Diffractive Processes at the LHC\textsuperscript{1}

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Abstract: We consider diffractive processes which can be measured at the LHC. Analysis of diffractive events will give unique information about the high energy asymptotics of hadron scattering. In semihard diffraction one may study the partonic structure of the Pomeron. Central Exclusive Diffractive production provides a possibility to investigate the new particles (Higgs bosons, SUSY particles,...) in an exceptionally clean environment.

1 Introduction

It was shown about 40 years ago that the behaviour of the diffractive cross sections, together with the crucial role played by unitarity constraints, determine the high energy asymptotics of hadron-hadron interactions. The LHC collider is the first accelerator which will have enough energy to produce the events with a few ($n = 2 - 4$) large rapidity gaps. This will be the first time we could measure diffractive and multi-Pomeron processes sufficiently close to their asymptotic regime.

Our discussion is based on the ideas (and publications) of V.N. Gribov. Remarkably, Gribov played the pivotal role in investigating almost all aspects of this field. He introduced the Reggeon diagram technique \textsuperscript{1}. He discussed in detail the possible high energy behaviours of hadron interaction amplitudes \textsuperscript{2, 3}. He found the relations between the diffractive and inelastic cross

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sections \[4\] — the AGK cutting rules. He discovered the constraints on the diffractive amplitudes coming from the unitarity conditions, and the specific asymptotic behaviour of the elastic cross section \[5\].

Our brief review is divided into three parts. First, we discuss pure soft interactions: the behaviour of the total cross section and the slope of differential elastic cross section, the \( t \)-dependence of the diffractive dissociation and the survival probability of one (or a few) large rapidity gaps. Next, we consider the semihard diffractive processes, where high \( E_T \) jets or a heavy boson (e.g. \( J/\psi, W, Z, \ldots \)) may be produced. Finally, we describe the advantages of studying New Physics (in particular Higgs bosons) in Central Exclusive Diffractive (CED) events.

2 Soft diffractive events

2.1 Unitarity constraints for elastic amplitude

It is known that the present data on high energy elastic hadron-hadron scattering are well described by a simple parametrization proposed by Donnachie and Landshoff (DL) \[6\]. The nucleon-nucleon amplitude is written as

\[
A(s, t) \simeq i\sigma_0 F_1^2(t) (s/s_0)^{\alpha_P(t)},
\]

where \( s \) is the square of the incoming c.m. energy \((s_0 = 1 \text{ GeV}^2)\), \( F_1(t) \) is the electromagnetic proton form factor \((t \text{ is the momentum transfer squared})\), and the Pomeron trajectory \( \alpha_P(t) = 1.08 + t \cdot 0.25 \text{ GeV}^{-2} \). The corresponding cross section is

\[
\sigma = (1/s)\text{Im}A(s, 0) \propto \sigma_0(s/s_0)^{0.08}.
\]

It is convenient to transform (1) to impact parameter, \( b_t \), space

\[
A(s, b_t) = \frac{-i}{2s(2\pi)^2} \int A(s, t = -q_t^2) e^{i\vec{q}_t \cdot \vec{b}_t} d^2 q_t
\]

If the power growth \((\sigma \propto s^{0.08})\) continues, then the amplitude, which at the Tevatron reaches \( A(s_{\text{Tev}}, b_t = 0) \simeq 0.96 \), will exceed the black-disk limit at the LHC, \( A(s_{\text{LHC}}, b_t = 0) > 1 \).

In the DL approach the high energy amplitude is described by single Pomeron (\( P \)) exchange only. To account for the unitarity constraints, we must include multi-Pomeron diagrams. In particular, the KMR model \[7\].
which accounts for multi-Pomeron contributions, and successfully describes the same data in the ISR–Tevatron energy range, predicts $A(b_t = 0) < 1$ (but close to 1) at the LHC energy. However in such models \[7, 8\], due to the multi-Pomeron effects, the interaction radius $R^2$ (that is the elastic slope $B(t = 0)$) grows faster than that in DL model. At the LHC energy, $B_{\text{KMR}} \sim 22 \text{ GeV}^{-2}$, while $B_{\text{DL}} = 19 \text{ GeV}^{-2}$ (see \[9\] for more details). Thus it will be important to measure the elastic slope (i.e. interaction radius) at the LHC, since the unitarity-induced corrections caused by the multi-Pomeron cuts, first reveal themselves in the value of the slope $B$.

### 2.2 Possible asymptotics of the high energy amplitude

Detailed analyses performed at the end of 60’s \[2, 3\] had showed that there could be a few different regimes with different energy dependences of the cross section $\sigma_{\text{tot}}$ as $s \to \infty$.

(a) $\sigma \to \text{const.}$ – the so-called ‘weak coupling’ regime \[2\].

In this case, as $s \to \infty$, the major contribution comes from $\mathbb{P}$-pole exchange, while the $\mathbb{P}$-cut contribution dies out; the elastic slope $B \propto \ln s$.

(b) $\sigma \sim (\ln s)^{\epsilon}, B \sim (\ln s)^{\eta}$ with $0 < \epsilon \leq \eta < 2$ – the ‘critical Pomeron’ \[3\].

(c) $\epsilon = \eta = 2$ – the ‘supercritical Pomeron’, which leads to the Froissart regime.

In terms of the bare $\mathbb{P}$-pole, the critical and/or supercritical Pomeron amplitudes are $\mathbb{P}$-cuts in which the single $\mathbb{P}$-contribution is completely screened by multi-Pomeron rescatterings.

(d) Finally, it may be possible for the cross section to first grow as $\sigma_{\text{tot}} \propto s^\epsilon$, but then at larger energies to decrease like $s^{-\epsilon}$, due to the increasing role of Pomeron-Pomeron self-interactions (see for example \[10\]).

Surprisingly, this last possibility is still allowed by the present data! The Tevatron energy is not sufficient to reject it, since the transition to the $\sigma \sim s^{-\epsilon}$ behaviour is expected to occur only after the possible size of the rapidity gap becomes much larger than $1/\epsilon \sim 12$ (for $\epsilon = 0.08$).
2.3 Diffractive dissociation and the triple- P vertex

The diffractive dissociation into a high mass ($M_X$) state is described by the triple-Pomeron diagram. If we assume that the triple-Pomeron vertex $G_{3\text{IP}}$ is just a small constant, then we face a problem. In this ‘naive’ approximation the cross section of diffractive dissociation $\sigma_{\text{SD}}$ grows faster than $\sigma_{\text{tot}}$. This applies to cases (a), (b) and (c) above. Indeed, even for $\alpha_{\text{IP}} = 1$, after the integration over the mass $M_X$ ($\int s dM^2_X / M^2_X \sim \ln s$), the cross section $\sigma_{\text{SD}} \propto (\ln s)\sigma^2_{\text{tot}} > \sigma_{\text{tot}}$. An analogous, and more severe, problem occurs in processes with so-called multi-Reggeon kinematics. The cross section of the events with a few large rapidity gaps grows faster than the total inelastic cross section [11-12].

In the ‘weak coupling’ regime, (a), the resolution of the problem is the vanishing of the triple-Pomeron coupling (that is of the vertex $G_{3\text{IP}}$) at small transverse momenta, $t \to 0$. The same vanishing is predicted [5] for any diffraction dissociation vertex, say $V(N \to N^*) \to 0$ as $t \to 0$. Observation of this ‘vanishing’ will be a strong argument in favour of the ‘weak coupling’ asymptotic regime (a), where at extremely high energies all the cross section are predicted to become equal to each other – $\sigma(aa) = \sigma(ab) = \sigma(bb)$ – independent of the type of each incoming hadron [5].

However, in reality, the situation is not so simple. Besides single $\text{P}$-exchange, there is the $\text{P}$-cut contribution, which does not vanish as $t \to 0$. At relatively low energies we practically do not see dissociation due to the single $\text{P}$-pole; the $\text{P}$-cut contributions dominate.

An exception is the ‘weak coupling’ regime, (a), where the $\text{P}$-cut terms die out with increasing energy. At the LHC we would get a chance to observe a dissociation amplitude arising almost entirely from single-Pomeron-exchange. The cut corrections are much smaller than those occurring in the lower (ISR – S$\bar{p}$S – Tevatron) energy range. Thus in case (a) we expect that the cross section of diffractive dissociation in forward direction (i.e. $d\sigma_{\text{SD}}(s,t)/dt$ as $|t| \to 0$) to decrease with energy. Also, the diffractive minimum caused by the destructive interference between the pole and cut contributions will take place at a rather small $|t| = t_0$. Moreover the value of $t_0$ will decrease with energy faster than the position of the diffractive dip in elastic scattering.

\[\text{In terms of the Good-Walker model [13] (or Additive Quark Model) the vanishing is provided by the orthogonality of different diffractive eigenstates – if the Pomeron couples to a single parton then, at } t = 0, \text{ one-Pomeron-exchange does not change the distributions of partons in incoming wave function.}\]
However, the $t$-behaviour of $d\sigma^{\text{SD}}/dt$ has, not as yet, been studied with enough precision. On the other hand, it is crucial to know this $t$-behaviour in order to construct a realistic model for the high-energy asymptotics of the strong interaction amplitude.

There is another solution to the problem (that $\sigma^{\text{SD}} > \sigma_{\text{tot}}$), which should be realized for the more realistic (b,c) scenarios. That is to assume that, due to the screening corrections arising from the multi-loop Pomeron graphs, the strength of the 'effective' triple-Pomeron vertex $G_{3P_{\text{eff}}}$ decreases with energy, or with the size of the gap ($\Delta y$). Using modern terminology, we would say that the gap survival factor $S^2 \to 0$ when $s \to \infty$ (or $\Delta y \to \infty$).

Thus, it is important to study the dependence of $S^2$ on the initial energy $\sqrt{s}$, on the gap size ($\Delta y$), and on the number of the gaps. The LHC is the first collider with the sufficient energy to produce 2,3 (or may be even 4) large rapidity gaps\(^3\). Note that the cross section for 3-gap formation at the LHC is not too small. In Ref. \cite{15} is was evaluated to be $\sigma \sim 1 - 3 \mu b$.

Finally, recall that diffractive dissociation comes mainly from the periphery of the interaction disk, due to stronger absorptive corrections in the center of the disk. This has the important consequence that the mean transverse momenta of the secondaries produced in a diffractive dissociation process should be smaller than the transverse momenta of secondaries coming from an ordinary inelastic collision at the corresponding energy $s_{\text{inel}} = M_X$ \cite{16}.

3 Semihard diffractive dissociation

The formation of a system of mass $M_X$ by diffractive dissociation of the proton may be considered as an inelastic proton-Pomeron interaction.

3.1 Partonic structure of the Pomeron and the LHC

The production of high $E_T$ jets, or heavy bosons ($W, Z$) or heavy quarks ($J/\Psi, b\bar{b},...$) within the diffractive system $M_X$ can be described in the usual way as the convolution of the incoming parton distributions (in the proton

\(^3\)Contrary to the model of Ref. \cite{14}, for the case of supercritical Pomeron (c), the survival factor $S^2$ decreases as the number of gaps $n$ grows. Note that the KMR model \cite{7} already predicts a lower $S^2$ for 'central exclusive' production (with 2 gaps) than that for single dissociation (with one gap).
and in the Pomeron) with the cross section of the ‘hard’ subprocess. The parton distributions in a proton are well known. Therefore, by selecting events with a high $E_T$ or heavy quarks (or bosons) in the diffractive dissociation ($M_X$), we have the possibility to study the internal partonic structure of the Pomeron. The expected cross sections are typically of the order of $1 - 10 \text{ nb}$ \cite{17}.

Recall that the global parton analyses of the HERA deep inelastic scattering data indicate that at low $Q^2 = 1 - 2 \text{ GeV}^2$ we have Pomeron-like sea quarks (behaving as $xq \sim x^{-0.2}$, but valence-like gluons (typically of the form $xg \sim \sqrt{x}$); see Refs. \cite{18, 19}). Does this mean that the Pomeron is built up of quarks and not gluons, or the Pomeron at low scales does not couple to gluons but only to quarks? LHC has to answer this question!

### 3.2 The ‘direct’ hard Pomeron interaction

Note, however, that contrary to the Ingelman-Schlein ansatz \cite{20}, the Pomeron is not a hadron-like object of more or less fixed size. In perturbative QCD the Pomeron singularity is not an isolated pole, but a branch cut which may be regarded as a continuum series of poles in the complex angular momentum plane \cite{21}. That is, the Pomeron wave function consists of a continuous number of components. Each component $i$ has its own size, $1/\mu_i$. A ‘direct’ hard interaction of a small-size component of the Pomeron with the parton coming from the beam proton will violate conventional collinear factorization. At first sight such a contribution would appear to be suppressed by the form-factor-like dependence of the effective Pomeron flux $f_{IP}(x_{IP}, \mu^2) \sim 1/\mu^2$. Here $x_{IP}$ is the longitudinal momentum fraction of the beam particle transferred through the Pomeron, and $\mu$ is the scale corresponding to the specific component of the Pomeron.

On the other hand, at small $x_{IP}$ this power-like suppression coming from the form factor is compensated by a large gluon density $g(x_{IP}, \mu^2)$ which grows as $(\mu^2)\gamma$, with an anomalous dimension which behaves as $\gamma \rightarrow 1/2$ as $x_{IP} \rightarrow 0$ \cite{21}. Thus, at very low $x_{IP}$ the integral over the Pomeron size $1/\mu_i$ takes the logarithmic form

$$f_{IP} \propto \frac{1}{x_{IP}} \int \left[ \frac{\alpha_s}{\mu} x_{IP} g(x_{IP}, \mu^2) \right]^2 \frac{d\mu^2}{\mu^2} \sim \frac{1}{x_{IP}} \int \frac{d\mu^2}{\mu^2}. \quad (4)$$

Actually at sub-asymptotic energies the anomalous dimension $\gamma$ is a bit less than $1/2$ and the integral (4) is convergent at large $\mu^2$, but numerically we
cannot neglect this ‘direct’ Pomeron-parton hard interaction at the LHC (or even at HERA) energies (see [22] for more details, including a discussion of other sub-asymptotic violations of collinear factorization).

Note that high $E_T$ dijets (or heavy quarks, or bosons) produced in ‘direct’ hard Pomeron interactions carry away the whole momentum of the Pomeron. For example we have $\gamma\text{IP} \rightarrow jj$ fusion in deep inelastic scattering, or $g\text{IP} \rightarrow jj$ fusion in $pp$-collisions which corresponds to the process $pp \rightarrow Xjj + p$, where the + sign denotes a large rapidity gap. In these examples, $jj$ indicates a pair of high $E_T$ jets. In fact, the ‘direct’ hard interaction of the small-size components of the Pomeron is the origin of the so-called ‘extra hard’ component, $\propto \delta(x - 1)$, in the parton distributions of the Pomeron, which was proposed in Ref. [23] to describe the events in which high $E_T$ dijets carry away Pomeron momentum fractions $x$ close to 1. The identification of such a component is important for the extraction of diffractive parton densities from diffractive deep inelastic data [22]. Clearly, at the LHC, it will be informative to measure dijets ($jj$) in the Pomeron fragmentation region.

4 CED probes of New Physics at the LHC

Central Exclusive Diffractive (CED) reactions offer the opportunity to study the New Physics (such as Higgs bosons, SUSY particles,...) in an exceptionally clean environment. These new objects produced in CED events are expected to be rather heavy. Thanks to this large scale, the process can be described within the framework of perturbative QCD. It was shown in [15] that the CED cross section may be calculated as the convolution of the effective (diffractive) gluon luminosity $L(gg^{\text{IP}})$, and the square of the matrix element of the corresponding hard subprocess.

4.1 An example – Higgs production

As an example, we consider the production of the SM Higgs boson by the CED process

$$pp \rightarrow p + H + p$$

(5)

at the LHC, where, again, the + signs denote large rapidity gaps. Let us take the mass range, $M \lesssim 140$ GeV, where the dominant decay mode is $H \rightarrow b\bar{b}$. Demanding such an exclusive process (5) leads to a small cross section [24].
At the LHC, we predict

$$\sigma_{\text{excl}}(H) \sim 10^{-4} \sigma_{\text{incl}}^{\text{tot}}(H).$$

(6)

In spite of this, the exclusive reaction (5) has the following advantages:

(a) The mass of the Higgs boson (and in some case the width) can be measured with high accuracy (with mass resolution $\sigma(M) \sim 1$ GeV) by measuring the missing mass to the forward outgoing tagged protons.

(b) The leading order $b\bar{b}$ QCD background is suppressed by the $P$-even $J_z = 0$ selection rule [25, 26], where the $z$ axis is along the direction of the proton beam. Therefore one can observe the Higgs boson via the main decay mode $H \rightarrow b\bar{b}$. Moreover, a measurement of the mass of the decay products must match the 'missing mass' measurement. It should be possible to achieve a signal-to-background ratio of the order of 1. For an integrated LHC luminosity of $L = 300$ fb$^{-1}$ we predict about 100 observable Higgs events, after acceptance cuts [27].

(c) The quantum numbers of the central object (in particular, the C- and P-parities) can be analysed by studying the azimuthal angle distribution of the tagged protons [28]. Due to the selection rules, the production of $0^{++}$ states are strongly favoured.

(d) There is a very clean environment for the exclusive process – the soft background is strongly suppressed.

(e) Extending the study to SUSY Higgs bosons, there are regions of SUSY parameter space were the signal is enhanced by a factor of 10 or more, while the background remains unaltered. Indeed, there are regions where the conventional Higgs signals are suppressed and the CED signal is enhanced, and even such that both the $h$ and $H$ $0^{++}$ bosons may be detected [29].

4.2 A ‘gluon factory’

In some sense, the CED processes may be considered as a filter which suppresses the production of the light quark dijets, of unnatural parity objects, and of some meson states made of quarks. For example, in the SUSY Higgs
sector, the production of the pseudoscalar $A$ boson is suppressed in comparison to the scalars, $h$ and $H$. Another example, is the suppression of the production of non-relativistic $2^+$ quarkonia.

On the other hand, CED reactions are a good place to search for ‘glue-balls’ or for studying gluon dijets. Indeed the CED production of high $E_T$ dijets, via the $IPiP \rightarrow jj$ hard subprocess, may be used as an excellent ‘gluon factory’ [26]. This is a good way to study the properties of gluon jets – multiplicity, jet shape,... – without an admixture of quark jets.

5 Conclusion

The study of diffractive processes at the LHC can be very rich and fruitful\footnote{Indeed, already the TOTEM collaboration [30] is geared to study various aspects of soft and semihard physics at the LHC. Also novel aspects of diffractive studies are included in the physics case for forward proton tagging at 420m at the LHC [31].}. We have a chance to answer a number of important and outstanding questions. What is the high energy asymptotic behaviour of the strong interaction amplitude? Does Nature select the weak Pomeron-Pomeron coupling regime, or do we have a ‘critical’ or a ‘supercritical’ Pomeron? In the last case, the total cross section reveals a Froissart-like behaviour, while diffractive dissociation, and events with a few large rapidity gaps, are suppressed by small gap survival factors $S^2$.

What are the parton distributions generated by the Pomeron? Just as we can obtain universal parton distributions from global analyses of data for deep inelastic and related hard scattering processes, so we can obtain universal diffractive parton distributions from the analysis of diffractive data. However in the latter case the analysis is more subtle and we have to take into account violations of collinear factorization. Here we have seen that studies at the LHC can give important information.

One interesting possibility to consider, concerns the LHCb experiment, where the detector covers the rapidity region of $2 < \eta < 5$. The LHCb detector will have a high track reconstruction efficiency and good $\pi/K$ separation [32], which may be very useful for glueball searches. It is going to operate at a luminosity $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$, for which there will be usually a single collision per bunch crossing, and hence practically no ‘pile-up’ problems. Thus installing a forward detector at LHCb would offer the possibility of observing
asymmetric events, with one very large rapidity gap, and so probe the region of very small $x_{\text{IP}} \sim 10^{-5}$ or even less.

Finally, we emphasize again that Central Exclusive Diffractive production provides a unique opportunity to search for New Physics in a very clean experimental environment. Recall that for such an experiment we need detectors to tag the outgoing forward protons, as well as using the main central detector to observe secondaries produced in the central region.

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