DIFFRACTION AND VECTOR MESON PRODUCTION

Y. YAMAZAKI

High-energy accelerator research organisation (KEK), Oho 1-1, Tsukuba, 305-0801 Japan
E-mail: yuji.yamazaki@kek.jp

A review is given of the measurements of the diffractive process in recent years from two high-energy colliders, the HERA ep collider and the Tevatron $p\bar{p}$ collider. The energy dependence of the cross sections and the factorisation properties of diffractive processes are discussed.

1. Introduction

The diffractive process, defined as hadron-hadron scattering with an exchange of the vacuum quantum numbers and a small momentum transfer, has been understood in the framework of Regge theory in the past. The exchange was interpreted as the Pomeron trajectory, whose counterpart as a particle has not yet been observed. The concept of the particle-like Pomeron is therefore not satisfactory. The aim of studying diffractive processes in the era of high-energy colliders is to understand the partonic structure of the diffractive exchange in terms of perturbative QCD (pQCD).

The diffractive exchange has two distinguishing features. One is that it is a colour-singlet exchange. This means that the emission of hadrons from the exchange is suppressed. Another is that the diffractive events are observed with a small momentum transfer in both the transverse and longitudinal coordinates. The four-momentum of the exchange, t, and the longitudinal momentum fraction of the exchange, $x_{\mathbb{P}}$, are both small; $|t|$ is typically less than the square of the nucleon mass and $x_{\mathbb{P}}$ is smaller than 0.05. The two incoming hadrons are scattered through a small angle without losing any significant longitudinal momentum. As a consequence, the two diffractively dissociated systems are separated in rapidity space, forming a large rapidity gap (LRG).

In pQCD, the colour-singlet configuration of the exchange at leading order is described by either two gluons or two quarks with opposite colour charges. Assuming that the partons in the exchange originated from partons in the hadron emitting the exchange, the partonic content of the exchange at low-$x_{\mathbb{P}}$ is expected to be mainly gluons since they dominate in the low-x regime of the parent hadron, where x is the Bjorken variable, representing the longitudinal momentum fraction of the parton in the nucleon. At lowest order, pQCD models describe the diffractive exchange as a gluon pair.

The partonic structure of the exchange can be studied using processes with a hard scale, like large Q^2, the negative of the four-momentum squared of the exchanged virtual photon in deep-inelastic scattering (DIS), large E_T in jet production or a heavy-quark mass. In this review, the data on such processes from the HERA ep collider and the highest energy $p\bar{p}$ collider, the Tevatron, are presented. This article concentrates on two topics, the factorisation properties of diffractive processes and the energy dependence of the diffractive cross sections, both of which give insight into the partonic structure of the diffractive exchange. Before reviewing the data, a short discussion on the parton densities of the nucleon and their relation to the diffractive cross section is given.

2. Diffractive Processes and Parton Densities in Hadronic Collisions

As already discussed, the partonic contents of the diffractive exchange in most of the pQCD models originate from the partons in the incoming hadrons, i.e. protons for HERA and the Tevatron. The partonic contents of the protons are primarily determined from the $F_2(x, Q^2)$ results measured using DIS interactions (see Fig. 1). A fast rise towards low x is observed in the F_2 data. The parton densities, extracted using NLO DGLAP fits of the F_2 data, show a corresponding increase towards lower x. In particular, the gluon density shows a faster increase than that of the quarks and dominates at low x. Such behaviour of F_2 is also expressed in the form of virtual photon-proton total cross section, $\sigma_{\rm tot}^{\gamma^* p}$, as a function of Q^2 and W, the $\gamma^* p$ centre-of-mass energy through the relation $\sigma_{\rm tot}^{\gamma^* p}(W, Q^2) \approx (4\pi\alpha^2/Q^2)F_2$. Since $W^2 \approx Q^2/x$ for small x, the increase of F_2 cor-

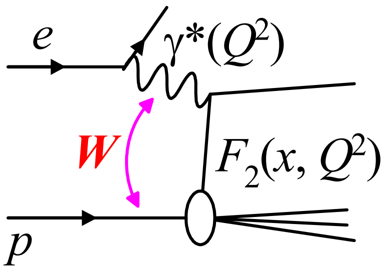

Figure 1. A diagram of DIS.

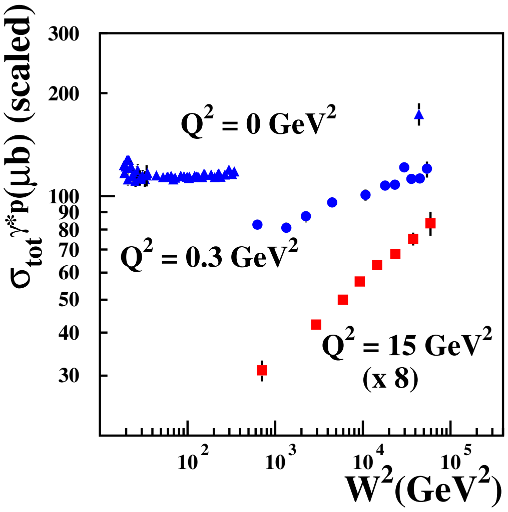

Figure 2. The total $\gamma^* p$ cross section measured at HERA.[1,2]

responds to the increase of the cross section towards high W. An example at $Q^2 = 15\,\mathrm{GeV}^2$ is shown in Fig. 2.

This behaviour of $\sigma_{\mathrm{tot}}^{\gamma^* p}$ is in contrast to that of soft processes, e.g. the total photoproduction cross section, that is, the collision of a quasi-real photon with the proton at HERA. The lack of a hard scale in this process means that it is not possible to resolve partons in the proton. The W dependence of the cross section for this process shows only a slow increase. The size of the slope of the cross section in W is, therefore, considered to be evidence of a hard interaction. Such processes are expected to be described by pQCD. Similar argument can be applied for the centre-of-mass dependence of the cross sections in hadron-hadron collisions, where $\sqrt{s}$ is substituted in place of W.

Once the parton densities in the proton are known, a simple model where the probability to exchange a parton between two incoming particles is proportional to the parton density can be made. The energy dependence of the inelastic and diffractive processes from this model would be the following: the mechanism of the inelastic process for nucleon-nucleon collisions can be modelled by one-gluon exchange (Fig. 3(a)) in the low-x regime. This argument can also be applied for the low-x DIS where the virtual photon can be regarded as a quark-antiquark ($q\bar{q}$) dipole with a long lifetime when it collides with the nucleon. Under this assumption, the cross section behaviour is $\sigma(\sqrt{s}) \propto g(x)$ where $g(x)$ is the gluon density of the nucleon. Similarly, the diffractive process can be regarded as two-gluon exchange (Fig. 3(b)). The cross section behaviour could then be $\sigma(\sqrt{s}) \propto |g(x)|^2$, with a suppression factor of 1/9 to form a colour-singlet state. If the colour is not cancelled between two gluons, which is naïvely expected to be the case in 8/9 of the interactions, the scatter results in a process with a multi-parton interaction (Fig. 3(c)). As the centre-of-mass energy of the scattering increases, the collisions will be increasingly dominated by low-x processes. Therefore, the probability to have two-gluon exchange should increase with $\sqrt{s}$ (or W). Indeed, assuming the inelastic cross section behaves like s^a, the diffractive cross section as well as the multi-parton interaction should increase approximately like s^{2a}. Therefore, the fraction of the cross section attributed to diffraction would increase with energy and may play an important role in understanding the total cross section behaviour of hadron-hadron collisions. In this article, the energy dependence of the diffractive cross sections are reviewed in detail.

It is conceivable that, with such a high density of partons in the nucleon at low x, the probability to exchange a gluon in a nucleon-nucleon crossing at a given impact parameter is close to unity. The probability to exchange three or more gluons could also be sizable. In this case, the colour combination of the multi-gluon state becomes complicated. For example, in the case of three-gluon exchange, an incoherent colour configuration would result in an inelastic multi-parton interaction as in the two-gluon case (Fig. 3(e)). In addition, two of the three glu-

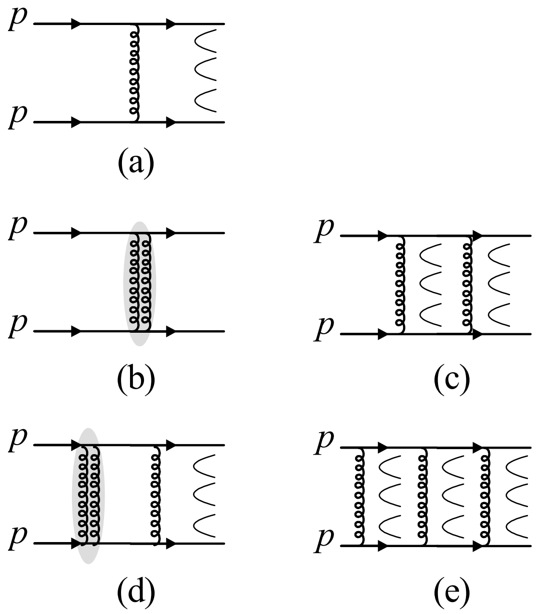

Figure 3. The diagram of the inelastic and diffractive events by multi-parton exchange: (a) inelastic scattering with one-gluon exchange; (b) diffractive exchange by two gluons; (c) inelastic multi-parton interaction by two gluons; (d) diffractive exchange with additional one gluon exchange; and (e) inelastic three-gluon exchange.

ons may form a colour-singlet state while the other is a colour-octet. In this case, the total colour is not neutral and is therefore considered to be an inelastic process (Fig. 3(d)) even though a diffractive state is formed. Thus, the fraction of the diffractive cross section to the total cross section may be suppressed at high energies where the gluon density in the proton is very large. In fact, measurements at the Tevatron shows the suppression of the cross section, in accord with this naïve expectation. This issue is also reviewed in detail below.

The above exercise shows that the two processes, the diffractive process and multi-parton interactions, should be discussed on the same theoretical basis. Both processes, copiously observed at HERA and Tevatron, are lacking a state-of-the-art understanding in terms of pQCD.

3. Inclusive Diffraction at HERA

The main diffractive process at HERA is in electroproduction, and is referred to as diffractive DIS

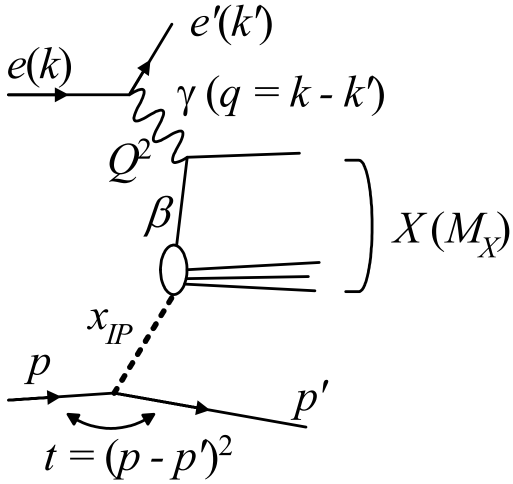

Figure 4. An example of the diagram of the diffractive process in deep-inelastic scattering.

(DDIS). The presence of the hard scale, Q^2, ensures that the virtual photon is point-like and that the photon probes the partonic structure of the diffractive exchange (Fig. 4), in analogy with the inclusive DIS processes. The primary measurement is the determination of the diffractive structure function, $F_2^{D(3)}$, which is derived from the diffractive cross section integrated over t,

$$\int dt \frac{d^4\sigma}{d\beta dQ^2 dx_{\mathbb{P}} dt} \simeq \frac{4\pi\alpha^2}{Q^2}(1-y-y^2/2) \\ \times F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$$

where $\beta = x/x_{\mathbb{P}}$ is the longitudinal momentum fraction of the parton which couples to the photon in the diffractive exchange. $F_2^{D(3)}$ is sensitive to the quark content of the exchange. In order to determine the gluonic content, other processes such as jet or heavy-quark production are used. The gluonic content can also be obtained from the scaling violation of the F_2^D assuming DGLAP evolution.

In this section, three issues relating to F_2^D at HERA are reviewed: hard-scattering factorisation and the universality of the parton densities in the diffractive process; tests of the resolved Pomeron model and the W dependence of the diffractive cross sections.

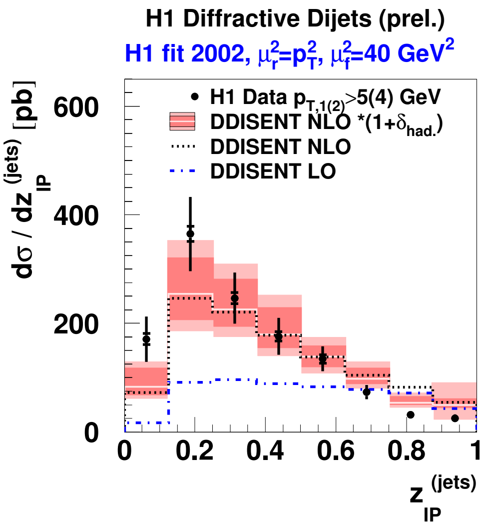

Figure 5. The measured dijet cross section in DDIS in comparison to the NLO calculation DISENT using NLO diffractive parton densities extracted from the H1 data.[5]

3.1. *Factorisation Properties in Diffractive DIS*

For hard QCD processes in general, like high-E_T jet production or DIS, the cross section can be factorised into two terms; the parton density and the hard parton-parton cross section. In the case of DIS, the cross section can be written as

$$\sigma = \sum_i f_i(\xi, \mu^2)\hat{\sigma}_{i\gamma}(\xi, \mu^2)$$

where i runs over all parton types, f_i is the parton density function for the i-th parton with longitudinal momentum fraction ξ, which is probed at the factorisation scale μ. $\hat{\sigma}_{i\gamma}$ denotes the cross section for the interaction of the i-th parton and the virtual photon. Such an expression, often referred to as the QCD factorisation theorem, is well supported by the data. If the theorem holds, only one parton per hadron is coupled to the hard scattering vertex.

The theorem is proven to be applicable also for DDIS,[3] namely

$$\frac{d\sigma(x, Q^2, x_{\mathbb{P}}, t)}{dx_{\mathbb{P}}dt} = \sum_i \int_x^{x_{\mathbb{P}}} dz \times [\hat{\sigma}_{i\gamma}(z, Q^2, x_{\mathbb{P}}) f_i^D(z, Q^2, x_{\mathbb{P}}, t)]$$

where z is the longitudinal momentum fraction of the parton in the proton, $\sigma_{i\gamma}$ is again the hard scattering parton-photon cross section for DDIS and f_i^D is the diffractive parton density for the i-th parton. f_i^D can be regarded as the parton density of the proton under the condition that the diffractive exchange occurs at a given $(x_{\mathbb{P}}, t)$. If such a theorem holds, f_i^D should be universal for all hard processes, e.g. DIS, jet or heavy-quark production etc.. An experimental confirmation of this hypothesis was performed[4] in the following way: first, the diffractive parton densities are obtained from a DGLAP fit to the F_2^D data.[5] The extracted densities are then used in the cross section calculation for a process which is directly sensitive to the gluon density, like jet or heavy-quark production, to check the universality of the diffractive parton densities.

Figure 5 shows a comparison between diffractive dijet production in DIS and the NLO QCD calculations using the parameterisation of the extracted parton densities from $F_2^{D(3)}$. The cross section is shown as a function of $z_{\mathbb{P}}^{(\text{jets})}$, the longitudinal momentum fraction of the partons in the diffractive exchange which participated in the hard scattering reconstructed from the dijet momenta. The prediction provides a good description of the data in both shape and normalisation. This shows that the extracted parton densities are universal, hence the factorisation theorem holds in diffractive DIS. Similar conclusions are obtained from the D^* production data.[4,6]

3.2. *Tests of the Resolved Pomeron Model*

The presence of a LRG in the diffractive processes and the success of Regge theory in describing the diffractive data implies that the exchange is a particle-like state with a long lifetime and has a partonic structure. This hypothesis, called the resolved Pomeron model, assumes factorisation of the diffractive exchange,

$$F_2^D \propto f_{\mathbb{P}/p}(x_{\mathbb{P}}, t) \cdot F_2^{\mathbb{P}}(\beta, Q^2) \qquad (1)$$

where $f_{\mathbb{P}/p}$ is the flux of the "Pomeron" (i.e. the diffractive exchange) and $F_2^{\mathbb{P}}(\beta, Q^2)$ is the structure function of the Pomeron. The Pomeron flux depends only on the kinematic variables of the nucleon-Pomeron vertex, $x_{\mathbb{P}}$ and t.

The validity of this model was examined as follows: Eq. (1) shows that $F_2^{D(3)}$ at a given (β, Q^2) can be written as $b \cdot f_{\mathbb{P}/p}(x_{\mathbb{P}})$ where $b = F_2^{\mathbb{P}}(\beta, Q^2)$ and after integrating over t. This shows that the cross

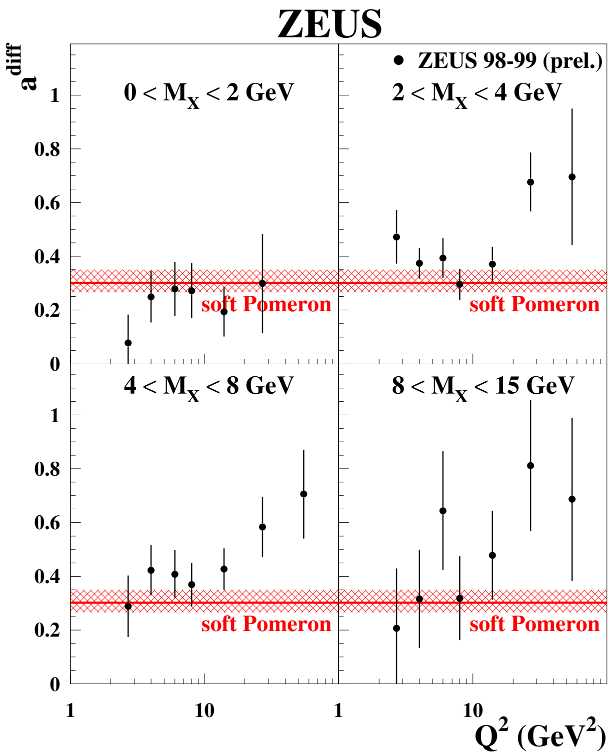

Figure 6. The exponent of the power-like fit $\sigma \propto W^{a_{\mathrm{diff}}}$ on the diffractive cross sections $d\sigma/dM_X$ for four regions in M_X.[7] The horizontal line and the band show the value and error expected from the soft scattering.

section dependence of $f_{\mathbb{P}/p}$ on $x_{\mathbb{P}}$ is the same for any fixed value of (β, Q^2) apart from the normalisation which is given by b. In order to quantify the possible change of shape in $x_{\mathbb{P}}$, the $x_{\mathbb{P}}$ dependence or, equivalently, the W dependence of the cross section for different values of (β, Q^2) are compared by parameterising the flux as a function of $x_{\mathbb{P}}$ or W: $f_{\mathbb{P}/p} \propto x_{\mathbb{P}}^{-a/2} \propto W^a$. Figure 6 shows the parameter a or a_{diff} as a function of Q^2 for different ranges in the diffractive mass, M_X, of the photon dissociation system X. The values are mostly above the expectation from soft scattering, i.e. the dependence of the total hadron-hadron or photon-hadron cross sections. The steeper rise of the diffractive cross sections indicates the onset of pQCD behaviour. In addition, the rise of a_{diff} as a function of Q^2 is seen for $4 < M_X < 8\,\mathrm{GeV}$. This indicates that the flux of the diffractive exchange depends on Q^2, demonstrating the break down of the resolved Pomeron model. This Q^2 dependence is expected from pQCD where the cross section goes as $|g(x,Q^2)|^2$, thus the rise of the cross section with $W \sim 1/\sqrt{x}$ is a function of Q^2, as in the case of inclusive DIS. Note, however, that the violation of the resolved Pomeron model is small.

3.3. *The Energy Behaviour of the Diffractive Cross Sections at HERA*

The rise of the inclusive diffractive cross sections with W at HERA is found to be steeper than that for soft scattering as described above. The rise in W can be further investigated by taking the ratio of the diffractive to the inclusive DIS cross section. The QCD models explain the diffraction process as the exchange of a diffractive state between the nucleon and the $q\bar{q}$ dipole, which originates from a virtual photon. The model with a pure two-gluon exchange, as discussed in Sec. 2, should show a rise, which is approximately twice as fast as that in the inclusive DIS: $\sigma_{\mathrm{tot}} \sim g(x)$ while $\sigma_{\mathrm{diff}} \sim |g(x)|^2$. This is under the assumption that both gluons obey the density probed at the factorisation scale μ^2.

Other types of models, like the semi-classical model[8] and the soft colour interaction model[9] assume that one gluon is probed with μ^2 and another soft gluon neutralises the colour-octet state of the hard gluon. Since the density of the soft gluon is expected to be approximately independent of $\sqrt{s}$ or W, the dependence of the cross section for the diffractive process is similar to the inelastic one: $\sigma_{\mathrm{diff}} \propto g_{\mathrm{hard}}(x) \cdot g_{\mathrm{soft}}(\sqrt{s}) \simeq g(x)$. A similar prediction is made by the saturation model[10] where the soft behaviour of the $\gamma^* p$ cross section at very low Q^2, namely the slow rise with W, is expected to continue up to higher Q^2 than in the inclusive case. In both types of models, the ratio $\sigma_{\mathrm{diff}}/\sigma_{\mathrm{tot}}$ is predicted to be approximately constant in W.

Figure 7 shows the measured ratio $\sigma_{\mathrm{diff}}(Q^2, W, M_X)/\sigma_{\mathrm{tot}}(Q^2, W)$ as a function of W in regions of Q^2 and M_X. The ratio is flat as a function of W except for very low M_X where the ratio decreases with W. The energy dependence of the diffractive process is not steeper than that of the total cross section, in contradiction to the expectation from the two-gluon exchange models. This implies that the two exchanged partons do not have the same property as the hard partons exchanged in the DIS processes. This suggests the presence of soft phenomena in the colour-singlet parton pair.

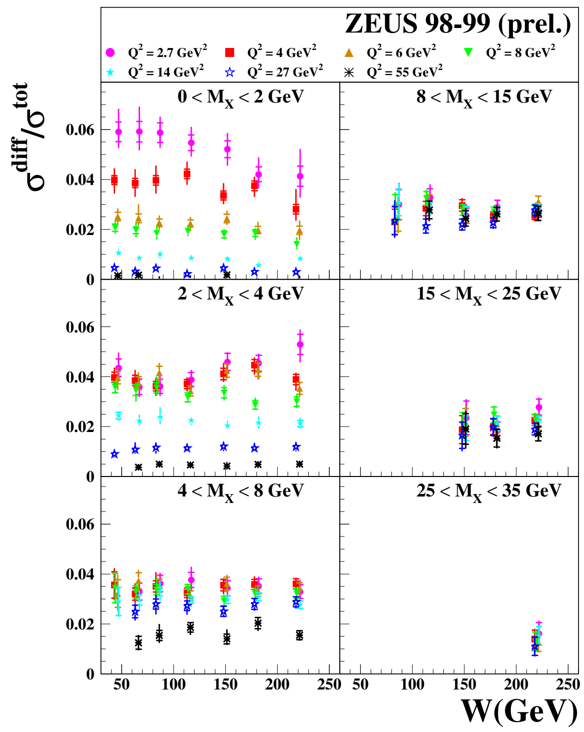

Figure 7. The ratio $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ as a function of W, differentially in Q^2 and W.[7]

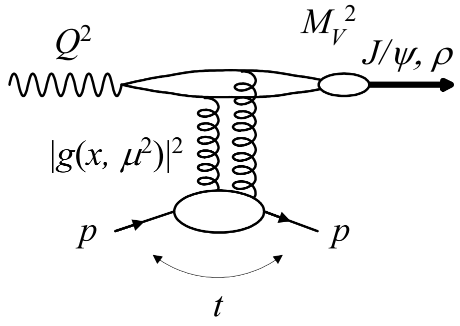

Figure 8. A typical diagram of the pQCD models for vector meson production at HERA.

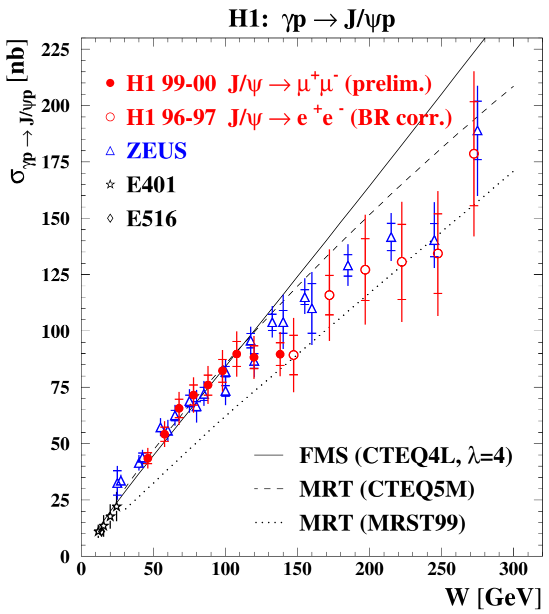

Figure 9. The W dependence of the total cross section of the J/ψ in photoproduction at HERA,[11] in comparison with two theoretical models: FKS[12] and MRT.[13]

4. Vector Meson Production at HERA

Vector meson production in diffractive scattering is part of the inclusive diffraction but with a particular final state. The pQCD models use the same framework: a virtual photon dissociating into a $q\bar{q}$ dipole, exchanging two gluons or a higher order state, then dissociating into a vector meson (Fig. 8).

4.1. *Energy Behaviour of Vector Meson Production*

The cross section is expected to be proportional to $|g(x)|^2$, similar to inclusive DDIS. The energy dependence of the cross section is expected to show a steep rise. Figure 9 shows the cross section for J/ψ in photoproduction at HERA[11] in comparison to pQCD. The different models provide a good description of the rise in W. The power-law parameterisation of the W dependence gives $\sigma \propto W^{0.7-0.8}$, which is close to the value expected from the gluon density at $\mu^2 \simeq 10\,\text{GeV}^2$ given by $M^2_{J/\psi}$. The figure also shows the effect of using different parton densities, indicating that the cross section is sensitive to choice of the densities, in particular the gluon density.

Similar behaviour was also found in the W dependence of deeply-virtual Compton scattering (DVCS)[14,15] where the vector meson is actually a real massless photon. The hard scale of this process is given by Q^2. The measured cross sections at $\langle Q^2 \rangle \simeq 8$ GeV^2 are well described by a $W^{0.8}$ dependence; similar to that observed in J/ψ photopro-

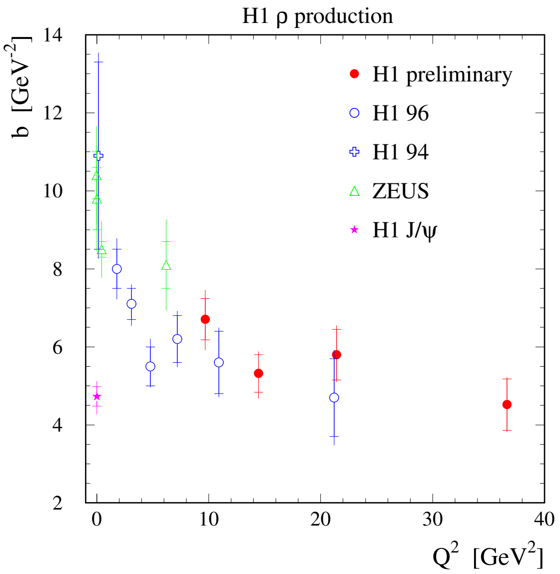

Figure 10. The B-parameter of the momentum distribution of the scattered proton, parameterised as $d\sigma/dt \propto e^{Bt}$, for ρ production at HERA.[16] The values are shown as a function of Q^2. The value from J/ψ photoproduction is also shown.

duction. These two measurements show that vector meson production with a sufficiently large hard scale can basically be understood by the exchange of two perturbative gluons. This is in contrast to inclusive DDIS where the energy dependence indicates the presence of soft physics.

4.2. *Forward Slope in the Vector Meson Production*

The observations described in the previous section imply that the interaction is point-like since it can be described by pQCD. In diffractive scattering, the size of the interaction can be determined from the scattering angle of the outgoing nucleon, measured using either the forward proton spectrometer, or from the final-state particles in case of an exclusive process like vector meson production. Typically the diffractive process shows an exponential fall-off with the transverse momentum of the scattered nucleon like e^{Bt} ($t \simeq -p_T^2$ for $x_{\mathbb{P}} \ll 1$). The value of B indicates the size of the interaction.

The slope was measured for ρ production at HERA[16] as a function of Q^2, as shown in Fig. 10. The slope B is found to be about 10 GeV^{-2} for photoproduction ($Q^2 \approx 0$), where the hard scale is given by neither Q^2 nor the mass of the vector meson. The slope decreases towards higher Q^2 and asymptotically approaches a value of about 4.5 GeV^{-2}. This value of B is similar to the proton radius, meaning that the size of the dipole from the virtual photon is very small. In the case of photoproduction, the size of the dipole is large enough to establish an interaction even if the distance between the photon and the proton is more than twice the size of the proton radius. The B value for J/ψ photoproduction is also similar to the asymptotic value observed in ρ electroproduction. These observations indicate that the interaction is point-like provided a hard scale is present, supporting further the validity of the pQCD description of the data.

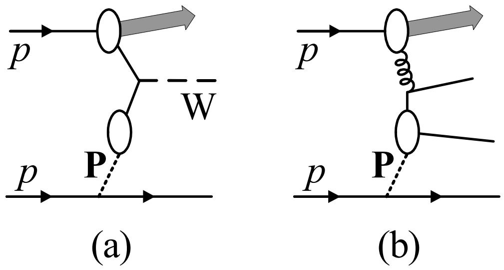

Figure 11. Example of the diagrams of single diffraction at the Tevatron: (a) W production (b) the jet and HQ production. **P** indicates the diffractive exchange.

5. Hard Diffraction at the Tevatron

At the Tevatron, the diffractive process occurs in various combinations of the LRG configuration since the both incoming protons can emit the diffractive exchange. The partonic content of the exchange is mainly studied using single-diffractive processes, where the colour-octet parton emitted from one proton undergoes a hard scatter with the diffractive exchange emitted from the other proton; the partons in the exchange are probed by the colour-octet parton (see Fig. 11).

Various hard processes have been studied in Tevatron Run I data, such as W production (Fig. 11(a)),[17] which is sensitive to the quark content of the exchange, and dijet[18,19] and b-quark production[20] (Fig. 11 (b)), which are more sensitive to the gluonic content.

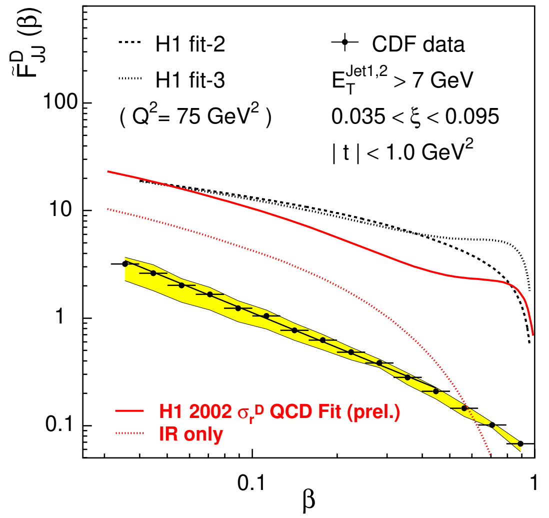

Figure 12. The measured dijet cross section in single-diffractive processes,[18] in comparison with the LO prediction of the cross section using the diffractive PDF's obtained with HERA F_2^D data.[4]

5.1. *Hard Diffraction at the Tevatron from Run I Data and the Factorisation Breaking*

One of the most striking features of the hard diffractive process measured at the Tevatron is a large suppression of the cross section with respect to the prediction based on the diffractive parton densities obtained from the HERA F_2^D data. Figure 12 shows the comparison of the dijet cross section in the single-diffractive process at the Tevatron[18] to the prediction using the parton density parametrisation discussed in Sec. 3.1. Although the prediction reproduces the shape of the data in the low-β region, the magnitude of the cross section is smaller by about a factor 5 to 10. A similar degree of suppression was observed in the other hard diffractive processes.[17−19] This indicates a strong factorisation breaking between HERA and the Tevatron: the diffractive parton densities are not universal between these two environments.

The reason for the breaking is not yet clearly known. It is currently attributed to re-scattering between the two beam remnants where one or more colour-octet partons are exchanged. This destroys the already formed colour-singlet state, as discussed in Sec. 2. The probability to preserve the colour-singlet state is often denoted as the "gap survival probability" S^2, which decreases as the re-scattering cross section increases.

There has been rapid progress in understanding the nature of the re-scattering on the theoretical side. Various attempts have been made in predicting the survival probability S^2: the renormalised Pomeron model,[21] where the Pomeron flux above 1 was renormalised to unity; the estimation of the re-scattering probability from the soft hadron-hadron cross sections;[22] estimating the re-scattering probability from the multi-parton interaction model tuned to Tevatron data;[23] and the soft-colour interaction model,[9,24] where the soft colour exchange between the remnants gives the probabilities of both re-scattering and the formulation of the colour-singlet state. Many of these models attempt to establish a unified understanding of the multi-parton phenomena in both diffractive and multi-parton scattering.

All these models are equally valid since they give a good description of the existing Tevatron data. The model should have, however, an ability to predict S^2 for higher energy reactions like those at the LHC. The predictive power of the models can be tested by comparing with the measurements of various processes that have not been explored so far. Providing such measurements is an important task for the experimentalists. Two examples of such measurements are discussed in the following sections.

5.2. *Factorisation Test with Hard Photoproduced Diffraction at HERA*

The first example is testing of QCD factorisation by looking at the diffractive dijet photoproduction at HERA, where the hard scale is provided by the E_T of the jets. Factorisation is expected not to hold in photoproduction events, where the resolved process has a photon remnant, allowing re-scattering. On the other hand, the direct process does not have a beam remnant and the suppression of diffractive events is expected to be much smaller than in the resolved process.

Figure 13 shows the dijet cross section in diffractive photoproduction as a function of x_γ^{jets}, the longitudinal momentum fraction of the parton that participated in the hard scatter, reconstructed from the dijet momenta. Resolved events dominate in the low-x_γ^{jets} region while the direct process is concentrated at x_γ^{jets} close to one. The cross sections were com-

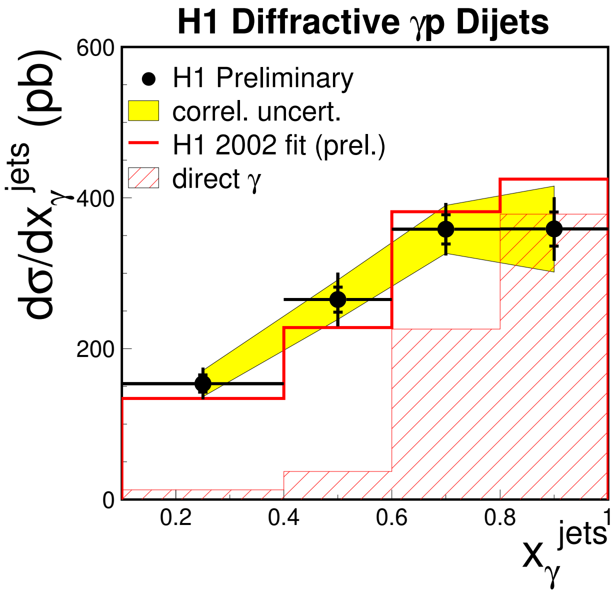

Figure 13. Dijet cross section in photoproduction at HERA[25] as a function of x_γ^{jets}. The solid line shows the prediction from the RAPGAP model.

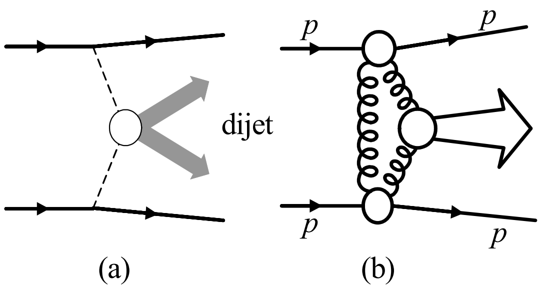

Figure 14. (a) Diagram of the double Pomeron exchange with a dijet in the final state. (b) An example of the pQCD diagram of the double Pomeron exchange with exclusive production.

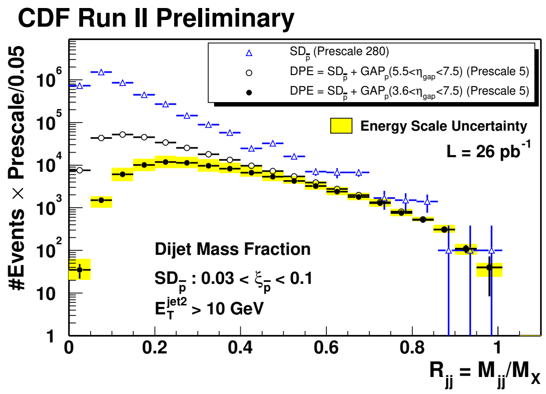

Figure 15. The dijet cross section with two rapidity gaps as a function of $R_{jj} = M_{jj}/M_X$, where M_{jj} is the dijet mass and M_X is the mass of the system X, produced by the fusion of two diffractive exchanges.[26]

pared to the leading-order RAPGAP Monte Carlo. No significant deviation was found from the model in the x_γ^{jets} dependences, implying that the resolved process is not suppressed. Also the magnitude of the cross section is reproduced by RAPGAP when using the diffractive parton densities obtained from the HERA DDIS data. This means that the overall cross sections are not suppressed with respect to DIS, implying that factorisation is not significantly broken between DDIS and photoproduction at HERA. This is in strong contrast to the large suppression observed in the Tevatron data. This measurement should constrain the models of the gap survival probability.

5.3. *Exclusive Dijet Production*

Another example of a newly explored process is the exclusive dijet production through the so-called double Pomeron exchange (DPE) at the Tevatron. This process produces the diffractive dissociative system X through a fusion of two diffractive exchanges (Fig. 14(a)). The system X can then decay into two partons resulting in exclusive dijet production.

This process is of particular interest since the same final state is expected for diffractive Standard Model Higgs production. The system X may produce a light scalar Higgs through a top quark loop, which would then decay mainly into $b\bar{b}$. The cross section is estimated in QCD assuming that the dominant diagram is that shown in Fig. 14(b). The estimation of the cross section of such processes, however, is difficult for the following reasons: (1) the diagram in Fig. 14(b) has a gluon loop, which means that the diagram is not factorisable and hence the diffractive parton densities cannot be used; (2) the cross section may be suppressed by the survival probability S^2. The value of S^2 depends on the details of the process; and (3) initial- and final-state radiation suppress exclusive dijet production. The measurements should help to constrain the model of this process; more specifically, it gives a stringent test of the theoretical framework for estimating diffractive dijet production through the diagram shown in Fig. 14(b).

The exclusive dijet cross section has been measured by the CDF collaboration using the Tevatron Run II data. Prior to the start of Run II, the CDF collaboration has improved many of its forward detectors, which are required for measuring the rapidity gap near the outgoing protons. The cross sections were measured as a function of $R_{jj} = M_{jj}/M_X$, where M_{jj} is the dijet mass and M_X is the mass of the system X produced by the fusion of the two diffractive exchanges. The presence of rapidity gaps are requested at both ends of the system X.

Exclusive dijet production should be concentrated near $R_{jj} = 1$. There is, however, no clear peak found in the R_{jj} spectrum near unity. The region corresponding to the exclusive region was defined as $R_{jj} > 0.8$. The dijet cross section for $R_{jj} > 0.8$ and $E_T^{jet} > 25\,\mathrm{GeV}$ is $34 \pm 5(\mathrm{stat.}) \pm 10(\mathrm{syst.})$ pb. The value gives an upper limit of exclusive dijet production. The smooth transition of the R_{jj} spectrum from the inclusive to the exclusive region suggests that the exclusive process is part of the cross section where the effect of initial- and final-state QCD radiation is small. This data should also play an important role in understanding the cross section for exclusive dijets, which is a background for diffractive Higgs production at the LHC.

6. Data Expected from the Near Future

In addition to the already mentioned detector upgrade in CDF, both the D0 and H1 collaborations are commissioning upgraded detectors for diffractive physics. D0 has installed a forward proton spectrometer system consisting of nine Roman pots. The benefits of the new detector are a very high acceptance also at low $x_{\mathbb{P}}$ (below 0.02) and towards high-t. The initial alignment of the spectrometer has been completed.

H1 has also installed a new system of Roman pots in the proton beamline downstream of the main detector at about 200 m. The pot locations have been optimised so that the acceptance is high for the diffractively produced protons. The spectrometer system indeed has a very high acceptance, typically above 80%, at low-t in the $x_{\mathbb{P}}$ range of the diffractive regime. The pots are installed and ready for commissioning after HERA resumes running after the shutdown, which is expected to start in September 2003.

7. Summary

In this contribution some important aspects of the diffractive process for interpreting diffraction in the framework of pQCD have been reviewed, namely the factorisation properties and the energy dependence of the cross sections. The experimental results can be summarised as follows.

- The resolved Pomeron model is mildly broken, implying that diffractive exchange is not a particle. A framework not based on the Regge theory is clearly necessary.
- The factorisation theorem holds for diffractive DIS. The extracted diffractive parton densities are universal within DIS.
- The energy dependence of vector meson production is as expected from two-gluon exchange models taking the gluon density from the F_2 data.
- The energy dependence of the cross section for inclusive diffractive DIS, however, shows a flat ratio to the total $\gamma^* p$ cross section. This means that the rise of the inclusive diffractive DIS cross section is slower than the expectation of the two-gluon model.
- A large suppression of the hard diffractive cross sections at the Tevatron was observed with respect to the predictions based on the diffractive parton densities obtained at HERA. This implies a strong breaking of factorisation between HERA and the Tevatron. It is attributed to the re-scattering of partons between the two beam remnants.

While the first three items show the success of the pQCD approach, the latter two suggest that calculations based on non-perturbative QCD are necessary for explaining the features observed in the data. Rapid developments have been made on the theoretical side addressing these questions, one of which is the survival probability of the rapidity gap which was reviewed in this article. In order to examine these new ideas, more precise data and new measurements should be provided by the experiments. The high-statistics run of Tevatron Run II and HERA II as well as the improved forward detectors should provide these much needed measurements.

8. Acknowledgments

The author would like to thank K. Goulianos, K. Terashi, C. Royon, P. Newman, M. Arneodo, R. Yoshida, A. Bruni, J. Cole, K. Borras and other members of the four collaborations, CDF, D0, H1 and ZEUS, for valuable discussions and suggestions. The author is also thankful to G. Ingelman, who gave important insight into the soft-gluon exchange models through discussion.

References

1. ZEUS collaboration, S. Chekanov *et al.*, *Phys. Lett.* B **549**, 32 (2002).
2. ZEUS collaboration, S. Chekanov *et al.*, *Eur. Phys. J.* C **21**, 443 (2001).
3. J.C. Collins, *Phys. Rev.* D **57**, 3051 (1998).
4. H1 collaboration, "Measurement and NLO DGLAP QCD Interpretation of Diffractive Deep-Inelastic Scattering at HERA", Contributed paper ♯172 to this Symposium.
5. H1 collaboration, "Measurement of the Inclusive Cross Section for Diffractive Deep-Inelastic Scattering at High Q^2", Contributed paper ♯173 to this Symposium.
6. ZEUS collaboration, S. Chekanov *et al.*, DESY-03-094.
7. ZEUS collaboration, "Deep Inelastic Diffractive Scattering with the ZEUS Forward Plug Calorimeter using 1998-1999 Data", Contributed paper ♯107 to this Symposium.
8. W. Buchmüller, M. McDermott and A. Hebecker, *Phys. Lett.* B **410**, 304 (1997).
9. A. Edin, G. Ingelman and J. Rathsman, *Phys. Lett.* B **366**, 371 (1996); J. Rathsman, *Phys. Lett.* B **452**, 364 (1999).
10. K. Golec-Biernat, M. Wüsthoff, *Phys. Rev.* D **59**, 014017 (1999); K. Golec-Biernat, M. Wüsthoff, *Phys. Rev.* D **60**, 114023 (1999).
11. H1 collaboration, "Elastic Photoproduction of Jpsi Mesons", Contributed paper ♯188 to this Symposium.
12. L. Frankfurt, W. Koepf and M. Strikman, *Phys. Rev.* D **54**, 3194 (1996).
13. A. Martin, M. Ryskin and T. Teubner, *Phys. Rev.* D **55**, 4329 (1997).
14. ZEUS collaboration, DESY-03-059.
15. H1 collaboration, "Deeply Virtual Compton Scattering at HERA", Contributed paper ♯193 to this Symposium.
16. H1 collaboration, "Elastic electroproduction of rho mesons at high Q^2", Contributed paper ♯175 to this Symposium.
17. CDF Collaboration, F. Abe *et al.*, *Phys. Rev. Lett.* **78**, 2698 (1997).
18. CDF Collaboration, T. Affolder *et al.*, *Phys. Rev. Lett.* **84**, 5043 (2000).
19. D0 collaboration, B. Abbott *et al.*, *Phys. Lett.* B **531**, 52 (2002).
20. CDF Collaboration, T. Affolder *et al.*, *Phys. Rev. Lett.* **84**, 232 (2000).
21. K. Goulianos, *Phys. Lett.* B **358**, 379 (1995); K. Goulianos and J. Montanha, *Phys. Rev.* D **59**, 114017 (1995).
22. A.B. Kaidalov *et al.*, *Eur. Phys. J.* C **21**, 521 (2001); E. Gotzman, E. Levin and U. Maor, *Phys. Rev.* D **60**, 094011 (1999);
    A. Bialas and R. Peshanski, hep-ph/0306133.
23. B. Cox, J. Forshaw and L. Lönnblad, hep-ph/0012310; B. Cox, J. Forshaw and B. Heinemann, *Phys. Lett.* B **540**, 263 (2002).
24. R. Enberg, G. Ingelman and N. Tîmneanu, *Phys. Rev.* D **64**, 114015 (2001).
25. H1 collaboration, "Dijets in Diffractive Photoproduction at HERA", Contributed paper ♯170 to this Symposium.
26. CDF collaboration, available on http://www-cdf.fnal.gov/ physics/new/qcd/dpe_run2/dpe_ex_run2.html.

DISCUSSION

Silvia Tentindo-Repond (Florida State University): In Run I of the Tevatron we had diffractive results from CDF and D0 concerning W and Z gauge boson production. What is the status of Run II?

Yuji Yamazaki: Of course there are already data. However, the cross sections are not yet available to the public. W and Z production turned out to be processes where the cross section measurement is very difficult, therefore I imagine it will take time to prepare new results. For example, the uncorrected number of events agrees between the two Tevatron experiments, but they differ at the cross section level. They are working on the cross section result and I believe we will have them soon.