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BFKL Tests at the Tevatron

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Abstract

The azimuthal decorrelation of jets as a function of their rapidity separation and the dependence of the fraction of jet events with central rapidity gaps on the center of mass energy are studied in $\bar{p}p$ collisions at the Tevatron. The preliminary results on jet decorrelation are in disagreement with calculations based on the Leading Logarithmic Approximation for BFKL resummation. The preliminary results on the $\sqrt{s}$-dependence of the central rapidity gap events are in disagreement with the two-gluon model for color-singlet exchange.

1 Introduction

The advent of new DIS data at a previously unexplored kinematic region from the HERA ep collider has generated a renewed interest in the Balitsky-Fadin-Kuraev-Lipatov (BFKL) equation[1)].

In high energy scattering (at large center-of-mass energy $\sqrt{s}$) and for one-scale processes (e.g. for fixed momentum transfer Q), the radiative corrections to the parton-parton scattering contain large logarithms $\ln(s/Q^2)$. In this case, the $\alpha_s \ln(s/Q^2)$ contributions need to be summed to all orders in α_s. This summation, currently done only in the leading logarithmic approximation (LLA), is accomplished by the BFKL equation using a space-like chain of an infinite number of gluon emissions. The gluons are strongly ordered in their longitudinal momentum fractions x_i, $x_n \ll x_{n-1} \ll \ldots \ll x_1$. However, there is no ordering in the gluon transverse momenta k_{Ti} along the chain, but rather a random walk in k_T. That is, the transverse momentum of a gluon in the chain is close to that of the previous gluon but can be either smaller or larger.

In the context of deep inelastic scattering, the large logarithms of s/Q^2 take the form of logarithms of $1/x$, corresponding to the region of small Bjorken x. In this region, the BFKL equation predicts the strong rise of the proton structure function F_2 with decreasing x. However, the conventional DGLAP evolution[2)] also gives a satisfactory description of the current HERA F_2 measurements[3)]. In addition, it is difficult to extract information about the BFKL equation from F_2 data, due to the intermixing of perturbative and non-perturbative effects in the very low x, low Q^2 region, and to the loss of the BFKL-characteristic diffused k_T dependence. Thus, structure function measurements alone are not sufficient for observing BFKL dynamics. For this reason, alternative quantities have been investigated, where DGLAP evolution is suppressed while BFKL evolution is enhanced, and where the characteristic x and k_T dependences of the BFKL gluon ladder can both be exposed. Hadronic final states provide such observables. In DIS events, forward jet production with jet transverse momentum $k_{Tj} \simeq Q$ and jet longitudinal momentum fraction $x_j \gg x$ has been studied[4)]. BFKL predicts a rise in the forward jet cross section with $\log(x_j/x)$, and the preliminary HERA results seem to support such behaviour. Alternatively, in high energy hadron-hadron collisions the inclusive dijet production can be studied. For large values of x_j, the large logarithms $\ln(s/Q^2)$ reduce to $\ln(\hat{s}/Q^2)$ (where $\sqrt{\hat{s}}$ is the partonic center-of-mass energy) which are of the order of the (pseudo)rapidity[1] interval $\Delta\eta$ between the two jets. In this case, the BFKL equation predicts a rise in the dijet cross section with $\Delta\eta$, as first discussed by Mueller and Navelet[5)].

The experimental observation of the rise of the inclusive dijet cross section with $\Delta\eta$ in $p\bar{p}$ collisions is hampered by the dependence of the cross section on the parton distributions. At large $\Delta\eta$ the behaviour of the cross section is dominated by the $x \to 1$ suppression of the parton distributions. An alternative method to look for the BFKL signature in the inclusive dijet production is the study of the azimuthal angle separation $\Delta\phi$ between the two jets. In leading order (LO) the two jets are back-to-back in ϕ and balanced in transverse momentum k_{Tj}. As $\Delta\eta$ increases, more and more soft gluons are emitted in the rapidity interval between the two highest-$|\eta|$ jets (tagging jets), resulting in the production of additional jets. Thus, the azimuthal correlation between the tagging jets is gradually lost[6)]. The effect has been studied by the DØ experiment at the Tevatron collider[7)]. New results from the 1994-95 Tevatron run with increased statistics, symmetric cuts on the two jet transverse energies $E_{T_{1,2}}$, and extended $\Delta\eta$ range are presented here.

An extension of the BFKL gluon ladder is the so-called Hard Pomeron, also referred to as

[1]Henceforth, the term ***rapidity*** will be used to refer to pseudorapidity $\eta = -\ln\tan(\theta/2)$.

the QCD or bare Pomeron. It is supposed to be a perturbative, colorless object, exchanged between quarks and gluons, carrying large momentum transfer. It is usually modelled by two (or more) gluons. In $p\bar{p}$ collisions, hard color-singlet exchange is expected to produce rapidity gaps between jets, i.e. regions of rapidity phase space containing no particles. Both the DØ and CDF experiments at the Tevatron have observed central rapidity gap events[8)]. In ep collisions, central rapidity gaps have been observed in photoproduction events at HERA[9)]. The dependence of the fraction of rapidity gap events on the center-of-mass energy $\sqrt{s}$ can provide a test of the two-gluon model. Preliminary Tevatron results on this study are presented here.

2 Jet Azimuthal Decorrelation

In order to identify azimuthal decorrelation in the inclusive dijet production, we look for broadening of the $\Delta\phi$ distribution with $\Delta\eta$. Quantitatively, we expect the average of the $\cos(\pi - \Delta\phi)$ distribution (equal to unity in LO) to decrease with increasing $\Delta\eta$.

The data for this study were collected during the 1994-95 Tevatron run under special low luminosity conditions using the DØ detector[10)]. The hardware trigger required localized (0.2×0.2 in $\Delta\eta \times \Delta\phi$ space) transverse energy deposits in the calorimeter. Jets were defined as E_T sums in a cone of radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$ using calorimeter cell information. The software trigger, using a fast version of the jet finding algorithm, required one jet with $E_T > 12$ GeV. In order to enhance the statistics in forward jets, an additional trigger condition was used, requiring localized E_T deposits greater than 2 GeV in the $|\eta| > 2$ rapidity region at the hardware level, and one jet with $E_T > 12$ GeV in the $|\eta| > 1.6$ region at the software level. Offline, jet energy scale corrections were applied and multiple $p\bar{p}$ interactions and spurious jets were removed. A minimum jet E_T cut of 20 GeV and a maximum absolute rapidity cut of 3.5 were applied, in order to ensure good jet reconstruction efficiency over the entire region of acceptance. The remaining jets were ordered in rapidity, i.e. $\eta_1 > \eta_i > \eta_2$, where η_1 and η_2 refer to the most forward and most backward jet, respectively. In order to avoid any trigger bias, the absolute rapidity boost, defined as $|\bar{\eta}| = |(\eta_1 + \eta_2)/2|$, was required to be smaller than 0.5.

In the selected sample, the quantities studied are $\Delta\eta = \eta_1 - \eta_2$ and $\Delta\phi = \phi_1 - \phi_2$. The available $\Delta\eta$ range extends to six units of rapidity. The azimuthal angle separation, in the form of the $|1 - \Delta\phi/\pi|$ distribution, is plotted in Fig. 1 for two extreme bins of $\Delta\eta$ centered at $\Delta\eta \approx 1$ and 5. The error bars in both figures represent statistical errors only. It is evident that the $\Delta\phi$ distribution broadens as $\Delta\eta$ increases. The $\cos(\pi - \Delta\phi)$ distribution is plotted in Fig. 2. The data error bars represent the statistical and uncorrelated systematic (mostly due to jet energy resolutions) errors added in quadrature. The correlated systematic error due to the jet energy scale is shown as an error band at the bottom of the plot. The data show a decorrelation effect with increased rapidity interval. Also shown in the plot are the theoretical predictions from the parton shower Monte Carlos HERWIG[11)] and PYTHIA[12)], as well as from a calculation based on BFKL resummation in LLA done by Del Duca and Schmidt[6)]. The latter, expected to be valid only for large $\alpha_s\Delta\eta$, is plotted for $\Delta\eta \geq 2$. The errors for all theoretical predictions are statistical only. We see that the jet azimuthal decorrelation in the parton shower Monte Carlos is similar to the one observed in the data. The LLA resummation calculation predicts stronger decorrelation effects than seen in the data. It would be interesting, however, to see the effect of the next-to-leading logarithmic terms in resummation, currently being calculated.

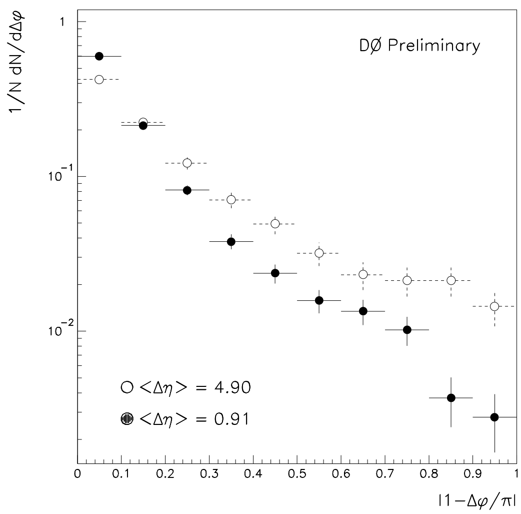

Figure 1: The azimuthal angle separation, $\Delta\phi = \phi_1 - \phi_2$, between the most forward and most backward jets, plotted as $1 - \Delta\phi/\pi$, for $\Delta\eta = 1$ and 5. The errors are statistical only.

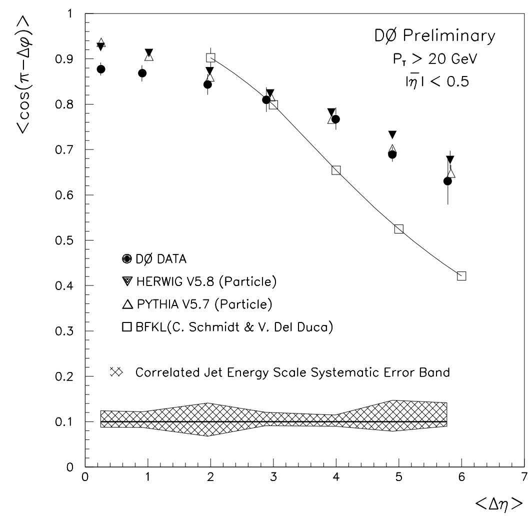

Figure 2: The average value of $\cos(\pi - \Delta\phi)$ plotted vs. $\Delta\eta$, for the DØ data, HERWIG, PYTHIA, and the BFKL LLA calculation of Del Duca and Schmidt. The data errors are statistical and uncorrelated systematic added in quadrature. The band represents the error on the jet energy scale. The theoretical errors are statistical only.

3 Central Rapidity Gaps

The data for this study were collected during brief low luminosity Tevatron runs in 1996 at $\sqrt{s} =$ 1800 and 630 GeV, using the DØ detector. The hardware trigger required two localized (0.2×0.2 in $\Delta\eta \times \Delta\phi$ space) transverse energy deposits greater than 2 GeV in opposite hemispheres of the calorimeter, with $|\eta| > 1.6$. The software trigger required two jets in the opposite sides of the detector with jet $E_T > 10$ GeV and $|\eta| \geq 1.6$. Offline, jet energy scale corrections were applied, multiple $p\bar{p}$ interactions and events with spurious jets were removed, and a minimum jet E_T cut of 12 GeV and minimum jet $|\eta|$ cut of 1.9 were imposed. The particle multiplicity in the central rapidity region is approximated by the multiplicity, n_{cal}, of localized (0.1×0.1 in $\Delta\eta \times \Delta\phi$ space) transverse energy deposits above 200 MeV in the electromagnetic (EM) part of the calorimeter within $|\eta| < 1$. The n_{cal} multiplicity distributions for the two samples are shown in Fig. 3. The leading edge of each n_{cal} distribution is fitted using a single negative binomial distribution. The fraction of rapidity gap events is calculated from the excess of events over the fit in the first two bins divided by the total number of entries. It is found to be $0.6\pm0.1\%$(stat.) at $\sqrt{s} = 1800$ GeV and $1.6 \pm 0.2\%$(stat.) at $\sqrt{s} = 630$ GeV. The ratio R of the rapidity gap fractions at 630 and 1800 GeV is equal to $2.6 \pm 0.6\%$(stat.). The survival probablity of the rapidity gap, defined as the probability of no spectator interactions, is expected to have only a logarithmic dependence on $\sqrt{s}$ [13] and therefore, can not account for the observed ratio of the rapidity gap fractions at the two center-of-mass energies.

The average E_T and $|\eta|$ of the opposite-side jets in the $\sqrt{s} = 1800$ GeV sample are 18.9 GeV and 2.4 units of rapidity, respectively. The corresponding values for the $\sqrt{s} = 630$ GeV sample are 16.8 GeV and 2.1 units of rapidity, respectively. The average proton x, given by $x = E_T \cdot e^{|\eta|}/\sqrt{s}$, is 0.116 and 0.218 for the 1800 and 630 GeV samples, respectively. Using parton distributions from CTEQ4L[14] and a Q^2 value equal to the average jet E_T^2, the average x values correspond to a proton composition of 54% quarks and 46% gluons at $\sqrt{s} = 1800$ GeV, and of 75% quarks and 25% gluons at $\sqrt{s} = 630$ GeV.

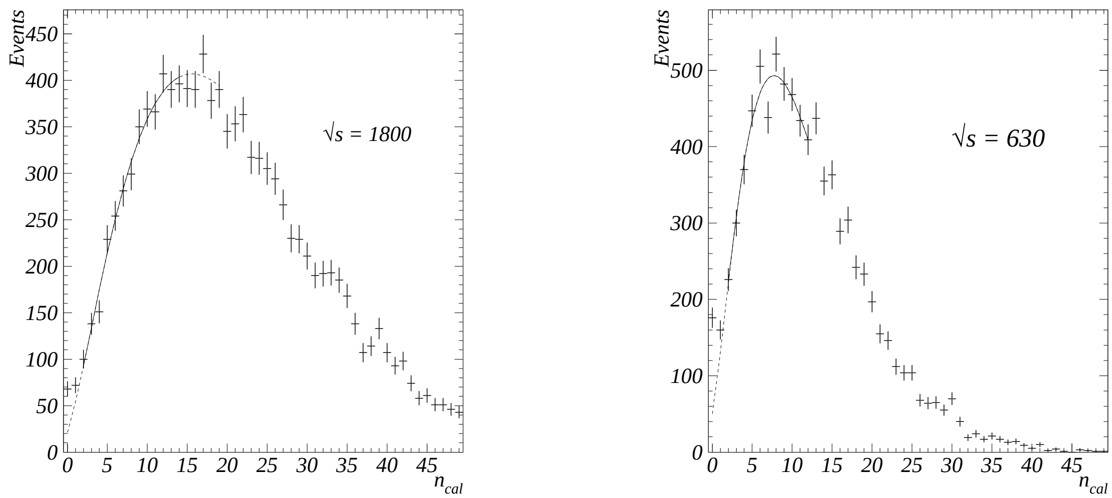

Figure 3: Central EM calorimeter multiplicities for the $\sqrt{s} = 1800$ GeV and 630 GeV samples. The negative binomial fits are also shown.

In the simple two-gluon model[15], implemented in leading order and without including BFKL dynamics, the color singlet is represented as a two gluon exchange in qq, qg, or gg scattering. Each scattering process has different color factors contributing to its cross section. The color factors are contained in the fractional weighting of the parton distribution functions in the QCD color singlet and color octet states. The rapidity gap fraction can be calculated from these color factors. For the quark and gluon fractions corresponding to the average x values of this analysis, the ratio of the fraction of rapidity gap events at the two center-of-mass energies is predicted to be $R \approx 0.7$. Since the average jet E_T and $|\eta|$ are approximately the same in the $\sqrt{s} = 1800$ GeV and 630 GeV samples, the ratio of the rapidity gap fractions depends mainly on the parton distributions in the (anti)proton, whereas it is effectively independent of the hard scattering process. Therefore, including the BFKL formalism does not alter the prediction of the two-gluon model for the ratio R.

An alternative model, referred to as the soft color-singlet model[16], asserts that the formation of a rapidity gap is a random process occuring long after the hard scattering process, due to color rearrangement. The hard scatter is mediated by one gluon exchange. However, random color flow between the scattered partons and the proton remnants can produce an effective color-singlet state, as opposed to a hard color-singlet object. According to this model, producing a color-singlet from gg scattering is highly suppressed by statistics compared to $q\bar{q}$ scattering. For the quark and gluon fractions of this analysis, the soft color-singlet model predicts a ratio of the rapidity gap fractions at the two center-of-mass energies of $R \approx 2$.

The preliminary measurement of the ratio R disagrees with expectations from two-gluon exchange. The soft color model, while still under development, predicts a ratio close to that observed in the data.

4 Conclusions

The azimuthal decorrelation as a function of rapidity separation in dijet systems, and the dependence of the fraction of dijet events with a central rapidity gap on the center-of-mass energy, have been studied in $\bar{p}p$ collisions at $\sqrt{s} = 1800$ and 630 GeV using data collected with the DØ detector. The preliminary results from the decorrelation study agree qualitatively with the predictions from parton shower Monte Carlo programs and are in disagreement with the current analytical calculations based on LLA BFKL resummation. Preliminary results from the $\sqrt{s}$-dependence of the central rapidity gap events disagree with expectations from the two-gluon model for color-singlet exchange. The soft color-singlet model predicts a ratio close to that observed in the data.

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