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Results on Soft Gluon Resummation and Color Coherencce in p$\overline{\text{p}}$ Collisions at $\sqrt{s}$ = 1.8 TeV

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Results on Soft Gluon Resummation and Color Coherence in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We present two QCD studies based on data collected by the DØ detector during the 1992-1993 run and data recorded by the CDF detector during the 1988-1989 run of the Fermilab Tevatron $p\overline{p}$ collider at a center of mass energy of $\sqrt{s} = 1.8$ TeV. The first study by the DØ collaboration presents preliminary results on jet-jet angular decorrelation as a function of rapidity separation. This measurement is compared to HERWIG shower-level and JETRAD NLO parton-level Monte Carlo simulations. Data are also compared to predictions based on the techniques of Balitsky, Fadin, Kuraev, and Lipatov to resum soft gluon emissions which are expected to cause decorrelation of the produced jets. The second study demonstrates initial-to-final state color coherence effects by measuring spatial correlations between soft and hard jets in multijet events. Both CDF results and DØ preliminary measurements are presented and compared to several Monte Carlo simulations with different color coherence implementations. The DØ data, which include both central and forward jets, are also compared to the predictions of JETRAD Monte Carlo.

SOFT GLUON RESUMMATION

The high quality data accumulated at the Tevatron on hadronic jets provide a unique opportunity to test QCD. Currently, the next-to-leading-order (NLO) QCD parton level calculations (1,2), in the region where all large scales can be assumed to be of the order of the jet transverse energy, appear to be in a reasonable agreement with the one- and two-jet inclusive cross section measurements (3–5). However, at Tevatron energies the *semihard region* of the kinematic phase space where $\sqrt{s} \gg Q \sim E_T$ is also accessible. This region corresponds to jet production with large rapidity separations. In this case, logarithms of large ratios of kinematic variables, $\ln(\hat{s}/Q^2)$, of the size of the rapidity interval of the produced jets, may appear in the partonic cross section invalidating the standard perturbative expansion in a_s. These large logarithms, corresponding to gluon emissions between the scattering partons (Fig. 1), can be resummed by using the techniques of Balitsky, Fadin, Kuraev, and Lipatov (BFKL) (6,7). These soft gluon emissions are expected to decorrelate the transverse energy (E_T) and azimuthal angle (ϕ) of the produced jets as the rapidity interval increases between them.

The study of jet-jet decorrelations can provide important insights into the BFKL resummation theories and the significance of higher order processes in perturbative QCD. At leading order (LO), there are only two jets in the final state and they are perfectly correlated. As higher orders are allowed to contribute, the final state jets start to decorrelate in E_T and ϕ.

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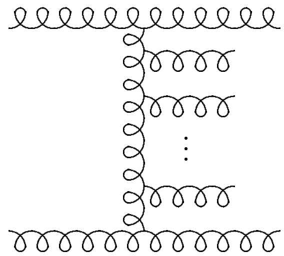

FIG. 1. Feynman diagram illustrating the gluon emissions included in the BFKL calculations.

The DØ detector (8) with its hermetic uranium-liquid-argon calorimetry is especially suited for studying jets with large rapidity separations (9). DØ preliminary results presented below study the ϕ decorrelation between jets with large pseudorapidity interval, $\Delta\eta = \eta_1 - \eta_2$, as a function of $\Delta\eta$. The data distributions are compared to predictions from BFKL resummation, HERWIG (10), and JETRAD (11); a parton-level calculation consisting of the $\mathcal{O}(a_s^2) + \mathcal{O}(a_s^3)$ one-loop $2 \to 2$ parton scattering, combined together with the $\mathcal{O}(a_s^3)$ tree-level $2 \to 3$ scattering amplitudes.

Event Selection

The data were taken during the 1992-1993 initial run of the DØ experiment. Events were selected using an inclusive jet trigger with E_T threshold of 30 GeV and pseudorapidity coverage of $|\eta| < 3.2$. The jets were reconstructed using a fixed-cone clustering algorithm with cone radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$.

The off-line analysis selected events with at least two reconstructed jets with $E_T > 20$ GeV after jet energy scale corrections and jet quality cuts applied. Jets were ordered in pseudorapidity and the most forward and most backward jets were selected. The corrected transverse energy of one of these two "tagged jets" was required to be above 50 GeV to avoid any biases introduced by the trigger threshold. Finally, it was also required that the average pseudorapidity, $\eta_{boost} = \frac{\eta_1+\eta_2}{2}$, of the tagged jets must be $\eta_{boost} < 0.5$.

Results

DØ results on ϕ decorrelation are shown in Figures 2 and 3. Figure 2 shows distributions of $1 - \frac{\Delta\phi}{\pi}$, with $\Delta\phi = |\phi_1 - \phi_2|$, for three different pseudorapidity intervals of the tagged jets. It is clear from the data that the decorrelation increases (i.e., the distributions are getting wider) as the pseudorapidity separation between the two jets increases from $\Delta\eta = 1$ to 5.

Figure 3 illustrates how the value of $< \cos(\pi - \Delta\phi) >$ varies as a function of $\Delta\eta$ for data and several Monte Carlo simulations. If the tagged jets were perfectly correlated the value of $< \cos(\pi - \Delta\phi) >$ would have been independent of $\Delta\eta$. However, the data show that the decorrelation increases with $\Delta\eta$, even more than that predicted by the JETRAD Monte Carlo. In contrast, HERWIG simulations at the particle level reproduce the observed decorrelation reasonably well. Finally, the BFKL calculations by Del Duca and Schmidt (6) predict too much decorrelation.

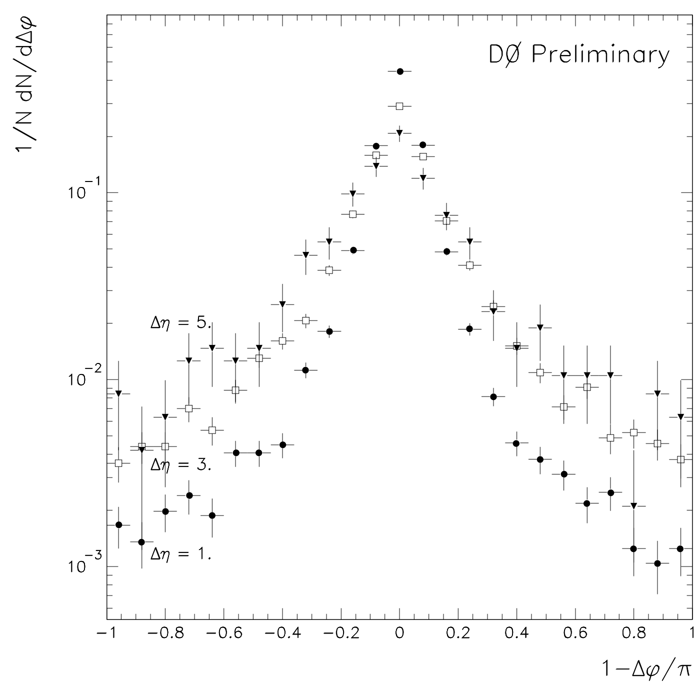

FIG. 2. $1 - \frac{\Delta\phi}{\pi}$ distributions for three pseudorapidity intervals of the tagged jets.

Conclusions

The first measurement of jet-jet angular decorrelation as a function of pseudorapidity separation has been performed by the DØ collaboration. Preliminary results show that the decorrelation seen in data is well reproduced by HERWIG. The JETRAD NLO Monte Carlo predicts too little decorrelation, whereas the BFKL resummation calculation seems to produce the correct trend in relative decorrelation but the overall amount is overestimated. The high statistics data sample expected by the current collider run will allow the DØ collaboration to study the jet decorrelations for lower E_T jets and extend the pseudorapidity coverage to $\Delta\eta = 6$.

COLOR COHERENCE

Color coherence phenomena have been observed in experiments (12–16) studying the angular flow of hadrons in three-jet events from e^+e^- annihilations, in what has been termed the "string" (17) or "drag" (18) effect. The particle population in the region between quark and antiquark jets in $e^+e^- \to q\bar{q}g$ events has been measured to be suppressed with respect to the region between (anti)quark and gluon jets. This asymmetry, in the language of perturbative QCD, arises from constructive and destructive interference among the soft gluons radiated from the q, $\bar{q}$, and g (coherence). While quantum mechanical interference effects are expected in QCD, of real importance is that the experimental results demonstrate that such interference effects survive the hadronization process, a phenomenon which the authors of Ref. (18) call *local parton-hadron duality* (LPHD).

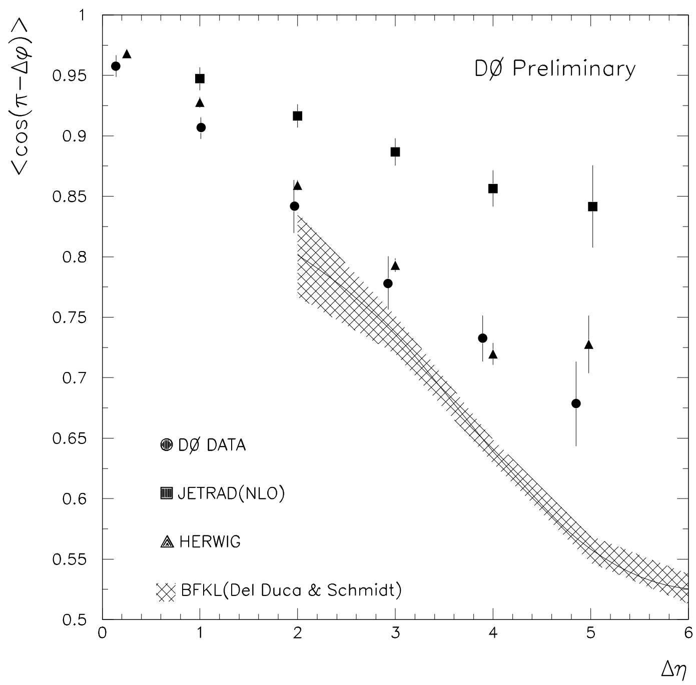

FIG. 3. $< \cos(\pi - \Delta\phi) >$ as a function of the pseudorapidity interval of the tagged jets for data and for the predictions of HERWIG and JETRAD simulations. The BFKL resummation prediction is also shown with the shaded band. The error bars shown on the data points are statistical errors added in quadrature with the systematic uncertainties.

The study of hard processes in hadron-hadron collisions is more complicated, experimentally and theoretically, than in e^+e^- annihilation due to the presence of colored constituents in both the initial and final states. In addition, any event-by-event fluctuations of the soft particles produced by the underlying event may complicate the experimental results further. During a hard interaction color is transferred from one parton to another. Examples of color flow diagrams are shown in Fig. 4 for $q\overline{q}$ and qg scattering. In Fig. 4a ($q\overline{q}$) the color system in which interference occurs is entirely between initial and final state, whereas in Fig. 4b (qg) interference also occurs in the initial and final states due to their explicit color connection. The color connected partons act here as a color antenna. Bremsstrahlung gluon radiation associated with the incoming (space-like) and the outgoing (time-like) partons leads to the formation of jets of hadrons around the direction of these colored emitters. It is the interference of such emissions that produces the color coherence effects in perturbative QCD calculations (19,20).

An important consequence of color coherence is the *Angular Ordering* (AO) approximation of the sequential parton decays. To leading order in N, the number of colors, AO leads to a suppression of soft gluon radiation in certain regions of phase space. In this sense, a way to describe the jet evolution incorporating QCD color coherence phenomena is to impose the AO condition — a uniform decrease of successive emission angles of soft gluons — as the partonic cascade evolves away from the interaction (21). Monte Carlo simulations including coherence via AO have been available for both initial and final state evolutions. However the matrix-element method, in which

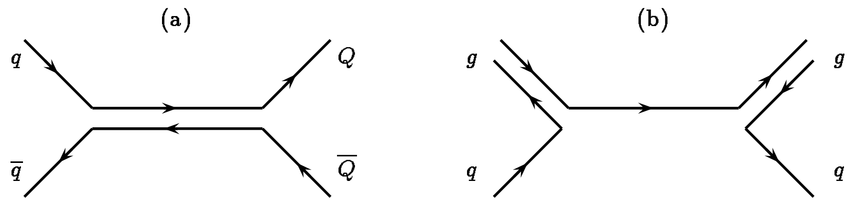

FIG. 4. Color flow diagrams for (a) $q\overline{q}$ and (b) qg scattering.

Feynman diagrams are calculated order by order, is in principle the correct approach, but it becomes increasingly difficult in higher orders, and thus its usage is limited.

Experimentally, initial-to-final state coherence effects in $p\overline{p}$ interactions have been studied by both the CDF (22) and DØ collaborations by measuring spatial correlations between soft and leading jets in multijet events. The CDF collaboration has published a study on evidence for color coherence in jet events (23), and the DØ collaboration has already presented preliminary results which showed similar evidence (24).

The sections below describe the method of analysis employed by both experiments, followed by a review of the CDF published results and updated DØ preliminary results which extend the previous study to forward rapidity regions.

Method of Analysis

To minimize any complications caused by the underlying event fluctuations, both experiments selected events where the two leading jets had sufficiently high energies so that the coherent radiation formed secondary jets. Events were selected to have three or more reconstructed jets. The jets were ordered in E_T and were labeled $E_{T1} > E_{T2} > E_{T3}$. The angular distribution of the softer third jet around the second highest-E_T jet in (η, ϕ) space was measured in a search disk as shown in Fig. 5. The expectation from initial-to-final state color interference is that the rate of soft jet emission around the event plane (i.e., the plane defined by the directions of the second jet and the beam axis) will be enhanced with respect to the transverse plane.

The data angular distributions are compared to several shower level Monte Carlo simulations (ISAJET (25), HERWIG, and PYTHIA (26)) that differ in their implementation of color coherence. ISAJET uses an independent shower development model without any color coherence effects, HERWIG and PYTHIA+ (a pre-release PYTHIA v5.7) incorporate initial and final state interference effects by means of AO approximation of the parton cascades. PYTHIA v5.6 uses the AO approximation only for the final state shower evolution. The DØ results are also compared to the JETRAD NLO parton-level Monte Carlo.

Event Selection

The CDF data sample was collected during the 1988-1989 run of the Tevatron collider and the analysis by DØ used data collected during the 1992-1993 run. The jets were reconstructed using a fixed-cone clustering algorithm with 0.7 cone radius for CDF and 0.5 for DØ. The corrected transverse energy of the highest-E_T jet of the event was required to be well above the trigger threshold, which for CDF was $E_T > 110$ GeV and for DØ $E_T > 120$ GeV. CDF required the third jet to have $E_T > 10$ GeV, while DØ required $E_T > 15$ GeV.

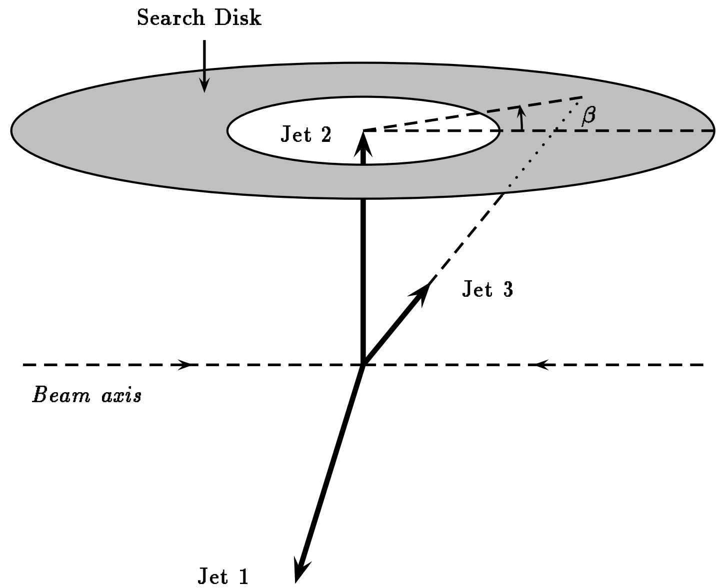

FIG. 5. Three-jet event topology illustrating the search disk (gray area) for studying the angular distribution of the softer third jet around the second leading-E_T jet.

For this analysis CDF required both leading jets to be central ($|\eta| < 0.7$) and back-to-back to within 20^0 in the transverse plane (ϕ plane). At DØ the interference effects were studied when the second leading-E_T jet was central ($|\eta_2| < 0.7$) or forward ($0.7 < |\eta_2| < 1.5$). The pseudorapidity of the leading jet was not explicitly constrained. The two leading jets were required to be in opposite ϕ hemispheres without imposing any tight back-to-back cut.

At CDF the interference between the second and the third jet was displayed using the polar variables $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\alpha = \tan^{-1}(\frac{sign(\eta_2)\cdot\Delta\eta}{|\Delta\phi|})$; where $\Delta\eta = \eta_3 - \eta_2$ and $\Delta\phi = \phi_3 - \phi_2$, in a search disk of $1.1 < R < \pi$.

At DØ the spatial correlations were studied using a slightly different definition of the angular variable (shifted by $\frac{\pi}{2}$ from the CDF angle); $\beta = \tan^{-1}(\frac{sign(\eta_2)\cdot\Delta\phi}{\Delta\eta})$ as shown in Fig. 5. The search domain was defined to be $0.7 < R < \frac{\pi}{2}$.

Color Coherence Results

Figure 6 shows the α distributions for the CDF data in comparison to several Monte Carlo predictions processed through the CDF detector simulation. The absence of color interference in ISAJET and of initial-to-final coherence in PYTHIA v5.6 results in a disagreement with the CDF data distributions. However, HERWIG and PYTHIA+, which both contain initial and final state interference effects, agree better with the data.

DØ β distributions along with Monte Carlo predictions are shown in Fig. 7. Detector position and energy resolution effects have been included in the Monte Carlo simulations. For both central ($|\eta_2| < 0.7$) and forward ($0.7 < |\eta_2| < 1.5$) regions, HERWIG and JETRAD are in satisfactory agreement with the data, whereas ISAJET disagrees with the DØ data. The ratios of the data β distributions relative to the Monte Carlo predictions for both η regions are shown in Fig. 8. The

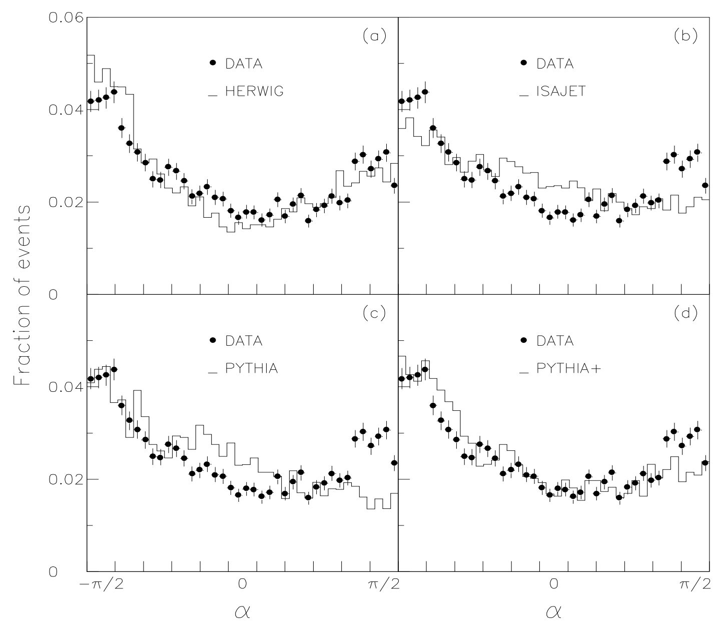

FIG. 6. Comparisons of the CDF α distribution to the predictions of (a) HERWIG v3.2, (b) ISAJET v6.25, (c) PYTHIA v5.6, and (d) PYTHIA+. The error bars shown on the data points are statistical errors only.

data show a clear excess of events compared to ISAJET near the event plane ($\beta = 0,\ \pi,\ 2\pi$) and a depletion at the transverse plane ($\beta = \frac{\pi}{2},\ \frac{3\pi}{2}$), as expected from initial-to-final state coherent radiation. From the $\frac{DATA}{HERWIG}$ and $\frac{DATA}{JETRAD}$ β distributions we conclude that the AO approximation and the matrix element approach describe the coherence effects seen in data reasonably well.

Color Coherence Conclusions

Color coherence effects between initial and final states in $p\overline{p}$ interactions have been observed and studied by both CDF and DØ. Monte Carlo simulations that implement color interference effects by means of AO reproduce the angular correlations between the second and the third leading-E_T jet seen in data reasonably well. Furthermore, DØ preliminary results indicate that coherence effects as predicted by a $2 \rightarrow 3$ parton level calculation are in agreement with the data.

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REFERENCES

1. S.D. Ellis, Z. Kunszt, and D.E. Soper, Phys. Rev. **D40**, 2188 (1989); Phys. Rev. Lett. **64**, 2121 (1990); Phys. Rev. Lett. **69**, 1496 (1992).

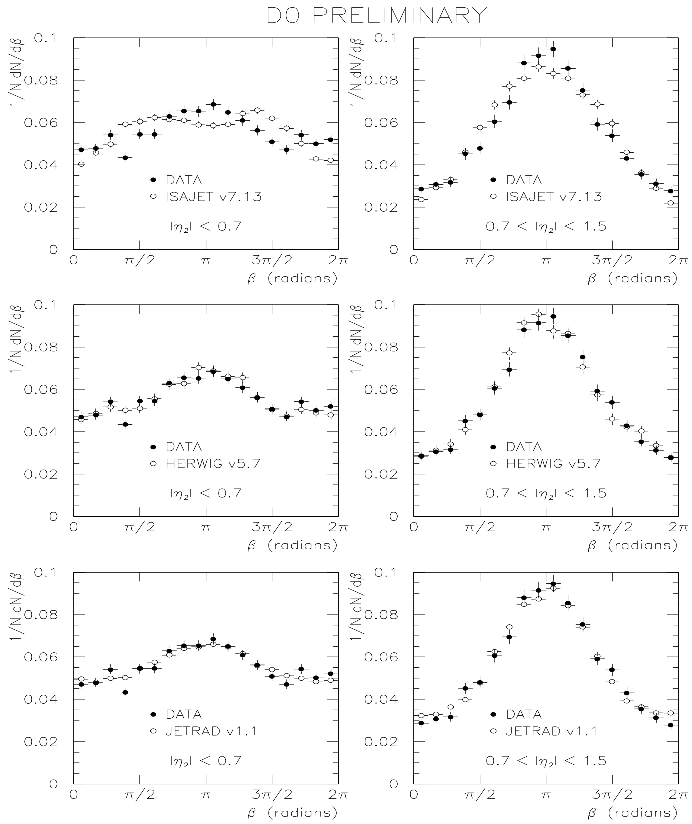

FIG. 7. Comparisons of the DØ β distributions for central ($|\eta_2| < 0.7$) and forward ($0.7 < |\eta_2| < 1.5$) jets to the predictions of ISAJET v7.13, HERWIG v5.7, and JETRAD v1.1. The error bars shown are statistical errors only.

2. W.T. Giele, E.W.N. Glover, and D.A. Kosower, Fermilab preprint FERMILAB-Pub-94/070-T (1994).
3. F. Nang (DØ Collaboration), Fermilab preprint FERMILAB-Conf-94/323-E (1994).
4. D. Elvira (DØ Collaboration), Fermilab preprint FERMILAB-Conf-94/323-E (1994).
5. E. Kovac (CDF Collaboration), Fermilab preprint FERMILAB-Conf-94/215-E (1994).
6. V.Del Duca and C.R. Schmidt, Phys. Rev. **D49**, 4510 (1994); DESY preprint 94-144 (1994), V.Del Duca, DESY preprint 95-023 (1995).
7. W.J. Stirling, Nucl. Phys. **B428**, 3 (1994).
8. F. Abachi *et al.* (DØ Collaboration), Nucl. Instr. Meth. **A338**, 185 (1994).
9. T. Heuring (DØ Collaboration), Fermilab preprint FERMILAB-Conf-94/323-E (1994).
10. G. Marchesini and B.R. Webber, Nucl. Phys. **B310**, 461 (1988).
11. W.T. Giele, E.W.N. Glover, and D.A. Kosower, Phys. Rev. **D46**, 1980 (1992); Nucl. Phys. **B403**, 633 (1993); Phys. Rev. Lett. **73**, 2019 (1994).
12. W. Bartel *et al.* (JADE Collaboration), Phys. Lett. **B101**, 129 (1981); Zeit. Phys. **C21**, 37 (1983); Phys. Lett. **B134**, 275 (1984).
13. H. Aihara *et al.* (TPC/2γ Collaboration), Phys. Rev. Lett. **54**, 270 (1985); Zeit. Phys. **C28**, 31 (1985); Phys. Rev. Lett. **57**, 945 (1986).

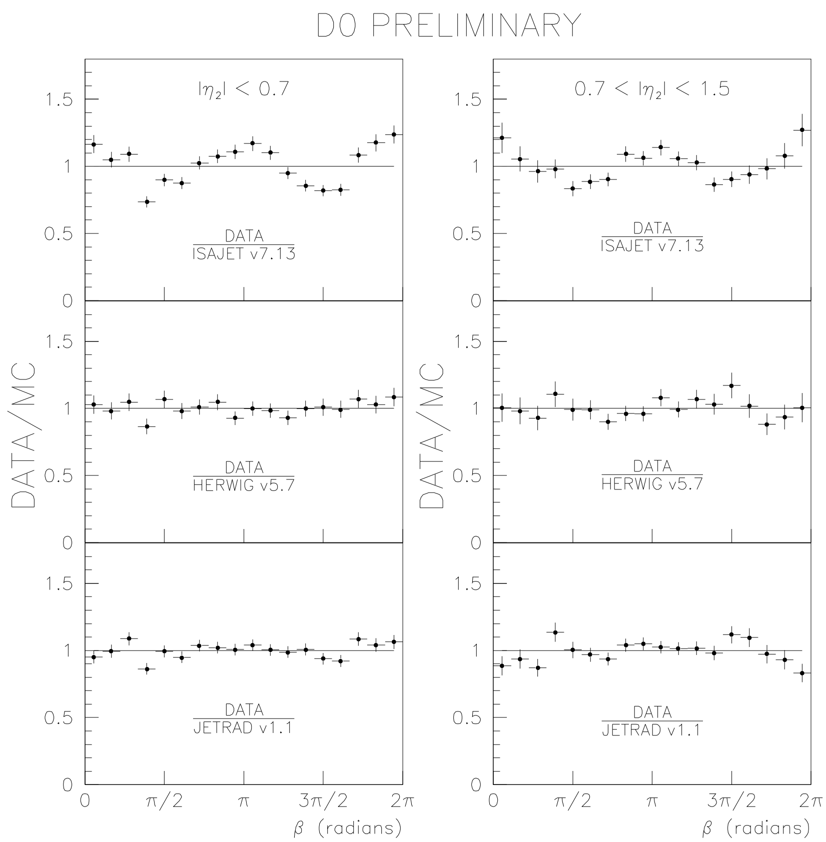

FIG. 8. Ratio of β distributions between data and Monte Carlo predictions for both central and forward jets.

14. M. Althoff *et al.* (TASSO Collaboration), Zeit. Phys. **C29**, 29 (1985).
15. P.D. Sheldom *et al.* (MARK2 Collaboration), Phys. Rev. Lett. **57**, 1398 (1986).
16. M.Z. Akrawy *et al.* (OPAL Collaboration), Phys. Lett. **B247**, 617 (1990); Phys. Lett. **B261**, 334 (1991); P.D. Acton *et al.* Phys. Lett. **B287**, 401 (1992); Zeit. Phys. **C58**, 207 (1993).
17. B. Andersson, G. Gustafson, and T. Sjöstrand, Phys. Lett. **B94**, 211 (1980).
18. Ya.I. Azimov, Yu.L. Dokshitzer, V.A. Khoze, and S.I. Troyan, Phys. Lett. **B165**, 147 (1985); Sov. Journ. Nucl. Phys. **43**, 95 (1986).
19. R.K. Ellis, G. Marchesini, and B.R. Webber, Nucl. Phys. **B286**, 643 (1987).
20. Yu.L. Dokshitzer, V.A. Khoze, A.H. Mueller, and S.I. Troyan, Basics of Perturbative QCD, Editions Frontières (1991); Rev. Mod. Phys. **60**, 373 (1988).
21. G. Marchesini, and B.R. Webber, Nucl. Phys. **B238**, 1 (1984); B.R. Webber, Nucl. Phys. **B238**, 492 (1984).
22. F. Abe *et al.* (CDF Collaboration), Nucl. Instr. Meth. **A271**, 387 (1988).
23. F. Abe *et al.* (CDF Collaboration), Phys. Rev. **D50**, 5562 (1994).
24. F. Borcherding (DØ Collaboration), Proceedings of the 9th Topical Workshop on Proton-Antiproton Collider Physics, Tsukuba, Japan, 218, 18-22 Oct. 1993.

25. F.E. Paige and S.D. Protopopescu, BNL report No. 38034 (1986).
26. H.U. Bengtsson and T. Sjöstrand, Comp. Phys. Comm. **46**, 43 (1987); T. Sjöstrand and M. Bengtsson, Comp. Phys. Comm. **43**, 367 (1987); T. Sjöstrand, Comp. Phys. Comm. **39**, 347 (1986).