Measurement of the ratios of the $Z/\gamma^* + n$ jet production cross sections to the total inclusive $Z/\gamma^*$ cross section in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV


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We present a study of events with Z bosons and associated jets produced at the Fermilab Tevatron Collider in \( p\bar{p} \) collisions at a center of mass energy of 1.96 TeV. The data sample consists of nearly 14,000 \( Z/\gamma^* \rightarrow e^+e^- \) candidates corresponding to an integrated luminosity of 0.4 fb\(^{-1}\) collected with the DØ detector. Ratios of the \( Z/\gamma^* + \geq n \) jet cross sections to the total inclusive \( Z/\gamma^* \) cross
section have been measured for $n = 1$ to $4$ jets, and found to be in good agreement with a next-to-leading order QCD calculation and with a tree-level QCD prediction with parton shower simulation and hadronization.

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Leptonic decays of electroweak gauge bosons, $W^\pm$ and $Z$, produced in association with jets are prominent signatures at present and future hadron colliders. Measurements of $W$ (or $Z$) + ≥ $n$ jet cross sections are important for understanding perturbative quantum chromodynamics (QCD) calculations and for developing Monte Carlo (MC) simulation programs capable of handling partons in the final state at leading order (LO), or, in some cases, next-to-leading order (NLO). Furthermore, the production of $W$ or $Z$ bosons with associated jets represents a significant background to Higgs boson searches, as well as to other standard model processes of interest, such as top quark production, and many searches for new phenomena at the Fermilab Tevatron Collider and at the CERN Large Hadron Collider.

Measurements of $Z + ≥ n$ jet cross sections with lower integrated luminosity and at lower center of mass energy were performed previously by the CDF collaboration [1]. In this study, we present the first measurement of the fully corrected ratios of the $Z/\gamma^* + ≥ n$ jet production cross sections to the total inclusive $Z/\gamma^*$ cross section for jet multiplicities $n = 1 - 4$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. Cross section measurements based on inclusive jet multiplicities provide theoretically sound observables, and can be compared to a variety of predictions. Our results are based on a data sample corresponding to an integrated luminosity of 0.4 fb$^{-1}$ accumulated with the DØ detector.

The elements of the DØ detector [2] of primary importance to this analysis are the uranium/liquid-argon sampling calorimeter and the tracking system. The DØ calorimeter has a granularity of $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$, forming projective towers, where $\eta$ is the pseudorapidity ($\eta = -\ln[\tan(\theta/2)]$, $\theta$ is the polar angle relative to the proton beam), and $\phi$ is the azimuthal angle. The calorimeter has a central section covering pseudorapidities up to $\approx 1.1$, and two end calorimeters that extend the coverage to $|\eta| \approx 4.2$. The tracking system consists of a silicon micro-strip tracker and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities of $|\eta| < 3$ and $|\eta| < 2.5$, respectively.

The data sample for this analysis [3] was collected between April 2002 and June 2004. Events from $Z/\gamma^* \rightarrow e^+e^-$ decays were selected with a combination of single-electron triggers, based on energy deposited in calorimeter towers ($\Delta \eta \times \Delta \phi = 0.2 \times 0.2$). Final event selection was based on detector performance, event properties, and electron and jet identification criteria.

Events were required to have a reconstructed primary vertex with a position along the beam direction within 60 cm of the detector center. Electrons were reconstructed from electromagnetic (EM) clusters in the calorimeter using a simple cone algorithm. The two electron candidates in the event with the highest transverse momentum components relative to the beam direction ($p_T$), and both with $p_T > 25$ GeV, were used to reconstruct the $Z$ boson candidate. The two electrons were required to be in the central region of the calorimeter $|\eta_{\text{det}}| < 1.1$ (pseudorapidity $\eta_{\text{det}}$ is calculated relative to the center of the detector), and at least one required to fire the trigger(s) for the event. The electron pair also had to have an invariant mass consistent with the $Z$ boson mass of 75 GeV $< M_{ee} < 105$ GeV.

To reduce background (mainly from jets misidentified as electrons), the EM clusters were required to pass three quality criteria based on the shower profile: (i) the electron had to deposit at least 90% of its energy in the 21-radiation-length EM calorimeter (ii) the lateral and longitudinal shape of the energy cluster had to be consistent with those of an electron, and (iii) the electron had to be isolated from other energy deposits in the calorimeter, with an isolation fraction $f_{\text{iso}} < 0.15$. (The isolation fraction is defined as $f_{\text{iso}} = (E(0.4) - E_{\text{EM}}(0.2))/E_{\text{EM}}(0.2)$, where $E(R_{\text{cone}})$ and $E_{\text{EM}}(R_{\text{cone}})$ are respectively the total and EM energies within a cone of radius $R_{\text{cone}} = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ centered around the direction of the electron.) Additionally, at least one of the electrons was required to have a spatially matched track associated with the reconstructed calorimeter cluster, and the track momentum had to be consistent with the energy of the EM cluster. A total of 13,893 events passed the selection criteria.

Jets were reconstructed using the “Run II cone algorithm” [4] that combines particles within a cone of radius $R_{\text{cone}} = 0.5$. Spurious jets from isolated noisy calorimeter cells were eliminated through selections on patterns of jet energy deposition. Jets were required to be consistent with energy depositions measured at the trigger stage. This requirement was introduced to address precision readout noise problems: The jet energy at the Level 1 trigger tower level was compared to the jet energy derived from the jet cone algorithm, which was based on calorimeter cell precision readout. The transverse momentum of each jet was corrected for multiple $p\bar{p}$ interactions, calorimeter noise, out-of-cone showering effects, and energy response of the calorimeter as determined from the missing transverse energy balance of photon–jet events [5]. Jets were required to have
The cross sections as a function of jet multiplicity were corrected for jet reconstruction and identification efficiencies, and for event migration due to the finite jet energy resolution of the detector. The correction factors were determined using two independent MC sam-
TABLE I: Cross-section ratios ($R_n$) with statistical and systematic uncertainties (all $\times 10^{-3}$) for different inclusive jet multiplicities.

<table>
<thead>
<tr>
<th>Multiplicity ($Z/\gamma^* + \geq n$ jets)</th>
<th>$n \geq 1$</th>
<th>$n \geq 2$</th>
<th>$n \geq 3$</th>
<th>$n \geq 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_n$</td>
<td>120.1</td>
<td>18.6</td>
<td>2.8</td>
<td>0.90</td>
</tr>
<tr>
<td>Total Statistical Uncertainty</td>
<td>$\pm 3.3$</td>
<td>$\pm 1.4$</td>
<td>$\pm 0.56$</td>
<td>$\pm 0.44$</td>
</tr>
<tr>
<td>Total Systematic Uncertainty</td>
<td>$-17.1, +15.6$</td>
<td>$-5.0, +6.2$</td>
<td>$-1.06, +1.43$</td>
<td>$-0.40, +0.48$</td>
</tr>
<tr>
<td>Jet Energy Calibration</td>
<td>$\pm 11.7$</td>
<td>$\pm 3.3$</td>
<td>$\pm 0.74$</td>
<td>$\pm 0.23$</td>
</tr>
<tr>
<td>Jet Reconstruction/Identification</td>
<td>$-7.0, +2.2$</td>
<td>$-2.9, +4.3$</td>
<td>$-0.64, +0.82$</td>
<td>$-0.30, +0.40$</td>
</tr>
<tr>
<td>Unsmearing Procedure</td>
<td>$-3.6, +2.2$</td>
<td>$-1.6, +2.4$</td>
<td>$-0.24, +0.85$</td>
<td>$-0.08, +0.09$</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>$-2.7, +3.4$</td>
<td>$-0.04, +0.13$</td>
<td>$-0.17, +0.15$</td>
<td>$-0.03, +0.04$</td>
</tr>
<tr>
<td>Acceptance</td>
<td>$\pm 1.8$</td>
<td>$\pm 0.7$</td>
<td>$\pm 0.10$</td>
<td>$\pm 0.003$</td>
</tr>
<tr>
<td>Efficiencies (Trigger, EM, Track)</td>
<td>$\pm 8.5$</td>
<td>$\pm 1.3$</td>
<td>$\pm 0.20$</td>
<td>$\pm 0.07$</td>
</tr>
<tr>
<td>Electron-Jet-Overlap</td>
<td>$\pm 3.2$</td>
<td>$\pm 0.7$</td>
<td>$\pm 0.14$</td>
<td>$\pm 0.05$</td>
</tr>
</tbody>
</table>

Figure 1: Ratios of the $Z/\gamma^* + \geq n$ jet cross sections to the total inclusive $Z/\gamma^*$ cross section versus jet multiplicity. The uncertainties on the data (dark circles) include the combined statistical and systematic uncertainties added in quadrature. The dashed line represents predictions of LO Matrix Element (ME) calculations using PYTHIA for parton showering (PS) and hadronization, normalized to the measured $Z/\gamma^* + \geq 1$ jet cross-section ratio. The dotted line represents the predictions of PYTHIA normalized to the measured $Z/\gamma^* + \geq 1$ jet cross-section ratio. The two open diamonds represent predictions from MCFM.

The fully corrected ratios, $R_n$, of the $Z/\gamma^* + \geq n$ jet production cross sections to the inclusive $Z/\gamma^*$ cross section

$$R_n = \frac{\sigma(Z/\gamma^* + \geq n \text{ jets})}{\sigma(Z/\gamma^*)}$$

for the mass region $75 \text{ GeV} < M_{ee} < 105 \text{ GeV}$ are summarized in Table I. Systematic uncertainties include contributions from jet energy calibration corrections, jet reconstruction and identification efficiency, the unsmearing procedure, jet energy resolution, and variations in the acceptance for different event generators. They also take into account uncertainties in the variation of efficiencies for the trigger, electron reconstruction, identification, and track matching as a function of jet multiplicity, as well as uncertainties due to the electron-jet overlap correction. All these uncertainties are assumed to be uncorrelated, and are added in quadrature to estimate the total systematic uncertainty. The statistical uncertainties include contributions from the number of candidate events, background estimation, acceptance, efficiencies, and the unsmearing correction.

Figure 1 shows the fully corrected measured cross-section ratios for $Z/\gamma^* + \geq n$ jets as a function of jet multiplicity, compared to three QCD predictions.
MC 

is a NLO calculation for up to $Z/\gamma^* + 2$ parton processes. CTEQ6M \cite{13} parton distribution functions (PDF) were used in MC, and the factorization and renormalization scales $\mu_F$, $\mu_R$ were both set to the $Z$ boson mass, $M_Z$. Varying the PDF set and the renormalization/factorization scales to $M_Z^2 + p_T^2_{Z,2}$ had a minimal effect on the MC cross-section ratios. The ME-PS predictions are normalized to the measured $Z/\gamma^* + 1$ jet cross-section ratio, and use the CTEQ6L PDF, with the factorization scale set to $\mu_F = M_Z$, and the renormalization scale set to $\mu_R = p_T^{jet}$ for jets from initial state radiation and $\mu_R = k_T^{jet}$ for jets from final state radiation ($k_T^{jet}$ is the transverse momentum of a radiated jet relative to its parent parton momentum). The PYTHIA predictions are also normalized to the measured $Z/\gamma^* + 1$ jet cross-section ratio. Here, CTEQ5L PDFs are used, and the factorization and renormalization scales are set to $\mu_F = \mu_R = M_Z$. The MCFM and ME-PS predictions are generally in good agreement with the data. PYTHIA predicts fewer events at high jet multiplicity because of missing higher order contributions at the hard-scatter level.

Figure 2 compares jet $p_T$ spectra of the $n^\text{th}$ jet, $n = 1, 2, 3$, in $Z/\gamma^* + n$ jet events to the ME-PS MC predictions. The MC events have been passed through the full detector simulation, and the jet $p_T$ spectra normalized separately to the data distributions. Good agreement can be seen over a wide range of jet transverse momenta.

In summary, we have presented the first measurements of fully corrected ratios of the $Z/\gamma^* + n$ jet ($n = 1 - 4$) production cross sections to the total inclusive $Z/\gamma^*$ cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The measured ratios were found to be in good agreement with MCFM and an enhanced leading-order matrix element prediction with PYTHIA-simulated parton showering and hadronization. PYTHIA simulations alone appear to exhibit a deficit in high jet multiplicity events.

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