Rates and Properties of Opposite-Sign Dimuons from Neutrinos and Antineutrinos

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Measured energy-dependent rates of opposite-sign dimuons produced by neutrinos and antineutrinos are presented and used to determine the fraction of strange quarks. Experimental distributions are compared with those expected from charm production and decay.

Dimuon production by neutrinos provided some of the earliest evidence for charm.[1] The characteristics of the events suggested a hadronic origin associated with a new quantum number. Subsequent measurements[2] have strengthened the interpretation that most opposite-sign neutrino-induced dimuon events arise from the production and semileptonic decay of charmed particles.[3] This paper presents new measurements of dimuon production by neutrinos and antineutrinos, and compares experimental distributions with those expected from charmed hadrons. Further, the measured dimuon rates are used to determine the magnitude of the strange-quark sea.

The apparatus was described in detail elsewhere.[4] Briefly, the target-detector consists of three components of different density: an iron target (FeT), a liquid scintillator calorimeter (LiqC), and an iron plate calorimeter (FeC). Following the target-detector is a muon spectrometer. The data were acquired at Fermilab in three runs, using quadrupole triplet (QT) and sign-selected bare-target beams (SSBT), with 400-GeV incident protons.[5] The QT and SSBT(ν) runs yielded 199 $\mu^-\mu^+$ and 46 $\mu^-\mu^-$ events, produced predominantly by neutrinos. The SSBT($\bar{\nu}$) run yielded 49 $\mu^+\mu^-$ and 2 $\mu^+\mu^+$ events, most produced by antineutrinos. Approximately 10% of the total QT data are presented here.

Comparison of experimental distributions and rates of dimuons with those predicted by a calculation based on the standard model of charm[3] can be used to better understand charm production by neutrinos and to search for other possible sources of dimuons. The experimental distributions must be corrected for geometrical acceptance and counter efficiencies, and the background due to pion and kaon decay must be determined. The geometrical acceptance was obtained by rotating observed events in φ, the azimuthal angle in the plane normal to the incident neutrino beam direction; events were given a weight based on the fraction of the φ angle subtended for which the event selection criteria were satisfied. With a minimum momentum requirement of 5 GeV/c, there is a background of approximately 25% in the observed dimuon sample arising from pion and kaon decay. This was determined empirically using the different density targets to measure the dimuon rate as a function of hadronic absorption length.[6] The result was consistent with a calculation, accurate to 25%, based on measured spectra and multiplicities of pions and kaons produced in neutrino interactions.[7]

Figure 1 shows the distribution of the observed momentum asymmetry, $\alpha \equiv (p_- - p_+)/(p_- + p_+)$, in the QT and SSBT($\nu$) samples of dimuon events with $p_\mu > 5$ GeV/c. The curves, obtained from a

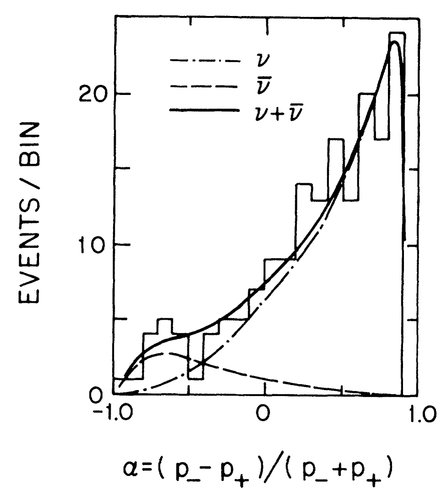

FIG. 1. Experimental distribution in the momentum asymmetry $\alpha = (p_- - p_+)/(p_- + p_+)$ for the QT and SSBT(ν) dimuon samples. The curves are obtained from a charm-model calculation.

Monte Carlo calculation of charmed-meson production and decay[8] (and including π and K decay), show separately the contributions due to ν and $\bar{\nu}$ and their sum. The good agreement is not especially sensitive to the detailed assumptions of the charm calculation. The $\bar{\nu}$ contamination in the ν sample is reduced to 4% by requiring $\alpha > -0.3$ in the distributions presented below. Similarly, the ν contamination in the SSBT($\bar{\nu}$) data (not shown) is reduced to 8% by requiring $\alpha < 0.3$.

Figure 2 shows the distributions of $x_{\rm vis}$ and $y_{\rm vis}$ for ν and $\bar{\nu}$ events.[9] Only those dimuon events which occur in the two calorimeter targets are included because knowledge of the hadronic energy E_H is required. In the standard charm model[3] neutrinos can produce a charmed quark from interactions with both strange (s) quarks in the sea and valence (d) quarks, while antineutrinos produce charm essentially only from strange ($\bar{s}$) antiquarks. Note that the $\bar{\nu}$ sample has a lower average value of $x_{\rm vis}$, as expected for production off sea quarks only, while the neutrino sample is consistent with equal contributions from valence and sea quarks assumed in the calculated curve in Fig. 2(b) (see also the dimuon rates below). After correction for pion and kaon decay the average values of $x_{\rm vis}$ obtained from the $\bar{\nu}$ and ν samples are 0.11 ± 0.03 and 0.20 ± 0.03, respectively.

Figure 3(a) shows the distribution of $Z_+ = p_+/(p_+ + E_H)$ for the neutrino sample. Curves are shown for two assumed forms of the fragmentation function $F(Z)$ for charmed-particle production.[8] Any distribution falling much faster than e^{-3Z} is rejected by the data. Figure 3(b) shows the measured distribution of $p_\perp$ for the neutrino sample, where $p_\perp$ is the momentum component of the μ^+ perpendicular to the plane formed by the incoming ν and the outgoing μ^-. The curve is obtained by assuming that D mesons are produced with a momentum transverse to the W direction of the form[10] $dN/dp_t^2 = \text{const} \times \exp[-6(p_t^2 + m_D^2)^{1/2}]$.

The measured ratios of dimuon to single-muon events, corrected for pion and kaon decay, are shown as functions of energy in Figs. 4(a) and 4(b) for $\bar{\nu}$ and ν, respectively. The curves show the energy dependence expected from the charm calculation with and without the requirement $p_\mu > 5$ GeV/c. The observed energy dependence arises primarily from that requirement in the analysis; it is thus not possible to distinguish between slow and fast rescaling[11] using these data. Above 80 GeV, the ratio of dimuon to single-muon events is $(0.65 \pm 0.13) \times 10^{-2}$ for ν and $(0.70 \pm 0.25) \times 10^{-2}$ for $\bar{\nu}$, for $p_\mu > 5$ GeV/c.

The magnitude of the strange-quark fractional momentum can be extracted from the measured dimuon rates and data on single-muon production by $\bar{\nu}$ and ν at high energy. Noting that the target of the experiment is isoscalar ($U = D$, where U, D

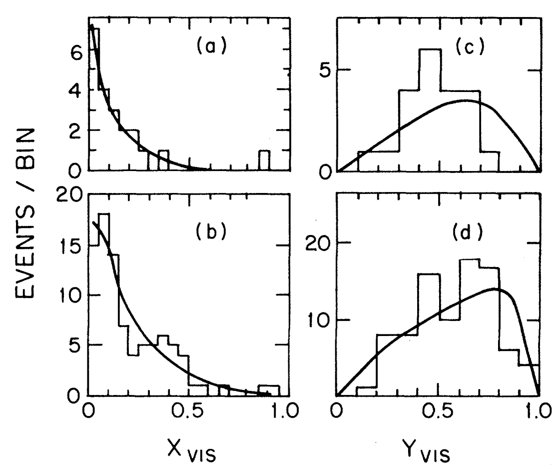

FIG. 2. Measured distributions in $x_{\rm vis}$ for (a) $\bar{\nu}$ and (b) ν, and in $y_{\rm vis}$ for (c) $\bar{\nu}$ and (d) ν (histograms) compared with the charm-model calculation.

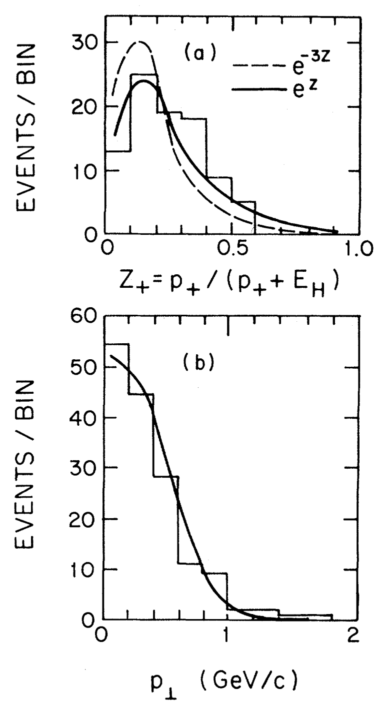

FIG. 3. Neutrino-induced dimuon distributions in (a) Z_+ and (b) $p_\perp$ compared with charm-model predictions. One event is off scale in $p_\perp$ in (b).

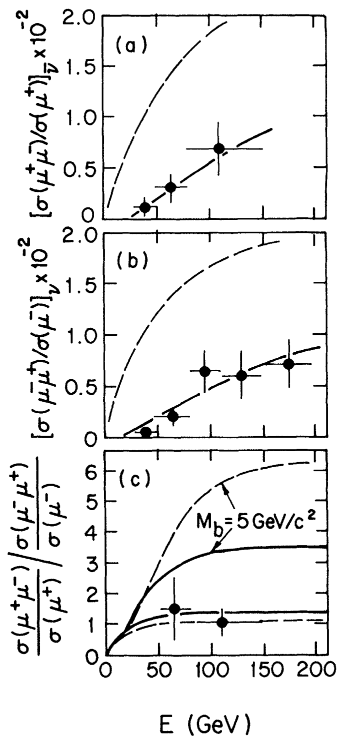

FIG. 4. Measured ratio of dimuon–to–single-muon rates (corrected for π and K decays) as a function of energy for (a) $\bar{\nu}$ and (b) ν. The errors shown are statistical only. The curves are from a charm-model calculation with (solid) and without (dashed) the requirement $p_\mu > 5$ GeV/c. (c) The ratio $[\sigma(\mu^+\mu^-)/\sigma(\mu^+)]/[\sigma(\mu^-\mu^+)/\sigma(\mu^-)]$ as a function of energy. The dashed curves (from Ref. 13) are for the standard four-quark model and for additional 5-GeV/c^2 b-quark production and decay. The solid curves include estimated asymptotic-freedom corrections to those alternatives.

are the fractional momenta carried by the u, d quarks), one determines[12] the ratios $\bar{S}/U$ and S/D independently from the $\bar{\nu}$ and ν dimuon data of Figs. 4(a) and 4(b). The correction for the cut $p_\mu > 5$ GeV/c is sensitive to the Z distribution assumed for charm production. We have taken a flat Z distribution consistent with Fig. 3(a); for $F(Z) \sim e^{-3z}$, the numerical values of $\bar{S}/U$ and S/D given in Table I would be increased by approximately 50% and by a factor of 2, respectively. If we use instead the ratio $[\sigma(\mu^+\mu^-)/\sigma(\mu^+)]/[\sigma(\mu^-\mu^+)/\sigma(\mu^-)]$ from Fig. 4(c), we obtain $\bar{S}/D$, independent of any correction from dimuon acceptance. These results and the value of $\bar{D}/U$ ($=\bar{D}/D$) obtained as indicated in Ref. 12 are given in Table I. Note that the fractional momentum carried by the strange quarks appears to be less than that carried by the ordinary antiquarks.

Figure 4(c) compares the measured energy dependence of the ratio $[\sigma(\mu^+\mu^-)/\sigma(\mu^+)]/[\sigma(\mu^-\mu^+)/\sigma(\mu^-)]$ with the calculated dependence assuming charm only, and assuming a right-handed, full-strength–coupled, charge $-\frac{1}{3}$ (b) quark in addition.[13] The latter quark, with a mass of 5 GeV/c^2, seems to be ruled out by more than four standard deviations, subject to uncertainties in the large asymptotic-freedom correction.[14]

TABLE I. Values of the fractional momentum carried by the strange quarks and by the ordinary antiquarks obtained from the data above 80 GeV of this experiment. The errors given are statistical only.

Ratio	Value
$\bar{S}/U$	0.076 ± 0.027
S/D	0.099 ± 0.035
$\bar{S}/D$	0.066 ± 0.061
$\bar{D}/D = \bar{U}/U$	0.13 ± 0.03

In summary, the opposite-sign dimuon data presented here are consistent in all respects with the production and decay of charmed particles, although a contribution from other sources at the level of roughly 20% cannot be excluded. Within experimental error, the strange quarks seem to carry a smaller fraction of the nucleon momentum than the ordinary antiquarks. Finally, there is no evidence for a charge $-\frac{1}{3}$ quark of mass 5 GeV/c^2 with right-handed, full-strength coupling to a u quark.

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[6] A. Benvenuti *et al.*, Phys. Rev. Lett. 41, 725 (1978).

[7] The 25% error of the pion- and kaon-decay calculation is determined from the measurement errors in data on charged-hadron production from inelastic neutrino in-

teractions and uncertainties in the pion- and kaon-absorption processes.

[8]Except where otherwise stated we assume that D mesons are produced with a distribution in $Z \equiv E_D/E_H$ of the form $F(Z) = Ce^{-3Z}$, where E_D and E_H are the laboratory energies, respectively, of the D meson and the total hadronic system. We assume an equal mixture of the decays $D \to K\mu\nu$ and $D \to K^*\mu\nu$.

[9]Here $y_{\rm vis} = (E_{\mu 2} + E_H)/E_{\rm vis}$ and $x_{\rm vis} = (E_{\mu 1}/M_p)(1 - \cos\theta_{\mu 1})/y_{\rm vis}$, where $E_{\rm vis} = E_{\mu 1} + E_{\mu 2} + E_H$. For ν-induced dimuons $\mu 1$ is μ^- and $\mu 2$ is μ^+. Because of the undetected energy of neutrinos from charmed-particle decays, $x_{\rm vis} > x$ and $y_{\rm vis} < y$, where $x = q^2/2M_pE_H$ and $y = E_H/E_\nu$.

[10]J. D. Bjorken, SLAC Report No. 191, 1975 (unpublished).

[11]R. M. Barnett, Phys. Rev. Lett. 36, 1163 (1976); H. Georgi and H. D. Politzer, Phys. Rev. Lett. 36, 1281 (1976).

[12]For example, for the $\bar\nu$ dimuon data well above the charm threshold, one has

$$\epsilon\frac{\sigma(\mu^+\mu^-)}{\sigma(\mu^+)} = \frac{b\sigma(\bar\nu\bar s \to \mu^+\bar c)}{\sigma(\bar\nu u \to \mu^+ d) + \sigma(\bar\nu\bar d \to \mu^+\bar u) + \sigma(\bar\nu\bar s \to \mu^+\bar c)}$$

$$= b\bar S/(\tfrac{1}{3}U + \bar D + \bar S)$$

and for the $\bar\nu$ single-muon data

$$\tfrac{1}{2}(1 - B^{\bar\nu}) = (\bar S + \bar D)/(U + \bar D + \bar S),$$

where, as usual, $\bar S \equiv \int x\bar s(x)dx$ is the fractional momentum carried by the strange antiquarks, etc., $B^{\bar\nu} \equiv -\int xF_3(x)dx/\int F_2(x)dx$, ϵ is the correction for dimuon acceptance, and b is the branching ratio for $(\bar c \to \bar\mu)$. Hence

$$\frac{\bar S}{U} = \frac{\sigma(\mu^+\mu^-)}{\sigma(\mu^+)}\frac{\epsilon}{b}\left(\frac{1}{3} + \frac{1 - B^{\bar\nu}}{1 + B^{\bar\nu}}\right)$$

and

$$\frac{\bar D}{U} = \frac{(1 - B^{\bar\nu})}{(1 + B^{\bar\nu})} - \frac{\bar S}{U}.$$

We use $b = 0.10$ [R. Brandelik *et al.*, Phys. Lett. 70B, 387 (1977); J. M. Feller *et al.*, Phys. Rev. Lett. 40, 274 (1978); W. Bacino *et al.*, Phys. Rev. Lett. 40, 671 (1978)], and for $E_{\bar\nu} > 80$ GeV we use $B^{\bar\nu} = 0.66 \pm 0.05$ [F. Bobisut, in Proceedings of the International Conference on Neutrino Physics and Neutrino Astrophysics, West Lafayette, April 1978 (to be published)], $\epsilon = 2.0$, and $\sigma(\mu^+\mu^-)/\sigma(\mu^+) = (0.70 \pm 0.25) \times 10^{-2}$ from Fig. 4(a). Similar calculations for the ν data and for the combined ν and $\bar\nu$ data yield S/D and $\bar S/D$.

[13]R. M. Barnett and F. Martin, Phys. Rev. D 16, 2765 (1977).

[14]See, for example, I. Hinchcliffe and C. H. Llewellyn Smith, Phys. Lett. 70B, 247 (1977).

Direct Electron-Pair Production in $\pi^\pm p$ Interactions at 18 GeV/c

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With use of the Stanford Linear Accelerator Center hybrid facility 1-m bubble chamber fitted with tantalum plates, a measurement was made of direct unexplained e^+e^- pair production in 18-GeV/c $\pi^\pm p$ interactions. Limits are set in π^+p processes. In π^-p a signal is observed which cannot be caused by η, ω, or ρ decay, and for masses $> m_{\pi^0}$, $e^\pm/\pi^\pm = (0.87 \pm 0.25) \times 10^{-4}$. Some properties of the events are discussed.

This report is based on data taken with the Stanford Linear Accelerator Center (SLAC) 1-m bubble chamber hybrid facility in an investigation of direct e^+ or e^- production in 18-GeV/c π^+p and π^-p interactions. At similar energies, and also at the CERN intersecting storage-rings, experiments using single-particle spectrometers[1] have shown a low-p_T enhancement of hadronically produced e^+ and e^- which is not yet understood.[2] (In the text, "electron" will refer to e^+ or e^-.) An earlier result from this experiment[3] has indicated that unpaired electron production is not significant. Here we report measurements on pair production.

The bubble chamber was equipped with three tantalum plates, each 1.0 radiation lengths thick.

