The Charm Content of $W + 1$ jet Events as a Probe of the Strange Quark Distribution Function

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ABSTRACT

We investigate the prospects for measuring the strange quark distribution function of the proton in associated $W$ plus charm quark production at the Tevatron. The $W + c$ quark signal produced by strange quark–gluon fusion, $sg \rightarrow W^- c$ and $\bar{s}g \rightarrow W^+ \bar{c}$, is approximately 5% of the inclusive $W + 1$ jet cross section for jets with a transverse momentum $p_T(j) > 10$ GeV. We study the sensitivity of the $W$ plus charm quark cross section to the parametrization of the strange quark distribution function, and evaluate the various background processes. Strategies to identify charm quarks in CDF and DØ are discussed. For a charm tagging efficiency of about 10% and an integrated luminosity of 30 pb$^{-1}$ or more, it should be possible to constrain the strange quark distribution function from $W + c$ production at the Tevatron.
1 Introduction

One of the main goals of deep inelastic scattering experiments is to obtain reliable measurements of the parton distribution functions of the proton. Recently, the CTEQ [1] and CCFR [2] collaborations have determined the ratio of momentum fractions of strange quarks versus $\bar{u}$ plus $\bar{d}$ quarks,

$$\kappa = \frac{2S}{\bar{U} + \bar{D}},$$

where

$$Q = \int_0^1 xq(x)dx$$

with $Q = \bar{U}, \bar{D}, S$ and $q(x)$ being the parton distribution function of the $\bar{u}, \bar{d}$ and s-quark, respectively. The CCFR collaboration obtained $\kappa \approx 0.4$ in its analysis of the process $\nu N \rightarrow \mu^+ \mu^- X$, whereas the CTEQ collaboration in its global fit found $\kappa \approx 1$. The statistical significance of the difference between the two results is approximately 3 – 4 standard deviations. The CTEQ result can be traced back to the appropriately weighted difference of $F_2^\nu$, measured by CCFR, and $F_2^\mu$ as determined by NMC, which is proportional to the s-quark distribution function (up to $\mathcal{O}(\alpha_s)$ corrections); see Ref. [4] for more details. The CCFR result of $\kappa \approx 0.4$, obtained from the di-muon analysis, is best represented by the MRSD0 parametrization [3]. The value of $\kappa$ in this set was fixed at a value of 0.5 at $Q^2 = 4$ GeV$^2$. As a representative of the CTEQ result, the CTEQ1M set will be used in the following.

The large difference in $\kappa$ results in substantially different s-quark distribution functions for the two parametrizations. This is demonstrated in Fig. 1, where the ratio of the strange quark distribution functions of the two sets is shown for $Q^2 = 5$ GeV$^2$ and $Q^2 = M_W^2$. At small $Q^2$ and $x < 0.1$, the two s-quark distribution functions differ approximately by a factor of two. At large $Q^2$, the ratio of the two sets is closer to unity. This is due to the fact that additional strange quark pairs originating from gluon splitting contribute to the strange quark distribution function. Because both sets have very similar gluon distribution functions, the additional strange quark contribution is almost identical for both sets, and hence the relative difference of the two distribution functions diminishes.

The discrepancy between the CTEQ and MRS parametrizations could be resolved by a direct and independent measurement of the strange quark distribution function. In this letter it is suggested that such a measurement could be carried out at the Tevatron by determining the charm content of $W+1$ jet events. Our paper is organized as follows. In Section 2, the signal for constraining the strange quark distribution function and the leading background processes are studied. In Section 3, different experimental techniques to tag a charm quark inside a jet are discussed and the
minimum integrated luminosity necessary to discriminate between the CTEQ and MRS strange quark distribution function is estimated. Finally, in Section 4, our conclusions are presented together with some additional remarks. Some preliminary results of the work described here were presented in Ref. [4].

2 Signal and Background

Associated $W + \text{charm}$ production proceeds, at lowest order, through $sg$ and $\bar{s}g$ fusion, $sg \rightarrow W^- c$ and $\bar{s}g \rightarrow W^+ \bar{c}$. The alternative process where the $s$-quark in the reaction is replaced by a $d$-quark, is suppressed by the quark mixing matrix element $V_{cd}$. This suppression is somewhat compensated by the larger $d$ quark distribution function, such that the $dg \rightarrow Wc$ cross section is about 10% of the $sg \rightarrow Wc$ rate. Since the final state is identical for these two subprocesses, the sum of the $dg$ and $sg$ contributions will be considered as the “signal”.

The potentially largest background originates from the production of a $c\bar{c}$ pair in the jet recoiling against the $W$. When only the $c$ or the $\bar{c}$ is identified in the jet, such a $W + c\bar{c}$ event looks like a signal event. Similarly, a $b\bar{b}$ pair can be produced in the jet, and the $b$ or the $\bar{b}$-quark misidentified as a charm quark.

For our subsequent discussion it is useful to define the following ratios of cross sections:

\[
\mathcal{R}_1 = \frac{\sigma(\text{signal})}{\sigma(W + 1 \text{ jet})},
\]

\[
R_1(p_T) = \frac{d\sigma(\text{signal})/dp_T(j)}{d\sigma(W + 1 \text{ jet})/dp_T(j)},
\]

\[
\mathcal{R}_2 = \frac{\sigma(\text{signal}) + \sigma(\text{bgd})}{\sigma(W + 1 \text{ jet})},
\]

\[
R_2(p_T) = \frac{d\sigma(\text{signal})/dp_T(j) + d\sigma(\text{bgd})/dp_T(j)}{d\sigma(W + 1 \text{ jet})/dp_T(j)},
\]

and

\[
\mathcal{R}_3 = \mathcal{R}_2 - \mathcal{R}_1, \quad R_3(p_T) = R_2(p_T) - R_1(p_T),
\]

where “bgd” includes the background processes mentioned earlier, assuming that all $b$ and $\bar{b}$-quarks in $W + b\bar{b}$ production are misidentified as charm quarks. The notation “$W + 1 \text{ jet}$” refers to the total inclusive $W + 1 \text{ jet}$ cross section within cuts. $\mathcal{R}_1$ represents the ideal situation in which all background events have been completely eliminated. $\mathcal{R}_2$ describes the conservative case where none of the leading background processes is reduced. Finally, $\mathcal{R}_3$ is useful to explore the sensitivity of the background
to differences between the CTEQ and MRS sets. The background processes receive contributions from quark – antiquark and quark gluon fusion, with all the quarks contributing. They are thus sensitive to global differences in the CTEQ and MRS sets, rather than to differences in the strange quark distribution functions.

In practice, the ratio of events with a tag for a charm quark inside the jet over the total number of events will be measured. The result will fall in between $R_1$ and $R_2$, because specific methods of tagging the charm quark inside of the jet will suppress some parts of the background (see Section 3). Compared to the absolute cross sections, the ratios $R_i$, $i=1,2,3$, have a number of advantages. Many experimental uncertainties, for example the uncertainty in the integrated luminosity, are expected to cancel, at least partially, in the ratios. Furthermore, the sensitivity to the factorization scale $Q^2$ is reduced in the cross section ratios.

To numerically simulate the signal and background processes we use the Monte–Carlo program PYTHIA [5] (version 5.6). All processes are studied at the parton level, i.e. final state showers are included but fragmentation is not. The $c$ and $b$-quark masses are taken to be $m_c = 1.35$ GeV and $m_b = 5$ GeV. For $W + c\bar{c}$ and $W + b\bar{b}$ production, the result of PYTHIA was compared with that of the matrix element calculation of Ref. [6]. The results of both calculations are in general agreement, with PYTHIA resulting in somewhat larger cross sections for the background. In our simulations, a “jet” is defined as follows. The direction of the sum of the momenta of all the partons produced in the shower is taken as the center of a cone of radius $\Delta R_{jet} = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.7$, where $\eta$ is the pseudorapidity and $\phi$ the azimuthal angle. All the partons inside that cone are considered part of the jet. Only events with a charm quark inside the jet cone are counted. Background events with two charm quarks inside the jet cone are counted twice. Only about one half of the background events has two charm quarks inside the cone.

The $W^\pm$ is assumed to decay into a $e^\pm \nu$ final state. To simulate the acceptance of a real detector, the following transverse momentum and pseudorapidity cuts on the final state particles are imposed:

\[
\begin{align*}
  p_T(e) & \geq 20 \text{ GeV}, & |\eta(e)| & \leq 1, \\
  p_T(\nu) & \geq 20 \text{ GeV}, \\
  p_T(j) & \geq 10 \text{ GeV}, & |\eta(j)| & \leq 1.
\end{align*}
\]

The ratios $R_i$ do not depend sensitively on the cuts imposed on the $W$ decay products, and the jet pseudorapidity cut chosen. They are, however, sensitive to the $p_T$ cut on the jet.

Figure 2 shows the differential cross section, $d\sigma/dx_s$, of the process $sg \rightarrow Wc$ for $pp$ collisions at $\sqrt{s} = 1.8$ TeV as a function of the momentum fraction of the strange quark, $x_s$, using the CTEQ1M parametrization and the cuts listed in Eq. 8.
$W$ plus charm quark production at the Tevatron thus is sensitive to the strange quark distribution mostly in the $x_s$ region between 0.04 and 0.1, in which the CTEQ and MRS parametrizations are indeed substantially different (see Fig. 1).

The cross sections for the signal, the various background processes, and inclusive $W + 1$ jet production at the Tevatron are given in Table 1. Approximately 75% (20%) of the background originates from a $c\bar{c}$ ($b\bar{b}$) pair produced in a jet initiated by a gluon, if we assume that all $b$ and $\bar{b}$-quarks are misidentified as charm quarks. The remaining 5% is due to the production of a $c\bar{c}$ pair in a quark–initiated jet. The combined background cross section is about equal to the signal rate. Numerical values for $R_1$, $R_2$ and $R_3$ are presented in Table 2 for the two sets of parton distribution functions. The signal accounts approximately for 4–5% of all $W + 1$ jet events ($R_1$), and the background for about 4% ($R_3$). As can be seen from Table 1, the two sets of parton distribution functions yield the same values for the inclusive $W + 1$ jet cross section and the three background processes to within 2%. Correspondingly, the variation of $R_3$ with the two sets is small. The signal rate, on the other hand, is quite sensitive to which set is chosen, as expected. The variation of the ratios $R_1$ and $R_2$ directly reflects the difference in the strange quark distribution.

Not surprisingly, the cross section ratios are relatively insensitive to changes in the factorization scale $Q^2$. Varying $Q^2$ between $1/4$ and 4 times the default average $Q^2$ of PYTHIA, the ratios change only by $\Delta R_i/R_i \approx 4\%$, although individual cross sections vary by up to 20%. The stability of $R_1$ and $R_2$ with respect to variations in $Q^2$ indicates that the sensitivity of the ratios to the strange quark distribution function is unlikely to be overwhelmed by uncertainties originating from higher order QCD corrections. The signal cross section is insensitive to variations in the $c$-quark mass, due to the high $p_T(j)$ cut used. The background is slightly sensitive to changes in the $c$ and $b$-quark masses, resulting in a $\sim 2\%$ variation in $R_2$ when $m_c$ ($m_b$) is changed from 1.5 GeV (5 GeV) to 1.35 GeV (4.5 GeV).

We have also investigated the sensitivity of our results to the jet cone size $\Delta R_{jet}$. Reducing the cone size from 0.7 to 0.4, the signal, background and inclusive $W + 1$ jet cross sections are reduced by approximately the same amount for both sets of parton distribution functions (10% for the signal, 40% for the background, and 20% for the inclusive $W + 1$ jet rate). A change in $\Delta R_{jet}$ therefore does not alter the sensitivity of $R_1$ and $R_2$ to the strange quark distribution function in first approximation. This result can be easily understood by the general insensitivity of the background and inclusive $W + 1$ jet cross sections to the choice of parton distribution functions, and by noticing that the ratio of the two strange quark distribution functions varies only little in the $x_s$ range accessible in $sg \rightarrow Wc$ (see Figs. 1 and 2). For a constant ratio of $s$-quark distribution functions, the relative change of the cross section ratios would be independent of the jet cone size.

The differential cross section ratios $R_1(p_T)$, $R_2(p_T)$, and $R_3(p_T)$ as a function of
the jet transverse momentum are displayed in Fig. 3. Due to the different $x$ behavior of parton distribution functions, the ratios slowly grow with $p_T(j)$. The difference in $R_1(p_T)$ and $R_2(p_T)$ for the two sets of parton distribution functions is fairly uniform in the jet transverse momentum. $R_3(p_T)$ is practically insensitive to parton distribution function effects over the whole jet $p_T$ range studied. Figure 3 demonstrates that the $W$ plus charm cross section is sensitive to the $s$-quark distribution function over the whole jet transverse momentum range. Of course, the region of low $p_T(j)$ will give better statistics.

We can now estimate the minimum charm tagging efficiency, $\epsilon_c^{\text{min}}$, required to be statistically sensitive to the variation of the $Wc$ production cross section with the strange quark distribution function. To quantify the difference between the two sets of parametrizations in the ratios $\mathcal{R}_i$, the following variable is used:

$$\Delta_i = 2 \frac{\mathcal{R}_i(\text{CTEQ1M}) - \mathcal{R}_i(\text{MRSD0})}{\mathcal{R}_i(\text{CTEQ1M}) + \mathcal{R}_i(\text{MRSD0})}.$$  \hspace{1cm} (9)

Using the numbers listed in Table 2, we find $\Delta_1 = 25\%$, $\Delta_2 = 14\%$, and $\Delta_3 = 2\%$. Assuming both electron and muon decay channel of the $W^\pm$ boson, an integrated luminosity of 10 pb$^{-1}$ yields about 1700 $W+1$ jet events for the cuts described in Eq. 8. This corresponds to approximately 75 – 90 $W$ plus charm quark signal events, and to about the same number of potential background events. To experimentally differentiate between the two sets MRSD0 and CTEQ1M, the experimental uncertainties in measuring $\mathcal{R}_1$ ($\mathcal{R}_2$) must be less or equal to $\Delta_1$ ($\Delta_2$). From the expected number of signal events it is straightforward to estimate $\epsilon_c^{\text{min}}$. Depending on how efficiently the various background processes can be suppressed, an efficiency $\epsilon_c^{\text{min}} \approx 20 – 30\%$ for an integrated luminosity of 10 pb$^{-1}$ is needed. Note that $\epsilon_c^{\text{min}}$ scales like $(\int L dt)^{-1}$.

3 Charm Quark Tagging in Tevatron Experiments

The two collider experiments, CDF and DØ, at the Tevatron explore three different strategies to identify charm quarks:

1. Search for a displaced secondary vertex in the silicon vertex detector (SVX). The efficiency to tag $b$-quarks with the SVX \cite{7} of CDF is about 10–20%, depending on the $p_T$ range. The tagging efficiency for the charm quarks is expected to be smaller than that for bottom quarks as a result of the smaller mass and decay track multiplicity of the charmed hadrons.

2. Reconstruction of exclusive nonleptonic charmed baryon or meson decays. CDF, for example, uses the decay channel $D^0 \rightarrow K\pi$ to identify semileptonic $B$ meson decays \cite{8}. Other exclusive channels will be added in the future, and an efficiency of a few percent should be reached.
3. Looking for inclusive semileptonic charm decays [9]. The average inclusive semileptonic charm decay branching ratio is $B(c \to e\nu, \mu\nu) \sim 10\%$. If one assumes a reconstruction efficiency for a muon inside a jet of the order of 50\% [10], a total charm tagging efficiency from semileptonic charm decays of the order of 5\% may well be possible.

Combined, the three methods may yield an overall charm detection efficiency of about 10\%. Based on this assumption, an integrated luminosity of $\mathcal{O}(30 \, \text{pb}^{-1})$ should provide the first statistically significant information on the strange quark distribution of the proton.

A more precise estimate of the minimum integrated luminosity required depends on a better understanding of the charm quark detection efficiency, and on more detailed background studies. In principle, the three background processes considered here can be reduced by:

- Charge reconstruction: for the signal, the $W$ and $c$ quark electric charges are correlated. For the $c\bar{c}$ background, the charm quark has the wrong charge 50\% of the time. Therefore, if the charges of the $W$ and of the charm quark can be determined, the $Wc\bar{c}$ background can be reduced by a factor of two. Furthermore, events with the wrong charge correlation provide a measurement of the background, that could subsequently be subtracted.

- Cut on the charm transverse momentum: since more than one charm quark is present in the background processes its average $p_T$ is smaller than in the signal. This is illustrated in Fig. 4 where the $c$-quark transverse momentum distribution for the signal (solid histogram) and the background (dashed histogram) is shown, using the CTEQ1M set of parton distribution functions. Due to the $p_T(j) > 10 \, \text{GeV}$ cut, the $p_T$ distribution of the charm quark in the signal sharply peaks at a value of about 10 GeV. On the other hand, the transverse momentum distribution of charm quarks originating from the background processes considered, peaks at $p_T \approx 5 \, \text{GeV}$.

- Flavor identification: if the bottom quark is identified, the $b\bar{b}$ background can be subtracted.

4 Conclusions

We have studied the prospects for constraining the strange quark distribution function in $W + c$ production at the Tevatron. The method we suggest is similar to the one described in Ref. [11] for measuring the charm quark distribution function in $\gamma$ plus charm production. Our results indicate that, for the data sample accumulated in the 1992-93 run, the expected charm tagging efficiencies are a limiting factor. For an integrated luminosity of 30 pb$^{-1}$, a charm tagging efficiency of at least 10\% is needed.
However, with an integrated luminosity of about 100 pb$^{-1}$, which is expected by the end of 1994, it should be possible to make a serious attempt at constraining the strange quark distribution function from $W + c$ production.

In our analysis we have concentrated on the charm content of $W + 1$ jet events with $p_T(j) > 10$ GeV. Alternatively one could search for $W + c$ production in the inclusive $W$ sample, without requiring the presence of a high transverse momentum jet. The advantage here would be a significant increase of the number of signal events. However, due to the smaller average transverse momentum of the charm quarks in the inclusive $W$ sample, the charm quark detection efficiency is expected to be reduced. Furthermore, the ratio of signal to background will decrease.

The largest uncertainties in our calculation arise from the overall charm tagging efficiency at CDF and DØ, and from uncertainties in the estimate of potential background processes. Clearly, more experimental and theoretical work is needed.

If the strange quark distribution function is measured precisely in other experiments, $W$ plus charm quark production may eventually be used to measure the quark mixing matrix element $V_{cs}$ at high $Q^2$ and compare it with the value extracted from low energy experiments [12].

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Table 1: Cross sections for associated $W$ plus charm quark production with $W \rightarrow e\nu$ at the Tevatron, using the MRSD0 and CTEQ1M parametrizations of the parton distribution functions. The cuts imposed are listed in Eq. 8.

|                | Cross section (pb) |
|----------------|--------------------|
|                | Signal | Background | Inclusive |
| $c \rightarrow c + X$ | $g \rightarrow c\bar{c} + X$ | $g \rightarrow b\bar{b} + X$ | $q \rightarrow q\bar{c} + X$ |
| $W + 1$ jet   |        |            |            |        |
| MRSD0         | 3.68   | 2.76       | 0.75       | 0.15   | 87.0 |
| CTEQ1M        | 4.58   | 2.80       | 0.77       | 0.15   | 85.6 |

Table 2: The ratios $\mathcal{R}_1$, $\mathcal{R}_2$ and $\mathcal{R}_3$ for the MRSD0 and CTEQ1M parametrization. The cuts imposed are listed in Eq. 8.

|          | $\mathcal{R}_1$ | $\mathcal{R}_2$ | $\mathcal{R}_3$ |
|----------|-----------------|-----------------|-----------------|
| MRSD0    | 0.042           | 0.084           | 0.042           |
| CTEQ1M   | 0.054           | 0.097           | 0.043           |
Figure 1: Ratio of the strange quark distribution functions as a function of $x$ for the CTEQ1M and MRSD0 sets and two different values of $Q^2$.

Figure 2: The differential cross section $d\sigma/dx_s$ for the process $sg \rightarrow Wc$ at the Tevatron, using the CTEQ1M set. The cuts imposed are listed in Eq. 8.
Figure 3: The differential cross section ratios \( R_1(p_T) \), \( R_2(p_T) \), and \( R_3(p_T) \) as a function of the jet \( p_T \) for the MRSD0 and CTEQ1M sets at the Tevatron. The cuts imposed are listed in Eq. 8.

Figure 4: The transverse momentum distribution of the charm quark inside the jet for the signal, and the three background processes combined, at the Tevatron, using the CTEQ1M set. The cuts imposed are listed in Eq. 8.
solid $\rightarrow Q^2 = 5 \text{GeV}^2$

dashes $\rightarrow Q^2 = M^2$
