Notes on Diffractive Hard Scattering at FELIX

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Abstract

I describe some of the issues involved in the theory of diffractive hard scattering as it relates to the FELIX proposal for the LHC.

1 Introduction

The proposed FELIX experiment will provide an unprecedented kinematic range for measuring QCD cross sections, in particular as regards diffractive cross sections. In this paper, I will summarize some ideas on what can be done.

I will use the definition that diffraction is the set of phenomena associated with non-exponentially suppressed rapidity gaps. In high-energy collisions, hadrons appear to be fragile, and their break up results in high particle multiplicities in the final state. Even so, about half of hadronic collisions should be elastic. Even more interestingly, ten or more per cent of the collisions (at present energies) result in single diffraction, where one of the incoming hadrons remains intact while the other breaks up.

In the two decades since QCD was discovered, there has been a noticeable lack of interest in diffraction. This can be perhaps ascribed to the difficulty of relating the phenomena to the fundamental microscopic theory. But now this situation is changing. The understanding of diffraction represents a first class challenge to theorists: how to understand the phenomena from first principles.

A new subject of active investigation is that of hard diffraction: diffractive processes that contain a hard (short-distance) collision. This opens up the possibility of experimentally probing the space-time structure of hadronic scattering, for example through a violation of hard-scattering factorization. The point here is that diffraction at high energy involves interactions that are coherent over very long longitudinal distances. Factorization for hard

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scattering only results after a set of cancellations of final-state interactions. Thus we expect a violation of factorization in hard diffraction because these cancellations no longer occur [1]. Related experimental results are the violation of the elementary triple-Regge formula for ordinary single diffraction [2, 3].

Variables I will use the variables $x_{\mathbb{P}}$ and t to describe diffractive processes ($p+p \to p+X$). $x_{\mathbb{P}}$ is the fractional energy loss of the proton, and t is the invariant momentum transfer from the proton to the rest of the system. The mass of the rest of the system is then $x_{\mathbb{P}}s$. One should use light-front variables to compute $x_{\mathbb{P}}$. Another name for $x_{\mathbb{P}}$ is ξ. The fractional light-front momentum of the diffracted proton is $x_F = 1 - x_{\mathbb{P}}$.

Center-of-mass energy I believe quite strongly that the experiment should be done with at least two substantially different values of the center-of-mass energy. Without this, any analysis of data becomes much more theory dependent. In fact, I believe that reduced energy running is an essential part of the running of any collider with a hadron beam (Tevatron, RHIC, HERA, LHC). Any analysis of data, whether it involves new physics or standard physics, necessitates a substantial application of perturbative QCD phenomenology. (For example the reports of extra high-Q^2 events at HERA or of high-p_T jets at the Tevatron really mean an excess of events over a predicted QCD cross section.) The QCD calculations have uncertainties, and running at reduced energy gives a cross check on the calculation by checking the scaling violations.

The two kinds of factorization: Regge and hard-scattering In many discussions of diffractive physics, one uses the word 'factorization'. It should be remembered that there are two distinct uses for this word. One is in the sense of Regge factorization and one is in the sense of hard-scattering factorization. Diffractive hard-scattering is concerned with both kinds of factorization, and one must be careful to distinguish the two different uses. In this note, the unqualified word 'factorization' will mean 'hard-scattering factorization'.

2 Soft, or "minimum bias" physics

As a part of any program of diffractive physics, it is important to do measurements of minimum bias processes, including the differential cross section of single diffractive excitation (SDE), as a function of all its variables, $x_{\mathbb{P}}$, t and s. SDE gives the most basic measurement of the pomeron as it appears in diffractive processes, and therefore provides an important set of basic data for all other diffractive processes.

In fact, experimental data are known to show a breakdown of Regge factorization in SDE [2,3]. As the UA8 analysis [3] has shown, it is essential to look at the SDE cross section as a function of all 3 variables to properly understand what is the breakdown of factorization. This implies that a full study of diffraction must involve varying the center-of-mass energy of the collisions.

Furthermore, to understand exactly where pure diffractive dominates, it is necessary to have data in regions of $x_{\mathbb{P}}$ where diffraction does not dominate, at least to $x_{\mathbb{P}} = 0.1$. Explicitly one should analyze data in terms of formulae that involve a non-leading trajectory; even if wants to work in the diffractive region, enough phenomenology must be done to measure where diffraction in fact dominates. These remarks apply to all diffractive processes.

3 Hard single diffraction

In this section I will discuss hard single diffraction, for example, jet production in single diffractive events. All the standard hard processes should be examined, as far as the detector allows:

- Jets at high p_T.
- Drell-Yan and W and Z production.
- Direct photon production
- Heavy flavor production

3.1 Diffractive hard factorization

There are many models available [4–11] to describe hard diffraction. Should one present a pot-pourri of these when trying to make estimates for hard diffraction at the LHC? I will argue that this is not necessary, *for the purposes of planning an experiment.* It is sufficient to use hard scattering factorization [12, 13]. For example, one would write the cross section for diffractive jet production as

$$\frac{d\sigma}{dE_T\,dy\,dx_{\mathbb{P}}\,dt} = \sum_{i,j} \int dx_a \int dx_b\, f_{i/A}(x_a,\mu)\, \frac{df^D_{j/B}}{dx_{\mathbb{P}}\,dt}(x_b/x_{\mathbb{P}}, x_{\mathbb{P}}, t, \mu)\, \frac{d\hat{\sigma}_{ij}}{dE_T\,dy}. \tag{1}$$

The sum is over all parton types i, j that enter the hard scattering, $\hat{\sigma}$ is the usual hard scattering coefficient, the *same* as in inclusive jet production, $f_{i/A}$ is the ordinary parton density in the non-diffracted hadron, and μ is the usual renormalization/factorization scale. The integrals are the usual ones over the momentum fractions of the two active partons, relative to their parent hadrons.

What is new in this formula are the diffractive parton densities $df^D_{j/B}/dx_{\mathbb{P}}\,dt$. They represent the number densities of partons in the initial hadron, but conditional on the detection of the diffracted outgoing hadron in the target fragmentation region.

Comparison with Ingelman-Schlein This formula is both weaker and stronger than the Ingelman-Schlein model [4]. It is weaker because there is no assertion that the diffractive parton densities are the product of a pomeron flux factor and a parton density in the pomeron. It is stronger because the statement applies at all $x_{\mathbb{P}}$ that keep the proton in the target fragmentation region, and not just to diffractive processes with small enough $x_{\mathbb{P}}$. But this statement of diffractive hard scattering factorization is compatible with the obvious QCD version of the Ingelman-Schlein model.

Once one remembers that parton densities of any kind have to be measured from experiment, one sees that the sole difference between the factorization formalism and the

Ingelman-Schlein model is that the Ingelman-Schlein model incorporates Regge factorization as well as hard-scattering factorization. That is, the model predicts the $x_{\mathbb{P}}$-dependence of cross sections.

Theoretical status As Berera and Soper [12] have shown, factorization for diffractive hard scattering would be provably valid if one did not have to worry about soft parton interactions. The arguments and the result are compatible with and similar to those in the fracture function formalism devised by Trentadue and Veneziano [14]. The difference is that in the fracture functions there is an integral over t, i.e., over all transverse momentum for the diffracted hadron. This integral includes a region of high transverse momentum where the hadron results from fragmentation of a high p_T jet instead of from the target fragmentation. Consequently the fracture functions have a more complicated evolution equation than the diffractive parton densities. Since the physics is different at low and high transverse momentum, I prefer not to do the integral.

In the presence of soft parton interactions (e.g., residual spectator interactions), factorization can be proved [1] not to hold, at least as a statement about perturbation theory. The known counterexamples are all in hadron-hadron scattering. The relevant physics has been known since discussions of the Drell-Yan model in pre-QCD days [15]. But [12] it looks possible to prove hard-scattering factorization for the class of diffractive hard processes in which there is only one hadron in the initial state (e.g., diffractive DIS and diffractive *direct* photoproduction). I hope to complete this proof in the next few months.

Models Many of the models available explicitly satisfy factorization. For example, this is true of the Buchmüller-Hebecker model [6]. Simple Feynman graph models, e.g., [5,9], often obey factorization, even if their authors say they don't.

To the extent that a model obeys factorization, its results may be put in terms of diffractive parton densities.

Why use factorization? Although hard scattering factorization is predicted to be violated by QCD, at least in some processes, it is useful in estimating cross sections for FELIX, provided it is used appropriately.

Diffractive quark and gluon distributions are being fit to processes in which factorization is most likely to be valid [16]. This procedure ensures that predictions made for other processes (e.g., [19]) are properly normalized, and account of known QCD effects (particularly evolution) is taken into account. This can result [19] in substantial changes, mostly to lower cross sections, of the simplest predictions from the Ingelman-Schlein model.

Improved fits, of a kind that have already been made [21] by the H1 collaboration, will fit the diffractive parton densities with a pomeron and a non-pomeron term in the $x_{\mathbb{P}}$ dependence. The predictions for FELIX will then include a quantitative estimate of where diffraction takes over from non-diffractive, as one decreases $x_{\mathbb{P}}$. (The fits appear to assume Regge factorization. In fact this is not really so. What one is doing is to assume that the $x_{\mathbb{P}}$-dependence for small $x_{\mathbb{P}}$ is usefully approximated by the sum of one or two powers of $x_{\mathbb{P}}$. It is known experimentally that, even if Regge theory doesn't work exactly, as in SDE [2], the power laws it predicts are a useful guide to what to expect. The strong violations of

Regge powers seen in F_2 at large Q^2 are somewhat of an exception to this rule. However this violation is probably more associated with the large k_T part of the process.)

Of course, we do not expect hard scattering factorization to be exactly valid. Indeed the mechanisms that violate Regge factorization in diffractive processes will also violate hard scattering factorization [22]. Suppose we represent the true cross section as a factorizing cross section times a suppression factor:

$$\sigma_{\rm true} = \sigma_{\rm fact} \times S. \tag{2}$$

The suppression factor S is like Bjorken's [10] gap survival probability.

We should not expect S to vary rapidly with energy, so it will be sufficient to estimate it from analyses that are underway involving present data — see below. One advantage of using the formalism of diffractive factorization is that standard Monte-Carlo event generators, specifically POMPYT, can be used, with all the resulting advantages. Of course, any calculation must be supplemented by an estimate of the suppression factor S. Of such calculations are not going to be perfect, particularly since the breakdown of factorization undermines the theoretical basis of the event generators. Nevertheless, they form a reasonable basis for the kinds of event and the rates that FELIX will be dealing with.

Bjorken [10] has given a very different picture of diffractive hard scattering. I suspect that many of his results can be presented in the form of a factorized cross section and a suppression factor. The factorization experts tend to work in the center-of-mass of the hard scattering, whereas Bjorken and many others tend to view the process in the target rest frame. The same physics can appear quite different in the two frames. This remains to be sorted out.

Current phenomenology A number of theorists and experimentalists are actively involved in fitting diffractive parton densities to data and in predicting further cross sections (e.g., [13, 17–19, 21]). In particularly there is a subgroup [19, 20] of the CTEQ collaboration that is actively promoting coordination of the diffractive physics between the HERA and the Tevatron experiments. Within a year, if not less, we should have useful results on both the parton densities and the suppression factors at a level of accuracy that will be adequate for work on FELIX at perhaps the factor of two level.

In addition, POMPYT has been modified to allow the use of arbitrary input diffractive parton densities, with full QCD evolution. (This is done by making an interface with the CTEQ evolution package.) This removes the restriction on POMPYT that it can only use one of a fixed set of parton densities in the pomeron. (Contact me or Lyndon Alvero `alvero@phys.psu.edu` for details.)

3.2 Delta function terms

One of the striking features of the UA8 diffractive jet data [23] is that a component of the cross section is close to a delta function: In a substantial proportional of the events (almost) all of the momentum of the pomeron goes into the jet system. Let us define this to be the super-hard part of the cross section. H1 [21] have presented a fit to their diffractive DIS data in which a similar peak appears in the gluon distribution in the pomeron.

There is theoretical evidence that such super-hard terms can occur at the leading twist level [1] as a strong violation of factorization. There are likely to be substantial Sudakov suppressions [24], which will get stronger for large mass systems.

So the best bet to look for these terms may be in fairly small E_T jets (5–10 GeV), as in UA8. In addition, it should be remembered that the UA8 data are at fairly large $|t|$, by the standards of soft physics, about 1 to 2 GeV^2. So the best place to verify the UA8 result is at such values of t. The pomeron is presumably a smaller object at such values of t, and one can expect the Sudakov suppressions to be less.

In any case, the phenomenology and theory of these super-hard terms is in its infancy. One should look for them under a range of conditions (large and small t, large and small E_T). Any experiment that is capable of seeing the kinds of cross section predicted by factorization will also be able to investigate the super-hard terms.

As data from CDF and D0 is analyzed over the next year or two, it should become apparent whether or not they confirm UA8's measurement of a super-hard component to diffractive hard processes.

3.3 Forward neutrons

In addition to diffractive DIS and photoproduction, ZEUS now has data with forward neutrons. This is presumably non-diffractive, since vacuum quantum numbers cannot be exchanged. All the same ideas of factorization and non-factorization can be applied to such a process. The kinematics are the same as for diffraction; all that changes is that a cross section with forward neutron production is power suppressed compared with the corresponding diffractive cross section when $x_{\mathbb{P}}$ is small enough.

Therefore FELIX should investigate such processes. The contrast between the factorization properties with neutron production and diffractive processes will be interesting. In particular, if the process

$$p + p \to n + X \tag{3}$$

can be thought of as a pion-proton collision, with the pion emitted from the proton *before* the collision, then factorization will probably hold. This will enable FELIX to probe pion structure in the variety of processes accessible to hadron-hadron collisions.

The presence or absence of factorization will be a direct probe of the space-time structure of the scattering. If a process $p+p \to p' + X$ is in reality $p \to p' + R$ followed by $R+p \to X$, then we expect factorization to hold. If the emission of R cannot be localized before the rest of the collision, then factorization is likely to be violated. Typical models for the pomeron have a multi-peripheral structure, so that pomeron emission is not localized before the rest of the collision. The situation is different for a light particle, of which the photon is the best known case.

4 Rapidity gaps between jets

An important subject, but I am not going to cover it here.

5 Double pomeron exchange

The ideas applied to single diffractive hard scattering can be applied to double pomeron induced processes as well:

$$p + p \to p + X + p, \tag{4}$$

with a large rapidity gaps on opposite sides of the central system X, between X and the two diffracted beam particles.

If super-hard pomeron collisions occur, then they will result in a spectacular signature in DPE events: the final state consists of a proton going down each beam pipe plus a central two-jet system. Unfortunately the current D0 data on DPE production of jets do not indicate that this occurs.

6 Calculational tools: Monte-Carlo event generators, etc

To fill in.

Acknowledgments

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