Measurement of the ratio of the $p\bar{p} \to W+c$-jet cross section to the inclusive $p\bar{p} \to W+jets$ cross section

We present a measurement of the fraction of inclusive $W$+jets events produced with net charm quantum number $\pm 1$, denoted $W+c$-jet, in $pp$ collisions at $\sqrt{s} = 1.96$ TeV using approximately 1 fb$^{-1}$ of data collected by the D0 detector at the Fermilab Tevatron Collider. We identify the $W$+jets events via the leptonic $W$ boson decays. Candidate $W+c$-jet events are selected by requiring a jet containing a muon in association with a reconstructed $W$ boson and exploiting the charge correlation between this muon and $W$ boson decay lepton to perform a nearly model-independent background...
In hadron-hadron collisions, the $W/Z+b$- or $c$-jet final state can signal the presence of new physics; however, only a few measurements \([1, 2, 3]\) of cross sections for these standard model processes exist. Charm quark production in association with a $W$ boson can be a significant background, for example, to top quark pair, single top quark and Higgs boson productions, and to supersymmetric top quark (stop) pair production when only the $t \to c x^3_1$ decay channel is allowed by the mass difference between the stop quark and the neutralino. Moreover, as the squared Cabibo-Kobayashi-Maskawa matrix element, $|V_{cd}|^2$, suppresses the expected leading order $d$ quark-gluon fusion production mechanism, $W+c$-quark production provides direct sensitivity to the proton’s $s$ quark parton distribution function (PDF), $s(x,Q^2)$, where $x$ is the momentum fraction of the proton carried by the $s$-quark and $\sqrt{Q^2}$ is the hard scatter scale. This PDF has been measured directly only in fixed target neutrino-nucleon deep inelastic scattering experiments using relatively low momentum transfer squared, $Q^2$, of the order $1 - 100 \text{ GeV}^2$. A probe of the $s$ quark PDF at the Tevatron tests the universality of $s(x,Q^2)$ and its QCD evolution up to $Q^2 = 10^4 \text{ GeV}^2$. The strange quark PDF initiates both standard model (e.g., $s g \to W^- +c$) and possible new physics processes (e.g., $s c \to H^-$) at both the Fermilab Tevatron and CERN LHC colliders. In this Letter, we present a measurement of the cross section ratio $\sigma(p\bar{p} \to W+c\text{-jet}) / \sigma(p\bar{p} \to W+jets)$ as a function of jet transverse momentum $p_T$, where $W+c$-jet denotes a $W$ boson plus jets final state in which the jets have a net charm quantum number $C = \pm 1$, and $W+jets$ denotes any $W$ boson final state with at least one jet. Several experimental uncertainties (e.g., luminosity, jet energy scale, and reconstruction efficiency) and theoretical uncertainties (e.g., renormalization and factorization scales) largely cancel in this ratio. This measurement utilizes approximately 1 fb$^{-1}$ of $p\bar{p}$ collision data at a center-of-mass energy $\sqrt{s} = 1.96 \text{ TeV}$ collected with the D0 detector at the Fermilab Tevatron collider. We identify $W$ bosons through their leptonic decays, $W \to \ell \nu$, where $\ell = e, \mu$. $W$ bosons decaying to tau leptons are included for leptonic tau decays $\tau \to e \nu_{\tau} \nu_{\tau}$ or $\tau \to \mu \nu_{\tau} \nu_{\tau}$. The electron or muon from $W$ boson decays are required to be isolated, and their transverse momentum $p_T$ must satisfy $p_T > 20 \text{ GeV}$. The presence of a neutrino is inferred from the requirement that the missing transverse energy $E_T$ satisfies $E_T > 20 \text{ GeV}$. Jets are defined using the iterative seed-based midpoint cone algorithm \([4]\) with cone radius of 0.5. We restrict the transverse momentum of the jet to $p_T > 20 \text{ GeV}$ after it is calibrated for the calorimeter jet energy scale (JES), and its pseudorapidity to $|\eta| < 2.5$, where $\eta = -\ln [\tan (\theta/2)]$ and $\theta$ is the polar angle with respect to the proton beam direction. We correct the jet measurement to the particle level \([5]\) for comparison with theory. A muon reconstructed within a jet (a “jet-muon”) identifies that jet (“$\mu$-tagged jet”) as a charm quark candidate. Events containing a jet-muon enrich a sample in $b/c$ semileptonic decays. Events with the jet-muon’s charge opposite to or equal to that of the $W$ boson are denoted as “OS” or “SS” events, respectively. In the $W+c$-jet process, the charm quark decays into a muon carrying an opposite-sign charge compared to that carried by the $W$ boson, and the numbers of OS and SS events, $N_{OS}$ and $N_{SS}$, respectively, satisfy $N_{OS} \gg N_{SS}$. In the $W+c$-jet sample, $N_{SS}$ can be zero because a jet initiated by a $c$ quark has a small probability of containing a muon from the decay of particles other than the leading charm quark. Other vector boson+jets physics processes ($W+g$, $W+c\bar{c}$, $W+b\bar{b}$, $Z+jets$) can produce $\mu$-tagged jets, but the charge of the jet-muon is uncorrelated with that of the boson, hence $N_{OS} \approx N_{SS}$ for these sources. Processes with light-quark ($u$, $d$ or $s$) initiated jets recoiling against the $W$ boson can produce a small fraction of charge-correlated $\mu$-tagged jets owing to leading particle effects \([6]\). Background from $WW$ production contributes only a small amount to the signal sample. The $WZ$ and $ZZ$ processes only rarely produce charge-correlated jets. Other final states that can produce charge-correlated jets ($t\bar{t}$, $tb$, $W+b\bar{c}$ and $W+b$) are suppressed by small production cross sections or tiny CKM matrix elements. These considerations allow a measurement of the $W+c$-jet production rate from OS events with the backgrounds determined in situ from SS events, up to small weakly model-dependent theory corrections. The D0 detector \([7]\) is a multi-purpose device built to investigate $p\bar{p}$ collisions. The innermost silicon microstrip detectors followed by the scintillating fiber tracking detector, covering pseudorapidity $|\eta| \lesssim 3.0$ and located inside the 2 T superconducting solenoid, are used for tracking and vertexing. The liquid-argon and uranium calorimeter, a finely segmented detector in the
transverse and the longitudinal directions, is used as the primary tool to reconstruct electrons, jets, and the missing transverse energy. It is housed in three cryostats, one central calorimeter in the region $|\eta| < 1.1$ and two end caps extending the coverage to $|\eta| \approx 4.0$. The outermost subsystem of the D0 detector is the muon spectrometer, consisting of three layers of muon tracking subdetectors and scintillation trigger counters, which is used to construct muons up to $|\eta| \approx 2.0$. The first layer is situated before the 1.8 T iron toroid and the other two layers are outside, enclosing the detector.

Candidate events in the electron (muon) decay channel of the $W$ boson must pass at least one of the single electron (muon) three-level (L1, L2 and L3) triggers used in each data taking period. Each level of trigger imposes tighter restrictions on the events compared to those of the preceding level. The single muon triggers at L1 impose hit requirements in the muon scintillators. Some of the triggers also require spatially matched hits in the muon tracking detectors. The conditions at L2 require a reconstructed muon with $p_T$ above a threshold in the range $0 - 5 \text{ GeV}$ for various triggers. At L3, certain triggers require a track reconstructed in the inner tracking system with $p_T > 10 \text{ GeV}$. The ratio measurement benefits from full cancellation of the trigger efficiency in the electron channel. This cancellation is partial in the muon channel due to the presence of two muons in the $W+c$-jet sample.

Selection of $W \rightarrow e\nu$ candidates begins with the requirement that a cluster of energy be found that is consistent with the presence of an electron in the calorimeter. The cluster must: have at least 90% of its energy contained in the electromagnetic part of the calorimeter; have a reconstructed muon pointing to it; be isolated from other clusters in the calorimeter; and have an azimuthal angular separation between the isolated electron and $E_T$ greater than 0.4. Events containing at least one jet with $p_T > 20 \text{ GeV}$ after the calorimeter JES correction is applied, and $|\eta| < 2.5$. Upon application of all selection criteria, $N^e_W$ and $N^\mu_W$ are obtained from a large data sample using a “matrix method” consisting of the following two steps: first, “loose” $W(\rightarrow \ell\nu)+\text{jets}$ datasets are selected through application of all previously described selection criteria in each channel with the exception that the lepton isolation requirements are relaxed. This produces a set of loose candidate events, $N'_W$, in each lepton channel consisting of a mixture of real $W+$jets events, $N^L_W$, and multi-jet background events, $N^\mu_{MJ}$, with $N^e_{L} = N^e_W + N^\mu_{MJ}$. Application of the stricter lepton isolation criteria used to extract the signal changes this mixture to $N^e_{L} = \epsilon^e_{W} N^\ell_{W} + \epsilon^\mu_{MJ} N^\mu_{MJ}$, where $N^\ell_{W}$ signifies the number of events in each channel satisfying the tighter isolation criteria and $\epsilon^e_{W}$ and $\epsilon^\mu_{MJ}$ denote the relative probabilities for loosely selected $W$ boson and multi-jet events, respectively, to satisfy the stricter isolation criteria. A large sample of two-jet events is used to measure $\epsilon^\mu_{MJ}$, and $\epsilon^\mu_{MJ}$ is estimated from a similar two-jet dataset using a sample of back-to-back muon-plus-jet events with low $E_T$. The factors $\epsilon^e_{W}$ are obtained from a large data sample of $Z \rightarrow \ell^+\ell^-$ events. Solving the equations for $N^\ell_{W}$ and $N^\mu_{MJ}$ yields estimates for the fractional contributions of multi-jet background to the inclusive $W+$jets signal of $f^\mu_{MJ} = (3.2 \pm 0.8)\%$ in the electron channel and $f^e_{MJ} = (4.1 \pm 3.0)\%$ in the muon channel.

The channel $Z(\rightarrow \ell^+\ell^-)+\text{jets}$ contributes as background when one of the leptons from the $Z$ boson decay fails to be reconstructed. An estimate of this background follows from MC simulations of $Z+$jets production produced with ALPGEN V2.05 [17] using the CTEQ6L [18] PDF set, the PYTHIA v6.323 [19] generator for the parton fragmentation and hadronization, the MLM prescri-
drawn with the 

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to avoid an over-counting of final state jets, and evtgen [21] to decay the heavy hadrons. A GEANT [22] based program simulates the effects of detector response, and the same reconstruction software is employed as used for data. This procedure results in estimates for the fractional contaminations of $f_Z^e = (0.9 \pm 0.1\%)$ for $Z\rightarrow e^+e^-$+jets and $f_W^e = (5.0 \pm 0.7\%)$ for $Z\rightarrow \mu^+\mu^-$+jets. Quoted uncertainties derive mainly from systematic effects in the $Z$+jets ALPGEN cross section model that are estimated by varying the relative cross section of $W$+jets with respect to $Z$+jets by its uncertainties.

Extraction of samples of $W$+c-jet event candidates from the $W$+jets samples follows from selecting events with a $\mu$-tagged jet. This jet must contain a reconstructed muon with $p_T > 4$ GeV and $|\eta| < 2.0$ that lies within a cone of $\Delta R(\mu, \text{jet}) < 0.5$ with respect to the jet axis, and have JES corrected $p_T > 20$ GeV before including the muon and neutrino energies. The muon must be detected in both of the outer two layers of the muon spectrometer, and its muon spectrometer track must be matched to a reconstructed track in the central tracker. Background suppression of $Z(\rightarrow \mu^+\mu^-)$+jets events entails rejecting events in which the dimuon invariant mass exceeds 70 GeV in the muon channel without restricting the charges of the muons. Application of all selection criteria yields $N^v_{\text{OS}}$ and $N^v_{\text{SS}}$ events in the electron channel, and $N^e_{\text{OS}}$ and $N^e_{\text{SS}}$ events in the muon channel as reported in Table I. Estimated multi-jet backgrounds in the $\mu$-tagged jet data samples determined following the matrix method are $N^{c,\text{MJ}}_{\text{OS}}$ and $N^{c,\text{MJ}}_{\text{SS}}$ events in the electron channel, and $N^{\mu,\text{MJ}}_{\text{OS}}$ and $N^{\mu,\text{MJ}}_{\text{SS}}$ events in the muon channel as listed in Table I. Estimates of the $WW$, $t\bar{t}$ and single top background from MC are denoted $N^{c,WW}_{\text{OS}}$, $N^{c,WW}_{\text{SS}}$, $N^{c,t\bar{t}}_{\text{OS}}$, $N^{c,t\bar{t}}_{\text{SS}}$, $N^{\mu,t\bar{t}}_{\text{OS}}$, $N^{\mu,t\bar{t}}_{\text{SS}}$, $N^{\mu,\text{tbb}}_{\text{OS}}$ and $N^{\mu,\text{tbb}}_{\text{SS}}$ events, respectively, in the electron channel, and $N^{\mu,WW}_{\text{OS}}$, $N^{\mu,WW}_{\text{SS}}$, $N^{\mu,t\bar{t}}_{\text{OS}}$, $N^{\mu,t\bar{t}}_{\text{SS}}$, $N^{\mu,\text{tbb}}_{\text{OS}}$ and $N^{\mu,\text{tbb}}_{\text{SS}}$ events, respectively, in the muon channel as given in Table I. The estimate of the single top background follows from the $t\bar{b}$ and $tbq$ events produced with the COMPEP [23] generator followed by full detector simulation. The quoted uncertainties on the $WW$, $t\bar{t}$ and single top background predictions given in Table I are dominated by the uncertainties in their cross section measurements [24, 25, 26]. Lepton charges are well measured at D0, and uncertainties from charge mis-identification are very small.

The acceptance times efficiencies, $c_c^\ell(\ell = e, \mu)$, of the $W$+c-jet selections relative to inclusive $W$+jets in each $W$ boson decay channel is estimated from the MC simulation, and includes MC to data correction factors estimated using independent data calibration samples. The absolute efficiency of reconstructing a $W$ boson with at least one jet cancels in the ratio. The relative acceptance includes effects of charm quark to hadron fragmentation, charmed hadron semi-muonic decay and the residual missing calorimeter energy from the muon and neutrino in the $\mu$-tagged jet. The relative efficiency accounts for muon identification and track reconstruction effects. Charm quark fragmentation and charm hadron decay uncertainties are constrained by previous experiments [27, 28] and contribute 4.5% and 9.5%, respectively, to the acceptance uncertainties in both channels.

The correction included in the acceptance for the missing contribution to the jet $p_T$ from the muon and neutrino energies adjusts the jet $p_T$ spectrum of $W$+c-jet candidate events appropriately to the particle level, as verified by a MC closure test. A large sample of $J/\psi \rightarrow \mu^+\mu^-$ events collected at D0 is employed to correct the jet-muon reconstruction efficiency, $(58.7 \pm 2.8\%)$, computed from the MC simulation, by a factor of 0.89 $\pm$ 0.06. This correction is found to be independent of the jet $p_T$. The final acceptance times efficiencies are found to be $c_c^e = (1.24 \pm 0.22\%)$ and $c_c^\mu = (1.22 \pm 0.23\%)$.

The presence of two muons in the muon channel increases the trigger selection efficiency of the $W$+c-jet candidates compared to the inclusive $W$+jets data sample. The divisor factor $K_T^c = 1.18 \pm 0.12$, extracted from the probability of events being selected when only the jet-muon fires the trigger, corrects for the bias in $W$+c-jet selection in the muon channel. In the electron channel the factor $K_T^e$ is unity as the trigger efficiency cancels in the ratio.

The $W$+c-jet cross section ratio is extracted using

$$
\frac{\sigma [W \rightarrow \ell \nu + \text{c-jet}]}{\sigma [W \rightarrow \ell \nu + \text{jets}]} = \frac{1}{K_T^e} \left[ N_{\text{OS}}^c - f_c^\ell \left( N_{\text{SS}}^c - N_{\text{SS}}^{\ell,MJ} - N_{\text{SS}}^{\ell,WW} - N_{\text{SS}}^{\ell,t\bar{t}} - N_{\text{SS}}^{\ell,\text{tbb}} \right) - N_{\text{OS}}^{\ell,MJ} - N_{\text{OS}}^{\ell,WW} - N_{\text{OS}}^{\ell,t\bar{t}} - N_{\text{OS}}^{\ell,\text{tbb}} \right] (1 - f_Z^e - f_{M1}^e)N_{W J}^c
$$

which requires one further correction in each channel, $f_c^\ell$, for the small correlation between the jet-muon and $W$ boson charges that arises in $W$+light-quark jet events. The factor $f_c^\ell$ is determined from fully simulated $W$+jet events as the ratio of the predicted number of $\mu$-tagged jets to SS $\mu$-tagged jets in all background samples that pass the same selection criteria as defined for the data sample. Processes considered include $W+u,d,s$, $W+g$, $W+c\bar{c}$, $W+\bar{b}b$, and $W+c$-jet, where the $c$ quark does not decay semi-muonically in the last case. The $f_c^\ell$
TABLE I: Summary of quantities to estimate the $W+c$-jet cross section ratio. The first uncertainties quoted are statistical and the second systematic.

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are parameterized in terms of jet $p_T$ as $f^e_\tau = a_\tau + b_\tau \times p_T$, with $a_\tau = 1.223 \pm 0.016$, $a_\mu = 1.241 \pm 0.023$, $b_\tau = -0.0017 \pm 0.003$, and $b_\mu = -0.0019 \pm 0.0004$, where all quoted uncertainties are the parameters are statistical; $f^e_\tau$ decreases with increasing jet $p_T$ because the sub-process $qq \to Wg$ dominates $gq \to Wq^\tau$ at high jet $p_T$. Systematic uncertainties in $f^e_\tau$ arise mainly from the cross section and jet fragmentation models. The $f^e_\tau$ are nearly independent of the absolute charged multiplicity per jet and the $W+\text{light-jets}$ cross section. This has been verified by comparing the ratio of all OS tracks to all SS tracks found in jets in the inclusive $W+\text{jets}$ data sample. The $f^e_\tau$ depend instead on the $K^{\pm}/\pi^{\pm}$ ratio per jet and the relative cross section for $W$ boson plus heavy quark jet final states compared to $W+\text{light-jets}$. A 6% uncertainty is assigned to the weighted $\pi^{\pm}$ multiplicity based on a comparison of the difference between tracking efficiency in data and simulation, and a 20% uncertainty on the $K^{\pm}/\pi^{\pm}$ ratio is estimated based on comparing $K_0^{\pi}$ production in data to MC. Uncertainties in ALPGEN cross sections are estimated to be 50% for $W+bb$, $W+c\bar{c}$, and $W+c$-jet, relative to $W+\text{light-jets}$ [24]. A change of the $W+c$-jet cross section by $\pm 100\%$ does not lead to a significant effect in $f^e_\tau$. The uncertainty due to PDFs on $f^e_\tau$ is estimated to be $\pm 0.97\%$. Overall systematic uncertainties are found to be 1.5% for $f^e_\tau$ and 1.1% for $f^\mu_\tau$, with the relative cross section contributions dominant. Adding a 0.6% uncertainty in each channel due to MC statistics yields $f^e_\tau = 1.149\pm0.018$ and $f^\mu_\tau = 1.148\pm0.015$ averaged over all $p_T > 20$ GeV.

Table I summarizes the cross section ratio measurements and their uncertainties for the electron and the muon channels for all jet $p_T > 20$ GeV and jet $|\eta| < 2.5$, and for three jet $p_T$ bins with $|\eta| < 2.5$ in each bin. The ratio measurements benefit from cancellation of several uncertainties, notably the integrated luminosity [30], lep-
to the relatively small contributions of $W+b\bar{b}$ and $W+c\bar{c}$ to inclusive $W+$jets, the model prediction of the $W+c$-jet rate has $\lesssim 5\%$ sensitivity to their cross sections. Figure 1 shows the differential $W+c$-jet fraction, and compares the data to a model prediction using leading order QCD augmented by ALPGEN and PYTHIA.

As a test of the $W+c$-jet signal hypothesis, Fig. 2(a) compares data to ALPGEN and PYTHIA expectations in the background-subtracted distribution of the signed impact parameter significance, $\alpha/\sigma_\alpha$, for the jet-muon, where $\alpha$ is the projected distance of closest approach of the jet-muon to the event interaction point in the transverse plane, and $\sigma_\alpha$ is the estimated uncertainty on $\alpha$. Data show satisfactory agreement with expectations for $W+c$-jet production and the underlying OS-SS ansatz after the subtraction of light and $b$ quark jet contributions. Similarly, the distribution of the relative transverse momentum of the jet-muon with respect to the jet axis, $p_T^{rel}$, shows the consistency between data and the $c$-jet expectation as illustrated in Fig. 2(b).

To quantify the probability that the observed excess of OS events over SS events is due exclusively to background fluctuations, ensembles for OS, SS backgrounds and inclusive $W+$jets are generated that incorporate all the systematic uncertainties together with the correlations among the OS, SS backgrounds and $W+$jets expectations using Gaussian samplings of the uncertainties. The probability that background fluctuations could produce the observed fraction of the signal events in the inclusive $W+$jets sample is $2.5 \times 10^{-4}$, corresponding to a $3.5 \sigma$ significance for the $W+c$-jet hypothesis.

In conclusion, we have performed a measurement of the $W+c$-jet/$W+$jets cross section ratio at a hadron collider using both electron and muon decay channels of the $W$ boson and utilizing the correlation between the charge of the jet-muon with that of the $W$ boson. The probability that background fluctuations could produce an estimated $W+c$-jet fraction in $W+$jets equal to or larger than the one measured in data is $2.5 \times 10^{-4}$, which corresponds to a $3.5 \sigma$ significance of the observation. We find our measurement to be consistent with LO pertur-
bative QCD predictions of the $W^{+}$c-jet production rate and with an s quark PDF evolved from $Q^2$ scales two orders of magnitude below those of this measurement. The measurement further provides direct experimental evidence of the underlying partonic process $qg \to Wq'$ that should dominate $W$ boson production at the CERN Large Hadron Collider (LHC).

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