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Hard Diffraction and Rapidity Gaps

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HARD DIFFRACTION AND RAPIDITY GAPS

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Abstract

I describe the evolution of experiments at hadron colliders on (a) high mass diffraction (b) double pomeron exchange, from the ISR through the $Spp\bar{S}$ to the Tevatron. I emphasize an experimental approach to the question: "What is the pomeron?".

1. Introduction

For over 30 years we have associated an exchanged entity with diffractive scattering, called the pomeron after I.Y.Pomeranchuk. Despite the fact that diffractive processes are a large fraction of all high energy hadron-hadron collisions, and directly relate to the total cross section, we still do not have an acceptable understanding of what the pomeron is. Experiments on inelastic pomeron interactions, both with protons and with other pomerons, should shed light on this question and perhaps teach us how to extend the domain of calculability of QCD. We may find that the pomeron is intimately related to the very low- x structure function of the proton which is now being probed by experiments at HERA and elsewhere. Quite new and perhaps unexpected phenomena may manifest themselves for example in pomeron-pomeron collisions (if that is permissible language), including changes of the vacuum state. That is admittedly very speculative, but would clearly be very fundamental. Compared with the major effort currently spent in detailed experimental tests of perturbative QCD, where we know how to calculate theoretical predictions, pitifully little effort is spent in exploring beyond its frontiers.

2. Prehistory: Up to the ISR

The angular distributions of elastically scattered hadrons in the few GeV/c region typically show a 0 deg peak followed by a dip and secondary maximum (a ring in 2-D) very much like the diffraction of light through a hole, hence the terminology. The phenomenology of elastic scattering and other reactions such as

$$\pi^- + p \rightarrow \pi^0 + n$$

was developed using the exchange in the t -channel of "Reggeons", virtual (negative M^2 , usually denoted t) hadronic states whose (complex) angular momentum J changes linearly with t . The graph of J vs t is called a Regge trajectory, and when this is extrapolated to the positive M^2 region passes through the J, M^2 values of known mesons (or baryons). The Regge trajectory in the negative t region can be measured

from the s -dependence (s is the square of the c.m. collision energy) at each t -value. Those associated with mesons have slopes around 1 GeV^{-2} and intercepts $J(0)$ less than about 0.5. This means that the cross section for scattering by meson exchange must decrease with s . In fact the cross section rises, due to the exchange of a “high, flat” trajectory with intercept $J(0)$ just above 1.0 and slope around 0.2 GeV^{-2} which had no known mesons associated with it. (I shall refer later to a new candidate state.) This trajectory is called the pomeron, and it is a long-standing goal to elucidate its nature. For high \sqrt{s} or equivalently for exchanges over large intervals of rapidity y the lower lying meson exchanges will be negligible and pomeron exchange dominates.

It is important not only in elastic scattering but in inelastic processes whenever there is a large rapidity gap, i.e. an interval of rapidity containing no hadrons; by “large” we mean typically 3 or 4 units, depending on how pure you want the pomeron to be. The leading meson trajectory falls off rapidly relative to the pomeron as Δy increases. Prior to the ISR, which turned on in 1971, it was known that one could “diffractively excite” a hadron into a state of mass around 2-3 GeV; this is called single diffractive excitation. One of the two incident hadrons emerges from the collision “quasi-elastically” scattered, having lost just a few percent of its energy in exciting the other (e.g. $p \rightarrow p\pi^+\pi^-$) and emerging with small momentum transfer t like in elastic scattering. There is necessarily, for kinematic reasons, a large rapidity gap in these events. It could be shown that the exchanged trajectory was the same as that in high energy elastic scattering, namely a pomeron.

3. ISR : High mass diffraction

The ISR, the first hadron collider, gave us a very dramatic increase in collision energy \sqrt{s} and equivalently in the rapidity span

$$\Delta y = 2 \times \ln \left(\frac{\sqrt{s}}{m_p} \right).$$

When the proton spectrum was measured at small angles to the incident beam, it was found that apart from the elastic δ -function peak at $x = p/p_{beam} = 1.0$ there was a large high- x peak from inelastic collisions that extends down to about $x = 0.95$. When plotted as the Lorentz invariant cross-section at fixed small values of the 4-momentum transfer squared, t , it was found to scale (be independent of s). The peak is due to the diffractive excitation of the other proton to masses well defined through the formula

$$M^2 = s(1 - x).$$

You see that the masses M to which a proton can be diffractively excited grow proportional to the center-of-mass energy \sqrt{s} , and at the top of the ISR energy range ($\sqrt{s} = 63 \text{ GeV}$) reach about 15 GeV. If this continues up to the LHC ($\sqrt{s} = 14 \text{ TeV}$) up to 3000 GeV can be “injected” into a proton by diffraction, i.e. by a pomeron. These numbers are simply given by the approximate rule of thumb that pomeron exchange dominates for scattered protons with $x \geq 0.95$; below that meson exchanges

are more important. The identity of the “high mass diffraction” exchange and the pomeron of elastic scattering could be shown also by the shape of the peak in x (or M) which goes approximately like $\frac{1}{M^2}$ but with a correction depending on the difference of the pomeron trajectory from 1.0. This matched the “elastic pomeron” well. Perhaps we can learn about the nature of this object from its collisions, either with a proton (as in these diffractive excitation experiments) or with itself?

4. ISR: double pomeron exchange

The first observation of double pomeron exchange was at the CERN ISR. Both incident protons are quasi-elastically scattered with small p_T and Feynman x , $x_F > 0.95$, and a low mass hadronic system is created in the central region, as if from a pomeron-pomeron collision. This central system necessarily has very constrained quantum numbers: $B = Q = S = 0$ and $I^G J^{PC} = 0^+ even^{++}$. Its mass can be calculated from the x_F of the fast protons through

$$M^2 = s(1 - x_1)(1 - x_2).$$

For the highest ISR energy of $\sqrt{s} = 63$ GeV this corresponds to $M \leq 3$ GeV. The quantum number filter, mass region and possibility that the pomeron might be dominated by gluons makes this process an excellent hunting ground for “glueballs” as well as more standard mesons. Experiments showed that the process exists, with reasonable cross sections, and that the dominating channel which is $\pi\pi$ contains interesting structures, see Fig. 1 [1].

The $\pi^+\pi^-$ mass spectrum shows no ρ as it should not if pomeron-pomeron is dominating; at lower energies similar experiments show a ρ signal from (e.g.) pomeron- ρ exchanges. The next striking feature of the data is a sudden drop in the cross section by an order of magnitude around 950 - 1000 MeV which is due to the $f_0(975)$ state (or states). This is a perfect example of a narrow resonance appearing not as a bump but as a sharp dip in a mass distribution! Although the nature of the $f_0(975)$ is not known, it would be a mistake to say that the possibly glue-rich nature of the pomeron argues for a gluonic f_0 . Final state interactions are strong and cause some “censorship” of the pomeron. However, absence of structure (dips) below the $f_0(975)$ allows one to rule out a lighter scalar glueball unless it were unreasonably narrow (e.g. 5 MeV). There are further structures in the higher mass region of the $\pi\pi$ spectrum, around 2 GeV, which have not been explained. The four- π mass spectrum appears to have an enhancement in the region of 2 GeV which was not clear enough to permit any special claims, but which could be the same object (Mass = 1.93 GeV, Width = 0.3 GeV, spin 2) found in similar central production experiments [2] [3] with lower energy but much higher statistics. As Landshoff and Donnachie have mentioned at this meeting this mass is compatible with the intersection of the pomeron trajectory and the line $J = 2$ so this might be a meson associated with the pomeron, presumably a glueball. Will there be a $J = 4$ state near 3.3 GeV (assuming the pomeron trajectory to be linear)?

Before leaving the subject of low mass double pomeron exchange I would just like to point out that the Axial Field Spectrometer experiment at the ISR showed that one could replace the protons with α particles and find the same central $\pi^+\pi^-$ spectrum. The fact that pions can be created while the α -particles fly past, not even excited, demonstrates the coherence of the phenomenon, that it is probably independent of the nature of the colliding hadrons and perhaps only to do with the vacuum. I think *VACUUM EXCITATION* is an appropriate term to describe this (although now the word *pomeron* is becoming more acceptable again we may have less need for alternatives!).

5. What is the pomeron?

I will take a purely experimental approach to the above question. This is something like: “If you don’t know what it is, hit it” and see what comes out. Consider single diffractive excitation at the Tevatron energy $\sqrt{s} = 1800$ GeV. Requiring a quasi-elastic p with $x_F \geq 0.95$ allows excitation masses up to 400 GeV, and we view this, perhaps naively, as a pomeron-proton collision at that $\sqrt{\hat{s}}$. This (sub-)energy is certainly enough for hard parton phenomena such as high p_T jet production, high mass Drell-Yan pairs and heavy flavor production in hadron-hadron collisions, and we can use them to map out the parton content, or structure functions, of the colliding hadrons. The argument was applied to pomeron-proton collisions by Ingelman and Schlein [4] in 1985, and tested at the CERN $p\bar{p}$ Collider by Experiment UA8 which coupled the central detectors of UA2 to some very forward spectrometers. They indeed found [5] events with both a high- x ($x_F \geq 0.9$) antiproton and a pair of central jets, not very high p_T by collider standards but above 8 GeV/c. Knowing the structure function of the proton, measurements of the central jets give a parton distribution for the exchanged object, assumed to be a pomeron. The data seem to show that this is a hard distribution with high- x partons and even a “*superhard*” component where essentially all the momentum of the pomeron participates in the hard scatter: pomeron + q/g \Rightarrow jet + jet. That would clearly be an important observation if confirmed but I do not find the UA8 data convincing on this point; there is no visible δ -function component, and any would be washed out by resolution effects, jet hadronization and so on. The UA8 group have done a good job in pioneering this study, but the energy even of the CERN Collider was marginal. It is important to separate protons scattering diffractively, through pomeron exchange, from a possibly large background of scatters by reggeized meson exchange. The best way to show that the “UA8-effect” has something to do with the pomeron is to repeat the experiment at higher energies. At the Fermilab Tevatron a mass of 200 GeV is associated with x_F of 0.988 compared with 0.90 at the $Spp\bar{S}$ and the ratio of pomeron:reggeon should be much larger (roughly 5:1 compared with 1:2, according to fits by CDF [6]).

6. Double pomeron exchange, CERN Collider

Two experiments at the CERN Collider looked at double pomeron exchange but

as a very peripheral activity. Experiment UA8, just discussed, selected events with two non-colinear (both “up”) forward protons with $p_T \approx 1$ GeV/c. The central hadronic system has a mass distribution peaking at 3 GeV and there are no events above 10 GeV. This mass is determined by the calorimeter and the mass resolution is not sufficient to allow resonance and glueball studies, but it will be interesting to have information on the general structure of this central system. I understand these studies are underway.

These UA8 studies are complemented by an experiment done in UA1 [7] which selected higher mass (10 - 70 GeV) events with a much smaller cross-section (about $0.3 \mu b$ compared to 30 - 150 μb) still consistent with DPE topology. There were no forward (anti-)proton detectors but events were selected with *two* rapidity gaps over the ranges $-6 \leq \eta \leq -3$ and $3 \leq \eta \leq 6$ together with some minimum transverse energy in the central region. This is admittedly not very clean: on the one hand inefficiencies of tracking and calorimetry in the gap regions could give artificial gaps, on the other hand a genuine DPE event can veto itself if hadrons are emitted forwards (one would rather select on true rapidity y than pseudorapidity η). Also the gap should be a region with no *primary* hadrons but the experiment selects on the decay products, e.g. the γ from η decay. Nevertheless the use of (pseudo-)rapidity gaps to select pomeron exchange is now becoming widespread. The UA1 mass spectrum peaks around 20 GeV (lower masses are suppressed by the trigger) and extends up to about 100 GeV (the highest masses surely include more background). I would like to mention a couple of observations made on the central hadronic system which, if not the result of above-mentioned biases, I find very interesting. The first is that the mean charged multiplicity rises with mass, M , with a much steeper slope than in e^+e^- or $p\bar{p}$ collisions plotted at $\sqrt{s} = M$. At 60 GeV a pomeron-pomeron collision has on average nearly twice the charged multiplicity of a $p\bar{p}$ collision. The multiplicity distribution is also odd in that, unlike most interactions, it does not obey KNO scaling. Making the standard KNO plot of $\langle n \rangle P(n)$ vs $n / \langle n \rangle$ the distribution shrinks and becomes more Poisson-like as the mass increases. Perhaps something new and interesting is happening here, and the next step should again be to improve and repeat the experiment at the higher energy Tevatron.

7. Single diffractive excitation, Tevatron

Experiments CDF and E710 at the Tevatron $p\bar{p}$ Collider have measured [6] [8] the mass or x_F dependence of single diffractive excitation at \sqrt{s} both 540 GeV and 1800 GeV. Fig. 2 shows a spectrum from the CDF experiment showing the data with a fit to the sum of a diffractive and estimated non-diffractive (shown separately) component.

Such fits support the conclusion that pomeron exchange only dominates for x_F greater than about 0.95. The integrated total SDE cross section at 1800 GeV is about 9 mb (both CDF and E710 agree on this), not having increased much with energy since the ISR ($\sqrt{s} = 63$ GeV) where it was about 7 mb.

It is unfortunate that when CDF took the above data, with a very forward spec-

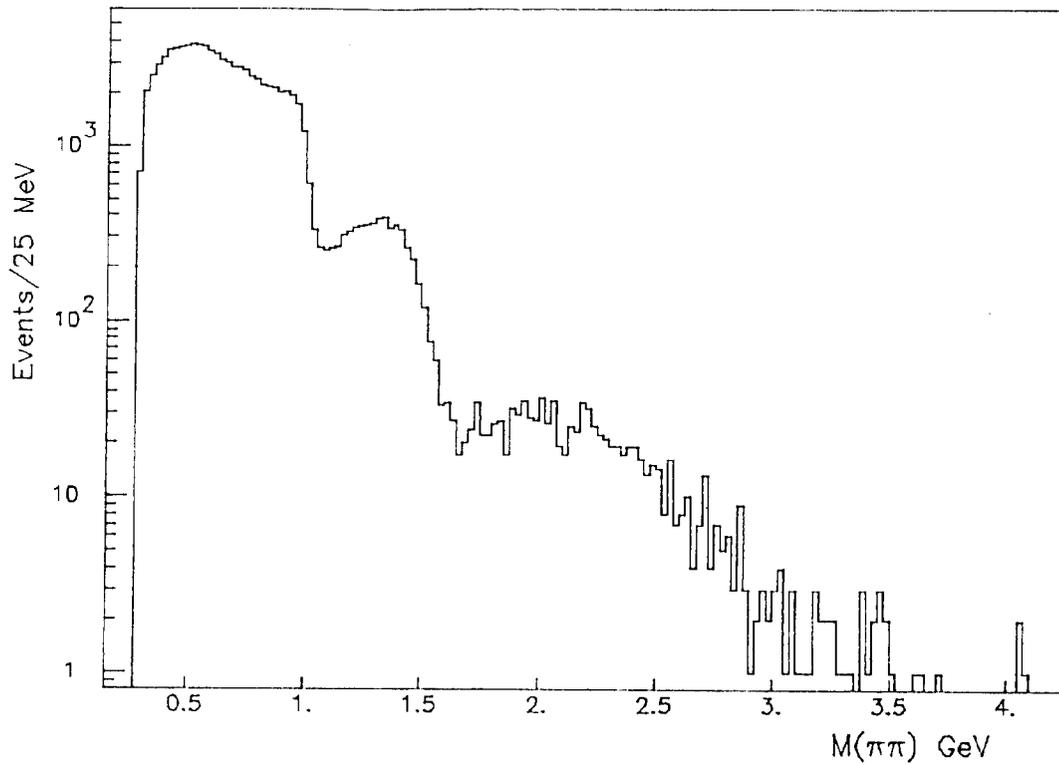


Figure 1: Mass spectrum of $\pi^+\pi^-$ produced in pomeron-pomeron interactions at the CERN ISR.

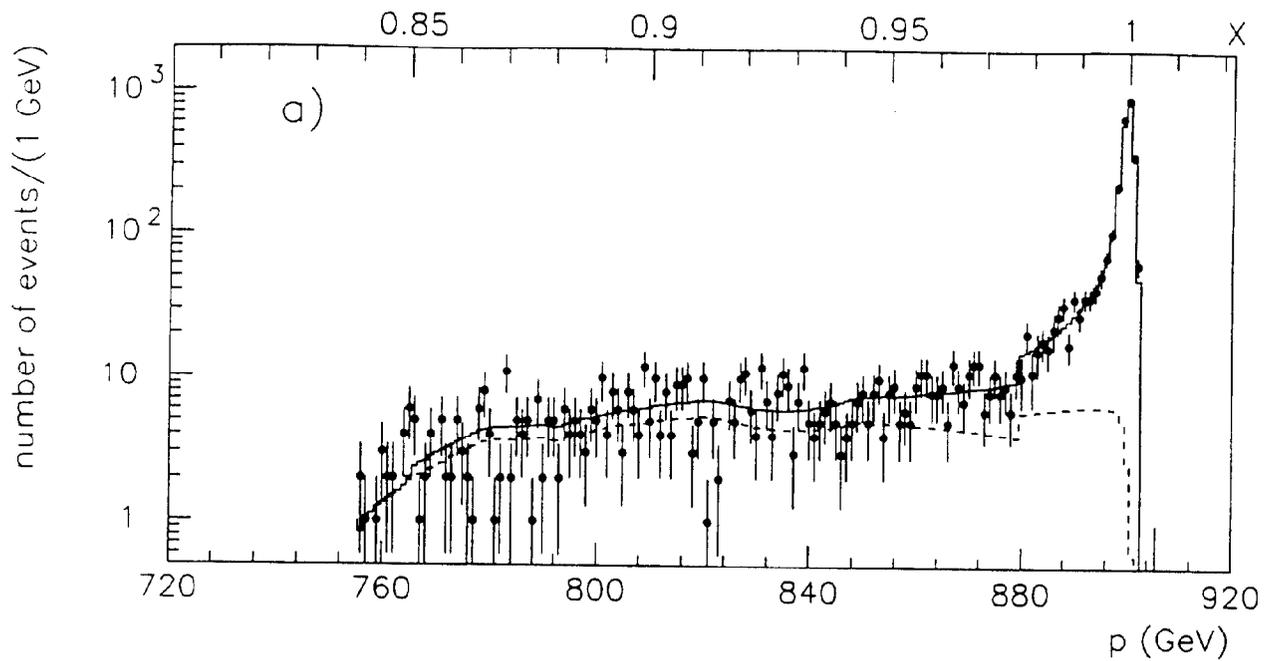


Figure 2: Longitudinal momentum spectrum of forward protons at Tevatron (CDF). The dashed line is the estimated non-diffractive background.

trometer system installed to detect high- x antiprotons, they did not simultaneously record the associated event, i.e. the final states with masses up to about 400 GeV “hadronizing” into the powerful central detector. It is important now to do this, but for technical and political reasons it is not as easy as it should be! We could trigger on events with M in a range such as 250 - 300 GeV and from the excited hadron study jets, and leptons (e, μ, ν) to measure Drell- Yan and heavy flavours. Such a program should take us a long way in either mapping out the pomeron structure function or in finding inconsistencies in such language. Possibly it will happen in 1998/9, but we have to hope (for *this* study) that the luminosity will still be low enough that there are plenty of single collisions (just one within the detector resolving time).

8. Central rapidity gaps, Tevatron

Meanwhile both Tevatron collider experiments, CDF and D0, as well as the HERA experiments, have been emphasizing rapidity gaps as a route to studying diffraction, either soft or hard. (Lack of time and up-to-date knowledge prevents me from covering the HERA data, but it shows much promise as possibly probing the pomeron directly with a photon.) One type of event, seemingly far removed from traditional “soft” diffraction but apparently showing a *hard pomeron*, contains a pair of high p_T jets separated by a large (4 is large) interval in rapidity containing no hadrons, i.e. a *gap*. This configuration has been stressed in particular by Bjorken [9]. The gap between the jets implies that whatever was exchanged to scatter the partons is colorless, therefore not a gluon or quark. Photon or W, Z exchange must occur at a low and calculable level. In the strong interaction sector meson exchanges must be negligible (because of the large $\Delta\eta$ and the large $|t|$) but two-gluon exchange is a possibility. One can guesstimate [9] that $2g/1g \approx 0.1$ and that only in about 0.1 of the cases does the gap survive (any additional soft gluon exchange can kill it). Bjorken thus expected that rapidity gaps would be seen in about 1% (to a factor of 3) of the large rapidity intervals, and this would be approximately independent of E_T of the jets and $\Delta\eta$.

Both experiments CDF and D0 have searched for this phenomenon, using different techniques. D0 [10] define a region of pseudorapidity between jet cones and measure the probability that there are no calorimeter clusters in that interval $\Delta\eta$. This probability falls steeply from 1.0 at $\Delta\eta = 0$ to become independent or almost independent of $\Delta\eta$ when that is larger than 2 or 3 up to the maximum interval size of 5, see Fig 3.

The level then is about 0.5 - 1.0%. D0 do not however claim a color singlet exchange because of uncertainties in detector inefficiencies (which can fake a gap) and in the contributions from the tails of color octet exchange. Rather they place an upper limit (95%cl) on the rapidity gap fraction $f(\Delta\eta_c > 3) < 1.1 \times 10^{-2}$.

CDF [11] use charged tracks rather than calorimeter clusters, and for a series of intervals between jets (about 60 GeV E_T) study the track multiplicity distribution, see Fig. 4. They find an excess of events with no charged tracks at the level of 0.86%, independent of $\Delta\eta$ once that exceeds about 1.0 and not significantly changing with

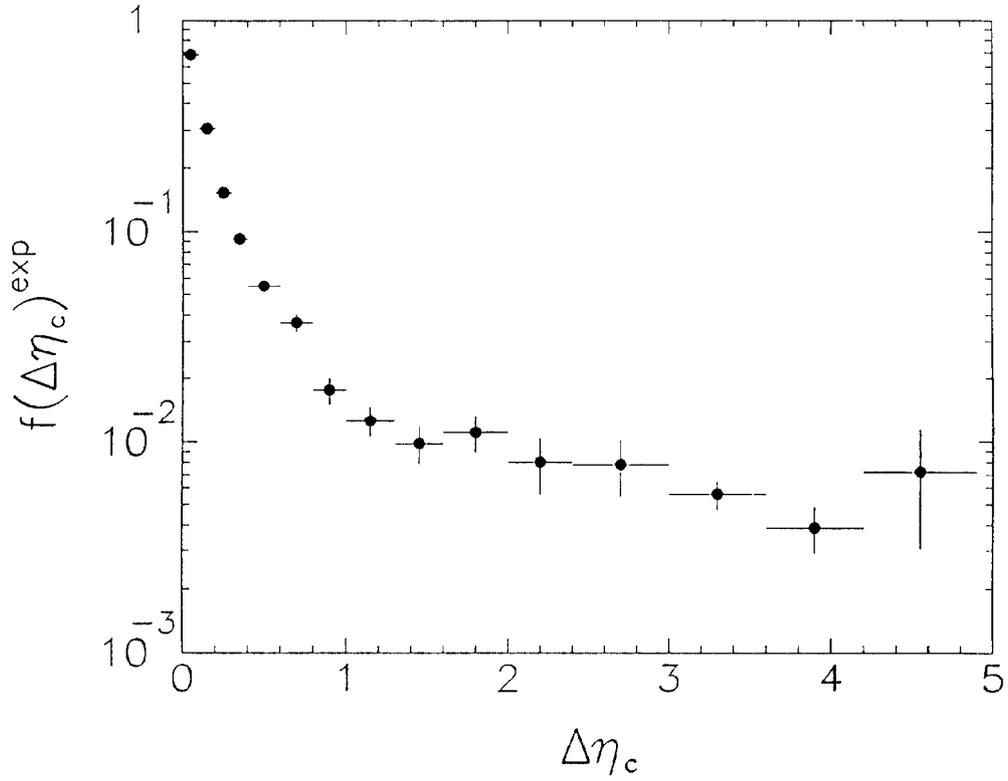


Figure 3: Probability $f(0)$ of no clusters in a rapidity interval of size $\Delta\eta_c$ between two high E_T jets (D0).

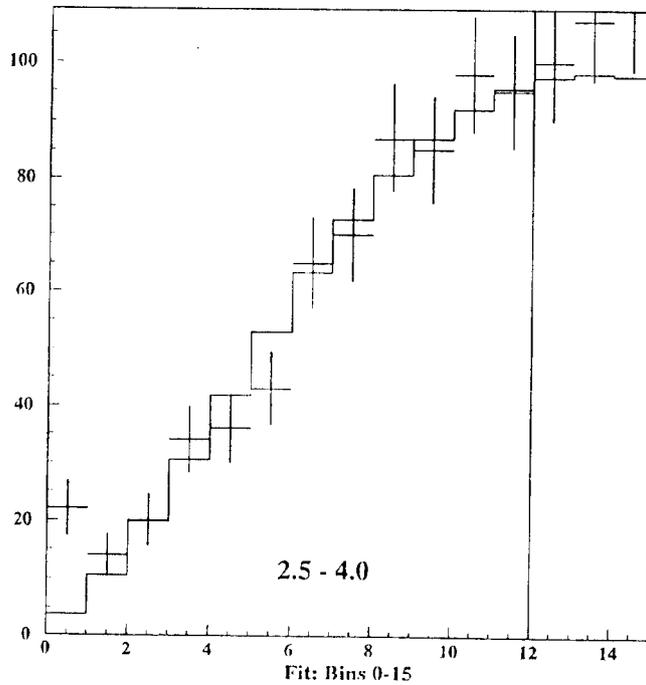


Figure 4: Multiplicity distribution of charged tracks with p_T above 400 MeV/c in rapidity intervals 2.5 - 4.0 units wide between high E_T jets (CDF). Crosses = data, histogram = fit.

E_T from 56 GeV to 85 GeV. This CDF study does not use calorimeter clusters or low p_T tracks, but assumes the tracks observed are a representative sample of all hadrons in the interval. They claim a rapidity gap signal at the above level, a little below the D0 upper limit, saying that it is “consistent with the exchange of color-singlet di-gluons”. These events look like classic double diffractive dissociation except that the momentum transfer between the left- and right-moving systems is not $t \approx 1 \text{ GeV}^2$ but $t \approx 5000 \text{ GeV}^2$! A high E_T jet in one system is balanced by one in the other. What carries this huge momentum transfer? The cross section is much too high for γ , W or Z exchange, and some form of di-gluon seems a possibility. More information about these gap events would be valuable and should be forthcoming over the next year or two.

Another rapidity gap study by CDF uses W production as a probe of the pomeron. In a model [12] in which the pomeron has a structure function, either $q\bar{q}$ or gluon dominated, one can estimate the fraction of all W events that are diffractive. If the pomeron is predominantly $q\bar{q}$ as much as 17% of all W should be diffractively produced at the Tevatron, having a rapidity gap between the W and a very forward particle or particles. One should also find twice as many W^+ as W^- in the proton fragmentation, and the inverse for antiproton fragmentation. The preliminary results [13] show a ratio of diffractive to non-diffractive W production of $(0.56 \pm 1.0)\%$, ruling out a hard- q -dominated pomeron. We need to understand the compatibility between these new results and the results on dijets from UA8, but the authors claim [13] that “our result disagrees with the interpretation that the UA8 dijets are due to a hard- $q\bar{q}$ component of the pomeron”.

9. Central vacuum excitation, Tevatron

Among the many possible future experiments in this field, one that I find particularly exciting is to study central vacuum excitation, or double pomeron exchange, at the Tevatron and eventually at the LHC. Central masses at the Tevatron should extend to about 100 GeV, and at LHC to about 700 GeV. At these center of mass (pomeron-pomeron) energies we should certainly be able to use hard phenomena (jets, Drell-Yan, W,Z and heavy flavors) to probe the pomeron and measure its structure function (if that is a valid concept). In CDF we are planning to do some preliminary studies by triggering on events with two forward rapidity gaps together with central activity. Later we may be able to add detectors to measure the high- x (anti-)protons. Perhaps the pomerons will sometimes behave like single “hard” gluons, producing a pair of central high- p_T jets with little additional activity. Gluon dominated pomerons will produce little Drell-Yan, W or Z but plenty of heavy flavors (including $t\bar{t}$ at LHC). Perhaps there will be events with a large number of very soft pions. This is purely speculation, but it could be that events where the pomeron “excites the vacuum” are a good place to look for exotic vacuum phenomena like a disoriented chiral condensate. This might show up as regions of $\eta\phi$ with very abnormal charged:neutral

ratios, as seen in the Centauro cosmic ray events.

Conclusions

It is an exciting challenge to try to understand the pomeron at a fundamental level, such as QCD. Theory and experiment need guidance from each other. Experimentally the new possibilities of studying hard diffraction at Colliders, especially single diffractive excitation and double pomeron exchange, allow us to investigate the relation between the pomeron and quarks and gluons. There is much to be done both at the Tevatron and HERA, and it is a field full of potential for new phenomena.

I would like to thank the organizers for inviting me to this conference, especially Peter Landshoff who also made helpful comments on this written version of my talk.

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