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Diffractive Production of Massive States

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DIFFRACTIVE PRODUCTION OF MASSIVE STATES

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Abstract

The nature of the pomeron, e.g. its quark and gluon structure in QCD, can be investigated by studying pomeron-proton interactions producing high E_T jets, heavy flavors, W/Z and lepton pairs. This study was initiated at the CERN S$p\bar{p}$S Collider and is now pursued at the Tevatron. A hard pomeron also manifests itself as a rapidity gap between two high E_T jets. In both cases there is evidence that the pomeron sometimes behaves like a single gluon. Pomeron-pomeron interactions may be extremely interesting.

1 Introduction

Diffraction of hadrons means pomeron exchange, something which is part of the strong interaction but not well understood. Current experiments are probing the pomeron with high Q^2 probes in attempts to reveal its structure. Consider the elastic scattering of two hadrons, say p and $\bar{p}$, see Fig. 1(a). At low energies $\sqrt{s}$ (or rapidity differences Δy)

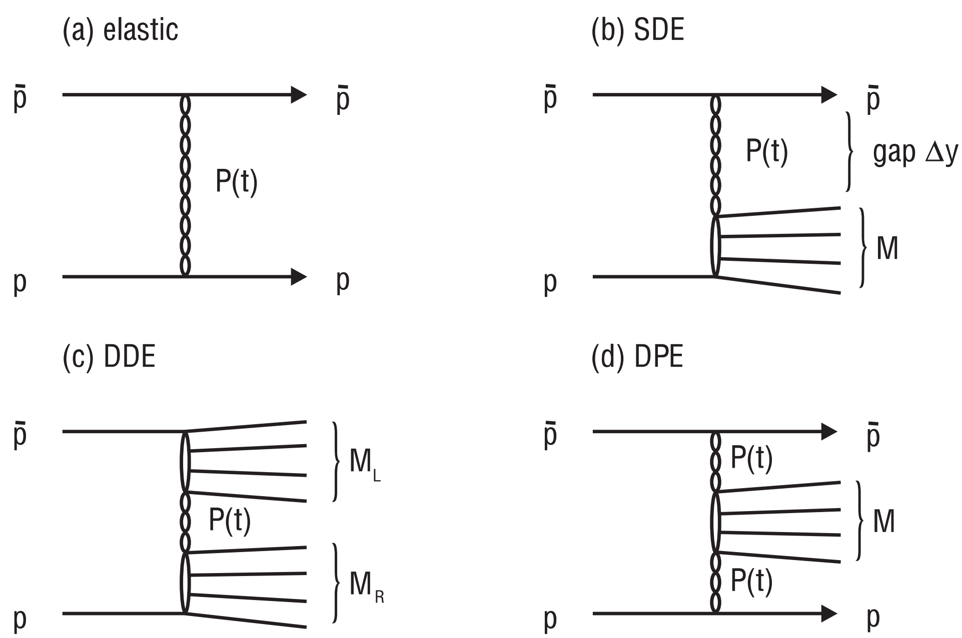

Figure 1: Diagrams of several diffractive processes (a) Elastic scattering with pomeron exchange (b) single diffractive excitation of a state of mass M (c) double diffractive dissociation (d) double pomeron exchange.

the exchanged 4-momentum transfer can be carried by a complicated mixture of objects including virtual pions and ρ, A_2, etc. As $\sqrt{s}$ and Δy increase the cross section decreases as these exchanges die away, except for *pomeron exchange* which becomes dominant and causes the cross section to rise. We can operationally define the pomeron as the principal entity which transfers 4-momentum ($\sqrt{t}$) between elastically-scattering hadrons at very high energy, apart from the photon (Coulomb scattering) which dominates at very small t. The pomeron is strongly interacting but carries no color, flavor or isospin, and it has + C and G-parities. In fact it does not carry much at all, it has the quantum numbers of the *vacuum*. What is it? The Standard Model of strong interactions contains only quarks q, antiquarks $\bar{q}$ and gluons g, all colored. Without extending this set, the pomeron must be made of colorless combinations such as gg, $q\bar{q}$, or $q\bar{q}gg$ with all possible mixtures. A picture where two gluons dominate, exchanging gluons between themselves to make a ladder diagram, together with occasional $q\bar{q}$ loops, seems to be reasonable. Two gluon exchange as a model for the pomeron was proposed by Low [1] and Nussinov [2] in 1975. If this were timelike, with $M > 0$, it would be a glueball; the pomeron is always spacelike, $M^2 < 0$, but pomerons and glueballs may be connected by a common Regge trajectory.

2 Single Diffractive Excitation

It would be very difficult to investigate the nature of the pomeron if it only appeared in elastic scattering. Fortunately it can also interact inelastically with one of the incident hadrons to produce systems of hadrons of mass M_x. In Single Diffractive Excitation SDE one hadron, say $\bar{p}$, is almost elastically scattered, emerging with Feynman $x_F = p_L/p_{beam} > 0.95$ or so, see Fig. 1(b). This will be isolated, for kinematic reasons, with no other hadrons within about 3 units of rapidity; the other hadrons will form a state of mass $M_x = \sqrt{s(1-x_F)}$. The process gives rise to a peak above $x_F = 0.95$ in the inclusive (anti-)proton spectrum which approximately obeys Feynman scaling. Thus as $\sqrt{s}$ increases the masses which can be diffractively excited grow like $0.22 \times \sqrt{s}$, from about 14 GeV at the ISR to 400 GeV at the Tevatron. These mass limits can also be derived from a requirement that there is a rapidity gap Δy of at least 3 units for pomeron exchange. Now if you make a transformation to the c.m. system of the produced hadrons, we can consider the interaction as a *pomeron-proton collision* at $\sqrt{\hat{s}} = M_x$. A total collision energy of 400 GeV is comparable to the total $p\bar{p}$ energy of the CERN collider and is easily high enough for production of W, Z and high E_T jets. If we can measure these, and heavy flavors $b\bar{b}$, in pomeron-proton collisions, we can map out the $q, \bar{q}$, and g content of the pomeron, on the assumption that such a concept is valid.

The first study along these lines was carried out by the UA8 Collaboration [3] at the S$p\bar{p}$S Collider at $\sqrt{s} = 630$ GeV. Detecting quasielastic antiprotons after they passed through quadrupole magnets they could *tag* the pomeron and look for jets (in the UA2 calorimeter) from the pomeron-proton collisions. Jets with $E_T > 8$ GeV were observed, and from their distribution (especially in the Feynman x_F distribution of the 2-jet pair in the pomeron-proton frame) it was concluded that the pomeron contains hard constituents. Together with a $\beta(1-\beta)$ term, where $\beta = p_{parton}/p_{pomeron}$, there seems to be a 30% component with β near 1.0, i.e. essentially *all* the momentum of the pomeron is carried by a single parton. Although the kinematic distributions in these events appear to be as expected for pomeron exchange (in more detail a t^2-dependent term is required in the pomeron trajecttory, usually assumed to be linear in t), the antiprotons generally had $0.90 < x_F < 0.96$, a region where non-diffractive background is large. A convincing demonstration that these jets are really produced in the diffractive component should come from seeing them at the same M_x at $\sqrt{s} = 1800$ GeV, when $x_F > 0.98$ and pomeron exchange is larger than the background by nearly two orders of magnitude. Data at various t at two or more s-values would be definitive. If it becomes established that the component with β close to 1.0 is in the pomeron exchange term it will be especially interesting, perhaps indicating that the pomeron behaves, to some approximation, like a single gluon.

3 The Hard Pomeron, or jet-gap-jet

By "hard pomeron" I mean that the pomeron (or something colorless and presumably related) has a very large $|t|$, more than several hundred GeV^2. This study was initiated by Bjorken, who argued [4] that two gluon exchange should occur in quark-quark scattering giving rise to back-to-back jets separated in rapidity by a "gap" containing no hadrons. If the gap is larger than about 3 units of rapidity the event is like double diffractive excitation, see Fig. 1(c), with a high E_T jet in each colorless system, so that the momentum-transfer-squared t across the gap is approximately -E_T^2, typically 1000 GeV^2. Experiments CDF and D0 both searched for rapidity gaps between jets, and both found [5][6] them at the level of about 1%, i.e. a 1% *excess* of events exists with no tracks or no calorimeter hits in about 3 units of rapidity. A problem is how to define the background level, but negative binomials fit all the multiplicity distributions very well except for the first (signal) bins. This is shown by Fig.2 (D0 data).

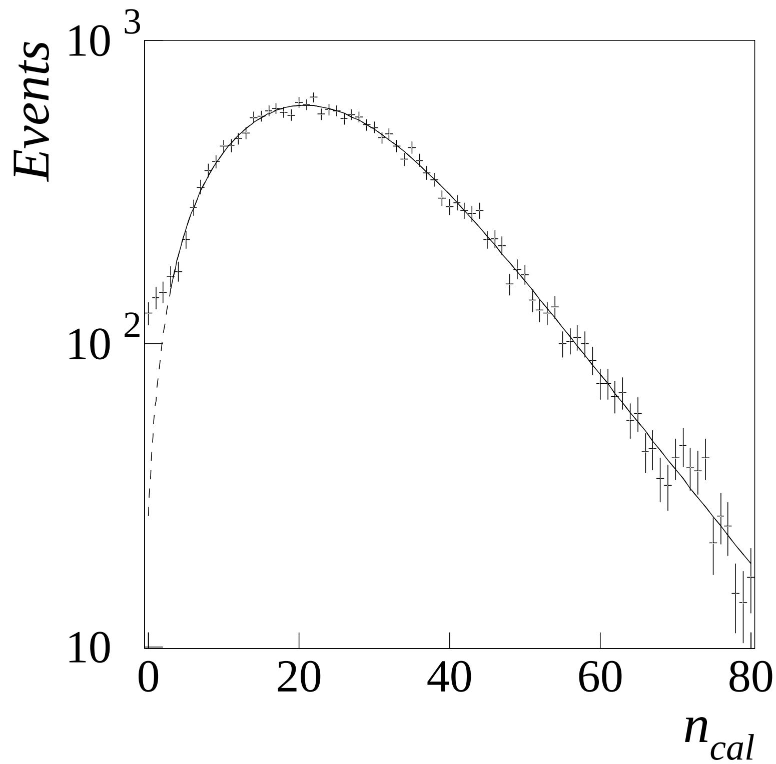

Fig.2 Multiplicity distribution (D0) of calorimeter towers exceeding 200 MeV in a $\Delta\eta$ region at least 2.6 wide between jets (>30 GeV). The excess in bins 0,1 and 2 is the signature for colorless exchange.

CDF also did a study comparing the very central region, $-1.2 < \eta < 1.2$, in events with two forward jets on opposite sides (OS) of this region and on the same side (SS). A 4σ excess of events with no tracks in the OS sample compared with the SS sample is seen, corresponding to a (2.0$\pm$0.7(stat))% gap effect. D0 measure a somewhat smaller fractional excess, $(1.07 \pm 0.10(stat)^{+0.25}_{-0.13}(syst))\%$, using calorimeter towers above 200 MeV rather than tracks and somewhat different $\Delta\eta$ and $E_T(jet)$ regions (Fig.2). Given these differences the agreement can be considered good. D0 observe a strong correlation between no (or few) calorimeter towers in the gap region and no tracks, as of course they should, and are studying whether the gap fraction changes with E_T of the jets over the region 15 GeV to 50 GeV. Any change is small, less than a factor about 2. They are also studying calorimeter multiplicities in the jets and outside the jets for both gap and non-gap events to see if the jets, or the associated particles, differ.

What is the physics in these jet-gap-jet events? It is clearly colorless exchange with very large Q^2 (t) between quarks and/or gluons. The cross section is too high by at least two orders of magnitude to be photon or W/Z exchange. The most reasonable explanation seems to be that a hard gluon is exchanged and one or more soft gluons or a coherent color field [7] cancel the color. If one were to ask about the structure function of the colorless exchanged entity it would be strongly peaked near $\beta = 1.0$. Progress in studying this jet-gap-jet phenomenon would come from systematic studies of its E_T, $\Delta\eta$ and $\sqrt{s}$ dependencies. It would be interesting to study the transition to soft double diffractive excitation (a very poorly studied subject) by letting E_T tend to zero. It would also be interesting to know whether the jets in these gap events have exactly the same characteristics as those in non-gap events. For example in leading order we can have $q+g \rightarrow q+g$ by quark exchange, and this term may well be missing from the gap events. One can make infra-red safe parameters, such as the E_T-weighted charge or E_T-weighted energy sum in the jets, which may be different for quark- and gluon-initiated jets, and try to classify the jet pairs according to the values of these parameters. Ideally one would classify the jet pairs as qq, qg and gg; in practice only some approximation to that can be done, but the point is that *any* differences between gap and no-gap jets would be interesting.

4 Diffractive W production

W-bosons are created from quarks, not directly from gluons, so W production is a good probe of a possible $q, \bar{q}$ content of the pomeron. So is Drell-Yan and Z production. To make a W diffractively at Tevatron energies requires relatively high diffractive mass and x_F for the quark in the proton. This means that valence quarks will dominate. As the pomeron is isosinglet we should have $W^+/W^- \approx 2$ when the proton (uud) dissociates and 0.5 when it is the antiproton. This correlation between the gap-side and the W charge is a good tool in searching for the diffractive process. Another tool is the so-called gap:angle correlation resulting from the fact that non-diffractively produced W do not favor positive or negative rapidity, while diffractive W tend to be in the rapidity hemisphere away from the gap.

Predictions [8] were that if the pomeron is dominated by q and $\bar{q}$ as many as about 20% of all W produced at the Tevatron would be diffractive! (This does not mean that the various QCD Monte Carlos were underestimating total W production by this much; presumably the calculations include the pomeron without explicitly putting it in.) How could the diffractive W fraction be so high, when the SDE cross section is not such a large fraction of the total inelastic cross section? The reason would have to be that the pomeron is more efficient at making W off a proton than a $\bar{p}$ is, which can be understood by realizing that although $q\bar{q}$ cross sections are independent of the incident "hadrons", the pomeron-proton cross section is small, only a few mb.

CDF's search for diffractive W production has so far been done using rapidity gaps (not seeing the quasielastic $\bar{p}$). In one method we select a region $2 < \eta < 4.2$ in rapidity and make a multiplicity distribution of calorimeter towers (> 200 MeV) for events with $W \rightarrow e\nu$. This is done separately for charge:gap correlated events (which should show a signal) and charge:gap anticorrelated (which should not). No difference is seen (looking especially in the sensitive low multiplicity bins), see Fig. 3, and we conclude that at 95% c.l. less than 6% of the Ws are diffractively produced.

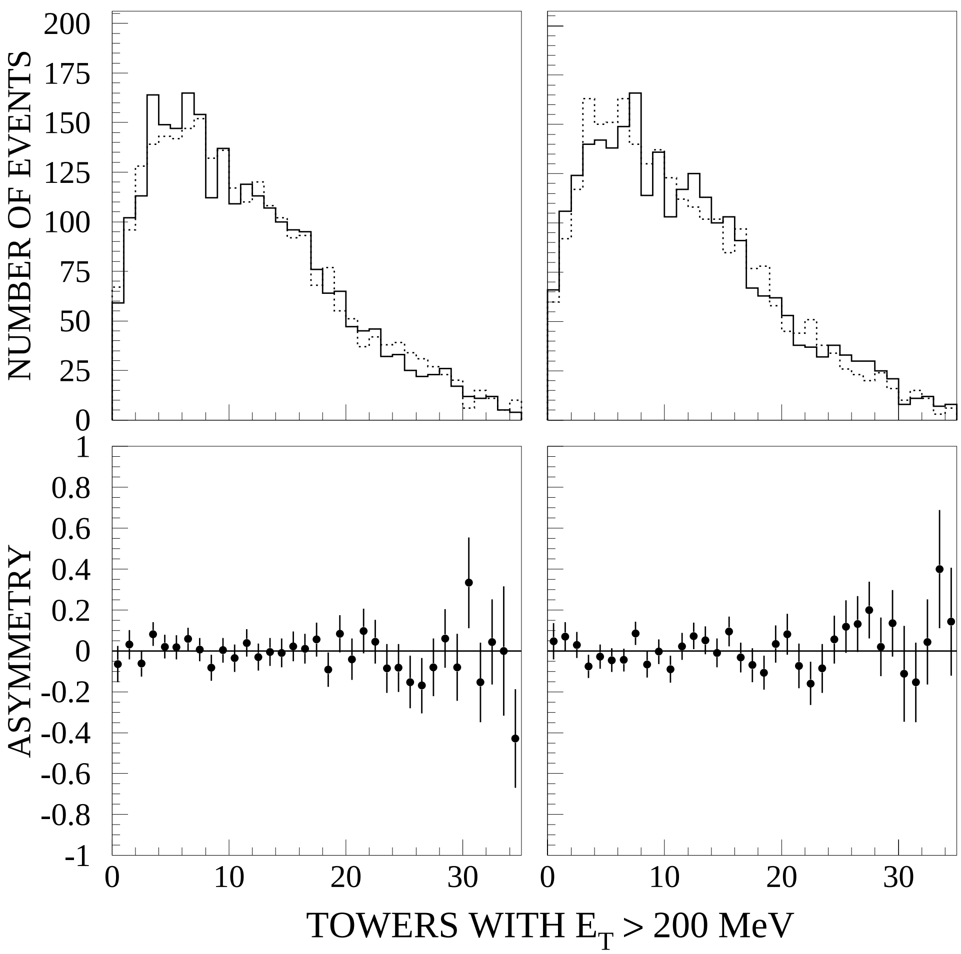

Fig. 3 Multiplicity distribution of calorimeter towers with $E_T > 200 MeV$ for 2804 W events with a central lepton. *Top*: charge:gap (left) and angle:gap (right) correlated (solid line) and anticorrelated (dashed line). *Bottom*: Asymmetry defined as the difference divided by the sum of the above distributions.

At face value this would clearly rule out a $q\bar{q}$-dominated model for the pomeron, which would be no surprise. If the pomeron were mostly glue (some quarks clearly have to be there from evolution) only about 1% of the W would be diffractive. However according to Goulianos [9] the predictions should be revised downwards by nearly an order of magnitude! Extrapolation of the single diffractive cross section using standard (Regge) procedures to Tevatron energies gives a cross section exceeding the total cross section. If we can speak of pomerons being "emitted" by protons [1] this is equivalent to having several pomerons simultaneously emitted. Goulianos proposed to *renormalize* the pomeron flux, not to exceed unity, and then the Tevatron cross sections agree with data. Then the fraction of W produced diffractively, even by a pomeron with a hard $\beta(1-\beta)$ structure is reduced to about 2.7% and the present CDF data are not sensitive enough to see or exclude that.

If this renormalization argument is correct, perhaps it can be pictured along the following lines. In diffractive scattering, with a $proton - proton - pomeron$ vertex, the pomeron is emitted coherently from the whole proton. The pomeron also has the quantum numbers of the vacuum. If you imagine superimposing two pomerons, perhaps you just get one; think of superimposing two volumes of vacuum! Then a proton could only emit at most one pomeron in an interaction, at least when $|t|$ is small. If $|t|$ increases the elastic and SDE cross sections decrease rapidly ... you are basically trying to keep the pomeron coherent over a whole proton even while its effective wavelength decreases. This can happen, but only to some extent, taking advantage of fluctuations of the proton's size (e.g. all three valence quarks may happen to fluctuate into a tiny volume). If you allow one, or better both, of the protons to dissociate you do not have to pay this price (at least not twice) and the $|t|$ distributions are much flatter. The slope for SDE is about half of that for elastic scattering and the slope for double dissociation is probably much less. Unfortunately the latter has never been measured at collider energies. At large $|t|$ the pomeron, having very short effective wavelength, couples predominantly to single quarks, and presumably gluons. The additive quark rule $\sigma_{\pi p} \approx \frac{2}{3}\sigma_{pp}$ suggests [10] that this is effectively true even at t ≈ 0. Maybe the jet-gap-jet events are just an extension of this view to very high $|t|$. But now it *should* be possible to have more than one pomeron in a single event, in double parton interactions. These have now been seen in CDF [11] as events producing a γ-jet pair and independently a jet-jet pair. It would be interesting to select events with two jets at large positive rapidity and two at large negative rapidity, find the fraction that are double parton scattering and measure the gap fraction in that rare case. So far no experiments have paid much attention to very forward jet physics,

[1] While this viewpoint may not be theoretically very sound, it seems to be phenomenologically useful.

which is a pity. If one could take this argument a step further, to three jets in each beam direction with a large rapidity gap in between, it would be even more interesting (triple-valence quark scattering?).

Returning to the W-gap search, which used charge-gap correlations to conclude that no signal is seen, we now compare the multiplicity distribution with W to that with forward dijets (η both > 0 or both < 0) with $E_T > 20$ GeV. The multiplicity distibutions are identical, within the statistics, including the "empty bin", see Fig. 4.

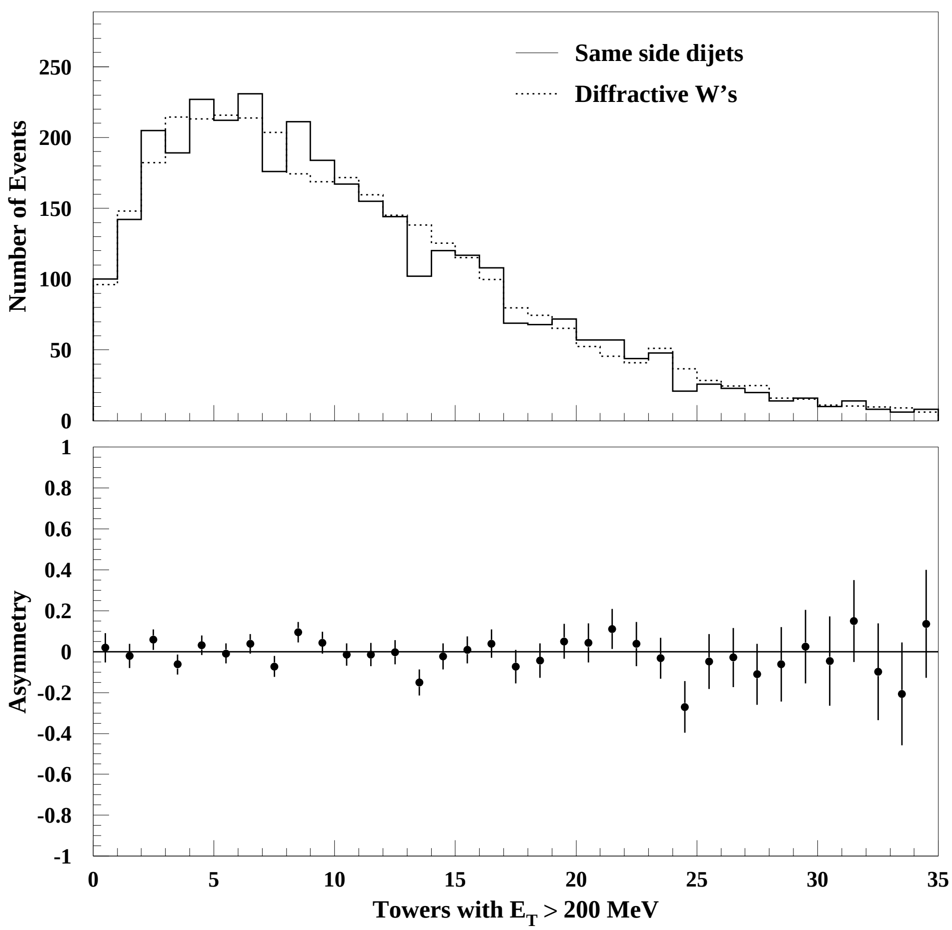

Fig. 4 *Top:* Multiplicity distribution of calorimeter towers of $E_T > 200 MeV$ in the pseudorapidity region $2 <| \eta |< 4.2$ opposite to the dijet system compared with W-production data. *Bottom:* Ratio of difference to sum of normalized multiplicity distributions.

We can then put an upper limit (95% c.l.) of 1.75% on the fraction of dijet events produced diffractively. Although the quasielastic beam particle is not detected we can estimate that this limit applies to a diffractive mass of roughly 180 GeV and t near 0 (given the steeply falling t-distribution, if the forward particle is not detected it is likely to have small t). The predictions for the standard pomeron flux are 5% for a hard glue pomeron and 2% for a hard quark pomeron (already ruled out by the W results). So the CDF gap studies are beginning to constrain the (standard flux) pomeron structure, but one would like an order of magnitude more statistics. If the flux is renormalized the expected diffractive fractions decrease by a factor near 10 and the data give no constraints. With the standard flux normalization we have to suppose that the momentum sum rule is not valid, i.e. that the integral of the fluxes of quarks and gluons weighted by their momentum fraction is not 1.0 but some fraction f_β. Suppose the fraction of gluons ($\frac{g}{g+q}$) is f_g. Then the CDF dijet and W results together exclude a region of the $f_\beta : f_g$ plane as shown in Fig. 5. The results of UA8 are compatible with the allowed region, so there is not an inconsistency.

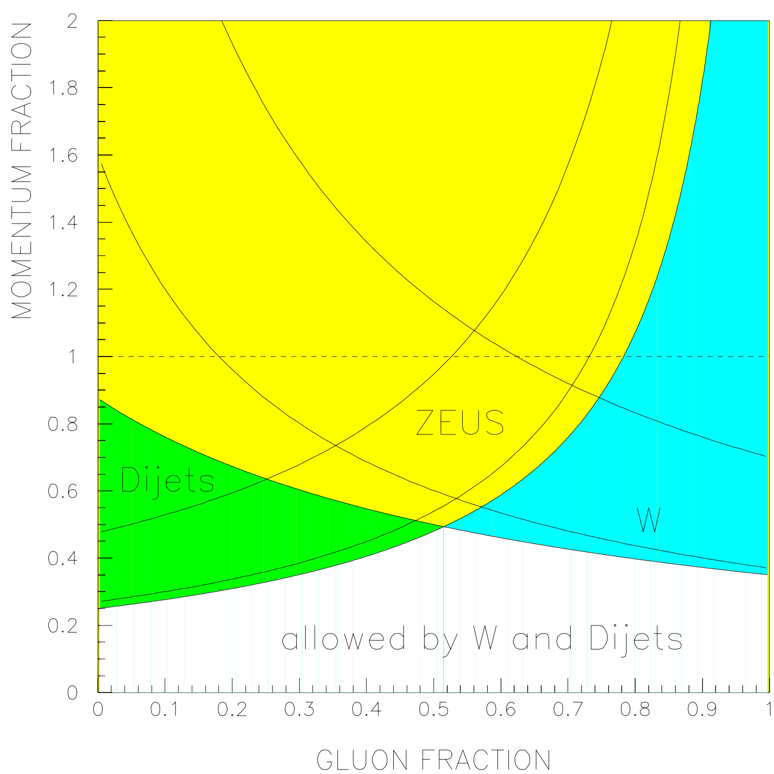

Fig.5 CDF limits on the pomeron momentum sum rule as a function of the gluon fraction, using the standard Regge pomeron flux factor. The 1σ preferred region from ZEUS data is given by the diamond-shaped region.

5 CDF Tagged Pomeron Data

For the Run 1C of the Tevatron, from October 1995 to February 1996, we installed very forward track detectors in CDF. These were scintillating fiber trackers with 100 μm resolution, placed within 1 cm of the beams, 57 m from the collision point. Antiprotons with $x_F > 0.90$ and $0 <\mid t \mid< 2$ GeV^2 were measured in these *Roman Pots.* This enabled us to trigger on diffractive events, and measure the central event with its jets, heavy flavors, perhaps Ws in the full CDF central detector. We recorded about 7×10^6 events, some of them with clean dijets in the central region. The jet E_T spectrum extends to about 40 GeV at $\sqrt{s} = 1800$ GeV; data were also taken at $\sqrt{s} = 630$ GeV, the same energy as UA8. The average η of the two jets is clearly in the rapidity hemisphere opposite the diffractive $\bar{p}$, being about 0.9 instead of 0.0. So we clearly see events with high-E_T jets and a high x_F antiproton, but are they diffractive? Much work is still necessary to answer this question. One can fit $x_F > 0.9$ (anti)proton spectra using triple Regge phenomenology. In scattering and losing energy the proton can emit either a pomeron (the diffractive part) or some other *reggeon* corresponding to virtual $\rho, A_2, \pi, etc.$ exchange (non-diffractive "background"). The very different form of the pomeron and reggeon trajectories corresponds to very different shapes for the inclusive proton spectra. At $t =$ -1 GeV^2 the pomeron exchange term M^2 distribution falls, roughly like $(M^2)^{-0.6}$ while the Regge term rises like $(M^2)^{+2.0}$. These terms become equal around $x_F = 0.95$, and data below that x_F (above M$^2 = 0.05$ s) have a major background fraction. There is no way of separating these on an event by event basis. For *inclusive* distributions (not demanding jets) the t, M^2 distributions allow one to fit the pomeron and reggeon contributions. This cannot be done for the di-jet subsample because the jet requirement will strongly bias the M^2 distibution. One could take the data in slices of M and use the jet data to extract an *effective* pomeron structure function for each M. To the extent that structure functions in pp scattering do not depend on $\sqrt{s}$, the pomeron (reggeon) structure function should not depend on M ... but the pomeron/reggeon mixture will vary from "all" pomeron to "all" reggeon as M increases. A better study in principle is to fix M and t and change $\sqrt{s}$, which keeps the pomeron/reggeon- proton collision identical kinematically but changes the pomeron/reggeon mix. Fortunately we have some data at 630 GeV as well as 1800 GeV. This is perhaps a bit simplistic, because the M-state goes into a different region of the detector at different $\sqrt{s}$, but we should eventually be able to statistically separate the pomeron and reggeon contributions and give structure functions for each.

6 Double Pomeron Exchange

In this process *both* beam particles are diffractively scattered and the two pomerons interact in the central region to produce hadrons, see Fig. 1(d). There will be rapidity gaps of at least 3 units (4 would be cleaner!) between the beam particles and the central particles. The condition $x_F > 0.95$ or equivalently $\Delta y > 3$ leads to an upper limit on the central mass $M < 0.05 \times \sqrt{s}$, which is 3 GeV for the ISR, 90 GeV at the Tevatron, 700 GeV at LHC and 10 TeV at the Omegatron. At the ISR, where the process was discovered, the mass range was ideal for glueball searches [13] and the highly constrained quantum numbers of the central system ($I^G J^{PC} = 0^+ EVEN^{++}$) made it unique.

The much higher masses reached at the Tevatron make it interesting to look for jets and heavy flavors, measure the pomeron structure and compare it with that found in pomeron-p as well as photon-pomeron collisions. This makes three channels! If the pomeron has the structure of a high-β gluon with some soft field or condensate neutralizing the color, we would expect either soft-soft, soft-hard or hard-hard collisions. The latter would stand out as a peak near 1.0 in the variable M_{JJ}/M. *If* that is observed it then becomes important to measure the jets' structure, especially perhaps the $b\bar{b}$ and $c\bar{c}$ fractions. The soft-soft collisions might be a good hunting ground for state changes such as the disoriented chiral condensate. Double pomeron events with four jets, if such are found, would be a good sample to look for a double parton scattering, DPS, contribution. This would give information on the size of the pomeron, and parton correlations. The DPS events may be non-existent if the pomeron is basically a single gluon and a semi-classical "bleaching field". Another handle on the pomeron size would come from Bose Einstein correlations. There are many other interesting studies, in fact *anything* of interest in pp collisions can be looked at afresh in pomeron-pomeron. I will give one more example: very soft (about 50 MeV to 100 MeV) direct photons [12]. And how do all these studies depend on the t of the pomeron, if at all? Moving up to LHC energies, $\sqrt{s} = 14$ TeV, the same rule of thumb (probably naive over such an extrapolation in energy) give a mass limit of about 700 GeV for the central cluster, so we can think of the LHC as a tagged pomeron-pomeron collider with $\sqrt{\hat{s}} \leq 700$ GeV. Given that this is well over the threshold for WW and probably Higgs production it could be exciting. Note that the signature of two large rapidity gaps can also come from W-exchange, a Higgs channel [4]. Unfortunately rapidity gap physics can only be done cleanly when single interactions are present, so modest luminosity must be used.

7 Summary

The pomeron has been known about for thirty years, and we are finally probing its structure in a QCD framework at hadron colliders (S$p\bar{p}$S and the Tevatron) and HERA (ep). Jet production in single diffractive excitation is probably seen by UA8 at the S$p\bar{p}$S, who also claim a superhard (β near 1.0) constituent in the pomeron. CDF see high-E_T jets with high-x_F (>0.90) antiprotons but do not yet know what fraction is diffractive. Studies of dijet and W production using just rapidity gaps found no signal, and put upper limits on the fraction of the total constituent momentum and the q/g mix. The limits are compatible with UA8's observations. HERA experiments are also studying the pomeron by photon-pomeron collisions (see the talks in session Va) and see indications of a large component near $\beta = 1.0$.

Both CDF and D0 observe a super-hard pomeron (with very high $|t|$) exchanged between partons making high E_T jets. The relationship with low-$|t|$ pomerons is interesting but unclear; perhaps they are both single gluons (to first order) with some soft color field.

The double pomeron exchange process is a clean but rather little exploited channel for understanding the pomeron. This will become particularly interesting at LHC thanks to the energy reach extending into the electroweak sector.

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