Probing the QCD pomeron in high-energy $\gamma^*\gamma^*$ collisions \(^a\)

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Based on the color dipole representation, we investigate consequences for the $\gamma^*\gamma^*, \gamma^*\gamma$ scattering of the finding by Fadin, Kuraev and Lipatov that incorporation of asymptotic freedom into the BFKL equation makes the QCD pomeron a series of isolated poles in the angular momentum plane. We present parameter-free predictions for the vacuum exchange contribution to the photon structure function which agree well with OPAL and L3 determinations. A good agreement is found between our predictions for the energy and photon virtuality dependence of the photon-photon cross section $\sigma_{\gamma^*\gamma^*}(W, Q^2, P^2)$ and the recent data taken by the L3 Collaboration.

High-energy virtual photon-photon scattering can be viewed as interaction of small size color dipoles from the beam and target photons, which makes $\gamma^*\gamma^*, \gamma^*\gamma$ scattering at high energies (LEP, LEP200 & NLC) an indispensable probe of short distance properties of the QCD pomeron exchange.

In this note we study scattering of virtual and real photons $\gamma^*(q) + \gamma^*(p) \rightarrow X$ in the regime of large Regge parameter $x$,

$$\frac{1}{x} = \frac{W^2 + Q^2 + P^2}{Q^2 + P^2 + m_r^2} \gg 1,$$

where $W^2 = (q+p)^2$ is the center-of-mass energy squared of colliding space-like photons $\gamma^*(q)$ and $\gamma^*(p)$ with virtualities $q^2 = -Q^2$ and $p^2 = -P^2$, respectively. The mass of the $\rho$ meson squared sets the natural scale for real photons.

In the color dipole (CD) basis the beam-target scattering is considered as interaction of color dipoles $r$ and $r'$ in both the beam ($b$) and target ($t$) particles. The fundamental quantity is the forward dipole scattering amplitude and/or the dipole-dipole cross section $\sigma(x, r, r')$. Once $\sigma(x, r, r')$ is known the total cross section of $bt$ scattering $\sigma^{bt}(x)$ is calculated as

$$\sigma^{bt}(x) = \int dz d^2r d^2r' |\Psi_b(z, r)|^2 |\Psi_t(z', r')|^2 \sigma(x, r, r').$$

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In (2) $\sigma(x, r, r')$ is beam-target symmetric and universal for all beams and targets, the beam and target dependence is concentrated in probabilities $|\Psi_b(z, r)|^2$ and $|\Psi_t(z', r')|^2$ to find a color dipole, $r$ and $r'$ in the beam and target, respectively. Hereafter we focus on cross sections averaged over polarizations of the beam and target photons.

The incorporation of asymptotic freedom into the BFKL equation makes the QCD pomeron a series of isolated poles in the angular momentum plane. The contribution of each isolated pole to the high-energy scattering amplitude satisfies the familiar Regge factorization, which in the CD basis implies the CD BFKL-Regge expansion

$$\sigma(x, r, r') = \sum_m C_m \sigma_m(r) \sigma_m(r') \left( \frac{x_0}{x} \right)^{\Delta_m}. \tag{3}$$

Here the dipole cross section $\sigma_m(r)$ is an eigen-function of the CD BFKL equation

$$\frac{\partial \sigma_m(x, r)}{\partial \log(1/x)} = \mathcal{K} \otimes \sigma_m(x, r) = \Delta_m \sigma_m(x, r), \tag{4}$$

with eigen value (intercept) $\Delta_m$.

Then, combining (2) and (3) and adding in the soft and quasi-valence (reggeon) components, we obtain ($m = \text{soft}, 0, 1, 2, ...$)

$$\sigma^{\gamma^* \gamma^*}(x, Q^2, P^2) = (\frac{4\pi^2\alpha_{em}^2}{Q^2 P^2}) \sum_m C_m f_m(Q^2) f_m(P^2) \left( \frac{3 x_0}{2x} \right)^{\Delta_m} + \sigma^{\gamma^* \gamma^*}_{\text{qval}}. \tag{5}$$

For DIS off (quasireal) real photons, $P^2 = 0$,

$$F_{2\gamma}(x, Q^2) = \sum_m A_m^{\gamma} f_m(Q^2) \left( \frac{3 x_0}{2x} \right)^{\Delta_m} + F^{\gamma}_{2\gamma}(x, Q^2). \tag{6}$$

Here $\sigma_m^{\gamma^*}(Q^2) = \langle \gamma^*_T | \sigma_m(r') | \gamma^*_T \rangle + \langle \gamma^*_L | \sigma_m(r') | \gamma^*_L \rangle$ is calculated with the well known color dipole distributions in the transverse (T) and longitudinal (L) photon of virtuality $Q^2$ derived in (6), and the eigen structure functions are defined as usual: $f_m(Q^2) = \frac{Q^2}{4\pi^2 \alpha_{em}^2} \sigma_m^{\gamma^*}(Q^2)$. The analytical formulas for eigen structure functions $f_m(Q^2)$ are found in (6). We do not need any new parameters compared to those used in the description of DIS and real photoabsorption on protons (6), the results for the expansion parameters $A_m^{\gamma}$ and $\sigma_m^{\gamma}(0)$ are summarized in (6).
Figure 1: Predictions from CD BFKL-Regge expansion for the vacuum exchange component of the $\gamma^*\gamma^*$ cross section for the diagonal case of $\langle Q^2 \rangle = \langle P^2 \rangle$ are confronted to the experimental data by the L3 Collaboration.

In fig. 1 we compare our predictions to the L3 data on the vacuum exchange contribution to $\gamma^*\gamma^*$ scattering. The solid curve is a result of the complete BFKL-Regge expansion for the vacuum exchange, the dashed curve is a sum of the rightmost hard BFKL exchange and soft-pomeron exchange. The agreement of our estimates with the experiment is good, the contribution of subleading hard BFKL exchange is negligible within the experimental error bars.

The discussion of the photon structure function (SF) follows closely that of the proton and pion SF’s in \cite{3, 4, 8}. There is a fundamental point that the distribution of small-size color dipoles in the photon is enhanced compared to that in the proton, which enhances the importance of the rightmost hard BFKL exchange.

Our predictions for the photon structure function are presented in fig. 2. At moderately small $x$ there is a substantial non-vacuum reggeon exchange contribution from DIS off quasi-valence quarks which can be regarded as well constrained by the large $x$ data, we use here the GRS parameterization. A comparison of the solid and dotted curves shows clearly that subleading hard BFKL exchanges are numerically small in the experimentally interesting region of $Q^2$, the rightmost hard BFKL pole exhausts the hard vacuum contribution for $2 \lesssim Q^2 \lesssim 100$ GeV$^2$. The data on the photon structure function at sufficiently small-$x$ are in good agreement with the predictions from the CD BFKL-Regge expansion. A comparison with the long-dashed curve which is the sum of the rightmost hard BFKL and soft exchanges shows that the experimental data are in the region of $x$ and $Q^2$ still affected by non-vacuum reggeon (quasi-valence) exchange, going to smaller $x$ and larger $Q^2$ would im-
Figure 2: Predictions from CD BFKL-Regge expansion for the photon structure function. The solid curve shows the result from the complete BFKL-Regge expansion the soft-pomeron (the dashed curve) and valence (the dot-dashed curve) components included, the dotted curve shows the rightmost hard BFKL (LH) plus soft-pomeron (S) plus quasi-valence (V) approximation (LHSVA). The long dashed line corresponds to the LH plus S approximation (LHSA).

prove the sensitivity to pure vacuum exchange greatly.

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