Understanding photoproduction of ηπ and η'π in the double Regge region

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In collaboration with V. Mathieu, A. Szczepaniak, et al. (JPAC)

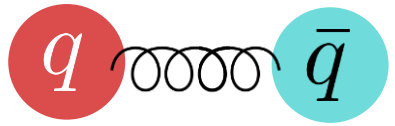
Joint International Workshop on Hadron Structure and Spectroscopy and the QCD Structure of the Nucleon

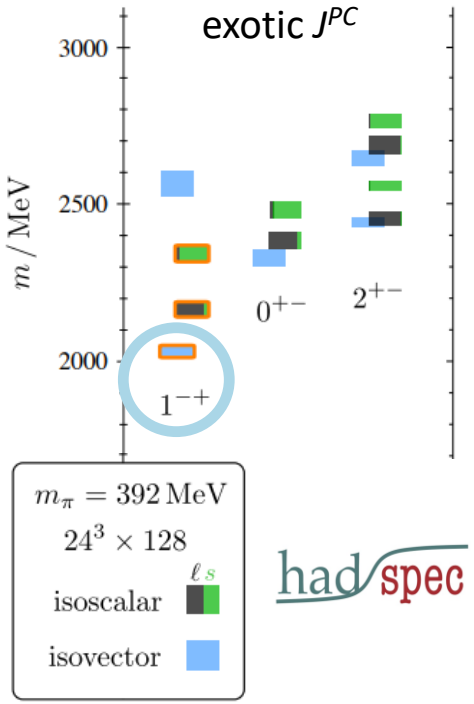
San Sebastián, 01-05 September 2025

Motivation

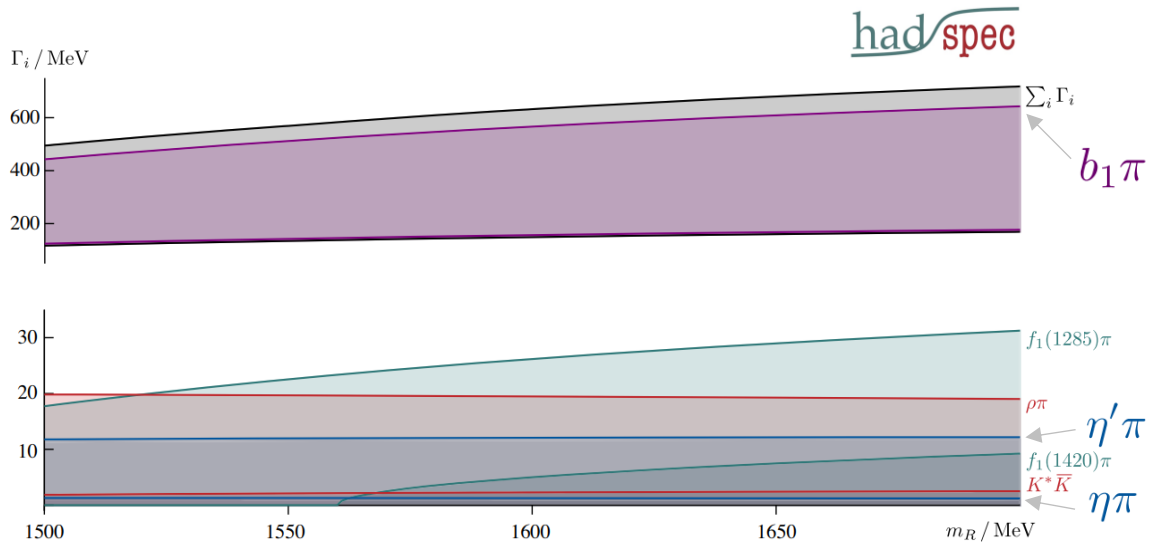
$\pi_1(1600)$ hybrid meson

- Predicted by lattice QCD as the lightest isovector with exotic $J^{PC} = 1^{-+}$
- Multiple decay channels: $b_1\pi$ with the largest decay rate
- Experimental signals in $\eta\pi$ and $\eta'\pi$ (and more) at COMPASS [talk by J. Beckers]





[*Phys.Rev.D* 88, 094505 (2013)]



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Motivation

Searches of the $\pi_1(1600)$ in photoproduction

- A primary goal of the GlueX experiment at Jefferson Lab [talk by A. Austregesilo]
- Amplitude analysis of multi-meson final states requires models for production amplitudes of several processes
  - Resonant contributions (π_1, conventional meson and baryon resonances)
  - Non-resonant backgrounds

↳ Role of JPAC

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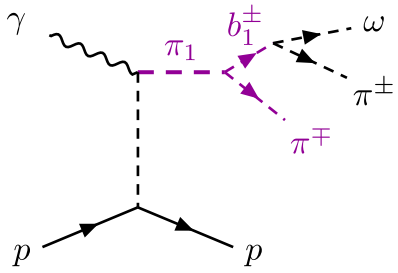

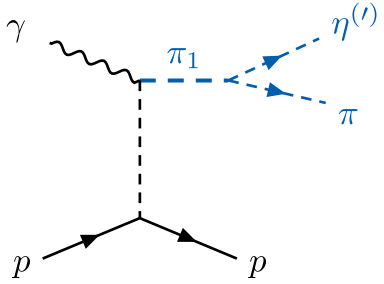

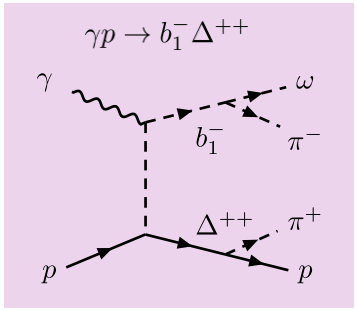

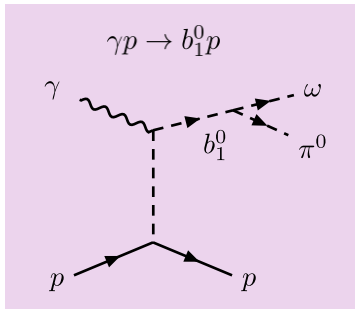

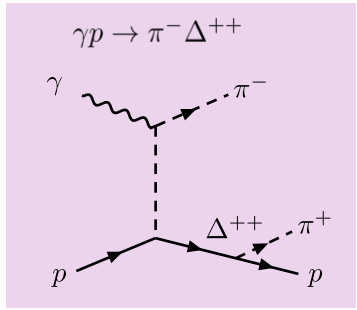

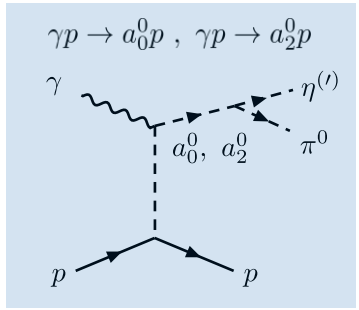

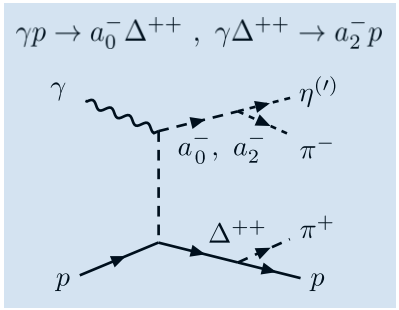

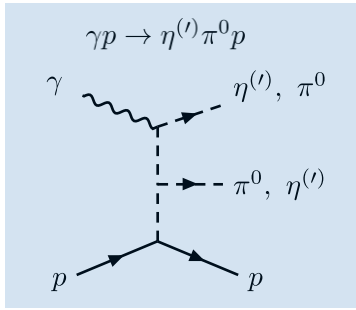

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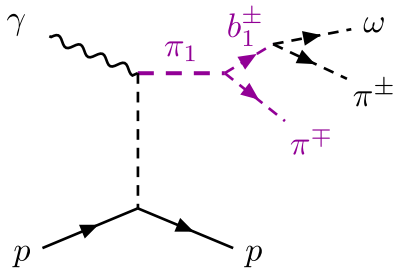
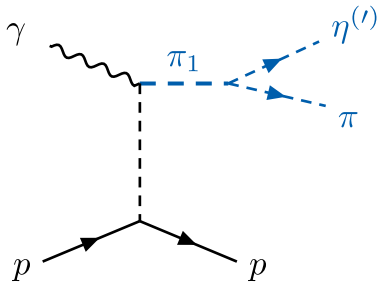
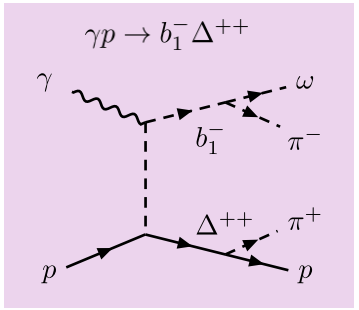
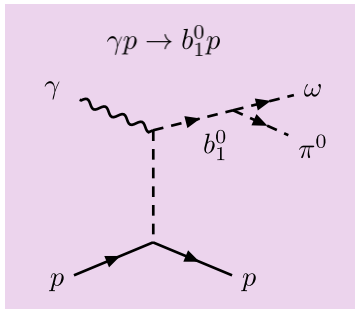
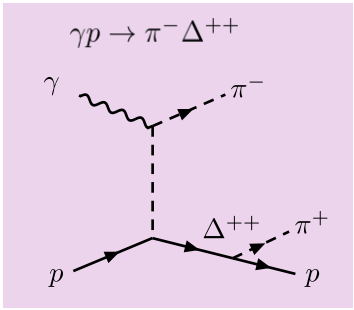
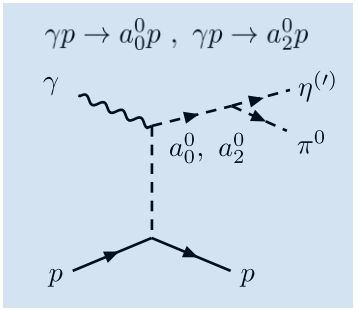


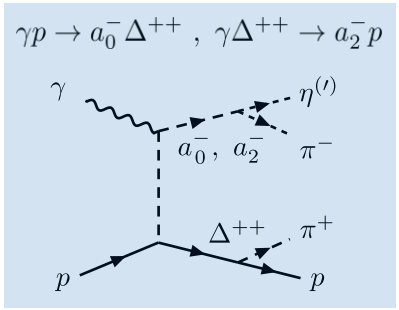


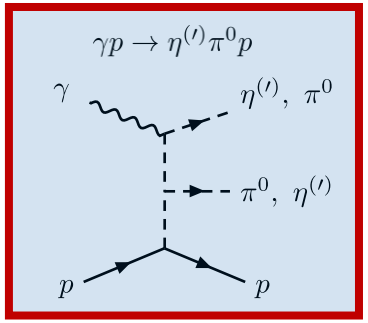












This talk

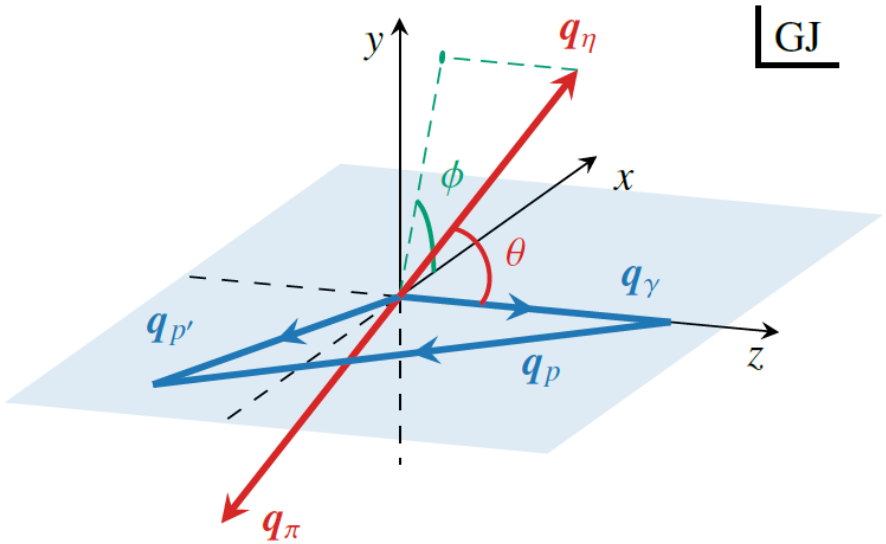
[talk by V. Mathieu]

Double Regge

- Dominant mechanism at high energies (forward, backward production)
- Reaction:

$$\gamma + p \rightarrow \eta^{(\prime)} + \pi^0 + p'$$

- COMPASS and GlueX analyses performed in the Gottfried-Jackson frame
  - Angles θ and ϕ define the direction of the η’



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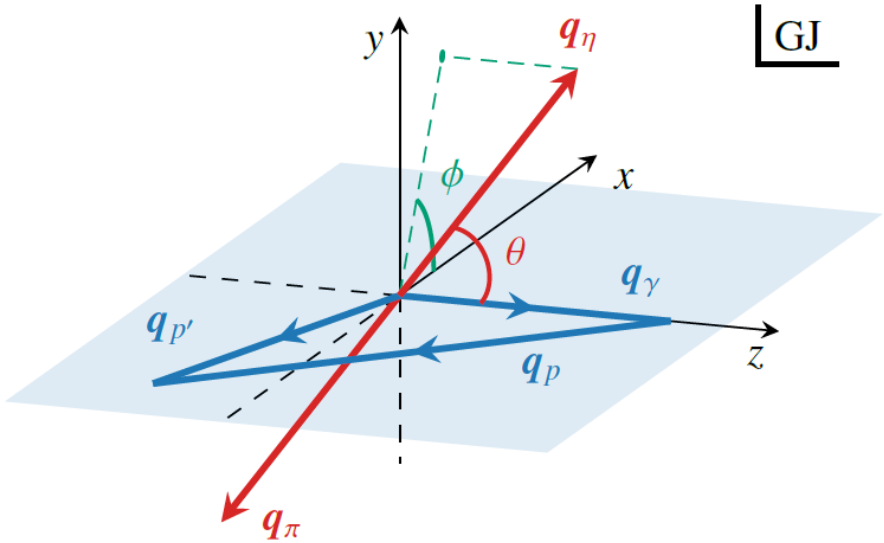
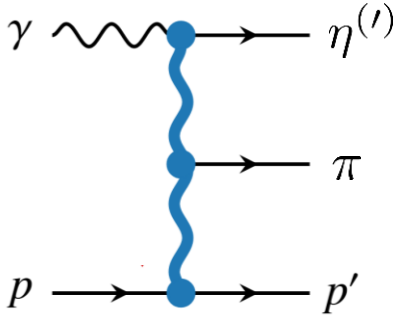
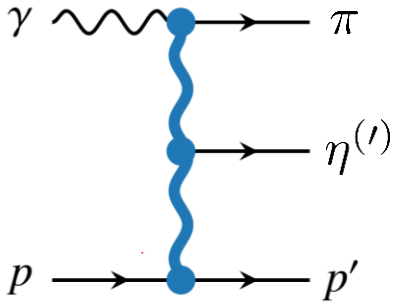


- Two types of diagrams:

Fast η
cos θ ≈ +1
η produced forward



Fast π
cos θ ≈ –1
η produced backward

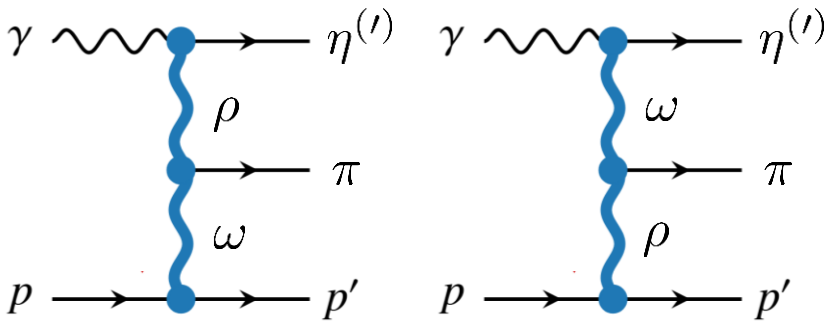


Double-Vector Exchange Model

[GM, V. Mathieu, et al. (JPAC), arXiv:2509.XXXX]

- Vector (natural parity) exchanges are dominant

Fast η



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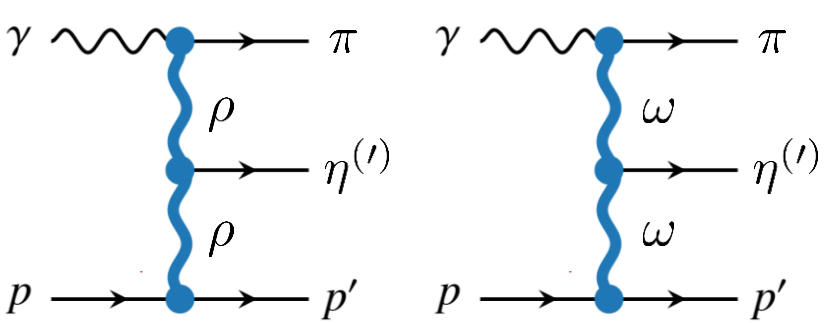

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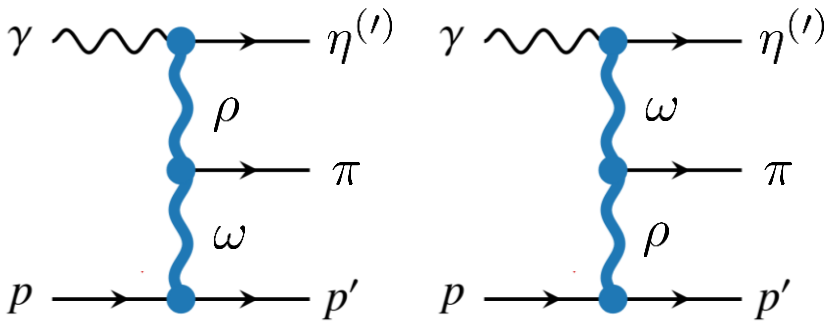

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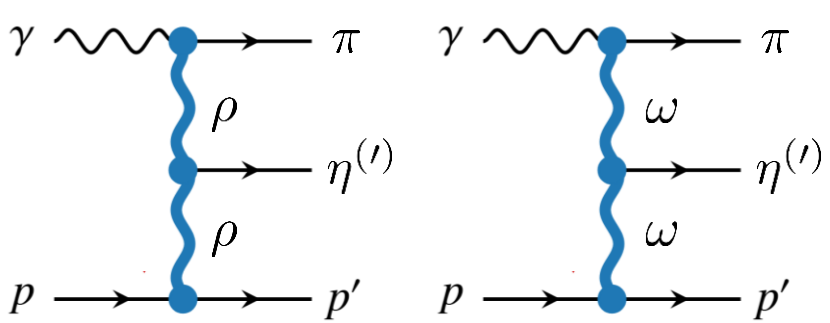
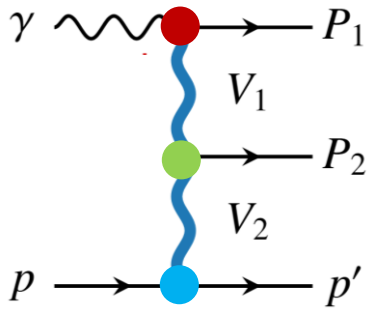


- Lorentz structure of the vertices:



Top vertex: $\langle V_1|\gamma P_1\rangle = \dfrac{g_{\gamma V_1 P_1}}{m_0} i\epsilon_{\alpha\beta\mu\nu}\varepsilon_\gamma^{\alpha *} q_\gamma^\beta q_{V_1}^\mu \varepsilon_{V_1}^\nu$

Middle vertex: $\langle V_2|V_1 P_2\rangle = \dfrac{g_{V_1 V_2 P_2}}{m_0} i\epsilon_{\alpha\beta\mu\nu}\varepsilon_{V_1}^{\alpha *} q_{V_1}^\beta q_{V_2}^\mu \varepsilon_{V_2}^\nu$

Bottom vertex: $\langle N'|V_2 N\rangle = \bar{u}(\vec{q}_{p'}, \mu') \left[(g_1^{V_2} + g_2^{V_2})\gamma_\nu - g_2^{V_2} \dfrac{(q_p + q_{p'})_\nu}{2m_p} \right] u(\vec{q}_p, \mu)$

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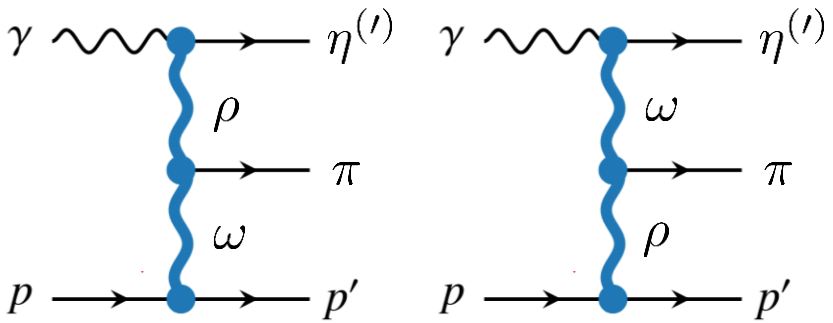

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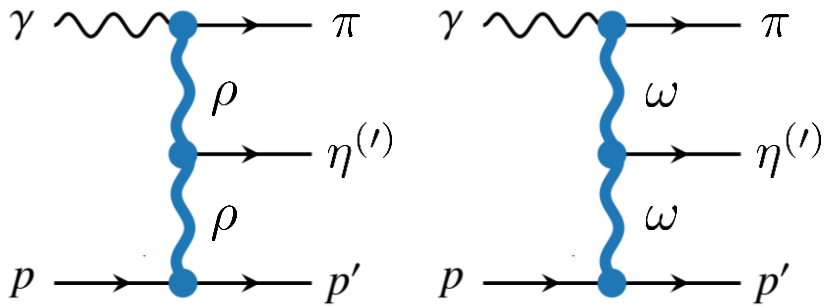

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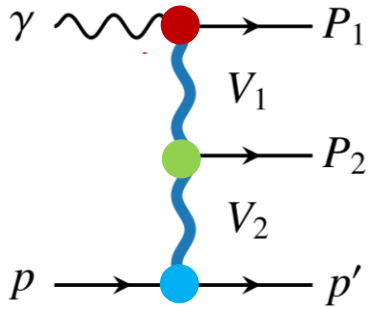

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All couplings are known

Double-Vector Exchange Model

[GM, V. Mathieu, et al. (JPAC), arXiv:2509.XXXX]

- Obtain the helicity amplitude $$A_{\lambda_\gamma \lambda \lambda'} = \sum_{\text{diagrams}} \left(\frac{g_{\gamma V_1 P_1}}{m_0} \frac{g_{V_1 V_2 P_2}}{m_0} \right) \frac{g_{\lambda_\gamma, \lambda' - \lambda} K_{\lambda_\gamma \lambda \lambda'}}{(m_{V_1}^2 - t_1)(m_{V_2}^2 - t_2)}$$

  and identify the kinematical factor $$g_{\lambda_\gamma \lambda \lambda'} K_{\lambda_\gamma \lambda \lambda'} \equiv \bar{u}_{\lambda'} \left[-g_2^{V_2} A_{\lambda_\gamma} + (g_1^{V_2} + g_2^{V_2}) B^{\mu}_{\lambda_\gamma} \gamma_\mu \right] u_\lambda$$

  with $$A_{\lambda_\gamma} = \varepsilon_{\alpha\beta\mu\nu} \epsilon^{\alpha}_{\lambda_\gamma} q_\gamma^\beta q_{P_1}^\mu \varepsilon^{\nu \bar{\beta} \bar{\mu} \bar{\nu}} q_{P_2, \bar{\beta}} (q_\gamma - q_{P_1})_{\bar{\mu}} \frac{(q_p + q_{p'})_{\bar{\nu}}}{2m_p}$$

  $$B^{\bar{\nu}}_{\lambda_\gamma} = \varepsilon_{\alpha\beta\mu\nu} \epsilon^{\alpha}_{\lambda_\gamma} q_\gamma^\beta q_{P_1}^\mu \varepsilon^{\nu \bar{\beta} \bar{\mu} \bar{\nu}} q_{P_2, \bar{\beta}} (q_\gamma - q_{P_1})_{\bar{\mu}}$$

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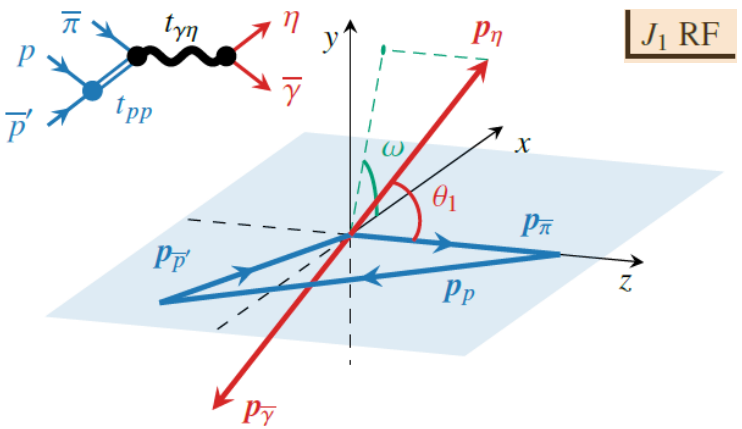
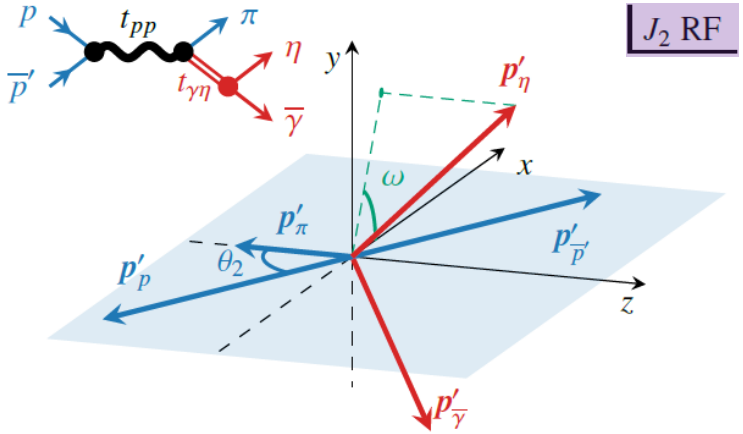
- Simple form in the rest frame of the exchanges $$K_{\lambda_\gamma \lambda \lambda'} = 2 m_p t_1 |\vec{p}_1| |\vec{p}_2| \lambda_\gamma \sum_{\xi=-1}^{1} (-\xi) e^{-i\xi\omega} d^1_{\lambda_\gamma \xi}(\theta_1)\, d^1_{\xi \Lambda}(\theta_2)$$





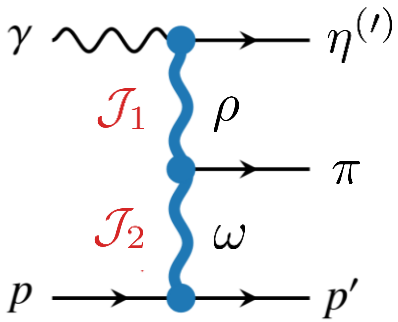
$$g_{\lambda_\gamma, \Lambda} = g_2^{V_2} \frac{|\vec{p}_p\,'|^2}{m_p^2} \delta_{\Lambda,0} + (g_1^{V_2} + g_2^{V_2}) \left(\delta_{\Lambda,0} - \sqrt{2} \frac{E'_p}{m_p} \delta_{|\Lambda|,1} \right)$$

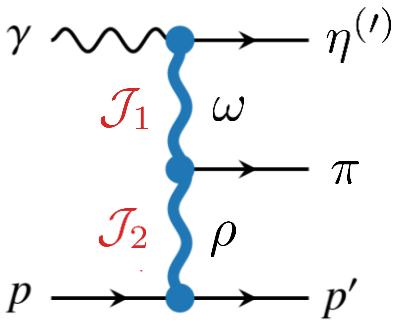
Reggeization

[GM, V. Mathieu, et al. (JPAC), arXiv:2509.XXXX]

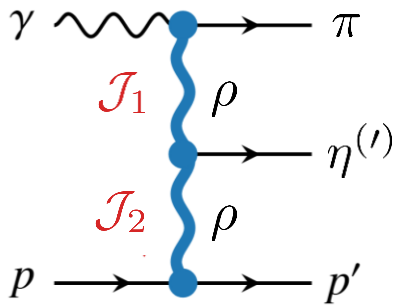
- The vector-vector model fixes the vertices and couplings
- Reggeization of the model needed to describe the double-Regge region:
  - Sum over all spins $\mathcal{J}_1^{\mathcal{P}_1}, \mathcal{J}_2^{\mathcal{P}_2} = 1^-, 3^-, 5^-, \ldots$ ⟶ Regge trajectories of the ρ and ω

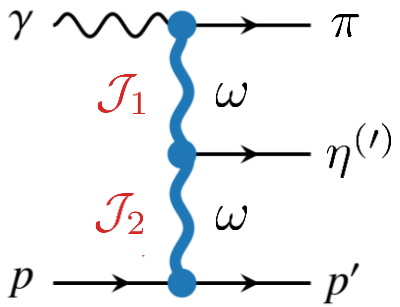
Fast η





Fast π



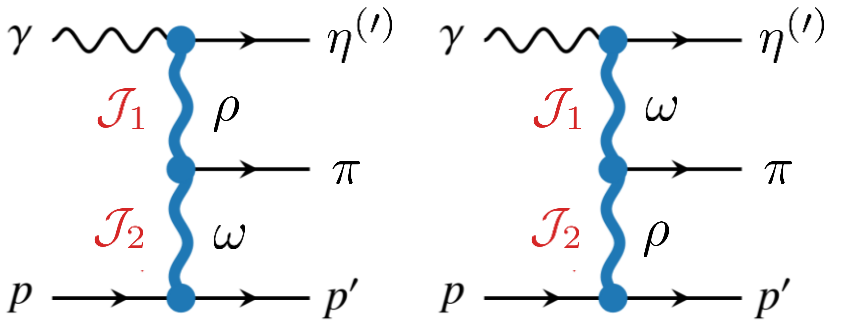


Reggeization

[GM, V. Mathieu, et al. (JPAC), arXiv:2509.XXXX]

- The vector-vector model fixes the vertices and couplings
- Reggeization of the model needed to describe the double-Regge region:
  - Sum over all spins $\mathcal{J}_1^{\mathcal{P}_1}, \mathcal{J}_2^{\mathcal{P}_2} = 1^-, 3^-, 5^-, \ldots$ ⟶ Regge trajectories of the ρ and ω

Fast η



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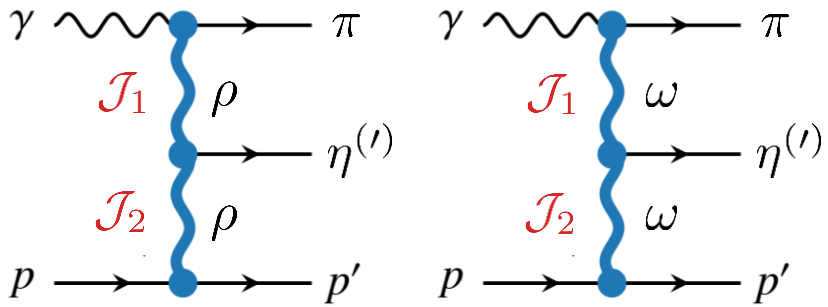

- Multiply the kinematic factor by a Regge factor:

$$K_{\lambda_\gamma \lambda \lambda'} \to K_{\lambda_\gamma \lambda \lambda'} \times R\left(\alpha_1(t_1), \alpha_2(t_2), s_1, s_2, \eta\right) \qquad \text{with} \quad \eta \equiv \frac{s}{\alpha' s_1 s_2}$$

such that the residue at the vector poles (α_1, α_2 = 1) is normalized to 1

Reggeization

[GM, V. Mathieu, et al. (JPAC), arXiv:2509.XXXX]

- Regge factor based on the model of Shimada, Martin, and Irving [*Nucl. Phys. B* 142 (1978)]

$$R(\alpha_1,\alpha_2,s_1,s_2,\eta) = [(\alpha_1-1)\Gamma(1-\alpha_1)]\,[(\alpha_2-1)\Gamma(1-\alpha_2)]$$
$$\times\ [\xi_1\xi_{21}\eta^{\alpha_1-1}V(\alpha_1,\alpha_2,\eta) + \xi_2\xi_{12}\eta^{\alpha_2-1}V(\alpha_2,\alpha_1,\eta)] \left(\frac{s_1}{s_0}\right)^{\alpha_1-1} \left(\frac{s_2}{s_0}\right)^{\alpha_2-1}$$

  - Linear Regge trajectories: $\alpha_i(t_i) = 1 + \alpha'(t_i - m_{V_i}^2)$, with α'=0.9 GeV^{-2}

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- Signature factors keep only odd signature poles $(-1)^{J_1} = (-1)^{J_2} = -1$

$$\xi_i = \frac{1}{2}(1 - e^{-i\pi\alpha_i})\ , \quad \xi_{ij} = \frac{1}{2}(1 + e^{-i\pi(\alpha_i-\alpha_j)})$$

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- Vertex function sums the infinite Reggeon-Reggeon-meson couplings in the middle vertex

$$V(\alpha_1,\alpha_2,\eta) = \frac{\Gamma(\alpha_1-\alpha_2)}{\Gamma(1-\alpha_2)}\,{}_1F_1(1-\alpha_1, 1-\alpha_1+\alpha_2, -\eta^{-1})$$

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- No simultaneous singularities in overlapping channels

Preliminary results

[GM, V. Mathieu, et al. (JPAC), arXiv:2509.XXXX]

- Use linear Regge trajectories: $\alpha_i(t_i) = 1 + \alpha'(t_i - m_{V_i}^2)$, with α'=0.9 GeV^{-2}
- All parameters of the model completely fixed $(s_0 = 1\ \mathrm{GeV}^2)$

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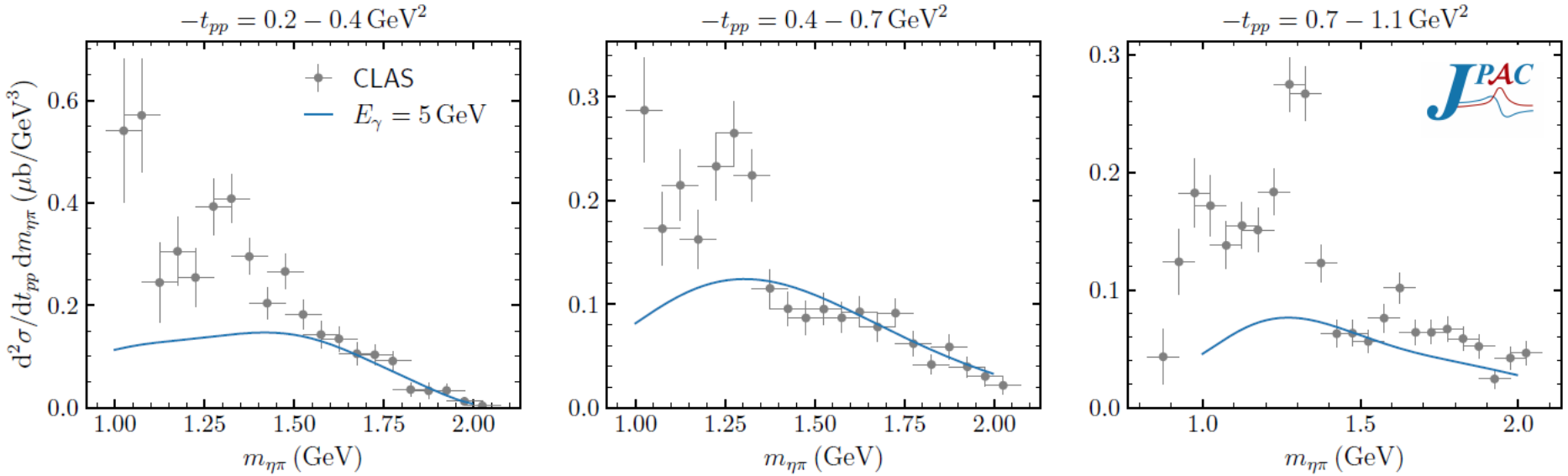
- Comparison with CLAS data: [Phys. Rev. C 102, 032201 (2020)]



Our model provides a good description of the data above the resonance region

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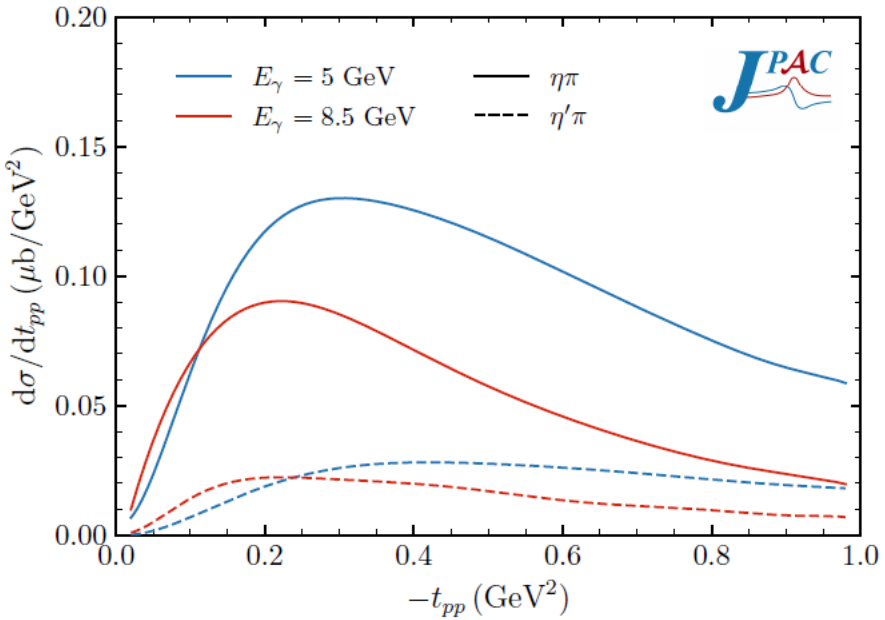
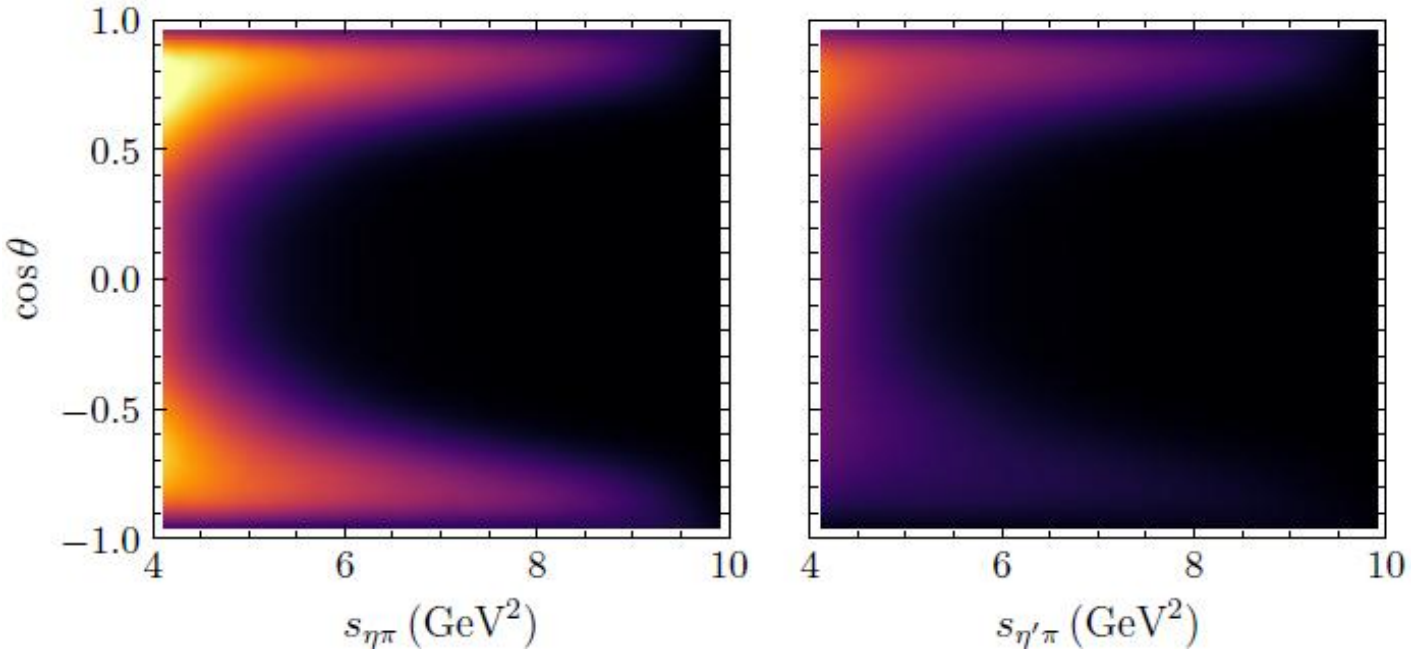
- Predictions for GlueX energy $E_\gamma = 8.5\ \mathrm{GeV}$





We see clear forward and backward peaks

Preliminary results

[GM, V. Mathieu, et al. (JPAC), arXiv:2509.XXXX]

- The **forward-backward asymmetry** is defined as

$$A(m_{\eta\pi}) = \frac{F(m_{\eta\pi}) - B(m_{\eta\pi})}{F(m_{\eta\pi}) + B(m_{\eta\pi})}$$

The forward and backward intensities contain cuts in the kinematic variables

$$F(m_{\eta\pi}) = \int \mathrm{d}^2\Omega_{\mathrm{GJ}}\mathrm{d}z_{\mathrm{cm}} \frac{\mathrm{d}^4\sigma}{\mathrm{d}^2\Omega_{\mathrm{GJ}}\mathrm{d}z_{\mathrm{cm}}\mathrm{d}m^2_{\eta\pi}} \theta(t_{\gamma\eta} > -2\ \mathrm{GeV}^2)\ \Theta(t_{pp}, s_{\eta\pi}, s_{\pi p}, s_{\eta p})$$

$$B(m_{\eta\pi}) = \int \mathrm{d}^2\Omega_{\mathrm{GJ}}\mathrm{d}z_{\mathrm{cm}} \frac{\mathrm{d}^4\sigma}{\mathrm{d}^2\Omega_{\mathrm{GJ}}\mathrm{d}z_{\mathrm{cm}}\mathrm{d}m^2_{\eta\pi}} \theta(t_{\gamma\pi} > -2\ \mathrm{GeV}^2)\ \Theta(t_{pp}, s_{\eta\pi}, s_{\pi p}, s_{\eta p})$$

$$\Theta(t_{pp}, s_{\eta\pi}, s_{\pi p}, s_{\eta p}) = \theta(t_{pp} > -2\ \mathrm{GeV}^2)\ \theta(s_{\eta\pi} > 4\ \mathrm{GeV}^2)\theta(s_{\pi p} > 4\ \mathrm{GeV}^2)\ \theta(s_{\eta p} > 4.75\ \mathrm{GeV}^2)$$

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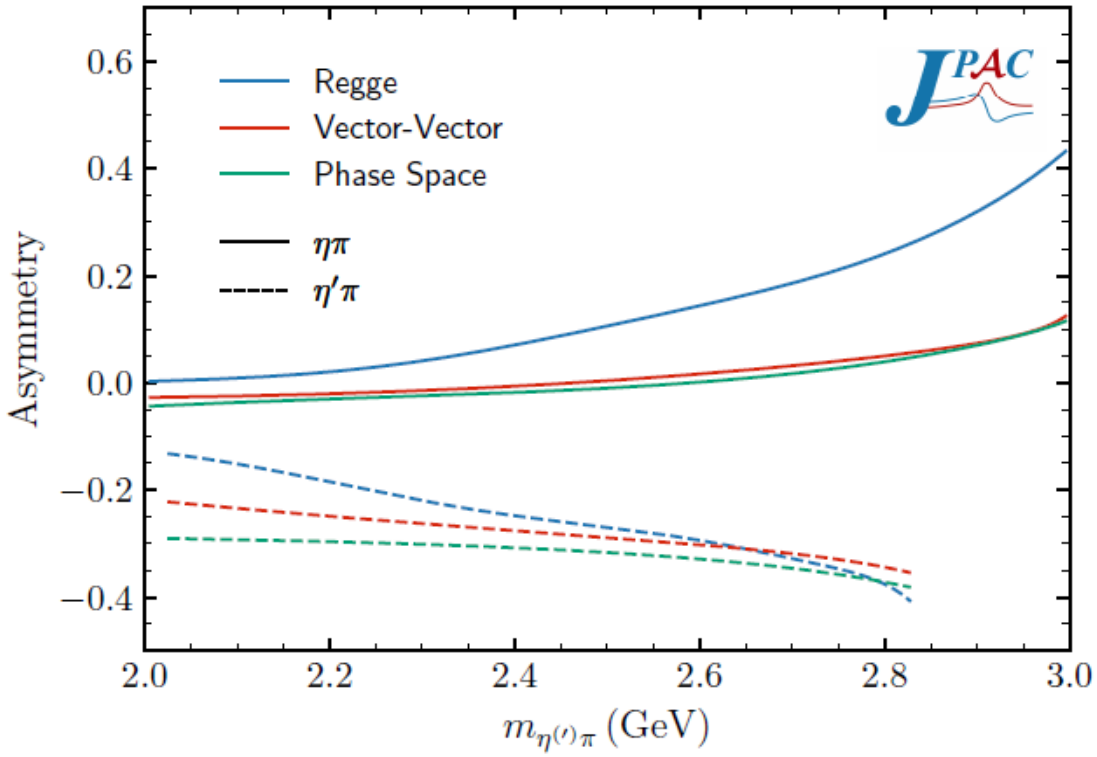
- Comparison between
  - Phase space
  - Double-vector exchange model
  - Regge model



The VV model predicts asymmetries similar to phase space

Reggeization produces the larger asymmetries observed in the data

Summary

- The **double-vector exchange** model fixes the helicity structure of the amplitude for ηπ and η'π photoproduction
- For **ρ and ω exchanges**, all couplings are known
- **Reggeization** provides the correct analytic structure of the amplitude in the double-Regge región
- Agreement with CLAS data at E_γ = 5 GeV
- Predictions for GlueX energy E_γ = 8.5 GeV
- Smaller asymmetry for η'π compared to COMPASS (no Pomeron Exchange in photoproduction)
- Provide a framework for future study of **finite-energy sum rules** (FESRs) to connect the double-Regge region to the contributions of low energy-resonances