Introduction to Diffractive Physics at Run II

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1. Diffraction

The word "diffraction" covers a rather large class of events at colliders and fixed target machines. The central thread in all the processes one calls diffractive is a rapidity gap (where no particles are produced) which is large enough to guarantee that no flavor or color quantum numbers are exchanged between the colliding particles. Thus, for example at a proton-antiproton collider the reaction $p+\bar{p} \rightarrow p^* + \bar{p}^*$ is diffractive if the particles (or jets) making up the p^* and the particles (or jets) making up the $\bar{p}^*$ are separated by a rapidity gap ΔY which is large enough to guarantee that the flavor and color quantum numbers of p^* are the same as p and those of $\bar{p}^*$ the same as $\bar{p}$. $\Delta Y \geq 3$ is a common criterion for such a gap size. The physics being studied varies considerably according to the type of diffraction and so we separate our discussion into (somewhat arbitrary) categories and attempt to highlight the physics issues in each of these categories. The emphasis here is physics at Fermilab, but there are often complementary reactions at HERA. The contrast and comparison between diffraction at these two colliders yields much more insight than the study of diffraction at either collider in isolation.

2. Soft Diffraction

Regge Theory gives a good description of two-body and quasi-two-body reactions, including diffraction, at ISR energies and below. This Regge picture continues to describe total and elastic cross sections through collider energies. However, it is known from studies of elastic and total cross sections of proton-proton and proton-antiproton scattering that the unitarity limit (blackness) has been reached for central impact parameter collisions. It is then somewhat of a mystery why the simple Regge pole picture, a picture only valid far from unitarity limits, works so well for total and elastic scattering. Soft diffraction adds a new piece of information here. Although the Regge pole picture fits the total and elastic cross sections at collider energies it does not work for diffraction[2,1]. The growth in the diffraction cross section is much less rapid through the collider energy region than predicted by fits at ISR energies and below. This fits nicely with the picture that central collisions are unitarity saturating but become weaker with increasing impact parameter. Let's see qualitatively how this looks.

A high energy proton is a state having many degrees of freedom which are built out of quarks and gluons. Schematically one may write

$$|\psi_{\rm proton}\rangle = \sum_i |\psi_i\rangle c_i \tag{1}$$

where i labels a state in terms of the fundamental degrees of freedom and where $\sum_i |c_i|^2 = 1$. From studying elastic and total cross sections we know that $S(b)|\psi_{proton}\rangle$ is small when b, the impact parameter, is small where S is the S-matrix for elastic reactions. This means that $S(b)|\psi_i\rangle$ is small at central impact parameters for all i having non-negligible c_i. This in turn gives equal inelastic and elastic cross sections because the T-matrix defined by

$$T(b) = i(1 - S(b)) \tag{2}$$

becomes equal to i at small impact parameters. Diffraction occurs when $S(b)|\psi_i\rangle$ is zero for some configurations, i, and far from zero for other configurations. In such a case the "shadow" of the inelastic collisions is not just the proton state but a wide variety of other states as well, that is diffractive states. Below ISR energies the proton is not black at any impact parameter and the shadow of these inelastic events is both elastic scattering and diffractive production. Here Regge theory works well. As one goes through the ISR region and into collider energies, central impact parameter collisions are becoming black and these regions contribute more strongly to elastic scattering and give much less diffraction than at lower energies.

Diffraction comes from those impact parameters where the S-matrix is changing from strong to relatively weak interactions. The Regge picture (pomeron exchange) now does not work because a single pomeron cannot properly describe a region where $S \approx 0$. In Regge language one needs multiple pomeron exchange for small impact parameter collisions and this considerably complicates the whole Regge picture and robs it of much of its predictive power.

Thus we qualitatively understand the behavior of the soft diffractive cross section. Attempts to make this explanation more quantitative are hampered by the lack of control over nonperturbativie QCD, but there are interesting phenomenological attempts in terms of multiple pomeron exchange[8] (absorption) and a suggestion that the "pomeron flux" may in some sense need to be renomalized as one reaches unitarity limits[2,1].

3. Hard Diffraction

We have seen that soft diffraction comes about at impact parameters corresponding to the transition from the region where $S = 0$ to the region where $S = 1$. This should also be the case for hard diffraction at Fermilab, while new elements come into diffraction at HERA, partly because a virtual photon is weakly interacting, and partly because a virtual photon is not quite a "state."

The motivation for looking at hard diffraction is clear. Unbiased hard interactions probe the parton structure of the proton and tell how many quarks and gluons are in a proton. In hard diffraction one probes the quark and gluon structure of diffraction itself. This is often described in a picturesque language as saying that hard diffraction studies the quark and gluon distribution of the pomeron[1,3,4] In a typical Fermilab diffractive reaction

$$\text{proton(p)} + \text{antiproton } (\bar{p}) \to \text{proton } (p') + X$$

with a large rapidity gap between p' and X one often pictures the process as $p \to p' +$ pomeron followed by the reaction

$$\text{pomeron } (p - p') + \text{antiproton}(\bar{p}) \to X.$$

If there are jets in X then this reaction can be used to study the parton structure of the pomeron and the antiproton in a standard way. This picture is a little suspect because we have already seen that in low impact parameter reaction a single pomeron does not dominate diffractive reactions. Also it is far from clear in what sense a pomeron can be treated as an incoming state. Nevertheless, it is clear that hard diffraction does study what partons are involved in diffractive reactions, and one may consider the whole description in terms of the structure of the pomeron as simply a picturesque language for describing the quark and gluon structure of diffraction. Similar hard diffraction can be studied at HERA[5] with the reaction

$$\text{proton}(p)\text{+photon } (Q) \to \text{proton}(p') + X$$

with, again, a rapidity gap between p' and the particles making up X.

Comparing hard diffraction at Fermilab and HERA gives a disagreement between the pomeron structure function of about an order of magnitude[3]. This is strong evidence for factorization breaking with HERA distributions much larger than the corresponding Fermilab ones. This result is not unexpected, and the cause is the same as that leading to the slowing of the growth of soft diffraction. Namely the pomeron is not really a universal object. In pomeron language there should be many pomeron exchanges occuring at Fermilab because unitarity bounds are being reached. The hard part of the reaction then does measure properties of this exchange. At HERA the exchange is much simpler because deep inelastic scattering is a point-like probe and it is this probe itself which is one of the scatterers initiating the reaction. Also in deep inelastic scattering one can view the virtual photon as turning into a quark-antiquark pair before the scattering. This quark-antiquark pair then scatters on the proton and both elastic and diffractive scattering of this pair will be counted as diffractive events in deep inelastic scattering. Thus there is no suppression of diffraction of HERA events at central impact parameter in contrast to what happens at Fermilab.

The nature of diffraction at HERA and at Fermilab is fundamentally different. In neither case have theorists been able to frame the discussion in sharp enough terms to make good use of the large amount of data which is already available and that which can be expected in Run II. Thus in the case of Fermilab it is certainly true that hard diffraction tells us something about the partonic structure of diffraction. But, to what extent are we probing the diffraction that occurs in soft processes at Fermilab, and to what extent is the hard process creating or modifying the diffraction? That is, what properties of diffraction are universal? Similar issues hold at HERA where one might say that large Q^2 diffraction is determining a particular event rather than measuring any particular property of a universal quantity, the pomeron.

In fact it may be that the focus on viewing diffractive hard scattering as probing a preexisting object is misleading. In particular another point of view has proved very successful in understanding and correlating diffraction and small-x structure functions in a low to moderate Q^2 regime at HERA. In this picture one chooses a frame where the virtual photon breaks up into a quark-antiquark pair before the scattering. Then the process is quark-antiquark pair scattering on a proton. If the scattering is inelastic then the process contributes to the inelastic part of F_2. If the scattering is elastic then the process contributes to the diffractive part of F_2. Thus, here, hard diffraction is the shadow of inelastic events. A rather simple model proposed by Goelec-Biernat and Wüsthoff incorporates unitarity limits (saturation) for the small-x scattering of moderate spatial-sized quark-antiquark pairs along with the probability that a photon will breakup into a pair of a certain size. This model comfortably describes moderate Q^2 deep inelastic scattering, F_2, and diffraction in a semiquantitative way which matches well with theoretical ideas of saturation and dense gluon systems. It is a great challenge to theorists to invent a comparably well-motivated model to deal with hard diffraction at Fermilab.

4. Rapidity Gaps Between Jets

There is a special class of diffractive events which have been pioneered at Fermilab in which one looks for events with a sizeable rapidity gap and where there is a hard jet on either side of the gap. For a gap size $\Delta Y \geq 3$ such events constitute about 1% of all two-jet events at Fermilab and about 10% of all two-jet events at HERA.

There is a good QCD motivation for studying such events. The basic hard process is elastic quark-antiquark (or gluon-gluon) scattering at large momentum transfer and at large rapidity. This seems a good place to measure the BFKL pomeron. However, for the rapidity gap to be present it is also necessary that the spectator parts of the colliding proton and antiproton not produce particles in the rapidity gap. The probability that the latter happens is called the "survivial probability" of the gap and is estimated to be about 10% at Fermilab[8]. From the BFKL pomeron point of view the most unfortunate part of the data is the fact that the percentage of gap events decreases when one goes from a center of mass energy of 630 GeV to 1800 GeV. At Fermilab the 1800 GeV runs should be predominately gluon jets while at 630 GeV quarks should dominate the hard scattering. The BFKL contribution (at comparable rapidity gaps) to the gap fraction should be enhanced for hard gluon scattering by a factor of $(\frac{N_c}{C_F})^2 = (\frac{9}{4})^2$ as compared to hard quark scattering. Thus we might expect the gap fraction to grow as one goes from 630 GeV to 1800 GeV while in fact the gap fraction decreases by a factor of 2.

What has gone wrong[9]? The most likely problem is that the survival probability also has an energy dependence[8] and that the survival probability is decreasing between 630 and 1800 GeV. It may be that there are still important contributions from secondary trajectories and that the BFKL pomeron is not dominating the hard scattering. Oderda and Sterman[10] have a variant on rapidity gaps where one requires less than a certain amount of transverse energy be emitted in the gap. This allows the QCD calculation, including color non-singlet exchanges, to be done reliably, but it does not eliminate the difficult survival probability questions. It would be interesting to analyze the data in the Oderda-Sterman way to see if the survival probabilities become significantly larger, and even more importantly, to see if the survival probability becomes energy independent.

There is a very simple picture, the "color evaporation" picture, which qualitatively describes the data[11,12]. Here one takes the hard scattering scattering to be given by a single hard gluon exchange. For example in $p+\bar{p} \to QX + \bar{Q}Y$ one views the X as the remnant of p after the quark Q is taken out and Y the remnant of $\bar{p}$ after $\bar{Q}$ is taken out. Q and $\bar{Q}$ are the (in this case quark) jets being measured. Thus X is a $\underline{3}\times\underline{3}$ representation of color $SU(3)$ while Q, $\bar{Q}$, and Y are $\underline{3}$, $\underline{3}^*$, and $\underline{3}^*\times\underline{3}^*$ representations respectively. The final state color singlet structure is then formed just by counting the ways in which the color representations can be combined into singlets. For example, Q and X have 27 different color states of which only one of them is a singlet. It is necessary to take this singlet in order to have a color singlet state on one side of the rapidity gap. These simple counting rules give reasonable numbers for the gap fractions and predict a decreasing gap fraction as one goes from 630 GeV to 1800 GeV because of the color counting change when Q and $\bar{Q}$ are replaced by gluons.

The color evaporation model is an interesting picture and may be a good hint about how the dynamics is working. However, without a stronger underlying QCD framework it will remain an intriguing curiosity. It is an important challenge to see if a QCD dynamical framework can be developed which leads to something like the color evaporation model.

5. BFKL Searches

There has been an important activity at Fermilab, at HERA and at LEP trying to measure the BFKL pomeron intercept. In the Fermilab analysis the reaction is

$$\text{proton}(p)+ \text{ antiproton } (\bar{p}) \to \text{jet}(k_1) + \text{jet}(k_2) + X$$

where $k_{1\perp}$ and $k_{2\perp}$ are greater than 20 GeV, and where $k_1/p = x_1$ and $k_2/\bar{p} = x_2$ are fixed to be the same at 630 and 1800 GeV. If one takes the ratio

$$R = \frac{\sigma_{2jet}(1800)}{\sigma_{2jet}(630)}$$

then BFKL predicts

$$R = \sqrt{\frac{\Delta Y(630)}{\Delta Y(1800)}} exp\{(\alpha_P - 1)[\Delta Y(1800) - \Delta Y(630)]\}.$$

ΔY is the rapidity interval between the two jets, but this is a purely inclusive measurement so there are no survival probability worries. At HERA one of the jets is replaced by the virtual photon and a similar formula holds. At LEP one simply measures the energy dependence of vitual photon-virtual photon scattering. Each of the accelerators have strong and weak points. The LEP analysis is certainly the cleanest, but so far there is a marginal amount of data. The Fermilab DØ experiment has very robust jets but $\Delta Y(630)$ is only about 2.4 and one may worry that this is not yet large enough for BFKL dominance. At HERA the jets have a rather small $k_\perp$ and the worry is that the jet cross section has not been properly identified.

Perhaps the surprising result[18] is that both Fermilab and HERA suggest that α_P is near 1.5, close to the leading order BFKL calculation. The present theoretical prejudice is that α_P will likely turn out to be nearer 1.25-1.3 when, and if, the dust settles over attempts to give a reliable answer for the higher order corrections. What is perhaps even more striking is that the BFKL evolution seems to be so prominent in this inclusive reaction while it appears to be completely masked by other effects in the more exclusive rapidity gap analysis.

Monte Carlo calculations[19] incorporating BFKL evolution suggest that BFKL effects should be suppressed by various kinematic and nonasymptotic effects. Is there another explanation of the strong small x growth seen in the Fermilab dijet data and the HERA forward jet data, or are the Monte Carlos overcompensating nonleading factors as perhaps the next-to-leading analytic calulations are doing? Much remains to be understood.

6. Run II Diffraction Prospects

Improved understanding of this new field of hard diffraction, requires new detectors for tagging and measuring scattered protons. In Ref [3], new results from a short data taking period with the CDF Roman pot spectrometer, show some of the possibilities of this new sub-detector. In Run II, this detector will be available for the whole run, and will be more fully exploited. The CDF Run II plans, including addition of new forward calorimeters and gap veto counters are outlined in Ref. [20].

DØ is in the process of installing a new Forward Proton Detector (FPD) (see Ref. [21]). This sub-detector consists of nine independent spectrometers which will maximize the acceptance for scattered protons *and* anti-protons. The FPD will be fully integrated into the DØ triggering and data acquisition systems and will provide unprecedented samples of hard diffractive events of all types.

Double pomeron exchange is the most intriguing process that can be studied with these new detectors [14], and there were many talks on this subject at the workshop [22]. In this process both the incoming proton and anti-proton are scattered but remain intact, and a massive central system may be produced. At the Tevatron objects with a mass of more than 100 GeV could be produced. With both arms instrumented it would be possible to measure both the proton and anti-proton using the FPD, and jets (for example) using the central calorimeter. This allows the kinematics of the event to be fully determined.

In addition, CDF can expand on its "gap+track" double pomeron results in Run I, where they tag an anti-proton and a gap. Although, these events are not gold-plated like the DØ double-tagged events, the acceptance penalty of tagging with both proton and anti-proton is avoided, and are thus the data sample is larger. DØ , of course can study both types of events, and combine the results to gain a deeper understanding of this process. Both collaborations will also be able to exploit double gap events as done by DØ in Run I [4], which will be especially valuable for rare events.

Measurement of hard double pomeron exchange would help determine the pomeron structure and provide unique information on the pomeron flux. Double pomeron exchange would have a normalization proportional to the square of the flux factor, unlike other hard diffractive processes. In addition, this process has been proposed as a trigger for Higgs production at the LHC, with optimistic assumptions [15], it might be possible to observe a handful of Higgs events via this mechanism during Tevatron Run II [17]. While this may be unlikely, these would be spectacular events with only the decay products of the Higgs in the central detector, and a proton and an anti-proton in the forward pot spectrometers. In any case, knowledge gained at the Tevatron would indicate if this approach is worth pursuing at the LHC.

Double pomeron interactions are also an ideal place to look for glueball production (bound states of gluons) and states with exotic quantum numbers, and the clean event topologies would make them easier to detect [14, 16,17].

In conclusion, the Run II outlook for hard diffraction and related topics appears to be quite bright and will require the best efforts of the experimental collaborations along with a recently invigorated theoretical community to finally unravel the mysterious pomeron.

REFERENCES

1. K. Goulianos, “Diffractive parton densities”.
2. M. Convery, “CDF results on double diffraction”.
3. K.Hatakeyama, “Diffractive dijets at CDF”.
4. A. Brandt, “DØ Rapidity Gap Studies”.
5. C. Royon, “QCD analysis of the diffractive structure functions measured at HERA and factorisation breaking at Tevatron”.
6. A. Solodsky, “Diffractive heavy flavor production at CDF”.
7. M. Wang, “Diffractively produced charm final states in pp interactions at 800 GeV/c”.
8. E. Levin, “Cost of Survival for Large Rapidity Gaps”.
9. B. Cox, “Is BFKL ruled out by the Tevatron gaps between jets data?”.
10. G. Sterman, “Interjet Energy and Color Flow”.
11. E. Gregores, “Color Evaporation Induced Rapidity Gaps”.
12. R. Engel and J. Ranft, “Monte Carlo simulation of color singlet exchange between jets”.
13. M. Strikman, “Hard color coherent phenomena”.
14. J. Pumplin, “Double Pomeron Physics in Run II”.
15. E. Levin, “Higgs and Heavy Quarks Diffractive Production”.
16. D. Kharzeev, “Diffractive Production of Glueballs”.
17. M. Albrow, “Glueballs and Exclusive Hadron Production at the Tevatron”.
18. R. Peschanski and C. Royon, “A determination of pomeron intercepts at colliders”.
19. L. Orr, “BFKL Monte Carlo for Dijet Production at Hadron Colliders”.
20. K. Goulianos, “Run 2 plans for hard diffraction studies in CDF”.
21. A. Brandt, “The DØ Forward Proton Detector”.
22. Working Group VI Web page, http://www.pa.msu.edu/˜schmidt/soft.html.