# Model of Dimuon Production by Neutrinos*

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In an attempt to confirm the charm interpretation of dimuons, we have constructed an explicit quark-parton model for the production and decay of a new hadron in neutrino interactions. The model produces, among other results, a distribution for the muon energy ratio $E(\mu^+)/E(\mu^-)$, which is independent of the neutrino spectrum and in remarkable agreement with observations. The model encourages the hope that the study of dimuon characteristics could reveal the charge of the charmed quark and the chirality of the charmed current.

Analysis of the dimuon events observed in the Harvard-Pennsylvania-Wisconsin-Fermilab neutrino experiment[1] has made it plausible that the odd muon ($\mu^+$) appearing in these reactions is the decay product of a hadron of mass 2–3 GeV carrying a new quantum number:

$$\nu_\mu + N \to \mu^- + C + \dots \qquad C \to \mu^+ + \nu_\mu + \dots . \tag{1}$$

This interpretation would gain in strength if a model could be constructed that reproduced the observed distributions of the two muons and the accompanying hadron shower. One model that has been investigated in this connection is the diffractive production of a charmed vector meson $F^*$.[2] We describe below a model of dimuon production, based on parton concepts, that is expected to be an asymptotic description of this process. The model is in significant agreement with the data and lends support to the charm interpretation of this phenomenon.

Our basic point of view is that the production of the charmed hadron $C$ takes place in a deep inelastic collision to which the ideas of scaling and the parton model may reasonably be applied.[3] There are two experimental facts[1] that support this view: (i) The dimuon events possess a high inelasticity as well as a broad $v$ distribution. These are characteristics of a deep inelastic process (large $\nu$ and large $Q^2$). (ii) The secondary muon ($\mu^+$) is observed to emerge with high energy ($\langle E_+\rangle \sim 14$ GeV) but with only limited momentum (~1 GeV) transverse to the $\nu_\mu \mu^-$ plane. This suggests that the parent hadron $C$ is produced with high energy ($\gg$ mass of $C$) in the direction of the momentum transfer vector $\vec{q}$, an attribute that is characteristic of a current fragment in a deep inelastic reaction.

In accordance with this view, we write the semi-inclusive cross section for $C$ production as

$$\frac{d\sigma(C)}{dx\,dy\,dz} = \frac{G^2 ME}{\pi} \nu F(x,y) D(z). \tag{2}$$

$F(x,y)$ is the inclusive distribution of the reaction $\nu_\mu + N \to \mu^- + X(C=1)$ and $D(z)$ is the "fragmentation function"[4] expressing the average multiplicity of $C$ as a function of the scaling variable,

$$z = E_C/\nu \tag{3}$$

($E_C$ denotes the energy of $C$ in the lab). The form of $F(x,y)$ will depend on the structure of the charm-changing current. Within a quark model, one can envisage for this current several simple possibilities, depending on the charge of the charmed quark ($Q_c$) and the chirality of the charmed current ($\chi_c$). These possibilities are listed in Table I.[5] The models fall into two classes, which we call $L$ and $R$, depending on whether $Q_c\chi_c$ is negative or positive. The former is characterized by a flat $y$ distribution, the latter by $(1-y)^2$.

To guess the form of the function $D(z)$, we

TABLE I. Parton-model expressions for $F(x,y)$ in various models. ($Q_c$ is the charge of charmed quark; $\chi_c$ is the chirality of charmed current; $u$, $d$, $s$, $\cdots$, are the parton densities in proton.) Contributions from $c\bar{c}$ pairs in the nucleon are neglected. Analogous functions $\bar{F}(x,y)$ in $\bar{\nu}$ reactions are obtained by interchanging $(u,d,s) \to (\bar{u},\bar{d},\bar{s})$.

| Charmed current | $Q_c$ | $\chi_c$ | Class | $F(x,y)$ |
|---|---|---|---|---|
| $\bar{c}\gamma_\mu(1+\gamma_5)n$ | $+2/3$ | $-$ | $L$ | $u+d$ |
| $\bar{c}\gamma_\mu(1+\gamma_5)\lambda$ | $+2/3$ | $-$ | $L$ | $2s$ |
| $\bar{c}\gamma_\mu(1-\gamma_5)n$ | $+2/3$ | $+$ | $R$ | $(u+d)(1-y)^2$ |
| $\bar{c}\gamma_\mu(1-\gamma_5)\lambda$ | $+2/3$ | $+$ | $R$ | $2s(1-y)^2$ |
| $\bar{p}\gamma_\mu(1+\gamma_5)c$ | $-1/3$ | $-$ | $R$ | $(\bar{u}+\bar{d})(1-y)^2$ |
| $\bar{p}\gamma_\mu(1-\gamma_5)c$ | $-1/3$ | $+$ | $L$ | $\bar{u}+\bar{d}$ |

shall assume $C$ to be a charmed meson,[6] and appeal to both theory and experiment for guidance. The theoretical prejudice is that in the true scaling limit, $D(z)$ would behave as $z^{-1}$ for $z \to 0$, and would vanish as a power of $1-z$ for $z \to 1$. These expectations receive support from recent measurements of $\pi^-$ multiplicity in $\bar{\nu}$ interactions, which determine the analogous function $D^\pi(z)$ for $\pi$ production.[7] As can be seen in Fig. 1, the data can be fairly represented by the simple form $z^{-1}(1-z)$ for values of $z$ not too close to the origin. We are thus encouraged to adopt for $D(z)$ the same simple form

$$D(z) = Kz^{-1}(1-z), \tag{4}$$

recognizing that deviations are to be expected in the small-$z$ region.[8] With the specification of $D(z)$, the model of charm production is complete, and we proceed to a discussion of the decay.

There are two general possibilities for the decay of $C$ leading to a final $\mu^+$: (i) Two-body decay $C \to \mu^+ + \nu_\mu$, (ii) $n$-body decay $C \to \mu^+ + \nu_\mu$+hadrons. Our interest is in the $\mu^+$ spectrum in the two cases. Category (ii) can be treated only approximately. We have taken the view that the essential features in this case can be abstracted from the four-fermion interaction $c \to q + \mu^+ + \nu_\mu$ describing the transformation of the charmed

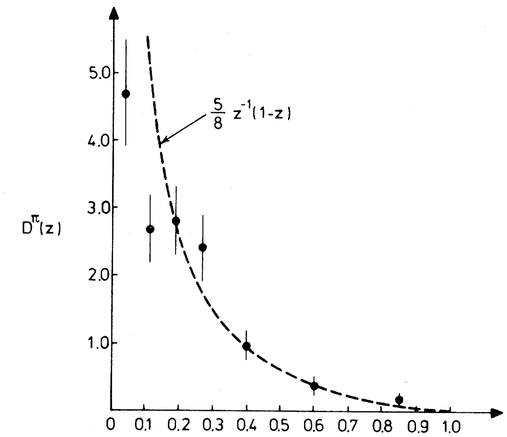


FIG. 1. Fragmentation function $D^\pi(Z)$ obtained from $\pi^-$ multiplicity in $\bar{\nu}+N \to \pi^- + \cdots$ (Ref. 7).

constituent of $C$ into an uncharmed quark $q$. (We take the mass of $c$ to be close to that of the meson, and neglect other masses.[9])

Since the hadron $C$ (in our model) moves in the plane defined by the incident $\nu$ and the $\mu^-$, it is convenient to resolve the momentum of the $\mu^+$ into components perpendicular ($k_\perp$) and parallel ($k_\parallel$) to this plane. The distribution of $k_\perp$ is obtained easily by going to the rest frame of the decaying particle. The result is

$$\frac{d\sigma}{d\xi_\perp} \propto H(\xi_\perp) = \begin{cases} 1 \quad \text{(two-body)}, & \text{(5a)} \\ 6(1-\xi_\perp^2) - 4(1-\xi_\perp^3) \quad (n-\text{body}; L), & \text{(5b)} \\ 3(1-\xi_\perp^2) - \frac{4}{3}(1-\xi_\perp^3) \quad (n-\text{body}; R), & \text{(5c)} \end{cases}$$

where $\xi_\perp = 2k_\perp/M_C$. A comparison with the data is shown in Fig. 2. The data are clearly compatible with an $n$-body decay (or a combination of two- and $n$-body decays) of a particle of mass 2–3 GeV.[10] To obtain the distribution in $k_\parallel$, we boost the $k_\perp$ distribution to a frame in which the decaying particle has energy $E_C$. Defining

$$\xi = k_\parallel/E_C \simeq E_+/E_C, \tag{6}$$

we obtain

$$\frac{d\sigma(\mu^-\mu^+)}{dx\,dy\,dz\,d\xi} = \frac{G^2ME}{\pi}\nu F(x,y)D(z)BH(\xi), \tag{7}$$

where $B$ is the branching ratio $\Gamma(C \to \mu^+\nu_\mu \ldots)/\Gamma(C \to \text{all})$ and the function $H$ is defined in Eq. (5). Equation (7) is the essential statement of our model and permits the calculation of any distribution involving $x$, $y$, $z$, and $\xi$. We consider below some important consequences.

(1) A key prediction is the distribution of the muon energy ratio $E_+/E_-$ [$= yz\xi/(1-y)$]. Within the model, this distribution is independent of the incident neutrino energy, and so may immediately be compared with the wide-band data of the Harvard-Pennsylvania-Wisconsin-Fermilab experiment. The results are shown in Fig. 3(a). (The two-body and $n$-body cases give almost identical distributions.) The agreement with the data is quite striking, considering that the model is an asymptotic description. The discrepancy at the smallest values of $E_+/E_-$ can be understood: It arises from the singularity of $D(z)$ at small $z$, which gives too strong an emphasis to small $E_+$ values.[11]

(2) We have calculated also the distribution of

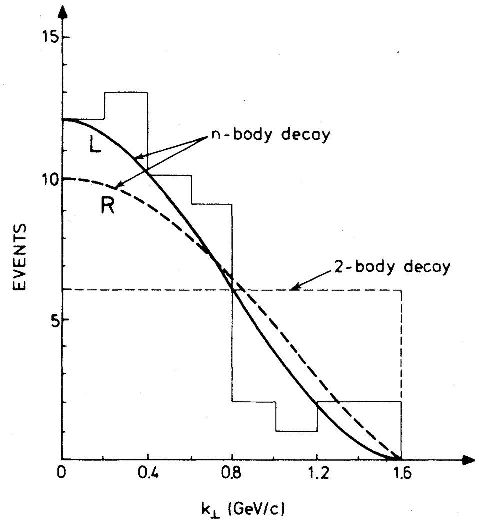


FIG. 2. $k_\perp$ distribution of $\mu^+$ compared with the predictions of the model.

the muon-to-hadron energy ratios $E_-/E_h$ and $E_h/E_+$. The results (for the $n$-body case) are compared in Figs. 3(b) and 3(c) with the limited data available. ($E_h$ is measured in only 17 events.) Again there is a qualitative agreement. Note that discrepancies occur mainly at small $E_-/E_h$ and large $E_h/E_+$, which is just the region most sensitive to the small-$z$ behavior of $D(z)$.

(3) In addition, we have considered distributions that are relatively independent of the production and decay mechanisms but which are sensitive to the structure of the charm-changing current. An example is the distribution of

$$y_{\text{vis}} = \frac{E_+ + E_h}{E_- + E_+ + E_h} \leq y. \tag{8}$$

In our model, this differs only slightly from the distribution in $y$. The data indicate a flat $y_{\text{vis}}$ distribution, pointing to an $L$-type model. As a further probe of the charmed current, we have compared the $v_-$ ($=xy$) distribution of the dimuon events with the various models of Table I. The data indicate the presence of the current $\bar{c}\gamma_\mu(1+\gamma_5)n$ ($Q_c = +\frac{2}{3}$, $\chi_c = -1$) but admixtures of other currents are easily possible.

(4) The distributions shown in Fig. 3 remain valid for dimuons induced by antineutrinos[12] (provided we replace $E_+ \leftrightarrow E_-$). An investigation of such events could throw added light on the nature of the charmed current.

(5) The model predicts several other dimuon characteristics which can be compared with the data if the neutrino spectrum is reliably known. These, along with details of our calculations, will be published elsewhere.[13]

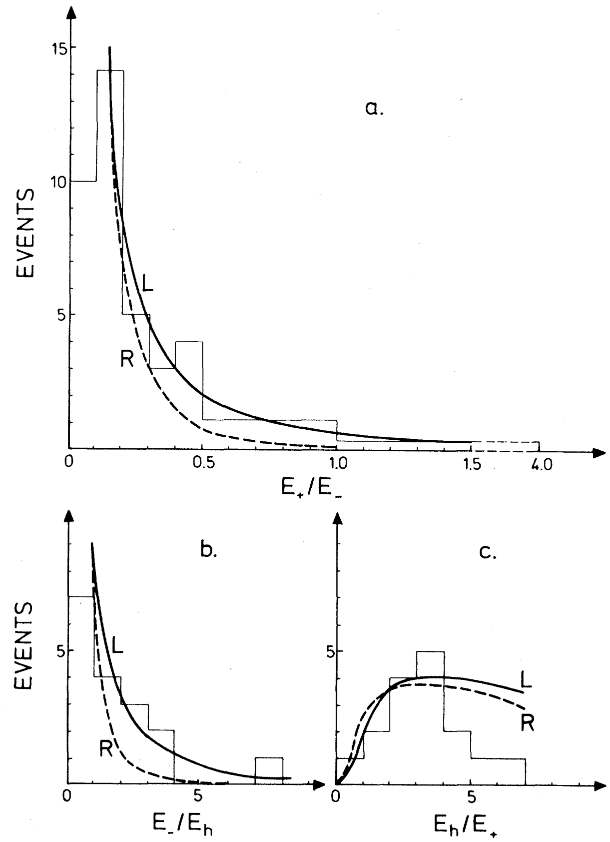


FIG. 3. Distribution of (a) $E_+/E_-$, (b) $E_-/E_h$, and (c) $E_h/E_+$. Curves are the theoretical predictions.

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[1]A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1199, 1203 (1975).

[2]L. N. Chang, E. Derman, and J. N. Ng, Phys. Rev. Lett. 35, 1252 (1975); see also M. B. Einhorn and B. W. Lee, Fermilab Report No. Fermi-Lab-Pub-75/56-Thy (unpublished).

[3]V. Barger, T. Weiler, and R. J. N. Phillips, Phys. Rev. Lett. 35, 692 (1975).

[4]R. P. Feynman, *Photon-Hadron Interactions* (Benjamin, New York, 1972); J. D. Bjorken, in *Proceedings of the Fourth Hawaii Topical Conference in Particle Physics, 1972,* edited by D. E. Yount and P. N. Dobson (Univ. Press of Hawaii, Honolulu, 1972).

[5]We exclude charges other than $Q_c = +\frac{2}{3}$ or $-\frac{1}{3}$. Currents of mixed chirality have not been included, but the discussion can easily be generalized to include them.

[6] Many of our conclusions follow from features of $D(z)$ that are expected to be quite general. Such results should have a qualitative validity even if $C$ is a baryon.

[7] S. J. Barish *et al.*, ANL Report No. ANL-HEP-CP-75-39 (unpublished); B. P. Roe, in Proceedings of the Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975 (to be published).

[8] A $z^{-1}$ behavior implies logarithmically growing multiplicity with energy. In the dimuon events under consideration, however, the multiplicity of $C$ (neglecting associated production) is one per event. A realistic form for $D(z)$ should behave more smoothly at small $z$.

[9] Most of the dimuon characteristics in our model depend only weakly on the details of the decay mechanism.

[10] The decaying hadron $C$ can carry a "natural" transverse momentum associated with the production process. This momentum will be of order 300–400 MeV if the transverse characteristics of $C$ are similar to those of ordinary current fragments, but could conceivably be higher. A transverse momentum of order 200 MeV can also arise from the Fermi motion of the nucleon in the target nucleus. The cumulative effect of these corrections will be to smear the $k_\perp$ distribution of the secondary muon so that the observed $k_\perp$ cutoff exceeds $M_C/2$. The empirical distribution shown in Fig. 2 can thus be consistent with a charmed-particle mass as low as 2 GeV.

[11] We have examined possible modifications of our asymptotic results arising from finite neutrino energies and the nonvanishing mass of $C$ (L. M. Sehgal and P. M. Zerwas, to be published). For the $E_+/E_-$ distribution shown in Fig. 2(a), these corrections are found to be of relative order $(M_C/E_\nu)/(E_+/E_-)$. These corrections are significant only at very small values of $E_+/E_-$, and tend to improve the agreement with the data in that region.

[12] A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1249 (1975).

[13] Sehgal and Zerwas, Ref. 11.

# Observation of the Decay $\psi(3684) \to \psi(3095)\eta$†

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We have observed the decay $\psi(3684) \to \psi(3095)\eta$ with a branching fraction of $(4.3 \pm 0.8)\%$. This measurement, together with previous measurements of $\psi(3684) \to \psi(3095) + \text{anything}$, $\psi(3684) \to \psi(3095)\pi^+\pi^-$, and $\psi(3684) \to \psi(3095)\gamma\gamma$, indicates that isospin is conserved in the decay $\psi(3684) \to \psi(3095)\pi\pi$ and establishes the isospin and $G$ parity of the $\psi(3684)$ to be $I^G = 0^-$.

Since the discovery of the $\psi(3684)$ ($\psi'$),[1] there has been speculation about its relationship to the $\psi(3095)$ ($\psi$).[2] Some models such as the charm model[3] assign the $\psi'$ to a radial excitation of the $\psi$, in which case the observed quantum numbers of the two states should be identical. Indeed, we know that both states have spin 1, odd parity, and odd charge conjugation.[4,5] We also know that the $\psi$, in its decays, behaves as a state with zero isospin and odd $G$ parity.[6] The observation of the decays of the $\psi'$ into $\psi$ with a large branching ratio[7] suggests a close relationship between the $\psi$ and $\psi'$. From this previous report we can easily calculate that

$$\frac{\Gamma(\psi' \to \psi + \text{neutrals})}{\Gamma(\psi' \to \psi\pi^+\pi^-)} = 0.78 \pm 0.10\,. \qquad (1)$$

If $\psi'$ decays to $\psi$ proceeded entirely via the reaction $\psi' \to \psi\pi\pi$ with the $\pi$-$\pi$ in a state of definite isospin, the ratio would have the value $\frac{1}{2}$, 0, or 2 for $\pi$-$\pi$ isospin 0, 1, or 2, respectively.[8] Isospin zero is clearly preferred, yet if we assume isospin zero, the excess of the ratio over its predicted value suggests the presence of $\psi' \to \psi + \text{neutrals}$ other than $\psi' \to \psi\pi^0\pi^0$. The presence of $\psi' \to \psi\gamma\gamma$[9,10] does not completely account for the excess. In this Letter we show that the decay $\psi' \to \psi\eta$ accounts for the remaining excess, thus indicating the conservation of isospin in the decay $\psi' \to \psi\pi\pi$ and establishing the isospin and $G$ parity of the $\psi'$ to be $I^G = 0^-$.

The primary evidence for $\psi' \to \psi\eta$ comes from a