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$\mu^+\mu^-$ Distributions from the Production of a New Hadron in Neutrino Scattering

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We have analyzed dimuon distributions due to the diffractive production of a new hadronic vector boson in neutrino scattering. Characteristic features that distinguish this mechanism from heavy-lepton-mediated dimuon distributions are presented.

Observed dimuon characteristics[1] in neutrino-induced reactions are not compatible with the events being mediated by heavy leptons.[2] The more probable source is the production of hadrons with new quantum numbers. However, the attendant dimuon characteristics will be dependent upon the details of the production mechanisms, which are unknown at the moment. To appreciate the kinds of characteristics expected from such reactions, one must appeal to models. If the new hadron can carry spin 1, then the diffractive mechanism would play an important role. In this note we examine dimuon distributions due to the diffractive production of a new vector hadron, F^{*+}. Specifically, we consider

$$\nu(k)+N(p)\to \mu^-(k_-)+F^{*+}(f)+X(p_x) \tag{1a}$$

$$\hookrightarrow \mu^+(k_+)+X'+\nu(k'). \tag{1b}$$

We shall only be concerned with dimuon distributions, in this initial analysis of hadron-mediated dimuon events, which are largely independent of the details of the model for (1a), and are basically controlled by the kinematics of hadron production. Thus we shall not discriminate among currently popular hadron spectroscopic schemes, nor shall we specify quantitatively the precise coupling strength of the hadrons, all of which information can only be forthcoming with further analysis of the data. For definiteness in the following discussion, we assume a mass, M_F, of 3 GeV/c^2 for the F^*, although our results are insensitive to variation in M_F for $M_F < 5$ GeV/c^2.

Although the precise way in which the semiweak diffractive scattering occurs is yet unclear, the following features may be deduced from photoelectroproduction of ρ mesons.[3] Firstly, there is a pronounced peak in the square of the momentum transfer, $t=(p-p_x)^2$, from the nucleon to the hadrons, with a width $1/b$. This means that the recoil hadrons get very little energy in the laboratory frame. Secondly, s-channel helicity conservation apparently holds; finally, diffractive dissociation of the target gives a distribution in recoil hadronic mass of the form $f(M_x^2)\sim 1/M_x^2$ for fixed t. We shall assume that all these features persist in Reaction (1). The inclusive cross section for (1a) will be controlled by the structure function

$$W_{\mu\alpha;\nu\beta}\sim \textstyle\sum_x \langle N|J_\nu^+|X;F_\beta^{*+}\rangle\langle X;F_\alpha^{*+}|J_\mu|N\rangle\,\delta^4(q+p-f-X), \tag{2}$$

where J_μ is the hadronic weak current and α, β denote the polarization indices of the F^{*+} boson. We assume that $W_{\mu\alpha;\nu\beta}$ may be adequately represented by

$$W_{\mu\alpha;\nu\beta} = (q\cdot f g_{\mu\alpha} - q_\alpha f_\mu)(q\cdot f g_{\nu\beta} - q_\beta f_\nu) W(q^2, q\cdot p, q\cdot f, M_x^2). \quad (3)$$

This tensorial form assumes the conservation of both the weak current and the source current responsible for F^{*+} production, and that the weak current is pure vector. Note that $W_{\mu\alpha;\nu\beta} = W_{\nu\beta;\mu\alpha}$ and W is real.

For $q^2 = f^2$, and for forward scattering with $q = f$ and $t = 0$, (2) conserves helicity. Since the dominant contributions in the cross section in diffractive scattering will come from $t \simeq 0$, and for q^2 small (see below), this matrix element therefore approximates s-channel helicity conservation. The precise dependence of $W(q^2, q\cdot p, q\cdot f, M_x^2)$ on its arguments is obtained by assuming the same tensorial structure of (2) for calculating ρ^0 photoproduction. Requiring that the t and M_x^2 dependence be as described above yields

$$W \sim \frac{\exp[btf(M_x^2)^2(s)^2]}{(1 - q^2/M_F^2)^2(t - M_F^2)^2}, \quad (4)$$

where $s = (q + p)^2$, and the factor $(1 - q^2/M_F^2)^2$ is the empirical dependence on q^2 deduced from electroproduction data for small q^2, consistent with vector-meson dominance. For simplicity we shall suppose that (4) holds for all q^2. We set $b = 3$ GeV^{-2} from ψ photoproduction.[4] The semileptonic decay is calculated for a fixed missing mass $M_{x'}$. The range of $M_{x'}$ from 0.1 to 2.8 GeV/c^2 is investigated. The final distributions are then obtained by a Monte Carlo integration with 200 000 events.[5] We estimate an accuracy of about 20%.

The crucial factor determining hadron-mediated dimuon events is that the primary μ^- is scattered promptly, so that dimuon pairs are produced nonlocally (see Fig. 1). The dimuon mass ($M_{\mu\mu}$) distribution will therefore tail out towards larger values, with a shape and upper limit which depend upon the incoming neutrino energy E_ν (see Fig. 2). This is in marked contrast to heavy-lepton-mediated pairs, which are produced locally[2] and therefore have an $M_{\mu\mu}$ shape and upper bound independent of E_ν. Furthermore, with $M_{x'} = 1.5$ GeV/c^2, the F^{*+} passes only a small fraction of its energy on to the μ^+; the energy asymmetry $\alpha = (\langle E_-\rangle - \langle E_+\rangle)/(\langle E_-\rangle + \langle E_+\rangle)$ between the two muons is 0.5 with neutrino flux folded in. For $M_{x'} = 0.15$ GeV/c^2 we obtain $\alpha = 0.3$, whereas $M_{x'} = 2.5$ GeV/c^2 gives $\alpha = 0.82$. This is in contrast to heavy-lepton-mediated pairs, where optimal values are ~0.3.

Figures 3(a) and 3(b) show the μ^-, μ^+, and hadronic energy (E_h) spectrum for $E_\nu = 150$ GeV. The E_- distribution extends to large values, characteristic of hard, prompt scattering, whereas the E_+ and E_h spectra resemble each other by sharply peaking for small values. This similarity is due to the fact that since diffraction imparts little energy to the nuclear target both the μ^+ and hadrons obtain their energy through the semileptonic decay of the F^{*+}. By contrast, in heavy-

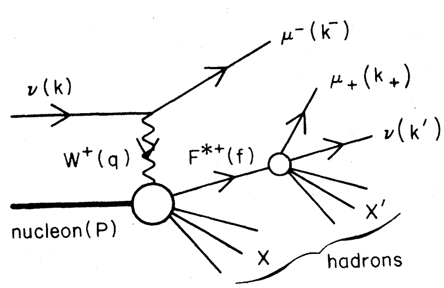

FIG. 1. Schematic diagram of diffractive neutrino production of hadronic vector meson F^{*+} which decays semileptonically. Symbols for particle momenta are shown in brackets.

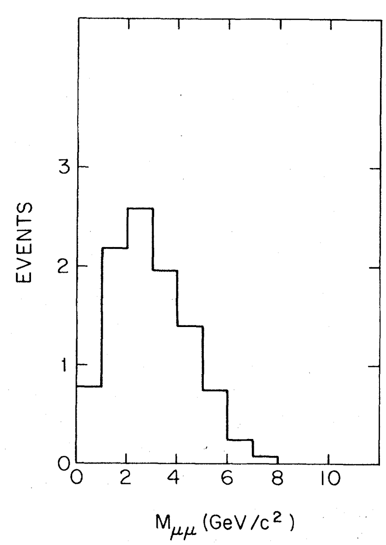

FIG. 2. Dimuon mass distribution for $E_\nu = 150$ GeV and $M_F = 3$ GeV/c^2 (normalized to ten events).

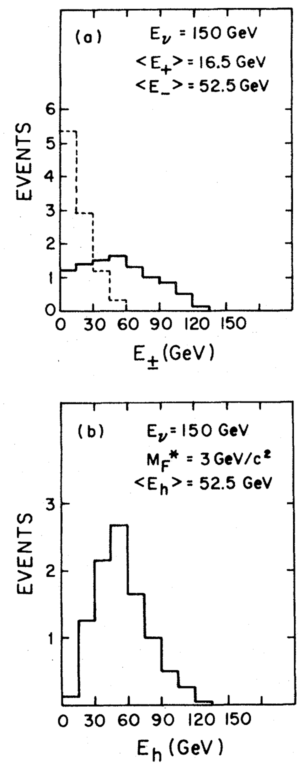

FIG. 3. (a) Energy, $E_\pm$, distributions for $\mu^\pm$ in the process of Fig. 1. Solid curve denotes E_- and dashed curve denotes E_+ (normalized to ten events). These curves reflect the decay of the F^{*+} into hadrons of average mass 1.5 GeV/c^2. (b) Distribution in hadronic energy, E_h, normalized to ten events.

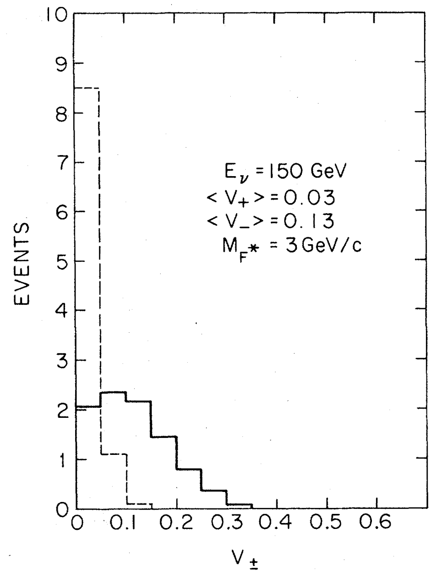

FIG. 4. Distribution in scaled momentum transfer $v_\pm = Q_\pm^2/2ME_\nu$ (see text). Solid line denotes v_- and dashed line v_+. Normalization is to ten events.

lepton-mediated events,[2] the μ^- and μ^+, being decay products, have similar energy spectra, peaked for small energies, whereas the hadronic distribution extends to large energies.

Another distinguishing feature between heavy-lepton- and diffractive-hadron-mediated dimuon events is the behavior of Q_-^2, or $v_- = Q_-^2/2ME_\nu$, where $Q_\pm^2 = -(k - k_\pm)^2$, and M denotes the nucleon mass. For diffractive production the v_- distribution (Fig. 4) has a zero at $v_- = 0$. This occurs because of the current-conserving form of $W_{\mu\alpha;\nu\beta}$ based on ρ^0 electroproduction, which leads to a kinematic zero in Q_-^2, and hence in v_-. Such a zero does not occur in heavy-lepton production, where the kinematic zero is canceled in the deep-inelastic limit by the behavior of the structure functions at $x_- = 0$. A similar compensation could occur in a diffractive framework too, although it would not lie within the spirit of weak Q_-^2 dependence we are using here. In our calculation the x_- distribution is found to peak at small x_- and cut off at 0.4 with $\langle x_-\rangle = 0.15$. This is to be contrasted with deep-inelastic production where x_- is found to be large.

Yet another signal for nonlocal or local dimuon production is the energy dependence of the ratio $\gamma = \langle Q_+^2\rangle/\langle Q_-^2\rangle \equiv \langle v_+\rangle/\langle v_-\rangle$. The Q_-^2 distribution from (4) approaches scaling to within logarithms rapidly as E_ν increases, reflecting primary μ^- emission at an average angle $\theta_- \sim (M/E_-)^{1/2}$ relative to the incident neutrino. The secondary μ^+ is, however, a decay product of the F^{*+}. At lower E_ν, the F^{*+} emerges slowly from the diffractive scattering. The average angle θ_+ between the incident neutrino and the μ^+ is then determined by the mass of the parent, M_F, to be $\theta_+ \sim M_F/2E_+$, with average $Q_+^2 = \langle 4E_\nu E_+ \sin^2(\theta_+/2)\rangle \sim (E_\nu/\langle E_+\rangle)M_F^2$, which varies slowly with E_ν compared to the scaling Q_-^2. As E_ν increases so that M_F is negligible, the μ^+ emerges parallel to the F^{*+}, with $\theta_+ = \theta_- \approx (M/E_-)^{1/2}$, since the diffractively excited hadrons carry little momentum. At this stage both Q_+^2 and Q_-^2 scale. The ratio γ decreases rapidly with E_ν between 50 and 200 GeV, shown in Table I, and then remains constant. In contrast, for L^0 mediated events, γ is constant over the whole range since *both* muons reflect the behavior of their parent L^0.

We point out also that a possible asymmetry, τ, of the μ^+ about the μ^- production plane is actually absent in our model. A nonzero τ could

TABLE I. Average $\langle Q_\pm{}^2\rangle$ for various incoming neutrino energies E_ν, for $M_F = 3$ GeV/c^2. $\gamma \equiv \langle Q_+{}^2\rangle/\langle Q_-{}^2\rangle$ measures the asymmetry.

E_ν (GeV)	$\langle Q_+{}^2\rangle$ (GeV/c^2)	$\langle Q_-{}^2\rangle$ (GeV/c^2)	γ
50	4.74	10.42	0.45
100	5.66	22.62	0.25
150	8.469	36.70	0.23
200	11.28	48.89	0.23

arise either from time-reversal violation or from strong final-state interactions which change the relative phases of interfering amplitudes, or both.[2] Thus, unless time reversal is violated, a finite τ would rule out heavy-lepton-mediated pairs. The form of (2) chosen here with $W_{\mu\alpha;\nu\beta}$ ensures the absence of τ-inducing correlations of the type $\vec{k}_+\cdot(\vec{k}\times\vec{k}_-)$ in the cross section; this is expected for diffractive scattering since diffractive amplitudes are generally pure imaginary.

The most recent data on dimuon pairs[1] can be used to assess its compatibility with F^{*+} production considered above. The energy asymmetry α and the dimuon mass distribution $M_{\mu\mu}$ are in qualitative agreement. A value of $\alpha > 0.6$ would require the F^* to decay into hadronic states with mass greater than $\frac{2}{3}M_{F^*}$. The branching ratio for this is found to be small (~0.8%) and thus *persistence of high values of α in the data will rule out diffraction as the correct source of dimuons*. The v_- distribution of Ref. 1 for dimuons is consistent with the single muon v_- distribution, and within the limits of experimental resolution shows no zero at $v_- = 0$. This possible inconsistency with diffraction, if confirmed, would suggest that single and dimuon reactions both occur via scattering from valence partons, and could exclude diffractive production as a dimuon mechanism.

Finally, we stress the model-independent nature of our qualitative results for $M_{\mu\mu}$, the $E_\pm$ asymmetry, and the energy dependence of $Q_+{}^2/Q_-{}^2$. The behavior of these distributions in hadron or heavy-lepton-mediated production depends mainly on the nonlocal or local origin of the dimuons, and should obtain in any model for hadron production.

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[5]The energy dependence of the total cross section for F^{*+} production in our model is found to be $\sim s\ln^2(s/M_F{}^2)$ between 50 and 400 GeV. This logarithmic violation of scaling in neutrino diffraction production of the F^{+*}, if correct, should manifest itself in the total neutrino cross section above threshold.