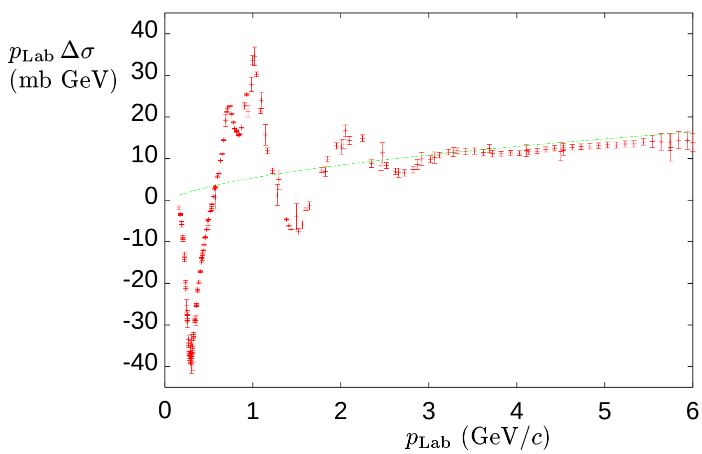
DUALITY IN VECTOR-MESON PRODUCTION

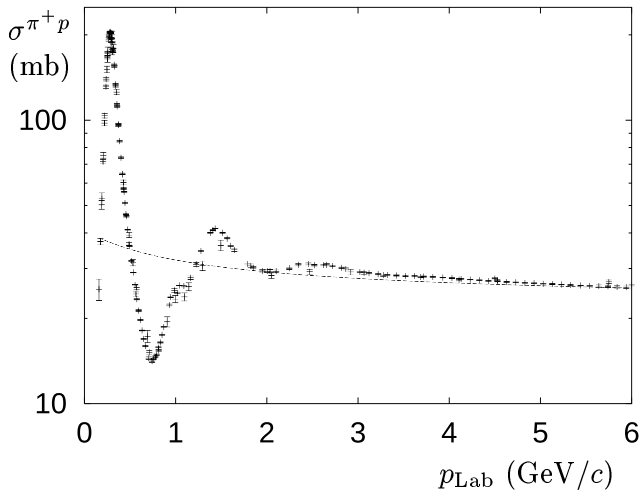
Pion-nucleon scattering

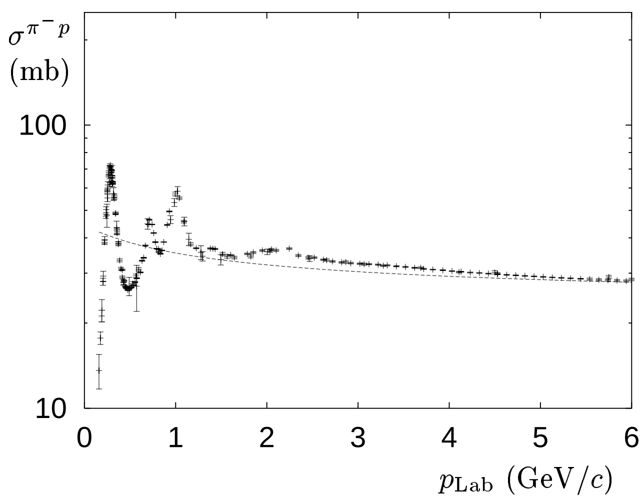
- Recall the origin of duality in pion-nucleon scattering: FESRs relate an integral over the resonance region at fixed t to a sum over the Regge-pole terms appropriate to higher energies $\Longrightarrow$ Regge-pole amplitudes describe the real physical amplitude at low energy on average and the averaging takes place over intervals much smaller than the range of integration.
- This does happen in practice. Compare $p_{\rm Lab}(\sigma^{\rm Tot}(\pi^- p) - \sigma^{\rm Tot}(\pi^+ p))$ with the extrapolation of Regge fits to higher-energy data:



- The $\pi^- p$ and $\pi^+ p$ high-energy elastic amplitudes receive equal contributions from pomeron exchange which cancels in the difference $\Longrightarrow$ non-Pomeron Regge-pole t-channel exchanges are dual to the s-channel resonances.
- What about the pomeron?

- Compare the low-energy $\pi^+ p$ and $\pi^- p$ total cross sections with extrapolated Regge fits to higher-energy data.





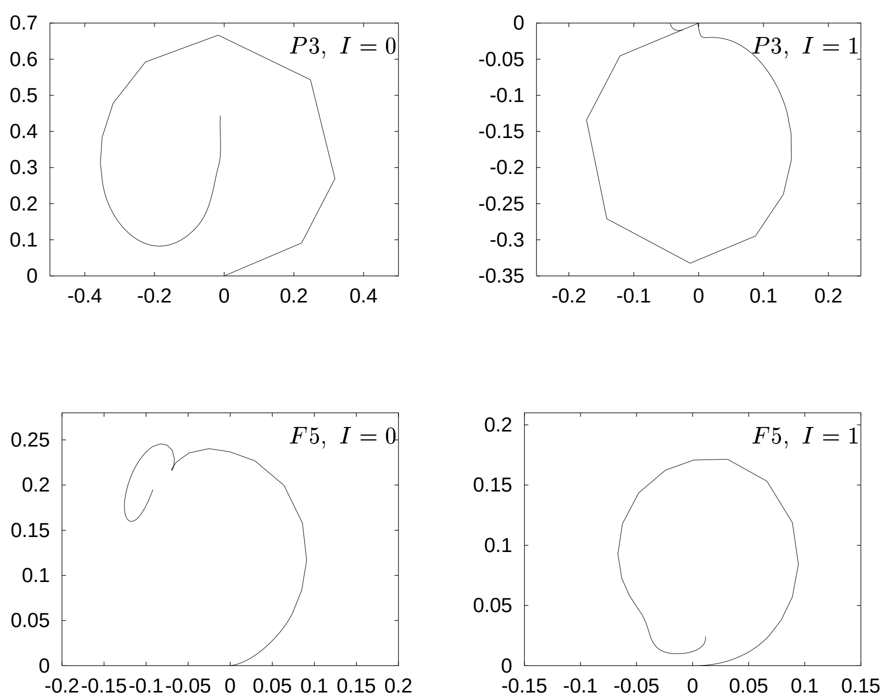
- In both cases the extrapolation of the Regge fits gives a good description of the average low-energy cross section.
  The resonances sit on a non-resonant background $\Longrightarrow$ pomeron exchange is dual to this background.

- This two-component duality is explicitly observed in the partial wave amplitudes in πN scattering. The linear combinations

$$f^{0}_{l\pm} = \tfrac{1}{3}\big(f^{\frac{1}{2}}_{l\pm} + 2f^{\frac{3}{2}}_{l\pm}\big) \qquad f^{1}_{l\pm} = \tfrac{1}{3}\big(f^{\frac{1}{2}}_{l\pm} - f^{\frac{3}{2}}_{l\pm}\big)$$

correspond to isospin 0 and isospin 1 exchange in the t-channel.

- As the pomeron does not contribute to the t-channel $I = 1$ exchange amplitude, two-component duality predicts that the $f^{1}_{l\pm}$ should be given entirely by s-channel resonances. The $f^{0}_{l\pm}$ should not be given by s-channel resonances alone, but have a smooth imaginary background on which the s-channel resonances are superimposed.
- P3 and F5 are shown as examples



- Note that despite these qualitative successes, duality is not a precise concept: for example pp scattering which does have a non-zero Regge contribution although much smaller than $\bar{p}p$

Vector-meson photoproduction

- Vector-meson dominance (VMD) gives a direct connection between πp scattering and ρ^0 photoproduction:

$$\frac{d\sigma}{dt}(\gamma p \to \rho p) = \alpha \frac{4\pi}{\gamma_\rho^2} \frac{d\sigma}{dt}(\rho^0 p \to \rho^0 p)$$

  where $4\pi/\gamma_\rho^2$ is the ρ-photon coupling, given by the e^+e^- width of the ρ:

$$\Gamma_{\rho \to e^+e^-} = \frac{\alpha^2}{3} \frac{4\pi}{\gamma_\rho^2} m_\rho$$

- In the additive-quark model, the amplitude for $\rho^0 p \to \rho^0 p$ is given by the average of the amplitudes for $\pi^- p$ and $\pi^+ p$ elastic scattering. In this combination of πp scattering amplitudes the $C = -1$ exchanges cancel (as they should) leaving the pomeron and f_2 exchanges.
- There are two omissions in this procedure: a_2 exchange and pion exchange. However both are extremely small relative to pomeron and f_2 exchange. The near-degeneracy of the f_2 and a_2 trajectories means that any contribution from a_2 exchange has minimal impact on the energy and t-dependence of the cross section. Pion exchange is relevant only near threshold.
- The trajectories of the pomeron, f_2 and a_2 are well-known from hadronic scattering, as is the mass scale by which we must divide s before raising it to the Regge power, namely the inverse of the trajectory slope.

- The trajectories couple to the proton through the Dirac electric form factor $F_1(t)$, which can be represented by

$$F_1(t) = \frac{4m_p^2 - 2.79t}{4m_p^2 - t}\frac{1}{(1-t/0.71)^2}$$

- Wherever it can be experimentally checked, the differential cross section for ρ^0 photoproduction is found to have the same slope at small t as the $\pi^\pm p$ elastic differential cross sections, so it is natural to assume that the form factor of the ρ, $F_\rho(t)$, is the same as that of the pion:

$$F_\rho(t) \approx F_\pi(t) = \frac{1}{1-t/0.5}$$

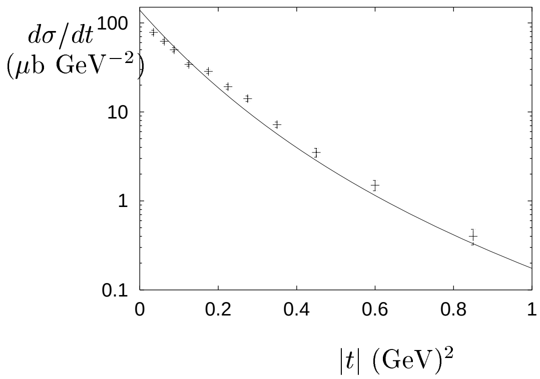
- The amplitude for $\gamma p \to \rho^0 p$ is then

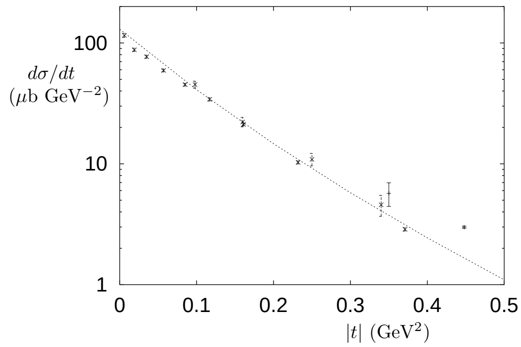
$$\begin{aligned} T(s,t) \;&=\; iF_1(t)F_\rho(t)\Big(A_P(\alpha'_P s)^{\alpha_P(t)-1}e^{-\frac{1}{2}i\pi(\alpha_P(t)-1)} \\ &\qquad + A_R(\alpha'_R s)^{\alpha_R(t)-1}e^{-\frac{1}{2}i\pi(\alpha_R(t)-1)}\Big) \end{aligned}$$

  A_P and A_R are obtained from standard fits to the $\pi^\pm p$ cross sections and the PDG value for the $\rho \to e^+e^-$ width

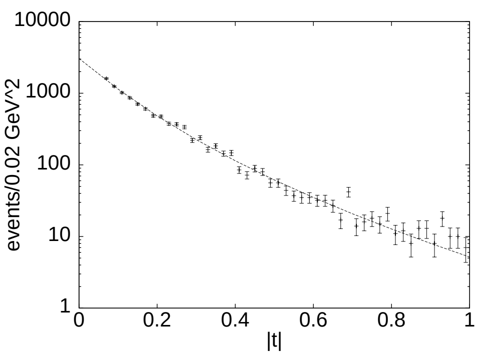
- Predictions of $\gamma p \to \rho^0 p$ at small t are remarkably good over a large energy range

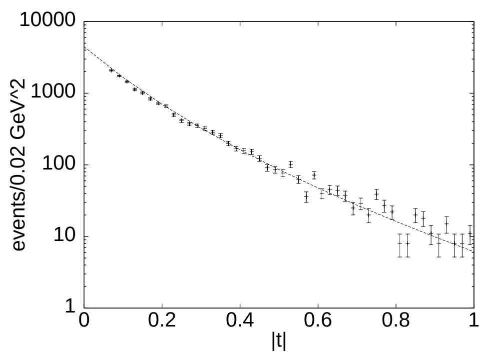
- $d\sigma/dt$ at $\sqrt{s} = 4.3$ GeV (left), 71.7 and 94 GeV (right)



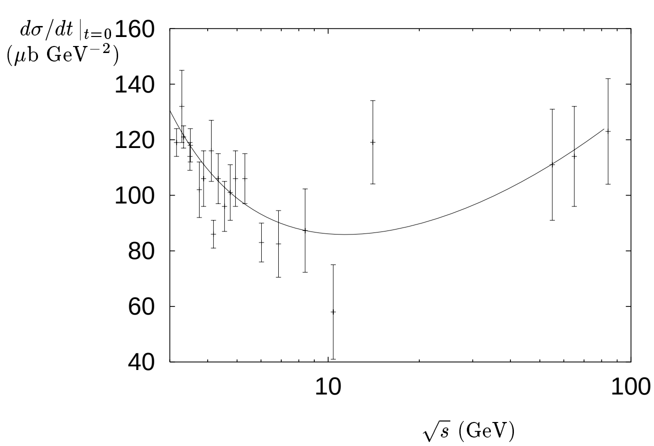


- $d\sigma/dt$ at $\sqrt{s} = 6.9$ GeV (left) and 10.8 GeV (right) (unnormalized data, given as events/0.02 GeV^{-2})

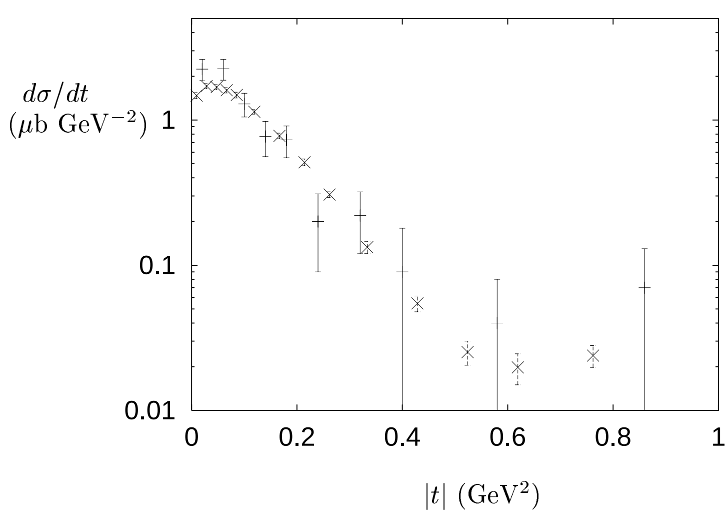




- $d\sigma/dt$ at $t = 0$



- The model has implications for polarization effects in ρ^0 photoproduction. It is known, to a very good approximation, that the helicity of the ρ^0 is the same as that of the photon, the phenomenon of s-channel helicity conservation (SCHC). What is less well known is that pomeron and f_2 exchange also conserve helicity to a good approximation at the nucleon vertex, deduced from polarized-target asymmetries in $\pi^{\pm}p$ scattering.
- Target polarization effects in ρ photoproduction will arise primarily from the interference of the dominant pomeron and f_2 exchange with the a_2 and other small unknown exchanges. They are not predictable and essentially measure the small amplitudes.
- The model is is extendable to charged-ρ photoproduction, relating $\gamma p \to \rho^+ n$ to $\pi^- p \to \pi^0 n$ via $\rho^0 p \to \rho^+ n$. Expect the t dependence and energy dependence of $\gamma p \to \rho^+ n$ and $\pi^- p \to \pi^0 p$ to be the same, because of the near-degeneracy of the ρ and a_2 trajectories, but the absolute normalization to be unspecified.
- Comparison at $\sqrt{s} = 4.3$ GeV: cross section $\sim 70\%$ larger than naive VDM prediction



- Note different scale between $\gamma p \to \rho^0 p$ and $\gamma p \to \rho^+ n$.

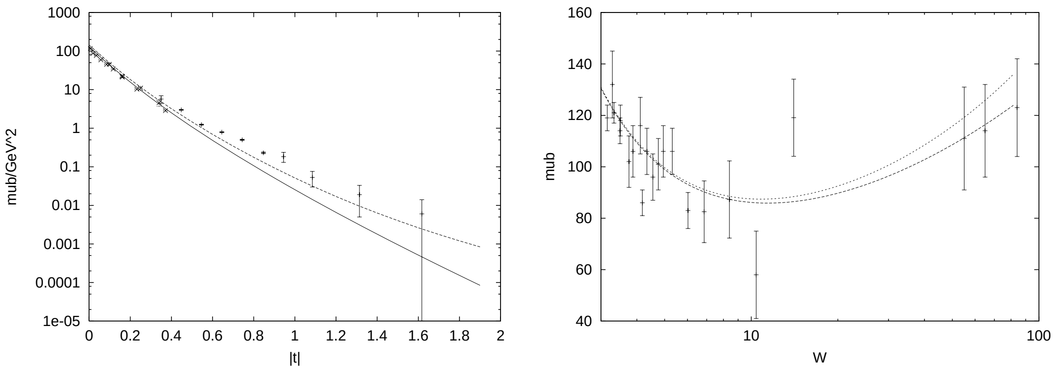
- It is reasonable to conclude that ρ photoproduction is as dual, in the original sense, as $\pi^{\pm}p$ scattering. Within the context of naive VMD, ρp scattering is the same as πp scattering and one can sensibly talk of the "ρp total cross section" which is directly related to the forward $\gamma p \to \rho^0 p$ differential cross section.
- This approach to ρ^0 photoproduction can be applied to ω photoproduction, but there are two differences.
  1. The cross section from pomeron and f_2 exchange is a factor of 9 smaller due to the difference between $4\pi/\gamma_\rho^2$ and $4\pi/\gamma_\omega^2$.
  2. The cross section from pion exchange is a factor of 9 larger and dominates at low energy.
- Using plane-polarized photons, natural-parity ($J^P = (-1)^J$) and unnatural parity ($J^P = (-1)^{J+1}$) exchanges can be separated. This confirms that pion-exchange is the dominant contribution near threshold. At energies above $\sqrt{s} \approx 5.0$ GeV the cross section is well described in magnitude and shape by naive VMD.
- Pomeron exchange dominates ϕ photoproduction because of Zweig's rule. The cross section should behave as $s^{2\epsilon}/b$, where b is the near-forward t-slope. The data are compatible with this, but are not sensitive to constant b or to letting the forward peak shrink in the canonical way, i.e. by taking $b = b_0 + 2\alpha' ln(\alpha' s)$.

- It is clear that photoproduction of the ρ, ω, ϕ satisfy "old-fashioned" resonance-Regge duality. What do we know about quark-hadron duality in these reactions?
- We have considered only small t, $|t| < 1$ GeV^2 at low energy and $|t| < 0.5$ GeV^2 at high energy. Data exist at larger $|t|$ at high energy and still satisfy the Regge requirement $|t| \ll s$. At these larger values of $|t|$ the predicted cross section falls below the data, the discrepancy increasing with increasing $|t|$.
- To describe the proton structure function $F_2(x, Q^2)$ at small x within the framework of conventional Regge theory it is necessary to introduce a second pomeron, the hard pomeron, with intercept a little greater than 1.4. This concept is also compatible with the data for the charm component $F_2^c(x, Q^2)$ of $F_2(x, Q^2)$ which seem to confirm its existence. The slope of the trajectory can be deduced from the data for the differential cross section for $\gamma p \to J/\psi p$:

$$\alpha_{P_h}(t) = 1.44 + \alpha'_{P_h} t \qquad \alpha'_{P_h} = 0.1 \text{ GeV}^{-2}$$

- The data for F_2 at small x and for F_2^c suggest that the coupling of the hard pomeron to quarks is flavour-blind. Thus the hard-pomeron contribution to $\gamma p \to \rho p$ can be obtained from that in $\gamma p \to J/\psi p$ by including the effect of the vector-meson wave functions and the quark charges.

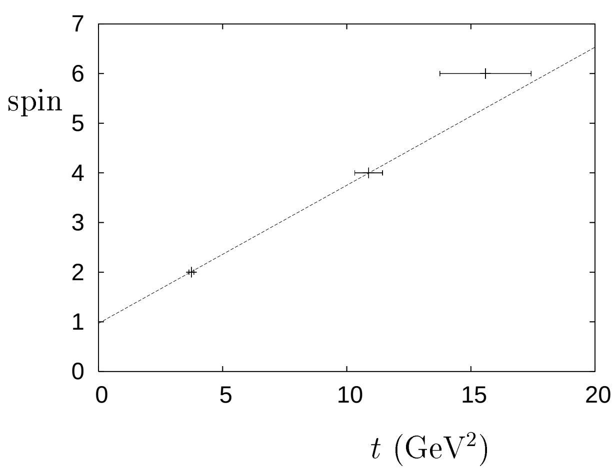
- $d\sigma/dt$ for $\gamma p \to \rho^0 p$ at $\sqrt{s} = 71.7$ and 94 GeV.



- The hard pomeron is also necessary for and compatible with the data on $\gamma p \to \phi p$ at $\sqrt{s} = 71.7$ and 94 GeV.

- The soft pomeron is nonperturbative in origin: the glueball equivalent of meson trajectories. The pomeron trajectory from lattice gauge theory is

$$\alpha_P(t) = (0.93 \pm 0.24) + (0.253 \pm 0.020)t$$



- The hard-pomeron is perturbative in origin. To what is it dual?

Vector-meson electroproduction

- In the lab frame, the incoming photon develops hadronic fluctuations some distance from the proton target, typically

$$l_c \approx \frac{s}{m_N(Q^2 + m_h^2)}$$

  for fluctuation into a hadron of mass m_h at energy $s \gg m_h^2, Q^2$.

- In photoproduction of a light vector meson, V,

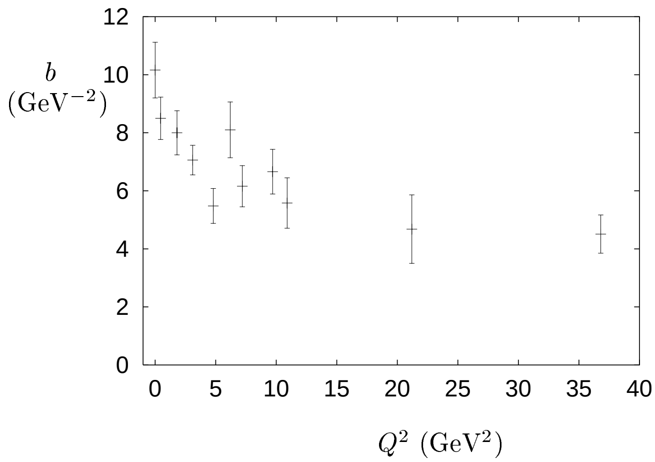
$$l_c \approx \frac{s}{m_N m_V^2}$$

  which is large compared to the size of the proton or the range of the strong interaction even at modest photon energies.

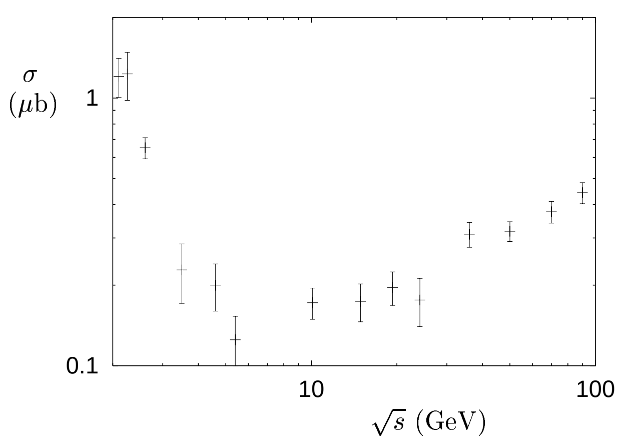
- This allows the amplitude to be factorized into the amplitude for the conversion of the photon to the vector meson times the amplitude describing the interaction of the vector meson with the proton target. This is the basis of the VMD approach to ρ and ω photoproduction and is applicable also at large Q^2 provided that s is sufficiently large.

- However at large Q^2 it is necessary to include many vector mesons in the photon fluctuation and the simplicity of VMD is lost. It is more sensible to consider the photon fluctuating into a $q\bar{q}$ pair which scatters on the target proton and then recombines into the vector meson. This is the basis of the dipole model, two-gluon exchange models and extensions to generalized parton distributions.

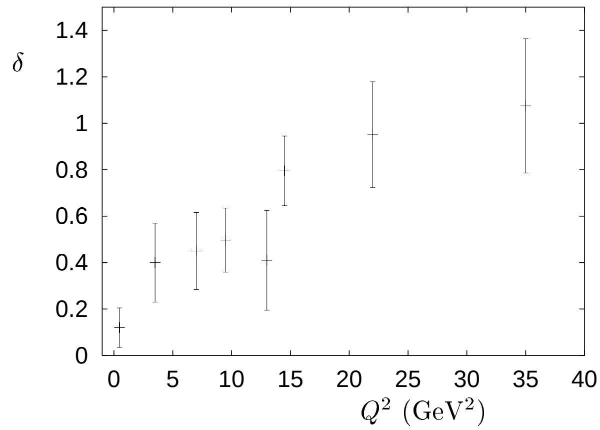
- The change from soft to hard QCD can be observed directly in the variation of the forward slope, b, of $d\sigma/dt$ for $\gamma^* p \to \rho p$ as a function of Q^2.



- b falls from the typical hadronic value of ~ 10 GeV^{-2} at $Q^2 = 0$ to about 5 GeV^{-2} at $Q^2 \approx 15$ GeV^2. This latter value for b corresponds to what one would expect from the proton form factor. There is no contribution to the differential cross section from structure at the photon $\to \rho$ transition vertex.
- The "mix" of hadron-like behaviour and perturbative behaviour at moderate Q^2 is easily seen from the energy dependence of the cross section, in this case at $\langle Q^2 \rangle = 3.5$ GeV^2.

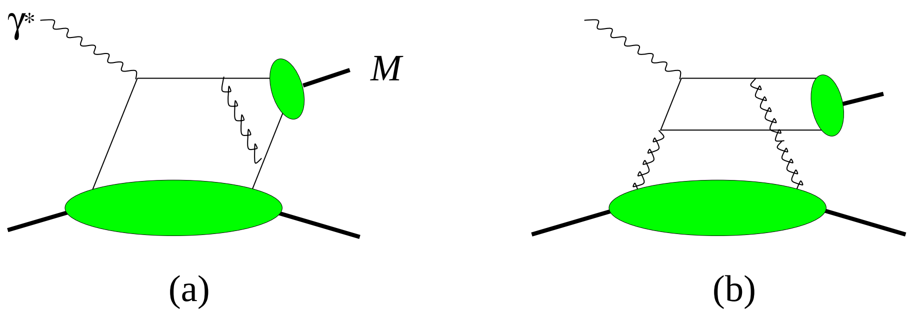


- The data still show the "Regge + Pomeron" behaviour of the real photon data, but as Q^2 increases the energy dependence at high energy increases. Parameterize as W^δ and plot δ:



- In two-gluon exchange and GPD models (indistinguishable with current data) this energy dependence reflects the proton's gluon distribution. In dipole models it appears through the structure of the dipole cross section or by explicitly introducing soft and hard pomeron terms. The limit of $Q^2 \to 0$ is handled by modifying the gluon propagator and/or the photon wave function, for example through a Q^2-dependent quark mass, which simulates the hadron-like nature of the photon at small Q^2 but introduces additional model dependence. There is ambiguity between the wave functions and the reaction mechanism.

- In all pictures, ρ electroproduction at moderate Q^2, those accessible at HERMES and to the JLab upgrade, the data require a combination of nonperturbative and perturbative effects. Are they distinct, that is additive, or dual representations of each other? The latter seems to hold in $\gamma^*\gamma \to \rho^0\rho^0$, for which generalized VMD and the parton model are equally successful in describing the data down to $Q^2 = 1.2$. This dual picture, which is well understood for heavy quarks, appears to be applicable empirically for light quarks and real photons, for example for $\gamma\gamma \to \rho^+\rho^-$.
- So are the standard GPD perturbative amplitudes



the whole story for vector mesons. Or is the hadron-like photon dual to higher twist and/or power corrections?

- As an example of the potential importance of the hadron-like photon, the application of simple VMD to the DVCS reaction shows that the ρ contribution can account for up to 20% of the DVCS amplitude measured by H1 and up to 50% of the DVCS beam spin asymmetries measured at HERMES and CLAS.
- As measurements of GPDs by vector-meson electroproduction will not be in the fully-perturbative domain, even for the JLab upgrade, it is essential that the role of duality in these reactions be fully understood.