Spin-Density Matrix Elements for Vector-Meson Photoproduction at GlueX

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for the GlueX Collaboration

15th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon (MENU2019)

Carnegie Mellon University, Pittsburgh, PA
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Outline

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1. Introduction
2. Method
   - Extended Maximum-Likelihood Fit
   - Fit Evaluation
3. Results
   - $\rho(770) \to \pi^+\pi^-$
   - $\omega(782) \to \pi^+\pi^-\pi^0$
   - $\phi(1020) \to K^+K^-$
4. Outlook

GlueX Detector

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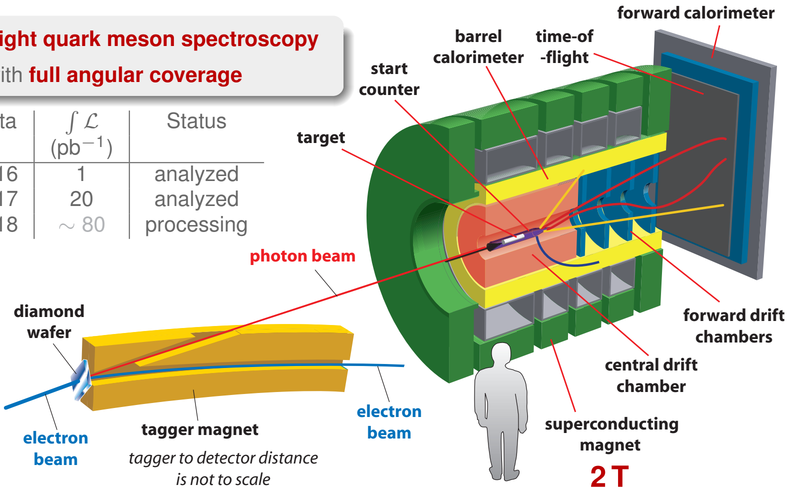
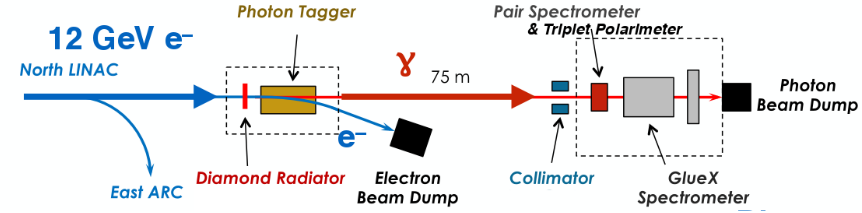
Light quark meson spectroscopy
with **full angular coverage**

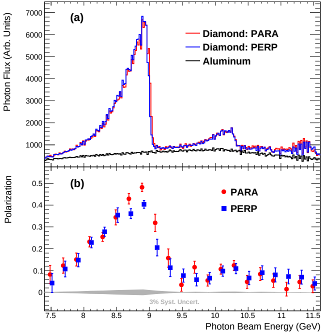
Data	$\int \mathcal{L}$ (pb^{-1})	Status
2016	1	analyzed
2017	20	analyzed
2018	$\sim$ 80	processing



→ S. Dobbs, Searching for Exotic Hadrons at GlueX (Monday morning)

Photon Beam Line





9 GeV Polarized Photon Beam

- Coherent Bremsstrahlung on thin diamond
- Energy tagged by scattered electrons
- Collimator to suppress incoherent part
- Linear polarization in peak $P_\gamma \sim 40\%$, measured by Triplet polarimeter: $\gamma e^- \to e^- e^+ e^-$
- Rotate polarization into 4 different orientations
- Beam intensity: $1 - 5 \cdot 10^7\ \gamma/s$ in peak

Photoproduction

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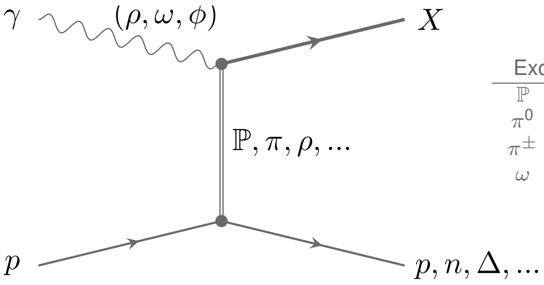


Exchange		Exotic Final States	
$\mathbb{P}$	0^{++}	b, h, h'	$2^{+-}, 0^{+-}$
π^0	0^{-+}	b_2, h_2, h'_2	2^{+-}
$\pi^\pm$	0^{-+}	$\pi_1^\pm$	1^{-+}
ω	1^{--}	π_1, η_1, η'_1	1^{-+}

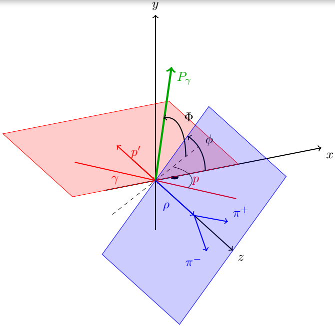
Complementary Production Mechanism

- Photon coupling via **vector meson dominance**
- Wide variety of quantum numbers $I^G J^{PC}$ accessible
- Photon polarization provides **constraints** on produced systems
- Understanding of **production mechanism** is prerequisite for interpretation
- Very limited photoproduction data existing at these energies

Production Mechanism

Spin-Density Matrix Elements

- 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



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

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

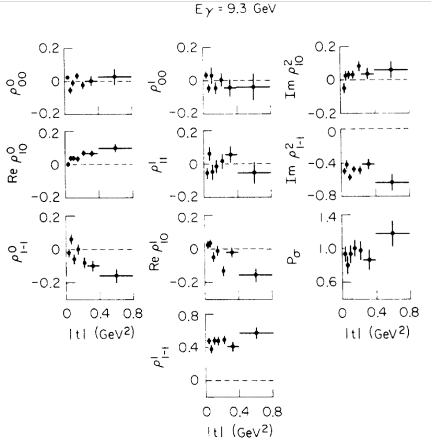
$$W^1(\cos\vartheta, \varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

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

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

Previous Measurements

SLAC, Ballam *et al.* [Phy. Rev. D, 7 (1973) 3150]



$\rho(770)$

- Few thousand events, 7 bins in t
- s-channel helicity conservation: $\rho^1_{1-1} = -\text{Im}\rho^2_{1-1} = 0.5$ in helicity frame, all others $= 0$
- Parity asymmetry: $P_\sigma = 2\rho^1_{1-1} - \rho^1_{00}$
- Dominated by natural parity exchange $P = (-1)^J$

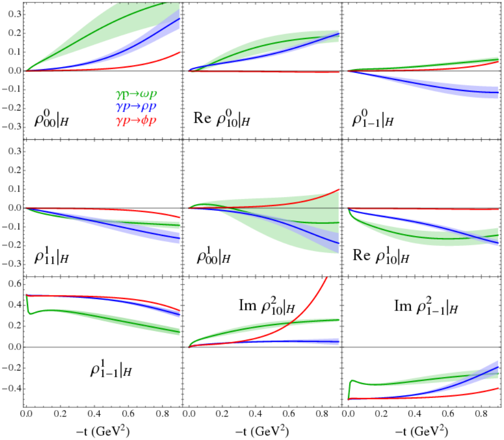
$\omega(782)$

- Several hundred events, 3 bins in t

$\phi(1020)$

- Few hundred events, not binned in t

JPAC Model

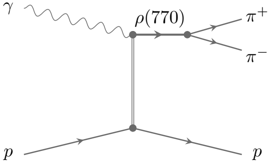


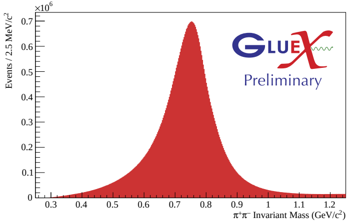
- Regge model, fit to SLAC data
- Detailed prediction for t-dependence of ρ, ω and ϕ meson production
- s-channel helicity conservation at $t = 0$

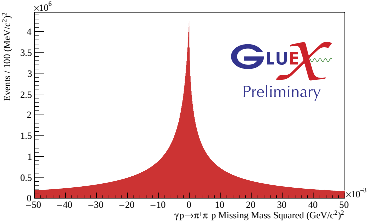
Mathieu *et al.* [Phy. Rev. D, 97 (2018) 094003]
→ Single and Double Meson Production at JLab (Tuesday)

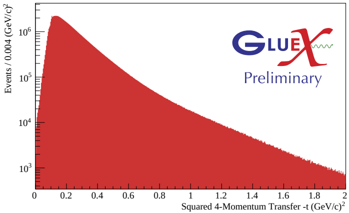
Vector-Meson Photoproduction

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









- Full 2017 data: $>$10M signal events in each of the 4 orientations

Extraction of SDMEs

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

Measured Intensity $I(\Omega) \propto W(\cos\vartheta,\varphi,\Phi)$

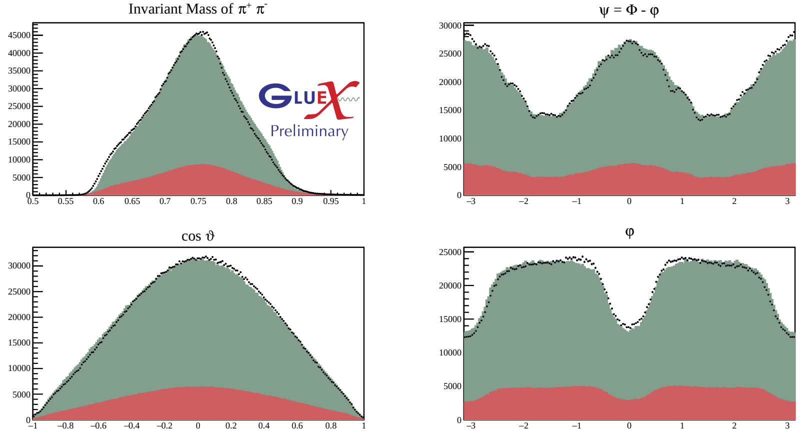
Extended Maximum-Likelihood Fit

$$\ln L = \underbrace{\sum_{i=1}^{N} \ln I(\Omega_i)}_{\text{Signal Events}} - \underbrace{\sum_{j=1}^{M} \ln I(\Omega_j)}_{\text{Background}} - \underbrace{\int d\Omega\, I(\Omega)\,\eta(\Omega)}_{\text{Normalization Integral}}$$

- Maximize by choosing SDMEs such that the intensity fits the observed N events
- Accidental background subtracted in likelihood
- Normalization integral evaluated by a phase-space Monte Carlo sample with the acceptance $\eta(\Omega) = 0/1$

Fit Evaluation

$\gamma p \to \rho(770) p, \quad -t \in [0.05, 0.15]\,\mathrm{GeV}^2/c^2$



- **black**: measured distribution
- **green**: accepted MC, weighted with fit result
- **red**: accidental background

Result in Bins of Momentum Transfer t

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

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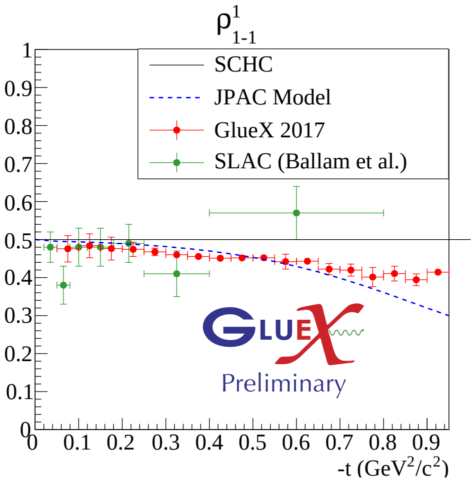

- $0.05\,\mathrm{GeV}^2/c^2$ bin width in t
- Average of 4 orientations
- Errors dominated by systematics
- SCHC valid for $t \to 0\,\mathrm{GeV}^2/c^2$
- Agree with JPAC to $\sim 0.5\,\mathrm{GeV}^2/c^2$

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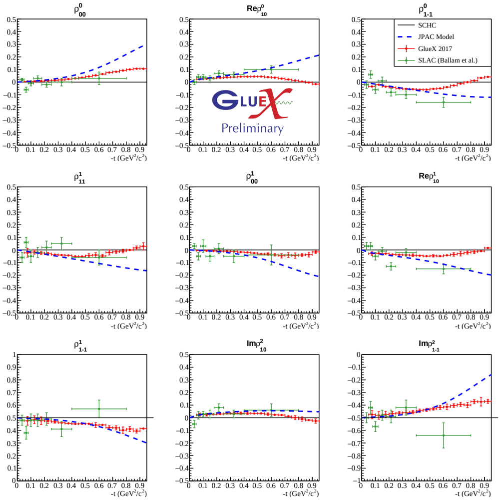

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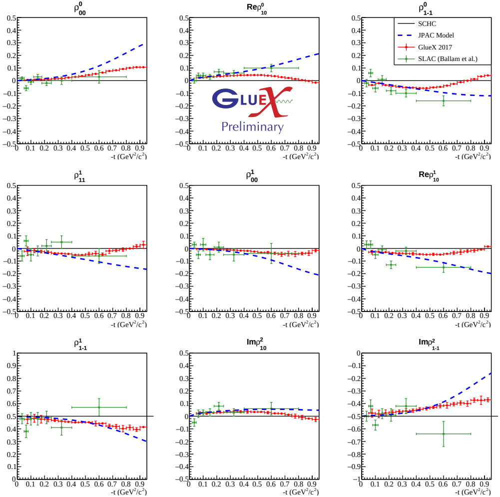

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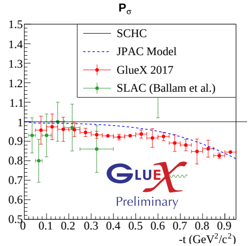

$$P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U} = 2\rho^1_{1-1} - \rho^1_{00}$$

Parity Exchange

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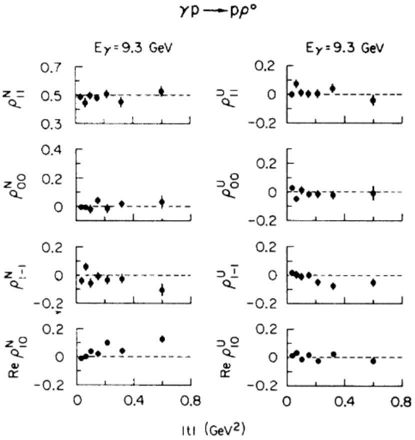

Ballam *et al.* [Phy. Rev. D, 7 (1973) 3150]

Spin-density matrix can be separated in contributions from **natural** and **unnatural** parity exchange in the *t* channel

$$\rho_{ik}^{N,U} = \frac{1}{2}(\rho_{ik}^{0} \mp (-1)^{i} \rho_{-ik}^{1})$$

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

Only significant contribution from ρ_{11}^{N}

⇒ Dominant natural parity exchange

Parity Exchange

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

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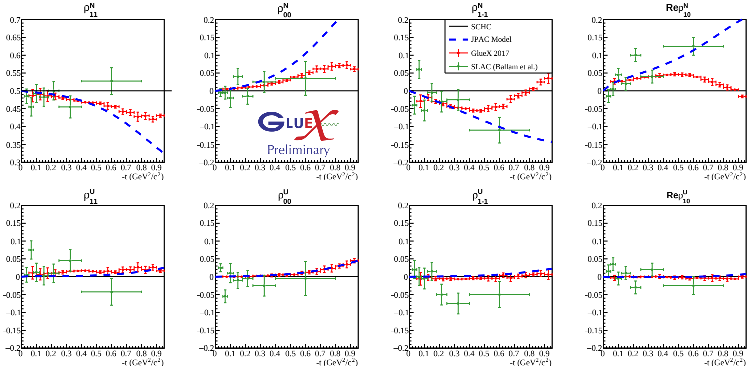

- Good agreement with JPAC for natural parity exchange at below 0.5 GeV^2/c^2
- Excellent agreement for unnatural parity exchange

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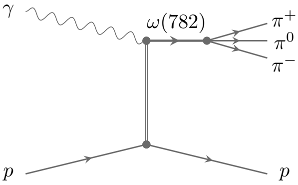
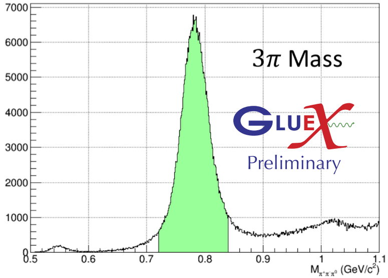
$$\gamma p \to \omega(782)p$$
$$\hookrightarrow \pi^+\pi^-\pi^0$$





$\omega(782)$ SDMEs

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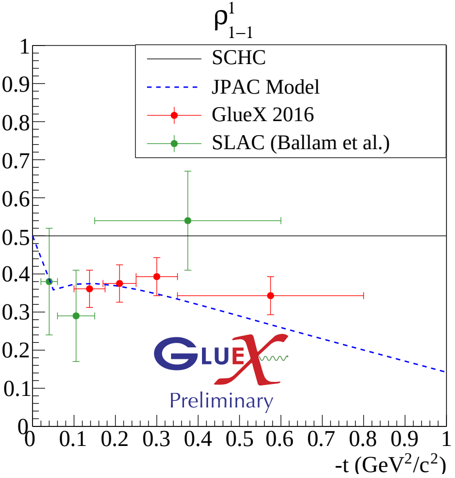

- Only data of commissioning run
- 4 t bins in $[0.1, 0.8]\,\mathrm{GeV}^2/c^2$
- Average of 2 orientations
- Good agreement with prediction
- Radiative decay also analyzed

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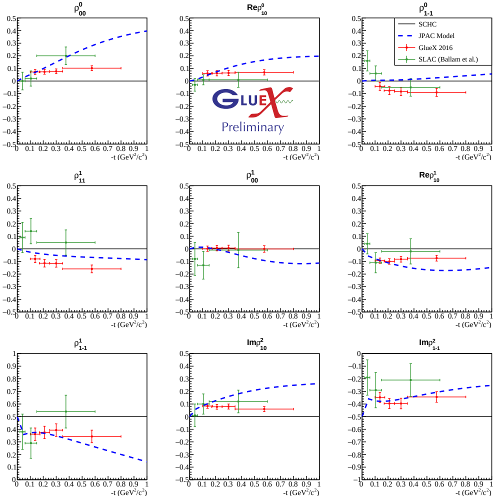

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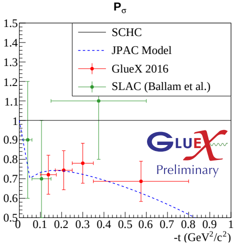

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$$\gamma p \rightarrow \phi(1020)p$$
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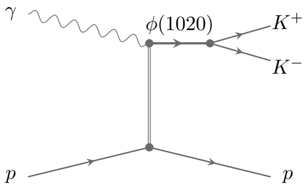

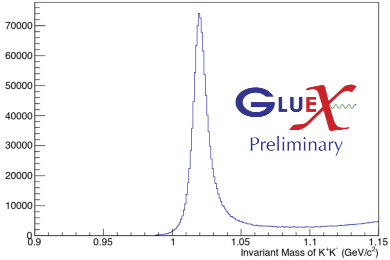

ϕ(1020) SDMEs

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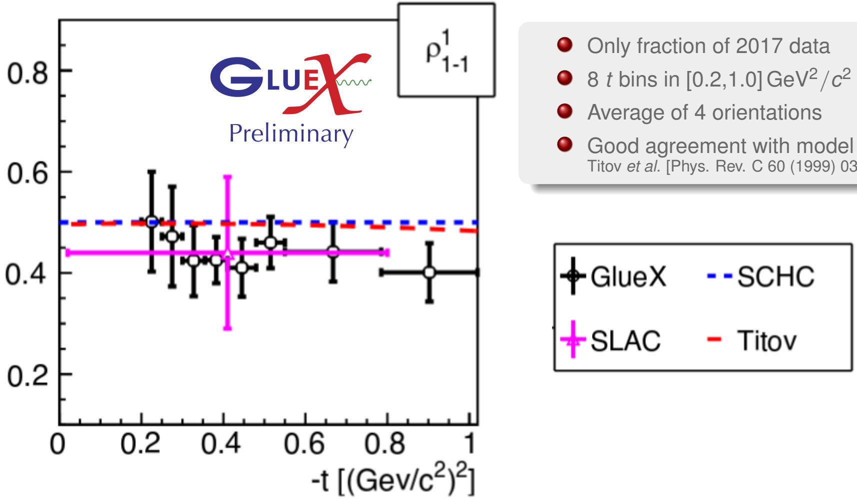

- Only fraction of 2017 data
- 8 t bins in [0.2,1.0] GeV$^2/c^2$
- Average of 4 orientations
- Good agreement with model
  Titov *et al.* [Phys. Rev. C 60 (1999) 035205]

$\phi(1020)$ SDMEs

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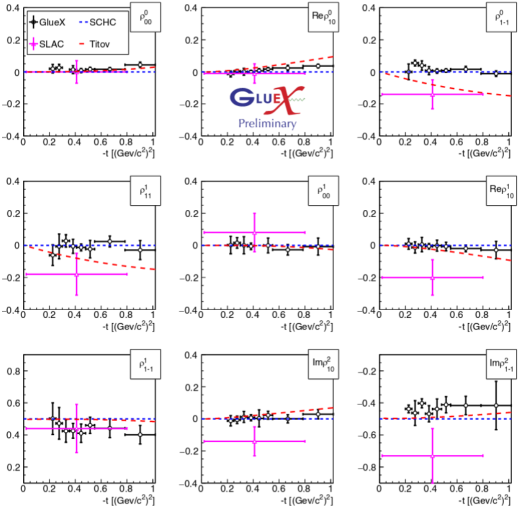

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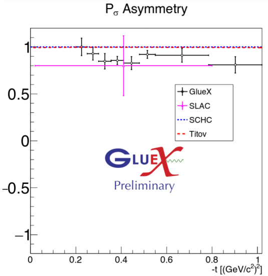

$$P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U} = 2\rho^1_{1-1} - \rho^1_{00}$$

Summary and Outlook

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Summary

- Spin-density matrix elements extracted for **ρ(770), ω(782)** and **ϕ(1020)**
- Statistical precision increased by **orders of magnitude**
- **Natural parity exchange** dominates at $E_\gamma = 9\,\text{GeV}$ for $t \to 0$
- General agreement with models for $t \lesssim 0.5\,\text{GeV}/^2c^2$
- Analysis also used to tune and confirm MC simulation

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Outlook

- Full GlueX-I data set will be available this summer
- Results serve as input to **improved model** of production process
- Prerequisite for **interpretation of exotic signals**