Transverse Momentum Distributions of W and Z Bosons Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

The transverse momentum distributions of W and Z bosons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV are measured with the DØ detector at Fermilab. The results are compared to QCD calculations which include soft gluon resummation. The transverse momentum distribution of the Z boson is consistent with the calculation of Ladinsky and Yuan, and is used to extract their non-perturbative parameter g_2.

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I. INTRODUCTION

The transverse momentum (p_T) spectra of W and Z intermediate vector bosons have been measured previously by the UA1 [1], UA2 [2], and CDF [3] collaborations. We present a new measurement of the p_T spectra of W and Z bosons produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV, using data samples taken with the DØ detector [10] at Fermilab during the 1992–1993 and 1994–1995 collider runs.

The transverse momentum of W and Z bosons produced in proton-antiproton collisions is coupled to the associated production of one or more gluons or quarks. At low transverse momentum, multiple soft gluon emission is expected to dominate the cross section. In this regime, soft gluon resummation techniques [4–6,8,9] must be used to make reliable QCD predictions. At high transverse momentum, standard perturbative QCD [7] is expected to be applicable. Prescriptions [8,9] have been proposed for matching the predictions at high and low p_T in order to provide a prediction for all p_T. In the calculation by Arnold and Kaufmann (AK) [8], next-to-leading order QCD is matched with a resummed calculation at low p_T. Two parameters, g_1 and g_2, are introduced to account for non-perturbative effects. The Ladinsky and Yuan (LY) calculation [9] matches leading order QCD with the resummed region, and introduces an additional non-perturbative parameter, g_3. These non-perturbative parameters have been previously determined using low energy fixed target Drell-Yan data and the 1988–89 CDF Z p_T spectrum [3].

A measurement of the transverse momentum distributions thus may be used to constrain the non-perturbative parameters, test soft gluon resummation calculations in the low p_T region, and test perturbative QCD calculations at high p_T. In this paper, we concentrate on the low p_T region.

II. METHOD OF ANALYSIS

For this measurement, we use the decay modes $W \to e\nu$ and $Z \to e^+e^-$. Electrons were detected in hermetic, uranium liquid-argon calorimeters with an energy resolution of about $15\%/\sqrt{E(\mathrm{GeV})}$. The calorimeters have a transverse granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, where η is the pseudorapidity and ϕ is the azimuthal angle. For the W boson analysis, electrons in the region $|\eta| < 1.1$ were used. For the Z boson analysis, electrons were accepted in the regions $|\eta| < 1.0$ and $1.5 < |\eta| < 2.5$. In reconstructing the p_T of the W boson, we determined the transverse momentum of the neutrino using the calorimetric measurement of the missing transverse energy ($\not\!\!E_T$) in the event. The W boson sample was obtained during the 1992–1993 collider run, corresponding to 7086 events from an integrated luminosity of 12.8 pb^{-1}. The Z sample comes from the 1994–1995 run, with 4006 events and a luminosity of 97 pb^{-1}.

Electrons were identified by applying a series of quality cuts. A "loose" electron was required to be highly electromagnetic, isolated, and to have a transverse and longitudinal shower shape consistent with that expected for an electron (based on test beam measurements). For a "tight" electron we also required a good match between a reconstructed track in the drift chamber system and the shower position in the calorimeter. For the W boson sample we required one "tight" electron with $E_T > 25$ GeV, and no second "loose" electron with $E_T > 20$ GeV (to remove Z candidates). W boson candidates were required to have $\not{E}_T > 25$ GeV. For the Z boson sample we required one electron to be "tight" and the other to be either "tight" or "loose," and also the dielectron invariant mass to be in the range 76–106 GeV/c^2. Figure 1 shows the transverse mass and invariant mass distributions for the final W and Z samples, respectively.

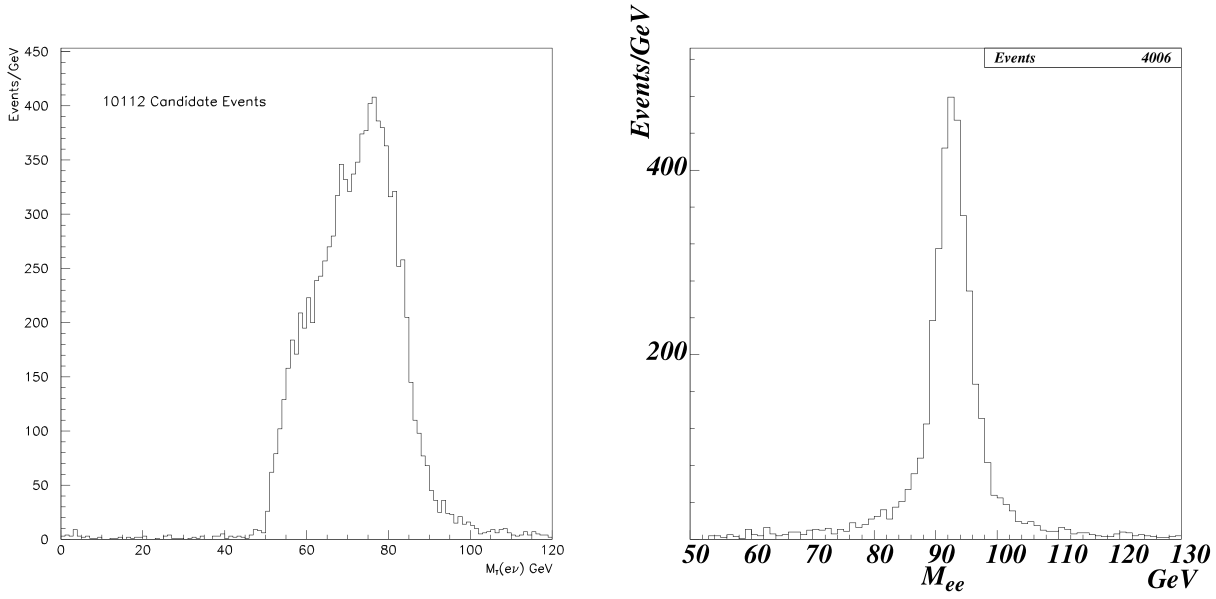

FIG. 1. Transverse mass distribution of the $e\nu$ system for the W boson sample and invariant mass distribution of the ee system for the Z boson sample.

The cross section as a function of p_T can be written as:

$$\frac{d\sigma}{dp_T}(i) = \frac{N_{obs}(i) - N_{bkg}(i)}{\epsilon(i)\Delta\mathrm{Bin}(i)\mathrm{Br}(e)\mathcal{L}} \tag{1}$$

where $N_{obs}(i)$, $N_{bkg}(i)$, $\epsilon(i)$, and $\Delta\mathrm{Bin}(i)$ are the number of observed events, number of expected background events, efficiency, and p_T bin width for the ith p_T bin. $\mathrm{Br}(e)$ and $\mathcal{L}$ are the branching fraction to the electron channel and the luminosity respectively. For the current measurements, we have not yet accounted for the finite resolution of the detector, and thus we determine the cross section as a function of the *observed* p_T. To facilitate comparisons to theory, we *smear* the theory with the experimental resolutions.

Electron selection efficiencies were determined using $Z \rightarrow e^+e^-$ data events, HERWIG Monte Carlo events run through a GEANT-based detector simulation, and events where electrons generated by GEANT were superimposed on W data events and reanalyzed. These efficiencies were determined as a function of the p_T of the vector boson in question.

The dominant source of background in both the W and Z boson samples is multijet events where one or more of the jets fluctuates to fake an electron. Some multijet events can also have significant $\not{E}_T$ due to fluctuations and mismeasurements of the jet energies, which would fake a neutrino from W boson decay. In both the W and Z boson analyses the shape of this multijet background in p_T was determined. The total multijet background was $(3.0 \pm 0.5)\%$ in the W boson sample, ranging from $\sim 2\%$ at low p_T to $\sim 10\%$ at $p_T = 40$ GeV/c. The multijet background in the Z boson sample was $(4.6 \pm 0.7)\%$ ($\sim 3\%$ at low p_T and $\sim 10\%$ at $p_T = 40$ GeV/c). Additional backgrounds to the W sample include $Z \rightarrow e^+e^-$, where one of the electrons is not detected $(0.6 \pm 0.1)\%$, and $t\bar{t}$ production $(0.11 \pm 0.03)\%$. $Z \rightarrow \tau^+\tau^-$ and $t\bar{t}$ backgrounds in the Z boson sample are negligible.

A fast Monte Carlo, tuned to collider data, was used to calculate the effects of detector resolution. As mentioned before, such effects were applied to the theoretical predictions, and the resulting *smeared* theory points are compared to the data. For the W p_T comparisons, the distributions of data and theory are normalized to unity within the region studied ($p_T < 40$ GeV/c). For the Z p_T results, both data and theory are normalized to the DØ measured total Z cross section times branching ratio [11]. Therefore, in either case, only the shapes of the p_T distributions are compared.

III. RESULTS

Figure 2 shows the preliminary W boson p_T spectrum for $p_T < 40$ GeV/c. The error bars are the sum in quadrature of the statistical and systematic uncertainties. Also shown are the (smeared) predictions from AK (solid lines) and LY (dashed lines). The two sets of lines represent the experimental uncertainties in the hadronic response and resolution. Also included in Figure 2 are (Data - Theory) / Theory plots, comparing the data to these calculations. We observe that both calculations are able to describe the shape of the W boson p_T spectrum for $p_T < 40$ GeV/c. However, the differences between the AK and LY predictions are small and occur mainly in the region $p_T < 15$ GeV/c, where they are washed out by the experimental W boson p_T resolution (~ 4 GeV/c at $p_T = 10$ GeV/c).

Figure 3 shows the preliminary Z boson p_T spectrum (circles), and the (smeared) predictions from AK (squares) and LY (triangles). The error bars on the data points are the statistical and systematic uncertainties added in quadrature. Figure 4 shows the (Data - Theory) / Theory comparisons. Because of the superior p_T resolution for Z bosons (~ 1.5 GeV/c at $p_T = 10$ GeV/c), differences between the two predictions are clearly observable, with the data prefering the LY calculation. For the comparison of data with the AK (LY) prediction, the χ^2 is 105.9 (24.4) for 20 degrees of freedom.

Using the LY calculations, we have examined the sensitivity of the Z boson p_T distribution to the non-perturbative parameter g_2. This parameter effectively introduces additional gaussian p_T smearing in the low p_T region. Fixing Λ_{QCD} and the other non-perturbative parameters g_1 and g_3 to values determined by previously published data [9], we have fit for g_2 in the region $p_T < 15$ GeV/c. We have performed this fit using various recent parton distribution functions (pdf), and find that the value of g_2 is relatively insenstive to this choice (we assign a systematic uncertainity of 0.04 to g_2 based on the largest differences observed). From this analysis, we obtain a preliminary value of $g_2 = 0.59 \pm 0.10(\mathrm{stat}) \pm 0.05(\mathrm{sys}) \pm 0.04(\mathrm{pdf})$ GeV^2. This value agrees well with the original LY determination, $g_2 = 0.58^{+0.1}_{-0.2}$ GeV^2 [9].

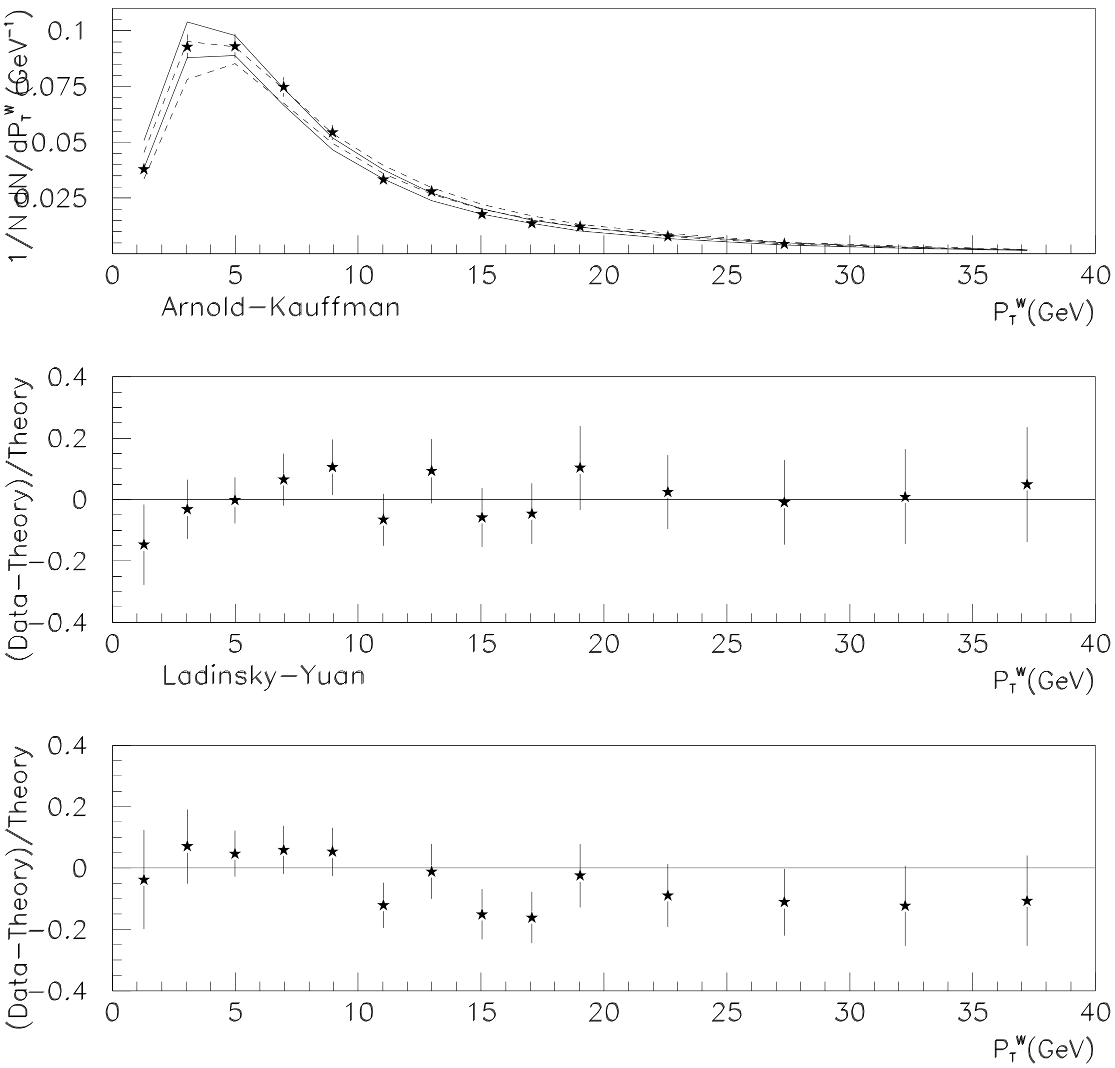

FIG. 2. The W boson p_T distributions, normalized to one, for data (points with error bars), and smeared predictions of AK (solid lines) and LY (dashed lines). Also show are (Data - Theory) / Theory plots for the two different predictions.

IV. CONCLUSIONS

We have presented preliminary measurements of the transverse momentum distributions of W and Z bosons produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV, in the region $p_T < 40$ GeV/c for the W boson and $p_T < 50$ GeV/c for the Z boson. Comparisons have been made to two predictions which include soft gluon resummation effects. While the W boson p_T spectrum does not differentiate between the two predictions, the Z boson p_T distribution prefers the Ladinsky and Yuan calculation over the one from Arnold and Kauffman. Using the Ladinsky

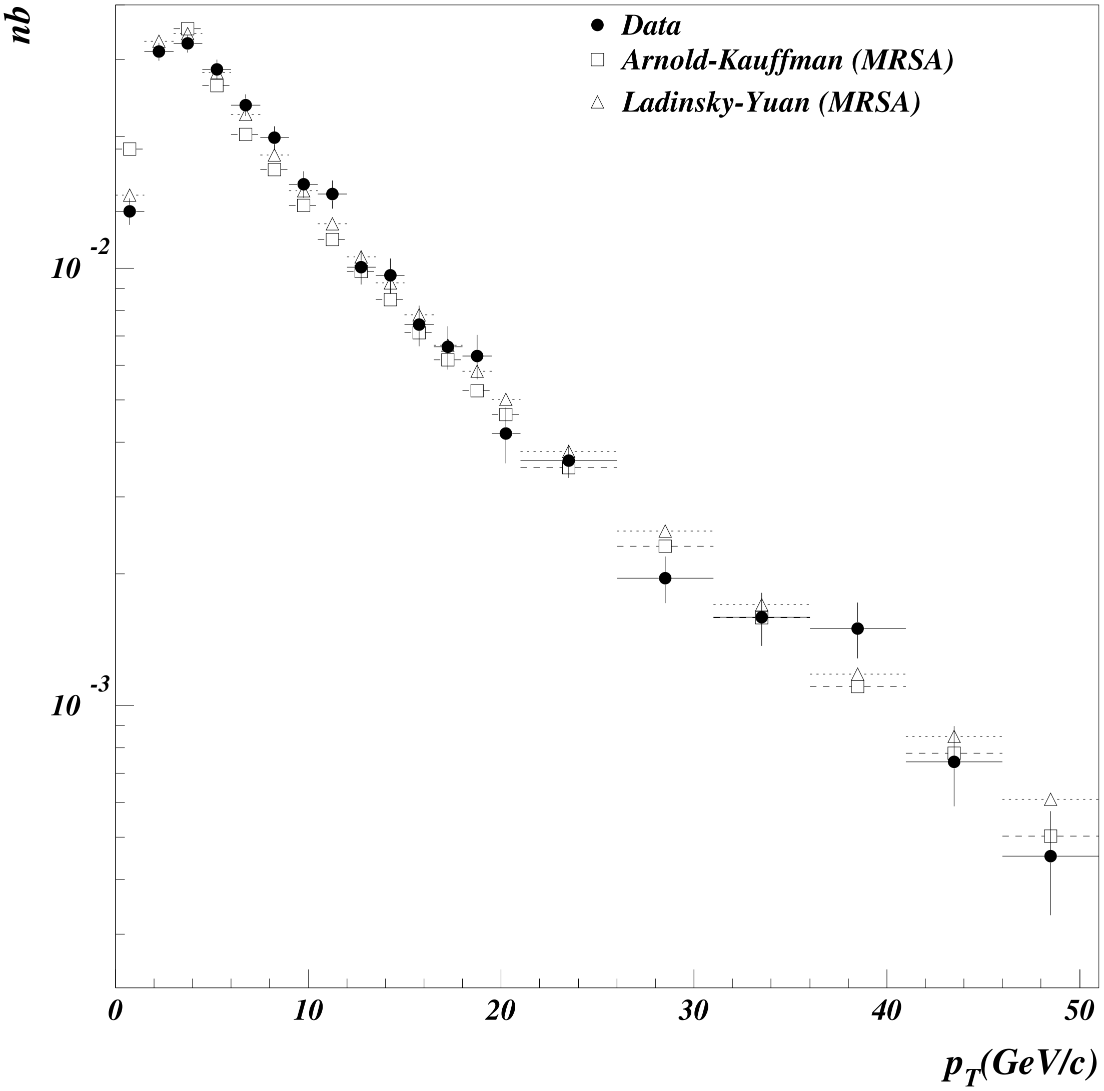

FIG. 3. Z boson p_T distribution for data (circles), and smeared AK (squares) and LY (triangles) predictions.

and Yuan formalism, we have fit the Z boson p_T distribution to obtain a preliminary value for the non-perturbative parameter $g_2 = 0.59 \pm 0.12$ GeV^2, which is in good agreement with the original Ladinsky and Yuan determination.

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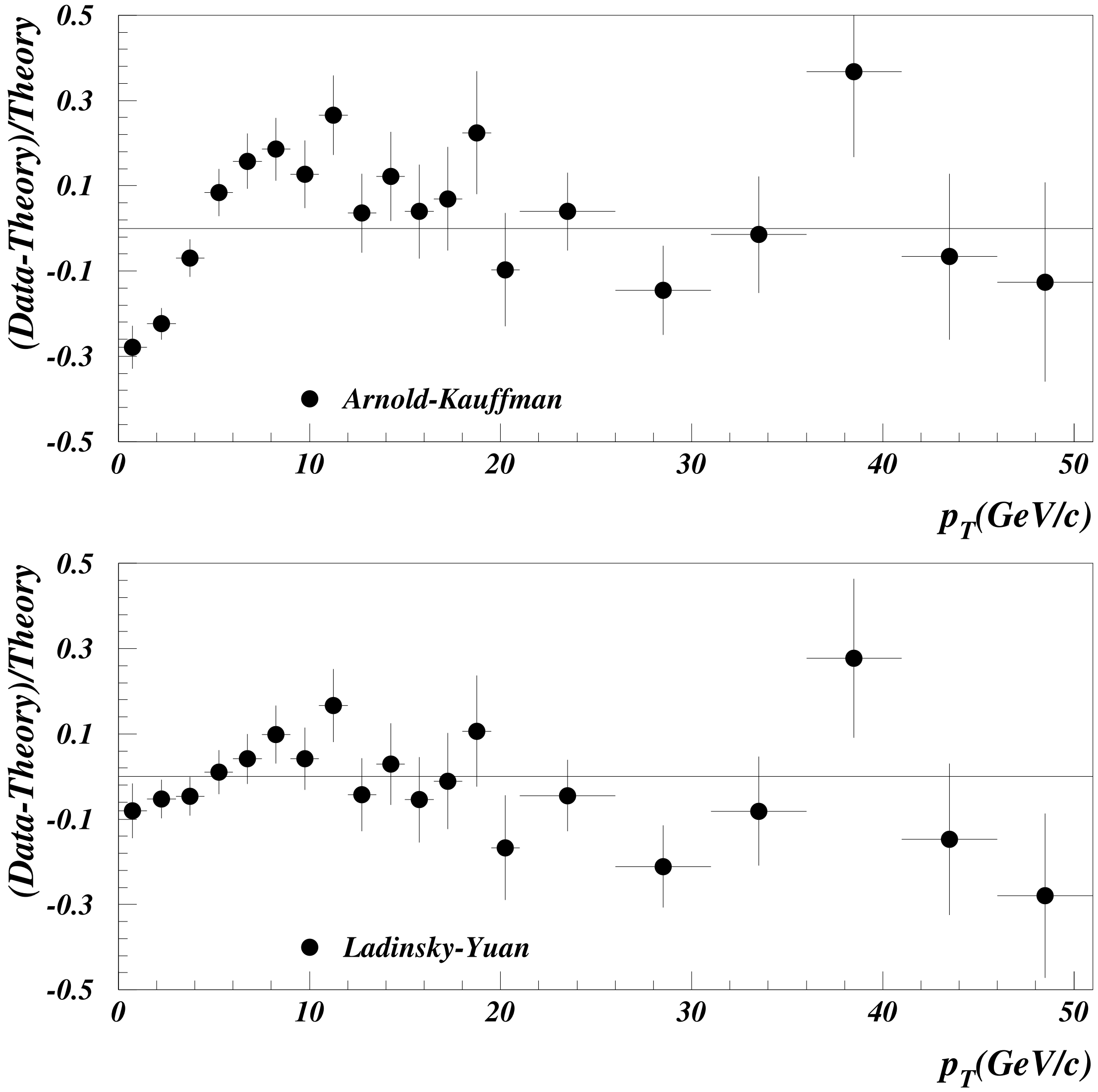

FIG. 4. (Data - Theory) / Theory comparisons between the measured Z p_T distribution and smeared AK and LY predictions.

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REFERENCES

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[1] C. Albajar *et al.*, UA1 Collaboration, Z. Phys. C **44**, 15 (1989).

[2] J. Alitti *et al.*, UA2 Collaboration, Z. Phys. C **47**, 523 (1990).

[3] F. Abe *et al.*, CDF Collaboration, Phys. Rev. Lett. **66**, 2951 (1991) and Phys. Rev. Lett. **67**, 2937 (1991).

[4] J. Collins, D. Soper and G. Sterman, Nucl. Phys. **B250**, 199 (1985); J. Collins and D. Soper, Nucl. Phys. **B193**, 381 (1981), Nucl. Phys. **B197**, 446 (1982), and erratum Nucl. Phys. **B213**, 545 (1983).

[5] C. Davies, B. Webber and W. J. Stirling, Nucl. Phys. **B256**, 413 (1985); C. Davies and W. J. Stirling, Nucl. Phys. **B244**, 337 (1984).

[6] G. Altarelli, R. K. Ellis, M. Greco and G. Martinelli, Nucl. Phys. **B246**, 12 (1984).

[7] P. B. Arnold and M. H. Reno, Nucl. Phys. **B319**, 37 (1989); R. J. Gonsalves, J. Pawlowski and C-F. Wai, Phys. Rev. D **40**, 2245 (1989).

[8] P. B. Arnold and R. Kauffman, Nucl. Phys. **B349**, 381 (1991).

[9] G. A. Ladinsky and C. P. Yuan, Phys. Rev. D **50**, 4239 (1994).

[10] S. Abachi *et al.*, DØ Collaboration, Nucl. Instrum. Methods Phys. Res. A **338**, 185 (1994).

[11] S. Abachi *et al.*, DØ Collaboration, Phys. Rev. Lett. **75**, 1456 (1995).