Understanding pion exchange in meson photoproduction from a Regge theory perspective

Glòria Montaña

Theory Center, Thomas Jefferson National Accelerator Facility

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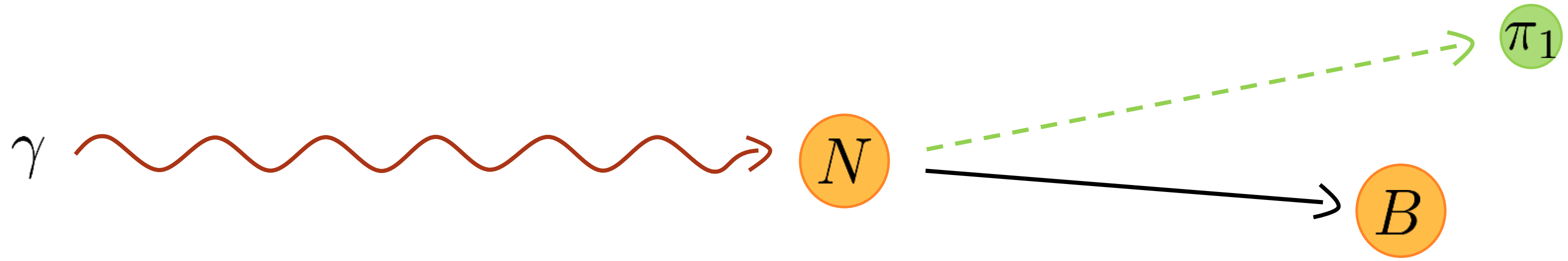
Search for exotic hybrid mesons in photoproduction with GlueX at JLab

- Peripheral meson photoproduction:



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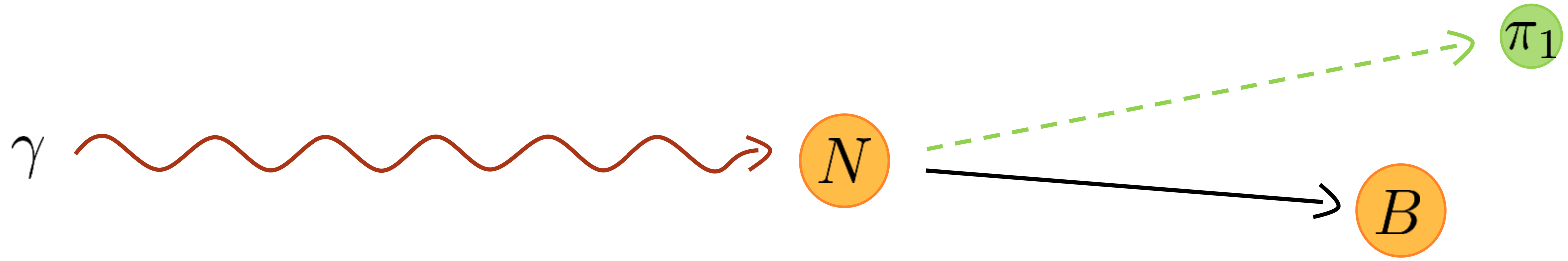
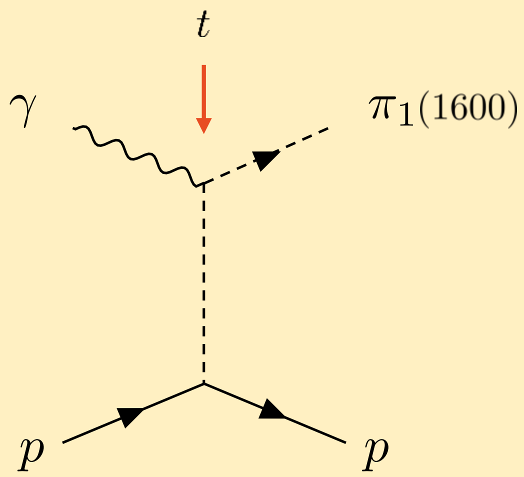


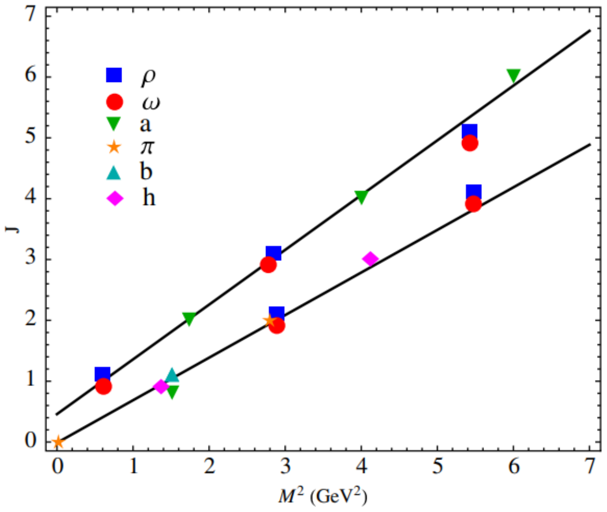
Production mechanism:

exchange of Regge trajectories in the t-channel



Regge trajectories

- Families with same quantum numbers but different spin J (even or odd parity).
- Almost straight lines (Chew-Frautschi plot)
- In standard Regge theory parameterized by: $\alpha(t) = \alpha' t + \alpha_0$



[V.Mathieu et al., *Phys.Rev.D* 98 (2018) 1, 014041]

$$\alpha_\pi(t) = 0.7(t - m_\pi^2) = 0.7t - 0.014$$
$$\alpha_\rho(t) = 0.9(t - m_\rho^2) + 1 = 0.9t + 0.466$$

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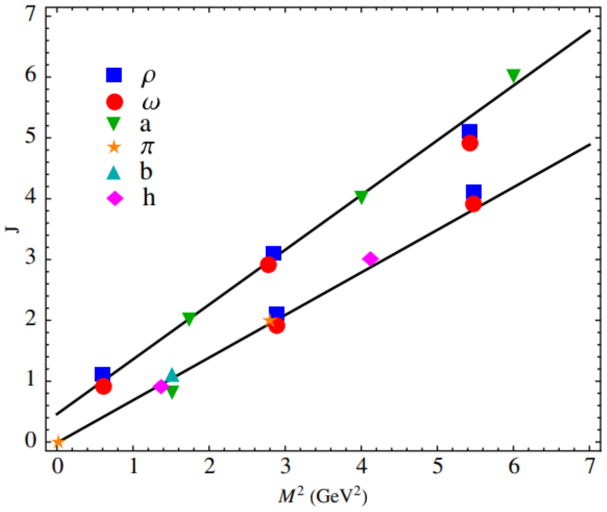

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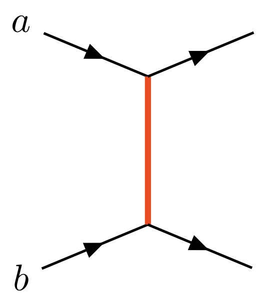
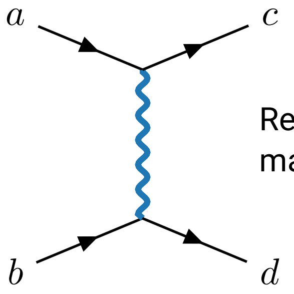


Real particle with mass m and spin J

$$\frac{1}{t - m^2}$$



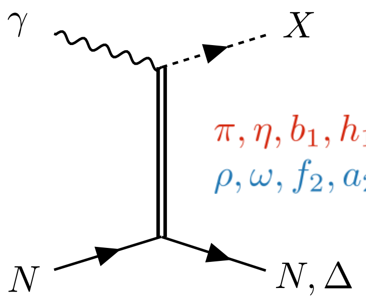
Reggeon with mass $\sqrt{t}$ and spin $\alpha(t)$

$$\mathcal{P}_{\text{Regge}} = \frac{\pi\alpha'}{\sin(\pi\alpha(t))} \frac{1 + \eta e^{-i\pi\alpha(t)}}{2} \left(\frac{s}{s_0}\right)^{\alpha(t)} \frac{1}{\Gamma(1 + \alpha(t))}$$

poles for integer $\alpha(t)$ | signature factor | asymptotic behavior | cancel non-physical poles

Polarized photoproduction at high energies

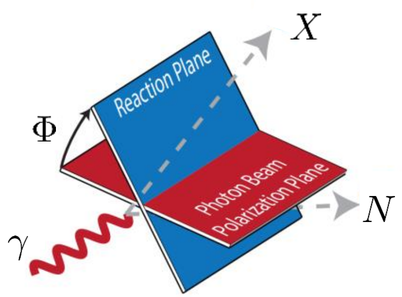
- Linear photon beam polarization used to filter out the “naturality” of exchanged particle.



→ Unnatural ($P(-1)^J = -1$) parity: $0^-, 1^+, 2^-, 3^+, \ldots$

→ Natural ($P(-1)^J = 1$) parity: $0^+, 1^-, 2^+, 3^-, \ldots$

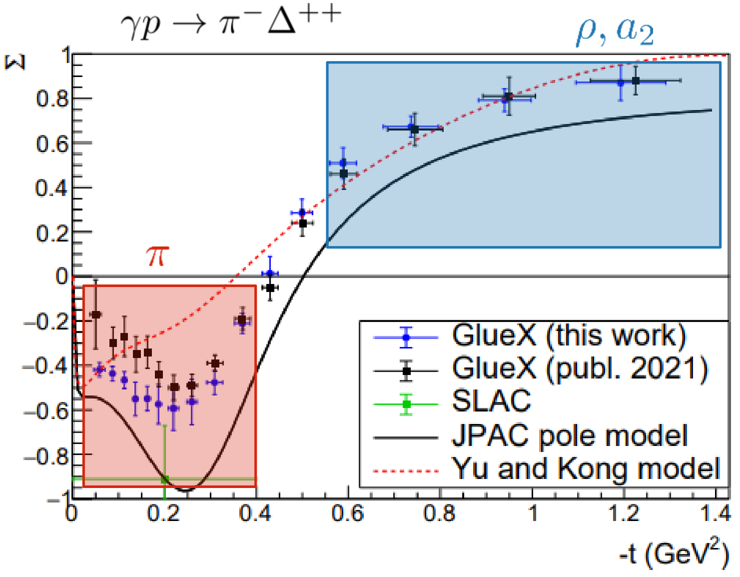
- Beam asymmetry



$$\Sigma = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel} \approx \frac{d\sigma_N - d\sigma_U}{d\sigma_N + d\sigma_U}$$

$\Phi = \frac{\pi}{2}$ $\Phi = 0$ Natural exchange Unnatural exchange

[V.Mathieu et al., *Phys.Rev.D* 92 (2015) 7]



[GlueX Collaboration, arXiv:*2406.12829*]
JPAC Model: [Nys et al. PLB 779, 77 (2018)]

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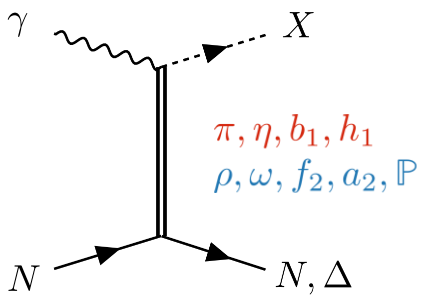

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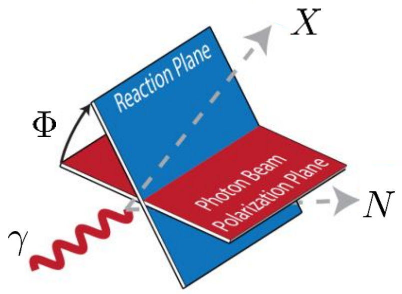

$$\Sigma = \frac{d\sigma_\perp - d\sigma_\parallel}{\underset{\Phi = \frac{\pi}{2}}{d\sigma_\perp} + \underset{\Phi = 0}{d\sigma_\parallel}} \approx \frac{d\sigma_N - d\sigma_U}{\underset{\text{Natural exchange}}{d\sigma_N} + \underset{\text{Unnatural exchange}}{d\sigma_U}}$$

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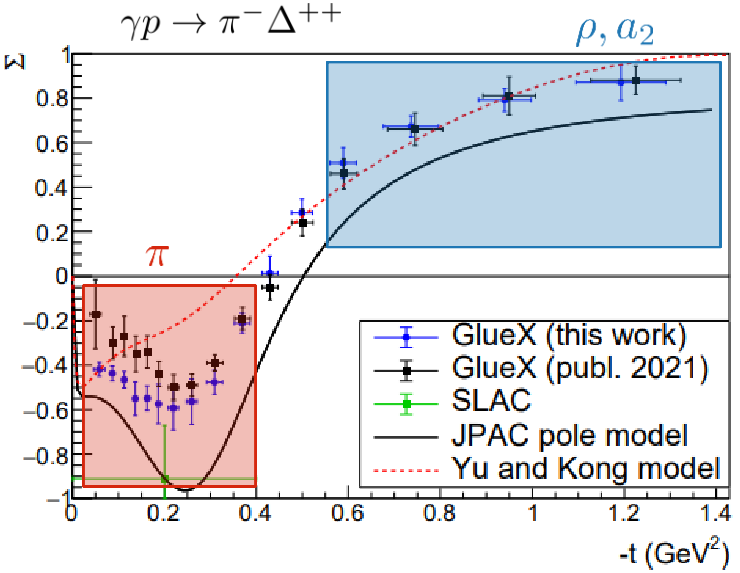

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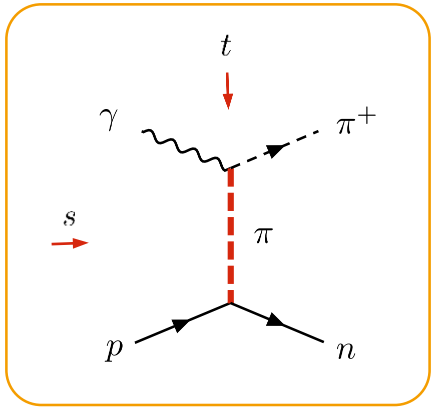
→ **Focus of this talk:** pion exchange mechanism in pion photoproduction

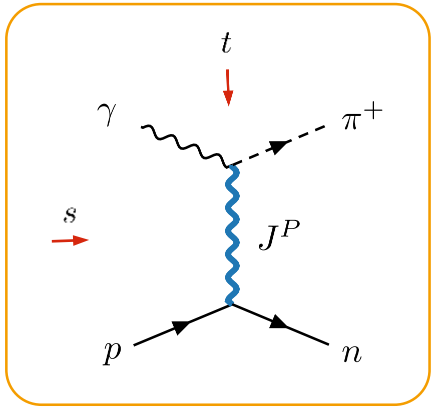
Reggeization of pion exchange

- The exchanged pion is expected to reggeize.
- In the Regge-pole approximation:

$$\frac{1}{t-m_\pi^2} \quad \longrightarrow \quad \mathcal{P}_\pi^{\text{Regge}} = \frac{\pi\alpha'_\pi}{\sin\pi\alpha_\pi(t)} \frac{1+e^{-i\pi\alpha_\pi(t)}}{2} \frac{1}{\Gamma(\alpha_\pi(t)+1)} \left(\frac{s}{s_0}\right)^{\alpha_\pi(t)}$$

Pion trajectory: $\alpha_\pi(t) = \alpha'_\pi(t-m_\pi^2)$ with $\alpha'_\pi = 0.7$





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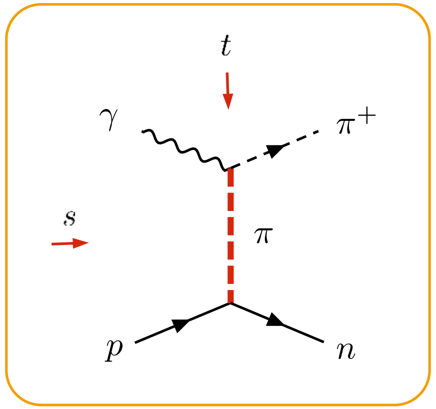
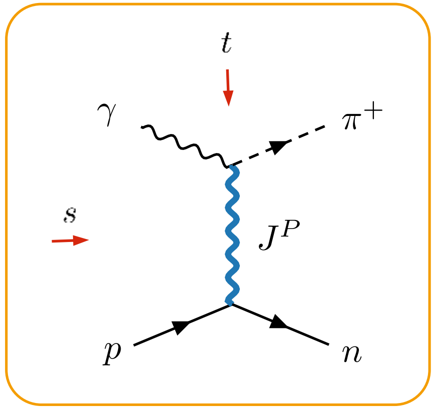




Our approach:

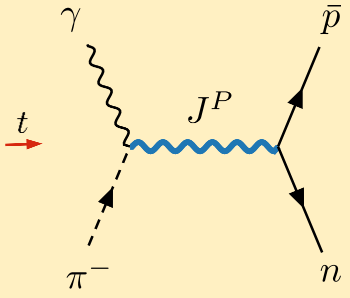
1. Explicit exchange of particles with spin J in the crossed channel (t-channel).

$$\gamma(k) + \bar{\pi}(-p_\pi) \to \bar{N}(-p_i) + N(p_f)$$

2. Sum the tower of exchanges.

$$A_{\lambda_\gamma\lambda_i\lambda_f}(s,t) = \sum_J (2J+1)\, a^J_{\lambda_\gamma\lambda_i\lambda_f}(t)\, d^J_{\lambda_\gamma\lambda_i-\lambda_f}(\theta_t)$$

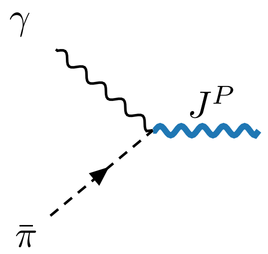
3. Analytical continuation to s-channel physical region.



$J = 0, 2, 4, \ldots$
$P = -1$

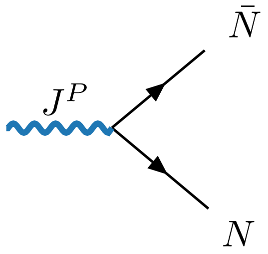
1.1 Exchange of arbitrary spin $J^P = (\mathrm{even})^-$

Build amplitudes for the exchange of arbitrary spin:



$$1^- \otimes 0^- = 1^+ \quad \left\{ \begin{array}{ll} L = 1 & J = 0 \\ L = \{J-1, J+1\} & J \geq 2 \end{array} \right\}$$ one L vs two L's

$$V^J_{\lambda_\gamma}(M) = 2\sqrt{2} g_{\gamma\pi} \left[k^{\nu_1} \cdots k^{\nu_J} \epsilon_\mu(k, \lambda_\gamma) p^\mu_\pi - (k \cdot p_\pi) k^{\nu_1} \cdots k^{\nu_{J-1}} \epsilon^{\nu_J}(k, \lambda_\gamma) \right] \epsilon^*_{\nu_1 \cdots \nu_J}(M)$$ → Gauge invariant by construction



$$\tfrac{1}{2}^+ \otimes \tfrac{1}{2}^- = 0^- \oplus 1^- \rightarrow L = J$$

$$V^J_{\lambda_i \lambda_f}(M) = g_{N\bar{N}} P^{\nu_1} \cdots P^{\nu_J} \epsilon_{\nu_1 \cdots \nu_J}(M)\, \bar{u}(p_f, \lambda_f)\, \gamma_5\, v(-p_i, \lambda_i) \qquad (P^\nu = p^\nu_i + p^\nu_f)$$

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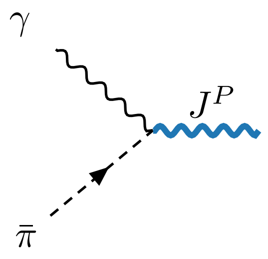

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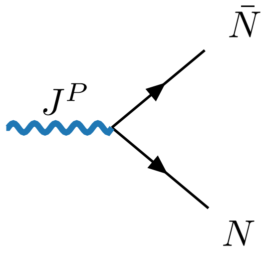

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$$A^J_{\lambda_\gamma \lambda_i \lambda_f}(s,t) = \sum_M \frac{V_{\lambda_\gamma}(J,M) V_{\lambda_i \lambda_f}(J,M)}{J - \alpha_\pi(t)} = a^J_{\lambda_\gamma \lambda_i \lambda_f}(t)\, d^J_{\lambda_\gamma \lambda_i - \lambda_f}(\theta_t)$$

$\boldsymbol{J > 0}$

pole in J

spin - J amplitude ($J > 0$): $\quad a^J_{\lambda_\gamma \lambda_i \lambda_f}(t) \equiv \dfrac{2 e_\pi g_J t}{J - \alpha_\pi(t)} (2\lambda_i \delta_{\lambda_i \lambda_f}) c^2_J \sqrt{\dfrac{J+1}{J}} (-2 p_t k_t)^J$

$(e_\pi g_J = g_{\gamma\pi} g_{N\bar{N}})$

1.2 Analytical continuation to $J = 0$

To include the pion, we must extend definition of the spin-J amplitude to $J = 0$. The general expression diverges:

$$a^J_{\lambda_\gamma \lambda_i \lambda_f}(t) \equiv \frac{2e_\pi g_J t}{J - \alpha_\pi(t)}(2\lambda_i \delta_{\lambda_i \lambda_f}) c_J^2 \sqrt{\frac{J+1}{J}}(-2p_t k_t)^J$$

- Wigner d-functions can be expressed in terms of Jacobi polynomials:

$$d^J_{\lambda_\gamma 0}(\theta_t) = \sqrt{\frac{J+1}{2J}} d^1_{\lambda_\gamma 0}(\theta_t) P^{11}_{J-1}(z_t)$$

- We impose definite signature: $P^{ab}_n(-z) = (-1)^n P^{ba}_n(z)$, $P^{11}_{J-1}(z_t) \to \frac{1}{2}(P^{11}_{J-1}(z_t) - P^{11}_{J-1}(-z_t))$
- Analytical continuation using the hyperbolic function: $P^{11}_{J-1}(z_t) = J \, {}_2\tilde{F}_1\left(1-J, J+2; 2; \frac{1-z_t}{2}\right)$

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The contribution to the amplitude from $J = 0$ is finite!

$$\begin{aligned}
A^{J=0}_{\lambda_\gamma\lambda_i\lambda_f}(s,t) = a^{J\to 0}_{\lambda_\gamma\lambda_i\lambda_f}(t)\, d^{J\to 0}_{\lambda_\gamma\lambda_i-\lambda_f}(\theta_t) &= \frac{e_\pi\, g_{J\to 0}\, t}{\alpha_\pi(t)}(2\lambda_i\lambda_\gamma\delta_{\lambda_i\lambda_f})\sqrt{1-z_t^2}\,\frac{1}{2J}\left[P^{11}_{J-1}(z_t) - P^{11}_{J-1}(-z_t)\right]\Big|_{J=0} \\
&= \frac{2\, e_\pi\, g_0\, t}{-\alpha_\pi(t)}(2\lambda_i\lambda_\gamma\delta_{\lambda_i\lambda_f})\frac{z_t}{\sqrt{1-z_t^2}} \\
&\approx -i2e_\pi g_{\pi NN}\lambda_\gamma(2\lambda_i\delta_{\lambda_i\lambda_f})\frac{t}{m_\pi^2 - t}
\end{aligned}$$

This term projects back into all partial waves!

$(g_{J\to 0} = \alpha' g_{\pi NN})$

2. Spin summation

$$A^{\text{Regge}\,\pi}_{\lambda_\gamma\lambda_i\lambda_f}(s,t) = \sum_{J=0,2,\ldots}(2J+1)a^J_{\lambda_\gamma\lambda_i\lambda_f}(t)d^J_{\lambda_\gamma,\lambda_i-\lambda_f}(\theta_t)$$

$$= -2e_\pi\lambda_\gamma(2\lambda_i\delta_{\lambda_i\lambda_f})t\sin\theta_t\sum_{J=0,1,2,\ldots}(-2)^J g_J c_J^2\frac{(2J+1)(J+1)}{2J(J-\alpha_\pi(t))}(p_tk_t)^J\frac{1}{2}\left[P^{|\lambda_\gamma-\lambda'||\lambda_\gamma+\lambda'|}_{J-1}(z_t) - P^{|\lambda_\gamma+\lambda'||\lambda_\gamma-\lambda'|}_{J-1}(-z_t)\right]$$

- For high spins, the coupling reflects the internal structure of the hadronic radii: $g_J = \alpha' g_{\pi NN}h_J(r_tr_b)^J$
- The kinematical factor has alternating poles and zeros for $J<0$. We approximate: $c_J^2h_J(2r_tr_b)^J \to \frac{j_p}{j_z}\frac{J+j_z}{J+j_p}R^{2J}$

effective zero

hadronic radius

effective pole

- Use the generating function of the Jacobi polynomials to perform the spin summation.

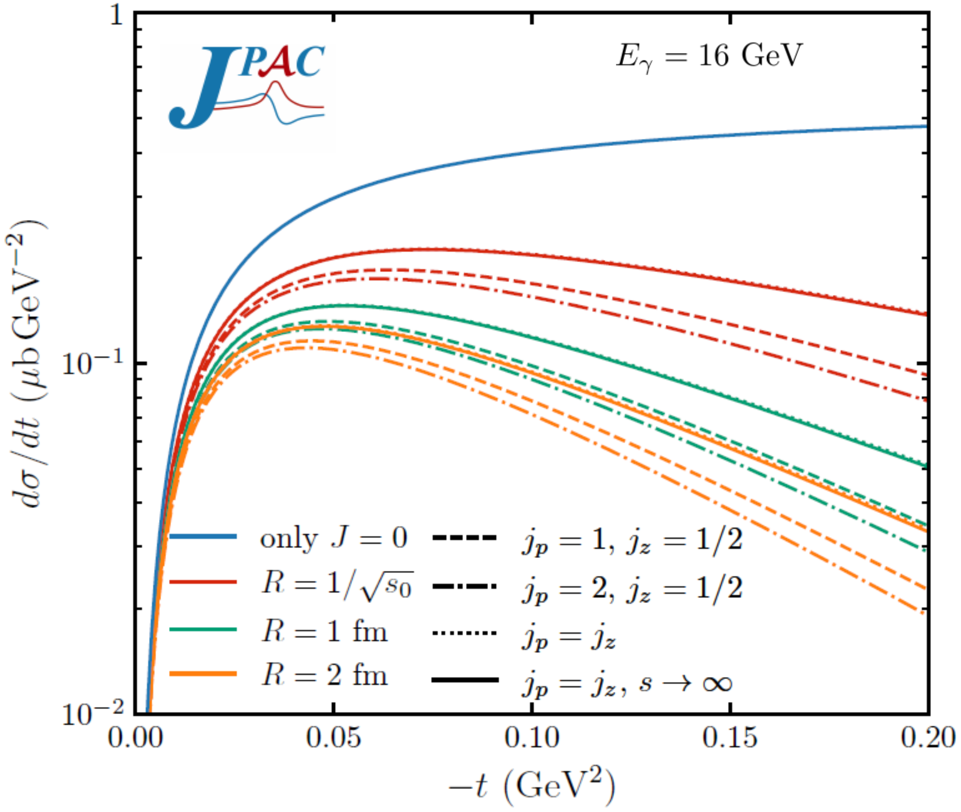
Option 1: solve numerically an integral equation with parameters $R,\ j_p,\ j_z$.

Option 2: consider the dominant contribution of the Regge pole, in the limit of large s.

Results

- We define $A^{\text{Regge}\,\pi}_{\lambda_\gamma\lambda_i\lambda_f}(s,t) = -i2e_\pi g_{\pi NN}\lambda_\gamma(2\lambda_i\delta_{\lambda_i\lambda_f})t \times \mathcal{A}(s,t)$

[G.Montana et al. (in preparation)]



Only J = 0 contribution: $\mathcal{A}^{J=0} = \mathcal{P}_\pi = -\dfrac{\alpha'}{\alpha(t)} = \dfrac{1}{m_\pi^2 - t}$.

Option 1:

$$\begin{aligned}\mathcal{A}_\pi^{j_p,j_z}(s,t) = \mathcal{P}_\pi - \Bigg\{ &\frac{i\alpha'\kappa\sin\theta_t}{2}\int_0^1 dy \left[\frac{1}{-\alpha} + y^{-\alpha}\frac{j_p(\alpha+j_z)(\alpha+1)(2\alpha+1)}{\alpha j_z(\alpha+j_p)}\right. \\ &\left. + y^{j_p}\frac{(j_z-j_p)(1-j_p)(1-2j_p)}{j_z(j_p+\alpha)}\right] \\ &\times 2\left[\frac{1}{G(z_t,y)}\frac{1}{(1+G(z_t,y))^2-(\kappa y)^2} - (z_t\to -z_t)\right] \\ &+ \frac{4j_p}{j_z}\left[\frac{1}{G(z_t,\kappa)}\frac{1}{1+G(z_t,\kappa))^2-\kappa^2} - (z_t\to -z_t)\right]\Bigg\}\end{aligned}$$

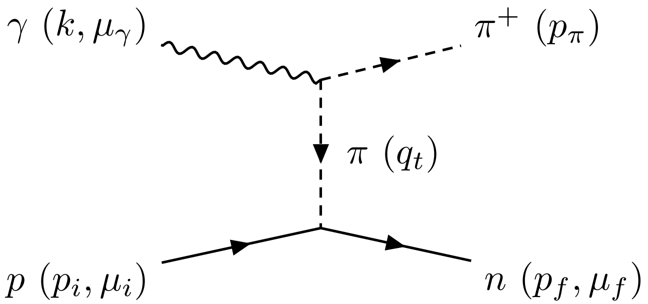
Option 2:

$$\mathcal{A}^{s\to\infty}(s,t) = \mathcal{P}_\pi^{s\to\infty} = -\frac{\alpha' 2\sqrt{\pi}}{\sin\pi\alpha}\frac{\Gamma(\alpha+3/2)}{\Gamma(\alpha+1)}\frac{1+e^{-i\pi\alpha}}{2}(sR^2)^\alpha$$

vs $\mathcal{P}_\pi^{\text{Regge}} = -\dfrac{\pi\alpha'}{\sin\pi\alpha}\dfrac{1}{\Gamma(\alpha+1)}\dfrac{1+e^{-i\pi\alpha}}{2}\left(\dfrac{s}{s_0}\right)^\alpha$ $\quad(s_0 = 1\ \text{GeV}^2)$

Born diagrams

t - channel diagram



\+

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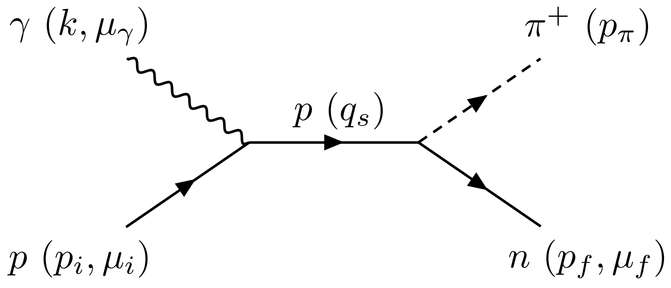
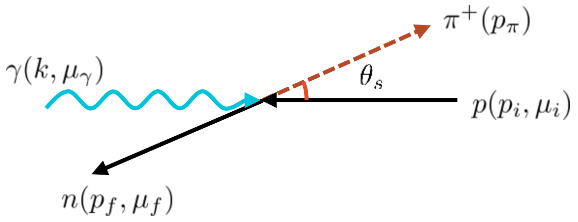


- Separate electric and magnetic contributions:

s - channel CM frame

$\gamma + p \to \pi^+ + n$



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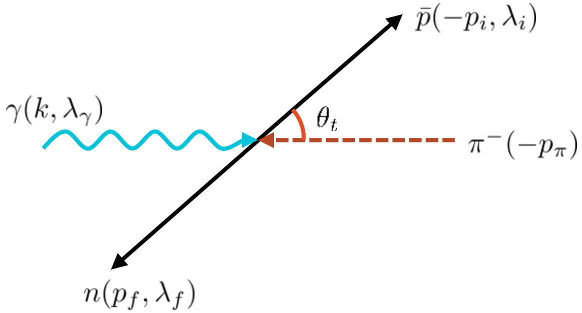
$$A^{\rm e}_{\mu_\gamma\mu_i\mu_f} = 2\sqrt{2}eg_{\pi NN}\left[\frac{(\epsilon(k,\mu_\gamma)\cdot p_\pi)}{t-m_\pi^2} + \cancel{\frac{(\epsilon(k,\mu_\gamma)\cdot p_i)}{s-m_p^2}}\right]\bar{u}(p_f,\mu_f)\,\gamma_5\,u(p_i,\mu_i)$$

dominant

vanishes

t - channel CM frame

$\gamma + \pi^- \to \bar{p} + n$



$$A_{\lambda_\gamma\lambda_i\lambda_f} = A^{\rm e}_{\lambda_\gamma\mu_i\mu_f} + A^{\rm m}_{\lambda_\gamma\lambda_i\lambda_f}$$

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vanishes

dominant

Minimal gauge invariant decomposition of the Born amplitude

- Necessary and sufficient Lorentz structure to ensure gauge invariance of pion diagram:

$$F^{\mu\nu} P_\mu \, p_{\pi,\nu} = (\epsilon(k,\lambda_\gamma)\cdot P)\,(k\cdot p_\pi) - (\epsilon(k,\lambda_\gamma)\cdot p_\pi)\,(k\cdot P) \qquad \text{with} \qquad F^{\mu\nu} = \epsilon^\mu k^\nu - \epsilon^\nu k^\mu$$

→ "minimal gauge invariant" pion exchange amplitude:

$$A^{\pi\text{-m.g.i.}}_{\lambda_\gamma\lambda_i\lambda_f} = 2\sqrt{2} e_\pi g_{\pi NN} \left(\frac{\epsilon(k,\lambda_\gamma)\cdot p_\pi}{t - m_\pi^2} + \frac{\epsilon(k,\lambda_\gamma)\cdot P}{s-u} \right) \bar{u}(p_f,\lambda_f)\,\gamma_5\, v(-p_i,\lambda_i)$$

restores gauge invariance of the bare pion exchange

- We can rewrite the electric Born term:

(t - channel CM frame)

$$A^{\mathrm{e}}_{\lambda_\gamma\lambda_i\lambda_f} = 2\sqrt{2} e g_{\pi NN} \left[\left(\cancel{\frac{\epsilon(k,\lambda_\gamma)\cdot p_\pi}{t - m_\pi^2}} + \frac{\epsilon(k,\lambda_\gamma)\cdot P}{s-u} \right) \right.$$
$$\left. + \frac{1}{2} \left(\cancel{\frac{\epsilon(k,\lambda_\gamma)\cdot p_\pi}{s - m_N^2}} + \frac{\epsilon(k,\lambda_\gamma)\cdot P}{s-u} \frac{t - m_\pi^2}{s - m_N^2} \right) \right] \bar{u}(p_f,\lambda_f)\,\gamma_5\, v(-p_i,\lambda_i) \approx -i\, 2 e_\pi g_{\pi NN} \lambda_\gamma \left(2\lambda_i \delta_{\lambda_i\lambda_f}\right) \frac{t}{m_\pi^2 - t} = A^{J=0}_{\lambda_\gamma\lambda_i\lambda_f}(s,t)$$

→ Minimal gauge invariant (m.g.i.)

subleading at large s

- Gauge invariance relates the pion and nucleon exchanges.
- The nucleon exchange diagram originates the pion pole in the t - channel CM frame.

Magnetic term

[G.Montana et al. (in preparation)]

- The magnetic term is gauge invariant by itself.

$$A^{\mathrm{m}}_{\mu_\gamma \mu_i \mu_f} = \sqrt{2} g_{\pi NN} \left[\frac{e_{N_i}}{s - M^2} + \frac{e_{N_f}}{u - M^2} \right] \bar{u}(p_f, \mu_f) \gamma_5 \not{k} \not{\epsilon}_{\mu_\gamma} u(p_i, \mu_i)$$
$$\approx \mu_\gamma 2 g_{\pi NN} (e_{N_i} - e_{N_f}) \delta_{\mu_\gamma \mu_i} \delta_{-\mu_i \mu_f}$$

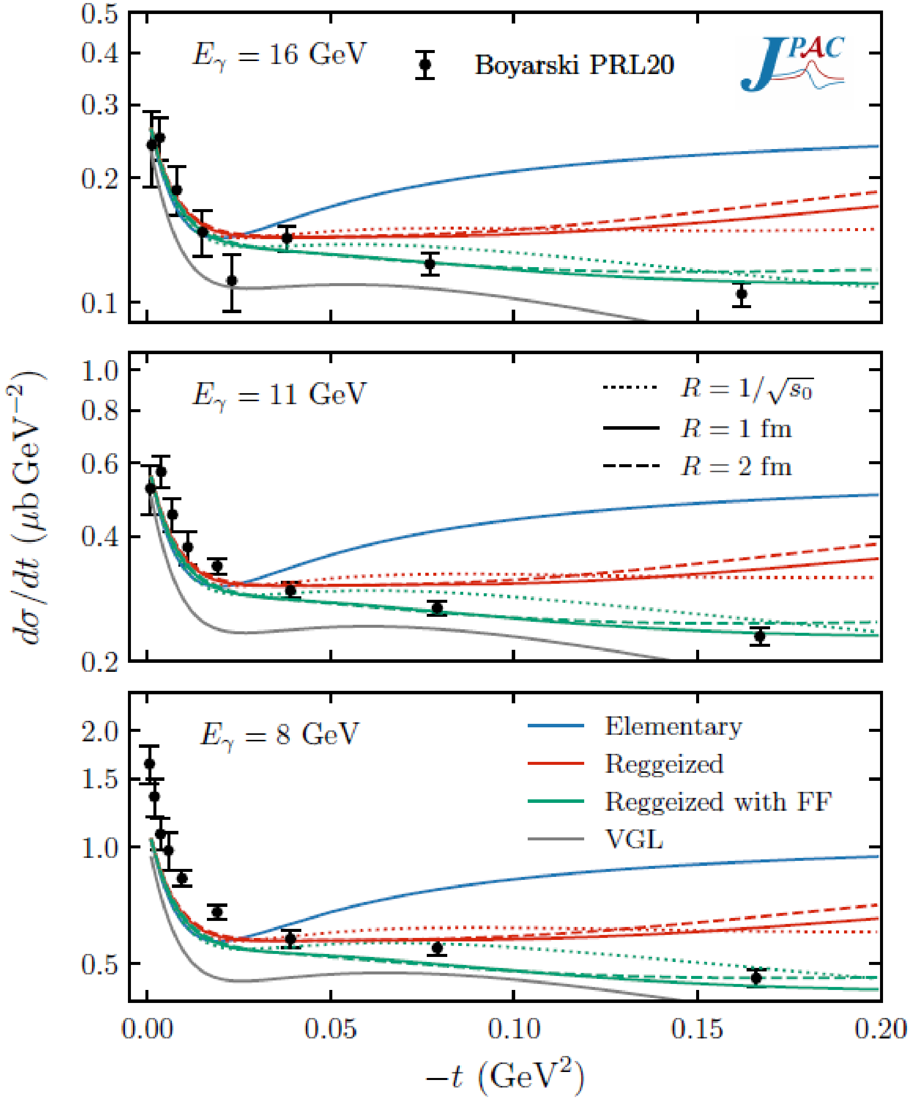
- At $t \sim 0$ the electric term of the amplitude vanishes.
- The magnetic term has small dependence in t.
- Size of the cross section agrees with the data at $t \sim 0$.
- Corrections: add form factor to magnetic term

$$\beta(t) = \frac{\Lambda}{\Lambda^2 - t} \quad \text{with} \quad \Lambda \sim 1 \text{ GeV}$$

- Comparison with the VGL model

→ reggeizes by multiplying full Born amplitude by $(t - m_\pi^2) \times \mathcal{P}_{\text{Regge}}$

[M.Guidal, J.M.Laget and M. Vanderhaeghen, *Nucl.Phys.A* 627 (1997) 645-678]



CONCLUSIONS

- A precise comprehension of the production mechanisms is crucial for the light hybrid meson searches.
- At high energies, meson photoproduction reactions are dominated by the exchange of Regge trajectories, in particular, the pion trajectory plays a major role at low momentum transfer.
- How do we reggeize the pion in an appropriate way?
    - Current conservation requires the nucleon Born terms (gauge invariance).
    - It was not clear how to add t - and s -channel consistently without double counting: t -channel and s -channel partial wave series should independently represent the full amplitude.
    - Examination of the analytical J dependence emerging from the contraction of the vertices coupling $\gamma\pi$ and $N\bar{N}$ to $J^P = (\text{even})^-$ reveals that it is analytical at $J = 0$ and physically contains part of the (s-channel, or u-channel depending on charge) nucleon exchange.

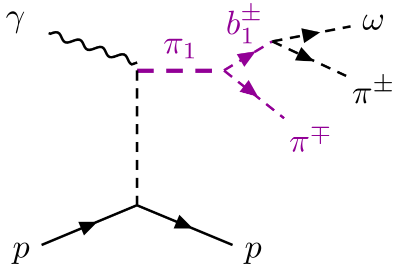
What's next?

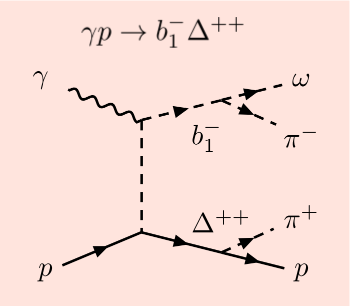
- Revisit the pion exchange in $\gamma p \to \pi^- \Delta^{++}$ and understand Δ^{++} SDMEs.
- Extension of the formalism to natural parity exchanges.
- Amplitudes for photoproduction of $b_1,\ a_2,\ \pi_1$ with proton and Δ^{++} recoils.

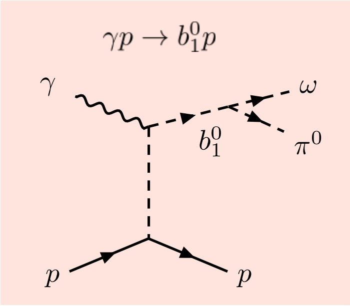
BACKUP

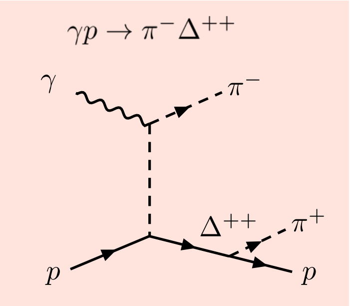
Search for exotic hybrid mesons in photoproduction with GlueX at JLab

- Amplitude analyses of multi-meson final states require models for production amplitudes of several processes.



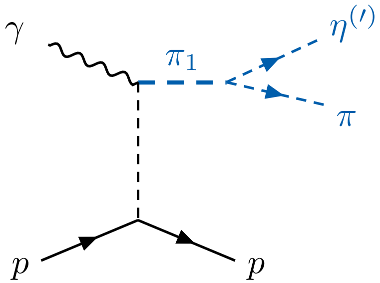


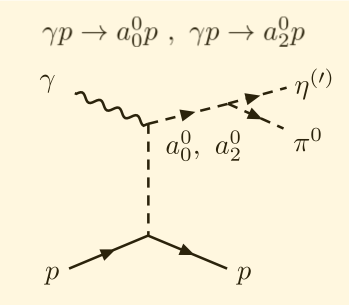


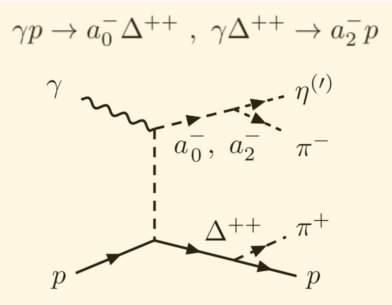


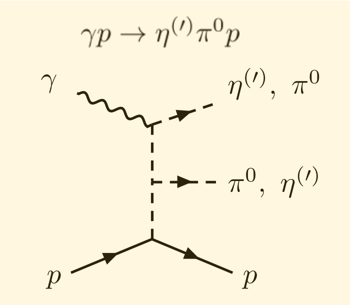
[Talk by A. Schertz, Fri PM]

[Talk by V. Shastry, Sat AM]









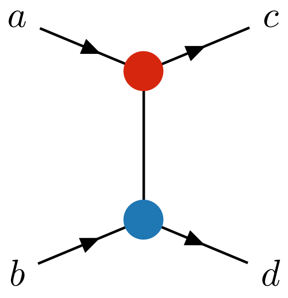
[Talk by M. Albrecht, Tue AM]

Begin by understanding the production mechanism of non-exotic mesons.

Implications of Regge pole amplitudes

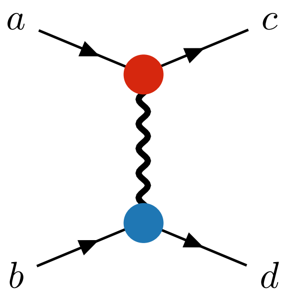
Factorization

Amplitude for particle exchange "factorizes" (follows from unitarity).



$$A(s,t) = g_{ac}\frac{1}{t-m^2}g_{bd}$$

The reggeon residue $\beta(t)$:



- Contains all information about incoming and outgoing particles.
- Related to the reggeon-hadron interaction vertices.
- Satisfies factorization: $\beta(t) = \beta_{ac}(t)\beta_{bd}(t)$

Power law energy dependence

$$A(s,t) \sim s^{\alpha(t)}$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}|A(s,t)|^2 = s^{2\alpha(t)-2}$$

Leading Regge poles (biggest $\alpha(t)$) dominate asymptotically.

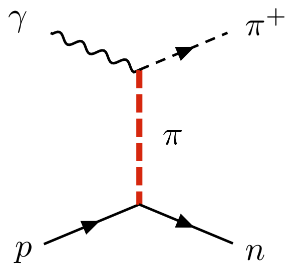
Phase

The phase comes from the signature factor: $\dfrac{1+\eta e^{-i\pi\alpha(t)}}{2}$

Exchange degeneracy (equal trajectories with opposite signatures) leads to rotating or constant phases.

- Corrections to these hypothesis, usually ~10-20%. [J.Nys et al. (JPAC), *Phys.Rev.D* 98 (2018) 3, 034020]

Charged pion photoproduction within Born models



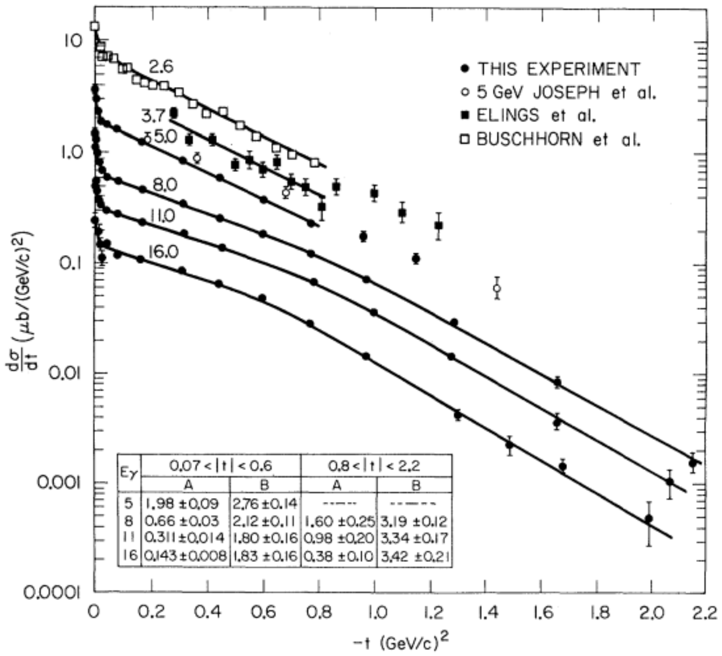
- Description at low energies in terms of effective Lagrangians.
- High energies: reggeization of the pion Born diagram.

Known issues

- What is pion exchange and how does it reggeize?
- Cannot describe forward cross-section data in $\gamma p \to \pi^+ n$ (same for $np \to pn$).

Proposed solutions

- Existence of parity-doublet conspirator of the pion.
  [J.S.Ball, W.R. Frazer and M. Jacob, *Phys.Rev.Lett.* 20 (1968) 518]
- Regge cuts and absorption (final state interactions).
  [F. Henyey, G.L.Kane, J.Pumplin, *Phys.Rev.* 182 (1969) 1579]
- Nucleon Born terms.
  [L.Jones, *Rev.Mod.Phys.* 52 (1980) 545]



[A. Boyarski et al., *Phys.Rev.Lett.* 20 (1968) 300]