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Measurement of the Ratio of the $Z/\gamma^*(e^+e^-)+\geq n$ Jet Production Cross Sections to the Total Inclusive $Z/\gamma^* \to e^+e^-$ Cross Section in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present a study of events with Z bosons and hadronic jets produced at the Tevatron in $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV. The data sample consist of $\approx 14,000$ $Z/\gamma^* \to e^+e^-$ decay candidates from 343 pb^{-1} of integrated luminosity collected using the DØ detector. Ratios of the $Z/\gamma^*(e^+e^-)+\geq n$ jet cross sections to the total inclusive $Z/\gamma^* \to e^+e^-$ cross section has been measured for $Z/\gamma^*+\geq 1$ to 5 jet events. We find our results to be in good agreement with QCD predictions.

Preliminary Results for Spring 2005 Conferences

The signatures of the leptonic decays of the electroweak gauge bosons, $W^{\pm}$ and Z, in association with jets is one of the most prominent processes at hadron colliders. The measurements of $W/Z+\geq n$ jet cross sections are important for studying the perturbative quantum chromodynamics (QCD) calculations and the Monte Carlo (MC) simulation programs capable of handling more particles in the final state at leading order (LO), or in some cases, next- to-leading order (NLO). Furthermore, the associated production of W/Z bosons with jets represents a serious background to other interesting physics processes within or beyond the Standard Model (SM). For example, the most promising modes for a light Higgs discovery at the Tevatron are those where the Higgs is produced in association with a vector boson $(W/Z)H$ with $(W/Z) \rightarrow$ leptons and $H \rightarrow b\bar{b}$; the W+3/4 jets channel in which at least one jet was identified as a b-quark is important to the top-quark studies; many extensions of the SM predict new particles which decay into SM gauge bosons and accompanied by jets.

In this study we present the first measurement of the ratio of the $Z/\gamma^*(e^+e^-)+\geq n$ jet production cross section to the total inclusive $Z/\gamma^* \rightarrow e^+e^-$ cross section for the jet multiplicities $n \geq 1-5$ jets in $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions using a 343 pb^{-1} data sample accumulated by the DØ detector.

The elements of the DØ upgrade detector[1] of primary importance to this analysis are the tracking system and the uranium/liquid-argon sampling calorimeter. The DØ calorimeter has a transverse granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ forming projective towers, where η is the pseudorapidity ($\eta = -\ln[\tan(\theta/2)]$, θ is the polar angle with respect to the proton beam), and ϕ is the azimuthal angle. The calorimeter has a central section covering pseudorapidities up to ≈ 1.1, and two end calorimeters that extend coverage to $|\eta| \approx 4.2$. The tracking system consists of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively.

The data sample for this analysis was collected during the April 2002 and June 2004 Tevatron Collider run. Events from $Z/\gamma^* \rightarrow e^+e^-$ decays were selected on line 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 off-line event selection was based on run quality, event properties, electron, and jet criteria.

In the off-line analysis events were required to have a measured vertex with longitudinal position within 60 cm of the detector center. Electrons were reconstructed from electromagnetic (EM) clusters in the calorimeter using a simple cone algorithm. The two highest-E_T electron candidates in the event, both having transverse energy $E_T > 25$ GeV, were used to reconstruct the Z boson candidate. Both electrons were required to be in the central region of the calorimeter $|\eta_{det}| < 1.1$ with at least one of them to fire the trigger(s) for the event. The electron pair was required to have an invariant mass near the world average Z boson mass, 75 GeV $< M_{ee} <$ 105 GeV.

To reduce background contamination, mainly from jets faking electrons, the EM clusters were required to pass three quality criteria based on shower profile: (i) the ratio of the EM energy to the total shower energy had to be greater than 0.9, (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 isolation fraction $f_{\rm iso} < 0.15$. The isolation fraction is defined as $f_{\rm iso} = [E(0.4) - E_{\rm EM}(0.2)]/E_{\rm EM}(0.2)$, where $E(R_{\rm cone})$ ($E_{\rm EM}(R_{\rm cone})$) is the total (EM) energy within a cone of radius $R_{\rm cone} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ centered around the electron. Additionally, at least one of the electrons was required to have a track matched spatially to it and the track transverse momentum had to be close to the transverse energy of the EM cluster. A total of 13,893 candidates passed the above selection criteria.

Jets in the events were reconstructed off line using the "Run II cone algorithm" [2] which combines particles within a cone of radius $R_{\rm cone} = 0.5$. Spurious jets from isolated noisy calorimeter cells were eliminated by cuts on the jet shape. The transverse momentum, p_T, of each jet was corrected for offsets due to the underlying event, multiple $p\bar{p}$ interactions, and noise; out–of–cone showering; and detector energy response as determined from the missing transverse energy balance of photon–jets events. Jets were required to have $p_T > 20$ GeV and $|\eta| < 2.5$. Jets were eliminated if overlapped with the electrons coming from the Z boson within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$. Jet losses due to this separation cut from the Z boson electrons were estimated as a function of the number of associated jets using a Z+jet PYTHIA[3] MC sample.

The efficiencies for trigger, electron track-match, reconstruction and identification were determined from data based on a "tag-and-probe" method. Z candidates were selected with one tight electron (tag) and another electron (probe) with all other cuts applied except the one under study. The fraction of events with the probe electron passing the requirement under study determines the efficiency of a given cut. The overall trigger efficiency for Z candidates was found to be $> 99\%$. The electron reconstruction and identification efficiencies were measured as a function of azimuth angle and p_T, and the overall average efficiency was found to be $\approx 79\%$. The overall track-match efficiency was measured to be $\approx 95\%$. The average electron reconstruction, selection, trigger, and track-match efficiencies were examined as a function of jet multiplicity. No significant variations of the efficiencies were observed, except for the track-match efficiency where adjustments were made to accommodate its multiplicity dependance.

The kinematic and detector geometric acceptance for electrons from Z/γ^* decays in the mass region of 75 GeV $< M_{ee} <$ 105 GeV was measured as a function of jet multiplicity. For the acceptance calculation of the inclusive

TABLE I: Cross section ratios with statistical and systematic uncertainties for different inclusive jet multiplicities.

Multiplicity (≥n jets)	$R_n = \frac{\sigma_n}{\sigma_0}$ [$\times10^{-3}$]	Statistical Uncertainty [$\times10^{-3}$]	Systematic Uncertainty [$\times10^{-3}$]
1	119.1	±3.3	+17.2 / -16.2
2	18.1	±1.3	+4.5 / -4.3
3	2.6	±0.52	+0.90 / -0.89
4	0.61	±0.28	+0.29 / -0.27
5	0.42	±0.30	+0.42 / -0.24

Z/γ^* sample an inclusive PYTHIA MC sample was used. The inclusive PYTHIA events were weighted so that the MC p_{TZ} distribution agreed with the data. For the jet-multiplicity dependence of the acceptance measurement the ALPGEN[4] $Z + n$ leading-order parton generator was used, with the evolution of partons into hadrons carried out by PYTHIA. This procedure represents a partial higher-order correction to tree-level diagrams. All MC samples were processed through full detector simulation.

The reconstruction and identification efficiency of jets was determined from a data-tuned PYTHIA MC sample with full detector simulation. A scaling factor was applied to the MC jets to adjust their reconstruction and identification efficiency to that of data jets as compared using the "Z p_T-balance" method. The Z p_T-balance method relies on the recoil of a jet against the Z boson. Events were selected with Z candidates and searched for a recoiling jet opposite to the Z boson in azimuth. The probability of finding a recoiling jet as a function of the Z p_T was measured in data and MC. The ratio of these probabilities in data and MC defines the scaling factor that was applied to the MC events. After applying the scale factor the reconstruction and identification jet efficiency was measured by matching particle (i.e. hadron) level jets to calorimeter jets. The efficiency was parametrized as a function of particle jet p_T, where the p_T values were smeared with the data energy resolutions.

The main source of background to the Z/γ^* signal comes from QCD events and it was estimated for each jet multiplicity. For the $Z/\gamma^* + \geq 0-2$ jet samples a convoluted Gaussian and Breit-Wigner function was fitted to the Z resonance, assuming an exponential shape for both the QCD background and the Drell-Yan component of the signal. In case of the $Z/\gamma^* + \geq 3$ jet sample the size of the QCD and Drell-Yan components was estimated based on the sidebands of the di-em invariant mass spectrum. In each case an inclusive Z/γ^* PYTHIA MC was used to disentangle the QCD component from the Drell-Yan contribution. The background contributions for higher jet multiplicity samples were estimated by extrapolating an exponential fit to the QCD background of the $0-3$ jet multiplicity bins.

The measured $Z/\gamma^* + \geq n$ jet production cross sections are normalized with respect to the inclusive Z/γ^* cross section for the mass region 75 GeV $< M_{ee} <$ 105 GeV.

$$R_n = \frac{\sigma_n}{\sigma_0} = \frac{\sigma(Z/\gamma^* \to e^+e^-) + \geq n\text{jets}}{\sigma_{Z/\gamma^*}} \quad (1)$$

The cross section ratios as a function of jet multiplicity were corrected for jet reconstruction and identification efficiencies, and migrations due to the finite p_T resolution of the detector.

Table I summarizes the cross section ratios for the $Z/\gamma^* + \geq 1$ to 5 jet samples. Systematic uncertainties include variations in the jet energy scale, jet reconstruction and identification efficiency, electron-jet overlap correction, and jet energy resolution. They also take into account uncertainties in the variation of efficiencies for trigger, electron reconstruction, identification, and track matching as a function of jet multiplicity. The statistical uncertainties include contributions from the number of candidate events, background estimation, acceptance, efficiencies, and unsmearing correction.

Figure 1 shows the measured cross section ratios for $Z/\gamma^* + \geq n$ jets as a function of n, with two QCD predictions. MCFM is a NLO calculation including up to $Z + 2$ parton processes. The CKKW theory is based on MADGRAPH $Z + n$ parton LO predictions using PYTHIA for parton showering and hadronization, and the CKKW method to map the $Z + n$ parton event into a parton shower history. The CKKW predictions were produced with MADGRAPH three level processes up to 3 partons, and have been normalized to our measured $Z/\gamma^* + \geq 1$ jet cross section ratio. Both predictions agree well with our data.

Figure 2 compares jet p_T spectra of the n^{th} jet in $Z/\gamma^* + \geq n$ jet events to MC predictions based on ALPGEN $Z + n$ LO partonic predictions using PYTHIA for parton showering and hadronization. The MC events have been passed through full detector simulation. Reasonable agreement can been seen over a wide range of jet transverse momenta.

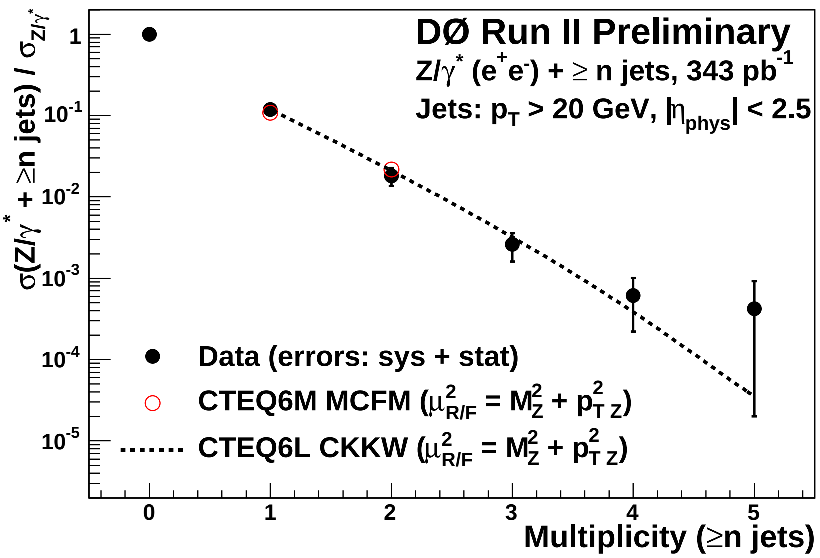

FIG. 1: Cross section ratios in data with total errors compared with theoretical predictions.

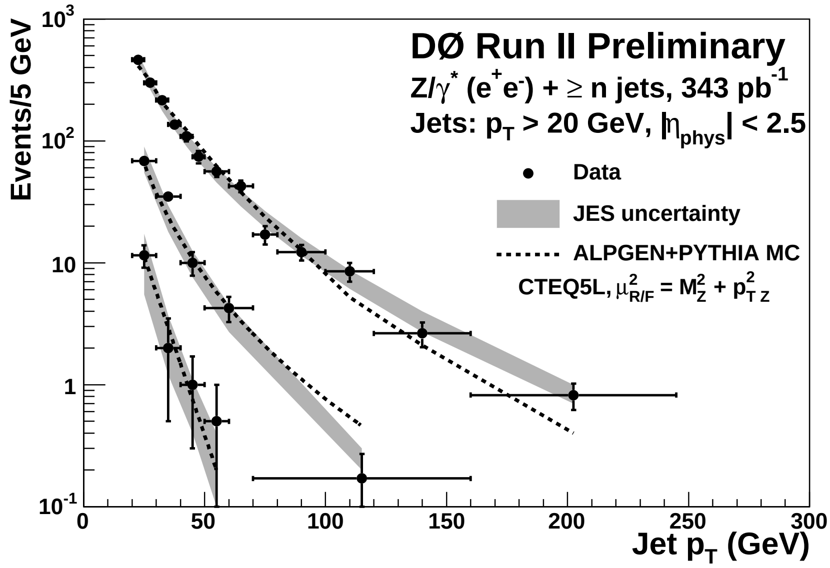

FIG. 2: Data to theory (ALPGEN+PYTHIA) comparison for the highest p_T jet distribution in the $Z+\geq 1$ jet sample, for the second highest p_T jet distribution in the $Z+\geq 2$ jet sample and for the third highest p_T jet distribution in the $Z+\geq 3$ jet sample. The gray band shows the uncertainty due to the jet energy scale.

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