Probing the meson photoproduction mechanism through spin-density matrix elements at GlueX

MENU conference 2023

Farah Afzal for the GlueX Collaboration

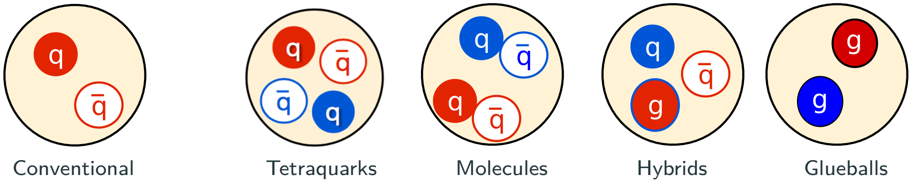
19.10.2023

University of Bonn

Light meson spectroscopy

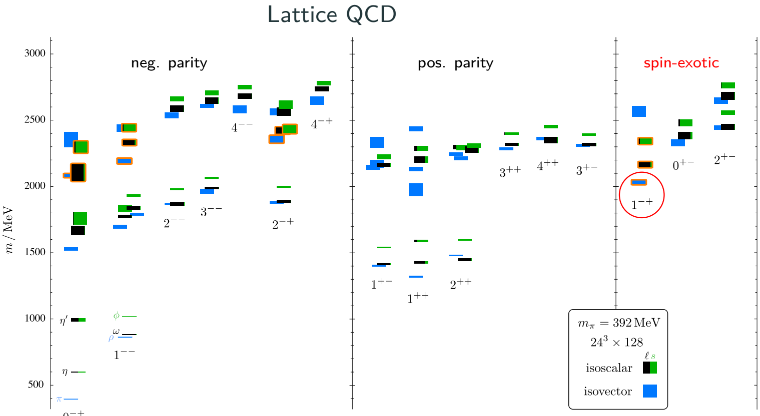
Light meson spectroscopy

- Fundamental question in hadron physics: How do hadrons emerge?
- QCD allows for a much richer meson spectrum beyond $q\bar{q}$ states



- Quark model: $J = L + S, P = (-1)^{L+1}, C = (-1)^{L+S}$
- How to identify exotics in the meson spectrum?
  - Supernumerary states
  - Spin-exotic: $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+} \ldots$ (not allowed for $q\bar{q}$ states!)
    $\rightarrow$ "Smoking gun" for finding evidence for exotic mesons!
- Experimental confirmation of exotic mesons is an essential direct test of QCD!

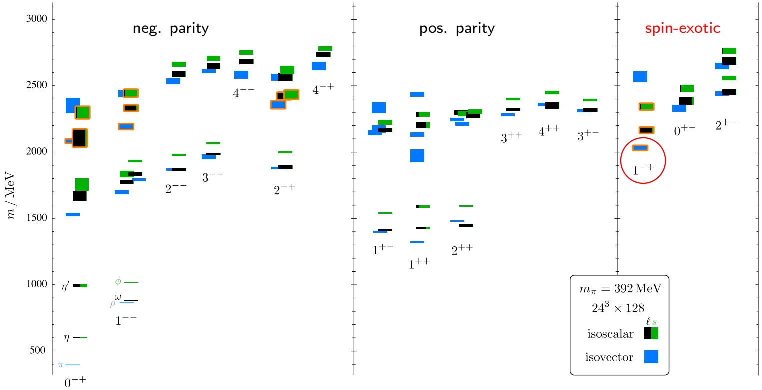
Light meson spectrum and search for exotic mesons



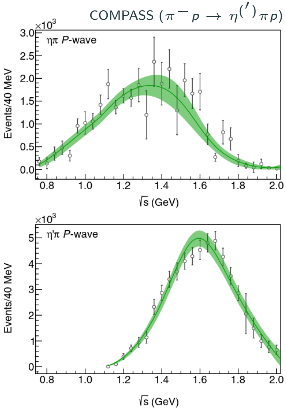
[HadSpec: J. Dudek et al. PRD 88 094505(2013)]

- Lightest spin-exotic state: π_1 with $J^{PC} = 1^{-+}$

Lattice QCD



[HadSpec: J. Dudek et al. PRD 88 094505(2013)]

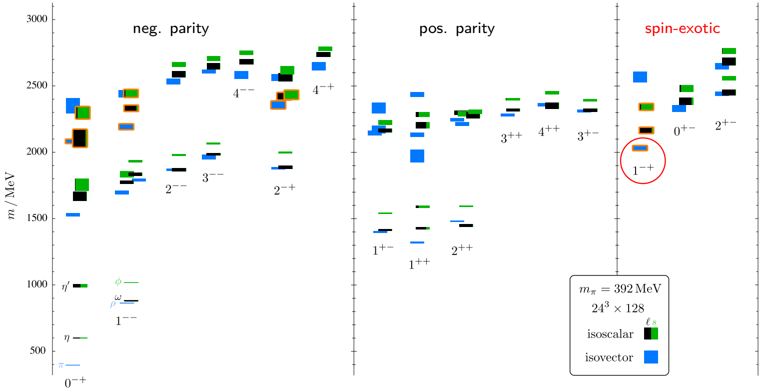


[A.Rodas et al. (JPAC), Phys. Rev. Lett. 122, 042002 (2019)]

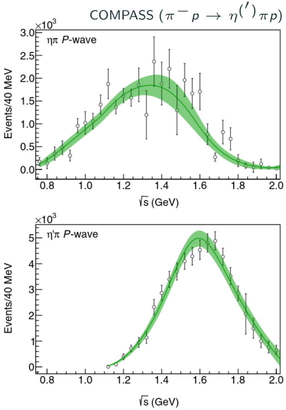
mass $= 1564 \pm 24 \pm 86$
width $= 492 \pm 54 \pm 102$

- Lightest spin-exotic state: π_1 with $J^{PC} = 1^{-+}$
- Experimentally two hybrid meson candidates: $\pi_1(1400), \pi_1(1600)$
  $\rightarrow$ coupled channel analysis requires only a single pole to describe both peaks

Lattice QCD



[HadSpec: J. Dudek et al. PRD 88 094505(2013)]

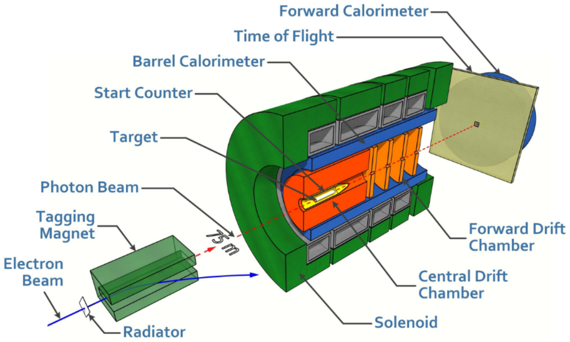


[A.Rodas et al. (JPAC), Phys. Rev. Lett. 122, 042002 (2019)]

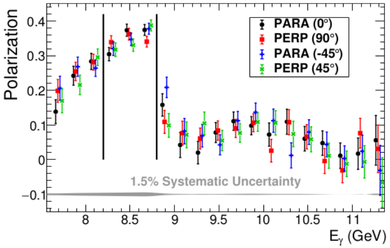
mass $= 1564 \pm 24 \pm 86$
width $= 492 \pm 54 \pm 102$

- Lightest spin-exotic state: π_1 with $\boldsymbol{J^{PC} = 1^{-+}}$
- Experimentally two hybrid meson candidates: $\pi_1(1400), \pi_1(1600)$
  $\rightarrow$ coupled channel analysis requires only a single pole to describe both peaks
- Important to establish π_1 through several production and decay modes!

The GlueX experiment at CEBAF (JLab)

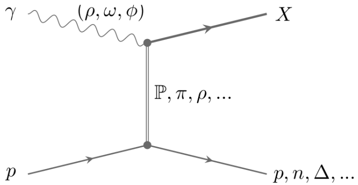


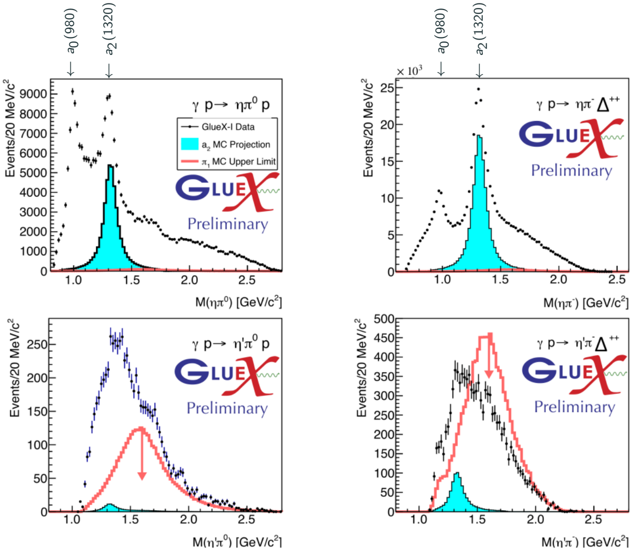
[(GlueX) NIMA 987 (2021) 164807]



- Complementary to πN production mechanism used at COMPASS, E852, VES
- 12 GeV electron beam from CEBAF accelerator
- Coherent Bremsstrahlung on diamond radiator
- Beam intensity: 1-5$\times 10^7 \gamma/s$ in peak
- GlueX Phase-I completed ($\int L = 400$ pb^{-1}), Phase-II: ongoing, 3-4 $\times$ Phase-I data

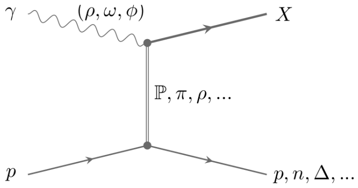
Ongoing analyses at GlueX e.g. $\pi_1(1600) \to \eta^{(\prime)}\pi$



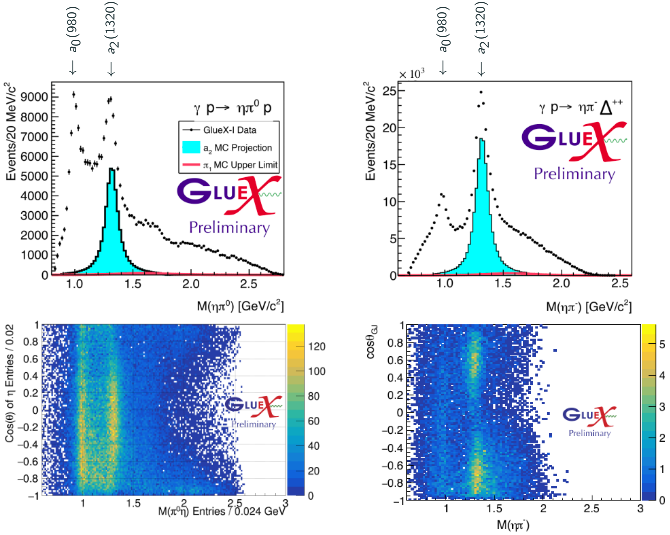


- Many analyses ongoing with recoil
  p: $\eta^{(\prime)}\pi^0 p$, ρp, $\omega\pi^0 p$...
  Δ^{++}: $\eta^{(\prime)}\pi^-\Delta^{++}$, $\rho^-\Delta^{++}$, $\omega\pi^-\Delta^{++}$...

Ongoing analyses at GlueX e.g. $\pi_1(1600) \to \eta^{(\prime)}\pi$



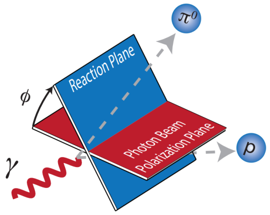
- Many analyses ongoing with recoil
  $\boldsymbol{p}$: $\eta^{(\prime)}\pi^0 \boldsymbol{p}$, $\rho \boldsymbol{p}$, $\omega\pi^0 \boldsymbol{p}$...
  $\boldsymbol{\Delta^{++}}$: $\eta^{(\prime)}\pi^- \Delta^{++}$, $\rho^- \Delta^{++}$, $\omega\pi^- \Delta^{++}$...
- Different spin-projection states populated in neutral vs. charged meson systems
- Understanding of **production mechanism** is crucial for **search of exotic states**!



Probing photoproduction mechanism with Σ and SDMEs

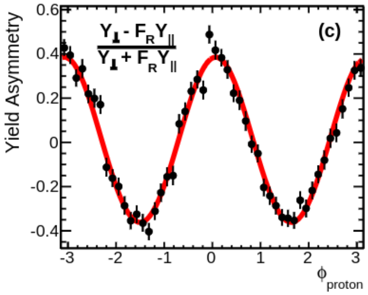
UNIVERSITÄT BONN

- Measurement with linearly polarized photon beam:
  $\sigma_{\text{pol}}(\phi) = \sigma_{\text{unpol}}\,[1 - p_\gamma \mathbf{\Sigma} \cos 2\phi]$
- Measurement with two perpendicular settings



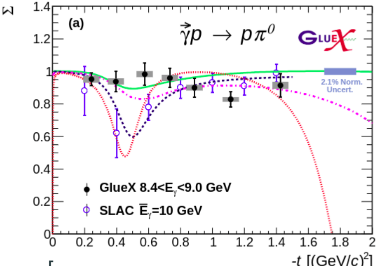
- Σ is sensitive to exchanged particle J^{PC}
  Sign of $\Sigma \rightarrow$ naturality: $\eta = P(-1)^J$
- **natural** parity exchange ($\eta = +1$):
  $J^P = 0^+, 1^-, 2^+ \ldots$
- **unnatural** parity exchange ($\eta = -1$):
  $J^P = 0^-, 1^+, 2^- \ldots$

$\gamma p \rightarrow p\pi^0$



Probing photoproduction mechanism with Σ

- Σ is sensitive to exchanged particle J^{PC}
  Sign of $\Sigma \to$ naturality: $\eta = P(-1)^J$
- **natural** parity exchange ($\eta = +1$):
  $J^P = 0^+, 1^-, 2^+ \ldots$
- **unnatural** parity exchange ($\eta = -1$):
  $J^P = 0^-, 1^+, 2^- \ldots$



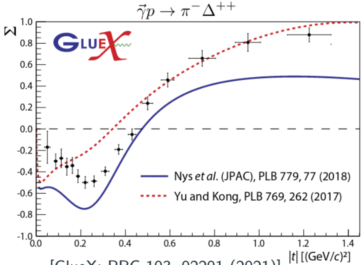
[GlueX: PRC 95, 042201 (2017)]

neutral exchange:

- $\pi^0 p$: natural parity (ρ, a_2) exchange dominates
- Similar observations ($\Sigma \approx 1$) for ηp, $\eta' p$ and $K^+\Sigma^0$
  GlueX: PRC 100, 052201 (2019)
  GlueX: PRC 101, 065206 (2020)

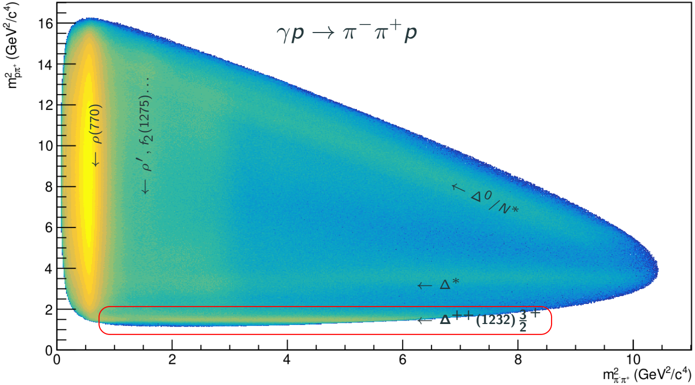
charge exchange:

- Low $-t$: unnatural exchange ($\Sigma < 0 \to \pi$, b_1) preferred
- High $-t$: natural exchange ($\Sigma > 0 \to \rho$, a_2) preferred

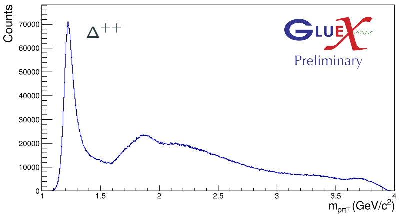


[GlueX: PRC 103, 02201 (2021)]

Study of charge exchange mechanism $\gamma p \to \pi^- \Delta^{++} \to \pi^- \pi^+ p$



- High statistics available
- Clear Δ^{++} signal with small background contributions from $\pi^+\pi^-$ system

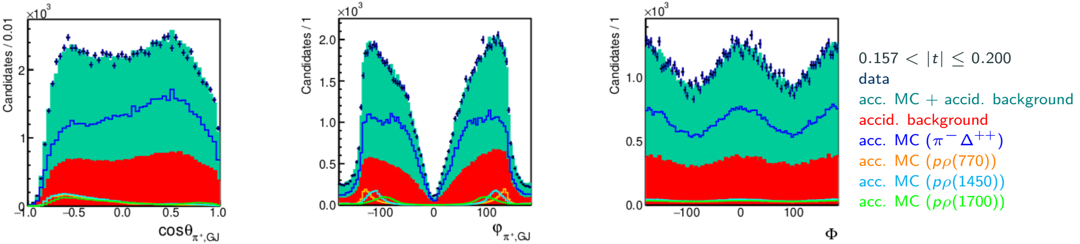


Analyzing decay angles of $\Delta^{++} \to p\pi^+$ gives access to Spin-density matrix elements!

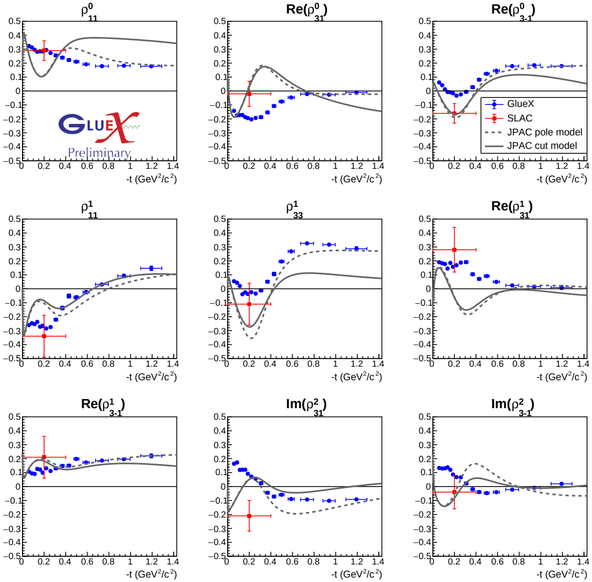
Study of exchange mechanism with SDMEs in $\gamma p \to \pi^- \Delta^{++} \to \pi^- \pi^+ p$

- Spin-density matrix elements (SDMEs) ρ^k_{ij} describe full angular distribution of Δ^{++} production and decay
- Linearly polarized beam provides access to nine linearly independent SDMEs

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



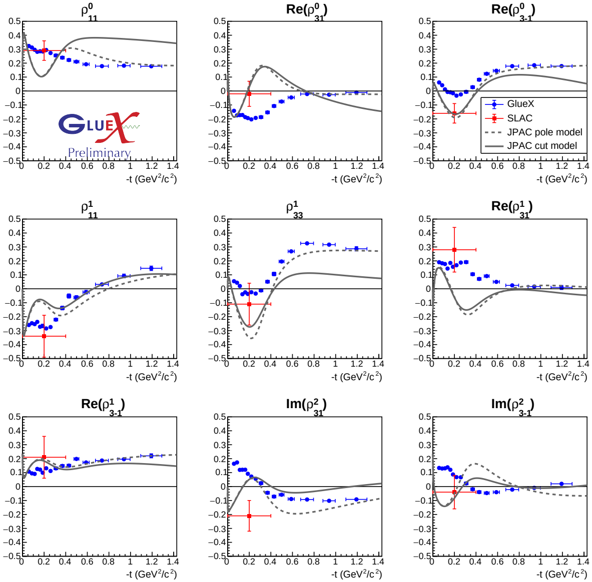
Spin-Density Matrix Elements in Δ^{++} production



- GlueX data (not full data set, only statistical uncertainties)
- SLAC: J. Ballam et al., Phys. Rev. D 7 (1973), 3150

JPAC: PLB 779, 77 (2018)

Spin-Density Matrix Elements in Δ^{++} production



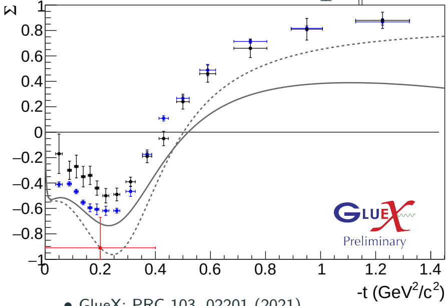
- GlueX data (not full data set, only statistical uncertainties)
- SLAC: J. Ballam et al., Phys. Rev. D 7 (1973), 3150

JPAC: PLB 779, 77 (2018)

Integrating over Δ^{++} decay angles leads to systematic deviations!

Important for including Δ^{++} in amplitude analyses!

$$\Sigma = 2(\rho^1_{11} + \rho^1_{33}) \quad \text{vs.} \quad \Sigma = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$$



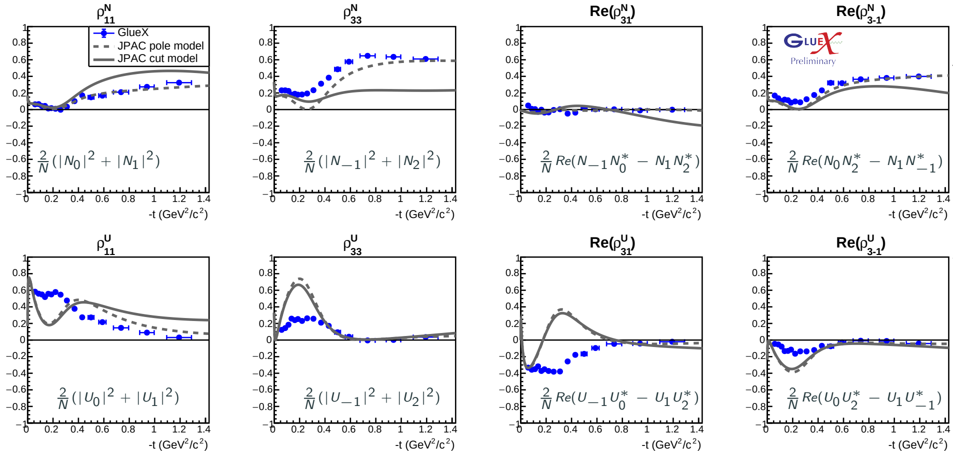
- GlueX: PRC 103, 02201 (2021)

Separation of natural and unnatural exchanges using combinations of SDMEs

8 amplitudes in the reflectivity basis: $T^{(\epsilon)}_{\lambda_N \lambda_\Delta}$, N_σ and U_σ with $\sigma = \lambda_N - \lambda_\Delta = \{-1, 0, 1, 2\}$

$$N_{-1} = T^{(+)}_{\frac{1}{2}\frac{3}{2}} \qquad N_0 = T^{(+)}_{\frac{1}{2}\frac{1}{2}} \qquad N_1 = T^{(+)}_{\frac{1}{2}-\frac{1}{2}} \qquad N_2 = T^{(+)}_{\frac{1}{2}-\frac{3}{2}}$$

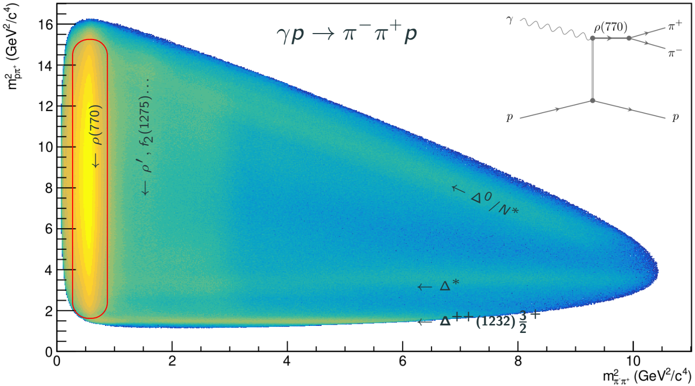
$$U_{-1} = T^{(-)}_{\frac{1}{2}\frac{3}{2}} \qquad U_0 = T^{(-)}_{\frac{1}{2}\frac{1}{2}} \qquad U_1 = T^{(-)}_{\frac{1}{2}-\frac{1}{2}} \qquad U_2 = T^{(-)}_{\frac{1}{2}-\frac{3}{2}}$$

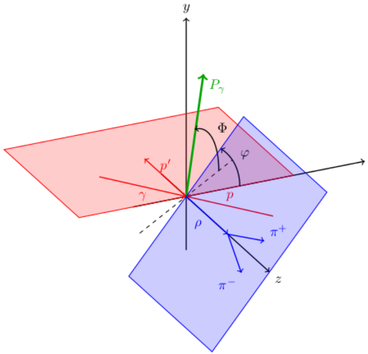


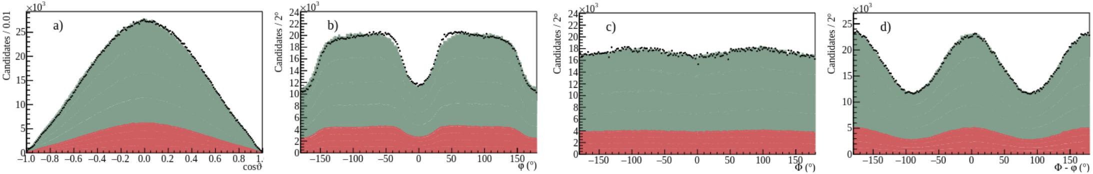
JPAC: PLB 779, 77 (2018)

$\rightarrow$ unnatural exchange not well understood!

Spin-Density Matrix Elements in $\rho(770)$ production



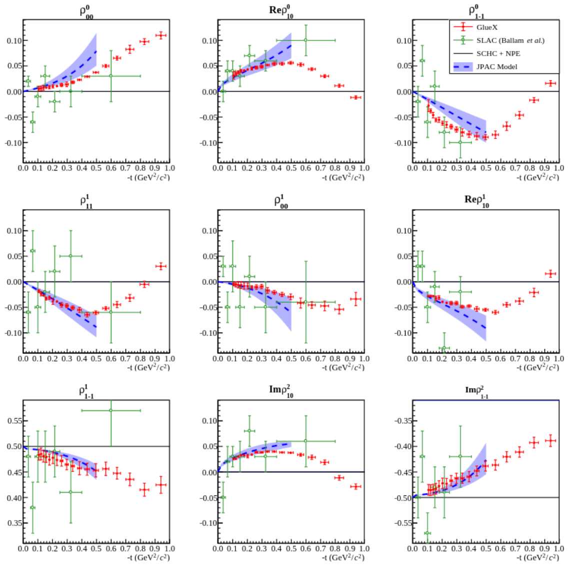




GlueX: arXiv:2305.09047 (2023), Accepted for publication in Phys. Rev. C

● data accidental background weighted MC

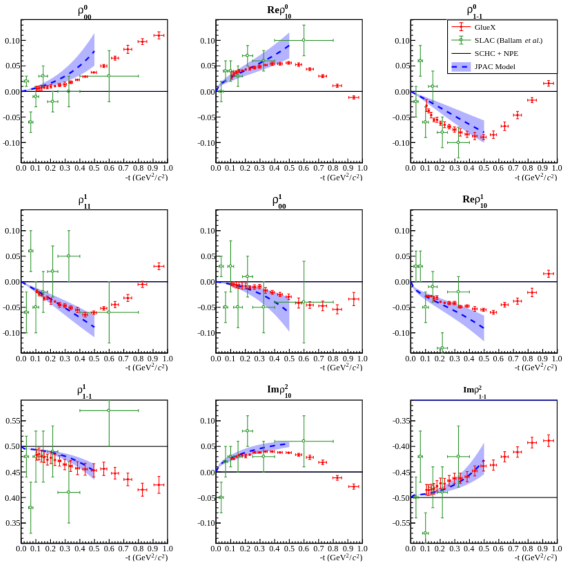
Spin-Density Matrix Elements in $\rho(770)$ production



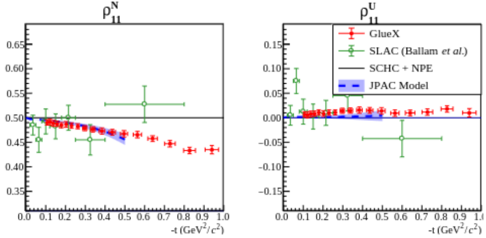
- High-precision data, uncertainties dominated by systematics
- s-channel helicity conservation: $\rho^1_{1-1} = 0.5$, $Im\rho^2_{1-1} = -0.5$ (valid at very low $-t$)
- Good agreement to JPAC: Regge model at low $-t$ [JPAC: PRD 97 094003 (2018)]
- Natural-parity exchange ($\mathbb{P}$) dominates

GlueX: arXiv:2305.09047 (2023), Accepted for publication in Phys. Rev. C

Spin-Density Matrix Elements in $\rho(770)$ production



- High-precision data, uncertainties dominated by systematics
- s-channel helicity conservation: $\rho^1_{1-1} = 0.5$, $Im\rho^2_{1-1} = -0.5$ (valid at very low $-t$)
- Good agreement to JPAC: Regge model at low $-t$ [JPAC: PRD 97 094003 (2018)]
- Natural-parity exchange ($\mathbb{P}$) dominates



GlueX: arXiv:2305.09047 (2023), Accepted for publication in Phys. Rev. C

Summary

UNIVERSITÄT BONN

- Photoproduction mechanism can be studied with polarization observables:
  Beam asymmetry Σ and Spin-density matrix elements (SDMEs)
- $\boldsymbol{\Sigma}$:
  - neutral exchange e.g. $\boldsymbol{\pi^0 p}$: natural parity exchange dominates ($\Sigma \approx 1$)
  - charge exchange e.g. $\boldsymbol{\pi^- \Delta^{++}}$: unnatural parity exchange dominant at low $-t$
    Important to not integrate over Δ^{++} decay angles
- **SDMEs**:
  - High-precision GlueX data
  - $\boldsymbol{\pi^- \Delta^{++}}$: unnatural parity exchange not well understood
  - $\boldsymbol{\rho p}$: SCHC + NPE fulfilled at very low $-t$
    Natural parity exchange ($\mathbb{P}$) dominates
  - More ongoing analyses: $p\omega$, $p\phi$, $K^+\Lambda(1520)$ (GlueX: Phys.Rev.C 105 035201 (2022))

- Σ, SDMEs provide important input for modeling exchange mechanism and search for exotic states
  - Many exciting amplitude analyses ongoing:
  - $\boldsymbol{p}$: $\eta^{(\prime)}\pi^0 p$, ρp, $\omega\pi^0 p \dots$
  - $\boldsymbol{\Delta^{++}}$: $\eta^{(\prime)}\pi^-\Delta^{++}$, $\rho^-\Delta^{++}$, $\omega\pi^-\Delta^{++} \dots$

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