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CDF

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

The CDF Collaboration

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Abstract

In $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV we have identified a sample of events with a rapidity gap topology. The events were collected at the Tevatron collider with the CDF detector and a trigger requiring at least one jet with transverse energy over 60 GeV. The population of hadrons in the rapidity interval, $\Delta\eta_D$, between leading-jet cones was sampled by counting the number of charged tracks with P_T above 400 MeV/c. We found an excess of trackless events beyond that expected from fluctuations of a smooth track-multiplicity distribution. In an $\eta - \phi$ control region outside this interval, and not including the leading jets, no excess was found. For events with $\Delta\eta_D > 0.8$, the ratio of excess trackless events to the total number of events is:

$$R(\text{gap}) = \frac{\sigma_{\text{jet}}(\text{gap})}{\sigma_{\text{jet}}} = 0.0086 \pm 0.0012(\text{stat.})\ ^{+0.0024}_{-0.0012}(\text{syst.}).$$

This ratio and its dependence on kinematic parameters are consistent with estimates for the exchange of color-singlet di-gluons.

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In 1958, investigators on three continents[1] studied cosmic ray interactions 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 studies and experiments using cosmic-ray and accelerator data, e.g. Refs. 2–4. Since the early experiments had few events, they were restricted to relatively low transverse momentum. The idea of diffractive dissociation of projectile and target, introduced by Good and Walker,[5] offers a natural explaination for these events.[6] In Regge theory, diffraction occurs through pomeron exchange.

Connections between the pomeron and perturbative QCD, viz. color-singlet di-gluon ladders, were explored theoretically by Lipatov and his collaborators.[7-9] The availability of large numbers of high-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. They further suggested that such studies might be a tool for understanding the parton structure of the pomeron. Support for this idea was provided by a study of jets with $P_T > 8$ GeV/c associated with a scattered p (or $\overline{p}$) in a kinematic domain normally considered diffractive.[11]

In collider experiments, if the exchange of a color-singlet QCD object occurs, one should observe events free of soft hadrons in the rapidity interval between the resulting jets.[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 in Equation 4.21 of his paper, viz.

$$R(\text{gap}) = \frac{\sigma_{\text{jet}}(\text{gap})}{\sigma_{\text{jet}}} \approx 0.1 < |S|^2 >, \qquad (1)$$

where $< |S|^2 >$ is the "survival probability" for the gap, i. e. the probability that no interactions occur other than the hard collision of interest. Bjorken estimates this probability to lie between 1.5% and 15%. Thus, these events should be observed at a level of 0.15% to 1.5% of normal QCD events in the same kinematic range.

Rapidity gaps have been reported in deep inelastic scattering at HERA.[15] For events with $Q^2 > 10$ GeV^2, they observe an anomolously high number of events for which 99% or more of the hadronic energy is well separated in rapidity from the forward proton direction. At the Tevatron Collider, the D0 collaboration has studied events with leading jet transverse energy $E_T > 30$ GeV. They searched for events with rapidity gaps and placed an upper limit of 1.1% (95% C.L.) on the fraction of such events.[16] In their study, a rapidity gap was defined as the absence of any calorimeter tower with E_T above 200 MeV in the interval $\Delta\eta_C$ between the two leading jets (Fig. 1).

We report here the observation of rapidity gaps between jets in events collected by the CDF detector in the 1988-89 run of the Tevatron Collider. This detector has been described elsewhere.[17] We use a coordinate system with z along the proton beam, azimuthal angle ϕ, polar angle θ, and pseudorapidity $\eta = -\ln\tan(\theta/2)$. In this paper we use "rapidity" to refer to η. Three components of the detector were crucial to this study: the calorimeter system, which covered a region $-4 < \eta < +4$; the central tracking drift chamber (CTC) and vertex time projection chamber (VTPC), which allowed 3-dimensional reconstruction of charged tracks for $-2.1 < \eta < +2.1$, and the Level 2 trigger with fast calorimeter clustering.

The data set comes from 3.93 pb^{-1} of integrated luminosity and includes 304,346 events with a Level-2 trigger requiring a single jet cluster with $E_T > 60$ GeV. We eliminated events with an interaction vertex further than 60 cm from the center of the detector or with more than one vertex. We also deleted events with unbalanced E_T, i.e. with $\not{E}_T > 5\sqrt{\Sigma E_T}$, where $\not{E}_T$ is the missing transverse energy and ΣE_T is the total E_T in the event. This implicitly required at least two jet clusters. We placed no other constraint on the number of calorimeter clusters. The jet cone used here has a radius of 0.7 in $\eta - \phi$. We define a rapidity interval $\Delta\eta_{\mathrm{C}}$ as the distance in rapidity between the tangents to the cones of the two leading (highest $\mathrm{E_T}$) jets (Fig. 1). We also define $\Delta\eta_{\mathrm{D}}$ as the overlap between $\Delta\eta_{\mathrm{C}}$ and the rapidity region covered by our track detectors. A cut requiring $\Delta\eta_D > 0$ yielded 95,302 events.

Any search for rapidity gaps must rely on sampling hadrons which populate $\Delta\eta_{\mathrm{D}}$. Only $\sim 50\%$ of all tracks are above CDF's rather sharp $\mathrm{P_T}$ threshold of 400 MeV/c.[18] The magnetic field prevents low-$\mathrm{P_T}$ charged particles from reaching the outer layers of the CTC. Neutral particles are not detected by the tracking system. A different set of limitations prevents calorimeters from being fully efficient.[19] For sampling we used charged tracks, which are virtually noise-free and can unambiguously be traced to the primary event vertex. Only tracks with good, three-dimensional reconstruction from CTC and VTPC data were accepted, i.e. those which passed through at least the inner superlayer of the CTC. We also required that they extrapolate back to the primary event vertex within 0.6 cm transverse to the beam direction and 18 cm along the beam.

For each event we counted the number of tracks in the rapidity interval $\Delta\eta_{\mathrm{D}}$ (the G region of Fig. 1) and formed a two-dimensional distribution of the number of events N(M, $\Delta\eta_{\mathrm{D}}$) vs. $\Delta\eta_{\mathrm{D}}$ (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 $\Delta\eta_{\mathrm{D}}$ and excluding the two leading jets.

A very simple model for these distributions considers two contributions. For normal QCD gluon exchange, N(M, $\Delta\eta_{\mathrm{D}}$) rises monotonically with M to a maximum at a value of M which depends on $\Delta\eta_{\mathrm{D}}$ and falls monotonically thereafter. The fraction of zero-multiplicity events should drop with increasing $\Delta\eta_D$. Rapidity gap events should contribute only to the M=0 bin and, if Eq. 1 is correct, should be a fixed fraction of the total number of events, provided $|S|^2$ is independent of $\Delta\eta_D$. Thus, the fraction $R(\Delta\eta_D) = N(0, \Delta\eta_D)/N(\text{all } M, \Delta\eta_D)$ should fall monotonically with increasing $\Delta\eta_D$ and should flatten when gap events dominate the M=0 bin. $R(\Delta\eta_D)$ must be 1.0 at $\Delta\eta_D = 0.0$. In our data, R falls monotonically through $R(0.8) = 0.05$, and it flattens at ~ 0.01 for $\Delta\eta_D > 2.0$. Based on this curve, we chose to use only data with $\Delta\eta_D > 0.8$ to search for a signal, for scanning events and for other auxilliary studies. For the G (N) region, this represents a further cut to 37,860 (94,667) events.

The D0 result was based on this type of study (Ref. 16, Fig. 3). We concur with their statement that this type of analysis can only be used to set an upper limit on the gap fraction. Some method is needed to estimate the "background" of normal gluon-exchange events in the M=0 bin. These events should be part of a smooth distribution including other low values of the track multiplicity. Therefore, we fit the multiplicity distribution to determine the contribution to the zero multiplicity bin from gluon exchange.

The function used to represent the track population in each $\Delta\eta_D$ interval was a negative-binomial (NBI) distribution.[20] As an alternate, we used a KNO scaling function proposed by Slattery[21] for the entire 16 units of η in the event and folded it with a Poisson distribution to account for the average number of tracks falling in $\Delta\eta_D$. Aside from normalization, both NBI and KNO functions can be parametrized by a mean and a width, and they yield closely similar but not identical results. Both functions have a finite contribution at M=0, rise monotonically to a maximum and fall smoothly at high multiplicity. We tried fitting both the full multiplicity distribution and just the rising portion. We fit with independent parameters in each $\Delta\eta_D$ bin for the means and widths of the distributions, and also with these quantities represented by 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 shape of the distribution. We fit all twenty bins in $\Delta\eta_D$, but used only the twelve bins with $\Delta\eta_D > 0.8$ in our final result.

With the NBI function fit only to the rising portion of the distributions for the G region, we obtained a reasonable fit χ^2/d.f. = 81.7/69, with the values $N_x(\Delta\eta_D)$ allowed to vary, and an extremely poor fit, χ^2/d.f. = 216.5/81, when they were fixed at zero. The change is 134.8/12 = 11.2 per d.f. Results from all other fitting procedures were similar in quality of fit. All fits with $\Delta\eta_D > 0.8$ required significant positive values of $N_x(\Delta\eta_D)$, totalling 325 "signal" events above the estimated gluon-exchange "background" of 753 events. Summed over $0.8 < \Delta\eta_D < 4.0$, R(gap) = N_x/N(all M) varies from 0.0074 to 0.0106 (≥ 7 standard deviations above zero) depending on the fitting procedure. An analysis which allowed for excesses in both the M=0 and M=1 bins produced no further improvement in χ^2/d.f.

Identical procedures applied to the N-region yielded quite different results: χ^2/d.f. = 169.4/112 with the values $N_x(\Delta\eta_D)$ allowed to vary, and χ^2/d.f. = 198.7/131 when they were fixed at zero. The change is 29.3/19 = 1.5 per d.f. The values of $N_x(\Delta\eta_D)$ were positive for some fits and negative for others with a net 112 "signal" events above the estimated 681 "background" events. Summed over $0.8 < \Delta\eta_D < 4.0$, N_x/N(all M) varies from -0.0014 to 0.026, depending on the fitting procedure. A sampling of comparisons between the fits for the G and N regions is shown in Figs. 2.

The results of the G-region multiplicity fits, i.e. the ratio of $N_x(\Delta\eta_D)$/N(all M,$\Delta\eta_D$) as a function of $\Delta\eta_D$, are shown in Fig. 3(a). The value of the ratio averaged over the region

$0.8 < \Delta\eta_D < 4.0$, R(gap) $= 0.0086 \pm 0.0012$, is also shown as a horizontal line with a dashed error corridor. If we interpret $N_x(\Delta\eta_D)$ as the population of true rapidity gap events, this ratio is directly comparable with Eq. 1.

The corresponding N-region multiplicity fits are plotted in Fig. 3(b). They should not show a rapidity gap, and the observed ratio is 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, $E_{T12} = [E_T(\text{jet-1}) + E_T(\text{jet-2})]/2$. Analysis of the higher sample, $<E_{T12}> = 85.2$ GeV, yielded R(gap) $= 0.0089 \pm 0.0016$, while the lower sample, $<E_{T12}> = 56.0$ GeV, yielded R(gap) $= 0.0079 \pm 0.0018$. From these results, we calculate a logarithmic derivative evaluated at $<E_{T12}> = 76.7$ GeV for the whole sample:

$$\frac{1}{R(\text{gap})} \frac{dR(\text{gap})}{dE_{T12}} = 0.004 \pm 0.009 \text{ GeV}^{-1}, \tag{2}$$

i.e. the change in R(gap) with E_{T12} is less than 1% per GeV.

To build confidence that the $N_x(\Delta\eta_D)$ are not artifacts of the fitting procedure in the G region, we superimposed the leading jet coordinates in $\eta - \phi$ from our data on the tracks from events collected with minimum-bias trigger and performed similar fits. The values of $N_x(\Delta\eta_D)$ obtained were consistent with zero. (See Fig. 3(a).)

All events in this analysis came from the same trigger and were subjected to the same offline analysis and jet cuts. Therefore, there is cancellation of all systematic uncertainties arising from luminosity and online/offline jet acceptance and efficiency.

The effect of out-of-cone tracks from the leading jets was also studied, along with a similar control region away from the jet. The studies suggest a possible upward correction of R(gap) by 0.0014. We have not made this correction, but treat it as a systematic uncertainty.

The major source of systematic uncertainty is the fitting procedure used to estimate the background contribution to the trackless sample. The values of R(gap) for the G- and N-regions both varied with high positive correlation as the fitting procedure was changed, suggesting that these variations are purely an artifact of the procedure. We adopt this range of variation as an estimate of systematic uncertainty: $0.0074 < \mathrm{R(gap)} < 0.0106$.

With the two sources of systematic uncertainty combined, our final result is:

$$\mathrm{R(gap)} = \frac{\sigma_{\mathrm{jet}}(\mathrm{gap})}{\sigma_{\mathrm{jet}}} = 0.0086 \pm 0.0012(\mathrm{stat.})\ ^{+0.0024}_{-0.0012}(\mathrm{syst.}). \tag{3}$$

The existence of an excess of trackless events in the G region of this magnitude and the absence of a corresponding signal in the N region are consistent with the color-singlet exchange suggested by Bjorken.[13] At low E_T, Regge theory predicts that amplitudes for meson exchange over large $\Delta\eta$ should fall with some power of $\sqrt{s}$ and should be negligible at 1.8 TeV. Contributions from the exchange of other known colorless objects such as electroweak bosons are too small to explain our result. Another point of consistency with Bjorken's calculation is that R(gap) shows no significant variation with $\Delta\eta_D$ or E_{T12}. This applies only to the product in Eq. 1, and not necessarily to the individual factors. The full distribution of tracks in $\eta - \phi$ suggested by Bjorken, i.e. correlation of the population of soft hadrons in the N and G regions, is difficult to measure for each event because of the limited tracking coverage of CDF. Thus, these results suggest, but do not prove, a connection between our results and Bjorken's model.

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[19] Although calorimeter towers offer wider coverage in rapidity, they can be populated by photons from π^0 and η mesons outside $\Delta\eta_D$, by accidentals and by electronic noise. A high threshold reduces these effects, but results in loss of efficiency.

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List of Figures

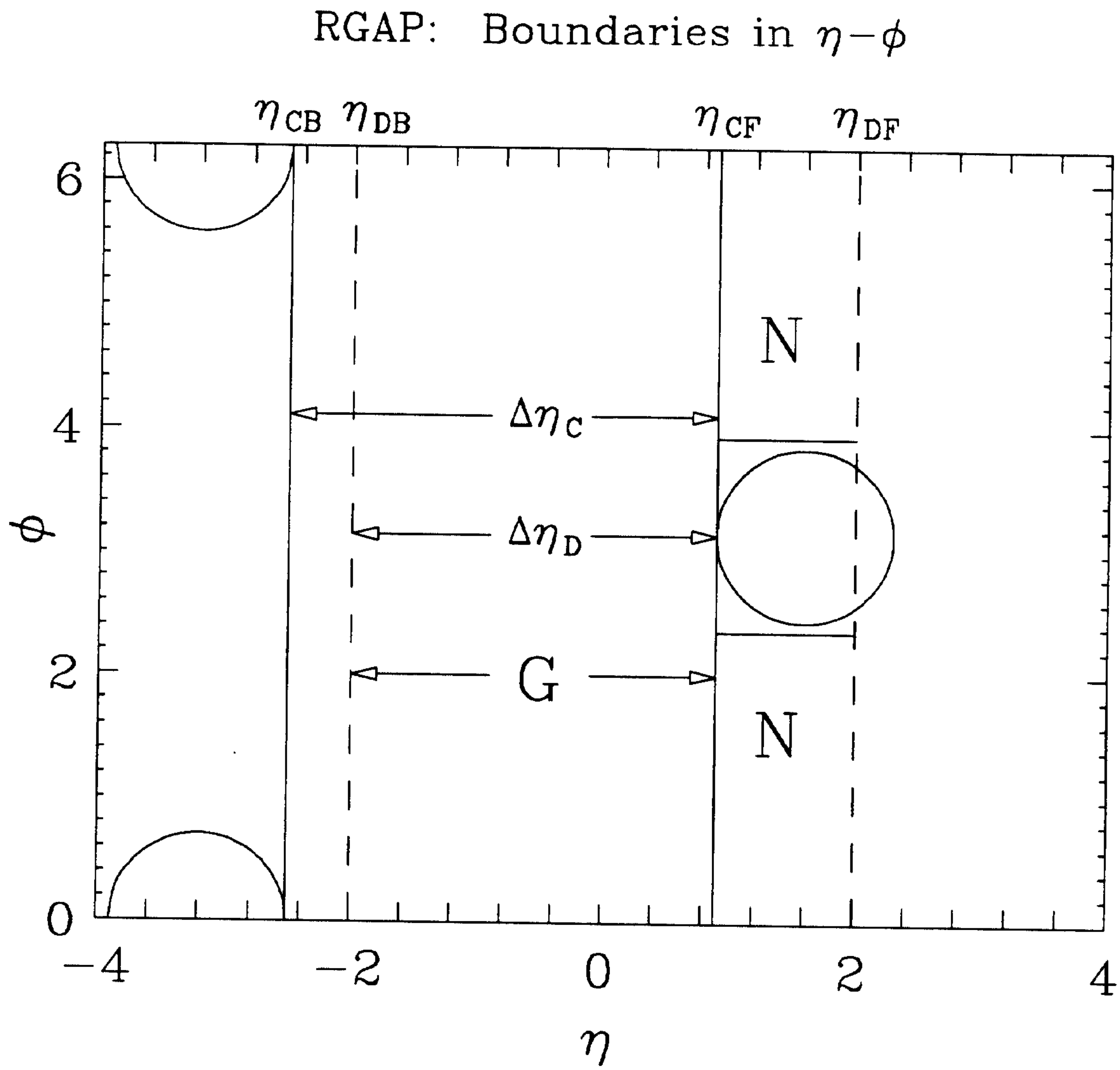

Figure 1: Regions in $\eta - \phi$. The circles define the 0.7-unit-radius around the two leading jets. The solid vertical lines are tangent to the leading jet cones at η_{CB} and η_{CF}, and $\Delta\eta_C$ is the interval between them. The relative direction "F" ("B") is toward the proton ($\bar{p}$) beam. Vertical dashed lines are the tracking limits, η_{DB} and η_{DF}. Here, $\Delta\eta_D$ the width of the G region, is bounded by the forward jet cone and by the backward tracking boundary, and only one "N" region exists covering the ϕ interval >45° (horizontal lines) from the leading jet in its η–interval. Depending on the locations of the jets, events can have zero, one or two "N" regions.

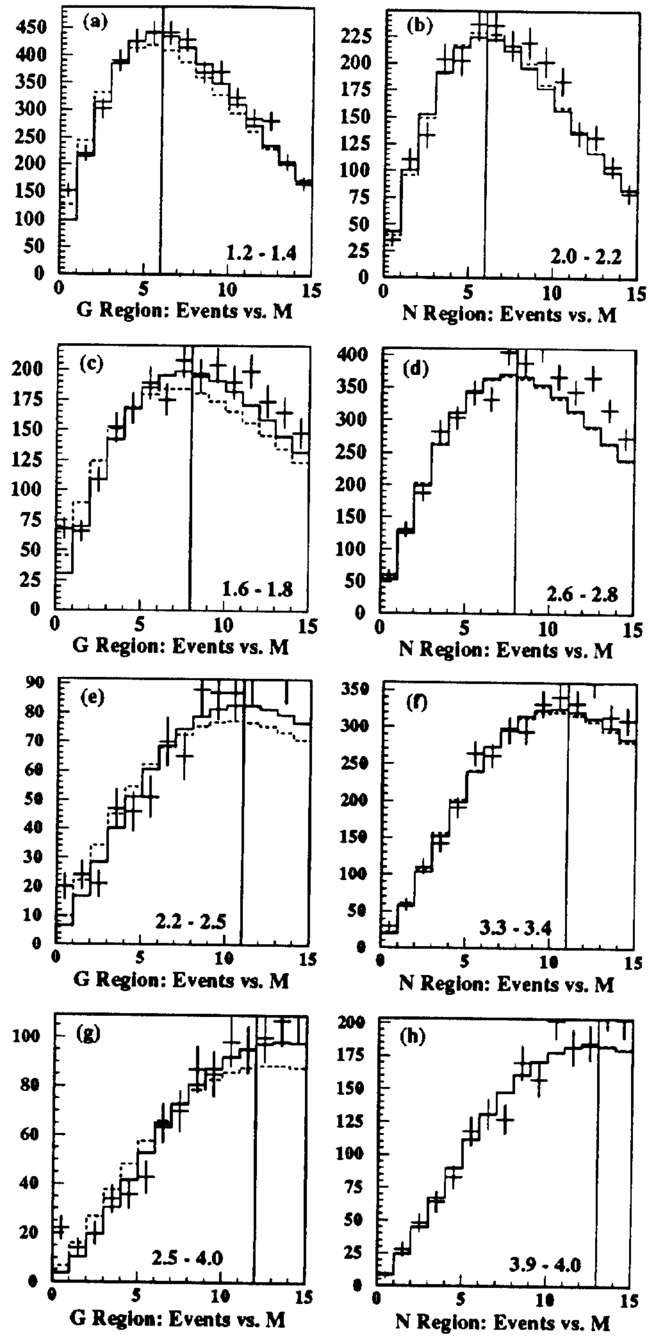

Figure 2: Comparisons between multiplicity fits to G and N regions. Crosses represent data. Solid histograms are fits with N_x allowed to vary, and the shape unconstrained by the M=0 population. Dashed histograms are fits with $N_x \equiv 0$. For these fits, only data to the left of the vertical line were used. Adjacent G- and N-region plots, e. g. (a) and (b), were selected for similarity of shape. The $\Delta\eta_D$ range is indicated in each plot. The three highest bins in $\Delta\eta_D$ are combined in (g).

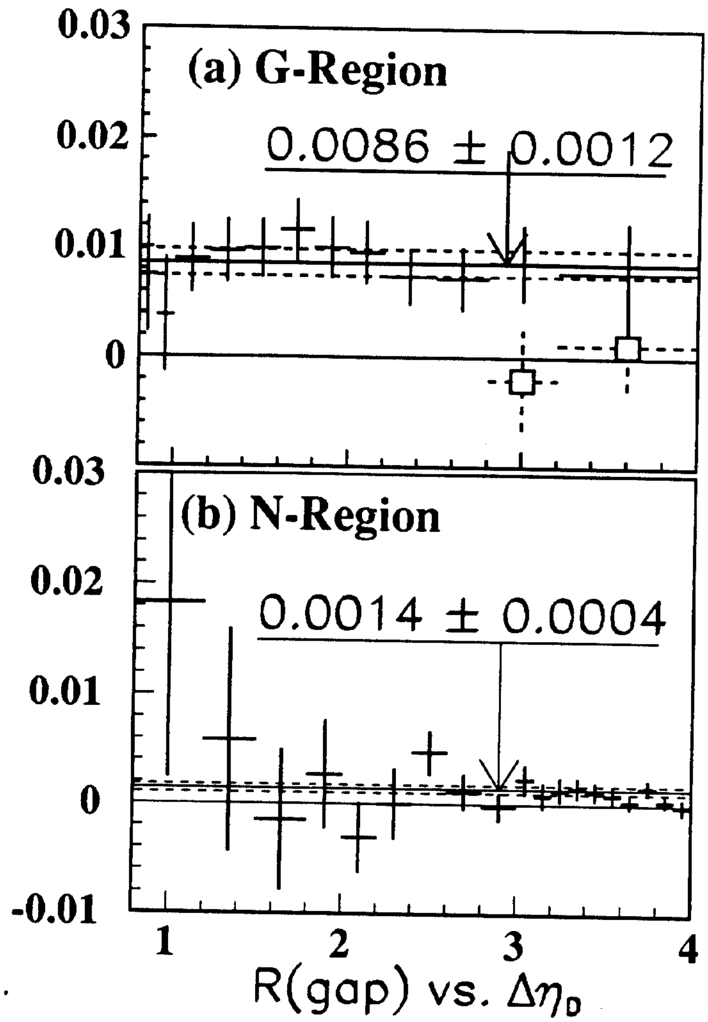

Figure 3: A plot of the ratio of the background-subtracted population of MTRK=0 events to total events as a function of $\Delta\eta_D$ for (a) the G-region and (b) the N-region. The average is indicated by the solid horizontal line and dashed error corridor. The two points in (a) indicated by squares are from the minimum-bias trigger (see text).