Recent Low x and Diffractive Collider Data

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Abstract.

Selected recent data from collider experiments pertaining to the understanding of QCD at low Bjorken-x are reviewed. The status of QCD and Regge factorisation in hard diffractive interactions is discussed in terms of data from HERA and the Tevatron. The possibility of anomalous behaviour in the $\gamma\gamma$ total cross section is confronted with the most recent measurements from LEP. Data from all three colliders that are sensitive to possible BFKL effects are presented and different interpretations are discussed.

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1. Introduction

Since the HERA and Tevatron colliders have been operational, abundant data have become available that are sensitive to proton structure at low parton-x. Data on photon structure from HERA and LEP have been similarly impressive. This latest generation of colliders has pushed back the limits of our understanding of QCD considerably. There is not space here to do justice to all low x data. Instead, three particularly topical areas that were discussed at the 1999 Durham Phenomenology Workshop are singled out.

2. Factorisation in Hard Diffraction

The HERA and Tevatron experiments have now produced abundant high quality data on the 'single diffractive' processes $\gamma^* p \rightarrow Xp$ and $\bar{p}p \rightarrow X \overset{(-)}{p}$ at low momentum transfer. Hard scales, provided for example by a highly virtual photon (in the $\gamma^* p$ case) or final state jets or heavy quarks, encourage the use of perturbative QCD as a tool with which to understand the parton level dynamics. The development of techniques which simultaneously describe the $\gamma^* p$ and $\bar{p}p$ single dissociation processes is a major current issue in hadron phenomenology.

The generic diffractive process at HERA of the type $ep \rightarrow eXp$ is illustrated in figure 1a. A photon of virtuality Q^2 interacts with a proton at a $\gamma^* p$ invariant mass W and squared four momentum transfer t to produce a dissociating photon system X of invariant masses M_X, the proton remaining intact. In the corresponding process at the

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Tevatron, the photon is replaced by an anti-proton, with either of the beam particles dissociating.Two further variables are usually introduced; the fraction of the proton momentum that is exchanged to the system X is denoted ξ§, whilst $\beta = x/\xi$ is the fraction of the exchanged momentum carried by the quark coupling to the photon.

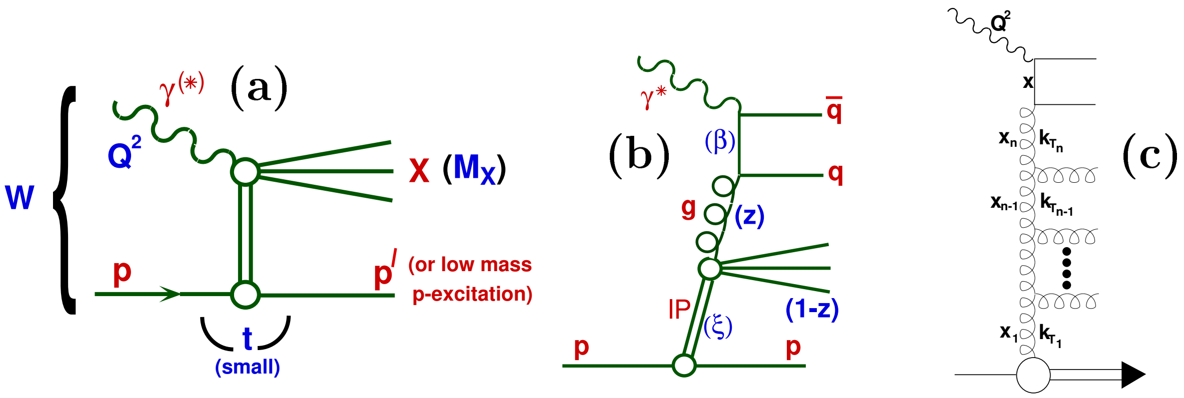

Figure 1. (a) The generic photon dissociation process at HERA. (b) Diagram of the dominating leading order QCD process in models involving a pomeron with partonic sub-structure. A $q\bar{q}$ pair is produced via photon-gluon-fusion ($\gamma^* g \rightarrow q\bar{q}$). (c) Illustration of the low x parton ladder in DIS.

A QCD factorisation theorem has recently been proved for a general class of semi-inclusive processes in deep-inelastic scattering (DIS), which include the single diffractive process [1]. This implies that a concept of 'diffractive parton distributions' can be introduced [2], expressing proton parton probability distributions under the constraint of an intact final state proton with particular values of ξ and t. The cross section for diffractive DIS can then be expressed as

$$\sigma^{\gamma^* p \rightarrow Xp}(\xi, t, x, Q^2) \sim \sum_i f_{i/p}(\xi, t, x, Q^2) \otimes \hat{\sigma}_{\gamma^* i}(x, Q^2) \ ,$$

where $f_{i/p}(\xi, t, x, Q^2)$ are the diffractive parton distributions, evolving with x and Q^2 according to the DGLAP equations at fixed ξ and t, and $\hat{\sigma}_{\gamma^* i}(x, Q^2)$ are parton interaction cross sections.

The phenomenology of soft hadronic interactions suggests that it is possible to introduce a universal factorisable pomeron exchange with a flux factor dependent only on ξ and t. With this additional assumption of 'Regge factorisation', the framework of diffractive parton distributions can be used to define parton distributions for the pomeron [3], which should describe all hard diffractive scattering processes. The diffractive DIS cross section can then be written as

$$\sigma^{\gamma^* p \rightarrow Xp}(\xi, t, \beta, Q^2) \sim f_{\mathrm{IP/p}}(\xi, t) \otimes \sum_i f_{i/\mathrm{IP}}(\beta, Q^2) \otimes \hat{\sigma}_{\gamma^* i}(\beta, Q^2) \ .$$

The validity of this second hypothesis for diffractive DIS, incorporating both QCD and Regge factorisation, has been extensively tested at HERA. Measurements of the

§ At HERA, ξ is usually referred to as $x_{I\!P}$. Here ξ is used to make explicit the correspondence with the equivalent variable at the Tevatron.

total cross section for diffractive deep-inelastic scattering, usually presented in the form of a t-integrated diffractive structure function $F_2^{D(3)}(\beta, Q^2, \xi)$ [4–6] have shown that, to the present level of accuracy, the factorisation between the ξ and the (β, Q^2) dependence is obeyed.‖ Parton distributions for the pomeron have been extracted [4, 7] from QCD analyses of the β and Q^2 dependence of F_2^D using the DGLAP evolution equations. All such extractions yield parton distributions which are heavily dominated by gluons at low scales, the gluon density remaining large even at high fractional momentum. Figure 1b then represents the dominant process at leading order of QCD. A gluon carrying a fraction z of the pomeron momentum undergoes boson-gluon fusion ($\gamma^* g \to q\bar{q}$) with the virtual photon.

Monte Carlo models based on the parton distributions extracted from F_2^D describe HERA diffractive final state data well [8, 9]. The most stringent tests come from diffractive dijet and open charm cross sections, as both are sensitive to the magnitude as well as the shape of the gluon distribution. Recent data from H1 on diffractive dijet electroproduction [10] are shown in figure 2a. The factorisable partonic pomeron model (labelled "res $\mathbb{P}$") gives a reasonable description of the measurement. Similarly good agreement is found with ZEUS data on diffractive charm electroproduction [11], though a diffractive D^* measurement from H1 in a slightly different kinematic region suggests deviations from factorisation [12]. With this single exception, HERA data support the hypothesis that both QCD and Regge factorisation can be applied to all hard diffractive processes in DIS.

There are good reasons to believe that the QCD factorisation theorem for diffractive DIS [1] cannot be extended to hard diffraction in hadron-hadron interactions [14]. The factorisation hypothesis for $p\bar{p}$ scattering has now been tested in some detail by taking parton distributions extracted from F_2^D data at HERA and using them to predict cross sections for hard diffractive processes at the Tevatron. By now it is clear that this approach universally predicts cross sections well in excess of those measured.

One example [15] is a measurement of the fraction $N^{\rm diff}/N^{\rm incl}$ of all dijet events that arise from the single dissociation process $\bar{p}p \to Xp$, where the intact final state proton has $0.035 < \xi < 0.095$ and is scattered at $|t| < 1$ GeV^2. From this ratio, the quantity

$$F_{\rm JJ}^D = \frac{N^{\rm diff}}{N^{\rm incl}}(x_{\bar{p}}) \left\{ x_{\bar{p}} g(x_{\bar{p}}) + \frac{4}{9} \left[q(x_{\bar{p}}) + \bar{q}(x_{\bar{p}}) \right] \right\}_{\bar{p}}$$

is formed, where $x_{\bar{p}}$ is the Bjorken scaling variable for the antiproton and $x_{\bar{p}} g(x_{\bar{p}}) + \frac{4}{9}\left[q(x_{\bar{p}}) + \bar{q}(x_{\bar{p}})\right]$ represent the (known) effective parton densities in the anti-proton after allowing for the leading order colour factor of 4/9. Assuming factorisation is valid, the resulting quantity should correspond to the effective parton densities of the pomeron;

$$F_{\rm JJ}^D = \left\{ \beta g(\beta) + \frac{4}{9} \left[q(\beta) + \bar{q}(\beta) \right] \right\}_{\mathbb{P}} \otimes f_{\mathbb{P}/\rm p}(\xi) \ .$$

The quantity $F_{\rm JJ}^D$ is shown as a function of β in figure 2b and is compared with predictions based on parton densities extracted from F_2^D by H1 [4]. The predictions are scaled down

‖ The deviations from this factorisation shown to be present in [4] can be explained in full when a sub-leading exchange (f, ω, ρ and / or a trajectory) is introduced.

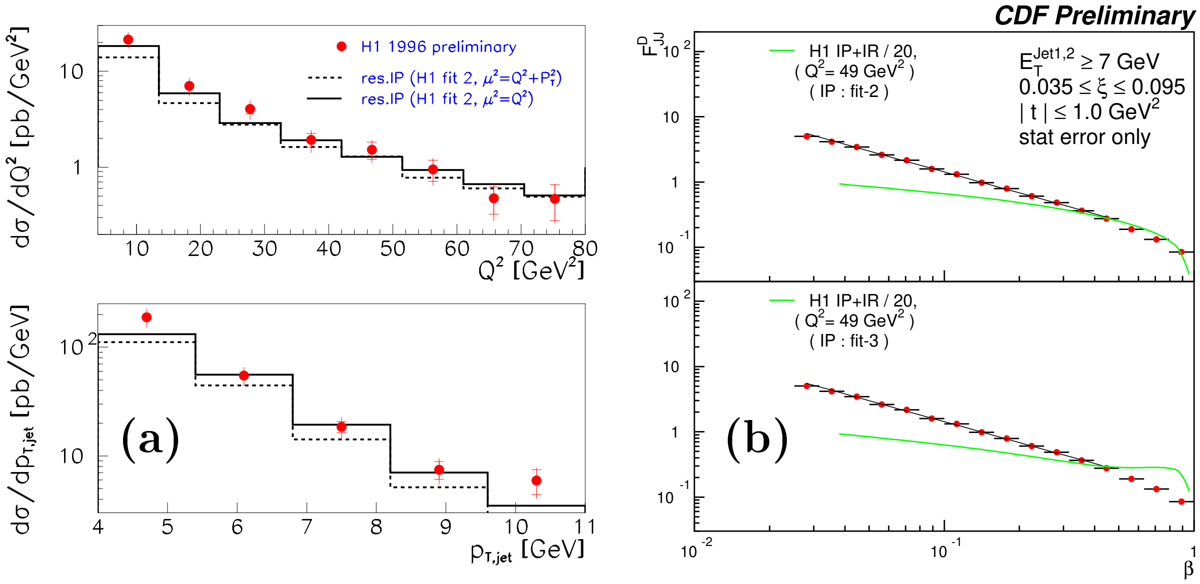

Figure 2. (a) Q^2 and jet transverse momentum ($p_T^{\rm jet}$) distributions for diffractive dijet electroproduction data, compared with the predictions of the RAPGAP Monte Carlo model incorporating a set of pomeron parton distributions extracted from F_2^D data. (b) β dependence of the quantity $F_{\rm JJ}^D$ (see text), related to the fraction of $p\bar{p}$ dijet events that are produced diffractively. The data are compared with predictions based on two slightly different sets of diffractive parton densities extracted from F_2^D (top and bottom plots), the predictions being reduced by a factor of 20 for the plots.

by a factor of 20, illustrating the size of the factorisation breaking effects. At least for $\beta \lesssim 0.3$, the data and prediction are also rather different in shape.

Another recent measurement from CDF is the fraction of visible beauty production that is attributable to diffraction, which yields the result [16]

$$\frac{\sigma_{b\bar{b}}^{\rm diff}}{\sigma_{b\bar{b}}^{\rm incl}} = 0.62 \ \pm 0.19 \ ({\rm stat.}) \ \pm \ 0.16 \ ({\rm syst.}) \ ,$$

whereas the predictions on the basis of diffractive parton densities extracted from ep data are at the level of 10%.

In a complementary analysis, Alvero et al [7] have extracted diffractive parton distributions from F_2^D and photoproduction dijet data from HERA and made predictions for various Tevatron measurements. Similarly large discrepancies are found when predicting the rate of W and dijet production as components of the system X in the process $\bar{p}p \rightarrow X \overset{(-)}{p}$ [17,18], with even larger differences for dijet production in the double pomeron exchange process $p\bar{p} \rightarrow pX\bar{p}$.

Something beyond the simplest Regge and QCD factorisation assumptions is clearly required to describe simultaneously diffractive data from HERA and the Tevatron. The pertinent question now is whether it is possible to build a phenomenological model of this breakdown of factorisation. One possibility is that where beam remnants are present on both sides of a rapidity gap, rescattering takes place, tending to destroy the gap. A very interesting place to study this possibility is in photoproduction, where both factorisable (direct photon) and non-factorisable (resolved photon) interactions may be expected to be present. A first study can be found in [20].

3. Total Cross Sections

Total hadron-hadron cross sections are well described over a very wide energy range by two component Regge fits [21], corresponding (via the optical theorem) to the exchange of the pomeron and a sub-leading (ρ, ω, f, a) trajectory in the elastic amplitude. The intercept of the leading pomeron trajectory is most accurately determined from the high energy rise in the $\bar{p}p$ cross section. Other total cross sections such as $\pi^{\pm}p$ match this scheme well, though no data exist at centre of mass energies $\gtrsim 30$ GeV.

In the case where one or both of the interacting hadrons is replaced by a photon, arguments have been made that the presence of a bare photon coupling in addition to the vector meson dominance hadronic component may lead to a faster rise of the total cross section with energy than is the case for pure hadron-hadron scattering. Eikonalised minijet models [22], incorporating semi-hard QCD interactions whilst avoiding the eventual violation of unitarity associated with simple Regge pole models, can be made to fit the available data [23]. HERA data on the total γp cross section at centre of mass energy $W_{\gamma p} \sim 200$ GeV [24] are consistent with the simple Regge pole model, though the systematic errors are large and no strong conclusion is yet possible. The increasingly precise data from LEP on the total $\gamma\gamma$ cross section, which may be expected to rise faster even than the γp cross section, may shed some light on this issue.

Both L3 [25] and OPAL [26] have measured the total $\gamma\gamma$ cross section in the region $10 \lesssim W_{\gamma\gamma} < 100$ GeV. For the data used, both electrons and many final state hadrons are lost down the beam-pipe, making the kinematics difficult to constrain. The data are shown, together with lower energy fixed target data, in figure 3a. The LEP data clearly show the high energy rise with W observed in the $\bar{p}p$, pp and γp cross sections. A simple factorisation law of the type $\sigma_{\gamma\gamma} = \sigma_{\gamma p}^2/\sigma_{pp}$ describes the data remarkably well.

It is not yet clear whether the rise with W is faster than that observed for total hadron-hadron cross sections; the OPAL data are consistent with the pomeron intercept describing soft hadronic interactions whereas the L3 result is significantly larger. The results are rather sensitive to the assumptions on $\alpha_{\mathbb{P}}(0)$. As can be seen from figure 3a, a model based on minijets [23] also gives a reasonable description of the data, as do the Schuler and Sjöstrand [27] and PHOJET [28] models, which attempt to make smooth transitions between the photon in its hadronic and point-like manifestations.

Improved data are required before a firm conclusion can be reached concerning the possible anomalous behaviour of $\sigma_{\gamma\gamma}^{\rm tot}$. The main source of error in the measurements arises from the model dependence of the acceptance corrections, with results different at the level of $\sim 20\%$ obtained when PHOJET or PYTHIA [29] is used for the corrections. The principal reason for this is the different treatments of the diffractive channels in the two models. Any constraints that can be placed on the diffractive processes in $\gamma\gamma$ scattering will improve the total cross section measurement considerably. Processes involving the quasi-elastic production of vector mesons are likely to be the easiest to

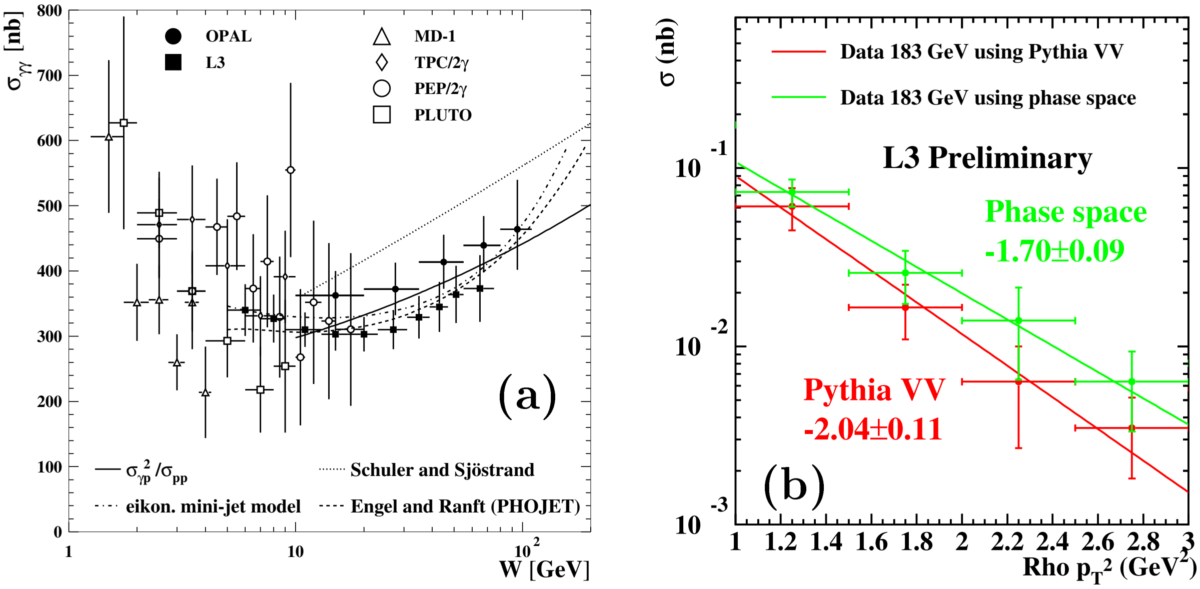

Figure 3. (a) A compilation of total $\gamma\gamma$ cross section data. The L3 data are corrected using the PHOJET Monte Carlo model. The OPAL data are the average of the values obtained when correcting with PHOJET or PYTHIA, with a systematic error reflecting the difference between the two cases. (b) Distribution in $p_T^2(\rho) \simeq |t|$ for the 'single dissociative' process $\gamma\gamma \to \rho^0 X$.

measure, due to the well known decay angular distributions. L3 have taken the first steps towards measurements of the 'quasi-elastic' ($\gamma\gamma \to \rho^0\rho^0$) and 'single dissociation' ($\gamma\gamma \to \rho^0 X$) processes. A measurement of the t distribution of the single dissociation process is shown in figure 3b. Fitting the data to the usual exponential parameterisation $d\sigma/dt \propto e^{bt}$ yields a slope parameter in the region $b \sim 2$. Information of this sort provides very useful input to soft physics models and should ultimately reduce the model dependence uncertainties on the total cross section.

4. Searches for BFKL Dynamics

The BFKL evolution equation, which resums terms where large logarithms of the form $\ln 1/x$ multiply the coupling constant, must represent a valid approximation to parton dynamics in some region of low x phase space. The search for evidence for BFKL behaviour is one of the principle current experimental activities in low x physics. Although it has been shown that introducing BFKL effects can improve the description of F_2 at low x [30], it is not yet accepted that anything more than standard DGLAP evolution is required to describe current inclusive DIS data. Exclusive final state measurements may ultimately produce the clearest BFKL signatures. Some of the more promising areas of study are discussed below.

BFKL and DGLAP evolution have rather different implications for the details of the parton ladder governing low x DIS processes (figure 1c). In the DGLAP case, one expects an ordering in virtuality (k_t) of the partons in the ladder, leading to rapidity ordering of the transverse momenta of outgoing partons. The BFKL scheme has no such strong ordering and therefore results in anomalously large high p_T hadron yields away from the photon vertex, for example at central rapidity. The central region of the $\gamma^* p$ frame corresponds to the forward region of laboratory rapidity.

Both H1 and ZEUS have studied the production of jets in this difficult forward region [31]. H1 have also measured the cross section for high p_T forward π^0 production [32]. Similar conclusions are reached in each case. The ZEUS forward jet data are shown in figure 4a. The data cannot be described by standard DGLAP models (labelled LEPTO and HERWIG). Only models that do not impose strong transverse momentum ordering are able to describe the data. One example is the ARIADNE model [33], based on the colour dipole model and simulating BFKL ordering. However, the lack of strong k_T ordering can also be modelled through the introduction of partonic structure to the virtual photon. This can be implemented in the RAPGAP [34] Monte Carlo model, giving a successful description of all forward region data produced at HERA to date. Thus the final state data from the forward region at HERA demonstrate that something more than the simplest DGLAP model of the low-x parton ladder is required. However, resolved virtual photons provide an alternative mechanism to BFKL to restore a good description of the data. Work on events with large rapidity separations between pairs of jets, just beginning at the Tevatron, may help to resolve some of these ambiguities.

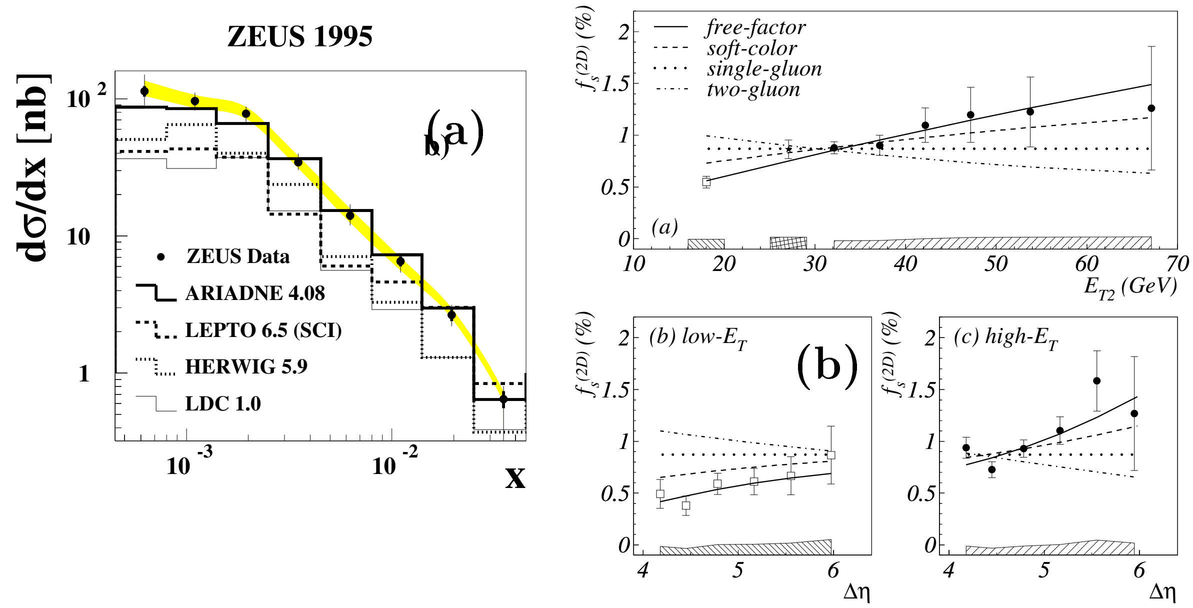

Figure 4. (a). Cross section for the production of jets with $E_T > 5$ GeV, $0.5 < E_T^2/Q^2 < 2$ and $p_z^{\rm jet}/E_p > 0.036$ in the Breit frame. (b). Data on the fraction $f_s^{(2D)}$ of Tevatron dijet events where a rapidity gap separates the jets at $\sqrt{s} = 1800$ GeV.

In appropriate kinematic regions, total, elastic and diffractive cross sections may all be describable in terms of the amplitude for elastic parton-parton scattering via the exchange of gluon ladders, evolving according to BFKL dynamics. BFKL calculations are most reliable where large scales are present at both vertices [35]. One example is the total $\gamma^*\gamma^*$ cross section [36]. Where both photons have sufficiently high virtuality, measurement conditions at LEP are favourable and first data have appeared [37]. The data suggest a relatively strong energy dependence, which may be consistent with BFKL predictions. However the present data can be described equally well by non-BFKL QCD models, for example those involving virtual photon structure [38].

Another process where large scales are present at both vertices is diffractive scattering at large $|t|$, where precision data are starting to appear from HERA and the Tevatron. The quasi elastic process $\gamma p \rightarrow VY$ where V denotes a vector meson and Y is a proton or low mass proton excitation has been measured for $V = J/\psi$, ρ and ϕ [39]. The results in the relatively low $|t|$ regions accessed to date are mixed, only the J/ψ fully conforming to the BFKL predictions.

The classic high $|t|$ diffractive process is the production of dijets separated by a rapidity gap, implying a net colour singlet exchange. Here, the magnitude of t is close to the jet E_T^2 and is thus very large. The size of the cross section is usually quantified as the fraction of all dijet events that have a rapidity gap between the jets. Clear signals have been observed at large jet pseudorapidity separation $\Delta\eta$ both in photoproduction at HERA [40] and in $p\bar{p}$ interactions at the Tevatron [41, 42]. The gap fraction at large $\Delta\eta$ decreases with centre of mass energy, being around 0.1 at $\sqrt{s} \simeq 200$ GeV at HERA, 0.025 at $\sqrt{s} = 630$ GeV at the Tevatron and 0.01 at $\sqrt{s} = 1800$ GeV at the Tevatron. This trend is opposite to that naively expected from BFKL calculations. However, it seems likely that rapidity gap destruction due to reinteractions of beam remnants plays an important role. Two very different models of these effects [43, 44] both predict a rapidity gap survival probability that falls with centre of mass energy in a manner that qualitatively resembles that in the data.

The Tevatron gap fractions have been measured as a function of jet E_T as well as $\Delta\eta$ (see figure 4b). The gap fraction is found to be flat or slowly rising with $E_T^{\rm jet}$, which matches predictions based on the creation of rapidity gaps by soft colour interactions in otherwise standard dijet events [45]. It has been demonstrated that if rapidity gap destruction effects are included, BFKL dynamics can also describe these data [44].

All of the measurements discussed above can be interpreted in terms of BFKL effects, yet none conclusively demonstrates the need for BFKL at present colliders. Data from the upgraded Tevatron and HERA may allow us to resolve this question.

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