Fermi National Accelerator Laboratory

FERMILAB-Conf-97/361-E
CDF

Hard Diffraction in CDF

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October 1997

Published Proceedings of the *7th Blois Workshop on Elastic and Diffractive Scattering - Recent Advances in Hadron Physics,* Seoul, Korea, June 10-14, 1997

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

HARD DIFFRACTION IN CDF

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The aim of these studies is to use hard (large Q^2) processes to investigate the partonic nature of the pomeron. We have measured events with large rapidity gaps between balancing high E_T jets, events with two forward (same-side) jets and a large gap (diffractive di-jet production), diffractive $W^{\pm}$ production and diffractive heavy flavor (J/ψ and b-quark) production. Candidate events of the type double-pomeron $\rightarrow$ di-jet are observed. I close with a look at the future (Run II).

1 Introduction

The observation[1] of high E_T jets in single diffractive excitation at the CERN $Sp\bar{p}S$ Collider, interpreted as resulting from a parton in the exchanged pomeron,$I\!P$, scattering on a parton in the excited proton, opened the way to studying the partonic structure of the pomeron. In this paradigm the pomeron, despite its t-channel virtuality and more mysterious attributes (such as complex angular momentum), is treated as if it were a hadron with well defined structure functions $q(\beta, Q^2)$ and $g(\beta, Q^2)$. Here β is the momentum fraction of a parton in the pomeron, equivalent to Bjorken-x for a hadron. Our aim is to measure these structure functions using as many different processes as possible to see whether a consistent picture emerges. If not we will be forced to change the (perhaps too simplistic) "hadronic pomeron paradigm".

A good signature for diffractive dijet production in hadron-hadron collisions is either a rapidity gap (no particles at all) exceeding about 3 units or a quasi-elastically scattered beam particle with Feynman x_F above about 0.95, or both. Neither of these limits are hard, but (e.g.) gaps of 4 units are strongly dominated by pomeron exchange while gaps of 2 units are not. Nevertheless a "gap detector" spanning only 2 units of rapidity (y, or pseudorapidity η) can still give a well measureable diffractive signal if one measures the multiplicity distribution of particles in the region. This is a broad distribution coming down to zero multiplicity but, in the case of a diffractive component, with a distinct **excess** of events in bin zero. If charged tracks are counted the signal is confined to bin zero, but if calorimeter towers above some low threshold are counted noise causes the diffractive signal to spill into bin 1 and perhaps 2. CDF has done several diffractive studies using just rapidity gaps, as has DØ [2].

If the high-x_F (anti-)proton is measured the four-momentum squared, t, of the pomeron is known. The fraction of the incident proton's momentum taken by the pomeron is ξ = 1 - x_F. The ξ and t distributions can be compared with what we expect from Regge theory and we can in principle measure the purity of the sample (pomeron fraction versus reggeon $\equiv$ non-$I\!P$ exchanges like ρ and π). Furthermore we can Lorentz transform to the c.m. frame of the pomeron-proton collision. Measuring the two jets and knowing the proton's structure function we can derive the structure function (actually a combination of $q(\beta)$ and $g(\beta)$) of the pomeron. If we measure not only dijet but also W or Drell-Yan production we can separate out the quark and gluon components $q(\beta, Q^2)$ and $g(\beta, Q^2)$ and see whether these can be well described by QCD and with what "starting point" (at low Q^2). Do these pomeron structure functions agree with those measured at HERA in $\gamma I\!P$ collisions and at the Tevatron/LHC in $I\!P I\!P$ collisions? Is the pomeron structure function varying with its t (effectively its mass^2) and ξ ... seeing the latter might be due to a varying contamination of reggeons.

These goals are very ambitious and we are far from them. So we make a simple model for the pomeron structure function, plug it into a Monte Carlo such as POMPYT (POMerons in PYThia)[3] and compare with data to see which *ansatz* structure function works best.

We are studying six diffractive processes in CDF. The first, Jet-Gap-Jet (JGJ) is different in that the (4-momentum transfer)^2 across the gap is typically $|t| \sim E_T^2 \sim 1000$ GeV^2 while for the others it is 1 GeV^2 or less. Single diffractive excitation (SDE) producing dijets (GJJ), W, J/ψ and b/c all show signals. Finally double pomeron exchange (DPE) where both beam hadrons emit a pomeron and these interact to make two jets (GJJG) shows a signal. We hope that by studying all these processes either a consistent picture will emerge, or we will find out how to make a better model.

2 CDF and Detectors

CDF is a big collaboration with over 400 physicists and it was designed to study high E_T physics in $p\bar{p}$ collisions at $\sqrt{s}$ = 1800-2000 GeV (1800 so far, 2000 in 2000 maybe). This means W/Z/top/hard jets etc. B-physics has been a somewhat unexpected bonanza. Some early diffractive measurements were made[4,5,6] ... this was "soft" physics and the Roman pots used to measure the quasi-elastically scattered (anti)-protons were then removed. Diffractive physics in CDF was revived with full emphasis on the **hard** component. Not having pots any more this was done using gaps: discovering rapidity gaps between high E_T jets and measuring forward gaps opposite dijets and W.

The CDF detector has central tracking to $|\eta| \sim 2.0$ and calorimeters of various types to $|\eta| = 5.4$. The FORWARD calorimeters which we use as gap detectors cover $2.2 < |\eta| < 4.2$. Beam-Beam Counters (BBC) are scintillator paddles from about 3.1 to 5.6 in $|\eta|$. We installed a small *microplug* calorimeter over $4.2 < |\eta| < 5.4$ for just the last 5 weeks of Run I (Run Ic), which was the only time we had new pots. These contained three small (2 cm $\times$ 2 cm) crossed hodoscopes of scintillating fibers which could move in to within about 10 mm of the circulating beams. They were installed 56 - 58 m downstream (for the $\bar{p}$) after dipoles to give momentum analysis. The acceptance of this spectrometer in the t, ξ plane is: at $t = 0$ GeV^2 for $0.04 < \xi$ and at $\xi = 0$ for $-t > 0.6$ GeV^2. A line drawn between these points is approximately the edge of the acceptance (we lose the low-ξ, low-t corner which is of course where pomeron exchange is most strongly dominant). The acceptance cuts off for $\xi > 0.1$; a region dominated by non-diffractive scattering. With the pots, we took data triggering on them inclusively and also on a pot track together with a jet in the central region. Some data were also taken with a pot track and vetoing on one or both microplugs (a rapidity gap "seed").

3 JET GAP JET Events

In 1993 Bjorken predicted [7] that sometimes a hard scattering producing two high E_T jets could take place by a color-singlet exchange, e.g. two-gluon exchange in a color singlet. (Remember that Low and Nussinov had proposed [8] (soft)$I\!P \equiv gg$ back in 1975.) This could give rise to a rapidity gap between the jets (if they are well separated) as they would not be connected by any color field (string). However this gap could be destroyed by another soft color exchange between spectators (it would survive this with a *survival probability SP* which could only be guesstimated). Both CDF and DØ set about looking for such gaps, and both found them at the level of about 1% of the well-separated jet pair events, consistent with Bjorken's expectations. DØ published first [9] but chose only to claim an upper limit R(gap) $< 1.1\%$ (95% cl). Their method was to move the jets apart in η and count the fraction of events with no tracks in the (expanding) region in between. This falls exponentially with $|\eta_1 - \eta_2|$ but then flattens out, which is their signal. CDF [10] studied the full multiplicity distributions in various rapidity intervals and fit to smooth functions, finding excesses in the bin zero. The excess is rather independent of gap width and is R(gap) = [0.085 $\pm$ 0.0012 (stat) $\pm^{0.0024}_{0.0012}$ (syst)]%.

We have just completed [11] a new analysis of JGJ events. We used a trigger which required two forward ($|\eta| > 1.8$) jets with $E_T > 20$ GeV, either both on the Same Side (SS = same sign of η) or on opposite sides (OS). We then compared the multiplicity (tracks and calorimeter towers separately) of these samples. If you take slightly different central $\Delta\eta$ "gap" regions (2.0 and 2.4 units wide) for the OS and SS cases, to account for different mean multiplicities, the OS and SS distributions agree excellently except for the bin zero excess. The signal:background ratio is about 1:1. It is obviously important to select single interactions and know the vertex finding efficiency. The new CDF result (with different cuts) is $R = 1.13 \pm 0.12(stat) \pm 0.11(syst)$ %. There does not seem to be any E_T-dependence of this fraction from 25 GeV to 55 GeV (DØ claim a dependence [2] but over a larger E_T range), and the dependence on the rapidity separation between the jets (but fixed $\Delta\eta$) also seems flat except for a possible drop beyond 5.6 (JJ separation).

Note that for fixed E_T the q/g ratio increases as the jet $\eta_1 - \eta_2$ increases. It would be interesting to know whether there is any preference for quarks or gluons to scatter via color singlet exchange. A q/g separation algorithm would be extremely useful. In the absence of that we can ask whether the fraction of events with an additional jet is the same in gap/nongap events. As gluons are more likely to radiate a third jet this could give some clue, but the requirement of a gap leaves a lot less room for third jets, and it is a tricky bias. Nevertheless 85% of the non-gap events have a third jet above 5 GeV, only 22% of the gap events, and this reduction is larger than you would expect just from the gap requirement. I would not go so far as to suggest that this indicates color singlet exchange has a bias towards qq scattering (but it might!). In the future, in Run II, we would like to push to larger rapidities and both higher and lower E_T (how does this merge into soft double diffractive dissociation?). The possibilities at LHC are very interesting, provided there is enough running with low enough luminosities to have single interactions.

4 Single Diffractive Dijet production

A new study [12] was made with the 2-forward-jet (SS) trigger; two SS jets above 20 GeV and with $\eta > 1.8$. Then look in a rapidity region on the opposite side and count calorimeter towers hit ($2.4 < \eta < 4.2$) and BBC counter hits ($3.2 < \eta < 5.9$); these are plotted against each other in Fig.1 and a strong gap signal is seen. We find, after correcting for gap

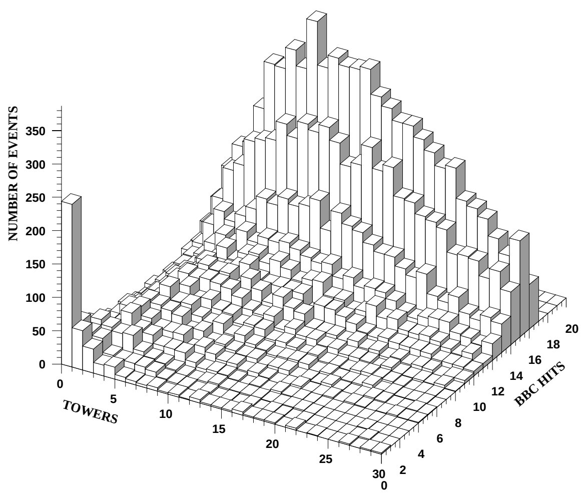

Figure 1: Calorimeter towers vs BBC counter hits in region opposite a forward dijet.

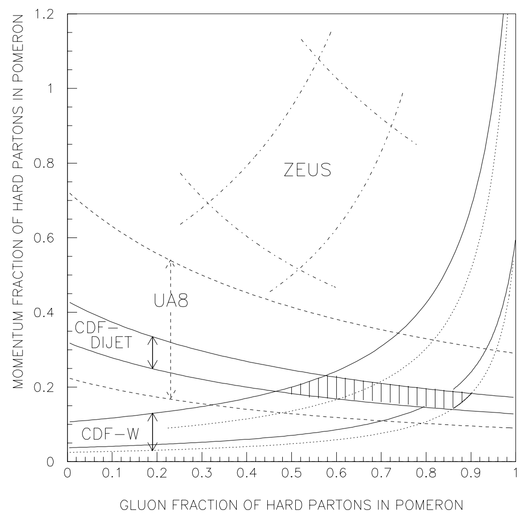

Figure 2: Diffractive dijet and W constraints on the fraction of gluons in the pomeron.

efficiencies and multiple interactions, that of these dijets $(0.75 \pm 0.10)\%$ are diffractively produced. The E_T and $\eta(> 1.8)$ distributions of the jets in gap and non-gap events seem to be identical (the data has run out by $E_T \sim 40$ GeV). The gap dijets are slightly more back-to-back in ϕ and any third jet is slightly softer.

Data on diffractive dijet production with a roman pot track (and hence with t and ξ known) are still being analysed. The activity in the microplug on the pot side is very low, as expected, but we are not requiring a gap there ... that would bias us unnecesarily against the higher masses. We do see the expected correlation between the ξ from the pot track and η_{max}, the edge of the observed calorimeter signals. We have two data samples: an inclusive $\bar{p}$ trigger (diffractive inclusive) which contains 2500 clean 2-jet events with $E_T > 10$ GeV, and another larger sample requiring a jet in the trigger; they extend to about 50 GeV in E_T. For the first sample we find that the ratio of diffractive to non-diffractive dijets with $E_T > 10$ GeV, $0.05 < \xi < 0.10$ and $|t| < 1$ GeV is:

$R_{\bar{p}JJ} = [0.109 \pm 0.003(\text{stat}) \pm 0.016(\text{syst})]\%$ (preliminary).

The main reason this is nearly an order of magnitude lower than the studies using gaps is the restriction $0.05 < \xi < 0.10$. There seems to be no strong t-dependence to this fraction, and the jet E_T distribution looks like the non-diffraction one (again). The jet $< \eta >$ distribution is shifted about 1 unit away from the $\bar{p}$, and the $\Delta\phi$ distribution between the two leading jets is significantly narrower in the diffractive case. (If the pomeron were *purely* gluonic one would expect the opposite effect.) We are looking at how $R_{\bar{p}JJ}$ depends on ξ; variations are expected both because of the changing fraction of $I\!P$-exchange and the change in excitation mass $M = \sqrt{\xi s}$. The measured value of $R_{\bar{p}JJ}$ is much lower than expected with a "standard $I\!P$ flux" and in better agreement with a *renormalized* flux [13].

From the constrained kinematics of the $\bar{p}$-tagged events we reconstruct β distributions for jets above (say) 15 GeV. We are at present comparing these with expectations from POMPYT Monte Carlo using hard and soft structure functions, with and without evolution.

5 Diffractive W production

The importance of measuring diffractive W is that they come predominantly from $q\bar{q}$ annihilation and probe the quark content of $I\!P$, so GW and GJJ together give the g/q fraction. This is at rather large $Q^2 \sim M_W^2$ so the pomeron should have evolved quarks even if it is purely gluonic as $Q^2 \rightarrow 0$. A few W were found with pot tracks and are thus diffractive-W candidates, although it is not possible with such low statistics to exclude reggeon production. The most spectacular [14] is clearly a W and it has about 6 units rapidity gap, extremely unlikely for reggeon exchange. However the gap method (WG) was used to measure [15] the diffractive W fraction; it has the double advantages of an order of magnitude more integrated luminosity and a similar factor in forward acceptance. Extracting a signal was difficult and relied on two expected correlations (a) if the gap is on the p side we expect about twice as many W^- as W^+ and vice versa (b) the W should mostly be opposite in rapidity to the gap. The result is that $(1.15 \pm 0.55)\%$ of all W are diffractively produced; the significance is 3.8 σ. The diffractive W have fewer jets which suggests $q\bar{q} \rightarrow W$ rather than $qg \rightarrow qW$. An early prediction [16] for a *hard quark dominated* pomeron was around 20% for this fraction. However if the pomeron "flux" is much lower [13] the number will be correspondingly reduced.

Putting the fractions of diffractively produced W and dijets together we can select a favored region in the plane, see Fig.2 : [gluon fraction F_g of hard partons in the pomeron] vs [momentum fraction of hard partons in the pomeron]. "Hard" means energetic enough to participate in the measured processes. We get two crossing bands; the dijet data decrease with F_g because the larger the gluon fraction the fewer partons you need, and the W data rise because if F_g is high you need more partons. A band derived from the $Sp\bar{p}S$ experiment UA8 is also shown. The CDF data clearly favor a gluon fraction between 0.5 and 0.9 [a]; the lower end of this range agrees with ZEUS ($\gamma I\!P$). The difference in the momentum fraction between CDF and ZEUS remains to be explained; is it a non-factorization effect and/or a difference in the pomeron flux and are these the same thing?

6 Heavy Flavor Production

A search for diffractive production of J/ψ using the gap method is being carried out starting with 39,400 J/ψ events with a single vertex from data taken without any requirements on

[a] presumably at $Q^2 \sim M_W^2$

forward BBC counters. The J/ψ are central, $|\eta| < 2.0$ (most < 1.0).

Open heavy flavor production $Q\bar{Q}$, a gg-favored process, has been studied using a sample of prompt high-p_T electrons and the gap method. Using Run I data and good e-candidates with $|\eta_e| < 1.1$ and $7 < E_T(e) < 20$ GeV, rejecting photon conversions and e from W, Z leaves 713,000 events. Some of these are residual conversions and some are fake electrons (hadrons) but (65$\pm$7)% are estimated to be from heavy flavors. There is a clear gap signal, and the events with gaps seem to be (48$\pm$7)% $b + c$. The signed impact parameter distribution from the silicon vertex detector shows a long lifetime component; we are still working on using this to distinguish c and b. Our preliminary result is that (0.18$\pm$0.03)% of central high-p_T b/c are diffractively produced.

7 Double Pomeron Exchange

It is very interesting and important to study double pomeron exchange: both p and $\bar{p}$ are quasielastically scattered, there are two large rapidity gaps and an isolated central hadronic system. Of course we would like a pure sample of $I\!P I\!P \rightarrow$ hadrons but as the central mass gets large reggeon exchanges can contaminate the data. Comparing jet production and J/ψ and $Q\bar{Q}$ production with SDE tests factorization and the "quasiparticle paradigm". A central detector such as CDF and DØ can see the complete central state (in this sense being comparable to LEP experiments) and we can reconstruct parton momentum fractions from the jets. However the DPE cross section is very small compared with other strong processes, $\sigma_{DPE} \sim 100\mu b$ in total and much less if you ask for jets. Ideally one would like pots on both arms, but if their acceptance (weighted by distribution of forward protons, approximately $e^{b.t}$ with $b \sim -7$) is small they cost a lot in rate. The gap-gap method or even the pot-gap method will have more statistics.

In CDF we have done a first study using the pot-gap method, i.e. taking events with a well-measured track in the pots ($0.05 < \xi < 0.10, |t| < 1$ GeV^2) together with two central jets above $E_T = 7$ GeV. Looking at the gap detectors on the opposite side we have 33 events in the (0,0) bin expecting 10 events by extrapolating in the neighboring bins. The average E_T of the jets is 10 GeV, they are nicely back-to-back in ϕ, but as we estimate the total central mass to be 50 - 100 GeV we are not yet seeing $\beta \sim 1$ jets. We hope to collect much higher statistics in Run II to search for such "LEP-like" events. The (very preliminary) rates show (DPE/SDE) $\sim$ 0.17%, the same as (SDE/ND) $\sim$ 0.16% (with about 30% errors). Thus only about 3×10^{-6} of central jet-pairs with $E_T > 7$ GeV are produced by DPE with the cuts used (in particular note the high ξ range on the pot side).

8 The Future

Run II starts in 2000 with more bunches (36) and higher luminosity. We hope to do a lot more hard diffraction by

- (a) replacing the Run Ic microplugs with better "miniplugs" covering 0.5° to 3.0° as gap detectors. The calorimetry from 3° to 30° will also be much better.

• (b) improving the acceptance of the existing roman pots, getting closer to the $\bar{p}$ beam and thus to smaller t, ξ

• (c) improved triggers, including requiring gaps in the trigger to improve sample purity and reject multiple interactions (with appropriate controls).

• (d) installing wherever possible counters along the beam pipe $5 < |\eta| < 7$ to detect showers ... these are inefficient gap detectors but are better than nothing.

Acknowledgments

I would like to acknowledge valuable collaboration with my colleagues in CDF, especially the hard diffraction group. Funding from the US Department of Energy and the Ministry of Education, Science and Culture of Japan is gratefully acknowledged.

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