Comments and Addenda

The section Comments and Addenda is for short communications which are not appropriate for regular articles. It includes only the following types of communications: (1) Comments on papers previously published in **The Physical Review** *or* **Physical Review Letters**. *(2) Addenda to papers previously published in* **The Physical Review** *or* **Physical Review Letters**, *in which the additional information can be presented without the need for writing a complete article. Manuscripts intended for this section must be accompanied by a brief abstract for information-retrieval purposes. Accepted manuscripts follow the same publication schedule as articles in this journal, and page proofs are sent to authors.*

Angular correlations in neutrino-induced trimuon events

V. Ganapathi
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794

J. Smith*
CERN, Geneva, Switzerland
(Received 7 June 1979)

Spin-parity selection rules are examined for the neutrino trimuon events seen in the CERN-Dortmund-Heidelberg-Saclay experiment. The muon-energy cuts seriously reduce the acceptance in the c.m. frame and make it impossible to isolate terms from partiy-violating decays. The results agree with the models where the secondary dimuon pairs are produced in a 1^- state via electromagnetic or hadronic radiation.

The production of multimuon events in neutrino and muon beams is being actively pursued with the aim of identifying new signals from the production and decay of particles containing heavy quarks. In neutrino physics it is now known that the trimuon events are primarily due to the electromagnetic and hadronic production of secondary dimuon pairs of low invariant mass.[1,2] Clearly, in the case of muon beams, there is a tremendous trimuon background from conventional electromagnetic sources, for instance Bethe-Heitler and Compton pairs.[3,4] Hence, we are looking for small effects in situations where the background is large and it is therefore not easy to establish the existence of a genuine signal. Most theorists working in this field need to run complicated Monte Carlo programs which include acceptance cuts, etc., before comparing their results with the available data. Many distributions are insensitive to changes in the initial parameters and/or the models themselves, so the primary aim of the analysis is to pinpoint some crucial feature which will distinguish one model from another.

Recently Tung[5] has proposed that spin-parity analysis may be helpful in distinguishing heavy-quark and/or heavy-lepton decays from background effects. The idea is to look for asymmetric effects in angular distributions just as one does in the case of normal weak decays. If all the secondary particles are produced via electromagnetic interactions, then the angular distribution of the muons in the dimuon rest frame will be $a+b\cos^2\theta$. A departure from this distribution would indicate that some new physics was taking place. Up to now the data have been so limited that nobody has tried to make such an analysis. The purpose of this note is to examine these tests more carefully to see if there is any hope of learning something from them either now or in the near future. We use the recent neutrino trimuon data from the Cern-Dortmund-Heidelberg-Saclay (CDHS) group for this purpose.[1] To make the paper reasonably self-contained, we give a brief discussion of the physics involved before presenting our results.

We assume that trimuon events are seen, either in neutrino interactions, or in muon interactions. A leading muon is *defined* according to some criterion and a secondary pair is identified and their momenta measured. This allows a complete reconstruction of each event in both the laboratory frame and any other frame defined by Lorentz transforming the muon momenta. Our particular analysis will be made in the center-of-mass frame of the secondary pair. In this frame we can define the muon momenta as

$$p_+=\left(\frac{W}{2},\ \frac{|\vec{p}|}{2}\sin\theta\cos\phi,\ \frac{|\vec{p}|}{2}\sin\theta\sin\phi,\ \frac{|\vec{p}|}{2}\cos\theta\right)$$

and

$$p_-=\left(\frac{W}{2},\ -\frac{|\vec{p}|}{2}\sin\theta\cos\phi,\ -\frac{|\vec{p}|}{2}\sin\theta\sin\phi,\ -\frac{|\vec{p}|}{2}\cos\theta\right),$$

where W is the invariant mass of the pair and $|\vec{p}| = (W^2 - 4\mu^2)^{1/2}$. The angles θ and ϕ are measured with respect to some convenient coordinate frame defined by the momenta of the remaining particles. We choose the z axis as the direction of the Lorentz transformation necessary to boost the pair back into the laboratory frame and define the (x, z) plane to contain the incident neutrino (muon). This leaves the leading muon, i.e., the muon produced in the original interaction, completely arbitrary. In principle, therefore, one can check the angular correlations between all the muons in this frame just as one does in the laboratory frame. The form of the angular distribution expected from conventional processes, namely those involving a spin-1 photon, is well known. Owing to parity nonconservation in the original neutrino interaction, one can divide the angular distribution into a parity-conserving part $(VV+AA)$ and a parity-violating part $(VA+AV)$. The former piece satisfies

$$\frac{d\sigma}{d\Omega} = W_T(1+\cos^2\theta) + W_L(1-\cos^2\theta) + W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta} \sin^2\theta \cos 2\phi. \qquad (1)$$

It has no term linear in $\cos\theta$ and is even in $\phi \to 180° + \phi$. This corresponds exactly to the situation in muon production. The latter piece satisfies

$$\frac{d\sigma}{d\Omega} = \overline{W}_\Delta \sin 2\theta \sin\phi + \overline{W}_{\Delta\Delta} \sin^2\theta \cos 2\phi \qquad (2)$$

and is absent for muon beams, hence a complete description of the neutrino interaction requires knowledge of six structure functions. The terms in (1) and (2) can be separated, in principle, by using ν and $\bar{\nu}$ interactions. If other sources of trimuons exist, such as those expected from the associated production of charmed or heavier quarks, and heavy-lepton decays, then the forms given above will no longer hold due to an explicit parity violation in the decays. Thus it is interesting to check whether the present data are consistent with Eqs. (1) and (2).

Unfortunately, there are not enough data[6] on $\bar{\nu}$ events to try to disentangle the six structure functions given above, so we have first integrated over ϕ or θ. We expect that the θ distribution has the form $d\sigma/d\cos\theta = A + B\cos^2\theta$. The presence of an additional parity violation would lead to an extra term involving $\cos\theta$. To check for the presence of such a term we require a good angular acceptance in the dimuon c.m. frame. Unfortunately, this is not easy to obtain because the present experiments cannot identify muons unless their energy is greater than 4.5 GeV. We demonstrate the severity of these cuts by showing, in Fig. 1, the $\cos\theta$ plot for the trimuon events from the CDHS group.[1] The plot contains sixty events because we have left out those events where the $P_\perp$ of any muon with respect to the neutrino axis is below 0.2 GeV/c (which means that its azimuthal angle is only known with a large error). The data have been taken from the table in Ref. 1 and no effort has been made to incorporate smearing due to the errors on the measurements of the muon momenta. The limited angular acceptance of the experiment is very obvious. Only those muon pairs which are oriented at 90° with respect to the direction of the Lorentz transformation manage to survive the cuts. The asymmetrical configuration with one muon directed along the positive z axis is completely suppressed. In other words, the Lorentz transformation does not boost the backward moving muon to a sufficiently high momentum to satisfy $p_\mu > 4.5$ GeV/c.

To compare these results with theory, we show the distributions expected form the hadronic model (solid curve) and from the electromagnetic

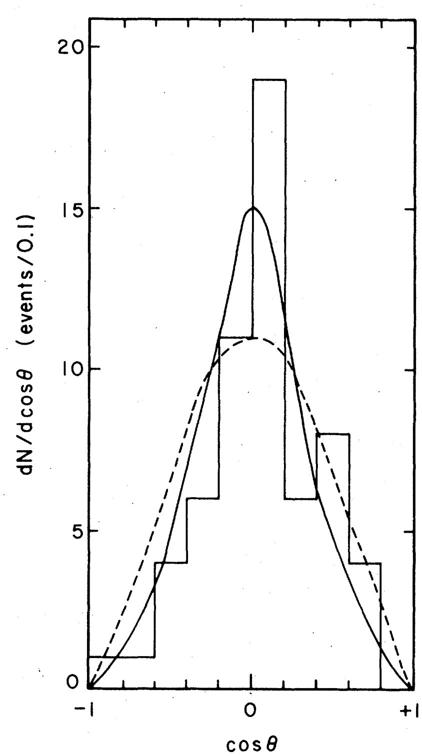

FIG. 1. The $\cos\theta$ distribution in the secondary dimuon rest frame for the CDHS trimuon events. Also shown are the results of the hadronic model (solid curve) and the electromagnetic model (dashed curve), each curve normalized to the total number of events.

model. The electromagnetic calculation of course produces muons in a 1^- state, i.e., $A+B\cos^2\theta$ before cuts, whereas the input for the hadronic model is taken to be flat in $\cos\theta$. Hence the electromagnetic contribution is larger near $\cos\theta=\pm 1$. Note that even though the data seem to show an excess of events in the region $\cos\theta>0$, this effect is not statistically significant. There is no momentum smearing on the theoretical models, or on the measured muon momenta. Such effects would tend to reduce the height of the central peak near $\cos\theta=0$. It is clear that there is no disagreement between the experimental data and the theoretical prediction. To detect the presence of a $\cos\theta$ term, an experiment would need a much larger acceptance in the c.m. frame. This can be achieved by either reducing the muon energy cuts, or by having available much higher beam energies.

It would be unfair not to make some statement about the spectrum in the variable ϕ. Of course this combines both vector and axial-vector matrix elements and, with so limited data, there is no hope to disentangle the two. However, to show the hadronic and electromagnetic components give a completely satisfactory explanation of the events, we give the distribution in Fig. 2. From Eqs. (1) and (2) we see that the ϕ distribution is expected to have the form

$$\frac{d\sigma}{d\phi}=A+B\cos\phi+C\sin\phi+D\cos^2\phi+E\sin 2\phi. \quad (3)$$

In a situation where all the terms are of the same magnitude, this distribution will be effectively flat, and that is what we see, in Fig. 2, for the sixty CDHS events. The input for the hadronic model assumes a flat spectrum and therefore we are not surprised by the output. For the electromagnetic model there is a ϕ dependence but the dominant term seems to be the one which is constant in ϕ. Note that the models require the evaluation by Monte Carlo mehtods of eight-dimensional integrals. The statistical accuracy in the evaluation is not sufficient to see small effects.

The results given above only confirm our present understanding of the physics behind trimuon events. However, the question arises as to how much parity violation would be present if we suppose the contrary to be true, i.e., if all the dimuons came from the decay of, say, charmed particles. To examine this point, let us take the gluon bremsstrahlung model.[7] In that model a pair of charmed particles are produced from single gluons (ignoring the question of color recombination) and they decay into the channels $c\to s+\mu^+ +\nu_\mu$ and

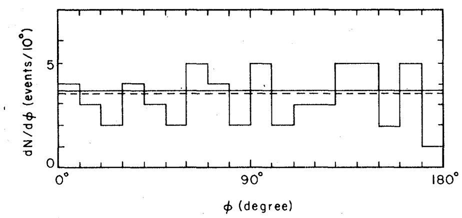

FIG. 2. The ϕ distribtuion in the secondary dimuon rest frame for the CDHS trimuon events. The solid line shows the result expected from the hadronic model and the dashed curve gives the result from the electromagnetic model, normalized as in Fig. 1.

$\bar{c}\to\bar{s}+\mu^- +\bar{\nu}_\mu$. We assume for simplicity that the decay interaction is $V-A$ with maximal parity violation. With this scenario the angular distribution in the dimuon rest frame can, in principle, contain all multipoles. However, there is no reason to believe that the coefficients of the terms in $\cos\theta$ or $\cos^2\theta$, etc., are larger than the constant term. To a first approximation therefore the angular distribution in $\cos\theta$ will be flat without cuts. We have checked this by calculating the spectra in $\cos\theta$ using our program for the $c\bar{c}$ production and decay, and that is indeed the result. Note that this statement follows from the numerical evaluation of an eighteen-dimensional integral, i.e., seven for the production of the pair of charmed particles, five for each decay, and one for the neutrino spectrum. It is impossible to look for small effects while such calculations are carried out completely numerically. Therefore if we incorporate cuts, we end up with a $\cos\theta$ curve which looks just like the hadronic curve in Fig. 1.

Hence the conclusion we reach is rather negative. So long as the multilepton studies are carried out with requirements that $E_\mu \geq 4.5$ GeV, there is little hope that the angular acceptance in the c.m. frame is large enough to test for the presence of parity-violating decays. Also as long as the theoretical work consists of the running of massive computer programs, it is impossible to pick up small effects in angular distributions. Unfortunately, we do not see any alternative theoretical approach because the evaluation of many of the integrations analytically is fine, but it completely destroys the possibility of introducing momentum smearing, acceptance cuts, definitions of leading muons, etc., and these effects must be incorporated before any meaningful comparison can be made between theory and experiment.

This work was supported in part by the National Science Foundation under Grant No. 78-11969.

*On leave from the Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, N. Y. 11794.

[1]T. Hansl *et al.*, Nucl. Phys. B142, 381 (1978); Phys. Lett. 77B, 114 (1978); A. Benvenuti *et al.* (unpublished).
[2]J. Smith, CERN Report No. TH-2657, 1979 (unpublished); J. Smith and J. A. M. Vermaseren, Phys. Rev. D 17, 2288 (1978); C. H. Albright, J. Smith, and J. A. M. Vermaseren *ibid.* 18, 108 (1978); V. Barger, T. Gottscnalk, and R. J. N. Phillips, *ibid.* 17, 2284 (1978); 18, 2308 (1978).
[3]K. W. Chen and A. Van Ginneken, Phys. Rev. Lett. 40, 1417 (1978); see the reports by P. Surko, P. Payre, and J. Feltesse at the XIVth Rencontre de Moriond, 1979 (unpublished).
[4]V. Ganapathi and J. Smith, Phys. Rev. D 19, 801 (1979); R. S. Nataf, Ann. of Phys. (N.Y.) (to be published); V. Barger, W. Y. Keung and R. J. N. Phillips, Phys. Rev. D 20, 630 (1979).
[5]W. K. Tung, Nucl. Phys. (to be published).
[6]J. H. G. de Groot *et al.*, Phys. Lett. (to be published).
[7]G. L. Kane, J. Smith, and J. A. M. Vermaseren, Phys. Rev. D 19, 1978 (1979); H. Goldberg, Phys. Rev. Lett. 39, 1598 (1977); B. L. Young, T. F. Walsh, and T. C. Yang, Phys. Lett. 74B, 111 (1978).