Towards the hybrid meson photoproduction at JLab: unraveling pion exchange from a Regge theory perspective

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Nuclear Theory Seminar

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Confined states of quarks and gluons

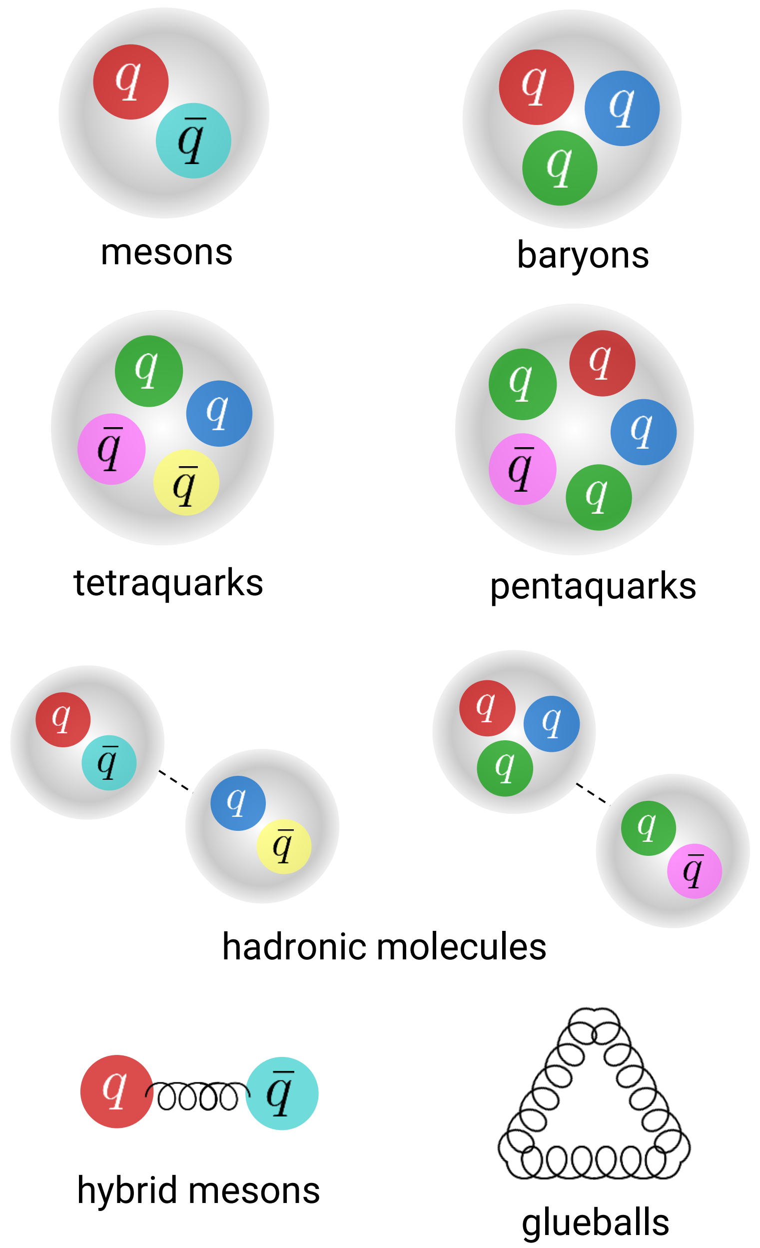
Mesons and baryons aren't the only states allowed by QCD.

> A SCHEMATIC MODEL OF BARYONS AND MESONS *
>
> M. GELL-MANN
> *California Institute of Technology, Pasadena, California*
>
> Received 4 January 1964
>
> ... Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. ...

[M.Gell-Mann, *Phys.Lett.* 8 (1964) 214]

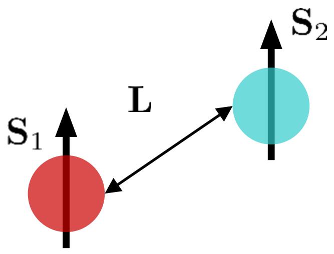
> AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
>
> G.Zweig *)
> CERN - Geneva
>
> In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

[G.Zweig, CERN-TH-401 (1964)]

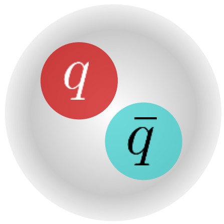


Hybrid mesons with exotic quantum numbers

- 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 $C = (-1)^{L+S}$



Conventional mesons



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

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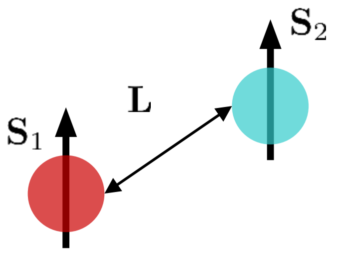

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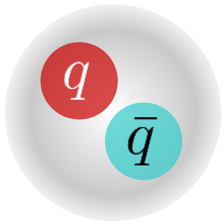

J^{PC}

0^{--}	0^{++}	0^{-+}	0^{+-}
1^{--}	1^{++}	1^{-+}	1^{+-}
2^{--}	2^{++}	2^{-+}	2^{+-}
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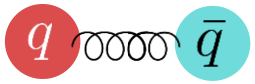
⋮	⋮	⋮	⋮

Hybrid mesons

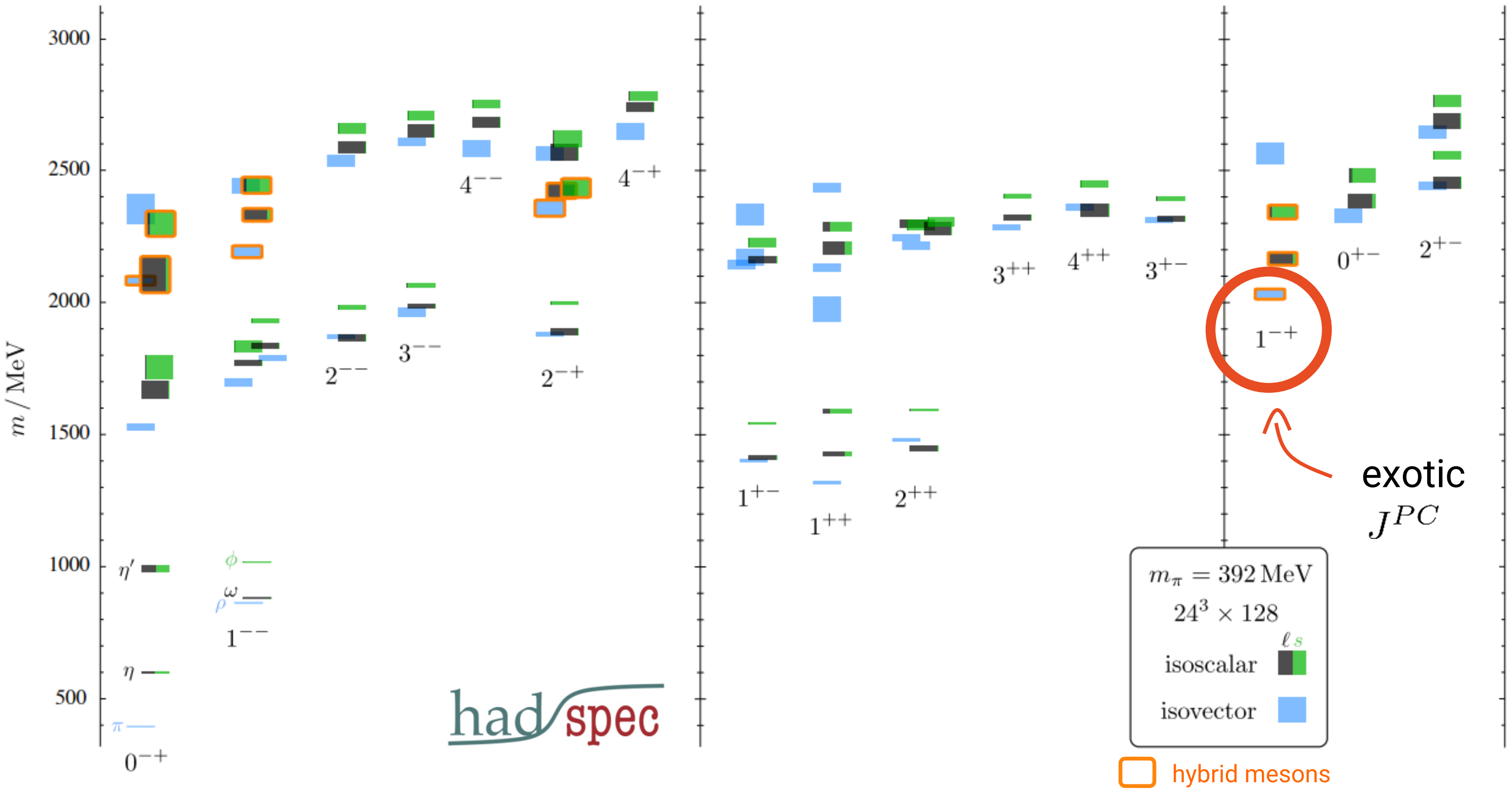


- Gluonic fields in hybrid mesons give rise to states with **"exotic" quantum numbers**

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

→ "Smoking gun"

Spectrum of light mesons from lattice QCD

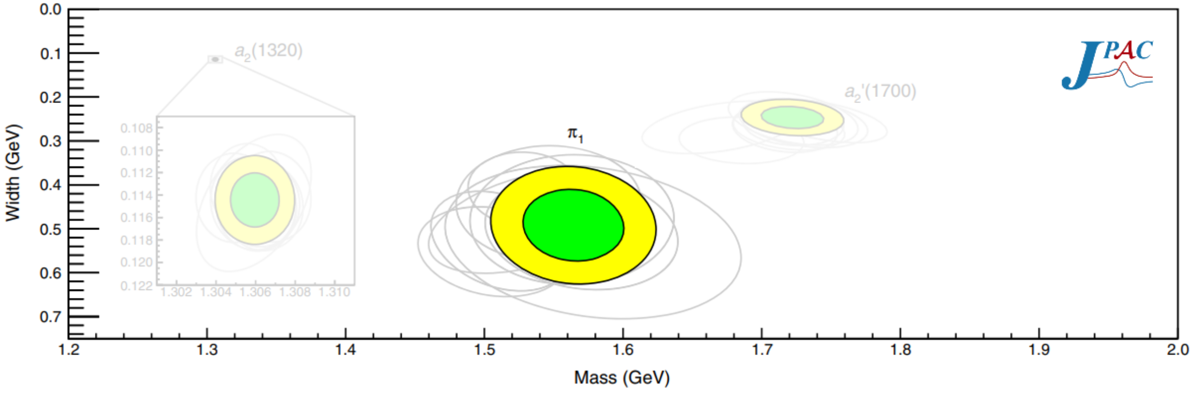


[J.J.Dudek, R.G.Edwards, P.Guo, and C.E.Thomas, *Phys.Rev.D* 88 (2013) 9, 094505]

Search for exotic hybrid mesons

- Best evidence for a hybrid meson is for π_1 in pion-production at COMPASS.
- Two 1^{-+} isovector states in the PDG.
- Coupled channel analyses favor existence of only one broad π_1 state consistent with $\pi_1(1600)$ in the 1400−1600 MeV region.

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



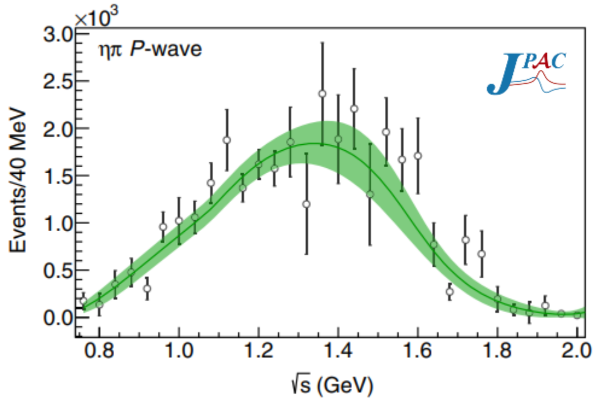
Data:
C.Adolph et al.,
Phys.Lett.B 740, 303 (2015)

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

$\pi_1(1400)$ 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



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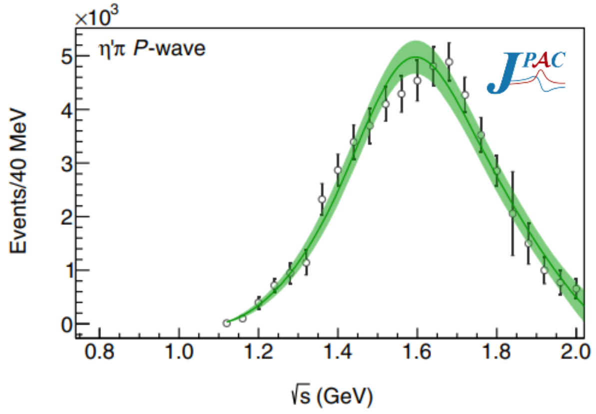
Γ_4	$b_1(1235)\pi$	seen
Γ_5	$\eta'(958)\pi^-$	seen
Γ_6	$\eta\pi$	seen
Γ_7	$f_1(1285)\pi$	seen



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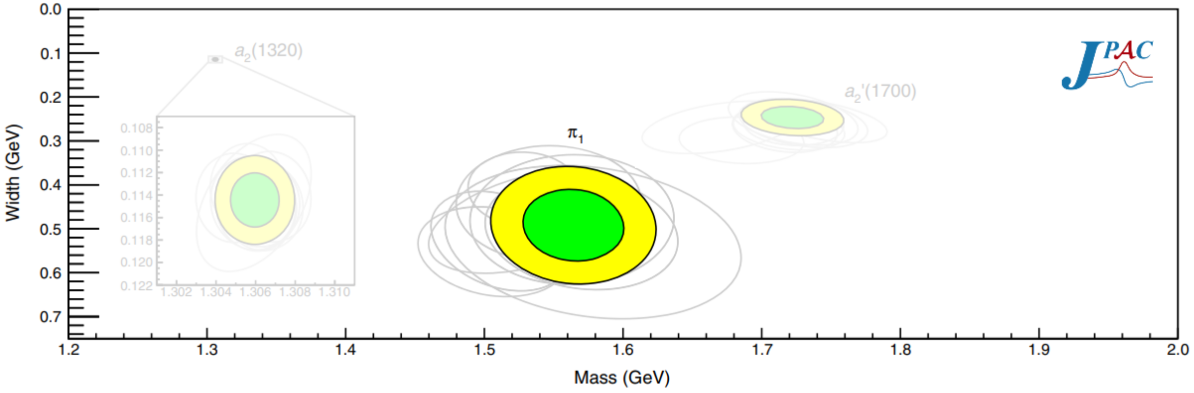

- Recent evidence for η_1 and η_1' from BES-III.
  [M.Ablikim et al., *Phys.Rev.Lett.* 129 (2022) 19]
- Need to confirm π_1 and $\eta_1^{(\prime)}$ and establish the light quark hybrid spectrum.

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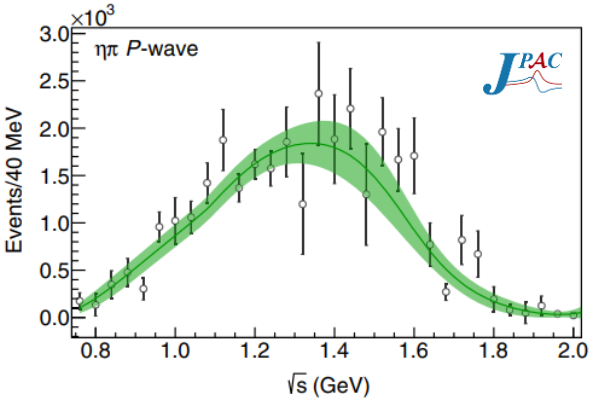

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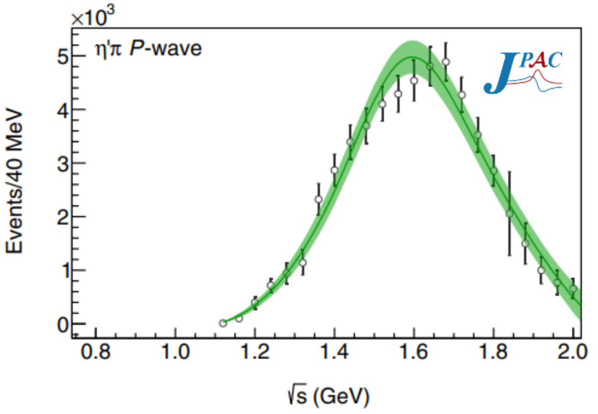
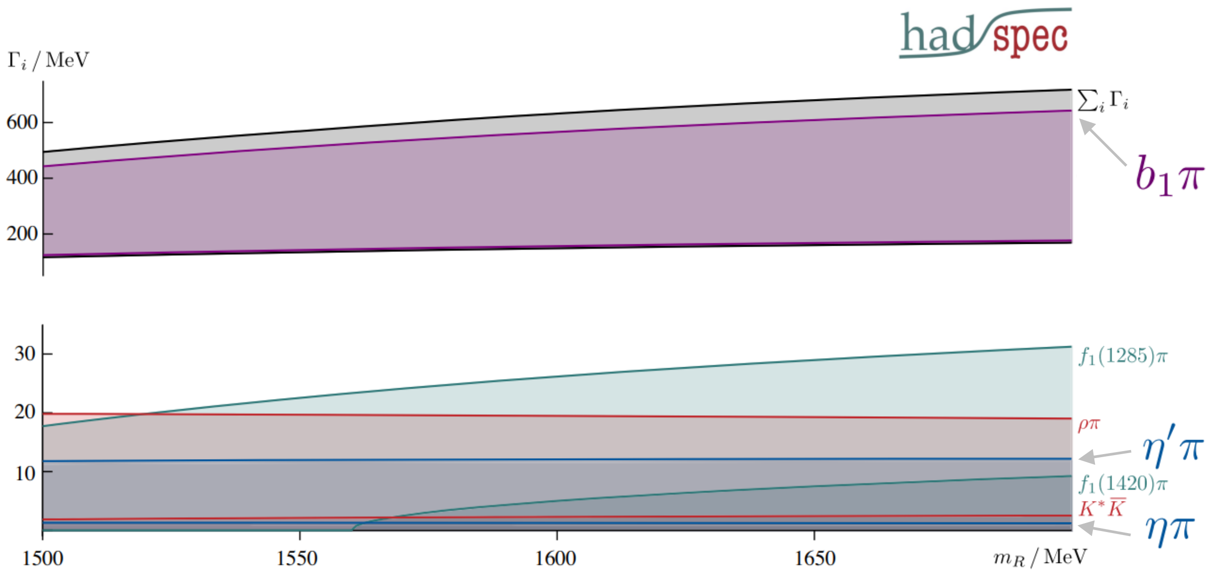
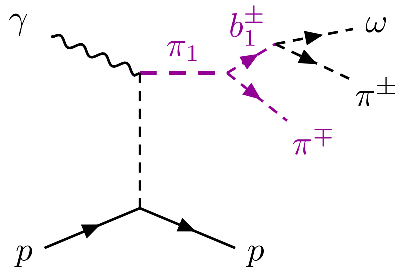


Search for exotic hybrid mesons in photoproduction at JLab

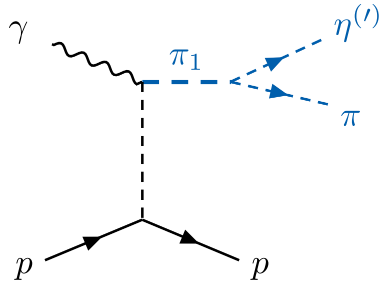
- Identifying the spectrum of hybrid mesons in photoproduction is the primary purpose of the GlueX experiment.
- Exotic hybrid cross-sections ($S_{q\bar{q}} = 1$) expected to be enhanced with photon beam.
- Experimentally challenging: production + decay.
- Lattice QCD calculations suggest $b_1\pi$ is the dominant decay channel of $\pi_1(1600)$.



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



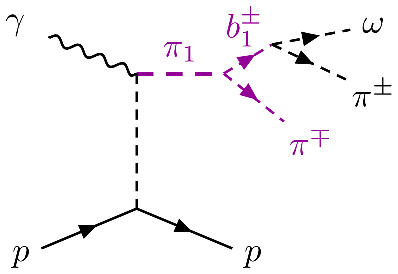
- ✓ More statistics
- ✗ Complicated final state

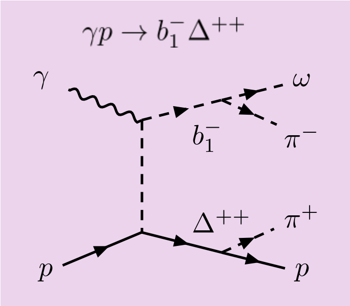


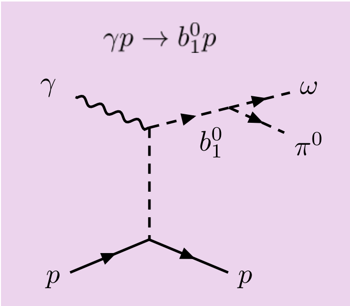
- ✗ Less statistics
- ✓ Easier (less particles)

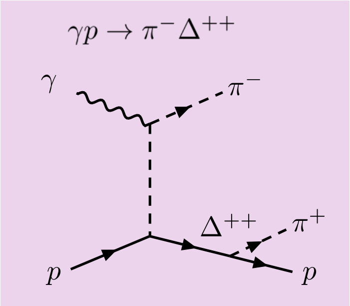
Search for exotic hybrid mesons in photoproduction at JLab

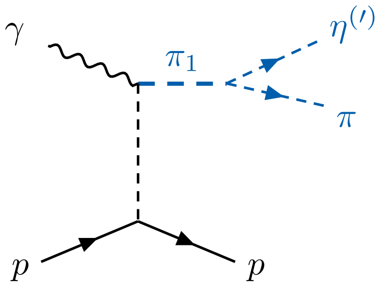
- Amplitude analyses of multi-meson final states require models for production amplitudes of several processes.
- Collaboration between experimentalists and theorists.

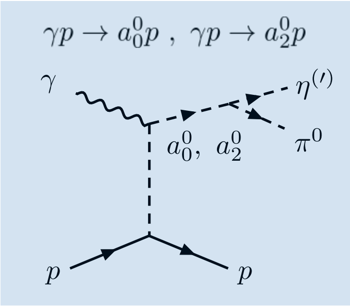


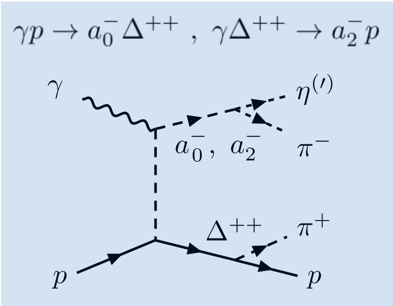


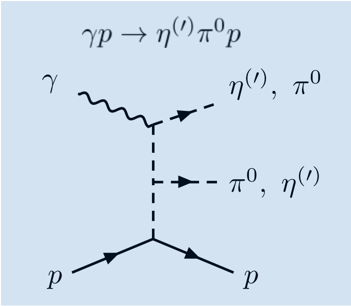








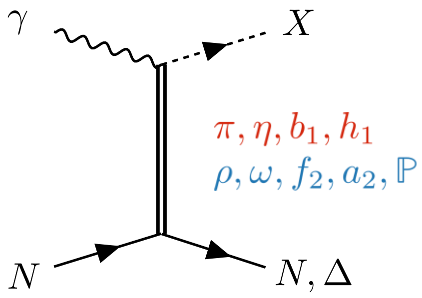




- Begin by understanding non-exotic J^{PC} production mechanism.

Polarized photoproduction at high energies

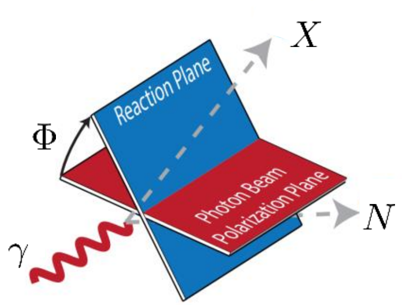
- At high energies, single meson photoproduction dominated by exchange of Regge trajectories in the t-channel.
- Linear photon beam polarization used to filter out the "naturality" of exchanged particle.



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

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

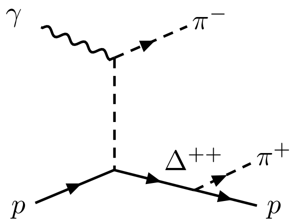
- Beam asymmetry

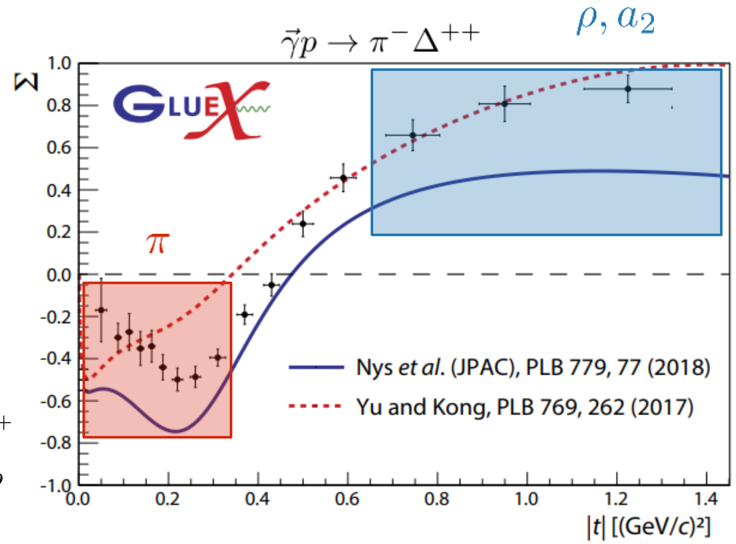


$$\Sigma = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel} \approx \frac{d\sigma_N - d\sigma_U}{d\sigma_N + d\sigma_U}$$

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

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



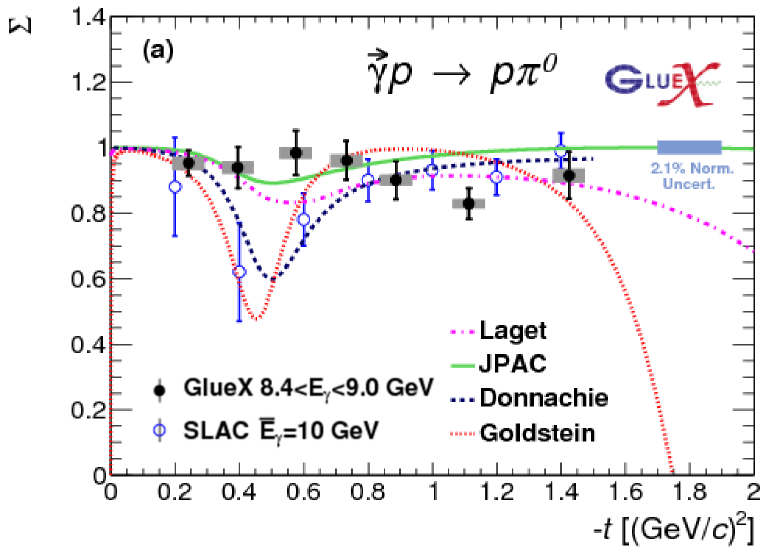


[GlueX Collaboration, *Phys.Rev.C* 103 (2021) 2, L022201]

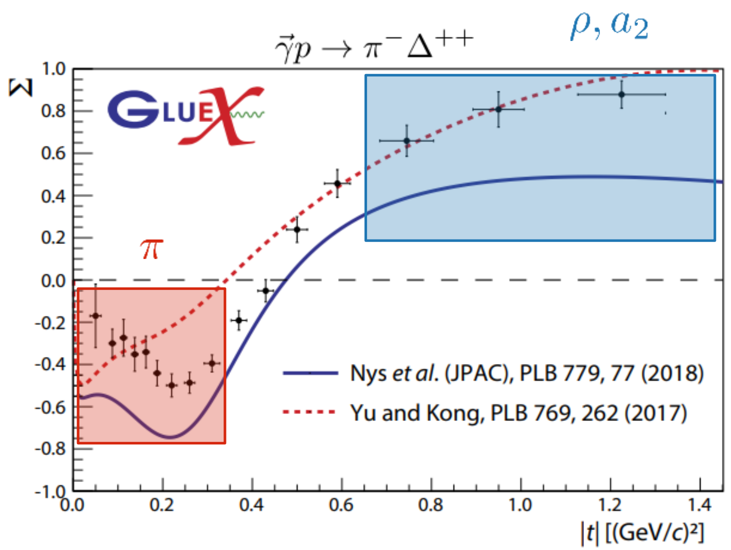
Production mechanism

- Neutral exchange reactions:
  - Natural parity exchanges dominate

- Charge exchange reactions:
  - Small $-t$: unnatural exchanges favored
  - Large $-t$: natural exchanges favored



[GlueX Collaboration, *Phys.Rev.C* 95 (2017) 4, 042201]



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- Crucial in the light (e.g. hybrid meson searches) and heavy (e.g. XYZ phenomenology) sectors.

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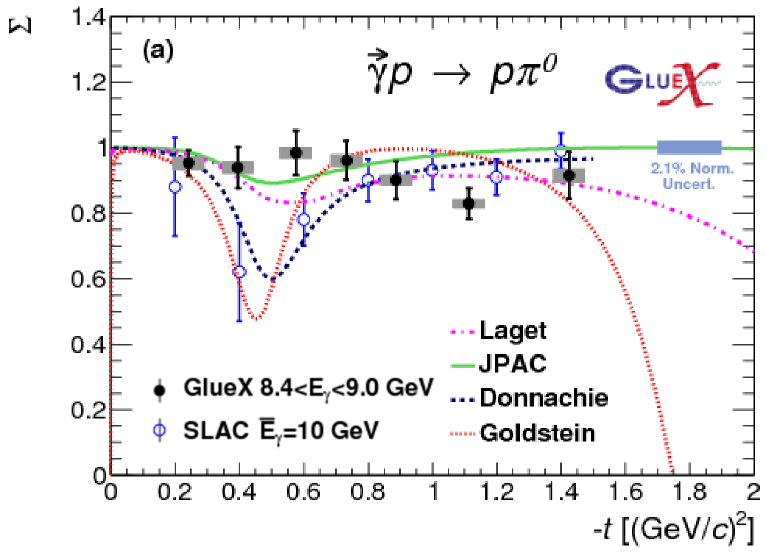

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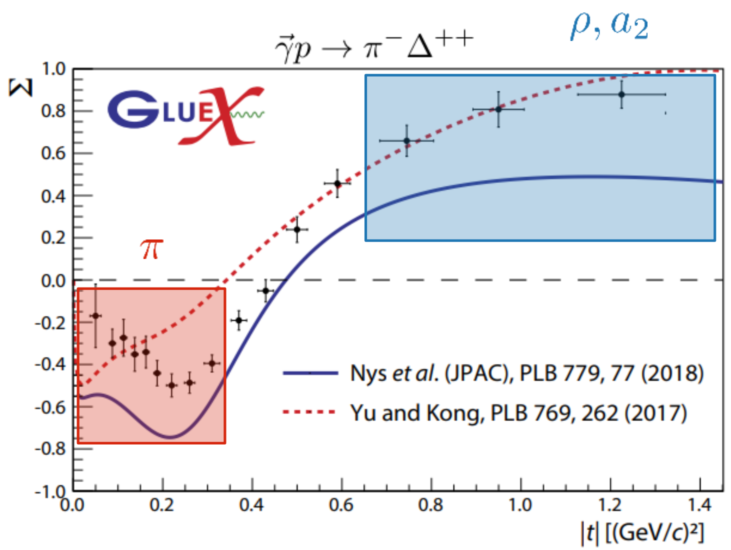

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Focus of this talk: Pion exchange mechanism

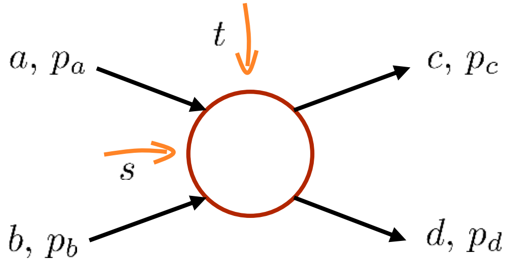
OUTLINE

- Motivation
- Remarks on Scattering and Regge Theory
- Pion exchange in pion photoproduction
  - Role of gauge invariance
  - Reggeization
- Other photoproduction reactions
  - $\eta^{(\prime)}\pi$
  - $b_1(1235)$
  - $\Delta^{++}(1232)$
- Conclusions

Principles of Scattering Theory

Unitarity $SS^\dagger = 1$

if $S = 1 + iA$ then $-i(A - A^\dagger) = 2\text{Im}\, A = AA^\dagger$



Analyticity

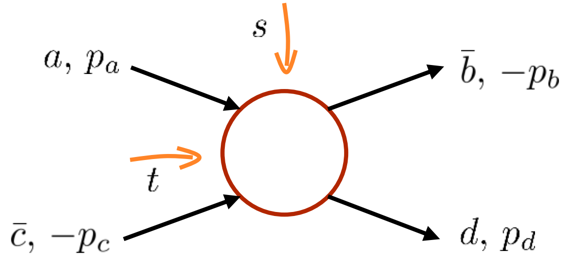
$A(s)$ has singularities (poles and branch cuts) in the complex s plane.

Crossing symmetry $A_{ab\to cd}(s,t,u) = A_{a\bar{c}\to\bar{b}d}(t,s,u)$

Physical regions (in the case of equal mass particles):

s-channel: $a + b \to c + d$ $s \geq 4m^2,\ t \leq 0,\ u \leq 0$

t-channel: $a + \bar{c} \to \bar{b} + d$ $t \geq 4m^2,\ s \leq 0,\ u \leq 0$



Partial wave expansion (no spin)

$$A(s,t) = \sum_{\ell=0}^{\infty}(2\ell+1) f_\ell(s) P_\ell(z)$$

$f_\ell(s)$: s-channel partial wave amplitudes
$P_\ell(z)$: Legendre polynomials

Duality

[Dolen, Horn, Schmid (1968), Veneziano (1968)]

- Property of scattering amplitude.
- Connection between low-energy and high-energy domains.

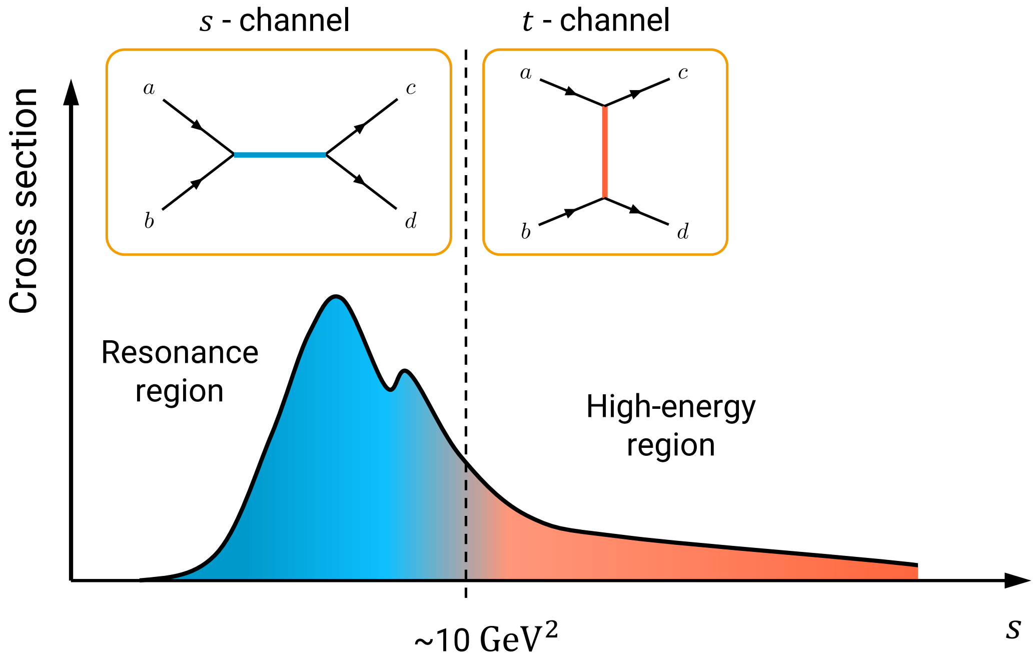
Low-energy: resonances

$$A(s,t) \sim \sum_r \frac{g_r}{s - s_r}$$

High energy: Regge exchanges

$$A(s,t) \sim \sum_i \frac{g_i}{t - t_i}$$

Analytically connected



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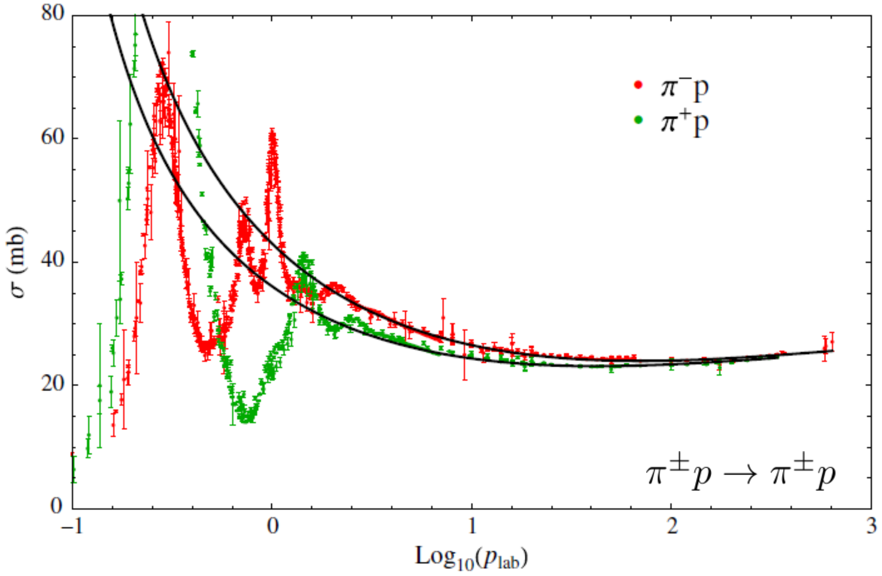

[V.Mathieu et al., *Phys.Rev.D* 92 (2015) 7]

Regge Theory

- At high energies, the scattering amplitudes in the physical region of the s-channel are related to particle exchanges in the t-channel.

Regge limit
$s \gg -t, m^2$

$$A(s,t) = \sum_{\ell=0}^{\infty} (2\ell+1) f_\ell(t) P_\ell(z_t) \quad \longrightarrow \quad A(s,t) \sim s^{\ell_{\text{eff}}}$$

t-channel partial wave amplitudes ($f_\ell(t)$)

$$z_t = \cos\theta_t = 1 + \frac{2s}{t-4m^2}$$

$$\lim_{z\to\infty} P_\ell(z) \sim z^\ell$$

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- The concept of partial wave can be extended to complex values of angular momentum.

$\{f_\ell(t)\} \longrightarrow f(\ell,t)$ with $f(\ell,t) \to f_\ell(t),\ \ell \in \{0,1,2,\dots\}$

Even and odd angular momenta have to be continued separately.

$$f_l(t) = \frac{1}{2}\int_{-1}^{+1} dz_t P_\ell(z_t) A(s,t)$$

$$A(s,t) = \frac{1}{\pi}\left[\int_{z_0}^{\infty} dz \frac{D_s(z,t)}{z-z_t} + \int_{z_0}^{\infty} dz \frac{D_u(-z_u,t)}{z_u+z_t}\right]$$

Froissart-Gribov projection

$$f_\ell^{\pm}(t) = \frac{1}{\pi}\int_{z_0}^{\infty} dz \left\{D_s(z,t) \pm D_u(-z,t)\right\} Q_\ell(z)$$

$f_\ell(t) = f^+(\ell,t)$ for even ℓ

$f_\ell(t) = f^-(\ell,t)$ for odd ℓ

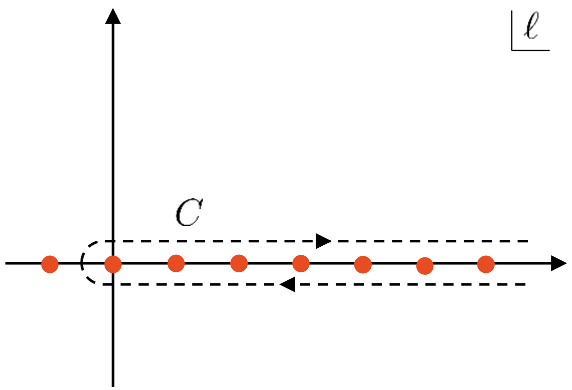
Regge Theory

signature

$$A(s,t) = A^+(s,t) + A^-(s,t) \quad \text{with} \quad A^{\pm}(s,t) = \sum_{\ell=0}^{\infty} (2\ell+1) f_\ell^{\pm}(t) \frac{1}{2} (P_\ell(z_t) \pm P_\ell(-z_t))$$

Procedure: Sommerfeld-Watson transform.

$$A^{\pm}(s,t) = -\frac{1}{2i} \int_C \frac{(2\ell+1) f^{\pm}(\ell,t)}{\sin \pi\ell} \frac{1}{2} (P_\ell(-z_t) \pm P_\ell(z_t)) \, d\ell$$



Regge Theory

signature

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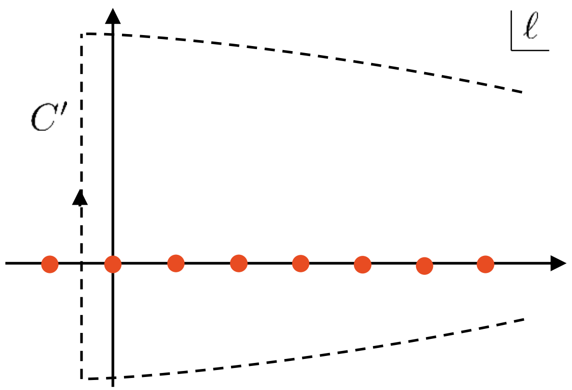
The next step is to deform the contour.



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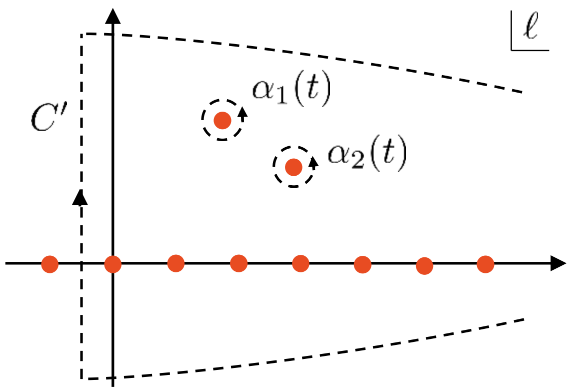


The next step is to deform the contour.

We consider that the only singularities of $f^{\pm}(\ell,t)$ in the region $\ell > -\frac{1}{2}$ are poles in the upper half ℓ plane.

Pole position Residue

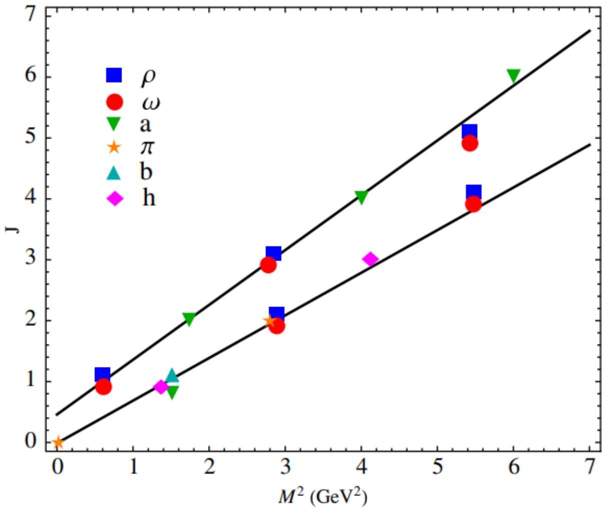
$$A^{\pm}(s,t) = -\frac{1}{2i}\int_{-\frac{1}{2}-i\infty}^{-\frac{1}{2}+i\infty} d\ell \ldots - \sum_i \frac{\pi(2\alpha_i^{\pm}(t)+1)\beta_i^{\pm}(t)}{\sin\left(\pi\alpha_i^{\pm}(t)\right)}\frac{1}{2}\left[P_{\alpha_i^{\pm}}(-z_t) \pm P_{\alpha_i^{\pm}}(z_t)\right]$$

background $\sim s^{-1/2}$ Contribution from each pole $\sim s^{\alpha(t)}$

$$A(s,t) \underset{s\to\infty}{\approx} \sum_i \left[\frac{\pi(2\alpha_i^+(t)+1)\beta_i^+(t)}{\sin\left(\pi\alpha_i^+(t)\right)}\frac{\left(1+e^{-i\pi\alpha_i^+(t)}\right)}{2}\left(\frac{s}{s_0}\right)^{\alpha_i^+(t)} - \frac{\pi(2\alpha_i^-(t)+1)\beta_i^-(t)}{\sin\left(\pi\alpha_i^-(t)\right)}\frac{\left(1-e^{-i\pi\alpha_i^-(t)}\right)}{2}\left(\frac{s}{s_0}\right)^{\alpha_i^-(t)}\right]$$

Reggeon trajectories

- Families with same quantum numbers but different spin J (even or odd).
- 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]

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

Reggeon trajectories

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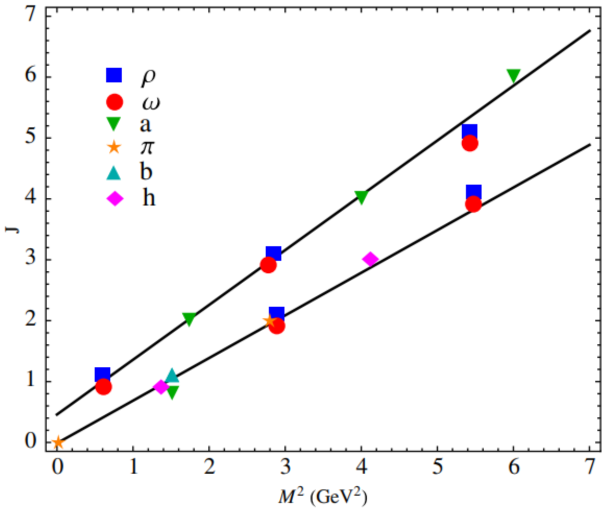

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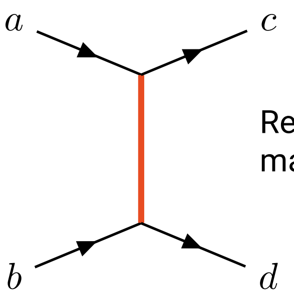
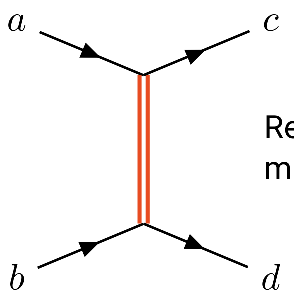


Real particle with mass m and spin J $\quad \dfrac{1}{t - m^2}$



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

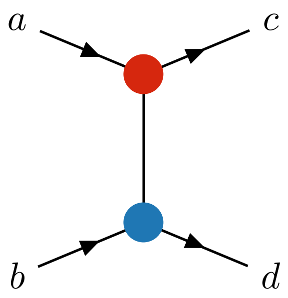
$$\mathcal{P}_{\text{Regge}} = \frac{\pi\alpha'}{\sin(\pi\alpha(t))} \frac{1 + \eta e^{-i\pi\alpha(t)}}{2} \left(\frac{s}{s_0}\right)^{\alpha(t)} \frac{1}{\Gamma(1+\alpha(t))}$$

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

Implications of Regge pole amplitudes

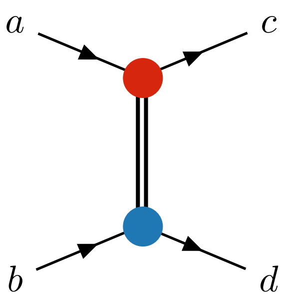
Factorization

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

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

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

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

Phase

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

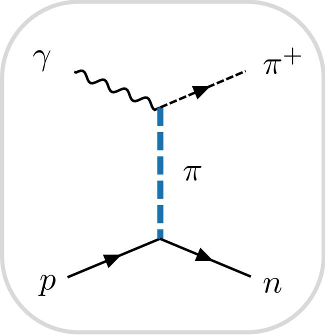
Exchange degeneracy (equal trajectories with opposite signatures) leads to rotating or constant phases.

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

Charged pion photoproduction

What do we know?

- Pion exchange dominates at small momentum transfer.
- Low energies: Constrained by effective Lagrangians of QCD.
- High energies: Regge theory.



$$A \sim \frac{t}{t - m_\pi^2}$$

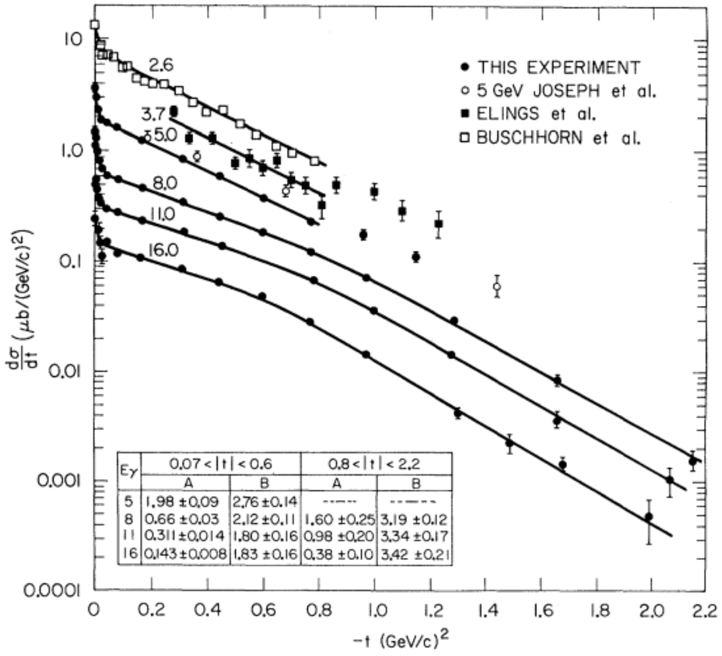
$$A^{\mathrm{R}} \sim (-t)^{(|\mu_\gamma|+|\mu_i-\mu_f|)/2}$$

Known issues

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

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]

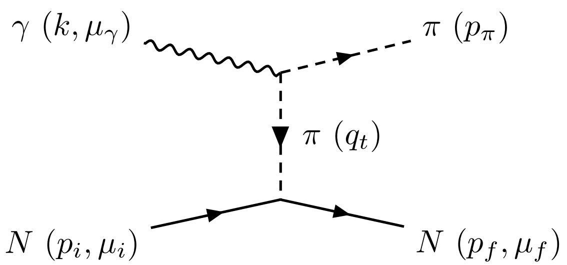


[A. Boyarski et al., *Phys.Rev.Lett.* 20 (1968) 300]

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: $A_{\mu_\gamma \mu_i \mu_f} = \epsilon_{\mu_\gamma}(k) \cdot J_{\mu_i \mu_f}$

t - channel Born diagram



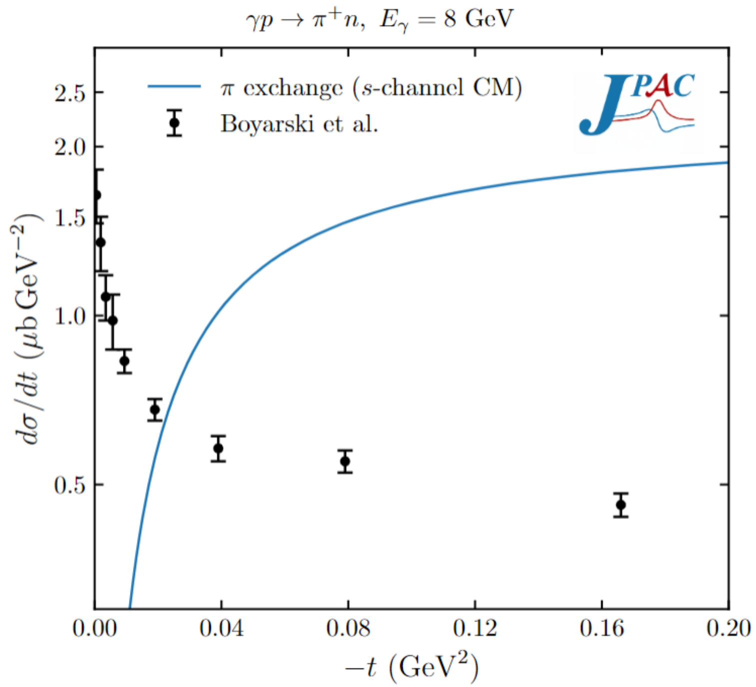
$$J^\mu_{\mu_i\mu_f,t} = -\sqrt{2} e_\pi g_{\pi NN} \frac{q_t^\mu - p_\pi^\mu}{t-\mu^2} \bar{u}_{\mu_f}(p_f)\gamma_5 u_{\mu_i}(p_i)$$

→ Current is not conserved

↓

amplitude is not gauge invariant (frame dependent)

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



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

- Pion exchange cannot reproduce experimental cross section at small momentum transfer

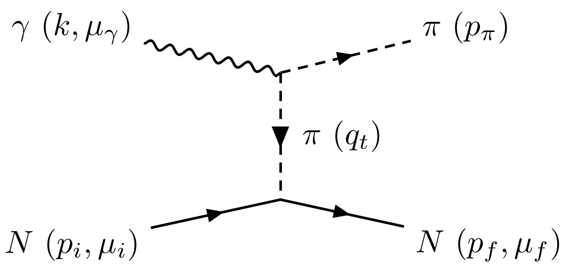
Adding the nucleon Born diagrams

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

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

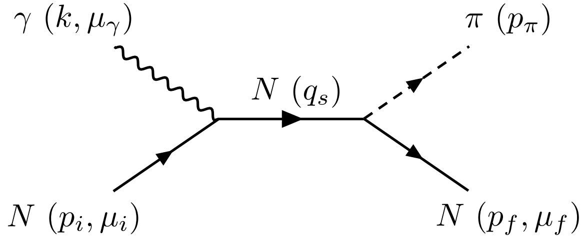
→ Total current is conserved

t - channel Born diagram



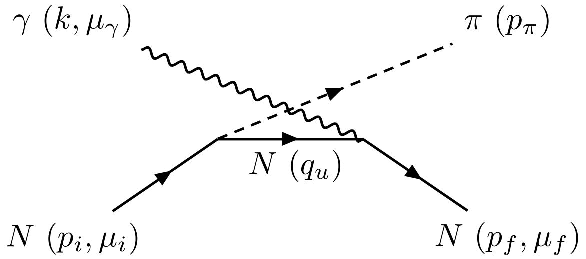
$$J^\mu_{\mu_i\mu_f,t} = -\sqrt{2} e_\pi g_{\pi NN} \frac{q^\mu_t - p^\mu_\pi}{t-\mu^2} \bar{u}_{\mu_f}(p_f)\gamma_5 u_{\mu_i}(p_i)$$

s - channel



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

u - channel



$$J^\mu_{\mu_i\mu_f,u} = \sqrt{2} e_N g_{\pi NN} \bar{u}_{\mu_f}(p_f)\gamma^\mu \frac{\not{q}_u + M}{u-M^2}\gamma_5 u_{\mu_i}(p_i)$$

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

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

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

Electric term

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

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

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

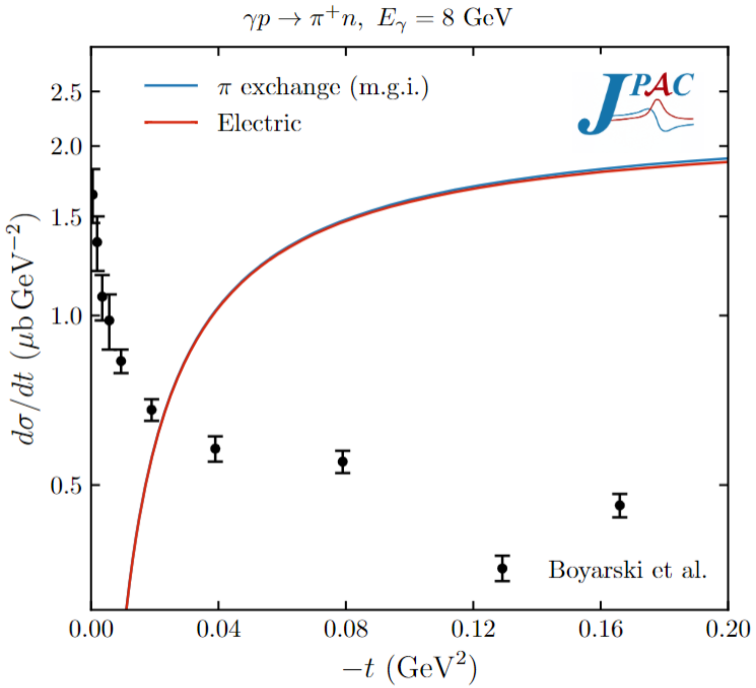
→ Minimal gauge invariant (m.g.i.)

- Differential cross section

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

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

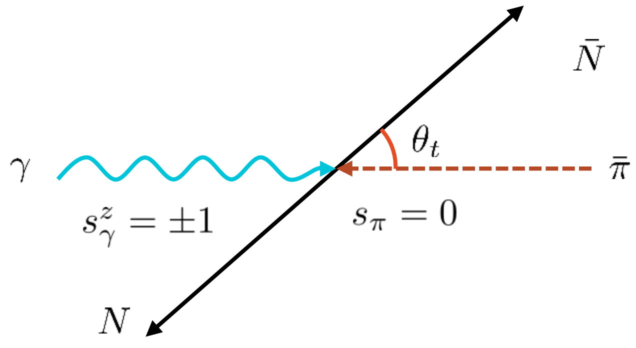
$$\left(\frac{d\sigma}{dt}\right)_{\mathrm{e},\ \gamma n\to\pi^- p} = 4 \left(\frac{s-M^2}{M^2-u}\right)^2 \left(\frac{d\sigma}{dt}\right)_{\pi\text{-bare, CM}} \overset{t\to t_{\min}}{\approx} \left(\frac{d\sigma}{dt}\right)_{\pi\text{-bare, CM}}$$



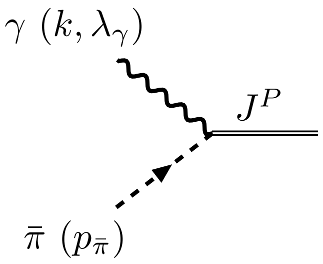
[G.Montana et al. (in preparation)]

Pion pole in the *t*-channel: where does it come from?

- *t*-channel reaction: $\gamma(k,\lambda_\gamma)+\bar{\pi}(-p_\pi)\to\bar{N}(-p_i,\lambda_i)+N(p_f,\lambda_f)$
- *t*-channel partial wave expansion $A(s,t)=\sum_{J=0}^{\infty}(2J+1)A_J(t)d^J_{\lambda_\gamma,\lambda_i-\lambda_f}(z_t)$



Partial wave with $J^P=0^-$ has the singularity closest to the physical region



… but π contribution to *t*-channel vanishes!

→ M_π would have to be ±1

- Crossing symmetry implies (parity conserving) helicity amplitudes in *s*- and *t*-channels are related by a rotation.
- The nucleon Born terms contain a "pion pole" that arises from kinematical factors.

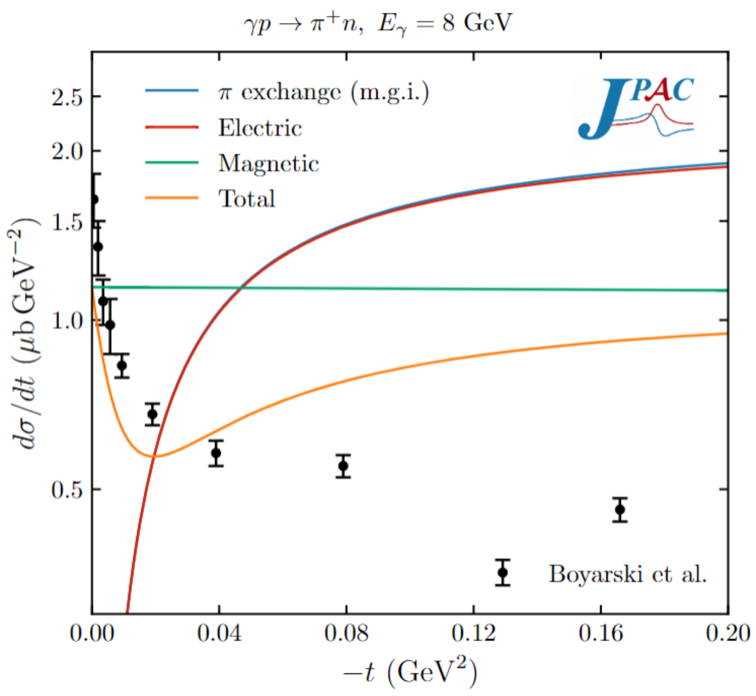
$$A^{\mathrm{e}}_{\lambda_\gamma\lambda_i\lambda_f}=2\sqrt{2}g_{\pi NN}\left(e_\pi+\frac{1}{2}e_{N_i}\frac{t-\mu^2}{s-M^2}-\frac{1}{2}e_{N_f}\frac{t-\mu^2}{u-M^2}\right)\frac{1}{s-u}(\epsilon_{\lambda_\gamma}\cdot(p_i+p_f))\,\bar{u}_{\lambda_f}(p_f)\gamma_5 v_{\lambda_i}(-p_i)$$

$$\approx i2g_{\pi NN}\lambda_\gamma 2\lambda_i\delta_{\lambda_i\lambda_f}\left(e_\pi+\frac{1}{2}e_{N_i}\frac{t-\mu^2}{s-M^2}-\frac{1}{2}e_{N_f}\frac{t-\mu^2}{u-M^2}\right)\frac{t}{t-\mu^2}$$

Magnetic term

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

- 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 $t \sim 0$.
- No need for alternative (unphysical) explanations of the experimental data:
  - Over-absorption
  - Parity doublet conspirator



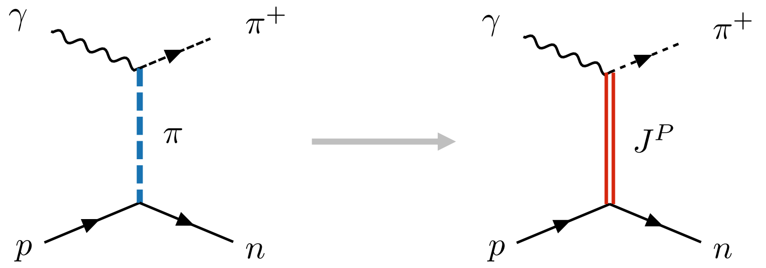
[G.Montana et al. (in preparation)]

Reggeization of pion exchange

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

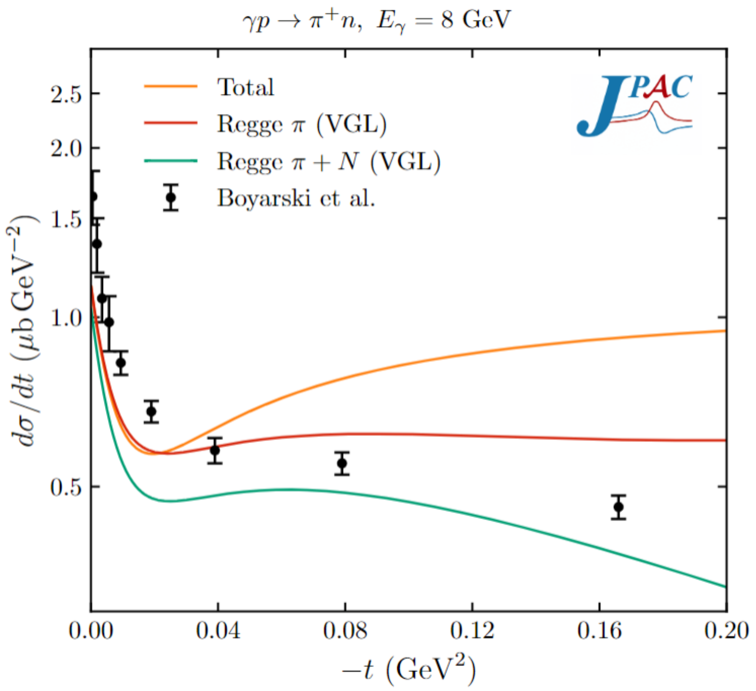
$$\frac{1}{t-\mu^2} \quad \longrightarrow \quad \mathcal{P}_\pi^{\text{Regge}} = \frac{\pi\alpha'_\pi}{2}\frac{1+e^{-i\pi\alpha_\pi(t)}}{\sin\pi\alpha_\pi(t)}\left(\frac{s}{s_0}\right)^{\alpha_\pi(t)}$$

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



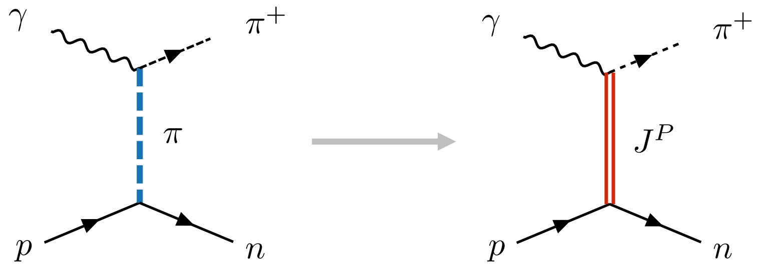
- VGL model: reggeize full Born amplitude ($\pi + N$ exchanges, electric and magnetic).

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



→ What does it mean to reggeized the π exchange?

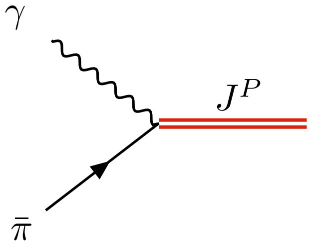
Reggeization of pion exchange



- Rigorous reggeization:

  Explicit exchanges of t-channel partial waves in the π trajectory

- Vertices coupling $\gamma\pi$ and $N\bar{N}$ to $J^P = (\text{even})^-$:

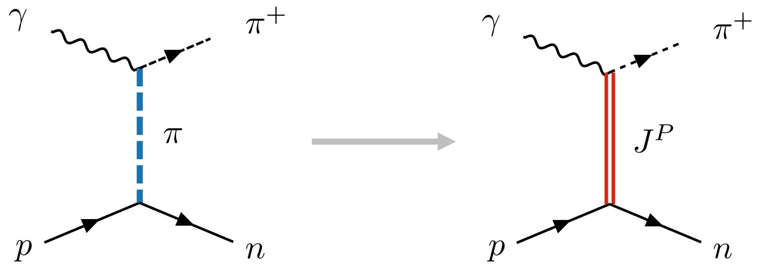


$$1^- \otimes 0^- = 1^+ \begin{cases} L = 1 & J = 0 \\ L = \{J-1, J+1\} & J \geq 2 \end{cases}$$ one L vs two L's

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

→ Gauge invariant by construction

Reggeization of pion exchange



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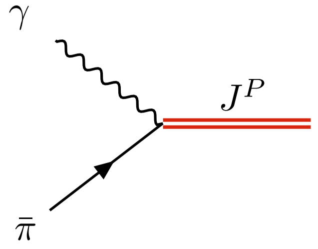

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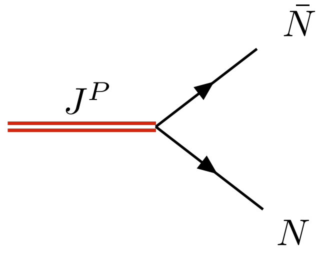


$$\tfrac{1}{2}^+ \otimes \tfrac{1}{2}^- = 0^- \oplus 1^- \rightarrow L = J$$

helicity non-flip (0^-), helicity flip (1^-)

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

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

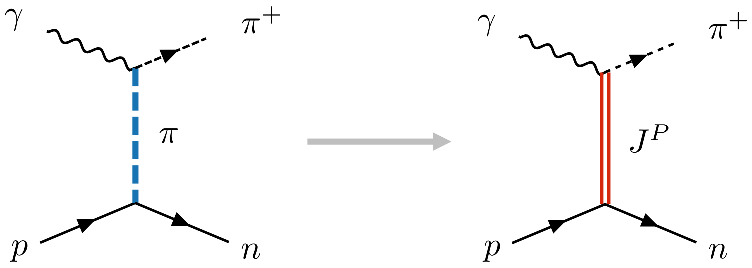
$$P^\nu = p_i^\nu + p_f^\nu$$

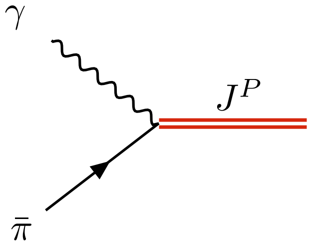
Reggeization of pion exchange

- Rigorous reggeization:

  Explicit exchanges of t-channel partial waves in the π trajectory

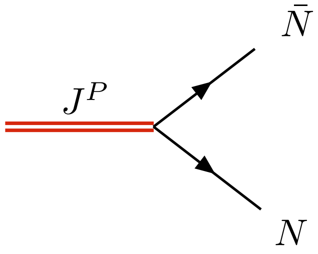
- Vertices coupling $\gamma\pi$ and $N\bar{N}$ to $J^P = (\text{even})^-$:





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

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



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

helicity non-flip (0^-), helicity flip (1^-)

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

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

$$P^\nu = p_i^\nu + p_f^\nu$$

$$V_{\lambda_\gamma}(J)\frac{1}{J-\alpha_\pi(t)}V_{\lambda_i\lambda_f}(J) = \frac{g^J_{\lambda_\gamma\lambda_i\lambda_f}(t)}{J-\alpha_\pi(t)}d^J_{\lambda_\gamma\lambda_i-\lambda_f}(\theta_t)$$

Regge pole propagator; partial wave amplitude; Wigner d-function

Reggeization of pion exchange

- Analytical continuation to $J = 0$: $\alpha_\pi(t) = \alpha'_\pi(t - \mu^2)$

$$\left.\frac{g^J_{\lambda_\gamma\lambda_i\lambda_f}(t)}{J-\alpha_\pi(t)} d^J_{\lambda_\gamma\lambda_i-\lambda_f}(\theta_t)\right|_{J=0} \approx i2\frac{g}{\alpha'_\pi}\lambda_\gamma 2\lambda_i \delta_{\lambda_i\lambda_f} e_\pi \frac{t}{t-\mu^2} \quad \text{with} \quad g = \alpha'_\pi g_{\pi NN}$$

Recover m.g.i. π exchange (or electric term)

- Spin summation

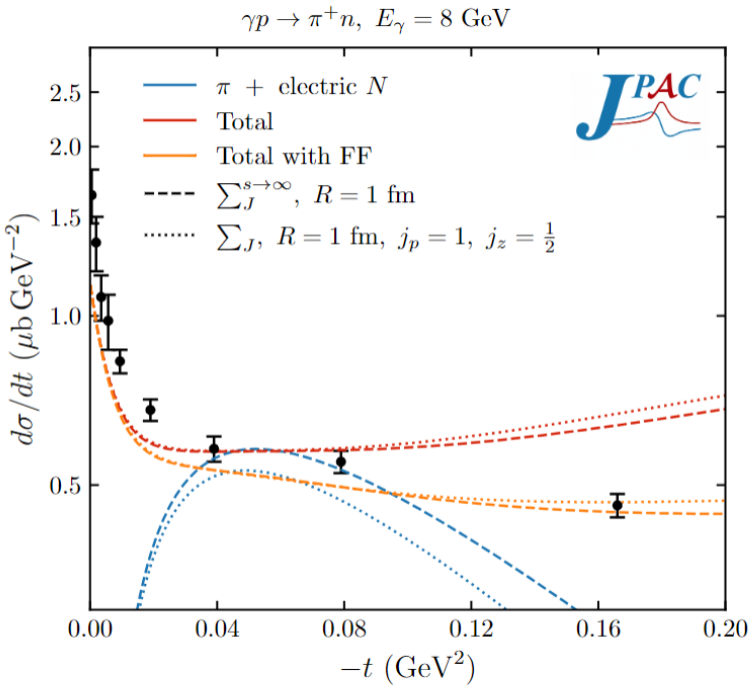
(e.g. Sommerfeld-Watson transform, generating function of Jacobi polynomials)

$$A^R_{\lambda_\gamma\lambda_i\lambda_f}(s,t) = \sum_{J=0,2,\ldots} (2J+1)\frac{g^J_{\lambda_\gamma\lambda_i\lambda_f}(t)}{J-\alpha_\pi(t)} d^J_{\lambda_\gamma,\lambda_i-\lambda_f}(\theta_t)$$

$$g = \alpha'_\pi g_{\pi NN}\Lambda_J(r_t r_b)^J \qquad c_J\Lambda_J(r_t r_b)^J \rightarrow \frac{j_p}{j_z}\frac{J+j_z}{J+j_p}R^{2J}$$

microscopic structure — hadronic radii — kinematic factors

- Corrections: add form factor to magnetic term $\beta(t) = \frac{\Lambda}{\Lambda^2 - t}$ with $\Lambda \sim 1$ GeV



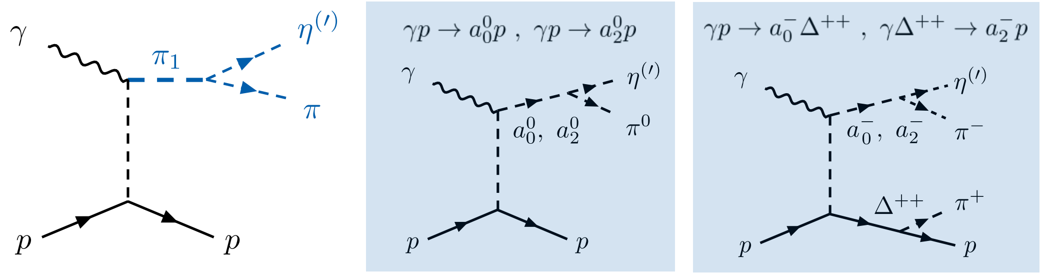
[G.Montana et al. (in preparation)]

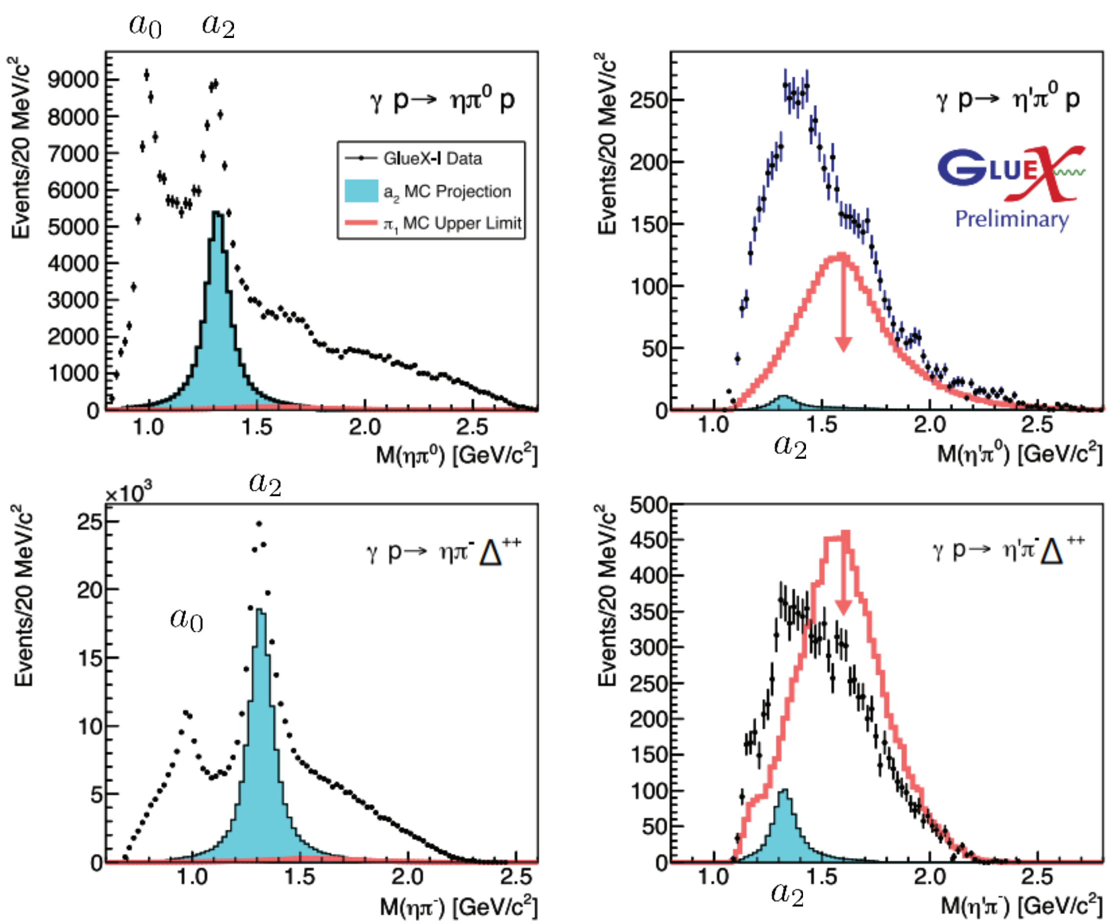
Photoproduction of $\eta^{(\prime)}\pi$

- GlueX can access different channels:

$$\gamma p \to \eta^{(\prime)} \pi^0 p$$
$$\gamma p \to \eta^{(\prime)} \pi^- \Delta^{++}$$

- Small signal of $\pi_1(1600)$ in partial wave with $\ell = 1$ (*P*-wave).
- Clear signals of non-exotic $a_0(980)$ (*S*-wave) and $a_2(1320)$ (*D*-wave).
- Overlapping resonances → need partial-wave analysis.





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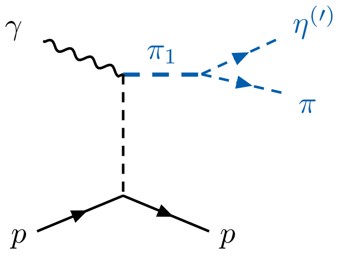

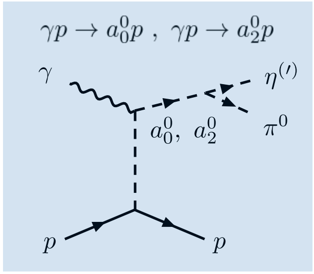

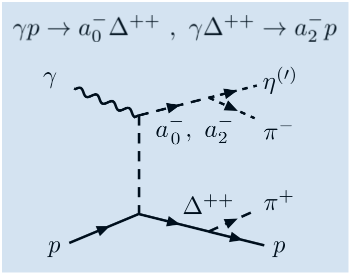

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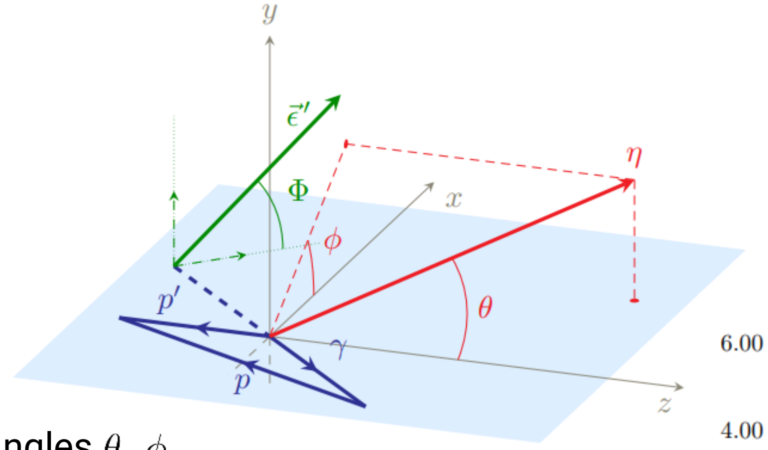

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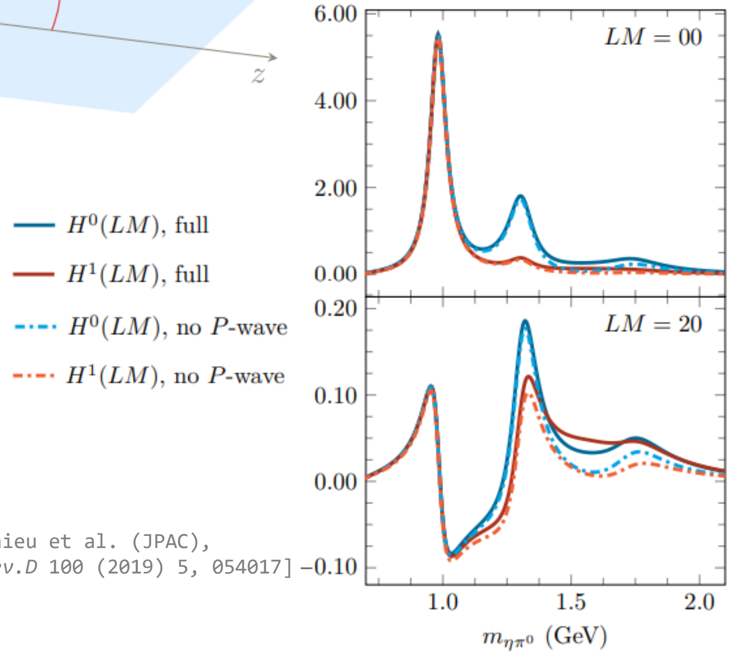
- Three angles needed to describe the intensity: polarization Φ and decay angles θ, ϕ.
- Observables:
  - Moments of angular distribution:
    ↳ sensitive to exotic signal via interference.
  - Polarization asymmetry
  - Spin-density matrix elements (SDMEs)
    ↳ 9 independent parameters

$$I(\Omega,\Phi) = \kappa \sum_{\lambda,\lambda',\lambda_1,\lambda_2} A_{\lambda;\lambda_1\lambda_2}(\Omega)\rho^{\gamma}_{\lambda\lambda'}(\Phi)A^*_{\lambda';\lambda_1\lambda_2}(\Omega)$$



[V.Mathieu et al. (JPAC), Phys.Rev.D 100 (2019) 5, 054017]

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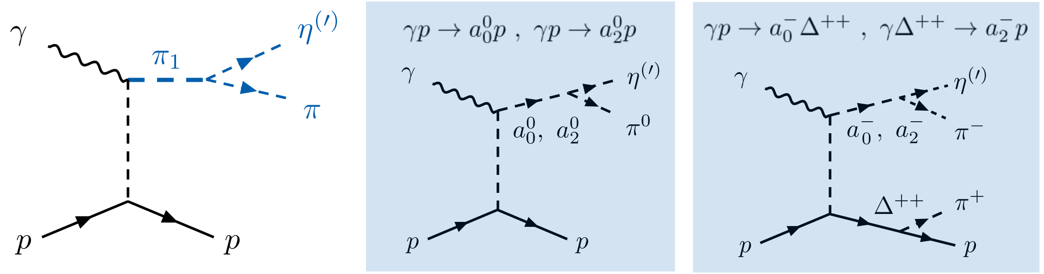

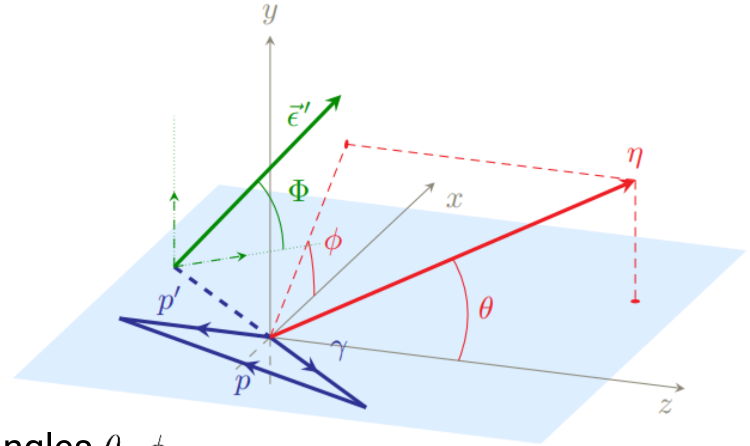

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[V.Mathieu et al. (JPAC), *Phys.Rev.D* 102 (2020) 1, 014003]

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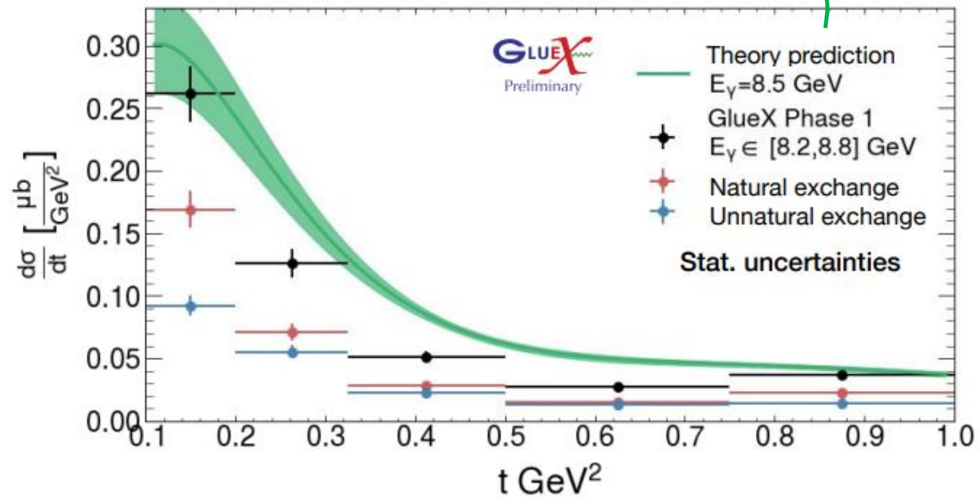
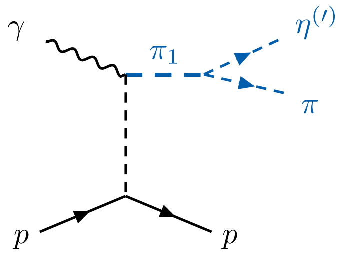
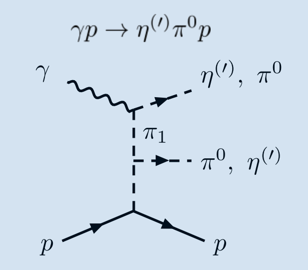
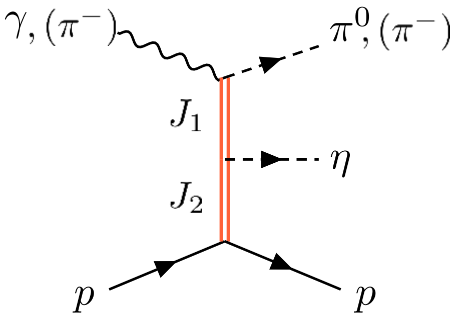


Double Regge contributions

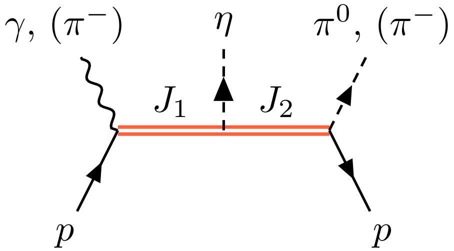




- Contributes to background.
- Models from the 70's (e.g. Venziano, Shimada) can't reproduce high-statistics data at COMPASS and GlueX.
- Need to develop new double-Regge amplitudes consistent with Regge phenomenology.



At high energy:



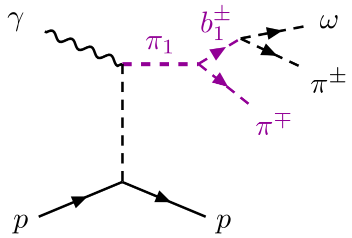
- Need to make the diagrams consistent with each other.
- Use quark string-breaking models to calculate helicity dependence explicitly, and give us insight into the Regge couplings.

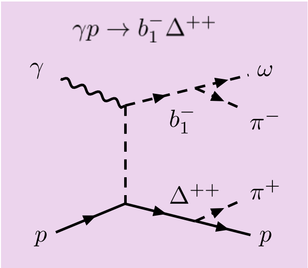
Photoproduction of $b_1(1235)$

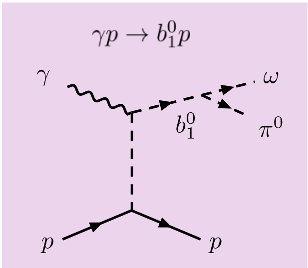
- Lattice QCD calculations predicts the dominant $\pi_1(1600)$ decay channel be the $b_1\pi(\rightarrow 5\pi)$.
- First step is to understand the b_1 production and decay to $\omega\pi$.
- GlueX can access charged and neutral b_1:

$$\gamma p \rightarrow b_1^0 p \rightarrow \omega\pi^0 p$$

$$\gamma p \rightarrow b_1^- \Delta^{++} \rightarrow \omega\pi^- \Delta^{++}$$







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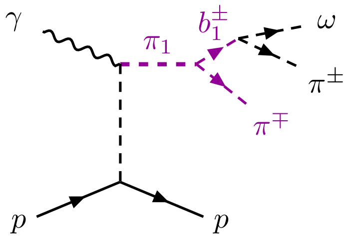
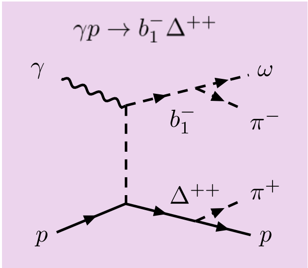
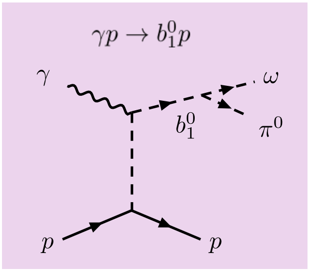
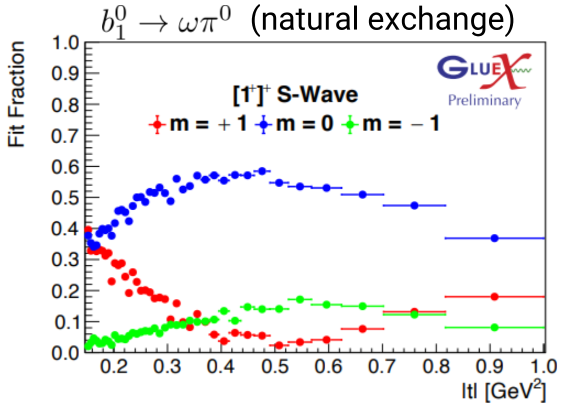
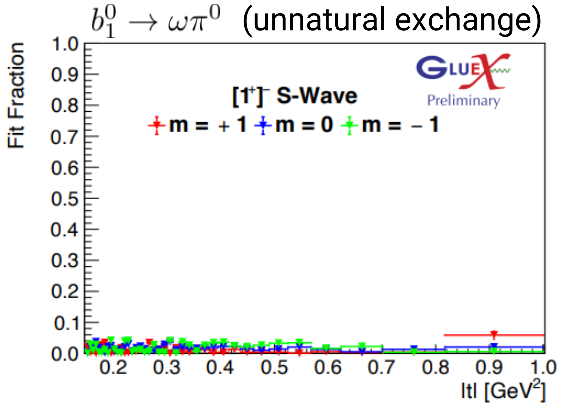


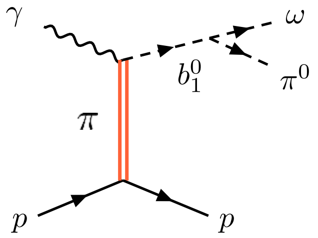








- Size of pion exchange consistent with preliminary GlueX data.



Interaction:

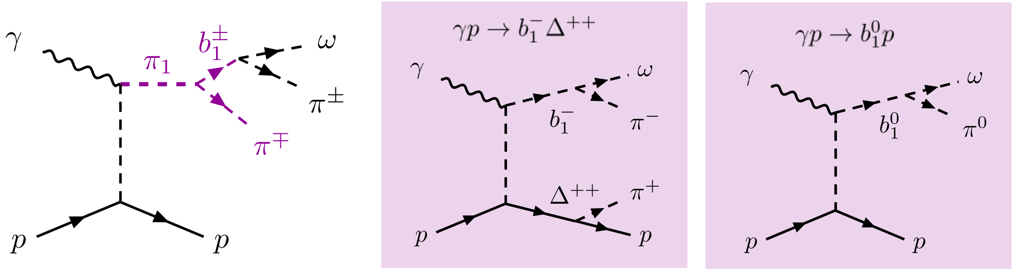
$$\langle \pi | \gamma b_1 \rangle = \frac{g_{b_1}}{m_{b_1}} \epsilon_\mu^{b_1 *} \epsilon_\nu^{\gamma *} \left[p_1^\mu p_3^\nu - (p_1 \cdot p_3) g_{\mu\nu} \right]$$

$$= \frac{g_{b_1}}{m_{b_1}} \frac{\delta_{\lambda_\gamma,\Lambda}}{2} (m_{b_1}^2 - t)$$

Regge propagator:

$$R_\pi(\alpha, s) = \alpha' \frac{\pi}{2} \frac{1 + e^{-i\pi\alpha}}{\Gamma(\alpha+1)} \frac{(s/s_0)^\alpha}{\sin \pi\alpha}$$

Photoproduction of $b_1(1235)$



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$$\boxed{\gamma p \to b_1^- \Delta^{++} \to \omega\pi^- \Delta^{++}}$$

- Derivation of cross section formula and implementation in AmpTools (GlueX analysis code).

Production

Decay chain

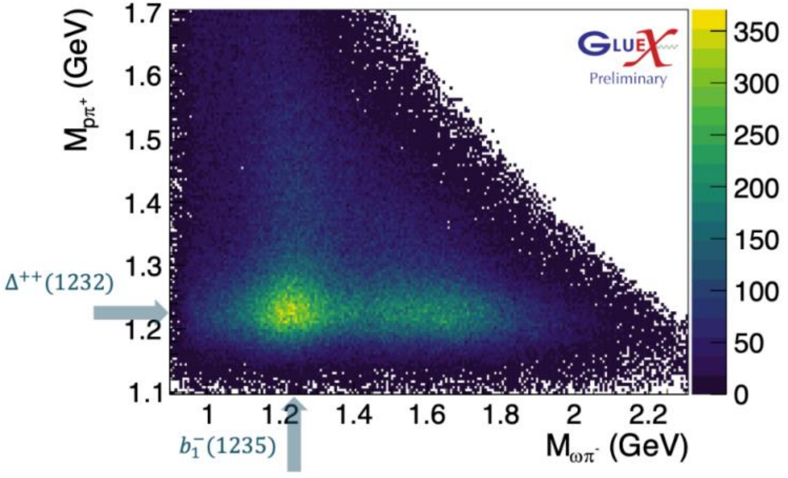
$$A_{\lambda_\gamma,\lambda_1,\lambda_2} = \sum_{i=1^\pm} \sum_{\Lambda=-1}^{1} \sum_{\lambda_\Delta=-\frac{3}{2}}^{\frac{3}{2}} V^i_{\lambda_\gamma,\Lambda;\lambda_1,\lambda_\Delta}(s,t) \sum_{\lambda=-1}^{1} F^i_\lambda D^{J*}_{\Lambda,\lambda}(\Omega_\omega) Y^1_\lambda(\Omega_H) G \tilde{F}_{\lambda_2} D^{\frac{3}{2}*}_{\lambda_\Delta,\lambda_2}(\Omega_p)$$

$\gamma(\lambda_\gamma)p(\lambda_1) \to b_1^-(\Lambda)\Delta^{++}(\lambda_\Delta)$

$b_1^-(\Lambda) \to \omega(\lambda)\pi^-$

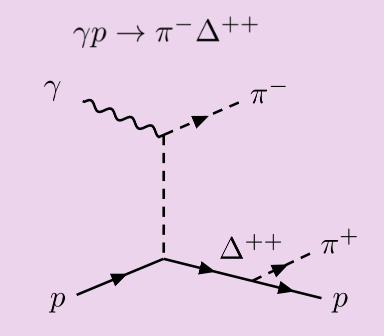
$\omega(\lambda) \to \pi^+\pi^-\pi^0$

$\Delta^{++}(\lambda_\Delta) \to \pi^+ p(\lambda_2)$



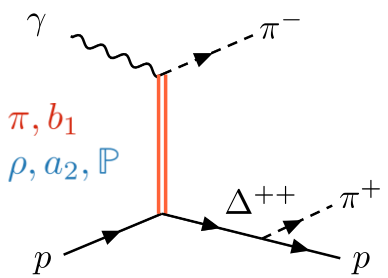
- Access SDMEs for b_1^- and Δ^{++}

SDMEs of the Δ^{++}



- Spin density matrix elements (SDMEs) of the $\Delta^{++}(1232)$ in $\gamma p \to \pi^- \Delta^{++}$ comparing with experimental data from GlueX.
- Three angles required to describe intensity: polarization Φ and Δ^{++} decay θ, ϕ
- 9 independent SDMEs
- JPAC previous model reproduces cross section but not SDMEs.

[J.Nys et al. (JPAC), *Phys.Lett.B* 779 (2018) 77-81]



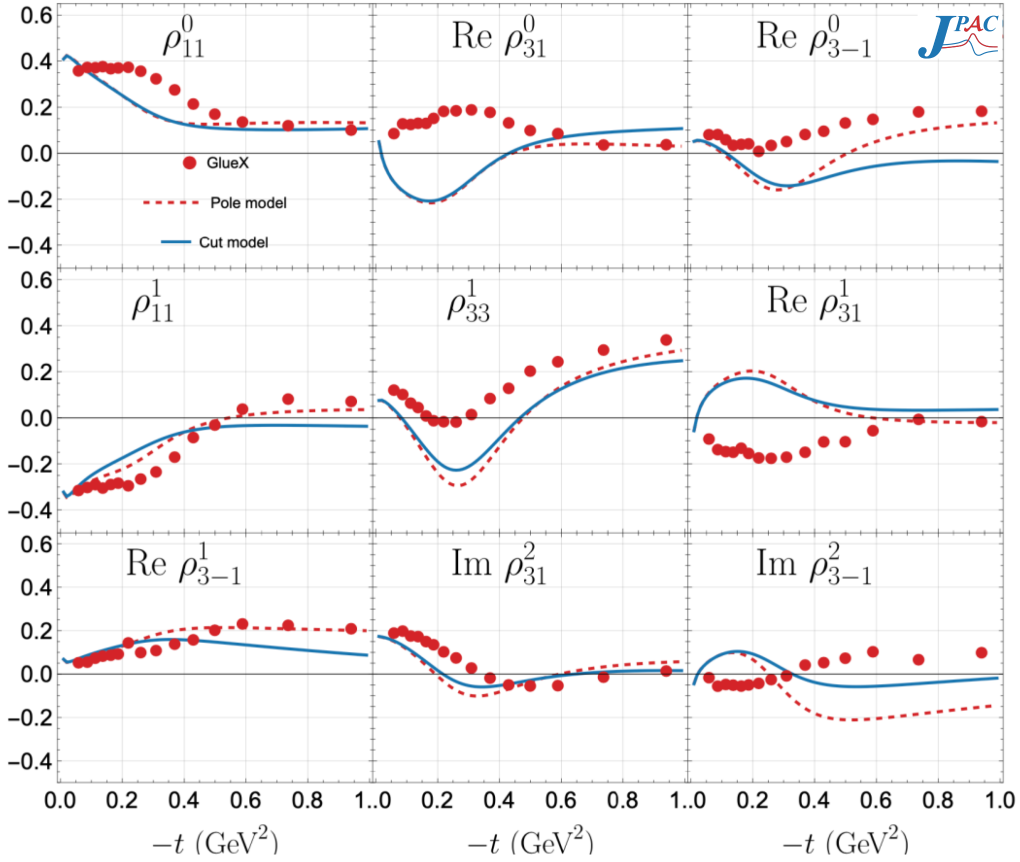
$$A_{\mu_\gamma \mu_1 \mu_2}(s,t) = \beta_{\mu_\gamma}(t)\beta_{\mu_1\mu_2}(t)\mathcal{P}_{\rm R}(s,t)$$

$$\mathcal{P}_R = \frac{\pi\alpha'_R}{2}\frac{\tau_R + e^{-i\pi\alpha_R(t)}}{\sin\pi\alpha_R(t)}\left(\frac{s}{s_0}\right)^{\alpha_R(t)}$$

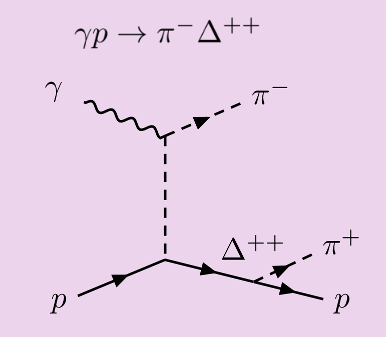
+ Poor Man's Absorption for pion exchange

[P.K.Williams, *Phys.Rev.D* 1 (1970) 1312]

Preliminary data from GlueX [V.Shastry et al. (JPAC) (in preparation)]



SDMEs of the Δ^{++}



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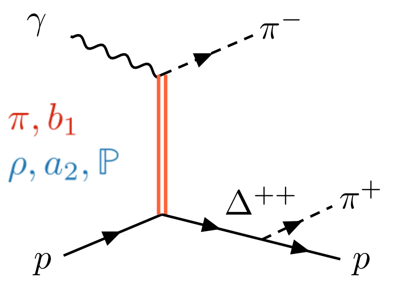

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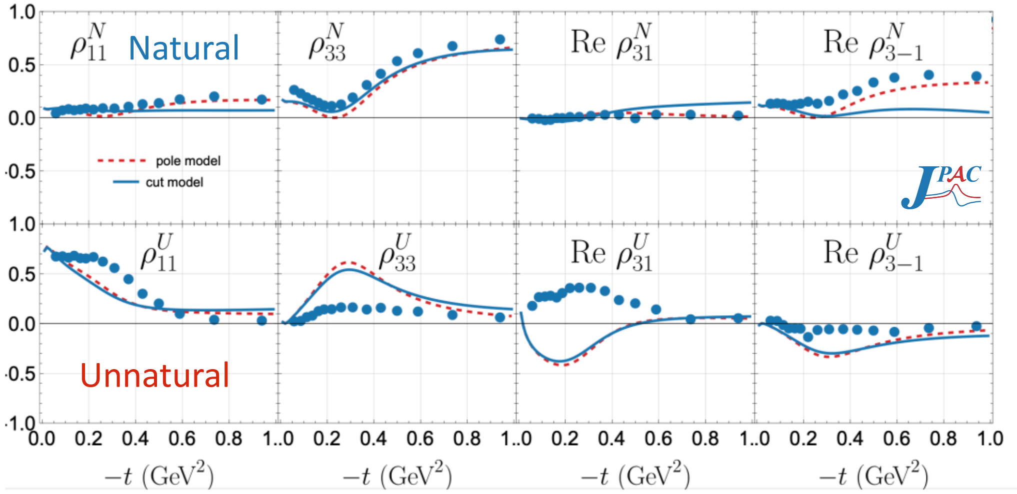

- Better agreement with natural exchange.

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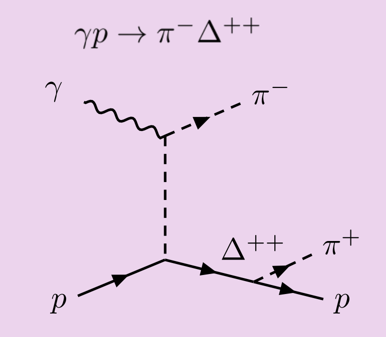

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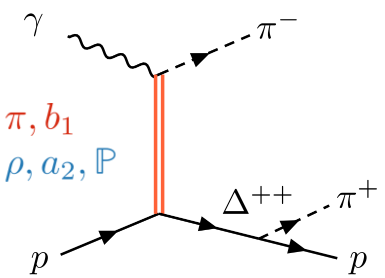

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+ Poor Man's Absorption for pion exchange

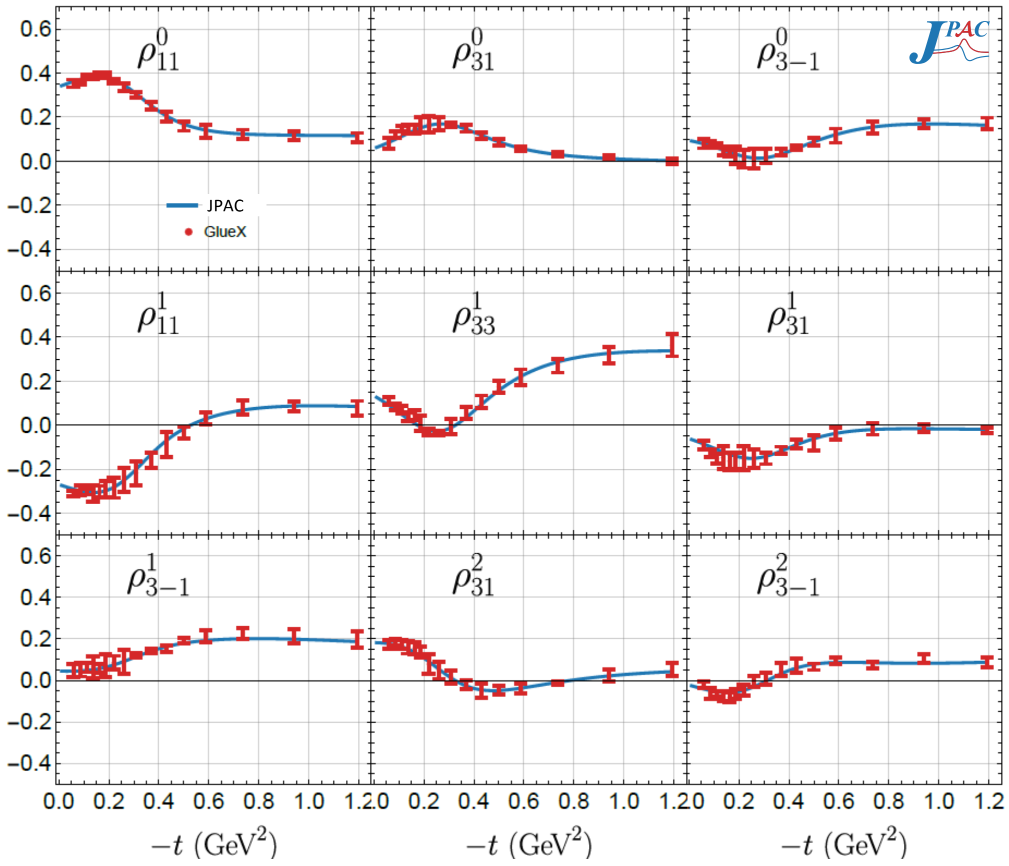
[P.K.Williams, *Phys.Rev.D* 1 (1970) 1312]

- Better agreement with natural exchange.
- Polynomial can fit the data.

$$V_{\lambda_\gamma,\lambda_1,\lambda_\Delta}(t) = (z^2_{\lambda_\gamma,\lambda_1,\lambda_\Delta}t^2 + z^1_{\lambda_\gamma,\lambda_1,\lambda_\Delta}t + z^0_{\lambda_\gamma,\lambda_1,\lambda_\Delta})e^{\alpha t}$$

- Work in progress to identify the Physics.

Preliminary data from GlueX [V.Shastry et al. (JPAC) (in preparation)]



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 reggeized the pion appropriately?
  - 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 NN to $J^P = (\mathrm{even})^-$ 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.
- Close collaboration with GlueX to provide them with theory support.

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