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THE SOURCE OF TRIMUON EVENTS IN NEUTRINO SCATTERING*

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ABSTRACT

A comprehensive study indicates that equally likely sources for trimuon events in neutrino scattering are a) charged heavy lepton production (with decay to three muons) and b) simultaneous production of a neutral lepton (with decay to two muons) and a heavy quark (with decay to one muon). The sequential decay of a heavy quark to two muons is less likely. An intriguing model yielding simultaneous M^O and b quark production is proposed.

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Two experiments[1, 2] have recently reported events in which three muons (plus other particles) were produced in neutrino-nucleon deep-inelastic scattering. The Fermilab-Harvard-Pennsylvania-Rutgers-Wisconsin (FHPRW) authors[2] argue that several features of these events, including the high rate and the large momenta of the muons, preclude production via any previously known particles. We share this view and consider alternative sources of these trimuon events.

A comprehensive study of three alternatives through both analytic and Monte Carlo techniques is reported here. We show that the common hypothesis[3] of charged heavy lepton production is by no means a unique explanation of the events. For example, an intriguing model with the simultaneous production[4] of a neutral lepton M^o and a heavy quark b (of charge $-\frac{1}{3}$) is completely consistent with the data. However, the sequential decay to two muons of a heavy quark t (of charge $\frac{2}{3}$) through a lepton M^o or a quark b is less likely to be the source of these trimuons.

As more data is accumulated, it should be possible to distinguish among these three classes of phenomena yielding trimuons: A) $\nu N \rightarrow M^- X$ with $M^- \rightarrow \mu^- M^o \bar{\nu}$ or $\mu^- \overline{M^o} \nu$ and $M^o \rightarrow \mu^- \mu^+ \nu$; B) $\nu N \rightarrow M^o b X$ with $M^o \rightarrow \mu^- \mu^+ \nu$ and $b \rightarrow \mu^- \bar{\nu} X'$; C) $\nu N \rightarrow \mu^- t X$ with $t \rightarrow \mu^+ M^o X'$ or $t \rightarrow \mu^+ \nu b$, etc.

To distinguish among quark-lepton models within each above class, the polarizations of each particle were kept whenever appropriate. However, our study shows that it may require much more extensive data to distinguish within each class, and such details are left for a full report.[5] In this letter we choose one representative model from each class in order to compare the three classes.

As this work was in progress, we have received many papers proposing models from class A. Here the following couplings were assumed where L and R refer to left- and right-handed fermions: $\nu N \rightarrow X_L \left(M_L \rightarrow \mu_R^- \nu_L \left(\overline{M_L^o} \rightarrow \mu_L^+ \mu_L^- \bar{\nu}_R \right) \right)$.

Other details of such models are discussed elsewhere.[3] We emphasize that all models of Class A give relatively similar results.

An interesting quark-lepton model representing Class B has the SU(3) × U(1) couplings (mixings neglected):

$$\begin{pmatrix} u \\ d \\ b \end{pmatrix}_L \begin{pmatrix} c \\ s \\ g \end{pmatrix}_L \begin{pmatrix} c \\ b \\ d \end{pmatrix}_R \begin{pmatrix} u \\ g \\ s \end{pmatrix}_R \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \\ \overline{M^o} \end{pmatrix}_R \begin{pmatrix} \mu^+ \\ \overline{M^o} \\ \bar{N}_\mu \end{pmatrix}_L$$

(similar triplets with e^+ and with τ^+ also occur). It is assumed that the usual W boson couples the top two fermions in each triplet while an X boson of comparable mass couples the bottom two: the W' boson coupling the top to the bottom fermions is assumed to be considerably heavier. This model is particularly interesting because the W couplings are similar to those of an SU(2) × U(1) model[6] which has been compared[7] in detail with all available data and found to be consistent. The X couplings do not affect the previous results; the trimuon events are presumed to be the first evidence for couplings via X. The details of the symmetry breaking and mass patterns will be discussed elsewhere. [5] We are primarily concerned with how models of this general class would produce trimuon events.

For t quark production the assumed couplings are $\nu N \to \mu_L^- \left(t_L \to d_R \mu_L^+ \left(M_R^o \to \mu_R^- X_L\right)\right)$. Decay schemes similar to these are found in the vector model.[8] Other models in this class (including t quark decay via a quark b) give somewhat inferior results.

Calculations for classes B and C require an assumption about the distribution of z ≡ the fraction of the "produced" quark's momentum kept by the produced hadron containing that quark. Since the produced quark is assumed to be quite heavy, conventional wisdom about z might fail. 1) As a result we considered all possibilities from a sharp peaking at small z to a sharp peaking at large z. Our results were rather insensitive to this choice (outside of extremes); a peaking at intermediate z = 0.5, was assumed (which is naively expected if light particles peak at small z).

In the discussion below, the fast μ^-, slow μ^- and μ^+ are labeled as 1, 2, and 3 respectively. The incoming neutrino's visible momentum is $\vec{k}$. The energy asymmetry and transverse momentum (to $\vec{k}$) asymmetry are defined as

$$E_{13}^{as} \equiv (E_1 - E_3)/(E_1 + E_3)$$

$$p_{\perp}^{as} \equiv \left(\Sigma|\vec{p}_{\perp}| - |\Sigma\vec{p}_{\perp}|\right)/\left(\Sigma|\vec{p}_{\perp}| + |\Sigma\vec{p}_{\perp}|\right)$$

where $\vec{p}_{\perp}$ sums are over three muons. $\theta_{ij} - \theta_k$ is the angle, in the plane transverse to $\vec{k}$, between $(\vec{p}_i + \vec{p}_j)$ and $\vec{p}_k$. $\theta_{W1\alpha}$ is the angle, in the plane transverse to $(\vec{k} - \vec{p}_1)$, between $\vec{p}_1$ and $\vec{p}_\alpha$ (for class C, $\vec{k} - \vec{p}_1$ corresponds to the W boson momentum). θ_{X2} is the angle, in the plane transverse to $(\vec{k} - \vec{p}_1 - \vec{p}_3)$, between $\vec{k}$ and $\vec{p}_2$.

A summary of some of the more interesting characteristics we calculated for each model is shown in the Table. It should be emphasized again that the differences among models in a class were found to be smaller than the differences among these classes. FHPRW event 119 (with muon momenta of 157, 32 and 47 GeV/c) was an unlikely event in each class; the odds against events with $E_1 > 130$, $E_2 > 25$ and $E_3 > 40$ GeV (compared with all trimuon events) are less than 1 in 10^4 for each class. (If additional events similar to 119 are observed, a completely different source will be required.) In addition, the experimental characteristics of all trimuon events (from two experiments) are similar except for event 119. It is therefore, of interest to consider averages with 119 excluded (see Table).

With a handful of events, it is obviously not possible to reach strong conclusions at this time. It is not even certain that all trimuon events have the same source. Given the poor statistics, each of the three classes could be the source of trimuons. However, class C appears to be furthest from the present average characteristics. Comparing class A (with M^-=8, M^0=3 GeV) and class B (with M^0=3, b=5 GeV), the largest differences appear in E_{13}^{as}, θ_{W13} and θ_{X2}, so that perhaps a modest increase in data will allow a distinction. Consequently we show the distributions in these variables in Figs. 1-3. Surprisingly the relative distribution of $p_\perp$ for the three muons (measured by $p_\perp^{as}$) is similar for the three classes and not a definitive characteristic. $\theta_{23} - \theta_1$ might distinguish C from A and B; but $\theta_{13} - \theta_2$ and θ_{W12} are not very useful.

All mass parameters were varied in our study.[2)] Changes in masses do not improve the fits for class C. The changes induced by variations in the masses of the heaviest fermions in classes A and B are indicated in the Table. For both classes other values for the mass of the M^0 give worse fits.

We conclude that at the present time, class A (M^- production) and class B (M^0 and b quark production) give equally adequate descriptions of the observed trimuon characteristics. Class C, however, is clearly less favored. Models within class B are, therefore, a viable alternative to those of class A. The specific model proposed here under class B is just such an alternative which is also consistent with all other relevant data.

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NOTE ADDED: After completion of this work, we became aware that Langacker and Segre[9] have also considered a model similar to the one proposed here.

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FOOTNOTES

1. While light particles peak at small z, J. Bjorken (private communication) suggests that hadrons containing a heavy quark might be expected to keep most of the momentum with which that quark was produced (causing a peaking at large z).

2. The value of ~ 5 GeV for the b quark mass suggested by the table ties in neatly with the recent report of the resonance at 9.5 GeV, which could be a $(b\bar{b})$ bound state. See S. W. Herb et al., Columbia University Preprint (1977). Notice that the b quark under discussion here may be different from that excited by charged currents from the u-quark. The latter, if heavier than 5 GeV, would not give rise to high y anomalies. In the model proposed under Class B, a switch of the positions of u_R and c_R would involve just the b in both transitions, instead of the b and g quarks as it now stands.

TABLE CAPTION

Calculated average characteristics of three classes of phenomena yielding trimuon events. Parenthetical numbers under experiment exclude event no. 119 (see text). To follow experiment, calculations included the experimental flux, required that for each muon $E_{\mu} > 4$ GeV, and always identified the fastest μ^- as μ_1 irrespective of its origin (μ_2 is always the slowest μ^- and μ_3 is the μ^+). M^2_{12} and M^2_{123} are invariant masses squared. All other variables are defined in the text. Masses given under "class" are in GeV. The phase space suppression (PSS) factor refers to the reduction in rate for heavy particle production relative to the ordinary single muon rate (other factors constant).

TABLE

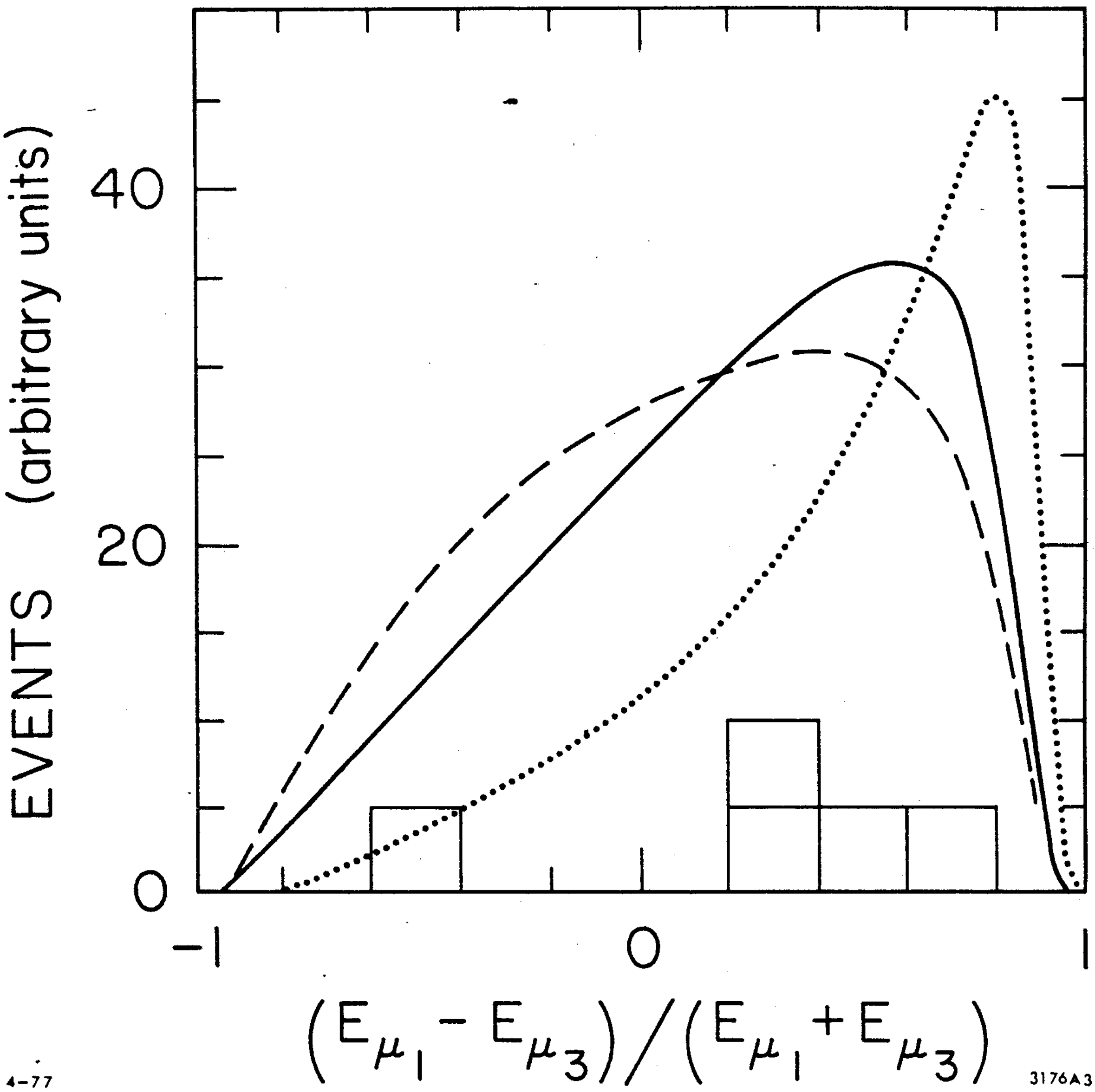
CLASS \ EXPT	P.S.S.	E_1 GeV	E_2 GeV	E_3 GeV	E_{13}^{as} (-1,+1)	M_{12}^2 GeV^2	M_{123}^2 GeV^2	$P_{\perp}^{as}$ (0,+1)	$\theta_{23}-\theta_1$ deg	θ_{W13} deg	θ_{X2} deg
EXPT	–	60(36)	13(9)	31(27)	.25(.18)	8.4(5.0)	17(13)	.26(.26)	90(93)	31(36)	93(115)
A $M^-=6$ $M^o=3$	.22	35	15	27	.16	4.2	12	.28	91	74	69
A $M^-=8$ $M^o=3$	.09	40	17	28	.21	7.8	19	.32	98	73	71
B $M^o=3$ b=5	.19	34	13	28	.12	8.7	21	.36	102	79	89
B $M^o=3$ b=6	.12	33	13	27	.14	10	24	.34	101	79	89
C t=5 $M^o=2$	.33	61	14	18	.46	14	34	.38	126	91	97

FIGURE CAPTIONS

1. Distribution in the energy asymmetry E_{13}^{as} (see text). Solid curve is for class A, masses 8 and 3 GeV; dashed curve is for class B, lepton and quark masses 3 and 5 GeV respectively; and dotted curve is for class C, with quark and lepton masses 5 and 2 GeV respectively. Data is from Ref. 2.

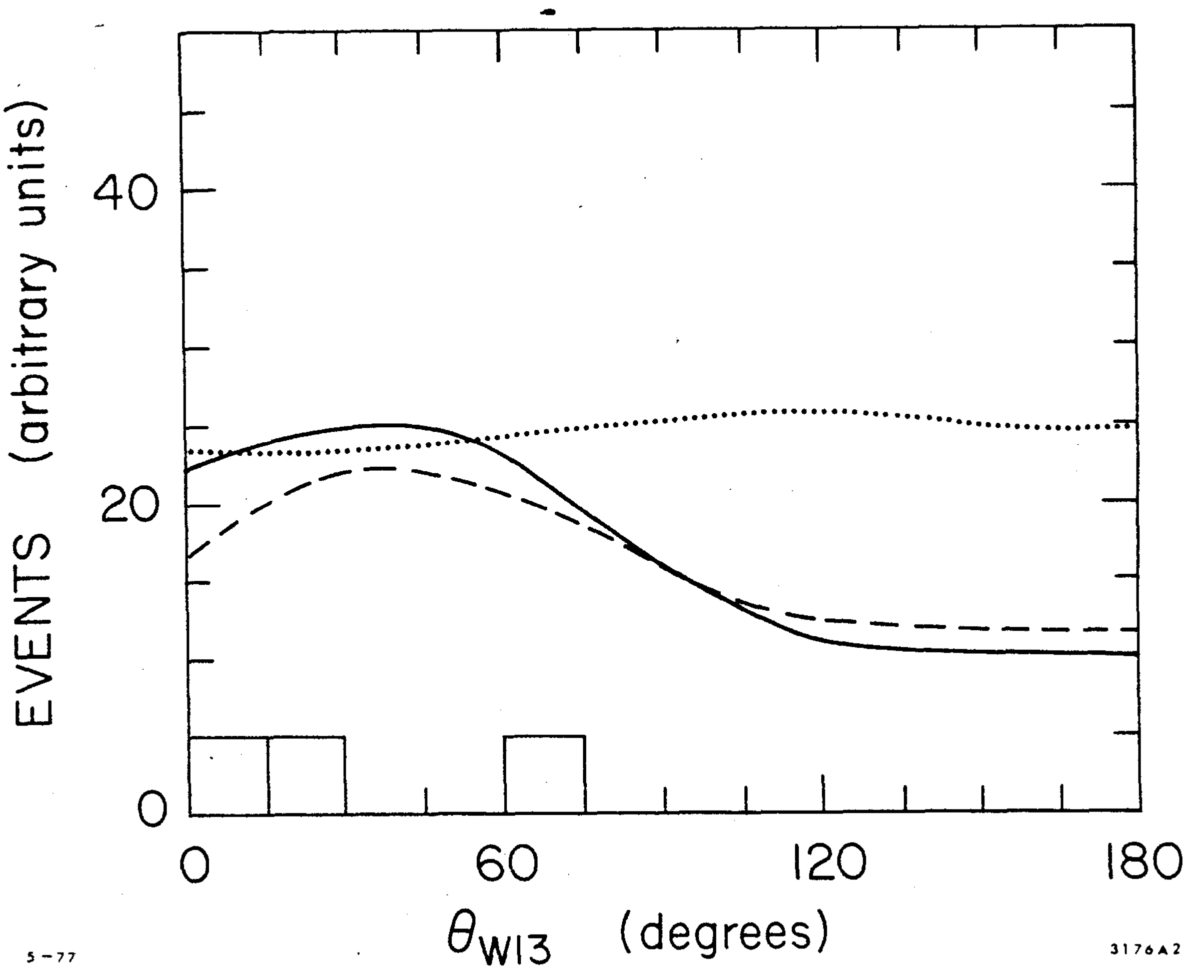
2. Distribution in the angle θ_{W13} (see text). The curves have the same significance as in Fig. 1. Data is from Ref. 2. Only for the three events with measured hadron energies can θ_{W13} be determined.

3. Distribution in the angle θ_{X2} (see text). The curves have the same significance as in Fig. 1. Data is from Ref. 2. Only for the three events with measured hadron energies can θ_{X2} be determined.



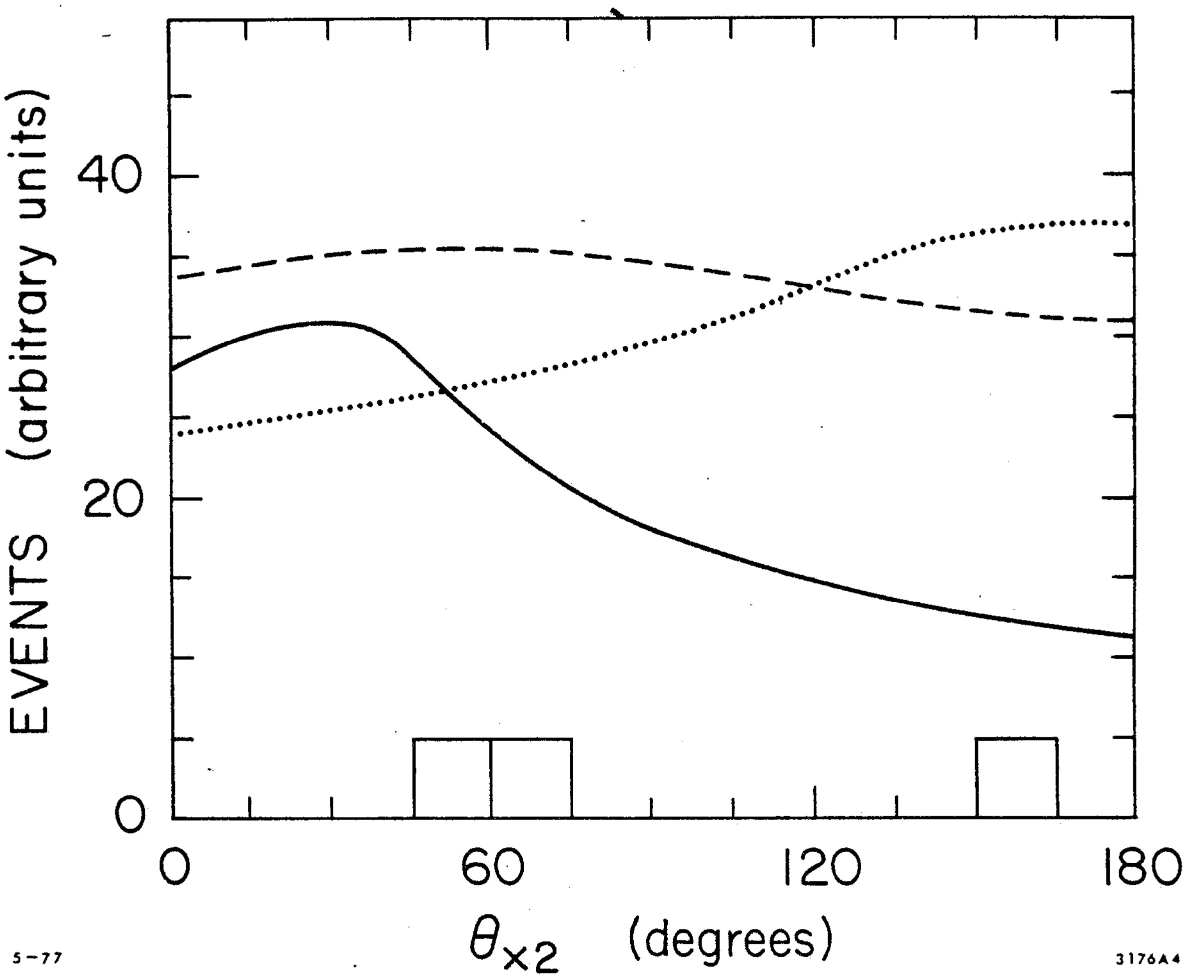
EVENTS (arbitrary units)
40
20
0
-1
0
1
$(E_{\mu_1} - E_{\mu_3})/(E_{\mu_1} + E_{\mu_3})$
4-77
3176A3

Fig. 1



EVENTS (arbitrary units)
40
20
0
0
60
120
180
θ_{W13} (degrees)
5-77
3176A2

Fig. 2



EVENTS (arbitrary units)
40
20
0
0
60
120
180
θ_{x2} (degrees)
5-77
3176A4

Fig. 3