New Results on Hard Diffraction from HERA and the Tevatron

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This contribution summarises selected recent measurements of hard diffractive scattering processes and their interpretation in the framework of perturbative QCD. Two themes are pursued in particular: first the extraction of diffractive parton densities at HERA and their application at HERA and the Tevatron; second the search for central exclusive diffractive production at the Tevatron.

1. Introduction

Our understanding of rapidity gaps and colour singlet exchange in terms of the fundamental quarks and gluons of the strong interaction has developed substantially over the past 15 years in the light of measurements of hard diffractive processes at HERA and the Tevatron. This parton level structure is usually expressed in terms of Diffractive Parton Distribution Functions (DPDFs), which are defined in the framework of semi-inclusive collinear hard scattering factorisation [1] and can be extracted from single- and double-dissociative diffractive processes such as those shown in figures 1a-c. Another class of diffractive processes which has generated recent interest is the central exclusive production of systems such as a pair of jets (figure 1d). This channel is of interest as a preparation for possible future studies of the exclusive production of Higgs bosons or other new 0^+ states [2,3]. These two classes of diffractive process are directly relevant to the LHC [4], and are thus the focus of this article. Space limitations prevent discussion of the many other intriguing aspects of diffraction at HERA and the Tevatron which are under current study.

2. Diffractive Parton Densities

2.1. Inclusive Diffractive DIS and DPDFs

There has been significant recent experimental progress from the H1 and ZEUS collaborations in measuring cross sections for the inclusive diffractive process $ep \to eXp$ (figure 1a). Data are now available from below $Q^2 = 1$ GeV^2 to above $Q^2 = 1000$ GeV^2. Notable among the many new results released in the past year is the good agreement between the two collaborations [5], between different selection methods with very different systematics [5–7] and between HERA-I and HERA-II data [8].

This consensus on diffractive cross sections is reflected in a correspondingly improved agreement on the DPDFs, which have been extracted recently by several groups [6,9–11] in the framework of next-to-leading order (NLO) DGLAP evolution. In [6], a full evaluation of both experimental and theoretical uncertainties is performed, leading to the results in figure 2, where the DPDFs are shown as a function of the momentum fraction z of the parton entering the hard scattering at different factorisation scales Q^2. The diffractive quark density, which is very closely related to the diffractive cross section itself, is known to around 5%. The gluon density accounts for around 70% of the total exchanged momentum. It is obtained in [6] from the Q^2 dependence (scaling violations) of the diffractive cross section, which is driven by the splitting $g \to q\bar{q}$ at low to moderate z. The uncertainty in this region is typically 15%. However, at the largest z, where the scaling violations become dominated by the quark-initiated process $q \to qg$, the sensitivity to the gluon density is lost and the uncertainties increase dramatically. This lack of a constraint on the high z gluon density is illustrated by the comparison in figure 2 between two

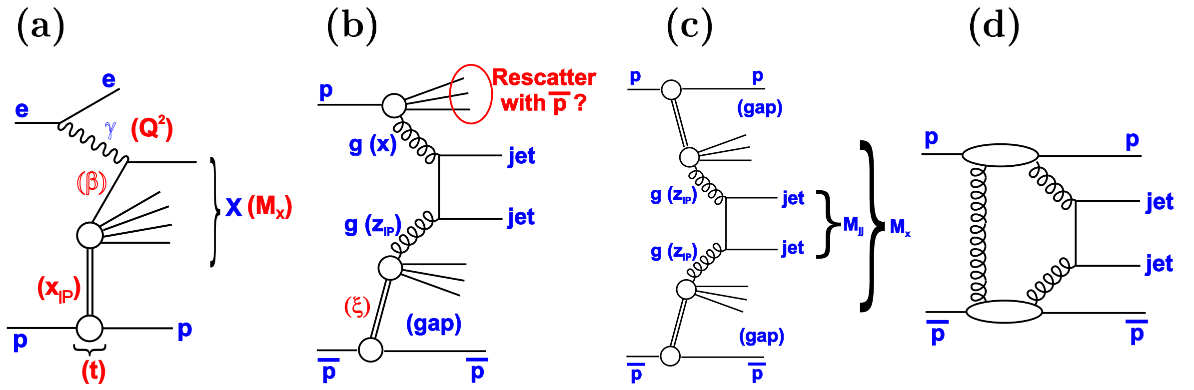

Figure 1. Illustrations of the processes and associated kinematic variables discussed: (a) inclusive diffraction at HERA; (b) inclusive diffractive dijet production at the Tevatron; (c) dijet production via 'double pomeron exchange' at the Tevatron; (d) central exclusive dijet production at the Tevatron.

different solutions, 'H1 2006 DPDF Fit A' and 'Fit B', which differ only in the parameterisations of the gluon density at the starting scale of the DGLAP fits. The gluon density at large z is very different in the two cases, although the quality of the description of the data by fit A is of only slightly higher quality than that by fit B.

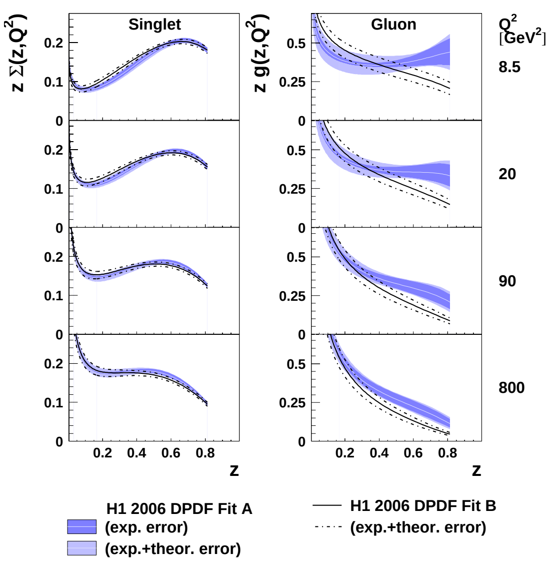

Figure 2. The diffractive singlet quark and gluon densities extracted from inclusive diffraction in two NLO DGLAP fits with slightly different gluon density parameterisations [6].

The DPDFs extracted from inclusive diffraction at HERA are expected [1] to be universally applicable to deep inelastic scattering (DIS), but to require further 'gap survival probability' [2] factors when applied to hadron-hadron scattering, due to rescattering between beam remnants (figure 1b).

2.2. Applying the DPDFs in DIS

Numerous tests of diffractive factorisation in DIS have been reported in the past year. Factorisation works well within the rather large uncertainties on the cross section for charged current diffraction ($ep \to \nu X p$) [6], which is sensitive to the quark flavour decomposition. Several measurements have been made of cross sections for high p_T dijet or charm production within the system X, which are directly sensitive to the diffractive gluon density via the leading order 'boson-gluon fusion' production mechanism $\gamma^* g \to q\bar{q}$. Although the DPDF-based predictions for such processes are now generally made at NLO in QCD, the limiting factor in the comparisons remains the scale uncertainties on these predictions.

Diffractive charm cross sections [12,13] are well described by predictions based on both sets of H1 2006 DPDFs. The same is true for diffractive dijet cross sections [11,14,15] at low z, where the DPDFs extracted from the inclusive cross section are reliable (see e.g. figures 3a,b).

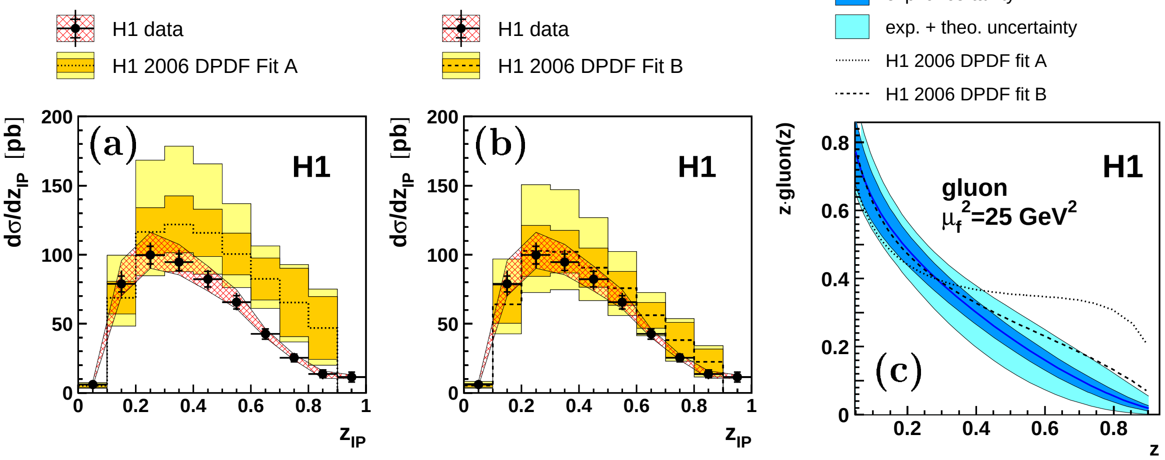

Figure 3. (a,b) Diffractive DIS dijet cross sections [11], measured as a function of $z_{\mathbb{P}}$, a hadron level estimator of z. The cross sections are compared with predictions based on (a) H1 2006 DPDF Fit A and (b) Fit B. (c) The diffractive gluon density from a combined fit to inclusive and dijet diffractive data, compared with extractions using inclusive data alone.

Dijet cross sections have been measured to reasonable precision up to the largest values of z, where they discriminate between the different DPDF sets obtained from inclusive data, as is clear from figures 3a and b. The H1 DPDF fits have been repeated with the jet cross sections also included [11]. Thus refined, the gluon density from the 'H1 2007 Jets DPDF' is shown in figure 3c. The resulting high z gluon is compatible with that from H1 2006 DPDF Fit B, but not with that from Fit A.

The recent 'ZEUS LPS+charm' fit [10] takes a similar approach to that of the H1 2007 Jets DPDF, but uses charm, rather than dijet, data to improve the sensitivity to the gluon density. Any residual tension at hgh z between inclusive and dijet data may be evidence for a contribution from perturbative 2-gluon exchange, as included in [9] by modifying the evolution equations to contain an inhomogeneous term.

2.3. Applying the DPDFs to Photoproduction and Hadron-Hadron Scattering

Factorisation is expected to break down wherever hadronic remnants are present [1]. This is not the case in DIS (figure 1a), nor in 'direct' photoproduction, where the exchanged real ($Q^2 \simeq 0$) photon enters the interaction in a point-like way. On the other hand, remnants may lead to rescattering in proton-proton collisions (e.g. figure 1b) and also in 'resolved' photoproduction, where the photon interacts via the partonic structure which it develops following the splitting $\gamma \to q\bar{q}$ well in advance of the target. The fraction of the photon momentum which enters the hard scattering is then characterised by the variable x_γ.

The factorisation properties of photoproduction have been investigated in a number of analyses published in the past year. The charm measurements [13,16] are restricted to large values of x_γ, such that typically 70% of the cross section is estimated to arise from direct photon interactions. Unsurprisingly, a good description is then obtained using NLO calculations based on DPDFs extracted from inclusive diffraction, as shown for example in figure 4.

Better sensitivity to differences between direct and resolved processes and to the DPDFs is obtained in the study of dijets, where both outgoing partons are reconstructed in a leading order picture. However, the status at the time of writing is somewhat confused. Neither H1 [15], nor ZEUS [17] observe a significant difference between the quality of the description in the resolved (low x_γ) and direct (high x_γ) regions. However, whilst

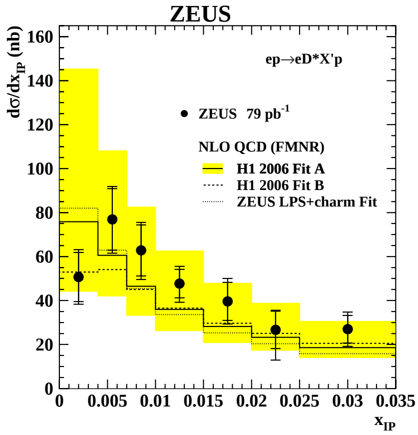

Figure 4. Cross section for diffractive D^* meson photoproduction [16], shown as a function of the fractional momentum $x_{\mathbb{P}}$ of the proton taken by the diffractive exchange and compared with NLO predictions based on different sets of DPDFs.

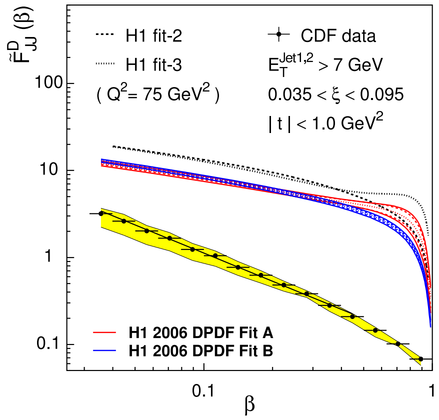

Figure 5. Effective diffractive parton density $\tilde{F}^D_{jj}$ from a CDF measurement of dijet production as a component of X in the process $\bar{p}p \to \bar{p}X$ [18].

ZEUS report an acceptable overall description by the NLO calculations, H1 obtain an excess of the prediction relative to the data by a factor of around 2, which surprisingly appears to be present in the direct as well as the resolved photon region. These issues require clarification before conclusions can be drawn.

When $p\bar{p}$ data from the Tevatron are confronted with predictions based on the DPDFs from DIS at HERA, very clear discrepancies become apparent. An example based on CDF run I dijet data (figure 1b) is shown in figure 5. The extracted effective diffractive parton density $\tilde{F}^D_{jj}$ lies below the predictions based on the H1 2006 DPDFs by a factor of around 10, somewhat dependent upon the parton momentum fraction β. This breaking of factorisation is broadly in line with a rapidity gap survival probability of around 10% [2].

3. Central Exclusive Production

In [3], it is estimated that the visible cross section for central exclusive Higgs production at the LHC, including a 3% gap survival probability, is around 3 fb, making it an accessible channel at high luminosity. Whilst the corresponding Higgs cross section at the Tevatron is expected to be prohibitively small, theoretical calculations and gap survival probability modelling can be tested and tuned using related channels such as that for exclusive dijets shown in figure 1d.

Exclusive dijet production may be selected as a subset of the inclusive 'double pomeron exchange' (DPE) process (figure 1c). Whilst the central system in the inclusive process contains remnants of the two diffractive exchanges, the exclusive process contains no such remnants at the parton level. A variable which may distinguish the two cases is $R_{jj} = M_{jj}/M_X$, where (figure 1c) M_{jj} is the invariant mass of the dijet system alone and M_X is the invariant mass of the full central system. At the leading order parton level, the central exclusive production signal should lie at $R_{jj} = 1$, with the remaining DPE distributed throughout the full R_{jj} range. However, matters are complicated by hadronisation effects and by higher order QCD radiation from the outgoing partons, both of which shift exclusive events to lower R_{jj} values. Unfolding the exclusive contribution from the component of the DPE background which involves large z gluons is thus non-trivial.

In figure 6a, the CDF DPE sample is plotted as a function of R_{jj}. Whilst the distribution does not clearly divide into two subsamples, it has not been possible to describe it with any reasonable model using only the DPE prediction based on

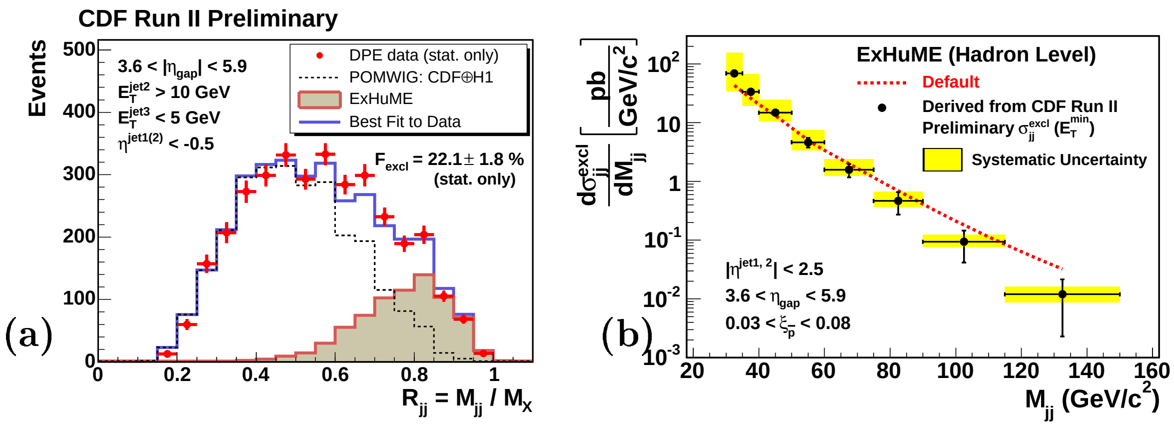

Figure 6. (a) CDF inclusive double pomeron exchange sample [19] plotted as a function of R_{jj} and compared with a Monte Carlo simulation of both the inclusive process of figure 1c (POMWIG) and the central exclusive production process of figure 1d (ExHuME). (b) Differential cross section for central exclusive production as a function of dijet mass, compared with the ExHuME prediction.

the DPDFs from HERA. For the example in figure 6a the H1 DPDFs are used, as implemented in the POMWIG [20] Monte Carlo model. The shortfall at large R_{jj} is well modelled in both shape and normalisation by the ExHuME Monte Carlo model [21], which is based on [3], with a gap survival probability of 4.5%. If this 'POMWIG + ExHuME' decomposition is used as a basis to extract the cross section for central exclusive production alone, the data are in good agreement with the prediction, as illustrated as a function of M_{jj} in figure 6b. The extracted signal extends to dijet masses in excess of 100 GeV, the region of interest for Higgs studies at the LHC.

In [22] the central exclusive system under study by CDF is replaced by a pair of photons, produced from $gg \to \gamma\gamma$ via a quark loop. The observed signal for exclusive di-photon production is 3 events, to be compared with an estimated background of less than 0.2 events and a prediction based on [3] of around 1 event with an uncertainty of a factor of around 5.

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