

SUMMARY OF THE DIFFRACTIVE WORKING GROUP AT DIS98

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Recent experimental and theoretical developments in the understanding of high energy diffraction, presented in the working group on diffraction at DIS98 in Brussels, are summarised. A template, giving the definition of the most commonly used kinematical variables in diffraction, which was provided in the working group sessions, is reproduced as an appendix. References to original papers may be found within the individual contributions.

1 Introduction

1.1 Why is diffraction interesting ?

Diffraction combines aspects of particle and wave-like nature of high energy scattering and straddles the interface between short and long distance domains of the strong interaction. Apart from being a very interesting problem in its own right, it is also a useful place to try to understand the transition between reliable, perturbative QCD calculations and the remarkably successful strong

interaction phenomenology of Regge theory. Such an understanding is clearly necessary if one is to ever understand the most difficult and important problem in strong interaction physics: confinement.

Given that a fundamental understanding of this transition is still lacking, progress in this area may be characterised as follows: one investigates what can be understood in the regime of pQCD, extrapolates this hard QCD wisdom into the soft domain, often using experience and intuition gained from soft physics phenomenology, and then confronts the results with the data. This necessarily leads to a strong positive feedback between new experimental results in diffraction and the development and refinement of the phenomenological models. A great deal of experimental and theoretical progress has been made since DIS97 which we wish to summarise here.

1.2 *Physical picture of high energy diffraction*

Peschanski¹ reminded us of a very simple physical picture for diffraction based on an optical model, developed many years ago. Imagine two hadrons scattering at very high energies. Quantum mechanics tell us that each hadron is a complicated evolving superposition of virtual states (at long distances one can think of the proton emitting and reabsorbing pions, etc; at short distances one imagines fluctuations of the partonic structure due QCD radiation). Lorentz contraction of these ultra-relativistic systems ensures that this superposition is essentially frozen on the ‘snapshot’ timescale of the interaction of the two systems, thus each component constitutes an eigenstate of the interaction. Distinct eigenstates will suffer different levels of attenuation in the nuclear medium of the opposite hadron according to their physical characteristics (number of constituents/partons, transverse size etc). As a result the scattered state is different from the beam state and, in addition to elastic scattering, new *exclusive and continuum states* are ‘diffracted into existence’ by the interaction. In such diffractive production there is a large rapidity gap (LRG) between the beam excitation and the target recoil and the energy dependence is similar to that of elastic scattering: in the Regge terminology both elastic scattering and diffractive excitation are governed by Pomeron (vacuum) exchange in the t -channel.

If the Pomeron is an isolated Regge pole with the trajectory $j = \alpha_{IP}(t) \approx \alpha_{IP}(0) + \alpha'_{IP}t$, then diffractive amplitudes are expected to behave as $x_{IP}^{-\alpha_{IP}(t)}$. It would certainly be interesting to relate this rise in energy with that seen in the proton structure function at small- x . The Regge phenomenology of hadronic total cross sections provides a useful reference value

$$\alpha_{IP}^{soft}(0) \approx 1.09. \tag{1}$$

The QCD vacuum singularity seems to be more complex than an isolated pole with an effective Pomeron trajectory that changes with the hardness of the process. Any value larger than that given in Eq.(1) may be considered as evidence for a contribution from hard scattering.

2 Diffraction in deep inelastic scattering

2.1 Inclusive data

The two measurements reported on by Kowalski & Lindemann for ZEUS ² and by Nicholls for H1 ³, regarding the diffractive structure function $F_2^{D(3)}$, are based on two different methods and cover different kinematic ranges. The ZEUS data are analysed in the kinematic range $7 \leq Q^2 \leq 140 \text{ GeV}^2$ and $M_X \leq 15 \text{ GeV}$ and are based on the 1994 data. The diffractive data are obtained from an excess of events over the extrapolated invariant mass distribution at large M_X in generic DIS events. The H1 diffractive data are obtained from events with a large rapidity gap in the forward direction. The H1 diffractive structure function analysis is based on the 1994 data, complemented by the new 1995 shifted-vertex data which covers $0.4 \leq Q^2 \leq 5 \text{ GeV}^2, 0.001 \leq \beta \leq 0.65$, thereby extending the 1994 measurements to lower Q^2 , β and x_{IP} . A comparison of the inclusive $x_{IP}.F_2^{D(3)}$ data of H1, ZEUS and of the ZEUS Leading Proton Spectrometer (LPS) data shows that there is broad agreement, although in the low- Q^2 bins differences are observed. Phenomenological Regge model fits as used previously, based on a Pomeron and Reggeon trajectory describe the H1 data well. The intercept of the trajectories are consistent with the earlier published values and, given the large errors, no evidence is found for a possible dependence of the Pomeron intercept on Q^2 . The scaling violations, observed earlier in $x_{IP}.F_2^{D(3)}(x_{IP} = 0.005)$ of the 1994 data at higher Q^2 , are reconfirmed by the new data at lower Q^2 . The analysis of the data in terms of parton distribution functions subjected to a NLO DGLAP evolution, again indicate that the gluonic content of the Pomeron is of the order of (80-90)% with a gluon distribution which is large at $\beta \sim 1$, in contrast to a much softer gluon content in the proton.

From the ZEUS analysis an intercept of $\alpha_{IP}(0)$ is deduced which agrees with the H1 value obtained from the phenomenological fits of the 1994 data.

$$\alpha_{IP}(0) = 1.16 \pm 0.01 \text{ (stat)} \pm 0.02 \text{ (sys)} \quad \text{(ZEUS)} \quad (2)$$

$$\alpha_{IP}(0) = 1.203 \pm 0.020 \text{ (stat)} \pm 0.013 \text{ (sys)} \quad \text{(H1-'94 data)} \quad (3)$$

This intercept is clearly larger than that of Eq.(1), whereas the Reggeon intercept, obtained by H1, is close to $\alpha_R(0) \approx 0.5$ of standard Regge theory. The

ZEUS results for $x_{IP} \cdot F_2^{D(2)}$ indicate a weak β -dependence and are, within errors, consistent with scaling.

2.2 Models of diffractive DIS

Diffractive occurs in the small- x regime of DIS corresponding to the high energy (Regge) limit of the γ^*p sub-process ($W^2 \gg Q^2, M_p^2$). In the realm of QCD, the multi-parton Fock states of the photon are the natural diffraction eigenstates. At lowest order in α_s these are $q\bar{q}$ pairs: colour dipoles characterised by transverse size, or equivalently impact parameter, and momentum-fraction sharing, z . The dipole scattering amplitudes are proportional to the transverse area occupied by the dipole, hence it is large size configurations which are primarily responsible for diffraction (they also turn out to be asymmetric configurations $z \ll 1$, or $1-z \ll 1$). As the transverse size, or ‘scanning radius’, of the interacting dipoles is decreased one expects a transition from soft to hard diffraction. Genovese⁴ reviewed major applications of the colour dipole picture to diffractive DIS.

Using the predictions of a dipole model approach, based on leading-log BFKL dynamics and the large N_c approximation, Royon⁶ presented fits to the H1 diffractive data, as well as to the F_2 data. Both the proton and virtual photon are treated as a superposition of dipoles and both single and double diffraction are included in terms of elastic onium-proton scattering and a sum of inelastic dipole-dipole scattering. The gross features of the experimental data can be reproduced with relative few parameters, but the applicability of these approximations to diffractive DIS is certainly questionable, due to the large soft contribution to diffractive DIS.

Kopeliovich⁷ discussed how Drell-Yan production, which is usually treated as a $q\bar{q} \rightarrow \gamma^*$ annihilation, can be reformulated in the colour dipole picture as a sort of diffractive excitation of a Fock state of the projectile which contains the γ^* as a constituent. In this way, the similarity between Drell-Yan and DIS processes becomes apparent.

It is useful to focus attention on those (relative rare) diffractive processes which also contain a hard scale, in addition to Q^2 , such as a heavy quark mass or high- p_t pair, to be really sure that we can trust our perturbative calculations. The knowledge gained can then be used to try to build an understanding of the wider picture of diffractive processes. The QCD model for this ‘hard’ diffraction is the exchange of two interacting gluons in a colour-singlet configuration in the t -channel, which dominates the QCD evolution of the proton sea structure function at small x . The diffractive amplitudes are related to the target gluon structure function, $G(x_{IP}, \overline{Q}^2)$, at a process-dependent hardness

scale \bar{Q}^2 . As Schäfer⁵ has discussed, one can similarly view Reggeons as the exchange of colourless $q\bar{q}$ pairs in the t -channel and relate them to the valence quark component of the proton structure function.

In the case of hard diffraction, one calculates the characteristics of diffractive scattering of different dipoles ($q\bar{q}$, $q\bar{q}g$, etc) as a function of β and Q^2 , at fixed x_{IP} , largely by knowing the wavefunctions of the longitudinal and transverse photons. An important finding⁴ from these studies is a strong process dependence of the hardness scale \bar{Q}^2 and a lack of overall Regge factorization into an x_{IP} -dependent flux and a (β, Q^2) -dependent structure function of the Pomeron, apart from the region of small β . Furthermore, the values of \bar{Q}^2 and consequently the x_{IP} - and β -dependence are strongly affected by the presence of the additional hard scale (mass of the heavy flavour, k_{\perp}^2 of jets, etc). For large- β the fluctuation of the longitudinal photon into a $q\bar{q}$ is expected to dominate, even though formally it is higher twist, which is a situation unprecedented in inclusive DIS. Pronyaev⁸ discussed how this pQCD result, which is caused by the interference of diffraction of longitudinal and transverse photons, can be tested by measuring the azimuthal correlation of the (e, e') and (p, p') scattering planes. Moving to intermediate β , the $q\bar{q}$ from the transverse photon becomes increasingly important, whereas for very large masses at small β ($M_X^2 \gg Q^2$) it is likely that higher Fock states, e.g. $q\bar{q}g$ will dominate as the phase space opens up to allow additional radiation.

A recent reanalysis, in this context, involving a sensible extrapolation of this wisdom to the whole of the region covered by the diffractive cross section measurement was presented by Wüsthoff⁹. The diffractive structure function, parametrised as

$$x_{IP}F_2^{D(3)}(\beta, x_{IP}, Q^2) = c_t \cdot F_{q\bar{q}}^T + c_L \cdot F_{q\bar{q}}^L + c_g \cdot F_{q\bar{q}g}^T$$

is fitted to the diffractive data as a 9 parameter function where $F_{q\bar{q}}^T$, $F_{q\bar{q}}^L$ and $F_{q\bar{q}g}^T$ stand for the longitudinal and transverse contributions of the photon Fock states $q\bar{q}$ and $q\bar{q}g$. This expression has been fitted to the H1 and ZEUS diffractive data and is able to describe both data sets well. In the fit to the H1 data, which covers a wider kinematic range, a contribution of secondary Reggeons is also taken into account.

It turns out that the present data do not allow the β -dependence of the quark and gluon distributions in the Pomeron to be fixed uniquely. In one fit the $F_{q\bar{q}g}^T$ contribution dominates the diffractive structure function at low β and falls steeply as $\beta \rightarrow 1$, as preferred by some theorists. At medium and large β , respectively, the transverse $q\bar{q}$ term and the longitudinal $q\bar{q}$ higher twist term are dominant. The observed scaling violations can then be ascribed to

the (Regge-factorization breaking !) Q^2 -dependence of the x_{IP} exponent in the transverse $q\bar{q}$ term. In addition, the H1 data also allow a second solution in which the β -dependence of the F_{qqg}^T contribution is much harder and dominates over much of the β, Q^2 range of the data.

2.3 Are diffractive events universal ?

At the moment the Regge (Ingelman-Schlein) factorization ansatz remains the only tool to relate diffractive cross sections in DIS and hadronic collisions. It is of limited applicability and a better understanding of the consequences of the process-dependent hardness scale \overline{Q}^2 is needed. The related assumption of hard scattering factorization when all diffractive processes are described in terms of universal diffractive parton densities is also questionable because of strong absorption, which goes under the name of Bjorken's gap survival probability, in hadronic hard diffraction.

Whitmore¹⁰ has reported a detailed evaluation of hard diffraction cross sections at the Tevatron (dijets, W-production) based on fits to diffractive DIS but restricted to a subset of the inclusive H1 and ZEUS DIS data, as well as the ZEUS diffractive jet photoproduction data. He concludes from the comparison with the D0 and CDF data that there is a breaking of factorisation for the Tevatron ($p\bar{p}$) results, in line with Bjorken's small gap survival probability. A comparison of predictions for diffractive dijets and diffractive W production will eventually help to pin down the relative quark-gluon contents of the Pomeron.

Schaefer⁵ has reminded us that nuclear shadowing is a yet another observable which is calculable in terms of the diffractive structure function. The NMC data on scaling violations in nuclear structure functions are so accurate that one can evaluate nuclear modifications of the gluon structure functions from the DGLAP evolution analysis reliably. For the deuteron these results imply $\sim 3\%$ shadowing at $x \sim 10^{-4}$, in close similarity to the observed shadowing of the sea. Schaefer finds that if the gluons in the Pomeron carry about the same momentum as quarks and antiquarks, $\langle x_g \rangle \sim \langle x_{q,\bar{q}} \rangle$, then nuclear shadowing of gluons in the deuteron will be $\sim 3\%$ at $x \sim 10^{-4}$, whereas an unacceptably large 10-15% shadowing is found using the super-hard gluonic Pomeron advocated by H1. This apparent contradiction needs to be understood and resolved.

3 Aspects of exclusive production

3.1 Vector meson production: data

The study of diffractive vector meson production at HERA remains a very active research field and is an ideal place to study the transition between hard and soft diffraction. The former is characterised by stronger energy rises, broader diffractive peaks and considerably less shrinkage than the latter. The first observation of the photoproduction of the Υ -family was reported for ZEUS by Bruni¹¹. A cross-section ($\sigma_{\gamma p \rightarrow \Upsilon(nS)p} * BR(\Upsilon(nS) \rightarrow \mu^+ \mu^-)$ for $n = 1, 2, 3$) of ≈ 15 pb has been extracted using the full 95-97 data statistics, the branching ratios $\Upsilon(nS) \rightarrow \mu^+ \mu^-$, an estimate of proton-dissociation, and an assumption of the same relative contributions of $\Upsilon(1S)$, $\Upsilon'(2S)$ and $\Upsilon''(3S)$ states as measured at the Tevatron. In spite of the large scale given by the Υ mass (which should make pQCD prediction reliable), even taking into account the large uncertainties due to the choice of the gluon density, the scale it is sampled at, and the choice of light-cone wavefunction of the vector meson, it turns out that the predictions of a pQCD two-gluon exchange model, which successfully describes the J/ψ production, are about an order of magnitude below the measured cross section. Clearly further developments in both the experimental measurement (reduction of large errors) and theoretical understanding are urgently required.

Monteiro¹² reported for ZEUS on exclusive and proton-dissociative photoproduction of ρ^0 , ϕ and J/ψ mesons at $W \approx 100$ GeV and $0 < |t| < 4$ GeV². Using the Regge formalism and the measured elastic cross-sections, as well as the low- W data and other HERA measurements at low $|t|$, the exchanged Pomeron trajectory could be directly determined up to $|t| \approx 1$ GeV². For the ρ^0 and ϕ production the nominal ‘soft’ (linear) trajectory has been measured with an intercept compatible with Eq.(1). The slope of the trajectory is non-zero, but it is significantly smaller than 0.25 GeV⁻². In contrast, for J/ψ exclusive production, the corresponding trajectory has a much higher intercept *and* its slope is small, compatible with zero, indicative of a small transverse size and a ‘hard’ diffractive mechanism.

Thompson¹³ reported studies of diffractive J/ψ photo- and electroproduction and also photoproduction at high- $|t|$ for H1. For $|t| > 1$ GeV the measured cross-section for proton-dissociative diffraction can be successfully described by a model based on LO BFKL (see also Sec.(7)). New measurements of exclusive electroproduction of the small-size J/ψ confirm the strongly rising W -dependence already seen in photoproduction. The ratio of $\psi(2S)$ to J/ψ production is found to increase from about 0.15 in photoproduction to about 0.5 at $Q^2 \approx 15$ GeV², with large errors. This reflects the increase in hardness of the production scale of $\psi(2S)$ with Q^2 , which is similar in size to the pion, and may reveal important information about the light-cone wave-

functions of these heavy vector mesons.

The diffractive electroproduction of ρ^0 mesons was reported by Clerbaux¹⁴ for H1, Tytgat¹⁵ for HERMES and Kananov¹⁶ for ZEUS (also ϕ mesons). All three experiments measured the ratio $R = \sigma_L/\sigma_T$ from photoproduction up to large- Q^2 production. The Q^2 -dependence of R is consistent with a linear increase up to $Q^2 \approx 0.5 \text{ GeV}^2$, beyond which this strong increase becomes significantly weaker. The quantitative description of this behaviour, which is now well established experimentally, is a challenge to the pQCD based models.

Fredj¹⁷ reported on an interesting contribution to diffractive physics from the L3 experiment at LEP - the measurement of the $\gamma\gamma$ total cross section extending the energy range up to $W_{\gamma\gamma} \approx 130 \text{ GeV}$. Fits to $W_{\gamma\gamma}^{2(\alpha_{IP}(0)-1)}$ give effective Pomeron intercepts, depending on the unfolding method, of $\alpha_{IP}(0) \approx 1.16 \pm 0.03$ (PHOJET Monte Carlo) and $\alpha_{IP}(0) \approx 1.14 \pm 0.02$ (PYTHIA Monte Carlo), in excess of the value in Eq.(1).

3.2 Vector meson production : theory

Zoller¹⁸ presented results on expectations for the forward diffractive slope, B_D , within the framework of the gBFKL dipole model. Three components can be identified coming from the proton, the evolution and from the scattering dipole. As Q^2 increases the dipoles get smaller and the latter makes a smaller and smaller contribution to B_D , supporting the well-established notion that the geometrical size of the scattering objects determines B_D . Unfortunately the current experimental errors from HERA are too big to observe this Q^2 -dependence in J/ψ production yet, but for lighter vector mesons it has been well established experimentally. An approximate flavour independence is observed in the variable $Q^2 + M_V^2$.

The analyses^{14,15,16} of the vector meson production data, under the assumption of the s -channel helicity conservation, give a value for $R = \sigma_L/\sigma_T$ which tends to saturate at large Q^2 , whereas the theoretical estimates predict a steady rise, albeit slower than linear with Q^2 . In the framework of the two gluon exchange model of Low-Nussinov, Royen¹⁹ discussed the sensitivity of R to modifications of the wavefunction of the vector meson with the conclusion that the Fermi motion effects in the wavefunction can tame the growth of R without spoiling other predictions, in the kinematic region defined by the data.

3.3 Off-diagonal kinematics

A particularly active area of research at present concerns non-diagonal or off-forward parton distributions which arise in exclusive diffractive processes such

as heavy vector meson production, deeply virtual Compton scattering (DVCS) and photoproduction of dijets.

Conventional parton distributions involve products of operators sandwiched between identical hadronic states (e.g. *incoming* and *outgoing* protons in the same quantum state). The finite momentum transfer to the proton, in non-diagonal kinematics, means that the outgoing hadron (even if it is a proton) is in a different quantum state. This leads to universal distributions which are given by the quantum-mechanical interference between states characterised by the difference in the momentum fractions carried by the outgoing (x_1) and returning (x_2) partons, $x_{IP} = x_1 - x_2$, and as such probe new non-perturbative information about the proton. A renormalization group analysis of the operators leads to evolution equations, dependent on x_{IP} , which are known only to leading-log in Q^2 , at present. For $x_2 > 0$ they reduce to the DGLAP equations in the limit $x_{IP} \rightarrow 0$. For $x_2 < 0$ they obey ERBL equations for the distribution amplitudes. In the leading $\ln(1/x)$ approximation, at small- x , the non-diagonal distributions coincide with the conventional (diagonal) gluon distributions.

Golec-Biernat²⁰ presented interesting results on diffractive dijet production which showed that the next-to-leading $\ln(1/x)$ corrections for the non-diagonality of the process leads to a marked enhancement of jet production. It would be interesting to see the impact of other non-leading corrections on this finding.

Strikman²¹ presented an analysis of the related off-diagonal DVCS, and pointed out the feasibility of measuring the real part of the DVCS amplitude at HERA, which, via dispersion relations, constrains the behaviour of the imaginary part of the DVCS amplitude, and by extension F_2 , at smaller x -values than those in the HERA kinematic range.

In conventional definitions of parton distributions, after factorization into hard and soft physics, one exploits the optical theorem and treats the ‘soft blob’ (and the hard blob) as though it were on mass-shell (as a result of the cut). By considering the singularity structure of the four-point Green’s function for the soft blob in the non-diagonal case Diehl²² has shown that one may treat the soft part of the diagram *as though it had been cut* and explains some of the important physical implications of this result.

4 Diffractive final states

Various aspects of diffractive final states have been reported by Buniatian²³ and Waugh²⁴ for H1 (energy flow, seagull plot, average charged particle multiplicities, mean multiplicities in the forward/backward hemispheres) and Wich-

mann²⁵ for ZEUS (thrust and sphericity analysis) collaborations. The global features of diffractive final states, i.e. the rapidity and transverse momentum distributions at small k_{\perp} , mean multiplicities and multiplicity distributions, the seagull plot, are similar to those in hadronic collisions, hadronic diffraction, inclusive DIS and e^+e^- annihilation, at the same mass of the hadronic states. Non-trivial differences are found when one looks at the fine structure of final states. The thrust analysis reported by ZEUS is performed on a diffractive event sample selected by the LPS. A comparison of these results with those obtained from the LRG events in H1 indicates that the average event thrust in the ZEUS data is systematically higher although, because of the large errors, not inconsistent with the H1 findings. However, the average thrust in the LRG events is definitely smaller than in the e^+e^- data.

The stumbling block in the interpretation of these data is that the theoretical understanding of initial and final state radiation and of the related virtual radiative corrections to the formation of diffractive final states, is lagging behind the rapid experimental development. The experimentalists have taken the lead and, at the moment, the RAPGAP Monte Carlo, based on the Ingelman-Schlein approach, remains the only tool to describe the resolved Pomeron via partonic densities which are obtained from fits to the H1 $x_{IP}.F_2^{D(3)}$ structure function. The principal finding is that this particular version of RAPGAP describes almost all of the diffractive hadronic final states ranging from energy flow to particle correlations. In terms of this model a large gluonic Pomeron content, as determined from the $x_{IP}.F_2^{D(2)}$ analysis, is essential for a good description of the data, although it should be emphasized that other Monte Carlo's like LEPTO 6.5, based on the soft colour interaction model and which does not contain any special mechanism of diffraction describes the data equally well. At present, the data do not allow a discrimination between these conceptually different models to be made.

From the theoretical point of view one also should take into account that the presently available Monte Carlo models are assuming an illegitimate Regge factorisation, in which hard scale dependencies on x_{IP} and β as found in theoretical QCD analyses, and which characterise the final state, are neglected. For instance, one treats the charm production as entirely due to the familiar photon-gluon fusion, neglecting the direct charm-anticharm excitation which some theorists claim to be substantial. In this approximation, in order to reproduce the diffractive charm signal reported by Thompson¹³ one needs a hard glue in the Pomeron fits¹⁰. Therefore the conclusions drawn from these Monte Carlo studies as to the physical picture underlying the diffractive final states should be handled with care.

5 The Forward Region

In elastic scattering, the typical impact parameter is a sum of the size of the target, the projectile and of the range of interaction between the target and projectile constituents. In the generic diffractive reaction $ap \rightarrow XY$, the diffractive slope B_D is close to the slope of elastic hadronic scattering, $B_d \sim 10 \text{ GeV}^{-2}$ in the exclusive limit of small mass states, $M_{X,Y}^2 \approx \mathcal{O}(M_P^2)$, but the contributions from the $a \rightarrow X$ and $p \rightarrow Y$ transition vertices are known to vanish as soon as X or Y are high mass continuum states, so B_D decreases with the increase of M_X, M_Y . By the same token, only the size of the scattered proton and the interaction range contribute to B_D for single diffraction. Hence one expects a universal value for $B_D \sim 6\text{-}7 \text{ GeV}^{-2}$ in single diffraction for all projectiles a into continuum X (including hadrons, $a = p, \pi, K$, as well as real and virtual photons $a = \gamma, \gamma^*$) in good agreement with the observations. The related universality of the $|t|$ -dependence is to be expected at larger $|t|$, and Meng has presented empirical evidence for that²⁶. Pronyaev⁸ has reported an evaluation of B_D for diffractive DIS $ep \rightarrow e'p'X$ in the colour dipole picture of diffraction; a nontrivial prediction is a substantial rise of the diffraction slope B_D from the exclusive limit $\beta \approx 1$, when X is the 1S vector meson, to excitation of continuum at $\beta \sim 0.5$.

The crucial theoretical point about leading nucleon production for non-diffractive $z \approx 1 - x_{IP} \lesssim 0.9$, and in the fragmentation of protons in general, is that the QCD hardness scale for secondary particles (h) in semi-inclusive DIS, $ep \rightarrow e'Xh$, gradually decreases from Q^2 in the virtual photon (current) fragmentation region to a soft, hadronic, scale in the proton fragmentation region. This suggests a similarity between the inclusive spectra of leading baryons in high energy hadron-proton and virtual photon-proton (DIS) collisions. The standard QCD hadronization models fail in this manifestly soft part of the phase space, but were never really meant to describe it.

The non-perturbative mechanisms - pion exchange for the neutron production and Pomeron+pion+Reggeon exchange for the leading proton production - have been discussed by D'Alesio²⁷ and Nikolaev²⁸, respectively. As has been understood for many years, tagging leading neutrons selects DIS off pions. However, the extraction of the pion structure function at small values of the Bjorken variable $x_\pi = \beta$ requires the knowledge of the flux of pions. D'Alesio focused on the model dependence caused by absorption corrections, which are different for leading neutron production in hadronic collisions and DIS and spoil the Regge factorization leading to an uncertainty of 20 – 30% in the associated normalization between processes (a similar analysis has been reported in²⁸). The conclusion is that absorption effects are under reasonable

control, and do not preclude the experimental determinations of the gross features of the pion structure function. The related absorption corrections define the Bjorken's gap survival probability in hard diffractive pp collisions. The x, Q^2 evolution properties of the leading neutron production as reported by Nunnemann for H1²⁹ and Garfagnini for ZEUS³⁰ are consistent with expectations of the DGLAP evolution of the pion structure function.

The pQCD-motivated evaluation of Reggeon exchange in diffractive DIS has been reported by Schäfer⁵. Reggeon exchange is evaluated in terms of the valence quark distributions in the proton and comes out at the same order of magnitude as the H1 evaluations. In this analysis the strongest possible constructive interference of the Pomeron (IP) and Reggeon f exchanges appears, in contrast to expectations based on treating the Pomeron and Reggeon as hadronic states. Furthermore, he showed that the Pomeron, Reggeon, and the IPf interference structure functions must have a similar large- β behaviour and that the β, Q^2 evolution of all these structure functions must be similar. The latter point leads to an approximately x, Q^2 -independent yield of leading protons. Nunnemann²⁹ reported a good agreement of the H1 data on leading protons with the Pomeron+pion+Reggeon exchange model³¹, whereas LEPTO 6.5 Monte Carlo fails to reproduce the Q^2 -dependence of the observed cross section. In principle, Reggeon exchange is constrained by the diffractive data, but more detailed numerical evaluations of the IPf interference are needed for a unified description of the Reggeon effects in both the diffractive region $z \gtrsim 0.9$, and for $z \lesssim 0.9$.

6 Diffraction in proton-proton scattering

6.1 New data from the Tevatron

Hard diffraction at the Tevatron has been observed by both the DØ (reported by Rubinov³²) and CDF (reported by Borras³³) collaborations. Diffractive events are selected by requiring a large rapidity gap and/or by recording a beam particle recoil. The hard scale is set either by jets with large E_T , or by the mass of a diffractively-produced W-boson (CDF). In hard single-diffraction with a forward rapidity gap the gap fraction, defined as the excess of events at low multiplicity over the extrapolated multiplicity distribution from non-diffractive dijet events, has been measured. The dependence of the gap fraction on η_{boost} and the gap location and size indicates that these events are indeed consistent with a colour singlet production mechanism. The gap fractions measured by the DØ collaboration at two different energies ($\sqrt{s} = 630, 1800 \text{ GeV}$) are of the same order of magnitude ($\mathcal{O}(1\%)$). The jet transverse energy distribution is similar to those of non-diffractive event, indicating that the Pomeron has a

hard partonic structure. Combining the ratio's of diffractive to non-diffractive W and dijet production, the CDF collaboration determined a fraction of hard gluons in the Pomeron equal to 0.7 ± 0.2 . This value entails a momentum fraction of the hard partons in the Pomeron which is consistent with results from the ZEUS experiment only after introducing a discrepancy factor $D = 0.18$ (cf. flux renormalization). Both collaborations also observed events with two central jets and two gaps in the forward rapidity regions, consistent with hard double Pomeron exchange. The rate, $R(\text{DPE}/\text{SD}) = 0.26 \pm 0.05(\text{stat}) \pm 0.05(\text{syst.})\%$, as well as the kinematics of the dijets are well reproduced by Monte Carlo, provided a renormalized IP flux is used.

The fraction of dijet events with a central rapidity gap has been measured by $D\bar{O}$ (reported by Goussiou³⁴) and CDF (reported by Borras³⁵) at $\sqrt{s} = 630$ and 1800 GeV and is found to decrease with the $p\bar{p}$ centre-of-mass energy:

$$R_{D\bar{O}} = \frac{f_{JGJ}(630)}{f_{JGJ}(1800)} = 3.4 \pm 1.3 \quad ; \quad R_{CDF} = \frac{f_{JGJ}(630)}{f_{JGJ}(1800)} = 2.0 \pm 0.9 .$$

The gap fraction dependence on the dijet transverse energy and pseudorapidity separation shows a slightly rising ($D\bar{O}$) / rather flat (CDF) tendency, although the present errors do not allow a clear discrimination. Various Monte Carlo models for colour-singlet exchange have been fitted to the E_T and $\Delta\eta$ dependence of the measured gap fraction by the $D\bar{O}$ collaboration. Assuming that the survival probability of the gap does not depend on E_T and $\Delta\eta$, the data favour quark-initiated colour-singlet processes.

6.2 A resolution to Dino's paradox ?

It is well known that the bulk of elastic and total hadronic cross section data can be described by the exchange of a soft Pomeron pole with an intercept greater than one. Goulianos has pointed out that if one puts this Pomeron into the triple Regge formula, which results from factorization of the Regge pole, and fixes the normalization based on the FNAL-ISR data, then it overshoots the diffractive $p\bar{p}$ Tevatron data by a factor of 5-10 (this has become known as "Dino's paradox"). Clearly the classical Pomeron flux factor must be modified in some way to account for this and various modifications have been suggested. Tan³⁶ points out that in the Tevatron data the rapidity gap is such that the exchanged Pomerons are in a moderate energy regime. In the conventional Donnachie-Landshoff fits to total cross section, $\sigma_{tot} = \sigma_{IP} s^{\Delta_{IP}} + \sigma_R s^{\Delta_R}$, with an s -independent Δ_{IP} , the Reggeon exchange contribution is numerically very large. Tan has emphasized that because in pp scattering there are no s -channel resonances, such a large Reggeon contribution is in conflict with duality and exchange degeneracy ideas, according to which pp total cross section

must involve pure Pomeron exchange. Hence, in the moderate energy region relevant to the rapidity gaps in the Tevatron diffractive data, the intercept of the Pomeron must be close to unity, which removes the rapid growth of the triple Regge cross section from the FNAL-ISR to Tevatron and resolves Dino’s paradox. Tan has discussed flavouring - the effect of opening new inelastic channels - as the mechanisms for the energy dependent intercept of the Pomeron. Tan’s mechanism can be confirmed or ruled out at LHC.

At present, theory is not able to meet the challenge of the extremely interesting data on hard jet production in rapidity gap events observed in many jet and W -boson production channels, at the Tevatron. Bjorken’s point that absorption effects strongly affect the gap survival probability has been reiterated by Whitmore¹⁰, who has presented evaluations for diffractive jet and W -production for different parton model parameterizations of the H1-ZEUS diffractive structure functions based on the Regge factorization assumptions. In all the cases such estimates overshoot the observed cross sections, which testifies to the importance of absorption. Whitmore’s results show that the gap survival probability varies substantially from one hard diffractive reaction to another, the theoretical understanding of these variations is, as yet, lacking.

7 Superhard diffraction and BFKL dynamics

The evolution with energy (or $1/x$) of the cross section for scattering of two small objects of similar size, i.e. Mueller’s “onia”, also called the single-hard-scale problem, remains one of the most intriguing and difficult problems in perturbative QCD. Fadin³⁷ and Lipatov have presented corrections, next-to-leading in energy, to their famous BFKL equation; these subleading corrections are very large and reduce the strong rise in energy of hard cross sections, of the leading-order result. In view of this, it is vitally important that the experiments continue their efforts to measure hard small- x processes.

Cox³⁸ and Forshaw have suggested looking at double dissociation in photo-production (DDP) at high $|t|$, as an alternative to the traditional gaps-between-jets measurement. The latter has several distinct disadvantages: the demand for high enough p_t in the jets (typically $p_t^2 = 25 \text{ GeV}^2$) reduces statistics and diminishes the available rapidity space (the jets themselves occupy as much as two units in rapidity each and must be seen in the main detectors); one also relies strongly on being able to measure the size of the gap accurately (which in practice also requires an experimental definition). In contrast DDP at high $|t|$ which merely uses the gap to separate the two systems X and Y (following the H1 method), has a much wider reach in rapidity (or energy) and may be relevant to $|t|$ values as low as 1 GeV^2 . Monte Carlo studies, using HERWIG,

suggest that this measurement is a robust measure of *whatever the energy rise of the process is*. It will certainly be interesting to see the first data.

Appendix - Diffractive DIS: Convention Summary

Inclusive DIS

Lorentz-invariant variables

$$\begin{aligned}
Q^2 &\equiv -q^2 = -(k - k')^2 \\
W^2 &\equiv (p + q)^2 = M_p^2 + 2p \cdot q - Q^2 \approx 2p \cdot q - Q^2 \\
x &\equiv \frac{Q^2}{2p \cdot q} = \frac{Q^2}{W^2 + Q^2 - M_p^2} \approx \frac{Q^2}{W^2 + Q^2} \\
S &\equiv (p + k)^2 = M_p^2 + 2p \cdot k + m_e^2 \approx 2p \cdot k \\
y &\equiv \frac{2q \cdot p}{2k \cdot p} = \frac{W^2 + Q^2 - M_p^2}{S - M_p^2} \approx \frac{W^2 + Q^2}{S} \approx \frac{Q^2}{xS}
\end{aligned}$$

Diffractive Processes

In a general **doubly-dissociative diffractive (DD)** process the final state consists of fragments of the photon (X) and of the proton (Y) with a large rapidity gap $\Delta\eta$ (see Figure on page 17).

- Diffractive variables (Eilat convention)

$$\begin{aligned}
t &\equiv (p - p')^2 = M_p^2 + M_Y^2 - 2p \cdot p' \\
M_X^2 &\equiv (p - p' + q)^2 \\
x_{IP} &\equiv \frac{(p - p') \cdot q}{p \cdot q} = \frac{M_X^2 + Q^2 - t}{W^2 + Q^2 - M_p^2} \approx \frac{M_X^2 + Q^2 - t}{W^2 + Q^2} \\
\beta &\equiv \frac{Q^2}{2(p - p') \cdot q} = \frac{x}{x_{IP}} = \frac{Q^2}{M^2 + Q^2 - t}
\end{aligned}$$

- Pseudorapidity interval between the fragments X and Y

$$\Delta\eta \approx \log \frac{1}{x_{IP}} \frac{M_Y^2}{M_p^2}.$$

A **singly-dissociative diffractive (SD)** process is a special case in which Y is a proton and

$$M_Y^2 = p'^2 = M_p^2$$

- At HERA $t \leq 1 \text{ GeV}^2$, and can be neglected in the above expressions for β, x_{IP}
- $t \approx -p'_\perp{}^2$ with the transverse plane perpendicular to that defined by the incoming (p, γ^*) in the centre-of-mass frame
- The angular-averaged SD diffractive cross section can be decomposed as

$$Q^2 y \frac{d^4 \sigma(ep \rightarrow ep'X)}{dQ^2 dy dM_X^2 dt} = \quad (4)$$

$$\frac{\alpha_{em}}{\pi} \left\{ \left(1 - y + \frac{y^2}{2}\right) \cdot \frac{d^2 \sigma_T(\gamma^* p \rightarrow p'X)}{dM_X^2 dt} + (1 - y) \cdot \frac{d^2 \sigma_L(\gamma^* p \rightarrow p'X)}{dM_X^2 dt} \right\}$$

- Diffractive structure functions (H1/ZEUS convention)

$$x_{IP} F_2^{D(4)}(t, x_{IP}, \beta, Q^2) = \quad (5)$$

$$\frac{Q^2}{4\pi^2 \alpha_{em}} \cdot \left\{ \frac{x_{IP} d^2 \sigma_T(\gamma^* p \rightarrow hX)}{dx_{IP} dt} + \frac{x_{IP} d^2 \sigma_L(\gamma^* p \rightarrow hX)}{dx_{IP} dt} \right\}$$

$$x_{IP} F_L^{D(4)}(t, x_{IP}, \beta, Q^2) = \frac{Q^2}{4\pi^2 \alpha_{em}} \cdot \frac{x_{IP} d^2 \sigma_L(\gamma^* p \rightarrow hX)}{dx_{IP} dt}$$

- Parameterizing the t -dependence by the diffractive slope B_D :

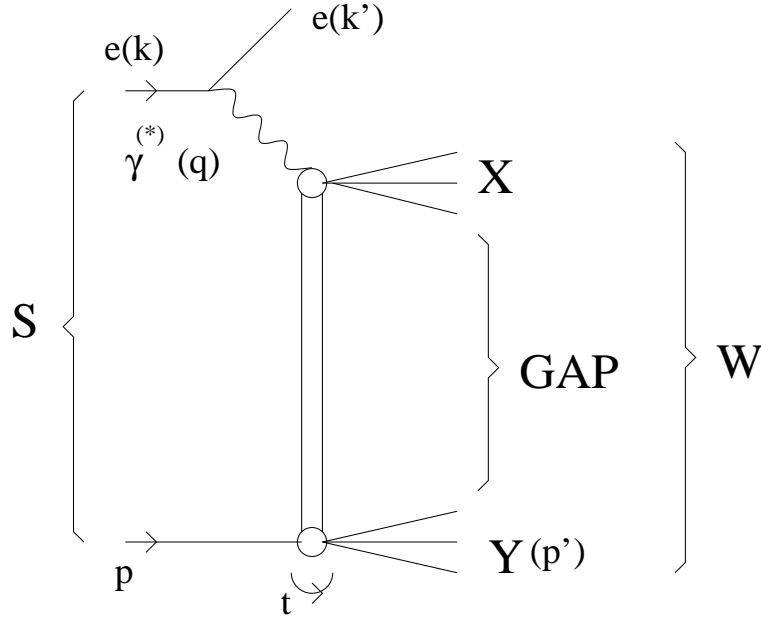
$$F_2^{D(4)}(t, x_{IP}, x, Q^2) \approx F_2^{D(4)}(0, x_{IP}, x, Q^2) \exp(B_D t)$$

where B_D can depend on x_{IP}, β, Q^2 .

- The t -integrated diffractive structure functions

$$x_{IP} F_i^{D(3)}(x_{IP}, \beta, Q^2) = \frac{Q^2}{4\pi^2 \alpha_{em}} \int dt \frac{x_{IP} d^2 \sigma_i(\gamma^* p \rightarrow Xp')}{dx_{IP} dt} \quad (6)$$

- **Exclusive singly-dissociative diffractive (ESD)** (or elastic) vector meson production is an exclusive limit of SD in which Y is a proton and X is a vector meson, $M_X = M_\rho, \dots, M_Y$.
- **Exclusive doubly-dissociative diffractive processes (EDD)**: X is a vector meson, $M_X = M_\rho, \dots, M_Y$ and the proton excites into nucleon resonances and/or continuum states Y .



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