Diffraction at the LHC; a theoretical review

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We discuss both soft and hard diffractive processes. We emphasize the sizeable effects of absorption on *soft* interactions, and hence the necessity to include multi-Pomeron-Pomeron interactions in the usual multi-channel eikonal approach. An example of such a model is described. *Hard* diffraction is illustrated by the timely example of the exclusive production of a heavy object at the Tevatron and the LHC. The predictions, and experimental checks, of various exclusive rates are discussed, including the complications due to eikonal and enhanced rescattering. The value of observing exclusive Higgs production at the LHC is emphasized.

1. Introduction

We discuss the description of the high energy behaviour of *soft* observables, such as σ_{tot}, $d\sigma_{\text{el}}/dt$, $d\sigma_{\text{SD}}/dt dM^2$, particle multiplicities etc., in terms of the basic physics. This physics predated QCD and is sometimes regarded as the Dark Age of strong interactions. However, it is unfair to call this the Dark Age. We had a successful description of these processes in terms of the exchange of Regge trajectories linked to particle states in the crossed channels. The dominant exchange at high energy is the Pomeron, and we have Gribov's Reggeon calculus [1] to account for multi-Pomeron interactions. It is timely to study such reactions again. In particular to quantify the effects of absorption. Clearly, it is of intrinsic interest to seek a reliable, self-consistent model which underlies of soft interactions. Indeed, a reliable model is essential to predict the structure of the underlying events at the LHC. Moreover, it has been appreciated that there is value in observing exclusive processes of the type $pp \to p + A + p$ at the LHC, where A is a new heavy object, such as a Higgs boson [2–4]. However, such processes are strongly suppressed by the small survival factor, $S^2 \ll 1$, of the rapidity gaps either side of A. Thus again, here, we need a reliable model of soft interactions to evaluate the corresponding value of S^2, and so we have an interplay of *soft* and *hard* physics.

2. Absorptive effects on soft scattering

The total and elastic proton-proton cross sections are usually described in terms of an eikonal model, which automatically satisfies *s*-channel elastic unitarity [5]. The unitarity relation is diagonal in impact parameter *b*, and so these data can be described in terms of the opacity $\Omega(s,b) \geq 0$

$$d\sigma_{\text{tot}}/d^2b = 2(1 - e^{-\Omega/2}), \qquad d\sigma_{\text{el}}/d^2b = (1 - e^{-\Omega/2})^2. \tag{2.1}$$

The Good-Walker formalism [6] is used to account for the possibility of excitation of the initial proton, that is for two-particle intermediate states with the proton replaced by N^* resonances. Diffractive eigenstates $|\phi_i\rangle$ are introduced which only undergo 'elastic' scattering. That is, we go from a single elastic channel to a multi-channel eikonal, Ω_{ik}. Already at Tevatron energies the absorptive correction to the elastic amplitude, due to elastic eikonal rescattering, gives about a 20% reduction of simple one-Pomeron exchange. After accounting for low-mass proton excitations, the correction becomes twice larger (that is, up to a 40% reduction).

At first sight, by enlarging the number of eigenstates $|\phi_i\rangle$ it seems we may even allow for high-mass proton dissociation. However, here, we face the problem of double counting when the partons originating from dissociation of the beam and 'target' initial protons overlap in rapidities. For this reason *high-mass dissociation* is usually described by "enhanced" multi-Pomeron diagrams. The first and simplest such contribution to $d\sigma_{\text{SD}}/dM^2$ is the triple-Pomeron graph, see Fig. 1(a). The absorptive effects in the triple-Regge domain are expected to be quite large ($\lesssim 80\%$), since there is an extra factor of 2 from the AGK cutting rules [7]. Recent triple-Regge analyses [8], which include screening effects, of the available data find that the *bare* triple-Pomeron coupling is indeed much larger than the (effective) value found in the original (unscreened) analyses (see, for example, [9]). This can be anticipated by simply noting that since the original triple-Regge analyses did not
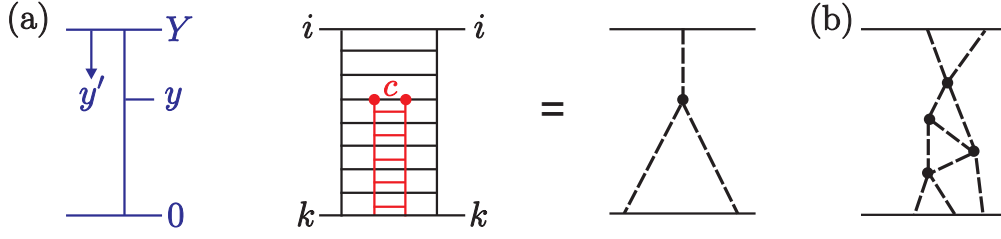
Figure 1: (a) The ladder structure of the triple-Pomeron amplitude between diffractive eigenstates $|\phi_i\rangle, |\phi_k\rangle$ of the proton; the rapidity y spans an interval 0 to $Y = \ln s$. (b) A multi-Pomeron diagram.

allow for absorptive corrections, the resulting triple-Regge couplings must be regarded, not as bare vertices, but as effective couplings embodying the absorptive effects. That is,

$$g_{3P}^{\text{effective}} = S^2 \, g_{3P}^{\text{bare}}, \qquad (2.2)$$

where S^2 is the survival probability of the rapidity gap. Due to the large bare triple-Pomeron coupling ($g_{3P} = \lambda g_N$ with $\lambda \simeq 0.25$, where g_N is the Pomeron-proton coupling), we need a model of soft high-energy processes which includes multi-Pomeron interactions.

Why, if $\lambda \simeq 0.25$, do we call the effect large? The reason is that the contribution caused by the triple-Pomeron vertex is enhanced by the logarithmically large phase space available in rapidity. In particular, the total cross section of high-mass dissociation is roughly of the form

$$\sigma_{\text{SD}} = \int \frac{M^2 d\sigma_{\text{SD}}}{dM^2} \frac{dM^2}{M^2} \sim \lambda \ln s \, \sigma_{\text{el}}, \qquad (2.3)$$

where λ reflects the suppression of high-mass dissociation in comparison with elastic scattering and the $\ln s$ factor comes from the integration $\int dM^2/M^2 \sim \ln s$. Thus actually we deal with the parameter $\lambda \ln s \gtrsim 1$ at collider energies

3. Multi-component s- and t-channel model of soft processes

Recently there have been several attempts to model soft processes [10, 11]. Here we outline the latest attempt [12]. The philosophy is that it is more reasonable to include multi-Pomeron contributions with n to m Pomeron vertices given by $g_m^n \propto \lambda^{n+m}$ than to assume that $g_m^n = 0$ for $n + m > 3$. These effects are included in the following evolution equation for the opacity Ω in rapidity space

$$\frac{d\Omega_k(y,b)}{dy} = e^{-\lambda \Omega_i(y',b)/2} \, e^{-\lambda \Omega_k(y,b)/2} \, \left(\Delta + \alpha' \frac{d^2}{d^2 b} \right) \Omega_k(y,b), \qquad (3.1)$$

where $y' = \ln s - y$. Let us explain the meanings of the three factors on the right-hand-side of (3.1). If only the last factor, $(...)\Omega_k$, is present then the evolution generates the ladder-type structure of the bare Pomeron exchange amplitude, where the Pomeron trajectory $\alpha_P = 1 + \Delta + \alpha' t$. The inclusion of the preceding factor allows for rescatterings of an intermediate parton c with the "target" proton k; Fig. 1(a) shows the simplest (single) rescattering which generates the triple-Pomeron diagram.

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Finally, the first factor allows for rescatterings with the beam i. In this way the absorptive effects generated by all multi-Pomeron diagrams are included, like the one shown in Fig. 1(b). There is an analogous equation for the evolution of $\Omega_i(y', b)$, and the two equations may be solved iteratively.

A novel feature is that four different t-channel states are included in the model. One for the secondary Reggeon (R) trajectory, and three Pomeron states (P_1, P_2, P_3) to mimic the BFKL diffusion in the logarithm of parton transverse momentum, $\ln(k_t)$ [13]. Recall that the BFKL Pomeron is not a pole in the complex j-plane, but a branch cut. Here the cut is approximated by three t-channel states of a different size. The typical values of k_t are $k_{t1} \sim 0.5$ GeV, $k_{t2} \sim 1.5$ GeV and $k_{t3} \sim 5$ GeV for the large-, intermediate- and small-size components of the Pomeron, respectively. Thus (3.1) is rewritten as a four dimensional matrix in t-channel space, as well as being a three-channel eikonal in diffractive eigenstate $|\phi_k\rangle$ space.

The model is tuned to describe all the available soft data in the CERN-ISR to Tevatron energy range. In principle, it may be used to predict all features of soft interactions at the LHC. All components of the Pomeron are taken to have a *bare* intercept $\Delta \equiv \alpha_P(0) - 1 = 0.3$, consistent with resummed NLL BFKL [14]. However, the large-size Pomeron component is heavily screened by the effect of 'enhanced' multi-Pomeron diagrams, that is, by high-mass dissociation, which results in $\Delta_{\text{eff}} \sim 0.08$ and $\alpha'_{\text{eff}} \sim 0.25$. This leads, among other things, to the saturation of the particle multiplicity at low p_t, and to a slow growth of the total cross section. Indeed, the model predicts a relatively low total cross section at the LHC – $\sigma_{\text{tot}}(\text{LHC}) \simeq 90$ mb [1]. On the other hand, the small-size component of the Pomeron is weakly screened, leading to an anticipated growth of the particle multiplicity at large p_t (~ 5 GeV) at the LHC. Thus the model has the possibility to embody a smooth matching of the perturbative QCD Pomeron to the 'soft' Pomeron.

4. Diffractive Higgs production at the LHC

The topical example of a *hard* diffractive process is $pp \to p + (H \to b\bar{b}) + p$, sketched in Fig. 2 with $A = (H \to b\bar{b})$. This exclusive process has many advantages. First, if the outgoing protons are measured far from the interaction point then the *missing mass* to the two protons gives an accurate measurement of the Higgs mass, $\Delta M_H = O(1$ GeV$)$. A useful constraint is that it should match the (less accurate) mass reconstructed from the $b\bar{b}$ decay products. Second, the $b\bar{b}$ QCD background is suppressed by a $J_z = 0$ selection rule. In principle, the tagged protons allow J^{PC} to be determined; the selection rule means 0^{++} production is dominant. The background comes from *irreducible* QCD $b\bar{b}$ production, from gluons mimicing b jets and from a $|J_z| = 2$ contribution. It turns out that the signal-to-background ratio is $O(1)$ for a SM 120 GeV Higgs, but the downside is that the Higgs cross section is only a few fb. However, the cross section may be enhanced by a factor of 10 or more for some SUSY Higgs scenarios. For example, consider MSSM where the Higgs sector contains h, H, A and $H^\pm$. If $M_A \gtrsim 150$ GeV, then h is like a SM Higgs, while H, A decouple from gauge bosons, whereas their decays to $b\bar{b}$ (and $\tau^+\tau^-$) are enhanced by large $\tan\beta$ [16]. Moreover the $gg \to H$ coupling is also enhanced leading to an order-of-magnitude larger cross section.

It is planned to exploit these advantages by deploying high precision "edgeless" silicon trackers less than a centimetre from the beam ± 420 m from the interaction point of the ATLAS and

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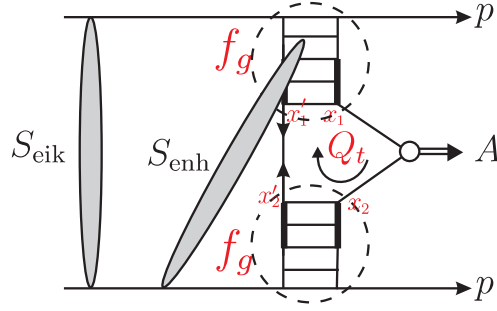[1]This value is also predicted by other 'soft' models which include absorptive effects [15, 11].

Figure 2: The mechanism for the exclusive process $pp \rightarrow p+A+p$, with the eikonal and enhanced survival factors shown symbolically. The thick lines on the Pomeron ladders, either side of the subprocess ($gg \rightarrow A$), indicate the rapidity interval Δy where enhanced absorption is not permitted [19].

CMS detectors[4]. So how reliable is the predicted event rate? The cross section is usually written in the form

$$\sigma(pp \rightarrow p+A+p) \sim \frac{\langle S^2 \rangle}{B^2} \left| N \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', Q_t^2, \mu^2) f_g(x_2, x_2', Q_t^2, \mu^2) \right|^2 \tag{4.1}$$

where $B/2$ is the t-slope of the proton-Pomeron vertex, and N is known in terms of the $H \rightarrow gg$ decay width. The amplitude-squared factor, $| ... |^2$, can be calculated in perturbative QCD, since the dominant contribution to the integral comes from the region $\Lambda_{QCD}^2 \ll Q_t^2 \ll M_A^2$, for the large values of M_A^2 of interest. The probability amplitudes, f_g, to find the appropriate pairs of t-channel gluons (x_1, x_1') and (x_2, x_2') of Fig. 2, are given by skewed unintegrated gluon densities at a hard scale $\mu \sim M_A/2$. To evaluate the cross section of such an exclusive processes it is important to know the probability, $\langle S^2 \rangle$, that the rapidity gaps survive and will not be filled by secondaries from *eikonal* and *enhanced* rescattering effects, sketched symbolically in Fig. 2.

5. Rapidity gap survival probabilities

There is some consensus that eikonal screening for exclusive production of a 120 GeV Higgs at the LHC is $\langle S_{\text{eik}}^2 \rangle_{\text{eff}} \simeq 0.025$ [17, 18, 11] corresponding to an exponential slope $B = 4$ GeV^{-2}. On the other hand, the effect of the inclusion of enhanced rescattering is the subject to controversy [18−20, 11], with values of $\langle S_{\text{enh}}^2 \rangle$ ranging from 0.01 to 1.

However, to compare the values of the survival factors in this way is too simplistic. The problem is that, with enhanced screening on intermediate partons, we no longer have exact factorisation between the hard and soft parts of the process. Thus, before computing the effect of soft absorption we must fix what is included in the bare exclusive amplitude calculated in terms of perturbative QCD. Several observations are important.

The *first* observation is that the bare amplitude is calculated as a convolution of two generalised (skewed) gluon distributions with the hard subprocess matrix element, see (4.1). These gluon distributions are determined from integrated gluon distributions of a global parton analysis of mainly deep inelastic scattering data. Now, the phenomenological integrated parton distributions already include the interactions of the intermediate partons with the parent proton. Thus calculations of

S_{enh} should keep only contributions which embrace the hard matrix element of the type shown in Fig. 2. The *second* observation is that the phenomenologically determined generalised gluon distributions, f_g, are usually taken at $p_t = 0$ and then the observed "total" exclusive cross section is calculated by integrating over p_t of the recoil protons assuming an exponential behaviour $e^{-Bp_t^2}$. However, the total soft absorptive effect changes the p_t distribution in comparison to that for the bare cross section determined from perturbative QCD. Thus the additional factor introduced by the soft interactions is not just the gap survival S^2, but rather the factor S^2/B^2 [2], which strictly speaking has the form $S^2 \langle p_t^2 \rangle^2$. The *third* observation is that enhanced screening is only operative outside a threshold rapidity gap Δy, sketched in Fig. 2.

The Durham model [12] gives $\langle S^2 \rangle_{\text{eff}} = \langle S_{\text{eik}}^2 S_{\text{enh}}^2 \rangle = 0.015 \pm 0.01$. But, as emphasized, really the different model predictions need to be compared at the exclusive cross section level.

6. Experimental checks of the theoretical formalism

Exclusive processes of the type $\bar{p}p \to \bar{p} + A + p$ have *already* been observed by CDF at the Tevatron, where $A = \gamma\gamma$ [21] or dijet [22] or χ_c [23]. There is a nice overview by Pinfold in the CERN Courier [24]. These processes are driven by the same mechanism as, but have much larger cross sections than, that for exclusive Higgs production. They therefore serve as "standard candles".

Moreover, in the *early* data runs of the LHC it is possible to observe a range of diffractive processes which will illuminate the different components of the theoretical formalism. Some information is possible even without tagging the outgoing protons [25]. For example, the observation of the rapidity distribution y_A of the ratio of diffractive (single gap) A production to inclusive A production will probe the effect of enhanced rescattering. The object A may be an Υ or a W boson or a dijet system. The ratio should avoid normalisation problems. Other examples are W (or Z) + rapidity gaps events or central 3-jet production. The exclusive process $pp \to p + \Upsilon + p$ is interesting. For low p_t of the outgoing proton, the process is mediated by photon exchange and probes directly the unintegrated gluon distribution. At larger p_t, the process is driven by odderon exchange [26] and could be the first hint of the existence of the odderon.

Finally, we note that the rates of the exclusive processes already observed by CDF are in good agreement with the predictions of the Durham model. This lends valuable support to the exciting proposal to instal proton taggers to observe exclusive Higgs production at the LHC.

Acknowledgements

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