Rapidity Gaps between Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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First experimental results are presented from a search for events with a rapidity gap between jets. The D0 detector was used to examine events produced by the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s}=1.8$ TeV. The fraction of events with an observed rapidity gap between the two highest transverse energy (E_T) jets is measured as a function of the pseudorapidity separation between the jet edges ($\Delta\eta_c$). An upper limit at the 95% confidence level of 1.1×10^{-2} is obtained on the fraction of events with no particles between the jets, for events with $\Delta\eta_c > 3$ and jet E_T greater than 30 GeV.

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Rapidity gaps, which are regions of rapidity containing no particles, have historically been associated with elastic and diffractive scattering. Rapidity gaps have also recently been observed in deep inelastic scattering events [1]. In addition to these typically low transverse momentum processes, rapidity gaps are also expected to occur in high transverse momentum processes when a color singlet is exchanged between interacting partons [2,3]. 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 [4]. Hadrons are produced only between the outgoing jets and spectator partons, resulting in an empty region of phase space between the jets.

Figure 1 depicts the distribution of particles in a two-jet event with a rapidity gap of size $\Delta\eta_c$, where $\Delta\eta_c$ is the pseudorapidity separation between the edges of the jet cones. The exchange of a photon, W, or Z is expected to give such an event topology. In addition, a hard Pomeron, which has been shown to be associated with jet production [5], is a color singlet which is expected to produce rapidity gaps. Although QCD interactions typically produce particles between jets due to the exchange of color via a quark or gluon (color octet exchange), rapidity gaps can also arise from fluctuations in the particle multiplicity.

A rapidity gap will not be observed in the final state, however, if spectator interactions produce particles be-

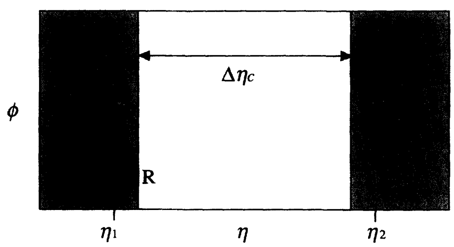

FIG. 1. Representation in η-ϕ space of the distribution of particles in a typical two-jet event containing a rapidity gap. The pseudorapidity region between the edges of the jet cones (of radius R), $\Delta\eta_c = |\eta_1 - \eta_2| - 2R$, contains no particles.

tween the jets. While both the cross section for producing a rapidity gap from the hard scattering (σ_{gap}) and the probability of the gap surviving spectator interactions (S) 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 two leading (highest transverse energy) jets, defined as

$$f(\Delta\eta_c) = \frac{\sigma_{\text{gap}}(\Delta\eta_c) S(\Delta\eta_c)}{\sigma(\Delta\eta_c)}, \quad (1)$$

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

For small $\Delta\eta_c$, a large fraction of events are expected to have a rapidity gap. These gaps occur in color octet exchange events due to fluctuations in the particle multiplicity between jets. The gap fraction decreases sharply with increasing $\Delta\eta_c$ because the rising average multiplicity between jets makes a fluctuation to zero particles much less likely. One Monte Carlo study indicates that $f(\Delta\eta_c > 2) \sim 10^{-5}$ [6] for color octet exchange, but the actual value depends strongly on the multiplicity distribution between jets, which is not well known.

For larger $\Delta\eta_c$, the gap fraction is expected to be dominated by color singlet exchange and to have little dependence on $\Delta\eta_c$ [3,6–8] or jet transverse energy (E_T) [8]. A rough estimate for the rapidity gap fraction from Pomeron exchange [3] is $10^{-2} < f < 3\times10^{-2}$, assuming that the probability of a gap surviving spectator interactions is in the range $0.1 < S < 0.3$ [3,6,7]. In contrast, the gap fraction from electroweak exchange is estimated to be more than 2 orders of magnitude smaller [6].

The D0 detector [9] is used to provide the first experimental information on the rapidity gap fraction. This analysis [10] primarily utilizes the uranium-liquid argon calorimeters which have full coverage for a pseudorapidity 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 transverse segmentation of the projective calorimeter towers is typically $\Delta\eta\times\Delta\phi = 0.1\times0.1$.

The electromagnetic section of the calorimeters is used to search for rapidity gaps. The EM section is particularly useful for identifying low energy particles due to its low level of noise and ability to detect neutral pions. A particle is tagged by the deposition of more than 200 MeV transverse energy in an EM calorimeter tower. This method results in a geometric acceptance for tagging particles of about 80%. In addition, low energy test beam studies indicate that this definition is 98% efficient at tagging 2 GeV electrons and 73% efficient for detecting 2 GeV charged pions. The electromagnetic section is also sensitive to minimum ionizing particles, which deposit about 200 MeV in an electromagnetic tower.

Data for this analysis was obtained using certain hardware and software components of the D0 triggering system. The first hardware level required a coincidence of scintillator hodoscopes to ensure the presence of an inelastic collision. The hardware jet trigger was based on calorimeter towers of size $\Delta\eta\times\Delta\phi = 0.2\times0.2$ with $|\eta| \leq 3.2$. The number of trigger towers above an 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 with cone size $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$ to find jets. Additional topology cuts could be applied in the filter to select specific jet pseudorapidity configurations.

The data sample 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 large $\Delta\eta_c$. The inclusive jet trigger required at least one jet with $E_G > 30$ GeV while the high-$\Delta\eta_c$ trigger required $\Delta\eta_c > 2.6$ for any two jets, each with $E_T > 25$ GeV and $|\eta| > 2$. The number of events from the inclusive trigger is 500000 based on an integrated luminosity of 120 nb^{-1}, while the high-$\Delta\eta_c$ trigger has 77000 events from 5.4 pb^{-1}. The triggers did 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.

Figure 2 shows the number of events from the two triggers as a function of $\Delta\eta_c$ (after the off-line 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 an obvious acceptance loss near the $\Delta\eta_c$ threshold caused by trigger requirements on the jet pseudorapidities. These requirements result in acceptance only for events with $\eta_{\text{boost}} = \frac{1}{2}(\eta_1 + \eta_2)$ near zero, but the rapidity gap fraction is expected to have little dependence on this variable [3,8].

In the off-line 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 triggering interaction. A cut on the width of the time distribution of luminosity counter hits is used to reject these events. Less than 5% of the events in the resulting data sample contain multiple interactions.

Jets are reconstructed using an iterative jet cone algo-

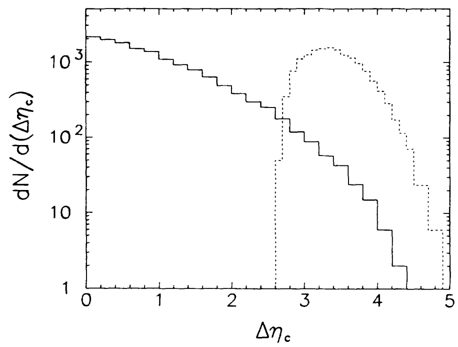

FIG. 2. The number of events (after the off-line cuts described in the text) as a function of $\Delta\eta_c$, the separation in pseudorapidity between the cone edges of the two leading jets. The solid line is used for the inclusive trigger and the dashed line for the high-$\Delta\eta_c$ trigger.

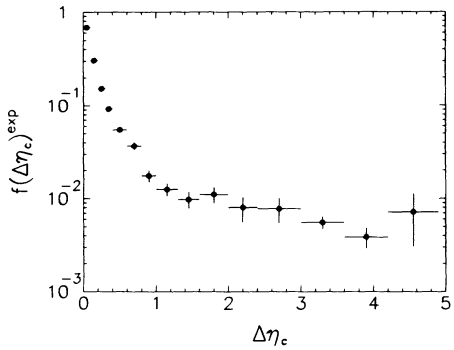

FIG. 3. The fraction of events that have no tagged particles between the two leading jets (each with $E_T > 30$ GeV) as a function of $\Delta\eta_c$. The error bars show the statistical uncertainty only.

rithm with a radius of 0.7 [11]. Events with spurious jets due to detector effects are removed with a series of cuts that are more than 95% efficient at rejecting these misidentified 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. Less than 5% of the events in the resulting data sample contain spurious jets. The transverse energy of jets in the remaining events is corrected for detector response, out-of-cone showering, and the underlying event.

Fiducial cuts are imposed in order to obtain the final data sample. Events are required to have a measured vertex within 50 cm of the average vertex position. Events are also required to have $|\eta_{\rm boost}| < 0.8$. This cut ensures that the jets in events with small $\Delta\eta_c$ 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 pseudorapidity of the jet cones overlap. Finally, the two leading 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 that have a rapidity gap as a function of $\Delta\eta_c$. For an ideal detector, Eq. (1) can be rewritten as

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

where $N(\Delta\eta_c)$ is the number of events which have 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 minimizes the effects of luminosity uncertainties and trigger inefficiencies.

A direct measurement of $f(\Delta\eta_c)$ is difficult due to the intrinsic inefficiencies of a real detector. It is possible, however, to obtain an upper limit on $f(\Delta\eta_c)$ using an experimental definition of the gap fraction, $f(\Delta\eta_c)^{\rm exp}$. Detection inefficiencies imply that $f(\Delta\eta_c)^{\rm exp} > f(\Delta\eta_c)$, because events with undetected particles are erroneously counted as rapidity gap events. Since the gap fraction includes contributions both from color singlet and color octet exchange, 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 is defined as an absence of tagged particles between the jets. Using this definition, the experimental rapidity gap fraction is

$$f(\Delta\eta_c)^{\rm exp} = a\frac{N_{\#{\rm EM}=0}(\Delta\eta_c)}{N(\Delta\eta_c)}, \qquad (3)$$

where $N_{\#{\rm EM}=0}(\Delta\eta_c)$ is the number of events with no EM towers above a 200 MeV E_T threshold between the jets.

This experimental gap fraction is sensitive to noisy calorimeter cells, as rapidity gap events with spurious energy will be lost. To minimize the impact of noise on the rapidity gap fraction, towers which have $E_T > 200$ MeV significantly more often (3σ) than their neighbors are ignored. This cut gives an acceptance loss of less than 1% for detecting particles, and results in less than 5% of the events containing a noisy tower.

Figure 3 shows $f(\Delta\eta_c)^{\rm exp}$ 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 has the anticipated qualitative behavior: For $\Delta\eta_c < 2$ it falls off steeply with increasing $\Delta\eta_c$ as expected from color octet exchange; for larger $\Delta\eta_c$ the fraction is relatively constant, which is consistent with the naive expectations from color singlet exchange. At this time, however, it is not possible to attribute the flattening in $f(\Delta\eta_c)^{\rm exp}$ to color singlet exchange, due to the uncertainty in the contributions from color octet exchange and detector inefficiencies.

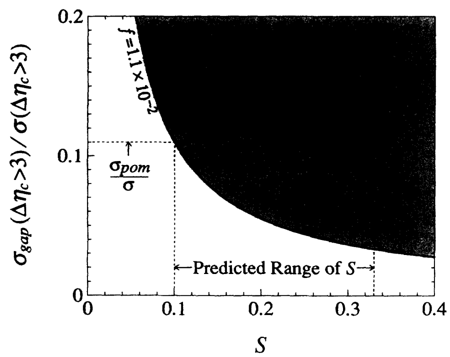

FIG. 4. A plot of σ_{gap}/σ versus S for $\Delta\eta_c > 3$ showing the values excluded by the measured upper limit (shaded region). The vertical lines show the predicted range of S [7], while the horizontal line shows the estimated value of σ_{gap}/σ assuming Pomeron exchange [3].

The rapidity gap fraction of Eq. (3) is measured to be $f(\Delta\eta_c > 3)^{\exp} = (5.3 \pm 0.7^{(\mathrm{stat})} \pm 0.6^{(\mathrm{sys})}) \times 10^{-3}$ where only events with $\Delta\eta_c > 3$ are used so that the contribution from color octet exchange is largely suppressed. The systematic error includes a 7% uncertainty from the jet energy scale, and 5% each from noisy cells, trigger acceptance effects, spurious jets, and multiple interactions.

Before an upper limit can be placed on $f(\Delta\eta_c > 3)$, it is necessary to correct for out-of-cone effects. These effects produce towers above threshold between the jets, erroneously reducing the measured gap fraction. Out-of-cone effects include particles associated with the jet that are emitted outside of a fixed jet cone, and particles within the cone that deposit energy outside of 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 measured in a similar area 180° away from the jet in ϕ. The corrected multiplicity distribution indicates that approximately (35 ± 5)% of rapidity gap events with $\Delta\eta_c > 3$ are lost due to out-of-cone effects.

Applying this correction to the measured fraction of events with no EM towers above threshold 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

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

at the 95% confidence level. This limit constrains the product of σ_{gap}/σ and S for $\Delta\eta_c > 3$ as shown in Fig. 4. The current theoretical estimates, which are subject to large uncertainties, are included for comparison.

The D0 detector has been used to search for events with rapidity gap between jets. Such events have been observed using an experimental definition of a rapidity gap, but, due to detector inefficiencies, it is possible only to set an upper limit on the product of the cross section for color singlet exchange and the survival probability. This limit provides a significant constraint on the theoretical estimates for these quantities, independent of the contribution from color octet exchange and the background from particle detection inefficiencies.

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[10] For further details of analysis see B. May, Ph.D. thesis, University of Arizona, 1994.
[11] For details about measuring jets in D0 see R. Astur, Ph.D. thesis, Michigan State University, 1992; A. Milder, Ph.D. thesis, University of Arizona, 1993.

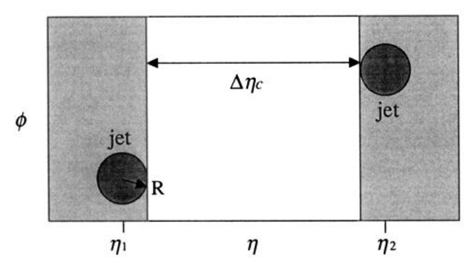

FIG. 1. Representation in η-ϕ space of the distribution of particles in a typical two-jet event containing a rapidity gap. The pseudorapidity region between the edges of the jet cones (of radius R), $\Delta\eta_c = |\eta_1 - \eta_2| - 2R$, contains no particles.

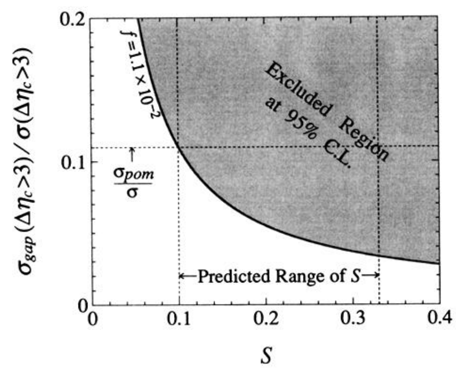

FIG. 4. A plot of $\sigma_{\mathbf{gap}}/\sigma$ versus S for $\Delta\eta_c > 3$ showing the values excluded by the measured upper limit (shaded region). The vertical lines show the predicted range of S [7], while the horizontal line shows the estimated value of $\sigma_{\mathbf{gap}}/\sigma$ assuming Pomeron exchange [3].