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SATURATION AND HADRONIC CROSS-SECTIONS AT VERY HIGH ENERGIES*

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We propose a simple model for the total $pp/p\bar{p}$ cross-section, which is a generalization of the minijet model with the inclusion of a window in the $p_{\rm T}$-spectrum associated to the saturation physics. Our model implies a natural cutoff for the perturbative calculations which modifies the energy behavior of this component, so that it satisfies the Froissart bound. Including the saturated component, we obtain a satisfactory description of the very high energy experimental data.

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Long ago a QCD based explanation for the growth of the hadronic cross-sections was proposed by Gaisser and Halzen [1]. In their approach, called minijet model, the total cross-section can be decomposed as $\sigma_{\rm tot} = \sigma_0 + \sigma_{\rm pQCD}$ where σ_0 characterizes the nonperturbative contribution and $\sigma_{\rm pQCD}$ is calculable in perturbative QCD. Unfortunately, this approach implies a power-like energy behavior for the total cross-section, violating the Froissart bound. Several attempts were made to reduce this too fast growth [2].

At high energies the small-x gluons in a hadron wavefunction should form a Color Glass Condensate (CGC) [3]. This new state of matter is characterized by gluon saturation and by a typical momentum scale, the saturation scale $Q_{\rm s}$, which determines the critical line separating the linear and saturation regimes of the QCD dynamics.

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Some attempts to reconcile the QCD parton picture with the Froissart limit using saturation physics were proposed in recent years [4]. Here we generalize the minijet model assuming the existence of a saturation window between the nonperturbative and perturbative regimes of QCD, which grows when the energy increases, since $Q_{\rm s}$ grows with the energy. The cross-section is then written as:

$$\sigma_{\rm tot} = \sigma_0 + \sigma_{\rm sat} + \sigma_{\rm pQCD}\,, \qquad (1)$$

where the saturated component, $\sigma_{\rm sat}$, contains the dynamics of the interactions at scales lower than the saturation scale. In our approach *the saturation scale is a cutoff at low transverse momenta of the perturbative cross-section*, $\sigma_{\rm pQCD}$, which is given by:

$$\sigma_{\rm pQCD} = \frac{1}{2}\int_{Q_{\rm s}^2} dp_{\rm T}^2 \sum_{i,j}\int dx_1\, dx_2 f_i\left(x_1,p_{\rm T}^2\right) f_j\left(x_2,p_{\rm T}^2\right)\hat{\sigma}_{ij}\,, \qquad (2)$$

where $f_i(x,Q^2)$ is the parton density of the species i, with fractional momentum x_1 (or x_2) in the proton and $\hat{\sigma}_{ij}$ is the elementary parton–parton cross-section. We have used the MRST parton distributions [5]. The saturation scale is given by $Q_{\rm s}^2(x) = Q_0^2(x_0/x)^\lambda$, where the parameters $Q_0^2 = 0.3$ GeV^2 and $x_0 = 0.3\times10^{-4}$ were fixed by fitting the *ep* HERA data. Following [6] we take $x = q_0^2/s$ and $q_0 = 1.4$ GeV. Therefore we have

$$Q_{\rm s}^2(s) \propto s^\lambda\,.$$

In Fig. 1 we show in arbitrary units the energy behavior of the ratio $\sigma_{\rm pQCD}/\ln^2 s$ (solid lines) and $\sigma_{\rm sat}/\ln^2 s$ (dashed lines) for two choices of λ. As it can be seen the choice $\lambda = 0.25$ leads to a fast growth of $\sigma_{\rm pQCD}$ until $\sqrt{s} = 10^4$ GeV. From this point on, it grows slower than $\ln^2 s$. A slight increase in λ $(= 0.3)$ is enough to tame the growth of $\sigma_{\rm pQCD}$ already at $\sqrt{s} \simeq 10^3$ GeV. On the other hand, a decrease in λ $(= 0.1)$ would postpone the fall of the ratio to very high energies $\sqrt{s} \simeq 10^6$ GeV. Although the energy at which the behavior of the cross-section becomes "sub-Froissart" may depend on λ, one conclusion seems very robust: *once λ is finite, at some energy the growth of the cross-section will become weaker than* $\ln^2 s$.

For the saturated component we shall use the model proposed in Ref. [6]:

$$\sigma_{\rm sat} = \int d^2r_\perp |\Psi_p(r_\perp)|^2 \sigma_{\rm dip}(x,r_\perp)\,, \qquad (3)$$

where the proton wave function Ψ_p is chosen to be a gaussian with the typical size of the proton [7] and the dipole-proton cross-section reads:

$$\sigma_{\rm dip}(r_\perp,x) = 2\int d^2b\,\mathcal{N}(x,r_\perp,b)\ . \qquad (4)$$

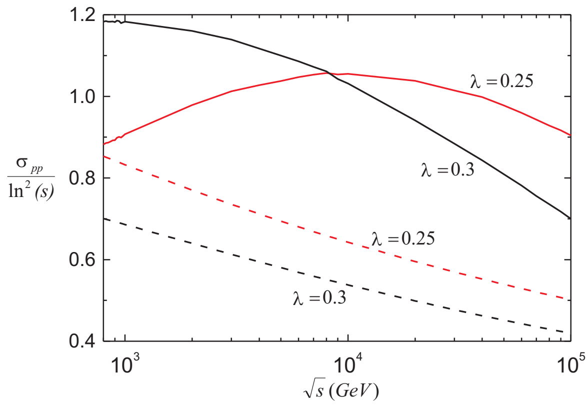

Fig. 1. Perturbative (solid lines) and saturated components (dashed lines) of the total cross-section (normalized by $\ln^2 s$).

We take the dipole scattering amplitude from [8] (we call it IIM) and, following [6], introduce the b dependence by witting:

$$\mathcal{N}(x, r_\perp, b) = 1 - e^{-\kappa S(b)/S(0)}\,, \tag{5}$$

where the parameter κ is related to the $b = 0$ solution through $\kappa = -\ln[1 - \mathcal{N}(b = 0)]$. In (5), the profile function is assumed to be $S(b) = e^{(-b^2/R_p^2)}$, where $R_p = 0.7$ fm is the proton radius.

In Fig. 2 we present our results for the total cross-section for different values of λ and compare them with experimental data. For references and details see [7]. σ_0 was assumed to be energy independent [9], important only at lower energies and therefore was not included in our calculations. There is only a small range of values of λ which allow us to describe the experimental data. If, for instance, $\lambda = 0.4$ the resulting cross-section is very flat and clearly below the data, while if $\lambda = 0.1$ (not shown in figure) the cross-section grows very rapidly deviating strongly from the experimental data. The best choice for λ is in the range 0.25–0.30, which is exactly the range predicted in theoretical estimates using CGC physics and usually obtained by the saturation models for the *ep* HERA data. In [7] we have replaced the IIM dipole cross-section by the more modern ones given in [10] but the results do not change very much.

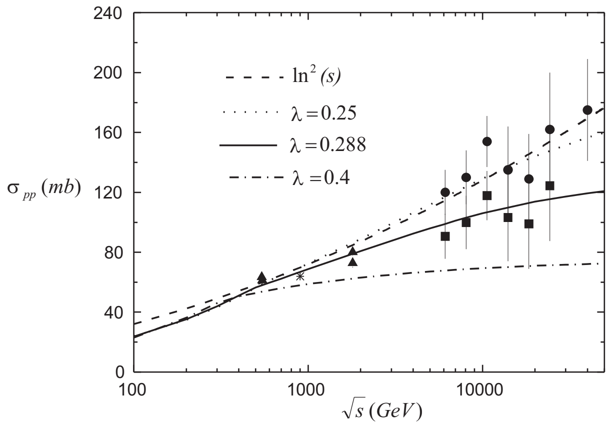

Fig. 2. Energy behavior of the total $pp/p\bar{p}$ cross-section for different values of λ.

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