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Rapidity Correlations Between High p_T Intermediate Vector Bosons and Jets in $\overline{\mathrm{p}}\mathrm{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

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DØ has used $W \rightarrow e\nu$ and $Z \rightarrow e^+e^-$ events produced in association with a high p_T jet to examine the effects of strong radiative corrections. We have compared the primary jet pseudorapidity distribution, as a function of reconstructed W or Z boson rapidity to leading order (LO) and Next-to-Leading order (NLO) QCD Monte Carlo generators, as well as a model based on extended color dipoles. We find that the primary jet is more central than either LO or NLO expectations. None of the Monte Carlo programs does a good job of predicting the shape of the jet distributions as a function of intermediate vector bosons rapidity.

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The transverse momentum of a massive electroweak vector boson, either a W or Z boson, produced in $\overline{p}p$ collisions arises from multiple gluon emission. For sufficiently large transverse momentum it has been expected that the lowest order processes indicated in Fig. 1 play a predominant role. In both processes a single jet originating from one of the two incident parton lines is mainly responsible for compensating the massive boson's transverse momentum. These cross sections are maximized when the jet has the same rapidity as the intermediate vector boson. This relationship will be altered by the proton's structure functions which determine the probability of finding suitable initial partons to produce a given event topology.

This correlation between the jet's pseudorapidity, η, and the intermediate vector boson's rapidity could also be affected by several additional physical processes. For instance, gluons are expected to be radiated preferentially between the primary jet and the nearest beam. The recoil from these jets could systematically shift the original jet to more central rapidities. An alternative process, based on the extended color dipole model (1), would preferentially produce central gluon jets (2) independent of the intermediate vector boson's rapidity. The extended color dipole model assumes that all the color charges inside the incident proton can contribute to determining the radiation pattern for the primary jet. It then assumes that the coherent interference effects associated with the proton's finite transverse size limit the available phase space and excludes gluon radiation at large rapidities.

We present a study of the rapidity correlation of a high p_T intermediate vector boson and the event's primary jet as a function of intermediate vector boson rapidity. We used W boson events identified in the $e\nu$ channel and Z boson events in the e^+e^- channel observed by the DØ detector. We do not distinguish between the different electron candidate charges. The resulting correlations were compared to the predictions from lowest order (3) (LO) and Next-to-Leading order (3) (NLO) QCD Monte Carlo generators, and ARIADNE (4), a model based on the extended color dipole. The NLO Monte Carlo program, DYRAD, is an order α_s^2 simulation.

This study is based on approximately 32 pb^{-1} for both the 1992-93 collider run and the 1994-95 collider run before January 1995. The DØ detector is described in detail elsewhere (5). We review here the features of the detector relevant for this analysis. Both the W and Z boson events were selected at the hardware trigger level by requiring a minimum of one electromagnetic (EM) trigger tower ($\Delta\eta \times \Delta\phi = 0.2 \times 0.2$) in the pseudorapidity range of $|\eta| \leq 3.2$ to have at least 10 GeV transverse energy or two such towers each with transverse energy above 7 GeV. The subsequent higher trigger levels required a cluster of EM cells with a transverse energy of 20 GeV as well as some rudimentary shape and isolation cuts. Additionally, the software trigger required that the $W \rightarrow e\nu$ events have a missing transverse energy, $\not\!\!E_T$, for the event in excess of 20 GeV. This missing transverse energy cut is increased to 25 GeV offline. The missing transverse energy vector, $\vec{\not\!\!E}_T$, is calculated using the hit information from the entire calorimeter, EM as well as hadronic, which covers pseudorapidity between ± 4 units.

The offline electron identification requires that the candidate shower have 90% or greater EM energy fraction and that an "H-matrix" analysis (6) of the shower shape be consistent with an electron. Furthermore, the candidate cluster must be isolated with $(E_{0.4} - EM_{0.2})/EM_{0.2} \leq 0.15$. The first term in the numerator, $E_{0.4}$, is the total energy (hadronic plus electromagnetic) in a cone of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ centered on the electron candidate. The denominator, $EM_{0.2}$, is the electromagnetic energy inside the $\Delta R = 0.2$ cone. Finally, the electron candidate is required to have a charged track pointing toward the shower centroid. Only electron candidates with absolute pseudorapidity less than 1.1 or between 1.5 and 3.2 are used since this insures that they are well contained in the electromagnetic calorimeter. We also require that the electron candidates have transverse energy greater than 25 GeV when forming W or Z boson candidates. The magnitude of $\vec{\not\!\!E}_T$ is also required to be greater than 25 GeV for the $W \rightarrow e\nu$ reconstruction. The W boson candidates are then selected by requiring the transverse mass, M_T, formed by the electron candidate and the event's $\vec{\not\!\!E}_T$ to be greater than 45 GeV and less than 82 GeV. The final Z boson sample required that the invariant mass of the e^+e^-system be between 86 and 96 GeV/c^2.

This analysis also requires at least one jet with $p_T \geq 20$ GeV/c and with pseudorapidity between -3 and 3 units. The jets are found using a cone algorithm with $\Delta R = 0.7$. The jets must also pass cuts designed to remove calorimeter clusters resulting from spurious calorimeter hits. These jet quality cuts are 95% effective at removing spurious jets and remove only 4% of real jets. The electron isolation cut is further strengthened by requiring that the ΔR separation between any reconstructed jet and the electron candidates be greater than 1.1. Finally, we reduce the QCD background for both W and Z boson samples, which is dominated by back to back dijet events, by requiring that the difference in azimuthal angle between the leading jet and the electron candidates, $\Delta\phi_{ej}$, be less than 2.5 radians.

The rapidity of the $Z \rightarrow e^+e^-$ is unambiguously reconstructed since we use the

e^+e^-system's momenta to determine all the components of the Z boson's 4-vector. The $W \rightarrow e\nu$ system is, however, less well defined. In reconstructing the W boson's rapidity we constrain the decay's kinematics to the world average mass, 80.22 GeV/c^2 (7). For this procedure the transverse momentum of the W boson, $\vec{p}_T(W)$, is determined by the event's missing transverse energy, $\vec{\not\!\!E}_T$, plus the transverse momentum of the electron. The W boson's momentum component along the beam direction, $p_Z(W)$, is not directly measurable since a considerable fraction of the collision's energy escapes detection down the beam pipe. Instead, $p_Z(W)$ is estimated for each event during the mass constraint. We are left with, in general, two solutions for $p_Z(W)$. *A priori*, there are a number of ways of choosing the "correct" solution. Monte Carlo studies indicate that choosing the minimum $|p_Z(W)|$ produces a good estimate. This is the algorithm that we use for this analysis. Given both the $p_Z(W)$ and $\vec{p}_T(W)$ we may calculate the W boson rapidity by $y_W = ln\sqrt{(E_w + Pz(W))/(E_w - Pz(W))}$. Figure 2 shows the distributions of reconstructed W boson rapidities from the final data sample as well as the electron pseudorapidity. The background contributions (see below) have been subtracted from both distributions. The ARIADNE and NLO predictions for the reconstructed W boson rapidity distribution are also shown. Both the NLO and ARIADNE do an acceptable job of predicting this distribution with the NLO doing a better job of predicting the fraction of central W bosons. We always use the same algorithms in reconstructing the Monte Carlo generated intermediate vector boson's rapidity as was used for the data. We have determined the y_W reconstruction resolution of our detector to be 0.097 ± 0.009 units of rapidity by considering the $Z \rightarrow e^+e^-$ sample and artificially removing one of the electrons from the event. The new $\vec{\not\!\!E}_T$ is then calculated and the event is subjected to the same procedure used in the W boson rapidity reconstruction algorithm, only now constraining the system to M_Z. This width is considerably smaller than the $\Delta y_W = 0.5$ bins that we use in the correlation study. We are not able to verify the Monte Carlo predictions for the fractional contributions of the actual y_W to each reconstructed y_W bin since $Z \rightarrow e^+e^-$ decays have a very different asymmetry from $W \rightarrow e\nu$ decays.

The backgrounds to both the $W \rightarrow e\nu + jets$ and $Z \rightarrow e^+e^- + jets$ are dominated by purely QCD processes where one or more of the jets fakes an electron. Monte Carlo studies indicate that processes involving real intermediate vector bosons but with the decay channel misidentified, such as $W + jets \rightarrow \tau\nu, \tau \rightarrow e\nu$ being identified as $W + jets \rightarrow e\nu$ contribute less than 4% of the sample at any reconstructed y_W . We determined the background from a sample of events taken with the same triggers used to collect the W and Z boson samples. These events were required to have either one or two "bad" electrons in order to be used in the W or Z boson background samples respectively. A bad electron consisted of an electromagnetic cluster which failed at least two of the three electron quality cuts but still satisfied the electron kinematic cuts. All other appropriate selection cuts were then applied to these background samples. The $\not\!\!E_T$ distribution of W boson background sample was normalized to the signal sample below $\not\!\!E_T$ of 20 GeV. The Z boson background sample was determined by normalizing the e^+e^- invariant mass distributions in the side bands, M_{ee} between 70 and 86 GeV/c^{2}and 96 and 110 GeV/c^2. The same rapidity reconstruction algorithms applied to the signal samples were then applied to the background samples. These procedures yielded a total of 1341 W boson candidates and 164 Z boson candidates with background fractions of 19% and 14% respectively.

The W and Z boson samples were then separately divided into five equal intervals of the absolute values of the reconstructed rapidity, either $|y_W|$ or $|y_Z|$, between 0. and 2.5. The pseudorapidity of each events highest E_T jet was then plotted for each intermediate vector boson rapidity interval reconstructed where the sign of the jet rapidity was defined on an event-by-event basis as $\eta_{jet} \times y_{ivb}/|y_{ivb}|$. Thus jets with positive pseudorapidity are on the same side of the event as the intermediate vector boson while jets with negative pseudorapidity are on the opposite side. The average jet pseudorapidities, as a function of the intermediate vector boson's rapidity are shown in Fig. 3. The contributions to these averages from the backgrounds have been subtracted. The errors associated with these averages have been determined by propagating the errors for the average of all candidate events and the weighted error of the average for the estimated background.

These indicate that the primary jet in these high p_T intermediate vector boson events is more central than either the LO or NLO predictions. We used the distribution of jets in each individual W boson rapidity bin to determine the significance of the shift. These are shown in Fig. 4. The background has been subtracted bin-by-bin and all the Monte Carlo generated events have been normalized to the total number of observed W bosons integrated over y_W . None of the Monte Carlo generators do a good job of reproducing the jet distributions. The probabilities that the discrepancies seen in Fig. 4 are due to statistical fluctuations alone are less than 10% for both ARIADNE and the NLO Monte Carlo program and less than 1% for the leading order prediction.

We varied the structure functions for the LO and NLO estimates using various modern sets; Morfin-Tung LO (8) and CTEQ2L (9) for the LO and CTEQ2M, CTEQ2MF, CTEQ2MS (9), MRSH, (10) and KMRSB0 (11) for the NLO. We saw only insignificant differences. We have also varied the energy scale for the LO structure functions between M_T^2 and $M_T^2/4$ without detecting a noticeable effect on the rapidity correlations. This insensitivity to the proton structure is expected given the large $Q^2 \approx M_W^2$ for these events. We ruled out η symmetric jet reconstruction inefficiencies by considering the ratio of jets on the same side as the W boson versus jets on the opposite side. Asymmetric η inefficiencies were eliminated by considering the production of jets with positive lab frame η (here defined as the direction of the incident proton) relative to those with negative lab frame η. We have also tried changing our definition of "primary" jet to be the jet with $|p_T|$ closest to the p_T of the intermediate vector boson's transverse momentum with no noticeable effect. It should be pointed out that the transverse momentum of the intermediate vector bosons are highly correlated with the primary jet when using either of these definitions. This implies that additional radiation is not playing a major role.

Finally, we have examined the dependence of our measurements on the algorithm for determining the rapidity of the W. We have tried both unfolding these mistakes on the data directly and using a weighting scheme without noticeable changes in our final distributions.

In conclusion, we have studied the rapidity correlation between the reconstructed intermediate vector boson and the event's highest p_T jet. None of the models for high p_T intermediate vector boson production in $p\overline{p}$ collisions do a particularly good job of reproducing the observed behavior of the data in that the primary jet remains central, independent of the intermediate vector boson's reconstructed rapidity. The model based on extended color dipoles does the best job of predicting the W boson-jet correlation.

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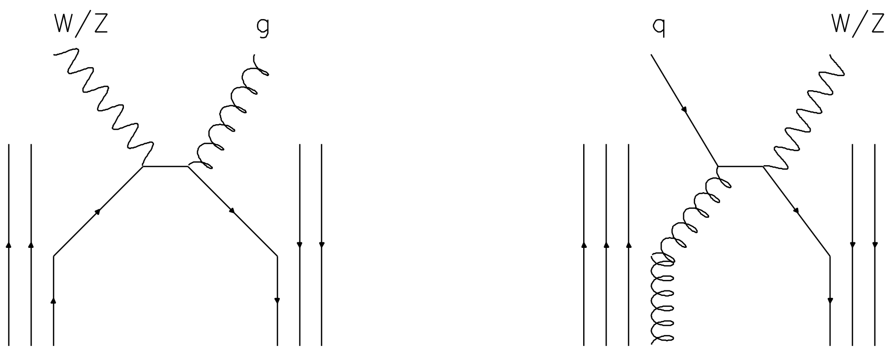

FIG. 1. The two dominant lowest order processes, the annihilation and Compton diagrams, yielding high p_T W bosons.

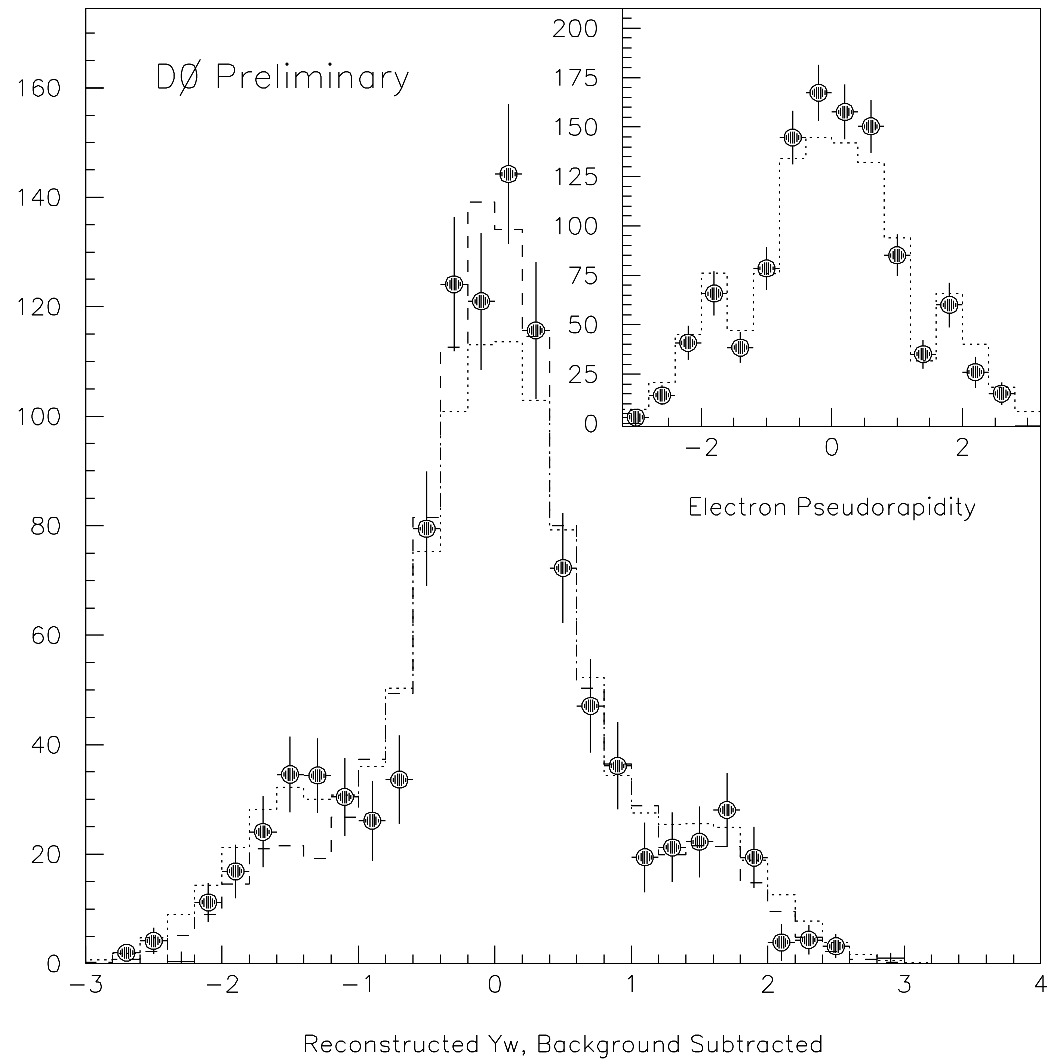

FIG. 2. The distribution of reconstructed W boson rapidities is shown together with the color dipole (dotted line) and the Next-to-Leading order (dashed line) expectations. The insert shows the electron pseudorapidity distribution and the color dipole (dotted line) prediction for this quantity. The background contributions have been subtracted from both distributions.

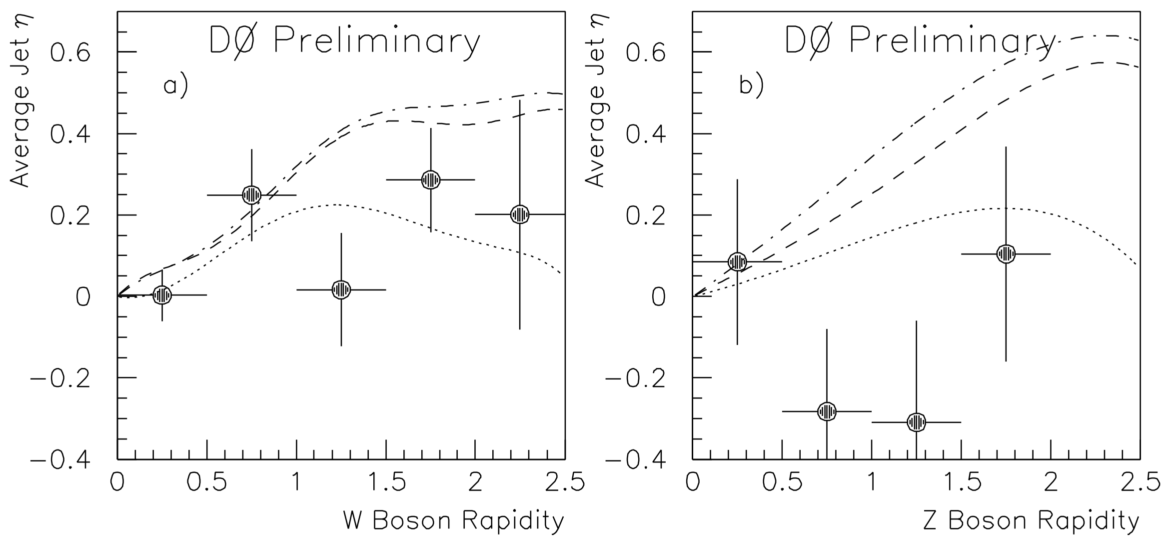

FIG. 3. The average jet pseudorapidity relative to the intermediate vector bosons (see text for explanation) is shown as a function of reconstructed W boson rapidity in figure 3a and Z boson rapidity in figure 3b. The Leading Order (dot-dashed lines), Next-to-Leading order (dashed lines), and Extended Color Dipole (dotted lines) expectations for these averages are also shown.

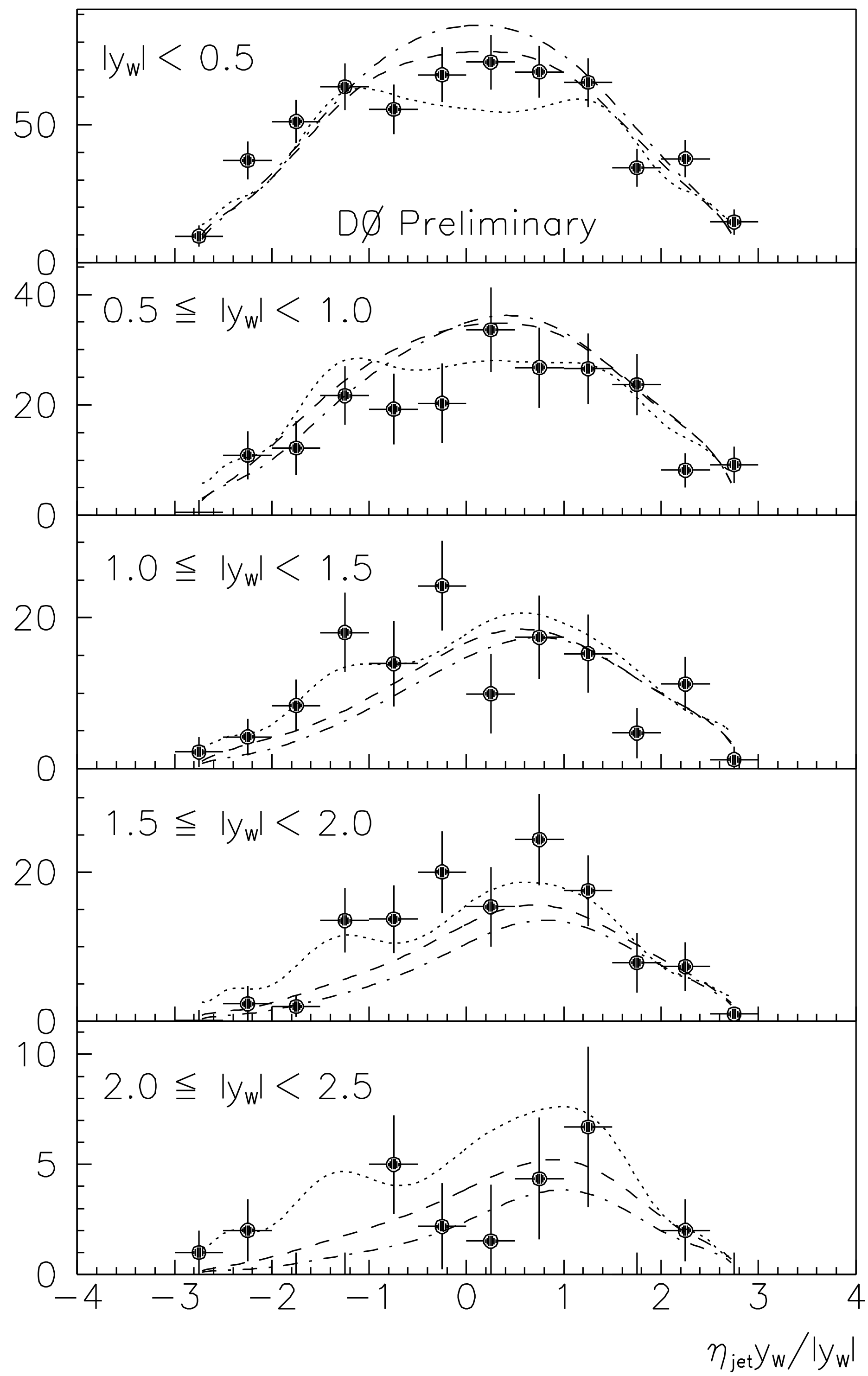

FIG. 4. The distributions of pseudorapidity of the leading E_T jets in W boson events are shown for the five intervals of y_W less than 2.5. The three different Monte Carlo expectations, ARIADNE — dotted lines, DYRAD NLO — dashed, and LO — dot-dashed lines are also shown.