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CDF and D0

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RAPIDITY GAP RESULTS FROM TEVATRON

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FOR THE CDF AND D ϕ COLLABORATIONS

Results of rapidity gap physics in the CDF and D ϕ Collaborations are presented. In particular, hard diffraction (diffractive dijet and heavy flavor quark production, dijet production in Double Pomeron Exchange) and color-singlet exchange are described.

1 INTRODUCTION

Rapidity gap, defined as the absence of particles in a rapidity or pseudorapidity* region, is a signature of the exchange of a color-singlet. In the soft diffractive and elastic interactions, the so-called “pomeron” with quantum numbers of the vacuum, is exchanged, and leaves a rapidity gap in the final state. “Hard diffraction” is characterized by the presence of rapidity gaps due to pomeron exchange, associated with a hard process in the pomeron-(anti-)proton interactions (such as the production of jets, W boson, etc). Another issue of interest is the exchange of a strongly interacting color-singlet. This process has been observed in dijet events with a central rapidity gap between jets at the Tevatron and the HERA.

2 DETECTOR APPARATUS

The calorimetry, one of the relevant detectors to this physics, plays an very important role in all analyses of rapidity gap physics. The D ϕ (CDF) calorimeter has full coverage for a pseudorapidity range of $|\eta| < 4.1$ (4.2), and both calorimeters use a projective tower geometry, whose transverse segmentation is approximately $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. The forward calorimeters (FCAL) which are often used to search for rapidity gap signal cover the ranges of $2.5 < |\eta| < 4.1$ ($2.3 < |\eta| < 4.2$) for the electromagnetic component, and $3.2 < |\eta| < 5.2$ ($2.2 < |\eta| < 4.2$) for the hadronic component in the D ϕ (CDF) detector. In addition to the calorimeter, forward scintillator detectors are also often used to tag inelastic and rapidity gap events. D ϕ uses two forward scintillator arrays called the L ϕ detector which cover the region of $1.9 < |\eta| < 4.3$, and CDF uses a set of scintillator hodoscopes called Beam-Beam Counters (BBC) which covers the region of $3.2 < |\eta| < 5.9$.

3 HARD DIFFRACTION AT CDF/D ϕ

3.1 Diffractive W Boson and Dijet Production

Based on the results of diffractive W boson and dijet analyses which reported the ratio of diffractive to non-diffractive W boson (dijet) production, R_W (R_{JJ}), for

* $\eta \equiv -\ln \tan(\theta/2)$ where θ is the polar angle relative to the beam.

$\bar{p}p$ collisions at $\sqrt{s} = 1800 \text{ GeV}^1$, the CDF collaboration determined a fraction of the gluon in the pomeron, f_g , independently of the pomeron flux normalization. Figure 1 shows, as a function of f_g , $\pm 1\sigma$ curves of discrepancy of the pomeron flux factor, D , defined as the ratio of R_W (R_{JJ}) of data to one predicted by simulation, assuming a hard structure of the pomeron and standard pomeron flux parameterization. From the overlap of the bands, CDF obtained $f_g = 0.7 \pm 0.2$, which does not depend on the pomeron flux normalization. This result is consistent with the ZEUS measurement² of $0.3 < f_g < 0.8$, but the discrepancy factor $D = 0.18 \pm 0.04$ obtained in CDF is quite below the ZEUS result, which implies a breakdown of the factorization.

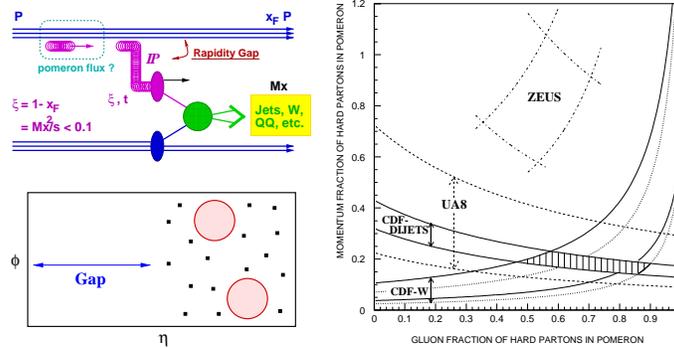


Figure 1. Hard diffraction dissociation in $\bar{p}p$ collisions (upper left), and dijet production with forward rapidity gap in hard diffraction (lower left). The flux discrepancy factor D versus gluon fraction of the pomeron f_g . Results from CDF-W and CDF-dijet are shown along with ZEUS (dot-dashed lines), UA8 (dashed lines) results (right).

3.2 Diffractive Bottom Quark Production

The CDF collaboration observed diffractive $b\bar{b}$ production in a sample of central high E_T electron events ($9.5 < E_T^e < 20 \text{ GeV}$, $|\eta^e| < 1.1$) at $\sqrt{s} = 1800 \text{ GeV}$ by searching for a rapidity gap signal in the BBC and FCAL detectors. After several quality cuts were applied, the BBC hit and FCAL tower-cluster (defined as a cluster of towers within the size of $\sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.25$ around the tower with $E_T > 100 \text{ MeV}$) multiplicities were measured. Evaluating an amount of excess events at the zero multiplicity, the ratio of diffractive to non-diffractive b -quark pair production was estimated to be $R_{b\bar{b}} = 0.26 \pm 0.08(\text{stat.}) \pm 0.04(\text{syst.}) \%$ without rapidity gap acceptance correction. This result would give a certain constraint to the pomeron structure (like a band shown in Figure 1), which is at present being studied by CDF.

3.3 Diffractive Dijet Production with Recoil Beam Particle Tagging

The CDF collaboration studied the dijet production in single diffraction (SD) using another technique to select diffractive events: a tag of a recoil beam particle with

“Roman Pot” detectors. Three Roman Pot stations were installed about 56m away from CDF interaction point along the outgoing \bar{p} direction. The typical acceptance region of ξ and t is $0.04 < \xi < 0.1$ and $0 < |t| < 2 \text{ GeV}^2$ respectively.

After applying several cuts to select events with a good reconstructed track in the Roman Pots, CDF obtained dijet events with $E_T > 7 \text{ GeV}^\dagger$. Then, CDF extracted the momentum fraction of the interacting parton in the pomeron, β , using the algorithm equivalent to the formula:

$$\beta = \frac{E_T^{jet1} \exp(-\eta^{jet1}) + E_T^{jet2} \exp(-\eta^{jet2})}{2 \xi P_{beam}} \quad (1)$$

The extraction of β shape of the pomeron was performed by subtracting several background contributions in the data, then dividing the β shape of data by reconstructed β of the simulations we have tried. The most important background sources in the data are 1) overlay background which means non-diffractive (ND) dijet accidentally overlapped with a Roman Pot hit, 2) meson exchange background, 3) double diffraction background. After subtracting these contributions from the data, then unfolding the detector acceptance by using simulations with a flat gluon distribution, the data was divided by simulations with parton density functions derived by the H1 Collaboration³, as shown in Figure 2 (left) for three jet energy thresholds. The comparison with the simulation shows flat β for $\beta > 0.2$, which means the shape agrees with the H1 pomeron structure, but the rate of H1 structure function is about a factor of 6 larger than the data.

As well known from soft diffraction, the pomeron flux parameterization of Donnachie and Landshoff has the form⁴:

$$f_{P/p}(\xi, t) = \frac{9 \beta_0^2}{4 \pi^2} \left[F_1(t) \right]^2 \left(\frac{1}{\xi} \right)^{2 \alpha_P(t) - 1} \quad (2)$$

This model, which is often referred to as the standard flux, predicts too high a rate for soft diffractive cross section. The standard flux also predicts much higher rates than the CDF measurements for diffractive W and dijet production. This discrepancy can be interpreted by the renormalized flux⁵, in which the total probability for having a diffractive rapidity gap, i.e, the integral of pomeron flux over all available phase space in (ξ, t) , cannot exceed unity. More precise evaluations of this renormalization concept gives not only the overall normalization at $\sqrt{s} = 1800 \text{ GeV}$ ($\sim 1/s^{2\epsilon}$), but also β dependence of the flux integral ($\sim 1/\beta^{2\epsilon}$) due to the minimum ξ of the available phase space, $\xi_{min} = \xi_{min}(\beta) \approx 1.5 \text{ GeV}^2/(s\beta)$. This indicates a flat parton distribution becomes softer in the renormalized flux. The comparison with the flat gluon simulations with the renormalized flux is also shown in Figure 2 (right). The rate and shape of β agrees with the renormalization prediction for $\beta > 0.2$ although an enhancement still exists in low β region.

3.4 Diffractive Dijet Production with Rapidity Gap Tagging

The D Φ Collaboration reported preliminary results of dijet production with forward rapidity gaps at both 1800 and 630 GeV center of mass energies. D Φ used the data

[†]Jet energy correction with about 2 GeV underlying event energy subtraction was applied. Now more reliable estimate of underlying event energy is in progress.

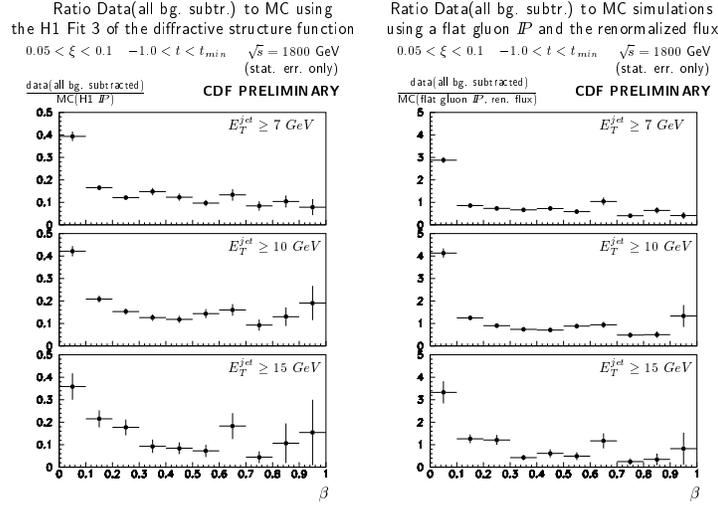


Figure 2. Ratio of the data, as a function of β , to simulation predictions with the H1 measured structure functions (left), a flat gluon density of the pomeron with the renormalized flux (right).

from a forward trigger which required at least two jets with $E_T > 12$ GeV in the region of $|\eta| > 1.6$. After removing events with multiple $\bar{p}p$ interactions, the number of calorimeter towers n_{CAL} within the region of $2.0 < |\eta| < 4.1$ (“near gap”) opposite the jets was measured to search for rapidity gaps. As a result, a peak at zero multiplicity in qualitative agreement with expectations for a diffractive signal was observed at two energies. The rapidity gap fraction is defined as the number of excess events in the range $0 \leq n_{\text{CAL}} \leq 9$ over a background predicted by a fit in larger n_{CAL} bins divided by the total number of events. Also, by using the same method with an optimized fit range for the 630 GeV data, the rapidity gap fractions were measured to be $f_{\text{gap}}^{1800(630)} = 0.76 \pm 0.04(\text{stat.}) \pm 0.07(\text{syst.})\%$ ($1.11 \pm 0.11(\text{stat.}) \pm 0.20(\text{syst.})\%$) for 1800 (630) GeV. We can expect that results of studies of the pomeron structure using dijet events with forward rapidity gaps will appear soon from D ϕ .

3.5 Dijet Production in Double Pomeron Exchange

Both CDF and D ϕ Collaborations presented preliminary results of dijet production in Double Pomeron Exchange (DPE), in which both the beam proton and anti-proton emit the pomerons, leaving forward rapidity gaps in both sides, while the two pomerons interact and produce a final massive state.

CDF used both techniques to search for DPE events: tag of a rapidity gap for the proton side, and a recoil beam particle with Roman Pot for the anti-proton side. Figure 3 (upper left) shows BBC hit multiplicity N_{BBC} versus forward calorimeter tower multiplicity N_{FCAL} opposite a tagged anti-proton with $0.04 < \xi < 0.095$ and $|t| < 1.0$ GeV², in a sample of dijet events with $E_T > 7$ GeV[‡] at $\sqrt{s} = 1800$ GeV. As seen in a figure, a clear rapidity gap signal was observed in the $N_{\text{BBC}} =$

[‡]No underlying event energy is subtracted from a jet. Study on this is in progress.

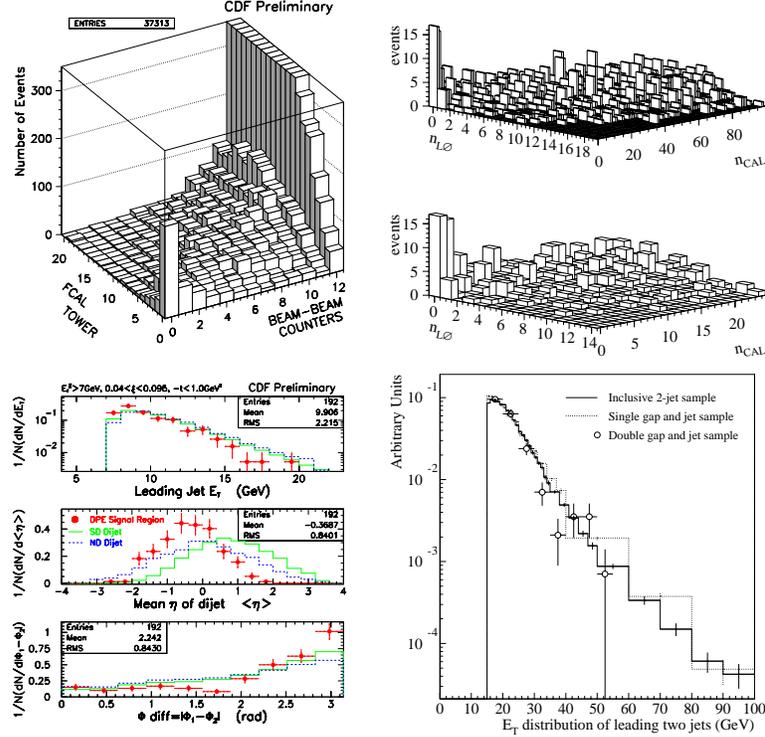


Figure 3. CDF: (upper left) BBC multiplicity versus forward calorimeter tower multiplicity opposite a tagged \bar{p} for $E_T > 7 GeV$ dijet events at $\sqrt{s} = 1800 GeV$. (lower left) Comparison of DPE dijets (black circles) with SD (solid line), ND dijets (dashed line). D ϕ : (upper right) Calorimeter tower multiplicity n_{CAL} versus $L\phi$ hit multiplicity $n_{L\phi}$ opposite a tagged rapidity gap for $E_T > 15 GeV$ dijet events at $\sqrt{s} = 1800 GeV$. The bottom shows an expanded view of low multiplicity region. (lower right) Comparison of jet E_T of double gap events (open circles) with no-gap (solid line), single gap events (dotted line).

$N_{FCAL} = 0$ bin, which is in qualitative agreement with predictions for DPE dijet events based on the Monte Carlo. By extrapolating linearly into the $N_{BBC} = N_{FCAL} = 0$ bin along the diagonal axis, CDF obtained the gap excess event fraction, defined as the number of excess events divided by the total number of Roman Pot dijet events, to be $R_{JJ\bar{P}}^{GJJ\bar{P}} = 0.36 \pm 0.05(stat.) \pm 0.03(syst.)\%$ ($0.26 \pm 0.09(stat.) \pm 0.04(syst.)\%$) for dijets with $E_T > 7$ (10) GeV . These results are in agreement with DPE Monte Carlo predictions based on the flat gluon structure of the pomeron, and the renormalized flux defined as the standard flux multiplied by a discrepancy factor $D = 0.18 \pm 0.04$ mentioned above (Section 3.1).

Figure 3 (lower left) shows a comparison of dijets produced in DPE, SD, ND at $\sqrt{s} = 1800 GeV$. All three samples show similar jet E_T spectra (top) in spite of decreasing effective center of mass energies ($\sqrt{s}_{DPE} < \sqrt{s}_{SD} < \sqrt{s}_{ND}$) from the (anti-)proton diffracting, which could suggest a hard structure of the pomeron. The

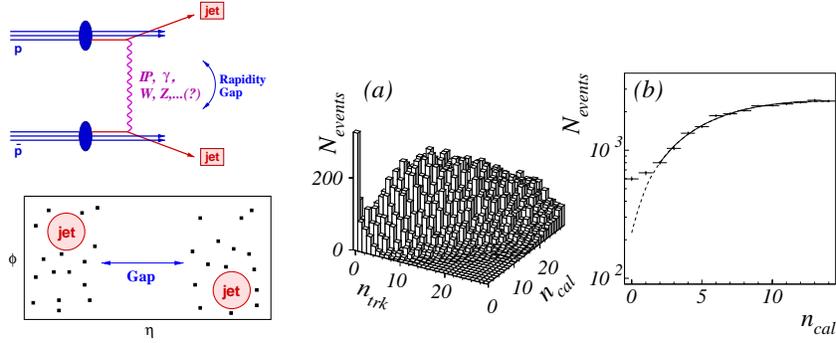


Figure 4. Dijet production via color-singlet exchange in $\bar{p}p$ collisions (upper left), and the distribution of particles in $\eta - \phi$ including a central rapidity gap between leading two jets (lower left). The tower multiplicity (n_{cal}) and track multiplicity (n_{trk}) in the region of $|\eta| < 1$ between leading two jets with $E_T > 30 \text{ GeV}$ for 1800 GeV OS events (right). 2-D plot of n_{cal} versus n_{trk} , 1-D plot of n_{cal} with negative binomial fitting.

η of dijets shows the boost qualitatively expected from the momentum imbalance of incoming particles (middle), and the azimuthal opening angle between leading two jets indicates less radiation in DPE, than SD or ND (bottom).

The $D\Phi$ Collaboration also observed an excess of events with two forward rapidity gaps in a sample of single gap events at both 1800 and 630 GeV center of mass energies. $D\Phi$ used a trigger which required a jet with $E_T > 15$ (12) GeV at 1800 (630) GeV , in conjunction with a requirement for a single rapidity gap in the $L\Phi$ detector to obtain DPE enriched sample. After requiring two jets above trigger threshold within $|\eta| < 1.0$ and selecting events with single interaction, multiplicity distributions between calorimeter towers n_{CAL} and $L\Phi$ hits $n_{L\Phi}$ were measured, as shown in Figure 3 (upper right). A signal which is qualitatively consistent with DPE dijet is seen as a clear peak at low multiplicity. $D\Phi$ observed the similar characteristics of DPE dijets to CDF results, as seen in Figure 3 (lower right) showing the same E_T spectrum of double gap events as samples of inclusive two jet events and a single gap events. Also, similar results were obtained for double gap events at 630 GeV .

4 COLOR SINGLET EXCHANGE AT CDF/ $D\Phi$

4.1 Dijet Production with a Central Rapidity Gap

Results of dijets with a central rapidity gap between jets (Figure 4, left), which implies a strongly interacting color-single exchange (CSE), have been reported by both $D\Phi$ ⁶ and CDF⁷ collaborations for $\bar{p}p$ collisions at the Tevatron. Recently both collaborations published new results (Ref.⁸ for $D\Phi$, Ref.⁹ for CDF) of color-singlet exchange at $\sqrt{s} = 1800 \text{ GeV}$ and 630 GeV .

The $D\Phi$ Collaboration reported new measurements of dijets in CSE at both center of mass energies. $D\Phi$ used a forward dijet trigger which required at least two jets with $|\eta| > 1.6$, and then, offline, two leading jets with $|\eta| > 1.9$ were se-

lected in a sample of single interaction events. Moreover, $\Delta\eta > 4.0$ was required for "opposite side" (OS) events ($\eta_1 \cdot \eta_2 < 0$). Events with two jets of same sign η ($\eta_1 \cdot \eta_2 > 0$) are called "same side" (SS) events. Then, multiplicities in the region of $|\eta| < 1$ between leading two jets were measured as n_{cal} and n_{trk} , using the electromagnetic calorimeter and central drift chamber, respectively. Figure 4 (right) shows the n_{cal} versus n_{trk} , and n_{cal} distributions for OS jets with $E_T > 30 GeV$ at $\sqrt{s} = 1800 GeV$. A large excess of events at low multiplicity is consistent with expectations for CSE signal. Then, the "color-singlet fraction" was measured to be $f_s = 0.94 \pm 0.04(stat.) \pm 0.12(syst.) \%$, by dividing the number of events for $n_{cal} \leq 1$ above negative binomial fit by the total number of events. The systematic error is dominated by the uncertainty in the background fitting. Applying same method to low E_T samples of $E_T > 12 GeV$ at both 1800 and 630 GeV , D ϕ obtained the color-singlet fraction of $0.54 \pm 0.06(stat.) \pm 0.16(syst.) \%$ ($1.85 \pm 0.09(stat.) \pm 0.37(syst.) \%$) for 1800 (630) GeV , which gives the ratio of color-singlet fractions at two energies, $R_{1800}^{630} = 3.4 \pm 1.2$, for jets with $E_T > 12 GeV$.

Figure 5 (left) shows the color-singlet fractions as a function of jet E_T (upper), η separation $\Delta\eta = |\eta_1 - \eta_2|$ (lower) at $\sqrt{s} = 1800 GeV$. The measured color-singlet fraction tends to increase with E_T and $\Delta\eta$, which would imply for CSE a different magnitude of coupling to quarks and gluons, and therefore could give a probe for the nature of "hard CSE". The lines in the figures represent the fits of "color-factor" models to the data, assuming the survival probability of rapidity gap S given by $f_s/(\sigma_{singlet}/\sigma)$ is independent of E_T and $\Delta\eta$, where $\sigma_{singlet}/\sigma$ is the fraction of dijet events produced in CSE. Color-factor models are based on the parameterization of color-singlet fraction as a weighted sum of quark/gluon fractions of p and \bar{p} where the weights (effective "color factors") determine the magnitude of couplings to initial quarks and gluons. As a result of this approach, it was found that color-factor model with soft-color rearrangement¹⁰ (dashed line), an alternative QCD motivated model for rapidity gaps, reasonably describes the data. This also indicates a color-singlet would preferentially couple to initial quark processes. The model of "two gluon" exchange (dot-dashed line), originally proposed as an explanation of rapidity gap between jets, does not describe the data, and "single gluon" model (dotted line) cannot be excluded from the fits.

New results of CSE from the CDF Collaboration are the measurement of CSE fraction at $\sqrt{s} = 630 GeV$ and a comparison with 1800 GeV result, CSE fraction as a function of jet E_T and η separation (in fact, $\Delta\eta/2$). CDF used dijet events with jets of $E_T > 8 GeV$ and $|\eta| > 1.8$ at $\sqrt{s} = 630 GeV$. The data was classified into OS and SS events. Then, from the track multiplicity in the region of $|\eta| < 0.9$ for OS events, the CSE fraction was evaluated using a fit to the bin-by-bin difference between OS and SS divided by the SS distribution, and dividing the number of excess events by the total number of events, yielding $R_{JGJ}(630) = 2.7 \pm 0.7(stat.) \pm 0.7(syst.) \%$ for $E_T > 8 GeV$. The ratio of CSE fractions at 1800 and 630 GeV center of mass energies was obtained to be $R_{1800}^{630} = 2.4 \pm 0.7(stat.) \pm 0.7(syst.)$, which is consistent with D ϕ result[§].

[§]Note that D ϕ used same jet E_T cut of 12 GeV at both energies, while CDF applied different E_T cuts (8 GeV at 630, 20 GeV at 1800) to see approximately same x -values of the partons at two

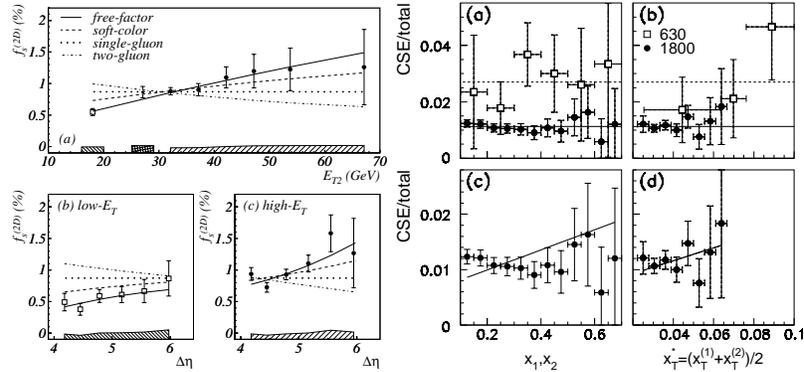


Figure 5. $D\Phi$: (left) Fits of color-factor models to color-singlet fraction at $\sqrt{s} = 1800 \text{ GeV}$ as a function of jet E_T (upper) and $\Delta\eta$ (lower left/right) for low(high) E_T data. Comparisons to free factor (solid line), soft-color (dashed line), single-gluon (dotted line) and two-gluon (dot-dashed line) models are shown. CDF: (right) Comparisons of the CSE fraction at $\sqrt{s} = 630$ (open squares) and 1800 GeV (black circles) as a function of (a)(c) x and (b)(d) x_T . The solid (dashed) lines in (a)(b) represent the average ratio $R_{JGJ}(1800)$ ($R_{JGJ}(630)$). The solid lines in (c)(d) show the HERWIG predictions of the fraction of dijet events from initial quark-quark process to all dijet events.

CDF observed jet E_T and $\Delta\eta/2$ dependence of CSE fraction, which shows approximately flat distributions over the measured range. From the measured E_T and η of jets at two energies the x ($\approx E_T^2 \cdot e^{|\eta^i|}/\sqrt{s}$ for the OS kinematics) and x_T ($= E_T^2/2\sqrt{s}$) values of the scattered partons were extracted as shown in Figure 5 (right). Both distributions are consistent with being flat over the range of the measurement, indicating the color-singlet and normal color-octet couplings to quarks and gluons have the same relative strength.

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energies.