QCD Subgroup on Diffractive and Forward Physics

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ABSTRACT

The goal is to understand the pomeron, and hence the behavior of total cross sections, elastic scattering and diffractive excitation, in terms of the underlying theory, QCD.

I. INTRODUCTION

Over the last few years, there has been a resurgence of interest in small-x or diffractive physics. This has been due to the realization that perturbative QCD techniques may be applicable to what was previously thought of as a non-perturbative problem and to the opening up of new energy regimes at HERA and the Tevatron collider.

A gedanken experiment can be used to illustrate the basic ideas and phenomenology. Consider the scattering of two mesons each built from heavy quark-antiquark pairs (such as the upsilon)[1]. If the quarks are sufficiently heavy (*i.e.* $M_Q\alpha_s(M_Q) >> \Lambda_{QCD}$) their binding and hence the structure of the meson will be determined by perturbative QCD. Now consider the dynamics of the scattering in the limit $s >> M_Q^2$. In the case of elastic scattering, the lowest order contribution arises from the exchange of two gluons between the mesons. Since the meson is a color singlet with a size of order $r \sim \frac{1}{M_Q\alpha_s(M_Q)}$, virtual gluons with a wavelength, $1/\sqrt{(Q^2)}$, larger than this value do not couple to it. Perturbation theory which is valid while $Q^2 >> \Lambda_{QCD}^2$ should therefore be applicable to the computation of this scattering.

The situation is not quite so simple because fixed order perturbation theory is not applicable. The addition of an extra gluon exchanged between the two mesons gives rise to a factor of $\alpha_s \ln(s/M_Q^2)$, so that in the limit of large s it is necessary to include the effects of all of these exchanges, *i.e.* to sum up the terms of order $\alpha_s^n \ln^n(s/M_Q^2)$ while neglecting those of order $\alpha_s^n \ln^{(n-1)}(s/M_Q^2)$. After these terms are summed up the total cross section (equivalent to the imaginary part of the forward scattering amplitude) can be estimated with the result

$$\sigma \sim exp((\alpha_{IP} - 1)\ln s)$$

with $\alpha_{IP} - 1 = \frac{12\alpha_s \ln 2}{\pi}$. This growth cannot continue for ever as it would eventually violate unitarity.

The s-dependence of the total cross-section is of the same functional form as predicted by Regge theory where the cross section is viewed as arising from the exchange of non-perturbative reggeons in the $t-$channel. In the limit $s \to \infty$ only one of these reggeons survives; the pomeron. The exchange of many gluons corresponds to the same quantum numbers as pomeron exchange and it is tempting to equate the two. Hence this multi-gluon system is referred to as the BFKL (Balitsky,Fadin,Kuraev,Lipatov) pomeron[2, 3, 4].

There are several experimental conditions under which this BFKL pomeron or related phenomena might be observed. In order for the theory to be applicable, the gluon exchanges that build up the pomeron must be such that there are no small momentum transfers involved. Consider the production of a pair of jets at large transverse momentum in $p\overline{p}$ collisions at high energy. In perturbative QCD, this process is viewed as due to the exchange of a gluon in parton parton scattering (*e.g.* $qq \to qq$); one parton from the proton and one from the antiproton scatter and produce jets as the outgoing partons hadronize. Suppose that there is a large separation in rapidity between these jets; one goes in the direction of the proton and the other in the direction of the antiproton. We have four partonic systems: the two jets and the two beam fragments. All of these carry color since a single gluon was exchanged. As this system hadronizes, color must be exchanged. In the normal case, the jet and its closest beam fragment do not form a color singlet (as the total system exchanged a gluon with the other fragment jet pair) and the whole of the rapidity interval between the two beam fragments is filled with hadrons as soft gluons are exchanged. Contrast this with the situation that would arise if the two scattering partons exchanged a color singlet object such as the pomeron. Now the jet and the nearest beam fragment form a color singlet and there is no necessity for gluon exchange, and hence particle production, in the rapidity region **between** the two jets. Events of this type have been observed [5, 6]. For more theoretical discussion of this issue see [7].

Another possible manifestation of the BFKL phenomenon in $p\overline{p}$ collisions is in the behaviour of the dijet cross section as a function of the rapidity interval between the two jets. As stated above, at lowest order in perturbative QCD, this is due to the exchange of a gluon between the partons that make up the jet. At next order in α_s there is a correction proportional to $\alpha_s y$ where y is the rapidity interval between the two jets. If y is sufficiently large, perturbation theory is not reliable and one must sum all orders in $\alpha_s^n y^n$. This resummation gives a cross section which has a factor of $exp(3\alpha_s |y| /\pi)$ [8]. This growth with y is not observable at the Tevatron since it is more than compensated by the drop off caused by the falling structure functions. It may be observable at LHC [9]. However other related effects should be observable. The rapidity region between the two jets is filled with many mini-jets since there is no penalty of α_s to pay for each gluon emission. The correlation in ϕ between the two trigger jets should show a rapid fall off as y is increased. Although the data [10] show a decorrelation stronger than that of a fixed order α_s^3 prediction, the fall-off is much slower than predicted by the BFKL phenomenon and is in fact consistent with that expected from showering Monte Carlos such as HERWIG[11].

The BFKL resummation can also be used to predict the behaviour of the proton structure function at small-x. The result is a structure function that rises very rapidly at small-x. While this behaviour is seen at HERA[12], it cannot be used to distinguish between evolution expected from BFKL and the usual DGLAP[13] Q^2 evolution predicted by perturbative QCD, so this may not be a good place to investigate the BFKL phenomena [14].

II. EXPERIMENTS AT HADRON-HADRON COLLIDERS

A. Elastic Scattering

We can distinguish three regimes in high energy elastic scattering, differing in their 4-momentum transfer squared t. At the smallest $|t|$ values, much less than about 10^{-2} GeV^2, Coulomb scattering dominates, and at higher values pomeron exchange produces an exponential t distribution with a slope of about 17 GeV^{-2} (at the Tevatron). The region near 10^{-2} GeV^2, where photon and pomeron exchanges are comparable and interfere, is especially interesting as it allows measurement of the phase of the pomeron amplitude (ρ, the ratio of real:imaginary parts). Experiment E811 took data in a special 5-day run in January this year in an attempt to improve our knowledge of ρ but results are not available at the time of writing. Apart from its intrinsic interest a good knowledge of ρ constrains, through dispersion relations, the total cross section at much higher energies, e.g. at LHC. When the results of E811 are final it will be time to assess whether better Coulomb scattering experiments are justified at the Tevatron, and how they could be done. This was not discussed in our Group.

The larger $|t|$ scattering region shows an exponential behavior within the limited region over which it has been measured at the Tevatron. From an experimental point of view this makes it simple, with only two parameters to measure: slope and intercept. (This assumes we neglect spins and do not try to measure polarizations; these may however show non-trivial behavior. Experiments at RHIC will study polarization in pp elastic scattering at $\sqrt{s} = 400$ GeV, with results perhaps by 2001? The possibility of polarized p beams in the Tevatron may exist, but has not to our knowledge been taken seriously, and we are not suggesting that it should be.) The elastic slopes and intercept are important on the one hand for relating to the total cross section (through the optical theorem), and on the other hand for relating to other diffractive processes such as single diffractive excitation. However it is not generally considered likely that elastic scattering will provide a breakthrough in understanding the pomeron.

The third region of Tevatron energy elastic scattering is beyond $|t|$ = 1 GeV^2 where at the lower energies of the ISR [15] and the $Sp\bar{p}S$ there is localized structure after which the slope becomes much less. This is certainly an interesting region which has been completely ignored at the Tevatron. According to A.Donnachie and P.Landshoff [16] it shows a transition between a 2-gluon exchange pomeron and a 3-gluon exchange "odderon" (C = -1). A good dedicated experiment to measure $p\bar{p}$ elastic scattering from about 0.5 GeV^2 to above 8 GeV^2 at preferably three $\sqrt{s}$-values would probably be most interesting. We do not know how feasible this is in terms of running conditions and time, but it is not obviously out of the question.

B. Single Diffractive Excitation, SDE

In single diffractive excitation one of the protons scatters almost elastically, and the other becomes a massive multiparticle system. A standard way of thinking about this is that a pomeron is emitted from one beam particle, which has a pomeron "flux" associated with it, and interacts with the other beam particle with a total cross section $\sigma_{I\!Pp}$ [17]. Although this paradigm is not theoretically very sound, it is very useful phenomenologically and enables us to compare experiments and easily think about future experiments to test it. With it comes the concept of a pomeron structure of quarks and gluons, a structure function which can be measured in different ways to study consistency. For example a great deal of work is being done at HERA (see Section on Electron-Proton Colliders) on what are considered (in this paradigm) as photon-pomeron collisions, while the study of hard processes in pomeron-proton collisions (SDE) can measure the partonic structure of the pomeron in quite a different way. If the quasi-elastically scattered particle is measured, the t of the pomeron and its momentum fraction ξ (nominally less than about 0.05, the quasi-elastic proton having Feynman-x, x_F above 0.95) are known. Transforming to the center of momentum of the pomeron-proton collision, measurements of produced high E_T jets, W, Z and Drell-Yan pairs, and heavy flavors b and c enable one to probe the structure function of the pomeron. Adjacent to the high x_F proton is a rapidity gap, a region of rapidity containing **no** hadrons. An alternative to measuring the quasi-elastic proton is to require a large rapidity gap, typically more than three units. This has the advantage and disadvantage of integrating over t and ξ of the pomeron. One can get a lot more rate, and without the trouble of making *Roman Pot detectors* to tag the quasi-elastic proton. On the other hand one cannot study the t and ξ behaviors, and the kinematics are not so well determined. Both the high-x_F method and the gap method are used by CDF, while DØ (who do not yet have Roman pots) use the gap method.

With two high-E_T jets in pomeron-proton collisions, in principle one can reconstruct the momentum fractions of the scattering partons (x for the parton in the proton, β for the parton in the pomeron). A third jet, if present, can be handled by e.g. combining it with the nearest neighbor. Then one could (with sufficient statistics!), knowing the proton's structure function, derive a (combined q and g, effective) structure function for the pomeron. One could in principle do a similar thing with W (although at the Tevatron, statistics will probably always be too limited) and Drell Yan pairs and with heavy quarks, and because the latter come from a different q/g mix obtain separate distribution functions for quarks and gluons in the pomeron. This should be done for different values of t. In practice what is done now is that distributions in the data such as the E_T of jets and their pseudorapidity η are compared with the results of a Monte Carlo simulation in which one has specified some simple function for the parton distribution G(β) in the pomeron. One sees differences in the predictions for a hard $\beta(1-\beta)$ distribution and soft (1-$\beta)^5$ distributions, in particular the jet η values are more central (closer to the gap) with a hard parton distribution.

First experimental results on this subject were published by the UA8 Collaboration, which showed the existence of jets in single diffractive events [18] and that these jets had rapidity distributions consistent with a hard pomeron structure [19]. There was also evidence for a "superhard" or "coherent" pomeron, where the entire momentum of the pomeron participates in the hard scattering.

The CDF data, with a Roman pot track with $0.05 < \xi < 0.10$ and two jets with $E_T > 10$ GeV, do not agree well with either soft or hard ansatz. A warning is that in this ξ range non-diffractive (e.g. Regge exchange) processes become important; this can be studied by measuring the ξ-dependence of the "pomeron" structure function which should be done, but of course demands even higher statistics. To make progress with the present data one should probably try to fit more differential data (e.g. the triple differential cross section vs E_T, η_1, η_2) with a wider choice of parton distribution forms, or $derive$ the parton distribution as outlined above. Another study that should be done is to take the β-distributions that fit the HERA $\gamma I\!P$ data and use them to predict the Tevatron data. CDF uses the diffractive event generator POMPYT 1.0 [20] which is based on PYTHIA [21], but allows a pomeron to be one of the beam particles. Currently the pomeron structure functions are not evolved with Q^2, but evolution should be implemented. The H1 data imply that at low-Q^2 the pomeron has a gluon β-distribution very strongly peaked near β = 1 (the pomeron is dynamically like a single gluon; the color is neutralized by "something else") which of course evolves away at large Q^2.

CDF has a few thousand diffractive dijet ($E_T > 10$ GeV) events taken with Roman pots in the last few weeks of Run 1. While these are still being analyzed it is clear that the statistics are at least one, and really two, orders of magnitude less than one would like to carry out a desirable program. This would include (a) extending the study to smaller ξ where the pomeron is more dominant, and measuring the ξ-dependence of the structure function of the exchanged object ($I\!P + R$); (b) deriving the β-distributions of quarks and gluons separately in the pomeron; (c) studying any t-dependence of these parton distributions; (d) studying the Q^2 (E_T^2) dependence of the parton distributions.

Both CDF and DØ have now very good evidence for diffractive dijets from seeing an excess of rapidity gaps in one beam direction (without seeing the high x_F particle), see Fig. 1.

The data are mostly at $\sqrt{s}$ = 1800 GeV, but DØ has also analyzed data at $\sqrt{s}$ = 630 GeV [22]. These are single diffractive events integrated over t and ξ and the cross section depends on the pomeron flux $\times$ $\sigma_{I\!Pp}$. About 1% of all dijets are diffractively

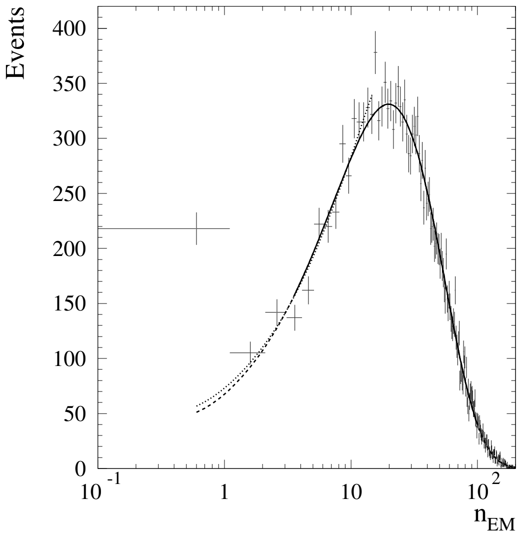

Figure 1: A DØ preliminary result showing the number of calorimeter electromagnetic towers (n_{EM}) above a 200 MeV threshold for the region $2 < \eta < 4.1$ on the side opposite dijets with $\eta > 1.6$ and $E_T > 12$ GeV. The curves are negative binomial fits to the data excluding low multiplicity bins. A striking excess of events is observed in the zero multiplicity bin, qualitatively consistent with expectations from hard single diffraction.

produced. Both CDF and DØ observe that the diffractive dijet events are cleaner (with less probability of a third jet etc.) than non-diffractive dijet events. The jet E_T spectra are very similar in events with and without a rapidity gap - this was also seen in the pot events of CDF.

CDF also have evidence for diffractive production of Ws. One beautiful event has a pot track and at least 4 units of rapidity gap. There are a couple of similar candidates but with such low statistics not many conclusions can be drawn. However the search for rapidity gaps in CDF's large sample of Ws was successful after exploiting the expected correlations between the lepton angle and charge with the rapidity gap side. The result is that (1.15$\pm$0.56)% of all Ws at the Tevatron are diffractively produced. While this is already useful, if the error bars were reduced by a factor 5 or more this would be a powerful constraint on the quark content of the pomeron. Unfortunately a factor of 5 reduction in error will be hard to get; in Run II the luminosity will be higher and the fraction of single events will be low. For studies using gaps it is of course necessary to select single interactions, and the optimal luminosity is when the average number per crossing is 1.0; it will be "several" in Run II.

The observed rates of diffractive dijets and Ws can be combined to limit a region in the plane: momentum sum (partons in pomeron) vs gluon momentum fraction. HERA can similarly constrain a region; rather than Ws they probe the quarks directly with photons. The combination of the two is shown in Fig. 2.

Other constraints on the pomeron structure function, and a check on the consistency of the jets and W, would come from diffractive heavy flavor production. UA1 claimed to see a signal [23]. CDF has looked [24] for central leptons from heavy flavor (mainly b) decay together with a high x_F antiproton. The statistics are very limited and at the present time only an upper limit can be given: at 90% c.l. less than 0.9% of central b/c-quarks are diffractively produced. Other channels (eg the

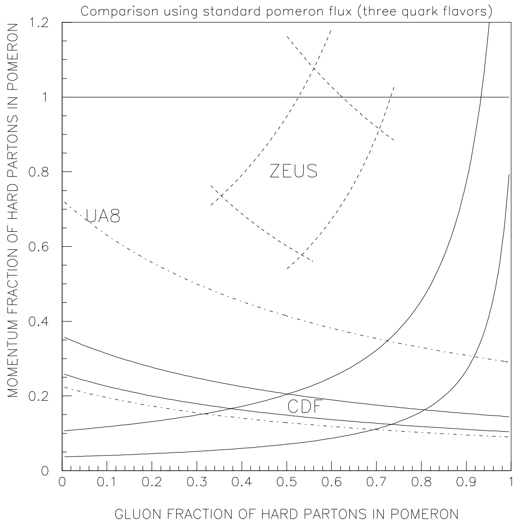

Figure 2: The fractional momentum sum of partons in the pomeron *vs* the fraction of momentum carried by gluons. Crossing CDF bands come from the dijet rate (decreasing with gluon fraction) and W-production (a larger momentum fraction needed as the gluon fraction increases). Crossing ZEUS bands come from the diffractive photoproduction rate and the total diffractive cross section in DIS. Q^2-dependence is neglected. The CDF and ZEUS diamonds overlap if the pomeron flux is "renormalized" down.

$D^* - D$ method) may be able to extract a positive signal, but one may have to resort to the rapidity gap method (where there are much more data as well as a larger cross section) to pursue diffractive charm before Run II.

C. Double Pomeron Exchange

It would be very interesting to compare a third process with SDE and ep, and *Double Pomeron Exchange* is such a process. Both incident hadrons emit pomerons which interact in the central region. Masses up to 90 GeV correspond to both $\xi < 0.05$ at the Tevatron, and this is in the range where jets can be produced. However it will not be easy unless the parton distributions in the pomeron are much harder than in the proton (after all it took very high statistics and excellent calorimetry to see jets at the ISR with $\sqrt{s}$ = 63 GeV!). But there were indications of jets in DPE at the lower energy CERN Collider [25] : 5% of events with two forward rapidity gaps (3 units) had a jet above 10 GeV. DØ have selected jet events with a rapidity gap on one side and looked for evidence for an excess of gaps on the other side. A sample of double gap events has been observed, although an interpretation in terms of hard double pomeron exchange requires further study [22]. It is clear that these double gap events are rare, on the order of 10^{-6} of inclusive dijet events. CDF looked for two gaps in their data with a small-ξ pot track but do not have evidence for a signal. Although double pomeron exchange producing jets (and heavy flavors) probably has a very small cross section, it is clearly worthwhile to search for such events. Apart from the fact that it gives us a third channel (with γIP and pIP) to study factorization and our whole picture of diffraction, double pomeron interactions have many special features. At low masses, such as were accessible at the ISR but should also be there at the Tevatron, albeit never looked at, the resonance region is a good hunting ground for new hadronic states, especially glueballs [26]. The central hadronic system is constrained to have $I^G J^{PC} = 0^+ J^{++}$ with J even, and any glueballs with these quantum numbers must be produced. The idea that the pomeron and glueballs may lie on the same trajectory reinforces this expectation. One pomeron, as a virtual glueball, will be diffractively scattered into its real state. There is a candidate from the Omega Spectrometer [27] at 1.93 GeV in 4 pions which could be the spin-2 glueball on the pomeron trajectory. To study this region (and higher masses) in a multiparticle spectrometer at the Tevatron could be very rewarding.

D. Gaps between Jets

In 1992 Bjorken and others [7] predicted that at a level which could be as high as a few percent, two high E_T jets well separated in rapidity could have a rapidity gap between them. This means, of course, an excess of events with no hadrons in the gap Δy compared with what one would expect from the overall multiplicity distribution. Such rapidity gaps were found by CDF [28] and DØ [29] at a level near 1%. In order to have a large gap, the right-moving and left-moving systems should be colorless. Therefore we must have a colorless "object" exchanged between the scattering quarks/gluons, and it carries very large momentum transfer, $t \approx 1000$ GeV^2. This is presumably related to the low-t pomeron, and is sometimes called the *hard pomeron*, not to be confused with a low-t pomeron with a hard structure. This hard pomeron may behave dynamically like a single hard gluon, with the color neutralized or "bleached" by a soft colored field. This is a picture which recurs increasingly, even in non-diffractive processes such as ψ, ψ' production at the Tevatron.

To progress with the study of JGJ or jet-gap-jet events we need to investigate the E_T and Δy dependencies and, to the very limited extent possible, the $\sqrt{s}$ dependence. DØ find that, keeping the gap region $\Delta\eta_c$ edges 0.7 units from the jet cores, the gap fraction is constant at about 1% as $\Delta\eta_c$ increases. They also find that is rises with jet E_T, from about 0.4% at 18 GeV to about 1.5% at 50 GeV. This is surprising, and the opposite of what a BFKL calculation expects. DØ have also looked at $\sqrt{s}$ = 630 GeV data and find the same gap fraction (for $E_T > 12$ GeV) as at $\sqrt{s}$ = 1800 GeV. Apart from extending and improving these measurements, it would be very interesting to apply quark/gluon jet tagging techniques to these samples. This can only be done on a statistical basis, but it could answer the question whether the gap events have the same q/g composition as the non-gap events. At least quark-exchange (in $qg \rightarrow qg$) probably never has gaps.

Another line of experimentation at the Tevatron (and LHC), which requires very good forward (large η) calorimetry is to look for gaps in multiple parton scattering. Double parton scattering, where two separate $2 \to 2$ processes occur, has been observed at the ISR [30] and in CDF [31]. Suppose we have an event with four jets, two at large +ve η and two at large -ve η. Suppose further that we can use the kinematic jet-balancing technique to select the subset of events that came from double parton scattering. Now measure the gap fraction for those: is it like 1% or $(1\%)^2$? This will provide information on the color-neutralization, and whether it acts between the scattering partons or the left/right-moving systems.

E. MiniMax, T864

A discussion of forward and diffractive physics at the Tevatron (Run I) would not be complete without mentioning the MiniMax initiative, although strictly speaking it was a test rather than a fully-fledged experiment. Nevertheless it seems very likely that physics results will be published on particle production in the forward region, with and without a very-forward particle tag (diffractive scattering)[1]. The focus is on a search for signs of events with Disoriented Chiral Condensate (DCC) which would have a very abnormal charged-to-neutral ratio. Some events with these characteristics have been seen in cosmic rays. If the DCC exists and can be studied it would be a very important breakthrough in our understanding of the vacuum.

F. Future Plans for Run II at the Tevatron

Both CDF and DØ have very similar plans for diffractive and forward physics for Run II and we discuss them together. Studies of SDE with tagged quasi-elastic (anti)protons really need to be increased in statistics by two or more orders of magnitude over what CDF were able to collect in Run Ic ($\sim$ 5000 dijets over 10 GeV). This can probably be achieved with (a) much longer running time (implying a trigger that can operate all the time, not for special runs); (b) acceptance to smaller values of t, ξ where the cross section is much bigger than in CDF's Ic pots; (c) pots on both downstream arms, gaining a factor $\times 2$; (d) more selective triggers e.g. pot+gap+lepton. It will probably be necessary to require at least the seed of a gap in the trigger, which will also usefully veto on multiple interactions. Such multiple interactions will be a serious limitation for gap physics in Run II, but by vetoing them at the trigger level the gap studies will not impose much dead time at the higher luminosities.

Another important physics goal for Run II should be to study fully constrained double pomeron events, with both high x_F tracks measured. This is another, perhaps more important, reason for needing pots on both beams. Acceptance at small ξ, about 0.01-0.04, is necessary to cover the region populated with jets with E_T 10-30 GeV. The jet spectra are given by convoluting the pomeron structure function with itself, now independent of the proton's structure function. We should study Q^2 dependence, and dependence on t_1, ξ_1, t_2, ξ_2 ... is there factorization? Does the pomeron structure function we derive from SDE and γIP work also for DPE?

Another important ingredient of the CDF and DØ detectors is maximizing the coverage at large rapidity. DØ are constrained by the liquid argon calorimeters but will insert downsteam counters where possible. The CDF plug upgrade calorimeters leave angles below 3^0 uninstrumented, an η of only 3.6. Ideas will be proposed to fill this region, down to the beam-pipe at 0.5^0 ($\eta = 5.4$) with a "Miniplug" calorimeter. This will be small and not deep enough to fully contain hadron showers, but it will be efficient at detecting photons and all charged and neutral hadrons. Not only is this excellent for gap detection but it will help extend the very forward jet physics. The physics of the jet-gap-jet events will benefit greatly from being able to use jets with η between 4 and 5.

Of course all these studies should benefit from the already approved upgrades to CDF and DØ (central tracking, calorimetry, magnetic field for DØ , etc.)

The possibility that a new experiment could be carried out in intersection CØ was investigated by a working group initiated by J.Peoples in Spring 1996. Apart from the possibilities of a dedicated central B-physics experiment there was a clear interest in pursuing forward and "full acceptance" physics, perhaps during an early part of Run II with modest luminosity. An "Expression of Interest" was prepared by the T864 group (Case Western Reserve Univ., Univ.Michigan and J.D.Bjorken (SLAC)) who, as discussed above, have been active in CØ in Run I looking for signatures of Disoriented Chiral Condensate in the forward direction. There is a very large physics agenda, mostly of studies that are inaccessible to CDF and DØ . It includes rapidity gaps in soft and hard diffraction, double diffractive dissociation (never measured at the Tevatron!) and the onset of BFKL enhancements, forward strangeness, charm and beauty production, multiparticle correlations, forward neutrons and a search for new long-lived neutral hadrons, etc. It is clear that there is a very extensive physics program which has been completely ignored at the Tevatron, in fact since the ISR in the 1970s, a factor 30 lower in energy. It may well be that when LHC starts the high mass (top, Higgs, SUSY etc.) physics at the Tevatron will become obsolete while this forward or full acceptance physics will be very interesting and could extend the useful life of the Tevatron. Of course we should not wait until the LHC starts before starting this program!

G. Opportunities at LHC

Along with the factor of seven increase in center of mass energy the LHC has important advantages over the Tevatron for diffractive physics. The overall rapidity span increases from 15 to 19 units, but perhaps more impressive is the mass reach of diffractively produced states. For example for double pomeron exchange (with $x_F > 0.95$) the central masses extend to 90 GeV at the Tevatron and 700 GeV at LHC. The former will enable high-E_T jet physics but the latter also electroweak probes, W, Z. There has been some speculation about Higgs production in DPE, but also (and with more justification) about electroweak Higgs production between rapidity gaps and thus with the same signature. This is the WW-fusion process, where exchanged Ws being colorless (spin-1) objects should leave rapidity-gaps like pomerons (modulo a survival probability). However a major problem with any rapidity gap physics at LHC is that the lu-

[1] see MiniMax Web page http://fnmine.fnal.gov for the latest MiniMax publications.

minosity will normally be so high that all interactions will be multiple. It is unlikely that good gap physics can be done when more than one interaction occurs. Also, in terms of rapidity space, the big central detectors CMS and ATLAS are only covering about half.

A proposal is therefore being developed for a "Full Acceptance Detector" called FELIX [32]. The plan is to have a good central detector based on re-use of ALEPH and the UA1 magnets, followed by very forward calorimeters and trackers extending about 450m for elastic and diffractive measurements. The physics goals are to measure all charged particles and photons over the entire phase space, not compromising the physics of rapidity gaps. Muons and jets should be measured also in the far forward region. Diffractive and elastically scattered protons should be well measured. It will also provide information much needed by the ultra-high energy cosmic ray community about forward particle production in 10^{17} eV cosmic ray interactions. In the view of this working group this represents an exciting and powerful tool and will hopefully be approved.

Even if FELIX proceeds there may be good reasons for CMS and ATLAS to install Roman pots to tag high-x_F protons and include triggers on diffractive jets, W, Z etc. We did not study the problem of random coincidences, which may be severe at standard luminosities. The pots may be needed anyway for luminosity monitoring.

H. Beyond LHC: the Very Large Hadron Collider

A major goal of the Snowmass meeting was to consider physics at possible future e^+e^-, $\mu^+\mu^-$ and pp colliders at very large energies. For lepton-lepton colliders the only physics we now see which is obviously relevant to the issues of this group is that of two-photon processes. Massive virtual photons convert to small $Q\bar{Q}$ (color dipole) states which can scatter elastically through "hard pomeron" or two-gluon exchange. The exclusive process $\gamma^*\gamma^* \to VV$, where V is a heavy vector meson appears to be calculable in pQCD, as explained in the introduction. However the proton-proton collider, $VLHC$ or $Pipetron$ or $Omegatron$, with 50 TeV - 100 TeV per beam, is obviously a very exciting machine from our point of view. There are 25 units of rapidity to work with. The equivalent lab energy is 10^{19} eV close to the Greisen Zatsepin Kuz'min (GZK) cut-off in the cosmic ray spectrum. Any of the several cosmic ray anomalies must be well into this energy regime, and even if they are due to nuclear collisions any pp machine can also collide heavy ions. Pomeron-pomeron collisions up to 5-10 TeV may be reached, presumably well into the SUSY and Higgs sectors. Any (almost inevitable) surprises at LHC will probably be amplified for the VLHC. A discussion of forward physics studies is included in these proceedings [33]. However the need for very high luminosity (10^{35} to $10^{36} cm^{-2}s^{-1}$) for the very high mass and point-like physics implies perhaps 100 interactions per crossing into a "central" detector, orthogonal to the requirements of a full acceptance detector. Therefore we envisage that the VLHC should have (at least) two big detectors, one for high luminosity, very high p_T and mass physics, and another that has perhaps 10^{-3} lower luminosity to be able to study single interactions, in a straight section of $\pm$ 2 km. A design for this insertion was presented by L.Jones [33], using alternating dipoles through tracking and calorimetry stations for 2 km along the beams. There would be an enhanced central detector (but not competitive for high luminosity) perhaps similar to upgraded CDF/DØ. It is important that the case for such a full acceptance detector be recognized early enough to ensure that a 4 km straight section is built in to the machine design.

III. ELECTRON-PROTON COLLIDERS

A. Introduction

The revival of the interest in diffractive phenomena has come, in part, from the observation of rapidity gap events at HERA that occur in Deep Inelastic Scattering (DIS) at high Q^2, the exchanged photon virtuality, and small x. These events can be explained in terms of the diffractive dissociation of a virtual photon, γ^*. These hard diffractive scattering events provide an opportunity to probe the interplay between hard and soft pQCD phenomena. By varying the Q^2 of the interaction from nearly zero to values $\sim$10 GeV^2, one can probe interactions from a large size configuration (soft processes) to those from a small configuration (hard processes) [34].

In analogy with the total DIS cross section, the diffractive cross section in DIS can be written as [35]

$$\frac{d\sigma^D}{dx_{I\!P}dtdxdQ^2} = \frac{4\pi\alpha_{em}^2}{xQ^4}\left[1 - y + \frac{y^2}{2[1+R^D(x,Q^2,x_{I\!P},t)]}\right] F_2^D(x,Q^2,x_{I\!P},t)$$

where D denotes the diffractive contribution, $R^D = F_L^D/(F_2^D - F_L^D) = \sigma_L^D/\sigma_T^D$ and $\xi = x_{I\!P} = \frac{Q^2+M_X^2-t}{Q^2+W^2-M_p^2} \approx \frac{Q^2+M_X^2}{Q^2}x$ where X refers to the hadronic final state system produced at the lower (proton) vertex. Within the specific framework of the Ingelman-Schlein model [17] where a pomeron flux is convoluted with a pomeron structure function and a hard two-body scattering cross section, it is expected that the diffractive structure function can be factorized: $F_2^D(x,Q^2,x_{I\!P},t) = f(x_{I\!P},t)F_2^{I\!P}(\beta,Q^2,t)$, where $\beta = \frac{Q^2}{Q^2+M_X^2-t} \approx \frac{Q^2}{Q^2+M_X^2} = x/x_{I\!P}$. In the case where t is not measured, but integrated over, F_2^D becomes $F_2^{D(3)}(\beta,x_{I\!P},Q^2)$. Comparison of this model with data provides an insight to the diffractive exchange mechanism and the partonic structure of the pomeron.

While most of the studies of diffraction at HERA are based on the rapidity gap method, more recent data have been collected with Leading Proton Spectrometers (LPS) involving Roman pot detectors. These data provide a sample of events with smaller statistics and different systematics but also with measured t and a cleaner interpretation as diffraction, with less background from reggeon exchanges.

In view of the substantial rise in the proton structure function $F_2(x,Q^2)$ at small x and large Q^2, which can also be viewed as a rise in the γ^*p total cross section, it is of great interest to understand the role that diffraction plays at small x (or equivalently, large $W^2 \sim Q^2/x$). A detailed report from the "Diffractive

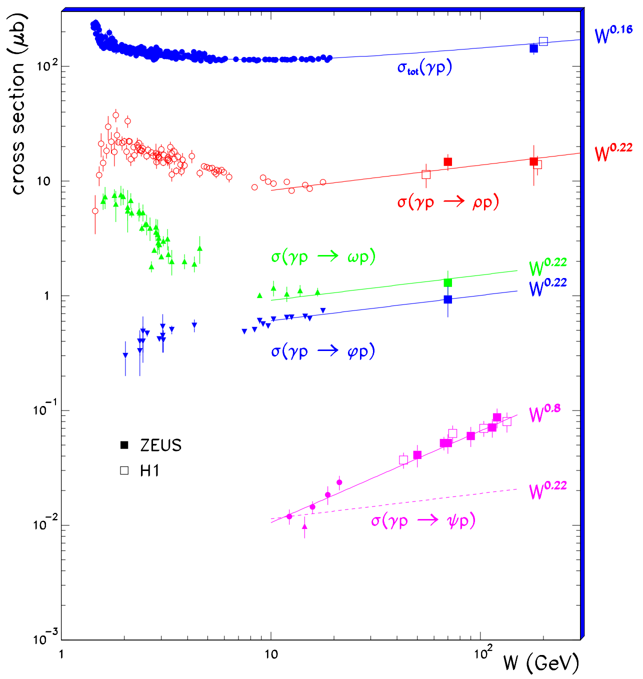

Figure 3: Cross sections for exclusive vector meson photoproduction as a function of the γp center of mass energy, W.

Hard Scattering" working group at HERA illuminates these and other issues [34]. The HERA experiments have obtained data on several exclusive final states as well as on inclusive diffraction. These are reviewed in the following sections.

B. Exclusive or "Elastic" Scattering

By studying the exclusive production of a vector meson (V) in the reaction $ep \to eVp$, the study of the process $\gamma^* p \to Vp$ has provided a means to examine the interplay between the soft processes at $Q^2 \approx 0$ and the hard processes that occur at large Q^2 ($\sim$ 10 GeV^2) and/or large M_V (e.g. for the J/ψ). The data show that the exclusive (elastic) cross sections rise with increasing γp center of mass (CM) energy like $W^{4\epsilon}$ with $\epsilon \approx 0.08$, as obtained by Donnachie and Landshoff for the πp, pp and $\overline{p}p$ total cross sections with a pomeron Regge pole intercept of $\alpha(0) = 1 + \epsilon = 1.08$. These results are summarized in Fig. 3.

On the other hand, J/ψ production at both small (see Fig. 3) and large Q^2 (not shown), as well as ρ and ϕ production at large Q^2 (not shown), appear to have cross sections which rise faster, with $\epsilon \approx 0.15 - 0.2$. In addition, it seems that the vector mesons are increasingly longitudinally polarized and the slopes of their t distributions are smaller than those produced in photoproduction (at $Q^2 = 0$). At the present time, these exclusive reactions are the only direct measurements showing that the longitudinal component is dominating the diffractive process. Clearly it is important to determine the longitudinal contribution to the inclusive diffractive final states.

These exclusive processes have recently provided a test of pQCD in that such processes have now been calculated explicitly, albeit at lower orders [36]. More recent calculations for the process $\gamma^* p \to Xp$ where X is a system consisting of two high p_T jets have not yet been confronted by data.

Viewed in the proton rest frame, the γ^* fluctuates into a $q\overline{q}$ pair with large relative transverse momenta (or small transverse separation) which then interacts with the proton. This interaction is then dominated by gluon exchange diagrams and the resulting cross section becomes related to the square of the gluon density in the proton, $\sigma \sim [xG(x, Q^2_{eff})]^2$.

C. Inclusive Diffraction at large Q^2

"Rapidity gap" events, observed as interactions with no particles produced in a rapidity region near the proton direction, showed that diffraction in DIS is about 10% of the inclusive DIS cross section and shows a significant leading twist effect when studied as a function of Q^2 [37]. More recent data from both the H1 and ZEUS experiments [38] have been used to measure the diffractive proton structure function, $F_2^{D(3)}(\beta, x_{I\!P}, Q^2)$. The dependence of $F_2^{D(3)}$ on $x_{I\!P}$ was found by H1 to be independent of Q^2 but to depend on β, indicating that the factorization into a universal pomeron flux (depending only on $x_{I\!P}$) and a structure function depending on β and Q^2 is not valid. However, these deviations were found to be consistent with two components individually satisfying Regge factorization. One component can be identified as the pomeron with $1/x_{I\!P}{}^{n_{I\!P}}$ behavior, and $n_{I\!P} = 1.29 \pm 0.03 \pm 0.07$. The other can be identified as a reggeon meson exchange contribution with $1/x_{I\!P}{}^{n_M}$ behavior, where $n_M = 0.3 \pm 0.3 \pm 0.7$. Similiar data from ZEUS yield a value for $n_{I\!P} = 1.46 \pm 0.04 \pm 0.08$. Since Regge factorization is satisfied, a DIS pomeron structure function $F_2^{I\!P}(\beta, Q^2)$ can be extracted. The results for the β and Q^2-dependence of $F_2^{I\!P}(\beta, Q^2)$ are very striking.

At fixed Q^2, $F_2^{I\!P}(\beta, Q^2)$ is essentially independent of β. There is no evidence for the fall with increasing parton momentum fraction characteristic of the structure functions of hadrons. $F_2^{I\!P}(\beta, Q^2)$ also shows no large variation with Q^2, although there are very clear logarithmic scaling violations. The most striking feature is that a rise with ln Q^2 persists to at least $\beta \sim 0.65$, far beyond the point ($x \sim 0.15$) at which the structure function of the nucleon is dominated by valence quarks rather than by gluons, and $\frac{\partial F_2(x,Q^2)}{\partial ln\ Q^2}$ correspondingly becomes negative. H1 have analysed the ln Q^2 scaling violations in terms of QCD DGLAP evolution. They find that at $Q^2 \approx 5$ GeV^2 a structure function in which gluons carry close to 90% of the pomeron momentum, with the gluon density extremely strongly peaked close to $\beta = x_{i/I\!P} = 1$, is necessary to fit the persistence of the logarithmic rise with Q^2 to large values of Q^2 and β. Such conclusions are also supported by analyses of diffractive DIS hadronic final states[39].

These last results are very difficult to understand in QCD-based models of the pomeron involving the color zero exchange of two (perturbative or non-perturbative) gluons. Indeed, the obvious conclusion from the data that the pomeron looks like a single gluon at large Q^2 is *a priori* difficult to reconcile with gauge invariance. Consequently DIS diffractive scattering may

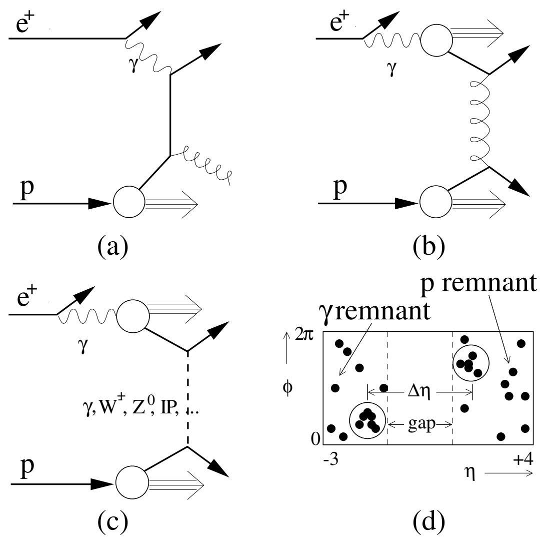

Figure 4: Feynman diagrams of LO processes in hard photoproduction: (a) and (b) are examples of direct and resolved contributions; (c) shows a color singlet exchange diagram and (d) shows how an event of the type displayed in (c) would appear in $\eta - \phi$ space.

be providing important insight into the origin of the pomeron in QCD[40].

Studies are in progress to compare models suggested by the HERA results with the data discussed earlier for diffractive W and diffractive dijet production at the Tevatron. Studies for the HERA workshop [41] indicate that higher luminosities (in excess of 100 pb^{-1}) are desirable in order to test in detail the validity of both factorization and NLO QCD in diffractive interactions, to measure $R = \sigma_L/\sigma_T$ for diffractive DIS and to obtain sufficient statistics for diffractive open charm production.

First measurements of inclusive DIS diffraction with the ZEUS LPS have yielded a t distribution with a $d\sigma/dt \sim e^{bt}$ dependence and $b = 5.9 \pm 1.2^{+1.1}_{-0.7}$ GeV^{-2}.

D. Inclusive Diffraction at low Q^2 (ie. photoproduction)

Initial studies of hard diffractive photoproduction at HERA have followed two lines: the first is the observation of high p_T jet production in diffractive (i.e. rapidity gap) photoproduction. If an event contains one or more high p_T jets, it is assumed to have a hard interaction and the process then can be perturbatively calculated in QCD. There are two main diagrams of leading order (LO) hard photoproduction: direct and resolved. In the direct case, see Fig. 4a, the whole photon interacts with a parton from the proton. In the resolved case, Fig. 4b, the photon "resolves" into partons, one of which then interacts with a parton from the proton. If the transverse momentum exchanged is high enough, outgoing partons give rise to jets of particles in the detector [42].

The results of the measured cross section [43] for hard rapidity gap photoproduction events with two jets of $E_T > 6$ GeV are shown in Fig. 5.

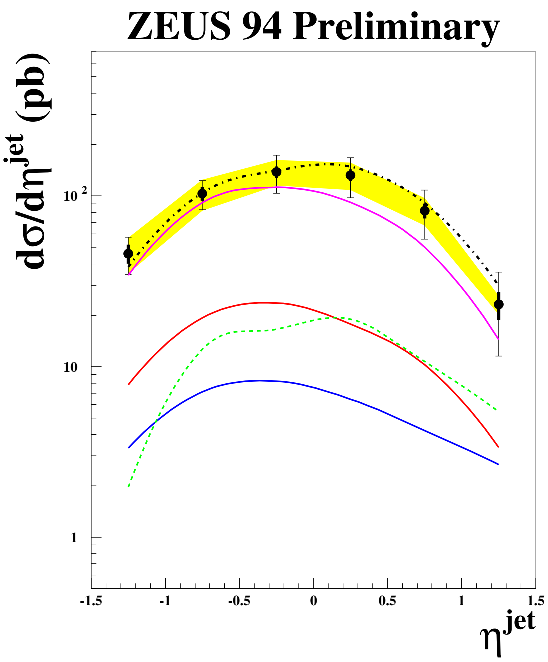

Figure 5: Cross sections for hard photoproduction as a function of the η of the jets. The solid curves are (from bottom up) a soft gluon, hard quark and hard gluon pomeron structure. The dotted line represents the contribution of non-diffractive jet production, as modelled by PYTHIA. The upper, dashed-dotted curve corresponds to a super-hard gluon. The shaded band indicates the energy scale normalization uncertainty.

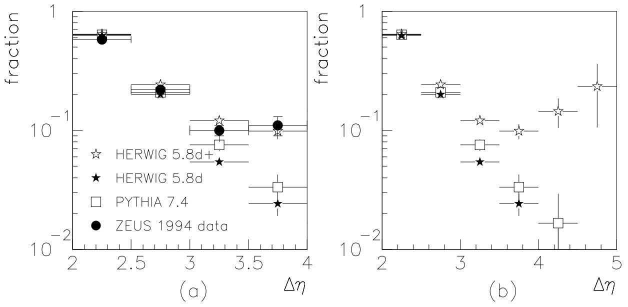

Figure 6: Gap fractions for ZEUS 1994 data, compared with Monte Carlo model predictions: (a) is for a standard detector, compared to the ZEUS data; (b) is for an extended detector at HERA. Similar results might be expected for a detector at higher center of mass energies.

These measured cross sections also suggest a dominant gluon content to the pomeron when compared to the Ingelman-Schlein formalism. The various curves show that the hard gluon structure functions give the best representation of the data. These data indicate both the dominance of direct photoproduction and the need to include some resolved photon contribution [43].

The second line of investigation relates to the observation of the photoproduction of jets separated by a large rapidity gap between the jets, see Figs 4c and 4d. Such studies could provide a test of the color transparency (CT) phenomenon in which a small color neutral parton configuration interacts with a nucleon target [34]. It is expected that the probability of survival (SP) of the rapidity gap should be larger for production by a direct (i.e. unresolved) photon than for the hadronic component. Recent ZEUS results [44] show a larger SP than that observed at the Tevatron and may thus hint at such a process [34]. Fig. 6a shows the ZEUS data.

As can be seen from the last two bins, PYTHIA, which does not contain any color singlet exchange, and HERWIG, also without color singlet exchange, do not agree with the data, while HERWIG 5.8d+ which contains such an exchange contribution, provides a good description [42] of the data.

E. Future Studies at ep Colliders

Additional diffractive studies at HERA with increased luminosity and extended coverage (i.e. LPS) in the very forward proton region will undoubtedly lead to a better understanding of the nature of the diffractive process and how it relates to QCD [34].

Studies for the HERA workshop [41] indicate that higher luminosities (in excess of 100 pb^{-1}) are desirable in order to test the validity of both factorization and NLO QCD in diffractive interactions and to measure $R = \sigma_L^D/\sigma_T^D$ for diffractive DIS. At next to leading order (NLO) a large gluon distribution in the pomeron would lead to a large longitudinal diffractive structure function F_L^{IP}. Thus a measurement of F_L^{IP} would enable a powerful test of both factorization and the applicablity of NLO QCD to diffraction at high Q^2.

The same study [41] indicates that with high luminosity at HERA it will be possible to obtain sufficient statistics to study diffractive open charm production. This would enable the measurement of the diffractive charm structure function which is very sensitive to the gluonic component of the exchange mechanism. As noted early, in the photoproduction of exclusive J/ψ, the large charm quark mass provides a sufficiently large scale to generate the onset of hard QCD dynamics. Similar studies of inclusive, diffractive charm production should also prove very interesting [41].

However, it is also important to consider the advantages of going to higher CM energies for a lepton-hadron (i.e. lepton-quark) collider. Studies by S. Ritz suggest that in order to reach values of $x < 10^{-6}$ for $Q^2 > 2$ GeV^2, required to see the damping in the rise of the $\gamma^* p$ cross section, one should consider a high energy lepton-hadron collider option at one of the future hadron-hadron colliders under consideration.

Additional impetus for a similar extension in the rapidity range comes from a study for the HERA workshop in which increasing the available rapidity gap between two photoproduced jets beyond the present $\Delta\eta \sim 4$ units to 5 or more units [42] could show a dramatic increase in the cross section for color singlet exchange. To date, the data for $\Delta\eta < 4$ units at HERA only show a possible flattening in the cross section (as observed first by DØ at the Tevatron). An increase in the rapidity range could come either from increased luminosity and an extended detector coverage at HERA or from an increase in the CM energy that would be available at a higher energy lepton-hadron collider. Fig. 6b shows the gap fraction that might be observed with a detector with extended rapidity coverage. At large $\Delta\eta$ the gap fraction could rise towards 60% [42].

IV. CONCLUSIONS

Until we understand the pomeron we cannot claim to understand the strong interaction, notwithstanding the often-heard statement that "We have a good theory of the strong interactions, namely QCD". Let us say (as Bjorken and others did at Snowmass): **QCD IS THE THEORY OF STRONG INTERACTIONS**. Nevertheless most of the total hadron-hadron cross section (elastic, diffractive and non-diffractive!) is not calculable and not well understood. This physics became unfashionable when QCD was developed and hard processes became experimentally accessible. It is now undergoing a revival, using QCD and hard processes at ep and $p\bar{p}$ colliders, and new and interesting phenomena are being discovered.

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