What HERA can tells us about saturation

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Abstract
Indications of gluon saturation in the proton in the HERA data are briefly discussed.

1 Saturation at HERA?

In 1992, HERA began to explore the proton structure below x of 10^{-3} for the first time. Many expected that at such low x the description of the proton structure function F_2 using the DGLAP equations will break down; this was a reasonable assumption based on the presence of terms of the type $\alpha_s log(1/x)$ in the DGLAP splitting functions. We expected the behavior of F_2 at low x to be described by BFKL equations, and perhaps observe saturation, i.e. that parton recombination processes will begin to be important as the gluon density increases at low x. The naive expectation at that time was that we may observe some type of flattening, even a turning down, of the rising gluon at low x visible at a fixed Q^2 as we probed lower and lower in x, as shown in Fig. 1(left).

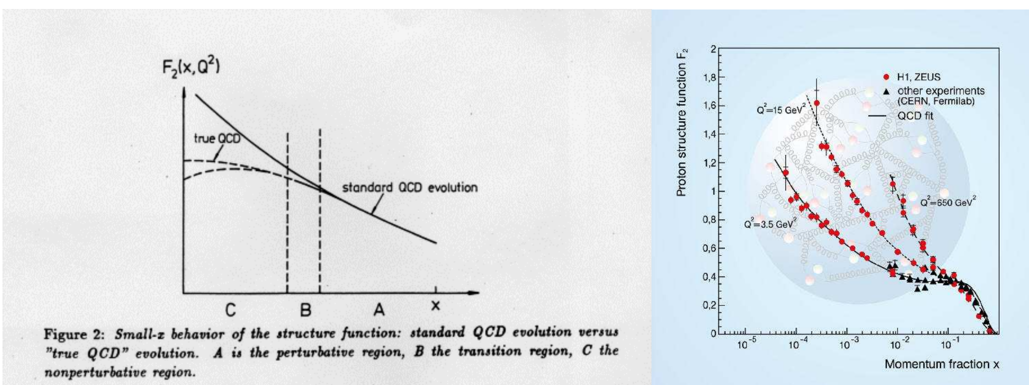

Fig. 1: Left: A figure from the 1991 HERA Workshop Proceeding showing the qualitative features expected in the HERA measurements of F_2. The region marked A is perturbative (including BFKL). In region B, non-linear recombination (saturation) effects become noticeable. Region C is the non-perturbative region. Right: F_2 as actually measured at HERA shown with the results of a perturbative QCD (DGLAP) fit.

HERA stopped data taking in 2007; a precision down to a few percent has been reached in the measurement of F_2 in large areas of the measureable phase space. The DGLAP description of the F_2 structure function to the lowest measured x has been excellent as shown in Fig. 1(right).

While DGLAP failed below Q^2 of 1 GeV [1], where the applicability of perturbative QCD is suspect in any case, there seemed to be no room in the data for any low-x effects, let alone saturation. Most HERA experimentalists considered then that saturation not to have been observed in the HERA data; this is also the case today. On the other hand, there are several indications in the HERA data that DGLAP may not be the whole story.

2 Diffractive DIS and the Saturation Model

One of the surprises at HERA has been the observation of diffractive deep inelastic scattering (diffractive DIS). While pQCD analyses in terms of diffractive (or Pomeron) structure functions have had successes in fitting the data (see for example [2]), it is not obvious how a description of the total DIS cross-section (F_2) in terms of DGLAP evolution is reconciled with the characteristics of diffractive DIS. In particular, the fact the diffractive DIS is a constant fraction of the total DIS cross-section as a function of x at a fixed Q^2 is difficult to understand.

In 1998, the saturation model of Golec-Biernat and Wuestoff [3] was introduced. In this model, both the DIS and diffractive DIS are formulated in terms of the cross-section of a color dipole (from the virtual photon) and a proton. The measurements at HERA (both diffractive and inclusive DIS) were qualitatively well-described in this model only if HERA data were probing the region in which the dipole-proton cross-section had saturated, i.e. become constant as a function of the dipole radius. The model implies that at Q^2 of 2-5 GeV^2, and at x of 10^{-5}, HERA has sensitivitiy to saturation effects.

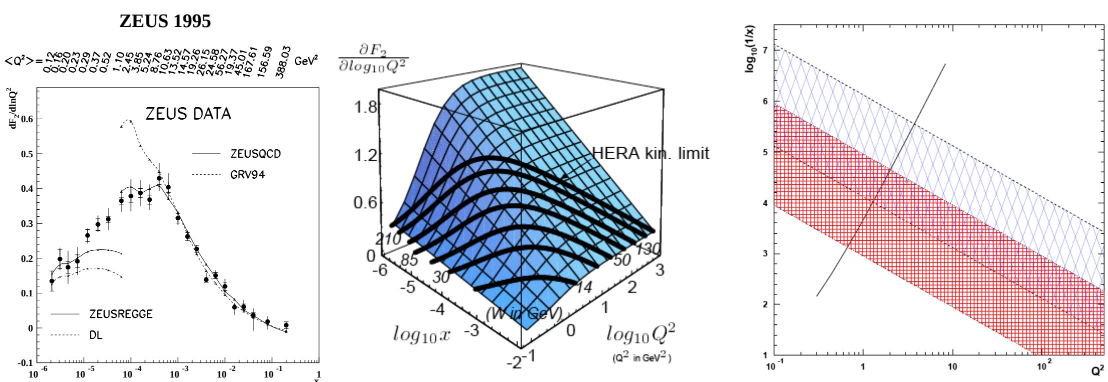

Fig. 2: Left: $dF_2/dlnQ^2$ as a function of x and changing Q^2 (scale at the top). Center: $dF_2/dlnQ^2$ as a function of x and Q^2 from the paramerized F_2 of D. Haidt. Right: Critical-line of saturation from the original paper of GBW.

3 Perturbative–non-peturbative boundary

Real photon-proton cross-section, as all hadronic cross-sections at high energy, obey the expectations of Pomeron exchange in the Regge framework. The cross-section rises slowly as a function of the cms energy. On the other hand, in DIS, interpreted as a collision of a virtual photon and a proton, the cross-section rises rapidly – corresponding to the increasing gluon density in the proton. The two behaviors must match together in the Q^2, x plane if physics is to remain smooth. Indeed it is possible to see where this transition takes place by looking at the derivative $dF_2/dlnQ^2$ as a function of x (and Q^2) as shown in Fig. 2(left) [4]. The shape of the Fig. 2(left) plot can be understood by visualizing $dF_2/dlnQ^2$ in the x and Q^2 plane in any reasonable model [5] that interpolates between the Regge behavior at Q^2 = 0 and in the DIS region as shown in Fig. 2(center). The Fig. 2(left) plot shows $dF_2/dlnQ^2$ essentially at a fixed W.

It should be noted then that the "critical line" (shown in Fig. 2(right)) in the Golec-Biernat–Wuestoff (GBW) model [3] that signifies the onset of saturation effects is at more-or-less the same position as the fold that can be seen in Fig. 2(center). It should also be noted that this behavior is very difficult to observe for F_2 as a function of x at a fixed Q^2 in the manner shown in Fig. 1.

If satuation in the model of GBW is taken seriously, it appears that the HERA data, at about Q^2 of 2-5 GeV^2 at x^{-5} is indeed in the saturation region. It also appears that the saturation transition-line is, perhaps unsurprisingly, related also to the boundary of Regge-like and pQCD-like behavior of F_2. Unfortunately, the Q^2 range at which HERA data could be observing saturation phenomena may be already too low for perturbative QCD to be strictly applicable.

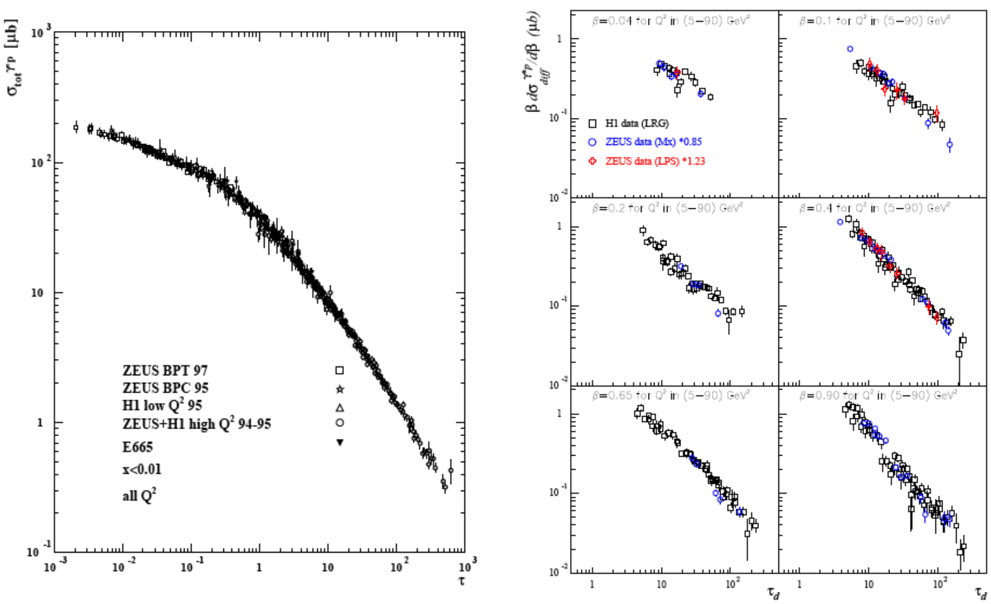

Fig. 3: Left: geometric scaling of F_2. Right: geometric scaling of diffractive DIS.

4 Geometric scaling

The saturation model predicts a behavior called geometric scaling of the cross-sections [6]. If cross-sections scale geometrically, they become a funcition only of $\tau = Q^2/Q_s^2(x)$ rather than x and Q^2 separately. This behavior for both inclusive DIS (F_2) and diffractive DIS [7] are shown in Fig. 3. Other exclusive DIS cross-sections which are expected to have the same behavior indeed show this behavior. These include exclusive Vector Meson production in DIS and Deeply Inelastic Compton Scattering.

It is somewhat curious, however, that geometric scaling behavior appears to extend to much higher x and Q^2 than would be expected from our understanding of the saturation region.

5 What does it all mean?

We've seen that DGLAP evolution describes F_2 at HERA very well. On the face of it, this precludes any type of saturation effect observable at HERA. On the other hand, saturation models based on the dipole picture give an elegant and simultaneously (qualitatively) correct description of low-x F_2, low-Q^2 F_2, diffractive DIS, VM production, DVCS and other phenomena (see, for example, C. Marquet in these proceedings) which are otherwise described by rather separate theoretical treatments. Furthermore, the saturation models match onto experimental and theoretical ideas at RHIC (see, for example L. McLerran in these proceedings).

While how saturation models correspond to more rigorous theoretical ideas such as BK, JIMWLK and BFKL is becoming clearer (see, for example, C. Marquet and C. White in these proceedings), there are also still quite a number of theoretical objections to the model to be found in the literature.

If indeed saturation is being observed at HERA, is appears to be in the regions of Q^2 at the edge of applicability of perturbative QCD. However, since it is likely that whatever physics governs the behavior of F_2 is continuous, DGLAP cannot then be the sole explanation of what is being measured at HERA – this is in apparent contraditions to the good description of F_2 using DGLAP alone.

The most precise F_2 at HERA in the low to medium Q^2 region will come from the HERA Structure Function Working Group soon. It maybe that this data will help in beginning to answer the question of whether saturation has been observed at HERA.

6 Acknowlegements

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