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MEASUREMENT OF THE STRANGE QUARK DISTRIBUTION FUNCTION IN $W + \text{CHARM}$ 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 $W + \text{charm}$ quark cross section to the parametrization of the strange quark distribution function, and evaluate the various background processes. The different prospects of tagging the charm quark with the CDF and DØ detectors are briefly discussed.

1. Introduction

One of the main goals of deep inelastic scattering experiments is to obtain reliable measurements of the parton distribution functions in the proton. Recently, the CTEQ¹ and CCFR² collaborations have determined the ratio of momentum fractions of strange, and $\bar{u}$ plus $\bar{d}$ quarks, $\kappa = 2S/(\bar{U} + \bar{D})$. The CCFR collaboration obtained $\kappa \approx 0.4$ 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

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Figure 1: Ratio of the strange quark distribution functions for the CTEQ1M set and the MRSD0 set for two different values of Q^2 .

parametrizations of the parton distribution functions the MRSD0³ set best represents the CCFR result. The κ of this set was fixed at a value of 0.5 at $Q^2 = 4 \text{ GeV}^2$. As a representative of the CTEQ result, we shall use the CTEQ1M set in the following. The difference in κ -values is a factor of two for 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 $Q^2 = 5 \text{ GeV}^2$ and $Q^2 = M_W^2$ is shown. At the 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 $W + \text{charm}$ 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 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

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sg contributions will be considered as the “signal”.

One background is due to 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, 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. Here, it is assumed that all the b quarks are misidentified as c quark. Approximately 75% (20%) of the background originates from a $c\bar{c}$ ($b\bar{b}$) pair produce in a jet initiated by a quark. 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 two ratios:

$$R_1 = \frac{\text{signal}}{W + 1 \text{ jet}}, \quad (1)$$

and

$$R_2 = \frac{\text{signal} + \text{background}}{W + 1 \text{ jet}}, \quad (2)$$

where “background” includes the three backgrounds mentioned earlier. R_1 represents the ideal situation in which all background events have been completely eliminated. R_2 describes the case where none of the background is eliminated. In practice, one will measure the ratio of events with a tag for a charm quark inside of the jet over the total number of events. 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 charm quark can be determined, the $c\bar{c}$ background can be reduced by a factor of two. Furthermore, it would provide a measurement of the background, that could subsequently be subtracted.
- **Charm transverse momentum measurement:** since more than one charm quark is present in the background processes its average p_T will be 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 Pythia⁴ (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 η is the pseudorapidity and ϕ the azimuthal angle. All the partons inside that cone are considered 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:

$$\begin{aligned} p_T(e) &\geq 20 \text{ GeV}, & |\eta(e)| &\leq 1. \\ p_T(\nu) &\geq 20 \text{ GeV}, & & \\ p_T(j) &\geq 10 \text{ GeV}, & |\eta(j)| &\leq 1. \end{aligned} \quad (3)$$

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

$$\Delta = \frac{R(\text{CTEQ1M}) - R(\text{MRSD0})}{\frac{1}{2}(R(\text{CTEQ1M}) + R(\text{MRSD0}))}, \quad (4)$$

where R stands for R_1 or R_2 . Δ is equal to 23%, and 14% for R_1 and R_2 , respectively. In Fig. 2, the ratios R_1 and R_2 are shown for the two parton distribution sets 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 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 $\Delta R/R \approx 4\%$. 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 channel of the W , an integrated luminosity of 10 pb^{-1} yield about 2000 $W + 1$ jet events for the cuts mentioned earlier. This corresponds to approximately 100 W plus charm quark signal events,

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.

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, ϵ_c , required to be statistically sensitive to the variation of the Wc production cross section with the strange quark distribution function. Depending on how efficiently the various background processes can be suppressed, we find $\epsilon_c \approx 20 - 30\%$ for an integrated luminosity of 10 pb^{-1} . Note that ϵ_c scales like $(\int \mathcal{L} dt)^{-1}$.

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 the b quarks with the SVX⁶ 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 the bottom quark 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.⁷ 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.⁸ 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. 9 for measuring the charm quark distribution function in γ 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 $p_T(j) > 10 \text{ GeV}$. 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.

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