Color Coherent Radiation in Multijet Events from $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We report on a study of color coherence effects in $p\overline{p}$ collisions at a center of mass energy $\sqrt{s} = 1.8$ TeV. The data were collected with the DØ detector during the 1992–1993 run of the Fermilab Tevatron Collider. We observe the presence of initial–to–final state color interference with the spatial correlations between soft and hard jets in multijet events in the central and in forward pseudorapidity regions. The results are compared to Monte Carlo simulations with different color coherence implementations and to the predictions of $\mathcal{O}(\alpha_s^3)$ QCD calculations.

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Color coherence phenomena in the final state have been observed in e^+e^- annihilations [1–6], in what has been termed the "string" [7] or "drag" [8] effect. Particle production in the region between the quark and antiquark jets in $e^+e^- \to q\overline{q}g$ events is suppressed. In perturbative quantum chromodynamics (QCD) such effects arise from interference between the soft gluons radiated from the q, $\overline{q}$, and g. While quantum mechanical interference effects are expected in QCD, it is important to investigate whether such effects survive in general the nonperturbative hadronization process, as predicted by local parton–hadron duality [8].

The study of hard processes in hadron–hadron collisions is complicated by the presence of colored constituents in both the initial and final states. Color is transferred from one parton to another and the color–connected partons act as color antennae. Color interference effects between initial and final states can occur. Gluon radiation from the incoming and outgoing partons forms jets of hadrons around the direction of these colored emitters. The soft gluon radiation pattern accompanying any hard partonic system can be represented, to leading order in $1/N_c$ where N_c is the number of colors, as a sum of contributions corresponding to the color–connected partons. Within the perturbative calculations, this is a direct consequence of interferences between the radiation of various color emitters, resulting in the QCD coherence effects [8–10].

Color coherence, which results in a suppression of soft gluon radiation in the partonic cascade in certain regions of phase space, can be approximated by *Angular Ordering* (AO). For the case of outgoing partons, AO requires that the emission angles of soft gluons decrease monotonically as the partonic cascade evolves away from the hard process. The radiation is confined to a cone centered on the direction of one parton, and is bounded by the direction of its color–connected partner. Outside this region the interference of different emission diagrams becomes destructive and the azimuthally integrated amplitude vanishes to leading order. Conversely the emission angles increase for the incoming partons as the process develops from the initial hadrons to the hard subprocess. Monte Carlo simulations including coherence effects by means of AO are available for both initial and final state evolutions. QCD calculations taken to sufficiently high order should in principle incorporate these effects to any accuracy. Use of the latter approach is limited, however, due to the current lack of higher order calculations.

Evidence for color coherence effects between initial and final states in $p\overline{p}$ interactions has been previously published [11] for the central pseudorapidity region. In this paper we report on a study of color coherence phenomena in $p\overline{p}$ interactions which extends the measurements into the untested forward region. We compare our measurements to the predictions of $\mathcal{O}(\alpha_s^3)$ QCD matrix element calculations as well as to several parton–shower Monte Carlo (MC) simulations.

The DØ detector is described in detail elsewhere [12]. This analysis uses the uranium liquid–argon sampling calorimeter to measure jet final states. The DØ calorimeter has fine segmentation in both azimuthal angle ϕ, and in pseudorapidity $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle of the jet with respect to the proton beam. It has hermetic coverage for $|\eta| < 4$ with fractional transverse energy E_T resolution of $\sim 80\%/\sqrt{E_T(\mathrm{GeV})}$ for jets.

The data sample for this analysis [13], representing an integrated luminosity of 8 pb^{-1}, was collected during the 1992–1993 Tevatron Collider run. Events were selected using a three level trigger. The first level required a coincidence of two scintillator hodoscopes located on either side of the interaction region, to ensure an inelastic collision. The next stage required the transverse energy of at least three calorimeter towers (0.2×0.2 in $\Delta\eta \times \Delta\phi$) to exceed a 7 GeV threshold in the region $|\eta| < 3.2$. The surviving events were analyzed by an online processor farm where jets were reconstructed using a simplified version of the final jet finding algorithm and an event was recorded to tape if it had a jet with $E_T > 85$ GeV.

Jets were reconstructed offline using an iterative fixed–cone clustering algorithm with cone radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$. Spurious jets from isolated noisy calorimeter cells and accelerator losses were eliminated by cuts on the jet shape. The E_T of each jet was corrected for offsets due to the underlying event, multiple $p\overline{p}$ interactions, and noise, out–of–cone showering, and detector energy response as determined from the missing transverse energy balance of photon–jets events [14]. Events were required to have a measured vertex within 50 cm of the detector center.

The remaining events were required to have three or more reconstructed jets. Jets were ordered in E_T and labeled $E_{T1} > E_{T2} > E_{T3}$. We required $E_{T1} > 115$ GeV to avoid any bias introduced by the trigger threshold, and the third jet to have $E_T > 15$ GeV. Color coherence effects are measured with the angular distribution in (η, ϕ) space of the softer third jet around the second jet. The polar variables R and $\beta = \tan^{-1}(\frac{\text{sign}(\eta_2)\cdot\Delta\phi_{32}}{\Delta\eta_{32}})$ were used to locate the third jet in a search disk of $0.6 < R < \frac{\pi}{2}$ around the second jet (Fig. 1). Here, η_i and ϕ_i are the pseudorapidity and azimuthal angle of the i^{th} jet, $\Delta\eta_{32} = \eta_3 - \eta_2$, and $\Delta\phi_{32} = \phi_3 - \phi_2$. We define $\beta = 0$ to point towards the beam nearest to the second jet, and $\beta = \pi$ to point towards the farther beam. We study the interference effects in regions $|\eta_2| < 0.7$ and $0.7 < |\eta_2| < 1.5$. The pseudorapidity of the leading jet was not constrained, but first and second jets were required to be in opposite ϕ hemispheres, i.e. $\frac{\pi}{2} < \Delta\phi_{21} < \frac{3\pi}{2}$.

The measured angular distributions (Fig. 2) are compared to the predictions of several MC simulations that differ in their implementation of color coherence. We employ the parton–shower MC event generators ISAJET 7.13 [15], HERWIG 5.8 [16], and PYTHIA 5.7 [17], and a partonic event generator, JETRAD 1.2 [18] to calculate the $\mathcal{O}(\alpha_s^3)$ QCD predictions. The ISAJET generator uses an independent shower development model without any color coherence effects. Both HERWIG and PYTHIA incorporate initial and final state color interference effects by means of the AO approximation of the parton cascades. In PYTHIA, the AO constraint can be turned off. HERWIG and PYTHIA each employ a phenomenological model to describe the hadronization process. HERWIG uses the cluster hadronization model and PYTHIA implements the Lund string fragmentation model, which are both supported by the observations of color coherence phenomena in e^+e^- annihilations.

The shower–based MC simulations were performed at the particle (hadron) level after the nonperturbative hadronization process, whereas the JETRAD predictions were at the parton level. Detector η and energy resolution effects were included in all predictions. The generated events were subsequently processed using the same criteria employed for analyzing the data.

The β distributions, normalized to the total number of events, for the data and HERWIG and ISAJET predictions are shown in Fig. 2 for both central and forward η regions. In each case the data peak near $\beta = \pi$ and this enhancement is more dramatic for higher η. The shape of these distributions is sensitive not only to the process dynamics but also to phase space effects resulting from our jet and event selection criteria. For both regions, HERWIG is in good agreement with the data, whereas ISAJET shows systematic deviations from the observed distributions.

The ratios of the observed β distributions relative to the MC predictions for both η regions are shown in Fig. 3. The data show a clear enhancement of events compared to ISAJET near the event plane (i.e., the plane defined by the directions of the second jet and the beam axis, $\beta = 0,\ \pi$) and a depletion in the transverse plane ($\beta = \frac{\pi}{2}$). This is consistent with the expectation from initial–to–final state color interference that the rate of soft jet emission around the event plane be enhanced with respect to the transverse plane. The PYTHIA predictions include string fragmentation. Without AO the PYTHIA distributions are significantly different from the data, while with AO turned on there is much better agreement, although there are still some residual differences in the "near beam" region. In addition, from the $\frac{\text{Data}}{\text{HERWIG}}$ and $\frac{\text{Data}}{\text{JETRAD}}$ β distributions, we conclude that both the AO approximation and $\mathcal{O}(\alpha_s^3)$ QCD describe the coherence effects seen in data in both η regions.

The main sources of uncertainty on the data β distributions are summarized in Table I. Since we report *per event* distributions, any possible uncertainty on quantities that affect the overall rate of events is minimized. For both η regions the statistical and systematic uncertainties are comparable. Sources of systematic uncertainty arise from the jet energy calibration, a possible η dependence of the jet reconstruction efficiency, and small η biases caused by the jet reconstruction algorithm.

We have also examined three main sources of systematic uncertainty related to the MC predictions. Varying the jet energy resolution within its measured uncertainties resulted in changes to the MC β distributions of less than 2.6% (2.8%) in the central (forward) region. The effect of using different parton distribution functions (CTEQ2ML, CTEQ2MF, and CTEQ2MS [19]) was examined with JETRAD and found to produce variations of less than 2.0% in the central and forward regions. The JETRAD β distributions varied by less than 1.3% (2.5%) in the central (forward) region when the renormalization and factorization scales varied from $E_{T1}/2$ to $2E_{T1}$.

Table II shows the χ^2 values of fits to the various $\frac{\text{Data}}{\text{MonteCarlo}}$ ratios with a constant, using the combined sample with $|\eta_2| < 1.5$. All uncorrelated systematic uncertainties (i.e., energy scale and η bias corrections) in the data were added in quadrature with the statistical uncertainties and were included in the calculation of χ^2. The uncorrelated systematic uncertainty due to jet energy resolution was also added in quadrature with the statistical uncertainties of the MC predictions. From the χ^2 values we conclude that HERWIG and JETRAD agree best with our data. In addition, from the data to PYTHIA comparisons we conclude that for the process under study, string fragmentation alone cannot accommodate the effects seen in the data. The AO approximation is an important contributor to color coherence effects in parton–shower event generators.

The data β distributions were also compared to the predictions of HERWIG at the parton level (before the nonperturbative hadronization stage). From the comparison of the $\frac{\text{Data}}{\text{HERWIG}}$ ratios at the parton and particle level we conclude that the hadronization effects as modeled by HERWIG are negligible and do not influence our results.

We processed a limited HERWIG event sample through a full GEANT based detector simulation [20] to investigate any possible detector effects not accounted for in the jet energy and η resolutions. From the comparison of the β distributions at the particle and detector levels such residual detector effects were found to be negligible.

We have presented a study of color coherent radiation in multijet events in $p\overline{p}$ collisions. We have measured the spatial correlations between the second and third leading E_T jets in the central and in forward pseudorapidity regions. Comparisons of the data distributions with various color coherence implementations demonstrate a strong presence of initial–to–final state interference. Parton shower MC simulations that implement color interference by means of angular ordering reproduce the data angular distributions well, with HERWIG giving the best representation. Our results also indicate that coherence effects as predicted by a $2 \rightarrow 3$ partonic level calculation provide a good representation of our data.

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TABLES

TABLE I. Major uncertainties in the data β distributions.

Source of uncertainty	$\lvert\eta_2\rvert < 0.7$	$0.7 < \lvert\eta_2\rvert < 1.5$
Jet energy scale corrections	2.2%	3.4%
Jet η bias correction	1.2%	1.7%
Jet reconstruction efficiency		
Near beam	+1.5%	+5.0%
Far beam	−0.5%	−2.0%
Statistical error	3.2%	4.3%

TABLE II. χ^2 values for 8 degrees of freedom of fits to the various $\frac{\text{Data}}{\text{MonteCarlo}}$ ratios of β distributions with a constant for the combined sample with $|\eta_2| < 1.5$. Statistical and uncorrelated systematic uncertainties were included.

Event Generator	χ^2
ISAJET	74.4
HERWIG	7.2
JETRAD	7.2
PYTHIA	
String fragmentation, but no AO	126.0
String fragmentation, and AO	19.3

FIGURES

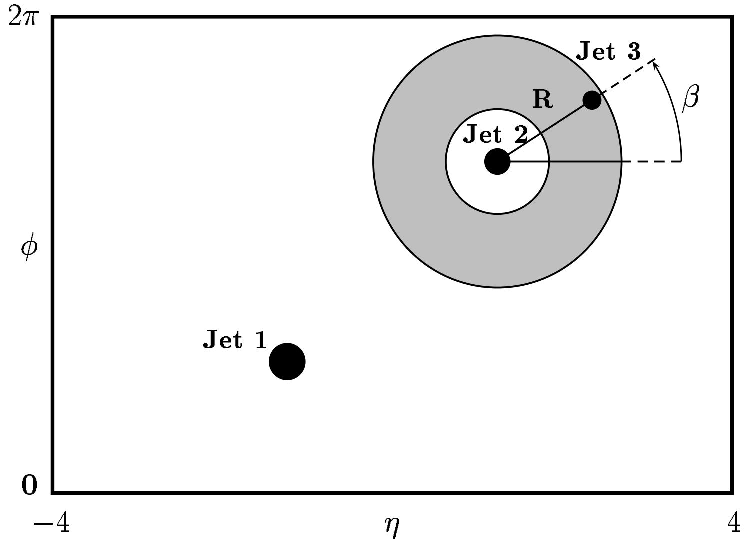

FIG. 1. Three jet event topology illustrating the search disk (shaded area) for the softer third jet around the second jet.

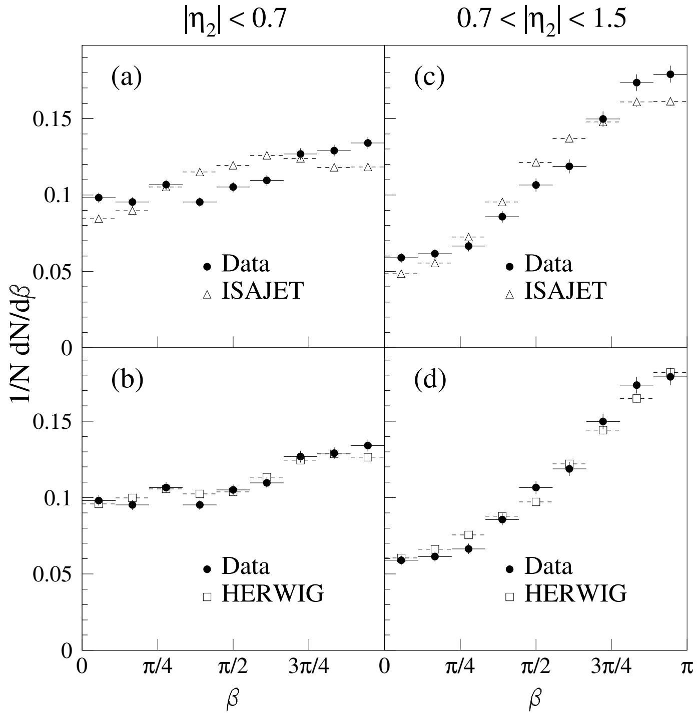

FIG. 2. Comparisons of the data β distributions to the predictions of ISAJET and HERWIG for (a), (b) central region and (c), (d) forward region. The error bars include statistical errors only.

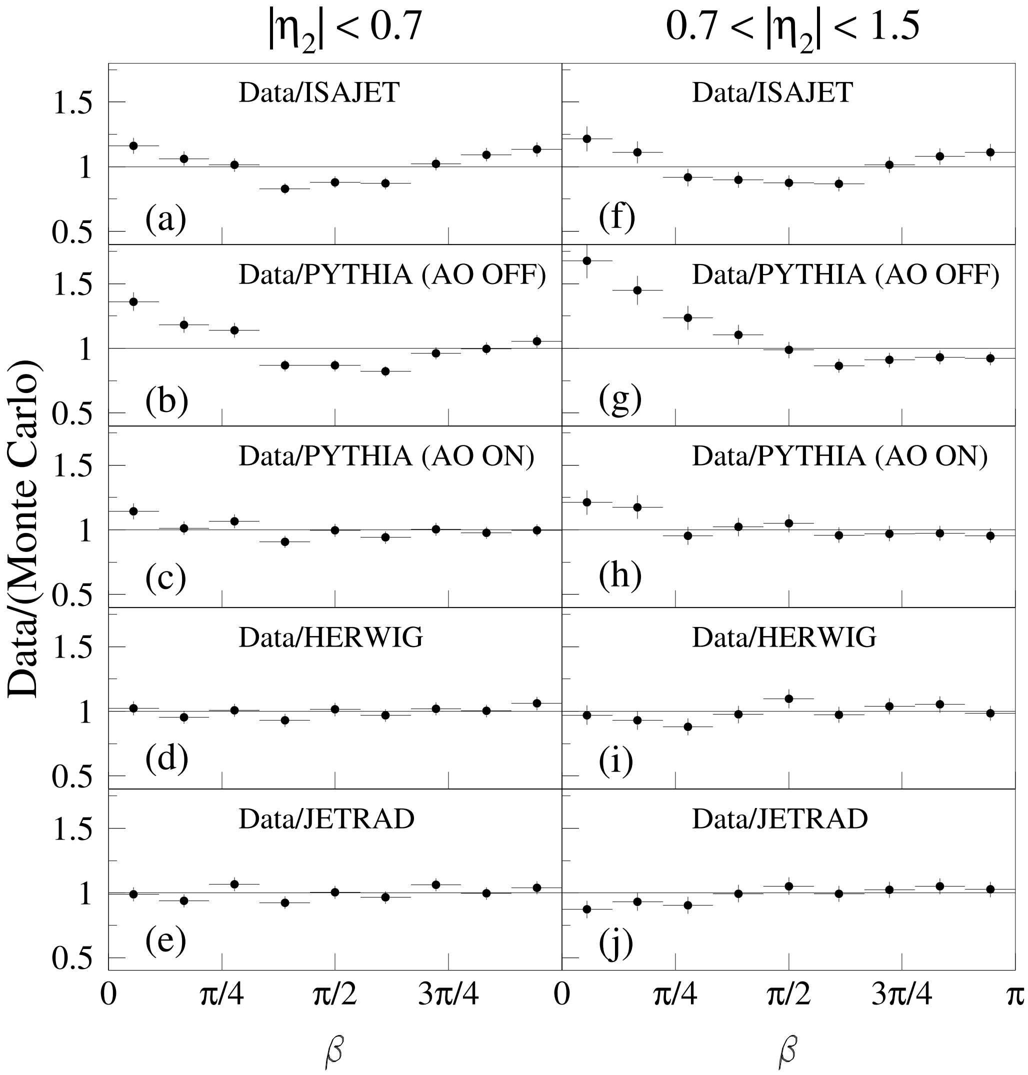

FIG. 3. Ratio of β distributions between data and the predictions of: (a) ISAJET, (b) PYTHIA with AO off, (c) PYTHIA with AO on, (d) HERWIG, (e) JETRAD for the central region; and (f)-(j) for the forward region respectively. The error bars include statistical and uncorrelated systematic uncertainties.