Observation of the Production of a W Boson in Association with a Single Charm Quark

CDF Collaboration; et al; Canelli, F; Kilminster, B

Abstract: The first observation of the production of a W boson with a single charm quark (c) jet in pp− collisions at s/√=1.96 TeV is reported. The analysis uses data corresponding to 4.3 fb−1, recorded with the CDF II detector at the Fermilab Tevatron. Charm quark candidates are selected through the identification of an electron or muon from charm-hadron semileptonic decay within a hadronic jet, and a Wc signal is observed with a significance of 5.7 standard deviations. The production cross section \( \sigma(Wc|p_Tc>20 \text{ GeV/c}, |c|<1.5)\times B(W\rightarrow \nu\nu) \) is measured to be 13.6±3.4−3.1 pb and is in agreement with theoretical expectations. From this result the magnitude of the quark-mixing matrix element \( |V_{cs}| \) is derived, \( |V_{cs}|=1.08±0.16 \) along with a lower limit of \( |V_{cs}|>0.71 \) at the 95% confidence level, assuming that the Wc production through c to s quark coupling is dominant.

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The first observation of the production of a $W$ boson with a single charm quark ($c$) jet in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV is reported. The analysis uses data corresponding to 4.3 fb$^{-1}$, recorded with the CDF II detector at the Fermilab Tevatron. Charm quark candidates are selected through the identification of an electron or muon from charm-hadron semileptonic decay within a hadronic jet, and a $Wc$ signal is observed with a significance of 5.7 standard deviations. The production cross section $\sigma_{Wc}$ is measured to be $13.6^{+3.4}_{-2.9}$ fb and is in agreement with theoretical expectations. From this result the magnitude of the quark-mixing matrix element $V_{cs}$ is derived, $|V_{cs}| = 1.08 \pm 0.16$ along with a lower limit of $|V_{cs}| > 0.71$ at the 95% confidence level, assuming that the $Wc$ production through $c$ to $s$ quark coupling is dominant.

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The associated production of the $W$ boson with a single charm quark in proton-antiproton collisions is described at lowest order in the standard model (SM) by quark-gluon fusion ($qq \to Wc$), where $q$ denotes a $d$, $s$, or $b$ quark. At the Tevatron proton-antiproton collider, the larger $d$ quark parton distribution function (PDF) in the proton is compensated by the small quark-mixing (Cabibbo-Kobayashi-Maskawa or CKM) matrix element $|V_{cd}|$, so that only about 20% of the total $Wc$ production rate is due to $gd \to Wc$, with the majority due to strange quark-gluon fusion. The contribution from $gb \to Wc$ is also heavily suppressed by $|V_{cb}|$ and $b$ quark PDF. The $Wc$ production cross section is therefore particularly sensitive to the gluon and $s$ quark PDFs $^{1,2}$, at a momentum transfer $Q^2$ of the order of the $W$ boson mass ($M_W$), and to the magnitude of the CKM matrix element $V_{cs}$. Measurements of $Wc$ production in high energy $p\bar{p}$ collisions are of interest because they constrain the proton’s $s$ quark PDF at momentum transfers about three orders of magnitude higher than in neutrino-nucleon scattering $^{3,4}$. Finally, the $Wc$ final state is similar to final state of other processes, such as single top-quark production, neutral and charged Higgs boson production, and supersymmetric top-quark production. The techniques developed here could lead to a better understanding of those samples and their searches. Calculations of $W$ + heavy quark production are available at leading order (LO) and next-to-leading order (NLO) in quantum chromodynamics (QCD) $^{4}$, with the NLO cross section prediction about 50% larger than the LO calculation. Overall, the uncertainty on the NLO theoretical expectation for the $Wc$ production cross section at the Tevatron is 10%–20%, depending on the charm phase space considered.

We present the first observation of $p\bar{p} \to Wc$ production. The charm quark is identified through the semileptonic decay of the charm hadron into an electron or muon

\[ Wc \rightarrow \ell^{+}\nu_{\ell} + \text{jet}, \]

where $\ell$ is an electron or muon. At the Tevatron proton-antiproton collider, $|V_{cd}| > 0.71$ at the 95% confidence level, assuming that the $Wc$ production through $c$ to $s$ quark coupling is dominant.

PACS numbers: 13.38.Bg, 13.20.Fc, 13.85.Lg
single charm quark and allows for additional jets; contributions from all sources of W bosons associated with c̅c pairs are not considered in the acceptance since they cancel out in the same-sign subtraction, owing to the largely charge-symmetric detector response.

The CDF II detector is described in detail elsewhere [5]. The data sample, produced in p̅p collisions at √s = 1.96 TeV during Run II of the Fermilab Tevatron, corresponds to 4.3 ± 0.3 fb⁻¹ and was collected between March 2002 and March 2009. Events are selected with an inclusive-lepton online event selection (trigger) requiring an electron (muon) with E_T > 18 GeV (p_T > 18 GeV/c) [6]. Further selection requires exactly one isolated electron (muon), both with isolation parameter I < 0.1 [10], with E_T (p_T) greater than 20 GeV (20 GeV/c) and |η| < 2.0. The transverse mass of the W boson candidates is required to be greater than 20 GeV/c². Jets are identified using a fixed-cone algorithm with a cone opening of ΔR ≡ (∆η)² + (∆φ)² = 0.4 and are constrained to originate from the p̅p collision vertex. The jet energies are corrected for detector response, multiple interactions, and uninstrumented regions of the detector [12].

Muon candidates inside jets are identified by matching the trajectories of charged particles (tracks) of the jet, as measured in the inner tracking system, with track segments in the muon detectors. An SLT (for SLT_l) must have p_T > 3 GeV/c and be within ΔR < 0.6 of a jet axis. Soft electrons from semileptonic heavy-flavor decays (SLT_e) are identified by tracks with p_T > 2 GeV/c that are associated with an electromagnetic shower in the central electromagnetic calorimeter, and must lie within ΔR < 0.4 of a jet axis. Furthermore, finely segmented wire and strip chambers are used to identify the collimated shower of the electron within the broader hadronic shower of the jet. Additional variables to discriminate soft electrons are based on the energy deposition, transverse shower shape, and track-shower distance [14, 15]. To reduce background from dielectron and dimuon resonances, events are discarded where the invariant mass, computed from the same-flavor oppositely charged soft lepton and primary lepton, is consistent with Υ or Z (for SLTₜ), or greater than 45 GeV/c² (for SLTₜ). Events are also discarded if the jet tagged by a soft muon has an electromagnetic fraction greater than 90%, reducing the contamination from Z → μ⁺μ⁻ decays with final-state radiation off one muon. To suppress QCD multijet background, we reject events for which the azimuthal angular difference between the E_T and the jet is less than 0.3 rad.

The dominant backgrounds to Wc are due to associated production of jets with the W boson (W + jets, excluding the Wc under investigation), and from Drell-Yan production of Z/γ* , with and without additional jets. Multijet QCD events and small contributions from diboson, single top, and ℓt̅ production are also...
the tracks in the jets recoiling against the W mistag probability parametrization \[9, 14\]. The proba-

jets events is obtained from this pretag estimate using a and all other backgrounds. The number of tagged 

from the data the initial pretag estimate of the signal 

before tagging the jet (“pretag sample”) by subtracting 

W decay are also simulated, as well as Zb and Zc final 

states. The production of Z/\gamma^* + jets in the simulation is 

normalized by the measured exclusive Z + 1 jet cross section \[20\].

The W boson events that can mimic the Wc signature consist of a W boson associated with heavy-flavor quark pairs (bb and cc) or light-flavor (LF) jets. How-

ever, since this measurement is sensitive to the excess of 

OS over SS events, such excess from Wb\bar{b} and Wc\bar{c} processes 

is negligible given the soft lepton can come from either the b (c) or \bar{b} (\bar{c}). On the other hand, W + LF events enter the data sample when the jet is identified as 

a charm jet via a misreconstructed soft electron or soft 

muon tag (“mistagging”). A small anticorrelation be-

 tween the charge of the W boson and the charge sign of 

the tracks in the jets recoiling against the W is present, 

leading to a residual background contribution. We rely 

on a combination of MC simulations and data-driven 
techniques to estimate this contribution to the tagged 
sample: first the number of W + jets events (\approx 97\% of 

which is W + LF) is estimated in the sample of events 

before tagging the jet (“pretag sample”) by subtracting 

from the data the initial pretag estimate of the signal 

and all other backgrounds. The number of tagged W + 
jets events is obtained from this pretag estimate using a 
mistag probability parametrization \[3, 4\]. The proba-

bility of misidentifying a hadron as an SLT, denoted as 

the SLT mistag probability, is parametrized as a func-
tion of the track curvature and \(\eta\). The number of OS 

and SS events due to W + LF are determined directly 

from the data by applying the mistag parametrizations 
to tracks in the W + jet pretagged sample, and appropri-
ately taking into account for the SLT the contribution 

from photon conversions.

The second largest background to Wc is due to the 

misreconstruction of Z/\gamma^* + jets events. The two lep-
tons from the Z/\gamma^* decay can be misidentified as one 

lepton from a W boson decay and one soft lepton, re-

sulting in approximately 90\% charge asymmetry. These 

events are suppressed by the veto on the Z-mass region. 

Alternatively, only one lepton from the Z boson decay 
is reconstructed in the event, which is typically assigned 
to be a W-decay lepton. In this case, the soft lepton 

results from the decay of heavy flavor or from the mis-

reconstruction of a track from hadrons, and these events

carry approximately 40\% asymmetry. The overall aver-

age charge asymmetry of Z/\gamma^* + jets for SLT, is smaller 

than for SLT, because of the stricter requirements on the 

dielectron mass.

Events due to QCD multijet production can enter the 

selection through hadronic misidentification or heavy-

flavor decay. Missing transverse energy can arise from 

mismeasured jet energy, detector effects, or neutrinos in 

the decay chain. We estimate this background by releasing 
the \(E_T\) requirement on the events and fitting tem-
pplates of the \(E_T\) distribution for the QCD multijet 

component, separately for OS and SS events. The template 
distribution for QCD multijet events is derived from a 
jet-enriched data sample in which candidate electrons fall 
two of the electron identification criteria. The remaining 

sample composition is modeled with MC simulations.

Finally, the production of dibosons (WW, WZ, ZZ) and \(t\bar{t}\) is modeled with a PYTHIA (v6.4) MC calculation, 
while single top-quark production is simulated using 
MADEVENT \[21\]. The WW events contribute the most 

and have a strong charge asymmetry. Table I summa-

rizes the data and the estimated background.

| Source | Events | Asymmetry | OS–SS |
|--------|--------|-----------|-------|
| W + LF, bb, cc | 1808 ± 271 | 0.048 ± 0.008 | 86 ± 14 |
| Z/\gamma^* + jets | 132 ± 30 | 0.63 ± 0.02 | 84 ± 18 |
| QCD multijet | 308 ± 17 | −0.03 ± 0.07 | −8 ± 17 |
| Diboson, t(\bar{t}) | 26 ± 3 | 0.33 ± 0.01 | 9 ± 1 |
| Wc (LO + PS) | 214 ± 19 | 0.75 ± 0.03 | 161 ± 13 |
| Total expected | 2488 ± 274 | ... | 331 ± 37 |
| Data | 2506 | ... | 458 |

| Source | Events | Asymmetry | OS–SS |
|--------|--------|-----------|-------|
| W + LF, bb, cc | 4076 ± 305 | 0.043 ± 0.005 | 174 ± 19 |
| Z/\gamma^* + jets | 138 ± 29 | 0.26 ± 0.01 | 36 ± 7 |
| QCD multijet | 374 ± 12 | 0.07 ± 0.03 | 27 ± 12 |
| Diboson, t(\bar{t}) | 35 ± 3 | 0.58 ± 0.01 | 20 ± 2 |
| Wc (LO + PS) | 174 ± 16 | 0.45 ± 0.02 | 78 ± 7 |
| Total expected | 4797 ± 307 | ... | 336 ± 28 |
| Data | 4582 | ... | 406 |

We assume that the total OS–SS rates observed in the 
data, after subtracting the background contribu-
tions, are due to the Wc signal; the SS-subtracted rates 
for the signal are then 287 ± 50(stat) ± 32(syst) and 
149 ± 68(stat) ± 26(syst) events, for the SLT, and SLT, 
tagged samples, respectively. The total systematic un-
certainty in the SS-subtracted rates is derived accounting 
for correlations between the uncertainties of the individu-
al background sources. Figure I shows the distributions
uncertainty on the SLT tagging includes contributions from the measurements of the efficiency of tagging leptons in a jet environment and of mistagging [11, 14]. The uncertainty on the backgrounds includes contributions from the theoretical cross sections, from the estimation technique, and from statistics for the backgrounds evaluated with inputs from a data control region. For the $Z/\gamma^*$ background, the dominant uncertainty on the event yield estimate comes from the measured $Z$ cross section uncertainty. To measure the effects of initial- and final-state gluon radiation, we measure the $W_c$ acceptance in different samples with the radiation enhanced or reduced, as in Ref. [22]. We compare charm jets modeled with the PYTHIA and HERWIG [23, 24] MC calculations to evaluate the uncertainty due to different hadronization models. The PDF uncertainty is derived by remeasuring the acceptance using the CTEQ and MRST [25] sets, following the same prescription as in Ref. [22]. The MC modeling of the efficiency for identifying the leptons from the $W$ boson decay (“$W$ lepton ID”) is measured using $Z$ boson data and MC samples. The charge misidentification rate is less than 1% and therefore has a negligible effect. The uncertainty due to the jet energy calibration is measured by shifting the energies of the jets in the $W_c$ MC simulation by $\pm 1\sigma$ of the jet energy calibration [12]. The uncertainty on the acceptance due to the factorization and renormalization scales is estimated by varying them in the ALPGEN MC program between 1/2 and twice the transverse mass of the $W$ boson, as well as using the charm quark $p_T$.

The results from the two SLT-tagged samples are combined by performing a profile likelihood ratio minimization [26] in which the number of signal and background events in each sample is modeled by a Poisson distribution. Systematic uncertainties are included as nuisance parameters with Gaussian constraints whose widths are fixed to the respective uncertainties, and are assumed to be either fully correlated, if they are shared between the two channels, or uncorrelated if not. The cross section, $\sigma_{W_c}$, is left as a free parameter in the fit of the likelihood function. The combination yields $\sigma_{W_c}(p_T > 20 \text{ GeV/c}, |\eta_c| < 1.5) \times B(W \to \ell\nu) = 13.6 \pm 2.2(\text{stat})^{+2.3}_{-1.0}(\text{syst}) \pm 1.1(\text{lum})$ pb = 13.6$^{+3.4}_{-3.1}$ pb. The significance for the $W_c$ signal is derived from the ratio of profile likelihoods $\lambda$, with $-2\ln \lambda$ in the hypothesis of no signal being interpreted as following a $\chi^2$ distribution, and is calculated to be $5.7\sigma$. The measurement is in agreement with a NLO calculation over the same phase space of $11.4 \pm 1.3$ pb [27], where the renormalization and factorization scales have been set to half the $W$ boson mass, and varied between 5 and 80 GeV in the uncertainty. The uncertainty also includes PDF variations using the CTEQ6M [28] and MSTW2008 [29] sets. The result can be also compared to the LO prediction of $8.2 \pm 1.5$ pb [27], giving a measurement to LO cross section ratio for this kinematic region of $1.6 \pm 0.5$. The of the measured $p_T$ spectrum for SLT muons and electrons in tagged events, compared to the prediction. For each contribution, SS events are subtracted. The $W_c$ production cross section is calculated using Eq. (1), with $\sigma_{W_c} \equiv \sigma_{W+c} + \sigma_{W-c}$, $B(W \to \ell\nu) = 0.108 \pm 0.009$ [3], $p_T > 20$ GeV/c, and $|\eta_c| < 1.5$; the values of the dilution $S$ for $W_c$ events are given in Table II. We measure $\sigma_{W_c} \times B(W \to \ell\nu) = 13.4 \pm 2.3(\text{stat})^{+0.5}_{-0.4}(\text{syst}) \pm 1.2(\text{lum})$ pb and $\sigma_{W_c} \times B(W \to \ell\nu) = 15.0 \pm 6.8(\text{stat})^{+4.4}_{-2.9}(\text{syst}) \pm 1.2(\text{lum})$ pb from the SLT$_\mu$ and SLT$_e$ samples, respectively.

TABLE II: Summary of systematic uncertainties, as a percentage of the measured $W_c$ cross section. Numbers shown in bold font indicate uncertainties treated as uncorrelated in the combination of the channels.

| Source                        | SLT$_\mu$ | SLT$_e$ |
|-------------------------------|-----------|---------|
| SLT uncertainties            | $\pm9.2$  | $\pm16.6$ |
| QCD multijet estimate        | $\pm6.3$  | $\pm9.9$ |
| Initial and final state radiation | $\pm6.0$  | $\pm6.0$ |
| Background cross sections    | $\pm5.7$  | $\pm4.7$ |
| $c$ quark hadronization      | $\pm4.6$  | $\pm4.6$ |
| PDFs                         | $\pm3.6$  | $\pm3.6$ |
| $W$-lepton ID                | $\pm2.2$  | $\pm2.2$ |
| Jet energy calibration       | $\pm2.0$  | $\pm2.0$ |
| Factorization, renormalization scales | $\pm1.3$  | $\pm1.3$ |
| Total                        | $\pm15.4$ | $\pm21.8$ |
| Luminosity                   | $\pm7.9$  | $\pm8.3$ |

Systematic uncertainties are shown in Table II. The

FIG. 1: (color online) The soft muon and soft electron $p_T$ distributions. The $W_c$ contribution is normalized to the measured cross section.
Since the majority of $Wc$ production proceeds through $c$ to $s$ quark coupling, we can relate the measured value of the cross section with the theoretical prediction and derive $|V_{cs}|$. Using $\sigma_{Wc}^{\text{theory}} = 9.8(\pm 1.1)|V_{cs}|^2 + 2.1(\pm 0.2) \text{ pb}$ [27] we obtain $|V_{cs}| = 1.08 \pm 0.16$, where the uncertainties in the cross section measurement and in the theoretical prediction have been added in quadrature. Restricting the range of $|V_{cs}|$ to the interval $[0, 1]$, a lower limit of $|V_{cs}| > 0.71$ at the 95% confidence level is extracted.

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