First Measurement of W Boson Production in Association with a Single Charm Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present the first measurement of the production cross section of a W boson with a single charm quark (c) in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, using soft muon tagging of c jets. In a data sample of $\sim 1.8\ \mathrm{fb}^{-1}$, recorded with the Collider Detector at Fermilab II detector at the Fermilab Tevatron, we select events with $W + 1$ or 2 jets. We use the charge correlation between the W and the muon from the semileptonic decay of a charm hadron to extract the Wc signal. We measure $\sigma_{Wc}(p_{Tc} > 20\ \mathrm{GeV}/c, |\eta_c| < 1.5) \times \mathrm{BR}(W \to \ell\nu) = 9.8 \pm 3.2$ pb, in agreement with theoretical expectations.

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In the standard model (SM), the associated production of W bosons with single charm quarks (Wc) in proton-antiproton collisions is described at leading order (LO) by the scattering of a gluon with a down, strange, or bottom quark. Despite the dominant d-quark parton density function (PDF) the first process contributes only $\sim 10\%$ at the Tevatron, suppressed by the small Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{cd}. The contribution from $gb \to Wc$ is also heavily suppressed by V_{cb} and the b quark PDF. Therefore, about 90% of the Wc signal is produced by strange quark-gluon fusion, and the production cross section is directly sensitive to the gluon and s-quark PDFs in the proton [1], at a scale of order of the W mass (M_W), and to the element of the CKM matrix V_{cs}.

Calculations of W + heavyquark production are available at LO and next-to-leading order (NLO) in QCD [2]. From direct measurements, $|V_{cs}|$ is known with a precision of $\sim$35% from $W^+ \rightarrow c\bar{s}$, and of $\sim$10% from D, D_s decays [3], largely due to theoretical uncertainties. The s-quark PDF is known from neutrino-nucleon deep inelastic scattering experiments at momentum transfers, Q^2, about 3 orders of magnitude lower than M_W^2 [4]. Moreover, a lack of constraints on the shape of the s-quark PDF has been shown to affect the calculation of the Wc cross section by up to 20% [5]. The dependence on the factorization and renormalization scales in the NLO calculation yields an additional uncertainty of $\sim$20% [2]. Overall, the uncertainty on the theoretical expectation of Wc production is $\sim$30%. Outside the SM, an exotic particle with high semileptonic branching ratio (BR) produced with a W boson, as in the hypothesis investigated in [6–8], could lead to a measured cross section of Wc higher than expected. In addition, charged Higgs production via $c + \bar{s} \rightarrow H^+$ is sensitive to the strange PDF [5]. Finally, Wc is an important component of the $W + 1, 2$ jet samples, a data set used in the search of signals such as a single top, the Higgs boson, and a supersymmetric top. In this context, the measurement of the associated production of W bosons with single charm at the Tevatron is an opportunity to test the SM calculation and set an experimental constraint to the theory.

This Letter documents the first measurement of Wc production in $p\bar{p}$ collisions. We use the correlation between the charge of the W and the charge of the muon from the semileptonic decay of the charm hadron in the $W + 1, 2$ jet sample. Charge conservation in the process $gq \rightarrow Wc$ ($q = d, s$) allows as final states only the pairings $W^+\bar{c}$ and W^-c. It follows that the charge of the lepton from the semileptonic decay of the c quark, and the charge of the lepton from the W decay, are always of opposite sign. The observed lepton charge correlation in Wc is expected to be less than 100%, due to dilution from hadronic decays in flight and hadrons misidentified as muons (“mistags”). We identify the W by its decay to an isolated electron (muon) carrying large transverse energy, E_T (momentum, p_T) with respect to the beam line, plus a neutrino. We refer to these high-p_T electrons or muons as “primary leptons” (PL). The neutrino escapes the detector causing an imbalance of total transverse energy, referred to as “missing E_T” ($\not{E}_T$) [9]. Quarks hadronize and are observed as jets of charged and neutral particles. We identify the charm jets from their semileptonic decay by looking for a muon within the jet (“soft-lepton tag” or “SLT”). We use the difference between events in which the PL and the SLT are oppositely charged (“OS”) and events in which they have the same charge (“SS”) as an observable and define the “asymmetry”: $A = (N_{OS} - N_{SS})/(N_{OS} + N_{SS})$. We measure A and determine the expected number of OS $-$ SS events due to background sources, primarily W + lightflavor (LF) hadrons, dimuon events from Drell-Yan (DY) production, and multijet events (referred to as “non-W QCD”). To a smaller extent, single top, $Z \rightarrow \tau\tau$ and WW events are also sources of charge-correlated background. Because the Wc signal produces mainly OS events, whereas most of the background is equally likely to give OS or SS events, we are able to extract the signal from a background-dominated sample using the excess of OS $-$ SS events over the expected (*not* including Wc) number.

The CDF II detector is described in detail elsewhere [10]. The components relevant to this analysis include the silicon vertex detector, the central outer tracker (COT), the central electromagnetic and hadronic calorimeters, the central muon detectors, and the luminosity counters. The data sample, produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV during Run II of the Fermilab Tevatron, was collected between March 2002 and April 2007. This analysis is based on an integrated luminosity of 1823 ± 109 pb^{-1}. Monte Carlo (MC) simulations of W + jets production are performed using ALPGEN (v2.1 [11]), coupled with CTEQ5L PDFs [12], and PYTHIA (v6.3 [13]) for the shower evolution. Modeling of b and c hadron decay is provided by EVTGEN [14]. DY and WW production are modeled with PYTHIA (v6.5). Events are selected with an inclusive lepton trigger requiring an electron (muon) with $E_T > 18$ GeV ($p_T > 18$ GeV/c). Further selection requires that candidate PLs are isolated ($I < 0.1$ [15]) and have E_T (p_T) greater than 20 GeV with $|\eta| < 1.1$. The event must also have $\not{E}_T > 25$ GeV. Jets are identified using a cone algorithm [16] with a cone opening of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ and are constrained to originate from the $p\bar{p}$ collision vertex. Muons inside jets are identified by matching the tracks of the jet, as measured in the COT, with track segments (“stubs”) in the muon detectors. Such a muon with $p_T > 3$ GeV/c and within $\Delta R < 0.6$ of a jet axis is an SLT. The probability of misidentifying a hadron as an SLT muon, denoted as the “mistag probability,” is measured using jets from data [17]. An SLT mistag probability look-up table is constructed as a function of the track p_T, η, and ϕ. The number of tags predicted with the look-up table agrees to within 10% of the observation in a variety of samples, including QCD multijets and Z + jet events. To reduce background from dimuon resonances and double-semileptonic B hadron decays, we remove events in which the muon PL and SLT are oppositely charged and have an invariant mass consistent with a Z, Υ, or, irrespectively of the PL flavor, less than 5 GeV/c^2. Remaining cuts are as in [17]. The jet energies are corrected to account for variations of the detector response in η and time, as well as multiple $p\bar{p}$ interactions, but are not corrected back to the parton energy. Finally, the W + jet data set is partitioned according to the number of jets with $E_T > 10$ GeV and $|\eta| < 2.0$ in the event (corresponding to the charm's $|\eta_c| \lesssim 1.5$, from the geometric acceptance of muons, and $p_{Tc} \gtrsim 20$ GeV/c). We refer to events in which the

PL is an electron (muon) as the "electron sample" ("muon sample"). In the electron (muon) sample we select 636 (425) OS and 450 (313) SS events with at least one jet tagged by the SLT algorithm. In rare cases where there is more than one tag in the same jet, or more than one tagged jet in the same event, we use the SLT candidate that has the best match between the COT track and muon stubs.

The composition of the $W + 1, 2$ jet sample includes primarily W + LF, $Wb\bar{b}$, $Wc\bar{c}$, Wc, non-W QCD, and DY events. $Wb\bar{b}$ and $Wc\bar{c}$ backgrounds reduce the statistical precision of the measurement but do not contribute to the measured asymmetry, since the presence of both heavy quark and antiquark allows with equal probability either charge combination of the leptons from the W and from the (anti)quark decays. Table I shows the data and expected background contributions. The dominant mechanism by which DY events contribute to the background is when one of the produced muons emits a high-energy photon, and the muon-photon pair is identified as a jet, while the muon passes the SLT-tagging requirements. In order to reduce this background we reject events based on the jet's electromagnetic energy fraction and number of tracks. Events with an OS primary muon and SLT that have a jet with less than 2 tracks in a cone of opening $\Delta R = 0.6$ around the jet axis and an electromagnetic fraction higher than 0.8 are rejected as potential radiative DY events. After the rejection we estimate the number of remaining DY events in the sample by measuring the number of OS − SS events in the data in a window of invariant mass containing the Z peak, $n_Z^{\rm data}$, and using MC simulation to extrapolate $n_Z^{\rm data}$ in the Wc signal region. The uncertainty shown is due to the size of the data and, to a lesser extent, MC samples.

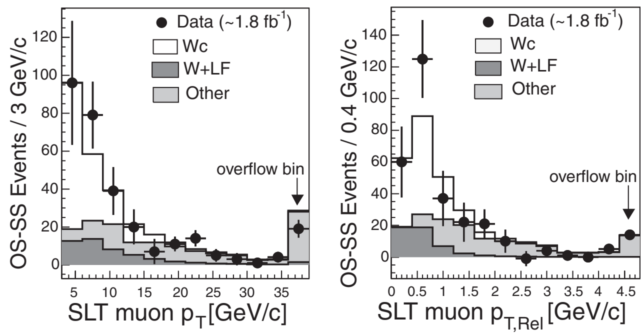
Events without W bosons that enter the signal sample are typically QCD jet events where one jet has faked a high-p_T lepton, mismeasured energies produce apparent $\not\!\!E_T$, and an additional jet contains an SLT muon. A fraction of these events is from $b\bar{b}$ and $c\bar{c}$, where the PL results from a semileptonic decay on one of the fragmenting heavy quark and the SLT from a semileptonic decay on the other, with a potentially large charge asymmetry. We estimate the number of non-W QCD events in the sample by extrapolating the number of SLT-tagged events with an isolated lepton ($I < 0.1$) and $\not\!\!E_T < 15$ GeV into the signal region of $\not\!\!E_T > 25$ GeV. The difference seen in Table I between the electron and muon channels reflects the higher likelihood for a jet to be misidentified as an electron than as a muon. The extrapolation uncertainty is determined by comparing with data the prediction for the number of events in the region of $0.1 < I < 0.2$ and $\not\!\!E_T > 25$ GeV, just outside the signal region. We assign a $\pm 20\%$ systematic uncertainty based on the difference between the two. We model the charge correlation of non-W events from the data using events with $\not\!\!E_T > 25$ GeV but with a nonisolated PL, and the dominant uncertainty is from the limited data sample size.

W + LF events enter the data sample when one of the LF tracks in the jet is misidentified as a muon. Since the same process that describes Wc production may be expected to describe Wu, we expect a small anticorrelation between the charge of the W and the charge of the tracks in the jets recoiling against the W. We estimate the total W + LF background using the mistag probability parametrization with the number of events before SLT tagging, correcting for a fraction due to non-W QCD. The uncertainties include contributions from the mistag prediction and from the correction for non-W QCD. We determine the expected asymmetry for these events using ALPGEN MC events; the asymmetry is lower in the muon sample as a result of the removal of events consistent with dimuon resonances, which removes only OS events. The remaining small backgrounds with expected asymmetries are from single top (t-channel) production, WW, and $Z \to \tau\tau$. These are estimated using theoretical cross sections and MC simulations. Finally, for $Wb\bar{b}$ and $Wc\bar{c}$ we measure a charge asymmetry from MC events, compatible with zero as expected.

After background subtraction we measure $149.3 \pm 42.1(\text{stat}) \pm 15.4(\text{syst})$ Wc events in the selected SS-subtracted sample. Figure 1 shows two kinematic distributions of the SLT muons in the tagged events. Each of the distributions is SS subtracted and the stacked histograms show the contribution from both the expected Wc signal and the estimated backgrounds. The higher-p_T muons in

TABLE I. Summary of data and charge-asymmetric background in the SLT-tagged $W + 1, 2$ jet sample.

Source	Events	Asymmetry	OS − SS events
Drell-Yan			41.6 ± 5.4
Non-W (e PL)	200.0 ± 41.5	0.179 ± 0.046	35.8 ± 11.8
Non-W (μ PL)	30.2 ± 6.5	0.252 ± 0.066	7.6 ± 2.6
W + LF (e PL)	695.5 ± 75.7	0.057 ± 0.002	39.6 ± 4.9
W + LF (μ PL)	491.4 ± 53.3	0.019 ± 0.002	9.3 ± 2.0
Single top			7.6 ± 1.1
$Z \to \tau\tau$, WW			7.2 ± 1.2
Total Background			148.7 ± 15.4
Data	1824		298



(a) (b)

FIG. 1. SS-subtracted distributions of the SLT muon p_T relative to (a) the beam axis and (b) the SLT-jet axis. The Wc contribution is normalized to this measurement.

both plots arise primarily from DY events misidentified as charm decay. The Wc production cross section is obtained using the cross section formula

$$\sigma_{Wc} \times \mathrm{BR}(W \to \ell\nu) = \frac{N_{\mathrm{tot}}^{\mathrm{OS-SS}} - N_{\mathrm{bkg}}^{\mathrm{OS-SS}}}{Acc \int L\mathrm{dt}}, \qquad (1)$$

where $\sigma_{Wc} \equiv \sigma_{W^+\bar{c}} + \sigma_{W^-c}$ with $p_{Tc} > 20$ GeV/c and $|\eta_c| < 1.5$, and $\mathrm{BR}(W \to \ell\nu) = 0.108$. In the denominator, Acc is the SS-subtracted acceptance times efficiency derived from a MC simulation of Wc events, and $\int L\mathrm{dt}$ is the integrated luminosity of the data. We find $Acc = (0.833 \pm 0.010) \times 10^{-2}$; the value implicitly includes the expected charge asymmetry of the Wc sample, which is $(70.6 \pm 0.5)\%$, as well as the semileptonic BR of charm hadrons to muon. The uncertainty is due to the size of the MC sample. Using Eq. (1), we find $\sigma_{Wc} \times \mathrm{BR}(W \to \ell\nu) = 9.8 \pm 2.8(\mathrm{stat})^{+1.4}_{-1.6}(\mathrm{syst}) \pm 0.6(\mathrm{lum})$ pb.

Systematic uncertainties are shown in Table II. MC modeling of the efficiency for identifying the PL ("lepton ID") is measured using Z-boson data and MC samples. The uncertainty on the efficiency for identifying the SLT includes a contribution from MC modeling of particle tracking efficiency in dense jet environments, and a contribution from the parametrization of the SLT efficiency as a function of the p_T of the muon [17]. The PDF uncertainty is derived by using CTEQ [18] and MRST [19] sets, as prescribed in [20]. We compare charm jets in PYTHIA and HERWIG [21,22] to evaluate the uncertainty due to different hadronization models. To measure the effects of initial state radiation (ISR) and final state radiation (FSR) we use inclusive Wc production in ALPGEN and compare the nominal acceptance with enhanced or reduced radiation as in [20]. The uncertainty on the factorization and renormalization scales is estimated by varying them in ALPGEN between the transverse mass of the W and that of the charm. Finally, uncertainties on the background estimations are included in the cross section as systematic uncertainties.

TABLE II. Summary of systematic uncertainties.

Source	$\Delta\sigma_{Wc}$ (%)
Lepton ID	± 1.4
SLT-tagging efficiency	± 5.1
Jet energy calibration	$+4.0/-2.7$
PDFs	± 3.6
c-quark hadronization	± 4.6
ISR, FSR	$+4.2/-9.5$
Factorization scale	± 1.3
Background	± 10.3
Luminosity	± 6.0
Total (excluding luminosity)	$+14.2/-16.3$

In conclusion, we present the first measurement of the Wc production cross section using ~ 1.8 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We measure $\sigma_{Wc}(p_{Tc} > 20$ GeV/c, $|\eta_c| < 1.5) \times \mathrm{BR}(W \to \ell\nu) = 9.8 \pm 3.2$ pb, in agreement with the NLO calculation over the same phase space region of $11.0^{+1.4}_{-3.0}$ pb [23]. The result provides an experimental validation of the theoretical Wc cross section for use in single top and Higgs search analyses. Within the quoted sensitivity, we see no evidence of the presence of an exotic particle with high semileptonic BR. Finally, the result provides the first experimental constraints to the theory uncertainties; an extrapolation indicates that a precision of $\sim 15\%$ can be achieved with ~ 6–7 fb^{-1} of data, expected by the end of Run II.

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