Neutrino Production of Opposite-Sign Dimuons at Fermilab Tevatron Energies

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We have measured the strange-quark content of the nucleon, $\eta_s = 0.057^{+0.012}_{-0.008}$, and the Kobayashi-Maskawa matrix element $|V_{cd}| = 0.220^{+0.015}_{-0.018}$ using a sample of 1797 ν_μ- and $\bar{\nu}_\mu$-induced $\mu^-\mu^+$ events with $P_\mu \geq 9$ GeV/c and $30 \leq E_\nu \leq 600$ GeV. The data are consistent with the slow-rescaling hypothesis of charm production in ν-N scattering and within this formalism yield a value of the charm-quark mass parameter $m_c = 1.31^{+0.64}_{-0.48}$ GeV/c^2.

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Opposite-sign dimuon ($\mu^-\mu^+$) production in neutrino-nucleon interactions originates primarily from the production of charmed quarks. Since charmed quarks are mainly produced from valence down quarks and sea strange quarks, measurements of the strange content of the nucleon can be extracted from the production rate and kinematics of $\mu^-\mu^+$ events. In addition, these events can be used to extract the Kobayashi-Maskawa (KM) matrix element V_{cd} and a parametrization of the threshold behavior of charm production. (Knowledge of this threshold behavior is a dominant source of systematic error[1] in extracting $\sin^2\theta_W$ from deep-inelastic ν-N scattering.) The high-statistics experiment presented here is the first measurement of opposite-sign dimuon production above 300 GeV and yields the first measurement of the m_c parameter of slow rescaling,[2] the first quantitative measurement of the momentum dependence of the strange sea, and a new measurement of V_{cd} with smaller errors than previous experiments.[3,4]

The phenomenology of neutrino $\mu^-\mu^+$ production involves the slow-rescaling prescription[2] for the production of the heavy charm quark, and a fragmentation model for charmed-meson production and decay. In the standard slow-rescaling parton model, the cross section for producing a charm quark of mass m_c from a light d or s quark in an isoscalar target is[4]

$$\frac{d^2\sigma(\nu N \to cX)}{d\xi\, dy} = \frac{G^2 M E_\nu}{\pi} \{\xi[u(\xi)+d(\xi)]\,|V_{cd}|^2 + 2\xi s(\xi)\,|V_{cs}|^2\} \left(1 - \frac{m_c^2}{2ME_\nu\xi}\right), \quad (1)$$

where M is the nucleon mass, and V_{cd} and V_{cs} are the KM matrix elements.[5] In this expression, the usual momentum fraction $x = Q^2/2MEy$ is modified to $\xi = x(1+m_c^2/Q^2)$. The function $q(\xi)$ ($q = u$, d, or s) is the probability distribution of a quark q to have a fraction ξ of the nucleon momentum. For $\bar{\nu}$-N interactions, the cross section is also given by Eq. (1) where the functions q are replaced by $\bar{q}$.

The data were accumulated using the Fermilab Tevatron quadrupole triplet neutrino beam (QTB) with the Columbia-Chicago-Fermilab-Rochester (CCFR) detector.[6] After fiducial and kinematic cuts, 670000 ν_μ-N and 124000 $\bar{\nu}_\mu$-N charged-current events remained with mean visible energies 160 and 120 GeV, respectively. From this charged-current sample, 1797 $\mu^-\mu^+$ events were extracted by searching for events with two tracks in the drift chambers. These events were required to have hadronic energy $E_{\rm had} \geq 4$ GeV, both muons with momentum $P_\mu \geq 9$ GeV/c, and an angle at the vertex $\theta_\mu \leq 0.250$ rad.

The $\mu^-\mu^+$ events were divided into those from incident ν or $\bar{\nu}$ by assuming that the leading muon has larger transverse momentum with respect to the direction of the hadron shower than the muon from the charm decay. This algorithm finds 1522 ν_μ-induced and 275 $\bar{\nu}_\mu$-induced $\mu^-\mu^+$ events. Monte Carlo studies, described below, indicate that the algorithm introduces a $(2 \pm 0.2)\%$ $[(26 \pm 3)\%]$ contamination in the ν_μ $[\bar{\nu}_\mu]$ sample where the errors are due to uncertainties in the Monte Carlo modeling.

The background to the $\mu^-\mu^+$ sample from muonic decays of π and K mesons in the hadron shower[6] was calculated to be 101.7 ± 15.4 events for the ν_μ and 11.4 ± 1.7 for $\bar{\nu}_\mu$ events. All other background sources of $\mu^-\mu^+$ events (trimuons, b quarks, J/ψ production, etc.) are calculated to be small ($<1\%$). After the background subtraction and the contamination correction, the charm signal consists of 1460.4 ± 42.1 ν_μ- and 223.5 ± 15.0 $\bar{\nu}_\mu$-induced $\mu^-\mu^+$ events.

A Monte Carlo program was employed to simulate both single-muon and $\mu^-\mu^+$ data in order to model the detector acceptance, resolution smearing, and missing energy associated with the charm decay. In this simulation, the quark and antiquark momentum densities were taken from the CCFR structure functions.[7] The strange-quark momentum density was parametrized as $x\bar{s}(x) = xs(x) = S_0(1+\beta)(1-x)^\beta$ with β and the normalization S_0 left as free parameters. [Throughout the paper, U_0, D_0, S_0, $\bar{U}_0$, $\bar{D}_0$, and $\bar{S}_0$ represent the integral of the quark momentum densities at the average $Q_0^2 = 16.85$ GeV^2/c^2 of the $\mu^-\mu^+$ data; i.e., $U_0 = \int_0^1 x \times u(x)dx$.]

The $\mu^-\mu^+$ Monte Carlo simulation follows Eq. (1), where the charm-quark fragmentation into a charmed D meson is modeled using the Peterson function[8] with $\epsilon = 0.19 \pm 0.10$ (Ref. 9) and the transverse-momentum distribution of the charmed mesons about the hadron shower direction by $dN/dp_t^2 \propto \exp(-ap_t^2)$ with $a = 1.1 \pm 0.3$ $(\mathrm{GeV}/c)^{-2}$.[10] The resulting dimuon Monte Carlo and data E_{μ_2} and p_t distributions are in good agreement. The semileptonic-decay kinematics of D mesons follows Ref. 11 with the mean muonic branching ratio B_c left as a free parameter.

Information about the strange sea, the branching ratio, and the charm mass parameter is extracted by comparing the data and Monte Carlo x_{vis} and E_{vis} distributions, where $E_{\mathrm{vis}} = E_{\mu_1} + E_{\mu_2} + E_{\mathrm{had}}$ and

$$x_{\mathrm{vis}} = E_{\mathrm{vis}}(E_{\mu_1} - P_{\mu_1}\cos\theta_{\mu_1})/M(E_{\mathrm{had}} + E_{\mu_2})$$

(μ_1 is the leading lepton-vertex muon and μ_2 is the muon from the charm decay). The $\mu^-\mu^+$ data and Monte Carlo events are divided into ten x_{vis} bins and five E_{vis} bins and the $\mu^-\mu^+$ Monte Carlo normalization is fixed by the relative number of charged-current single-muon events in the data and the Monte Carlo simulation. A four-parameter χ^2 fit of the binned data compared to the predictions of the Monte Carlo simulation yields

$$\eta_s = 2S_0/(U_0+D_0) = 0.057^{+0.010+0.007}_{-0.008-0.002},$$

$$B_c = 0.109 \pm 0.010^{+0.005}_{-0.010}, \quad \beta = 10.8^{+1.1}_{-1.0} \pm 0.7,$$

and

$$m_c = 1.31^{+0.31+0.56}_{-0.36-0.32}\ \mathrm{GeV}/c^2,$$

where the first error is statistical and the second is systematic. [These parameters are extracted using $V_{cd} = 0.220 \pm 0.003$ and $V_{cs} = 0.9744 \pm 0.0011$ (Ref. 5).]

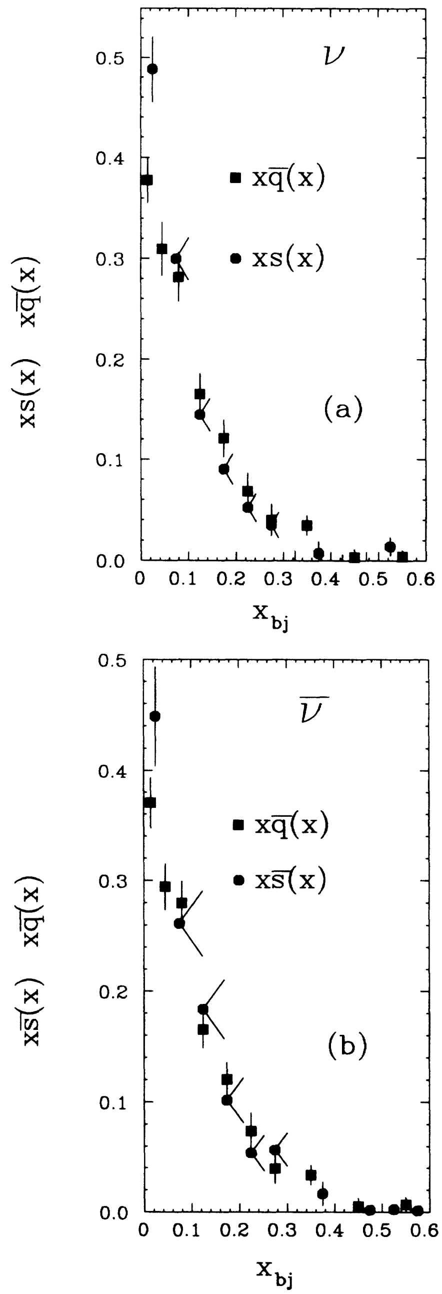

FIG. 1. Strange-quark momentum distributions $xs(x)$ and $x\bar{s}(x)$ (circles) and $x\bar{q}(x) = x\bar{u}(x) + x\bar{d}(x) + x\bar{s}(x)$ (squares) evaluated at the mean Q^2 of the dimuon data for each x bin, from (a) ν_μ data and (b) $\bar{\nu}_\mu$ data.

Combining η_s with the measured antiquark fraction,[7]

$$R_{\bar{Q}} = (\bar{U}_0 + \bar{D}_0 + \bar{S}_0)/(U_0 + D_0 + S_0) = 0.153,$$

we extract the more commonly quoted strange sea fraction, $\kappa = 2S_0/(\bar{U}_0 + \bar{D}_0) = 0.44^{+0.09+0.07}_{-0.07-0.02}$. The minimum χ^2 of the fit is 42 for 46 degrees of freedom, indicating good agreement between the data and Monte Carlo distributions.

In order to investigate the shape differences implied by the difference between β and the exponent α of the total sea, $\alpha = 6.93$,[7] we compare the extracted $xs(x)$ and $x\bar{s}(x)$ distributions with $x\bar{q}(x) = x\bar{u}(x) + x\bar{d}(x) + x\bar{s}(x)$ distributions from Ref. 7 evaluated at the same Q^2 as the dimuon data. The $xs(x)$ and $x\bar{s}(x)$ are taken from the prompt-dimuon x_{vis} distributions after corrections for acceptance, contamination, kinematic cuts, missing energy, threshold effects, and the valence-quark contribution (ν data only). The comparison is shown in Fig. 1 with $xs(x)$ and $x\bar{s}(x)$ normalized to the same integral as the $x\bar{q}(x)$ distribution. The two distributions agree for $x > 0.05$ but differ in the first x bin indicating either a softer x distribution for s quarks or deficiencies in the slow-rescaling and QCD model at low x.

The KM coupling $|V_{cd}|$, assumed to be known in the above fits, can be determined from the dimuon data by fitting for different parameters. Three quantities, representing the contributions of s (or $\bar{s}$), d-sea, and d-valence quarks to the dimuon cross section, are extracted assuming $m_c = 1.5^{+0.4}_{-1.5}$ GeV/c^2, $\beta = 10.1 \pm 2.0$, $\epsilon = 0.19 \pm 0.10$, and $R_{\bar{Q}} = 0.153$. This fit gives

$$[\kappa/(\kappa+2)]B_c|V_{sc}|^2 = (0.191^{+0.036+0.026}_{-0.039-0.074}) \times 10^{-1},$$

$$[1/(\kappa+2)]B_c|V_{cd}|^2 = (0.318 \pm 0.430 \pm 0.332) \times 10^{-2},$$

and

$$B_c|V_{cd}|^2 = (0.534 \pm 0.050^{+0.015}_{-0.060}) \times 10^{-2},$$

where the first error is statistical and the second is systematic (the sensitivity to various model parameters is small because of the high energy and relatively flat energy spectrum of the quadrupole beam). Since from the $\mu^-\mu^+$ data we can only measure the product $B_c|V_{cd}|^2$, we extract V_{cd} using $B_c = 0.110 \pm 0.009$ obtained from ν_μ-emulsion charmed-particle fractions[12] combined with measured lifetimes.[11] This procedure yields a value of $|V_{cd}| = 0.220^{+0.015}_{-0.018}$, including statistical and systematic errors. This measurement has smaller errors than the lower value reported by the CERN-Dortmund-Heidelberg-Saclay (CDHS) Collaboration[3] of $B_c|V_{cd}|^2 = (0.41 \pm 0.07) \times 10^{-2}$, where the errors given were statistical only.

We check the slow-rescaling model, by comparing the rate of 2μ production versus single muons $(\sigma_{2\mu}/\sigma_{1\mu}|_{\nu,\bar{\nu}})$ as a function of E_ν with the predictions of the model. The dimuon rates versus E_ν are shown in Fig. 2 (squares) for ν and $\bar{\nu}$ data. The dependence on energy of the 2μ rates is attributed to the production of a heavy quark (charm) in the final state as described in Eq. (1). After the charm threshold effect was removed using the slow-rescaling prescription with $m_c = 1.5$ GeV/c^2, the data (circles in Fig. 2) are consistent with the model predictions of no energy dependence.

From these studies of high-energy dimuon production at the Tevatron, we conclude that the slow-rescaling mechanism adequately describes our sample of single-

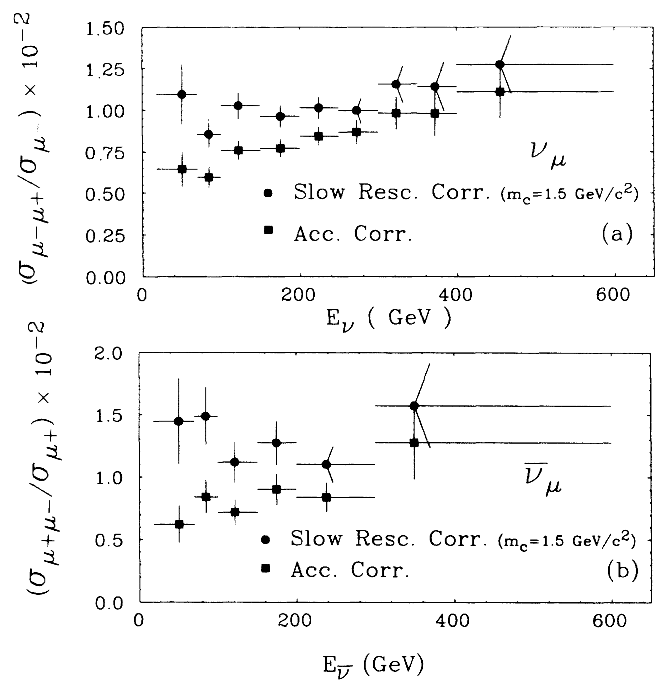

FIG. 2. Opposite-sign dimuon rates as a function of E_ν for (a) ν_μ and (b) $\bar{\nu}_\mu$ data corrected for acceptance, kinematic cuts, missing energy, and contamination (squares) and after corrections for slow rescaling (circles) assuming that $m_c = 1.5$ GeV/c^2. The systematic uncertainties due to the fragmentation model are 15%, 15%, 10%, and 10%, for the first four bins and 5% for the higher-energy bins.

charm production in ν-N scattering with $m_c = 1.31^{+0.64}_{-0.48}$ GeV/c^2 for energies between 30 and 600 GeV. We have measured the Kobayashi-Maskawa coupling $|V_{cd}| = 0.220^{+0.015}_{-0.018}$. The momentum fraction carried by the strange quarks relative to nonstrange quarks in the sea is found to be $\kappa = 0.44^{+0.09+0.07}_{-0.07-0.02}$, approximately half of that expected for an SU(3)-flavor-symmetric quark sea, and the strange-quark momentum distribution is consistent with the nonstrange sea for $x > 0.05$.

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