BFKL AND RAPIDITY GAPS AT THE TEVATRON

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Abstract

The results of several analyses of dijet systems produced in $\bar{p}p$ interactions at $\sqrt{s} = 1800$ GeV at the Fermilab Tevatron are presented. The effects of soft gluon emission are studied via the azimuthal decorrelation of jets as a function of their separation in pseudorapidity. Evidence is found for strongly interacting color–singlet exchange in the excess of events with low multiplicities of particles in the rapidity interval between jets (rapidity gaps). Preliminary results of hard diffractive analyses utilizing forward rapidity gaps in association with jets as well as W bosons are also presented.

Dijet Decorrelation at DØ

Dijet final states are copiously produced in proton–antiproton collisions at $\sqrt{s} = 1800$ GeV through quark–antiquark annihilation and quark–quark, quark–gluon or gluon–gluon scattering. Leading order (LO) quantum chromodynamics (QCD) has been very successful in explaining theoretically the dynamics of such 2–to–2 processes. At high momentum transfer scales (Q^2), the theory can be calculated perturbatively and the partons become synonymous with jets detected in experiments. The spectrum of final states which is produced in nature is, however, much richer in detail and intricacy. Initial and final state radiation conspire to produce additional partons with much lower energies, thus introducing additional Q^2 scales to the calculations which, along with collinear divergences, make the predictions much more difficult to calculate. Next–to–leading–order (NLO) QCD attempts to improve the theoretical understanding of multijet production by allowing for a third jet and calculating the 2–to–3 matrix elements. Alternatively, a recent calculation[1)] has attempted to account for the presence of multiple scales by resumming the effect of the soft gluons using the BKFL[2)] equation. Additionally, the parton showering Monte Carlo HERWIG[3)], which resums $\ln Q^2$ via the DGLAP[4)] splitting functions provides predictions for the behavior of such multiparton systems. The experimental picture is also clouded by this extra complexity, since low energy partons do not efficiently express themselves as jets in the experimental detectors, due either to their proximity to the primary jets or to their much lower energy.

The DØ collaboration[5)] has investigated the effects of this additional radiation by analyzing jets widely separated in pseudorapidity (η) [6)]. A pure two–parton final state will produce jets back–to–back in azimuthal angle (ϕ). As additional partons are produced, it is expected that this correlation will be perturbed; requiring jets to be well separated in η increases the phase space for such multiparton production.

The data for this study were collected during the 1992–1993 run (Run 1a) at the Fermilab Tevatron. Events were required to satisfy a single jet trigger with a transverse energy (E_T) cut of 30 GeV. Offline, jets were reconstructed using an iterative fixed–cone clustering algorithm with a cone radius of 0.7 in $\eta - \phi$ space, and events with at least two jets with $E_T > 20$ GeV and $|\eta| < 3.0$ were selected. The jets were ordered in η and those at the extremes of η were defined as jet 1 and 2. To remove any trigger inefficiencies, one of these two jets was further required to have $E_T > 50$ GeV. The online trigger limited the effective $\Delta\eta$ ($|\eta_{jet1} - \eta_{jet2}|$) to less than 6.

A single correlation variable, $\langle\cos(\pi - \Delta\phi)\rangle$, has been defined to quantify the effect of any additional parton emission, where $\Delta\phi$ is simply $\phi_{jet1} - \phi_{jet2}$. The behavior of this variable is then studied as a function of the η separation of the jets, $\Delta\eta$. Figure 1 presents the correlation variable as a function of $\Delta\eta$. The error bars on the data points represent the statistical and

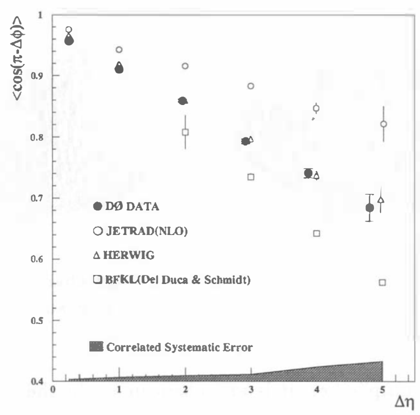

Figure 1: The dijet decorrelation, $\langle\cos(\pi - \Delta\phi)\rangle$ vs. $\Delta\eta$, for the data, JETRAD, HERWIG, and the BFKL calculations of Del Duca and Schmidt.

uncorrelated systematic uncertainties added in quadrature. The correlated systematic uncertainty is presented as a band at the bottom of the plot, the major contribution arising from the jet energy scale uncertainty. Also presented in Fig. 1 are the theoretical predictions from HERWIG, NLO QCD as implemented in JETRAD[7], and the BFKL resummation of DelDuca and Schmidt, with purely statistical error bars. Systematic effects arising from changes in renormalization and factorization scales and different choices of parton distribution functions were investigated and found to be small. Although all of the theories predict the measured linear decorrelation with increasing separation in pseudorapidity, only HERWIG describes the correct magnitude of the dependence. The single additional parton in the JETRAD predictions is unable to correctly account for the full amount of decorrelation, whereas the BFKL calculation, valid only for large $\alpha_s\Delta\eta$, predicts too large an effect.

Rapidity Gap Analyses at DØ and CDF

In addition to the color-exchange mechanisms listed above for jet production in $\bar{p}p$ annihilations, the exchange of an electroweak (photon, W or Z boson) or a strongly-interacting ($q\bar{q}$ or gg) color-singlet can also give rise to jets in the final state. It is estimated that up to 10% of jet production may be due to such colorless exchange. Gluon emission is highly suppressed between the outgoing partons in color singlet exchange; studying the multiplicity distribution of particles produced in the rapidity interval between jets therefore provides an experimental technique to distinguish color-singlet from color exchange processes. Since statistical fluctuations or detector inefficiencies in color exchange processes can also produce

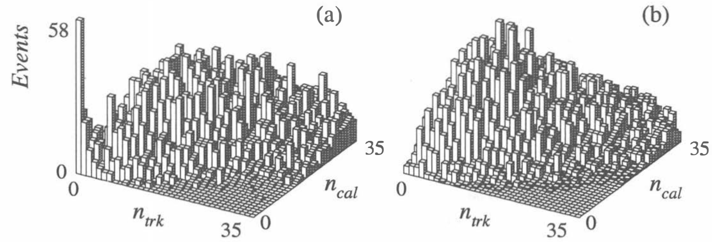

Figure 2: The calorimeter tower multiplicity (n_{cal}) versus the charged track multiplicity (n_{trk}) in the pseudorapidity region $|\eta| < 1.3$ for the (a) opposite-side and (b) same-side samples as described in the text.

events with low particle multiplicities, it is an enhancement in the number of events at low particle multiplicities above such expectations which is a signature for color-singlet exchange.

Rapidity gaps are experimentally defined as an absence of "particle" production in some pseudorapidity interval of the detector. DØ defines a canonical "particle" to be an electromagnetic calorimeter tower with an energy above threshold (200 MeV E_T in the central region ($|\eta| < 1.3$) and 200 MeV energy in the forward ($2 < |\eta| < 4$)). Subsidiary definitions include tracks in the central and forward drift chambers in front of the calorimeter, towers above threshold in the hadronic calorimeter behind the EM section, and hits in either the Level 0 scintillator hodoscope or the forward muon system.

CDF relies on tracks in their Central Tracking Chamber (CTC) in the central region ($|\eta| < 1.1$) and calorimeter towers above threshold (200 MeV E_T) in the forward region ($2 < |\eta| < 4$). Towers above threshold in the central calorimeter are used to crosscheck the tracks in the CTC.

Central Rapidity Gaps in Dijet Systems

DØ has completed an analysis[8)] of its 1992–1993 data sample selecting events with jet $E_T >$ 30 GeV, and $|\eta| > 2$. Figure 2 shows the particle multiplicity distribution for calorimeter towers versus central tracks within the η interval between the jets for such events for both opposite-side(a) and same-side(b) topologies. The same-side sample provides a qualitative measure of the color-exchange background multiplicity in the central rapidity region due to the color flow between the scattered and spectator partons. Diffractive contributions were minimized by requiring a coincidence of hits in forward and backward luminosity counters positioned around the interaction region. The enhancement of events at low multiplicities in the opposite-side versus same-side events is clear. By fitting the calorimeter tower multiplicity to a double negative binomial distribution above n=3 and extrapolating the fit to lower values DØ has measured a fractional excess of events at low multiplicity of $1.07 \pm 0.10(\mathrm{stat})^{+0.25}_{-0.13}(\mathrm{syst})\%$, which

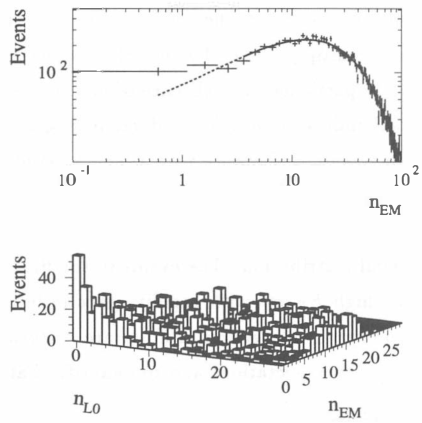

Figure 3: The multiplicity distributions for rapidity intervals in the hemisphere opposite a forward rapidity gap in the single veto sample as explained in the text. Above is shown the calorimeter tower distribution along with a fit to a negative binomial distribution. Zero multiplicity events have both forward and backward rapidity gaps. Below is shown the number of calorimeter towers versus the number of hit level 0 counters.

is consistent with expectations from strongly interacting color singlet exchange and with the published CDF result of $0.85\pm0.12(\mathrm{stat})^{+0.24}_{-0.12}(\mathrm{syst})\%$[9]. A preliminary study of the behavior of this excess as a function of the minimum jet E_T has been performed using a larger data sample collected during the 1994–1995 run (Run 1b). The data was divided into E_T bins of 15–20, 20–30, 30–40 and greater than 40 GeV using several dedicated triggers. Although the dijet production cross section falls by over three orders of magnitude over this range, the fractional excess was measured to be roughly constant on the order of 1%.

In a sample of two jet events with $E_T > 20$ GeV, and $|\eta| > 1.8$, CDF compares the multiplicity distributions for same–side dijet events to that of opposite–side events and measures an excess of events with a central rapidity gap corresponding to $2.0\pm0.7(\mathrm{stat})\pm0.3(\mathrm{syst})\%$ of all dijet events.

Forward Rapidity Gaps in Dijet Systems

DØ has expanded its study of hard diffractive processes by searching for events with jets and a forward rapidity gap along the beam direction. For this analysis, the online trigger required one jet above 15 GeV E_T. Additionally, the trigger either no longer required hits in the luminosity counters (inclusive), or actively vetoed on one side (single veto). Offline, a hard scatter was selected by requiring two jets with $E_T > 15$ GeV. The particle multiplicities in the forward rapidity interval were measured and an excess of events at low multiplicities was observed. The fractional excess is on the order of 10^{-3} of the inclusive sample and rapidity gaps were found to be multiply tagged by the other detector elements in the forward region mentioned previously. In particular, the absence of hits in the luminosity counters was determined to be a very good indicator of a forward rapidity gap. The single veto trigger thus provides a large, enriched sample of events with which to study the diffractive process. One such study entails selecting events with a rapidity gap in the forward or backward region and measuring the multiplicity distribution in the opposite hemisphere, shown in Fig. 3 along with a fit to a negative binomial distribution. The events in the first bin are most striking, in that they contain at least two high E_T jets with rapidity gaps in both the p and $\bar{p}$ directions, indicative of a hard double pomeron interaction. Efforts are underway to establish that the events represent a true excess over expectations and to quantify that excess, if confirmed.

Diffractive W Production

In contrast to dijet production, which primarily probes the gluon content of the color singlet being exchanged, diffractive W boson production is sensitive to the quark content. Investigation of both processes is crucial to a full understanding of color singlet exchange. The CDF collaboration has searched for evidence of diffractively produced W bosons[10)] in its Run 1a sample of W bosons decaying to electrons or muons[11)] by requiring a forward rapidity gap. To determine the fraction of diffractive events two related but distinct methods are employed. One relies on the fact that the W is heavily boosted in diffractive events, giving rise to leptons in the hemisphere opposite the gap. The other method recognizes that a proton (uud) interacting with a symmetric $q\bar{q}$ object is twice as likely to produce a $W^+(u\bar{d})$ as a $W^-(d\bar{u})$. Therefore, positive leptons are expected to be preferentially produced with rapidity gaps in the $\bar{p}$ direction, and vice versa for negative leptons. Although roughly 5% of the events exhibit a rapidity gap, there is no clear sign of an excess in the correlated events over the uncorrelated events. From the measured asymmetries the ratio of diffractive to non-diffractive W boson production is determined to be less than 6% at the 95% confidence level.

Conclusions

The azimuthal correlation of jets produced in $\bar{p}p$ annihilations has been measured to decrease linearly as a function of their separation in pseudorapidity. Although all theoretical models with which the data have been compared exhibit such a linear decrease, NLO QCD predicts too little while BFKL resummation predicts too much decorrelation. The HERWIG prediction is able to reproduce the data over the entire $\Delta\eta$ range explored. The increased data sample from Run 1b as well as low energy running ($\sqrt{s} = 630$ GeV) will extend the η reach of this analysis, as well as allow comparisons at the two center of mass energy points.

Clear evidence for jet production via strongly interacting color singlet exchange has been demonstrated in $p\bar{p}$ annihilations at the Tevatron. The measured fractional excess of rapidity gaps between jets widely separated in rapidity at DØ is $1.07 \pm 0.10(\mathrm{stat})^{+0.25}_{-0.13}(\mathrm{syst})\%$. The preliminary CDF measurement of $2.0 \pm 0.7(\mathrm{stat}) \pm 0.3(\mathrm{syst})\%$ is consistent within errors. Preliminary evidence has also been presented from DØ for forward rapidity gaps produced in association with jets. The single gap component represents on the order of 10^{-3} of the inclusive production, whereas the double gap component is on the order of 10^{-6}. Additionally, a preliminary limit on the ratio of diffractive to non–diffractive W boson production of less than 6% at the 95% confidence level has been placed on diffractive W production by the CDF collaboration.

An active and productive program of diffractive phenomena studies is taking place at the Tevatron collider, with both DØ and CDF continuing analyses of their full data sets. The final results of those analyses, as well as comparisons of data taken at $\sqrt{s}$=1800 and 630 GeV should be illuminating.

Acknowledgements

I would like to thank the many individuals on both DØ and CDF who have made results available to me, especially A. Brandt, R. Hirosky, T. Heuring, and K. Goulianos.

References

(1) V. Del Duca, C.R. Schmidt, Phys. Rev. D **51**, 2150 (1995); Phys. Rev. D **49**, 4510 (1994).

(2) L.N. Lipatov, Sov. J. Nucl. Phys. **23**, 338 (1976); E.A. Kuraev, L.N. Lipatov, V.S. Fadin, Sov. Phys. JETP **44**, 443 (1976); Sov. Phys. JETP **45**, 199 (1977); Ya.Ya. Balitsky, L.N. Lipatov, Sov. J. Nucl. Phys. **28**, 822 (1978).

(3) G. Marchesini, B.R. Webber, Nucl. Phys. **B310**, 461 (1988); I.G. Knowles, Nucl. Phys. **B310**, 571 (1988); G. Marchesini et *al.*, Comp. Phys. Comm. **67**, 465 (1992).

(4) V.N. Gribov and L.N. Lipatov, Sov. J. Nucl. Phys. **46**, 438 (1972); L.N. Lipatov, Sov. J. Nucl. Phys. **20**, 95 (1975); G. Altarelli and G. Parisi, Nucl. Phys. **B126**, 298 (1977); Yu.L. Dokshitzer, Sov. Phys. JETP **46**, 641 (1977).

(5) S. Abachi *et al.*, Nucl. Instrum. Methods **A338**, 185 (1994).

(6) S. Abachi *et al.*, to be published in Phys. Rev. Lett.

(7) W.T. Giele, E.W.N. Glover and D.A. Kosower, Nucl. Phys. B403, 633 (1993).

(8) S. Abachi *et al.*, Phys. Rev. Lett. **72**, 2332 (1994), Phys. Rev. Lett. **76**, 734 (1996).

(9) F. Abe *et al.*, Phys. Rev. Lett. **74**, 855 (1995).

(10) K. Goulianos, *Proceedings of the 10^{th} Topical Workshop on Proton–Antiproton Collider Physics* (1995), ed. R. Raja, J. Yoh, (AIP Press, 1996).

(11) F. Abe *et al.*, Phys. Rev. D **50**, 2966 (1994).