Leptoquark explanation of HERA anomaly in the context of gauge unification

N.G. Deshpande and B. Dutta

Institute of Theoretical Science, University of Oregon, Eugene, OR 97403

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Abstract

We examine the consequences of leptoquark explanation of HERA anomaly in the context of R parity conserving supersymmetric gauge unified theory with the gauge unification scale at $\sim 10^{16}$ GeV. We pointed out the difficulty of constructing a grandunified theory. However gauge unification is still possible at $\sim 10^{16}$ GeV when additional multiplets are introduced. We determine the mass spectrum of these additional fields (fermions and scalars) in gauge mediated and supergravity scenarios. Unique signatures and mass bounds are discussed.

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Recent observation of high Q$^2$ anomaly in $e^+p$ scattering seen by H1 \cite{1} and ZEUS \cite{2} collaboration at HERA, if confirmed by further experimentation, would be a clear indication of physics beyond the Standard Model (SM). Explanation of this anomaly have been advanced in terms of contact interactions generated by physics beyond the SM \cite{3}, in terms of s-channel leptoquark production \cite{4} or in terms of modification of the parton distribution function \cite{5}. Contact interactions have to satisfy various constraints e.g. atomic parity violation, LEP data, CCFR data etc. Although it is possible to construct such models, these typically predict similar anomalous events in $e^-p$ data and excess $e^+e^-$ events in Drell-Yan process at high Q$^2$ in FERMILAB, evidence for either is lacking at present. Leptoquark explanation has been pursued in the context of R-parity conserving or R-parity violating supersymmetric theory. These states occur as resonances at a mass of $\sim 200-220$ GeV. In this paper we shall pursue the leptoquark explanation of HERA data, but in the context of R-parity conserving supersymmetric gauge unification. We prefer to maintain R invariance because this allows the lightest SUSY particle to be a candidate for dark matter. Further, in R violating scenarios \cite{6} there are numerous arbitrary coupling e.g 27 of $\lambda'(\lambda'_{ijk}L_iQ_jD^c_k)$, 9 of $\lambda(\lambda_{ijk}L_iL_jE^c_k)$ and 9 of $\lambda''(\lambda''_{ijk}U^c_iD^c_jD^c_k)$, where $L_i, Q_i$ are the lepton and quark doublets and $E^c, U^c, D^c$ are the lepton, uptype and down type singlets respectively; and also $\lambda'$ and $\lambda''$ can not appear together in the same superpotential, since that gives rise to rapid proton decay. In this present paper we shall demand that any additional leptoquark states postulated in the $SU(3) \times SU(2) \times U(1)$ context be part of supersymmetric gauge unification picture so as to be theoretically attractive. Since the leptoquark mass is 200-220 GeV, we expect that there are other fields around this mass in order to maintain gauge unification.

We first consider gauge unification in the context of a grandunified theory like SU(5) \cite{7}. Lowest dimensional representation of SU(5) that we can have leptoquarks in is the $10$ dimensional representation. However, because $10$ dimensional representation is formed from the antisymmetric combination of $5 \times \bar{5}$, its SU(5) invariant coupling $\bar{5}_i5_j10_k$ is antisymmetric in the generation indices $i$ and $j$. Thus the leptoquark can not couple to the first generation quarks and lepton as needed to explain the HERA events. One then has
to consider a higher dimensional representation like $15$, which is symmetric in the product $\bar{5} \times 5$. To remove gauge anomalies one also requires $\bar{15}$ representation, which also makes the representation vector like. However $15$ representation has diquark fields which belong to $(6,1,-2/3)$ representation of $SU(3)_C \times SU(2)_L \times U(1)_Y$. This along with the leptoquark in $(3,2,1/6)$ representation makes the couplings blow up as they evolve at around $10^{11}$ GeV, long before unification. This is true for all representation with higher dimensions. We have also investigated flipped $SU(5) \times U(1)$ models where leptoquarks in $\bar{10}$ dimensional representation can arise from a product of $10 \times e^c$. These states can give rise to leptoquarks in $e^-p$ scattering as well as $e^+p$. Leptoquarks of the type $Qe^c$ and $d^c e^c$ are present. We will point out that their masses at the low energy scale are very close to each other in any realistic scenario. In this paper we give up grandunification for the most part, and instead consider the limited assumption of gauge coupling unification at a large scale.

We shall assume that there is a leptoquark field with transformation $(3,2,1/6)$ and to remove anomalies, the conjugate representation is also present. The leptoquark field will couple to $d_c$ and $(\nu, e^-)$, but the conjugate fields have no direct coupling to matter. The conjugate field has gauge couplings that will allow them to be produced in $p\bar{p}$ collisions at FERMILAB, but only indirectly through mixing at HERA. Since there are terms in the potential which allows mixing between the field and the conjugate field, the signature will bethe same as the original field. Consequently, if these masses are not well separated, Tevatron could have seen or will see the effect of this additional state in the near future. To maintain perturbative gauge unification we now add diquark and dilepton content of $10$ representation $(\bar{3},1,-2/3)$ and $(1,1,1)$ and their conjugate. We shall refer to these multiplets of new fields as $f$ and their conjugate as $\bar{f}$. Another interesting aspect of the R-parity conserving theory is the presence of the fermionic partners of the leptoquarks-the leptoquarkino \cite{9}. The leptoquarkino decays into missing energy plus the same final state as a leptoquark does. The leptoquarkino production crosssection at Tevatron is higher than the leptoquarks for the same mass, since they are fermions. Consequently the leptoquarkino has to be heavier than the leptoquark to escape detection. This can be a problem since
our natural expectation is the fermion masses are smaller than the scalar masses. We will show that it is possible to have the fermion masses become larger than the scalar masses by adding a singlet field. Since we are not using the SU(5), we can couple the leptoquark to just the first generation, diquarks and dileptons need to couple to additional generations. We will consider the possibility that the leptoquark couples to other generation and derive bounds on the coupling to the matter fields. Our strategy is to write the superpotential involving the new fields and find the mass spectrum of both the fermions and scalars at low scale using appropriate renormalization group equations (RGEs) and the D-terms using two specific supersymmetric breaking models. We shall consider both the gauge mediated SUSY breaking scenario as well as gravity induced SUSY breaking since the process of transmission of information of SUSY breaking to the observable sector is still an area of active interest. We shall explore the experimental signature for the new fields in present and future colliders.

We first show that with the choice of multiplets gauge unification is preserved even in two loop analysis. In Fig.1 we show the two loop evolution of gauge couplings assuming \( \alpha = 1/127.9, \sin^2 \theta_W = 0.2321 \) and \( \alpha_3 = 0.118 \) at \( M_Z \). If either the diquark or dilepton is left out, the gauge unification is not possible. As mentioned, a similar attempt with higher dimensional representation will cause coupling to diverge well below unification. In order to calculate the mass spectrum of this model we need a superpotential. Let us first discuss the superpotential in the gauge mediated symmetry breaking (GMSB) scenario. The gauge mediated SUSY breaking models have become very popular in last one year for several reasons. Since the SUSY breaking is communicated to the obsevable sector by SM gauge group or some other gauge group, the soft terms in these models are naturally flavor symmetric. These models also have less number of input parameters than the models where SUSY breaking is communicated by gravity eg. A (coefficient of the trilinear term) term and B term (coefficient of the bilinear term) in the potentials are 0 at the GMSB scale. The lightest supersymmetric particle (LSP) in these models is gravitino and the next to LSP (NLSP) is either a stau or a neutralino, depending on the parameter space. The signals of these kinds of SUSY breaking are spectacular since they have hard photon (neutralino is
the NLSP) or a lot of taus (stau is the NLSP) in addition to the missing energy in the final states.

The superpotential with the leptoquarks at the GMSB scale can be written as:

\[ W = \lambda_1 \phi_{\nu e} \bar{\phi}_{\nu e} S_1 + \lambda_2 \phi_{d^c d^c} \bar{\phi}_{d^c d^c} S_1 + \lambda_3 \phi_{L d^c} \bar{\phi}_{L d^c} S_1 \]
\[ + M_{L d^c} \phi_{L d^c} \bar{\phi}_{L d^c} + M_{d^c d^c} \phi_{d^c d^c} \bar{\phi}_{d^c d^c} + M_{\nu e} \phi_{\nu e} \bar{\phi}_{\nu e} + \frac{M'}{2} S_1 S_1 \]  

where \( S_1 \) is a SM singlet, the necessity of the singlet field will be discussed later. \( M_i \)'s are the soft breaking masses that get introduced by the same mechanism that generates the \( \mu \) at the GMSB scale. We will make an ansatz that there is a common value for \( M_i \) when we perform the calculation. Similarly, to make the theory predictive, we assume the \( \lambda \)s are unified to a common value of 1. When we write the potential from this superpotential there are terms like \( A_i \lambda_i \phi_i \bar{\phi}_i S_1 \) and \( M_i B_i \phi_i \bar{\phi}_i \). There are actually three more terms in the superpotential involving the leptoquark and the quark and lepton field, the diquark and the two quark fields and the dilepton and two lepton fields These terms arise from from a GUT scale term like \( h_k L d^c \phi \). The coupling \( h_k \) required to explain the HERA events is quite small (\( \sim 0.05 \)). Since the diquarks are color triplet (antisymmetric combination of two color triplet fields) fields and the dilepton are SU(2) singlet field, they need at least two generations for this kind of coupling to survive. We can assume that these new field couple to first and the 3rd generation. In fact if the leptoquarks (\( L d^c \)) are coupled to the first generation only, the latest CDF bound rules out the leptoquark mass of about 210 GeV at 95% C.L. [13] using the NLO QCD calculation [14]. If we assume that the leptoquark couples to all generations flavor diagonally, then \( K \rightarrow \mu e \) gets an unacceptable tree level contribution. We therefore forbid the leptoquark coupling to the second generation. However leptoquark can still couple to the third generation. This induces tree level contribution to \( B \rightarrow \tau e \). The bound we get is \( h_1 \times h_3 < 5.7 \times 10^{-3} \), where \( h_1 \) and \( h_3 \) are the leptoquark coupling to the first and the third generation. Consequently a third generation coupling to the leptoquark of the same magnitude as the first generation (\( \sim 0.05 \)) is allowed. Furthermore the inclusion of the third family implies that the leptoquark can decay into a \( \tau \) and a \( b \) quark. In this case
the crossection needs to be multiplied by a factor of 1/4 and the leptoquark mass bound reduces to 190 GeV.

There are also soft supersymmetry breaking gaugino (gluino, wino, bino) and scalar masses(squarks, sleptons, Higgs, fields in $f$ and $\bar{f}$) due the gauge mediated interaction with the messenger fields. These masses at the messenger scale $M$ are given by

$$\tilde{M}_i(M) = n g \left( \frac{\Lambda}{M} \right) \frac{\alpha_i(M)}{4\pi} \Lambda.$$ \hfill (2)

and

$$\tilde{m}^2(M) = 2 (n) f \left( \frac{\Lambda}{M} \right) \sum_{i=1}^{3} k_i C_i \left( \frac{\alpha_i(M)}{4\pi} \right)^2 \Lambda^2.$$ \hfill (3)

where $\alpha_i, i = 1, 2, 3$ are the three SM gauge couplings and $k_i = 1, 1, 3/5$ for SU(3), SU(2), and U(1), respectively. The $C_i$ are zero for gauge singlets, and 4/3, 3/4, and $(Y/2)^2$ for the fundamental representations of $SU(3)$ and $SU(2)$ and $U(1)_Y$ respectively. Here $n$ corresponds to number of $(5 + \bar{5})$ multiplets, and $g(x)$ and $f(x)$ are messenger scale threshold functions with $x = \Lambda/M$. The net scalar mass of the $\phi_{Ld}$ and $\phi_{e\nu,\phi_{d,d}^c}$ fields have contribution from $M_i$ and as well as $m_0$. The masses of the fields in $f$ and $\bar{f}$ are same at the gauge mediated scale. We run these $\lambda$’s from the GUT scale to the GMSB scale by the following RGEs:

$$2D\lambda_1 = \lambda_1(-\sum_i C_{1i}(4\pi\alpha_i) + 5\lambda_1^2 + 3\lambda_2^2 + 6\lambda_3^2),$$ \hfill (4)

$$2D\lambda_2 = \lambda_2(-\sum_i C_{2i}(4\pi\alpha_i) + \lambda_1^2 + 5\lambda_2^2 + 6\lambda_3^2),$$

$$2D\lambda_3 = \lambda_3(-\sum_i C_{3i}(4\pi\alpha_i) + \lambda_1^2 + 3\lambda_2^2 + 8\lambda_3^2),$$

where $i$ refers to the gauge group, $D \equiv \frac{16\pi^2}{3} \frac{dt}{dt}$ and $C1 = \left(0, 0, \frac{12}{5}\right), C2 = \left(\frac{16}{3}, 0, \frac{16}{15}\right), C3 = \left(\frac{16}{3}, 3, \frac{1}{15}\right)$.

We need to run the soft masses, B terms, A terms from the GMSB scale down to the weak scale wfor the new fields as well. The RGE’s for the soft masses are given as:

$$Dm^2_j = -\sum_i C_{ji}(4\pi\alpha_i)\tilde{M}_i^2 + \lambda_j^2(m^2_j + \tilde{m}^2_j + \frac{M^2_{\tilde{g}_i}}{2} + A^2_j),$$ \hfill (5)
where j=1,2,3 represent $Ld^c, d^c d^c, \nu e$. We also have a similar equation for $\bar{m}_j$. $\bar{M}_i$'s are the gaugino masses. The A's evolve according to the following RGE's:

$$D A_{Ld^c} = \sum_i C_{3i} (4\pi \alpha_i) \bar{M}_i + 6\lambda_2^2 A_{Ld^c} + 5\lambda_2^2 A_{d^c d^c} + \lambda_1^2 A_{\nu e},$$

(6)

$$D A_{d^c d^c} = \sum_i C_{2i} (4\pi \alpha_i) \bar{M}_i + 8\lambda_2^2 A_{Ld^c} + 3\lambda_2^2 A_{d^c d^c} + \lambda_1^2 A_{\nu e},$$

$$D A_{\nu e} = \sum_i C_{1i} (4\pi \alpha_i) \bar{M}_i + 6\lambda_2^2 A_{Ld^c} + 3\lambda_2^2 A_{d^c d^c} + 3\lambda_1^2 A_{\nu e}.$$ 

Similarly, B’s evolve according to the following RGE’s:

$$DB_j = \sum_i C_{ji} (4\pi \alpha_i) \bar{M}_i + 2\lambda_j^2 A_j$$

(7)

The mass parameters M’s evolve according to the RGEs:

$$2DM_j = M_j (- \sum_i C_{ji} (4\pi \alpha_i) + 2\lambda_j^2)$$

(8)

We can similarly write down the RGE for the soft breaking mass of the singlet $S_1$. We use the ref. \[12\] for the RGE’s for the gauge couplings, for the other soft masses e.g the gaugino ($\bar{M}_i$), squark and slepton masses and for the other parameters like $A_{t,b,\tau}$. We keep $\mu$ as free parameter which is determined at the weak scale in the tree level by:

$$\frac{M_Z^2}{2} = \frac{M_{H_1}^2 - M_{H_2}^2}{\tan^2 \beta - 1} - \mu^2$$

(9)

where $\tan \beta = \frac{v_2}{v_1}$. After we run these equations down to the weak scale we have to include the D term contribution to the scalar masses, which is of the form:

$$m_D^2(T_3, \frac{Y}{2}) = \pi(v_1^2 - v_2^2)(\alpha_2 T_3 - \alpha_1 \frac{Y}{2})$$

(10)

These D-terms cause a mass splitting between $f$ and $\bar{f}$ scalars. Further, there is mixing between $f$ and $\bar{f}$ scalars through the B term in the potential. This is a large effect for diquarks and leptoquarks but small for dileptons. This is because B term can be large for color fields at the weak scale even if its boundary value is 0 at the GMSB scale. The actual mixing for the leptoquark is very nearly 45°. Consequently at HERA, the lighter combination of the mixed state is produced although $e^+ q$ couples only to the f representation. The higher
mass state is out of reach for HERA with the present energy. Similarly at Tevatron, one can produce either state through gluon exchange, but mass limits apply to to the lower mass state. The mass of the singlet field and the coupling of the singlet to the leptoquarks are needed here since if we look at RGE’s we find the gauge part and the Yukawa part act in the opposite direction and we will want the leptoquark mass to be lower than the leptoquarkino mass. This is because the leptoquarkino production crosssection is always larger than the leptoquark production cross sections for the same mass, and the final state in the case of a leptoquarkino pair production will also have the leptons and jets. So the same bound which applies to leptoquark will also apply to the leptoquarkino. In Table 1 we show the masses of the new fields as well as the masses of the squarks, sleptons, neutralinos, charginos and gluino. The input parameters at the GMSB scale are $\Lambda$, $M$, $n$, $\tan \beta$, $M_i$s and $M'$. The Yukawa couplings for the regular fermions are evaluated from their masses. The Yukawa coupling ($\lambda_i$) for the leptoquarks are assumed to be unified at the GUT scale and its value at that scale is taken to be 1. At the GMSB scale $\lambda_1 = 0.3$, $\lambda_2 = 0.7$, $\lambda_3 = 0.8$. We have assumed the masses $M_i$ (where $i=\bar{Ld},d\bar{c},d\bar{c},\nu_e$) to be the same at the GMSB scale. We vary the common mass $M$ and $M'$ in such a way so as to get the leptoquark mass around 200-220 GeV. This fixes the diquark and dilepton masses also. From the table 1 it is easy to see that the leptoquark mass $\sim 200 – 220$ GeV can be obtained over a wide range of parameter space. In that parameter space the diquarks are much heavier than the leptoquarks and the leptoquarkinos are also heavier than the leptoquarks. The dileptons can be lighter or heavier. We can see from the table that the mass states of $\phi_{\bar{Ld}}$ are well seperated due to the large B term. This is also true for the diquarks but not for the dileptons where $B$ is small. If we take the $M_i$’s in the ratio of the Yukawa coupling ($\lambda_i$’s), the mass spectrum of the scalars would remain unchanged, only the dileptino mass will reduce to almost half the value showed in the tables.

Let us discuss the signals of the new fields in different colliders. In Tevatron the diquarks will be produced pairwise through s channel gluon exchange just like the squarks. Each diquark decays into a pair of jets. So we have 4 jets in the final state. The dileptons
can be seen at the Tevatron through Drell-Yan production with subsequent decay into 2 leptons plus missing energy. Similar signals can be produced by the charged Higgs pair, W pair or the selectron pair. Leptoquark pair decays into 2jet+2lepton. Beside Tevatron these particles can be pair produced in the electron-positron collider. One can also produce leptoquark [13] and dilepton singly in eγ collider through a t channel exchange. The final state will be l+jet in the case of leptoquark and a 2 leptons plus missing energy (one lepton has to be other than electron, since the dileptons are connected to two leptons of different generations) in the case of dilepton. The fermionic partners of these fields: leptoquarkino, dileptino or diquarkino have interesting signatures in the colliders. The diquarkino will decay into a quark and a squark. The squark will eventually decay into a quark and neutralino (quark gluino channel is not suitable since gluino mass is large in GMSB models). The neutralino will give rise to a photon and a gravitino. When diquarkinos are pair produced the final state will have 4 j+2 hard photons +missing energy. In the case of stau being the NLSP the diquarkino will decay into 4j+4τ lepton +missing energy, since each neutralino will decay 100% of the time into 2τ +plus missing energy. The $P_T$ distribution of those 4 $\tau$s will be different and two of them will have very high $P_T$. This signature is very hard to miss. The production of these diquarkinos will be similar to that of top quark. The diquarkino mass of about 370 GeV will approximately give rise to one event ($4jets+4\tau or 2\gamma$ plus missing energy) in Tevatron with a luminosity of 110 $pb^{-1}$. So far 6 events having 4 jets plus missing energy (missing energy $> 60$ GeV have been observed [14], but they are claimed to be consistent with the SM precesses plus detector induced background. The dileptino will decay to a lepton and a sneutrino or neutrino and slepton and sneutrino or slepton will decay into neutrino or lepton and a neutralino, which will give rise to final states lepton+missingenergy (slepton mass is less than the neutralino mass) when stau is lightest or the lepton+$\gamma+$ missing energy when neutralino is the lightest in the gauge mediated models. Consequently when they are produced in Tevatron or electron positron collider the dileptino pair can give rise to $l^+l^- + 2\gamma +missing energy$ signal. One such event 9where both the leptons are electrons) was claimed to be observed recently [17]. The same signal can be
produced by the selectrons also. In an $e\gamma$ collider the dileptino can be singly produced in the association of sneutrino through t-channel exchange of dileptino. Sneutrino decay gives rise to $\gamma$ plus missing energy (neutralino is NLSP) or $4\tau$ plus missing energy (lighter stau is the NLSP) in the final state. The leptoquarkino decays into a spositron (spositron decays into a positron and a neutralino with $\chi_0 \to \gamma\tilde{G}$) and d quark (or squark and an electron, but the squark masses are large in these models) with the final state in the leptoquarkino pair production process has $e^+e^-\gamma\gamma jj$ plus missing energy without any SM background. If lighter stau is the NLSP and neutralino is the NNLSP, the final state in the leptoquarkino pair production process has $e^+e^-2\tau^+2\tau^-jj$ plus missing energy (since in this case $\chi_0 \to 4\tau$ plus missing energy). Out of these six leptons in the final state, one $\tau$ pair (produced from the decay of stau) has much higher $P_T$ than the other leptons. So far each CDF [18] and D0 [19] have reported one event in the $e^+e^-jj$ plus missing energy channel. If we apply that bound we get leptoquarkino mass has to be greater than 345 GeV, since the pair production crosssection is around 0.04 pb and $e^+e^-$ detection efficiency is 0.2 assuming the leptoquarkino branching ratio to be 1. If however leptoquarkino branching ratio is 1/2 the bound becomes 290 GeV. One could also look for the signals of leptoquarkino production in $e^+\gamma$ colliders. The leptoquarkino can be singly produced in such a collider. In the gauge mediated SUSY breaking scenario, the final state has either a hard photon or $\tau^+\tau^-$ along with electron +jets+missing energy. In all the above cases the fermion component of the new multiplet can be distinguished from the spin 0 component by hard photon or excess $\tau$s and the missing energy.

If we had used the leptoquarks in SU(5)×U(1) unifying group, we would have 3 leptoquarks and a dilepton as discussed before. In this case the above analysis would be unchanged. However all the leptoquarks will have almost the same soft symmetry breaking mass at the GMSB scale (since all of them have color quantum number) and their masses at the weak scale also will be very close (D term can not produce much of a splitting). This means that not only HERA, but also the Tevatron will see these 3 leptoquarks within a small mass range. The dilepton ($\nu^c e^c$) can be produced at FERMILAB through Drell-Yan mech-
anism and has an interesting signature \((e^+e^-e^+e^-jjjj)\) arising from the decay of dilepton into \(e\nu_R\), followed by \(\nu_R \rightarrow eW^- \rightarrow ejj\).

In the supergravity motivated theory the soft masses are introduced at the GUT scale. We assume the squark, Higgs and slepton the new \(f\) multiplet all have same soft mass \(m_0\). The gaugino masses are also unified to a common mass \(m_{1/2}\). The other parameters are the bilinear coefficient of the \(f\bar{f}\) and the \(S_1S_1\) term in the superpotential and the coefficient of the same bilinear terms in potential. Unlike the gauge mediated model the bilinear coefficient need not be 0 to start with. In the case of supergravity motivated theory the signals are different from the GMSB models signals. Since neutralino is the LSP, there is no hard photon or high \(P_T\) \(\tau\)s in the final state. For example, the diquarkino would decay into quark and squark and the squark will decays into a quark and missing energy. The final state will be 4jets+missing energy when the diquarkino is pair produced. The leptoquarkino pair will give rise to a \(jjl^+l^-\) plus missing energy and the dileptino pair will give rise to \(l^+l^-\) plus missing. The missing energy however would distinguish the fermion signal from the boson one.

In Table 2 we show the masses of the new fields as well as the masses of the squarkss, sleptons, neutralinos, charginos and gluino. The input parameters at the GUT scale are the universal scalar mass \(m_0\), universal gaugino mass \(m_{1/2}\), \(M_i\)’s, \(M'\)’s, \(\tan\beta\), \(A\)’s and \(B\)’s. Again for simplicity we have assumed the masses \(M_i\) to be same at the GUT scale. We also have assumed that other than the \(B\) associated with the \(f\) and \(\bar{f}\), all the \(B\)’s are 0 at the unification scale. We also assume that all the \(A\)’s are 0 at the GUT scale. From the table 2 it is easy to see that the leptoquark mass \(\sim 200 \text{–} 220 \text{ GeV}\) can be obtained in wide range of parameter space. In that parameter space the diquarks are much heavier than the leptoquarks and the leptoquarkinos are also heavier than the leptoquarks. The dileptons can be lighter or heavier. The lighter combination of \(\phi_{Ld^c}\) and \(\phi_{\bar{L}d^c}\) is again much lighter than the heavier combination

So far we have considered the case with just one type of leptoquark i.e \(\phi_{Ld^c}\). If the charge current anomaly is also established, which is not at all clear from the present data,
we shall need an additional representation like $\mathbf{45}$ which has $Lu^c$ type of leptoquarks. These leptoquarks will then mix because of symmetry breaking with the $Ld^c$ type of leptoquarks and using the technique showed in the ref. [20] one can get a charge current excess. If charged current events do hold up, such additional multiplets will need to be considered.

In conclusion we have used leptoquark in the context of gauge unification and have discussed the mass spectrum and the signatures of the additional fields needed to maintain the unification. We have showed that the fermionic partner of the leptoquark will be heavier than the scalar part. We have also showed that one combination of the leptoquark field and conjugate field (we need to add in order to cancel the anomaly) is lighter than the other combination, even though the soft mass generation mechanism is same for both types of fields. The heavier combination is still out of reach of Tevatron.

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TABLE CAPTIONS

Table 1: Mass spectrum for the new fields (diquarks, leptoquarks and dileptons), stop and sbottom squarks ($m_{\tilde{t}}, m_{\tilde{b}}$), stau lepton ($m_{\tilde{\tau}}$), chargino ($\chi^\pm$), lightest neutralino ($m_{\chi^0}$), $\mu$, gluino mass ($m_{\tilde{g}}$) are shown in the gauge mediated supersymmetry breaking model. The scalar component of the new fields are written as $m_i$ and the fermionic components are written as $M_i$. The two entries for the scalars give the lighter and the heavier mass eigenstates.

Table 2: Same mass spectrum as in Table 1 is shown for the supergravity scenario.

FIGURE CAPTIONS

Figure 1: The evolution of the coupling constants are shown in presence of the new fields using two loop RGEs.
Table 1

| Scenario1 | Scenario2 | Scenario3 | Scenario4 | Scenario5 |
|-----------|-----------|-----------|-----------|-----------|
| masses (GeV) | $\Lambda = 60$ TeV, $n=1, M = 4\Lambda$, $\tan\beta = 3$ | $\Lambda = 60$ TeV, $n=1, M = 4\Lambda$, $\tan\beta = 3$ | $\Lambda = 60$ TeV, $n=1, M = 10^2\Lambda$, $\tan\beta = 3$ | $\Lambda = 60$ TeV, $n=1, M = 10^3\Lambda$, $\tan\beta = 3$ |
| $m_{\phi_{d}\bar{d}c}$ | 371,580 | 372,581 | 346,630 | 307,596 | 271,579 |
| $M_{d\bar{d}c}$ | 388 | 388 | 427 | 418 | 444 |
| $m_{\phi_{e\nu}}$ | 152,174 | 151,177 | 207,225 | 244,259 | 270,287 |
| $M_{e\nu}$ | 305 | 305 | 309 | 309 | 311 |
| $m_{\phi_{d\bar{d}c}}$ | 210,500 | 210,510 | 210,592 | 210,570 | 203,570 |
| $m_{\phi_{e\nu}}$ | 210,500 | 210,510 | 210,592 | 210,570 | 203,570 |
| $M_{Ld\bar{d}c}$ | 399 | 400 | 444 | 434 | 463 |
| $m_{\chi^0}$ | 78 | 80 | 77 | 75 | 72 |
| $m_{\chi^\pm}$ | 143,403 | 148,347 | 144,446 | 135,346 | 113,274 |
| $m_{\tilde{g}}$ | 111,222 | 54,223 | 119,230 | 89,171 | 65 |
| $m_{\tilde{t}}$ | 614,719 | 633,705 | 542,678 | 441,564 | 373,475 |
| $m_{\tilde{b}}$ | 685,726 | 653,700 | 638,655 | 509,547 | 414,435 |
| $m_{\tilde{g}}$ | 538 | 538 | 534 | 535 | 447 |
| $\mu$ | -379 | -322 | -426 | -315 | -238 |
Table 2

|       | Scenario1 | Scenario2 | Scenario3 | Scenario4 | Scenario5 |
|-------|-----------|-----------|-----------|-----------|-----------|
| masses (GeV) |           |           |           |           |           |
| $m_0 = 250\text{GeV}$, | $m_0 = 265\text{GeV}$, | $m_0 = 280\text{GeV}$, | $m_0 = 320\text{GeV}$, | $m_0 = 230\text{GeV}$, |
| $m_{1/2} = 250\text{GeV}$, | $m_{1/2} = 200\text{GeV}$, | $m_{1/2} = 180\text{GeV}$, | $m_{1/2} = 160\text{GeV}$, | $m_{1/2} = 240\text{GeV}$, |
| $\tan\beta = 3$ | $\tan\beta = 5$ | $\tan\beta = 30$ | $\tan\beta = 10$ | $\tan\beta = 10$ |
| $m_{\phi_{e,d,c}}$ | 350,789 | 321,651 | 304,605 | 302,562 | 333,727 |
| $M_{\phi_{e,d,c}}$ | 455 | 401 | 401 | 402 | 566 |
| $m_{\phi_{e\nu}}$ | 183,306 | 202,312 | 216,324 | 247,348 | 119,261 |
| $M_{e\nu}$ | 204 | 180 | 180 | 180 | 202 |
| $m_{\phi_{\nu,e,d,c}}$ | 212,841 | 212,692 | 205,642 | 204,593 | 207,772 |
| $M_{L_{e,d,c}}$ | 512 | 401 | 451 | 452 | 565 |
| $m_{\chi^0}$ | 100 | 80 | 72 | 64 | 97 |
| $m_{\chi^{\pm}}$ | 191,502 | 148,389 | 136,338 | 322,345 | 185,428 |
| $m_T$ | 269,311 | 277,305 | 248,316 | 89,171 | 244,293 |
| $m_{\tilde{b}}$ | 443,671 | 372,567 | 354,513 | 329,501 | 446,640 |
| $m_{\tilde{g}}$ | 596,650 | 498,548 | 429,498 | 438,498 | 570,619 |
| $\mu$ | -483 | -477 | -314 | -301 | -407 |
