Non-linear QCD dynamics in photon-photon interactions at high energies

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Abstract

We calculate the photon-photon cross section and the real photon structure function using the color dipole formalism. This formalism implies that, before interacting, each one of the photons fluctuates in a pair quark-antiquark (a color dipole). It allows us to factorize the photon-photon interaction as a product of three terms. Two of them are the probabilities for each photon to fluctuate in a dipole. These terms are calculated with perturbative QCD. The third term of the factorization is the dipole-dipole cross section, which must be modeled. We propose a new model to describe the dipole-dipole cross section and compare its results with the ones obtained using other model available in the literature. We demonstrate that both models are able to describe the high energies LEP data, but predict a very different behavior for the observables at higher energies. It is an indicative that the detailed study of photon-photon interaction in the future International Linear Collider (ILC) can be useful to constrain the QCD dynamics at high energies.

I – The dipole formalism for two photon interaction

The dipole formalism applied to photon-photon ($\gamma\gamma$) interaction implies that, before interacting, each one of the photons fluctuates in a color dipole.

In this formalism the photon-photon cross section is factorized as:

$$\sigma_{ij}(W^2,Q_1^2,Q_2^2) = \sum_{a,b=1}^{N_f} \int dz_1 \int d^2\vec{\rho}_1 \, |\Psi_i^a(z_1,\vec{\rho}_1)|^2 \int dz_2 \int d^2\vec{\rho}_2 \, |\Psi_j^b(z_2,\vec{\rho}_2)|^2 \, \sigma_{a,b}^{dd}(\vec{\rho}_1,\vec{\rho}_2,Y)$$

Where W is the total energy of the system photon-photon, Q_1^2 (Q_2^2) is the virtuality of the photon *1* (*2*), Ψ is the probability for the photon to fluctuate in a dipole, ρ is the dipole radius, Y is the rapidity, z ($1-z$) is the fraction of the longitudinal momentum of the photon carried out by the quark (antiquark) and the sum is made over the flavor content of the dipoles.

The probability for a photon to fluctuate in a color dipole is calculated with perturbative QCD, and is given by:

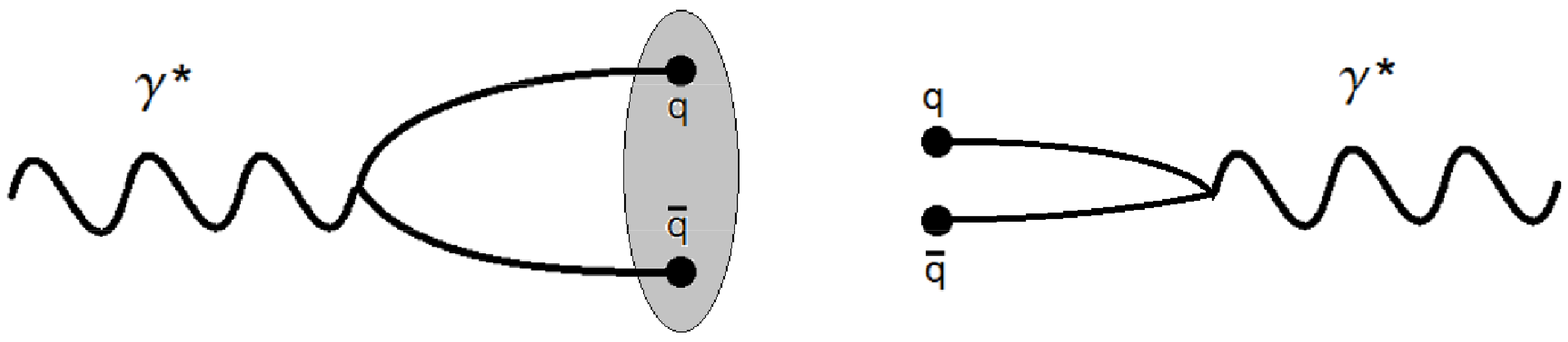
$$|\Psi_L^f(z,\rho)|^2 = \frac{6\alpha_{em}}{4\pi^2} e_f^2 \, [4Q^2 z^2 (1-z)^2 \, K_0^2(\epsilon_f \rho)]$$

$$|\Psi_T^f(z,\rho)|^2 = \frac{6\alpha_{em}}{4\pi^2} e_f^2 \{[z^2+(1-z)^2] \, \epsilon_f^2 K_1^2(\epsilon_f\rho) + m_f^2 \, K_0^2(\epsilon_f \rho)\}$$

Where $(\epsilon_f)^2 = z(1-z)Q^2 + m_f^2$, L and T represent respectively the longitudinal and transversal polarizations of the photon, K_0 and K_1 are the modified Bessel functions, α_{em} is the electromagnetic coupling constant and e_f is the electric charge fraction of the quark of flavor f.

The structure function of a real photon is given by:

$$F_2^\gamma(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}} [\sigma_{T,T}(W^2,Q^2,Q_2^2=0) + \sigma_{L,T}(W^2,Q^2,Q_2^2=0)]$$



II – The dipole-dipole cross section

The dipole-dipole cross section, σ^{dd}, cannot be calculated with perturbative QCD, and therefore it must be modeled.

Model 1

The authors of Ref. [1] proposed the following model, based on the additive quark model, for the photon-photon cross section:

$$\sigma_{a,b}^{dd}(\vec{r}_1,\vec{r}_2,Y) = \sigma_0^{a,b} \, N(\vec{r}_1,\vec{r}_2,Y)$$

$$\sigma_0^{a,b} = \frac{2}{3}\sigma_0$$

$$N(\vec{r}_1,\vec{r}_2,Y) = N(\vec{r}_{\rm eff}, Y = \ln(1/\bar{x}_{ab}))$$

$$r_{\rm eff}^2 = \frac{r_1^2 r_2^2}{r_1^2+r_2^2} \quad ; \quad \bar{x}_{ab} = \frac{Q_1^2+Q_2^2+4m_a^2+4m_b^2}{W^2+Q_1^2+Q_2^2}$$

With σ_0 a free parameter fixed through a fit to the data of HERA on electron-proton DIS. The factor 2/3 arises due the difference in the number of quarks inside a dipole (2 quarks) and a proton (3 quarks).

Model 2

We propose to consider the largest dipole ($R = {\rm Max}(r_1,r_2)$) as being the target and that only when there is superposition between the dipoles ($b < R$) we will have an interaction [2].

$$\sigma^{dd}(\vec{r}_1,\vec{r}_2,Y) = 2\,N(\vec{r},Y)\int_0^R d^2\vec{b} = 2\pi R^2 N(\vec{r},Y)$$

$$Y_j = \ln(1/x_j) \quad ; \quad x_j = \frac{Q_j^2+4m_j^2}{W^2+Q_j^2}$$

Where $r = {\rm Min}(r_1,r_2)$.

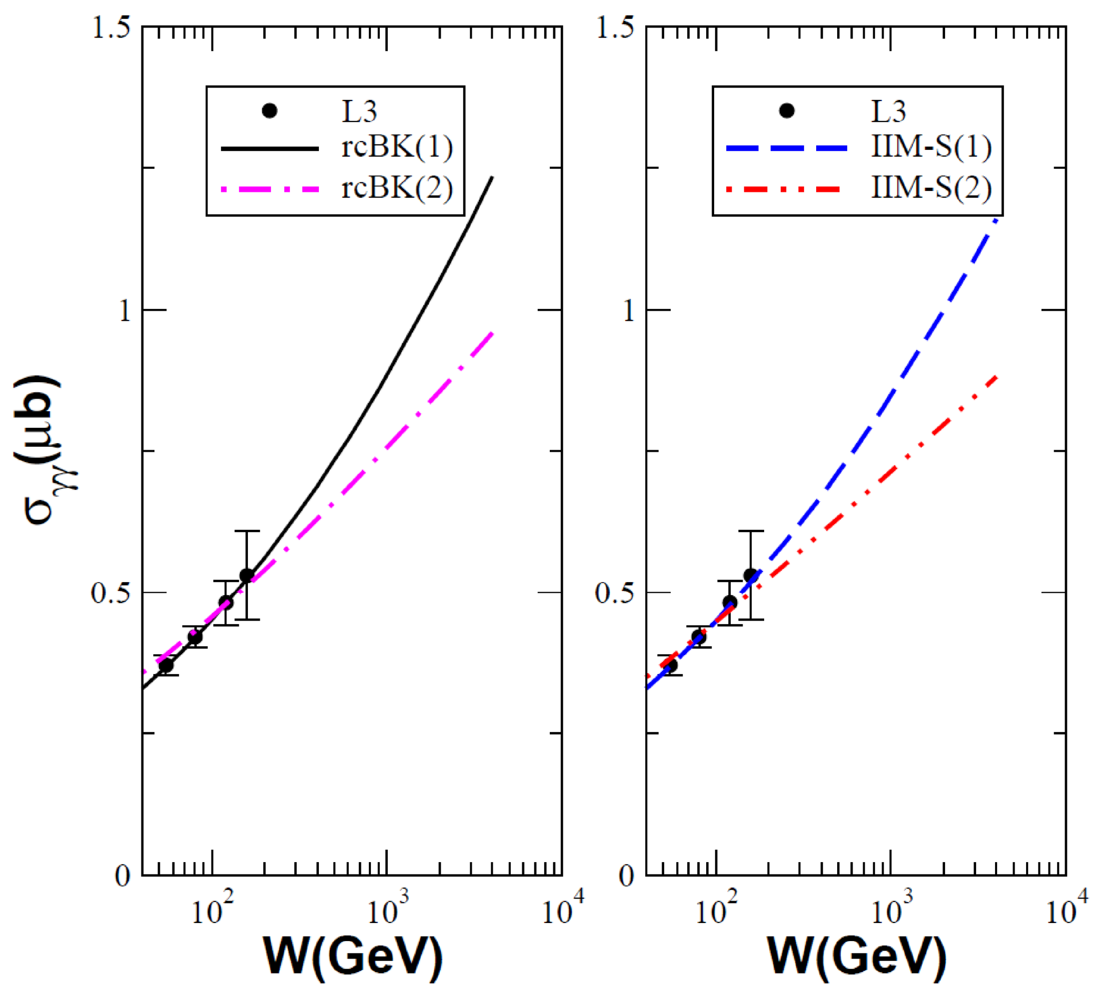
III – Results

published in [2]

The free parameters of the models were fixed by fitting the following data:

rcBK = numerical solution of BK equation with running coupling and with NLO corrections.

IIM-S = interpolation of two analytical solutions of BK equation. One is obtained in the limit of big dipoles and the other is obtained for small dipoles.



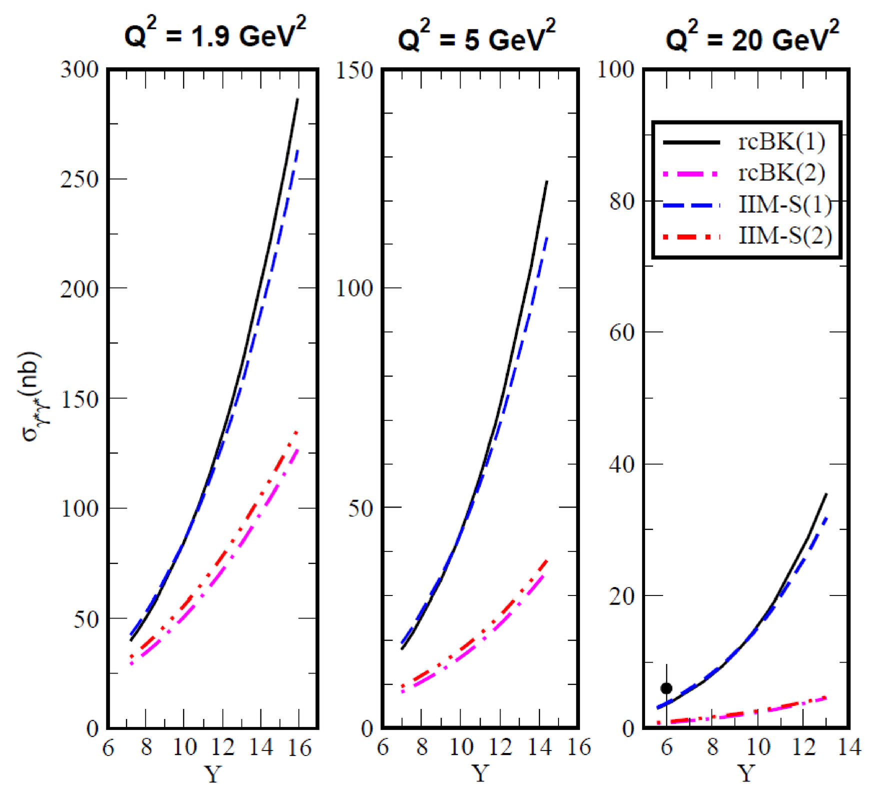
The free parameter of Model 1 is the mass of the light quarks, while the free parameter of the Model 2 is the inverse ($\Lambda = 1/R$) of the maximum radius of integration.

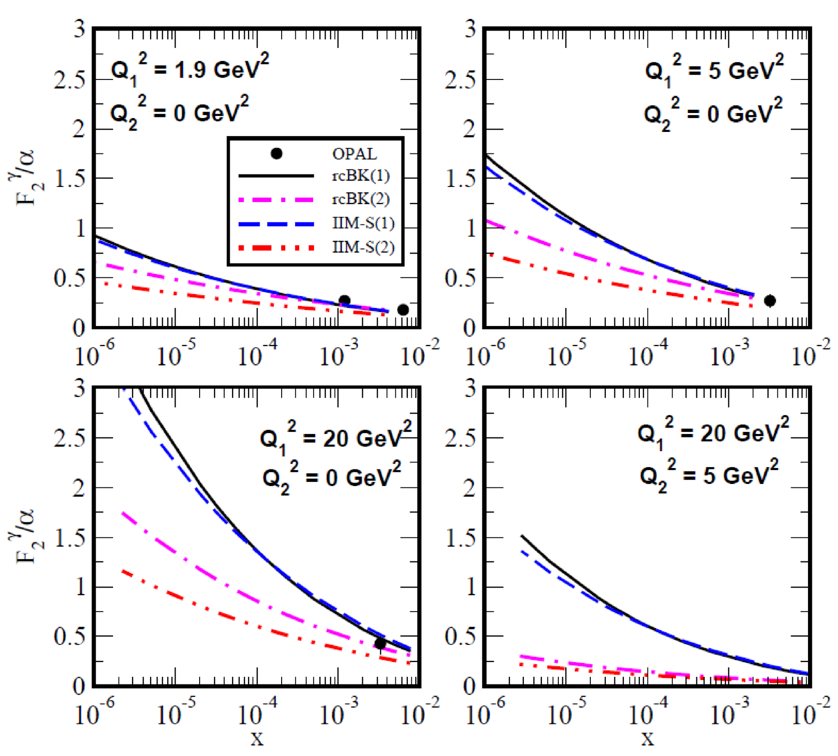
Modelo	$N(\vec{r},Y)$	m (MeV)	Λ (MeV)
Modelo 1	rcBK	198	—
	IIM-S	205	—
Modelo 2	rcBK	—	210
	IIM-S	—	230

$$m_{u,d,s} = 140\,MeV$$

$$\Lambda_{QCD} \approx 217\text{ MeV}$$

The free parameters are already fixed:





V - Conclusions

At the high energy regime, where there is no experimental data, the results are very sensitive to the model chosen for the dipole-dipole cross section (Model 1 or Model 2), but are not sensitive to the amplitude of interaction (rcBK or IIM-S).

The Model 2 has the advantage of using, for the quark masses, the same value used for them in the calculations of DIS. Furthermore, the free parameter of the Model 2 is approximately equal the parameter Λ_{QCD}, what is an indicative that this model captures the main characteristics of the interaction.

Our results are predictions for the future International Linear Collider (ILC).

IX - References

[1] N. Timneanu, J. Kwiecinski, L. Motyka, Eur. Phys. J. C **23**, 513 (2002).
[2] V.P. Gonçalves, M.S. Kugeratski, E.R. Cazaroto, F. Carvalho, F.S. Navarra, Eur. Phys. J. C **71** 1779 (2011).

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