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SATURATION MODEL FOR 2γ PHYSICS*

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We introduce a saturation model for photon-photon interactions, based on a QCD dipole picture of high energy scattering. The two-dipole cross-section is assumed to satisfy the saturation property. This pomeron-like contribution is supplemented with QPM and non-pomeron reggeon contributions. The model gives a very good description of the data on the $\gamma\gamma$ total cross-section, on the photon structure function $F_2^\gamma(x, Q^2)$ at low x and on the $\gamma^*\gamma^*$ cross-section.

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The saturation model [1] was proven to provide a very efficient framework to describe a variety of experimental results on high energy scattering. With a very small number of free parameters, Golec-Biernat and Wüsthoff (GBW) fitted low x data from HERA for both inclusive and diffractive scattering [1]. The central concept behind the saturation model is an x dependent saturation scale $Q_{\rm s}(x)$ at which unitarity corrections to the linear parton evolution in the proton become significant. In other words, $Q_{\rm s}(x)$ is a typical scale of a hard probe at which a transition from a single scattering to a multiple scattering regime occurs.

Our idea was to extend the saturation model constructed for $\gamma^* p$ scattering to describe also $\gamma^*\gamma^*$ cross sections. The successful extension, performed in [2], provided a test of the saturation model in a new environment and confirmed the universality of the model. The results obtained in [2] are also of some importance for two-photon physics, since the model is capable of describing a broad set of observables in wide kinematical range in a simple, unified framework.

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The saturation model for two-photon interactions is constructed in analogy to the GBW model [1]. Each of the virtual photons is decomposed into colour dipoles $(q\bar{q})_{\rm dipole}$ representing virtual components of the photon in the transverse plane and their distribution in the photon is assumed to follow from the perturbative formalism (see Fig. 1).

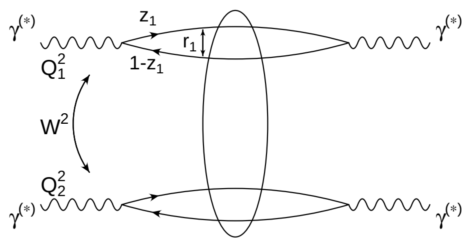

Fig. 1. The diagram illustrating the $\gamma^*\gamma^*$ interaction in the dipole representation

A formula for the two-photon cross-section part coming from the exchange of *gluonic* degrees of freedom reads

$$\sigma^G_{ij}(W^2,Q_1^2,Q_2^2) = \sum_{a,b=1}^{N_f}\int_0^1 dz_1\int d^2\boldsymbol{r}_1|\Psi_i^a(z_1,\boldsymbol{r}_1)|^2\int_0^1 dz_2\int d^2\boldsymbol{r}_2|\Psi_j^b(z_2,\boldsymbol{r}_2)|^2\sigma^{\rm dd}_{a,b}(\bar{x}_{ab},r_1,r_2)\,,$$

where $\Psi_i^a(z,\boldsymbol{r})$ represent the photon wave functions and $\sigma^{\rm dd}_{a,b}(\bar{x}_{ab},r_1,r_2)$ are the dipole–dipole total cross-sections. The indices i,j label the polarisation states of the virtual photons, *i.e.* T or L and the different flavour content of the dipoles are specified by a and b. The transverse vectors $\boldsymbol{r}_k$ denote the separation between q and $\bar{q}$ in the colour dipoles and z_k are the longitudinal momentum fractions of the quark in the photon k $(k=1,2)$.

Inspired by the GBW simple choice for the dipole–proton cross-section, we use the following parametrisation of the dipole–dipole cross-section $\sigma_{a,b}$

$$\sigma^{\rm dd}_{a,b}(\bar{x}_{ab},r_1,r_2) \;=\; \sigma_0^{a,b}\left[1-\exp\left(-\frac{r^2_{\rm eff}}{4R_0^2(\bar{x}_{ab})}\right)\right],$$

where for $\bar{x}_{ab}$ we take the following expression $\bar{x}_{ab}=\frac{Q_1^2+Q_2^2+4m_a^2+4m_b^2}{W^2+Q_1^2+Q_2^2}$, which allows an extension of the model down to the limit $Q^2_{1,2}=0$. We use the same parametrisation of the saturation radius $R_0(\bar{x})$ as in equation (7) in [1], and adopt the same set of parameters defining this quantity as those in [1]. For the saturation value $\sigma_0^{a,b}$ of the dipole–dipole cross-section we set $\sigma_0^{a,b}=\frac{2}{3}\sigma_0$, where σ_0 is the same as defined in [1], which for light flavours can be justified by the quark counting rule in photon/proton.

For the effective separation $r_{\rm eff}(r_1,r_2)$, we consider three scenarios, all exibiting colour transparency, *i.e.* $\sigma^{\rm dd}_{a,b}(\bar{x},r_1,r_2) \to\ 0$ for $r_1 \to 0$ or $r_2 \to 0$: <u>model 1</u>: $r^2_{\rm eff}\ =\ r_1^2 r_2^2/(r_1^2+r_2^2)$; <u>model 2</u>: $r^2_{\rm eff}\ =\ \min(r_1^2,r_2^2)$; <u>model 3</u>: $r^2_{\rm eff}\ =\ \min(r_1^2,r_2^2)[1+\ln(\max(r_1,r_2)/\min(r_1,r_2))]$. The first two cases reduce to the original GBW model when one of the dipoles is much larger than the other, while option (3) is a controll case.

The saturation model accounts for an exchange of *gluonic* degrees of freedom, which dominate at very high energies (low x). In order to get a complete description of $\gamma^*\gamma^*$ interactions we should also add the non-pomeron reggeon and QPM terms [3], important at lower energies. The QPM contribution, represented by the quark box diagrams, is well known and the cross-sections are given in [4]. The reggeon contribution represents a non-perturbative phenomenon related to Regge trajectories of light mesons. We used the parametrisation of the reggeon exchange cross-section in two-photon interactions from [5]. We have chosen the intercept in concordance with the value of the Regge intercept of the f_2 meson trajectory $1-\eta = 0.7$ [6], while other parameters were fitted to the data on two-photon collisions.

The formulae describing the gluonic and reggeon components are valid at asymptotically high energies, where the impact of kinematical thresholds is small. The threshold effects are approximately accounted for by introducing a multiplicative correction factors, whose form is deduced from spectator counting rules (see [2]). Thus, the total $\gamma^*(Q_1^2)\gamma^*(Q_2^2)$ cross-section reads $\sigma^{\rm tot}_{ij}\ =\ \tilde{\sigma}^G_{ij}+\tilde{\sigma}^R\delta_{i{\rm T}}\delta_{j{\rm T}}+\sigma^{\rm QPM}_{ij}$, where $\tilde{\sigma}^G_{ij}$ is the gluonic component, corresponding to dipole–dipole scattering, with the additional threshold correction factor. The sub-leading reggeon $\tilde{\sigma}^R$ contributes only to scattering of two transversely polarised photons and also contains a threshold correction; the third term $\sigma^{\rm QPM}_{i,j}$ is the standard QPM contribution.

In the comparison to the data we study three models, based on all cases for the effective radius, as described above and we will refer to these models as Model 1, 2 and 3. We take without any modification the parameters of the GBW model, however, we fit the light quark mass to the two-photon data, since it is not very well constrained by the GBW fit. We find that the optimal values of the light quark (u, d and s) masses m_q are 0.21, 0.23 and 0.30 GeV in Model 1, 2 and 3 correspondingly. Also, the masses of the charm and bottom quark are tuned within the range allowed by current measurements, to get the optimal global description. For the charm quark we use $m_c = 1.3$ GeV and for bottom $m_b = 4.5$ GeV.

The available data for the $\gamma\gamma$ total cross-section range from the $\gamma\gamma$ energy W equal to about 1 GeV up to about 160 GeV, see Fig. 2, and were taken for virtual photons coming from electron beams and then the results were extrapolated to zero virtualities. Some uncertainty is caused by the reconstruction of actual $\gamma\gamma$ collision energy from the visible hadronic energy, using an unfolding procedure based on Monte Carlo programs. In Fig. 2 we show the total $\gamma\gamma$ cross-section from the Models, and find good agreement with data down to $W \simeq 3$ GeV for all the Models.

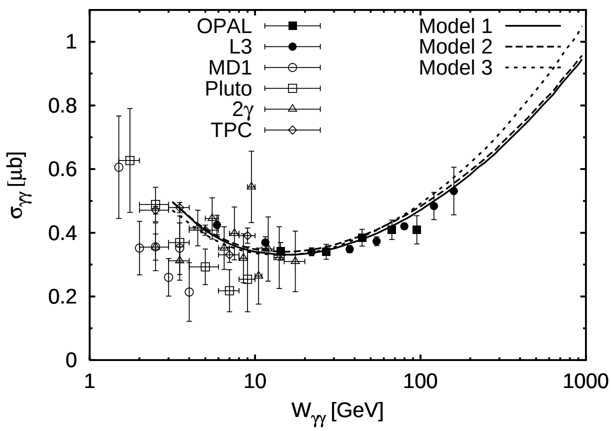

Fig. 2. The total $\gamma\gamma$ cross-section: data compared with all three models.

The data for the total $\gamma^*\gamma^*$ cross-section are extracted from so-called double-tagged events: e^+e^- events in which both scattered electrons are measured. In such events measurement of the kinematical variables of the leptons determines both the virtualities Q_1^2 and Q_2^2 of the colliding photons and the collision energy W. In Fig. 3 these data are compared with the curves from the Models. Models 1 and 2 fit the data well whereas Model 3 does not. The virtuality of both photons are large, so the unitarity corrections, the light quark mass effects and the reggeon contribution are not important here. Moreover, the perturbative approximation for the photon wave function is fully justified in this case. Thus, in this measurement the form of the dipole–dipole cross-section is directly probed.

The data on quasi-real photon structure are obtained mostly in single tagged e^+e^- events, in which a two-photon collision occurs. One of the photons has a large virtuality and probes the other, almost real photon. In Fig. 4 we show the comparison of our predictions with the experimental data. Model 1, favoured by the $\gamma^*\gamma^*$ data provides the best description of F_2^γ as well.

In conclusion, our extension of the saturation approach to two photon physics provides a simple and efficient framework to calculate observables in $\gamma\gamma$ processes and good agreement has been found with the available data.

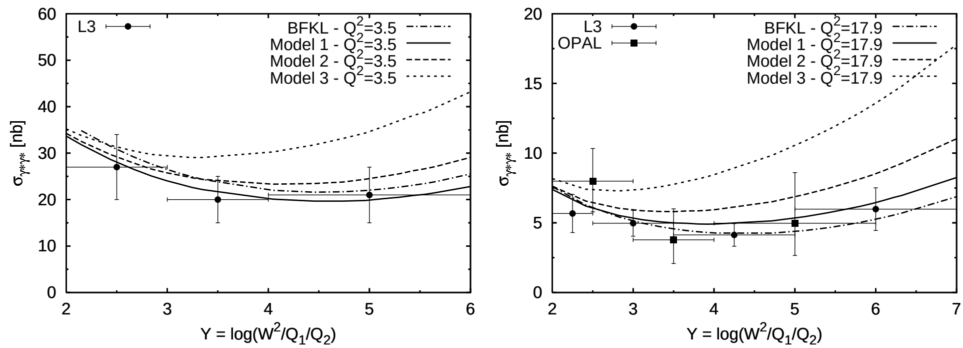

Fig. 3. Total $\gamma^*\gamma^*$ cross-section for $Q^2 = 3.5$ GeV^2 and $Q^2 = 17.9$ GeV^2 — comparison between LEP data and the Models. Also shown is the result of Ref. [3] based on the BFKL formalism with subleading corrections, supplemented by the QPM term, the soft pomeron and the subleading reggeon contributions.

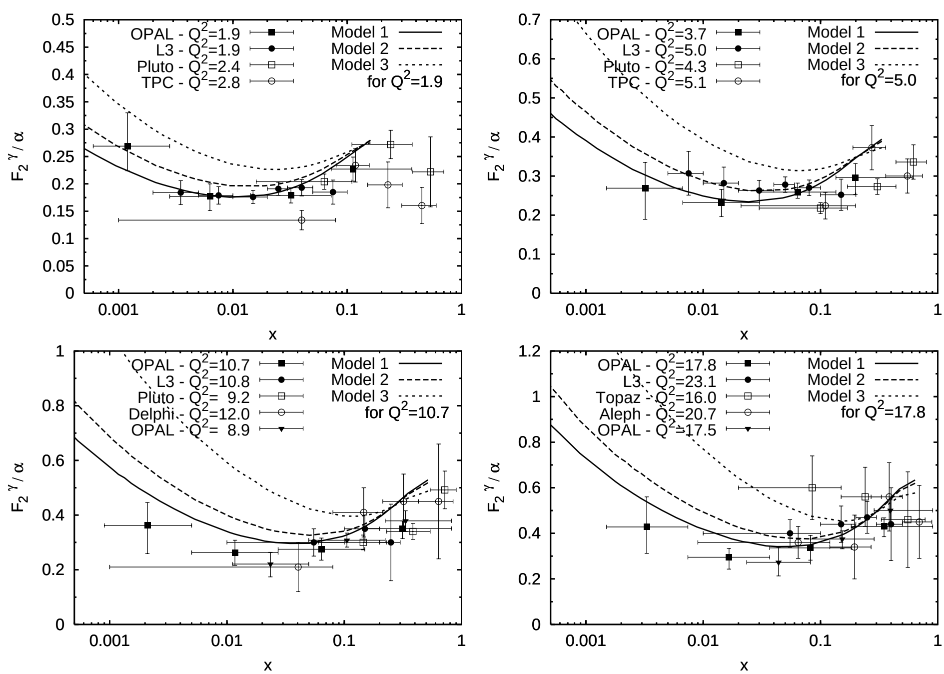

Fig. 4. The photon structure function $F_2^\gamma(x, Q^2)$: the experimental data compared to predictions following from the Models for various Q^2 values.

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