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Dimuon Measurements and the Strange-Quark Sea

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This paper discusses a method for the extraction of the ratio $f_s = \int xs(x)\,dx/\int xd(x)\,dx$ from dimuon rate measurements in neutrino and antineutrino scattering, which takes into account the threshold effects for heavy-quark production. From the y dependence of $\bar{\nu}$ scattering to dimuon final states the parameter $m_c^{\,2}$, which appears in the definition of the slow rescaling variable $\xi = x + m_c^{\,2}/2EM_p y$, is estimated. This paper further discusses the crucial uncertainties inherent in the measurement of f_s.

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One recurring problem in the parton interpretation of neutrino scattering is our meager knowledge of the amount of strange-quark sea in the proton. As the sea content at low Q^2 is an input to most quantum-chromodynamics (QCD) calculations, large uncertainties in this quantity are bound to have serious consequences. I discuss in this Letter a method of easily accounting for rescaling effects in the extraction of the quantity $S = \int xs(x)\,dx$ from charm production by neutrinos and antineutrinos at moderate energies where the threshold effects might dominate any QCD corrections of the parton distributions.

We are motivated by the recent observation by the Columbia–Brookhaven National Laboratory Bubble-Chamber Group[1] working at Fermilab that the excitation function for $\mu^- e^+$ events in neutrino charged-current interactions has a gradual energy dependence (see Fig. 1). This is the first observation of this phenomenon in the bubble chamber where momentum cuts on the leptons are not severe and serves, then, as the first observation of the threshold suppression in charmed-particle production by neutrinos. As has long been acknowledged,[3] the neutrino production of charm is a potentially good tool for determining the strange-quark sea because of the Cabibbo-allowed $s \to c$ ($\bar{s} \to \bar{c}$ in $\bar{\nu}$) transition. I take as *Ansatz* for this production the modification of the naive quark-parton model first described by Barnett[4] within the context of the possible right-handed $\bar{\nu}$ production of heavy quarks of a few years ago. Those ideas, as relevant to charmed-particle production by neutrinos and antineutrinos, suggest that the cross section is best represented by[4]

$$\frac{d^2\sigma}{dx\,dy} = \frac{G^2ME}{\pi} T(x,y,E)\left[a\xi d(\xi)\sin^2\theta_d + \xi s(\xi)\cos^2\theta_s\right]\theta(1-\xi) = \frac{G^2ME}{\pi}\left[(a\sin^2\theta_d)d_R + (\cos^2\theta_s)s_R\right], \tag{1}$$

where $a=1$ for ν, $a=0$ for $\bar{\nu}$; $d_R \equiv T(x,y,E)\,\xi d(\xi)\,\theta(1-\xi)$, $s_R \equiv T(x,y,E)\,\xi s(\xi)\,\theta(1-\xi)$ and I assume

$$xs(x) = x\bar{s}(x).$$

θ_d represents the mixing angle for the $d \to c$, $\Delta S = 0$ transition and θ_s is the angle for the $\Delta S = 1$ transition. The variable ξ is the so-called "slow rescaling variable" and is the fraction of momentum of the target which is carried by the struck quark (either down or strange). It is defined as[5]

$$\xi = x + m_c^{\,2}/2EM_p y. \tag{2}$$

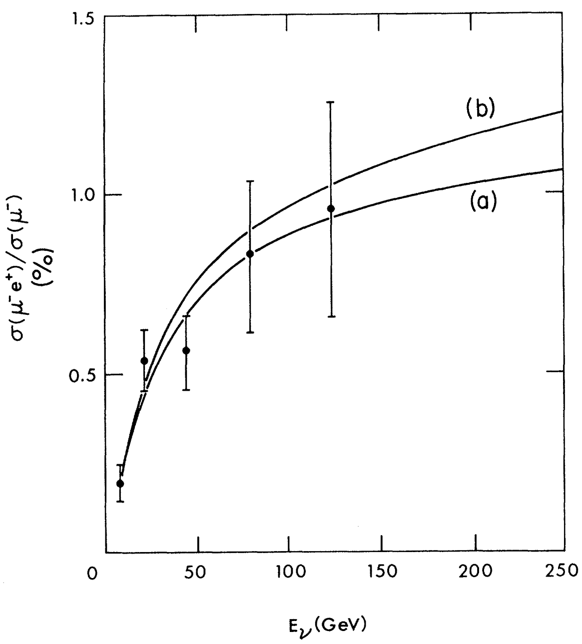

FIG. 1. The ratio $\sigma(\mu^- e^+)/\sigma(\mu^-)$ as a function of energy in neutrino scattering from an isoscalar target. The data come from the Columbia–Brookhaven National Laboratory collaboration (Ref. 1). The curves are the shapes predicted for this quantity using $m_c = 1.5\ \mathrm{GeV}/c^2$. Curve *a* was calculated using the Field and Feynman (Ref. 2) normalizations for the parton distributions and corresponds to a branching ratio of $c \to \mu^+$ of approximately 14%. Curve *b* was calculated using the same parton distributions with twice the amount of strange-sea quarks as in Ref. 5. Curve *b* corresponds to a branching ratio of approximately 11%.

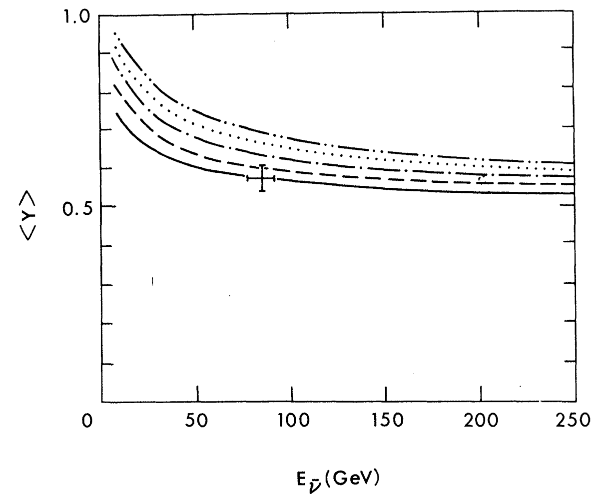

FIG. 2. Mean value of y as a function of antineutrino energy as defined in Eq. (5) for $\bar{\nu}$-induced $\mu^+\mu^-$ events. The datum point is $\langle y \rangle = 0.57 \pm 0.03$ at $\langle E \rangle = 85 \pm 6$ GeV for $\mu^+\mu^-$ events from antineutrino scattering in the experiment of Molder *et al.* (Ref. 6). The curves are $\langle y \rangle$ calculated using various values of m_c: solid curve, $m_c = 1.5\ \mathrm{GeV}/c^2$; dashed curve, $m_c = 2.0\ \mathrm{GeV}/c^2$; and dash-dotted curve, $m_c = 2.5\ \mathrm{GeV}/c^2$.

This cross section is suppressed relative to the rescaled form (at $E \to \infty$) by the functional dependence of the parton densities on ξ rather than x; by the factor $T(x, y, E)$, which is

$$T(x, y, E) = 1 - y + xy/\xi; \tag{3}$$

and by the $\theta(1-\xi)$ function which reduces the x-y phase space to

$$x < 1 - m_c^2/2EM_p y \tag{4a}$$

and

$$y > m_c^2/2EM_p. \tag{4b}$$

A problem in all approaches to the strange-sea measurement through a charm signal is that the extraction of S from the measured quantities is complicated by the presence of $T(x, y, E)$ and $\xi s(\xi)$ rather than $xs(x)$ alone.

Apart from whatever fundamental uncertainties there may be in the basic rescaling approach, the only uncertain parameter in the model is m_c. I take the approach that m_c is simply a parameter defined so that the maximum value of ξ is unity [see Eq. (3.12b) in Albright and Shrock in Ref. 4]. This preserves the useful identification of ξ as a momentum fraction and allows us to treat m_c as a measurable phenomenological parameter. In the following I assume that the shape of $xs(x)$ $[=x\bar{s}(x)]$ can be reasonably taken as that of Field and Feynman[2] (FF), which is $(1-x)^8$. Assuming this, I will describe a simple method of obtaining the coefficient of this function (which is 0.1 in FF). In order to do this, I use $\langle y \rangle$ vs E in $\bar{\nu}$ scattering to $\mu^+\mu^-$ final states to give a reasonable value for m_c. $\bar{\nu}$ data are used because

$$\langle y \rangle = \int y s_R\, dx\, dy \Big/ \int s_R\, dx\, dy \tag{5}$$

is independent of the normalization for the strange quark parametrization. Figure 2 shows the result of the present calculation of this quantity for various values of m_c. Also shown are the results of Holder *et al.*[6] for $\mu^+\mu^-$ events at the average energy of 85 ± 6 GeV. A value for the parameter m_c of 1.5 GeV is reasonable and is used in the following.

One can now investigate the amount of suppression that would be experienced in the neutrino and antineutrino production of charm. This suppression is rather severe (larger values of m_c leading to still larger suppression). I demon-

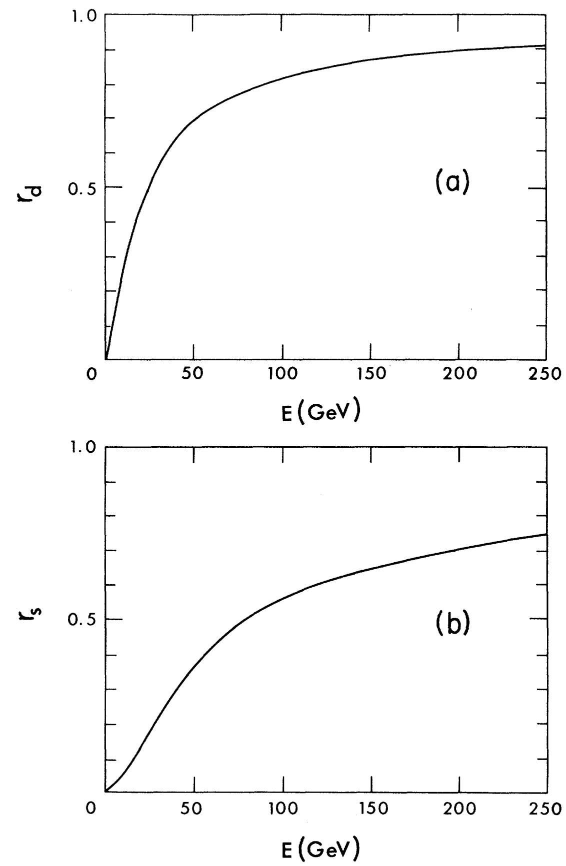

Fig. 3. (a) r_d and (b) r_s, as a function of energy. r_d and r_s are defined in Eqs. (6a) and (6b) which are normalized to unity at asymptotic energies. The shapes of the individual parton distributions are from Ref. 2, and the normalizations of the distributions are arbitrary when displayed as r_d and r_s.

strate this suppression by plotting the ratios

$$r_s \equiv S^{-1}\int s_R dx dy \qquad (6a)$$

and

$$r_d \equiv D^{-1}\int d_R dx\, dy \qquad (6b)$$

[with $D \equiv \int x d(x)\, dx$] in Figs. 3(a) and 3(b). Note that at 50 GeV the down quark is only 75% activated while the strange sea is less than half activated.

In Fig. 1, curve a is the shape of the total cross section for charmed-quark production using FF normalizations. Curve b is the same quantity with twice the FF strange-quark sea. The data are uncertain enough at high energies to accommodate either of these normalizations. Clearly, this is not a useful method of determining S.

A better method for accomplishing this is to determine the quantity

$$F_s(E) = \int s_R dx\, dy / \int d_R dx\, dy \qquad (7)$$

in dimuon production by both neutrinos and antineutrinos. This can be obtained by rates at a particular energy—the rescaling effects making $F_s(E)$ an energy-dependent quantity. One assumes that the cross sections for dimuon production via charm for neutrinos and antineutrinos can be schematically represented by

$$\sigma(\mu\mu, \nu) \propto v \sin^2\theta_d \int d_R dx\, dy + s\cos^2\theta_c \int s_R dx\, dy, \qquad (8a)$$

$$\sigma(\mu\mu, \bar{\nu}) \propto \bar{s}\cos^2\theta_c \int \bar{s}\, dx\, dy, \qquad (8b)$$

where v, s, and $\bar{s}$ are the semileptonic branching ratios for charmed particles originating from valence d quarks, s sea quarks, or $\bar{s}$ sea quarks where d_R and s_R are defined in Eq. (6) (I assume that $\bar{s}_R = s_R$). By a measurement of

$$R_{21}(E) = \sigma^{\nu}(\mu\mu)/\sigma^{\nu}(\mu^-), \qquad (9a)$$

$$\bar{R}_{21}(E) = \sigma^{\bar{\nu}}(\mu\mu)/\sigma^{\bar{\nu}}(\mu^+), \qquad (9b)$$

and

$$R(E) = \sigma^{\bar{\nu}}(\mu^+)/\sigma^{\nu}(\mu^-) \qquad (9c)$$

and a simple manipulation of Eqs. (8a) and (8b), the following is obtained:

$$F_s(E) = \frac{(v/s)(\sin\theta_d/\cos\theta_s)^2}{(1/R)(\bar{s}/s)[R_{21}(E)/\bar{R}_{21}(E)] - 1}. \qquad (10)$$

In principle, this can vary with energy and hence is not the desired quantity which is

$$f_s = S/D = \int x s(x)\, dx / \int x d(x)\, dx. \qquad (11)$$

We can, however, scale $F_s(E)$ to asymptotic energies by constructing the function shown in Fig. 4 which is the ratio of the curves in Fig. 3. We then obtain

$$f_s = [r_d(E)/r_s(E)] F_s(E). \qquad (12)$$

The normalization of S can then be fixed by some other determination of D.[7]

There are three uncertain ratios in Eq. (10). They are (a) v/s, (b) $\bar{s}/s$, and (c) $\tan^2\theta = \sin^2\theta_d/\cos^2\theta_s$. The ratios of branching ratios [(a) and (b)] are in principle accessible by studying charmed-particle decays in e^+e^- experiments and charmed-baryon production in neutrino interactions. Evidence from D^0 decays suggests that the value for $\sin\theta_d/\cos\theta_s$ may not be the Cabibbo tangent.[8] An acceptable value for this quantity is

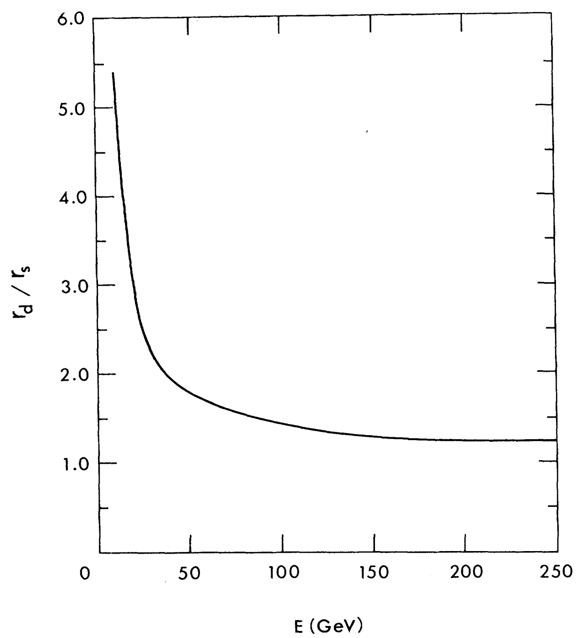

FIG. 4. r_d/r_s as a function of energy. The curve is the ratio of the curves of Figs. 3(a) and 3(b) used to scale $F_s(E)$ to its asymptotic value as in Eq. (11).

not yet determined, while many efforts are underway.[9] The range for this value has been calculated within the context of the Kobayashi-Maskawa model with six quarks[10] to vary widely from $\tan\theta_C$, where θ_C is the standard Cabibbo angle. One approximation to Eq. (10) would be to assume $v=s$ and/or $s=\bar{s}$ and $\tan^2\theta=\tan^2\theta_C$. One could then make only the correction outlined here for the rescaling effects. However, because of the potentially huge uncertainties in these ratios, I have refrained from doing so.

I thank Professor Lincoln Wolfenstein for encouraging this idea and for many valuable discussions. I also thank Professor C. Baltay, Dr. M. Murtagh, and Mr. M. Hibbs for permission to quote from unpublished results and discussions of the Columbia–Brookhaven National Laboratory experiment. This work was supported by the U. S. Department of Energy.

[1]I am grateful to Professor C. Baltay for permission to first show these data in publication. They were previously reported in Proceedings of the Lepton-Photon Symposium, Fermilab, August 1979 (unpublished).

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[5]Here $x=Q^2/2M_p\nu$ and $y=\nu/E_\nu$, where Q^2 is the four-momentum transfer, ν is the energy transfer, and $E_{\bar{\nu}}$ is the neutrino energy.

[6]See Holder *et al.*, Ref. 3.

[7]I have investigated the effects of asymptotic freedom (AF) by repeating the calculation with the Q^2-dependent parton distributions of A. J. Buras and K. J. F. Gaemers [Nucl. Phys. B132, 249 (1978)]. I find that AF effects change the curves of Fig. 4 by less than 5%. I have also checked that the results are relatively insensitive to assumptions about the shape of $xs(x)$. By changing the exponent in the sea-quark parametrization from 8 to 6 or from 8 to 10 results in changes to r_s of less than 10%.

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