CDF note 8962

First Measurement of the Cross Section for the Production of a W Boson in Association with a Single Charm Quark

The CDF Collaboration
URL http://www-cdf.fnal.gov

(Dated: August 23, 2007)

We present a measurement of the Wc production cross section using soft muon tagging of charm jets. In the W+1 and W+2 jet data sample selected within $\sim$1.8 fb^{-1} of proton-antiproton collision data at $\sqrt{s} = 1.96$ TeV, we identify jets with a muon from the semileptonic decay of the candidate c-quark. We study the charge correlation of the W boson with the muon. After considering the sources of background, the same-sign subtracted sample is used to measure the Wc contribution. We measure $\sigma_{wc}(P_{\mathrm{T}}(c) > 8\mathrm{GeV/c}, \quad | \eta(c) |< 3.0) \times BR(W \rightarrow \ell\nu) = 28.5 \pm 8.2(\mathrm{stat})^{+4.1}_{-4.4}(\mathrm{sys}) \pm 1.7(\mathrm{lum})$ pb.

Preliminary Results for Summer 2007 Conferences

Contact e-mail: lucio@fnal.gov, tml@uiuc.edu

I. INTRODUCTION

Leading order production of Wc in proton-antiproton collisions at the Tevatron is due to the scattering of a gluon with a strange ($\sim$ 90%) or down ($\sim$10%) quark. Figure 1 shows the leading-order diagram for $g\bar{s} \rightarrow W^{+}\bar{c}$. Since this diagram can only produce $W^{+}\bar{c}$ or $W^{-}c$, the charge of the lepton from the semileptonic decay of the charm quark, and the charge of the lepton from the W boson decay, are always of opposite sign. This can be used to single out Wc events against the large background of W plus light flavor and other W plus heavy flavor processes present in W+1,2 jet events.

We measure the correlation between the charge of the primary lepton (from the decay of the W boson, "TL") and the charge of a relatively low $P_{\rm T}$ muon from the putative semileptonic decay of the charm jet ("soft-lepton tag" or "SLT"[1]) in the W+1,2 jet sample. In the absence of correlation, we would expect an equal number of same sign as to opposite sign events. However Wc is produced either as $W^{+}\bar{c}$ or $W^{-}c$, and therefore there is a strong correlation between the sign of the muon (which identifies the c or $\bar{c}$) and the sign of the lepton from the W decay. The observed correlation is less than 100% due to dilution from hadronic decays in flight and hadrons misidentified as muons ("mistags"). The per-track probability of such mistags is parameterized as a function of $P_{\rm T}$, η and ϕ using jets recoiling against a cluster of electromagnetic energy that provides the trigger for the sample. The mistag probability is corrected for the measured heavy-flavor fraction of the sample[1].

The behavior of Wc events is unlike that of a sample of $Wb\bar{b}$ or $Wc\bar{c}$, in which the presence of both particle and antiparticle of the heavy flavor quarks makes it equally likely to find a final state with the soft muon and the primary lepton of same sign as of opposite sign. On the other hand, there will also be some correlation between the charge of the W boson and the charge of light flavor hadrons mis-identified as soft muons in events where a W boson is produced with a single light quark. Di-muon events from Drell-Yan (DY), in which one of the muons is identified as a soft muon in a jet and the other as the primary muon of a W decay, are a source of background due to the opposite sign charge correlation. Finally, di-jets and multi-jets events (referred to as "non-W QCD"), in which one of the jets is identified as a primary lepton from W boson decay, are also a small source of charge-correlated background due to $c\bar{c}$ and $b\bar{b}$ events, as are single-top, $Z \rightarrow \tau\tau$ and WW events.

We use the difference between opposite-sign ("OS", in which the TL and SLT are oppositely charged) and same-sign ("SS", in which they have the same charge) events as an observable: $N_{\rm OS} - N_{\rm SS}$. We define the "asymmetry", A, as

$$A = \frac{N_{\rm OS} - N_{\rm SS}}{N_{\rm OS} + N_{\rm SS}} \qquad (1)$$

Using ALPGEN+PYTHIA[2][3] Monte Carlo, we measure the asymmetry from Wc events in W+1 and 2 jets at 0.721$\pm$0.008. This technique allows extraction of the Wc signal from a large background of tagged events, most of which are equally likely to have opposite-sign tags as same-sign tags.

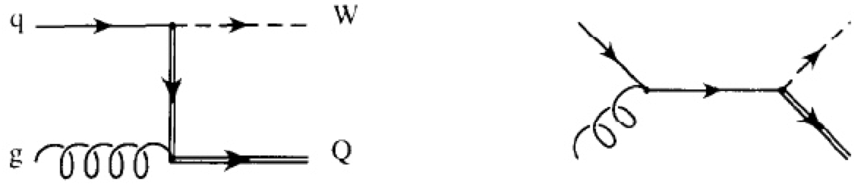

FIG. 1: The Born graphs for W+Q production in $p\bar{p}$ collisions.

II. EVENT SELECTION & DATA SAMPLE

This analysis is based on an integrated luminosity of 1.8 fb^{-1} collected with the CDFII detector between March 2002 and March 2007. The CDF detector is described in detail in [4]. The data are collected with an inclusive lepton trigger that requires an electron or muon with $E_{\rm T}$ >18 GeV ($P_{\rm T}$ >18 GeV/c for the muon). From this inclusive lepton dataset we select events offline with a reconstructed isolated electron $E_{\rm T}$ (muon $P_{\rm T}$) greater than 20 GeV, missing $E_{\rm T}$ >25 GeV and jets with $E_{\rm T}$ >10 GeV. Jet energies are corrected for calorimeter non-uniformities, but are not corrected back to the parton energy. To reduce backgrounds from di-muon resonances, we remove events in which the TL and SLT are oppositely-charged and have an invariant mass consistent with a Z boson or Υ. In addition we remove events in which the TL and SLT are oppositely-charged and have an invariant mass less than 5 GeV/c^2, which removes both double-semileptonic B hadron decays and J/ψ decays. We refer to events in which the TL is an electron as the "electron sample", and those in which it is a muon as the "muon sample".

There are 1085 W+1,2 jet candidates with at least one jet tagged by the SLT algorithm in the electron channel (CEM), 635 of which are OS and 450 SS. In the muon channel there are 737 W+1,2 jet candidates with at least one jet tagged, consisting of 424 OS and 313 SS events.

III. BACKGROUNDS

The sample composition of W+1,2 jets includes primarily W+light flavor, $Wb\bar{b}$, $Wc\bar{c}$, Wc, non-W QCD and Drell-Yan events. $Wb\bar{b}$ and $Wc\bar{c}$ backgrounds reduce the statistical precision of the measurement, but do not contribute to the measured asymmetry because they are equally likely to result in OS as SS events.

The dominant background contribution from Drell-Yan is caused by highly radiative muons events, where one of the muons emits an high-energy photon. When the photon's energy is higher than 10 GeV, the pair muon-photon is identified as a jet, while the muon passes all the SLT-tagging requirements. In order to reduce this background we reject events based on the electromagnetic fraction of the jet and number of tracks. Events with opposite sign primary muon and SLT muon, whose jet's electromagnetic fraction is higher than 0.8 and with less than 2 tracks in a cone of opening 0.6 around the jet axis are rejected as potential radiative Drell-Yan events. After the rejection we estimate the number of remaining DY events in the sample as follows: We measure the OS-SS events under the Z-boson peak in the data and use the `PYTHIA` Monte Carlo ratio of same-sign subtracted events outside the peak to under the peak to extrapolate the measured value in the data under the peak to expected Drell-Yan events outside the peak. The total number of DY events is obtained dividing by the charge asymmetry of 0.651±0.041, giving $N_{DY} = 63.9 \pm 8.3$.

Events without W bosons that enter the signal sample, "non-W QCD background", are typically QCD jet events where one jet has faked a high-$P_{\rm T}$ lepton, mismeasured energies produce apparent missing $\not\!\!E_{\rm T}$ and an additional jet contains an SLT muon. A large fraction of these events are from $b\bar{b}$ and $c\bar{c}$ where the TL results from a semileptonic decay on one side and the SLT from a semileptonic decay on the other. These events therefore have a large charge asymmetry that must be accounted for. We estimate the number of non-W QCD events in the sample by extrapolating the number of SLT-tagged events with an isolated lepton and low missing $\not\!\!E_{\rm T}$ into the signal region of large missing $\not\!\!E_{\rm T}$. We determine that in the signal region of W+1,2 jets there are 200±11(stat) non-W QCD events in the electron sample and 30.2±2.4(stat)non-W QCD events in the muon sample. We determine the systematic uncertainty on this prediction by using the technique to predict the number of events just outside the signal region defined by the isolation requirement on the lepton and the missing $\not\!\!E_{\rm T}$ requirement. We compare this prediction with the actual number of events (corrected for the contamination from real W bosons) and assign a 20% systematic uncertainty based on the difference between the predicted and observed events.

Once the expected number of non-W events in the signal region is determined, we need to model their charge asymmetry properties. We model the charge correlation using the data sample itself, using events with missing $\not\!\!E_{\rm T}$ >25 GeV but with a non-isolated TL. In the electron channel, the measured charge asymmetry is 17.9±4.6%, where the uncertainty is purely from the limited data sample size. Therefore out of a total of 200±11(stat) events, we expect 35.8±9.4 same-sign subtracted events, where the uncertainty includes both the uncertainty on the charge asymmetry and on the total number of non-W events. In the muon channel we measure a charge asymmetry of 25.2±6.6%. The total number of events expected is 30.2±2.4. The expected same sign subtracted events are then 7.6±2.1. These uncertainties do not include a ±20% systematic uncertainty assigned to the technique used to estimate the non-W QCD background, which is common to the two channels.

W+light flavor events enter the data sample when one of the light flavor tracks in the jet is mis-identified as a muon. The same Feynman diagram that describes Wc production describes also Wu, replacing the s quark in the initial state with a d quark, therefore we do expect a correlation between the charge of the W boson and the charge of the tracks in the jets recoiling against the W. We estimate the total W+light flavor background using the mistag probability parametrization described above, and correct for the fraction of events that are expected from non-W QCD, which is estimated separately. We expect 695.5±29.9 W+light flavor events in the electron channel and 491.4±20.6 events in the muon channel. The uncertainties of ±29.9 events and ±20.6 events in the electron and muon channels respectively are fully correlated, since they are due to the systematic uncertainty on the correction for non-W QCD and to the uncertainty on the heavy-flavor fraction correction to the mistag probability. We measure the asymmetry, A, for these events using `ALPGEN+PYTHIA` Monte Carlo events. The charge asymmetry is 5.7±0.2% in the electron channel and 1.9±0.2% in the muon channel. The value is lower in the muon channel as a result of the removal of events consistent with di-muon resonances, described above, which removes only OS events from the sample. We therefore expect 39.6±4.9 and 9.3±2.0 same-sign subtracted events in the electron and muon channels respectively due to W+light flavor events. The total uncertainty on SS-subtracted events, including correlations between the electron and muon estimates, is ±6.6 events.

Remaining small backgrounds with expected asymmetries, are from single-top production, WW and $Z \to \tau\tau$. These are estimated using theoretical cross sections and Monte Carlo simulations. Finally, for $Wb\bar{b}$,$c\bar{c}$, we measure a charge asymmetry <2% from the Monte Carlo, compatible with no asymmetry as expected, since it's equally likely to tag a c as it is to tag a $\bar{c}$. Table I summarizes the data and expected background contributions.

Physics process	Events	Asymmetry	OS-SS events
W+l.f. (e)	695.5±75.7	0.057±0.002	39.6±4.9
W+l.f. (μ)	491.4±53.3	0.019±0.002	9.3±2.0
Non-W (e)	200.0±41.5	0.179±0.046	35.8±11.8
Non-W (μ):	30.2±6.5	0.252±0.066	7.6±2.6
Drell-Yan	63.9±8.4	0.651±0.041	41.6±5.4
Single Top (t-ch)	31.0±4.2	0.25±0.01	7.6±1.1
$Z \to \tau\tau$			5±1
WW			2.4±0.1
Total Predicted			149.0±15.4
Data			296 (111 μ, 185 e)
Measured Wc		0.721±0.008	147.0±42.1(stat)±15.4(sys)

TABLE I: Summary of the data and background in the $W + 1, 2$ SLT-tagged jets sample. The second column shows the total events expected and the fourth column shows the expected same-sign subtracted events. The uncertainties shown in percent are fully correlated between the electron and muon channel, hence shown separately from the remaining systematic uncertainties. The difference between the observed total and the predicted (from background) number of same-sign subtracted events is the Wc measured contribution.

Overall, out of a total of 1822 events, 1059 are opposite sign and 763 are same sign, leading to a same sign subtracted sample of 296 events (111 in the muon channel and 185 in the electron channel).

IV. W-CHARM PRODUCTION CROSS SECTION

The Wc production cross section is obtained using the cross-section formula:

$$\sigma_{\rm Wc} = \frac{N_{\rm tot}^{OS-SS} - N_{\rm bkg}^{OS-SS}}{Acc \cdot \int L{\rm dt}}, \tag{2}$$

where Acc is the same-sign-subtracted acceptance times efficiency derived from a simulation of Wc events and $\int L$ is the integrated luminosity of the sample. The same-sign-subtracted acceptance implicitly includes the charge asymmetry of the Wc sample, measured from the Monte Carlo to be 72.1±0.8%. From `ALPGEN+PYTHIA` Monte Carlo, we find a same-sign subtracted acceptance for $W \to \ell\nu$ events of $Acc = (0.283 \pm 0.005) \cdot 10^{-2}$, where the uncertainty includes uncertainty on the lepton ID scale factors and efficiencies. Note that the acceptance is relative to the generated events which have $P_{\rm T}(c) > 8$ GeV/c and $\mid \eta \mid (c) < 3.0$, and includes the semileptonic branching fraction of charm hadrons to muons. The integrated luminosity $\int L$dt is 1823±109 pb^{-1}.

V. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in this analysis are summarized in Table II. Uncertainties on the acceptance are due to several factors. Monte Carlo modeling of the efficiency for identifying the TL ("Lepton ID and Scale Factor"), is measured using Z boson data and Monte Carlo samples. The uncertainty on the efficiency for identifying the semileptonic charm decay is evaluated using Monte Carlo data and the uncertainty in the parametrization of the SLT efficiency curve as a function of the $P_{\rm T}$ of the muon. The acceptance uncertainty due to the uncertainty on the jet energy scale is evaluated by measuring the acceptance with the jet energy scale shifted by plus or minus one standard deviation. The uncertainty due to PDF variations is determined by re-evaluating the acceptance with PDFs varied according to the 40 CTEQ eigenvectors, and by comparing the acceptance using MRST72 and MRST75. We compare charm jets in `PYTHIA` and `HERWIG`[5] to evaluate the uncertainty due to different hadronization models. To measure the effects of enhanced or reduced radiation we use inclusive Wc+zero parton `ALPGEN` and compare the acceptance with enhanced or reduced FSR to the nominal (we do not at this time vary the amount of ISR, which is expected to be a much smaller effect for this analysis). Finally, uncertainties on the background estimations are included in the cross-section as systematic uncertainties.

Source	Factional Syst. Unc.	Contribution to σ_{Wc}
Lepton ID and Scale Factors	$\pm 1.4\%$	$\mp 1.4\%$
SLT tagging Efficiency	$\pm 5.1\%$	$\mp 5.1\%$
Jet Energy Scale	$\pm 1\sigma(JES)$	$+3.3/-2.1\%$
PDF's	$\pm 3\%$	$\mp 3\%$
Hadronization	$\pm 4.6\%$	$\mp 4.6\%$
ISR/FSR	-4.4/+7.7%	+4.4/-7.7%
$P_{\rm T}$ Modeling	$\pm 3\%$	$\mp 3\%$
W+l.f.	$\pm 13.6\%$	$\mp 4.5\%$
non-W	$\pm 29\%$	$\mp 8.6\%$
Drell-Yan	$\pm 13.0\%$	$\mp 3.7\%$
Luminosity	$\pm 6\%$	$\mp 6\%$
Total (not including luminosity)		+14.4/-15.5%

TABLE II: Summary of systematic uncertainties.

VI. RESULTS

Putting everything together into Equation 2, and using the acceptance, luminosity, measured number of same-sign-subtracted events and expected same-sign-subtracted backgrounds, described in Sections II through IV, and using the systematic uncertainties from Table II, we find

$$\sigma_{wc}(P_{\rm T}(c) > 8{\rm GeV/c}, \ \mid \eta(c) \mid < 3.0) \times BR(W \to \ell\nu) = 28.5 \pm 8.2({\rm stat})^{+4.1}_{-4.4}({\rm sys}) \pm 1.7({\rm lum})\ {\rm pb}$$

This is in good agreement with the LO prediction from ALPGEN of 22.2±1.2 (PDF)$^{+3.8}_{-3.0}$ (scale) pb [6].

Figure 2 shows two kinematic distributions of the selected data, the $P_{\rm T}$ relative to the beam axis and the $P_{\rm T}$ relative to the putative charm-jet axis of the SLT muons in the tagged events. Each of the distributions is same-sign subtracted. The stacked histograms show the expected contribution from both Wc signal and backgrounds.

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; the European Community's Human Potential Programme; the Slovak RD Agency; and the Academy of Finland.

[1] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **72**, 032002 (2005).
[2] M. Mangano et al., JHEP **07**, 001 (2003).
[3] T. Sjostrand et al., High-Energy-Physics Event Generation with PYTHIA 6.1, Comput. Phys. Commun. **135**, 238 (2001).
[4] F. Abe, et al., Nucl. Instrum. Methods Phys. Res. A **271**, 387 (1988); D. Amidei, et al., Nucl. Instum. Methods Phys. Res. A **350**, 73 (1994); F. Abe, et al., Phys. Rev. D **52**, 4784 (1995); P. Azzi, et al., Nucl. Instrum. Methods Phys. Res. A **360**, 137 (1995); The CDFII Detector Technical Design Report, Fermilab-Pub-96/390-E
[5] G. Corcella et al., HERWIG 6: An Event Generator for Hadron Emission Reactions with Interfering Gluons (including supersymmetric processes), JHEP **01**, 10 (2001).
[6] Michelangelo Mangano, private communication The scale uncertainty is obtained by changing the Q scale from its default value μ_0 to $\mu_0/2$ and $2\mu_0$.

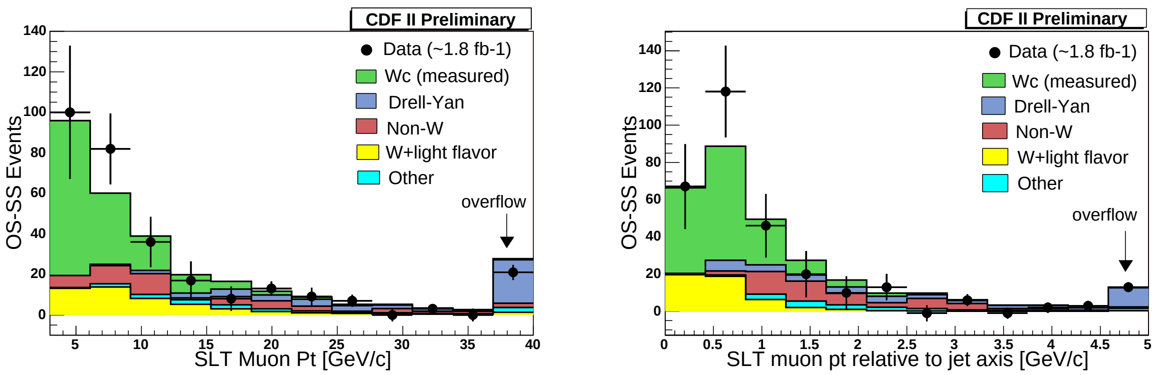

FIG. 2: Same-sign subtracted kinematic distributions of data overlayed to Wc signal and background. The Wc contribution is set to the measured number of events.