Searching for New Strongly Interacting Fermions with Future Colliders

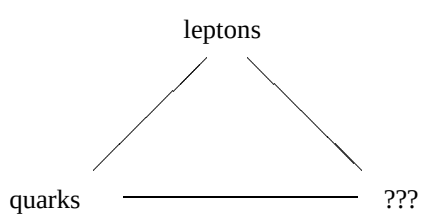
Richard Vidal*
Fermi National Accelerator Laboratory, Batavia, IL 60510-0500

I. INTRODUCTION

The Standard Model accommodates much without explanation. It contains many elements that are difficult to motivate theoretically, although they are accommodated easily. The existence of two extra generations of fermions is one good example. Since the next generation of colliders should be capable of discovering other new pieces of "non-essential", low-energy phenomenology, it is important that simple, obvious, and easily-accomodated extensions of the Standard Model be considered. This kind of new physics may not resolve any of the current problems with the Standard Model, but in the future, could provide the needed pieces that reveal a more comprehensive and complete picture.

One important motivation of the original idea for GUT's was the unification of quarks and leptons. This was first attempted in an SU(4) model [1] where lepton number was considered as the fourth "color", (the other three colors coming from QCD). Later, SU(5) models [2] incorporated the leptons and quarks in various SU(5) representations. However, to achieve full unification at some large energy, we must be sure we have all the pieces at lower energy. Is a significant piece missing?

By examining the differences as well as the similarities between fermions, we may be able to understand their common origin, and get a hint about any other missing particles. Since it is the SU(3) QCD interaction which distinguishes leptons from quarks, this observation might suggest by analogy the existence of another SU(3) interaction that would distinguish a new, third type of strongly interacting fermions from the other two types, quarks and leptons, with which we are already familiar:



This new SU(3) strong interaction could be similar to QCD, but have a scale which is at least 1000 times larger (or greater than 100 GeV). Because of this new interaction, pairs of these new fermions might bind together and be confined into pseudo-scalar pions, as in QCD. The masses of the new particles typically might be greater than $1-10\ GeV$, rather than the $1-10\ MeV$ for the light quarks, and they might form "pion-like" bound states with masses greater than $100-200\ GeV$, similar to the quark bound-states at $100-200\ MeV$.

If the new fermion pair had an electro-weak interaction similar to the Standard Model, then they might form an SU(2) electro-weak doublet. If the "pion" mass is larger the the "W-boson" mass, then the "pion" bound state of the two fermions would decay predominantly via the "triangle anomaly" to $W+\gamma$, and we might get decays very different from the familiar QCD pions [3].

Since the new fermions are colorless, hadron colliders could not produce these new fermions copiously, but rather, they would be produced, like the leptons, via U(1) gauge bosons, or possibly, via spin-1 "rho" resonances (as we find in QCD). Here, of course, the spin-1 states would have masses greater than $200-1000\ GeV$. Since the new fermions are confined and exist only in bound states with masses above $100\ GeV$, they cannot be produced at any existing e^+e^- or $e-p$ machines, despite their relatively small masses, but might be seen in the next generation of linear colliders. To illustrate how such fermions might appear, we can examine a particular model.

II. EXPANDING THE STANDARD MODEL

The basic idea then is that we might have much larger gauge group than the Standard Model. The group would be:

$$SU(3)_c \times SU(2)_L \times U(1)_L \times U(1)_R \times SU(2)_R \times SU(3)_{c'}$$

The group $\mathrm{SU(3)_c}$ is just QCD of the Standard Model, and the group $\mathrm{SU(2)_L} \times \mathrm{U(1)_L}$, just the Weinberg-Salam sector. There are two new non-Abelian groups: an $\mathrm{SU(3)_{c'}}$ representing a new strong-interaction, and an $\mathrm{SU(2)_R}$ corresponding to a new "right-handed" weak interaction, and one new Abelian group $\mathrm{U(1)_R}$. The new $\mathrm{SU(3)_{c'}}$ has eight gauge bosons – gluons – just like QCD, and the new $\mathrm{SU(2)_R}$ has three gauge bosons like the Weinberg-Salam model.

How do the fermions transform in this expanded model? Let us limit the discussion to only a single generation of fermions. All fermions have both kinds of $\mathrm{U(1)}$ hypercharges, but varying strong and weak charges. The u-quark and d-quark are still triplets under $\mathrm{SU(3)_c}$, but are singlets under the new $\mathrm{SU(3)_{c'}}$, *i.e.* they do not interact via this new strong force. They transform as the usual left-handed doublet under $\mathrm{SU(2)_L}$, but again, are singlets under the new $\mathrm{SU(2)_R}$ (so they ignore this force too). The electron and neutrino, however, do interact via the $\mathrm{SU(2)_R}$, as well as via $\mathrm{SU(2)_L}$, but are singlets under both $\mathrm{SU(3)}$ groups (they have no strong interactions). We will discuss the consequences of these assignments shortly.

The model also contains a pair of new fermions (called here v and r) that are not found in the original Standard Model. They transform as triplets under $\mathrm{SU(3)_{c'}}$, but are singlets under $\mathrm{SU(3)_c}$, so they are like "mirror-images" of the u and d-quark. The fermions v and r (specifically, their right-handed pro-

* email address rvidal@fnal.gov

jections) transform as an $\mathrm{SU(2)_R}$ doublet, but are $\mathrm{SU(2)_L}$ singlets – again opposite to the two quarks.

Of course, not all the symmetries represented in this extended gauge group are apparent in low-energy interactions. They are hidden by the presence of Higgs bosons, just as in the Standard Model. Here, however, there are two pairs of Higgs particles – one transforming as a doublet under $\mathrm{SU(2)_L}$ (and a singlet under $\mathrm{SU(2)_R}$), and the other pair, transforming as a doublet under $\mathrm{SU(2)_R}$ (and a singlet under $\mathrm{SU(2)_L}$). The left doublet has no Y_R hypercharge, while the right, no Y_L hypercharge, which keeps the sectors separate and unmixed. There is also a third Higgs which is a singlet under both $\mathrm{SU(2)}$ groups, and has no Y_L hypercharge (but does have Y_R hypercharge). All three of these Higgses develop vacuum expectation values, effectively hiding the $\mathrm{SU(2)_L}$, $\mathrm{SU(2)_R}$, and $\mathrm{U(1)_R}$ symmetries at low energies.

If we define the vacuum expectation values to be v_L and v_R for the neutral components of the two Higgs doublets, define the $\mathrm{SU(2)_L}$ and $\mathrm{SU(2)_R}$ coupling constants to be g_{2L} and g_{2R} respectively, define the expectation value of the singlet to be v_S, and the $\mathrm{U(1)_L}$ and $\mathrm{U(1)_R}$ coupling constants to be g_{1L} and g_{1R} respectively, then the masses (at tree-level) for the gauge bosons are:

$$M_{W_L} = \frac{1}{2}\, g_{2L}\, v_L \qquad\qquad M_{W_R} = \frac{1}{2}\, g_{2R}\, v_R$$

$$M_{Z_L} = \frac{1}{2}\sqrt{g_{2L}^2 + g_{1L}^2}\, v_L \qquad\qquad M_\gamma = 0$$

$$M_{Z_1}^2 = \frac{1}{4}\,(g_{2R}\cos\theta_R + g_{1R}\sin\theta_R)^2\, v_R^2 \;+\; g_{1R}^2\,\cos^2\theta_R\, v_S^2$$

$$M_{Z_2}^2 = \frac{1}{4}\,(g_{2R}\sin\theta_R - g_{1R}\cos\theta_R)^2\, v_R^2 \;+\; g_{1R}^2\,\sin^2\theta_R\, v_S^2$$

where we have assumed the hypercharges and weak charges of the Higgs bosons are one half, the hypercharge of the Higgs singlet is one, and:

$$\tan\theta_L = \frac{g_{1L}}{g_{2L}}$$

$$\sin^2\theta_R = \frac{1}{2} \;+\; \frac{1}{2}\sqrt{\frac{K^2}{K^2+4}}$$

$$K \equiv (m_s^2 \;+\; m_{1R}^2 \;-\; m_{2R}^2)\;/\;(m_{1R}\, m_{2R})$$

$$m_s \equiv g_{1R}\, v_S$$

$$m_{1R} \equiv \frac{1}{2}\, g_{1R}\, v_R \qquad\qquad m_{2R} \equiv \frac{1}{2}\, g_{2R}\, v_R$$

Here the angle θ_L is just the Weinberg angle of the Standard Model, and we associate the massive bosons $W_L^\pm$ and Z_L with the charged and neutral resonances discovered at CERN. The other angle θ_R has not been measured yet, and the "right-handed" bosons $W_R^\pm$, Z_1 and Z_2 remain to be confirmed.

III. FERMION COUPLINGS TO THE WEAK BOSONS

The fermions couple to the neutral bosons via vector and axial-vector currents. For a generic fermion f, the Lagrangian contains the terms:

$$Q_f\; q_e\; \bar{f}\,\gamma_\mu\; f\; P^\mu + Q_{Z_L}\; \bar{f}\,\gamma_\mu\,(V_L - A_L\,\gamma_5)\; f\; Z_L^\mu$$
$$+\; \bar{f}\,\gamma_\mu\,(V_1 - A_1\,\gamma_5)\; f\; Z_1^\mu \;+\; \bar{f}\,\gamma_\mu\,(V_2 - A_2\,\gamma_5)\; f\; Z_2^\mu$$

where:

$$Q_f \equiv T_{3L}^{f_L} + Y_L^{f_L} \;=\; Y_L^{f_R}$$

$$V_L \equiv Q_f\sin^2\theta_L - \frac{1}{2}T_{3L}^{f_L} \qquad\qquad A_L \equiv -\frac{1}{2}T_{3L}^{f_L}$$

$$q_e \equiv g_{1L}\cos\theta_L \qquad\qquad Q_{Z_L} \equiv \sqrt{g_{2L}^2 + g_{1L}^2}$$

$$V_1 \equiv \frac{1}{2}(T_{3R}^{f_L} + T_{3R}^{f_R})\; g_{2R}\;\sin\theta_R + \frac{1}{2}(Y_R^{f_L} + Y_R^{f_R})\; g_{1R}\;\cos\theta_R$$

$$A_1 \equiv \frac{1}{2}(T_{3R}^{f_L} - T_{3R}^{f_R})\; g_{2R}\;\sin\theta_R + \frac{1}{2}(Y_R^{f_L} - Y_R^{f_R})\; g_{1R}\;\cos\theta_R$$

$$V_2 \equiv \frac{1}{2}(T_{3R}^{f_L} + T_{3R}^{f_R})\; g_{2R}\;\cos\theta_R - \frac{1}{2}(Y_R^{f_L} + Y_R^{f_R})\; g_{1R}\;\sin\theta_R$$

$$A_2 \equiv \frac{1}{2}(T_{3R}^{f_L} - T_{3R}^{f_R})\; g_{2R}\;\cos\theta_R - \frac{1}{2}(Y_R^{f_L} - Y_R^{f_R})\; g_{1R}\;\sin\theta_R$$

Y_L, Y_R, T_L and T_R are the hyper and weak-charges of the left or right-handed doublets or singlets.

The fermions couple to the charged bosons via vector and axial-vector charged currents. For a generic fermion pair u and d, the Lagrangian contains the terms:

$$\frac{g_{2L}}{2\sqrt{2}}\;\bar{u}\,\gamma^\mu\;(1-\gamma_5)d\; W_L^{+\mu} \;+\; \frac{g_{2L}}{2\sqrt{2}}\;\bar{d}\,\gamma^\mu\;(1-\gamma_5)u\; W_L^{-\mu}$$
$$\frac{g_{2R}}{2\sqrt{2}}\;\bar{u}\,\gamma^\mu\;(1+\gamma_5)d\; W_R^{+\mu} \;+\; \frac{g_{2R}}{2\sqrt{2}}\;\bar{d}\,\gamma^\mu\;(1+\gamma_5)u\; W_R^{-\mu}$$

Since the quarks do not interact via the right-handed weak interaction, then $T_R = 0$, and they can be assigned a value for the "right" hypercharge equal to their electric charge (the quarks have the same "left" hypercharge assignments as in the Standard Model). This will assure that all the anomalies cancel each other in the model. Similarly, for the new v and r fermions, $T_L = 0$, so they get the "opposite" hypercharge assignments (assuming they have the same fractional electric charge as the quarks). For the leptons to transform under both $\mathrm{SU(2)_L}$ and $\mathrm{SU(2)_R}$, there must exist a right-handed neutrino.

Since we have observed experimentally only a light, left-handed neutrino, we can incorporate a right-handed neutrino by assuming that the neutrinos are Majorana fermions and invoking the "see-saw mechanism". The W_L boson then couples mostly to the light, left-handed mass eigenstate, with a small coupling

to the heavy neutrino, reduced by a small mixing angle. The W_R boson then couples mostly to the heavy, right-handed neutrino, with a small coupling to the light neutrino, again reduced by the same small mixing angle. If the mass of the W_R is less than the mass of the heavy neutrino, then the W_R partial width to leptons is greatly reduced since it can decay then only to the light neutrino state. The partial width is suppressed by the small mixing angle.

IV. MASSES OF THE NEW GAUGE BOSONS

Because the u and d-quark do not couple to W_R at tree-level, the W_R gauge boson cannot be produced with any significant rate in any existing hadron machines. However, the neutral gauge bosons Z_1 and Z_2 do couple to u and d-quarks, and so can be produced at the hadron colliders. We know from Tevatron limits on Z' production that their masses must be large – typically greater than about $600\ GeV$. If the mass of the W_R is about $100\ GeV$, then $\cos\theta_R$ must be small to get a large mass for Z_1 and Z_2. For example, for $v_R = 2\ TeV$, $v_S = 1\ TeV$, $M_{W_R} = 100\ GeV$, and the coupling constants $g_{2R} = 0.1$ and $g_{1R} = 0.9$, then $M_{Z_1} \approx M_{Z_2} \approx 900\ GeV$ and $\sin\theta_R \approx 0.998$ ($\cos\theta_R \approx 0.056$). Unlike the left-handed weak sector where the W_L and Z_L masses are nearly degenerate, the right-handed sector could have a larger separation between the masses of the W_R and Z_1 or Z_2, due to a much smaller coupling constant and much larger symmetry-breaking scales.

Since the electron couples to both sets of gauge bosons, the new gauge bosons could be produced at e^+e^- machines. However, such large masses would prohibit their production at any existing facility. The NLC or LHC would be the only machines in the near future to produce these bosons in sufficient quantity to be directly observed.

V. $\mathrm{SU(3)_{C'}}$ BOUND STATES OF TWO FERMIONS

Assuming that the new strong interaction generates a confining potential similar to QCD (*i.e.* the number of fermion generations is small), there should exist only bound states of v and r fermions, with relatively long lifetimes, and no "free" fermions. Like the charged pions of QCD, there should exist pseudo-scaler states such as $\pi_R^+(v\bar{r})$ and $\pi_R^-(\bar{v}r)$, as well as the neutral state π_R^0 made from $v\bar{v}$ and $r\bar{r}$. If we assume that these are the lowest mass states, then these states can decay only via the right-handed weak interaction (similar to QCD where the charged pions can only decay via the left-handed weak interaction). Of course, quarks do not interact via $\mathrm{SU(2)_R}$, so only the lepton channel is open to these new pions. However, if the mass of π_R is greater than the mass of W_R, then the π_R will decay to $W_R+\gamma$ via the "triangle anomaly". The W_R will subsequently decay to a charged lepton and a neutrino. The new neutral pion π_R^0 will also decay predominantly via the "triangle anomaly" to $\gamma+\gamma$, since the photon has zero mass.

We will assume that the "scale" of the the new strong interaction $\mathrm{SU(3)_{c'}}$ is approximately 1000 times the "scale" of QCD. The mass of the pseudo-scalar state π_R is then approximately $140\ GeV$, rather than $140\ MeV$ for the pion of QCD, and the vectors and other pseudo-scalars made from other generations have masses in the hundreds of GeV range. For a W_R around $100\ GeV$, then the π_R will decay predominantly to a photon and a lepton pair. If we assume that hadron colliders produces only $\pi_R^+\pi_R^-$ pairs, then we should observe two photon plus two charged leptons plus $\not{E}_T$ in the final state [3].

VI. COLLIDER PRODUCTION OF π_R PAIRS

Since quarks do not interact via the new strong interaction $\mathrm{SU(3)_{c'}}$, π_R pairs can only be produced at colliders via a Drell-Yan photon or a Z_L. We can estimate the production rate by considering the rate relative to the production of lepton pairs at and above the same invariant mass of the pair. As in other electroweak production, we expect the rate for $\pi_R^+\pi_R^-$ to be small – we expect only about $\frac{1}{4}$ unit of $R_{e^+e^-}$. This is similar to the case for an e^+e^- machines with a beam energy just above the pion threshold. However, as in the QCD case, the rate can be considerably larger on the vector resonances.

In addition to the pseudo-scalar π_R, there should also exist a vector particle ρ_R, similar to the ρ of QCD, corresponding to the bound state with spin one. The coupling strength of this ρ_R resonance to the Drell-Yan photon is unknown, but could be quite large. If it is like QCD, then the rate of $\pi_R^+\pi_R^-$ events at colliders will be dominated by resonance production as long as the ρ_R is not too large – a few hundred GeV. The mass of the ρ_R is unknown and probably as difficult to calculate as the ρ mass in QCD.

Production of the new fermions via a ρ_R resonance would then exclude the production of $\pi_R^0\pi_R^0$, since the spin-1 ρ cannot decay to two identical pseudo-scaler π^0's. The only way to produce $\pi_R^0\pi_R^0$ events is off resonance, at a greatly reduced rate. Thus, we do not expect many events with four photons, relative to two photons plus two leptons plus $\not{E}_T$. If the production of π_R pairs at colliders proceeds via a ρ resonance, then we would expect the momenta of the π_R's to be quite large, and easily recognized.

VII. OTHER DECAYS OF π_R

Since the W_R boson is assumed to have a mass less than mass of the π_R pseudo-scalar, then the dominant decay of the π_R should be to $W_R+\gamma$. Unlike the pion of QCD, the pure leptonic decay of π_R should occur considerably less often. For $\pi_R^+\pi_R^-$ production, both W_R^+ and W_R^- will decay to an electron and a neutrino. If we assume "universality" between the generations of leptons (for this new weak interaction), then W_R should decay to muons (and taus) equally as often. Thus, in addition to events containing two photons plus two electrons, colliders should also observe events with two photons plus two muons, and events with two photons, an electron, and a muon.

Observation of $e\mu$ events is a critical test of this model. Unless we are ready to discard universality for the right-handed weak interaction, these other decays must eventually be observed or this model should be discounted.

VIII. $SU(3)_{C'}$ BOUND STATES OF THREE FERMIONS

If the new strong interaction is similar to QCD, then there should also exist bound states of three fermions. Like the proton and neutron of QCD, there should be two fermion states, one charged and one neutral, that are relatively stable. They would be spin-$\frac{1}{2}$ fermion states such as $p_R^+(vvr)$ and $n_R(vrr)$ with masses near $1\ TeV$. It is not clear whether the charged or neutral state would be heavier. Using QED, the calculation of the mass difference between the charged and neutral pion of QCD has the correct sign and approximately the correct magnitude. However, the proton-neutron mass difference appears with the opposite sign from what is observed, casting considerable doubt on the calculation. Given how little we know about this new strong interaction, we can only speculate about which is the heavier of these two new baryons.

If the mass of neutral state is heavier than the charged state (as in QCD), then the n_R will decay into p_R, and we may be able to form "atoms" of electrons and very heavy "nuclei". There may be cosmological observations which provide limits on "matter" in this form. If the mass of the charged state is heavier than the neutral state, then the p_R will decay into n_R, and there will exist heavy neutral matter in the universe that we have not yet detected.

IX. ACKNOWLEDGMENTS

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X. REFERENCES

[1] J.C. Pati and A. Salam, Phys. Rev. D10 (1974) 275.

[2] H. Georgi and S.L. Glashow, Phys. Rev. Lett. 32 (1974) 438.

[3] This contribution was inspired in part by CDF's recent e-gamma-e-gamma-$\not{E}_T$ event, although this event may have nothing to do with new strongly interacting fermions.