\textbf{W+c production at the Tevatron}

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\textbf{Abstract.} The DØ experiment at the Tevatron collider presents a first measurement of the production rate of the $W+c$ final state relative to $W+\text{jets}$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The measured rate is $0.071 \pm 0.017$ for jet transverse momentum $p_T > 20 \text{ GeV/c}$, and is consistent with the theoretical prediction.

1. Introduction
Charm quark production in association with a $W$ boson is a significant process for studying the Standard Model (SM) and physics beyond the SM in hadron-hadron collisions. It can be a significant background for example to $t\bar{t}$ and SM Higgs production, and also to supersymmetric top (stop) production when the stop quark's mass limits its possible decays to a charm quark and a neutralino, $\tilde{t} \rightarrow \chi^0_1 c$. Moreover, as the CKM matrix element $|V_{cd}|^2$ suppresses the expected leading order $d$-quark-gluon fusion production mechanism, $Wc$ production provides direct sensitivity to the $s$-quark parton distribution function (PDF) $s(x, Q^2)$ in the proton[1]. The $s$-quark PDF has so far only been directly measured at fixed-target neutrino-nucleon deep inelastic scattering experiments using relatively low momentum transfer $Q^2$ probes of the order of $10^{0-2}$ GeV$^2/c^2$[2, 8]. The strange quark PDF is dominant for both SM (e.g., $p\bar{p}/pp \rightarrow s g \rightarrow W^{-}+c$) and possible new physics processes (e.g., $p\bar{p}/pp \rightarrow s\bar{c} \rightarrow H^{-}$) [9] at both the Tevatron and the LHC collider.

The first measurement of the cross section ratio $\sigma(pp \rightarrow W+c\text{-jet}) / \sigma(pp \rightarrow W\text{-jets})$ is performed by the DØ experiment at the Fermilab Tevatron collider($\sqrt{s} = 1.96$ TeV), 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. The luminosity of the data taken by the DØ detector [10] utilized for this measurement is approximately 1 fb$^{-1}$ [11].

2. Measurement of $W+c$-jet fraction in inclusive $W$-jets sample
In a selected sample of $W$+jets final state, the $W$-bosons are identified through their leptonic decays, $W \rightarrow \ell\nu$, where $\ell = e, \mu, \tau$ with $\tau \rightarrow e\nu\nu$, or $\mu\nu, \nu\nu$. An isolated electron or muon as defined in Ref. [12] is selected, whose transverse momentum $p_T$ must satisfy $p_T > 20 \text{ GeV/c}$, and the presence of a neutrino is inferred by the requirement that the missing transverse energy $E_T$ satisfies $E_T > 20 \text{ GeV}$. Each event must have a transverse mass $m_T$ computed from the isolated lepton $p_T$ and the $E_T$ in the range $40 – 120 \text{ GeV}/c^2$, and have an azimuthal angular separation between the isolated lepton and $E_T$ direction greater than 0.4 radians. Jets are defined using the iterative seed-based cone algorithm including midpoints with the cone radius...
The jet’s transverse momentum is restricted to $p_T > 20$ GeV/c and its pseudorapidity $|\eta| < 2.5$, where $\eta = -\ln \tan(\theta/2)$, with $\theta$ the polar angle with respect to the proton beam direction. Upon application of all selection criteria there are $N_{Wj} = 89442 \pm 299$ and $N_{Wj}^m = 58868 \pm 243$ $W+$jets candidates in the electron and muon channels respectively, where the estimated fractional contamination of background from mis-identified $W$-bosons is $f_B^e = (3.3 \pm 0.5)\%$ in the electron channel arising from photons or jets and $f_B^\mu = (4.7 \pm 0.6)\%$ in the muon channel arising from $Z \rightarrow \mu^+\mu^- +$jets events.

$W+$c-jet candidates are selected out of the $W+$jets sample, by identifying a reconstructed muon within the charm jet candidate (a “$\mu$-tagged jet”), and in particular utilizing the correlation of that muon’s electric charge with that of the $W$-boson’s decay lepton. Events with the jet muon’s charge opposite or the same as that of the $W$-boson are denoted as “OS” or “SS” events, respectively. In the $W+$c-jet process, the $c$ quark decays into a muon carrying an opposite-sign charge compared to that carried by the $W$ boson, and the number of OS and SS events, $N_{OS}$ and $N_{SS}$ respectively, satisfy $N_{OS} \gg N_{SS}$ for a $W+$c-jet sample. Other vector boson-$+$jets physics processes ($W+g$, $W+c\bar{c}$, $W+b\bar{b}$, $Z+$jets) can produce muons contained within the final state, but the jet muon’s charge 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 $W$ can produce a small fraction of charge-correlated jets owing to jet leading particle effects such as $\pi \rightarrow \mu$ or $K \rightarrow \mu$ decay. Other final states that can produce charge-correlated jets, $t\bar{t}/tb$ and $W+b$, are suppressed by small cross sections and the tiny CKM matrix element $|V_{ub}|^2$, respectively. With these considerations, the $W+$c-jet production rate is measured from OS events with the backgrounds determined from SS events, up to small weakly model-dependent theory corrections.

The reconstructed muon that lies within a cone of $\Delta R(jet, \mu) < 0.5$ with respect to the jet axis must have transverse momentum $p_T > 4$ GeV/c and pseudorapidity $|\eta| < 2.0$. The contribution from $Z \rightarrow \mu^+\mu^- +$jets events in which one of the muons from the $Z$ decay is found inside a jet cone in the $W \rightarrow \mu\nu$ channel is suppressed by rejecting events in which the dimuon invariant mass exceeds 70 GeV/c$^2$.

Application of all selection criteria yields $N_{OS} = 254 \pm 16$ and $N_{SS} = 166 \pm 13$ events in the $W \rightarrow e\nu$ channel, and $N_{OS}^b = 203 \pm 14$ and $N_{SS}^b = 122 \pm 11$ events in the $W \rightarrow \mu\nu$ channel.

A background correction factor to $W+c$, $f_c^e$, is applied to the background SS events to account for the small correlation between the tag muon and $W$ boson charge because the decay of the most energetic pion or kaon has an enhanced probability of containing the highest $p_T$ quark recoiling against $W$-boson generated at the hard scatter vertex that fragments into jet. The factor determined from fully simulated ALPGEN-PYTHIA-EVTGEN-GEANT [14, 17] $W+$ jet events is parameterized in terms of jet $p_T$ as $f_c^e = a_0 + b_0 \times p_T$, with $a_0 = 1.214 \pm 0.012$, $a_0 = 1.241 \pm 0.023$, $b_0 = -0.0016 \pm 0.0002$, and $b_0 = -0.0019 \pm 0.0004$: $f_c^e$ decreases with increasing jet $p_T$ because the sub-process $q\bar{q} \rightarrow Wq'$ dominates over $qg \rightarrow Wq'$ at high jet $p_T$.

As a test of the $W+$c-jet signal hypothesis, Fig. 1(a) compares data to ALPGEN/PYTHIA expectations of heavy flavor and light-jet shapes in the background-subtracted distribution of the signed impact parameter significance $b/\sigma_b$ for the jet muon, where $b$ is the projected distance of closest approach of the jet muon to the event interaction point in the transverse plane and $\sigma_b$ is the estimated uncertainty on $b$. In Fig. 1 (b), the distribution of the invariant mass of well reconstructed tracks in the jet cone divided by the jet $p_T$ is shown to compare the background-subtracted distribution in data with b-jet, c-jet and light-parton jet templates. The asymmetry found in the data distribution in Fig. 1 (a) indicates the presence of heavy flavor, while the data in Fig. 1 (b) favors the c-jet template more than the b-jet.
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Figure 1. Comparison of the background-subtracted data in the combined electron and muon channels with the simulation in shape. (a) Signed significance in impact parameter of the jet muon track with respect to the interaction point, (b) the jet mass divided by the jet $p_T$.

2.1. Relative efficiency of $W + c$ selection

The Monte Carlo simulation of $W+c$-jet and a large D0 data sample is used to calculate the relative acceptance $\times$ efficiencies $\epsilon_c^\ell (\ell = e, \mu)$ in each $W$ decay channel for finding a reconstructed jet muon that satisfies the selection criteria in a jet initiated by a $c$-quark to that of simply reconstructing a $W$-boson with at least one jet in the final state. The acceptance incorporates effects of charm quark to hadron fragmentation and charmed hadron semi-muonic decay. The efficiency accounts for muon identification and track reconstruction effects. For the electron and muon channels the total relative acceptance $\times$ efficiencies are found to be $(1.24 \pm 0.12)\%$ and $(1.22 \pm 0.12)\%$, respectively.

3. $W+c$ production rate

The relative $W+c$-jet cross section is extracted from the expression

$$\sigma [W \rightarrow \ell \nu + c - jet] \sigma [W \rightarrow \ell \nu + jets] = \frac{N_{OS}^{\ell} - f_B^\ell N_{SS}^\ell}{(1 - f_B^\ell) N_{Wj}^\ell \times \epsilon_c^\ell}.$$  

Figures 2(a) and (b) compare the data with model predictions using leading order QCD augmented by alpgen and pythia for the electron and the muon channels respectively. Due to relatively small contribution of $W+b\bar{b}$ and $W+c\bar{c}$ in inclusive $W+jets$, the $W+c$-jet rate has $\approx 1\%$ sensitivity to their cross-sections. The grey band shown around the theory curve is the systematic uncertainty on the $W+c$-jet fraction estimated from simulation due to Jet Energy Scale (JES) only, and the blue outer band is the combined systematic uncertainty due to the JES, the jet’s relative $p_T$ resolution in data and simulation, the background correction factor $f_B^\ell$ and the relative acceptance $\times$ efficiency $\epsilon_c^\ell$. The intermediate cyan band shows only the systematic uncertainty due to JES and jet’s relative $p_T$ resolution. The measured $W+c$-jet fractions integrated over $p_T > 20$ GeV/c are $\sigma [W \rightarrow e\nu + c - jet] / \sigma [W \rightarrow e\nu + jets] = 0.060 \pm 0.021$ (statistical) $\pm 0.007$ (systematic) and $\sigma [W \rightarrow \mu\nu + c - jet] / \sigma [W \rightarrow \mu\nu + jets] = 0.093 \pm 0.029$ (statistical) $\pm 0.005$ (systematic). Combining the two measurements yields $\sigma [W + c - jet] / \sigma [W + jets] = 0.071 \pm 0.017$, with a significant excess of OS events relative to SS events which we attribute to $W+c$-jet production. The result is consistent with the alpgen-pythia prediction of $0.040 \pm 0.003$.

4. Conclusion

A first measurement of the $W+c$-jet/$W+jets$ cross-section ratio at a hadron collider is performed by the D0 experiment. The result is consistent with the Leading Order (LO) perturbative QCD
predictions of the $W+c$-jet, and with an $s$-quark PDF evolved from $Q^2$ scales two orders of magnitude below that of the Tevatron. This measurement provides direct experimental evidence of the underlying partonic process $qg \rightarrow q'W$ that should dominate $W$ production at the LHC collider.

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