Extraction of Spin-Density Matrix Elements for Vector Mesons at GlueX

- Systematic Studies and Validation -

Alexander Austregesilo
for the GlueX Collaboration

EMMI Rapid Reaction Task Force (RRTF):
Impact of Vector Mesons on the Studies of the 3D Structure of the Nucleon
CERN, Switzerland
June 16th, 2026

Outline

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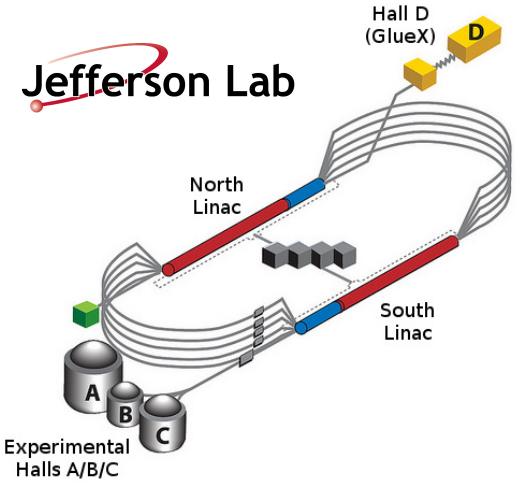
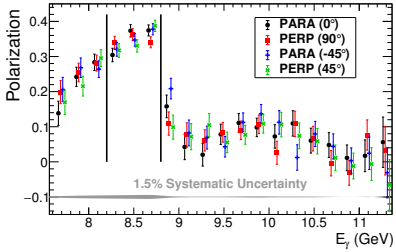


- 12 GeV electron beam from CEBAF accelerator
- Coherent Bremsstrahlung on diamond radiator
- Linear polarization peak $P_\gamma \sim 40\%$
- Photon energy tagged by scattered electrons
- Beam intensity: $1 - 5 \cdot 10^7\ \gamma/\mathrm{s}$ in peak



GlueX Detector

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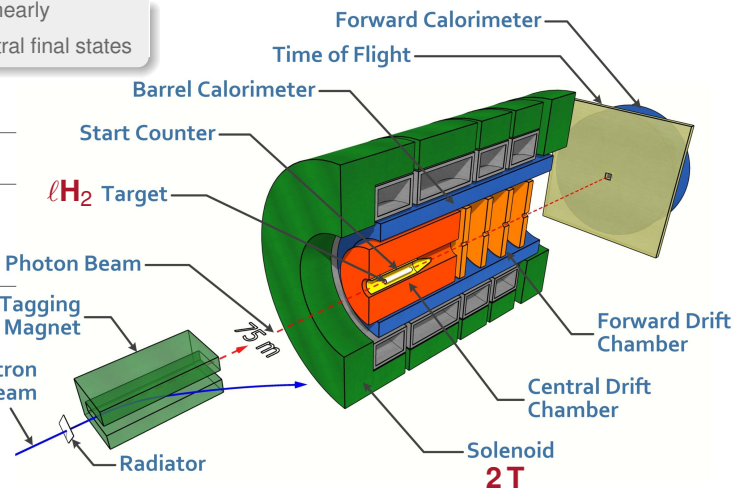
Light quark meson spectroscopy with nearly **complete coverage** for charged and neutral final states

Year	Phase	$\int \mathcal{L}$ (pb^{-1})	Status
2017	1	22	analyzed
2018	1	103	analyzed
2020	2	132	analyzed
2023	2	60	analyzed
2025	2	$\approx$ 130	calibrating
2026	2	$\approx$ 60	running
2027+	3	800	proposed



The Path to Exotic Hadrons

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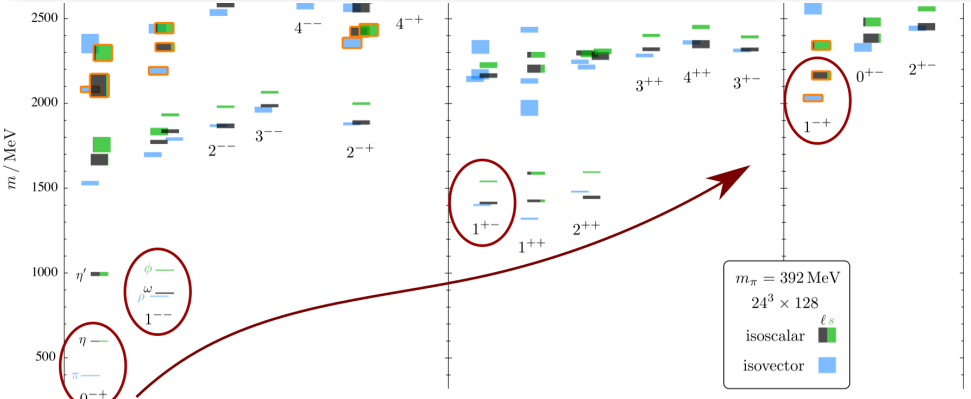


ExoHad
Exotic Hadrons Topical Collaboration

JPAC

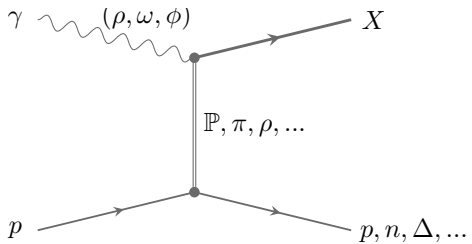
hadspec

and many more...

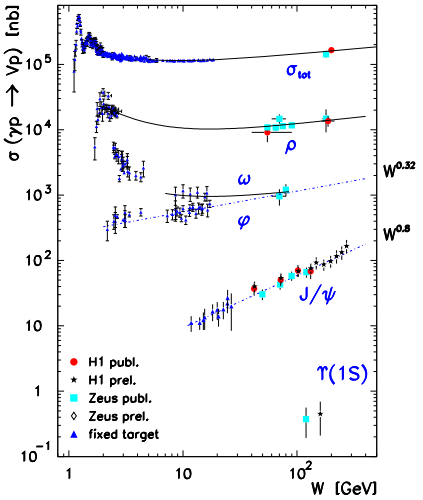
Close Collaboration between GlueX Experiment and Theory / Phenomenology

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

Photoproduction



- Photon coupling via **vector meson dominance**
- Photon polarization provides **constraints** on produced systems
- Understanding of **production mechanism** is prerequisite for interpretation of exotic signals
- Limited photoproduction data existing at GlueX energies



- Intensity = observed number density distribution of events for fixed s, t:

$$\mathcal{I}(\cos\vartheta, \varphi) \propto |\mathcal{M}_{fi}|^2 = |\sum_{JM}^{\infty} \mathcal{Y}_J^M(\cos\vartheta, \varphi)\mathcal{T}_{JM}|^2$$

  $\mathcal{Y}_J^M(\cos\vartheta, \varphi)$: spherical harmonic functions
  $\mathcal{T}_{JM}$: transition amplitudes

- Rewrite intensity for truncated sum (e.g. vector meson $J = 1$)

$$\mathcal{I}(\cos\vartheta, \varphi) \propto \sum_{M}\sum_{M'} \mathcal{Y}_1^M(\cos\vartheta, \varphi) \underbrace{\mathcal{T}_M \mathcal{T}_{M'}^*}_{=\rho_{MM'}} \mathcal{Y}_1^{M'*}(\cos\vartheta, \varphi)$$

Spin-Density Matrix ρ

- Complex-valued matrix
- Hermitian matrix: $\rho^\dagger = \rho \Rightarrow$ real-valued diagonal elements
- Positive semi-definite $\Rightarrow$ all eigenvalues are non-negative

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

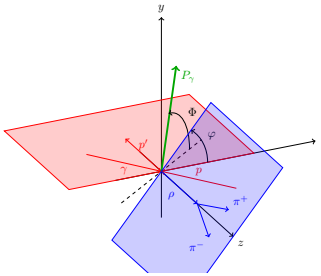
$$\mathcal{I}(\cos\vartheta,\varphi,\Phi) = \mathcal{I}^0(\cos\vartheta,\varphi) + \sum_{\alpha=1}^{3} P_\gamma^\alpha \mathcal{I}^\alpha(\cos\vartheta,\varphi) \quad \text{with} \quad \begin{cases} 0\text{: unpolarized} \\ 1, 2\text{: linearly polarized} \\ 3\text{: circularly polarized (only GlueX II \& III)} \end{cases}$$

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

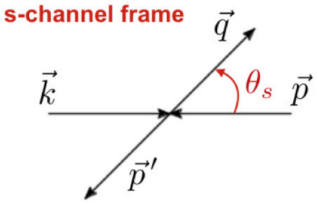
$$\mathcal{I}^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

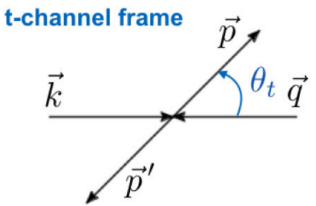
$$\mathcal{I}^2(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\right)$$

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



Helicity Conservation





s-channel helicity conservation (SCHC)

- Helicity transfer from beam to vector meson
- Evaluated in **helicity frame**
- All independent SDMEs are zero except $\rho^1_{1-1} = -\mathrm{Im}\rho^2_{1-1} = 0.5$

t-channel helicity conservation (TCHC)

- Helicity conserved by exchange particle
- Evaluated in **Gottfried-Jackson frame**
- All independent SDMEs are zero except $\rho^1_{1-1} = -\mathrm{Im}\rho^2_{1-1} = 0.5$

Extraction of SDMEs from Data

with Amplitude Analysis Technique

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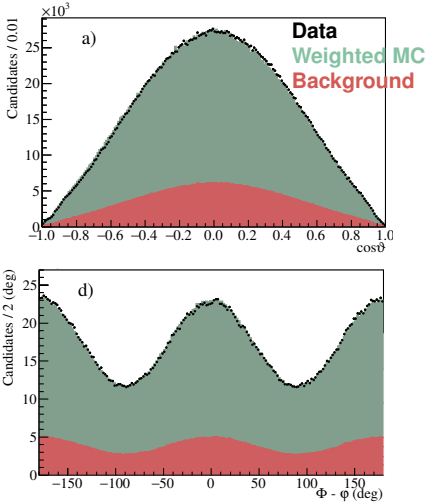
Extended Maximum-Likelihood Fit

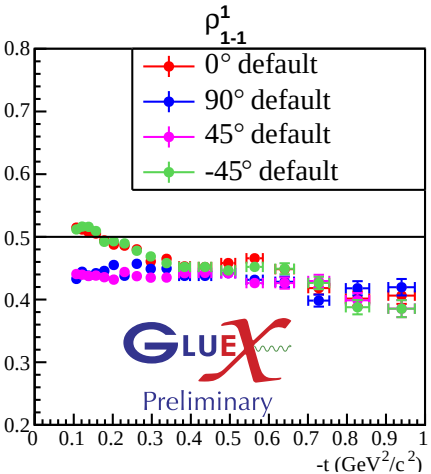
$$\ln L = \underbrace{\sum_{i=1}^{\text{events}} \ln \mathcal{I}(\tau_i)}_{\text{Experiment}} - \underbrace{\int d\Omega\, \mathcal{I}(\tau)\, \eta(\tau)}_{\text{Normalization Integral}}$$

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

GlueX Analysis Strategy

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





Example: orientation of polarization plane

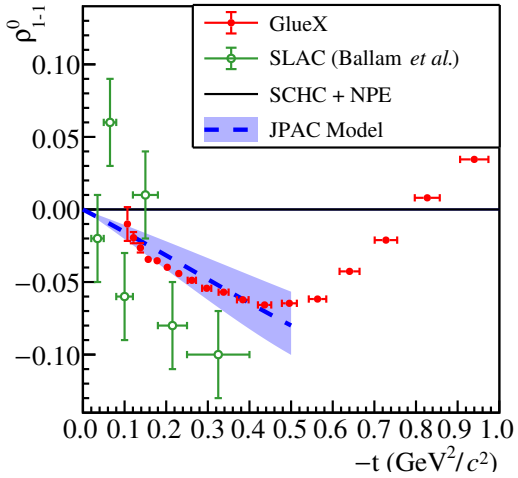
- Initially observed strong dependence on beam polarization orientation
- Led to improvements in track reconstruction and MC description
- Combined fit of 4 orientations for final result

Other examples for validation:

- Comparison of different datasets
- Consistency between decay modes
- Model expectations

$\rho(770)$ Meson SDMEs

PRC 108, 055204 (2023)



$\gamma p \to \rho(770)p, \rho(770) \to \pi^+\pi^-$

- High precision with only fraction of data set
- Orders of magnitude more precise than previous measurements
- Uncertainties dominated by systematics

$\rho(770)$ Meson SDMEs

PRC 108, 055204 (2023)

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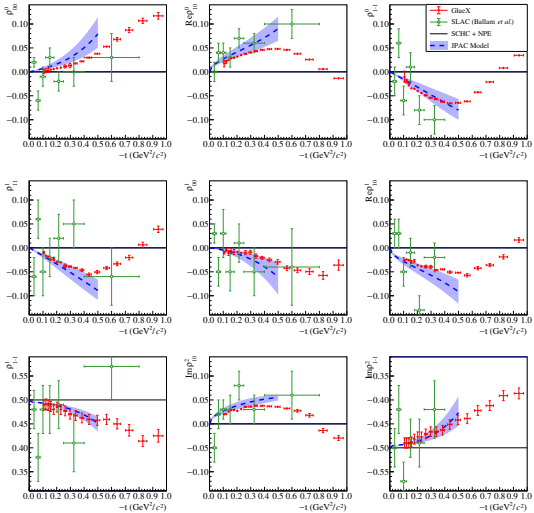

$\gamma p \to \rho(770)p, \rho(770) \to \pi^+\pi^-$

- 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)]
- More detailed studies of mass or energy dependence and interference with non-resonant production ongoing

Parity-Exchange Components

PRC 108, 055204 (2023)

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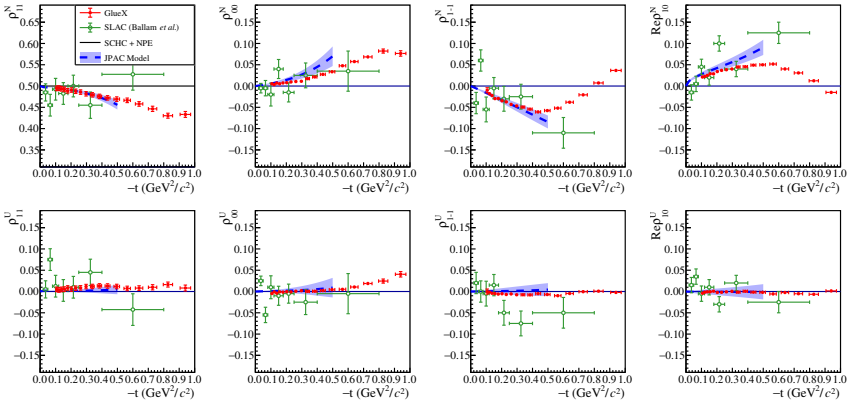
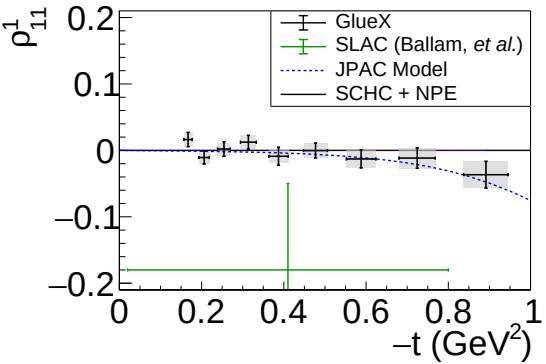
$$\rho^{\mathrm{N,U}}_{ik} = \frac{1}{2}\left[\rho^{0}_{ik} \mp (-1)^{i}\rho^{1}_{-ik}\right]$$



- Natural parity exchange dominates across t range
- Deviation from s-channel helicity conservation $\Rightarrow$ Contribution from f_2, a_2 exchanges

$\phi(1020)$ Meson SDMEs

PRC 112, 023203 (2025)



$\gamma p \to \phi(1020) p, \phi(1020) \to K_S K_L$

- Reconstruction of K_L via missing mass
- First measurement of t-dependence

$\phi(1020)$ Meson SDMEs

PRC 112, 023203 (2025)

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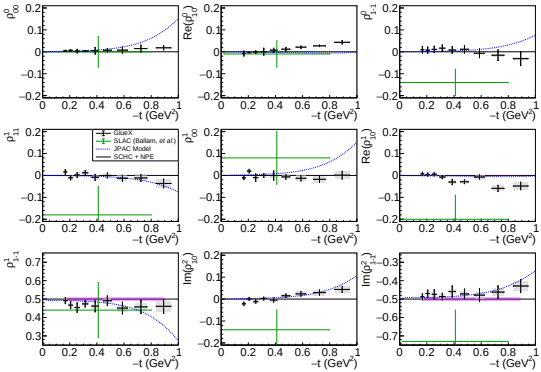


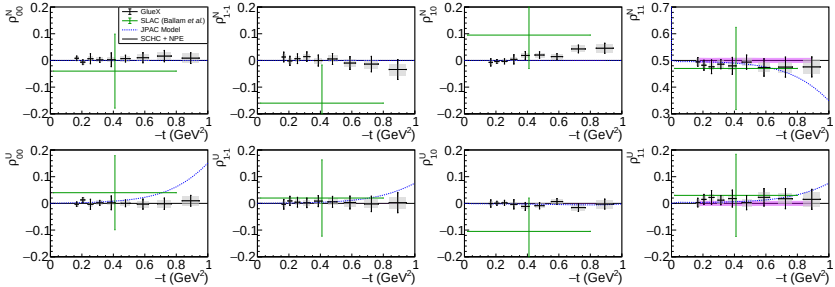
$\gamma p \to \phi(1020) p, \phi(1020) \to K_S K_L$

- Reconstruction of K_L via missing mass
- First measurement of t-dependence
- Good agreement with Regge model
  [JPAC, PRD 97 094003 (2018)]
- Parallel analysis of $\phi(1020) \to K^+K^-$ decay: **different systematic effects**

Parity-Exchange Components

PRC 108, 055204 (2023)

$$\rho^{\mathrm{N,U}}_{ik} = \frac{1}{2}\left[\rho^{0}_{ik} \mp (-1)^{i}\rho^{1}_{-ik}\right]$$



- Natural parity exchange dominates across t range
- s-channel helicity almost exactly conserved

J/ψ Photoproduction at Threshold

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

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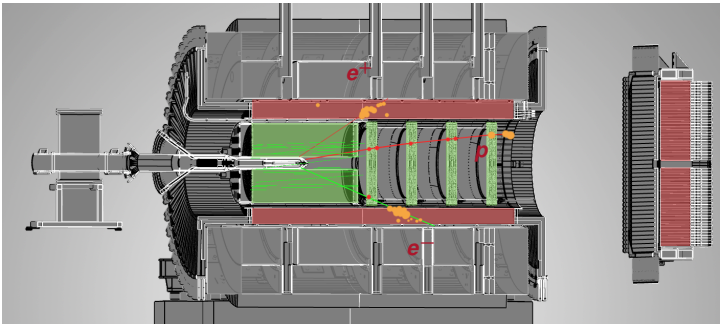
Threshold for J/ψ production: $E_\gamma = 8.22\,\text{GeV}$

$\gamma \to$



- 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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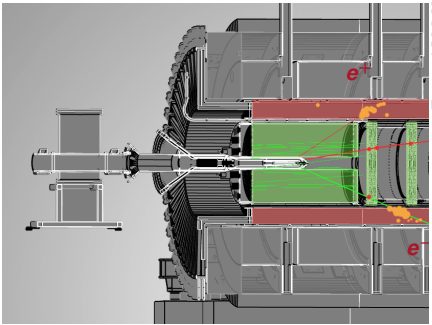

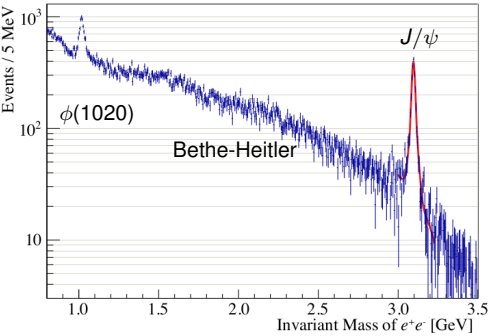

- Electron identification: E/p in calorimeters, pion background suppression by 10^{-4}
- Kinematic Fit with 0.1% precision on photon beam energy
- Cross section normalized by non-resonant e^+e^- production (Bethe-Heitler)

J/ψ Cross Section with GlueX-I Data

PRC 108, 025201 (2023)

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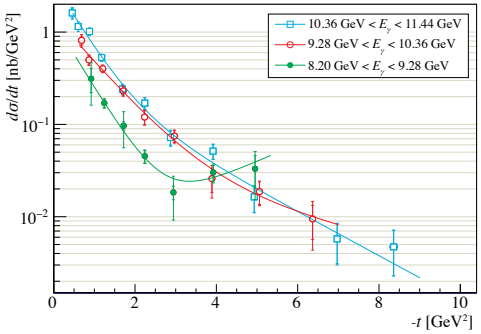

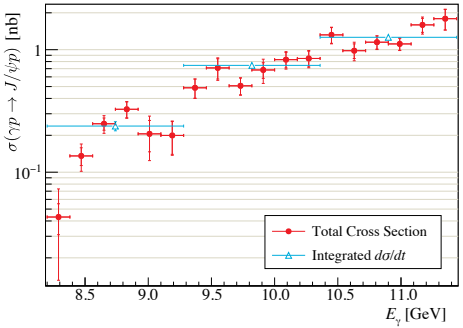

- About 2000 J/ψ signal events, precise measurement of dσ/dt
- Results relevant for fundamental properties: proton mass, gravitational form factors, scattering length

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PRC 108, 025201 (2023)

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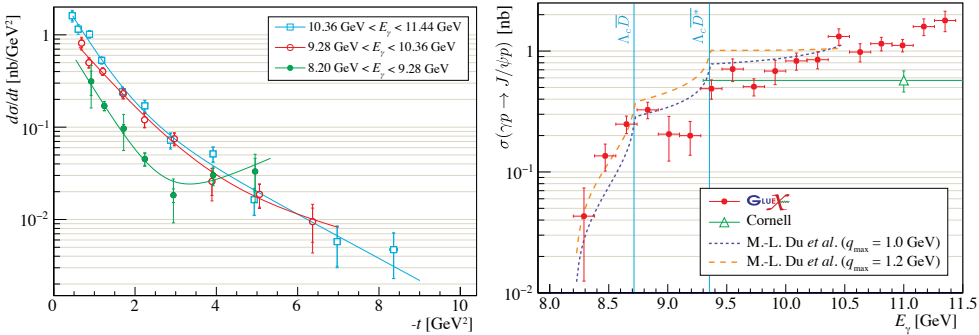


- About 2000 J/ψ signal events, precise measurement of dσ/dt
- Results relevant for fundamental properties: proton mass, gravitational form factors, scattering length
- Possible evidence for contribution from open charm production

$\Rightarrow$ Angular distributions will distinguish between production models

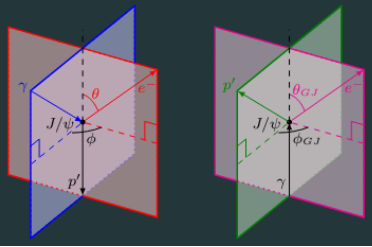
$$W^0(\theta,\phi) \propto \left[\frac{1+\rho^0_{00}}{2} - \frac{3\rho^0_{00}-1}{2}\cos^2\theta + \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\theta\cos\phi + \mathrm{Re}\rho^0_{1-1}\sin^2\theta\cos 2\phi\right]$$

$$W^1(\theta,\phi) \propto \left[\rho^1_{00}\sin^2\theta + \rho^1_{11}(1+\cos^2\theta) + \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\theta\cos\phi + \mathrm{Re}\rho^1_{1-1}\sin^2\theta\cos 2\phi\right]$$

$$W^2(\theta,\phi) \propto \left[-\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\theta\sin\phi - \mathrm{Im}\rho^2_{1-1}\sin^2\theta\sin 2\phi\right]$$

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

$W^i(\theta,\phi)$ for $V \to LL$ are different from $V \to PP$!



J/ψ Polarized SDMEs

Integrated over E_γ and t

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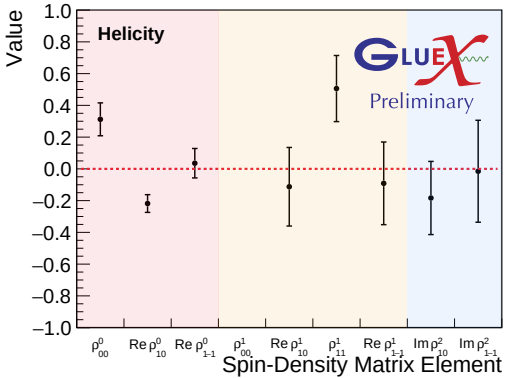
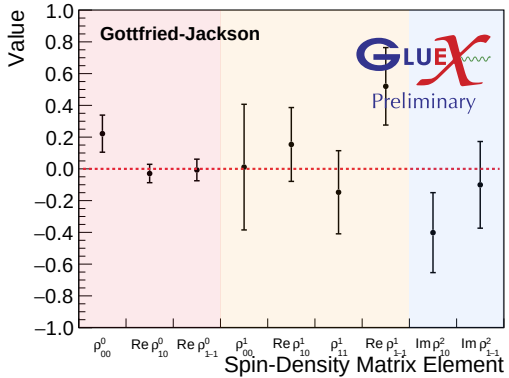
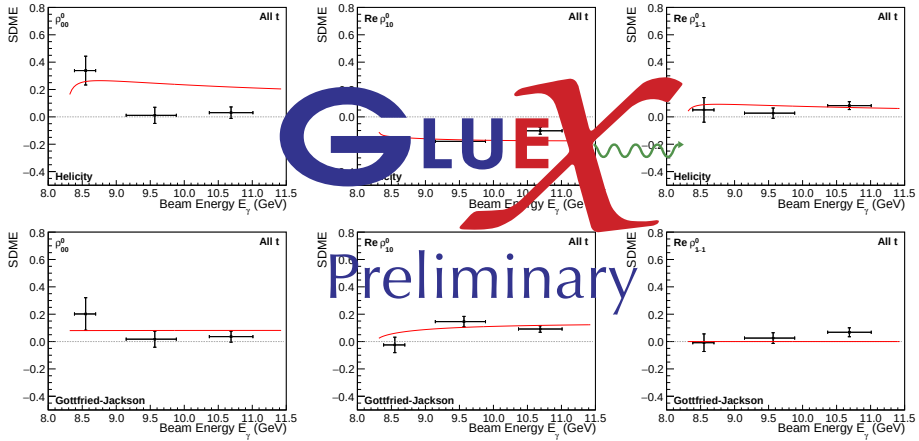




- Data appears to be **consistent with TCHC** and disfavor SCHC (ρ^1_{00} unphysical), but large uncertainties
- Full GlueX-II and GlueX-III data sets are expected to improve precision substantially

J/ψ Unpolarized SDMEs

E_γ-dependence



- SCHC: $\rho^0 = 0$ in helicity frame
- TCHC: $\rho^0 = 0$ in GJ frame
- JPAC amplitude from [PRD 102, 114010 (2020)]

Summary

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Status of the GlueX Experiment

- Full data set for initial phase of GlueX **available** and under **active analysis**
- Ideal for **high precision** measurements of **light meson** photoproduction
- **GlueX Phase II** in process, **Phase III** scheduled: world-leading dataset for J/ψ photoproduction

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Extraction of Spin-Density Matrix Elements for Vector Mesons

- Understanding of **polarized photoproduction** mechanism necessary for light meson spectroscopy
- Robust **amplitude analysis framework**, scales up to large data sets (e.g. $>$100M $\rho(770)$ events)
- Improve description of detector **acceptance** and **systematics**
  $\Rightarrow$ Comparison with previous measurements and models

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Thank you!

J/ψ Cross Section at Threshold

PRL 123, 072001 (2019)

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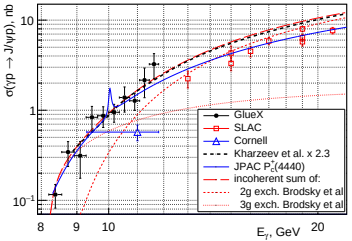

Energy dependence probes

- 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)

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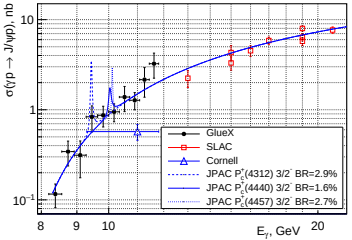

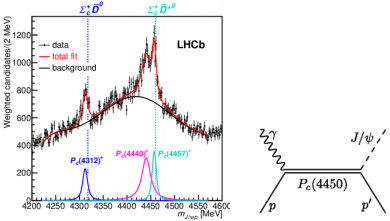

LHCb, PRL 122, 222001 (2019) JPAC, PRD 94, 034002 (2016)

Energy dependence probes

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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

SDME Mass Dependence