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A theoretical Overview on Single Hard Diffraction

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The concept of the Pomeron structure function and its application in Single Hard Diffraction at hadron colliders and in diffractive Deep Inelastic Scattering is critically reviewed. Some alternative approaches are briefly surveyed with a focus on QCD inspired models.

1 Introduction

Single Diffraction has been investigated along with elastic scattering throughout all hadron collider experiments. It was only a question of time, the increase of energy and the capability of jet-finding that jets were discovered in diffractive events (Single Hard Diffraction). The diffractive production of jets was at first observerd by UA8[1]. At the present time similar measurments are carried out at the Tevatron including the diffractive production of W's.

Large rapidity gap events in Deep Inelastic Scattering (or diffractive DIS) form another group of events associated with Single Hard Diffraction. The required hardness in this case is provided by the virtuality of the photon. It is crucial for theoretical considerations that the hard part of the process appears in the initial state and not in the final state as in hadron collisions. The popularity of Single Hard Diffraction has strongly increased with the start of HERA where diffractive events occur as an excess over conventional DIS events when a large rapidity gap is required. They contribute roughly 10% to the total amount of DIS events.

Theoretically Single Hard Diffraction is challenging, since it does not fit into the usual framework of hard collinear factorization. It rather requires a deeper understanding of the interplay between hard and soft physics which goes beyond the standard methods.

2 Single Hard Diffraction at Hadron Colliders

2.1 The Pomeron structure function

The first theoretical approach to Single Hard Diffraction was made by Ingelman and Schlein[2] based on the triple Pomeron picture of soft Single Diffraction (fig.1). The Pomeron is defined as a Regge-pole in the angular momentum plane of high energy elastic scattering amplitudes and is associated with the slow rise of the hadron total and elastic cross section. The Pomeron-pole depends on the momentum transfer t and has a trajectory which is roughly linear according to the present data ($\alpha_{\mathbb{P}}(t) = 1.08 + 0.25\; t/GeV^2$). An important feature of the Pomeron-pole is its uniqueness, i.e. it does not depend on the type of the hadrons involved in the scattering. The Pomeron-hadron couplings $\beta(t)$ can be absorbed in the residue of the Pomeron-pole. Meson trajectories also contribute to high energy scattering amplitudes. Their Regge-intercepts $\alpha_R(0) \simeq 1/2$ (spin 1/2 exchange), however, is smaller than the Pomeron-intercept ($\alpha_{f\mathbb{P}}(0) \simeq 1$), and they become subleading at very high energies. A common way to calculate high mass soft Diffraction is illustrated in fig.1.

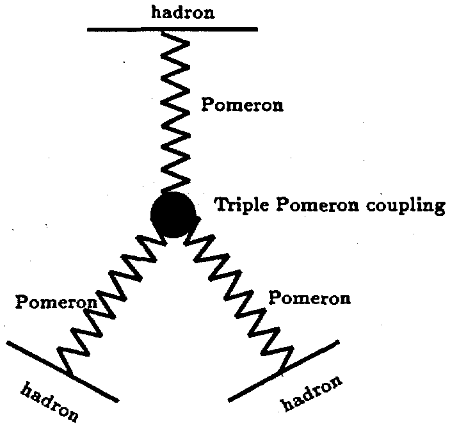


Figure 1: Triple Pomeron diagram

The triple Pomeron coupling $G_{\mathbb{P}\mathbb{P}\mathbb{P}}$ appears as free and new parameter in the triple Pomeron diagram:

$$\frac{d\sigma}{dt dx_{\mathbb{P}}} = \frac{|\beta(t)|^2}{16\pi}\, x_{\mathbb{P}}^{1-2\alpha_{\mathbb{P}}(t)}\, G_{\mathbb{P}\mathbb{P}\mathbb{P}}\, \beta(0)\, (M^2)^{\alpha_{\mathbb{P}}(0)-1} \; . \tag{1}$$

M is the missing mass and $x_{\mathbb{P}}$ the Pomeron momentum fraction given by $\frac{M^2}{s}$. In a more sophisticated analysis this simple formula has to be improved by including secondary meson trajectories which give corrections at low energies.

The simple triple Pomeron approach which worked well for ISR-energies suffered a setback at higher energies (UA4 and the Tevatron). The data undershoot the prediction based on the extrapolation from ISR-energies significantly [3]. A possible explanation are strong unitarity corrections [4]. For the sake of simplicity and due to the lack of a well founded theoretical alternatives eq.(1) is still in use.

The basic idea of Ingelman and Schlein about how to include hard events into the scheme of Single Diffraction was to treat the Pomeron as an on-shell particle, like hadrons, with a certain partonic substructure. This concept may have an intuitive justification, but the related collinear factorization cannot be proven, i.e. there is no proper way of factorizing the soft part from the hard part. Moreover, partons are considered to form s-channel states associated with real particles, not with t-channel exchanges, in particular not with the Pomeron. Despite all these objections the model introduced by Ingelman and Schlein is the only one which provides an applicable, phenomenological description for Single Hard Diffraction.

Related to the previous criticism about treating the Pomeron as an on-shell particle is the problem of defining a Pomeron-hadron total cross section $\sigma_{\mathbb{P}h}(M^2)$ in combination with a Pomeron flux factor $f_{\mathbb{P}}(t, x_{\mathbb{P}})$. The form of eq.(1) suggests the following factorization:

$$\begin{aligned}
\frac{d\sigma}{dt\,dx_{\mathbb{P}}} &= f_{\mathbb{P}}(t, x_{\mathbb{P}})\sigma_{\mathbb{P}h}(M^2) \\
f_{\mathbb{P}}(t, x_{\mathbb{P}}) &= \frac{|\beta(t)|^2}{16\pi}\, x_{\mathbb{P}}^{1-2\alpha_{\mathbb{P}}(t)} \\
\sigma_{\mathbb{P}h}(M^2) &= G_{\mathbb{P}\mathbb{P}\mathbb{P}}\,\beta(0)\,(M^2)^{\alpha_{\mathbb{P}}(0)-1}
\end{aligned} \tag{2}$$

which is somewhat arbitrary. The natural extension for hard events is:

$$\sigma_{\mathbb{P}h}^{\mathrm{hard}} = \int dx_1 \int dx_2\, d_{\mathbb{P}}(x_1) d_h(x_2) \hat{\sigma}(x_1, x_2) \tag{3}$$

where $\hat{\sigma}$ is a conventional parton-parton matrix element and $d_{\mathbb{P}}$ the parton density of the Pomeron or Pomeron structure function. With the introduction of a Pomeron structure function the question arises what its momentum sum is. Since the Pomeron is not a well defined particle in the classical sense, there exists no momentum sum rule. One can certainly renormalize the parton density by absorbing the total momentum sum into the flux factor, but the overall normalization remains arbitrary. Ingelman and Schlein assumed a flux factor as defined in eq.(2) and set the momentum sum equal to one:

$$\int_0^1 dx\, x d_{I\!P}(x) \;=\; 1 \; . \tag{4}$$

The parton distributions themselves have to be determined by experiment. As trial functions Ingelman and Schlein suggested two extreme choices, a hard (5) and a soft (6) gluon dominated structure function:

$$\begin{aligned} x d_{I\!P}(x) &= 6x(1-x) & (5)\\ x d_{I\!P}(x) &= 6(1-x)^5 \; . & (6) \end{aligned}$$

The soft structure function is characterized by large contributions at low x. As alternative one may also think of a purely quark dominated Pomeron which would be of relevance for diffractive W-production [5]. In contrast to gluons valence-like distributions for quarks cannot be 'soft', so that only one natural choice remains:

$$x q_{I\!P}(x) \;=\; \frac{6}{4} x(1-x) \; . \tag{7}$$

The coefficient is derived for four quark flavors.

A slightly more elaborate approach can be found in [6]. The low-x regime of the structure function is determined by the triple Pomeron coupling. A hard contribution is added, so that the total distribution satisfies the momentum sum rule:

$$x d_{I\!P}(x) \;=\; (0.18 + 5.46x)(1-x) \; . \tag{8}$$

Donnachie and Landshoff [7] came out with a different normalization for the flux factor ($\frac{2}{\pi} f_{I\!P}$). They also did not insist on a momentum sum rule, instead, they argued that according to the additive quark model the Pomeron should predominantly couple to quarks rather than gluons. Within their model the following Pomeron structure function emerges:

$$x q_{I\!P}(x) \;\simeq\; 0.2x(1-x) \; . \tag{9}$$

The coefficient '0.2' includes a phenomenological parameter which was extracted from inclusive DIS. It is important to point out that there is no arbitrariness in the overall normalization, an advantage of this approach. In a more complete analysis Donnachie and Landshoff [8] also included other contributions like the triple Pomeron coupling and secondary meson trajectories. Still, the main contribution was found to be given by eq.(9). Consequently the cross section for Single Hard Diffraction following eq.(9) will be much lower than in previous approaches. Another important feature is the large quark content of the Pomeron which should be visible in an enhanced rate of diffractive W's versus diffractive dijets.

Over a couple of years UA8 has contributed to the experimental investigation of Single Hard Diffraction by looking at diffractive dijet-production[1]. The analysis of these data is continued and new results have been published [9,10]. At CDF and D0 the data of the recent runs were processed and first results have been presented (details see [11,12]). Both, D0 and CDF, have looked for diffractive dijets, and CDF has also measured diffractive W's. Up to now only qualitative statements have been made and limits set on the relative fraction of the diffractive production of dijets and W's versus their total rate. More detailled studies of distributions necessary to test the Pomeron structure are expected to come.

The measurements at UA8 sofar have delivered the most precise results on the shape of the Pomeron structure function. The main conclusions was that the data in general prefer a hard momentum distribution (5), that, however, the standard parametrization does not fit the data completely, but requires an additional 'superhard component' (see next subsection). Hopefully, CDF and D0 will add new information to this issue, allthough a direct comparison may not be possible.

Another important issue is the absolute normalization for hard diffractive processes. New results here would shed more light on the question whether the simple factorization assumption of eq.(2) plus the momentum sum rule (eq.(4)) holds. Goulianos pointed out [3] that the data on Single Hard Diffraction in hadron collisions collected sofar seem to favor a reduced Pomeron flux which as he claims should be one Pomeron per proton. Such a renormalized flux fits the data. It also seems to be consistent with Hard Diffraction when the momentum sum rule is kept [3].

The increase of data on Hard Diffraction allows to draw a more consistent phenomenological picture, however, the existence of a unique Pomeron structure function should not be taken for granted. It is a purely phenomenological approach and may turn out to be inadequate at the end. Its virtue certainly is the possibility of applying standard and well established QCD-methods.

2.2 The superhard component

A superhard component of the Pomeron structure function was predicted by [13] and detected by UA8 [9] as an excess over the conventional hard distribution (2) at large x. The terminology 'superhard component of the Pomeron structure function' is missleading, since the contributions which are responsi-

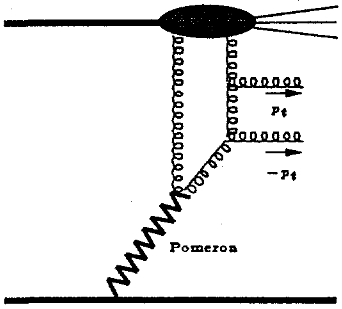


Figure 2: Diagram contributing to the superhard component

ble for the superhard component are related to the break down of factorization [14] and therefore question the concept of a Pomeron structure function. Fig.2 shows a diagram with jets emerging directly from the Pomeron taking all its momentum ($x \sim 1$). The second t-channel gluon which does not participate in the hard process stays soft. It is exactly this soft gluon which spoils factorization. The emerging jets represent what in a conventional hadron reaction the remnant would be, a remnant, however, which is hard and does not disappear in the beam hole.

The superhard component may be modelled by adding to the conventional distributiona a term like $\delta(1-x)$ or $1/(1-x)$ [13]. The need for such a term, however, signals the break down of factorization and is inconsistent with the concept of a uniform and process independent Pomeron structure function.

3 Hard Diffraction in DIS

Conceptually it would have made more sense to start with Single Hard Diffraction in DIS, since we are interested in the substructure of the Pomeron and DIS is the natural place to study this issue. One may recall the analogous case with hadrons where the parton model with its scaling behavior was first tested in DIS and then applied in hadron collisions (Factorization fortunately could be proven [15]). Historically, however, Single Hard Diffraction was first discovered at a hadron collider before HERA provided enough energy to see Hard Diffraction in DIS.

3.1 The Pomeron structure function in DIS

Following the line of arguments made in the first section and adopting the point of view that there is a unique Pomeron structure function one is lead to the following factorized form of the Diffractive structure function F_2^D:

$$F_2^D(Q^2,\beta,x_{I\!P},t) = f_{I\!P}(x_{I\!P},t)\, F_2^{I\!P}(Q^2,\beta) \tag{10}$$

$$F_2^{I\!P}(Q^2,\beta) = \sum_f Q_f^2\, 2\,\beta\, q_f^{I\!P}(Q^2,\beta) \tag{11}$$

where $f_{I\!P}$ is the Pomeron flux factor as defined in eq.(2) and $q_f^{I\!P}$ denotes the quark density with the flavor f. Q_f is the quark charge, and the variable β is defined as the ratio $x_B/x_{I\!P}$ (x_B = Bjorken-x). For F_2^D the same conventions as for F_2 are assumed.

As in conventional DIS the gluon structure is not directly accessible and can only be determined by the amount of sea-quarks which are generated radiatively. The very simple model eq.(7) with only valence quarks overshoots the data and was basically ruled out (see [16]). The Donnachie-Landshoff approach eq.(9), on the other hand, lies below the data. It is, however, not too far off due to the fact that the phenomenological paramter which enters the coefficient in (9) was determined in inclusive DIS.

The early HERA-results [16,17] have triggered quite some activity in trying to find a suitable combination of gluon and quark densities [18,19,20]. All these approaches include QCD-evolution. An initial distribution of gluons and quarks is introduced at some scale, large enough to justify the use of perturbative QCD, and then evolved up to the desired Q^2. One example of initial ditribution taken from ref.[19] has the following parametrization:

$$\sum_f \beta\, q_f^{I\!P}(\beta,Q_0^2) = \left(0.0528\,\beta^{-0.08} + 0.801\,\beta\right)\,(1-\beta) \tag{12}$$

$$\beta\, g^{I\!P}(\beta,Q_0^2) = \left(0.218\,\beta^{-0.08} + 3.3\,\beta\right)\,(1-\beta) \tag{13}$$

It basically combines a lot of aspects of the previous section. The total momentum sum is equal to one, the distributions are predominatly hard without neglecting the triple Pomeron coupling (it is hidden in the coefficient of the first term in each equation), and the driving term (the second term on the rhs of eq.(12)) is similar to what Donnachie and Landshoff predicted. Together with the Donnachie-Landshoff flux factor a remarkably good agreement with the data from refs. [16,17] was achieved, requiring only a rather mild adjustment by hand. The same data also seem to support the factorization scheme of eq.(10) with the soft Pomeron-intercept $\alpha_{I\!P}(0) = 1.08$. In ref.[20] the emphasis was put on the f-exchange which contains quarks to which the photon directly couples. No direct Pomeron-quark coupling a là Donnachie-Landshoff and no momentum sum rule was considered. The gluon contribution was basically motivated by the triple Pomeron coupling. Both quark- and gluon-densities had to be extended from small to large β according to the spectator counting rule, and the overall normalization derived phenomenologically from diffractive hadron scattering as $I\!PI\!PI\!P$- and $I\!PfI\!P$- couplings was scaled up by a factor of three based on the assumption that absorption is less by this amount in diffractive DIS. After evolving the proposed intial distribution this approach, as well, exhibits good agreement with the same data mentioned above. A common feature of all approaches based on the Pomeron structure function is the necessity of introducing a hard gluon-distribution to avoid a decrease of F_2^D with increasing Q^2 at large β. Such a behavior is not present in the data.

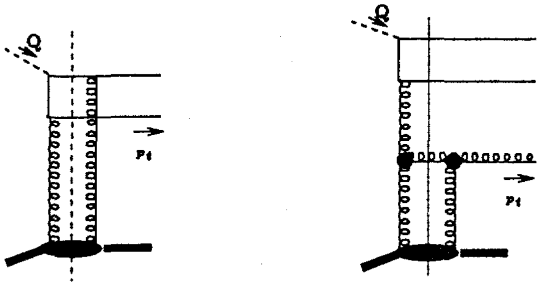
In the meantime new results have been published by H1 and ZEUS [21,22] which are unfortunately not completely consistent. Two different methods were used, the conventional rapidity gap method by H1 and the new M-spectrum method by ZEUS, leading to two different conclusions. The H1 data with a much higher statistic seem now to disfavor an exact factorization of the form (10) (for details see also [23]). Sofar no convincing explanations for the observed and rather strong breaking of Regge-factorization has been found. It may well be that in future analyses this effect turns out to be milder, a slight breaking of factorization is conceivable. The ZEUS data roughly coincide with Regge-factorization, however, the Pomeron-intercept $\alpha_{I\!P}$ is considerably larger than the soft Pomeron-intercept (see [16,23]).

Collinear factorization, i.e. the factorization of hard and soft contributions, may hold to a certain degree of accuracy in diffractive DIS [24]. This would eventually allow to introduce some kind of diffractive structure function which, however, would only be applicable in diffractive DIS. The lack of factorization in hard diffractive hadron scattering is due to a 'soft' hadron in the initial state in place of the 'hard' photon. Even in diffractive DIS there are contribution like those in fig.2 which explicitely break factorization. They, however, happen to occur with a much lower rate.

In the end when the data become more conclusive the ultimate test for the concept of a Pomeron structure function would be its common applicability in diffractive DIS and diffractive hadron collisions.

3.2 Diffractive DIS and QCD

In a gedankenexperiment one might think of studying DIS with very heavy quarkonia, heavy enough to allow the use of perturbative QCD. The leading contribution for DIS in the small-x_B regime would be given by the exchange of one gluon between the two quark- antiquark pairs which emerge from the virtual photon and the quarkonium. A direct coupling of the photon to the quarkonium or in other words probing the valence structure of the quarkonium is suppressed at small x_B. Diffractive scattering of quarkonia associated with a colorless t-channel exchange would require at least two gluons to be exchanged. In real life, though, we have to deal with protons instead of quarkonia, and we do not have control over nonperturbative effects. Still, the virtual photon remains as a hard component in our consideration and certainly couples perturbatively, as long as Q^2 is large enough, to quarks rather than nonperturbatively to hadrons. Fig.3 shows two diagrams at leading and next-to-leading order of perturbation theory, each diagram representing one out of a complete set of gauge-invariant diagrams with similar topologies. The lower blob represents the proton and can be factorized with regard to the k_t-factorization theorem[25]. The remaining part can be calculated in a rather straight forward way without encountering any infrared divergencies[26,27,28,29,30]. For the sake of simplicity and with the main focus on the dominant contribution the momentum transfer had been set to zero.



a) b)

Figure 3: Diffractive DIS in leading and next-to-leading order of pQCD

The diagram shown in fig.3.b dominates, allthough it is next-to-leading order in perturbation theory, when β is small (triple Regge limit). The gluon exchange beats the quark exchange at large M (small β). At leading twist level fig.3.b gives a contribution roughly like $\alpha_s(1-\beta)^3$. For fig.3.a one approximately finds $\beta(1-\beta)$ [27,30], i.e. configurations with only quarks in the final state dominate at medium and large β. Another contribution arises from fig.3.a when the photons are longitudinally polarized. This contribution is closely related to vector meson production in DIS. It has the same property of being a higher twist contribution and may roughly be parametrized by β^4/Q^2, i.e. it does not vanish at $\beta \sim 1$.

The blob representing the proton may as well be used to calculate the inclusive structure function F_2. This allows to build a model from the F_2-data and reinsert this into the diffractive cross section formula. In this way one achieves a completely determined result which may be confronted with the data. The agreement is fairly good [30]. In an improved version of this approach one might include higher order corrections (leading $\log(Q^2)$ parton shower). What kind of effect this has on the scaling behavior needs to be studied. Beyond the leading twist level QCD-calculations exist for the triple Regge limit [31] showing that the triple Pomeron coupling has a much more complicated and nonlocal structure than suggested by fig.1.

An important scale in diffractive DIS is the transverse momentum p_t of the final state. In the case of F_2^D the dominant contribution comes from low p_t with the possible presence of nonperturbative contributions. To be on the safe side and to avoid unwanted nonperturbative contributions one has to require a sufficiently high p_t, i.e. one has to study diffractive DIS with jets. The simplest case are dijets which may be calculated by means of diagram 3.a [32,33]. The blob can now be identified with the standard gluon structure function. The scale which enters the gluon structure function is $p_t^2/(1-\beta)$.

3.3 A brief survey of other models

In ref.[34] diffractive DIS was considered to be given by the conventional boson-gluon-fusion diagram together with the usual gluon density and additional soft color rearrangement which bleaches the quark-antiquark final state. The result is a constant ratio of F_2^D and F_2. Its value, 1/9, is the probability of emitting a colorsinglet final state. A theoretically more profound, new analysis based on a semiclassical gluon field is performed in [35].

The assumption that the hard part of the process may be explained by the exchange of only one gluon with an additional, color compensating soft exchange can also be found in a recent work by [36].

The hard Pomeron or BFKL-Pomeron [38] has a large Pomeron-intercept $\alpha_{I\!P}(0) \simeq 1.5$. The strong power-behavior in $1/x_{I\!P}$, however, is slightly diminished by a term $(1/\log(x_{I\!P}))^3$ according to [37]. This leads to an effective Pomeron-intercept smaller than 1.5 and closer to what is observed in the data.

The author of ref.[39] proposed the hard part of the soft Pomeron to be effectively a single gluon in a soft background field. This view of the Pomeron leads to similar phenomenological consequences as in [34].

4 Conclusions

The Ingelman-Schlein model[2] and the concept of a Pomeron structure function enjoys great popularity by virtue of its simple and straight forward applicability. There are theoretical concerns like the identification of a t-channel exchange (Pomeron) with an on-shell particle or the presence of contributions not collinearly factorizable (superhard component) which make this approach debatable. The oncoming data from the Tevatron and HERA will show how consistent the concept of a unique and universal parton structure of the Pomeron is.

In perturbative QCD the Pomeron is represented in the simplest approach by a colorsinglet two gluon state. In diffractive DIS this approach allows to make explicite prediction for the β-spectrum. It remains, however, unclear to what extend nonperturbative contributions affect these results. More data are needed to dicriminate between the various models.

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