Role of current conservation, reggeization and absorption in pion photoproduction

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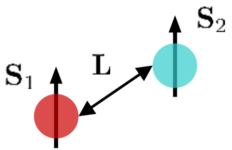
Excited QCD 2024 Workshop
Benasque Science Center, January 14-20, 2024

Hybrid mesons with exotic quantum numbers

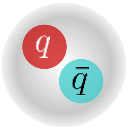
- Mesons are experimentally characterized by quantum numbers:
  - → Isospin
  - → Total angular momentum $\mathbf{J} = \mathbf{L} + \mathbf{S} \quad (\mathbf{S} = \mathbf{S}_1 + \mathbf{S}_2)$
  - → Parity $P = -(-1)^L$
  - → Charge conjugation $C = (-1)^{L+S}$



- The gluonic fields in hybrid mesons can give rise to states with **"exotic" quantum numbers**

"Smoking gun"

Conventional mesons

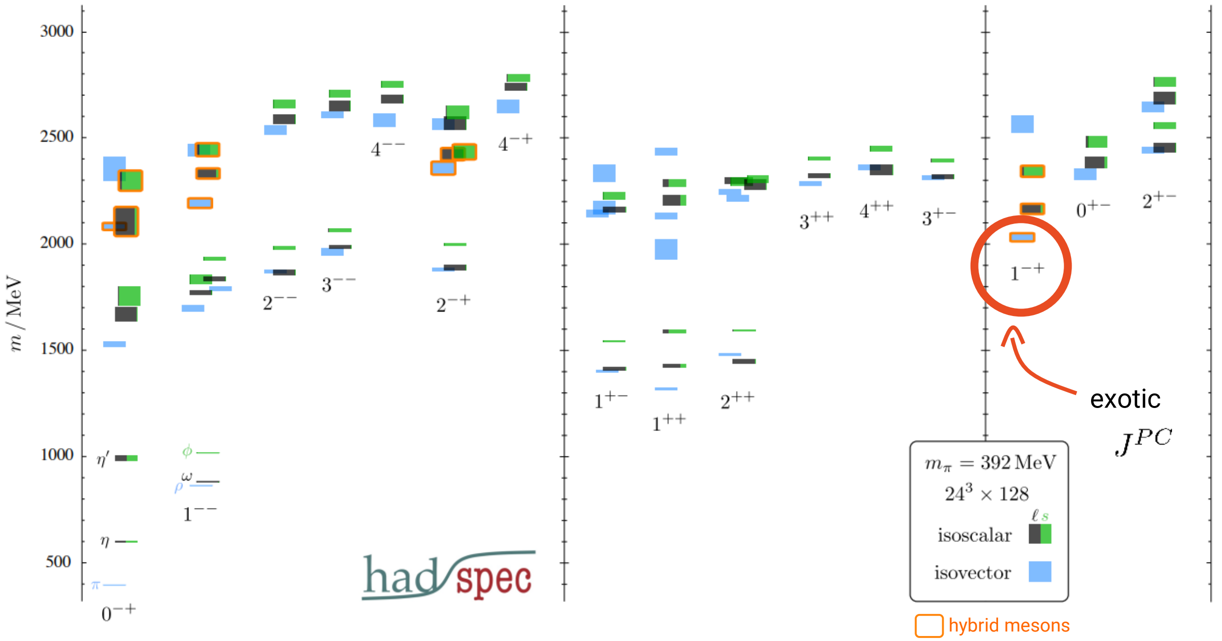


Hybrid mesons

$$J^{PC} \left\{ \begin{array}{cccc} \boxed{0^{--}} & 0^{++} & 0^{-+} & \boxed{0^{+-}} \\ 1^{--} & 1^{++} & \boxed{1^{-+}} & 1^{+-} \\ 2^{--} & 2^{++} & 2^{-+} & \boxed{2^{+-}} \\ 3^{--} & 3^{++} & \boxed{3^{-+}} & 3^{+-} \\ \vdots & \vdots & \vdots & \vdots \end{array} \right.$$

[C.A.Meyer and Y.Van Haarlem, *Phys.Rev.C* 82 (2010) 025208]

Spectrum of light mesons from lattice QCD

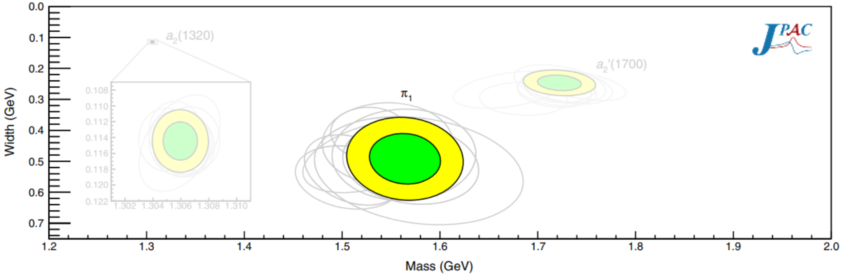


[J.J.Dudek, R.G.Edwards, P.Guo, and C.E.Thomas, *Phys.Rev.D* 88 (2013) 9, 094505]

Two experimental π_1 states vs one pole

- There are two 1^{-+} isovector states in the PDG.
- Coupled channel analyses favor the existence of only one broad 1^{-+} isovector state consistent with $\pi_1(1600)$ in the 1400–1600 MeV region.

[A.Rodas, A.Pilloni et al. *Phys.Rev.Lett.* *122 4, 042002 (2019)*]



$$\text{mass} = 1564 \pm 24 \pm 86 \text{ MeV}$$
$$\text{width} = 492 \pm 54 \pm 102 \text{ MeV}$$

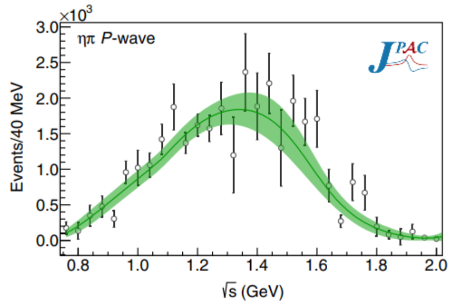
Data:
C.Adolph et al., *Phys.Lett.B* 740, 303 (2015)

$\pi_1(1400)$ $\quad I^G(J^{PC}) = 1^-(1^{-+})$

$\pi_1(1400)$ T-MATRIX POLE $\sqrt{s}$	$(1405 \pm 4^{+15}_{-18}) - i(314 \pm 14^{+18}_{-69})$ MeV
$\pi_1(1400)$ MASS	1354 ± 25 MeV (S = 1.8)
$\pi_1(1400)$ WIDTH	330 ± 35 MeV

Decay Modes

	Mode	Fraction (Γ_i / Γ)
Γ_1	$\eta\pi^0$	seen
Γ_2	$\eta\pi^-$	seen
Γ_3	$\eta'\pi$	
Γ_4	$\rho(770)\pi$	not seen

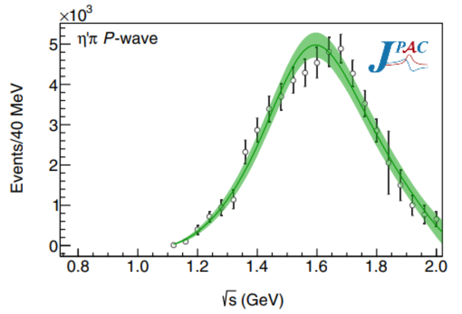


$\pi_1(1600)$ $\quad I^G(J^{PC}) = 1^-(1^{-+})$

$\pi_1(1600)$ T-Matrix Pole $\sqrt{s}$	$(1480 - 1680) - i(150 - 300)$ MeV
$\pi_1(1600)$ MASS	1661^{+15}_{-11} MeV (S = 1.2)
$\pi_1(1600)$ WIDTH	240 ± 50 MeV (S = 1.7)

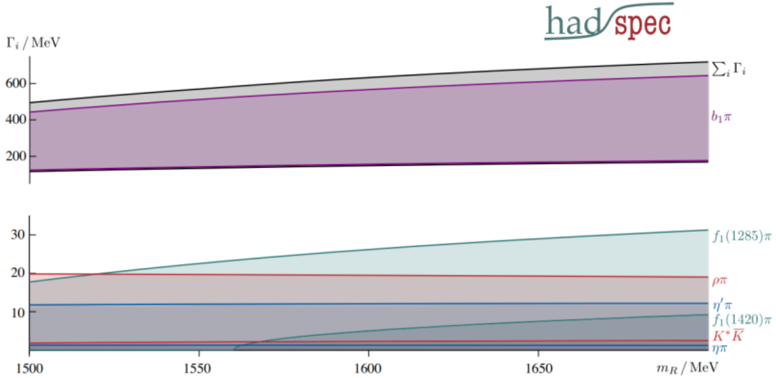
Decay Modes

	Mode	Fraction (Γ_i / Γ)
Γ_1	$\pi\pi\pi$	seen
Γ_2	$\rho^0\pi^-$	seen
Γ_3	$f_2(1270)\pi^-$	not seen
Γ_4	$b_1(1235)\pi$	seen
Γ_5	$\eta'(958)\pi^-$	seen
Γ_6	$\eta\pi$	seen
Γ_7	$f_1(1285)\pi$	seen

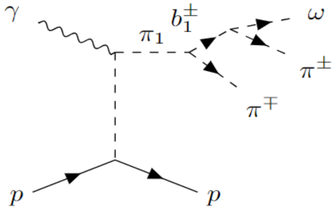


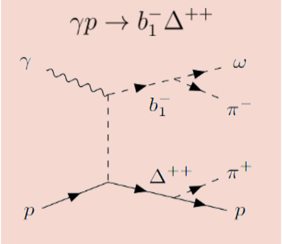
Search for the hybrid mesons

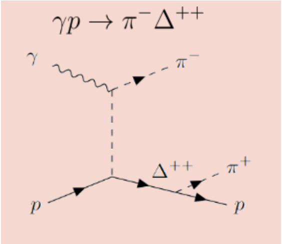
- Identifying the spectrum of hybrid mesons in photoproduction is the primary purpose of the GlueX experiment at Jefferson Lab (Newport News, VA).
- Lattice QCD calculations suggest that $b_1\pi$ is the dominant decay channel of the $\pi_1(1600)$.



[A.J.Woss, J.J.Dudek, R.G.Edwards, C.E.Thomas and D.J.Wilson, *Phys.Rev.D* 103 5, 054502 (2021)]



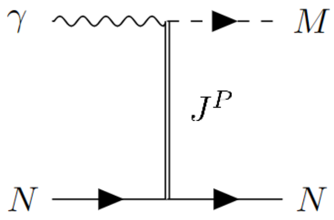


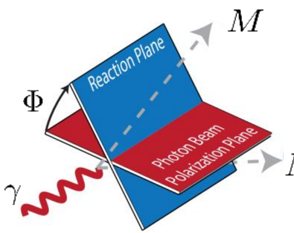


[Talk by V. Shastry, Tue 15th]

- Understanding the production mechanism in light meson photoproduction reactions is essential for the hybrid meson searches in GlueX!

Generalities of meson photoproduction at high photon energies



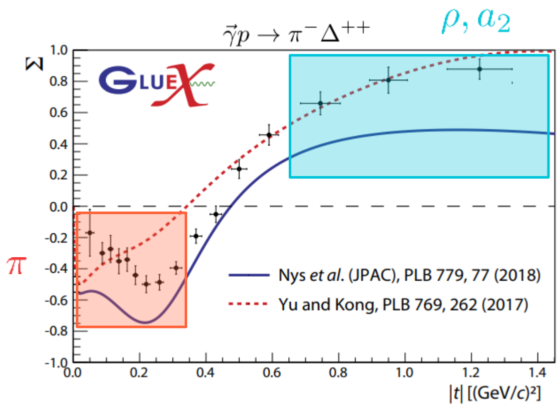


- At high energies, single meson photoproduction is dominated by the exchange of Regge trajectories in the t-channel.

- The beam polarization allows one to distinguish between exchange of

  → unnatural $(P(-1)^J = -1)$ parity

  → natural $(P(-1)^J = 1)$ parity



[GlueX Collaboration, *Phys.Rev.C* 103 (2021) 2, L022201]

- In peripheral high energy **pion photoproduction**, pion exchange dominates at small momentum transfer:

  → The t-channel pion exchange process is not gauge invariant by itself

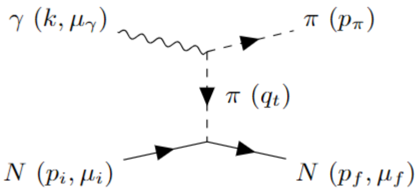
  → It is most susceptible to absorption corrections (longest range interaction)

  → Reggeization scheme

Pion Born diagram

- s-channel reaction: $\gamma(k,\mu_\gamma) + N(p_i,\mu_i) \to \pi(p_\pi) + N(p_f,\mu_f)$
- Helicity amplitude: $A_{\mu_\gamma \mu_i \mu_f} = \epsilon_{\mu_\gamma}(k)\cdot J_{\mu_i \mu_f}$

t-channel Born diagram



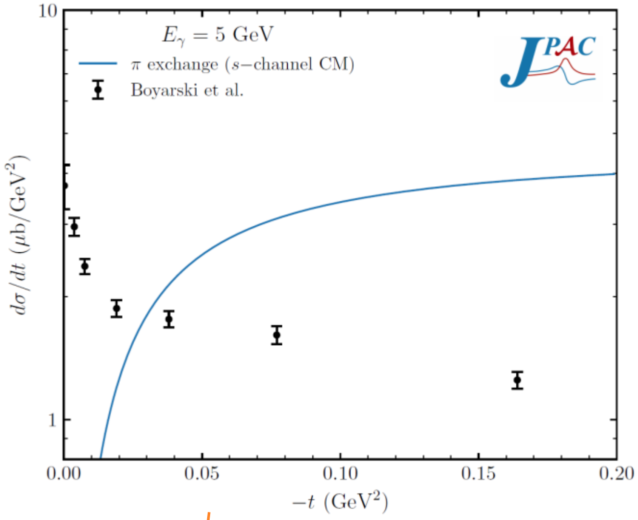
$$J^{\mu}_{\mu_i\mu_f,t} = -e_\pi g_{\pi NN}\frac{q_t^\mu - p_\pi^\mu}{t-\mu^2}\bar{u}_{\mu_f}(p_f)\gamma_5 u_{\mu_i}(p_i)$$

$g_{\pi NN} = 13.48$ → PS πNN coupling

The current is not conserved

↓

the amplitude is not gauge invariant (frame dependent)



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

Pion exchange cannot reproduce experimental cross section at small momentum transfer

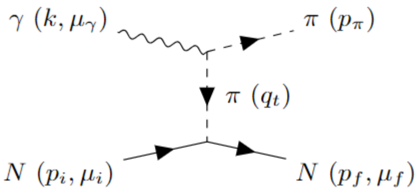
Adding the nucleon Born diagrams

- s-channel reaction: $\gamma(k,\mu_\gamma) + N(p_i,\mu_i) \to \pi(p_\pi) + N(p_f,\mu_f)$
- Helicity amplitude: $A_{\mu_\gamma\mu_i\mu_f} = \epsilon_{\mu_\gamma}(k)\cdot J_{\mu_i\mu_f}$

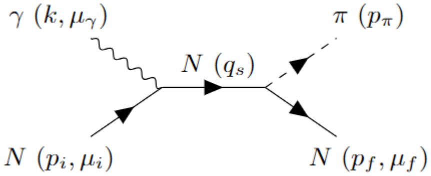
$$J^\mu_{\mu_i\mu_f} = J^\mu_{\mu_i\mu_f,t} + J^\mu_{\mu_i\mu_f,s} + J^\mu_{\mu_i\mu_f,u}$$

The total current is conserved

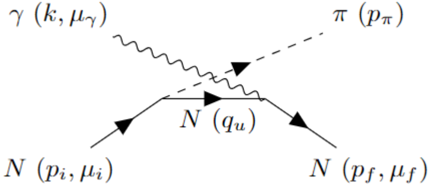
t-channel Born diagram



s-channel



u-channel



$$J^\mu_{\mu_i\mu_f,t} = -e_\pi g_{\pi NN}\frac{q_t^\mu - p_\pi^\mu}{t-\mu^2}\bar u_{\mu_f}(p_f)\gamma_5 u_{\mu_i}(p_i) \qquad J^\mu_{\mu_i\mu_f,s} = e_N g_{\pi NN}\bar u_{\mu_f}(p_f)\gamma_5\frac{\not{q}_s + M}{s-M^2}\gamma^\mu u_{\mu_i}(p_i) \qquad J^\mu_{\mu_i\mu_f,u} = e_N g_{\pi NN}\bar u_{\mu_f}(p_f)\gamma^\mu\frac{\not{q}_u + M}{u-M^2}\gamma_5 u_{\mu_i}(p_i)$$

- Separate electric and magnetic contributions: $A_{\mu_\gamma\mu_i\mu_f} = A^{\mathrm{e}}_{\mu_\gamma\mu_i\mu_f} + A^{\mathrm{m}}_{\mu_\gamma\mu_i\mu_f}$

$$A^{\mathrm{e}}_{\mu_\gamma\mu_i\mu_f} = 2g_{\pi NN}\left[e_\pi\frac{(\epsilon_{\mu_\gamma}\cdot p_\pi)}{t-\mu^2} + e_{N_i}\frac{(\epsilon_{\mu_\gamma}\cdot p_i)}{s-M^2} + e_{N_f}\frac{(\epsilon_{\mu_\gamma}\cdot p_f)}{u-M^2}\right]\bar u_{\mu_f}(p_f)\gamma_5 u_{\mu_i}(p_i)$$

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

Electric term

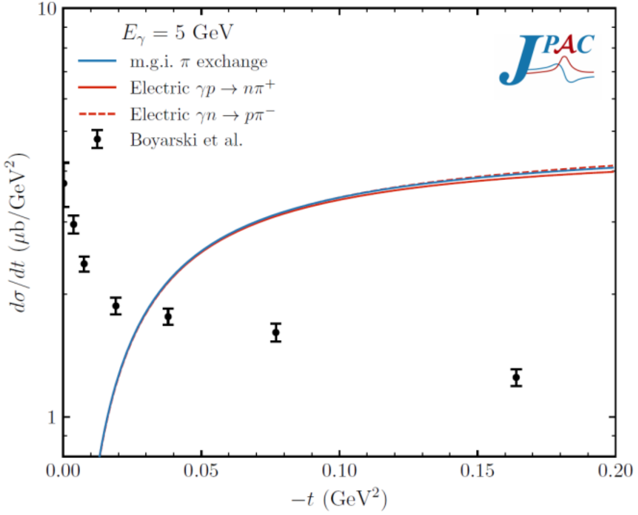
$$A^{\mathrm{e}}_{\mu_\gamma \mu_i \mu_f} = 2 g_{\pi NN} \left[e_\pi \frac{(\epsilon_{\mu_\gamma} \cdot p_\pi)}{t-\mu^2} + e_{N_i} \frac{(\epsilon_{\mu_\gamma} \cdot p_i)}{s-M^2} + e_{N_f} \frac{(\epsilon_{\mu_\gamma} \cdot p_f)}{u-M^2} \right] \bar{u}_{\mu_f}(p_f) \gamma_5 u_{\mu_i}(p_i)$$

- Using momentum conservation and electric charge conservation ($e_{N_i} = e_\pi - e_{N_f}$):

$$\begin{aligned} A^{\mathrm{e}}_{\mu_\gamma \mu_i \mu_f} = & \boxed{g_{\pi NN} \Bigg[2 e_\pi \left(\frac{(\epsilon_{\mu_\gamma} \cdot p_\pi)}{t-\mu^2} + \frac{(\epsilon_{\mu_\gamma} \cdot (p_i + p_f))}{s-u} \right)} \\ & + e_{N_i} \left(\frac{(\epsilon_{\mu_\gamma} \cdot p_\pi)}{s-M^2} + \frac{(\epsilon_{\mu_\gamma} \cdot (p_i + p_f))}{s-u} \frac{t-\mu^2}{s-M^2} \right) \\ & - e_{N_f} \left(\frac{(\epsilon_{\mu_\gamma} \cdot p_\pi)}{u-M^2} + \frac{(\epsilon_{\mu_\gamma} \cdot (p_i + p_f))}{s-u} \frac{t-\mu^2}{u-M^2} \right) \Bigg] \bar{u}_{\mu_f}(p_f) \gamma_5 u_{\mu_i}(p_i) \end{aligned}$$

→ Minimal gauge invariant (m.g.i.)

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



- Differential cross section

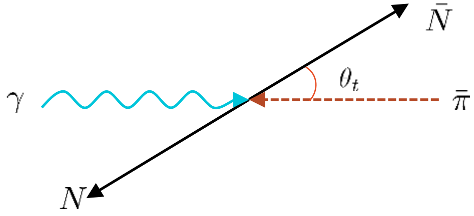
$$\left(\frac{d\sigma}{dt}\right)_{\pi\text{-m.g.i.}} = 4 \left(\frac{s-M^2}{s-u}\right)^2 \left(\frac{d\sigma}{dt}\right)_{\pi\text{-bare, CM}} \overset{t\to t_{\min}}{\approx} \left(\frac{d\sigma}{dt}\right)_{\pi\text{-bare, CM}}$$

$$\left(\frac{d\sigma}{dt}\right)_{\mathrm{e},\ \gamma p \to \pi^+ n} = \left(\frac{d\sigma}{dt}\right)_{\pi\text{-bare, CM}}$$

$$\left(\frac{d\sigma}{dt}\right)_{\mathrm{e},\ \gamma n \to \pi^- p} = 4 \left(\frac{s-M^2}{M^2-u}\right)^2 \left(\frac{d\sigma}{dt}\right)_{\pi\text{-bare, CM}} \overset{t\to t_{\min}}{\approx} \left(\frac{d\sigma}{dt}\right)_{\pi\text{-bare, CM}}$$

Pion pole in the *t*-channel rest frame

- *t*-channel reaction: $\gamma(k,\lambda_\gamma)+\bar{\pi}(-p_\pi)\to\bar{N}(-p_i,\lambda_i)+N(p_f,\lambda_f)$.



$$A^{\mathrm{e}}_{\lambda_\gamma\lambda_i\lambda_f}=g_{\pi NN}\left[2e_\pi\left(\frac{1}{s-u}\right)+e_{N_i}\left(\frac{1}{s-M^2}-\frac{2}{s-u}\right)-e_{N_f}\left(\frac{1}{u-M^2}-\frac{2}{s-u}\right)\right](\epsilon_{\lambda_\gamma}\cdot(p_i+p_f))\,\bar{u}_{\lambda_f}(p_f)\gamma_5 v_{\lambda_i}(-p_i)$$

→ The nucleon Born terms contain a "pion pole" that arises from kinematical factors

$$\bar{\epsilon}_{\mu\nu}\equiv\sum_{\lambda_\gamma=\pm1}\epsilon_{\lambda_\gamma,\mu}(k)\epsilon^*_{\lambda_\gamma,\nu}(k)=-g_{\mu\nu}-\frac{k_\mu k_\nu}{(k\cdot n)^2}+\frac{k_\mu n_\nu+k_\nu n_\mu}{k\cdot n}\qquad\text{with}\qquad n=(1,\mathbf{0})$$

$$\bar{\epsilon}_{\mu\nu}P^\mu P^\nu=\frac{2(k\cdot P)(n\cdot P)(k\cdot n)-P^2(k\cdot n)^2-(k\cdot P)^2}{(k\cdot n)^2}\sim\frac{1}{t-\mu^2}\qquad\text{with}\quad P^\mu=(p_i+p_f)^\mu$$

→ Reggeization of the pion should involve the electric components of the nucleon Born terms

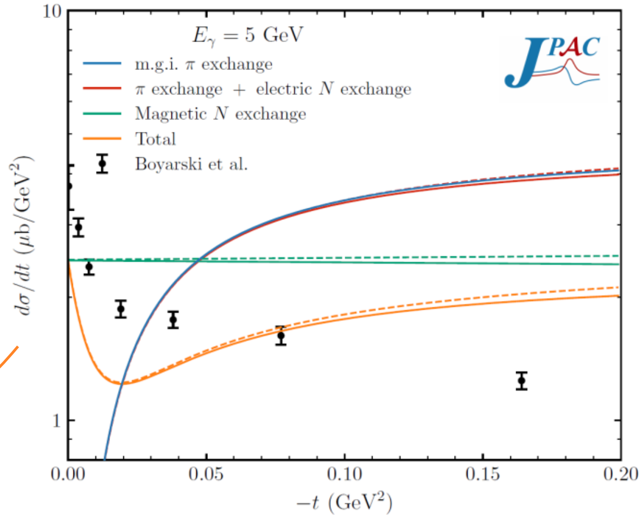
Magnetic term

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

- In the limit $t \to t_{\min}$:
  - $\to$ The pion exchange diagram vanishes.
  - $\to$ The electric component of the nucleon exchanges also vanish.
  - $\to$ The magnetic component of the nucleon exchanges has small dependence in t.

The size of the cross section agrees reasonably well with the data when the magnetic contribution of the nucleon-exchange diagrams is taken into account.

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



Alternative explanations of the experimental data:

- Absorption corrections
- Pion conspiracy

Reggeization of pion exchange

- The exchanged pion is expected to reggeize:

  → Consider the exchange of all the members of the pion trajectory i.e. all the particles with different spin J but the same parity $P = -(-1)^J$, isospin, as the pion.

- In the Regge-pole approximation:

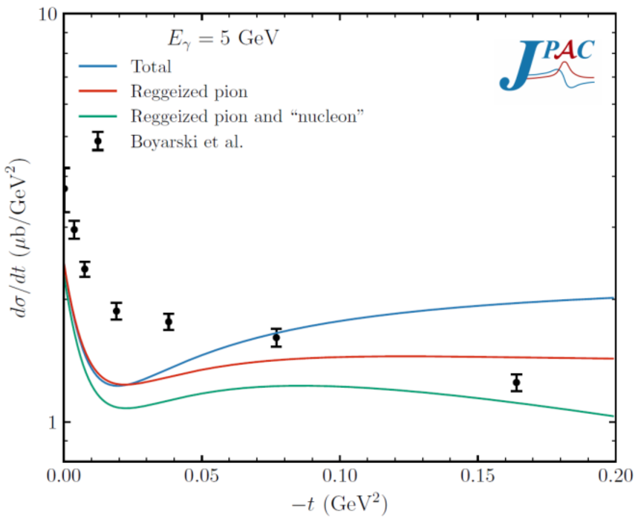
$$\frac{1}{t-\mu^2} \quad \longrightarrow \quad \mathcal{P}_\pi^{\text{Regge}} = \frac{\pi\alpha'_\pi}{2}\frac{1+e^{-i\pi\alpha_\pi(t)}}{\sin\pi\alpha_\pi(t)}\left(\frac{s}{s_0}\right)^{\alpha_\pi(t)}$$

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

- In the VGL model, the full Born amplitude (pion and nucleon exchanges, electric and magnetic) was reggeized.

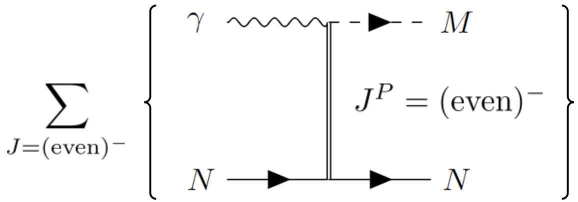
[M.Guidal, J.M.Laget and M. Vanderhaeghen, *Nucl.Phys.A* 627 (1997) 645-678]

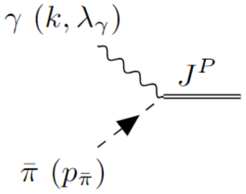
[G.Montana et al. (in preparation)]



New approach to Reggeization of pion exchange

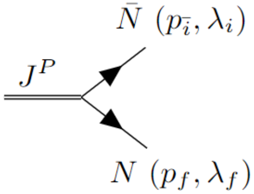
- Consider the explicit exchange of all the t-channel partial waves that have different spin J but the same parity, $P=-(-1)^J$, isospin, as the pion.
- Perform the summation over J
- Vertices coupling $\gamma\pi$ and $N\bar{N}$ to $J^P=(\text{even})^-$:





$$1^-\otimes 0^- = 1^+ \quad \begin{cases} L=1 & \text{for } J=0 \\ L=\{J-1,J+1\} & \text{for } J\geq 2 \end{cases}$$

$$V^{\text{un}}_{\lambda_\gamma}(J) = 2e_{\bar{\pi}}\left[k^{\nu_1}\cdots k^{\nu_J}\epsilon_{\lambda_\gamma,\mu}(k)p^\mu_{\bar{\pi}} - k^{\nu_1}\cdots k^{\nu_{J-1}}\epsilon^{\nu_J}_{\lambda_\gamma}(k)(k\cdot p_{\bar{\pi}})\right]\epsilon^*_{\nu_1,\cdots,\nu_J}(M)$$



$$\frac{1}{2}^+\otimes\frac{1}{2}^- = 0^-\oplus 1^- \longrightarrow L=J$$

helicity non-flip

helicity flip

$$V^{\text{un,NF}}_{\lambda_i\lambda_f}(J) = gP^{\nu_1}\cdots P^{\nu_J}\epsilon_{\nu_1,\cdots,\nu_J}(M)\bar{u}_{\lambda_f}(p_f)\gamma_5 v_{\lambda_i}(p_{\bar{i}})$$

$$V^{\text{un,F}}_{\lambda_i\lambda_f}(J) = gP^{\nu_1}\cdots P^{\nu_{J-1}}\epsilon_{\nu_1,\cdots,\nu_J}(M)\bar{u}_{\lambda_f}(p_f)\gamma^{\nu_J}\gamma_5 v_{\lambda_i}(p_{\bar{i}})$$

New approach to Reggeization of pion exchange

- Compute the full helicity amplitudes. We take the frame in which the exchanged particle is at rest (t-channel frame).

$$A^{\text{un,NF}}_{\lambda_\gamma\lambda_i\lambda_f}(J) = \left[(k\cdot P)(\epsilon_{\lambda_\gamma}\cdot p_{\bar\pi}) - (k\cdot p_{\bar\pi})(\epsilon_{\lambda_\gamma}\cdot P)\right] A_J(s,t)\,\bar u_{\lambda_f}(p_f)\gamma_5 v_{\lambda_i}(-p_i)$$
$$= -(k\cdot p_{\bar\pi})2|\mathbf{p}|d^1_{\lambda_\gamma 0}(\theta_t)A_J(s,t)\,\bar u_{\lambda_f}(p_f)\gamma_5 v_{\lambda_i}(-p_i)$$

$$A^{\text{un,F}}_{\lambda_\gamma\lambda_i\lambda_f}(J) = \bar u_{\lambda_f}(p_f)\Big[(k\cdot\gamma)(\epsilon_{\lambda_\gamma}\cdot p_{\bar\pi}) - (k\cdot p_{\bar\pi})(\epsilon_{\lambda_\gamma}\cdot\gamma)\Big]\gamma_5 v_{\lambda_i}(-p_i)A_J(s,t)$$
$$= (k\cdot p_{\bar\pi})\lambda'\delta_{\lambda'\pm 1}4\sqrt{2}|\mathbf{p}|d^1_{\lambda_\gamma\lambda'}(\theta_t)A_J(s,t)$$

with the scalar function ($J\geq 2$) $A_J(s,t) = -(-1)^{J+\lambda'}2e_{\bar\pi}g\mathcal{P}_J\left(2|\mathbf{k}||\mathbf{p}|\right)^{J-1}(c_J)^2\dfrac{J+1}{2J}P^{|\lambda_\gamma-\lambda'||\lambda_\gamma+\lambda'|}_{J-1}(z_t)$,

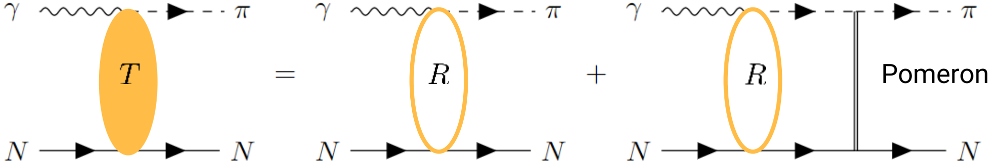
- Extend the definition to $J=0$ by comparing with m.g.i. pion exchange amplitude.

- Next, sum the Regge poles (work in progress):

$$\sum_{J=0,2,4\ldots} A_J(s,t)$$ using the Reggeon propagator $\mathcal{P}_J \to \mathcal{P}_J^{\text{Regge}} = \dfrac{\alpha'}{J-\alpha(t)}$

Absorption

- Multiple elastic rescattering of the final state particles.
- We can write a Bethe-Salpeter-like equation that combines the Reggeized exchange amplitude with an elastic scattering amplitude (Pomeron exchange):



$$A^{T}_{\lambda,\lambda'}(\mathbf{k},\mathbf{p}) = A^{R}_{\lambda,\lambda'}(\mathbf{k},\mathbf{p}) - i\sum_{\lambda''}\int \frac{\mathrm{d}q^4}{(2\pi)^4}\frac{A^{R}_{\lambda,\lambda''}(\mathbf{k},\mathbf{q})A^{P}_{\lambda'',\lambda'}(\mathbf{k},\mathbf{p})}{[q^2-m^2][(P-q)^2-M^2]}$$
$$\equiv A^{R}_{\lambda,\lambda'}(\mathbf{k},\mathbf{p}) + \delta A^{R}_{\lambda,\lambda'}(\mathbf{k},\mathbf{p})$$

- For the partial waves:

$$a^{T,J}_{\lambda,\lambda'}(s) = a^{R,J}_{\lambda,\lambda'}(s) + \delta a^{R,J}_{\lambda,\lambda'}(s)$$

- Absorptive Regge cut models rely on the fit a free parameter, accounting for the “strength” of the intermediate inelastic channels

[F.Henyey, G.L.Kane, J.Pumplin, M.H.Ross, *Phys.Rev.* 182 (1969) 1579-1594]

$$A^{T}_{\lambda,\lambda'}(s,t) = A^{R}_{\lambda,\lambda'}(s,t) + \lambda\,\delta A^{R}_{\lambda,\lambda'}(s,t) \qquad \text{with} \quad \lambda > 1$$

- If λ is too large, the lowest partial waves undergo an unphysical sign change instead of being absorbed

$\rightarrow$ over-absorption (no fundamental physics behind)

SUMMARY

- Understanding the features of pion exchange in hadronic reactions has been of fundamental interest for many decades, and not yet satisfactorily established.
- A precise comprehension of the production mechanisms is crucial for the light hybrid meson searches.
- At high energies, meson photoprodution reactions are dominated by the exchange of Regge trajectories, in particular, the pion trajectory plays a major role at low momentum transfer.
- In single pion photoproduction, pion exchange is not able to explain the cross-section data at small t:

  → The t-channel pion exchange process is not gauge invariant.

  → Electric current conservation requires to include the s- and u-channel nucleon exchanges.

  → The magnetic contribution of the nucleon exchanges gives a non-zero cross section at $t = 0$ of similar size than the data.

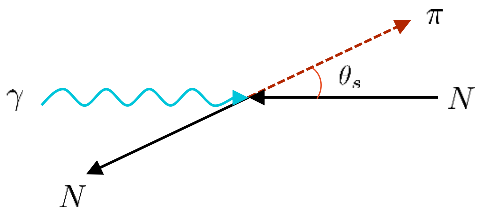
  → Proper Reggeization of the pion exchange has to take into account gauge invariance.

  → New approach to Reggeization is on its way:

  → Explicit exchange of all the members of the pion trajectory.

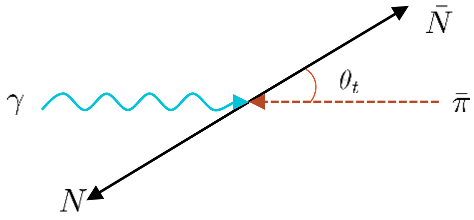
Frame dependence of pion exchange

- s-channel reaction: $\gamma(k,\mu_\gamma) + N(p_i,\mu_i) \to \pi(p_\pi) + N(p_f,\mu_f)$



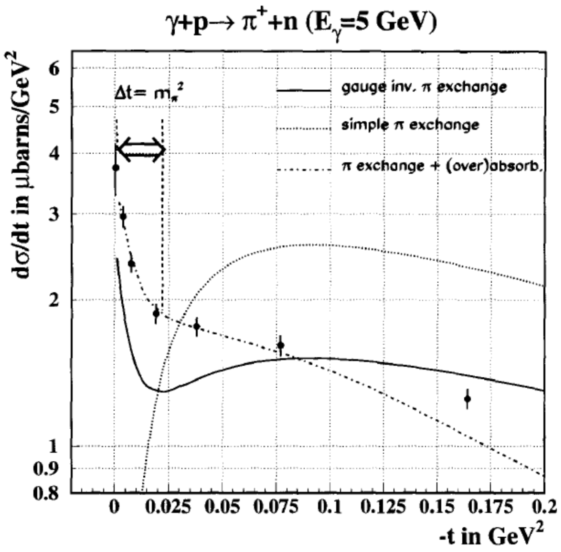
$$A^{\text{e},\ s\text{-CM}}_{\mu_\gamma\mu_i\mu_f} = g_{\pi NN}\Bigg[2e_\pi \left(\frac{1}{t-\mu^2} - \frac{1}{s-u}\right) + 2e_{N_i}\left(\frac{1}{s-u}\right) - 2e_{N_f}\left(\frac{1}{u-M^2} + \frac{1}{s-u}\right)\Bigg](\epsilon_{\mu_\gamma}\cdot p_\pi)\ \bar{u}_{\mu_f}(p_f)\gamma_5 u_{\mu_i}(p_i)$$

- t-channel reaction: $\gamma(k,\lambda_\gamma) + \bar{\pi}(-p_\pi) \to \bar{N}(-p_i,\lambda_i) + N(p_f,\lambda_f)$.

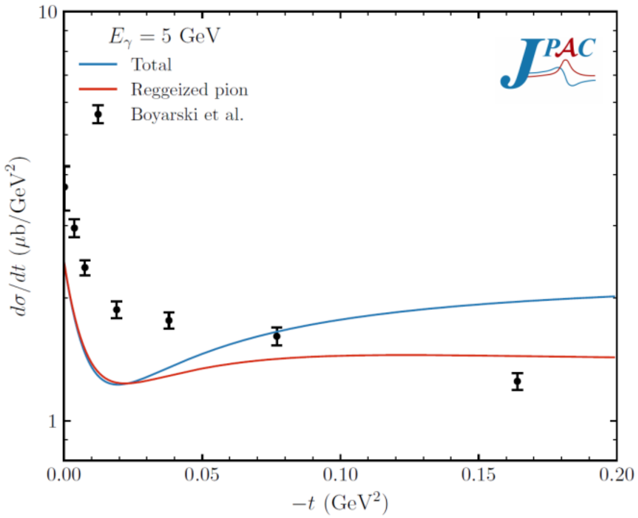


$$A^{\text{e}}_{\lambda_\gamma\lambda_i\lambda_f} = g_{\pi NN}\Bigg[2e_\pi \left(\frac{1}{s-u}\right) + e_{N_i}\left(\frac{1}{s-M^2} - \frac{2}{s-u}\right) - e_{N_f}\left(\frac{1}{u-M^2} - \frac{2}{s-u}\right)\Bigg](\epsilon_{\lambda_\gamma}\cdot(p_i+p_f))\ \bar{u}_{\lambda_f}(p_f)\gamma_5 v_{\lambda_i}(-p_i)$$

Reggeization of pion exchange (comparison with VGL)



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



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