S and T for Leptoquarks and Bileptons

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We calculate contributions to the oblique parameters S and T for leptoquarks and bileptons, and find phenomenological constraints on their allowed masses. Leptoquarks suggested by the neutral and charged current anomalies at HERA can give improved agreement with both S and T. If bileptons are the only new states, the singly-charged one must be heavier than the directly-established lower limit. We also consider SU(15) grand unification to find when it can be consistent with precision electroweak measurements.

Model building for particle theory at and below the TeV energy scale is not rendered redundant by the standard model but is certainly very constrained by it. There can be little that we do not already know much below the W mass. In the mass region up to the TeV regime one expects the Higgs boson and perhaps supersymmetric partners. But otherwise one must tread softly to avoid upsetting the delicate agreement between the standard model and precision experimental data.

In the present paper we take a fresh look at how certain additional bosons can co-exist with one another and with the successful standard model. Of special interest are particles which can contribute negatively to the very useful parameters S and T which measure compatibility with precision electroweak data. This is because these parameters are generally positive especially for the majority of fermionic particles which one might add. We shall focus on bileptonic gauge bosons and scalar leptoquarks.

The H1 and ZEUS collaborations reported a possible excess of neutral current (NC) events in e+ p collisions. This excess can be explained by the existence of the leptoquark of mass around 200 GeV. In addition to the NC channel, an excess in the charged current (CC) was also reported.

Recently, D0 and CDF gave the 95% C.L. lower limit on the masses of 225 GeV and 213 GeV with assuming unit branching fraction into a first-generation charged lepton plus jet. For compatibility with the HERA anomaly, therefore, the scalar leptoquark must have a significant branching ratio to other decay channels.

In Ref. a mixing between two scalar leptoquark doublets carrying different weak hypercharges (Y = 7/6 and 1/6) was introduced to simultaneously explain the NC and CC anomaly at HERA. Since the lightest leptoquark couples to both e + j and ν + j, the CDF/D0 limits are weakened. They also studied the contributions to ρ parameter, and showed that Δρ from leptoquark could be negative. Since a relatively large mixing is needed, another electroweak precision parameter S should be also studied. [The parameter T is equivalent to Δρ.]

Let us write these doublets as Φ7/6 (Y = 7/6) and Φ1/6 (Y = 1/6), both of which belong to a 3 representation of SU(3)c. The electric charges are Φ7/6(Q = 5/3, 2/3) and Φ1/6(Q = 2/3, −1/3). The SU(3)c × SU(2)L × U(1)Y invariant mass terms are given by

\[ \mathcal{L}_M = -M^2 \Phi_{7/6} \Phi_{7/6} - M^2 \Phi_{1/6} \Phi_{1/6}. \]

The interactions to the standard Higgs field H are given by

\[ \mathcal{L}_H = -\lambda_1 |H^\dagger \Phi_{7/6}|^2 - \lambda_2 |H^\dagger \Phi_{1/6}|^2 \]
\[ -\lambda_3 \left( (\Phi_{7/6})^3 + (\Phi_{1/6})^3 + \text{h.c.} \right), \]

where \( \hat{H} = (i\tau_2 H)^T \). After electroweak symmetry breaking by the vacuum expectation value (VEV) of H, the \( \lambda_1 \) and \( \hat{\lambda}_1 \) terms give mass splittings between \( Q = 5/3 \) and \( Q = 2/3 \) components (\( \Phi_{7/6}^6 \), \( \Phi_{7/6}^7 \)) of \( \Phi_{7/6} \), and \( \lambda_2 \) and \( \hat{\lambda}_2 \) terms make mass difference between \( \Phi_{1/6}^2 \) and \( \Phi_{1/6}^{-1/3} \). On the other hand, the \( \lambda_3 \) term gives mixing between two \( Q = 2/3 \) leptoquarks of \( \Phi_{7/6} \) and \( \Phi_{1/6} \). Let α denote this mixing angle:

\[ \left( \Phi_{2/3}^6 \Phi_{1/6}^3 \right) = \left( \begin{array}{c} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{array} \right) \left( \begin{array}{c} \Phi_{7/6}^2 \\ \Phi_{1/6} \end{array} \right). \]

where \( \Phi_{2/3}^6 \) and \( \Phi_{1/6}^3 \) denote mass eigenstates. [We use the convention where the mass of \( \Phi_{2/3}^6 \) is lighter than that of \( \Phi_{1/6}^3 \).] We do not write explicit form of masses \( (m_{5/3}, m_{-1/3}, m_{2/3}, m_{1/3}) \) and the mixing angle \( \alpha \) in terms of original parameters in Eqs. (1) and (2), since all of them are independent parameters. [Note that originally there are seven parameters.] However, it should be noticed that for the consistency of the model any differences among all the masses are less than a few 100 GeV.

* There are other terms like |H^† H|Φ1/6 Φ7/6. But their contributions are absorbed into the redefinitions of M and M’ in Eq. (1).
The contributions from a single SU(2)\textsubscript{L} doublet of leptoquarks to S and T are studied in Ref. [14]. It is shown that the contribution to S can be negative while that to T is positive semidefinite. However, in the present case, the situation is different due to the existence of relatively large mixing between two doublets. The contributions to S and T from two doublets with mixing are studied in [14]. In the present case the leptoquarks give negative contributions to both S and T for a reasonable range of parameters. As an example, we show in Fig. 1 the possible region of values of S and T for 250 GeV \( \leq m_{3/2}, m_{-1/2}, m_{2/3h} \leq 350 \) GeV with \( m_{2/3l} = 200 \) GeV and \( \alpha = \pi/4 \) together with the experimental fit [12] for Higgs mass \( M_H = 300 \) GeV. As can be read from this figure the values of S and T from leptoquarks for reasonable parameter choices agree with experiment better than the standard model. The contours in Fig 1 (and 2) are for 39\%, 90\%, 99\% confidence levels respectively.

![Figure 1](image)

**FIG. 1.** The possible region of values of S and T for 250 GeV \( \leq m_{3/2}, m_{-1/2}, m_{2/3h} \leq 350 \) GeV with \( m_{2/3l} = 200 \) GeV and \( \alpha = \pi/4 \). Three points indicated by (A), (B) and (C) correspond to the parameter choices \((m_{2/3l}, m_{-1/2h}, m_{3/2}) = (325, 250, 350), (350, 350, 350)\) and \((250, 250, 250)\), respectively.

In certain extensions of the standard model, there occur bileptonic gauge bosons [13, 15] which typically occur in SU(2) doublets \((Y^{--}, Y^-)\) and the conjugates \((Y^{++}, Y^+)\). The experimental data currently constrain the masses of bileptons differently for the singly-charged than the standard model. The contours in Fig 1 (and 2) are for 39\%, 90\%, 99\% confidence levels respectively.

For the doubly-charged bilepton \( Y^{--} \) a tighter lower bound has been found recently from muonium - antimuonium conversion limits, also at PSI [13]. The data require that \( M(Y^{--}) > 360 \) GeV.

In the models which predict bileptonic gauge bosons SU(2)\textsubscript{L}×U(1)\textsubscript{Y} is part of a gauged SU(3)\textsubscript{L}, and the bileptonic gauge bosons become massive when the SU(3)\textsubscript{L} is broken. There are generally two types of models for this kind of bileptons: (1) bilepton gauge bosons couple to only leptons as in SU(15) [3, 4]; (2) bilepton gauge bosons couple to quarks as well as leptons as in 3-3-1 model [15].

In the case (1) the usual SU(2)\textsubscript{L} gauge bosons are certain linear combinations of gauge bosons of the unbroken SU(2) subgroup of SU(3)\textsubscript{L} and other gauge bosons coupling to quarks. The generators of SU(2)\textsubscript{L} and U(1)\textsubscript{Y}, \( T^a \) and Y, are embedded as \((a = 1, 2, 3)\)

\[
I^a = T^a_l + \cdots, \quad Y = -\sqrt{3}T^8_l + \cdots, \quad (4)
\]

where \( T^a_l \) denote the generators of SU(3)\textsubscript{L}, and dots stand for other contributions. The relations of the gauge bosons \( W^a_l \) and \( B_\mu \) of the standard SU(2)\textsubscript{L}×U(1)\textsubscript{Y} to the \( A^a_l \) of SU(3)\textsubscript{L} are given by

\[
g_l A^a_\mu = g W^a_\mu + \cdots, \quad (a = 1, 2, 3) \quad (5)
\]

where \( g, g' \) and \( g_l \) denote the corresponding gauge coupling constants. The bileptonic gauge bosons are expressed as

\[
Y^{\pm}\mu = \frac{1}{\sqrt{2}} (A^6_\mu \mp A^7_\mu), \quad Y^{\pm}\mu = \frac{1}{\sqrt{2}} (A^6_\mu \mp A^7_\mu). \quad (6)
\]

In the models of type (2) the unbroken SU(2)\textsubscript{L} subgroup of SU(3)\textsubscript{L} is nothing but the electroweak SU(2)\textsubscript{L}. Then the first relations of Eqs. (4) and (5) become

\[
I^a = T^a_l, \quad g_l A^a_\mu = g W^a_\mu, \quad (a = 1, 2, 3), \quad (7)
\]

with \( g_l = g \). The dots parts in the second relations of Eqs. (4) and (5) are modified. The definitions of bileptonic gauge fields in Eq. (6) remain intact.

In both types of models the bileptonic gauge bosons of SU(3)\textsubscript{L} makes SU(2)\textsubscript{L} doublet with hypercharge 3/2 and its conjugate. It is convenient to use SU(2)\textsubscript{L} doublet notation \( Y_\mu = (Y^{++}_\mu, Y^{--}_\mu) \). The effective Lagrangian for bileptonic gauge bosons at the scale below SU(3)\textsubscript{L} breaking scale can be written as

\[
\mathcal{L}_0 = -\frac{1}{2} (Y_\mu\nu)^{\dagger} Y^{\mu\nu} + (D_\mu Y^{\mu})^\dagger (D^\mu Y^{\mu}) \quad (8)
\]

\[
-igY^{\dagger}_\mu F^{\mu\nu}(W)Y^\mu + i\frac{3}{2}g'Y^{\dagger}_\mu F^{\mu\nu}(B)Y^\mu \quad (8)
\]
where \( \Phi \) are the would-be Nambu-Goldstone bosons eaten by bileptonic gauge bosons: \( \Phi = (\Phi_{++}, \Phi_+) \). The \( Y_{\mu\nu} \) and \( D_{\mu} \Phi \) are given by

\[
Y_{\mu\nu} = D_\mu Y_\nu - D_\nu Y_\mu ,
\]

\[
D_\mu \Phi = \left[ \partial_\mu - igW_\mu + i\frac{3}{2}g'B_\mu \right] \Phi .
\]  

In the simplest case the SU(2)\(_L\) doublet Higgs field is introduced as a part of SU(3)\(_L\) triplet (or anti-triplet). The other component field generally carries lepton number two, and SU(2)\(_L\) singlet with hypercharge one or two:

\[
\phi = \left( \begin{array}{c} H_1 \\ \phi_+ \end{array} \right) , \quad \phi' = \left( \begin{array}{c} H_2 \\ \phi_- \end{array} \right) ,
\]  

where \( H_1 (H_2) \) is a SU(2)\(_L\) doublet field with hypercharge 1/2 (−1/2), and \( \phi_+ (\phi_-) \) is a SU(2)\(_L\) singlet field with hypercharge −1 (−2).

Both the VEVs of these Higgs fields \( H_1 \) and \( H_2 \) give masses to \( W \) and \( Z \) bosons, and the standard electroweak SU(2)\(_L\)×U(1)\(_Y\) is broken. The VEV of \( H_1 \) gives a mass correction to \( Y^- \), while the VEV of \( H_2 \) gives a mass correction to \( Y^{--} \). If only one Higgs doublet had VEV, the mass difference of bileptons would be related to the mass of \( W \) boson. But in realistic models several Higgs fields are needed to have VEVs. In such a case both the masses of bileptons and \( W \) boson are independent with each other. In the following we regard the bilepton masses as independent quantities. Moreover, the actual would-be Nambu-Goldstone bosons eaten by bileptonic gauge bosons are certain linear combinations of \( \Phi \) in Eq. (9) with \( \phi_- \) or \( \phi_{--} \).

We assume that the contributions to \( S \) and \( T \) due to these mixings are small compared with the bilepton contributions. Thus we use the following effective Lagrangian for the kinetic term of would-be Nambu-Goldstone bosons and bilepton masses after SU(2)\(_L\)×U(1)\(_Y\) is broken:

\[
\mathcal{L}_{NG} = (D_\mu \Phi - i\hat{M}Y_\mu)^\dagger (D^\mu \Phi - i\hat{M}Y^\mu) ,
\]  

where \( \hat{M} \) is a \( 2 \times 2 \) matrix given by

\[
\hat{M} = \begin{pmatrix} M_{++} & 0 \\ 0 & M_+ \end{pmatrix} .
\]  

The contributions to \( S \) and \( T \) from bilepton gauge bosons are given by

\[
S = \frac{9}{4\pi} \ln \frac{M_{++}^2}{M_+^2} + \frac{3}{\pi} \left[ \ln \frac{M_{++}^2}{M_+^2} - 1 - \frac{1}{18} M_{++}^2 \right] ,
\]

\[
T = \frac{3}{16\pi^2 \sin^2 \theta_W} \times \left[ M_{++}^2 + M_+^2 - \frac{2 M_{++}^2 M_+^2}{M_{++}^2 - M_+^2} \ln \frac{M_{++}^2}{M_+^2} \right] + \frac{1}{4\pi \sin^2 \theta_W} \ln \frac{M_{++}^2}{M_+^2} - 2 + 3 \tan^2 \theta_W \ln \frac{M_{++}^2}{M_+^2} ,
\]  

where the first terms in \( S \) and \( T \) are coming through the conventional transverse self-energies \([20]\), and the second terms from pinch parts \([21]\). These pinch parts are introduced to make \( S \) and \( T \) gauge invariant. [The derivations of these pinch parts are given in \([22]\).]

Setting the \( Y^{--} \) mass equal to its lower limit and assuming that the bileptons are the only states additional to the SM, the singly-charged bilepton must be heavier than 346 GeV to be within the 99% CL contour of the \( S - T \) plane \([12]\) for Higgs mass \( M_H = 300 \) GeV. As another example, we put the mass of the doubly-charged bilepton at \( M(Y^{--}) = 500 \) GeV, and conclude that the singly-charged partner must lie in the mass range 479 GeV \( < M(Y^-) < 540 \) GeV for consistency. If we lower \( M_H \) to 100 GeV, the lower limit on \( M(Y^-) \) decreases to 324 GeV. This is an improvement on the single-charge bilepton empirical limit (230 GeV) found in \([13]\).

In a grand unified model based on SU(15) \([3,14]\) each generation of quarks and leptons is represented by a fundamental \( 15 \). To cancel anomalies of three generations, three generations of mirror fermions are needed. Since these mirror fermions obtain their masses from the VEV which breaks standard SU(2)\(_L\)×U(1)\(_Y\) symmetry they necessarily are close to the weak scale in mass and give significant contributions to \( S \) and \( T \). Even if we assume that members of the same SU(2)\(_L\) doublet have degenerate masses, and hence the mirror fermions give no contribution to \( T \), they do give a very large contribution to \( S \) parameter: \( S_{\text{mirror}} = 2/\pi \). Then one might think that this model is already excluded by the precision electroweak analysis? However, there are many extra particles including bileptons and leptoquarks in the model. These extra particles could give non-negligible contributions \( S \) and \( T \) as discussed above. As is easily read from Eqs. \([13]\), there is a negative contribution to \( S \) coming from bileptons if the singly-charged bilepton \( (Y^-) \) is heavier than the doubly-charged one \( (Y^{--}) \). This negative contribution can cancel the large positive contribution coming from mirror fermions. On the other hand, such a mass difference of bileptons gives a large positive contribution to the \( T \) parameter. But this could, in turn, be canceled by a negative contribution of leptoquarks without affecting the \( S \) parameter.

To be specific, we show in Fig. 3 a possible region of values of \( S \) and \( T \) coming from mirror fermions, bileptons and leptoquarks for 425 GeV \( < M(Y^-) \leq 475 \) GeV, 250 GeV \( \leq M_{5/3} \leq 300 \) GeV and 300 GeV \( \leq M_{-1/3} \leq 350 \) GeV with \( M(Y^{--}) = 360 \) GeV, \( m_{2/3} = 200 \) GeV and \( \alpha = \pi/4 \) fixed. This demonstrates that there exists a region where \( S \) and \( T \) are acceptable: SU(15) grand unification is not yet excluded by experiment!
neighborhood in parameter space where bileptons and leptoquarks in SU(15), there is an extended fermions. Because of the simultaneous presence of both positive the death of SU(15) grand unification due to the large bound available from direct measurement.

The continued robustness of the standard model with respect to more and more accurate experimental data gives tight constraints on any attempt at ornamentation of the theory by additional "light" physics. The parameters $S$ and $T$ provide a very convenient measure of compatibility with the precision electroweak data. Here we have discussed two examples: bileptons and leptoquarks.

If we identify the putative leptoquark at HERA with

For bileptons we have derived a lower bound of 324 GeV

Finally we have addressed the exaggerated reports of the death of SU(15) grand unification due to the large positive $S$ value from its three generations of mirror fermions. Because of the simultaneous presence of both bileptons and leptoquarks in SU(15), there is an extended neighborhood in parameter space where $S$ (and $T$) can be acceptably small in magnitude.

More complete details of this work are in the article

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