A Search for Jet Events with Rapidity Gaps in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

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First experimental results from a search for events with a rapidity gap between jets are presented. These events were produced in the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.8$ TeV and measured with the DØ detector. The fraction of events with a rapidity gap between jets is measured as a function of the pseudo-rapidity separation of the leading two jet cone edges ($\Delta\eta_c$). An upper limit at the 95% confidence level of 1.1×10^{-2}on the fraction of events with no particles between the jets is obtained for events with $\Delta\eta_c > 3$ and jet transverse energies greater than 30 GeV.

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Rapidity gaps, which are regions of rapidity containing no particles, have typically been associated with low transverse momentum processes such as elastic and diffractive scattering. However, rapidity gaps are also expected to occur in high transverse momentum processes when a color singlet is exchanged between interacting partons [1,2]. These gaps occur between the final state jets due to the absence of radiation from the color singlet and the resulting destructive interference between initial and final state radiation [3]. Hadrons are produced only between the outgoing jets and spectator partons, resulting in an empty region of phase space between the jets.

The particle lego plot of Fig. 1 shows an example of a two-jet event with a rapidity gap of size $\Delta\eta_c$, where $\Delta\eta_c$ is the pseudo-rapidity separation between the jet cone edges. The exchange of a photon, W, or Z is expected to give such a rapidity gap topology. In addition, a hard Pomeron, which has been shown to be associated with jet production [4], is also a color singlet which is expected to produce rapidity gaps. Although standard QCD interactions do not typically produce rapidity gaps due to the exchange of color via a quark or gluon, some portion of these events also contain a rapidity gap due to fluctuations in the particle multiplicity between the jets.

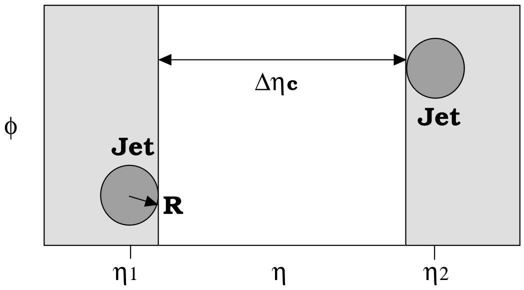

FIG. 1. The distribution of particles in a typical two-jet event with a rapidity gap is shown in an η-ϕ lego plot. The pseudo-rapidity region between the jet cone edges, $\Delta\eta_c = |\eta_1 - \eta_2| - 2R$, contains no particles.

The absence of particles in the $\Delta\eta_c$ region due to the hard scattering subprocess is not enough to insure a rapidity gap, however, since interactions between the spectator partons frequently produce particles between the jets. The probability of having no spectator interactions is called the survival probability of the gap $<|S|^2>$ [2]. While both the cross section for producing a rapidity gap from the hard scattering (σ_{gap}) and the survival probability are of theoretical interest, experiments are only directly sensitive to the product of these factors. An experimentally accessible quantity is the fraction of events with a rapidity gap between the leading two jets, defined as

$$f(\Delta\eta_c) = \frac{\sigma_{gap}(\Delta\eta_c) \cdot <|S|^2>}{\sigma(\Delta\eta_c)} \qquad (1)$$

where $\sigma(\Delta\eta_c)$ is the cross section for producing jets with $\Delta\eta_c$ separation between the jet cone edges.

A crude estimate for the range of the rapidity gap fraction from color singlet exchange is $10^{-4} < f < 3 \times 10^{-2}$. The lower bound assumes electroweak exchange [5] and a conservative value for the survival probability of $<|S|^2> = 0.1$ [2,5,6], while the upper bound assumes Pomeron exchange [2] with the largest predicted value of $<|S|^2> = 0.3$ [6]. These values are expected to have little dependence on $\Delta\eta_c$ [2,5–7]. In contrast, the rapidity gap fraction from standard QCD (color octet exchange) is expected to have a strong dependence on $\Delta\eta_c$. For $\Delta\eta_c \sim 0$ a large fraction of events have a rapidity gap, but this fraction decreases sharply with increasing $\Delta\eta_c$, assuming that the average particle multiplicity between jets increases with $\Delta\eta_c$. The degree of suppression depends on the actual multiplicity distribution between jets, which is not well-known, but a PYTHIA Monte Carlo study indicates that $f(\Delta\eta_c > 2) \sim 10^{-5}$ [5].

The DØ detector [8] is used to provide the first experimental information on the rapidity gap fraction. This analysis utilizes the uranium-liquid argon calorimeters which have full coverage for a pseudo-rapidity range of $|\eta| < 4.1$. The calorimeters are azimuthally symmetric and have electromagnetic (EM) and hadronic resolutions of $15\%/\sqrt{E}$ and $50\%/\sqrt{E}$, respectively. The electromagnetic section averages 21 radiation lengths and the hadronic section contains 9 nuclear interaction lengths. The transverse segmentation of the projective calorimeter towers is typically $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$.

The response of the electromagnetic section to low energy particles is of particular interest for this analysis. Test beam studies indicate that 96%(100%) of 2(10) GeV electrons deposit more than 200 MeV in an EM tower, while this threshold is 40%(62%) efficient for detecting 2(10) GeV charged pions. The electromagnetic section is also sensitive to minimum ionizing particles, which deposit about 200 MeV in an electromagnetic tower.

During the 1992-1993 run, the DØ triggering system consisted of hardware and software components. The first hardware level required a coincidence of scintillator hodoscopes to insure an inelastic collision. The calorimeter hardware trigger was based on trigger towers of size $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ and was instrumented for $|\eta| \leq 3.2$. The number of towers above a transverse energy (E_T) threshold and the position of the towers could be specified at this level. The software jet filter was applied to events passing the hardware trigger by invoking a jet cone algorithm to find jets with cone size $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$. Additional topology cuts could be applied in the filter to select certain jet pseudo-rapidity configurations.

Data used for this analysis is derived from two triggers: an inclusive jet trigger for small values of $\Delta\eta_c$ and a high-$\Delta\eta_c$ trigger implemented in order to increase the statistics for this analysis. The inclusive jet trigger required at least one jet with $E_T > 30$ GeV while the high-$\Delta\eta_c$ trigger required $\Delta\eta_c > 2.6$ for any two jets with $E_T > 25$ GeV and $|\eta| > 2$. Figure 2 shows the number of events in bins of $\Delta\eta_c$ for the two triggers after the offline cuts described below. The more restrictive high-$\Delta\eta_c$ trigger allowed a larger fraction of triggered events to be recorded, enhancing the statistics for $\Delta\eta_c \geq 2.7$. The high-$\Delta\eta_c$ trigger has a clearly observable acceptance loss near the $\Delta\eta_c = 2.6$ threshold caused by trigger requirements on the jet pseudo-rapidities. These requirements result in an acceptance only for events with $\eta_{boost} = \frac{1}{2}(\eta_1 + \eta_2)$ near zero, but the rapidity gap fraction is expected to have little dependence on this variable [2,7]. The number of events from the inclusive trigger is 500,000 based on an integrated luminosity of 120 nb^{-1}, while the high-$\Delta\eta_c$ trigger has 77,000 events from 5.4 pb^{-1}. The triggers do not include requirements on the multiplicity or energy between the jets, as this would cause a bias on the measured fraction of events with a rapidity gap.

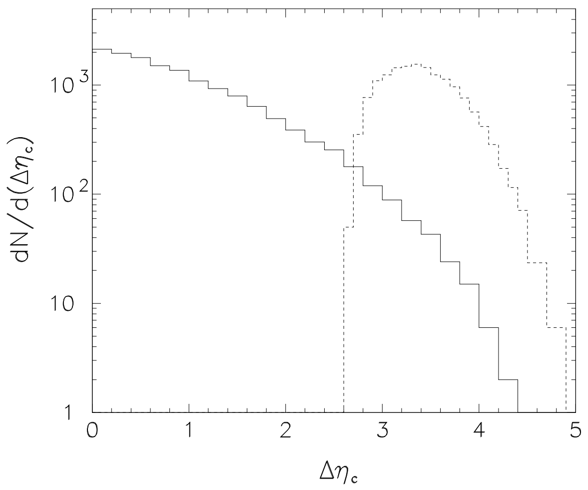

FIG. 2. The number of events after the offline cuts described in the text is plotted in bins of $\Delta\eta_c$, the separation in pseudo-rapidity between the cone edges of the leading two jets. The solid line represents the inclusive trigger and the dashed line is used for the high-$\Delta\eta_c$ trigger.

In the offline analysis, events with more than one interaction in a proton-antiproton bunch crossing are removed since they include a source of particles not associated with the triggered event. The width of the time distribution of hits in the luminosity counters is used to determine whether events have single or multiple interactions. This method is 75% efficient at finding single interactions, while misidentifying less than 5% of multiple interaction events as single interactions.

Jets are reconstructed using an iterative jet cone algorithm with a radius of 0.7 [9]. Events with spurious jets due to detector effects are removed with a series of cuts that are more than 95% efficient at rejecting fake jets while removing only 4% of real jets. These cuts also remove events in which electrons or direct photons are misidentified as jets, which should not be included in the rapidity gap fraction measurement. The transverse energy of the jets in the remaining events is corrected for detector response, out-of-cone showering effects, and underlying event.

Fiducial cuts are imposed on the remaining events in order to obtain the final data sample. Events are required to have a measured vertex within 2σ (50 cm) of the average since the detector is optimized for interactions near $z = 0$. Events are also required to have $|\eta_{boost}| < 0.8$. This cut does not affect the high-$\Delta\eta_c$ events which already are constrained towards small $|\eta_{boost}|$ as discussed earlier, but insures for lower $\Delta\eta_c$ that the jets are centered about the central calorimeter where the particle detection efficiency is highest. A cut of $\Delta\eta_c > 0$ is also imposed to remove events in which the pseudo-rapidity of the jet cones overlap. Finally, the leading two jets are each required to have $E_T > 30$ GeV and $|\eta| < 3.2$ in order to minimize differences between the two triggers. The final data sample contains 27,500 events with $\Delta\eta_c < 2.7$ from the inclusive trigger and 15,200 events with $\Delta\eta_c \geq 2.7$ from the high-$\Delta\eta_c$ trigger (see Fig. 2).

This data sample is used to measure the fraction of jet events with a rapidity gap as a function of $\Delta\eta_c$. For an ideal detector, Eq. 1 can be rewritten in the following form

$$f(\Delta\eta_c) = \frac{N_{n=0}(\Delta\eta_c)}{N(\Delta\eta_c)} \tag{2}$$

where N is the number of events with the leading two jet cones separated by $\Delta\eta_c$, and the subscript $n = 0$ refers to the subset of the sample with no particles between the jets. This definition has the advantage that luminosity uncertainties and trigger efficiencies do not enter into the calculation.

A direct measurement of $f(\Delta\eta_c)$ is experimentally unattainable since tracking chambers are only sensitive to charged particles and calorimeters only measure energy flow, while both types of detectors have inherent inefficiencies. It is possible to place an upper limit on $f(\Delta\eta_c)$, however, given a reasonable detector and a suitable experimental gap definition. The particle detection inefficiencies associated with an experimental gap definition imply that $f(\Delta\eta_c)^{exp} > f(\Delta\eta_c)$, because events with undetected particles add a background contribution which increases the measured gap fraction. Since a measurement of the gap fraction will contain contributions from color singlet and octet exchange as well as background due to inefficiencies, an upper limit on the gap fraction provides a conservative upper limit on the amount of color singlet exchange.

For this analysis, a rapidity gap event is required to have no electromagnetic (EM) towers above a transverse energy threshold of 200 MeV between the jets. The ideal definition of Eq. 2 is replaced by the experimental definition of the rapidity gap fraction,

$$f(\Delta\eta_c)^{exp} = \frac{N_{\#EM=0}(\Delta\eta_c)}{N(\Delta\eta_c)} \tag{3}$$

where $N_{\#EM=0}$ is the number of events with no EM towers above threshold between the jet cones.

In order to utilize this rapidity gap definition it is necessary to remove noisy calorimeter cells which have spurious energy due to instrumental effects since they artificially contaminate rapidity gap events. Towers which have $E_T > 200$ MeV significantly more often (3σ) than their neighbors are suppressed. This cut reduces the contamination to less than 5% and results in an acceptance loss for detecting particles of less than 1%.

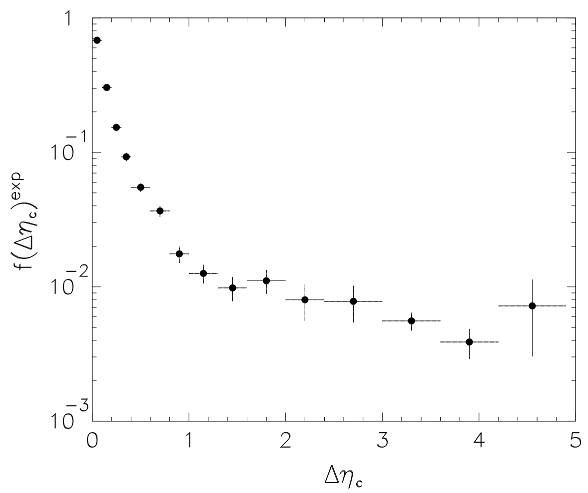

FIG. 3. The fraction of events with no electromagnetic towers above 200 MeV between the leading two jets (each with $E_T > 30$ GeV) is plotted for the data sample described in the text. The error bars show the statistical uncertainty only.

Figure 3 shows $f(\Delta\eta_c)^{exp}$ for the final data sample. Data from the high-$\Delta\eta_c$ trigger has been corrected for the acceptance loss observed in Fig. 2, and the two triggers have been determined to be consistent within statistical errors in the region of overlap. The gap fraction is observed to have the expected qualitative behavior: for $\Delta\eta_c < 2$ it falls off steeply with increasing $\Delta\eta_c$ due to the decrease in gap events from fluctuations, while for larger $\Delta\eta_c$ the fraction is relatively flat, which is consistent with the naive expectations from color singlet exchange. It is not possible to definitively associate this flat region with color singlet exchange due to theoretical uncertainties and detector inefficiencies.

The rapidity gap fraction of Eq. 3 is measured to be $f(\Delta\eta_c > 3)^{exp} = (5.3 \pm 0.7^{(stat)} \pm 0.6^{(sys)}) \times 10^{-3}$ where only events with $\Delta\eta_c > 3$ are used in the calculation so that the contribution from color octet exchange is largely suppressed. The systematic error term includes a 7% uncertainty from varying the jet energy scale corrections, 5% from noisy cells which have eluded the spurious cell cuts–estimated from data taken with no $p\bar{p}$ interactions, 5% from trigger acceptance effects, as well as 5% each from the fake jet cuts and from the single interaction requirement discussed earlier.

Before placing an upper limit on $f(\Delta\eta_c > 3)$, the gap fraction must be corrected for out-of-cone effects which introduce hit towers between the jets that erroneously reduce the measured gap fraction and upper limit. Out-of-cone effects include particles which fall outside a fixed jet cone due to fragmentation and particles within the jet cone which deposit energy outside the cone due to calorimeter shower broadening. The out-of-cone effects are determined by first measuring the multiplicity distribution of electromagnetic towers in the portion of the $\Delta\eta_c$ region that is subtended by the annulus formed by the standard 0.7 cone and a larger cone of radius 1.5. This multiplicity distribution is then corrected for the underlying event by subtracting the multiplicity in a similar area 180° away from the jet in ϕ. The corrected multiplicity distribution is used to calculate that approximately $35 \pm 5\%$ of the events with $\Delta\eta_c > 3$ are contaminated by out-of-cone effects.

Applying this correction to the fraction of events with no EM towers between the jets, an upper limit on the fraction of events with no particles between the jets is obtained. The upper limit on the rapidity gap fraction is calculated to be

$$f(\Delta\eta_c > 3) < 1.1 \times 10^{-2} \tag{4}$$

at the 95% confidence level. This limit constrains the product of the survival probability and the cross section for color singlet exchange regardless of the contributions from color octet exchange and the background from particle detection inefficiencies. Fig. 4 shows how the constraint on σ_{gap}/σ and $<|S|^2>$ imposed by the upper limit compares with existing theoretical predictions.

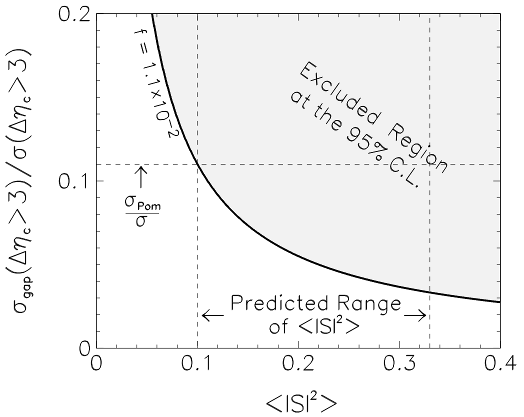

FIG. 4. A plot of σ_{gap}/σ versus $<|S|^2>$ for $\Delta\eta_c > 3$ shows the values excluded by the measured upper limit (shaded region). The vertical lines show the predicted range of $<|S|^2>$ [6], while the horizontal line shows the estimated value of σ_{gap}/σ assuming Pomeron exchange [2].

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