Color Coherence in W + Jet Events

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(June 30, 1997)

Abstract

We report on preliminary studies of color coherence effects in $p\overline{p}$ collisions, based on data collected by the DØ detector during the 1994–1995 run of the Fermilab Tevatron collider, at a center of mass energy $\sqrt{s} = 1.8$ TeV. Color interference effects are studied by examining particle distribution patterns in W + Jet events. The data are compared to Monte Carlo simulations with different color coherence implementations and to a recent analytic Modified-Leading-Log perturbative calculation based on the Local Parton-Hadron Duality hypothesis. Soft particle radiation is enhanced in the event plane relative to the transverse plane, in agreement with calculations in which the effects of color coherence are fully included.

*Submitted to the *XVIII International Symposium on Lepton Photon Interactions,* July 28 – August 1, 1997, Hamburg, Germany.

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I. INTRODUCTION

Color coherence phenomena have been observed in experiments [1–6] studying the angular flow of hadrons in three-jet events from e^+e^- annihilations, in what has been termed the "string" [7] or "drag" [8] effect. The particle population in the region between quark and antiquark jets in $e^+e^- \to q\overline{q}g$ 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, $\overline{q}$, and g. While quantum mechanical interference effects are expected in QCD, it is important that experiments test whether such interference effects survive the hadronization process, a phenomenon which the authors of Ref. [8] call *Local Parton-Hadron Duality* (LPHD).

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. At leading-order, W + Jet events are produced either via $q\overline{q}$ or qg interactions. In the $q\overline{q}$ case, interference occurs solely between the partons in the initial and final state, whereas in qg interactions, the resulting interference is between initial states in addition to that between the initial and final state. Note that in both cases, no color connections exist to the (colorless) W boson. The color connected partons act as a color antenna. Bremsstrahlung gluon radiation associated with the incoming and the outgoing partons leads to the formation of jets of hadrons around the direction of these colored emitters. It is the interference of such emissions that give rise to the color coherence effects in perturbative QCD calculations [9,10].

An important consequence of color coherence is the *Angular Ordering* (AO) approximation of the sequential parton emissions. AO leads to a suppression of soft gluon radiation in certain regions of phase space. In the case of outgoing partons, AO reduces the available phase space to an angular-ordered region, in which the successive emission angles of soft gluons decrease as the partonic cascade evolves away from the hard process. Outside this angular-ordered region the interference of different emission diagrams becomes destructive and the azimuthally integrated amplitude vanishes to leading order. For incoming partons, the emission angles increase as the process develops from the initial hadrons to the hard subprocess. Monte Carlo simulations including coherence via AO are available for both initial and final state evolutions [11,12]. While AO provides an approximate description of color coherence effects, QCD calculations taken to sufficiently high order should model the effects properly. Use of the latter approach, however, is limited, due to the current lack of higher-order calculations.

In the non-perturbative regime, color coherence effects can also be modeled by fragmentation schemes that account for color connections among partons, with results qualitatively similar to perturbative angular ordering effects.

Color coherence effects in $p\overline{p}$ interactions have been previously studied [14,15] by measuring spatial correlations between soft and leading-E_T jets in multi-jet events. In this paper we report evidence of color coherence in W + Jet events. This analysis takes advantage of the sensitivity of the DØ detector [13] by examining soft particle distributions in W + Jet events and provides additional evidence for color coherence interference between initial and final states. This measurement is the first observation of color coherence effects in $p\overline{p}$ events containing W bosons and jets.

II. METHOD OF ANALYSIS

To study color coherence in W + Jet events, we compare the distributions of soft particles around the W boson and opposing jet. Since the W boson is a colorless object, it does not contribute to the production of secondary particles, thereby providing a template against which the pattern around the jet may be compared. This comparison reduces the sensitivity to global detector and underlying event biases that are present in the vicinity of both the W boson and the jet.

The distribution of soft particles in the collider data is approximated in this analysis by measuring the distribution of projective calorimeter towers (columns of cells of area $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ radiating outward from the center of the detector) with $E_T > 250$ MeV. This threshold was chosen in order to minimize contributions from low-energy calorimeter noise.

Events with the decay $W \rightarrow e + \nu$ are used. The W boson is reconstructed from the decay products, resulting in a twofold ambiguity in the W boson rapidity (y_W) (due to a similar ambiguity in the neutrino longitudinal momentum p_Z). Monte Carlo studies have shown that the smaller $|y_W|$ is correct approximately 2/3 of the time, so this is the solution chosen. This choice is also made in the Monte Carlo W boson reconstruction to retain consistency in the comparison with collider data.

Once the W boson direction has been determined in the detector, the opposing jet is tagged by selecting the highest-E_T jet in the ϕ hemisphere opposite to the W boson. Annular regions are drawn around both the W boson and the jet in (η, ϕ) space, as shown in Fig. 1.

The angular distributions of towers above the 250 MeV threshold are measured in these annular regions using the polar variables $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\beta_{W,Jet} = \tan^{-1}(\frac{sign(\eta_{W,Jet}) \cdot \Delta\phi_{W,Jet}}{\Delta\eta_{W,Jet}})$; where $\Delta\eta_{W,Jet} = \eta_{Tower} - \eta_{W,Jet}$ and $\Delta\phi_{W,Jet} = \phi_{Tower} - \phi_{W,Jet}$, in a search disk of $0.7 < R < 1.5$. Color coherence effects are expected to manifest themselves as a depletion in the energetic tower distribution around the tagged jet in the transverse plane relative to the event plane (when compared with the W boson distribution). In order to minimize the statistical uncertainties in the W + Jet sample, the annuli are folded about the ϕ symmetry axis, thereby reducing the β range to 0–π.

The data angular distributions are compared to the PYTHIA parton shower Monte Carlo simulation, with AO turned on or off, and with string or independent fragmentation schemes. PYTHIA with both AO and string fragmentation implemented accounts for color coherence effects at both the perturbative and non-perturbative levels. Turning off AO removes the perturbative contribution, and using independent fragmentation eliminates the non-perturbative component.

The data were collected during the 1994–1995 run of the DØ experiment. Candidate $W \rightarrow e + \nu$ events were required to have at least one jet with $E_T > 10$ GeV, reconstructed using a fixed-cone clustering algorithm with cone radius $R = 0.7$. Both the electron and the event's missing E_T were required to be greater than 25 GeV.

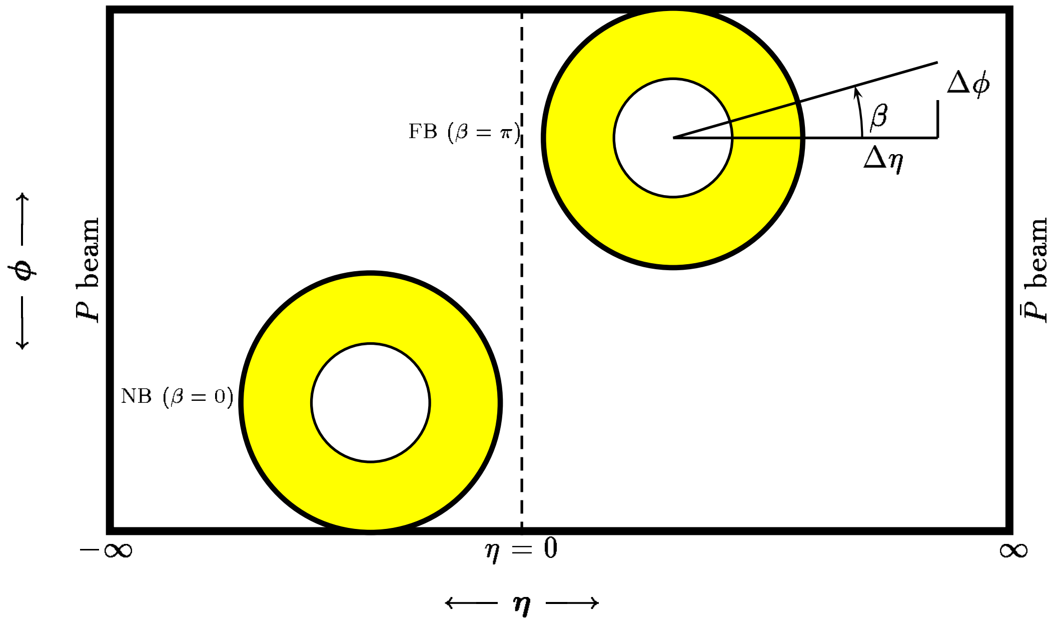

FIG. 1. Annular regions around the W boson and the jet in (η, ϕ) space.

After electron and jet quality cuts were applied, the rapidity of the W boson was restricted to $|y_W| < 0.5$ and the jet pseudo-rapidity to $|\eta_{Jet}| < 0.5$. The W boson and the jet were required to be in opposite ϕ hemispheres. Additionally, the z component of the event vertex was restricted to $|z_{vtx}| < 20$ cm to retain the projective nature of the calorimeter towers.

III. RESULTS

Fig. 2 shows the ratio of the number of towers above threshold around the jet to the number of towers around the W as a function of β (data are the solid circles). The number of towers is greater for the jet than for the W boson and the excess is enhanced in the event plane ($\beta = 0, \pi$) and minimized in the transverse plane ($\beta = \frac{\pi}{2}$), consistent with the expected trends of interference from color coherence effects. The errors include only statistical uncertainties, which are significantly larger than all systematic uncertainties considered. Also shown in Fig. 2 is the prediction from PYTHIA, where color coherence effects are included via AO and string fragmentation. The Monte Carlo events have been analyzed at the particle level, and have been normalized to the data. PYTHIA with AO and string fragmentation is in good agreement with the W+Jet data. PYTHIA with AO off and string fragmentation agrees less well (Fig. 3), and PYTHIA with AO off and independent fragmentation (Fig. 4) does not reproduce the data. Default parameters have been used in all PYTHIA predictions.

A measure of the observed color coherence effect is obtained by calculating the Jet/W tower multiplicity enhancement of the event plane ($\beta = 0, \pi$) to the transverse plane ($\beta = \pi/2$). This ratio of ratios is insensitive to the overall normalization of the individual distributions, and Monte Carlo studies have shown that it is relatively insensitive to

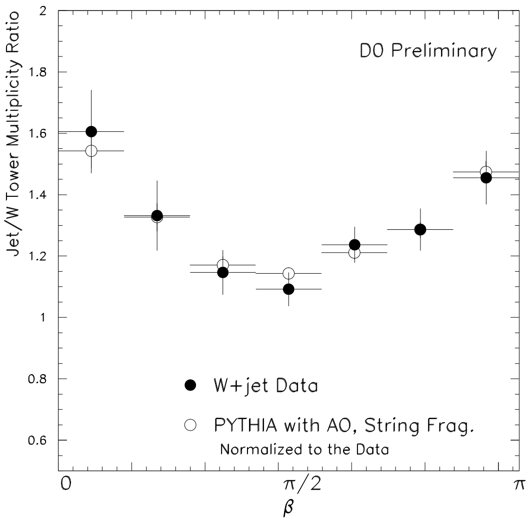

FIG. 2. Comparison of the tower ratio from data to PYTHIA with AO on and string fragmentation.

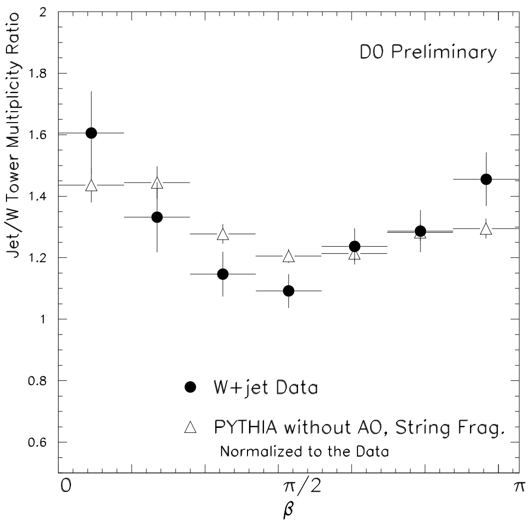

FIG. 3. Comparison of the tower ratio from data to PYTHIA with AO off and string fragmentation.

detector effects. Fig. 5 compares the data to the various PYTHIA predictions. Again, we see good agreement with PYTHIA with AO on and string fragmentation, and disagreement with AO off and string fragmentation or AO off and independent fragmentation. Finally, a comparison to a recent perturbative calculation of Khoze and Stirling [16] based on the Modified Leading-Log Approximation (MLLA) also shows very good agreement. We note that, in the absence of color coherence effects, the event plane to transverse plane ratio is expected to be unity.

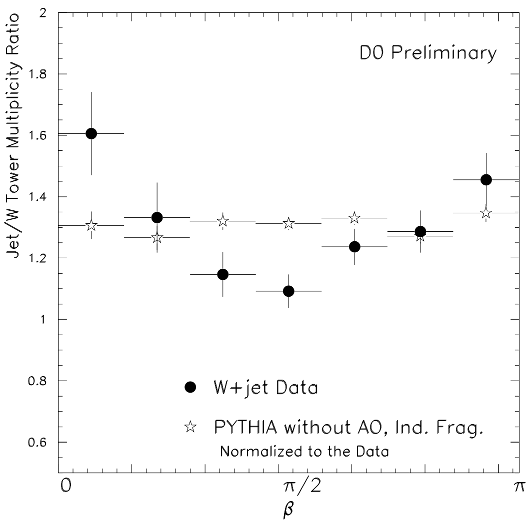

FIG. 4. Comparison of the tower ratio from data to PYTHIA with AO off and independent fragmentation.

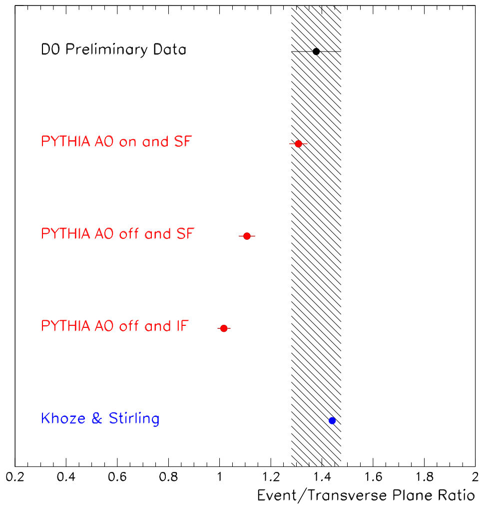

FIG. 5. Comparison of the ratio of event plane to transverse plane β ratios between data, PYTHIA and an partonic QCD calculation.

IV. CONCLUSIONS

Color coherence effects in $p\overline{p}$ interactions have been observed and studied by the DØ collaboration. We have presented the first preliminary results on color coherence effects in W+Jet events. Data show an enhancement of soft particle radiation in the event plane with respect to the transverse plane, consistent with color coherence as implemented in the PYTHIA parton shower Monte Carlo, which includes the AO approximation and string fragmentation. In addition, the relative amount of enhancement is consistent with a recent analytic perturbative calculation based on MLLA and LPHD.

ACKNOWLEDGEMENTS

We thank V. Khoze and J. Stirling for valuable discussions. We also thank the staffs at Fermilab and collaborating institutions for their contributions to this work, and acknowledge support from the Department of Energy and National Science Foundation (U.S.A.), Commissariat à L'Energie Atomique (France), State Committee for Science and Technology and Ministry for Atomic Energy (Russia), CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), and CONICET and UBACyT (Argentina).

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