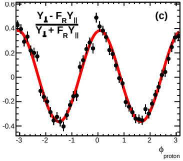
GlueX + Theory

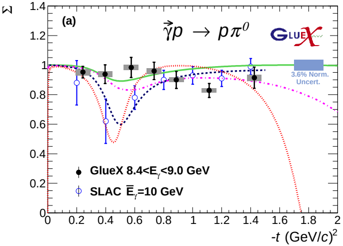
- High statistical precision requires robust theoretical models and capable analysis frameworks
- Collaboration: experiment and theory working together on analysis and interpretation

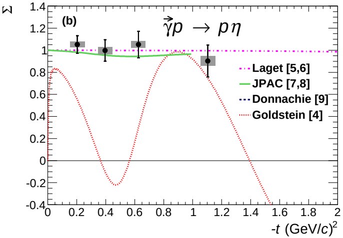
Polarization Transfer

First GlueX Publication: PRC 95, 042201 (2017)









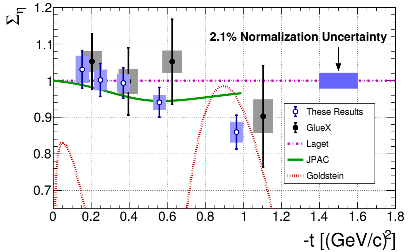
$$\sigma_{\text{pol}}(\phi) = \sigma_{\text{unpol}}\left[1 - P_\gamma \boldsymbol{\Sigma} \cos 2\phi\right]$$

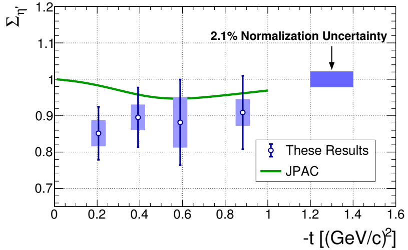
π^0 and η from 2016 Commissioning Data

- 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

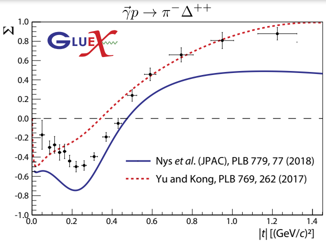
Pseudoscalar Meson Photoproduction

Jefferson Lab
Thomas Jefferson National Accelerator Facility

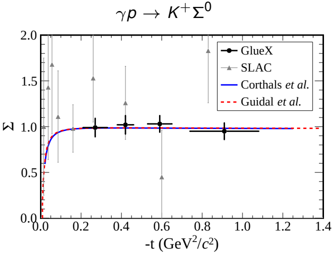




PRC 100, 052201 (2019)



PRC 103, 02201 (2021)



PRC 101, 065206 (2020)

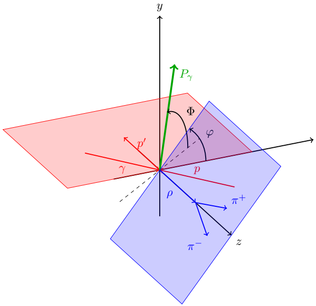
Beam Asymmetry Measurements

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

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]

t-dependence of SDMEs
arXiv:2305.09047 (2023)

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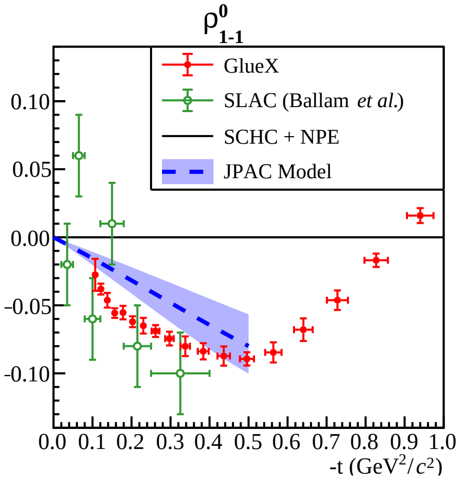

$\gamma p \to \rho(770)p$

- High precision with only fraction of data set
- Uncertainties dominated by systematics
- Agree with model up to $-t \approx 0.5\,\mathrm{GeV}^2/c^2$
  [PRD 97 094003 (2018)]

t-dependence of SDMEs

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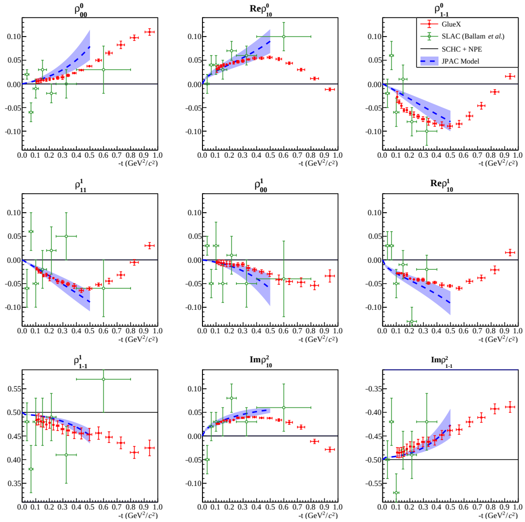

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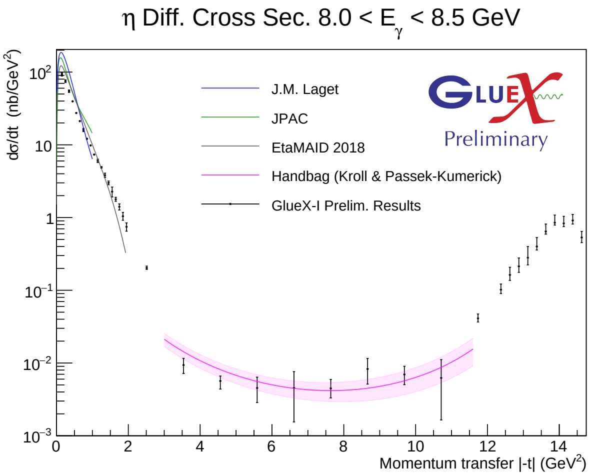
- Uncertainties dominated by systematics
- Agree with model up to $-t \approx 0.5\,\mathrm{GeV}^2/c^2$
  [PRD 97 094003 (2018)]
- Detailed studies of mass and energy dependence will follow

Other Channels...

- Analysis of $\omega(782)$, $\phi(1020)$ ongoing
- Natural-parity exchange generally dominates
- Improve theoretical description of photoproduction process
- Understand and evaluate detector acceptance

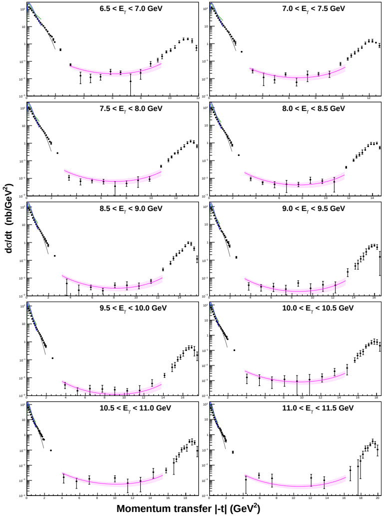
Cross Section Measurements



$\gamma p \to \eta p$

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

Cross Section Measurements



GlueX Preliminary

$\gamma p \to \eta p$

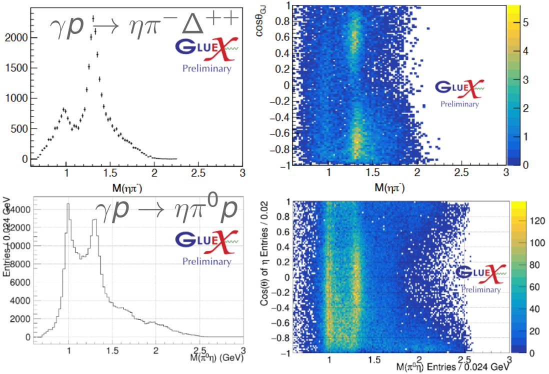
- t-channel dominant, but coverage of entire kinematic regime
- Regge models at low $|t|$, Handbag for intermediate $|t|$
- Energy coverage: $3 - 12\,\mathrm{GeV}$ Overlap with previous measurements

Other Channels...

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

The $\eta^{(\prime)}\pi$ Systems
$\rightarrow$ M. Albrecht [Tuesday, Exotic Hadrons]

- Strongest evidence for exotic $\pi_1(1600)$ from COMPASS in this channel
- 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

V. Mathieu (JPAC) [PRD 100 (2019) 054017]

Jefferson Lab
Thomas Jefferson National Accelerator Facility

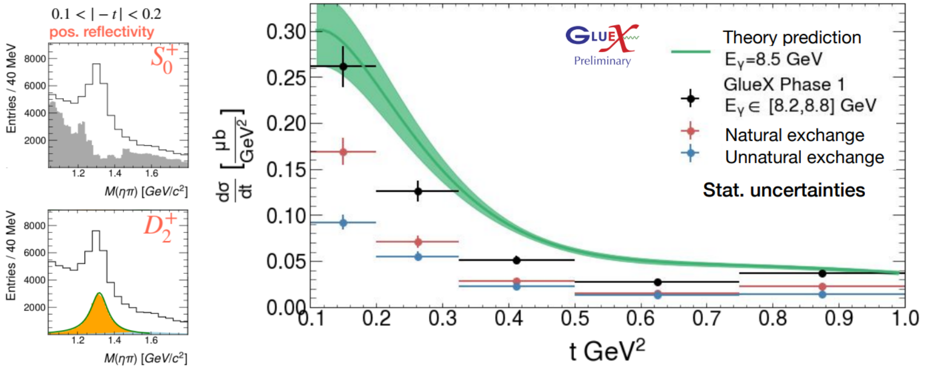
- New amplitude formalism with $Z_\ell^m(\Omega,\Phi) = Y_\ell^m(\Omega)e^{-i\Phi}$:

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

- Describes all two-pseudoscalar meson systems ($\pi\pi$, KK, $\pi\eta$, etc.), extension to vector-pseudoscalar systems $\to$ A. Schertz [this Session, 10:35am]

- Fully mass-independent analysis difficult due to complexity of wave set: $S_0^\pm$, $P^\pm_{-1,0,1}$, $D^\pm_{-2,-1,0,1,2}$, $\cdots$
- Require theory input to limit amplitudes (TMD model) or constrain mass dependence of known resonances

a_2(1320) Cross Section

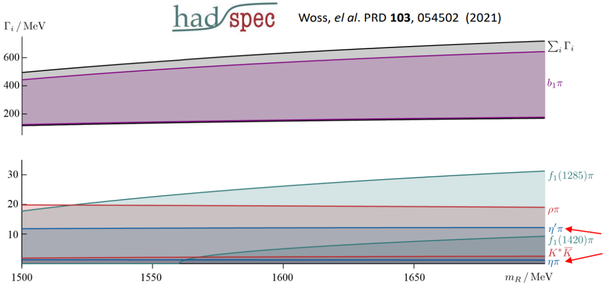


Semi-Massdependent Method: Impose Breit-Wigner Shape for a_2(1320)

- Good agreement with theory prediction, demonstrate validity of method
- Separation of natural and unnatural parity exchange mechanisms
- a_2(1320) signal as reference wave for exotic π_1(1600) in $\eta'\pi$

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

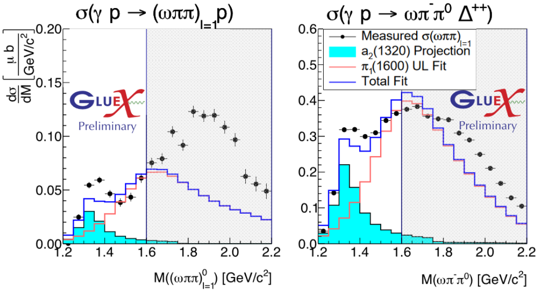
- Upper limits for $\pi_1(1600)$ branching fractions from LQCD

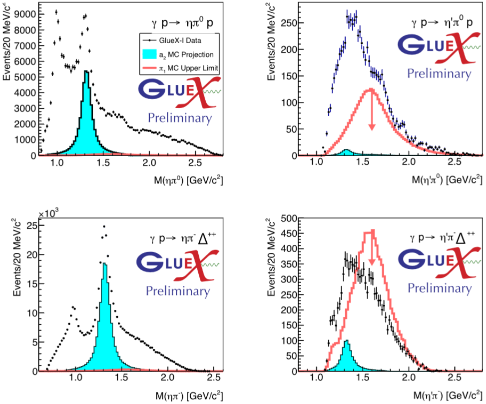


- Projections combine LQCD with measured $a_2(1320)$ and (iso-vector) $b_1\pi$ cross sections

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

- Upper limits for $\pi_1(1600)$ branching fractions from LQCD
- Saturate measured $\omega\pi\pi$ cross section ($I = 1$)



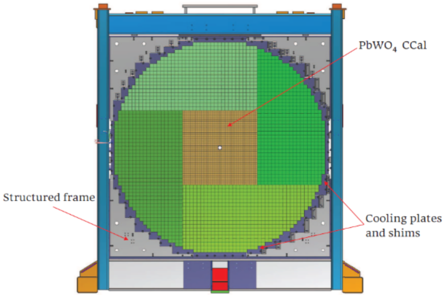


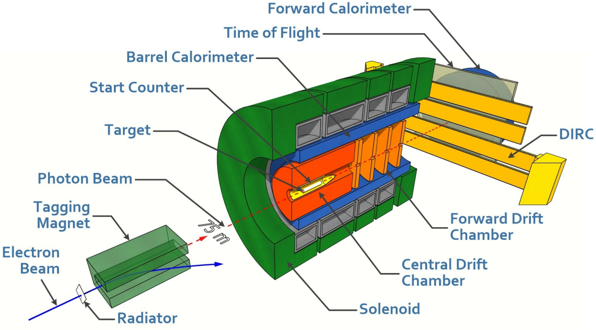
- Projections combine LQCD with measured $a_2(1320)$ and (iso-vector) $b_1\pi$ cross sections
- Expect small signal in $\eta\pi$, but signal could saturate $\eta'\pi$ channels $\to$ **enforced effort**

The Future of GlueX

Detector Upgrades

- DIRC: Extend kaon/pion separation,fully commissioned in Fall 2019
- FCal2: $PbWO_4$ insert with higher granularity, will be completed in 2024

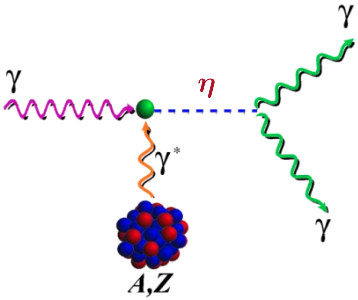




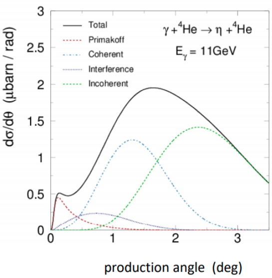
GlueX Phase II + JLab Eta Factory

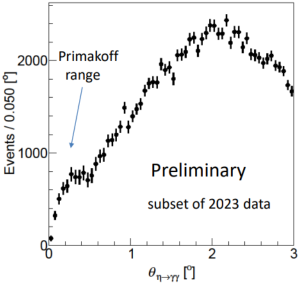
- Started 2020, 2023, continue with FCal2 in 2024
- Emphasis on final states with strangeness
- Higher luminosity: rare η decays

$\rightarrow$ S. Schadmand [Tuesday, New Facilities]



MC predictions

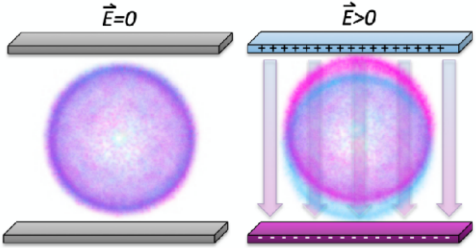




PrimEx-η: Precision measurement of η decay

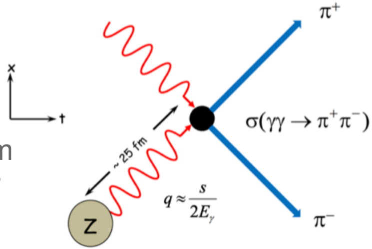
- Primakoff production of η meson on nuclear target (Helium)
- Precise measurement of $\eta \to \gamma\gamma$ decay width
- Determine fundamental properties: light quark mass ratio, $\eta - \eta'$ mixing angle
- Experiment completed in three beam times 2019, 2021 and 2022 $\to$ L. Gan [Thursday, BSM]

$\pi^{\pm}$ and π^{0} Polarizability



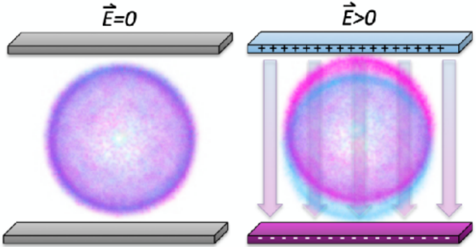
$$\vec{p} = -\alpha \vec{E}$$

$$E \approx 10^{23} \mathrm{V/m}$$
$$\alpha \approx 10^{-4} \mathrm{fm}^3$$



Status and Projection for Sensitivity

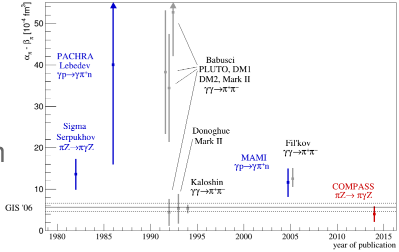
- Fundamental property of the strong interaction, precise predictions from χPT
- Primakoff production of $\pi^+\pi^-$ and $\pi^0\pi^0$ with 6 GeV polarized photon beam on Pb target
- New wire chambers behind forward calorimeter to detect muon background, data recorded in 2022



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

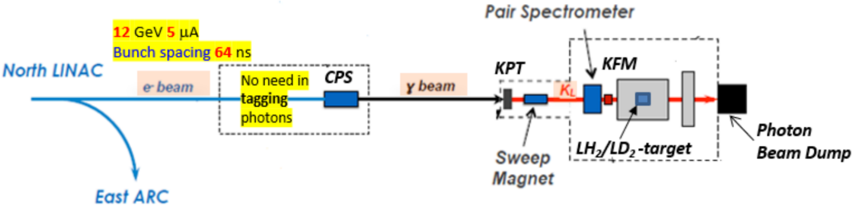
$$E \approx 10^{23}\text{V/m}$$

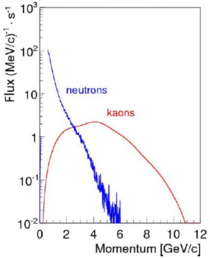
$$\alpha \approx 10^{-4}\text{fm}^3$$



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 complementary systematic effects
- Neutral pion polarizability has never been measured





Strange Hadron Spectroscopy with Secondary K_L Beam

- Use photon beam to produce beam of neutral Kaons, sweep away charged tracks
- World-wide unique facility combined with versatile GlueX detector, planned to be ready in 2026
- Hyperon spectroscopy to identify missing baryon resonances
- $K\pi$ scattering to study κ meson

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

Jefferson Lab
Thomas Jefferson National Accelerator Facility

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Beyond GlueX

- Light meson 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**:
  $\rightarrow$ P. Rossi "New opportunities with Jefferson Lab at 22 GeV" [Thursday, Plenary]

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

Dedicated GlueX Presentations

HADRON2023

- E. Chudakov
  "J/ψ photoproduction close to threshold at GlueX"
  Monday June 5, 3:12pm, 5H (Hadron decays, production and interaction)
- M. Albrecht
  "Search for Exotic Hadrons in $\eta()\pi$ at GlueX"
  Tuesday June 6, 4:30pm, 4H (Exotic hadrons and candidates)
- S. Schadmand
  "Precision tests of fundamental physics with light meson decays"
  Tuesday June 6, 5:40pm, 1B (New facilities)
- F. Nerling
  "Measurement of the photoproduction cross section for $\gamma p \to \phi\pi^+\pi^- p$ and search for the $Y(2175)$ at GlueX"
  Tuesday June 6, 5:00pm, 4H (Exotic hadrons and candidates)
- A. Schertz
  "Vector-Pseudoscalar Partial Wave Analysis at GlueX"
  Friday June 9, 10:35am, 5L (Light meson spectroscopy)

Backup

Step 1: Mass-Independent Partial-Wave Analysis

- 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

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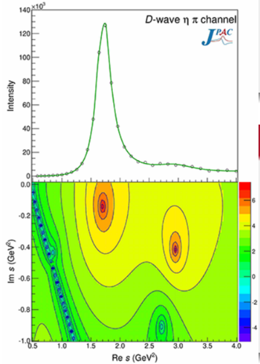
$$\mathcal{I}(\tau) = \left| \sum_{w}^{waves} T_w \, \psi_w(\tau) \right|^2$$

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

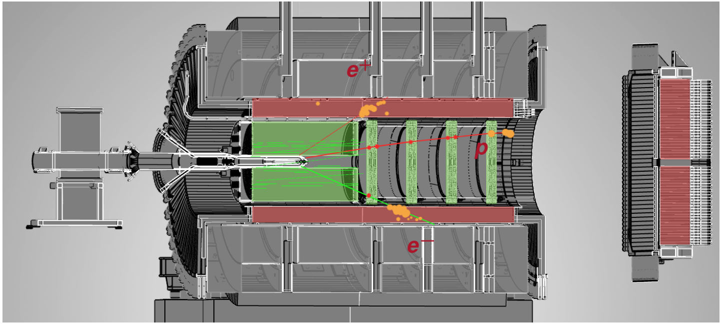


J/ψ Photoproduction at Threshold

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

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

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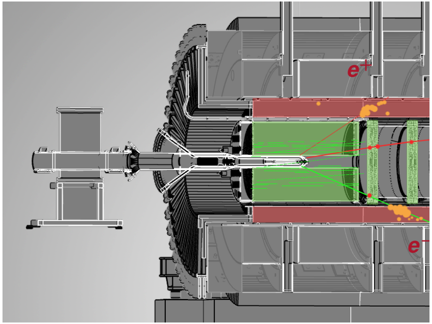
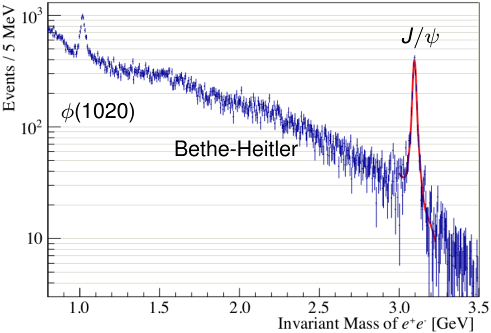
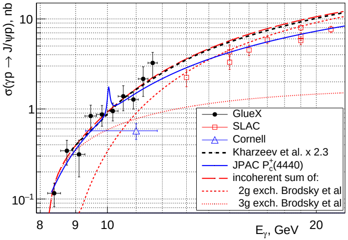




- Electron identification: E/p in calorimeters, pion background suppression by 10^{-4}
- Kinematic Fit with 0.1% precision on photon beam energy
- Cross section normalized by non-resonant e^+e^- production (Bethe-Heitler)

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
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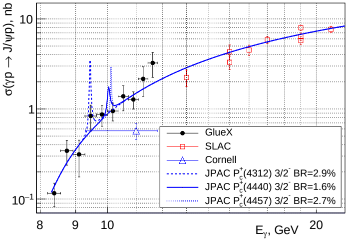

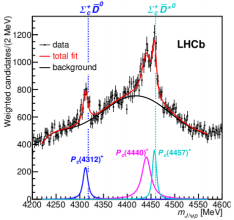

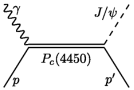

LHCb, PRL 122, 222001 (2019)

JPAC, PRD 94, 034002 (2016)

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Search for Resonance in J/ψp

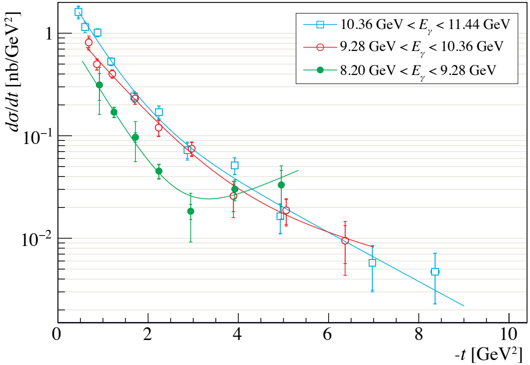
- No evidence for P_c^+ states
- Upper limit for $J^{PC} = 3/2^-$

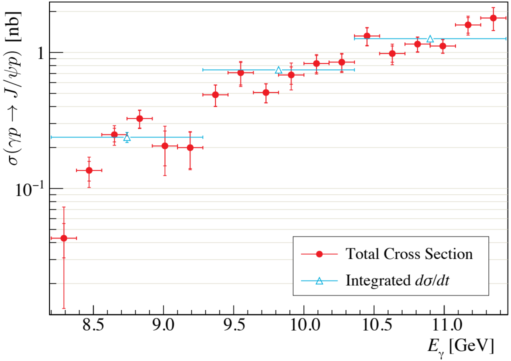
State	BR
P_c^+(4312)3/2-	$<$ 2.9%
P_c^+(4440)3/2-	$<$ 1.6%
P_c^+(4457)3/2-	$<$ 2.7%

- Disfavors hadrocharmonium and some molecular models

J/ψ Cross Section with GlueX-I Data

→ E. Chudakov [Monday], arXiv:2304.03845 (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

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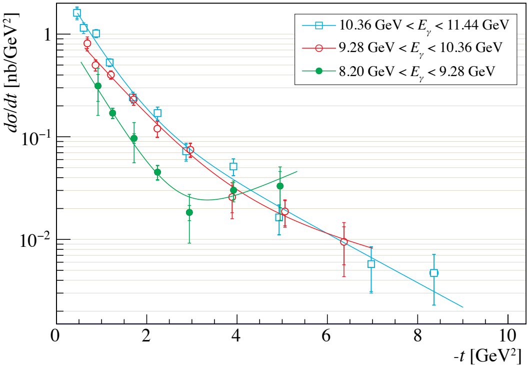

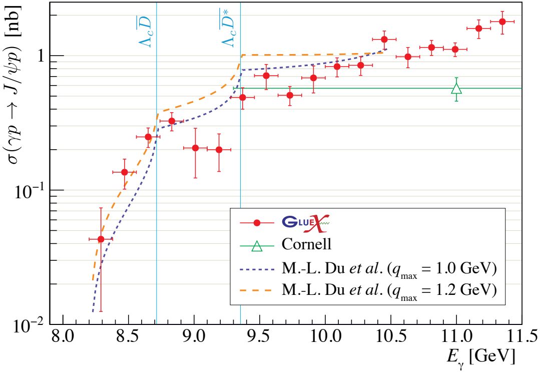

- 4 times more data, smaller systematic uncertainties, precise measurement of dσ/dt
- Results relevant for fundamental properties: proton mass, gravitational form factors, scattering length
- Possible evidence for contribution from open charm production