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Radiative and hadronic tetralepton production by neutrinos

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We calculate characteristics of $\nu N \to 4\mu X$ and $\nu N \to \mu 3eX$ events in neutrino scattering, arising from conventional charm production accompanied by a dimuon pair from three sources: (i) radiation from the primary lepton-quark interaction, (ii) direct pair production from the subsequent hadronic interactions, deduced empirically from observed prompt muon-pair production in hadron-hadron collisions and (iii) charm-pair production from the primary lepton-quark interaction. Sources (i) and (ii) predict spectrum-averaged 4μ rates of a few times 10^{-8} and $\mu 3e$ rates of order 10^{-7}; (iii) is much smaller. These rates are smaller than the preliminary experimental estimates, but other characteristics of the two published tetralepton events are compatible with a radiative plus hadronic interpretation. We consider an additional hadronic contribution from F production with $F \to \phi l \nu$ and $\phi \to l\bar{l}$ decays, that may contribute appreciably.

I. INTRODUCTION

The multilepton events[1-4] observed in high-energy neutrino interactions may contain a signal for new physics, but first one must determine whether they may have a conventional explanation in terms of known mechanisms. Indeed it appears that most of the trimuon events have a simple conventional explanation, as normal charged-current events accompanied by a $\mu^+\mu^-$ pair of radiative or hadronic origin.[2,5] In the present paper we examine whether the tetralepton events may have a similar explanation, as normal charged-current charm production accompanied by a $\mu^+\mu^-$ pair of radiative or hadronic origin.

Following the lines of our previous paper,[5] where the trimuon case was discussed, we consider three distinct components of tetralepton production illustrated in Fig. 1. All three components have normal charm production $\nu d(s) \to \mu^- c$ with fragmentation to a D meson and semileptonic decay $D \to \mu^+ \nu X$. This part of the calculation is based on a parton model, using a slow-rescaling variable[6] and a flat D-fragmentation function[7] that gives $\langle z\rangle = 0.5$; inclusive D decay is represented by the $D \to K^* \mu\nu$ mode. In our model $\vec{p}_D$ is collinear with the momentum transfer $\vec{q}$. The three components also have additional $\mu^+\mu^-$ pairs, produced in three distinct ways as follows.

(i) $\mu^+\mu^-$ pair radiated electromagnetically in the initial lepton-quark interaction. This contribution is calculated assuming free quarks in the final state, by standard methods.[8] The three radiative diagrams in Fig. 1 cannot be separated gauge invariantly.

(ii) $\mu^+\mu^-$ pair emitted from the hadronic interactions in the final state. This contribution is calculated empirically by reference to observed $\mu^+\mu^-$ production in πN scattering in the corresponding kinematical conditions. This approach has previously been used in trimuon calculations[2,5]; in the present case it is necessary to take account of the leading D-meson production that takes away some of the available hadronic energy and momentum. Our model for this calculation is described in Sec. II.

(iii) Associated charm-anticharm production by single-gluon radiation in the initial lepton-quark scattering, with semileptonic decays. This contribution is distinct from associated charm production in the final hadronic interaction that is presumably included in the empirical component (ii). We calculate the gluon-$c\bar{c}$ production by standard methods[8] assuming free quarks in the final state and taking the effective quantum-chromodynamics coupling constant to be $\alpha_s = g^2/4\pi = 0.4$. We treat the charm fragmentation and semileptonic decays as described above.

These three components have distinct dynamical origins and are arguably incoherent to a fair approximation. We simply add the corresponding cross sections. Components (i) and (iii) have been calculated previously[8] but not (ii); we put all three together here, because they represent the sum of known conventional mechanisms. In the following sections we describe our hadronic tetralepton production model for component (ii), present a range of predictions for all three components, discuss the comparison with the meager present data, and suggest some conclusions. We draw attention to an addition hadronic contribution from F production with $F \to \phi l \nu$ and $\phi \to l\bar{l}$ decays that may also contribute appreciably.

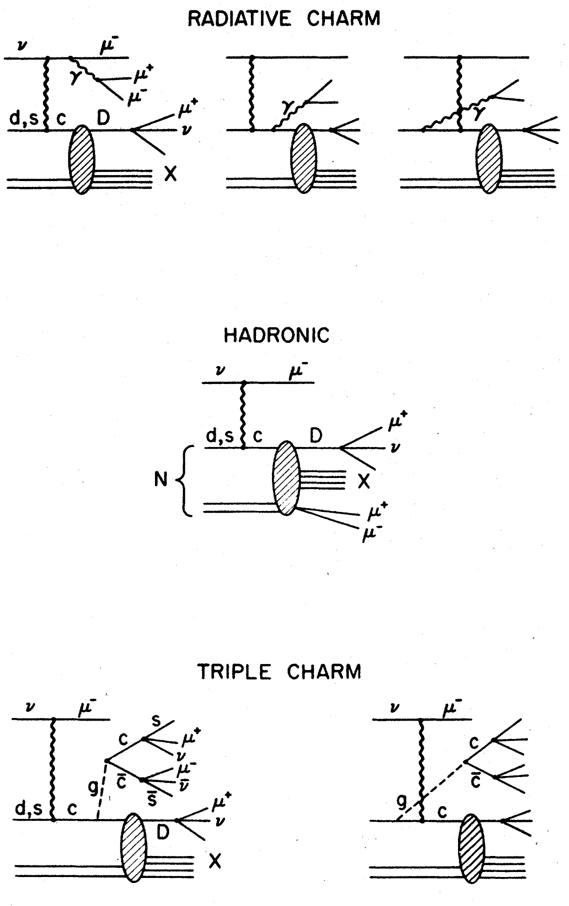

FIG. 1. Three components of tetralepton production.

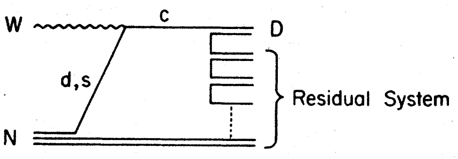

FIG. 2. Schematic of leading D-meson and residual hadronic system produced by a weak current.

II. HADRONIC MODEL FOR NEUTRINO TETRALEPTON PRODUCTION

In the usual theoretical picture, multiparticle hadronic production is controlled by short-range correlations in rapidity,[9,10] so that the distributions and multiplicities of secondaries are largely independent of the initial excitation mechanism (except for leading particle effects). One therefore expects that particles produced in the hadronic recombination phase of neutrino scattering should have distributions similar to those in purely hadronic interactions with the same hadronic c.m. energy and overall momentum, with the momentum transfer axis in neutrino scattering corresponding to the usual longitudinal axis for hadrons. This expectation has been extensively confirmed experimentally,[11] and we can include here the approximate correspondence between neutrino trimuons and hadronic dimuons.[2,5]

The present problem is neutrino D production, where we wish to estimate the production of additional $\mu^+\mu^-$ pairs in the hadronic final-state interaction from comparable hadron-hadron data. We first note that the produced D is a leading particle that will carry off a substantial fraction of the available energy, and that the dominant semileptonic decays $D\rightarrow K(K^*)_{\mu\nu}$ will not contribute toward additional prompt $\mu^+\mu^-$ pairs. These pairs must come from the residual system X (sketched in Fig. 2), which has four-momentum

$$p_X = p_N + q - p_D ,$$

and invariant mass squared

$$m_X{}^2 = p_X{}^2 , \tag{1}$$

where p_N, q, and p_D are the four-momenta of the target nucleon, the weak current, and the produced D meson, respectively. In the laboratory frame $\vec{p}_D$ and $\vec{p}_X$ are collinear with $\vec{q}$. According to the general considerations discussed above, the probability of soft secondary production depends only on p_X and the longitudinal axis. The probability for soft-dimuon emission $X\rightarrow\mu\bar{\mu}X'$ in the c.m. frame of X is deduced from the c.m. distributions of $\pi N\rightarrow\mu\bar{\mu}X'$, evaluated at $s_{\pi N}=m_X{}^2$. We use πN data[12] rather than NN because the πN system has the same baryon number and leading particle behavior as the residual hadronic system of interest.

Based on the preceding arguments, we describe the cross section by the factorized form

$$\frac{d\sigma(\nu N\rightarrow\mu D(\mu\bar{\mu})X')}{dx\,dy\,dz\,d^3p\,dm} = \frac{d\sigma(\nu N\rightarrow\mu DX)}{dx\,dy\,dz}\,\frac{\lambda}{\sigma_t(\pi N)}\,\frac{d\sigma(\pi N\rightarrow\mu\bar{\mu}X')}{d^3p\,dm} , \tag{2}$$

where p and m are the momentum and invariant mass of the $\mu\mu$ pair. Charm production $\nu N\rightarrow\mu DX$ is calculated with the usual parton-fragmentation model.[13] At a given x, y, z, the momentum and mass of the residual system X is specified by Eq. (1). The final factor in Eq. (2) comes from the identification of X with the final-state products of the reaction $\pi N \rightarrow \mu^+ \mu^- X'$. Accordingly the $\mu\bar{\mu}X'$ system has four-momentum p_X and c.m. energy $\sqrt{s} = m_X$. The factor λ in Eq. (2) is a phenomenological scale parameter.

Equation (2) applies to soft recombinations of quark-antiquark pairs but not the hard Drell-Yan annihilation process; however, for the low-dimuon-mass region of interest, $m < 1.4$ GeV, where 90% of pairs are found, the soft-parton annihilations are known to dominate over the Drell-Yan contribution by an order of magnitude.

We use the parametrization of the measured $\pi N \rightarrow \mu^+ \mu^- X'$ invariant cross section[12] that we previously constructed for the trimuon calculation,[5] namely,

$$p^0 \frac{d\sigma}{d^3p\,dm}\,(\pi N \rightarrow (\mu\bar{\mu})X') = a(m)(1 - |x_F|)^{c(m)} e^{-bm_t}\,, \tag{3}$$

with (p^0, p, m) the energy, momentum, and mass of the dimuon pair, $x_F = p_l/p_{\max}$ in the πN c.m. system, and $m_t = (p_t^2 + m^2)^{1/2}$. p_l and p_t are the longitudinal and transverse components of p, with the longitudinal axis given by $\vec{q}$ (i.e., $\vec{p}_X$ and $\vec{q}$ are collinear in our model). The parameter values, fitted to $x_F > 0.1$ data at 16, 150, and 225 GeV, are

$$\begin{aligned} &b = 5.7\ \text{GeV}^{-1}, \quad c = 1 + (0.5\ \text{GeV/m})^2 \\ &a = a_c + a_{\rho\omega} + a_\phi, \\ &a_c = 2.3 \times 10^4 \left(\frac{m}{2m_\mu} - 1\right)^2 e^{-3.2(m/2m_\mu)}, \\ &a_{\rho\omega} = \frac{2.0m}{(m^2 - m_\rho^2)^2 + (m_\rho \Gamma_\rho)^2}, \\ &a_\phi = \frac{0.15m}{(m^2 - m_\phi^2)^2 + (m_\phi \Delta\Gamma)^2}, \end{aligned} \tag{4}$$

with a in units μb/GeV^3; $\Delta\Gamma = 0.05$ GeV is the experimental resolution in m. Hadronic ψ production has been omitted. We take the total cross section to be $\sigma_t(\pi N) = 25$ mb and adopt the scale parameter $\lambda = 2.5$ found from fitting trimuons.[5] We assume the muon pairs decay isotropically, for which there is some experimental support.[12]

The tetralepton calculation is completed by representing the inclusive semileptonic D decay by $D \rightarrow K^* \mu\nu$. For the semileptonic branching fraction we take $B(D \rightarrow \mu\nu X) = 0.15$, as determined from fitting our charm model to the CERN-Dortmund-Heidelberg-Saclay (CDHS) dimuon production data.[14] This branching ratio effectively subsumes both D and F semileptonic decay contributions.

Many D mesons probably come from fragmentation first to D^*, with subsequent $D^* \rightarrow \pi D, \gamma D$ decays. However, since the D, D^* masses are fairly close and the $D^* \rightarrow D$ decays do not produce prompt leptons, the net result is not much different for present purposes.

F or F^* production is another matter. If the decay mode $F \rightarrow \phi\mu\nu$ turns out to be important, F and F^* production could give a substantial tetralepton contribution via $\phi \rightarrow \mu^+ \mu^-$ (branching fraction 2.5×10^{-4}). This contribution would be a leading particle effect that is not included in the hadronic πN analogy; it would have to be calculated separately. Note that the analogous $D \rightarrow V^0 \mu\nu$ ($V^0 = \rho, \omega$) decays are suppressed by the Cabibbo angle and also have smaller $V^0 \rightarrow \mu^+ \mu^-$ branching fractions of order 7×10^{-5}. Similarly $D \rightarrow A_2 \mu\nu$ and $D \rightarrow f\mu\nu$ are suppressed by the Cabibbo angle, while $A_2 \rightarrow \omega\mu^+ \mu^-$ and $f \rightarrow \rho\mu^+\mu^-$ are estimated to have[15] branching fractions of the order of 2×10^{-4}.

Similar methods would allow us to calculate other neutrino tetralepton modes, namely,

$$\nu N \rightarrow \mu^- e^+ \mu^+ \mu^- X, \tag{5a}$$

$$\rightarrow \mu^- \mu^+ e^+ e^- X, \tag{5b}$$

$$\rightarrow \mu^- e^+ e^+ e^- X, \tag{5c}$$

where either the D decay or the hadronic pair or both appear in the electron mode. There is some ambiguity about the channels (5a) and (5b), however, because in principle the hadronic interaction could yield $e^+\mu^-$ and μ^+e^- pairs as well as e^+e^-, $\mu^+\mu^-$ (from associated charm production); no definite data are yet available. Note that the channels

$$\nu N \rightarrow \mu^- \mu^- e^+ e^+ X, \tag{5d}$$

$$\rightarrow \mu^- e^- \mu^+ \mu^+ X, \tag{5e}$$

can arise only from triple-charm production (direct or hadronic) in our approach. In calculating (5b) and (5c), we expect the model parameters for hadronic e^+e^- production to differ from the $\mu^+\mu^-$ case [e.g., the $m(e^+e^-)$ distribution for $\omega \rightarrow \pi^0 e^+ e^-$ is considerably softer than $m(\mu^+\mu^-)$ from $\omega \rightarrow \pi^0 \mu^+ \mu^-$].

Antineutrino tetralepton modes can be calculated similarly:

$$\begin{aligned} \bar{\nu} N &\rightarrow \mu^+ \mu^- \mu^+ \mu^- X \\ &\rightarrow \mu^+ e^- \mu^+ \mu^- X \\ &\rightarrow \mu^+ \mu^- e^+ e^- X \\ &\rightarrow \mu^+ e^- e^+ e^- X \\ &\rightarrow \mu^+ \mu^+ e^- e^- X \\ &\rightarrow \mu^+ e^+ \mu^- \mu^- X. \end{aligned} \tag{6}$$

III. RESULTS AND DISCUSSION

Our calculations are based throughout on the 6%-sea scaling parton-model distributions of Ref. 16. Small alterations to the relative strength of the sea components, and nonscaling corrections, are not expected to affect our results dramatically. We ignore D production from the c, $\bar{c}$ sea distribution in the target because this distribution is suppressed; also the resulting D is rather slow so that decay muons tend to fail the acceptance cuts. We consider all three components described in Sec. I.

We concentrate on the (4μ) and $(\mu 3e)$ tetralepton channels, corresponding to the currently observed events. Predictions for other tetralepton channels are similar. We include in our calculations the lepton-energy cuts $E_\mu > 4.5$ GeV and $E_e > 0.8$ GeV, corresponding to typical experimental acceptances. For $\nu \to \mu 3e$, we impose an additional cut $m(e^+e^-) > 600$ MeV, typical of experimental cuts to eliminate π^0 decay backgrounds. In the restricted e^+e^- mass range, the hadronic e^+e^- signal comes largely from vector-meson decays; we can therefore use the parameterization of Eq. (4), deduced from μ-pair data, as a reasonable representation of hadronic electron pair production.

It is instructive to average the predicted four-lepton rates over typical experimental E spectra. We take two examples: $\nu \to 4\mu$ with the CDHS broad-band neutrino spectrum with incident 350 GeV protons; for $\bar{\nu} \to \mu 3e$ we take the broadband spectrum of the Berkeley-Fermilab-Hawaii-Seattle-Wisconsin (BFHSW) group. With $E > 30$ GeV, taking the energy and mass detection cuts discussed above, the relative strengths of the three components are

		ν (CDHS)	$\bar{\nu}$ (BFHSW)
$\sigma(4l)/\sigma(\mu)$	radiative =	1.0×10^{-8}	1.2×10^{-8}
	hadronic =	2.1×10^{-8}	1.7×10^{-7}
	triple charm =	1.0×10^{-10}	1.8×10^{-10}.

(7)

The triple-charm rate is far too low to be significant, and we omit this mechanism in subsequent considerations. Note also that the predicted radiative contribution to $\bar{\nu} \to \mu 3e$ is very small; this is due to the $m(e^+e^-) > 600$ MeV cut.

In Fig. 3 we show the energy dependence of tetralepton production by neutrinos and antineutrinos in the (4μ) and $(\mu 3e)$ channels with acceptance cut as described above. The solid curve represents the sum of radiative and hadronic contributions; the dashed curve represents the radiative component. The $E(\mu) > 4.5$ GeV acceptance cuts severely depress the $\nu \to 4\mu$ rate for $E < 100$ GeV.

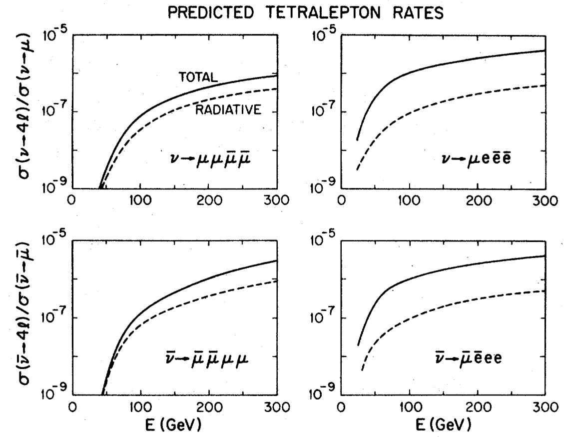

FIG. 3. Energy dependence of (4μ) and $(\mu 3e)$ relative to single μ production by neutrinos and antineutrinos, for typical experimental acceptances $E_\mu > 4.5$ GeV, $E_e > 0.8$ GeV, and $m(e^+e^-) > 600$ MeV. The solid curves represent the sum of hadronic and radiative components; the dashed curves represent the radiative contribution.

Experimental data are very sparse. The CDHS group[2] have the highest multilepton statistics, gained mostly with the 350 GeV broad-band beam, and find one $\nu \to 4\mu$ event among 76 $\nu \to 3\mu$ events. Since they quote a spectrum-averaged trimuon rate of 3×10^{-5}, this suggests a tetralepton rate of a few times 10^{-7}. However, isolated events can be notoriously misleading; for what it is worth, this crude estimate is an order of magnitude high-

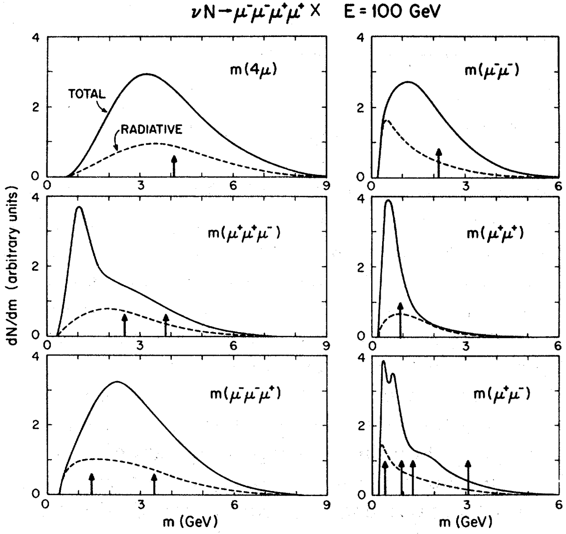

FIG. 4. Invariant-mass distributions for $\nu \to 4\mu$ events at $E = 100$ GeV. Solid lines: total model prediction. Dashed lines: radiative component alone. The arrows denote values for the CDHS event with $E_{\text{VIS}} = 91$ GeV.

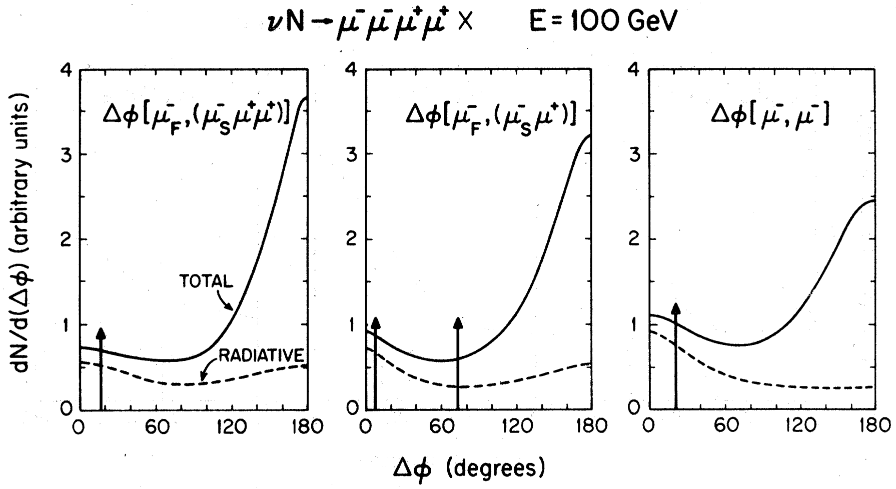

FIG. 5. Azimuthal correlations about the beam axis, between the fast μ^- and vector sums of other lepton momenta, in $\nu \rightarrow 4\mu$ events at $E = 100$ GeV. Solid lines: total model prediction. Dashed lines: radiative component alone. The arrows denote values for the CDHS events.

er than our model predictions.

The CDHS $\nu \rightarrow 4\mu$ event has $E_{\text{vis}} = 91 \pm 7$ GeV. According to our interpretation, there should be some missing energy carried off by at least one decay neutrino—of order 5–10 GeV perhaps. Figures 4 and 5 show the predicted invariant-mass distributions and azimuthal correlations in $\nu \rightarrow 4\mu$ production at $E = 100$ GeV, with $E_\mu > 4.5$ GeV cuts, compared with the CDHS event. This event seems to lie in a region favored by our model; more precisely, it seems rather consistent with the radiative component. Indeed one $\mu^+\mu^-$ pair has very low mass 0.4 GeV and is closely correlated in azimuth with the other μ^-, compatible with the radiative mechanism. The corresponding parameters would be either $x = 0.6$, $y = 0.8$, $W^2 = 50$ GeV^2 or $x = 0.4$, $y = 0.9$, $W^2 = 100$ GeV^2 (depending on which of the radiative diagrams in Fig. 1 is used), not inconsistent with charm production from a valence quark at the hadron vertex.

The BFHSW group[4] have one $\bar{\nu} \rightarrow \mu^+ e^+ e^- e^-$ event with $E_{\text{vis}} = 32$ GeV which seems rather low. However, this event can be interpreted as $\bar{\nu}N \rightarrow \mu^+ D^* \phi X$ with $D^* \rightarrow D\pi^0$, $D \rightarrow K^* e^- \bar{\nu}$, $\phi \rightarrow e^+ e^-$, in which case the missing ν is 8 GeV and $E = 40$ GeV, $x = 0.15$ ($x' = 0.21$), $y = 0.46$, $W^2 = 30$ GeV^2, not inconsistent with the charm production hypothesis. Figures 6 and 7 show the hadronic mechanism predictions for invariant mass and azimuthal correlation distributions at $E = 40$ GeV, with acceptance cuts appropriate to the BFHSW experiment. The $\bar{\nu} \rightarrow \mu 3e$ cross section comes dominantly from the hadronic component. The predicted rate relative to single muons is of order 10^{-7}: see Fig. 3. When we weight with the incident $\bar{\nu}$ spectrum, this energy is not particularly improbable.

Wrong-sign trimuons $\nu \rightarrow \mu^-\mu^+\mu^+$ and $\bar{\nu} \rightarrow \mu^+\mu^-\mu^-$ can arise from our tetramuon mechanisms, from events in which one of the muons lies below the

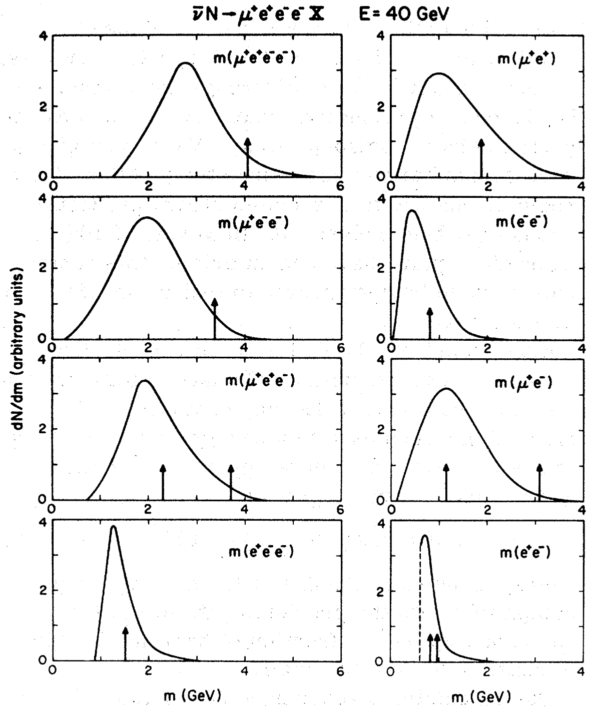

FIG. 6. Invariant-mass distributions for hadronic $\bar{\nu} \rightarrow \mu 3e$ events at 40 GeV. (The radiative contribution at this energy is more than an order of magnitude smaller.) The arrows denote values for the BFHSW event.

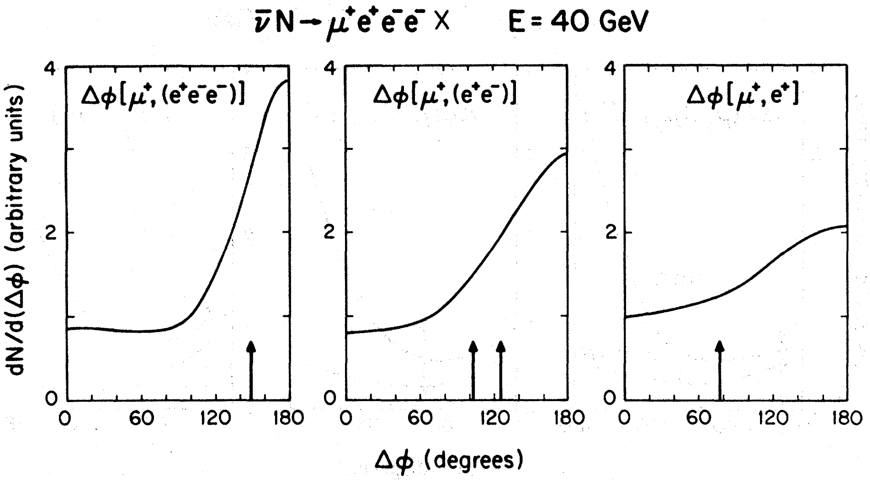

FIG. 7. Hadronic mechanism predictions for azimuthal correlations about the beam axis of the μ^+ and vector sums of various electron momenta in $\bar{\nu}\to\mu 3e$ at 40 GeV. The arrows denote data values for the BFHSW event.

acceptance cuts. These cuts are especially severe on the slow muons generated at small or negative x_F in the hadronic component. Hence the wrong-sign 3μ rate from this source is comparable to the 4μ rate. For example we find

$$\sigma(\nu\to\mu^-\mu^+\mu^+)/\sigma(\nu\to\mu^-)=4\times10^{-8} \tag{8}$$

from misidentified 4μ averaging over the CDHS ν spectrum with $E>30$ GeV and $E_\mu>4.5$ GeV cuts.

An alternative source of wrong-side trimuons is triple-charm production, where one of the charmed particles has nonmuonic decay. We cannot give a precise number for this, since the fraction of hadronic muons due to associated charm production has not yet been measured. However, if 10% of hadronic μ pairs have charm origin, this contribution would be comparable to that in Eq. (8) from misidentified 4μ.

Experimentally the CDHS group report four $\nu\to\mu^-\mu^+\mu^+$ events, with a calculated background of 6 events from π or K decays, compared to 76 right-sign trimuons with a background of 6. This indicates a 90% confidence upper limit on the wrong-sign trimuon signal of

$$\sigma(\nu\to\mu^-\mu^+\mu^+)/\sigma(\nu\to\mu^-)\leq1\times10^{-6} \tag{9}$$

averaged over the CDHS spectrum. This is quite compatible with the predicted rate in Eq. (8); it does not require the fraction of hadronic μ pairs of charm origin to be small.

Our calculations above have not included $F(F^*)$ production with $F\to\phi l\nu$, $\phi\to l\bar{l}$ decays, because we lack necessary information. However, it is interesting to make a rough estimate of the possible rate from this source. We expect the leading F/D production ratio to equal approximately the K/π ratio in the fragmentation region of hadron scattering, which is typically $\frac{1}{5}$. Assuming the inclusive semileptonic decay functions and distributions for F and D are similar, we obtain

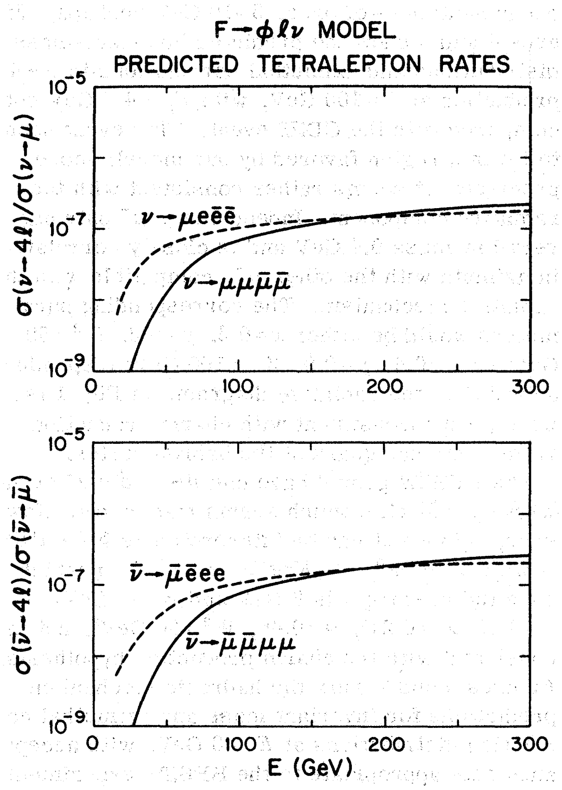

FIG. 8. Predictions of (four-lepton)/(single muon) rates in the F-production model with $B(F\to\phi l\nu)=0.1$. The curves are based on acceptance cuts of $E_\mu>4.5$ GeV, $E_e>0.8$ GeV, and $m(e^+e^-)>600$ MeV.

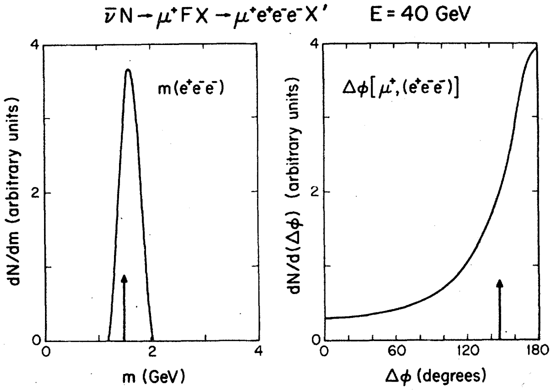

FIG. 9. *F*-production model predictions for the $e^+e^-e^-$ invariant-mass distribution and the azimuthal correlation $\Delta\phi[\mu^+, (e^+e^-e^-)]$ at an incident $\bar{\nu}$ energy of 40 GeV. The arrows denote values for the BFHSW event.

from this source

$$\sigma(\nu N \to \mu^-\mu^+l\bar{l}X) = \tfrac{1}{5}\sigma(\nu N \to \mu^+\mu^-X)\frac{B(F\to\phi\mu\nu)}{B(D\to X\mu\nu)} \times B(\phi\to l\bar{l})D(l\bar{l}),$$

where $D(l\bar{l})$ is the detection efficiency for the lepton pair. Here the branching fraction $B(F \to \phi\mu\nu)$ is unknown, but if it is as high as 10% this mechanism could contribute a $(4\mu)/(\mu)$ rate of order 1×10^{-7} at high energy. Figure 8 shows the energy dependence of the $(4\mu)/(\mu)$ and $(\mu3e)/\mu$ rates, based on $B(F\to\phi\mu\nu)=0.1$.

The invariant mass and $\Delta\phi$ distributions from F production do not differ dramatically from those of the hadronic model, apart from the $m(e^+e^-) = m_\phi$ constraint. The $m(e^+e^-e^-)$ distribution is kinematically restricted to a narrower band, $m_\phi < m(e^+e^-e^-) \leq m_F$, as shown in Fig. 9. The $\Delta\phi$ distributions have smaller contributions near 0^0, as illustrated in Fig. 9 for $\Delta\phi[\mu^+,(e^+e^-e^-)]$. The e^+e^- pair from ϕ decay is somewhat more energetic than for the hadronic model of Sec. II and as a result mass distributions of the muon with these electrons are slightly broader in the F model.

It is interesting that the BFHSW event admits an interpretation as $\bar{\nu}N\to\mu^+F^*X$, $F^*\to F\pi^0$, $F\to\phi e^-\nu$, $\phi\to e^+e^-$, with $E=35$ GeV, $W^2=22$ GeV^2, $y=0.38$, and $x=0.18$; these parameters are somewhat more marginal than for the D^* interpretation above, but not impossible. The CDHS event cannot be interpreted as F decay without stretching the quoted uncertainties considerably or assuming it is initiated by $\bar{\nu}$.

IV. CONCLUSIONS

Our results suggest the following conclusions:

(i) The predicted rate of four-lepton production by the "conventional" mechanisms considered, when averaged over the CDHS ν spectrum with $E > 30$ GeV, is an order of magnitude smaller than the preliminary value suggested by the single CDHS 4μ event. However, since single events can be notoriously deceptive, there is not necessarily a disagreement here.

(ii) The other predicted characteristics of four-lepton production are compatible with the observed events. Although there are only two published events, their details contain a surprising amount of information and the agreement with the calculations is not trivial. In particular, the CDHS 4μ event is consistent with a radiative interpretation, and the BFHSW $\mu3e$ event is consistent with a hadronic origin.

(iii) The predicted wrong-sign trimuon rate from these mechanisms is compatible with the experimental upper limit.

(iv) Our treatment of hadronic lepton pairs omits leading F-meson production with $F\to\phi l\nu$, $\phi\to l\bar{l}$ decays. If the branching fraction for $F\to\phi\mu\nu$ is as high as 10%, these modes could contribute of order 1×10^{-7} to the $4\mu/\mu$ rate at high energy. If this contribution is in fact significant, it will be clearly signaled by an excess of lepton pairs at the ϕ mass. (The BFHSW $\mu3e$ event may belong in this category).

(v) Associated charm production in hadronic interactions is an important open question— relating also to the hadronic production of prompt single leptons and neutrinos, and to the neutrino production of same-sign dileptons. We note that it will also lead to tetralepton events with characteristic charge signatures, as in Eqs. (5d) and (5e).

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[1] Fermilab-Harvard-Ohio State-Penn-Rutgers-Wisconsin (FHOPRW) experiment: A. Benvenuti *et al.*, Phys. Rev. Lett. 38, 1110 (1977); 40, 488 (1978); 38, 1110 (1977); D. Reeder, in Proceedings of the Ben Lee Memorial Conference, 1977 (to be published); D. Cline, talk at Irvine Conference, 1977 (unpublished); T. Y. Ling, talk at Rencontre de Moriond, 1978 (unpublished).

[2] CERN-Dortmund-Heidelberg-Saclay (CDHS) experiment: M. Holder *et al.*, Phys. Lett. 70B, 393 (1977); 73B, 105 (1978); J. Steinberger, talk at Irvine Conference, 1977 (unpublished); K. Kleinknecht, talks at Coral Gables Conference, 1978 (unpublished) and Rencontre de Moriond, 1978 (unpublished); D. Schlatter, talk at Vanderbilt Conference, 1978 (unpublished); T. Hansl *et al.*, CERN reports, 1978 (unpublished).

[3] Caltech-Fermilab (CITF) experiment: B. C. Barish *et al.*, Phys. Rev. Lett. 38, 577 (1977).

[4] Berkeley-Fermilab-Hawaii-Seattle-Wisconsin (BFHSW) experiment: R. J. Loveless *et al.*, Report No. COO-088-29 (unpublished).

[5] V. Barger *et al.*, Phys. Rev. D 18, 2308 (1978).

[6] R. Barnett, Phys. Rev. Lett. 36, 1163 (1976); H. Georgi and H. D. Politzer, *ibid.* 36, 882 (1976).

[7] R. Odorico and V. Roberto, Nucl. Phys. B136, 333 (1978).

[8] V. Barger *et al.*, Phys. Lett. 76B, 494 (1978).

[9] J. D. Bjorken, in *Proceedings of the SLAC Summer Institute on Particle Physics*, 1973, edited by M. Zifp (SLAC, Stanford, 1973), p. 1.

[10] R. P. Feynman, in *Proceedings of the Fifth Hawaii Topical Conference on Particle Physics*, 1973, edited by P. N. Dobson, Jr., V. Z. Peterson, and S. F. Tuan (University of Hawaii Press, Honolulu, 1974).

[11] M. Derrick *et al.*, Phys. Rev. D 17, 1 (1978); G. Wolf in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies*, edited by W. T. Kirk (SLAC, Stanford, 1976); B. Roe, in *Particles and Fields '76*, proceedings of the annual meeting of the Division of Particles and Fields of the APS, edited by R. F. Peierls and H. Gordon (BNL, Upton, New York, 1977). T. H. Burnett *et al.*, Seattle Report No. VTL-PUB-50, 1978 (unpublished).

[12] K. J. Anderson *et al.*, Phys. Rev. Lett. 37, 799 (1976); University of Chicago Report No. 76-0686 (unpublished); J. G. Branson *et al.*, Phys. Rev. Lett. 38, 1334 (1977); K. Bunnell *et al.*, Phys. Rev. Lett. 40, 136 (1978); J. Alspector *et al.*, Univ. Rochester Report No. UR-617 (unpublished); J. G. Branson, thesis, Princeton Report No. COO-3072-81, 1977 (unpublished).

[13] L. M. Sehgal and P. Zerwas, Phys. Rev. Lett. 36, 399 (1976); Nucl. Phys. B108, 483 (1976); V. Barger and R. J. N. Phillips, Phys. Rev. D 14, 80 (1976); V. Barger *et al.*, *ibid.* 16, 746 (1977).

[14] M. Holder *et al.*, Phys. Lett. 69B, 377 (1977).

[15] I. H. Dunbar, Bristol University report, 1978 (unpublished).

[16] V. Barger *et al.*, Nucl. Phys. B102, 439 (1976).