Two Issues in Diffractive Physics at HERA

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Abstract. A recently proposed formulation of generalised vector dominance applicable to light vector meson electroproduction is introduced. Various models of inclusive diffractive deep-inelastic scattering are surveyed, common features discussed and differences highlighted.

This contribution concerns two phenomenological issues in diffractive ep physics that were discussed at the workshop. Section 1 summarises the talk given by D. Schildknecht, in which recent developments in the description of vector meson electroproduction using generalised vector dominance (GVD) were described. Section 2 reports on the present status of a number of models of inclusive deep-inelastic diffractive scattering. At the workshop, talks were given on this topic by J. Bartels, T. Gehrmann, and H. Kowalski.

1. Vector Meson Electroproduction

1.1. Survey of Present Status

A recent review of the large volume of vector meson data obtained by the HERA experiments and explanation of the kinematic variables used can be found in [1]. A complete model of vector meson production at HERA should be able to reproduce the recent observations of increasingly strong energy dependences as hard scales such as Q^2 or the vector meson constituent quark masses increase [2–4], the weakening Q^2 dependence of the longitudinal to transverse cross section ratio R as Q^2 increases [2, 3] and the s-channel helicity non-conservation demonstrated for the ρ and ϕ mesons at large Q^2 [2, 5].

Many authors have attempted to understand the parton dynamics of vector meson production using perturbative QCD [6, 7]. Where hard scales are available, many features of the data can successfully be reproduced in this way. However, there are still large uncertainties, notably those due to the ignorance of the effects of the vector meson wavefunction [3].

In the absence of a complete perturbative QCD description, the phenomenology of soft hadronic physics is often used to parameterise the kinematic dependences of the data. The centre of mass energy dependence is usually considered in the language of Regge theory in terms of the t-channel exchange of an “effective pomeron trajectory”.

The dependence of the cross section on Q^2 can be described using GVD [8]. Naively, both QCD and GVD predict a linear rise of R with Q^2 and often s-channel helicity conservation is assumed. However, recent models of both types [7,9] have been able to reproduce the HERA measurements. The vector dominance approach is described in more detail here.

1.2. A Vector Dominance Based Approach

In the vector dominance model [10], the photoproduction cross section is obtained by considering the fluctuation of the photon into the vector meson series ρ, ω, $\phi \ldots$, which then interact hadronically with the nucleon. In GVD [8], this vector meson series is extended to include more massive vector states, which become particularly important at non-zero Q^2. GVD can thus be used to relate vector meson electroproduction cross sections to those in photoproduction [11].

In a new formulation of GVD applicable to exclusive vector meson electroproduction [9], off-diagonal contributions are considered, where the photon fluctuates into an intermediate vector state V', which then collapses into the final state vector meson V during or after the interaction with the proton. When the off-diagonal contributions are included, the expressions [11] for the forward vector meson production cross sections are modified in a manner that can be approximated simply by introducing effective transverse and longitudinal masses $m_{V,T}$ and $m_{V,L}$ for the vector meson. The resulting transverse and longitudinal forward cross sections $\mathrm{d}\sigma_{T,L}^{\gamma^* p \to Vp}\left(W^2, Q^2, t=0\right)/\mathrm{d}t$ are then given by the photoproduction cross section $\mathrm{d}\sigma^{\gamma p \to Vp}\left(W^2, Q^2=0, t=0\right)/\mathrm{d}t$ multiplied by factors dependent on Q^2, $m_{V,T}$, $m_{V,L}$ and the ratio ξ_V of imaginary forward scattering amplitudes for longitudinal to transverse vector mesons [9, 12]. In order to make comparisons with the t-integrated cross sections that are measured at HERA, a simple exponential term e^{bt} is introduced, with the slope parameter b presently taken to be independent of Q^2 and equal for the transverse and longitudinal photon components.

Fits have been performed to ZEUS and H1 data on the Q^2 dependence of the total ρ and ϕ cross sections and the ratio R of longitudinal to transverse photon induced cross sections. The results [9] are shown in figure 1 for two different fits. In the first (solid lines), there are four free parameters, corresponding to $m_{V,T}^2$, $m_{V,L}^2$, ξ_{V} and the total vector meson cross section at $Q^2 = 0$. A reasonable description is obtained. When the number of free parameters is reduced to two (dashed lines) by fixing $\xi_V = 1$ and $m_{V,L}^2 = 1.5\ m_{V,T}^2$ (such that $R \to 5.5$ as $Q^2 \to \infty$), a comparable χ^2 is obtained, though the high Q^2 values of R are better reproduced.

Importantly, this model is able to reproduce the non-linearity of the dependence of R on Q^2 and in principle can also predict the observed violation of SCHC. The next steps in its development may be to introduce variations with Q^2 of the slope parameter b and of the W dependence of the cross section, both of which are experimentally observed [2,3]. The latter can in principal be generated through the off-diagonal contributions.

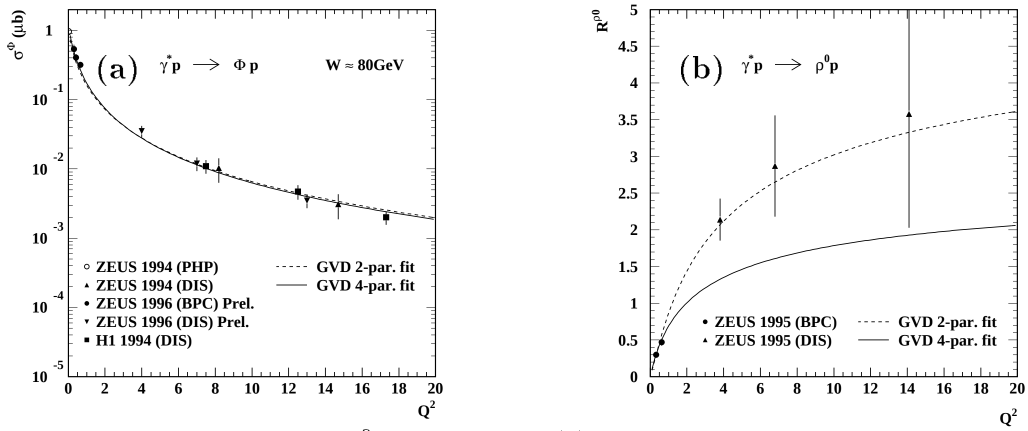

Figure 1. The Q^2 dependence of (a) the total ϕ production cross section and (b) the ratio $R = \sigma_L/\sigma_T$ for ρ production. In both plots, ZEUS and H1 data are compared to the results of two fits based on the GVD model.

2. Diffractive Deep-Inelastic Scattering

There are now copious HERA data on the diffractive contribution to the total $\gamma^* p$ cross section (usually presented in the form of a t-integrated diffractive structure function $F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$ [13,14] †) and on the properties of diffractively produced hadronic final states [15–18]. A number of models of diffractive DIS have been developed, which are usually based on a mixture of perturbative QCD and the phenomenology of soft hadronic interactions. Many of these models have much in common. In this section, some of the more popular models are introduced, similarities between them are identified and, where appropriate, major differences are highlighted.

2.1. Factorisable Pomeron Models

Often referred to as the 'Ingelman-Schlein' model, the first approach used to describe diffraction at HERA was to consider the exchange of a conventional pomeron trajectory from the proton, with deep-inelastic scattering taking place from a distinct set of parton distributions for the pomeron. This physical picture leads to the factorisation hypothesis [19]

$$F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}}) = A(\beta, Q^2) \left(\frac{1}{x_{\mathbb{P}}}\right)^{2\alpha_{\mathbb{P}}(\langle t \rangle)-1} , \qquad (1)$$

where $\alpha_{\mathbb{P}}(\langle t \rangle)$ is the t-averaged value of the effective pomeron trajectory describing the process and $A(\beta, Q^2)$ is proportional to the structure function of the pomeron.

Throughout most of the (β, Q^2) region studied, equation 1 is found to be valid at the present level of experimental precision. However, the value of $\alpha_{\mathbb{P}}(\langle t \rangle)$ is found to be larger than that expected from consideration of the 'soft' pomeron characterising diffractive and total cross sections in hadron-hadron and photoproduction interactions [20]. The simple $x_{\mathbb{P}}$ factorisation of equation 1 has been found [13] to break down at

† For definitions of $F_2^{D(3)}$ and the kinematic variables used to discuss diffraction, see for example [13,14].

large $x_{I\!P}$ and small β, an effect which is usually attributed to the exchange of sub-leading Regge trajectories, in addition to the pomeron.

Within this simple picture, analysis of $A(\beta, Q^2)$ using the DGLAP equations leads to the extraction of a set of parton distributions for the pomeron. Several authors have extracted parton distributions by this method that are found to be dominated by gluons carrying large fractions of the exchanged momentum (e.g. [13, 17]). The results of one such fit are shown in figure 2a. Models based on the extracted parton distributions are found to reproduce well the measured features of the hadronic final state in diffractive events [15–18].

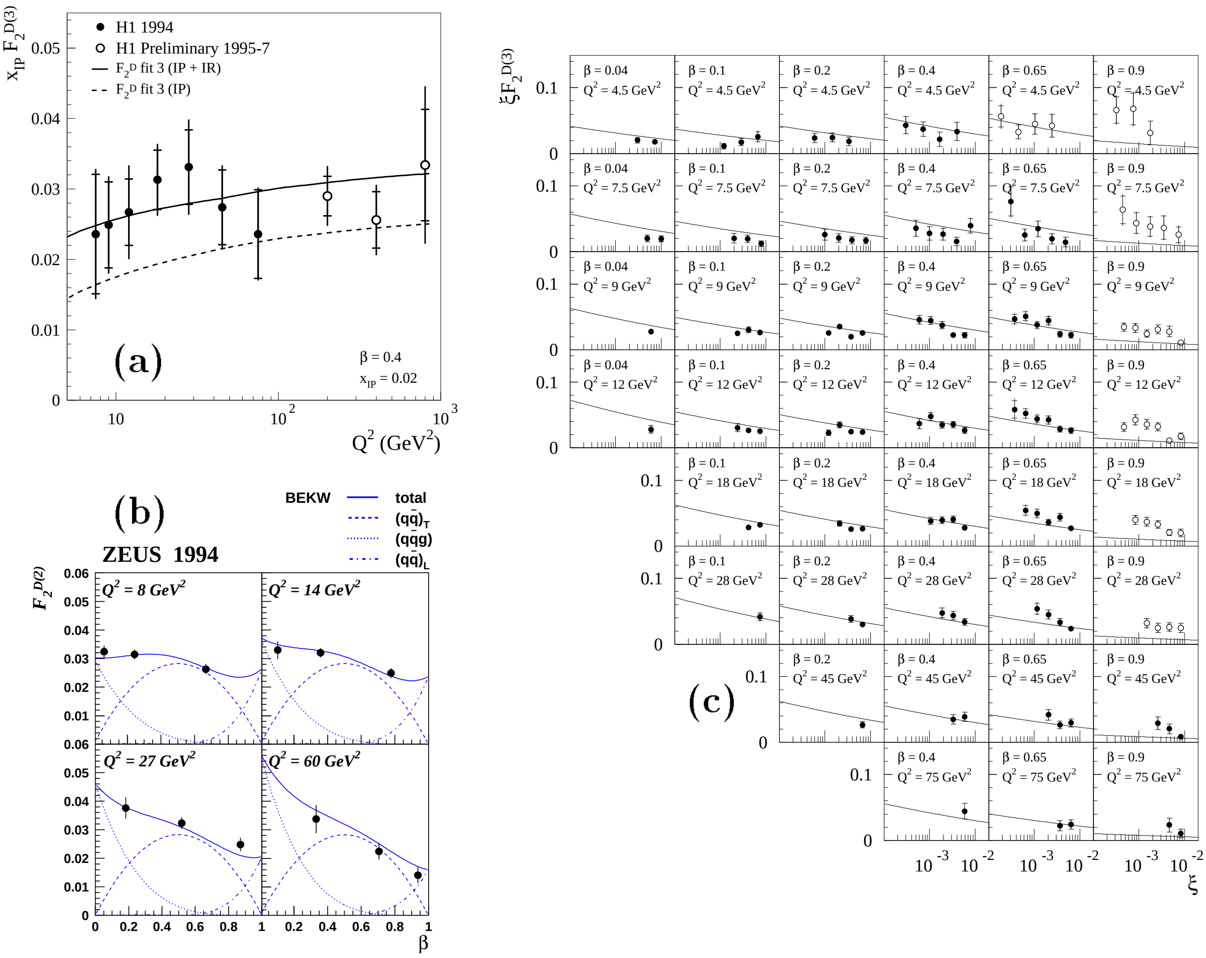

Figure 2. (a) H1 measurement of the Q^2 dependence of $x_{I\!P} F_2^{D(3)}$ at $\beta = 0.4$ and $x_{I\!P} = 0.02$. The results of a DGLAP fit to the data with $Q^2 < 75$ GeV^2 are also shown. In order to avoid regions in which higher twist contributions are likely to be important, data with $\beta > 0.6$ or $M_X < 2$ GeV are not considered in the fits. (b) The β dependence of F_2^D at various Q^2 values and $x_{I\!P} = 0.0042$, as measured by ZEUS. Fits based on the three component parameterisation of [21] are superimposed. (c) H1 measurements of $F_2^D(\xi, \beta, Q^2)$ where $\xi \equiv x_{I\!P}$, compared to the results of a combined fit to F_2 and F_2^D data using the semi-classical model. The open points lie in the region $M_X < 2$GeV where higher twist effects are likely to be important. They are excluded from the fit.

2.2. Dipole Models

It is often informative to think of diffractive $\gamma^* p$ scattering in the proton rest frame. In this frame, the interaction proceeds via a $\gamma^* \to q\bar{q}$ splitting well in advance of the target. The $q\bar{q}$ colour dipole may or may not develop further into a higher multiplicity partonic system before scattering diffractively from the proton.

The attractive feature of this approach is that the $q\bar{q}$ splitting of the photon is calculable using only QED. Though the $q\bar{q}g$ wavefunction of the photon is not yet fully calculated, for most purposes it can be approximated by a dipole consisting of a $q\bar{q}$ colour octet and a gluon [21]. A model for the diffractive interaction of the dipole with the proton is still required, though many properties of the final state (in particular the β distribution [21]) can be derived from the partonic wavefunctions of the photon alone.

The cross sections for the interaction of the dipole with the proton should be applicable not only to diffractive dissociation, but also to elastic and total $\gamma^* p$ cross sections. The dipole based approach allows the separate consideration of longitudinal and transverse photon contributions. Importantly, it can also take account of higher twist contributions such as the elastic production of the vector meson series ρ, ω, ϕ ....

2.3. A Model Based on the Exchange of Gluon Pairs

The simplest way to generate a net colour singlet exchange at the parton level is through a pair of gluons with opposite colour charges [22]. Approaches based on the exchange of perturbative or non-perturbative gluon pairs can be found in [21, 23].

In a recent parameterisation [21], leading and higher twist contributions from transverse and longitudinal polarised photons are all considered. The β and Q^2 dependences are derived from the $q\bar{q}$ and $q\bar{q}g$ photon wavefunctions and the two gluon exchange to the proton. The energy dependence of the gluon pair is not predicted and the $x_{I\!P}$ dependence is thus parameterised in a form similar to that of Regge asymptotics, the effective pomeron intercept being allowed to vary weakly with Q^2.

Three terms in the model are found to give significant contributions in the region of moderate Q^2. The production of $q\bar{q}$ final states from transversely polarised photons $(q\bar{q})_{\rm T}$ leads to a contribution approximately symmetric in β. At low β, the $q\bar{q}g$ states produced by transversely polarised photons $(q\bar{q}g)_{\rm T}$ become dominant, despite being $\alpha_{\rm s}$ suppressed. At high β and low Q^2, $q\bar{q}$ final states arising from longitudinally polarised photons $(q\bar{q})_{\rm L}$ are important. This contribution is formally higher twist and thus contains a $1/Q^2$ suppression factor.

Fits have been performed to the H1 and ZEUS data in which free parameters define the normalisations of the three main contributions, the speed with which the $q\bar{q}g$ contribution dies with increasing β and the exponents of the $x_{I\!P}$ dependences for the leading and higher twist contributions. Figure 2b shows an example fit using ZEUS data [14] and the decomposition of the data into the three components. The data are well described, notably even in the high β region where the higher twist contributions are expected to be present.

This model represents the first serious attempt to describe diffractive DIS beyond the leading twist level. In the future, it is hoped that DGLAP evolution of the gluon distribution in the proton can be incorporated.

2.4. A Semi-Classical Model

In [24, 25], a semi-classical model of the diffractive dipole-proton scattering was developed. The partonic fluctuations of the photon scatter from a superposition of colour fields of the proton according to a simple non-perturbative model that averages over all colour field configurations. All resulting final state configurations contribute to the inclusive proton structure function $F_2(x, Q^2)$. Those in which the scattered partons emerge in a net colour-singlet state contribute to the diffractive structure function F_2^D.

The forms of the diffractive and inclusive cross sections can be re-expressed as more conventional convolutions of parton distributions and parton cross sections [25]. The higher order corrections in the model have been shown to be equivalent to the leading logarithm corrections in a conventional parton approach, such that the usual DGLAP evolution equations can be used. The relevant variables for the evolution are β and Q^2 in the diffractive case [26].

In [27] fits are performed in which the semi-classical method is used to obtain initial inclusive and diffractive parton distributions at some low scale Q_0^2, which are then evolved to higher Q^2 using the DGLAP equations. Remarkably, the simultaneous description of both F_2 and F_2^D can then be reduced to a four parameter fit, which is performed to H1 [13,28] and ZEUS [14,29] data. Three of the free parameters correspond to Q_0^2, the average field strength and the target size. The fourth expresses the strength of the energy dependence of the colour field averaging procedure, which cannot be fully predicted in the model.

At sufficiently small x, the energy dependence of F_2^D factorises from the dependence on β and Q^2. The rise of F_2 and F_2^D at low x are explained as being due to the same non-perturbative energy dependence of the averaging of the soft colour configurations in the proton. The results for F_2^D from the best fit are compared to H1 data in figure 2c. Except in the excluded region, the description of the data is reasonable.

2.5. Prospects for the Future

The parton level dynamics of diffractive DIS are probably rather complicated, with a variety of distinct contributions, some of which are higher twist. It is clear that there are large areas of overlap between the various models on the market. For example, the dipole wavefunctions of the photon are commonly used and links have been established between the leading twist contributions in the dipole approach and the parton distributions in factorisable pomeron models. The treatment of the diffractive exchange to the proton, which is dominated by soft contributions, is the main area in which the models differ. Comparative analysis of the different approaches to this aspect of the problem would help to determine which are the more successful models.

As well as the inclusive diffractive DIS cross section, most available models can also predict various features of the hadronic final state. Charm [16] and dijet [17, 18] production measurements are particularly sensitive to the role of gluons in diffraction. In order to make hadron level comparisons of the models with final state measurements, it is imperative that the implementation of the models in the Monte Carlo generators used by the HERA experiments is kept up to date.

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