MEASUREMENT OF THE STRANGE QUARK DISTRIBUTION FUNCTION IN W + CHARM QUARK EVENTS

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Abstract
We investigate the prospects of measuring the strange quark distribution function at the Tevatron, using W plus charm quark events. The W plus charm 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 briefly described.

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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\cite{CTEQ} and CCFR\cite{CCFR} collaborations have determined the ratio of momentum fractions of strange quark versus $\bar{u}$ plus $\bar{d}$ quarks, $\kappa = 2S/(\bar{U}+\bar{D})$. The CCFR collaboration found $\kappa \approx 0.4$ in its analysis of di-muon events in deep inelastic scattering, whereas the CTEQ collaboration with its global fit analysis obtained a result of $\kappa \approx 1$. The difference between the two results is at the $3 - 4\sigma$ level. Among current parametrizations of the parton distribution functions the MRSD0 set\cite{MRSD0} best represents the CCFR result. The value of $\kappa$ in this set was fixed to $\kappa = 0.5$ at $Q^2 = 4$ GeV$^2$. As a representative of the CTEQ result, we shall use the CTEQ1M set in the following. The difference between the two parametrizations in $\kappa$ is approximately a factor of two at low $Q^2$, and decreases with increasing $Q^2$. This is illustrated in Fig. 1, where the ratio of the strange quark distribution functions for the CTEQ1M and MRSD0 set for $Q^2 = 5$ GeV$^2$ and $Q^2 = M_W^2$ is shown.

Figure 1: Ratio of the strange quark distribution functions for the CTEQ1M set and the MRSD0 set for two different values of $Q^2$.
At large $Q^2$, the strange quarks that originate from gluon splitting have comparable distribution for the two sets because the two gluon distribution functions are very similar.

Here, we point out that the discrepancy between the CTEQ and CCFR result could be resolved by a direct, independent measurement of the strange quark distribution function. At the Tevatron, such a measurement could be carried out by determining the charm content of $W + 1$ jet events. The paper is organized as follows. In Section 2, the signal and the leading background processes are studied. In Section 3, different experimental techniques to tag a charm quark inside a jet are discussed. Finally, in Section 4, we present our conclusions together with some additional remarks.

2 Signal and Background

Associated $W+$ 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 $V_{td}$. 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 $sg$ and $dg$ contributions will be considered as the “signal” in the following.

The largest background originates from the production of a $c\bar{c}$ pair in the jet recoiling against the $W$. If only the $c$, or the $\bar{c}$ quark, is identified in the jet, the 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. Assuming that all the $b$ quarks are misidentified, approximately 75% (20%) of the background originates from a $c\bar{c}$ ($b\bar{b}$) pair produced in a jet initiated by a gluon. The remaining 5% is due to the production of a $c\bar{c}$ pair in a quark–initiated jet.

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

$$R_1 = \frac{\text{signal}}{W + 1 \ jet}.$$ (1)
and

\[ R_2 = \frac{signal + background}{W + 1 \ jet}, \]

where “background” includes the three background processes mentioned earlier, and “\( W + 1 \ jet \)” refers to the total inclusive \( W + 1 \) jet cross section. \( R_1 \) represents the ideal situation in which all background events are completely eliminated. \( R_2 \) describes the case where none of the background is removed. In practice, the ratio of events with a tag for a charm quark inside of the jet over the total number of events will be measured. The result for this ratio will fall in between \( R_1 \) and \( R_2 \), because specific methods of tagging the charm quark inside of the jet will suppress some part of the background, see Section 3. There are three possibilities to reduce the background:

- **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 \( c \) quark are determined, the \( c\bar{c} \) 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 quark transverse momentum:** since more than one charm quark is present in the background processes, the average \( p_T \) of the charm quark is smaller than in the signal.

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

To numerically simulate the signal and background processes we have used the Monte–Carlo program PYTHIA\(^4\) (version 5.6). For \( W + c\bar{c} \) and \( W + b\bar{b} \) production, we have compared the result of PYTHIA with that of the matrix element calculation of Ref.\(^5\). The results of both calculations are in general agreement, with PYTHIA resulting in a somewhat larger background. In our simulations, a “jet” is defined in the following way. 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 \( \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.7 \), where \( \eta \) is the pseudorapidity and \( \phi \) the azimuthal angle. All the partons inside the cone are considered to be part of the jet. The \( W \) is assumed to decay into an electron (or positron)
and a neutrino. To simulate the acceptance of a real detector, we impose the following cuts on the final state particles:

\[
p_T(e) \geq 20 \text{ GeV}, \quad |\eta(e)| \leq 1.
\]
\[
\psi_T \geq 20 \text{ GeV},
\]
\[
p_T(j) \geq 10 \text{ GeV}, \quad |\eta(j)| \leq 1.
\]

Equation (3)

Our results for \( R_1 \) and \( R_2 \) do not depend sensitively on the cuts. Events with two charm quarks inside a jet are counted twice. Numerical values for \( R_1 \) and \( R_2 \) are presented in Table 1 for the MRSD0 and CTEQ1M parametrizations.

Table 1: The ratios \( R_1 \) and \( R_2 \) for the MRSD0 and CTEQ1M parametrization.

|       | \( R_1(\%) \) | \( R_2(\%) \) |
|-------|--------------|--------------|
| MRSD0 | 4.2          | 8.4          |
| CTEQ1M| 5.3          | 9.7          |

As can be seen in Table 1, \( R_2 \) is about twice as large as \( R_1 \), which means that the signal-to-background ratio is of order unity. The average values for the ratios \( R_1 \) and \( R_2 \) are roughly 5\% and 9\%, respectively. To quantify the difference between the two sets, we define the ratio

\[
\Delta = \frac{R(CTEQ1M) - R(MRSD0)}{\frac{1}{2}(R(CTEQ1M) + R(MRSD0))},
\]

Equation (4)

where \( R \) stands for \( R_1 \) or \( R_2 \). \( \Delta \) is equal to 23\% and 14\% for \( R_1 \) and \( R_2 \), respectively. In order to perform a meaningful measurement, the experimental uncertainty in measuring \( R_1 \) or \( R_2 \) must be less than the corresponding value for \( \Delta \). In Fig. 2, the ratios \( R_1 \) and \( R_2 \) are shown for the two parametrizations as a function of the \( p_T \) of the jet.

The two sets of parton distribution functions yield the same values for the inclusive \( W + 1 \) jet cross section and the background to within 1\%. The variation of the ratios \( R_1 \) and \( R_2 \) with the parton distribution functions therefore directly reflects the difference in the strange quark distribution. Not surprisingly, both cross section ratios are not very sensitive to changes in the factorization scale \( Q^2 \). Varying \( Q^2 \) between 1/4 and 4 times the default
Figure 2: The cross section ratios $R_1$ and $R_2$ as a function of the jet $p_T$ for the MRSD0 and CTEQ1M parametrizations of the parton distribution functions.

average $Q^2$ of PYTHIA, the ratios change only by $\Delta R/R \approx 4\%$. 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.

Assuming both electron and muon decay channels of the $W^{\pm}$, an integrated luminosity of 10 pb$^{-1}$ yields about 2000 $W+1$ jet events for the cuts summarized in Eq. (3). This corresponds to approximately 100 $W$ plus charm quark signal events, and to about the same number of potential background events. From the expected number of signal events it is straightforward to estimate the charm tagging efficiency, $\epsilon_c^{min}$, required to be statistically sensitive to the variation of the $W+c$ production cross section with the strange quark distribution function. Depending on how efficiently the various background processes can be suppressed, we find $\epsilon_c^{min} \approx 20 - 30\%$ for an integrated luminosity of 10 pb$^{-1}$. Note that $\epsilon_c^{min}$ scales like $(\int L dt)^{-1}$. 

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3 Charm Quark Tagging in CDF and DØ

CDF and DØ explore three different strategies to identify charm quarks:

1. Search for a displaced secondary vertex in the vertex detector. The efficiency to tag $b$ quarks with the SVX of CDF is about 10–20%, depending on the $p_T$ range. The tagging efficiency for charm quarks is expected to be smaller than that for bottom quarks, due to 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. Other exclusive channels will be added in the future, and an efficiency of a few percent should be reached.

3. Searching for inclusive semileptonic charm decays. The average inclusive semileptonic charm decay branching ratio is $B(c \rightarrow e\nu, \mu\nu) \sim 10\%$. If one assumes a reconstruction efficiency for a muon inside a jet of the order of 50%, 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%.

4 Conclusions

We have studied the prospects for measuring the strange quark distribution function in $W + c$ production at the Tevatron. The method is similar to the one described in Ref. 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 100 pb$^{-1}$, however, one could seriously attempt to determine 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.

Clearly, more experimental and theoretical work is needed in order to determine reliably whether a measurement of the $s$ quark distribution function in $W + c$ production is feasible.

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[10].

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solid $\rightarrow Q^2=5\text{GeV}^2$

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