SATURATION AND VECTOR MESONS* **

Stéphane Munier

Università di Firenze
via Sansone 1, 50009 Sesto Fiorentino, Italy

(Received June 13, 2002)

Through an analysis of diffractive vector meson production, we show that the proton appears quite dense to a small size probe at present HERA energies. This means that saturation effects are already important.

PACS numbers: 14.20.Dh, 12.38.Aw

1. Introduction

The question whether traditional leading twist QCD is the relevant description of HERA small-x data has still no clear-cut answer. A particularly successful saturation model proposed by Golec-Biernat and Wüsthoff (GBW) [1] suggests that the common picture of a proton looking like a dilute set of partons might be unjustified. We have recently shown *directly* that the proton is a dense system already at present HERA energies [2].

The method we used is summarized in the next section. We then dedicate a section to a by-product of our analysis: the measurement of total dipole–proton cross section.

2. A picture of the proton at HERA

Wave diffraction allows to obtain a picture of a microscopic object. A Fourier transform relates its density profile to the square root of the intensity of light measured on the interference pattern.

It turns out that one can analyse the HERA data for diffractive vector meson production in this way. Indeed, at high energy, such a process is equivalent to elastic diffusion of dipoles. The picture is the following [3]: in an appropriate reference frame, the photon of virtuality Q^2 splits in a

* Presented at the X International Workshop on Deep Inelastic Scattering (DIS2002) Cracow, Poland, 30 April–4 May, 2002.

** Work supported by QCDNET contract FMRX-CT98-0194.

$q\bar{q}$ dipole which scatters elastically off the target proton before recombining into a meson. The size of the interacting dipole is distributed around a mean value r_Q and the total flux $N(Q)$ is the scalar product of photon and meson wave functions $\langle\psi_{\gamma^*}|\psi_V\rangle$. The density profile is extracted by taking the Fourier transform of the square root of the differential cross section $d\sigma/dt$ with respect to the momentum transfer Δ ($t=-\Delta^2$). The variable conjugated to Δ is the impact parameter of the dipole relatively to the center of the proton. One then sees that this profile is related to the S-matrix element for elastic dipole–proton scattering (a key observation is that S is essentially real at high energy). It reads

$$S(x,r_Q,b) = 1 - \frac{1}{2\pi^{3/2}N(Q)}\int d^2\Delta \mathrm{e}^{-i\Delta b}\sqrt{\frac{d\sigma}{dt}}\,. \tag{1}$$

As a phenomenological model is needed for the meson wave function $|\psi_V\rangle$ which appears in $N(Q)$, checks of model-independence of the method are in order. We checked that the dipole size is indeed distributed around a mean size $r_Q = A/\sqrt{Q^2+M_V^2}$ independently of the model (M_V is the mass of the meson). We also verified that the dipole flux $N(Q)$ is strongly constrained by the well-known photon wave function $|\psi_{\gamma^*}\rangle$, and thus is quite model-independent.

We applied formula (1) to the ZEUS data for diffractive electroproduction of longitudinal ρ mesons [4]. As saturation is a high energy effect, we considered the lowest available values of x ($\sim 5\times 10^{-4}$) only. We varied the virtuality Q^2 of the photon so that the effective scale $Q^2+M_V^2$ is always larger than 1 GeV^2. The result of our analysis for 3 different values of the photon virtuality is represented on Fig. 1. The estimated error shown stems from the lack of data for large momentum transfer $t>0.6$ GeV^2. It does not include experimental errors on the measured quantities.

Why is S a good estimator of the importance of saturation effects? As argued before, the value of S tells us about how dense the proton looks. $S=0$ means blackness: it is the unitarity limit. For a more quantitative interpretation, one observes that $1-S^2$ is the interaction probability of a dipole that hits the proton at impact parameter b. If this probability is significant, it means that more rescatterings are likely to occur. We see that the interaction probability is more than 50% and could already reach 75% at the center of the proton.

A more common parameter characterizing the saturation regime is the saturation scale Q_{s}^2. Roughly speaking, it is defined as the maximal virtuality for which the photon sees the proton as a dense medium. We found Q_{s}^2 of order 1 to 1.5 GeV^2 near the center of the proton, and 0.2 GeV^2 on the periphery.

We refer the interested reader to Ref. [2] for all details of the analysis and more results.

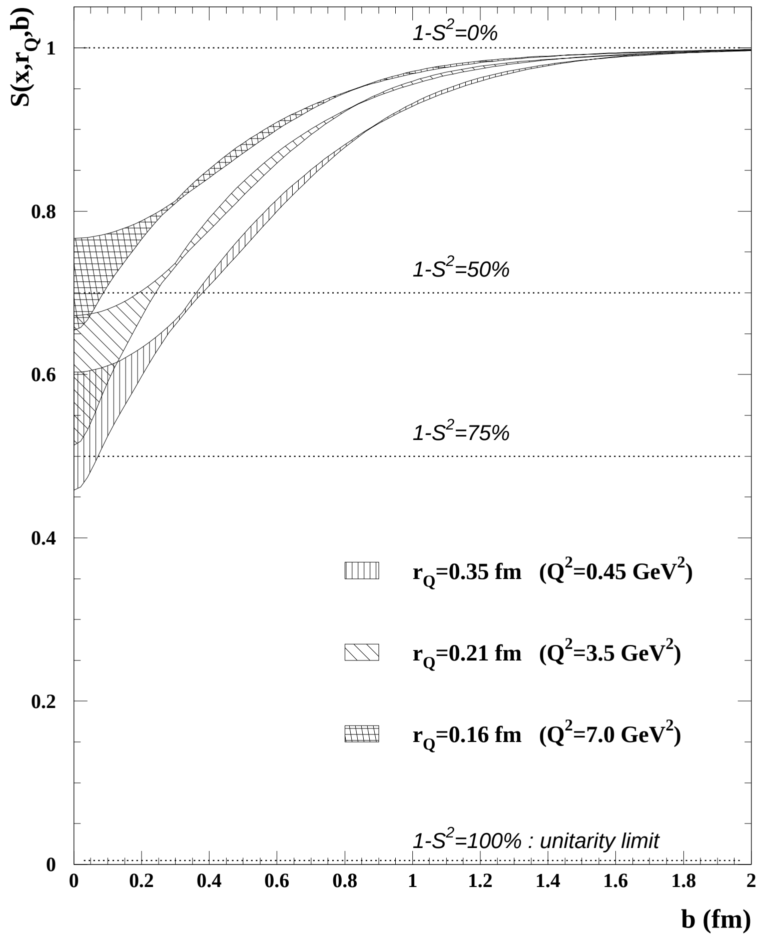

Fig. 1. S-matrix as a function of the impact parameter for $x \sim 5 \times 10^{-4}$ and $Q^2 = 0.45,\ 3.5,\ 7\ \mathrm{GeV}^2$. The width of the bands represents the uncertainty due to the lack of experimental data for $t > 0.6\ \mathrm{GeV}^2$. It is obtained by extrapolating the cross section with functions of t with behaviour between t^{-3} and $\mathrm{e}^{-\lambda t}$.

3. Extracting the dipole–proton total cross section

Having the S-matrix, one can easily obtain the total dipole–proton cross section. It is an interesting quantity because of its universality. One needs the forward differential cross section from the data and the dipole flux $N(Q)$

and average dipole size r_Q from the model. The cross section reads

$$\sigma_{\rm tot}(x, r_Q) = \frac{4\sqrt{\pi}}{N(Q)}\sqrt{\frac{d\sigma}{dt}}_{|t=0} . \tag{2}$$

In practice, we give an upper and a lower bound for r_Q. An approximate lower bound is obtained when the dipole size distribution is weighted by a flat (saturated) cross section (*i.e.* $\sigma_{\rm tot}(r) = {\rm const.}$). The upper bound comes for a colour transparent cross section $\sigma_{\rm tot}(r) \propto r^2$. A realistic average value can be computed by taking an interpolating weight. We took GBW cross section, and we checked that the expectation value r_Q is not very much dependent on the exact point where the transition occurs, as long as it is around $r_{\rm s} \sim 1$ GeV^{-1}. The result is plotted in Fig. 2.

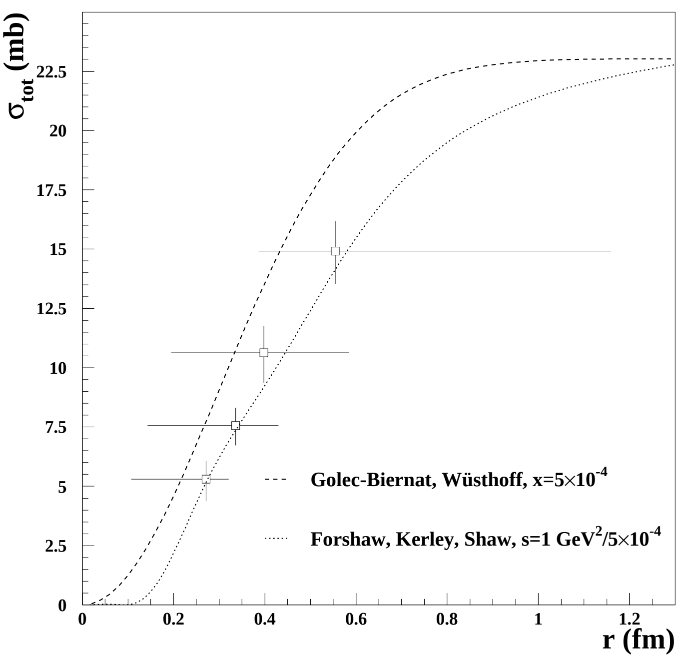

Fig. 2. The total dipole–proton cross section for different values of the dipole radius r. The errors on the cross section are estimated from experimental errors. The error bars on r are due to the width of the dipole distribution at the γ^*–ρ vertex. The points represent the average radius obtained with a weight given by GBW cross section. For comparison, in dashed line: Golec-Biernat and Wüsthof model [1]; dotted line: Forshaw, Kerley, Shaw model [5].

4. Summary

We have shown that perturbative saturation effects are already important at HERA. Our argument was that the proton appears quite dense to a relatively small size probe. We were able to give a quantitative estimate of its darkness by measuring the S-matrix element for elastic dipole–proton scattering. It turns out that the probability that a dipole of size 0.2 fm undergoes an inelastic interaction is more than 50% at small impact parameters, and for the high energy data from HERA. This translates into a saturation scale $Q_{\rm s}^2$ lying between 1 and 1.5 GeV^2 which is consistent with the assumptions contained in GBW model. More exclusive data for quasi-elastic processes at large momentum transfer on one hand, and impact parameter-dependent analysis on the other hand, would be very welcome in the future since saturation effects are expected to be maximal for central collisions.

[*The interesting question whether this statement is in contradiction with the successful description of vector meson photoproduction at large t by 2-gluon exchange enhanced by BFKL corrections was raised by Martin McDermott during the discussion. From our result, for high energies ($W^2 \sim 10^4$ GeV^2), low Q^2 and large t diffractive processes, one would expect significant saturation effects. In any case, it would be very instructive to construct a model of GBW type for large t processes.*]

REFERENCES

[1] K. Golec-Biernat, M. Wüsthoff, *Phys. Rev.* **D59**, 014017 (1999).

[2] S. Munier, A.M. Staśto, A. H. Mueller, *Nucl. Phys.* **B603**, 427 (2001).

[3] N.N. Nikolaev, B.G. Zakharov, *Z. Phys.* **C49**, 607 (1991); **C53**, 331 (1992); **C64**, 651 (1994); *Sov. Phys. JETP* **78**, 598 (1994); J. Nemchik, N.N. Nikolaev, B.G. Zakharov, *Phys. Lett.* **B341**, 228 (1994); A.H. Mueller, *Nucl. Phys.* **B415**, 373 (1994).

[4] J. Breitweg *et al.* [ZEUS Collaboration], *Eur. Phys. J.* **C6**, 603 (1999).

[5] J.R. Forshaw, G. Kerley, G. Shaw, *Phys. Rev.* **D60**, 074012 (1999).