Recent achievement in Regge theory for photoproduction of hadron

Applications of Regge model to photoproduction of $\pi\Delta$ and scaling with saturation of trajectory

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in collaboration with

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Outline

- Features of reaction mechanism of $\gamma p \rightarrow \pi^- \Delta^{++}$ & scaling

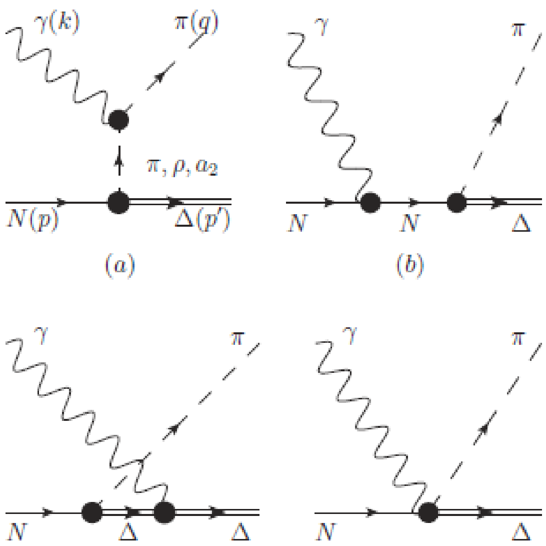
  - Minimal gauge for π exch. and tensor meson exch. at high E

  - EM multipoles of Δ in the resonance region

  - Scaling by saturation of trajectory at large -t

- Summary and outlook

Photoproduction of $\pi^-\Delta^{++}$ at high energy



B.-G. Yu, K.-J. Kong, Phys. Lett. B **769**, 262 (2017)

- Dominance of one pion exch.
  $\Longleftarrow$ Cross section steep decrease

- Charge conservation
  $e_p - e_{\Delta^{++}} - e_{\pi^-} = 0$

- Divergence of Δ due to $p^\mu p^\nu / M_\Delta^2$

$$iM_{u(\Delta)} = -\frac{f_{\pi N\Delta}}{m_\pi}\bar{u}_\nu(p')e_\Delta(g^{\nu\alpha}\not{\epsilon} - \epsilon^\nu\gamma^\alpha)\,\frac{(\not{p}' - \not{k} + M_\Delta)}{u - M_\Delta^2}\Pi^\Delta_{\alpha\beta}(p'-k)q^\beta u(p)$$

▶ Minimal gauge

$$\mathcal{M}_{\pi N\Delta} = \frac{f_{\pi N\Delta}}{m_\pi}\bar{u}_\nu(p')\Bigg[q^\nu\frac{2p\cdot\epsilon + \not{k}\not{\epsilon}}{s - M_N^2}e_N + e_\Delta\frac{q_\mu}{u - M_\Delta^2}\Bigg(2p'\cdot\epsilon g^{\mu\nu} + \sum_i G_i^{\nu\mu}(p', k, \epsilon)\Bigg)$$
$$+ e_\pi\frac{2q\cdot\epsilon}{t - m_\pi^2}(q-k)^\nu - e_\pi\epsilon^\nu\Bigg]u(p)$$

$\mathcal{M} \sim$ Coulomb charge terms + transverse terms $\Longleftrightarrow$ Remove transverse terms

- Tensor meson exch.

  - $\pi + \rho$? or $\pi + a_2$?

G. R. Goldstein and J. F. Owens, Nucl. Phys. B **71**, 461 (1974).

Regge-fit to high energy data

$\beta_{a_2 N\Delta} \approx -3\beta_{\rho N\Delta}$ from VMD and Duality

  - ρ meson exch.

$$\mathcal{L}_{\rho N\Delta} = i\frac{f_{\rho N\Delta}}{m_\rho}\bar{\Delta}_\nu \gamma_\mu \gamma_5 N(\partial^\nu \rho^\mu - \partial^\mu \rho^\nu)$$

  - New Lagrangian for tensor meson $a_2(1320)$ 2^{++} exch.

$$\mathcal{L}_{a_2 N\Delta} = i\frac{f_{a_2 N\Delta}}{m_{a_2}}\bar{\Delta}^\lambda \left(g_{\lambda\mu}\overleftrightarrow{\partial_\nu} + g_{\lambda\nu}\overleftrightarrow{\partial_\mu}\right)\gamma_5 N a_2{}^{\mu\nu}$$

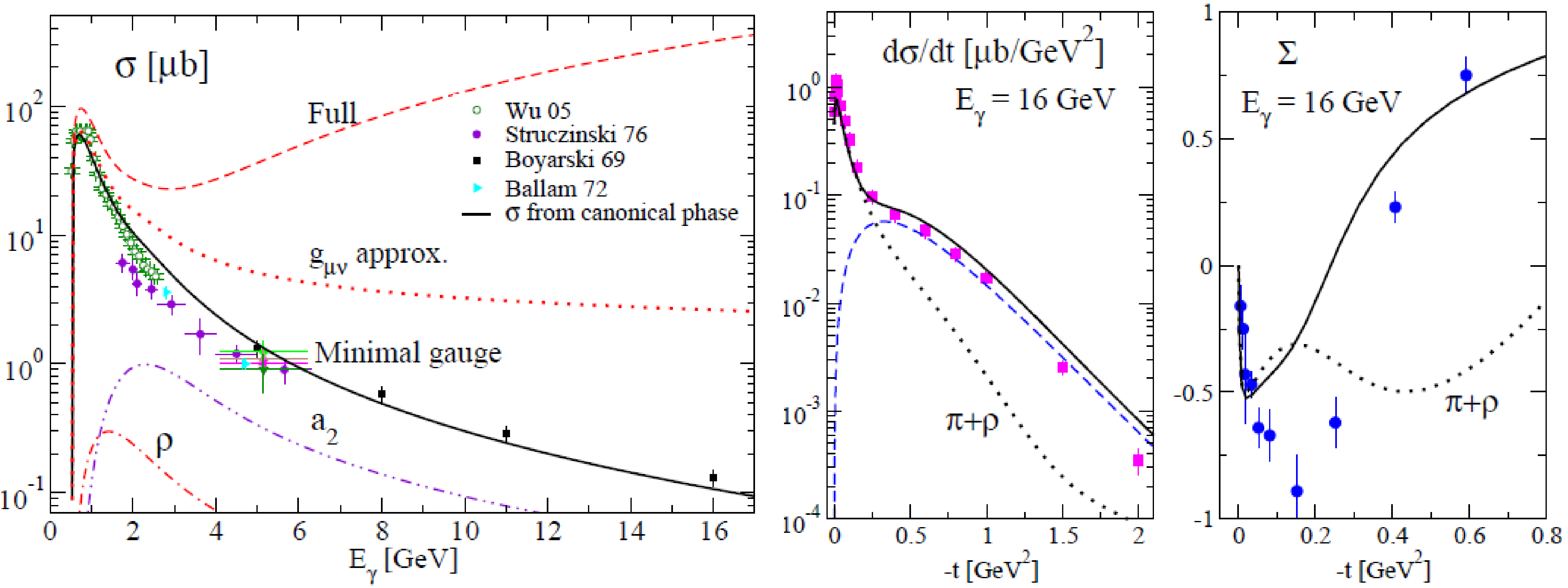
$$\frac{f_{a_2 N\Delta}}{m_{a_2}} = -3\frac{f_{\rho N\Delta}}{m_\rho}$$

Convergence & tensor meson dominance

$$\mathcal{M}(\pi^{\mp}\Delta) = \left\{ \begin{array}{c} 1 \\ 1/\sqrt{3} \end{array} \right\} [\mp \pi N\Delta + (\rho \mp a_2)]$$

$$\alpha_\pi(t) = 0.7\,(t - m_\pi^2)\,,$$
$$\alpha_\rho(t) = 0.8\,t + 0.55\,,$$
$$\alpha_{a_2}(t) = 0.85\,(t - m_{a_2}^2) + 2$$

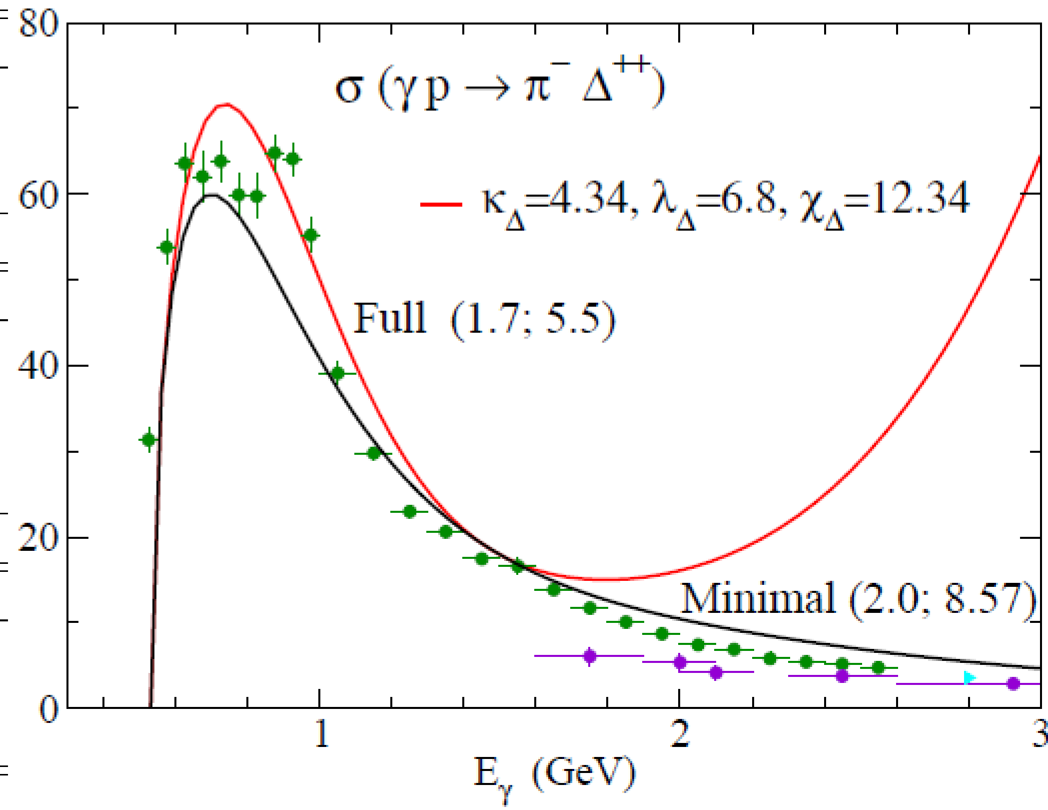
	Coupling const.	$^{(a)}$Phase
π	$f_{\pi N\Delta} = 2.0$	$\frac{1}{2}(1 + e^{-i\pi\alpha_\pi(t)})$
ρ	$g_{\gamma\pi^\pm\rho} = 0.224$ $f_{\rho N\Delta} = 8.57$	1
a_2	$g_{\gamma\pi a_2} = -0.276$ $\frac{f_{a_2 N\Delta}}{m_{a_2}} = -3\frac{f_{\rho N\Delta}}{m_\rho}$	1



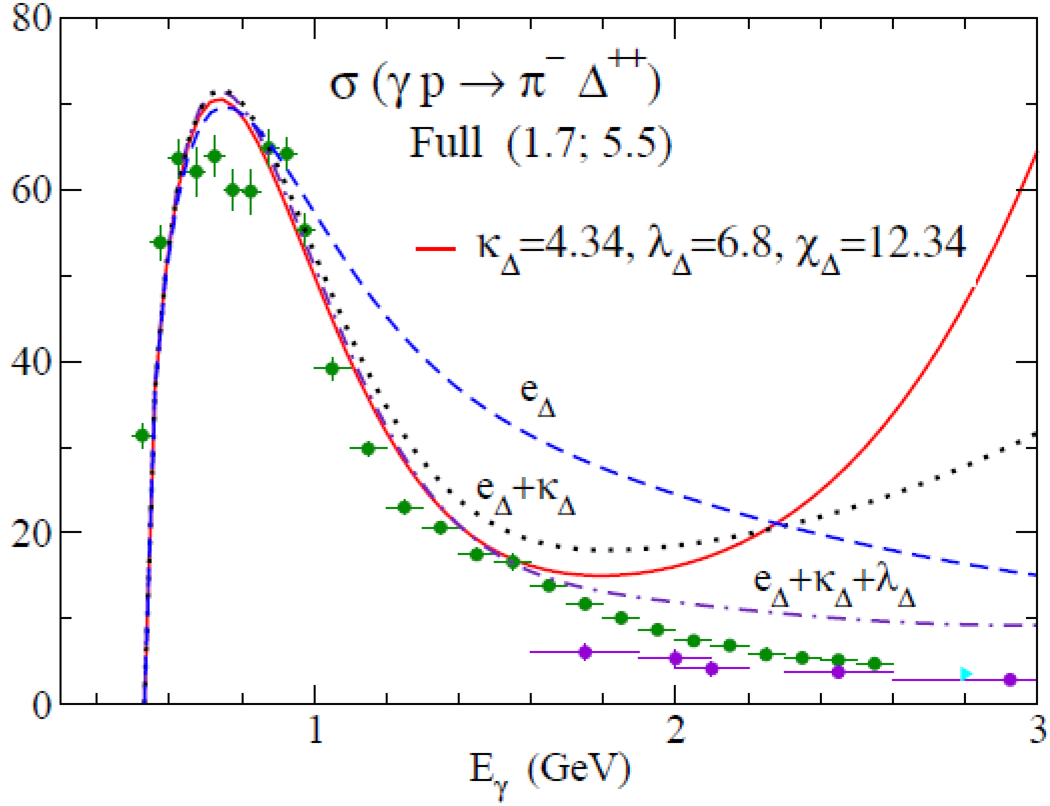
Photoproduction of $\pi^-\Delta^{++}$ at low energy

$$\epsilon_\mu \Gamma^{\lambda\mu\sigma}_{\gamma\Delta\Delta}(p',k,p) = -\Big\{ e_\Delta (g^{\lambda\sigma}\not\epsilon - \epsilon^\lambda\gamma^\sigma) - \frac{e}{4M_\Delta}\left(\kappa_\Delta\, g^{\lambda\sigma} + \chi_\Delta \frac{k^\lambda k^\sigma}{4M_\Delta^2}\right)[\not\epsilon, \not k] + \frac{e\lambda_\Delta}{4M_\Delta^2}\left[k^\lambda k^\sigma \not\epsilon - \frac{1}{2}\not k(\epsilon^\lambda k^\sigma + \epsilon^\sigma k^\lambda)\right]\Big\}$$

μ_Δ	Δ^{++}	Δ^{+}	Δ^{0}	Δ^{-}
LCSR	6.34	3.17	0	-3.17
CQM$^{(1)}$	6.93	3.47	0	-3.47
SU(6)	7.33	3.66	0	-3.66
Exp.	$7.34\pm2.49^{(a)}$	$3.54^{+4.59\,(b)}_{-4.72}$	-	$-\mu_{\Delta^+}$
$\mathcal{Q}_\Delta$	Δ^{++}	Δ^{+}	Δ^{0}	Δ^{-}
LCSR	-0.028	-0.014	0	0.014
CQM$^{imp\,(2)}$	-0.064	-0.032	0	0.032
CQM$^{exc\,(2)}$	-0.238	-0.119	0	0.119
SU(6)		$r_n^2 = -0.113\ \mathrm{fm}^2$		
Exp.				
$\mathcal{O}_\Delta$	Δ^{++}	Δ^{+}	Δ^{0}	Δ^{-}
LCSR	-0.006	-0.003	0	0.003
CQM$^{(3)}$	-0.024	-0.012	0	0.012
SU(6)		$\mathcal{Q}_{\Delta^+}\mu_N$		



EM multipoles of Δ in the resonance region



- Role of $\mu_\Delta = e(2+\kappa_\Delta)/2M_\Delta$

Photoproduction at large -t

Brodsky and Farrar, Phys. Rev. Lett. **31**, 1153 (1973)

- Constituents counting rule (CCR)

$$\frac{d\sigma}{dt} = f(t/s)s^{2\alpha(t)-2} \;\Rightarrow\; \frac{d\sigma}{dt} \propto s^{2-n}$$

$$n = (1+3) + (2+3) = 9$$

▶ $s^7 \dfrac{d\sigma}{dt} \sim$ independent of energy $\Rightarrow$ scaling

- Phenomena in scaled region

Q. Zhao and F. E. Close, Phys. Rev. Lett. **91**, 022004 (2003)

▶ Oscillatory behavior of scaled cross section

H. W. Huang, R. Jakob, P. Kroll *et al.*, Eur. Phys. J. C **33**, 91 (2004)

▶ Predictions of pQCD calculation:

handbag diagram of $\gamma q \to \pi q$ factorized nucleon GPDs

Scaling & trajectory saturated at large -t

Blankenbecler *et al.*, Phys Rev. D **8**, 4117 (1973)
P. D. B. Collins *et al.*, Z. Phys. C **22**, 277 (1984)
M. N. Sergeenko, Z. Phys. C **64**, 315 (1994)
GLV, Nucl. Phys. A **627**, 645 (1997)

- Interquark potential

$$V(r) = \underbrace{-\frac{4\alpha_s}{3}\frac{1}{r}}_{sat.} + \underbrace{\kappa r}_{linear} + V_0$$

- Saturation of trajectory for power law scaling

$$\alpha(t) \to -1 \Rightarrow \frac{d\sigma}{dt} \sim s^{2\alpha(t)-2} \sim s^{-4} \qquad s^7 \frac{d\sigma}{dt} \sim s^3 \Rightarrow \text{Form factor}$$

$$F(t) = \left(1 - \frac{t}{\Lambda^2}\right)^{-1}$$

- Trajectory $\alpha^*(t)$ saturated at $t = t_0$

$$\alpha(t) = \alpha_0 + \alpha' t \quad \Rightarrow \quad \alpha^*(t) = c_1 + c_2\sqrt{t_1 - t} \qquad (t_1 > t_0)$$

- Determination of c_1 and c_2 from continuity and differentiability at $t = t_0$

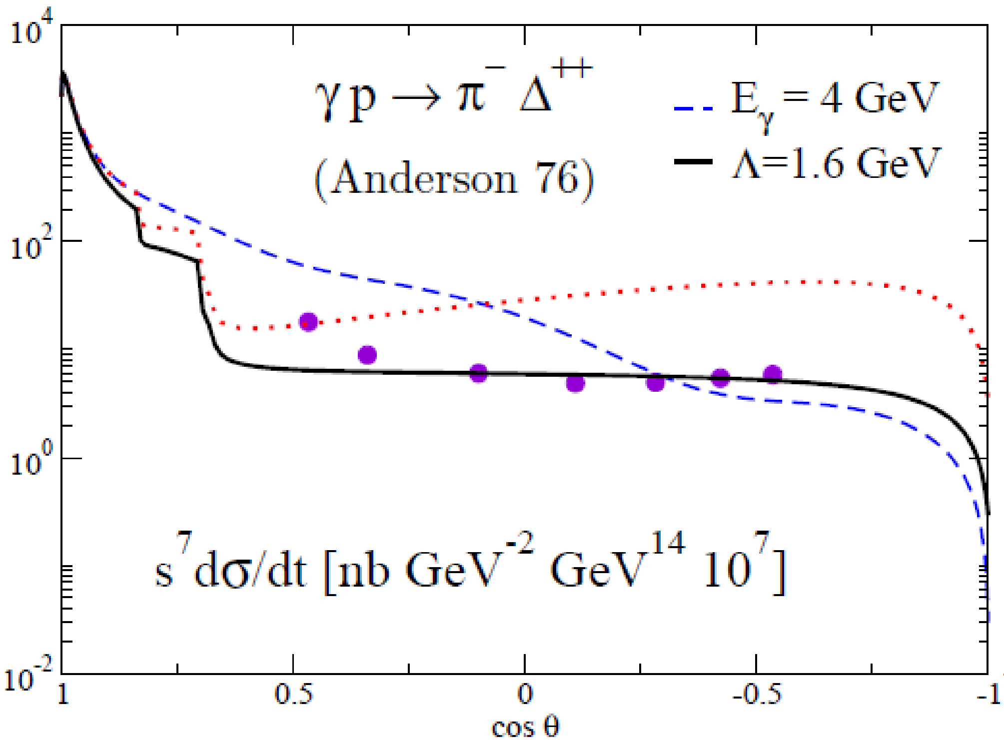
$$\alpha(t_0) = \alpha^*(t_0), \qquad d\alpha/dt(t_0) = d\alpha^*/dt(t_0)$$

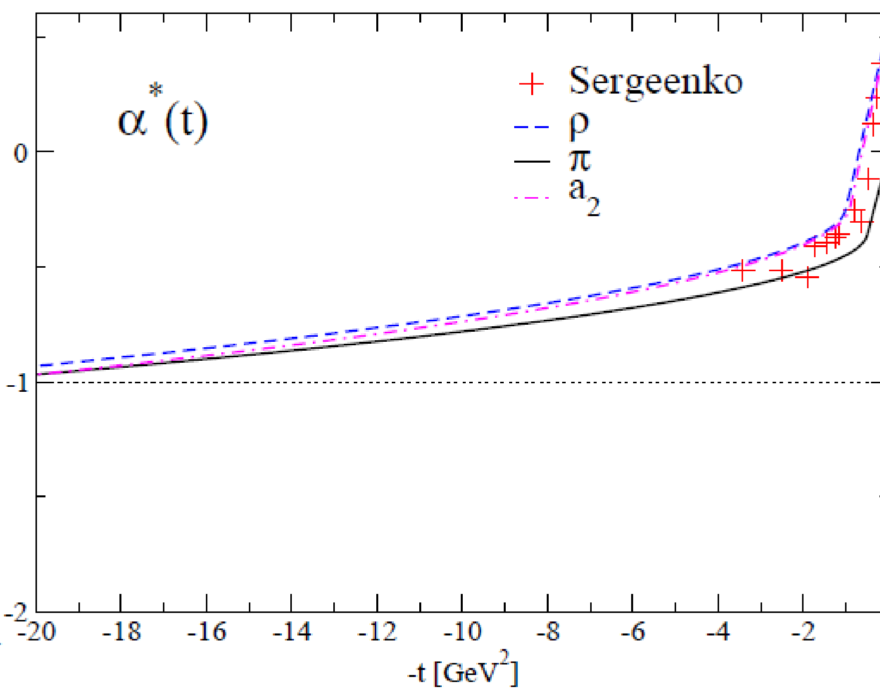
Scaling of cross sections @ SLAC

R. L. Anderson *et al.*, Phys. Rev. D **14**, 679 (1976)

- Saturation $\alpha(t) \to -1$
- Form Factor for $N\Delta$ Transition?

$$F(t) = \left(1 - \frac{t}{\Lambda^2}\right)^{-1} \qquad : \text{Simple monopole-type}$$

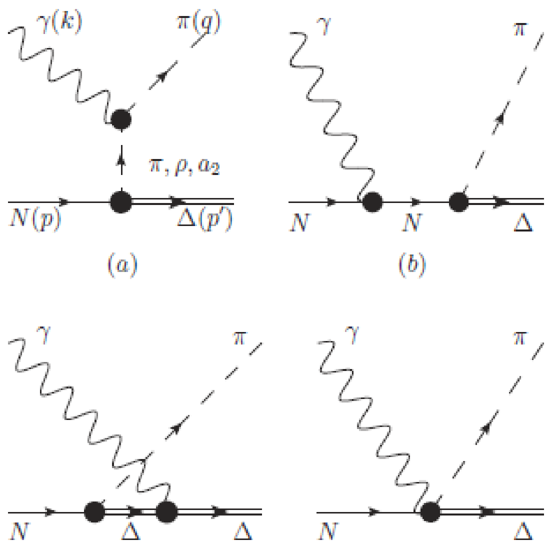




Summary and Outlook

- We have studied photoproduction of $\gamma p \to \pi^- \Delta^{++}$ in the Reggeized model.
- Good convergence of cross section at high energies is obtained based on the minimal gauge for π exch, and role of tensor meson a_2 is found to be crucial there.
- Scaling of differential cross section is well accounted for by a saturation of trajectory at large angle.
- Regge model is powerful to describe hadron reactions up to high energy and wide angle and applicable to analyze data from 12 GeV-upgrade at Jefferson Lab.

Photoproduction of $\pi^-\Delta^{++}$ at high energy



B.-G. Yu, K.-J. Kong, Phys. Lett. B **769**, 262 (2017)

- Dominance of one pion exch.
  $\Longleftarrow$ Cross section steep decrease
- Charge conservation
  $$e_p - e_{\Delta^{++}} - e_{\pi^-} = 0$$
- Divergence of Δ due to $p^\mu p^\nu / M_\Delta^2$

▶ Minimal gauge — P. Stichel and M. Scholz, Nuovo Cimento **34**, 1381 (1964)

$\mathcal{M} \sim$ Lowest order in e and $f_{\pi N\Delta}$

$\sim$ Charge coupling to photon $\Longleftrightarrow$ Remove transverse terms

$\sim T_{I=1,\, I_\gamma=1}$

▶ $\pi + \rho$? or $\pi + a_2$? — G. R. Goldstein and J. F. Owens, Nucl. Phys. B **71**, 461 (1974).

Regge-fit to high energy data

$\beta_{a_2 N\Delta} \approx -3\beta_{\rho N\Delta}$ from VMD and Duality

- Ward identity for charge coupling at $\gamma\Delta\Delta$ vertex

$$k_\mu \Gamma^{\mu\nu\alpha}_{\gamma\Delta\Delta}(p,k) = (D^{\nu\alpha})^{-1}(p+k) - (D^{\nu\alpha})^{-1}(p)$$

$$\epsilon_\mu \Gamma^{\mu\nu\alpha}_{\gamma\Delta\Delta} = e_\Delta \bar{u}_\nu(p') \left(g^{\nu\alpha}\not\epsilon \underbrace{-\epsilon^\nu \gamma^\alpha}_{\Downarrow} \underbrace{-\gamma^\nu \epsilon^\alpha + \gamma^\nu \not\epsilon \gamma^\alpha}_{=0} \right) u(p)$$

- Minimal gauge $\Rightarrow$ removal of transverse components

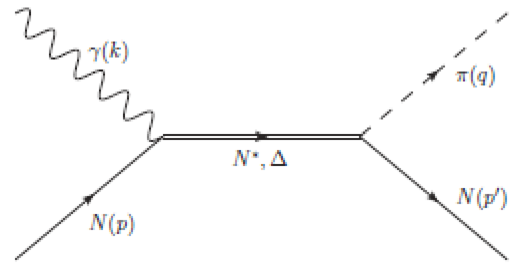
$$\begin{aligned} iM_{u(\Delta)} = e_\Delta \frac{f_{\pi N\Delta}}{m_\pi} \bar{u}^\nu(p') \Big[& q_\nu \underbrace{(2\epsilon\cdot p'}_{} - \not\epsilon \not k) + \frac{2}{3}(k_\nu \cancel{\not\epsilon} - \epsilon_\nu \cancel{\not k}) \not q \\ & + \frac{2}{3M_\Delta}(k_\nu \cancel{\not\epsilon} - \epsilon_\nu \cancel{\not k})\,(p'-k)\cdot q \\ & - \frac{1}{3M_\Delta}(2k_\nu \cancel{p}'\cdot\epsilon - 2\epsilon_\nu \cancel{p}'\cdot k - k_\nu \not\epsilon \not k) \not q \\ & + \frac{2}{3M_\Delta^2}(2k_\nu \cancel{p}'\cdot\epsilon - 2\epsilon_\nu \cancel{p}'\cdot k - k_\nu \not\epsilon \not k)\,(p'-k)\cdot q \Big] u(p) \times \frac{1}{u - M_\Delta^2} \end{aligned}$$

- Tensor meson $a_2(1320)2^{++}$

$$\mathcal{L}_{a_2 N\Delta} = i\frac{f_{a_2 N\Delta}}{m_{a_2}} \bar{\Delta}^\lambda \left(g_{\lambda\mu} \overleftrightarrow{\partial}_\nu + g_{\lambda\nu} \overleftrightarrow{\partial}_\mu \right) \gamma_5 N a_2{}^{\mu\nu}\,, \qquad \frac{f_{a_2 N\Delta}}{m_{a_2}} = -3\frac{f_{\rho N\Delta}}{m_\rho}$$

Scheme for Extension of Regge model

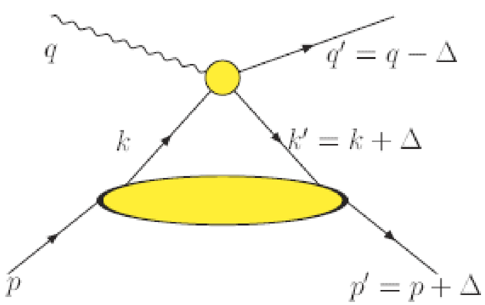
$$\boldsymbol{M = M_{N*} + M_{Regge} - < M_{N*} >}$$



$\sqrt{s} \sim$ **low** $\longrightarrow$ **Resonances**

$$\boldsymbol{s \gg 4M^2, \quad -t \sim small}$$

$-t\sim$**large** $\longrightarrow$ **saturation**



$$\boldsymbol{M_{hard}(\gamma N \to \pi N) \propto GPD \times M(\gamma q \to \pi q)}$$
$$\boldsymbol{\propto FF \times M_{Regge}(saturation)}$$

H. W. Huang, R. Jakob, P. Kroll *et al.*, Eur. Phys. J. C **33**, 91 (2004)