A New Kind of Scalar Particle

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Abstract

The pattern of quantum numbers in the leptons and quarks indicate that precisely two fixed hypercharge splittings are observed in nature. The $|\Delta Y| = 1$ splitting corresponds to the $SU(2)_L$ scalar and doublet spacing, indicative of the Yukawa interactions of the Higgs mechanism. A $|\Delta Y| = 4/3$ splitting is identified between corresponding $SU(3)_C$ scalars and triplets. The properties of this splitting are the basis for the prediction of a new kind of scalar particle that directly couples quarks and leptons. Possible experimental methods for detecting a strongly interacting, charge $-1e/3$ scalar particle are presented for the examples of exotic decay modes of the top quark and the analysis of $t\bar{t}\tau^+\tau^-$ production at hadron colliders.
INTRODUCTION

The matter content of the standard model is comprised of three mass generations of quarks and leptons with quantum number assignments derived from a spontaneously broken $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge interaction \cite{1}. The following list summarizes the $(SU(3)_C, SU(2)_L, U(1)_Y)$ quantum numbers of leptons and quarks:

\[
Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \text{transforms as} \quad (3, 1, 4/3) , \\
\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \text{transforms as} \quad (1, 2, -1) , \\
d_R \quad \text{transforms as} \quad (3, 1, -2/3) , \\
u_R \quad \text{transforms as} \quad (1, 1, 0), \\
e_R \quad \text{transforms as} \quad (1, 1, -2) .
\]

The assignment of the hypercharge quantum numbers are set according to the known electric charges of the fermions and are derived from the $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$ symmetry breaking relationship for the electric charge operator:

\[
Q = T^3 + \frac{Y}{2} .
\]

A particular pattern of hypercharge splitting can be observed between color-singlet $SU(2)_L$ singlets and doublets in that the magnitude of the difference is unity, $|\Delta Y| = 1$. The unity hypercharge splitting is also present in the difference between color-triplet $SU(2)_L$ singlets and doublets. This splitting is directly related to the Yukawa interaction terms that generate mass in the fermions via the Higgs mechanism. The minimal way to break $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$ through the Higgs mechanism is to have an isospin doublet scalar, the Higgs field $\Phi$, with a non-zero vacuum expectation value (vev) \cite{2}:

\[
\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} .
\]
FIG. 1. Two hypercharge splittings are observed in the leptons and quarks, a $|\Delta Y| = 1$ splitting along the $SU(2)_L$ singlet to doublet to singlet transformation and a $|\Delta Y| = 4/3$ splitting between corresponding $SU(3)_C$ singlets and triplets.

The hypercharge of the Higgs doublet is set to $Y_\Phi = 1$ so that $\langle \Phi \rangle$ is $U(1)_{EM}$-invariant. Hence, the value of hypercharge for the Higgs doublet sets the splitting between chiral components. Gauge-invariant fermion mass terms appear naturally from spontaneous symmetry breaking as shown here for the electron,

$$\Delta L_e = -\lambda_e \bar{L} \cdot \Phi e_R + h.c. . \quad (4)$$

If one examines the hypercharge splitting between corresponding $SU(3)_C$ singlets and triplets, one finds a constant splitting of $|\Delta Y| = 4/3$. The situation is summarized in figure 1.

The observation of this pattern suggests the potential existence of a new kind of scalar particle, $S$, whose $(SU(3)_C,SU(2)_L,U(1)_Y)$ quantum numbers are given by

$$S \quad \text{transforms as} \quad (3,1,-2/3) , \quad (5)$$

describing a strongly interacting, charge $-1e/3$ spin-0 boson. The hypercharge assignment, described below, follows from the charge conjugation operation in the Dirac current that couples to the $S$ boson, as required by the selection rules for a scalar interacting with a pair of chiral fermions.
GAUGE SUPERSYMMETRY

The pattern of fixed hypercharge splittings indicated in figure 1 suggests that the leptons and quarks are part of multiplet with $\Phi$ and $S$ acting as generators of the multiplet. The Lie group that is a direct product of the Poincaré group and the internal symmetry group of $SU(3)_C \times SU(2)_L \times U(1)_Y$ has a set of generators given by $P_\mu$, $M_{\mu \nu}$, $\tau_a/2$, and $\lambda_k/2$ for spacetime translation, rotations, $SU(2)_L$ and $SU(3)_C$ transformations, respectively. The addition of the generators $\Phi$ and $S$ into this set would introduce new symmetries into the Hamiltonian. The operators $\Phi^\dagger$ and $S^\dagger$ replace $SU(2)_L$ and $SU(3)_C$ singlets with doublets and triplets, respectively. In the Standard Model, the interactions enter through a gauge-covariant derivative given by

$$D_\mu = \partial_\mu + ig' 2 Y B_\mu + ig \frac{\tau_a}{2} W^a_\mu + ig_s \frac{\lambda_k}{2} G^k_\mu.$$  

We can show that the Hamiltonian is a constant under the replacement of gauge singlets with doublets or triplets by writing the gauge interaction explicitly in terms of the anticommutation relation

$$\{ \Phi, \Phi^\dagger \} + \{ S, S^\dagger \} = 2 H_{int} = 2 \gamma^\mu ( -g \frac{\tau_a}{2} W^a_\mu - g_s \frac{\lambda_k}{2} G^k_\mu ) .$$  

The introduction of an anticommutation relation to form a graded Lie group is a known technique of spacetime supersymmetric theories [3]. As the operators $\Phi$ and $S$ are holding the spin of the leptons and quarks constant, while forming a multiplet of gauge singlets and doublets or triplets, the symmetry operation is a gauge supersymmetry. The spin of the gauge bosons and, in general, the interplay between gauge supersymmetry and spacetime supersymmetry are topics for further investigation.

In the case of $SU(2)_L$, having the same symmetry group as spin, the operation of $\Phi$ and $\Phi^\dagger$ transforms isospin doublets into up-type and down-type singlets and vice versa,

$$\nu_R \Phi^\dagger \rightarrow L \frac{\Phi_2}{e_R}.$$  

In the case of $SU(3)_C$, there are three possible sets of $(\lambda_3, \lambda_8)$ eigenvalues of the fundamental triplet. We can therefore expect that the operation of $S$ will take a $Q$ triplet and lower it into three separate $L$ color-singlets. The triplet multiplicity of observed mass generations of lepton $L$ is therefore conjectured as being generated by the three possible gauge supersymmetric operators $S_a$. For example, one possible cyclic generation of the three families of
lepton and quark isospin doublets could be represented by

$$L_1 \xrightarrow{s_1^L} Q_1 \xrightarrow{s_2^L} L_2 \xrightarrow{s_3^L} Q_2 \xrightarrow{s_3^L} L_3 \xrightarrow{s_1^L} Q_3 \xrightarrow{s_1^L} L_1 .$$  \(9\)

As the gauge supersymmetries described by the operators \(\Phi\) and \(S\) are not respected in nature, the effective couplings of the scalar particles \(\Phi\) and \(S\) to the leptons and quarks are taken to be of similar magnitude and dependence as those predicted by the Higgs mechanism. The mass of the \(S\) boson is assumed to be generated by a coupling between \(S\) and the Higgs vacuum expectation value, giving an observed mass comparable to the electroweak scale, and potentially lighter than the top quark mass. The \(S\) boson couplings to lepton-quark pairs are assumed to have a mass dependence similar to that of a Yukawa interaction term of a charged Higgs boson in a two-doublet Higgs sector \([4]\), as given here:

$$L_S = (D_\mu S)^\dagger (D^\mu S) - \lambda_\Phi \Phi^\dagger \Phi S - \lambda_S (S^\dagger S)^2$$

\[-\lambda^{ij}_L \bar{L}_c^i \epsilon_{kl} Q_a^j \sigma_a^* \lambda^{R,ij} (\bar{q}_R^i)^c u_{R,a}^j S_a^* - \lambda^{ij}_R (\bar{\nu}_R^i)^c d_{R,a}^j S_a^* + h.c. \]  \(10\)

where \(\lambda^{ij}_L, \lambda^{R,ij}\) and \(\lambda^{ij}_R\) are general complex-valued matrices with \((ij)\)-indices over the three mass generations

$$Q' = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} = \begin{pmatrix} u_L \\ d_L \\ c_L \\ t_Q \\ s_L \\ b_L \end{pmatrix}, \quad L' = \begin{pmatrix} \nu_L^i \\ \ell_L^i \end{pmatrix} = \begin{pmatrix} \nu_e,L \\ \nu_{\mu,L} \\ \nu_{\tau,L} \end{pmatrix}, \quad u_R = \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix}, \quad \nu_R = \begin{pmatrix} \nu_{e,R} \\ \nu_{\mu,R} \\ \nu_{\tau,R} \end{pmatrix}, \quad d_R = \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix}, \quad \ell_R = \begin{pmatrix} \ell_R \end{pmatrix} = \begin{pmatrix} \epsilon_R \\ \mu_R \\ \tau_R \end{pmatrix} .$$  \(11\)

where \(\Psi_c = C\Psi^*\) indicates charge conjugation with \(C = i\sigma_2\) and \(\epsilon_{kl} = i\sigma_2\) is the \(SU(2)_L\) contraction of the two fundamental representations, \(L_L\) and \(Q_a\). The explicit appearance of the charge-conjugation operator \(C\) with the bilinear vertex term \(\sigma_2\) gives non-vanishing vertex terms when coupling a scalar particle to a fermion pair with the same chirality. The gauge-covariant derivatives in the kinetic energy term generate \(S - \bar{S}\) pair production diagrams for a gluon, photon or \(Z\) boson trilinear vertex. We also expect seagull diagrams of the \(S\) boson interacting with a pair of photons, \(Z\) bosons and gluons, respectively. The Higgs vev will generate an \(S\) boson mass term via the \(\Phi - S\) Yukawa interaction.

An investigation of possible \(SU(5)\) representations of the \(S\) boson indicates a possible match with the charge -1/e/3 color triplet Higgs boson in the \(5\) or \(24\) of \(SU(5)\) GUT models. However, the color triplet of \(SU(5)\) is known to be problematic due to the potential implications for proton decay. Here, the \(S\) boson Lagrangian \(L_S\) does not couple directly to
FIG. 2. The decay of a top quark into a $\tau^+$ lepton and an $S$ boson is shown on the left a). The $S$ boson subsequently decays into a $\nu_\tau$ neutrino and a $b$-quark. On the right b), the search for a charged Higgs boson in top quark decay has an identical final state with different kinematics.

di-quarks and appears to have only a subset of corresponding $SU(5)$ motivated interaction vertices.

PHENOMENOLOGY OF $S$ BOSON PRODUCTION AND DECAY AT HADRON COLLIDERS

If we assume that the coupling of $S$ to the first two mass generations is small in comparison to Standard Model interactions, then we can focus on the phenomenology of the heaviest generation of quarks and leptons. In particular, the heaviest known particle, the top quark couples directly to the $S$ particle and could be produced in top quark decays for values of $m_S$ lighter than the top quark mass. A top quark decay diagram involving the $S$ is shown in figure 2a). A similar final state appears in a standard charged Higgs search, as shown in figure 2b). The main difference in the two searches is in the kinematics of the final state. The charged Higgs search applied directly to a search for the $S$ boson would lack an explicit variable for the reconstructed $S$ mass. This would significantly reduce the cross sensitivity of the charged Higgs search applied to a search for the $S$ boson. However, limits on anomalous leptonic branching fractions constrained by the rate of $t \to \tau + X$ compared with non-$\tau$ decays would still apply. The branching fraction searches are currently limited at the few percent level, and would leave the possibility for $S$ production in top quark decay below a few percent [5]. Similarly, top quark mass measurements using methods sensitive to the detailed kinematics, such as the matrix method, are not normally applied to the $\tau$+four-jet final state and would not exclude the $S$ boson directly.

Another heavy-flavor search sensitive to $S$ production is pair production of third gen-
FIG. 3. The $S$ boson pair production search topology in the $t\bar{t}\tau^+\tau^-$ final state.

Generation scalar leptoquarks in the channel $b\bar{b}\nu\tau$. However, the search region for the third generation leptoquark has moved beyond the kinematic threshold for $LQ3$ decays into $t\tau^-$. If the branching fraction is dominantly in the $t\tau$-decay mode, then the previous searches will not be sensitive to the high-mass region [6]. A diagram for $S$ boson pair production in the $t\bar{t}\tau^+\tau^-$ final state is shown in figure 3. In the pair production search, two equal mass scalars are produced, each decaying to a $t$-quark and a $\tau$-lepton with the corresponding charge-conjugate decay products for the antiparticle.

The $S$ boson pair production search in the $t\bar{t}\tau^+\tau^-$ final state is a new search topology for which there are no reported experimental results. Previous searches in the $b\bar{b}\nu\tau$ pair production topology were able to achieve a mass sensitivity in excess of 200 GeV/$c^2$ [6] with less than $1 fb^{-1}$ of integrated luminosity. With the six-fold increase in integrated luminosity at the Tevatron and the well-understood status of the detectors, a search in the $t\bar{t}\tau^+\tau^-$ final state should provide a rapid test of the $S$ boson prediction for $m_S$ masses up to approximately 250 GeV/$c^2$. For single $S$ boson production, existing top quark charged Higgs search topologies can be readily adapted to searches for the $S$ boson. For higher sensitivity to rare top quark decays, the two orders of magnitude increase in top quark pair production at the LHC would be the highest sensitivity dataset for $m_S$ less than the top quark once the LHC has accumulated an integrated luminosity comparable to the Tevatron.
CONCLUSIONS

The $S$ boson prediction is an unexpected byproduct of a hypercharge splitting analysis of the tables of known leptons and quarks. However, there is little explanation in the current understanding of the Standard Model for the origin of the lepton and quark generations and in linking the presence of a Higgs boson, needed for spontaneous symmetry breaking, to the rest of the matter content in the model. The conjecture of a gauge supersymmetry in the Standard Model is a natural choice to generate fixed hypercharge splittings. Given that the $|\Delta Y| = 1$ splitting is directly related to the Higgs boson, it follows that the $|\Delta Y| = 4/3$ splitting could be attributed to a new kind of scalar particle, the $S$ boson. Assuming the couplings of the $S$ are dominately in the heaviest mass generation, the observation of lepton violation would be suppressed. Review of existing searches at hadron colliders sensitive to $S$ boson production highlight similar final states present in the search for charged Higgs bosons in top quark decay. A new search is proposed in the pair production process in the $t\bar{t}\tau^+\tau^-$ final state. The constraints coming from the existing searches applied to the $S$ boson would allow the possibility of $S$ boson production in top quark decay at the few percent level or less. The constraints on $S$ boson pair production in the high mass region from the $b\bar{b}\nu,\bar{\nu}$ search are expected to be weak if the coupling to the $t$-quark $\tau$-lepton final state dominates. The existing dataset at the Tevatron and the readily available search channels described above provide a clear path for rapid investigation of $S$ boson production. Ultimately, rare top quark decays at the LHC will have the highest sensitivity for the search of the $S$ boson for $m_S$ less than the top quark mass.

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