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Diffraction and Forward Physics: from HERA to LHC*

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I discuss and connect a number of topics in small-x physics at HERA and at LHC, pointing out recent progress and open questions in theory and phenomenology.

1 Leading protons and rapidity gaps

An anticipated highlight of diffraction at LHC is the study of new particles in central exclusive production, $pp \to p + X + p$. Detailed investigations have been made for the case where X is a Higgs boson in the Standard Model or its supersymmetric extension (see e.g. [2]), but other systems with a strong coupling to two gluons, like a gluino pair $X = \tilde{g}\tilde{g}$ [3], can be equally interesting. Provided that rates are sufficiently high, central exclusive production enables us to study the system X in a clean environment, with a signal-to-background ratio often much larger than in conventional, inclusive production channels. Measurement of the outgoing proton momenta in forward detectors gives the possibility of a precise determination of the mass and possibly the width of X, and the exclusive production mechanism strongly favours systems X with quantum numbers $CP = ++$. If the effective two-gluon luminosity for $pp \to p + gg + p \to p + X + p$ can be determined from Standard-Model channels such as $X =$ dijet or $X = \gamma\gamma$, the cross section measurement for a new particle X decaying into a final state f yields the combination $\Gamma_{X\to gg}\Gamma_{X\to f}/\Gamma_{\text{tot}}$ of widths. More detail is given in several presentations at this meeting [4].

HERA data provides essential nonperturbative input needed to calculate central exclusive production at LHC. This is important not only to estimate event rates before LHC measurements start, but also to control backgrounds and to help optimise triggers and selection cuts when LHC data will be available. An example are events where the central system X contains not only a Higgs but also relatively soft gluons. Diffractive parton densities from HERA [5] are crucial to estimate the importance of this channel, which would spoil the accuracy of a Higgs mass determination from the scattered protons alone [6].

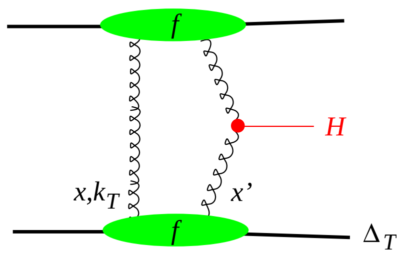

Figure 1: A simple graph for central exclusive Higgs production. The blobs represent the generalised gluon distribution.

The theory description of central exclusive production involves a number of nontrivial issues, some of which were discussed at this meeting [7]. The simplest leading-order graph for

*Talk given at the 16th International Workshop on Deep Inelastic Scattering and Related Subjects, University College London, England, 7–11 April 2008 [1] the production mechanism is shown in Fig. 1. There is no all-order factorisation theorem for this process, and indeed factorisation is broken by rescattering between spectator partons. Radiative corrections to the leading-order graph in Fig. 1 are known to be important and can in part be grouped into Sudakov factors. A full next-to-leading order calculation is, however, not available, and it has recently been argued that there may be important higher-order corrections which have not been evaluated so far [8].

The non-perturbative input to the graph in Fig. 1 is given by the generalised gluon distribution. Our present knowledge of this distribution derives essentially from HERA data on vector meson production and on deeply virtual Compton scattering [9]. From a theory point of view, Υ photoproduction is a particularly clean channel for this purpose, but the rate at HERA is too limited for detailed measurements. Along with J/Ψ photoproduction this channel could, however, be further studied in pp and pA collisions at LHC [10]. It is important to note that the calculation of central exclusive production involves generalised distributions f^g that depend explicitly on the transverse momentum k_T of the emitted gluon. Put in a simplified way, the graph in Fig. 1 involves an integral

$$\int \frac{d^2 k_T}{k_T^4}\, f^g(x_1, x_1', \Delta_{1T}, k_T)\, f^g(x_2, x_2', \Delta_{2T}, k_T)\,, \tag{1}$$

where the distributions in the two colliding protons are entangled. This cannot readily be reduced to the k_T integrated, collinear distributions

$$\int^{\mu^2} \frac{dk_T^2}{k_T^2}\, f^g(x, x', \Delta_T, k_T) \tag{2}$$

that appear in ep scattering processes. While the understanding and evaluation of higher-order corrections is fairly advanced for collinear generalised parton distributions, the same is unfortunately not the case for their k_T dependent counterparts.

As already mentioned, the simple mechanism shown in Fig. 1 receives important corrections from the rescattering of spectator partons in the two colliding protons. Most calculations assume that the dominant rescattering effects can be described by elastic or quasi-elastic proton-proton interactions. This leads to a simple representation $\sigma = \sigma_{\text{hard}} \otimes |S|^2$ for the physical cross section, where the convolution is in transverse-momentum space, σ_{hard} describes the hard-scattering mechanism sketched in Fig. 1, and the rapidity gap survival factor $|S|^2$ can be inferred from pp and $p\bar{p}$ scattering data. More complicated rescattering mechanisms have, however, been studied [11, 12]. The underlying physics is related to multiple scattering in inclusive pp collisions, which by itself is of high importance for understanding final states at LHC. The description of such rescattering effects involves considerable difficulties, and a reliable evaluation of their importance has not been achieved as yet.

It is all the more important to test the phenomenological models currently used for the description of central exclusive production. Fortunately, this is already possible by using data from the Tevatron, either for inclusive diffractive channels such as $\bar{p}p \to \bar{p} + \text{dijet} + X$ or for exclusive reactions like $\bar{p}p \to \bar{p} + \text{dijet} + p$ and $\bar{p}p \to \bar{p} + \gamma\gamma + p$ [13]. Possible tests using early data from LHC are discussed in [7]. HERA provides crucial input to these tests in the form of diffractive parton densities and of the generalised gluon distribution, which are needed to calculate the hard part σ_{hard} of the cross section. The importance of rescattering can also be probed in diffractive photoproduction at HERA, given the hadronic component of a real photon. This has turned out to be more complicated than initially thought, both from the experimental and the theoretical sides [14, 15]. It is probably too early to draw final conclusions here, but ultimately these studies might teach us more about the double nature of the photon as a pointlike particle and a hadron than about rescattering dynamics in diffraction.

2 Saturation and the dipole formalism

Parton saturation, caused by nonlinear dynamics that sets in when parton densities become very large, has become a central topic in high-energy QCD. It allows us to study a field theory in a strongly coupled regime, but with a small coupling constant, which makes it possible to use perturbative methods. Beyond this intrinsic interest, parton saturation entails the breakdown of a description based on collinear factorisation and DGLAP evolution. To quantify nonlinear effects at small x_B and moderate Q^2 at HERA is hence relevant for assessing the limits of precision in DGLAP based extractions of parton densities. For generic reasons, one expects such nonlinear, higher-twist corrections to be stronger in F_L than in F_2. Quantitative estimates based on the colour dipole model have been given several years ago [16], and work is underway to update these estimates taking into account the progress in dipole phenomenology [17].

A convenient framework to describe parton saturation in *ep* collisions is the colour dipole formalism. It permits the calculation of many inclusive and diffractive processes—from the inclusive structure functions F_2, F_2^{charm}, F_L and their diffractive counterparts to exclusive vector meson production and deeply virtual Compton scattering—with the *same* non-perturbative input, namely the scattering amplitude for a dipole on a proton target. The associated phenomenology is very successful, as presented in [19] at this meeting. On the theoretical side, this formalism is, however, still largely restricted to leading order in α_s. The fluctuation of a γ^* into $q\bar{q}$ is readily taken into account, but the next highest Fock state $q\bar{q}g$ has so far only been taken in certain approximations, which limits a reliable description of inclusive diffraction. The evolution of the dipole scattering amplitude with energy is described by the BFKL or the Balitsky-Kovchegov equations, whose leading-order solutions cannot account for the energy dependence seen in experiment. In practice one therefore typically takes a functional form of the dipole scattering amplitude motivated by theory, but fits the relevant parameters to data. Note that this is different from DGLAP type fits in collinear factorisation, where the relevant parton distributions are parametrised at a starting scale but evolved using the perturbative evolution equations. It remains an outstanding task to formulate BFKL and saturation dynamics in a dipole framework at NLO, in a manner that would allow one to pursue phenomenological analyses.

To which extent nonlinear dynamics is seen in HERA data remains rather controversial. Current saturation models find that the virtualities where saturation effects become important are below a GeV at HERA energies, which limits the possibilities of controlled perturbative calculations. A prominent experimental observation is the very flat energy dependence for the ratio F_2^D/F_2 of diffractive and total structure functions at given Q^2. This is explained in a natural way by the saturation mechanism [20]. It must, however, be noted that many dipole models, including versions without saturation, provide a good description of F_2^D and F_2 in a wide kinematic range [21]. To better assess the situation, it may be helpful to compare models with data specifically for the structure function ratio.

A striking feature observed in HERA small-x data is geometric scaling, i.e., the dependence of the total $\gamma^* p$ cross section (and also of diffractive cross sections) on a single scaling variable $\tau(x_B, Q^2)$ [22]. This is sometimes presented as evidence for saturation dynamics. However, several investigations have shown that, both analytically and numerically, one finds approximate geometric scaling also from the DGLAP and the BFKL equations [23]. To infer from geometric scaling on the underlying dynamics, one may have to focus on the *deviations* from exact scaling, which should differ among the various dynamical mechanisms. How well this can be quantified theoretically, and whether the precision and kinematic lever arm of the HERA data are sufficient for such a study, remains to be seen.

There are prospects to pursue the HERA studies of saturation effects for the much smaller parton momentum fractions achievable at LHC. This will require detection of particles at very forward rapidities [18]. Forward Drell-Yan pair production is of particular interest from a theory point of view. On the one hand, it permits a description in the dipole picture [24] and can thus be closely related with the studies performed at HERA. On the other hand this process is very well understood in collinear factorisation, with full next-to-next-to-leading order results [25] allowing for precise "non-saturated" calculations.

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