

Implications of Experiment on Gauge Theories of the Weak and Electromagnetic Interactions

R. Michael Barnett

In this addendum there is a short discussion of the 9.5 GeV resonance reported by Lederman for the Columbia-Fermilab-Stony Brook group (CFS) at this conference, as well as a listing of some new neutrino data also reported here and corrections and additions to references.

An unfortunate oversight in this report was the omission of the earliest references for the $SU(2) \times SU(2) \times U(1)$ model. The model was first discussed by Pati and Salam^{A1} and by Fritzsch and Minkowski.^{A2}

One of the interesting features of the CFS 9.5 GeV resonance produced in $pp \rightarrow \mu^+ \mu^- + X$ is that it appears to be wider than the experimental resolution.^{A3} It is, however, consistent with two resonances separated by several hundred MeV. At first glance this might suggest two new quarks. However, there are two different arguments why the two resonances may be just Υ and Υ' (a radial excitation). These involve different assumptions about the mode of production.

Consider, first, ψ production in pp collisions. The ψ may be produced directly or (as suggested by Einhorn, Ellis, Quigg^{A4} and Carlson, Suaya^{A4}) indirectly, occurring dominantly through ψ_p ($\equiv \psi_{p\text{-wave}}$) production and decay to ψ . Clearly ψ' cannot be produced via the indirect mode since it is heavier than ψ_p .

Ellis, Gaillard, Nanopoulos, and Rudaz,^{A5} proposing the direct mode, assume that ψ and Υ are produced by a Drell-Yan type mechanism, $A\bar{A} \rightarrow \psi$, for some constituents A. The production cross sections are proportional to

$$\sigma(pp \rightarrow \psi + X) B(\psi \rightarrow \mu^+ \mu^-) \propto m_\psi^{-3} \mathcal{L}(m_\psi/\sqrt{s}) \frac{\Gamma(\psi \rightarrow \mu\mu) \Gamma(\psi \rightarrow \text{hadrons})}{\Gamma(\psi \rightarrow \text{all})}$$

where $\mathcal{L}$ is the luminosity for $A\bar{A}$ collisions and is taken from the excitation function for ψ production. As a result EGNR find ψ'/ψ relative production (and decay to $\mu^+ \mu^-$) of a few percent, Υ'/Υ of 30% (for b quarks) and Υ/ψ of about 20×10^{-5} (for b quarks).

The indirect mode of Υ production makes use of the result of Eichten and Gottfried^{A6} that Υ_p and Υ'_p (and Υ'') are both below the threshold for Zweig-allowed decays. Clearly it follows that Υ and Υ' can be produced by the decays of Υ_p and Υ'_p respectively (unlike the case of ψ and ψ').

It should be noted that neither the direct nor the indirect mode implies equal $p\bar{p}$ and pp production of ψ . First, a different production mode may

dominate $p\bar{p}$. Second, the direct and indirect modes may occur via the $A\bar{A} \rightarrow (\psi \text{ or } \psi_p)$ process. With this latter assumption, S. Ellis and I have estimated the cross sections via the indirect mode (see also Ref. A7)

$$\sigma(pp \rightarrow \psi + X)B(\psi \rightarrow \mu^+\mu^-) \propto m_\psi^{-3} \mathcal{L}(m_\psi/\sqrt{s}) \frac{\Gamma(\psi \rightarrow \mu\mu)G}{\Gamma(\psi \rightarrow \text{all})}$$

$$G \equiv \Gamma(\psi_p \rightarrow \text{glue})\Gamma(\psi_p \rightarrow \gamma\psi)/\Gamma(\psi_p \rightarrow \text{all}) \approx \Gamma(\psi_p \rightarrow \gamma\psi)$$

With this we obtain Υ'/Υ of about 40% and Υ/ψ of about 5×10^{-5} (for b quarks) compared with 20×10^{-5} from EGNR and 3×10^{-5} from experiment. Theory increases by a factor of about four for top quarks, but these calculations are so crude that one cannot make any judgements on the charge of the quark and must rely on future results from e^+e^- experiments.

Therefore the CFS resonance may be the unresolved combination of Υ and Υ' , whose splitting Eichten and Gottfried^{A6} predict to be 400 MeV.

Many features of heavy quark states ($b\bar{b}$, $d\bar{d}$, etc.) have been discussed in Refs. A5-A8. They are fine tools for testing linear potential models, asymptotic freedom, and Zweig's rule. Below I always assume $\Upsilon = b\bar{b}$. Eichten and Gottfried^{A6} estimated $\Gamma(\Upsilon \rightarrow \mu^+\mu^-) = 0.7 \text{ keV}$ and $\Gamma(\Upsilon' \rightarrow \mu^+\mu^-) = 0.4 \text{ keV}$. One can also do a naive phenomenological fit to the ρ , ω , ϕ , and ψ decays to e^+e^- which gives the widths proportional to charge squared over $m^{1/8}$; this gives $\Gamma(\Upsilon \rightarrow \mu^+\mu^-) = 1 \text{ keV}$.

Using a leptonic width of 0.7 keV, I calculated^{A8} an integrated area for Υ in e^+e^- annihilation of 130 nb-MeV compared to 10,000 nb-MeV for ψ . For a resolution of 15 MeV (expected at PEP and PETRA) this gives a signal to background for Υ of 2/1 compared to 250/1 for ψ (the background is proportional to resolution). Clearly Υ will not be nearly so easy to see as ψ but will not be missed.

The leptonic width, 0.7 keV, yields $\Gamma(\Upsilon \rightarrow \gamma \rightarrow \text{hadrons}) = 3.5 \text{ keV}$ if $R=5$. However, the calculation of $\Gamma(\Upsilon \rightarrow \text{glue} \rightarrow \text{hadrons})$ involves some more severe assumptions. It is assumed that the three-gluon calculation is a reasonable approximation (which is not certain). Then one must choose the value of the strong coupling α_s where

$$\alpha_s \approx \frac{12\pi}{25 \log(s/\Lambda^2)}$$

Eichten and Gottfried^{A6} took α_s from the potential calculations with $\alpha_s(\sqrt{s} = 3.1) \approx 0.2$ (or $\Lambda = 0.07$ GeV). As an alternative, S. Ellis and I take α_s from $\bar{e}p$ and e^+e^- scattering with $\alpha_s(\sqrt{s} = 3.1) \approx 0.4$ (or $\Lambda = 0.5$ GeV). With $\Lambda = 0.07$, EGNR obtain $\Gamma(\Upsilon(\Upsilon') \rightarrow \text{glue} \rightarrow \text{hadrons}) = 14$ keV (9 keV) while we obtain 6.6 keV (3.7 keV) with $\Lambda = 0.5$ GeV. Also Eichten and Gottfried^{A6} obtain $\Gamma(\Upsilon' \rightarrow \gamma \Upsilon_p) = 8$ keV, while different methods give 1 or 2 keV.

Assuming the CFS resonance is $b\bar{b}$, what are the weak couplings of b ? Certainly the coupling $(u, b)_R$ through W is forbidden by the neutrino results discussed in this report since $m_b \approx 5$ GeV.

However, right-handed currents for b are not ruled out (and are worth considering in light of the atomic-parity-violation experiments). For example, all of the following couplings are allowed:

$$\begin{pmatrix} c \\ b \end{pmatrix}_R \quad \begin{pmatrix} t \\ b \end{pmatrix}_R \quad \begin{pmatrix} c \\ b \\ d \end{pmatrix}_R \quad \begin{pmatrix} t \\ b \\ d \end{pmatrix}_R$$

and even $(u, b)_R$ may be allowed if the coupling is not through the usual W boson but through a W' boson.

Of course, the b quark may well have left-handed couplings (or both left- and right-), such as:

$$\begin{pmatrix} t \\ b \end{pmatrix}_L \quad \text{or} \quad \begin{pmatrix} u \\ d \\ b \end{pmatrix}_L$$

All of the $SU(3)$ triplets shown here could lead to trimuon production if the coupling (μ^-, ν, M^0) also exists (see trimuon section). The couplings (c, b) and (t, b) are likely to lead to decays of b through c .

Each model discussed in Sec. I has a candidate for the CFS quark ($A - b$, $B - g$, $C - b$ or g , $D - b$, $E - b$ or g , $F - b$).

New neutrino results were announced at this conference. For deep-inelastic neutral currents (see Fig. 1), Cundy reported for BEBC

$$R_\nu = 0.33 \pm 0.04 \quad R_{\bar{\nu}} = 0.45 \pm 0.07$$

and Steinberger for CDHS

$$R_\nu = 0.30 \pm 0.015 \quad R_{\bar{\nu}} = 0.38 \pm 0.03$$

For deep-inelastic charged currents (see Figs. 6 and 7), Cundy (BEBC) reported (for E in GeV and σ/E in $10^{-38} \text{ cm}^2/\text{GeV}$):

Energy	$\sigma(\nu)/E$	Energy	$\sigma(\bar{\nu})/E$	Energy	Rc
20 - 60	0.65 ± 0.06	20 - 60	0.26 ± 0.03	40	0.40 ± 0.06
60 - 100	0.56 ± 0.05	60 - 90	0.25 ± 0.03	75	0.45 ± 0.06
100 - 150	0.61 ± 0.05	90 - 190	0.32 ± 0.04	145	0.56 ± 0.08
150 - 190	0.51 ± 0.05				

Steinberger (CDHS) reported the $\langle y \rangle$ was approximately constant at 0.32 for E = 30-200 GeV and Rc was approximately constant at 0.44 for E = 25-200 GeV; study of systematics in cross sections is still under way.

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References

- A1. J. Pati and A. Salam, Phys. Rev. D 10, 275 (1974).
- A2. H. Fritzsch and P. Minkowski, Nucl. Phys. B 103, 61 (1976).
- A3. S. W. Herb et al., Phys. Rev. Lett. (to be published).
- A4. M. Einhorn, S. Ellis, and C. Quigg, Phys. Rev. Lett. 36, 1263 (1976);
C. Carlson and R. Suaya, Phys. Rev. D 15, 1416 (1977).
- A5. J. Ellis et al., preprint CERN-TH-2346.
- A6. E. Eichten and K. Gottfried, Phys. Lett. 66B, 286 (1977).
- A7. R. Cahn and S. Ellis, University of Michigan report UM-HE 76-45 (1976).
- A8. M. Barnett, Proc. Orbis Scientiae, Coral Gables, 1977, preprint SLAC-PUB-1891; T. Walsh, DESY preprint.

IMPLICATIONS OF EXPERIMENT ON GAUGE THEORIES
OF THE WEAK AND ELECTROMAGNETIC INTERACTIONS*

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I. Introduction

The minimal group for gauge theories of the weak and electromagnetic interactions is $SU(2) \times U(1)$ (discussed by Weinberg and Salam¹ (WS)). Two models in this group (see Table 1) have done remarkably well in accounting for a very large variety of phenomenology. Model A (of WS and Glashow, Iliopoulos and Maiani² (GIM)) has only left-handed currents. Model B (discussed by various authors³⁻⁶) has both left- and right-handed currents. No other $SU(2) \times U(1)$ model⁷ seems likely to agree with experiment.

However, even these two models have shortcomings. Model A appears to be in serious conflict with experiments⁸ which find little or no parity violation in electronic transitions in heavy atoms. In Model B the required lack of mixing between b and d or s quarks (to avoid strangeness-changing neutral-currents) has been called "unnatural".⁹ If the reported observation¹⁰ in neutrino scattering of trimuon events (above background) is confirmed, both models might have difficulty accounting for them.

As a result, many authors¹¹⁻¹⁸ have considered other groups. Here I will examine four "simple" extensions (shown in Tables 2, 3 and 4) based on higher groups. These are from $SU(3) \times U(1)$ (Model C of Lee and Weinberg¹³ and Model D of Barnett and Chang^{14, 15}), from $SU(3) \times SU(3)$ (Model E of Gürsey, Ramond and Sikivie¹⁶ and of Bjorken and Lane¹⁷), and from $SU(2) \times SU(2) \times U(1)$ (Model F of De Rujula, Georgi and Glashow¹² and of Mohapatra and Sidhu¹¹). There are other versions of these models not considered here, and there are different models which are also interesting; it is my purpose only to discuss a sample of extensions of $SU(2) \times U(1)$ models.

Among other models of interest (which I do not have time to discuss) are the $SU(2) \times U(1) \times U(1)$ model of Fritzsche and Minkowski,¹⁸ the $SU(3)$ models of

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Table 1. $SU(2) \times U(1)$ Models (mixing angles neglected).

Model A (Refs. 1 and 2; expanded version)

$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	$u_R, c_R, t_R, d_R, s_R, b_R$
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	e_R, μ_R, τ_R

Model B (Refs. 3-6)

$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	b_L, g_L	$\begin{pmatrix} u \\ b \end{pmatrix}_R$	$\begin{pmatrix} c \\ g \end{pmatrix}_R$	d_R, s_R
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	E_L^0, M_L^0, T_L^0	$\begin{pmatrix} E^0 \\ e^- \end{pmatrix}_R$	$\begin{pmatrix} M^0 \\ \mu^- \end{pmatrix}_R$
				$\begin{pmatrix} T^0 \\ \tau^- \end{pmatrix}_R$	

Table 2. $SU(3) \times U(1)$ Models (mixing angles neglected).

<u>Model C</u> (Ref. 13)						
$\begin{pmatrix} u \\ d \\ b \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \\ g \end{pmatrix}_L$	t_L, v_L	$\begin{pmatrix} t \\ b \\ d \end{pmatrix}_R$	$\begin{pmatrix} v \\ g \\ s \end{pmatrix}_R$	u_R, c_R	
$\begin{pmatrix} \nu_e \\ e^- \\ E^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu^- \\ M^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau^- \\ T^- \end{pmatrix}_L$	E_L^0, M_L^0, T_L^0	$\begin{pmatrix} E^0 \\ E^- \\ e^- \end{pmatrix}_R$	$\begin{pmatrix} M^0 \\ M^- \\ \mu^- \end{pmatrix}_R$	$\begin{pmatrix} T^0 \\ T^- \\ \tau^- \end{pmatrix}_R$
<u>Model D</u> (Refs. 14, 15)						
$\begin{pmatrix} u \\ d \\ b \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \\ g \end{pmatrix}_L$		$\begin{pmatrix} u \\ g \\ s \end{pmatrix}_R$	$\begin{pmatrix} c \\ b \\ d \end{pmatrix}_R$		
$\begin{pmatrix} e^+ \\ \bar{\nu}_e \\ \overline{E^0} \end{pmatrix}_R$	$\begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \\ \overline{M^0} \end{pmatrix}_R$	$\begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \\ \overline{T^0} \end{pmatrix}_R$	$\bar{N}_{e_R}, \bar{N}_{\mu_R}, \bar{N}_{\tau_R}$	$\begin{pmatrix} e^+ \\ \overline{E^0} \\ \bar{N}_{e_L} \end{pmatrix}_L$	$\begin{pmatrix} \mu^+ \\ \overline{M^0} \\ \bar{N}_{\mu_L} \end{pmatrix}_L$	$\begin{pmatrix} \tau^+ \\ \overline{T^0} \\ \bar{N}_{\tau_L} \end{pmatrix}_L$

Table 3. $SU(3) \times SU(3)$ Models (mixing angles neglected).

Model E (Refs. 16, 17)			
$\begin{pmatrix} \bar{u} \\ \bar{d} \\ \bar{b} \end{pmatrix}_L$	$\begin{pmatrix} \bar{c} \\ \bar{s} \\ \bar{g} \end{pmatrix}_L$	$(u \ s \ b)_R$	$(c \ d \ g)_R$
$\begin{pmatrix} E^0 & e^+ & \tau^+ \\ e^- & \bar{\nu}_e & \bar{\nu}_\tau \\ \tau^- & \bar{\nu}'_\tau & E^0 \end{pmatrix}_R$	$\begin{pmatrix} M^0 & \mu^+ & M^+ \\ \mu^- & \bar{\nu}_\mu & \bar{\nu}_M \\ M^- & \bar{\nu}'_M & M^0 \end{pmatrix}_R$	or	$\begin{pmatrix} M^0 & M^+ & \mu^+ \\ M^- & \bar{M}^0 & \bar{\nu}_\mu \\ \mu^- & \bar{\nu}_M & \bar{\nu}'_M \end{pmatrix}_R$

Table 4. $SU(2) \times SU(2) \times U(1)$ Models (mixing angles neglected).

Model F (Refs. 11, 12)					
$\begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix}_L$	$\begin{pmatrix} \bar{c} \\ \bar{s} \end{pmatrix}_L$	$\begin{pmatrix} \bar{t} \\ \bar{b} \end{pmatrix}_L$	$(u \ b)_R$	$(c \ s)_R$	$(t \ d)_R$
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(E^0 \ e^-)_R$	$(M^0 \ \mu^-)_R$	$(T^0 \ \tau^-)_R$
and ? $\begin{pmatrix} M^0 \\ M^- \end{pmatrix}_L$			$(N_M, \ M^-)_R$		

Fritzsch and Minkowski¹⁸ and of Horn and Ross,¹⁵ the $SU(6)$ model of Abud et al.,¹⁸ and the $SU(8) \times U(1)$ model of Pakvasa et al.¹⁸ Furthermore there are models involving integer-charge quarks which I do not consider here.

Given the remarkable success of $SU(2) \times U(1)$ models, it is attractive to retain the basic features of that group. It will be seen that Models C and E resemble Model A, that Model D resembles Model B, and that Model F resembles a purely vector model.

Each of these models (C, D, E and F) is free of triangle anomalies. The suppression of strangeness-changing neutral-currents is "natural"⁹ in the sense that no parameter is arbitrarily made small; this suppression usually

is obtained through imposition of discrete symmetries. The universality of the $\bar{\nu}_e e$, $\bar{\nu}_\mu \mu$ and $\bar{u}d$ coupling strengths is assured in each model. In some cases¹² the Cabibbo angle is related to quark mass ratios. CP violation occurs although usually without any explanation of its small magnitude. There is no means to calculate the masses of b quarks or heavy leptons, and in each case there are other parameters which can only be determined experimentally.

By the introduction of higher groups, one has introduced additional gauge bosons, both charged and neutral. Among the neutral bosons can be those which change flavor. In the old $SU(2) \times U(1)$ models, there are two charged (W^+ and W^-) and two neutral (Z^0 and photon) bosons. In the tables, I have used the following conventions in every case: fermions in columns are coupled by W , V or U and fermions in rows by W' , V' or U' ; the first and second fermions in a column (row) are coupled by W (W'), the first and third by V (V') and the second and third by U (U').

In the $SU(3) \times U(1)$ models (C and D) there are nine bosons, $W^\pm$, $V^\pm$, Z^0 , Y^0 , U^0 , $\bar{U}^0$ and γ (or A). The Z , Y and A can be written as:

$$Z^\mu = \frac{1}{2} \cos \theta_3 \left(\sqrt{3} V_3^\mu + V_8^\mu \right) - \sin \theta_3 V_0^\mu$$

$$Y^\mu = \frac{1}{2} \left(V_3^\mu - \sqrt{3} V_8^\mu \right)$$

$$A^\mu = \frac{1}{2} \sin \theta_3 \left(\sqrt{3} V_3^\mu + V_8^\mu \right) + \cos \theta_3 V_0^\mu$$

where the V_a^μ (V_0^μ) interact with the currents $-\frac{i}{2} g \bar{\psi} \gamma_\mu \lambda_a \psi$ ($-\frac{i}{2} g' \bar{\psi} \gamma_\mu y \psi$). Also $W^\pm = (V_1 \mp iV_2)/\sqrt{2}$, etc. The quantity $y \equiv Q - I_3 - y'$ which are defined in Section II.

Model E ($SU(3) \times SU(3)$) has 16 gauge bosons, but most of them are quite heavy. Model E is similar to Model A except that the electron and muon have both left- and right-handed couplings through W , and their neutral currents are vector.

Model F has seven bosons, $W^\pm$, $W'^\pm$, Z_A^0 , Z_V^0 and γ (or A). A unique feature of this model is that Z_A is an axial-vector boson and Z_V is a vector boson which guarantees that most neutral currents are parity-conserving; however, neutrino and antineutrino cross sections need not be equal for neutral currents since the neutrino is an exception. The W' is somewhat heavier than the W . In Model F the Z_A , Z_V and A can be written as:

$$Z_A^\mu = (W_{3L}^\mu - W_{3R}^\mu)/\sqrt{2}$$

$$Z_V^\mu = \cos \theta_2 (W_{3L}^\mu + W_{3R}^\mu)/\sqrt{2} - \sin \theta_2 B^\mu$$

$$A^\mu = \sin \theta_2 (W_{3L}^\mu + W_{3R}^\mu)/\sqrt{2} + \cos \theta_2 B^\mu$$

In this review I will consider the phenomenology of the four new models (C-F) in contrast with that of models A and B. Much of the discussion is applicable to other models not discussed here. Included in the discussion will be the neutral-current phenomenology (neutrino-nucleon deep-inelastic, neutrino-proton elastic, neutrino-electron elastic and atomic parity violation). The charged-current neutrino scattering section includes discussion of the y -dependence, the ratio of $\bar{\nu}$ to ν cross sections, dilepton production and tri-lepton production. Other topics are also discussed.

II. Neutral Currents

A. Calculations

In Model C the diagonal neutral currents ($\bar{u}u$, $\bar{d}d$, $\bar{e}e$, $\bar{\nu}\nu$, etc.) occur through both the Y^0 and Z^0 bosons. In Model D the mass eigenstates are Z_1^0 and Z_2^0 which are mixtures of Y and Z . From the neutral-current phenomenology, these mixtures are approximately:

$$Z_1 = \frac{1}{2} Y + \frac{\sqrt{3}}{2} Z$$

$$Z_2 = \frac{\sqrt{3}}{2} Y - \frac{1}{2} Z$$

The coefficients of Y and Z couplings relative to couplings to W can be written for each fermion (of each handedness) of Models C and D as:

$$\frac{1}{\sqrt{2}} (I_3 - 3y') \quad \text{for } Y^0$$

$$\frac{\sqrt{3/2}}{\cos \theta_3} (I_3 + y' - Q \sin^2 \theta_3) \quad \text{for } Z^0$$

where Q is the charge, $I_3=1/2, -1/2, 0$ and $y'=1/6, 1/6, -1/3$ for the first, second and third fermion in each triplet; $\cos^2 \theta_3 \equiv g^2/(g^2+g'^2/3)$ is analogous to $\cos^2 \theta_W$ in $SU(2) \times U(1)$ theories. One can see that in Model C neutrino scattering and in Model D electron scattering do not occur via the Y^0 .

In calculating scattering in Model C, one uses the mass ratios

$$\frac{m_W^2}{m_Z^2} = \frac{3}{4} \frac{\cos^2 \theta_3}{\eta^2}, \quad \frac{m_Y^2}{m_Z^2} = 3 \frac{\cos^2 \theta_3 (1-\eta^2)}{\eta^2}$$

The parameter η^2 can vary from 0 to 1 and is related through the Higgs structure of the model to fermion masses (but η^2 is not well constrained). Best fits are obtained¹³ with $\sin^2 \theta_3 \approx 0.25$ and $\eta^2 \approx 0.85$.

For Model D the mass formulae are not quite so simple. The best fits are obtained¹⁴ with

$$\sin^2 \theta_3 = 0.5, \quad \frac{m_W^2}{m_{Z_1}^2} = 0.636, \quad \frac{m_{Z_1}^2}{m_{Z_2}^2} = 0.451$$

In Model E the neutral-current couplings of all quarks and of the neutrino are very close to those of Model A (since most gauge bosons are quite heavy). The electron and muon have vector couplings similar to those in Model B.

In Model F the coefficients of Z_A and Z_V for each fermion are proportional to (for left- and right-handed):

$$\frac{\pm I_3}{2\sqrt{2}} \quad \text{for } Z_A$$

$$\frac{I_3 - Q \sin^2 \theta_2}{2\sqrt{2} \cos \theta_2} \quad \text{for } Z_V$$

where $\cos^2 \theta_2 \equiv g^2/(g^2 + 2g'^2)$ and $I_3 = 1/2, -1/2$ for the first and second members of doublets.

The mass ratios for Model F are:

$$\frac{m_W^2}{m_{Z_A}^2} = \frac{1}{1+\epsilon}, \quad \frac{m_{Z_A}^2}{m_{Z_V}^2} = \frac{1+\epsilon}{1-\epsilon} \cos^2 \theta_2$$

where ϵ can vary from 0 to 1 and is related (through the Higgs structure of the model) to fermion masses. Best fits¹¹ are obtained with $\sin^2 \theta_2 \approx 0.4$ and $\epsilon \approx 0.0$.

B. Deep-Inelastic Scattering

The results of neutral-current deep-inelastic scattering experiments¹⁹ along with model predictions are shown in Fig. 1. For Models A and B a range of values of $\sin^2 \theta_W$ are shown. For Models C-F only the particular values of the parameters which give the best fits to all neutral-current phenomenology are shown. Asymptotic freedom corrections²⁰ induce 5 or 10% changes

which increase (decrease) the theoretical values of R_ν ($R_{\bar{\nu}}$). The b quark has been assumed heavy enough not to affect these results.

Clearly all of the Models A-F agree with the data while a purely vector model cannot. There is not complete freedom to fit data because of the additional parameters of higher groups. For example, no set of parameters in Model D can yield $\sigma(\bar{\nu} \rightarrow \bar{\nu})/\sigma(\nu \rightarrow \nu) < 0.634$.

C. Elastic Neutrino-Proton Scattering

Unlike the deep-inelastic scattering, the elastic neutrino-proton scattering provides a test which differentiates the models discussed here. While present HPW data²¹ shown in Fig. 2 (and CIR data²² for R_ν which is consistent with HPW) do not rule out any models, within a few months they will report results with much higher statistics and with a complete analysis of background. There should then be a clear test of these models.

The q^2 dependence reported by these groups does not distinguish among these models. All obtain q^2 dependences consistent with the data.

D. Elastic Neutrino-Electron Scattering

At the present time there are three experiments measuring elastic neutrino-electron scattering, all with quite low statistics, which are not entirely consistent with each other. These data²³ are shown in Fig. 3. For $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering the upper and lower limits of the Gargamelle experiment are shown; the average values of the Aachen-Padua data are in both cases very close to the upper limits for Gargamelle data.

Given the poor statistics and difficulties in estimating backgrounds, model-builders should probably be concerned only with obtaining approximate agreement with these experiments. It is, however, a crucial point to distinguish (experimentally) whether neutrino and antineutrino cross sections for this process are equal. Model F which has no atomic parity violation, has non-equal cross sections. Present experiments are not clear on this point.

E. Atomic Parity Violation

Experiments searching for evidence of parity violation from weak neutral-currents in atomic phenomena have been reported.²⁴ These experiments have been performed with a heavy atom, Bismuth, for which the term

$$J_A^e J_V^{\text{hadronic}}$$

dominates (where A and V refer to axial-vector and vector). Since Models B-F have a vector electron, they expect no contribution from this term. Model A,

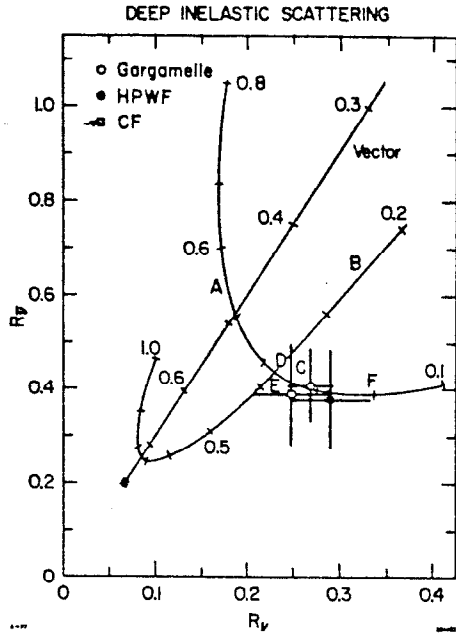


Fig. 1. The ratio $\sigma(\bar{\nu}N \rightarrow \bar{\nu}X) / \sigma(\bar{\nu}N \rightarrow \mu X)$ for anti-neutrinos vs. that ratio for neutrinos. Several values of $\sin^2 \theta_W$ are shown for Models A and B but only the best points for Models C-F. Data from Ref. 19.

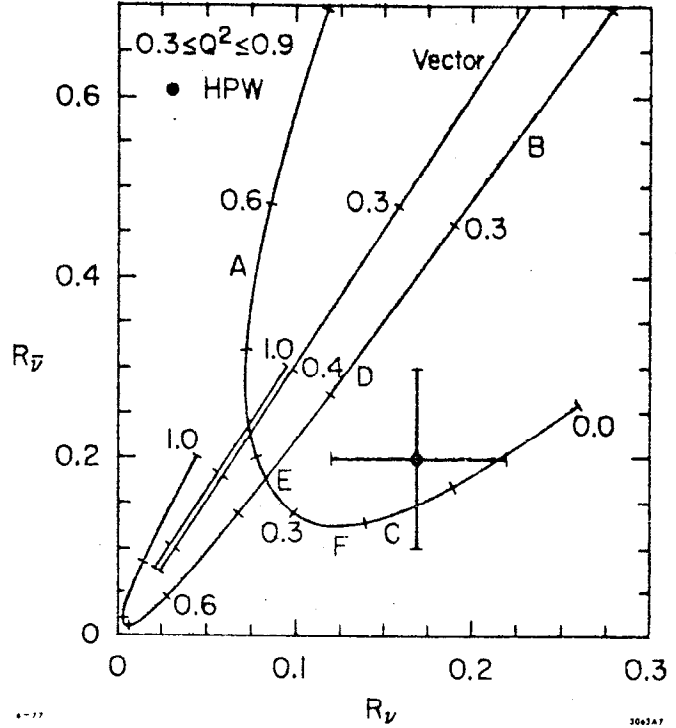


Fig. 2. The ratio of neutral (elastic) to charged (quasi-elastic) current cross sections for antineutrinos vs. that for neutrinos. Data from Ref. 21.

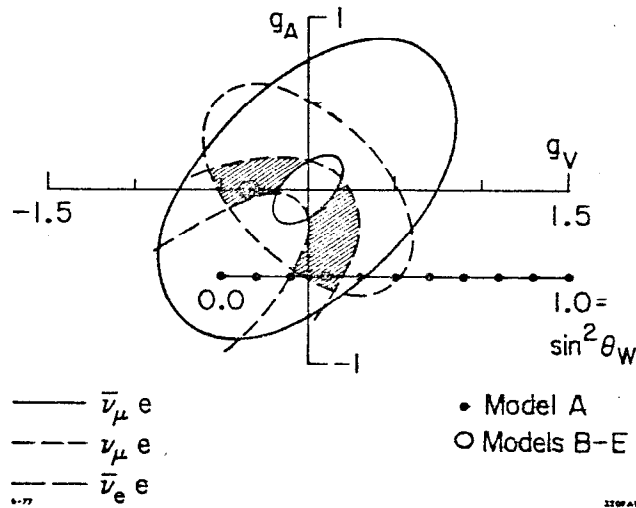


Fig. 3. The limits placed on g_A and g_V by νe scattering. Outer (inner) lines indicate 90% confidence upper (lower) limits. The best value for Models B-E is shown in the middle of the upper shaded region. Those shaded regions are the overlap or allowed regions for g_A and g_V . Model F coincides with $\sin^2 \theta_W = 0.3$ for Model A. Data from Ref. 23.

however, predicts an optical rotation of about -30×10^{-8} radians (the Washington and Oxford experiments use different transitions so that the actual numbers differ by a factor of about 3/4). The most recent results reported are $(-0.7 \pm 3.2) \times 10^{-8}$ (Washington) and $(3.2 \pm 4.6) \times 10^{-8}$ (Oxford). Despite some question about theoretical calculation of this number, the discrepancy between Model A and experiment is now so great that one should take this result seriously.

Clearly, however, the proposed experiments on hydrogen are vital since the theory is clear and in addition the other term

$$J_V^e J_A^{\text{hadron}}$$

can be measured also. These experiments will be quite difficult, and results are probably more than a year away. Predictions of the models for the parameters of Cahn and Kane²⁵ are shown in Table V. Note again that Model F gives no parity violation at all while Model D has a very small violation.

Table 5. Hydrogen Parity Violation. Parameters Described and Calculated by Cahn and Kane.²⁵

Model	C_{1p}	C_{1n}	C_{2p}	C_{2n}
A	-0.17	-0.50	-0.21	+0.21
B	0	0	0.13	-0.28
C	0	0	0.22	-0.10
D	0	0	0.04	-0.12
E	0	0	0.42	-0.42
F	0	0	0	0

F. Polarized e-p Deep-Inelastic Scattering

There is an experiment²⁶ starting at SLAC to measure polarized electron-proton deep-inelastic scattering at a level sufficient to provide another test of neutral-current couplings of electrons and quarks. The predictions of the models are shown in Fig. 4; experiment will measure the y region from about 0.15 to 0.50 with an accuracy for the parallel-antiparallel difference-sum ratio of about ± 0.06 on Fig. 4 (where it should be emphasized the units are such that -1.0 on Fig. 4 corresponds to $-16. \times 10^{-5} \times Q^2$ with Q^2 in GeV^2 and equal to about 1 GeV^2 for this experiment). The calculations shown here are those of Cahn and Gilman.²⁷

III. Charged Currents

A. Cross Sections

For some time now there has been debate on whether there is an anomalous behavior²⁸ for antineutrino charged-current cross sections, both in their magnitude and in their y dependence as a function of incoming energy. Simultaneously there has been discussion on whether such anomalous behavior can be understood as the scaling violations²⁹ expected in asymptotically free theories or alternatively whether there was evidence for a heavy quark b of charge $-1/3$ which has a right-handed coupling to u quarks. Given the results in both electron-proton deep-inelastic scattering and in electron-positron annihilation, it is safe to say there are scaling violations which should appear in antineutrino scattering as rises in both σ/E and $\langle y \rangle$ with increasing energy. While the asymptotic freedom calculations involve several approximations, there is general agreement²⁹ on the approximate magnitude of the effects in σ/E and $\langle y \rangle$. Irrespective of the existence of b quarks, these quantities should increase with energy.

The data²⁸ are shown in Figs. 5 and 6 along with the expectations for models with and without a $(u, b)_R$ coupling but always with asymptotic freedom corrections. It is clear that while the early data of HPWF indicate a need for a quark b of mass about 6 GeV, the later data of CF and CDHSB which have greater statistics and higher energies, rule out any b quark of mass less than 8 GeV which couples with full-strength to u quarks (right-handed). While there is no direct evidence for b quarks, it should be emphasized that there is no evidence against b quarks greater than 9 GeV, and no evidence against lighter b quarks which do not couple to u quarks or couple with reduced strength (as in Model F). In Model D for example another quark (g), which might be quite heavy, couples to the u quark while b couples to c (and to d through the heavy U^0 boson); this b quark could be as light as 4 GeV. The CF results²⁸ show the absolute cross sections also (see Fig. 7) and again, they are consistent with no b quark.

Given the present data, gauge theories need not have the $(u, b)_R$ coupling, but it is not ruled out.

B. Dimuons

The questions of the existence of b quarks and heavy leptons can be addressed through consideration of dimuon production in neutrino scattering. One of the best tests²⁰ for b quarks is the ratio of dimuons to single muons

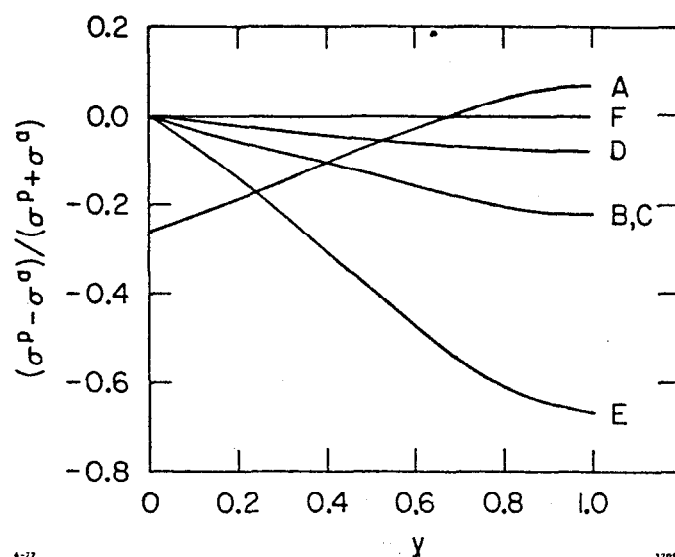


Fig. 4. The parallel-antiparallel asymmetry for polarized electron-proton scattering. See text for units and discussion. Curves are model predictions calculated by Cahn and Gilman.²⁷

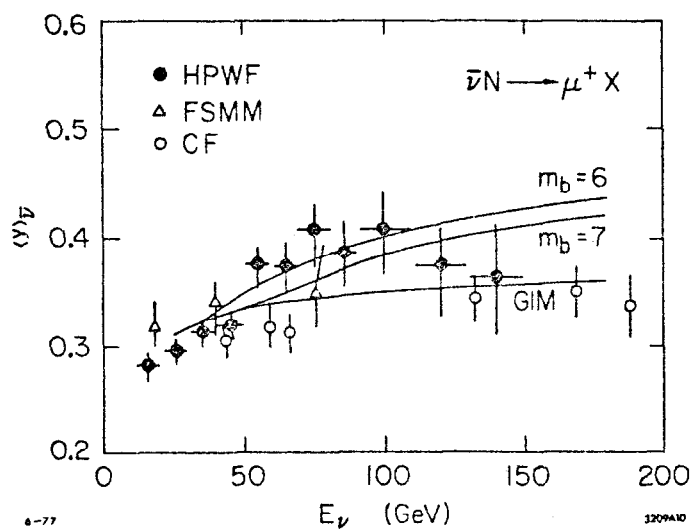


Fig. 5. The average y vs. E . Theory curves include asymptotic freedom corrections. Data from Ref. 28.

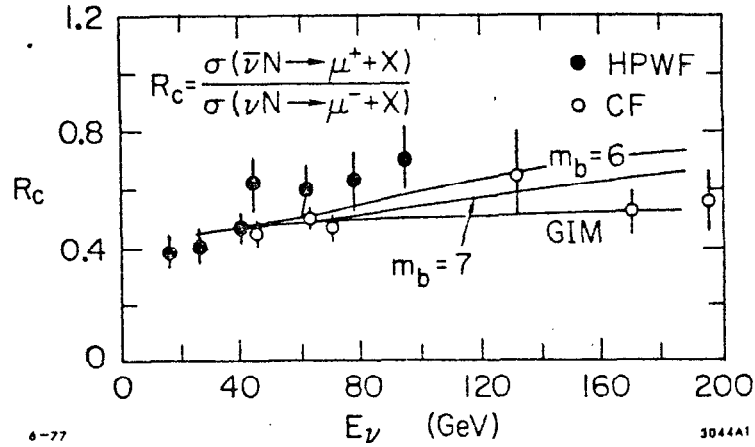


Fig. 6. The cross section ratio vs. E . Theory curves include asymptotic freedom corrections. Data from Ref. 28.

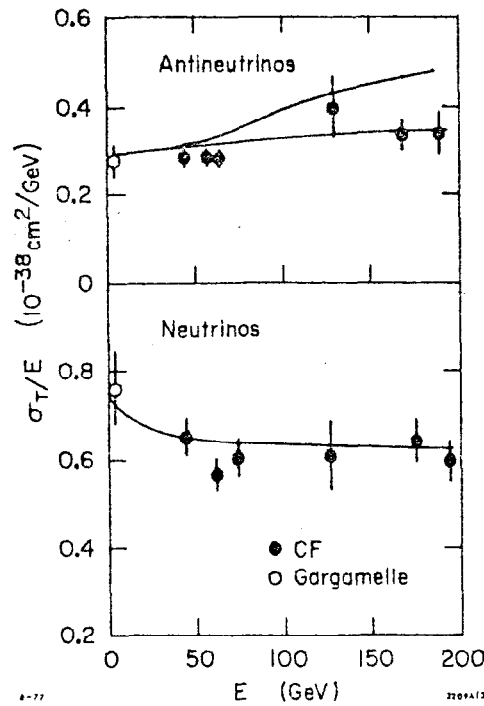


Fig. 7. The cross sections vs. E . Theory curves include asymptotic freedom corrections. The upper $\bar{\nu}$ curve includes a b quark of mass 6 GeV. Data from Ref. 28.

for antineutrinos divided by that ratio for neutrinos. Most cuts, efficiencies and branching ratios cancel out, with the exception of the branching ratio to muons of b quarks relative to c quarks. Asymptotic freedom corrections play an important role when (and only when) hadrons with b quarks are produced as can be seen in Fig. 8. However, with the new data³⁰ of CF and CDHSB (see Figs. 9 and 8), it is clear that these results like those of the last section, indicate that b quarks with $(u, b)_R$ couplings must be heavier than 8 or 9 GeV, unless the branching ratio to muons of b quarks is surprisingly small. It is very difficult to imagine that the branching ratio to muons of b quarks should be more than a factor of two less than charm.

If b quarks are produced which decay to muons, those muons should have $p_{\perp}$ which are considerably larger than that of muons from charm decay (almost in proportion to their relative masses). No such phenomena have been reported yet.

Most sources of trimuons lead to dimuon signals which may be different from ordinary dimuons.³¹ Model C can have $\mu^+\mu^+$ in both ν and $\bar{\nu}$ scattering. Model D will have $\mu^-\mu^-$ in ν scattering but less frequently in $\bar{\nu}$ scattering. The rates are dependent on several factors but especially on the trimuon rate which is certainly not well determined.

C. Trimuons

Three experiments³² have reported trimuon events in neutrino scattering. While it is not yet absolutely certain that these handful of events are not background, theorists have produced many papers³³ on the subject. It is difficult to reach strong conclusions from distributions containing a handful of events. Nonetheless if the signal is real, we can anticipate increasing statistics to which present analysis can be applied. Most (but not all) authors have argued that the five (clean) events of FHPRW do not appear to have characteristics indicating two of the muons were of hadronic origin, see for example Fig. 10. These authors have suggested that all three muons may be of leptonic origin as in the production and decay of a charged heavy lepton into three muons (plus other particles).

However, Chang and I have shown that the present limited data are equally consistent with one muon being of hadronic origin (and two leptonic), see again Fig. 10. There are distributions which with higher statistics could distinguish the source of trimuons, such as Fig. 11. Chang and I had in mind the simultaneous production of a heavy neutral lepton (which decays to two muons) and

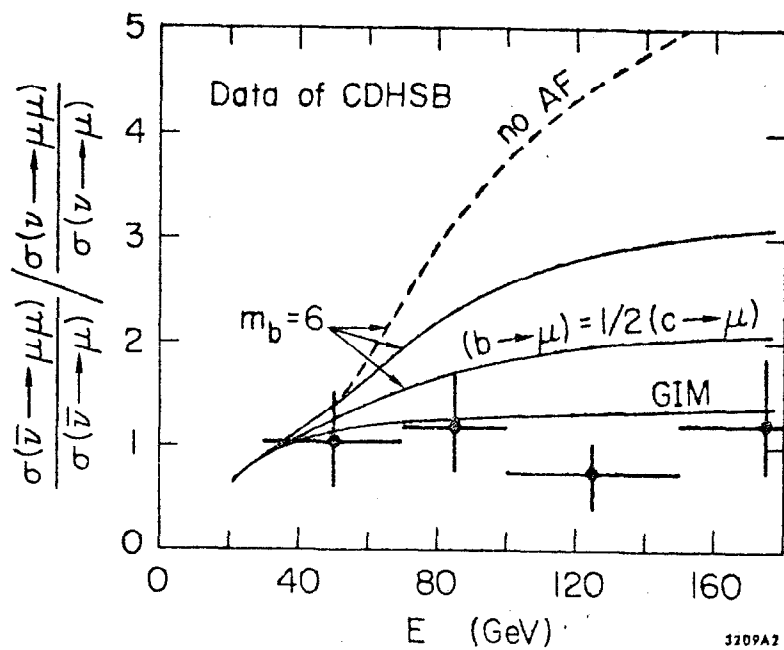


Fig. 8. The ratio of dimuon ratios vs. E . Solid curves contain asymptotic freedom (AF) corrections. Data from Ref. 30.

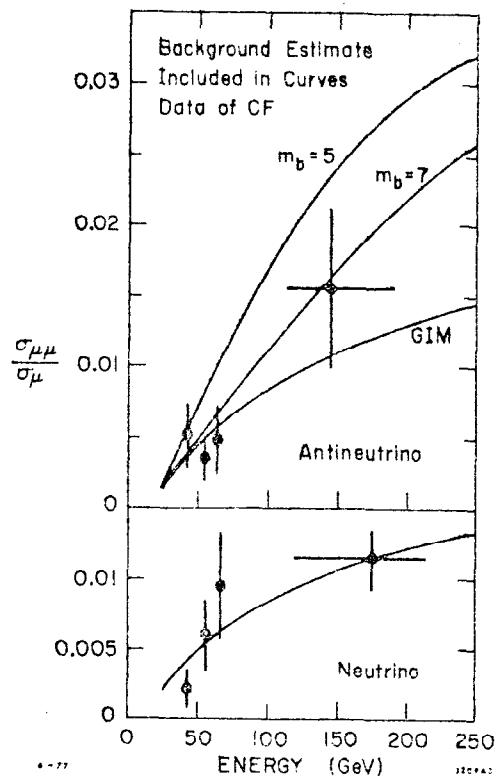


Fig. 9. Dimuon ratios vs. E . Theory fit to neutrinos and contains asymptotic freedom corrections. Data from Ref. 30.

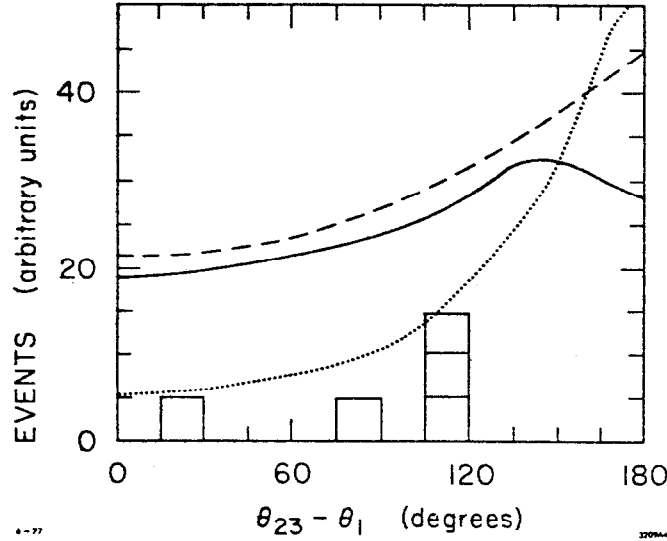


Fig. 10. The angle in the plane transverse to the incoming neutrino between $(\vec{p}_2 + \vec{p}_3)$ and $\vec{p}_1$ where 1, 2 and 3 label the fast μ^- , slow μ^- , and μ^+ . The dotted, dashed and solid curves have two, one and zero of the three muons from the hadronic vertex. Data of Ref. 10.

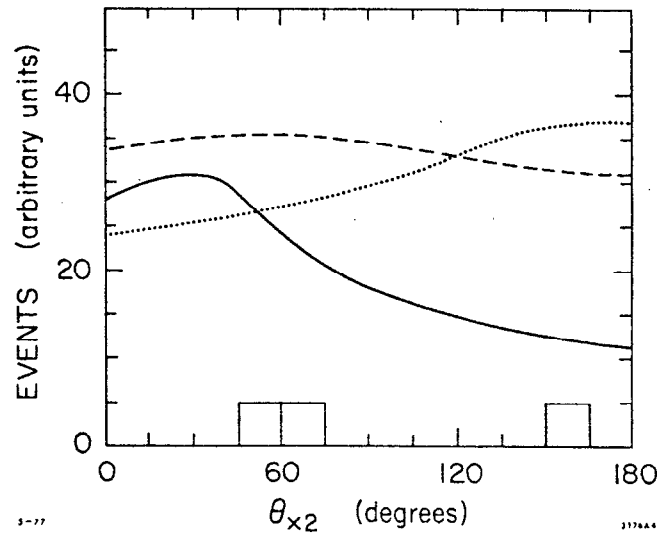


Fig. 11. The angle in the plane transverse to $(\vec{k} - \vec{p}_1 - \vec{p}_3)$ between $\vec{k}$ and $\vec{p}_2$; where $\vec{k}$ is the incoming neutrino's visible momentum and all other terms defined in Fig. 10's caption.

a b quark (which decays to one muon). This mode gives different charges (---) in antineutrino trimuon production than heavy charged lepton decay (-++).

One interesting point is that the most remarkable trimuon event (FHPRW event 119 with muon momenta of 157, 32 and 47 GeV/c) cannot be accounted for by any of these trimuon modes. Even if one lowers all momenta of this event by a standard deviation, all modes have less than one chance in 10^4 of producing this event (or events with higher momenta) compared to the other trimuon events.

IV. Other Phenomena

Lepton mixing³⁴ (leading to processes such as $\mu \rightarrow \gamma e$) can occur in most of the models discussed here, but there usually is great flexibility in determining the rates for experimentally observable processes. Nonetheless, measurement of such processes will provide important restrictions for model-builders.

Model E which does not have a coupling $(u, b)_R$ through the usual W boson, has a quark b which has only semileptonic decays (including $b \rightarrow s \nu \bar{\nu}$). In models such as this without $(u, b)_R$ the b quark could be as light as 4 GeV and only experiments at PEP, PETRA and CESR will detect it. There is no physical or aesthetic reason to expect the number of quarks to be limited to four, so searches at these e^+e^- colliding beam experiments are quite important.

Given the discovery of the 1.9 GeV heavy lepton τ^- (included in all models) and the possible new heavy leptons giving trimuon events, there is further motivation for e^+e^- searches. Even neutral heavy leptons might be easy to detect there. Several models give

$$e^+e^- \rightarrow \nu E^0 \quad \text{or} \quad E^0 \bar{E}^0$$

where E^0 can decay to $e^- \pi^+$, $e \pi \pi$, $e \mu \nu$, etc.

I believe there is much excitement ahead for us for the next few years. There are a wide range of experiments which hopefully will provide much insight. While present gauge theories may not survive, it is to be hoped they provide useful tools for investigating and understanding the structure of weak and electromagnetic interactions.

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L. N. Chang and F. Martin made substantial contributions to work reported in this talk for which I am grateful. I would like to thank the organizers of the European Conference on Particle Physics for inviting me to speak in Budapest.

It was with great sadness that I learned of the tragic and untimely death of Benjamin Lee. In preparing this report, as on many occasions in the past, I was privileged to learn from Ben.

References

1. S. Weinberg, Phys. Rev. Lett. 19, 1264 (1974); A. Salam, Elementary Particle Physics (Nobel Symposium No. 8), ed. By N. Svarthholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.
2. S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).
3. M. Barnett, Phys. Rev. Lett. 34, 41 (1975); Phys. Rev. D 11, 3246 (1975); and D 13, 671 (1976).
4. P. Fayet, Nucl. Phys. B78, 14 (1974).
5. F. Gürsey and P. Sikivie, Phys. Rev. Lett. 36, 775 (1976) and Yale preprint COO-3075-162 (February 1977).
6. P. Ramond, Nucl. Phys. B110, 214 (1976).
7. M. Barnett, Phys. Rev. D 15, 675 (1977); T. Hagiwara and E. Takasugi, Phys. Rev. D 15, 89 (1977) and Rockefeller preprint COO-2232B-120.
8. P.E.G. Baird et al. (Oxford and Washington experiments), Nature 264, 528 (1976) and results reported at Washington APS meeting, Spring 1977. Other recent papers on this subject include: C. Bouchiat, École Normale preprint LPTENS 77/2; H. Fritzsch, preprint CERN-TH-2297; Q. Shafi (see Ref. 12).
9. S. L. Glashow and S. Weinberg, Phys. Rev. D 15, 1958 (1977).
10. B. C. Barish et al., Phys. Rev. Lett. 38, 577 (1977); A. Benvenuti et al., Phys. Rev. Lett. 38, 1110 (1977).
11. R. N. Mohapatra and D. P. Sidhu, Phys. Rev. Lett. 38, 667 (1977).
12. A. De Rújula et al., Ann. Phys. (to be published) and preprint HUTP-77/A028; A. Zee et al., Princeton preprint; Q. Shafi and Ch. Wetterich, Freiburg preprint THEP 77/3.
13. B. W. Lee and S. Weinberg, Phys. Rev. Lett. 38, 1237 (1977) and B. W. Lee, R. Shrock and S. Weinberg, Fermilab preprint; see also G. Segre and J. Weyers, Phys. Lett. 65B, 243 (1976).

14. M. Barnett and L. N. Chang, Stanford Linear Accelerator Center SLAC-PUB-1932 (submitted to Phys. Rev. Lett.) and preprint (in preparation).
15. D. Horn and G. G. Ross, preprint CALT-68-597; and G. Segre and M. Golshani, Pennsylvania preprint UPR-0075T.
16. F. Gürsey, P. Ramond and P. Sikivie, Phys. Lett. 60B, 177 (1976).
17. J. D. Bjorken and K. D. Lane, Stanford Linear Accelerator Center preprint (in preparation).
18. H. Fritzsch and P. Minkowski, Nucl. Phys. B103, 61 (1976) ($SU_2 \times U_1 \times U_1$) and Phys. Lett. 63B, 99 (1976) (SU_3); S. Pakvasa et al., LBL preprint 6419 ($SU_8 \times U_1$); M. Abud and C. A. Savoy, Geneva preprint DPT 1977/03-132 and M. Abud et al., DPT 1977/02-127 (SU_6).
19. J. Blietschau et al., Nucl. Phys. B118, 218 (1977); A. Benvenuti et al., Phys. Rev. Lett. 37, 1039 (1976); B. C. Barish et al., preprints CALT 68-600 and 68-601 (1977).
20. M. Barnett and F. Martin, Stanford Linear Accelerator Center SLAC-PUB-1892; see also A. Bouquet and J. Kaplan, Paris preprint PAR/LPTHE 77/10; J. Bernabeu and C. Jarlskog, preprint CERN-TH-2313.
21. D. Cline et al., Phys. Rev. Lett. 37, 252 and 648 (1976); and A. B. Entenberg et al., presented at XII Rencontre de Moriond (March 1977).
22. W. Lee et al., Phys. Rev. Lett. 37, 186 (1976).
23. F. J. Hasert et al., Phys. Lett. 46B, 121 (1973); J. Blietschau et al., Nucl. Phys. B114, 189 (1976); W. Van Doninck et al., Brussels preprint IIHE-76.7 (1976 Aachen Neutrino Conference). F. Reines et al., Phys. Rev. Lett. 37, 315 (1976).
24. See Ref. 8.
25. R. Cahn and G. Kane, Michigan preprint UM HE 77-1.
26. C. Prescott et al., Stanford Linear Accelerator Center experiment.
27. R. Cahn and F. Gilman, private communication.
28. D. N. Perkins in 1975 Lepton-Photon Conference, p. 571. A. Benvenuti et al., Phys. Rev. Lett. 36, 1478 (1976) and 37, 189 (1976); B. C. Barish et al., preprints CALT 68-604, 68-605, 68-606, and 68-607 (1977).
29. G. Altarelli, G. Parisi, and K. Petronzio, Phys. Lett. 63B, 183 (1976); M. Barnett et al., Phys. Rev. Lett. 37, 1313 (1976); J. Kaplan and F. Martin, Nucl. Phys. B115, 333 (1976); B. W. Lee and R. E. Shrock, preprint Fermilab-Conf-76/61-THY (1976); V. I. Zakharov, preprint

- ITEP-127; G. Fox (private communication); J. Kaplan, Paris preprint PAR-LPTHE-77-04; A. J. Buras, preprint CERN-TH-2285. W. Furmanski, Jagellonian preprint TPJU-7/77.
30. B. C. Barish et al., preprint CALT 68-603 (1977); M. Holder et al., CERN preprint (1977).
 31. V. Barger et al., Wisconsin preprints COO-602 and 603.
 32. See Ref. 10.
 33. C. Albright et al., Stony Brook preprint ITP-SB-77-32; V. Barger et al., Wisconsin preprints COO-595, 596, 597, 598, and 600; M. Barnett and L. N. Chang, Stanford Linear Accelerator Center SLAC-PUB-1932; F. Bletzacker and A. Soni, Stony Brook preprints ITP-SB-77-26 and 34; G. C. Branco et al., Bonn preprint BN-HE-77-9; P. Cox and A. Yildiz, Harvard preprint HUTP-77/A033; P. Langacker et al., Pennsylvania preprint UPR-0072T; Pakvasa et al. (see Ref. 18); L. M. Sehgal and P. M. Zerwas, Aachen preprint (April 1977); A. Zee et al. (see Ref. 12).
 34. Most references can be found in B. Humpert, Stanford Linear Accelerator Center SLAC-PUB-1935. Some recent preprints include H. Fritzsch, CERN-TH-2302; S. Barshay and J. Leite Lopes, CRN/HE 77-4; G. Altarelli et al., LPTENS 77/4 and 77/8; S. T. Petkov; JINR-E2-10487.
 35. M. Barnett, Stanford Linear Accelerator Center SLAC-PUB-1891.