Exploring the meson spectrum with 3π photoproduction and the search for the exotic hybrid meson $\pi_1(1600)$ at the GlueX experiment

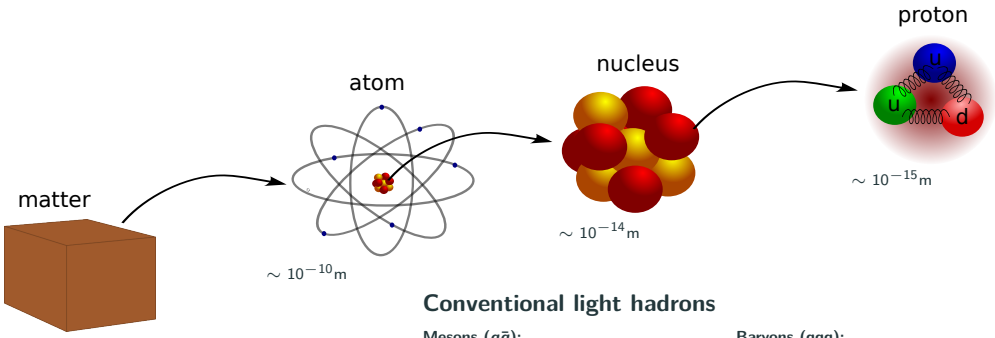
KHuK annual meeting 2024

Farah Afzal

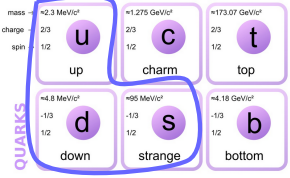
06.12.2024

University of Bonn

Building blocks of matter - Light hadrons



→ form light hadrons



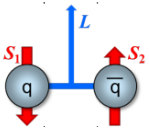
Conventional light hadrons

Mesons ($q\bar{q}$):

π	$\tau \approx 10^{-8}$s
$\rho \rightarrow \pi\pi$	$\tau \approx 10^{-24}$s

Baryons (qqq):

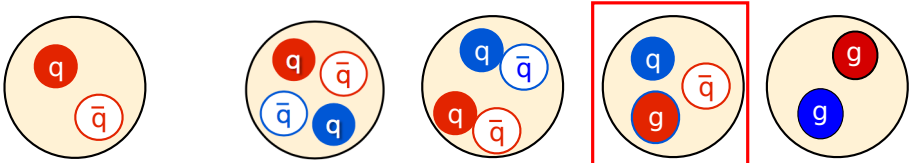
proton	stable
$\Delta(1232)\frac{3}{2}^+ \rightarrow p\pi$	$\tau \approx 10^{-24}$s



J^{PC} : $J = L + S$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$

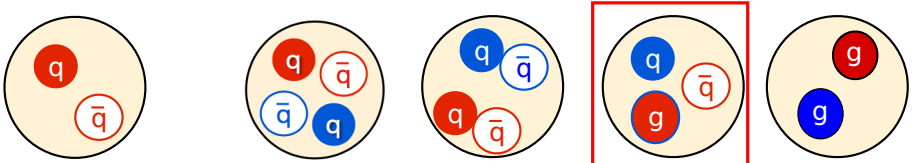
Exotic mesons

- Quantum numbers: $J = L + S$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$
- QCD allows other **color neutral** configurations beyond $q\bar{q}$ states



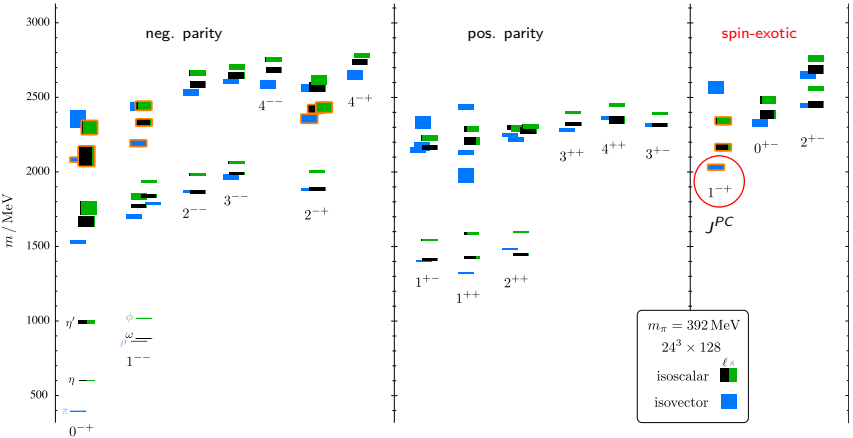
- **Hybrid mesons** $\rightarrow$ test **gluonic degrees of freedom of QCD**

- Quantum numbers: $J = L + S$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$
- QCD allows other **color neutral** configurations beyond $q\bar{q}$ states



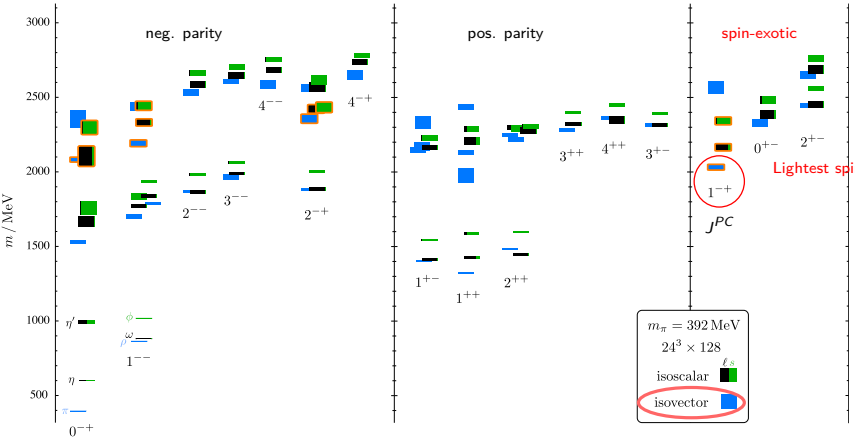
- **Hybrid mesons** → test **gluonic degrees of freedom of QCD**
- How to identify hybrid mesons in the meson spectrum?
  - Spin-exotic: $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}$ ... (forbidden for $q\bar{q}$ states!)
    → "Smoking gun" for finding evidence for exotic mesons!
- Experimental confirmation of exotic mesons is an **essential direct test of QCD**!

Predicted light meson spectrum - Lattice QCD



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

Predicted light meson spectrum - Lattice QCD

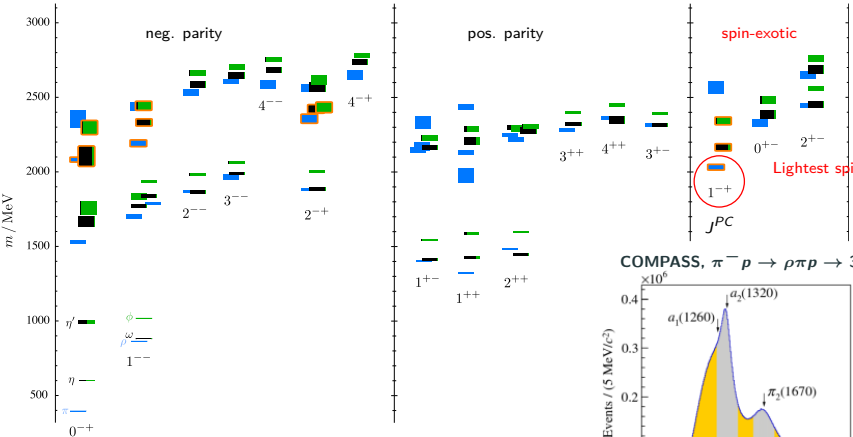


[HadSpec: J. Dudek et al. PRD 88 094505(2013)]

Important to establish $\pi_1(1600)$
→ several **production mechanisms** and **decay modes**!

Lightest spin-exotic state $\pi_1(1600)$

Predicted light meson spectrum - Lattice QCD



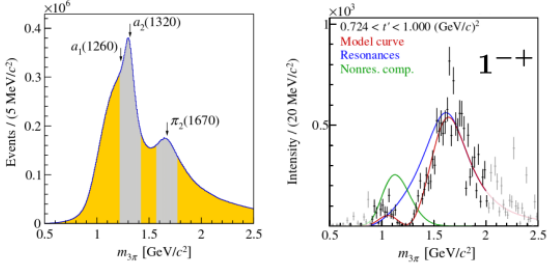
[HadSpec: J. Dudek et al. PRD 88 094505(2013)]

Important to establish $\pi_1(1600)$
$\rightarrow$ several **production mechanisms** and **decay modes**!

Lightest spin-exotic state $\pi_1(1600)$

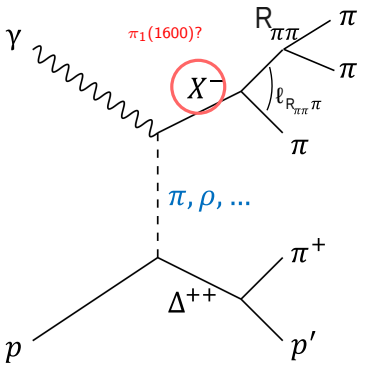
Golden decay mode: $\rho\pi$, $\eta\pi$, $\eta'\pi$

COMPASS, $\pi^- p \rightarrow \rho\pi p \rightarrow 3\pi p$ (46×10^6 events)



COMPASS, Phys. Rev. D 95, 032004 (2017)

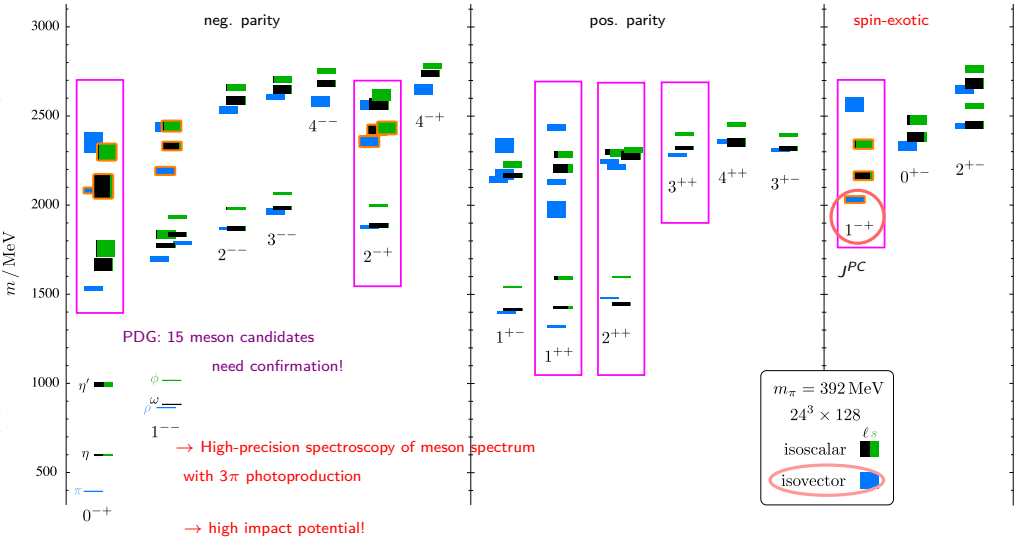
Goal of the Emmy Noether project



Goal:

- **New insights** into the meson spectrum with **unique, unexplored production mechanism**
- Confirm $\boldsymbol{\pi_1(1600)}$ through decay mode: $\pi_1(1600) \to \rho\pi \to 3\pi$
- Explore the meson excitation spectrum via $\mathbf{3\pi}$ **photoproduction with the GlueX experiment**:
  - $\gamma p \to \Delta^{++}\pi^+\pi^-\pi^-$
  - $\gamma p \to \Delta^{++}\pi^-\pi^0\pi^0$
  - High statistics $\sim 10 \times 10^6$ events already available

Goal of the Emmy Noether project

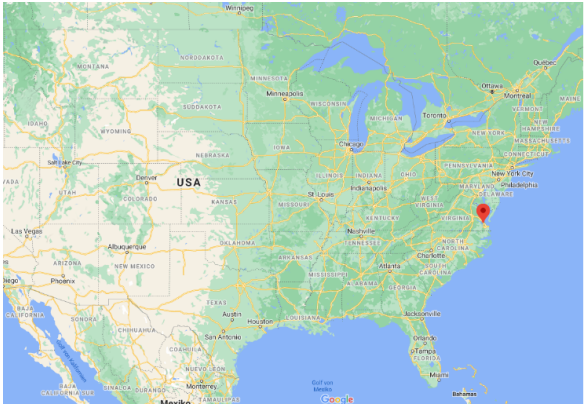


→ High-precision spectroscopy of meson spectrum with 3π photoproduction

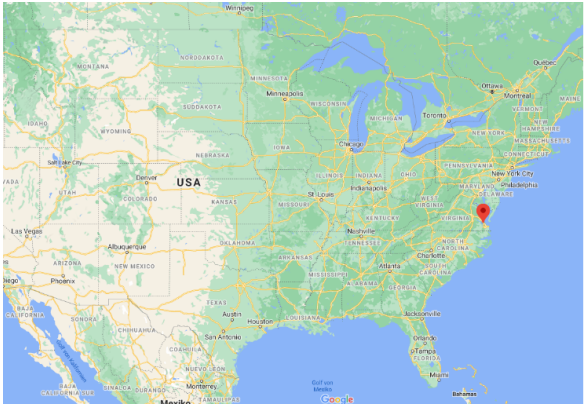
→ high impact potential!

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

Jefferson Lab in Newport News, Virginia



Jefferson Lab in Newport News, Virginia



CEBAF accelerator

high intensity

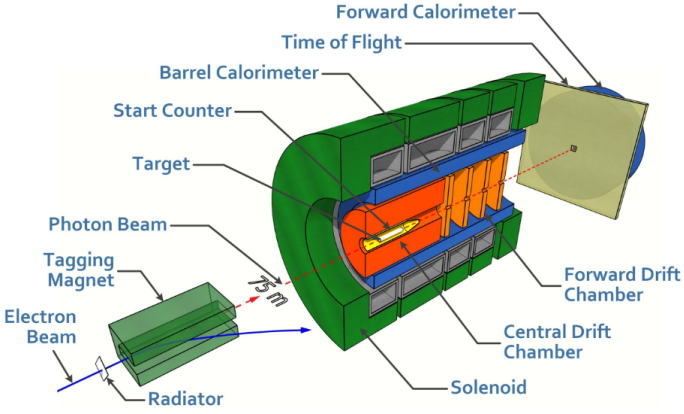
electron beam

E_{e^-} <12 GeV

Hall D:

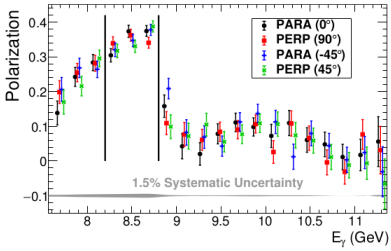
GlueX experiment

The GlueX experiment at CEBAF (JLab)



(GlueX) NIMA 987 (2021) 164807

Linearly polarized photon beam

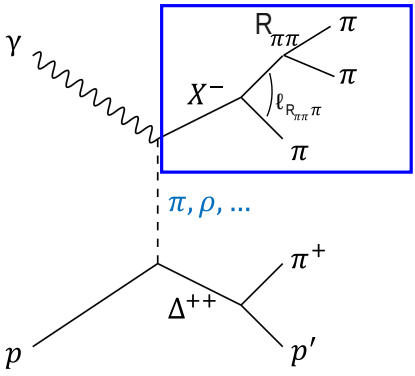


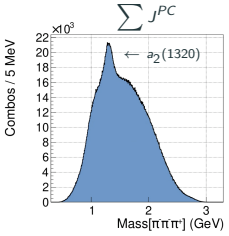
→ Gives insight to production processes

Experiment is optimized for light meson spectroscopy

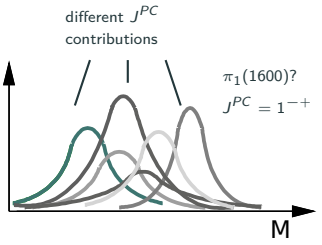
- Coherent Bremsstrahlung on diamond radiator
- Beam intensity: 1-5$\times 10^7 \gamma/s$ in peak
- GlueX Phase-I completed ($\int L = 125$ pb^{-1} in coherent peak), Phase-II: ongoing, 3-4 $\times$ Phase-I data

3π photoproduction off a Δ^{++} - Analysis approach

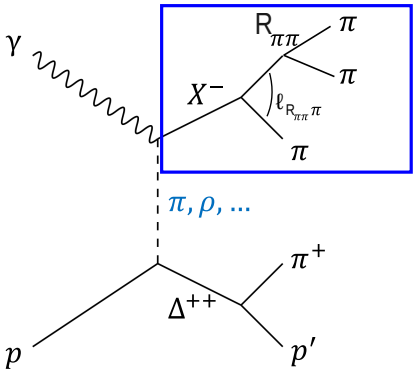


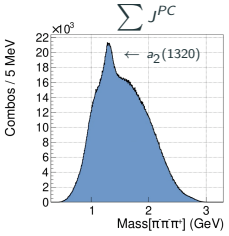


disentangle

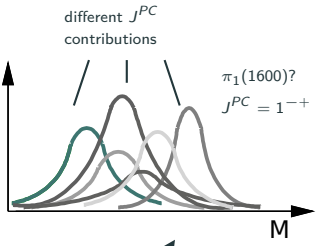


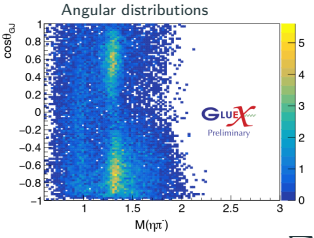
3π photoproduction off a Δ^{++} - Analysis approach





disentangle

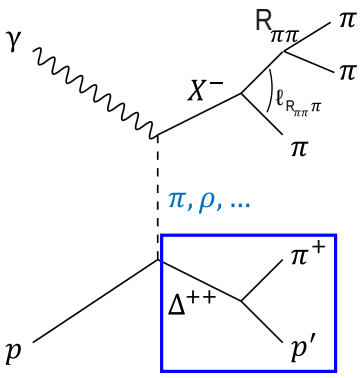


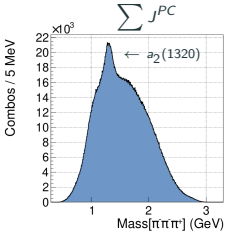


Angular pattern ↔ J^{PC}

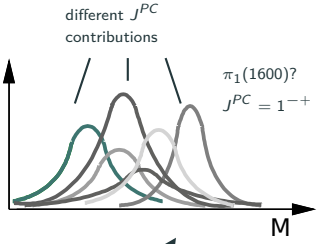
$$I(\theta, \varphi) = |\sum_{\ell, m} a_{\ell m} Y_\ell^m(\theta, \varphi)|^2$$

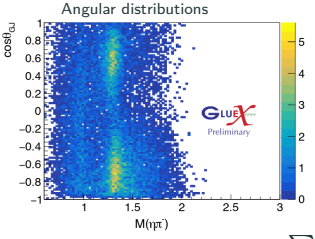
3π photoproduction off a Δ^{++} - Analysis approach





disentangle

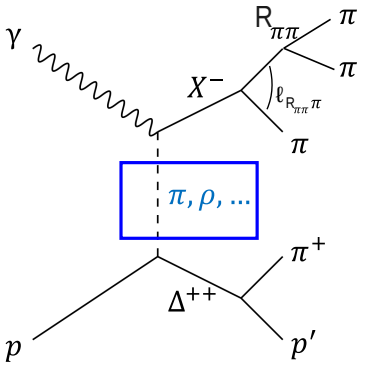


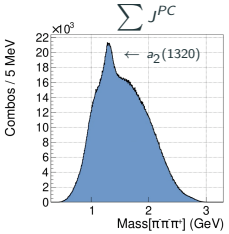


Angular pattern ↔ J^{PC}

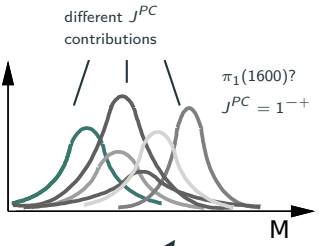
$$I(\theta, \varphi) = |\sum_{\ell,m} a_{\ell m} Y_\ell^m(\theta, \varphi)|^2$$

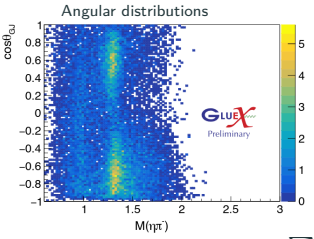
3π photoproduction off a Δ^{++} - Analysis approach





disentangle

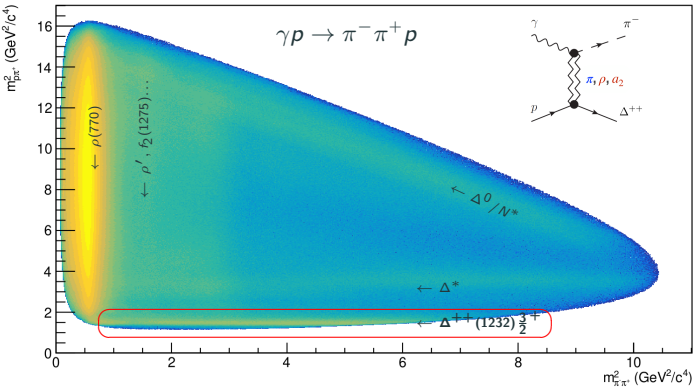




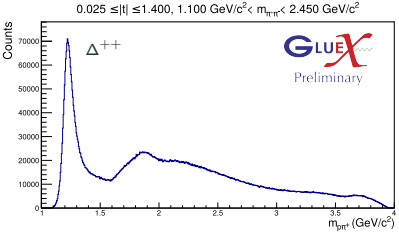
Angular pattern ↔ J^{PC}

$$I(\theta, \varphi) = |\sum_{\ell, m} a_{\ell m} Y_\ell^m(\theta, \varphi)|^2$$

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



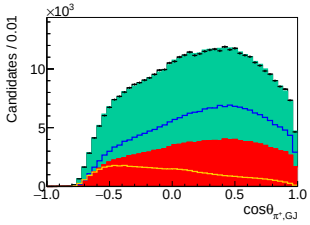
- High statistics available
- Clear Δ^{++} signal with small background contributions from $\pi^+\pi^-$ system

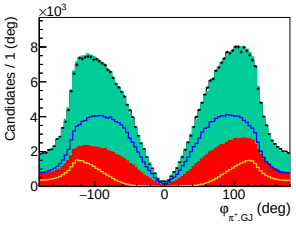


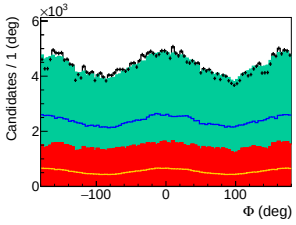
Analyzing decay angles of $\Delta^{++} \rightarrow p\pi^+$ gives access to Spin-density matrix elements!

- 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

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

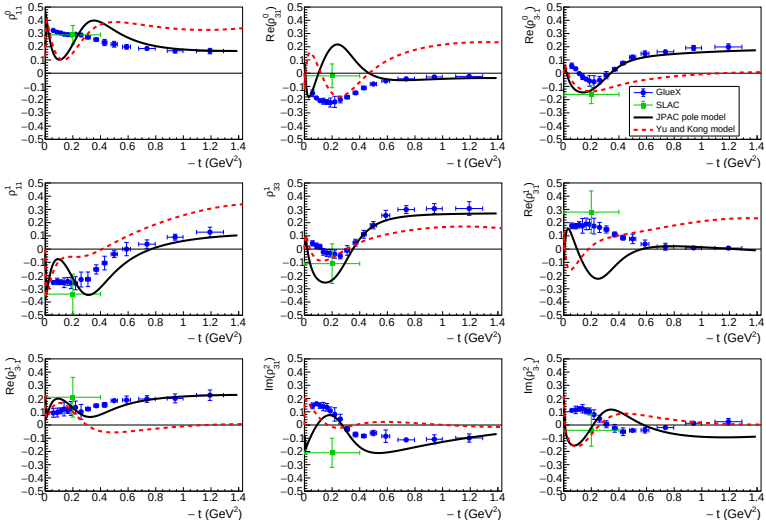






F. Afzal et. al. (GlueX), arXiv:2406.12829

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



- GlueX: arXiv:2406.12829
- SLAC: Phys. Rev. D 7 (1973), 3150

— JPAC: PLB 779, 77 (2018)

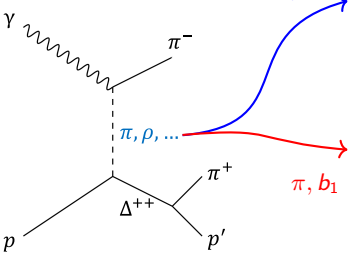
- - - Yu and Kong: PLB 769, 262-266 (2017)

- First precise determination of the *t*-dependence of the $\Delta^{++}(1232)$ SDMEs
- Data provide important constraints on the Regge-theory models
- Relative sign ambiguity of two helicity amplitude couplings in the JPAC model can be resolved with GlueX data

Charge exchange mechanism - $\pi^- \Delta^{++}$

- Separation of unnatural-parity (U) and natural-parity (N) exchanges

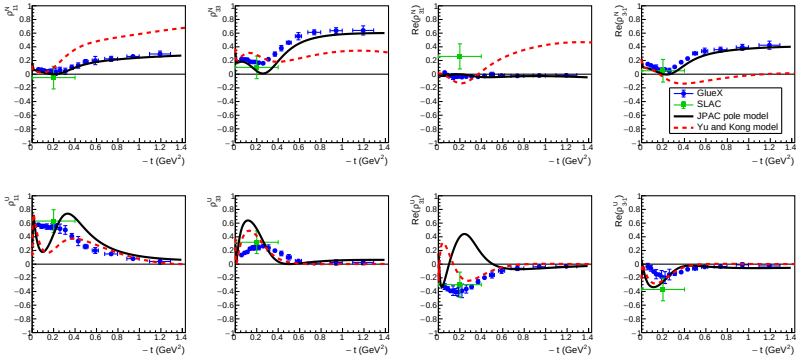
$$\rho_{ij}^{N/U} = \rho_{ij}^{0} \pm \rho_{ij}^{1}$$



naturality of exchanged particle: $\eta = P(-1)^J$

$\eta = +1$ → natural-parity exchange

$\eta = -1$ → unnatural-parity exchange



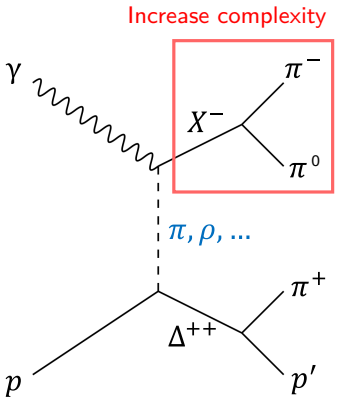
F. Afzal et al. (GlueX), arXiv:2406.12829

— JPAC: Phys. Lett. B 779, 77-81 (2018)

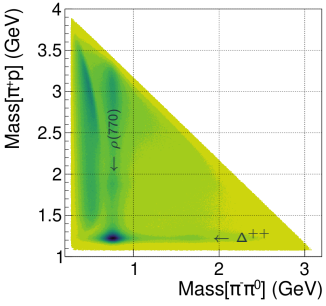
- - - Yu and Kong: PLB 769, 262-266 (2017)

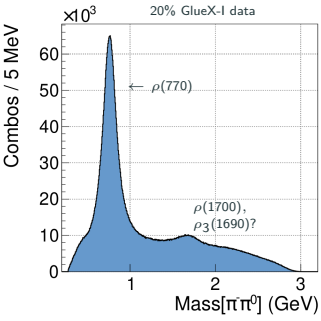
- JPAC model: π (a_2) is the dominant unnatural (natural) exchange
- Important for charge-exchange reactions e.g. $\gamma p \to \eta' \pi \Delta^{++}$, $\gamma p \to 3\pi \Delta^{++}$

Next step - Analysis of $\Delta^{++}\pi^-\pi^0$



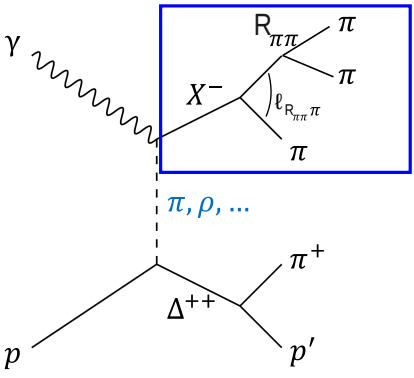
- Focus on $\rho^- \to \pi^-\pi^0$ recoiling off Δ^{++}
  → Important also for $\pi_1(1600)$ search in $\eta'\pi^-\Delta^{++}$

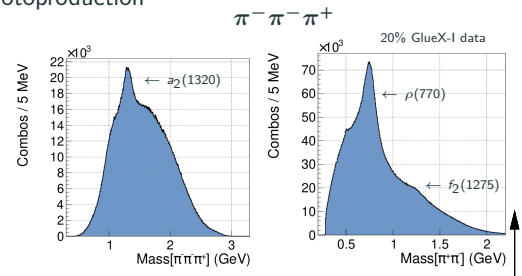


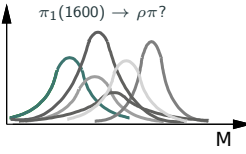


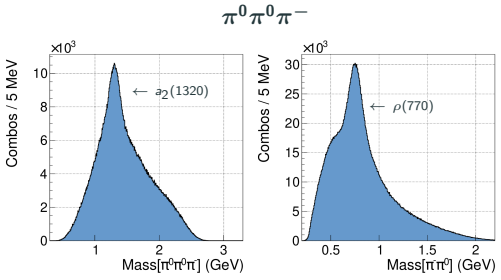
- Analyze entire $\pi^-\pi^0$ spectrum
  → Disentangle resonance contributions → e.g. excited ρ states
  → Important step for developing and testing analysis tools

Exploring the meson spectrum with 3π photoproduction









Summary

- The GlueX experiment has acquired an unprecedented polarized photoproduction dataset and the meson spectroscopy program is well underway
- Emmy Noether research project provides
  - Unique opportunity to explore meson spectrum with 3π photoproduction
  - Possibility to verify the existence of spin-exotic hybrid meson $\pi_1(1600)$
  - Important direct test of QCD
- Project will deepen our understanding of QCD in the non-perturbative regime
- I look forward to having my own research group within the excellent environment at RUB

Thank you!