# Observation of Rapidity Gaps in $\overline{p}p$ Collisions at 1.8 TeV

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In $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV we find jet events with a rapidity gap topology. The number of hadrons in the rapidity interval $\Delta\eta_D$ between leading-jet cones was sampled by charged tracks with $P_T > 400$ MeV/$c$. We find excess trackless events beyond that expected in a smooth multiplicity distribution. In a control region outside $\Delta\eta_D$ we see no excess. For $\Delta\eta_D > 0.8$, the fraction of excess trackless events, consistent with estimates based on exchange of color-singlet digluons, is $R(\text{gap}) = \sigma_{\text{jet}}(\text{gap})/\sigma_{\text{jet}} = 0.0085 \pm 0.0012(\text{stat})^{+0.0024}_{-0.0012}(\text{syst})$.

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In 1958, investigators on three continents [1] studied cosmic rays in emulsions and reported the existence of regions of rapidity space nearly devoid of particles between jets. Over the next two decades, clustering of particles into jets separated by sparsely populated rapidity intervals was the subject of theoretical and experimental [2–4] studies. Early experiments had few events and low transverse momentum. The idea of diffractive dissociation of projectile and target [5] offers a natural explanation for these events [6].

In Regge theory, diffraction occurs through Pomeron exchange. Connections between the Pomeron and perturbative QCD were explored theoretically by Lipatov and co-workers [7–9]. The availability of large numbers of high-transverse-momentum ($P_T$) events at colliders extended these ideas to a region not traditionally considered diffractive. Ingelman and Schlein [10] suggested that high-$P_T$ jets may emerge from diffractively produced high-mass states via Pomeron exchange and that this might probe the parton structure of the Pomeron. Support for this came from a study of jets with $P_T > 8$ GeV/$c$ [11].

The exchange of a color-singlet QCD object should yield events free of soft hadrons in the rapidity interval between the resulting jets but not outside that interval [12–14]. In a lowest-order QCD calculation, Bjorken [13] estimates the ratio of "gap" events to conventional gluon-exchange events with the same jet kinematics:

$$R(\text{gap}) = \sigma_{\text{jet}}(\text{gap})/\sigma_{\text{jet}} \approx 0.1\langle|S|^2\rangle\,, \qquad (1)$$

where $\langle|S|^2\rangle$ is the "survival probability" for the gap, i.e., the probability that no interactions occur other than the hard collision of interest. Estimates are $3\% < |S|^2 < 30\%$ [12,14] or $0.003 < R(\text{gap}) < 0.03$.

Rapidity gaps have been reported in deep inelastic scattering at DESY HERA [15] as an anomalously high number of $Q^2 > 10$ GeV$^2$ events, where >99% of the energy is well separated from the forward proton direction. The D0 collaboration placed a limit $R(\text{gap}) < 1.1\%$ (95% C.L.) [16], where a gap was defined as the absence between jet cones of any electromagnetic calorimeter tower with transverse energy $E_T > 200$ MeV.

We report the observation of rapidity gaps between jets in events collected by the Collider Detector at Fermilab in the 1988–89 run of the Tevatron Collider. The detector is described elsewhere [17]. We use coordinates with $z$ along the proton beam, azimuthal angle $\phi$, polar angle $\theta$, and pseudorapidity $\eta = -\ln\tan(\theta/2)$. (We use "rapidity" to refer to $\eta$.) Detector components crucial to this study are the calorimeter system, which covered $-4 < \eta < +4$; the level 2 trigger, and the central tracking chamber (CTC) and time projection chamber (VTPC), which allowed 3D reconstruction of tracks for $-2.1 < \eta < +2.1$.

The data are from 3.93 pb$^{-1}$ of integrated luminosity with 304 346 events from a level 2 trigger requiring a single calorimeter cluster with uncorrected $E_T > 60$ GeV. After off-line reclustering, use of true event vertex, and energy corrections, a loose threshold of 40 GeV was required of the leading (highest $E_T$) jet. We cut events with an interaction vertex >60 cm from the detector center, those with >1 vertex, and those with $\not{E}_T > 5\sqrt{\sum E_T}$ (in GeV), where $\not{E}_T$ is the missing transverse energy and $\sum E_T$ is the total $E_T$. We placed no constraint on the number of calorimeter clusters. We used a jet-cone radius of 0.7 in $\eta$-$\phi$, and $\Delta\eta_C$ is the $\eta$ distance between tangents to the two leading jets cones (Fig. 1). The overlap between $\Delta\eta_C$ and our track detectors is $\Delta\eta_D$. A cut requiring $\Delta\eta_D > 0$ yielded 94 639 events.

Any realistic search for rapidity gaps must rely on sampling hadrons which populate $\Delta\eta_D$. Only ~50% of all tracks are above our 400 MeV/$c$ $P_T$ threshold [18]. Neutral particles are not detected by tracking systems. For sampling we used charged tracks from the primary event vertex within 0.6 cm transverse to the beam direction and 18 cm along the beam.

For each event we counted tracks in the interval $\Delta\eta_D$ (the $G$ region of Fig. 1) and formed a two-dimensional distribution of the number of events $n(M, \Delta\eta_D)$ vs $\Delta\eta_D$ (from 0.0 to 4.0 in 20 bins of varying width) and the track multiplicity $M$ (from 0 to 49). A similar distribution was formed for the $N$ region, a "control region" outside $\Delta\eta_D$ and excluding the two leading jets.

The simplest adequate description of our multiplicity distributions includes the following: (1) colorless-exchange (gap) events with $M = 0$ and (2) color-exchange events with a range of multiplicities in which $n(M, \Delta\eta_D)$ rises to a maximum at $M_{\max}$ (roughly proportional to $\Delta\eta_D$) and falls thereafter. For color exchange, the fraction of zero-multiplicity events should drop as $M_{\max}$, i.e., $\Delta\eta_D$, increases. Gap events should contribute only to the

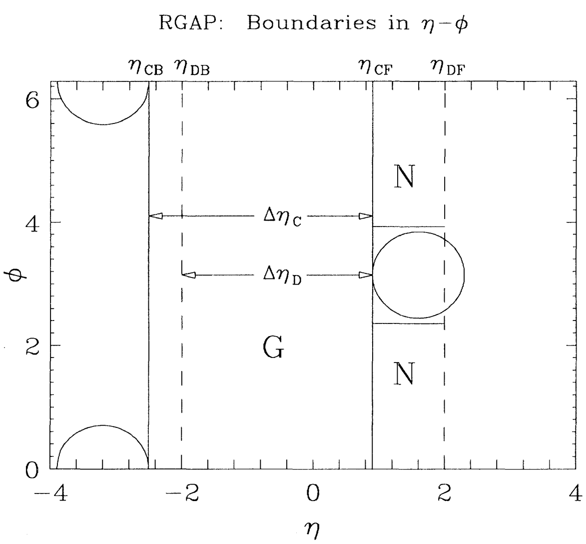


FIG. 1. Regions in $\eta$-$\phi$. Circles define the 0.7-unit cone around leading jets. Solid vertical lines are tangent to the leading jet cones at $\eta_{CB}$ and $\eta_{CF}$, and $\Delta\eta_C$ is the interval between them. $F$ ($B$) is toward the proton ($\bar{p}$) beam. Vertical dashed lines are tracking limits, $\eta_{DB}$ and $\eta_{DF}$. Here, $\Delta\eta_D$, the width of the $G$ region, is bounded by the forward cone and the backward tracking boundary. The $N$ region is the remainder of the $\eta$ region covered by tracking but excludes the $\phi$ band(s) within 45° of jet centroid(s). Depending on jet locations, events can have zero, one (shown here) or two $N$ regions.

$M = 0$ bin and, if Eq. (1) is correct, should be a fixed fraction of the total number of events if $|S|^2$ is constant. $R(\Delta\eta_D) = n(0, \Delta\eta_D)/n(\text{all}\, M, \Delta\eta_D)$ should fall with increasing $\Delta\eta_D$ (similar to Ref. [16]), and it should flatten when gap events dominate the $M = 0$ bin. By definition $R(0) = 1.0$. In our data, it falls to $R(0.8) = 0.05$ and flattens at ~0.01 for $\Delta\eta_D > 2.0$. We use only data with $\Delta\eta_D > 0.8$ to search for a signal. For the $G$ ($N$) region, this is a further cut to 37 598 (94 227) events.

A method is needed to estimate the "background" of normal color-exchange events in the $M = 0$ bin. For each $\Delta\eta_D$ bin, these should be part of a smooth distribution including other low values of the multiplicity. To determine this background we fit the multiplicity distribution in each $\Delta\eta_D$ bin to a negative-binomial (NBI) distribution [19]. As an alternate, we used a Koba-Nielsen-Olesen (KNO) scaling function [20] for the entire 16 units of $\eta$ and folded it with a Poisson distribution to account for the average number of tracks in $\Delta\eta_D$. Both NBI and KNO functions are parametrized by normalization, mean, and width. They give similar results. Both have a finite contribution at $M = 0$, rise to a maximum, and fall thereafter. We fit the full multiplicity distribution and just the rising portion. We fit the independent parameters in each $\Delta\eta_D$ bin and with the means and widths as linear functions of $\Delta\eta_D$.

An additional parameter $n_x(\Delta\eta_D)$ was included in the fitting function to represent an excess population at $M = 0$ for each $\Delta\eta_D$ interval. When they were allowed to vary freely, the $M = 0$ bin was removed as a constraint on the fit.

With the NBI function fit only to the rising portion of the distributions for the $G$ region, we obtained a reasonable fit $\chi^2/\text{DF} = 79.1/69$, with the values $n_x(\Delta\eta_D)$ allowed to vary, and an extremely poor fit, $\chi^2/\text{DF} = 207.6/81$, when they were fixed at zero. The change is $128.5/12 = 10.7$ per DF. Results from other procedures were similar. All fits required significant positive values of $n_x(\Delta\eta_D)$, totaling 319 "signal" events above the estimated gluon-exchange background of 752 events. Summed over $0.8 < \Delta\eta_D < 4.0$, $R(\text{gap}) = n_x/n(\text{all}\, M)$ varies from 0.0073 to 0.0105 (≥7 standard deviations above zero) depending on the fitting procedure. Fits which allowed excesses in both the $M = 0$ and $M = 1$ bins produced no further improvement in $\chi^2/\text{DF}$.

Identical procedures applied to the $N$ region yielded quite different results: $\chi^2/\text{DF} = 169.7/112$ with the values $n_x(\Delta\eta_D)$ allowed to vary, and $\chi^2/\text{DF} = 199.3/131$ when they were fixed at zero. The change is $29.6/19 = 1.6$ per DF. The values of $n_x(\Delta\eta_D)$ were positive for some fits and negative for others with a net 113 signal events above the estimated 679 background events. Summed over $0.8 < \Delta\eta_D < 4.0$, $n_x/n(\text{all}\, M)$ varies from $-0.0014$ to 0.026, depending on the fitting procedure. Figure 2 shows a sample of fits for the $G$ and $N$ regions.

The results of the $G$-region fits are shown in Fig. 3(a). Averaged over $0.8 < \Delta\eta_D < 4.0$, $R(\text{gap}) =$

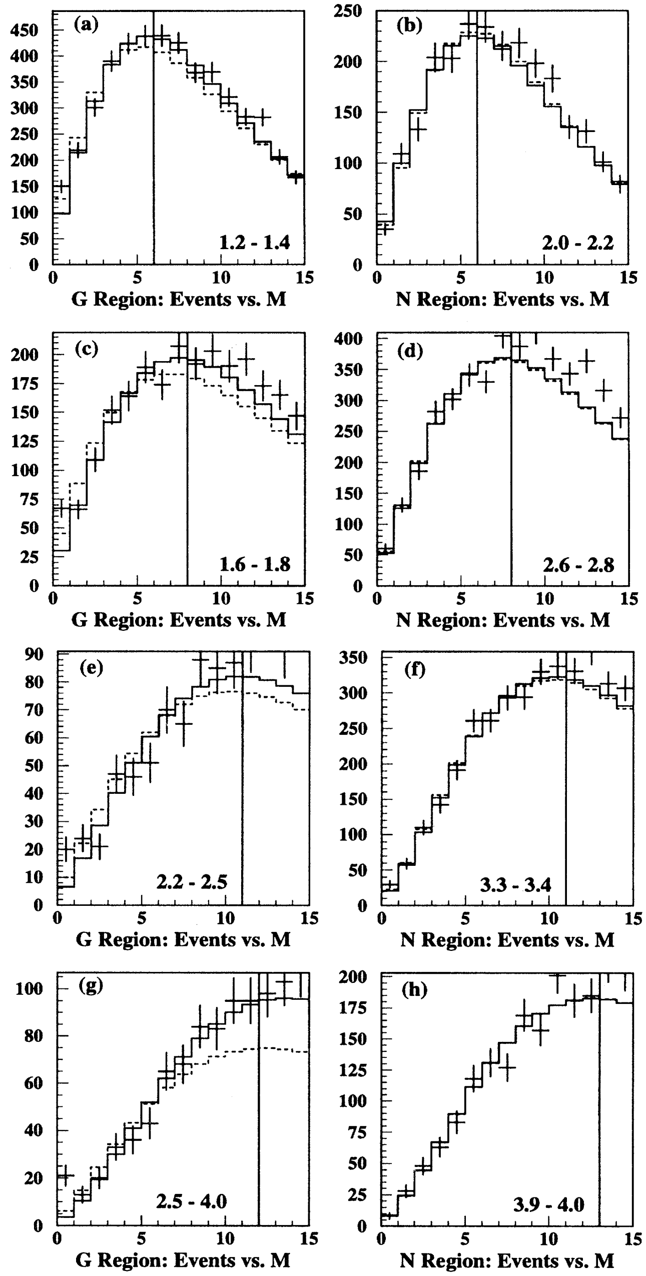


FIG. 2. Multiplicity fits to $G$ and $N$ regions. Crosses represent data. Solid histograms are fits with the $M = 0$ bin excluded. Dashed histograms are fits with $n_x \equiv 0$. Only data to the left of the vertical line were used. The $\Delta\eta_D$ range is indicated in each plot. The three highest bins in $\Delta\eta_D$ are combined in (g). Side-by-side plots compare similar shapes with and without an $M = 0$ excess.

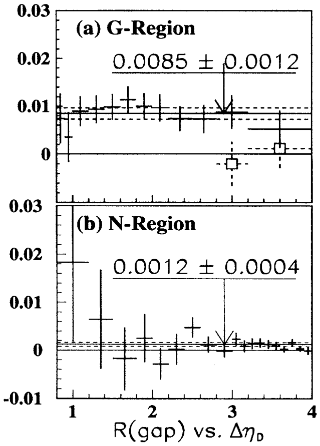


FIG. 3. The ratio of background-subtracted population of $M = 0$ events to total events vs $\Delta\eta_D$ for (a) the $G$ region and (b) the $N$ region. Theory predicts a signal in $G$ but not in $N$. The average is indicated by the solid horizontal line and dashed error corridor. The two points in (a) indicated by squares are from the minimum-bias tracks (see text).

$0.0085 \pm 0.0012$. If we interpret $n_x(\Delta\eta_D)$ as the population of true rapidity gap events, this ratio is directly comparable to Eq. (1). The corresponding $N$-region fits are in Fig. 3(b). They show a ratio consistent with zero within systematic uncertainties of the fitting procedure.

The data were divided into two samples at a boundary of 65 GeV for the average $E_T$ of the two leading jets, $E_{T12} = [E_T(\text{jet-1}) + E_T(\text{jet-2})]/2$. The higher sample, $\langle E_{T12}\rangle = 83.2$ GeV, yielded $R(\text{gap}) = 0.0089 \pm 0.0016$. The lower sample, $\langle E_{T12}\rangle = 55.2$ GeV, yielded $R(\text{gap}) = 0.0075 \pm 0.0019$. At $\langle E_{T12}\rangle = 73.5$ GeV we find $(1/R)dR/dE_T = 0.006 \pm 0.010\ \text{GeV}^{-1}$.

The $N$-region analysis shows that the $M = 0$ excess is not an artifact of the analysis. For another check, we formed hybrid events from our leading jet coordinates in $\eta$-$\phi$ with tracks in events from a minimum-bias trigger which should have no gap signal. Resulting values of $n_x(\Delta\eta_D)$ were consistent with zero [Fig. 3(a)].

All events came from the same trigger and the same off-line analysis and jet cuts. Therefore, all systematic uncertainties arising from luminosity and on-line/off-line jet acceptance and efficiency are independent of $M$ and cancel in the ratio $n(0, \Delta\eta_D)/n(\text{all}\, M, \Delta\eta_D)$. The shape (mean and width) of the multiplicity distribution depends only on $\Delta\eta_D$ and, within our precision, not on the $z$ position of the event vertex, the $E_T$ of the leading jets or the position of the $G$ region in the central four units of $\eta$.

$R(\text{gap})$ is increased by 0.0014 if we exclude tracks between 0.7 and 1.0 unit in $\eta$-$\phi$ from leading jet centroids and correct for the density of tracks from the underlying event. We treat this as a systematic uncertainty. The major source of systematic uncertainty is the fitting procedure described earlier. $R(\text{gap})$ for the $G$ and $N$ regions varied with high positive correlation as the fitting procedure was changed, indicating that the variations are an artifact of the procedure. We adopt this estimate of systematic uncertainty: $0.0073 < R(\text{gap}) < 0.0105$. With these two sources of systematic uncertainty combined, our final result is

$$R(\text{gap}) = \frac{\sigma_{\text{jet}}(\text{gap})}{\sigma_{\text{jet}}} = 0.0085 \pm 0.0012(\text{stat})^{+0.0024}_{-0.0012}(\text{syst}). \tag{2}$$

The number of excess trackless events in the $G$ region and their absence in the $N$ region are consistent with the Bjorken's color-singlet calculation [13]. Regge theory predicts that amplitudes for meson exchange over large $\Delta\eta$ should be negligible at 1.8 TeV. Contributions from exchange of other colorless objects such as electroweak bosons are two small to explain our result. In Ref. [13], $R(\text{gap})$ is independent of $\Delta\eta_D$ and $E_{T12}$ if $|S|^2$ is constant. This agrees with our result. These observations suggest, but do not prove, a connection between our results and Bjorken's model.

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